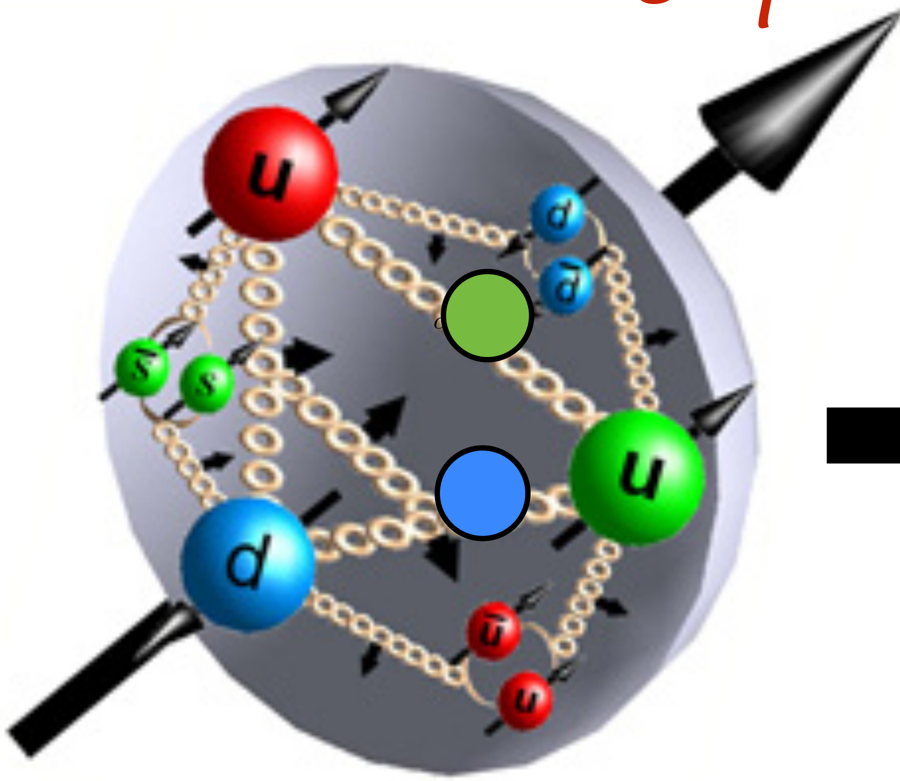
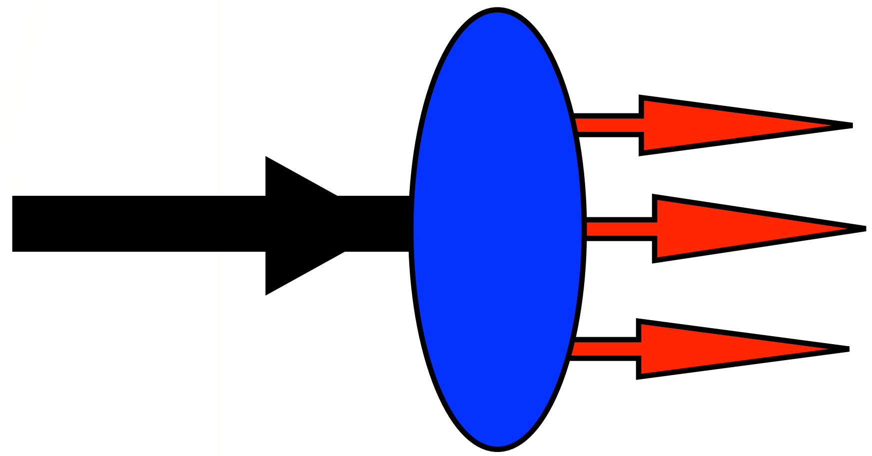
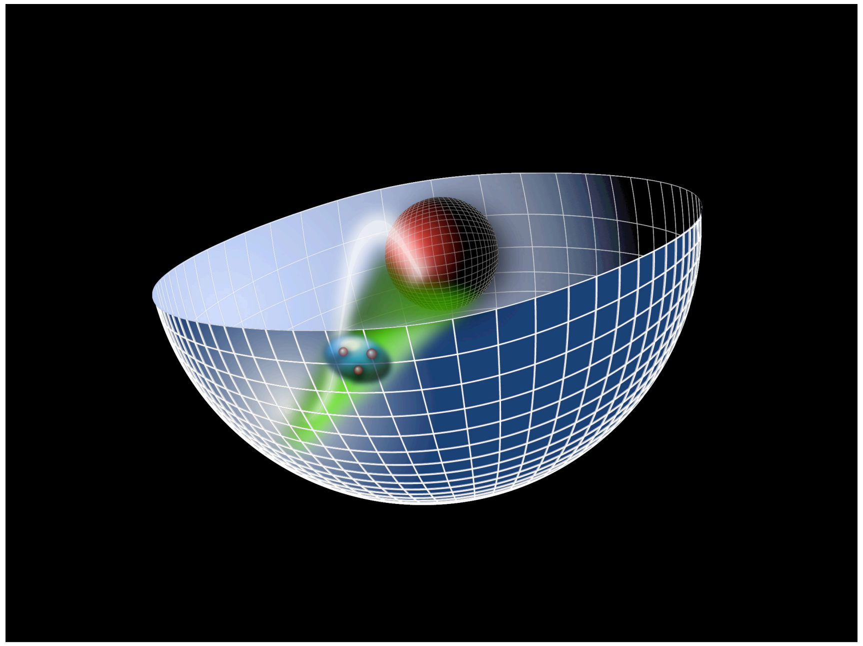
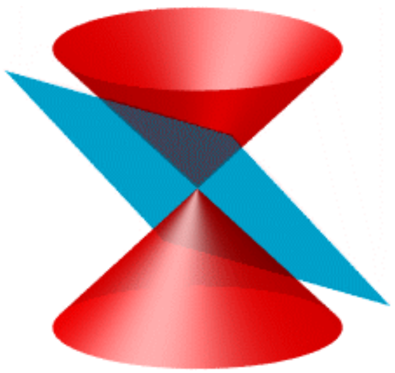
Light-Front Holographic QCD, Color Confinement, and Supersymmetric Features of QCD









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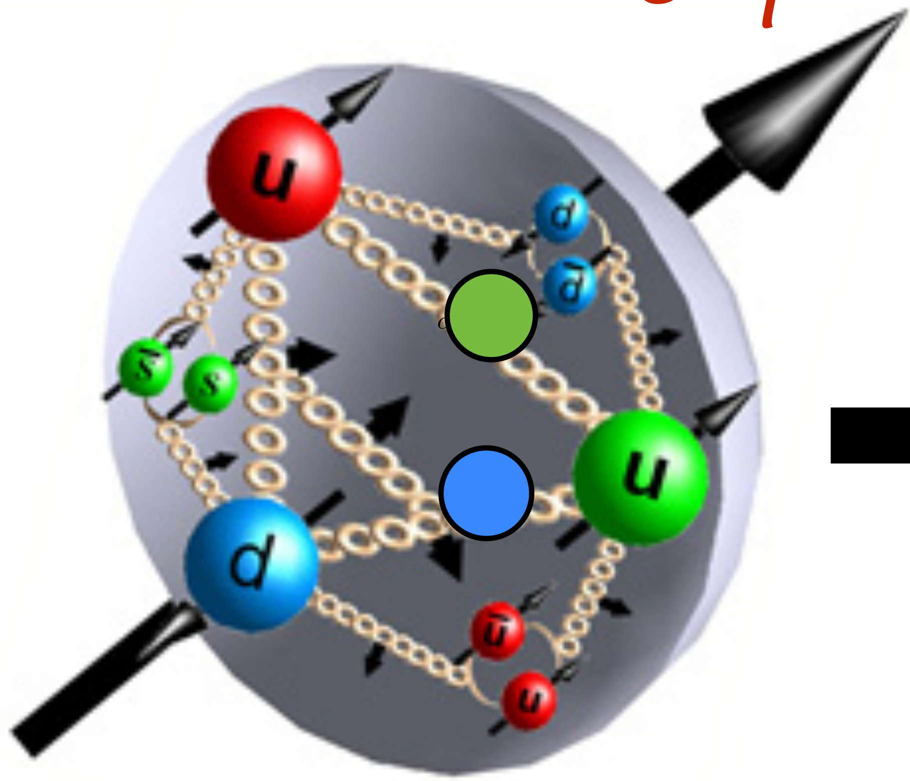

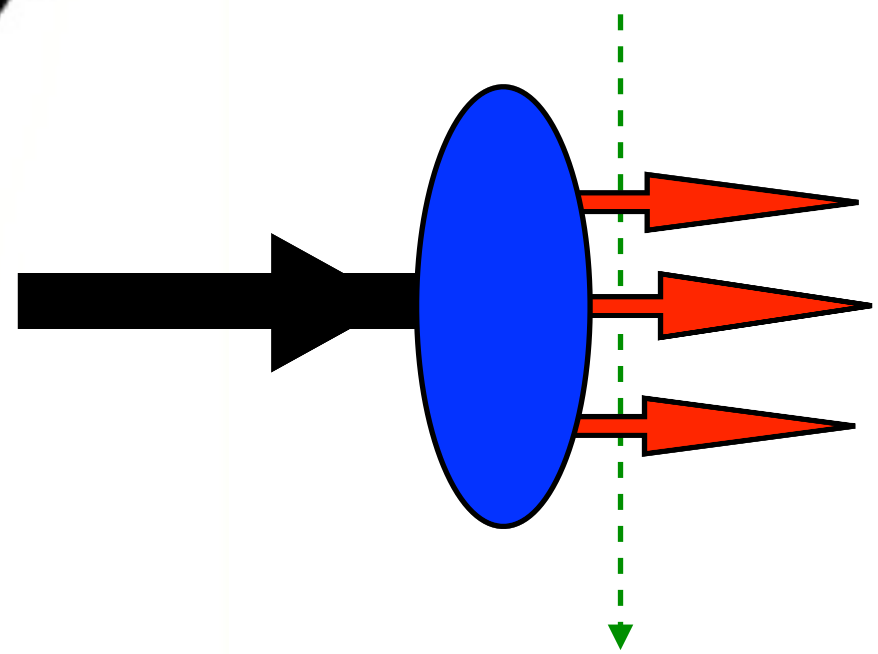

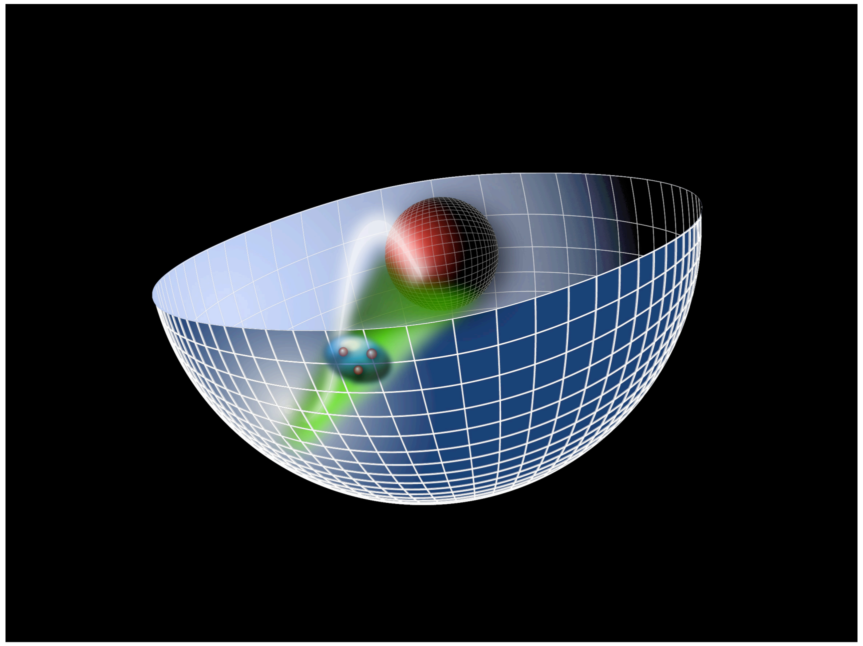

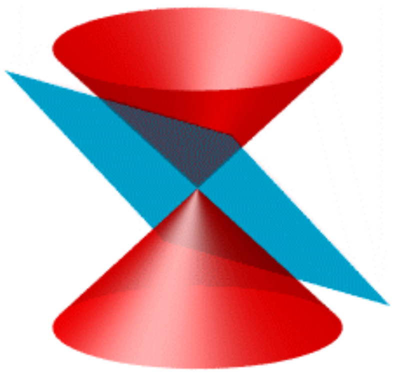

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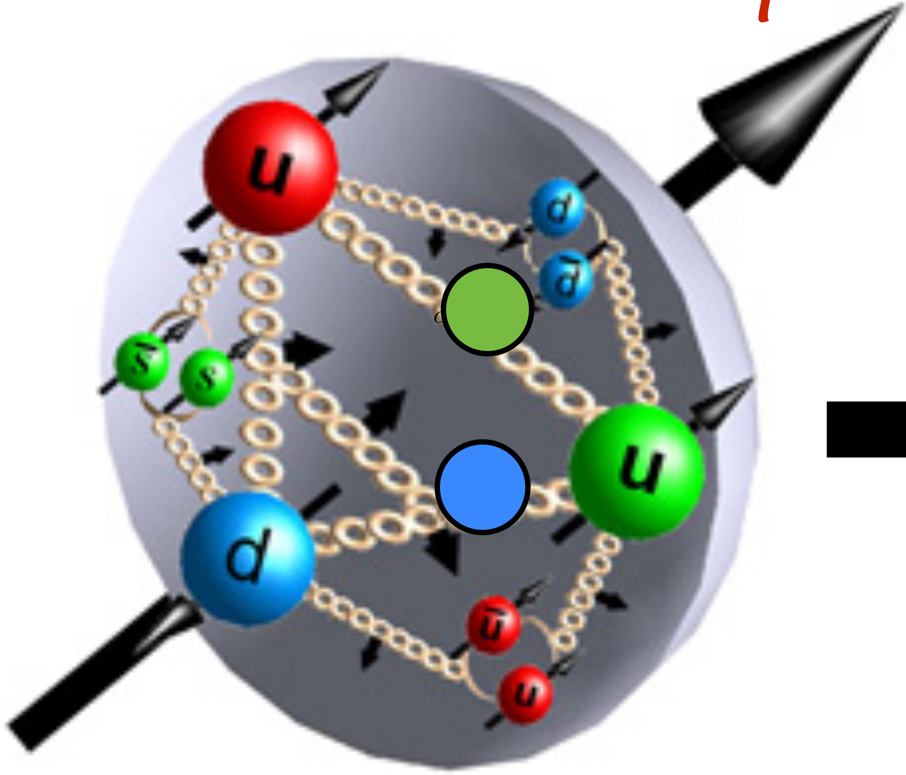

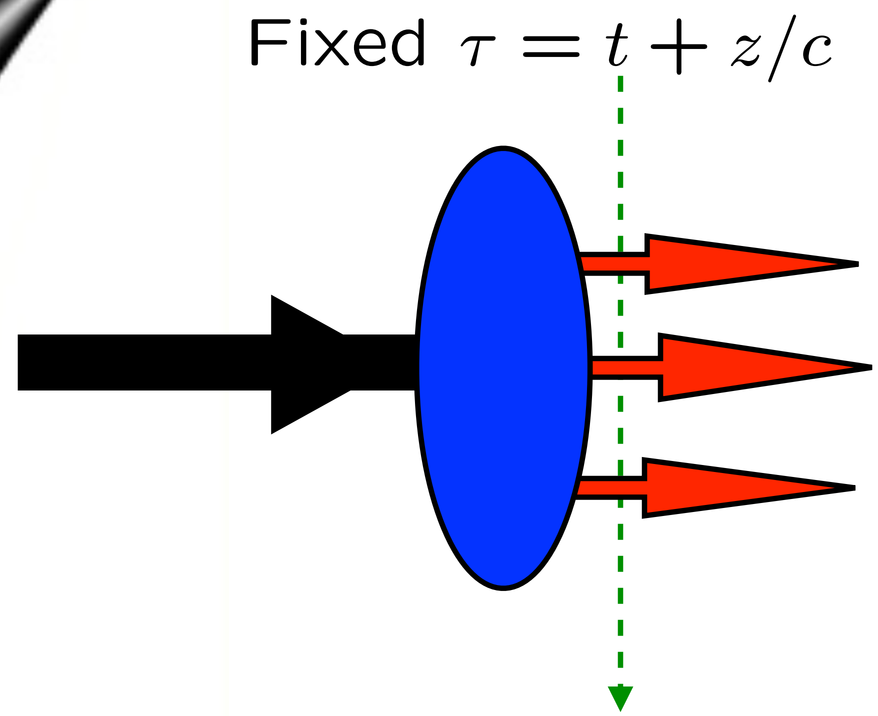

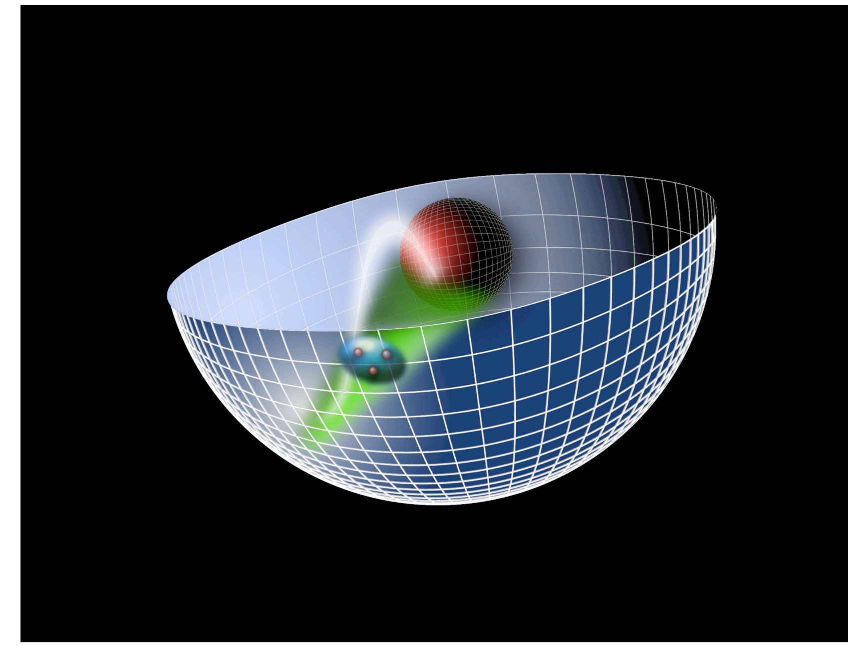

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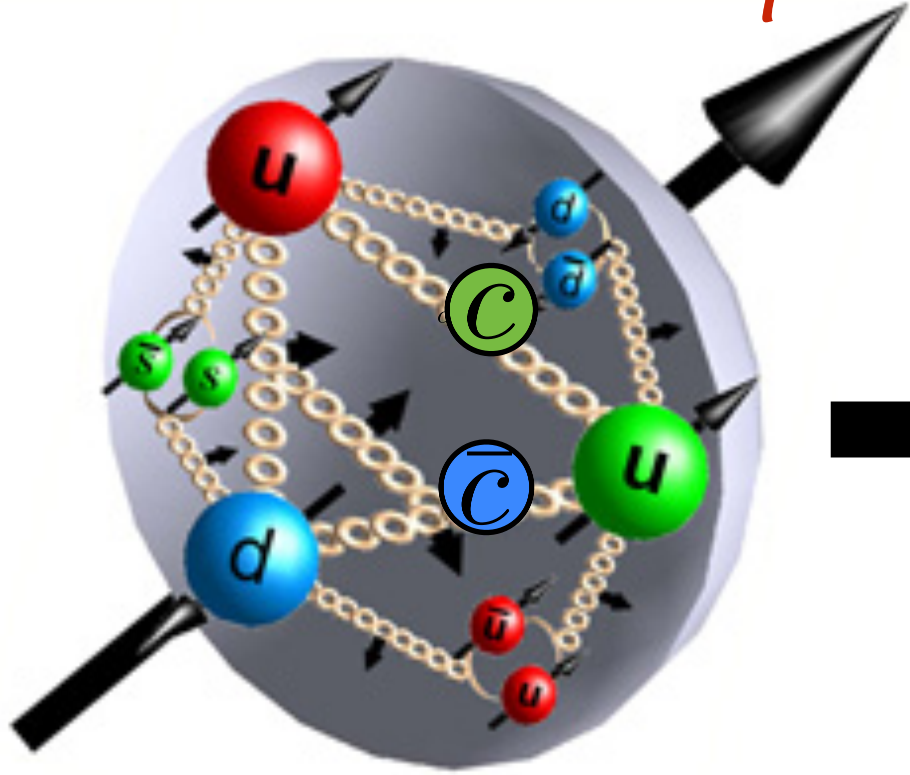

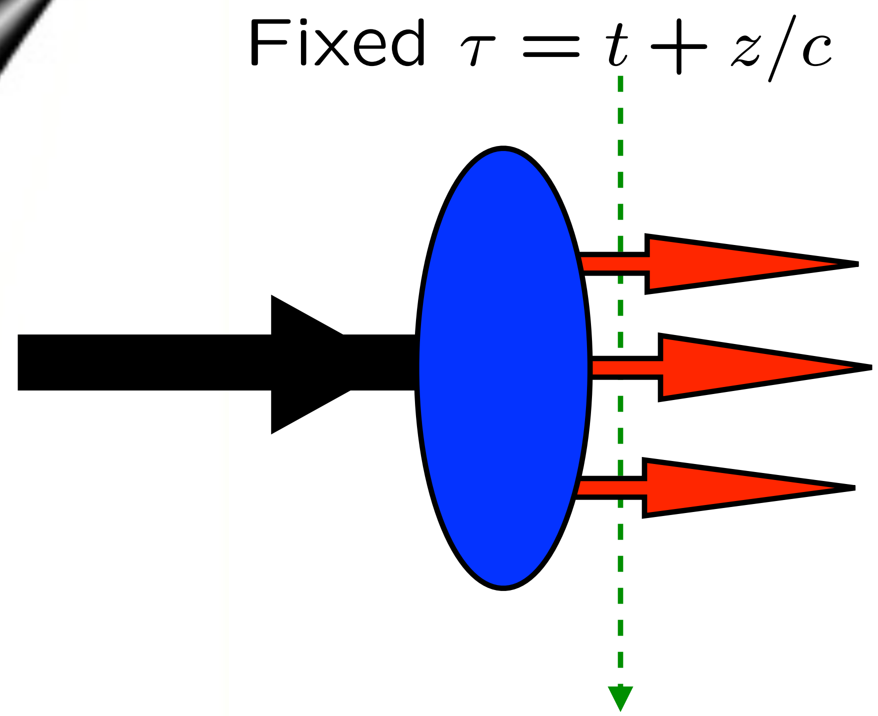

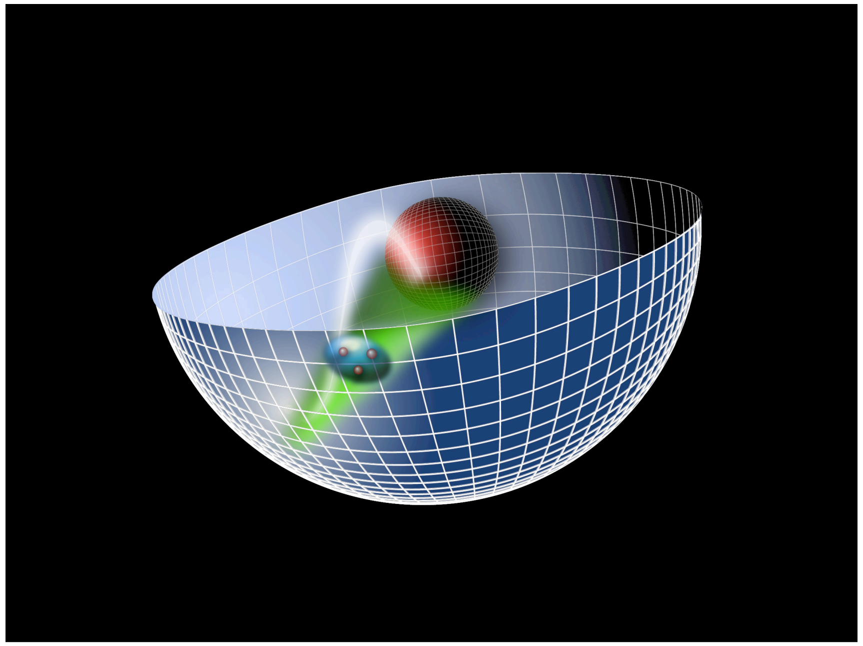

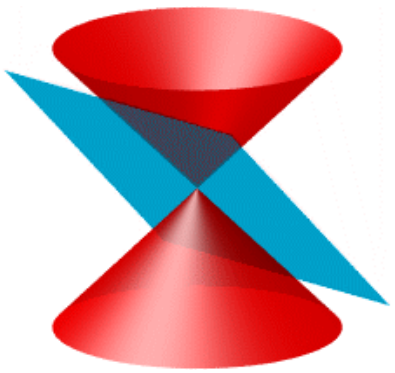

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DIE LUFT DER FREIHEIT WEHT
1891

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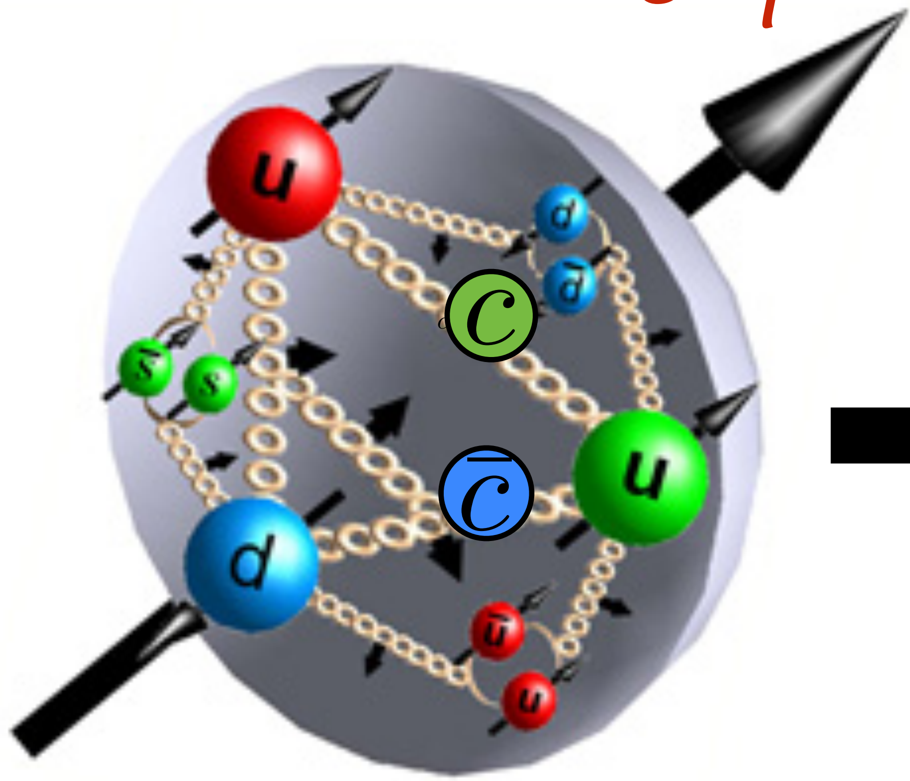

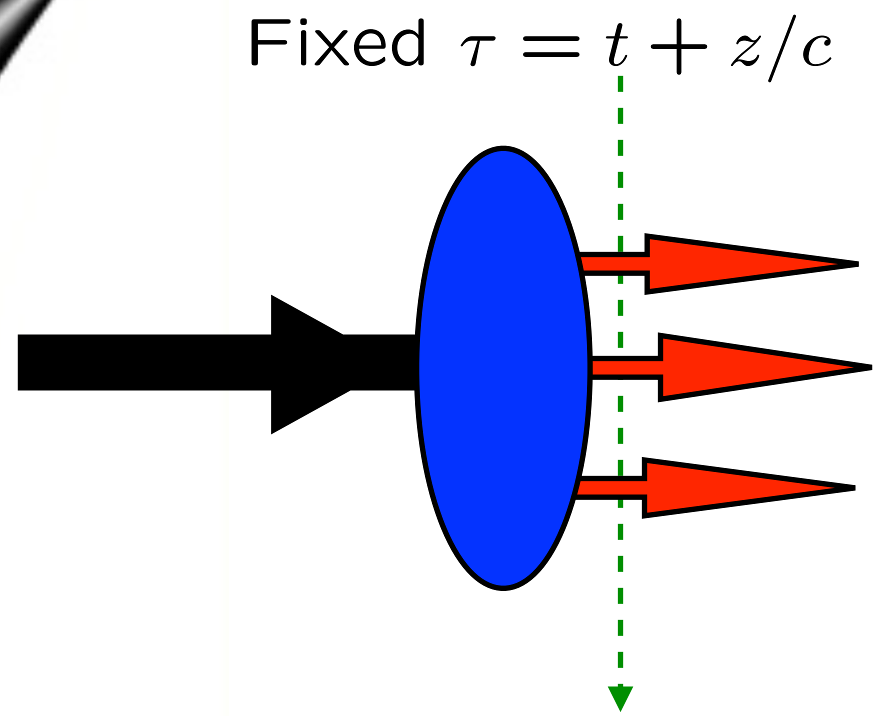

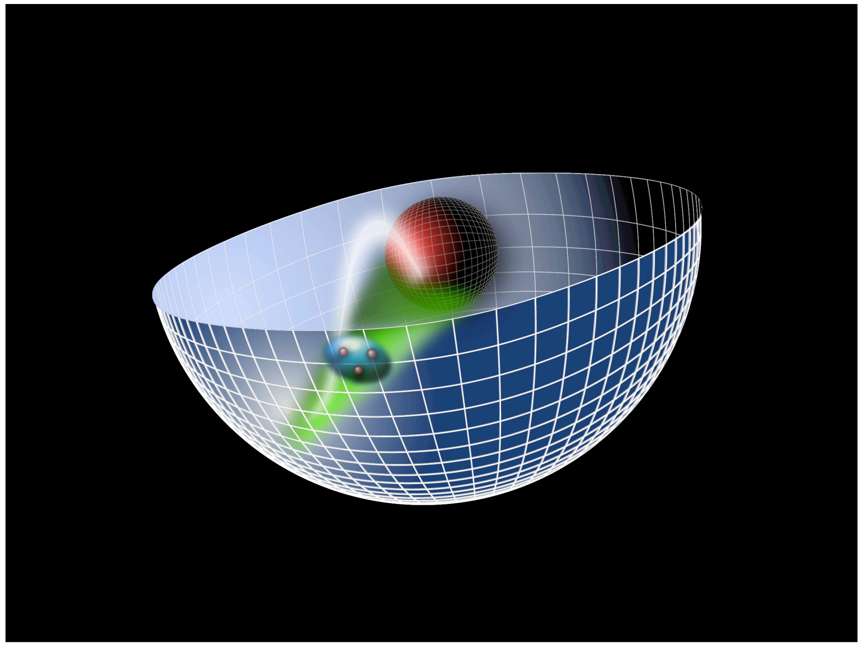

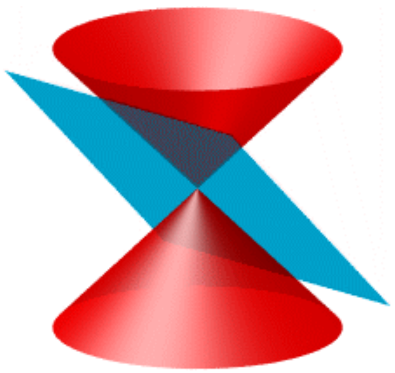

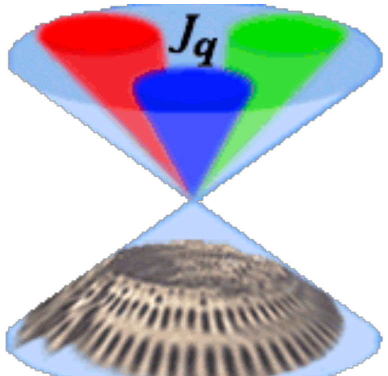

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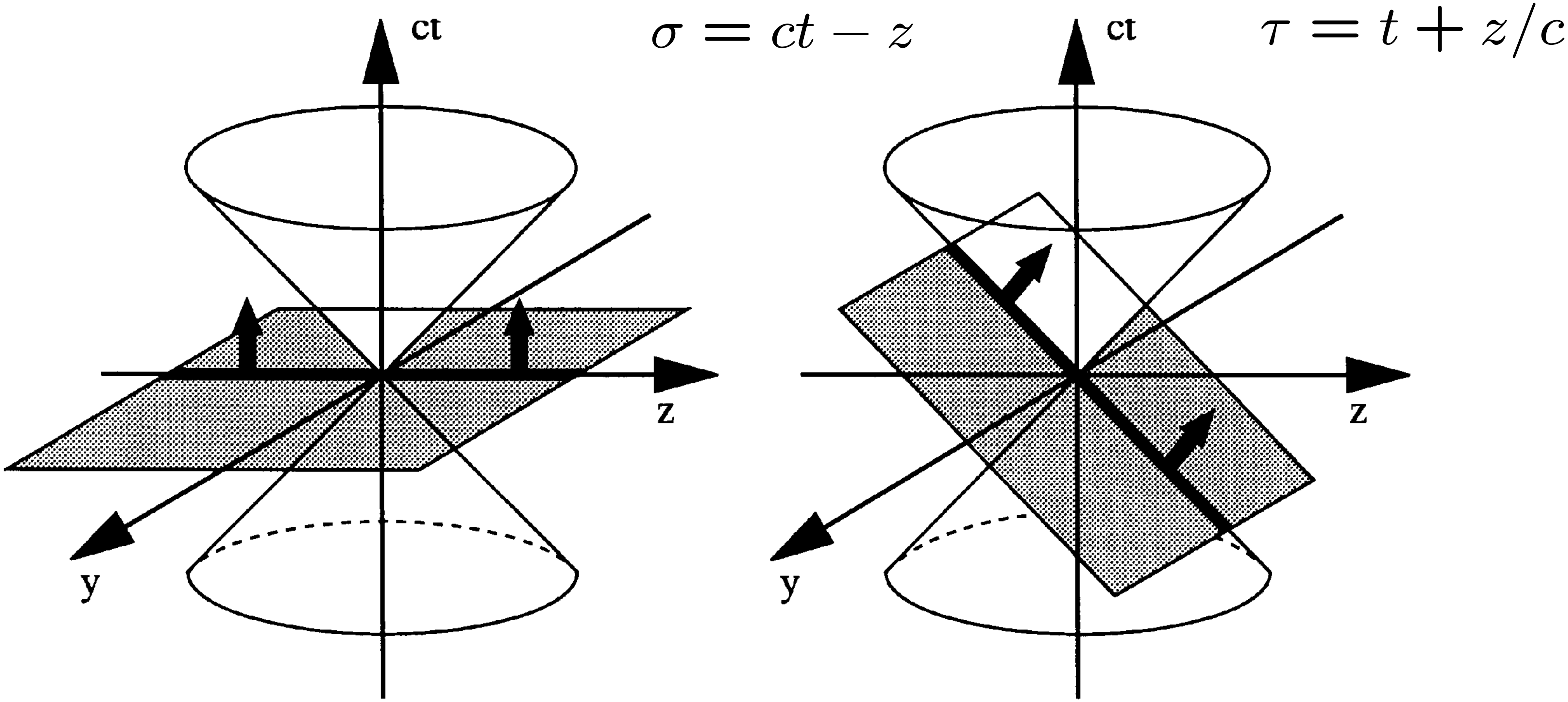
Dirac's Amazing Idea:
The "Front Form"



Instant Form **Front Form**

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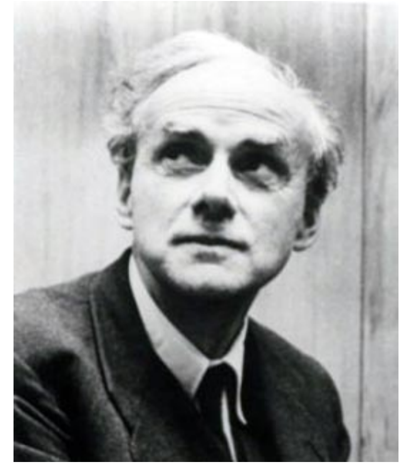
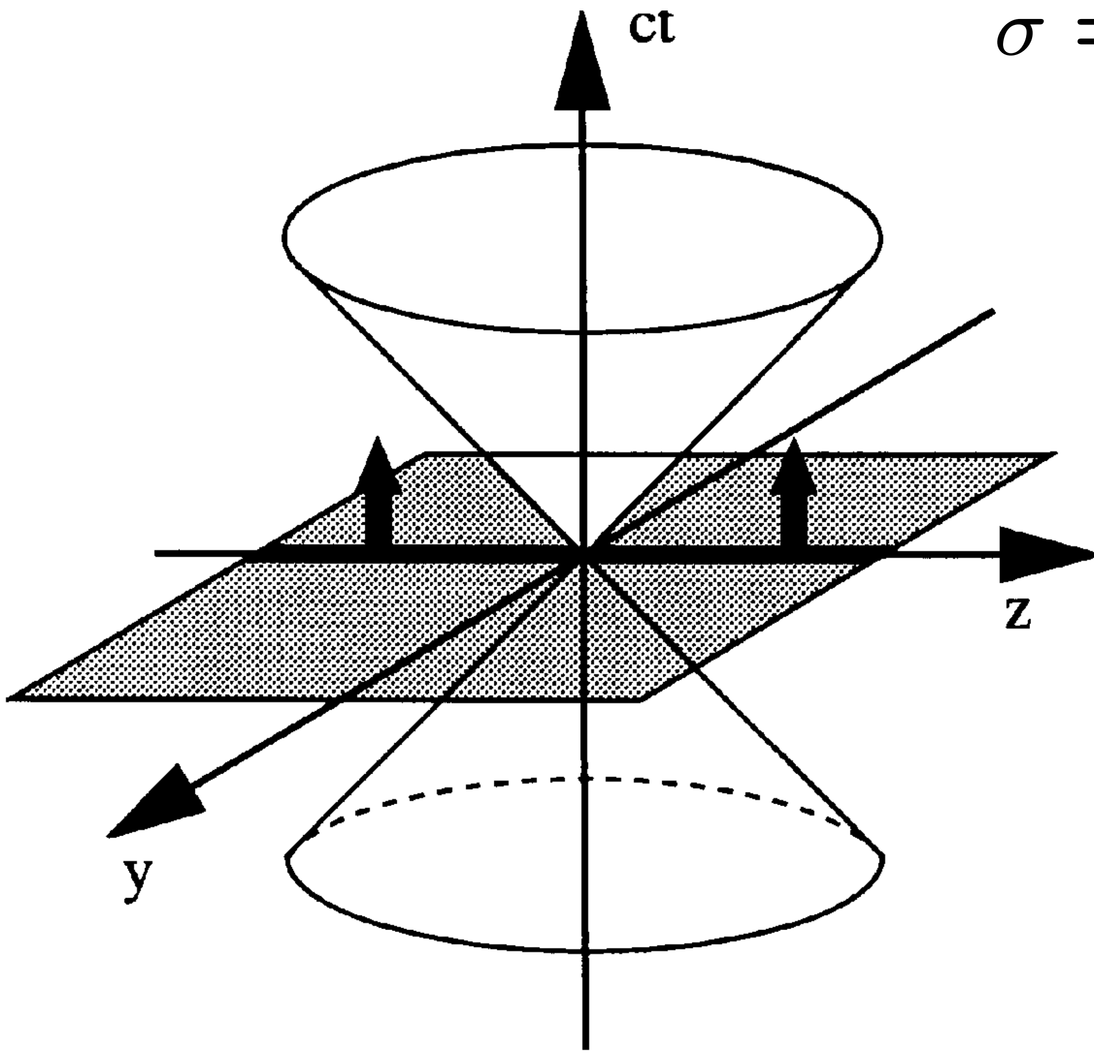


P.A.M Dirac, Rev. Mod. Phys. 21, 392 (1949)

$$\sigma = ct - z \qquad \tau = t + z/c$$



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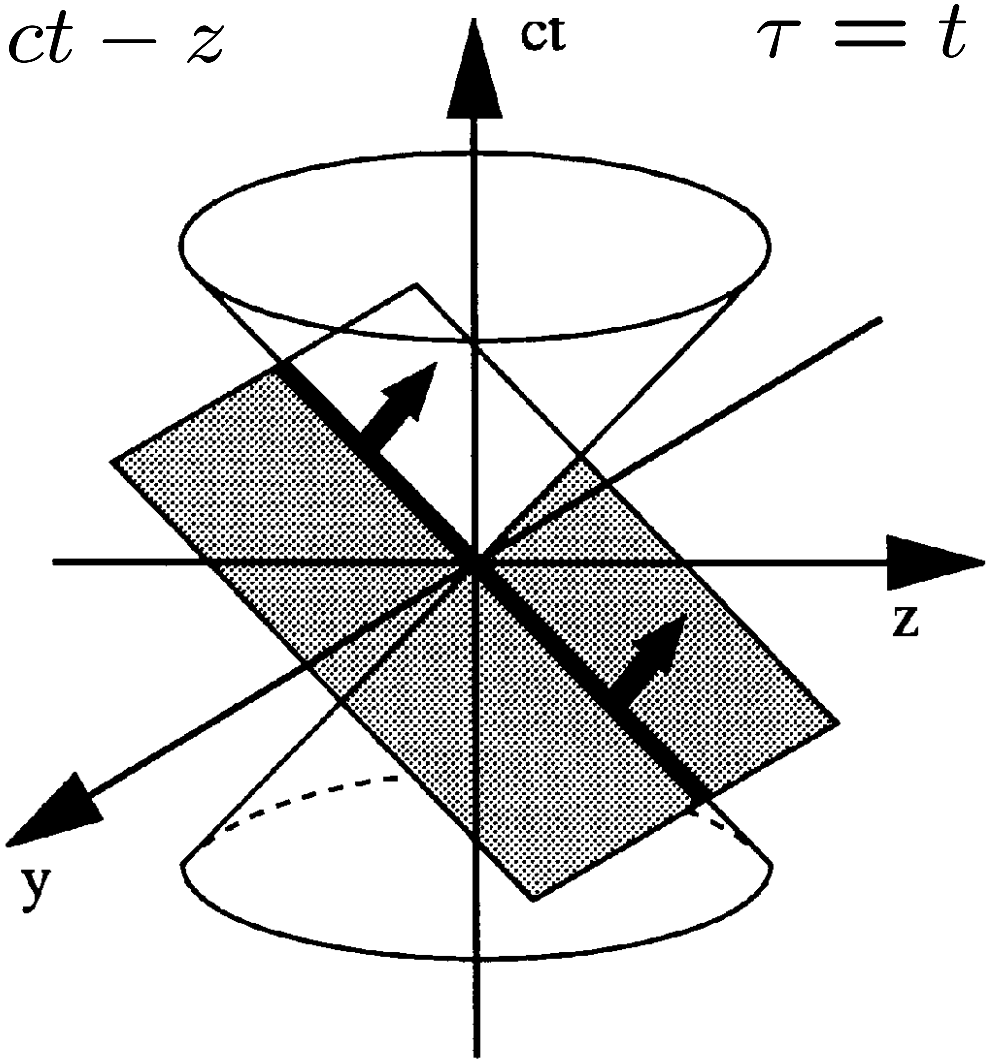

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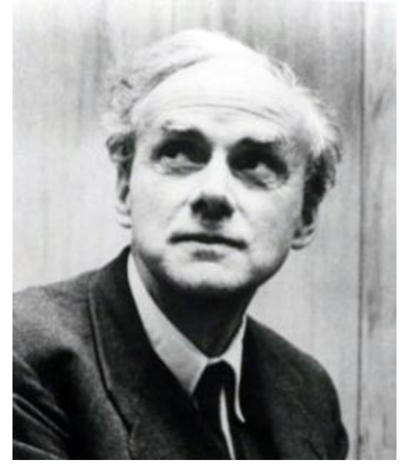

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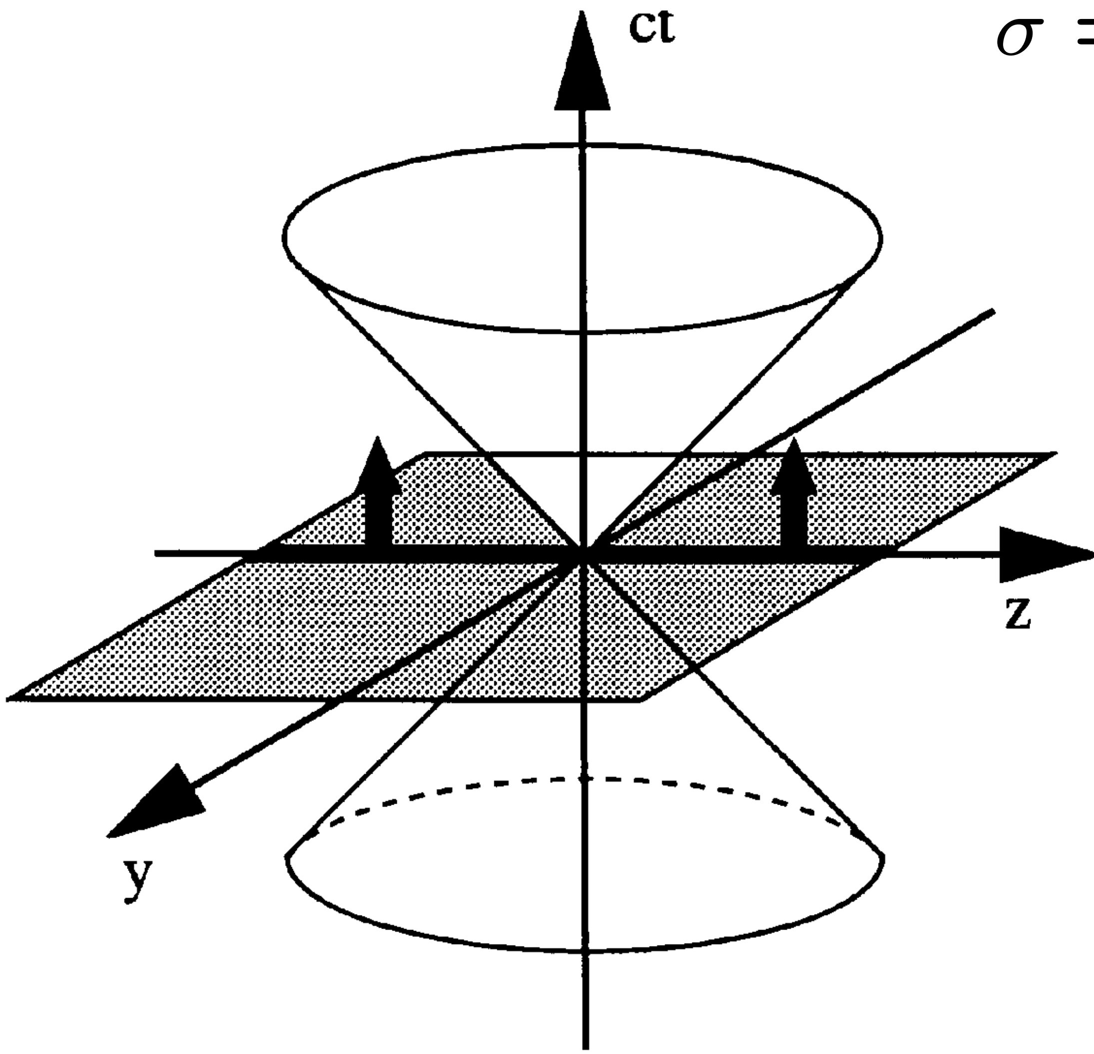
Evolve in ordinary time

$\sigma = ct - z$

$\tau = t + z/c$



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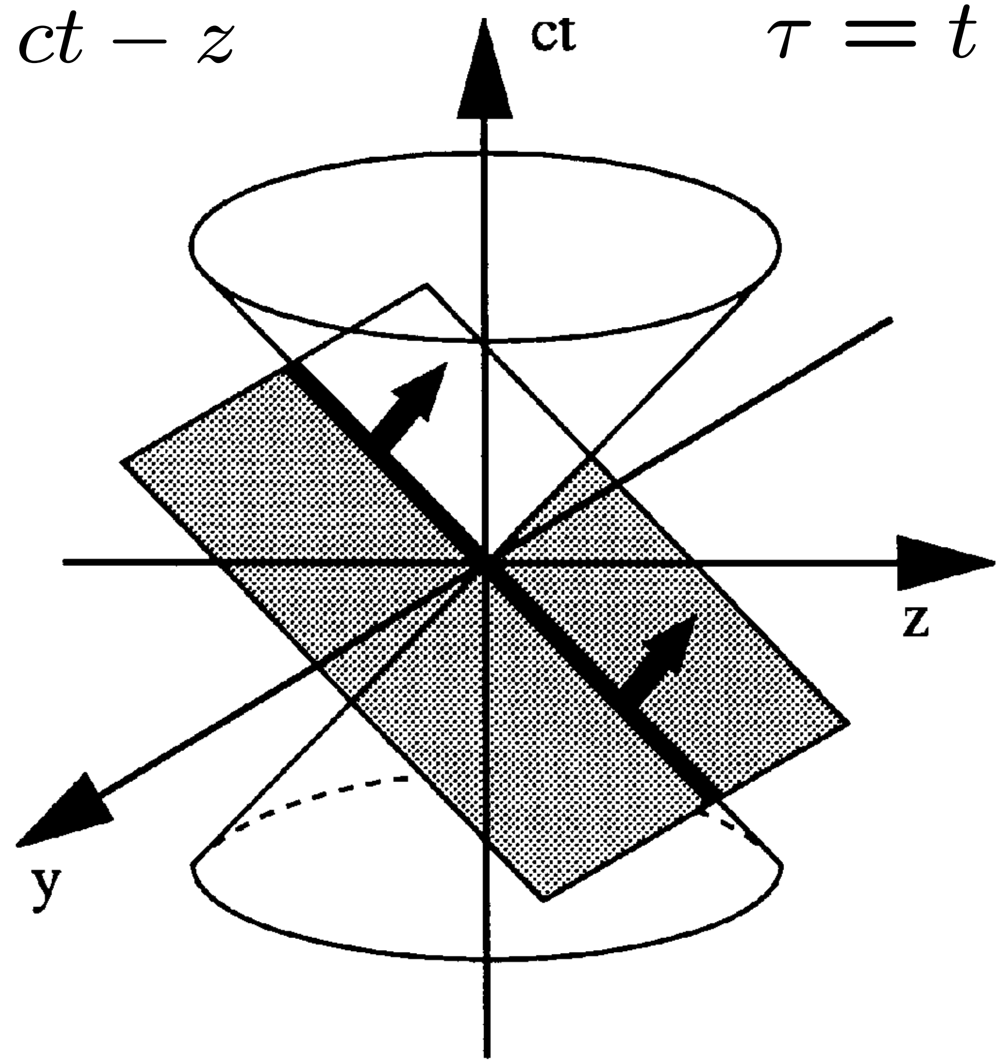

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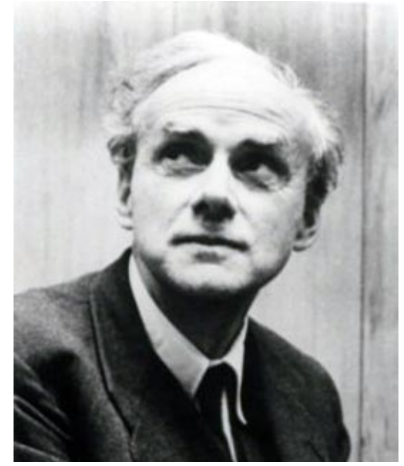

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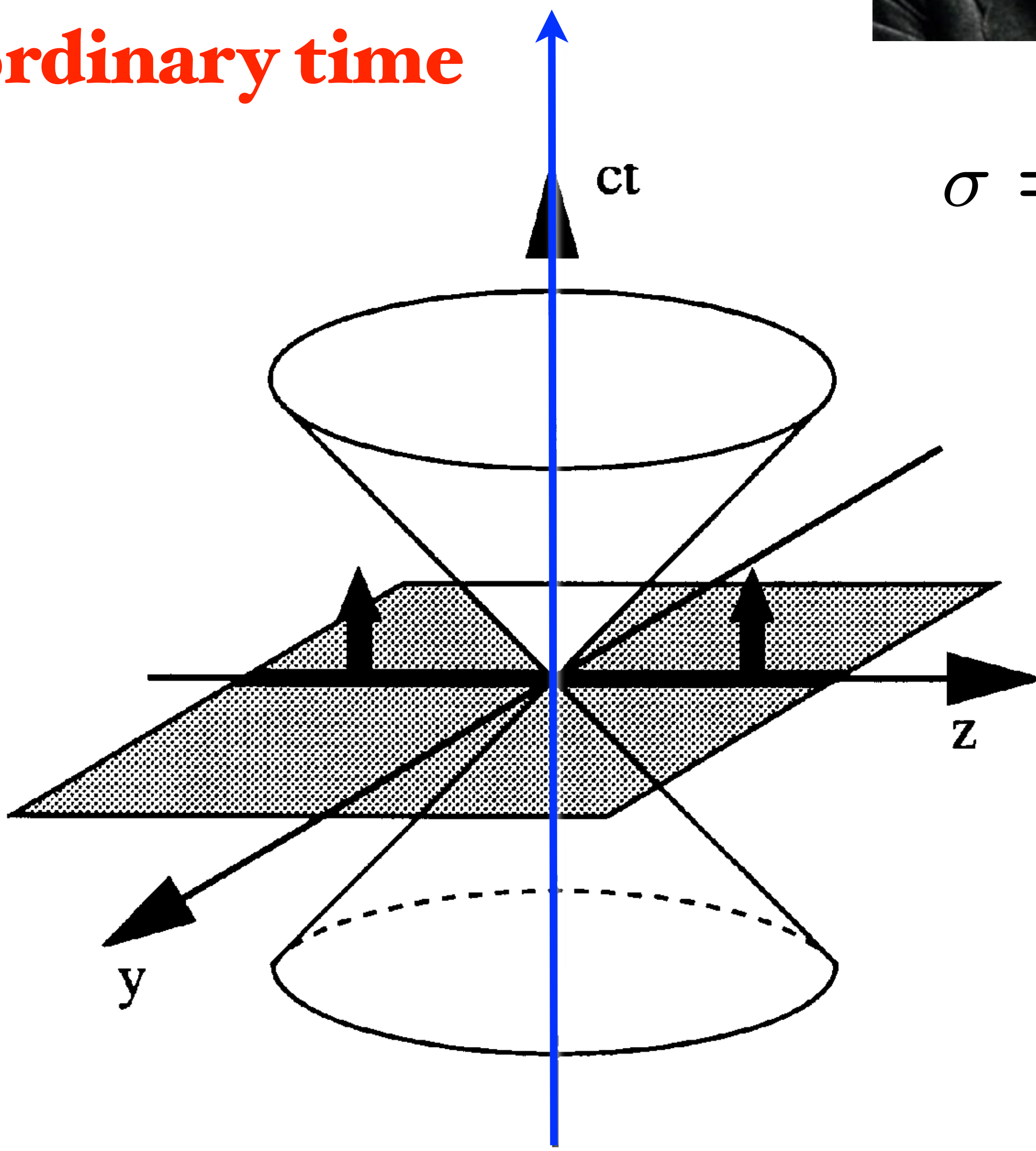

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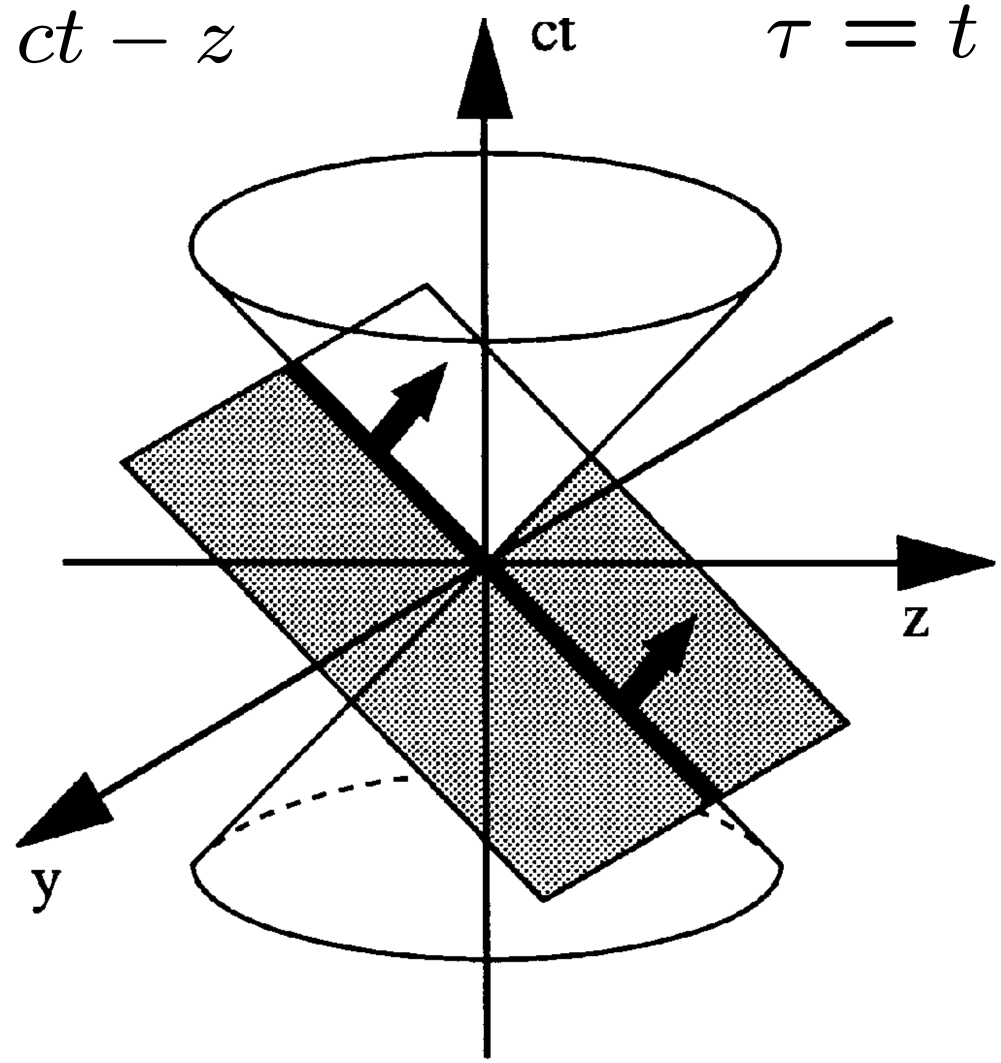

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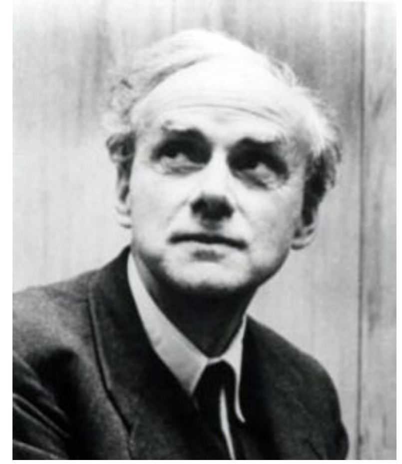

P.A.M Dirac, Rev. Mod. Phys. 21, 392 (1949)

Evolve in ordinary time

Evolve in light-front time!

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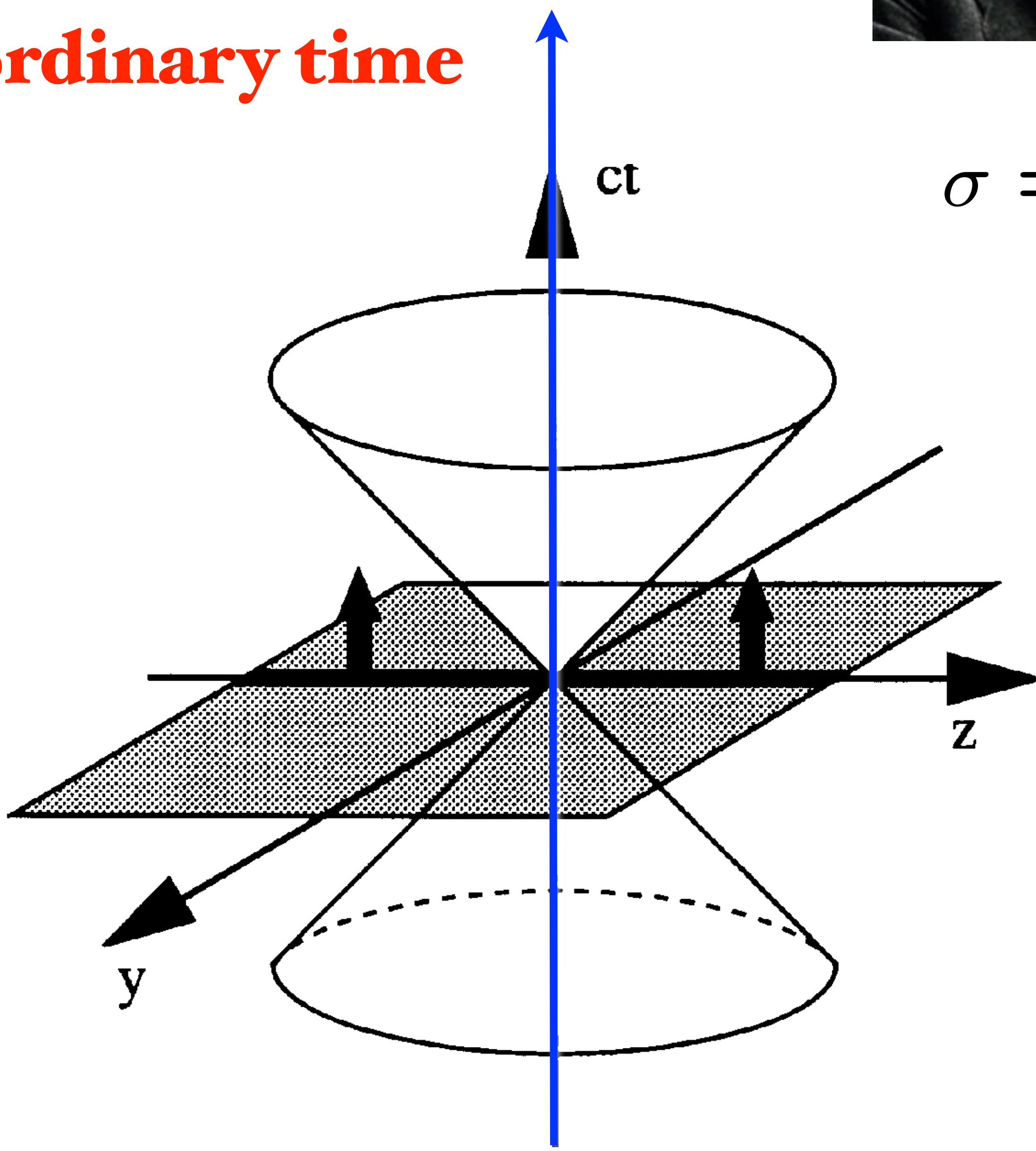

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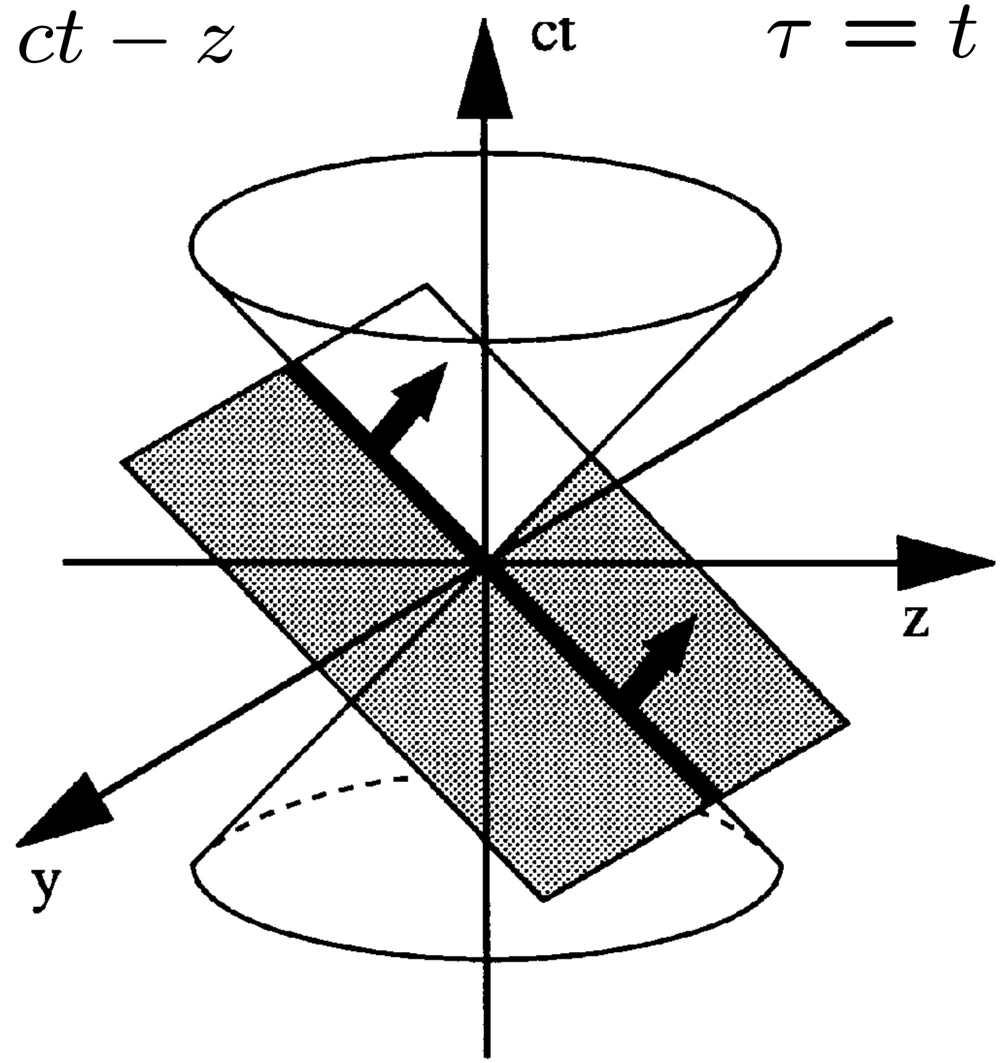

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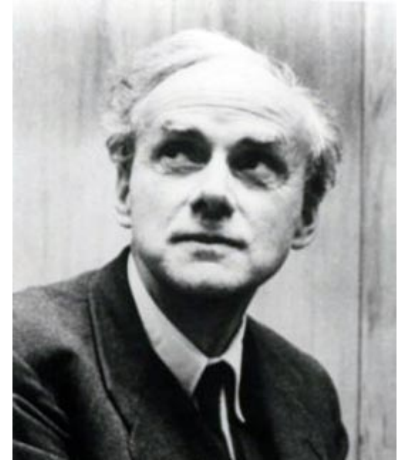

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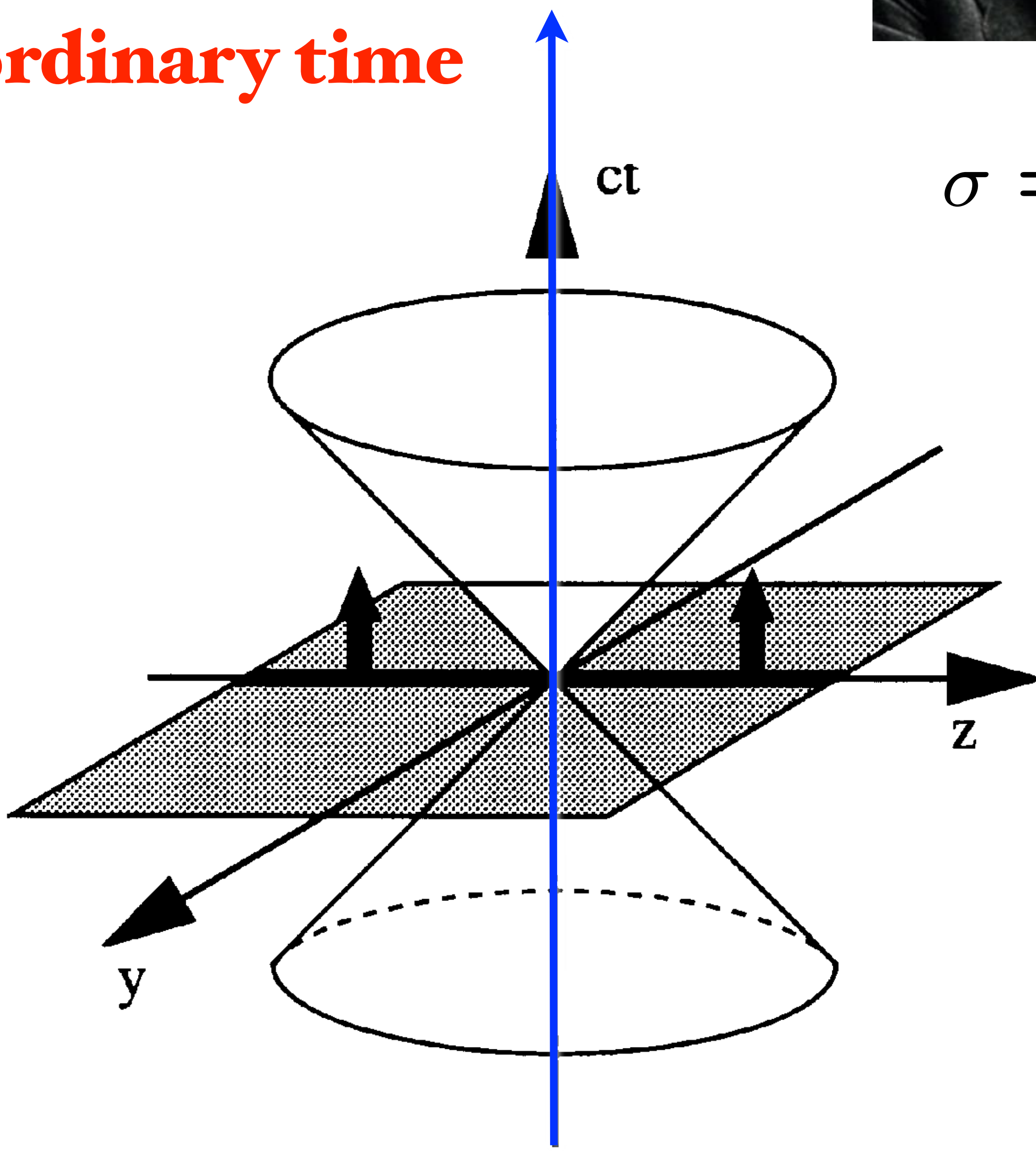

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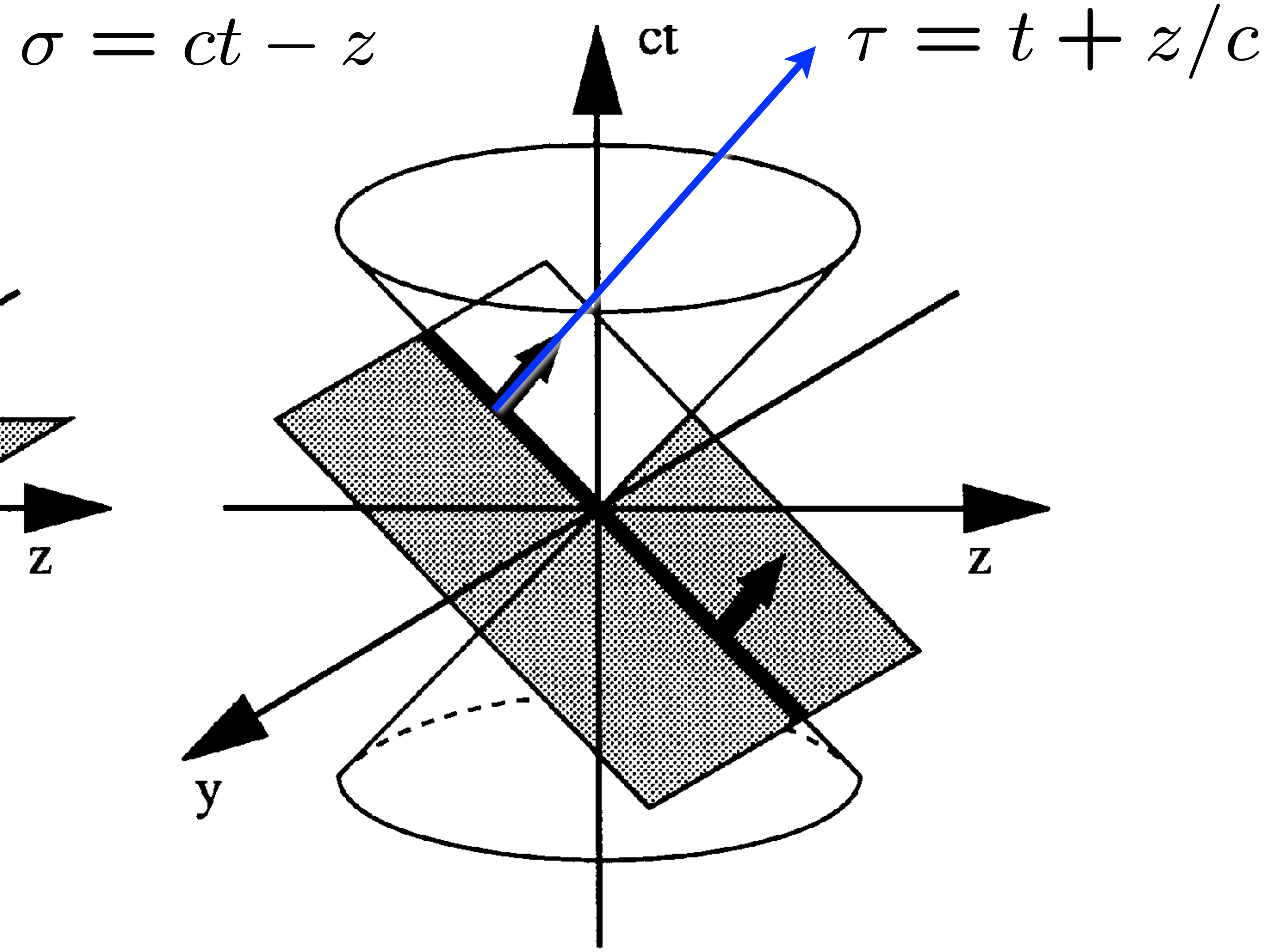
Evolve in light-front time!



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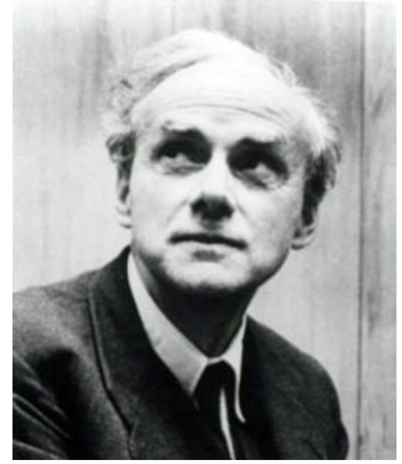

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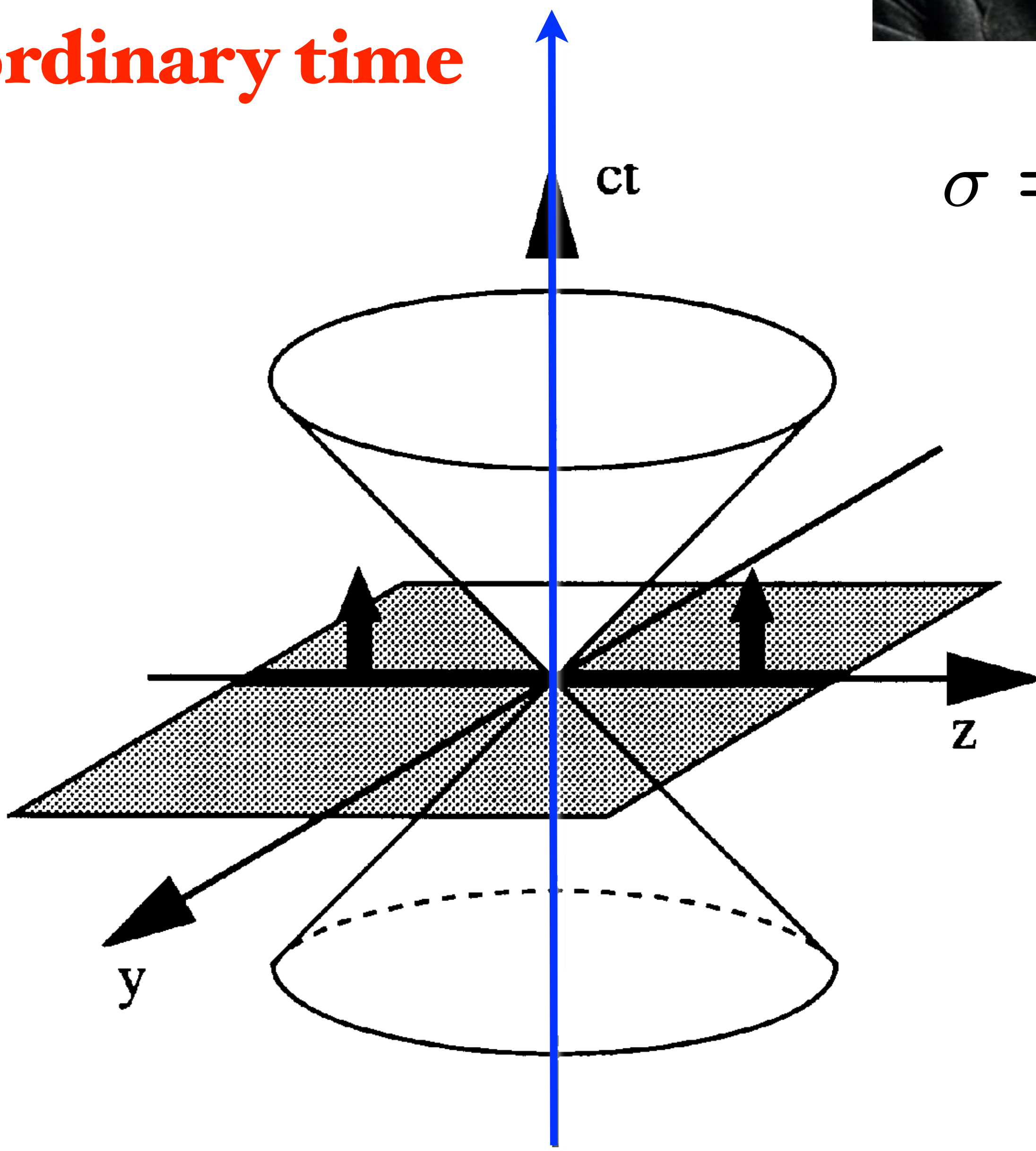

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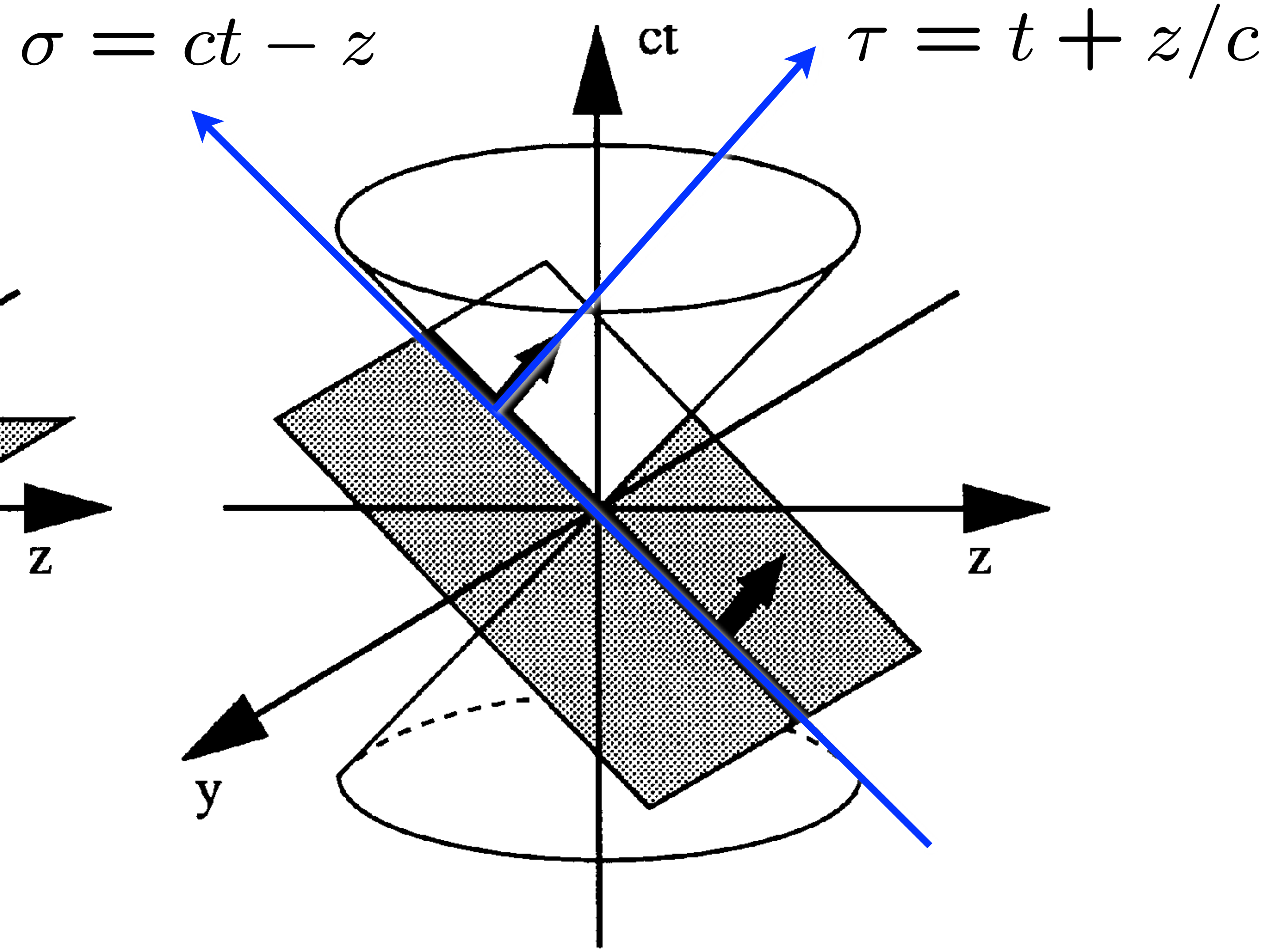

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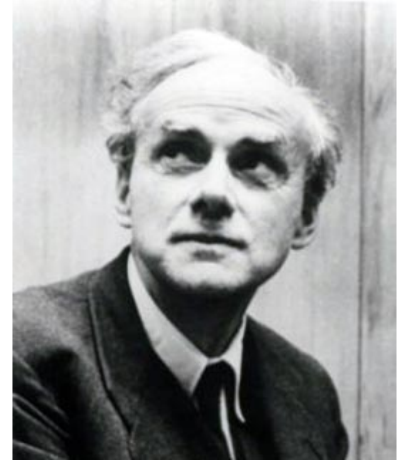

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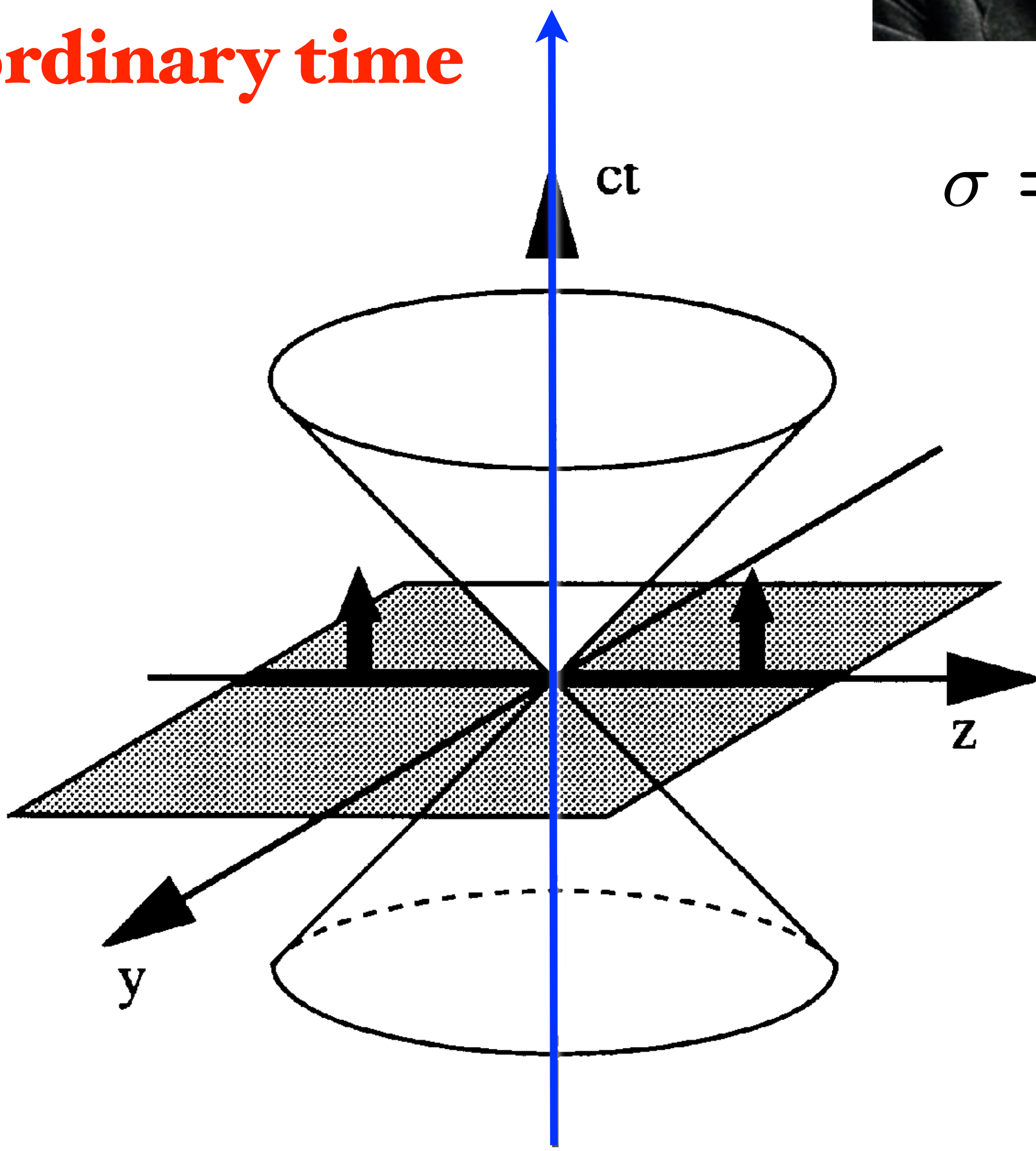

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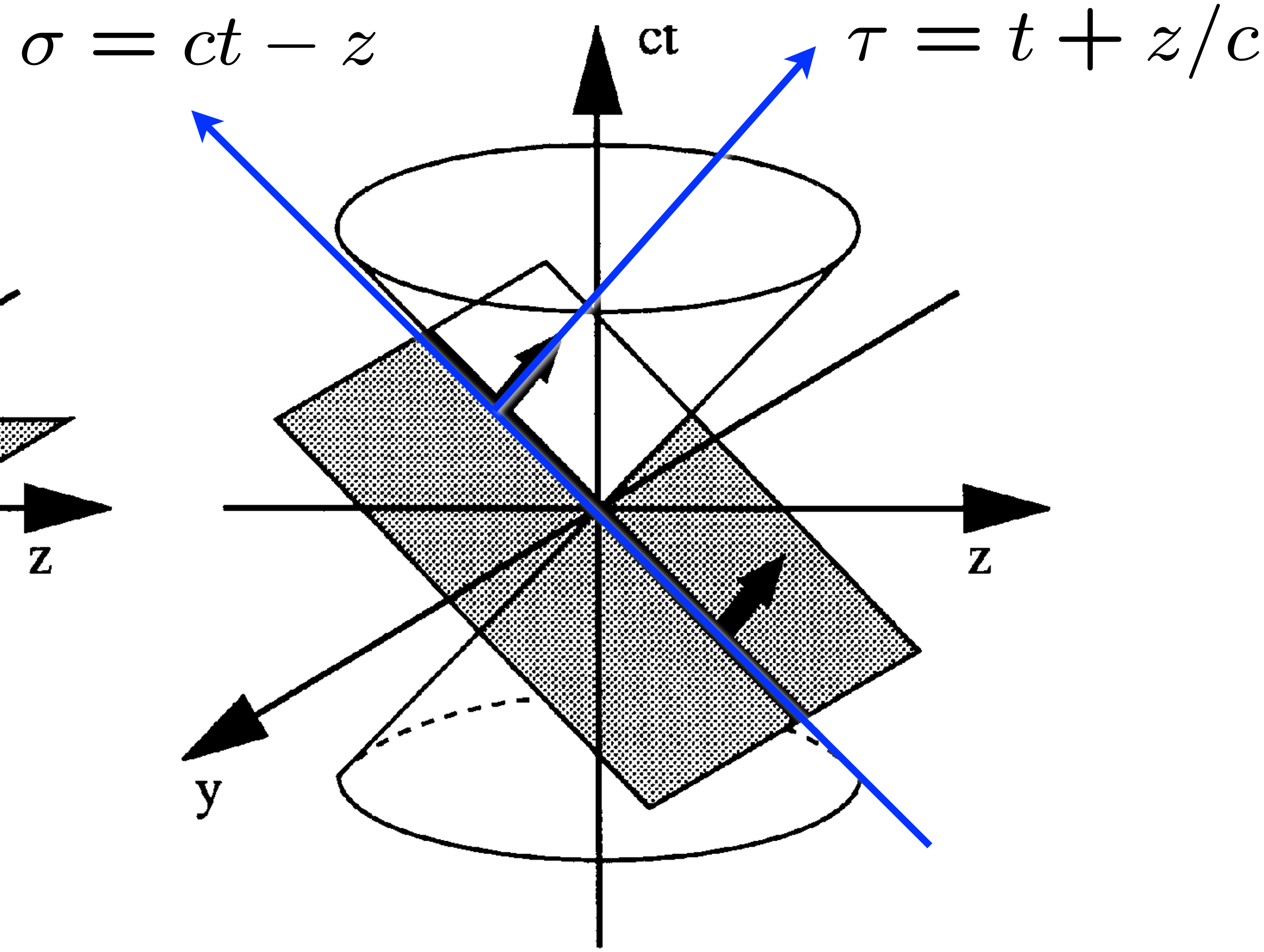
Evolve in light-front time!

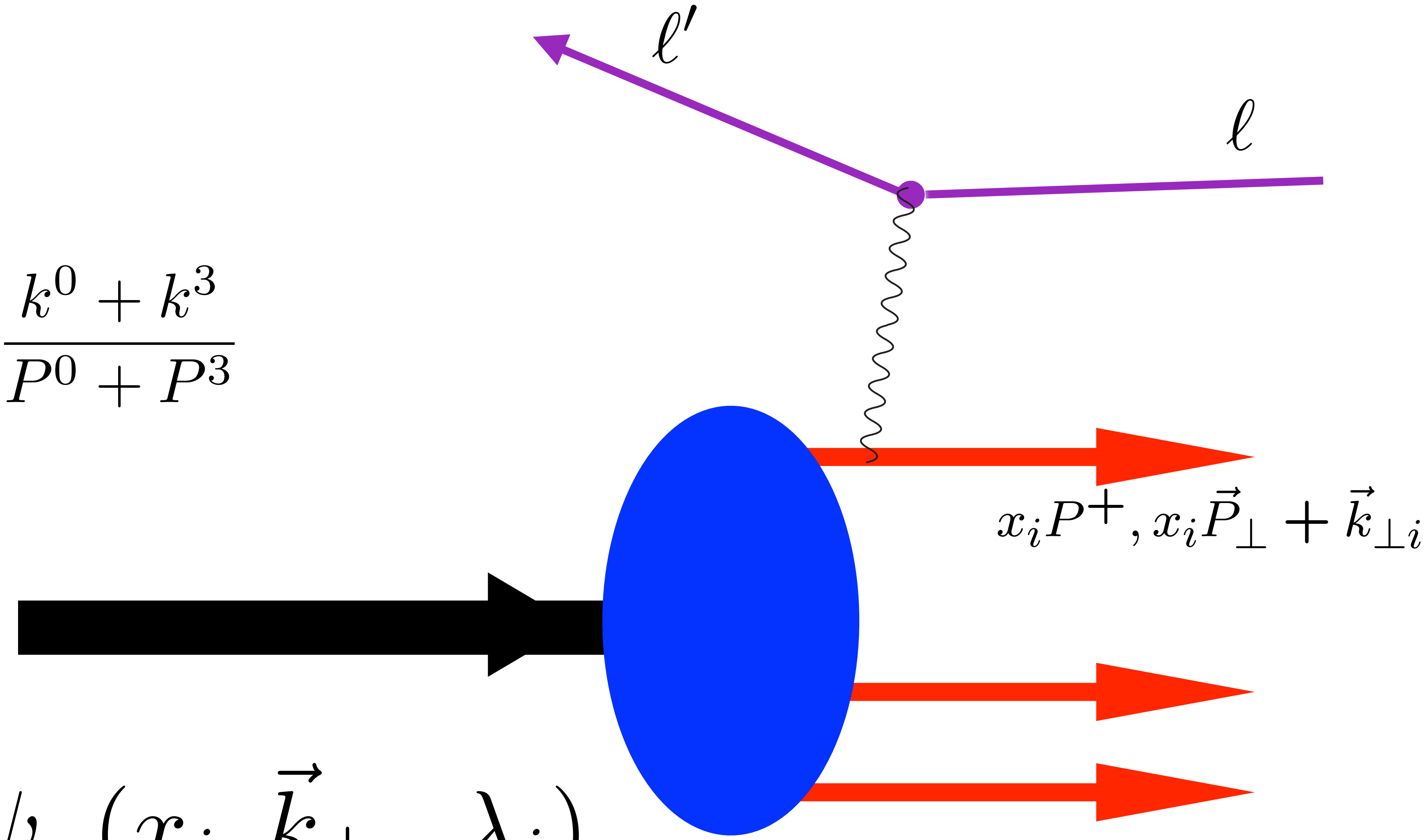


Front Form

Boost Invariant!

J. D. Bjorken

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$



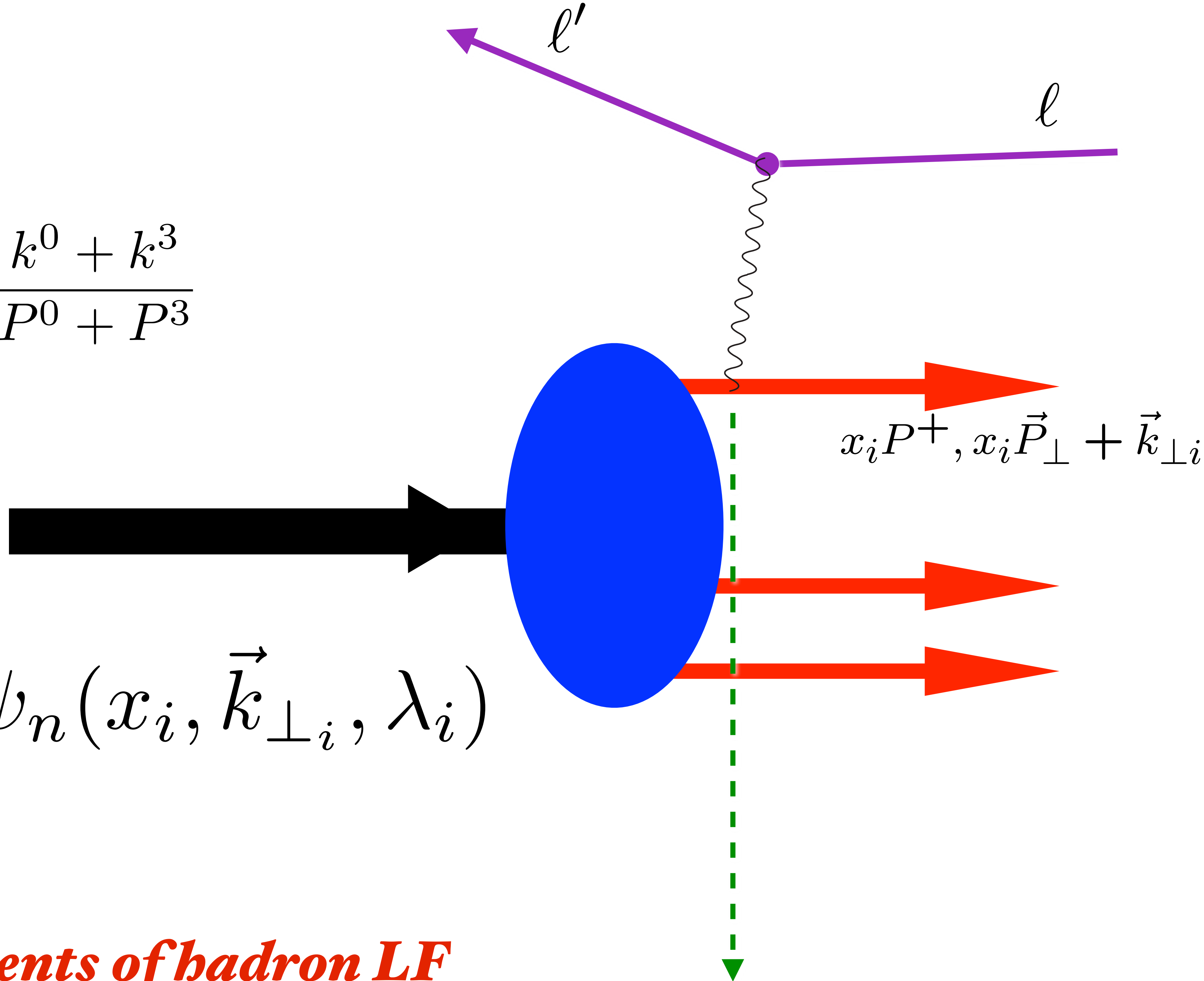
$$\psi_n(x_i, \vec{k}_{\perp_i}, \lambda_i)$$

Measurements of hadron LF wavefunction are at fixed LF time

Like a flash photograph

$$x_{bj} = x = \frac{k^+}{P^+}$$

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$



$P^+, \vec{P}_\perp$

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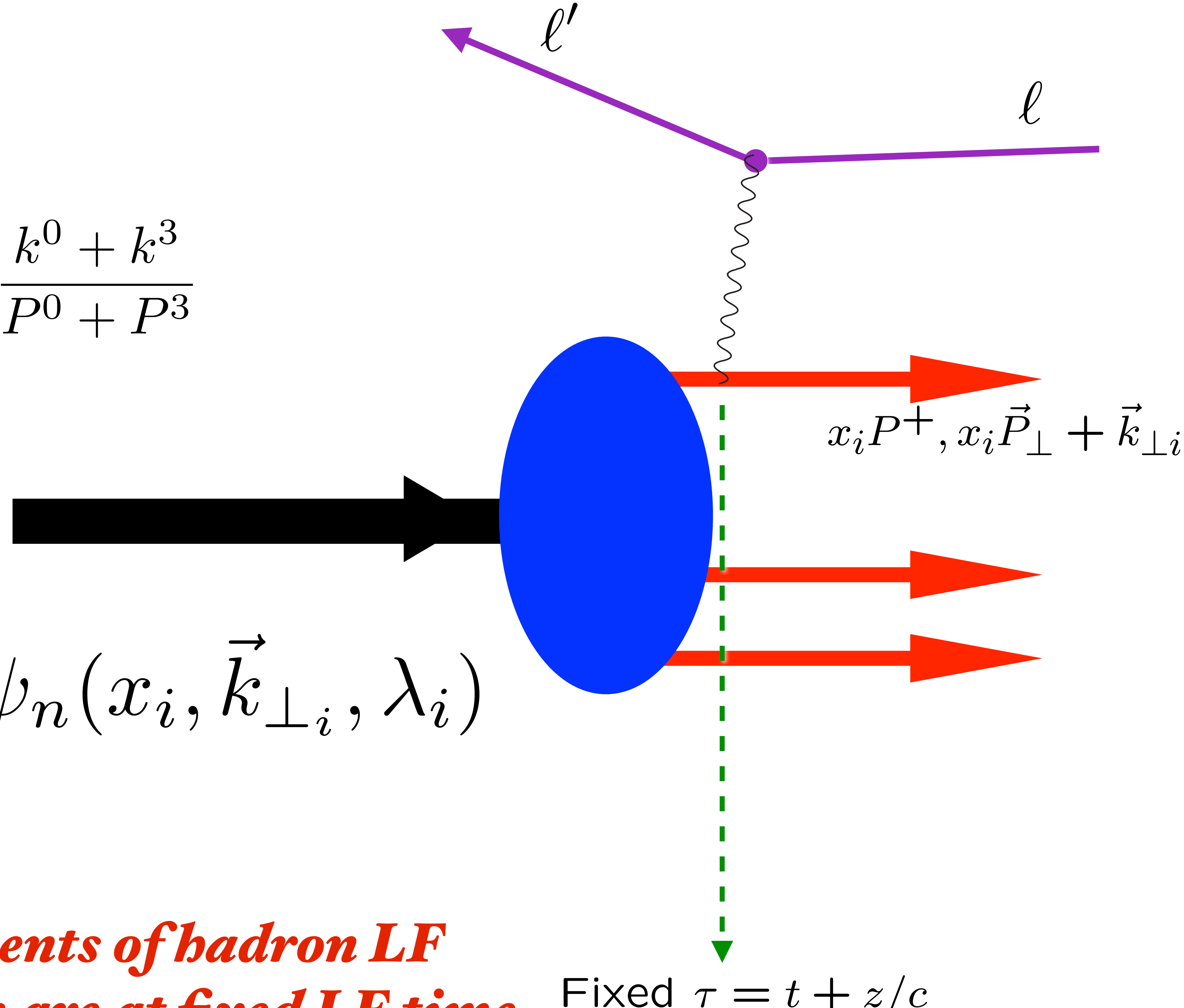

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Measurements of hadron LF wavefunction are at fixed LF time

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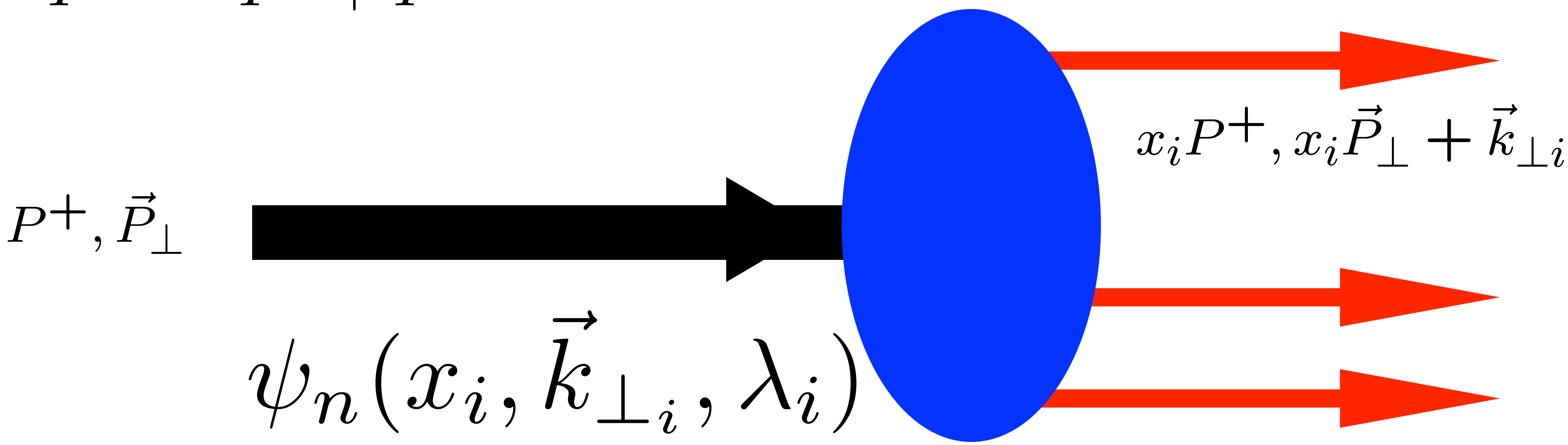
Like a flash photograph

Light-Front Wavefunctions: rigorous representation of composite systems in quantum field theory

Eigenstate of LF Hamiltonian

$$x = \frac{k^+}{P^+} = \frac{k^0 + k^3}{P^0 + P^3}$$



$$|p, J_z> = \sum_{n=3} \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) |n; x_i, \vec{k}_{\perp i}, \lambda_i>$$

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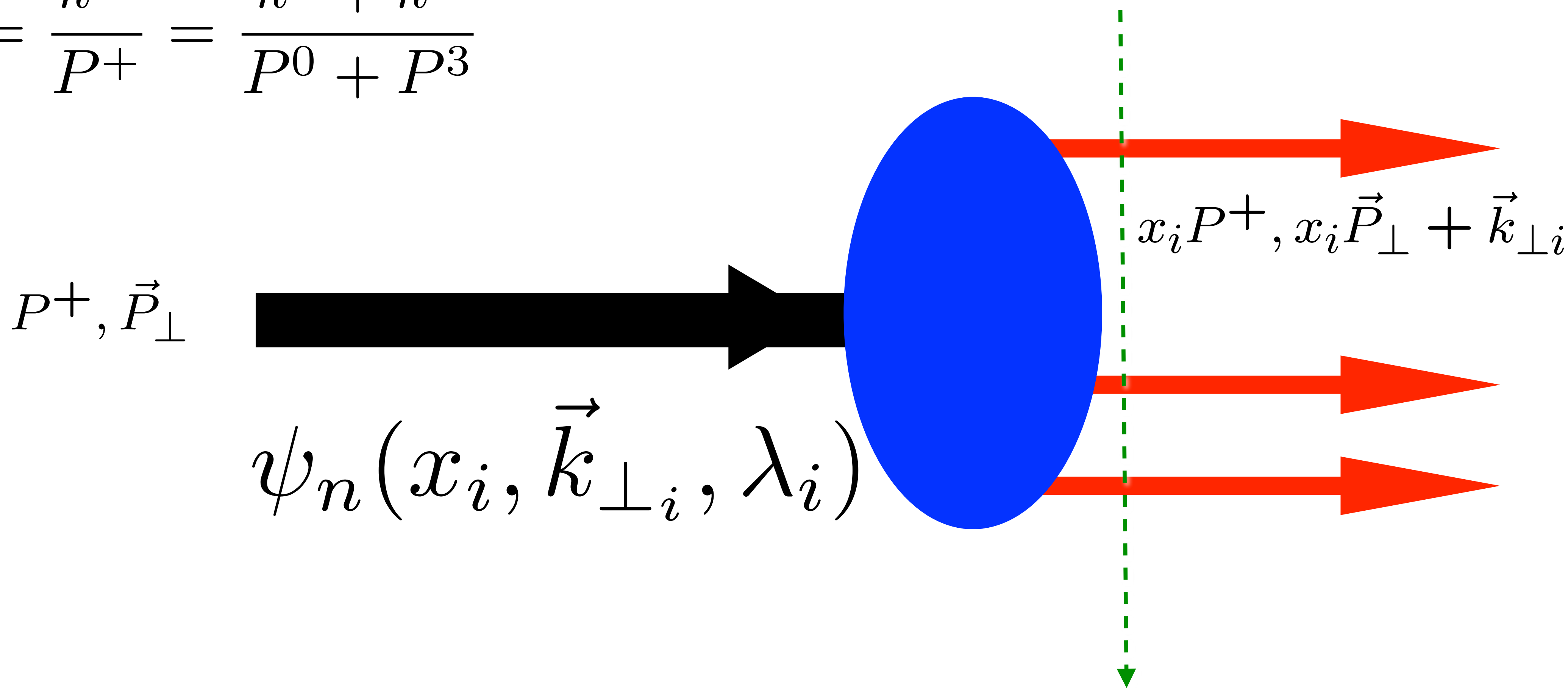

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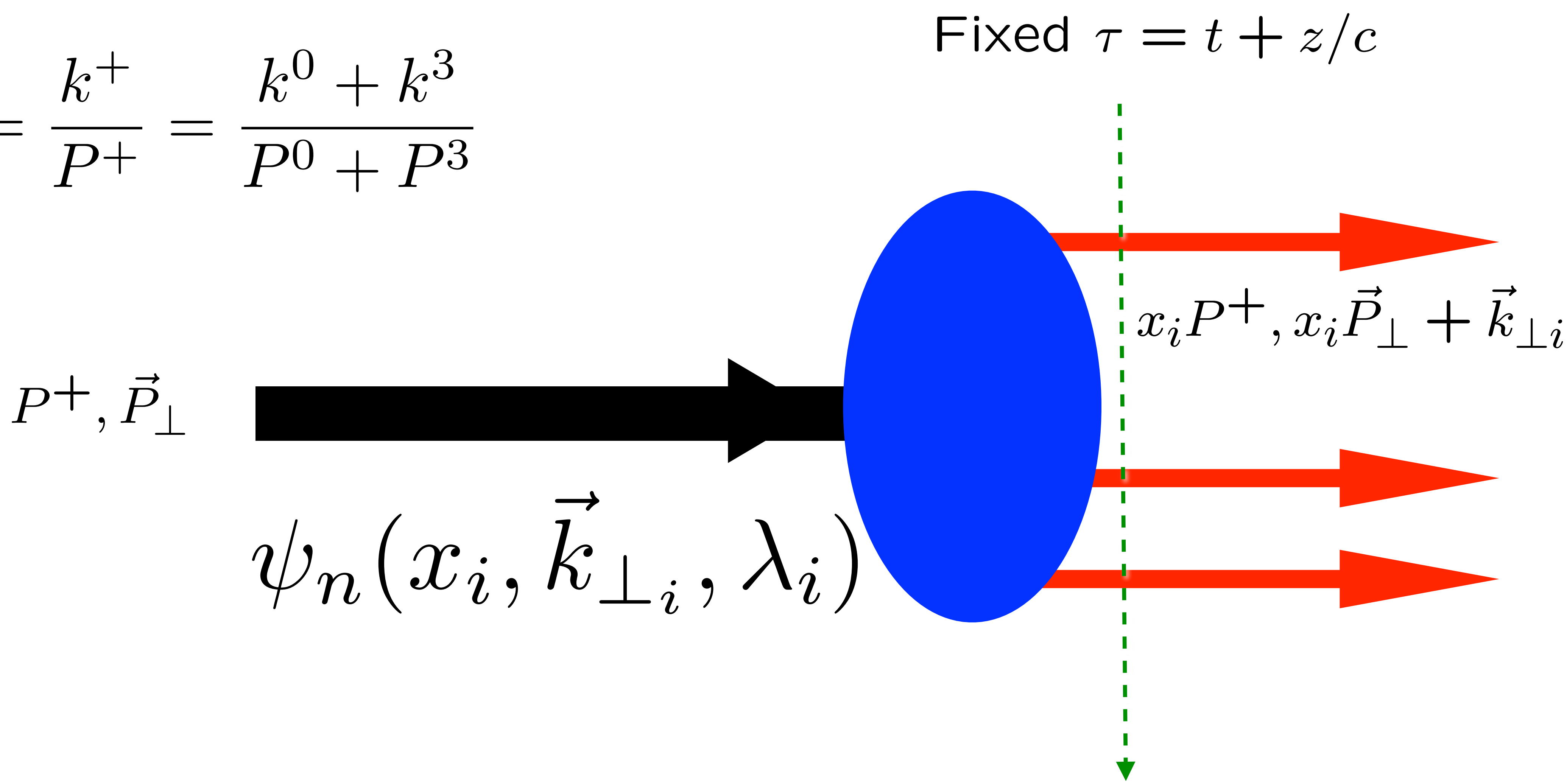

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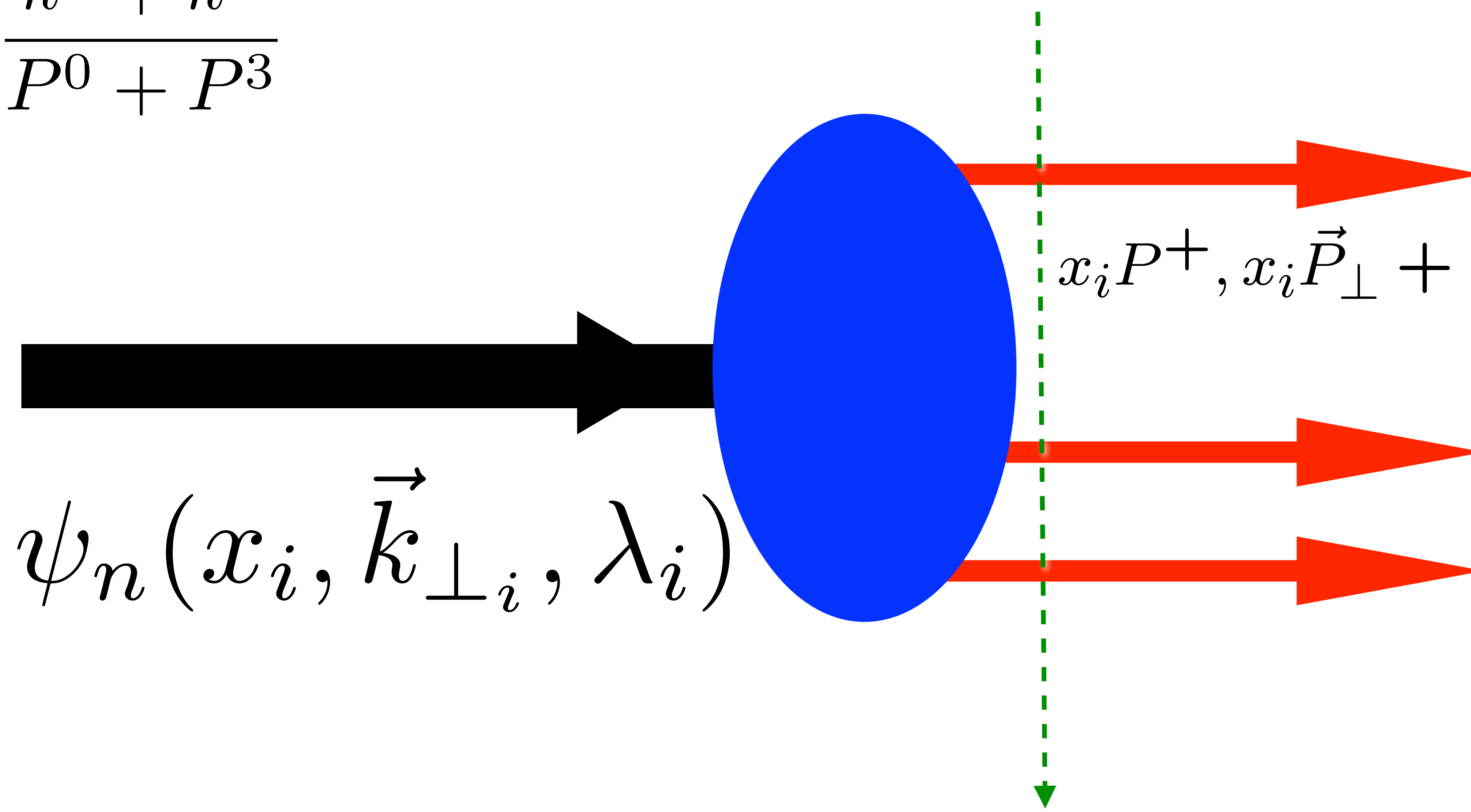
$P^+, \vec{P}_\perp$



$$\psi_n(x_i, \vec{k}_{\perp_i}, \lambda_i)$$

$$\sum_i^n x_i = 1$$

$$|p, J_z> = \sum_{n=3} \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)|n; x_i, \vec{k}_{\perp i}, \lambda_i>$$

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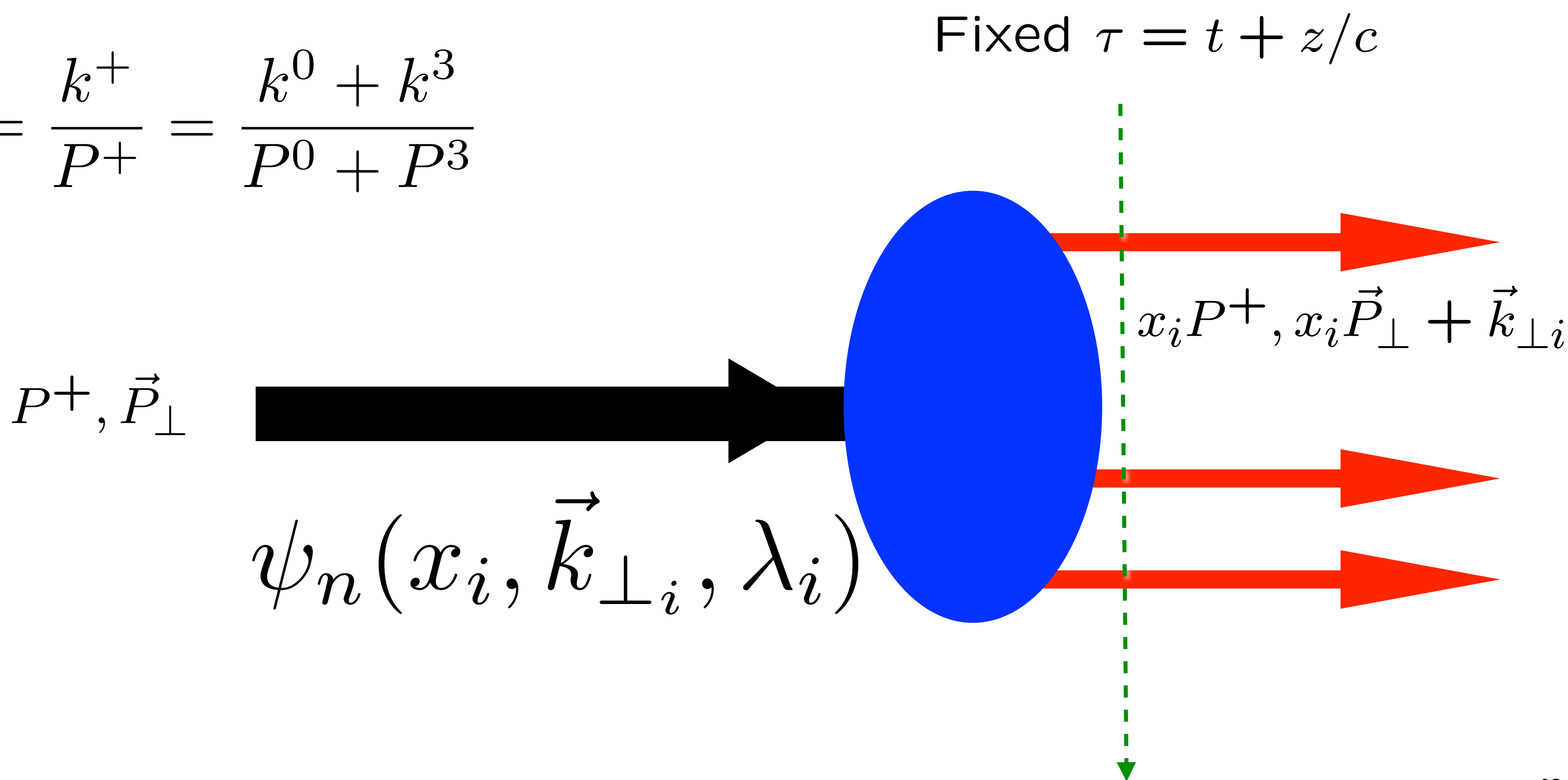

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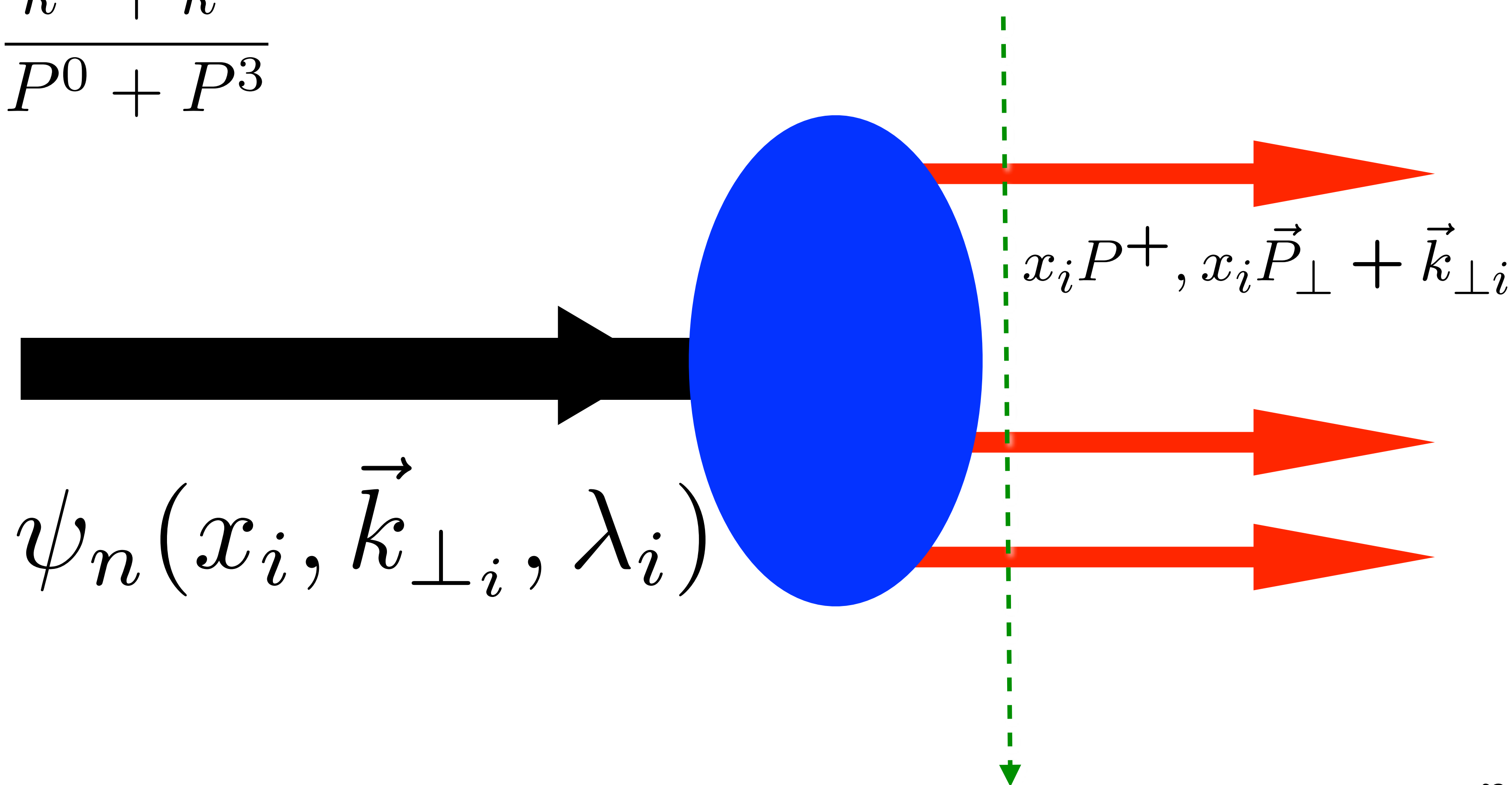

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Invariant under boosts! Independent of P^μ

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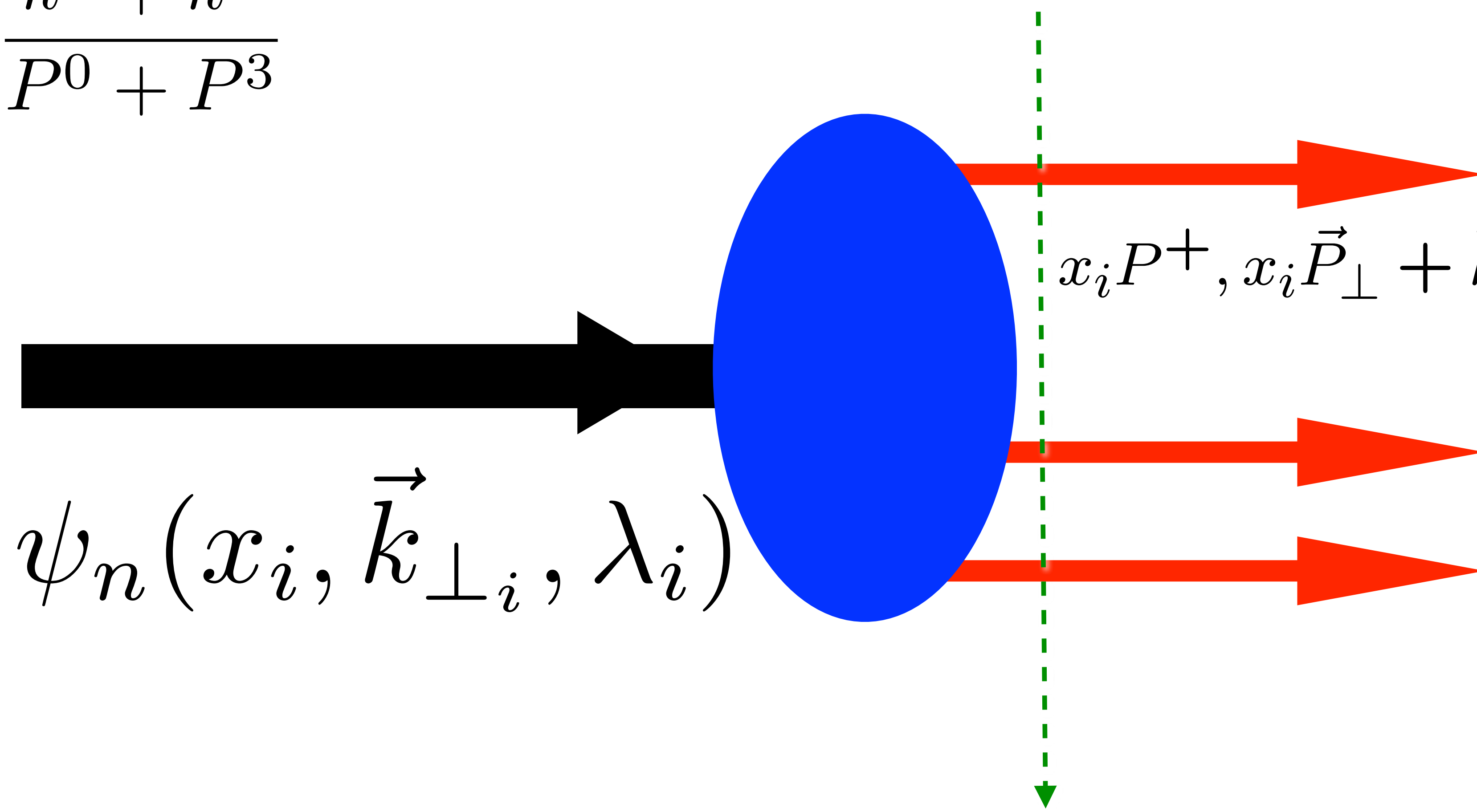

$P^+, \vec{P}_\perp$

$x_i P^+, x_i \vec{P}_\perp + \vec{k}_{\perp i}$

$$\psi_n(x_i, \vec{k}_{\perp_i}, \lambda_i)$$

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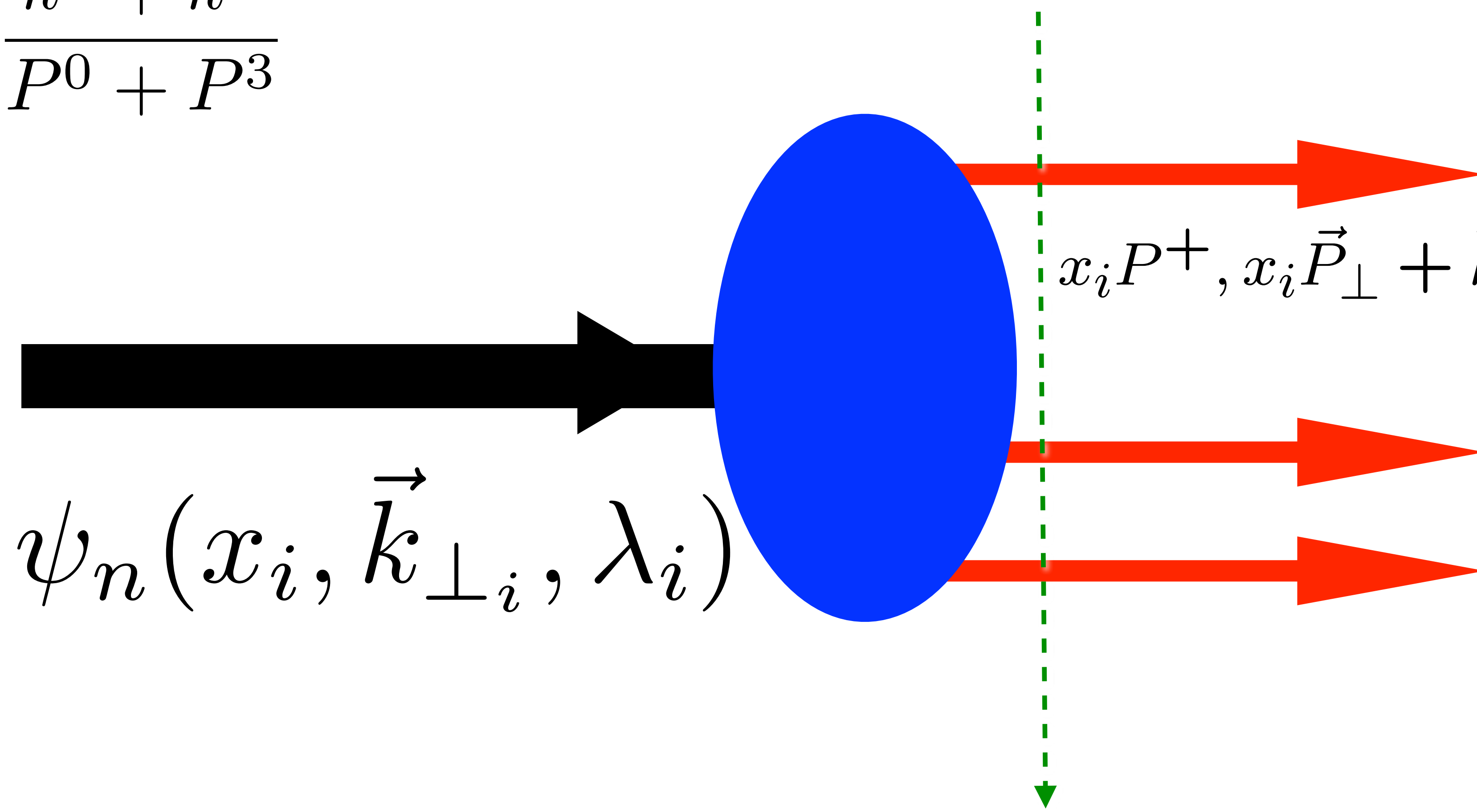

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$P^+, \vec{P}_\perp$

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Invariant under boosts! Independent of P^μ

Causal, Frame-independent. Creation Operators on Simple Vacuum, Current Matrix Elements are Overlaps of LFWFS

Each element of
flash photograph
illuminated
at same LF time

$$\tau = t + z/c$$

HELEN BRADLEY - PHOTOGRAPHY

Each element of
flash photograph
illuminated
at same LF time

$$\tau = t + z/c$$

HELEN BRADLEY - PHOTOGRAPHY

Each element of flash photograph illuminated at same LF time

$$\tau = t + z/c$$

Evolve in LF time

$$P^- = i\frac{d}{d\tau}$$

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Eigenstate -- independent of τ

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Causal, frame-independent

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$$H_{LF} = P^+ P^- - \vec{P}_\perp^2$$

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$$H_{LF}^{QCD}|\Psi_h> = \mathcal{M}_h^2|\Psi_h>$$

HELEN BRADLEY - PHOTOGRAPHY

Advantages of the Dirac's Front Form for Hadron Physics

- Measurements are made at fixed τ
- Causality is automatic
- Structure Functions are squares of LFWFs
- Form Factors are overlap of LFWFs
- LFWFs are frame-independent -- no boosts, no pancakes
- No dependence on observer's frame
- LF Holography: Dual to AdS space
- LF Vacuum trivial -- no condensates!
- Profound implications for Cosmological Constant

QCD Lagrangian

gluon dynamics

quark kinetic energy + quark-gluon dynamics

quark mass term

$$\mathcal{L}_{QCD} = -\frac{1}{4}Tr(G^{\mu\nu}G_{\mu\nu}) + \sum_{f=1}^{n_f} i\bar{\Psi}_f D_\mu \gamma^\mu \Psi_f + \sum_{f=1}^{n_f} m_f \bar{\Psi}_f \Psi_f$$

$$iD^\mu = i\partial^\mu - gA^\mu \quad G^{\mu\nu} = \partial^\mu A^\mu - \partial^\nu A^\mu - g[A^\mu, A^\nu]$$

QCD Lagrangian

Fundamental Theory of Hadron and Nuclear Physics

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Yang Mills Gauge Principle: Color Rotation and Phase Invariance at Every Point of Space and Time

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Scale-Invariant Coupling
Renormalizable
Asymptotic Freedom
Color Confinement

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Classically Conformal if $m_q=0$

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QCD Mass Scale from Confinement not Explicit

Light-Front QCD

Physical gauge: $A^+ = 0$

Exact frame-independent formulation of nonperturbative QCD!

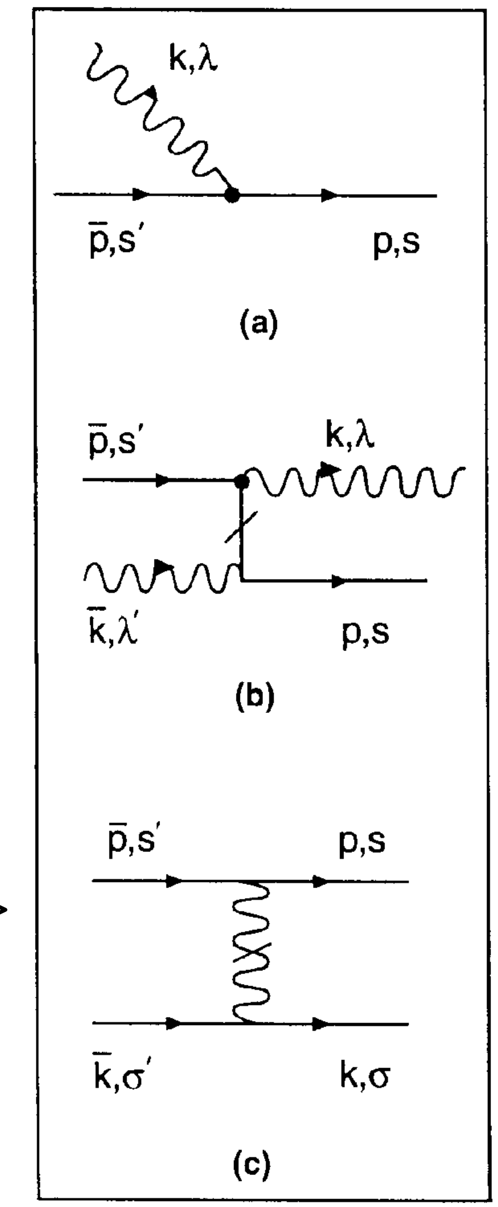
$$L^{QCD} \rightarrow H^{QCD}_{LF}$$

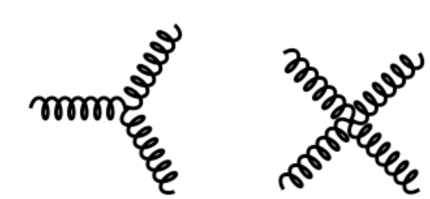
$$H^{QCD}_{LF} = \sum_i [\frac{m^2 + k^2_\perp}{x}]_i + H^{int}_{LF}$$

H^{int}_{LF}: Matrix in Fock Space

$$H^{QCD}_{LF} |\Psi_h > = \mathcal{M}^2_h |\Psi_h >$$

$$|p, J_z > = \sum_{n=3} \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) |n; x_i, \vec{k}_{\perp i}, \lambda_i >$$





H^{int}_{LF}

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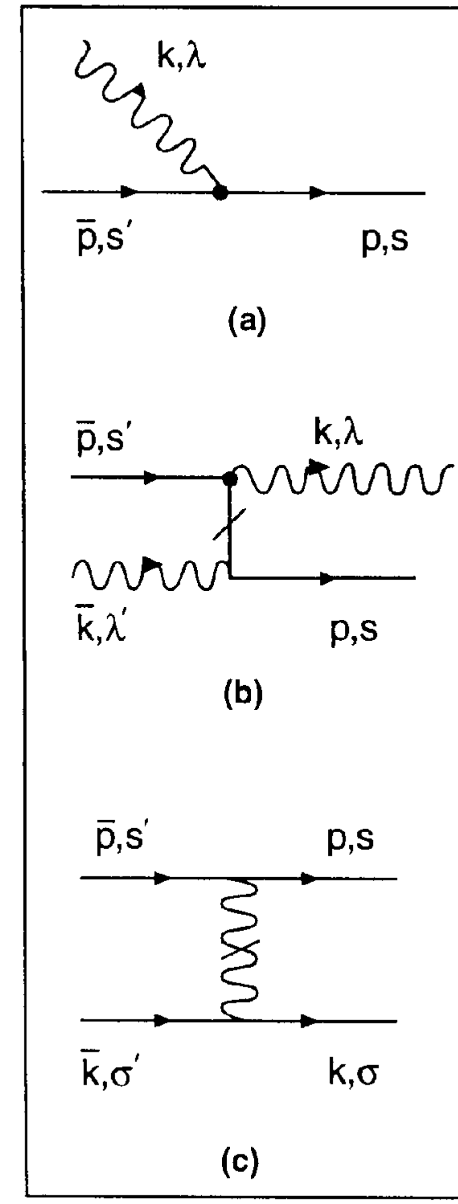

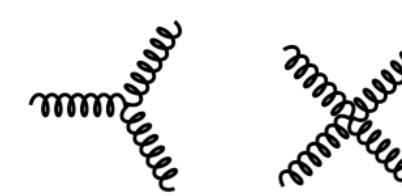

$$H^{int}_{LF}$$

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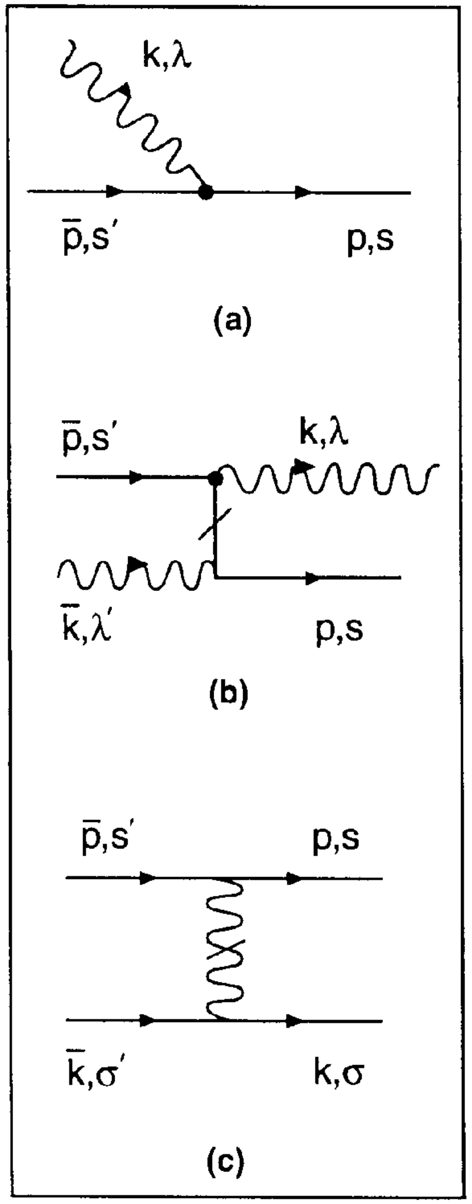
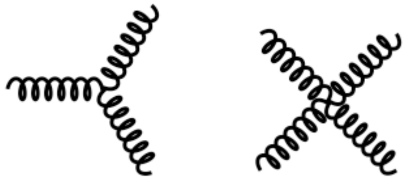
Eigenvalues and Eigensolutions give Hadronic Spectrum and Light-Front wavefunctions





H_{LF}^{int}

Light-Front QCD

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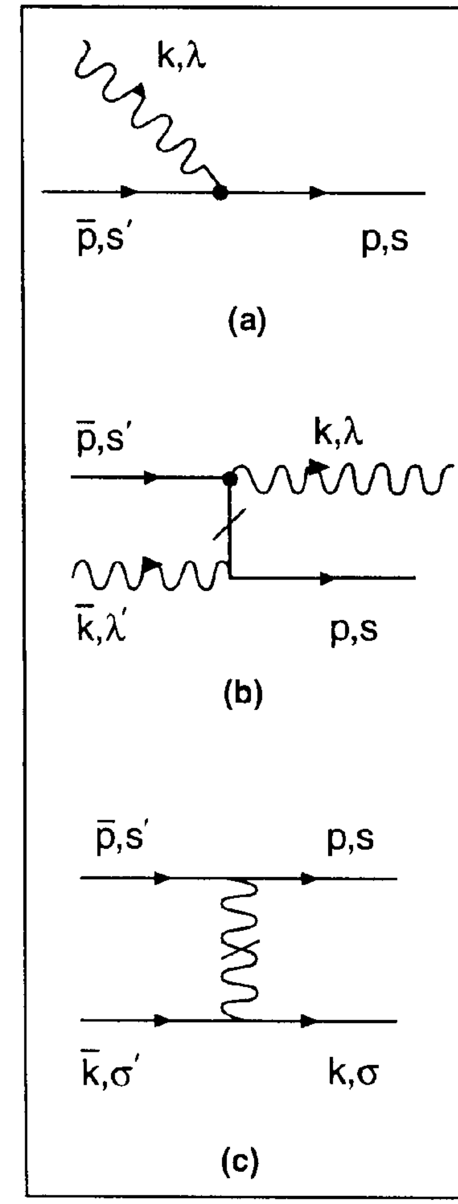

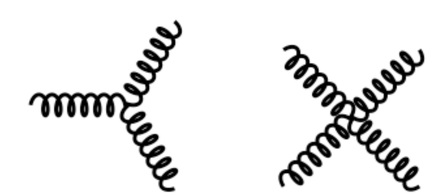

$$H^{int}_{LF}$$

Light-Front QCD

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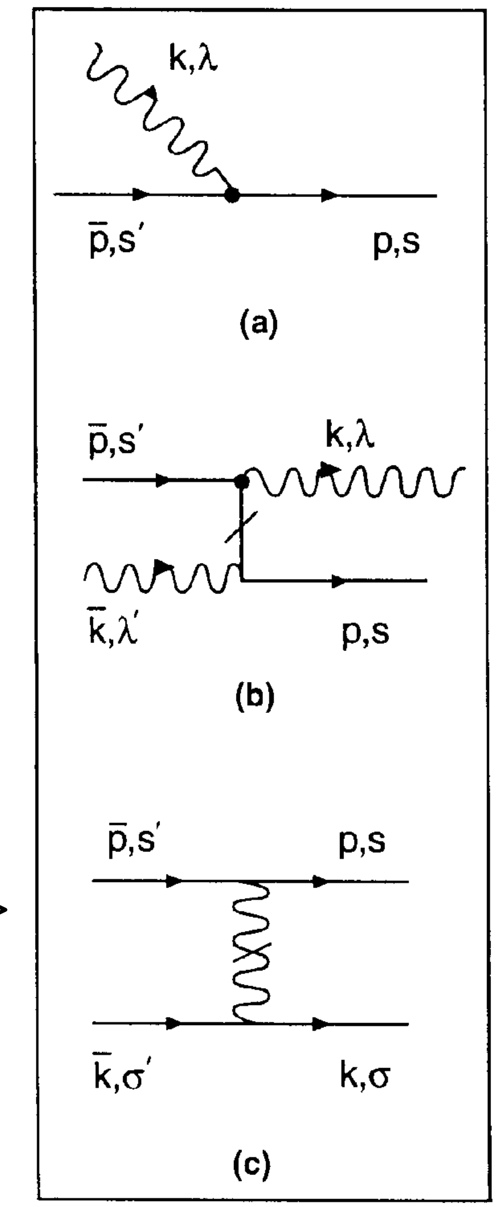
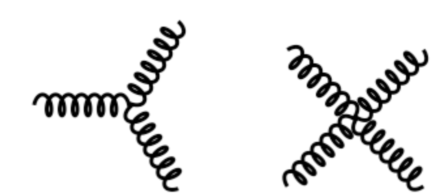
$$|p, J_z> = \sum_{n=3} \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) |n; x_i, \vec{k}_{\perp i}, \lambda_i>$$

Eigenvalues and Eigensolutions give Hadronic Spectrum and Light-Front wavefunctions

LFWFs: Off-shell in P- and invariant mass





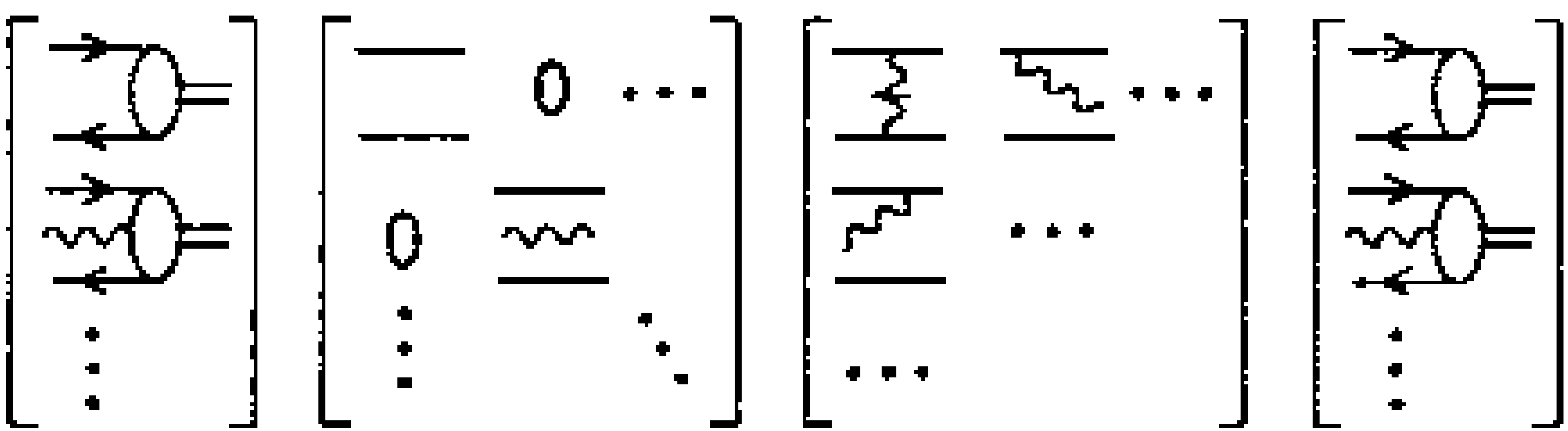
$$H_{LF}^{int}$$

LIGHT-FRONT MATRIX EQUATION

Rigorous Method for Solving Non-Perturbative QCD!

$$\left(M_\pi^2 - \sum_i \frac{\vec{k}_{\perp i}^2 + m_i^2}{x_i}\right)\begin{bmatrix}\psi_{q\bar{q}/\pi}\\ \psi_{q\bar{q}g/\pi}\\ \vdots\end{bmatrix} = \begin{bmatrix} \langle q\bar{q}|\,V\,|q\bar{q}\rangle & \langle q\bar{q}|\,V\,|q\bar{q}g\rangle & \cdots \\ \langle q\bar{q}g|\,V\,|q\bar{q}\rangle & \langle q\bar{q}g|\,V\,|q\bar{q}g\rangle & \cdots \\ \vdots & \vdots & \ddots \end{bmatrix}\begin{bmatrix}\psi_{q\bar{q}/\pi}\\ \psi_{q\bar{q}g/\pi}\\ \vdots\end{bmatrix}$$

$A^+ = 0$

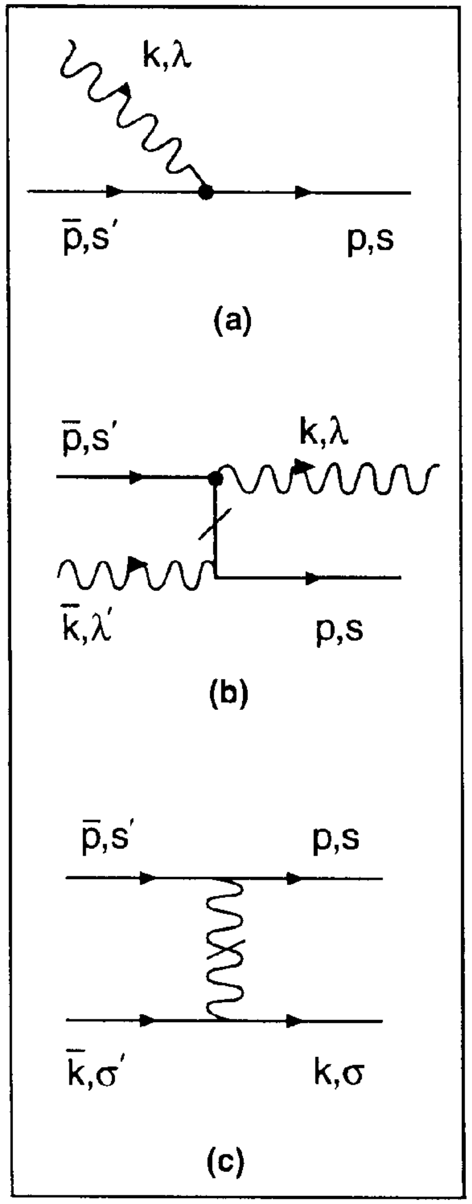


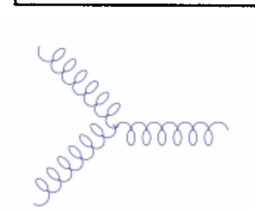
Minkowski space; frame-independent; no fermion doubling; no ghosts

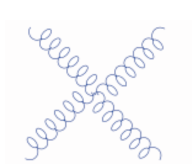
- *Light-Front Vacuum = vacuum of free Hamiltonian!*

$$H_{LC}^{QCD}|\Psi_h\rangle = \mathcal{M}_h^2\ |\Psi_h\rangle$$

Hornbostel, Pauli, sjb







Minkowski space; frame-independent; no fermion doubling; no ghosts
trivial vacuum

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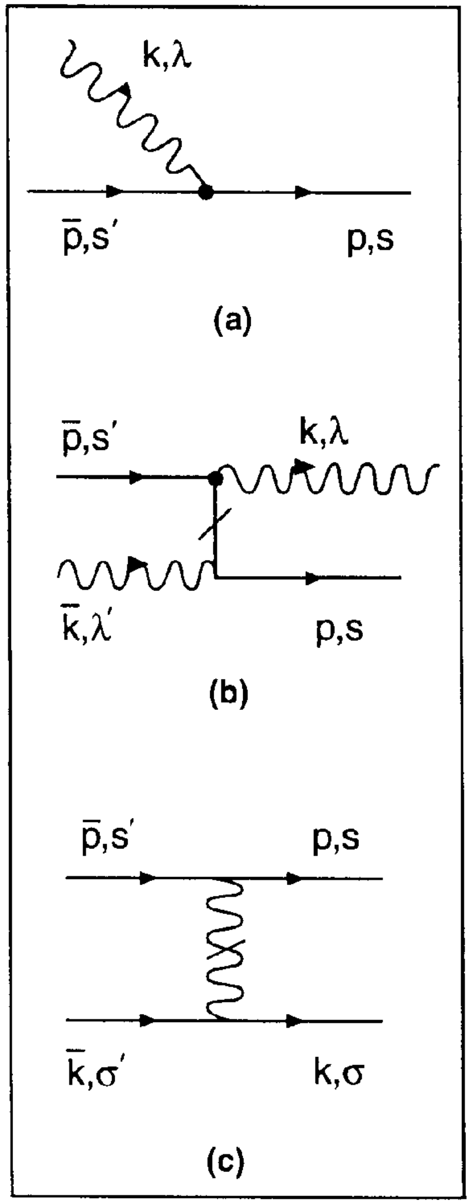

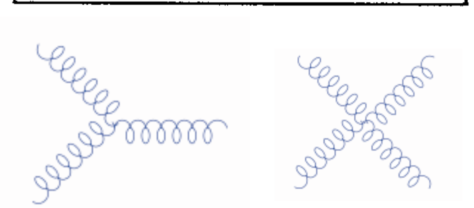

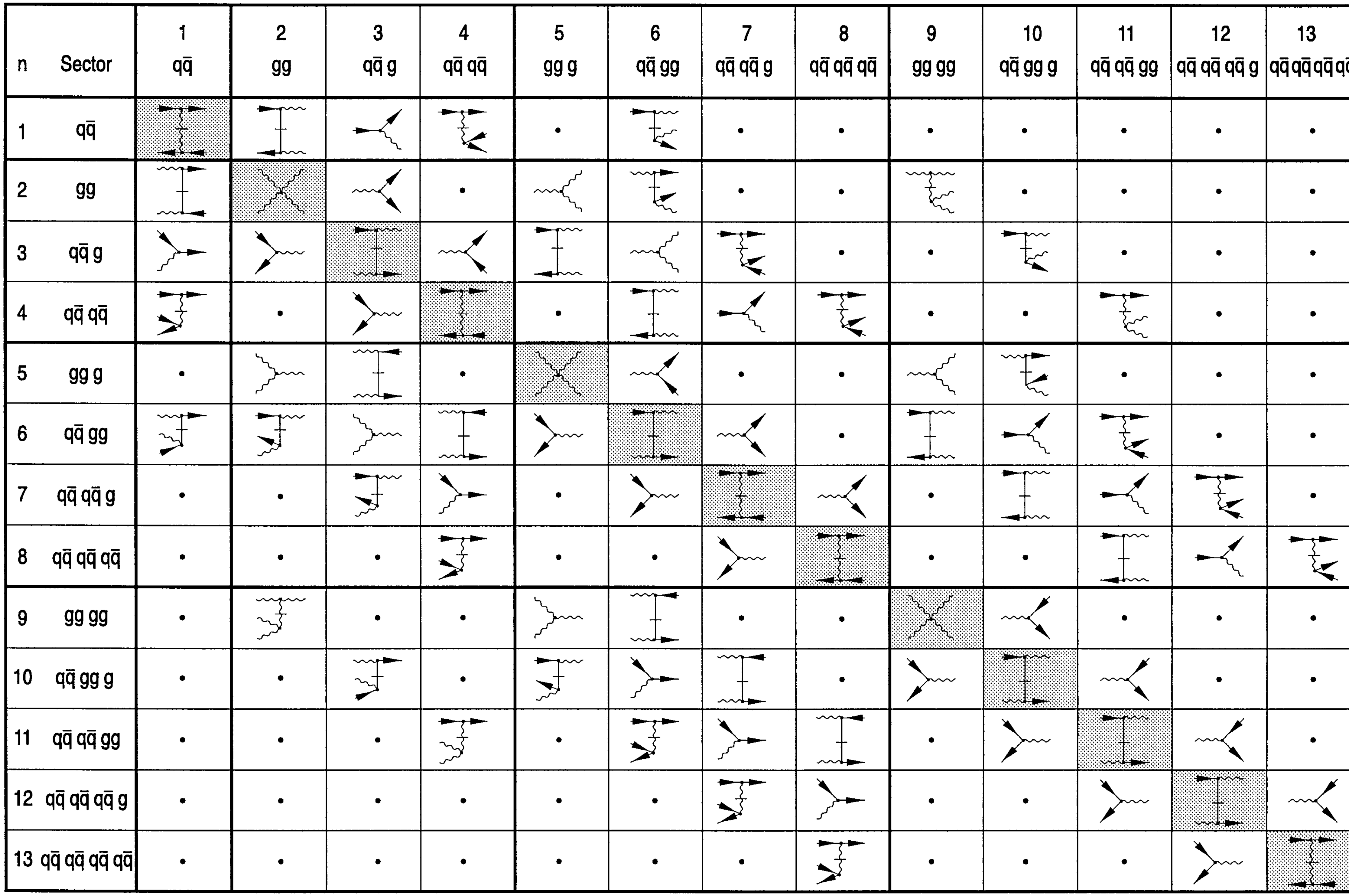

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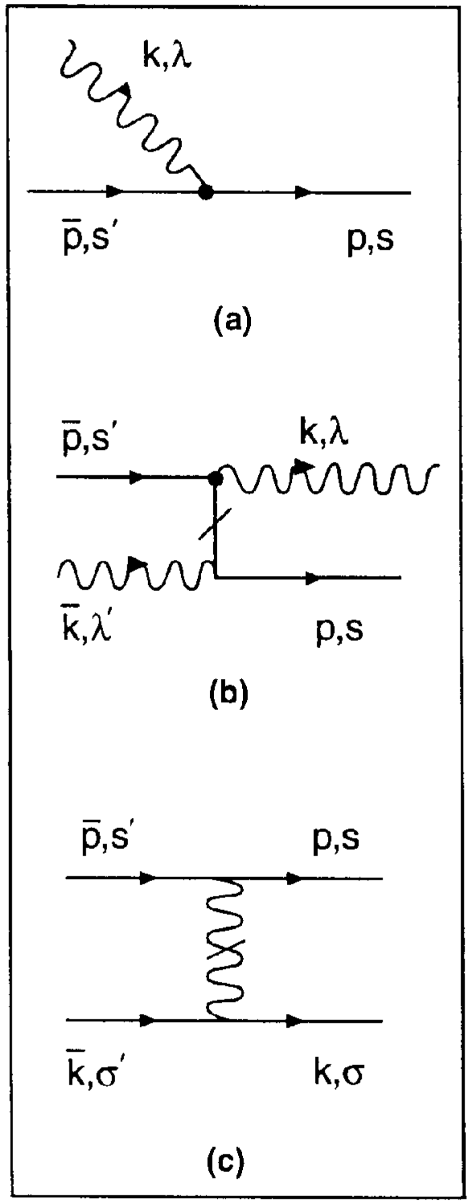

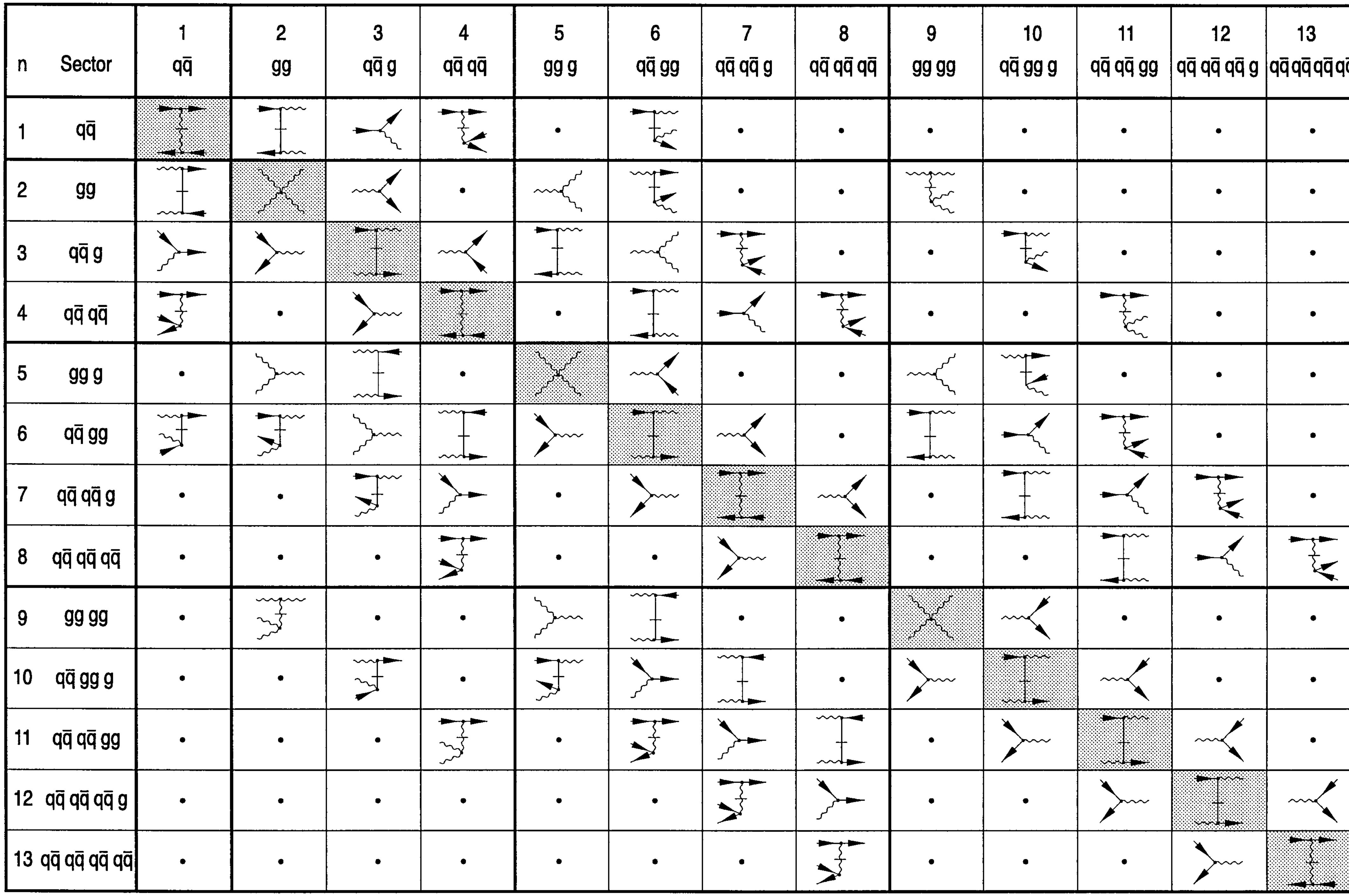

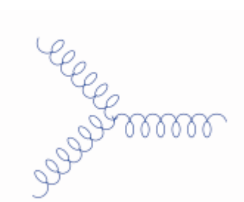

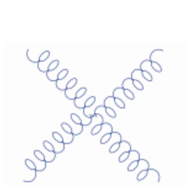

Minkowski space; frame-independent; no fermion doubling; no ghosts
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Light-Front QCD

$$H^{QCD}_{LC} |\Psi_h\rangle = \mathcal{M}^2_h \ |\Psi_h\rangle$$

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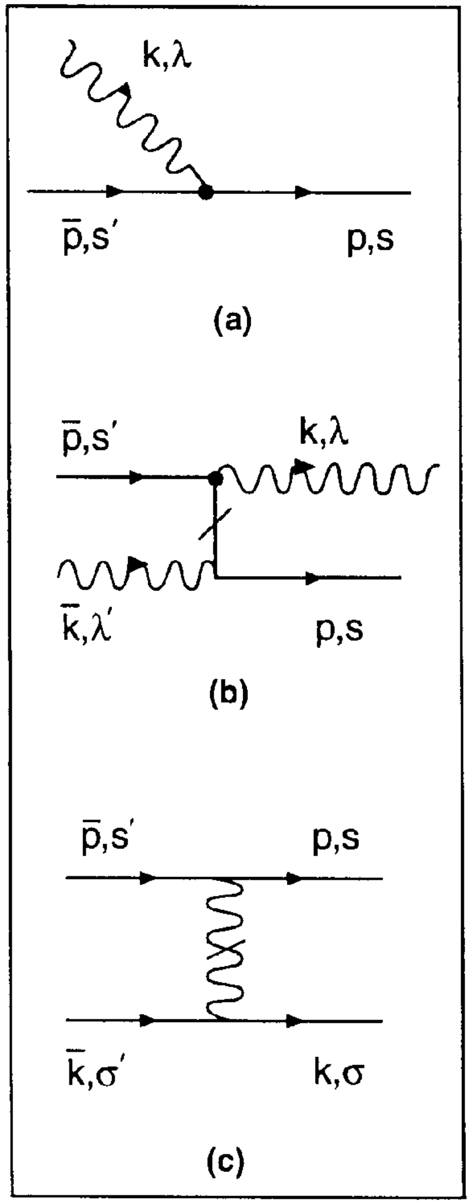
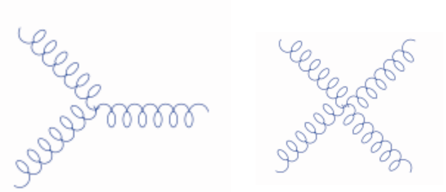


n	Sector	1 qq̄	2 gg	3 qq̄ g	4 qq̄ qq̄	5 gg g	6 qq̄ gg	7 qq̄ qq̄ g	8 qq̄ qq̄ qq̄	9 gg gg	10 qq̄ gg g	11 qq̄ qq̄ gg	12 qq̄ qq̄ qq̄ g	13 qq̄ qq̄ qq̄ qq̄
1	qq̄					•		•	•	•	•	•	•	•
2	gg				•			•	•		•	•	•	•
3	qq̄ g								•	•		•	•	•
4	qq̄ qq̄		•			•				•	•		•	•
5	gg g	•			•			•	•			•	•	•
6	qq̄ gg								•				•	•
7	qq̄ qq̄ g	•	•			•				•				•
8	qq̄ qq̄ qq̄	•	•	•		•	•			•	•			
9	gg gg	•		•	•			•	•			•	•	•
10	qq̄ gg g	•	•		•				•				•	•
11	qq̄ qq̄ gg	•	•	•		•				•				•
12	qq̄ qq̄ qq̄ g	•	•	•	•	•	•			•	•			
13	qq̄ qq̄ qq̄ qq̄	•	•	•	•	•	•	•		•	•	•		



Minkowski space; frame-independent; no fermion doubling; no ghosts
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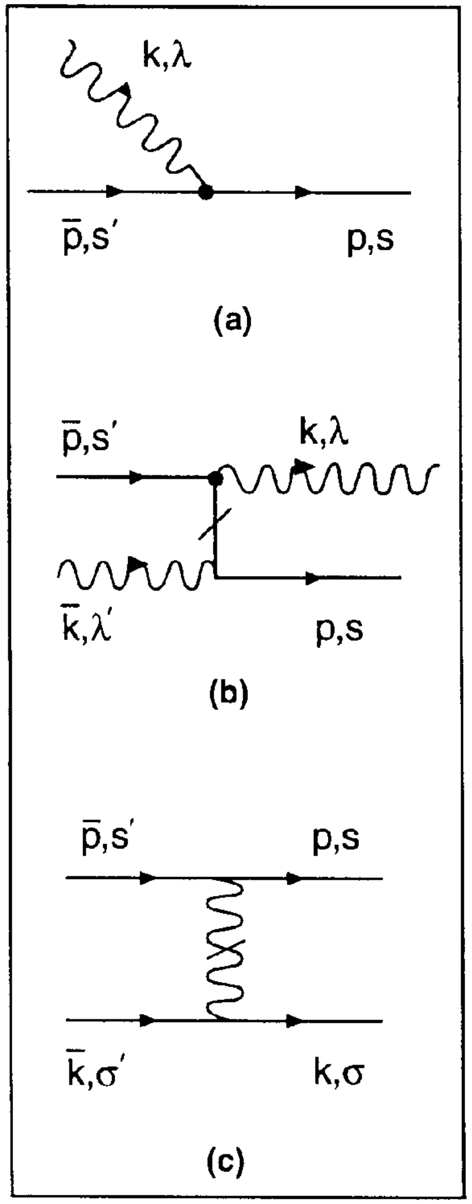
Light-Front QCD

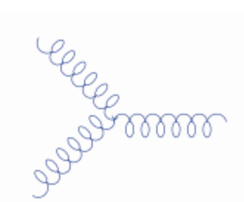
Heisenberg Equation

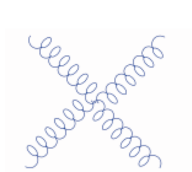
$$H_{LC}^{QCD}|\Psi_h\rangle = \mathcal{M}_h^2 \ |\Psi_h\rangle$$

Hornbostel, Pauli, sjb



n	Sector	1 qq̄	2 gg	3 qq̄ g	4 qq̄ qq̄	5 gg g	6 qq̄ gg	7 qq̄ qq̄ g	8 qq̄ qq̄ qq̄	9 gg gg	10 qq̄ gg g	11 qq̄ qq̄ gg	12 qq̄ qq̄ qq̄ g	13 qq̄ qq̄ qq̄ qq̄
1	qq̄					•		•	•	•	•	•	•	•
2	gg				•			•	•		•	•	•	•
3	qq̄ g								•	•		•	•	•
4	qq̄ qq̄		•			•				•	•		•	•
5	gg g	•			•			•	•			•	•	•
6	qq̄ gg								•				•	•
7	qq̄ qq̄ g	•	•			•				•				•
8	qq̄ qq̄ qq̄	•	•	•		•	•			•	•			
9	gg gg	•		•	•			•	•			•	•	•
10	qq̄ gg g	•	•		•				•				•	•
11	qq̄ qq̄ gg	•	•	•		•				•				•
12	qq̄ qq̄ qq̄ g	•	•	•	•	•	•			•	•			
13	qq̄ qq̄ qq̄ qq̄	•	•	•	•	•	•	•		•	•	•		





Minkowski space; frame-independent; no fermion doubling; no ghosts trivial vacuum

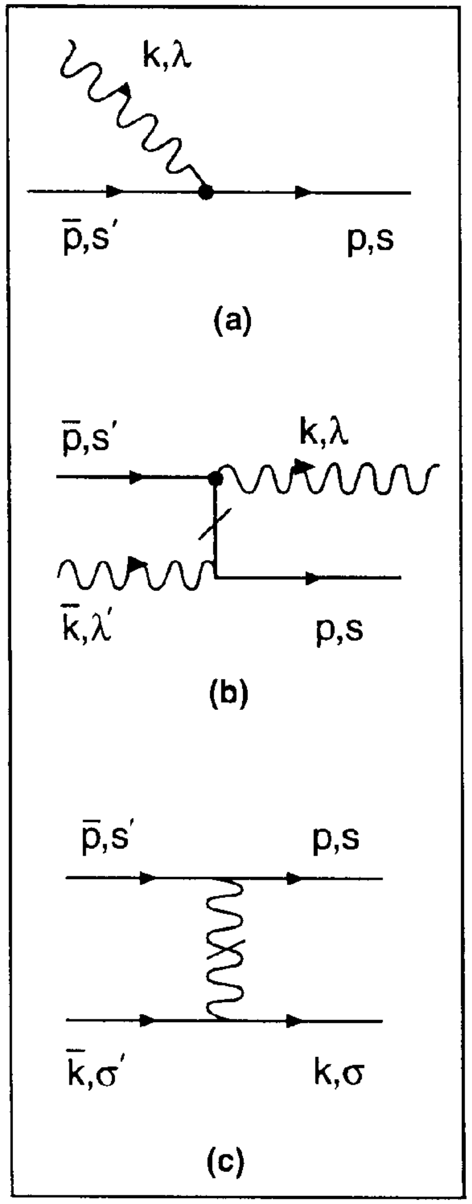
Light-Front QCD

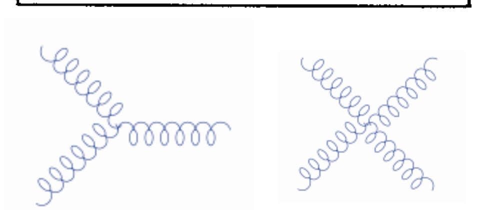
Heisenberg Equation

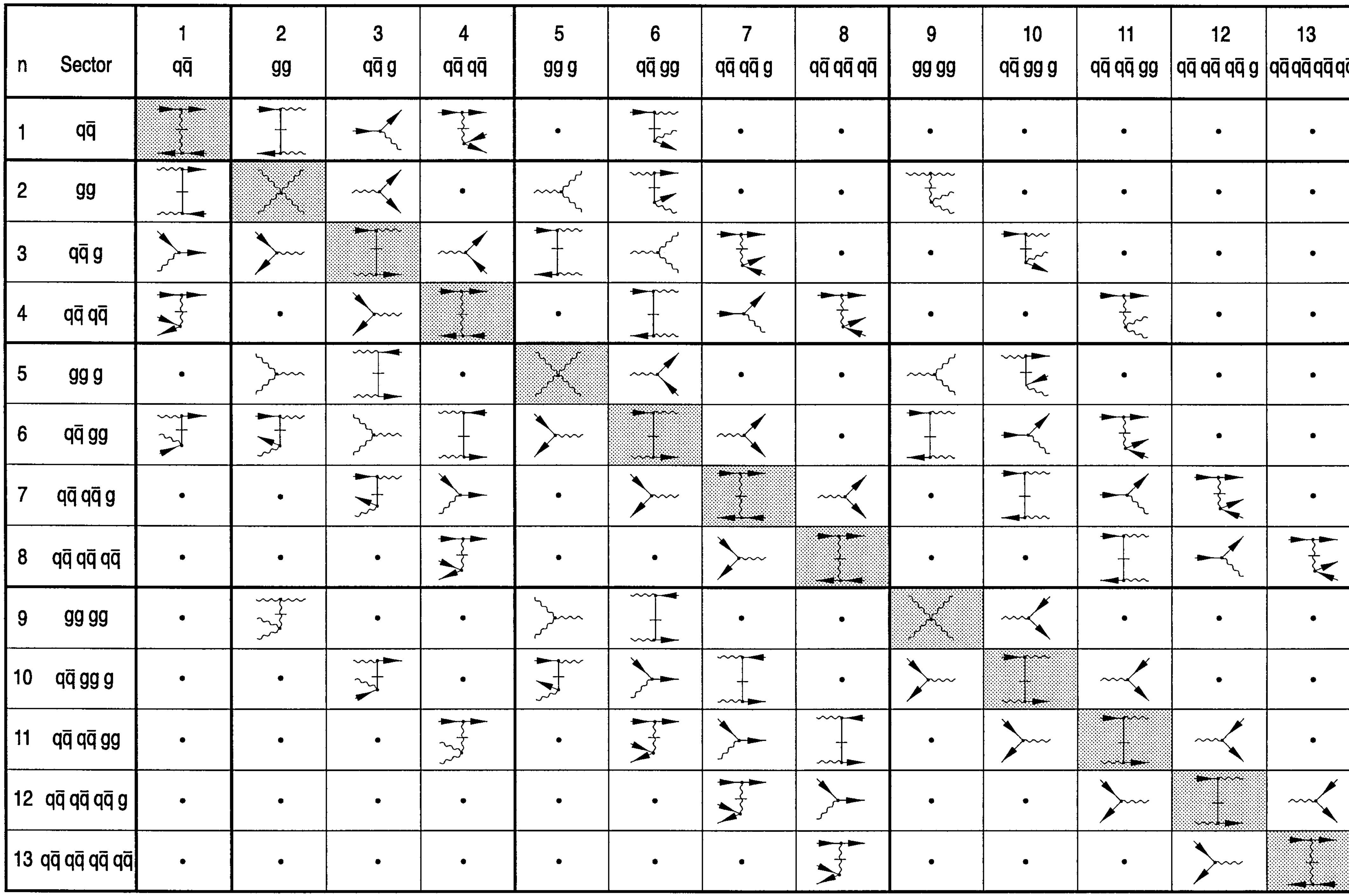
$$H_{LC}^{QCD}|\Psi_h\rangle = \mathcal{M}_h^2\,|\Psi_h\rangle$$

DLCQ: Solve QCD(1+1) for any quark mass and flavors

Hornbostel, Pauli, sjb







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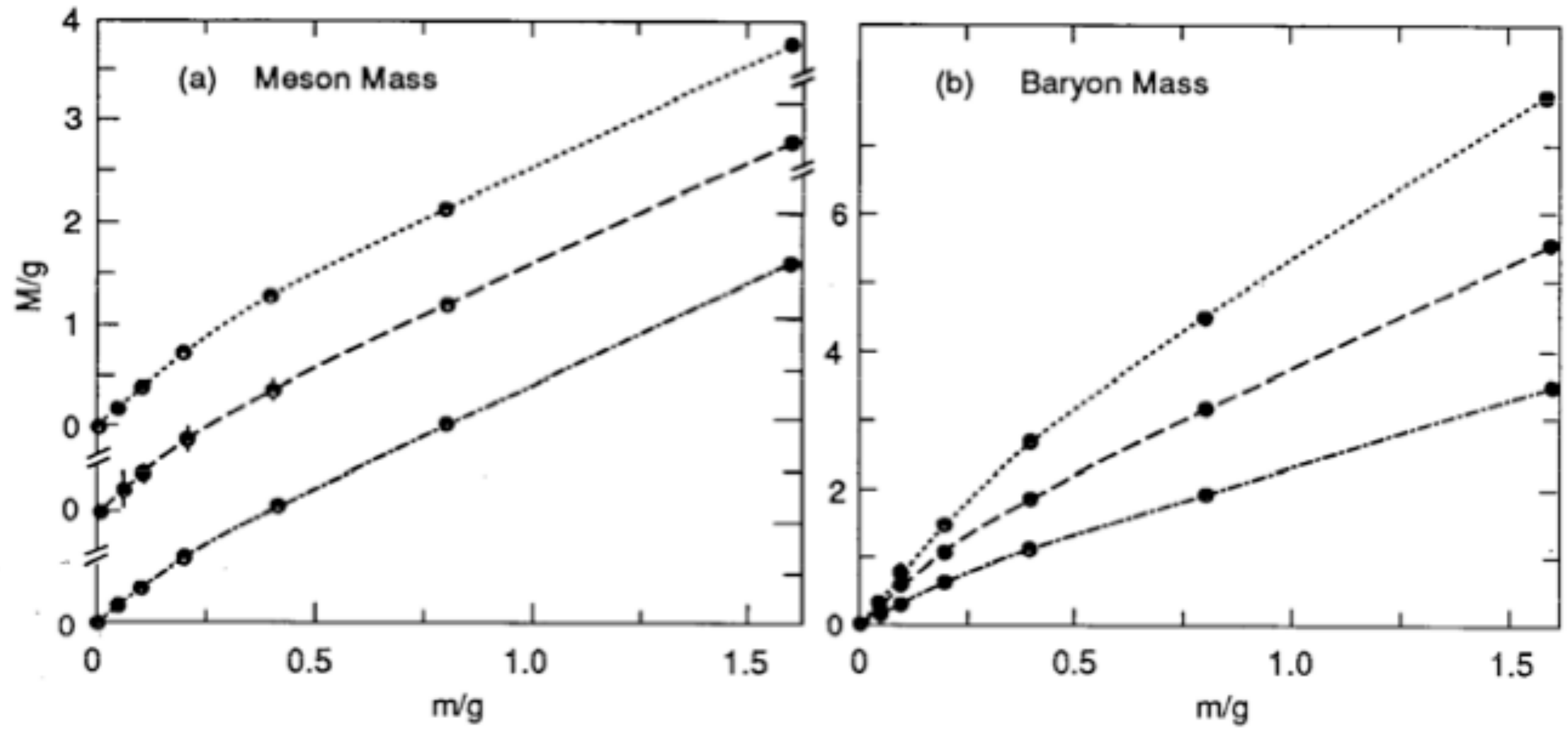
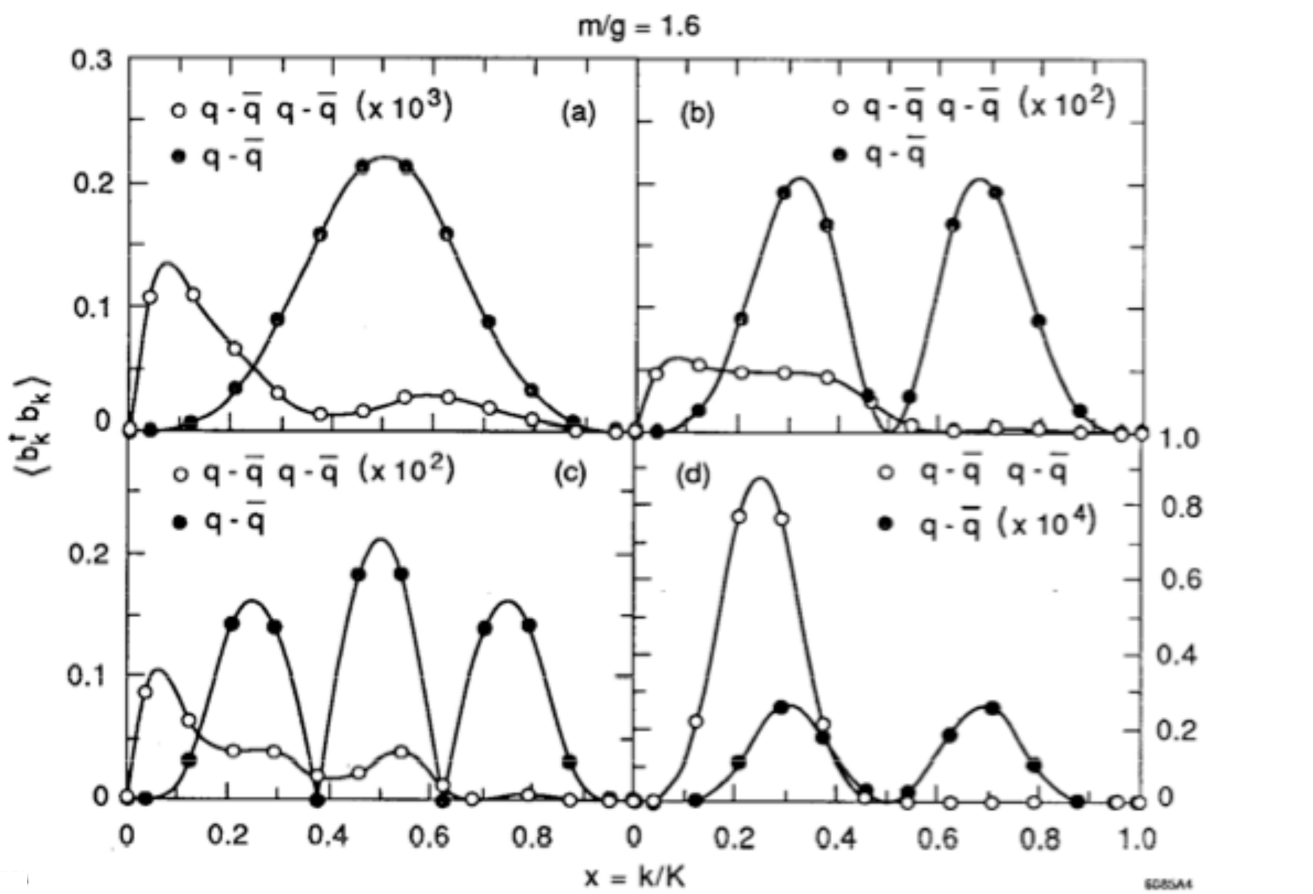
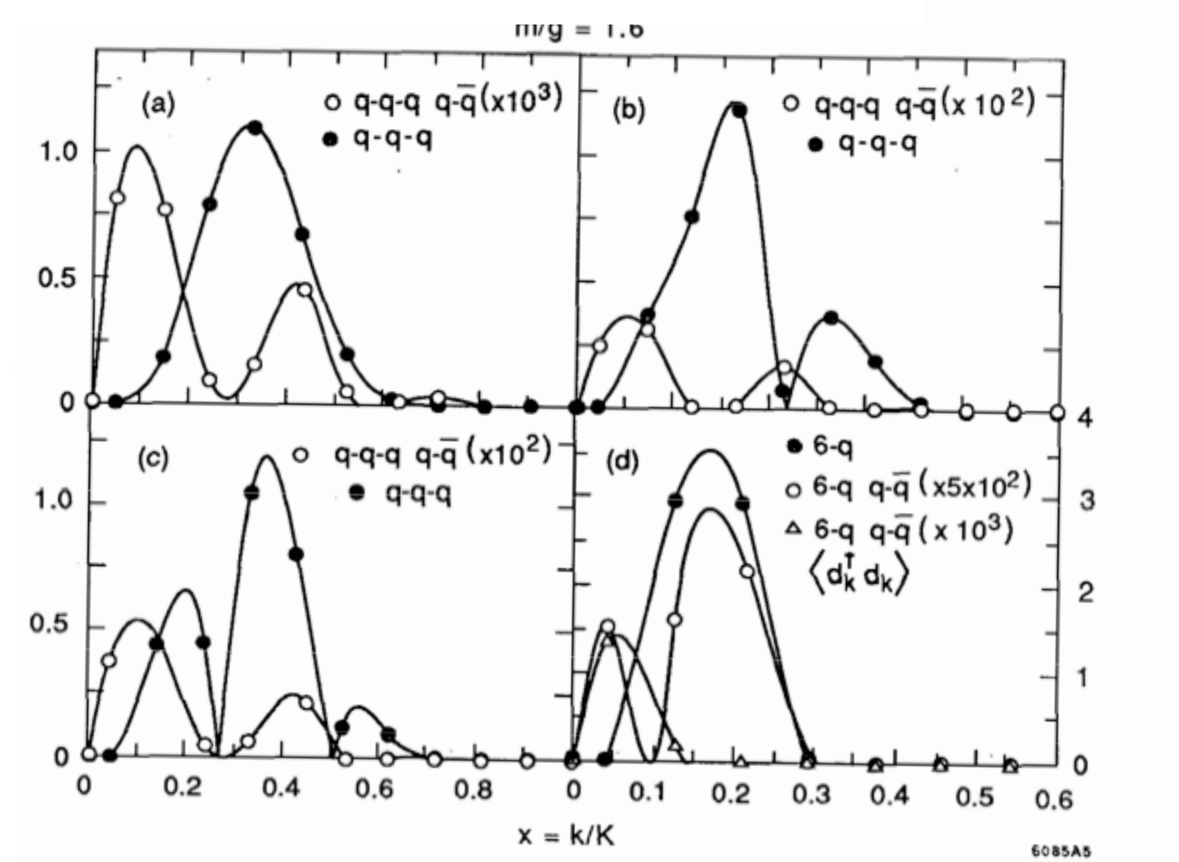


Extrapolated masses for $N = 2, 3$ and 4 meson and baryon.



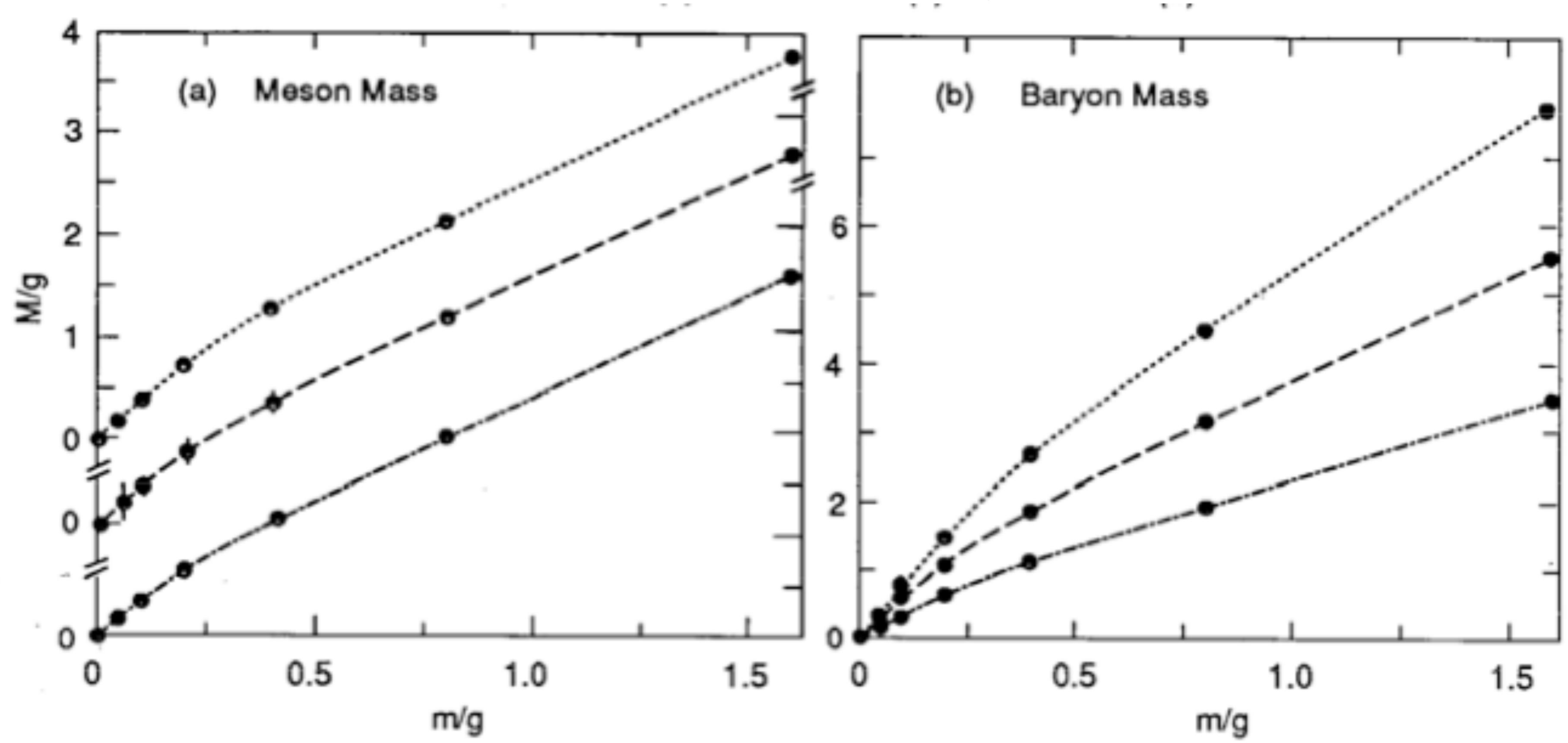
a-c) First three states in $N = 3$ meson spectrum for $m/g = 1.6$, 2K=24. d) Eleventh state.



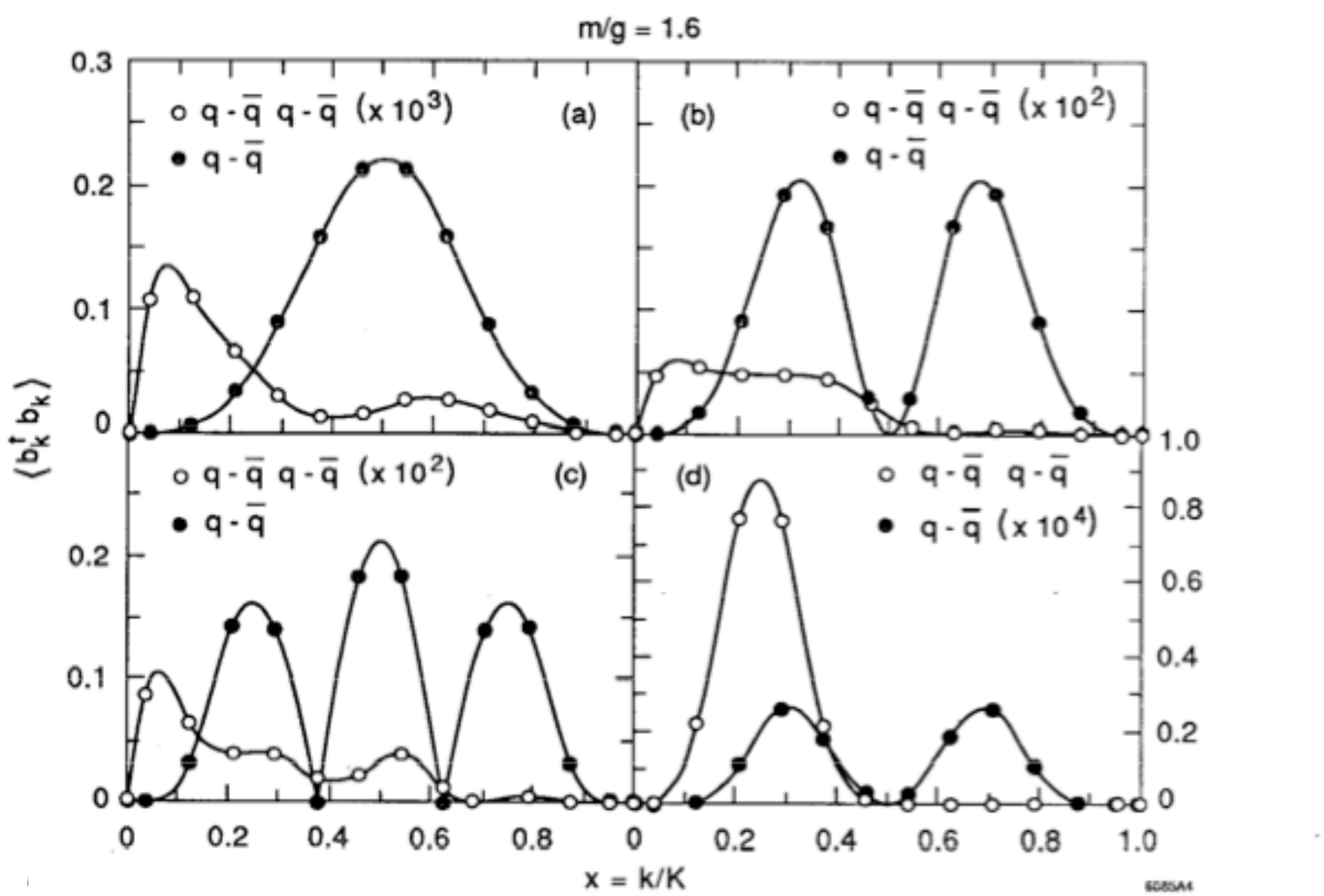
a-c) First three states in $N = 3$ baryon spectrum, 2K=21. d) First $B = 2$ state.

Hornbostel, Pauli, sjb

DLCQ: Solve QCD(1+1) for any quark mass and flavors



Extrapolated masses for $N = 2, 3$ and 4 meson and baryon.



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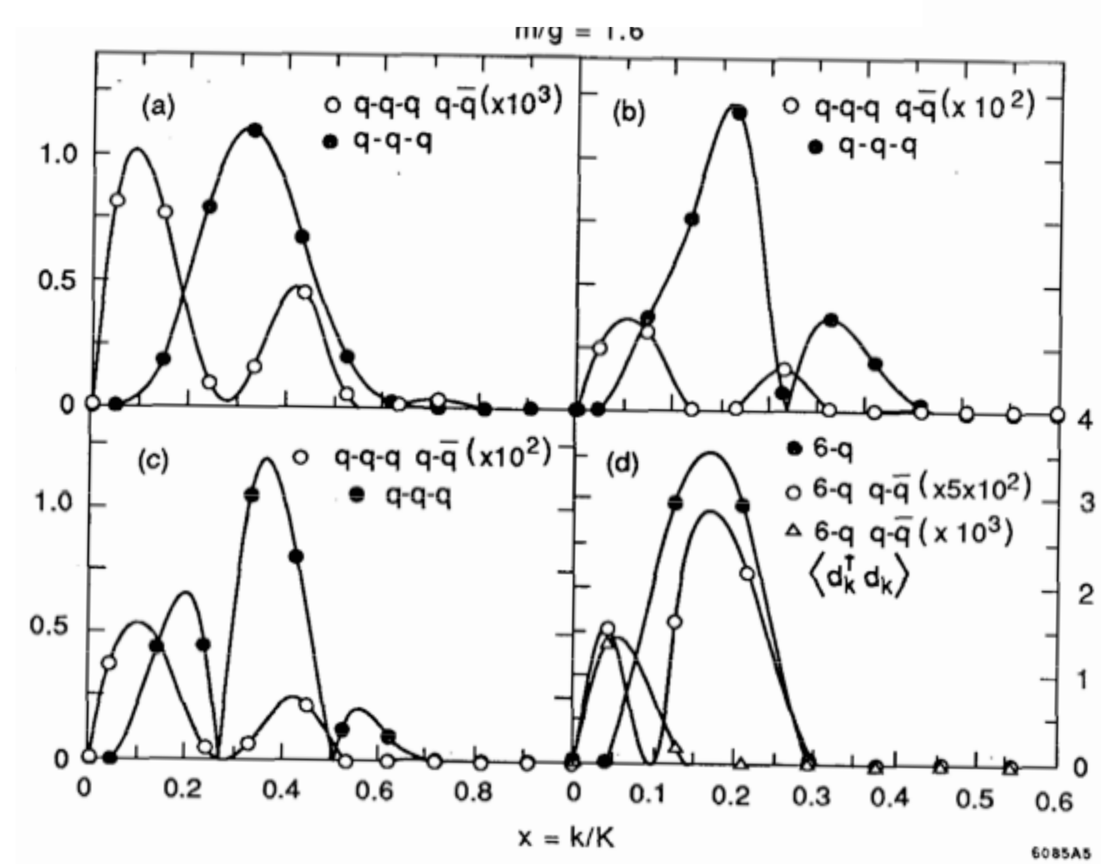

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Hornbostel, Pauli, sjb

Light Front Theory

- Frame-Independent, causal, Minkowski space,
- DLCQ, BLFQ: No fermion doubling
- Equivalent to Bethe-Salpeter $\int dk^- \psi_{BS} = \psi_{LF}$
- Hadronization at the Amplitude Level
- Holographically Dual to AdS_5

This meeting:

New LF methods for solving QCD

- Light-Front Holography
- Basis Light-Front Quantization
- Polynomial Basis
- Iterated Resolvent
- Rigorous gauge-invariant renormalization
- True muonium
- ....

$$|p, S_z> = \sum_{n=3} \Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i) |n; \vec{k}_{\perp_i}, \lambda_i>$$

sum over states with n=3, 4, ...constituents

The Light Front Fock State Wavefunctions

$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

are boost invariant; they are independent of the hadron's energy and momentum P^μ.

The light-cone momentum fraction

$$x_i = \frac{k_i^+}{p^+} = \frac{k_i^0 + k_i^z}{P^0 + P^z}$$

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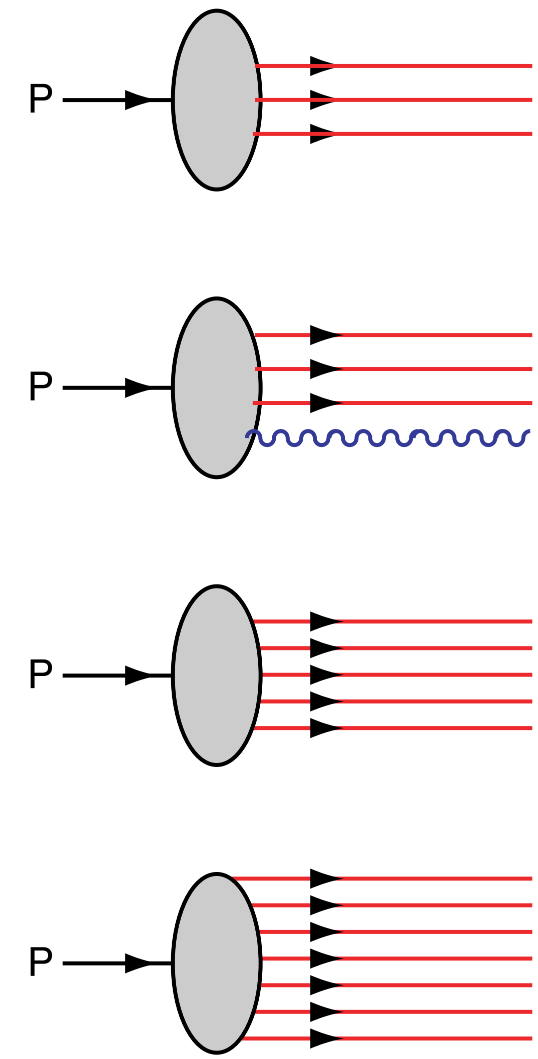

Intrinsic heavy quarks $\bar{s}(x) \neq s(x)$

s(x), c(x), b(x) at high x ! $\bar{u}(x) \neq \bar{d}(x)$

Mueller: gluon Fock states: BFKL Pomeron

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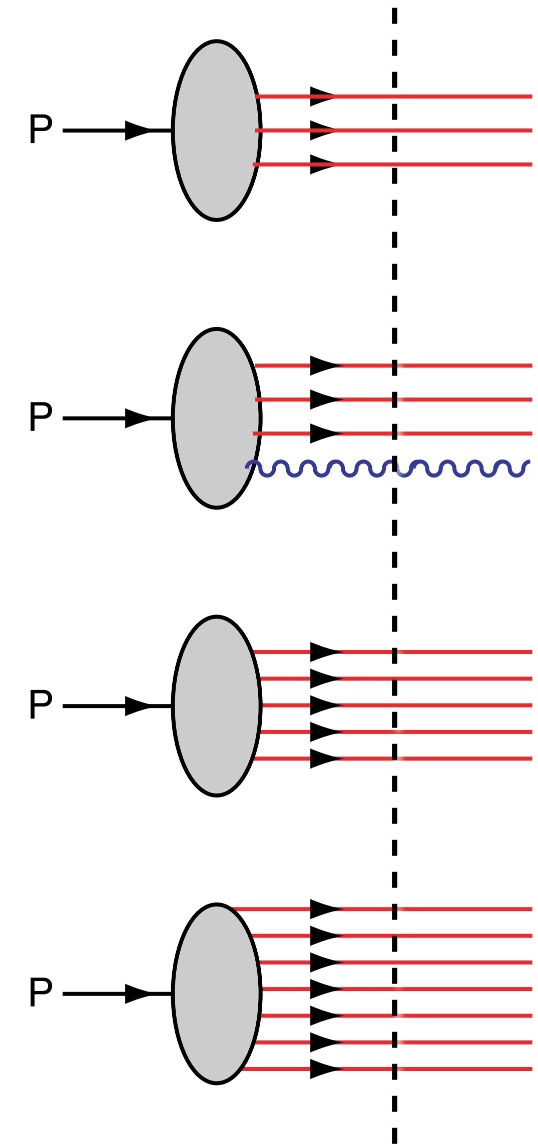

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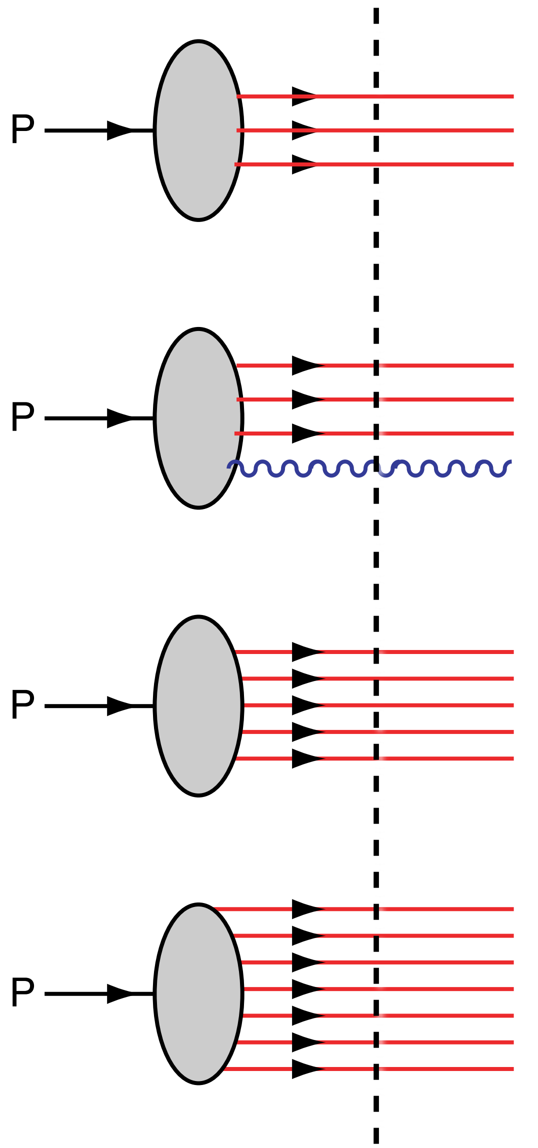

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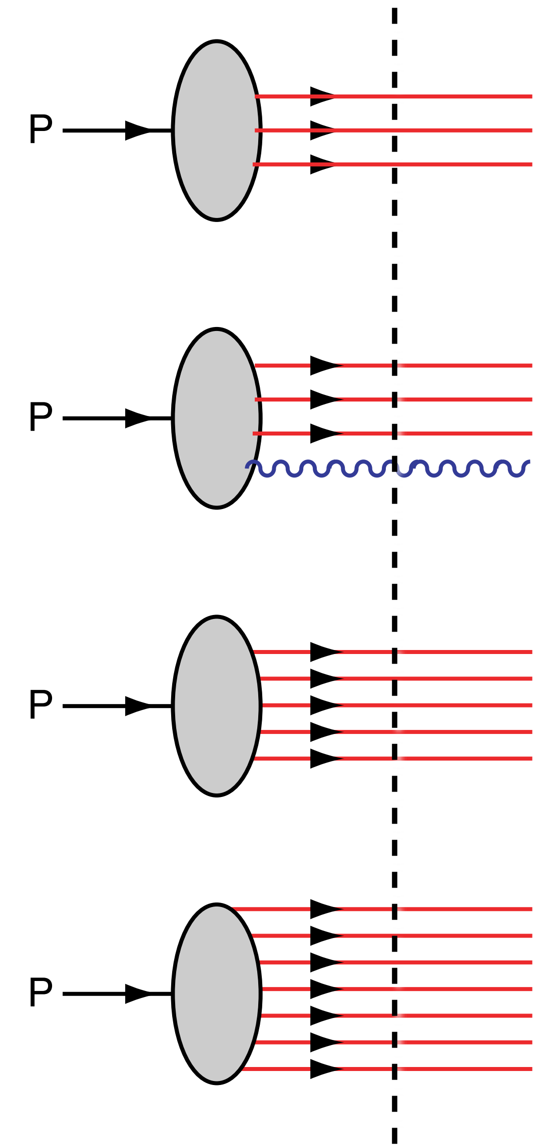

Fixed LF time

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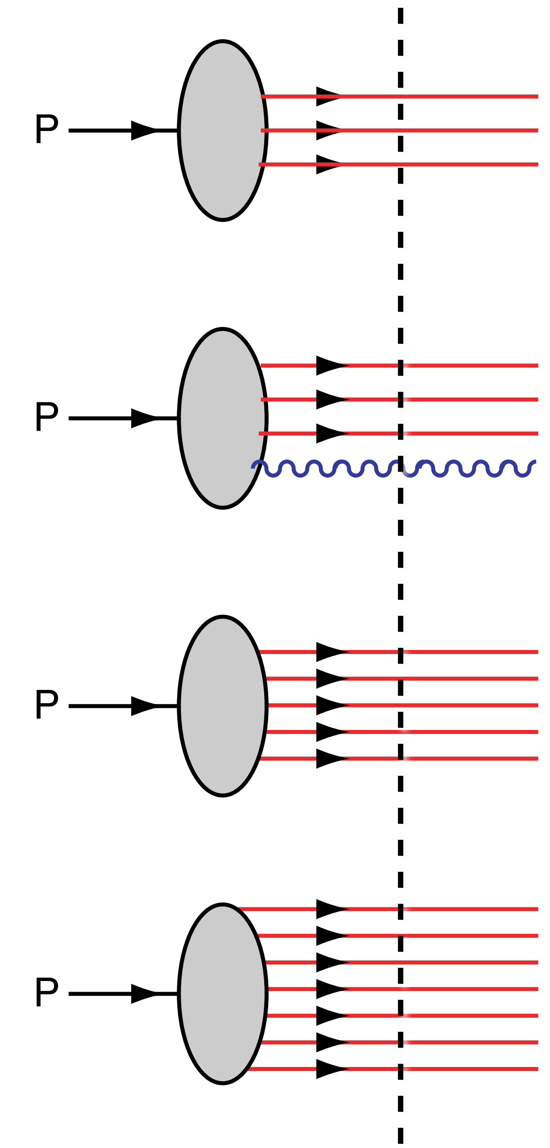

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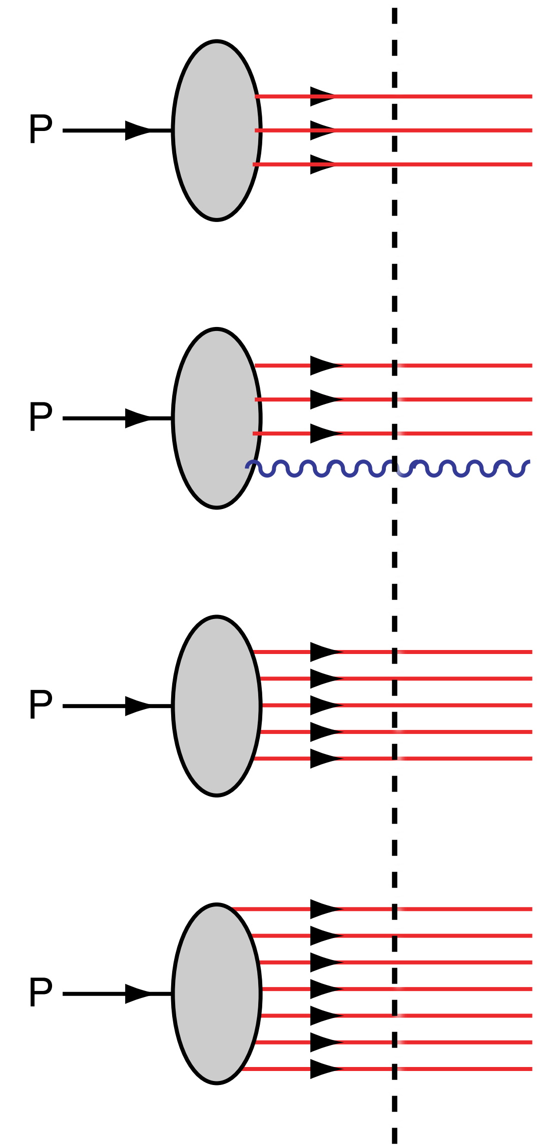

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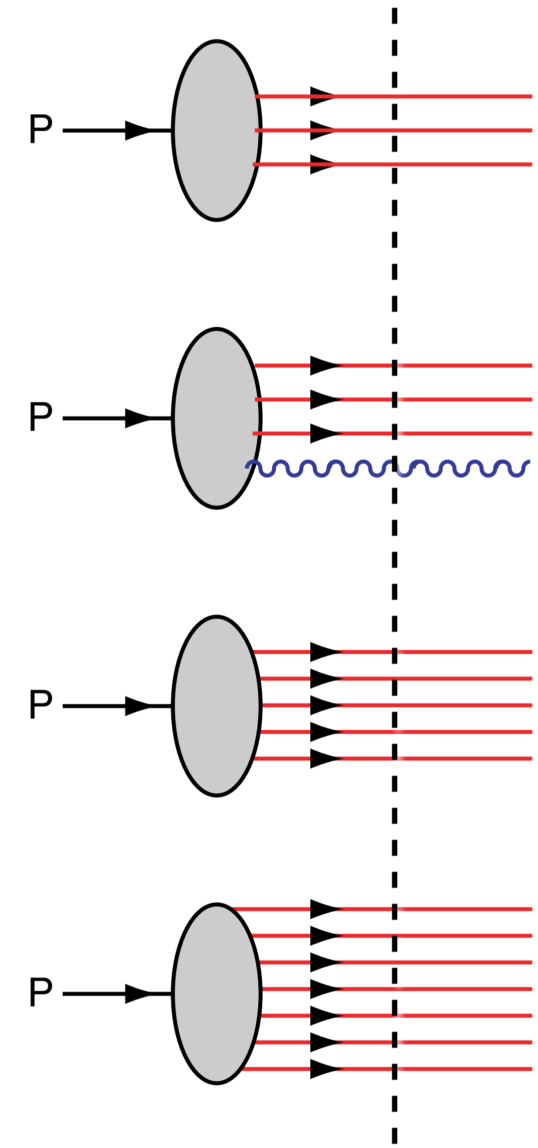

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Hidden Color

Angular Momentum on the Light-Front

LC gauge $A^+=0$

$$J^z = \sum_{i=1}^{n} s_i^z + \sum_{j=1}^{n-1} l_j^z.$$

Conserved
LF Fock state by Fock State

Gluon orbital angular momentum defined in physical lc gauge

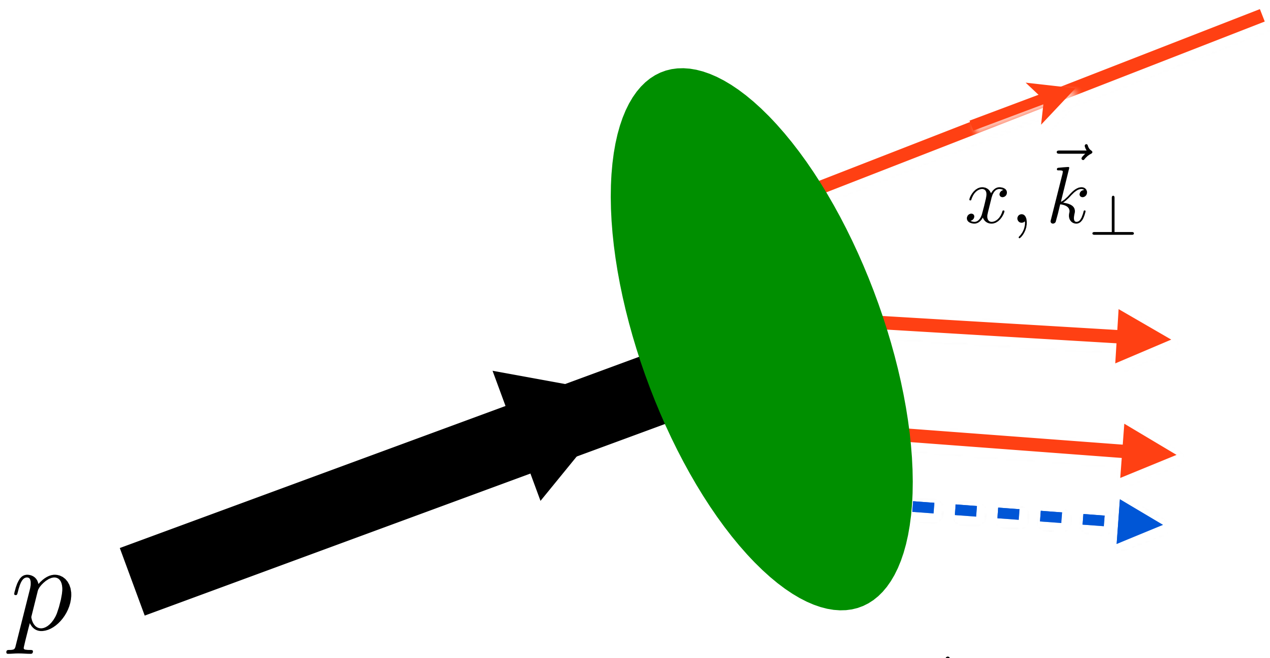
$$l_j^z = -\mathrm{i}\left(k_j^1 \frac{\partial}{\partial k_j^2} - k_j^2 \frac{\partial}{\partial k_j^1}\right)$$

n-1 orbital angular momenta

Orbital Angular Momentum is a property of LFWFS

Nonzero Anomalous Moment -->
Nonzero quark orbital angular momentum!

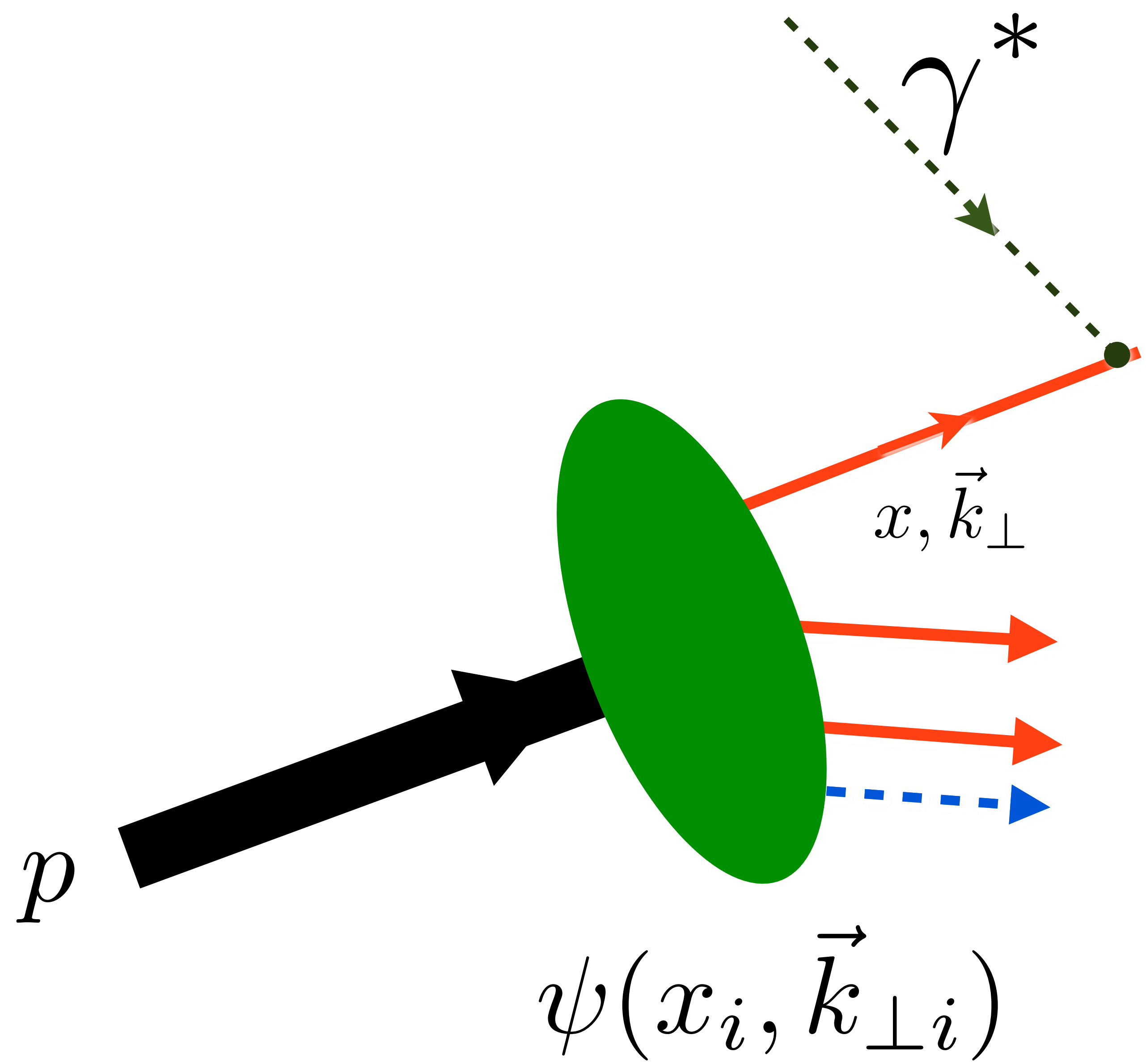
Interaction picture



$$\psi(x_i, \vec{k}_{\perp i})$$

Drell &Yan, West
Exact LF formula!

Interaction picture



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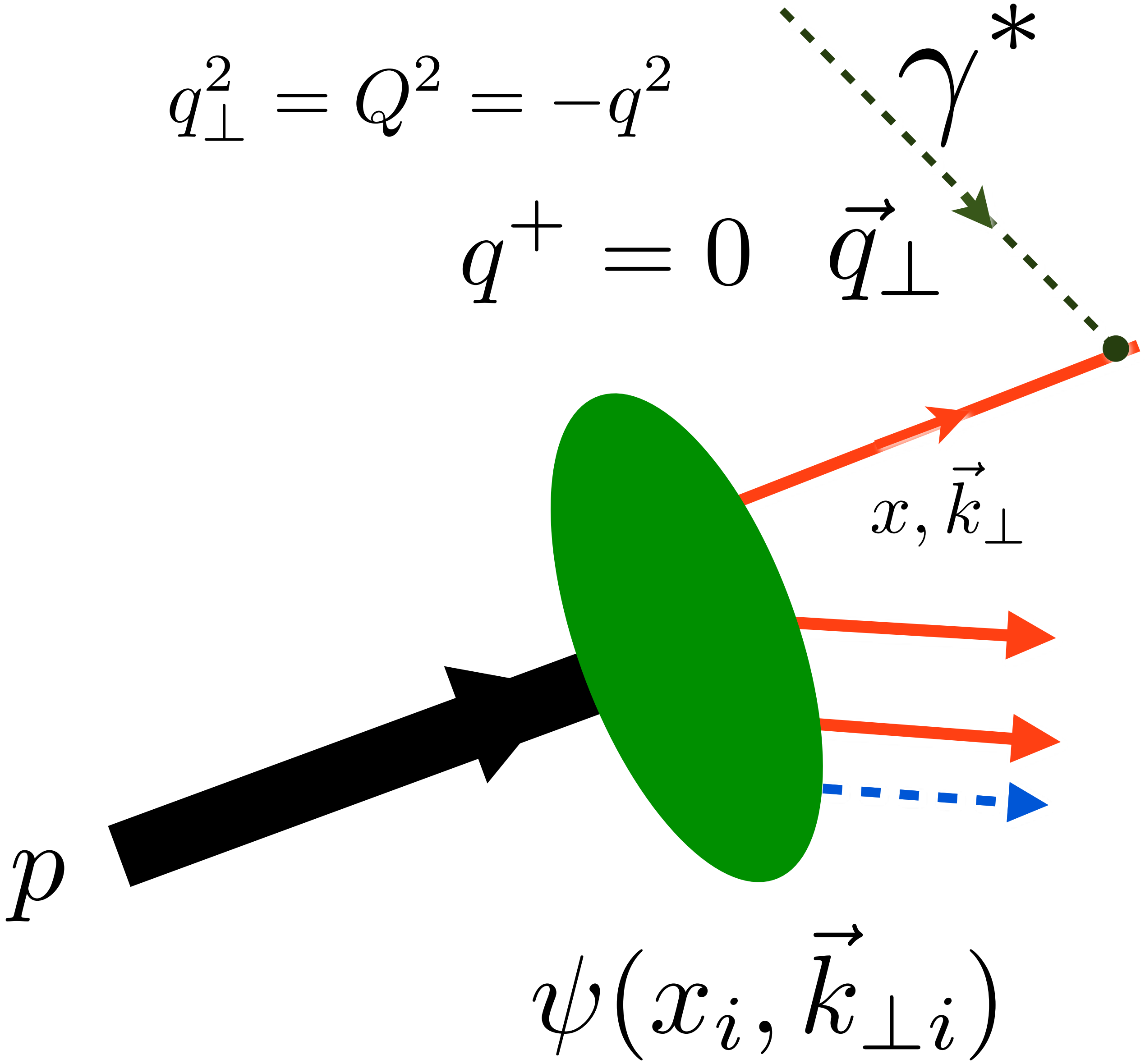

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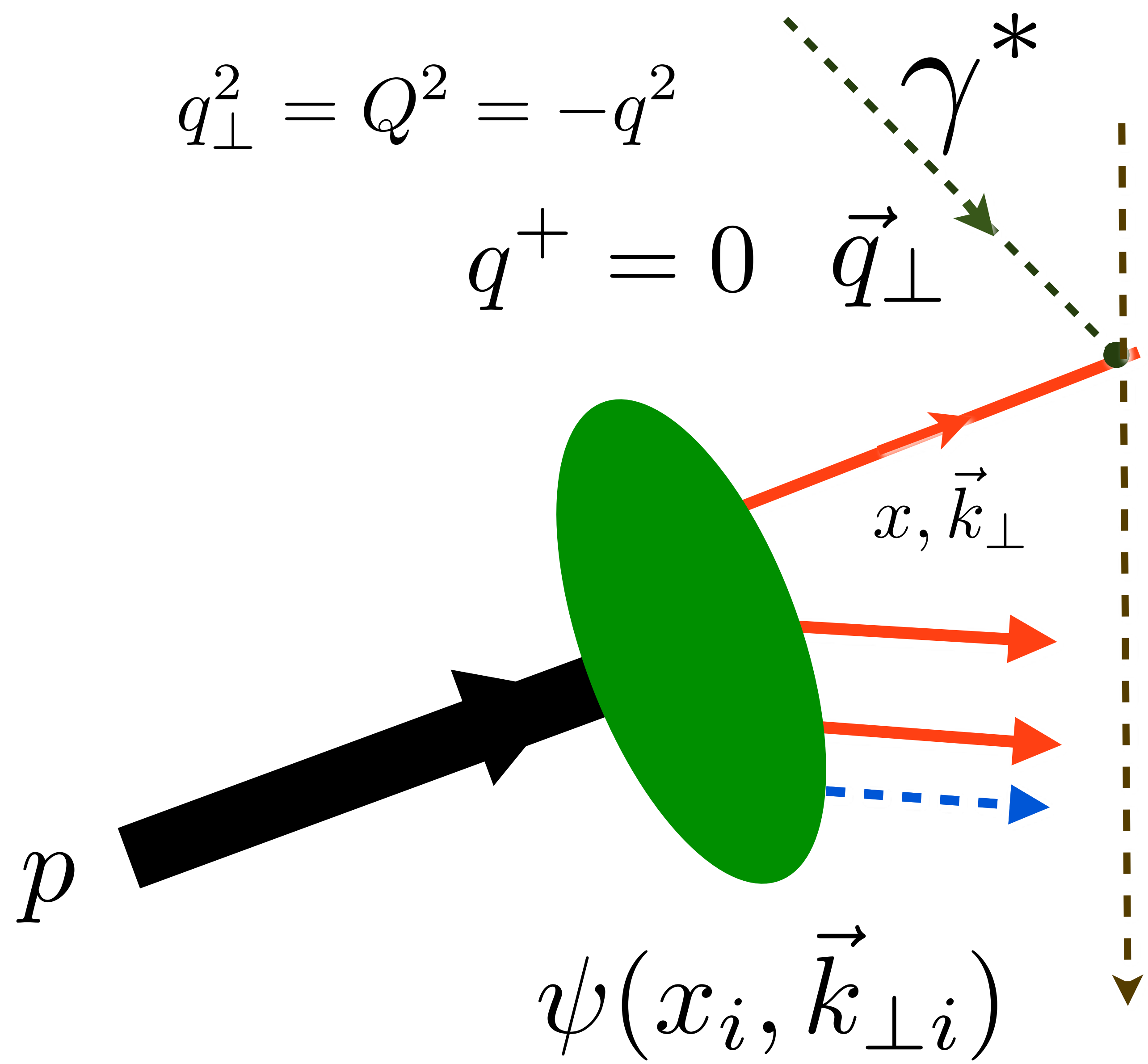

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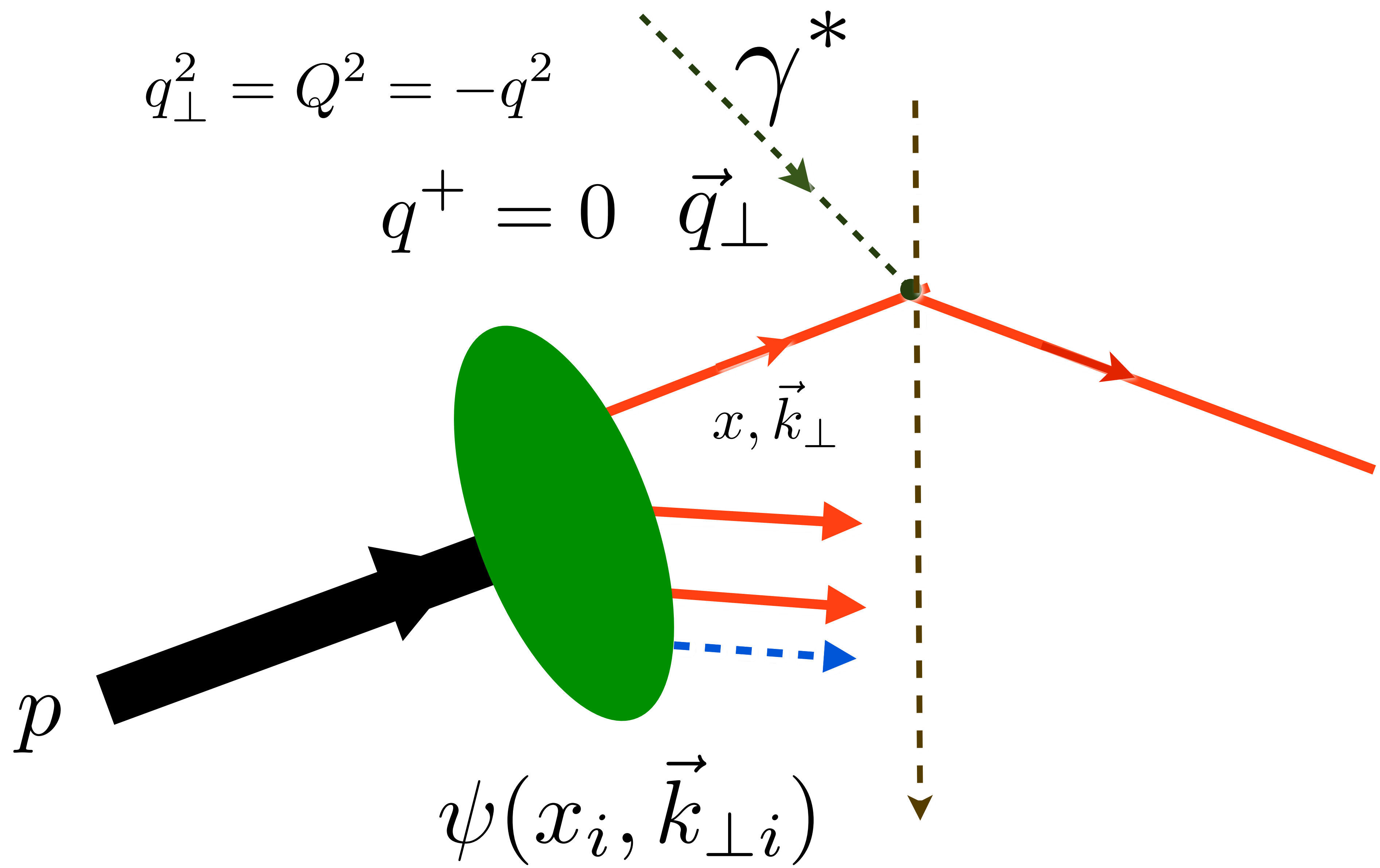

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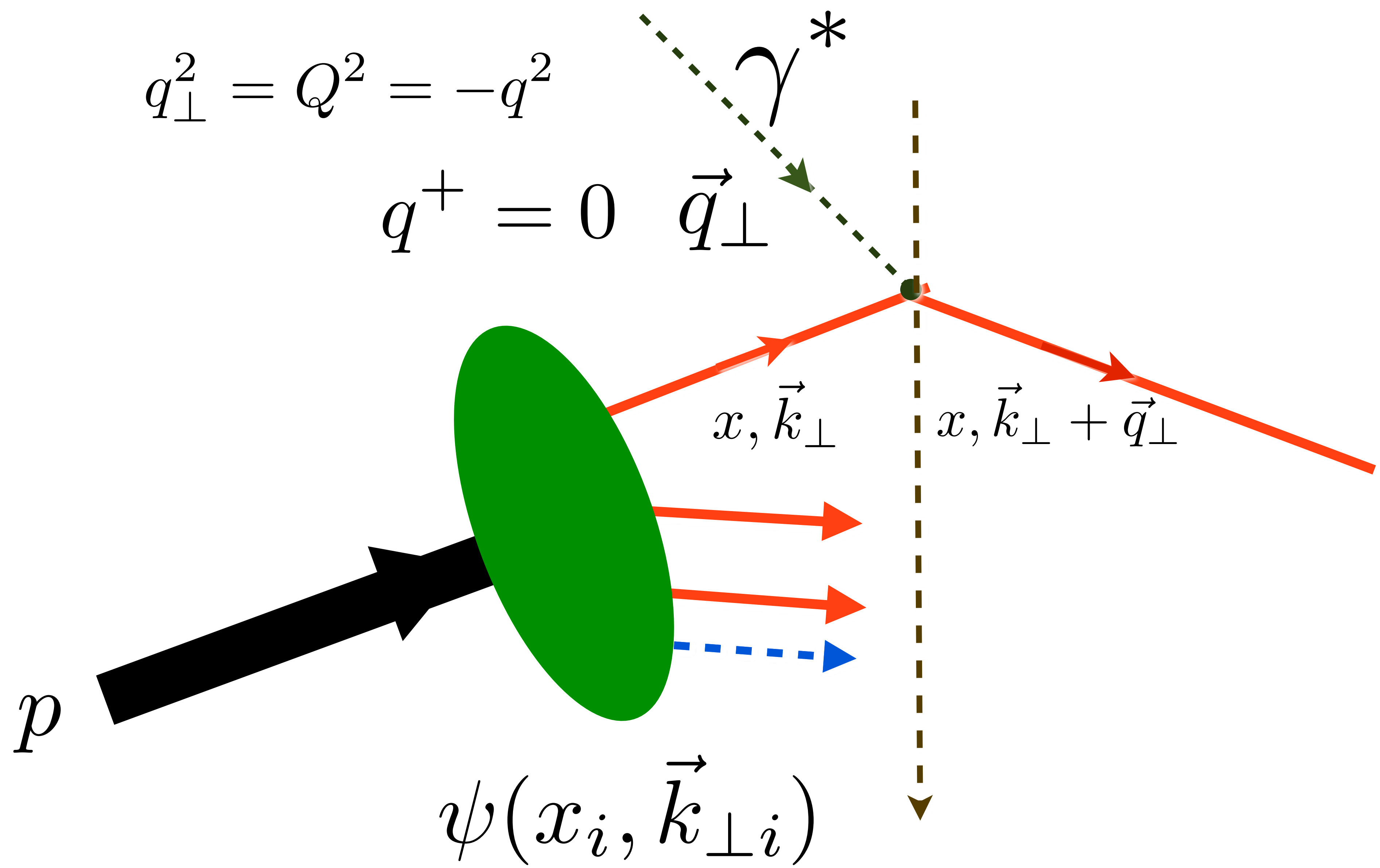

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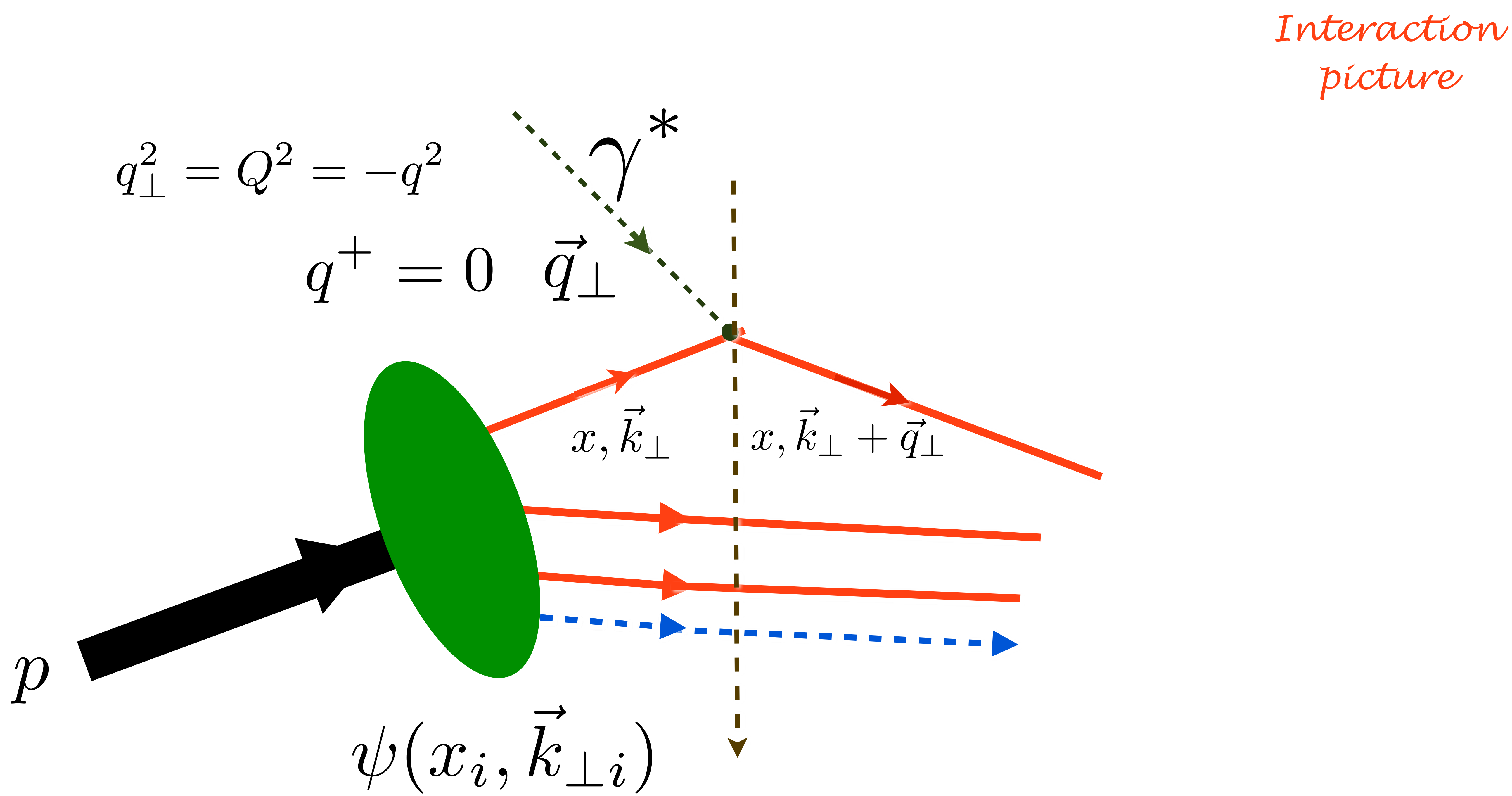

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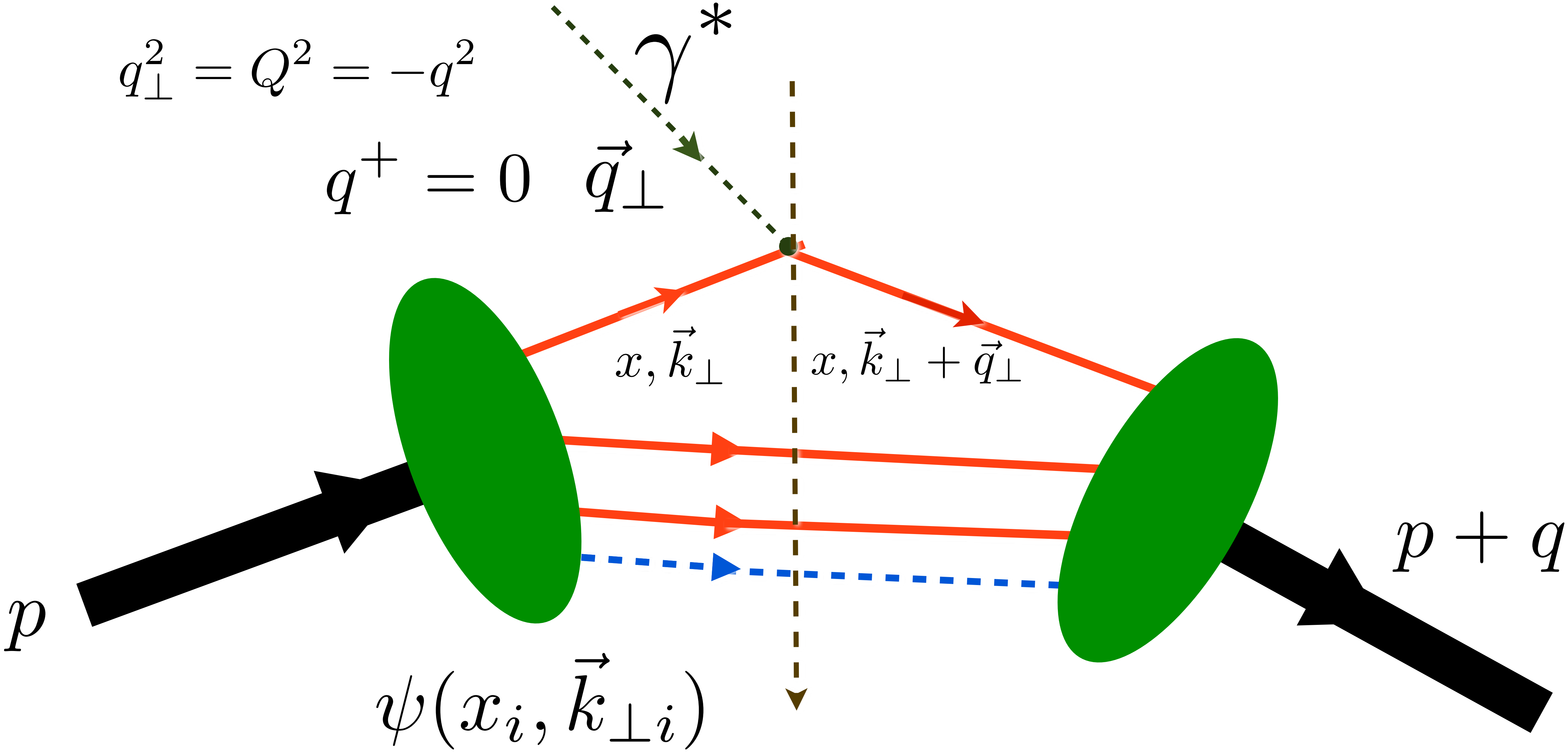

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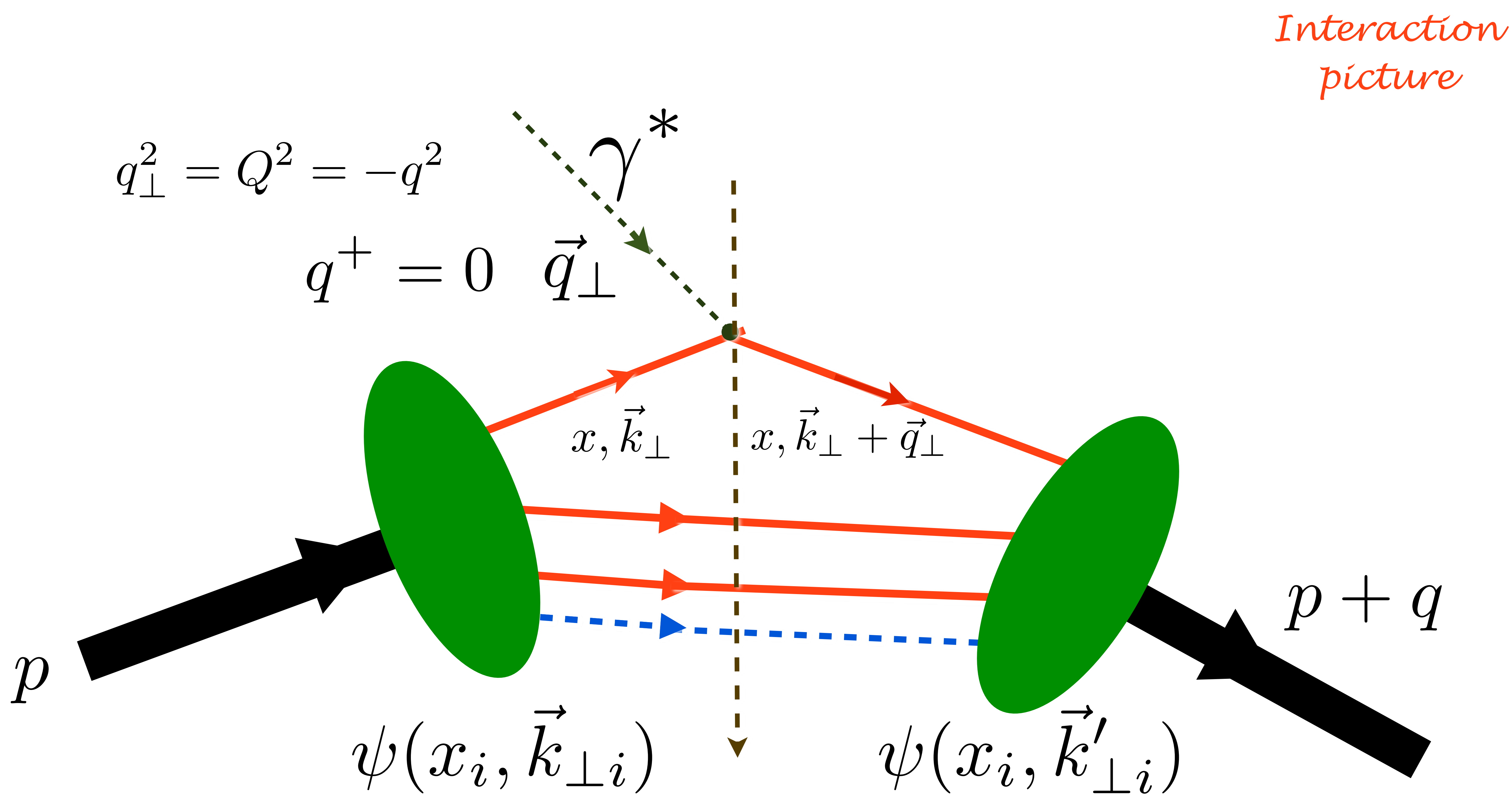

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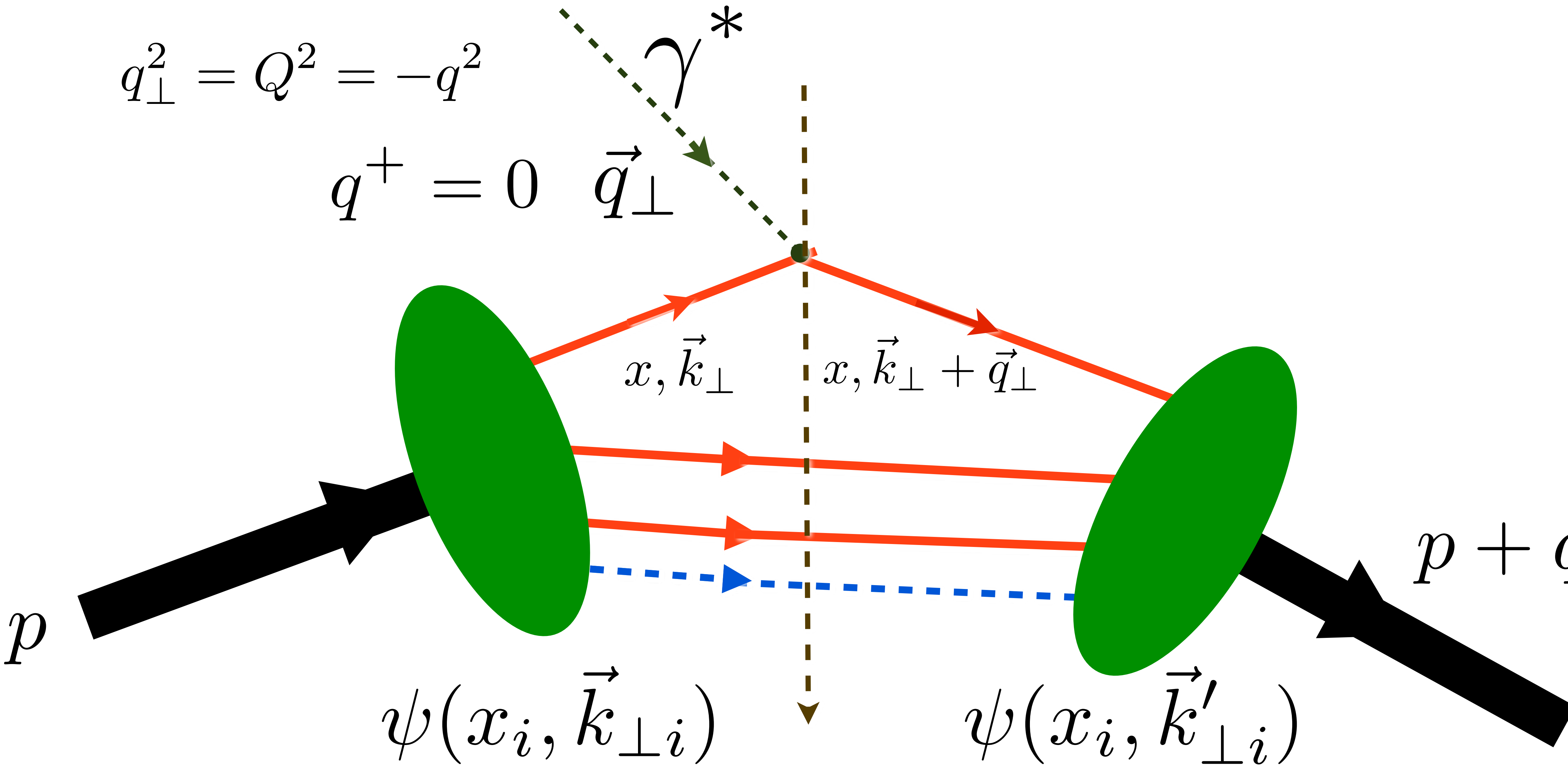

struck $\vec{k}'_{\perp i} = \vec{k}_{\perp i} + (1 - x_i)\vec{q}_\perp$

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Exact LF formula!

$$< p + q|j^+(0)|p > = 2p^+ F(q^2)$$

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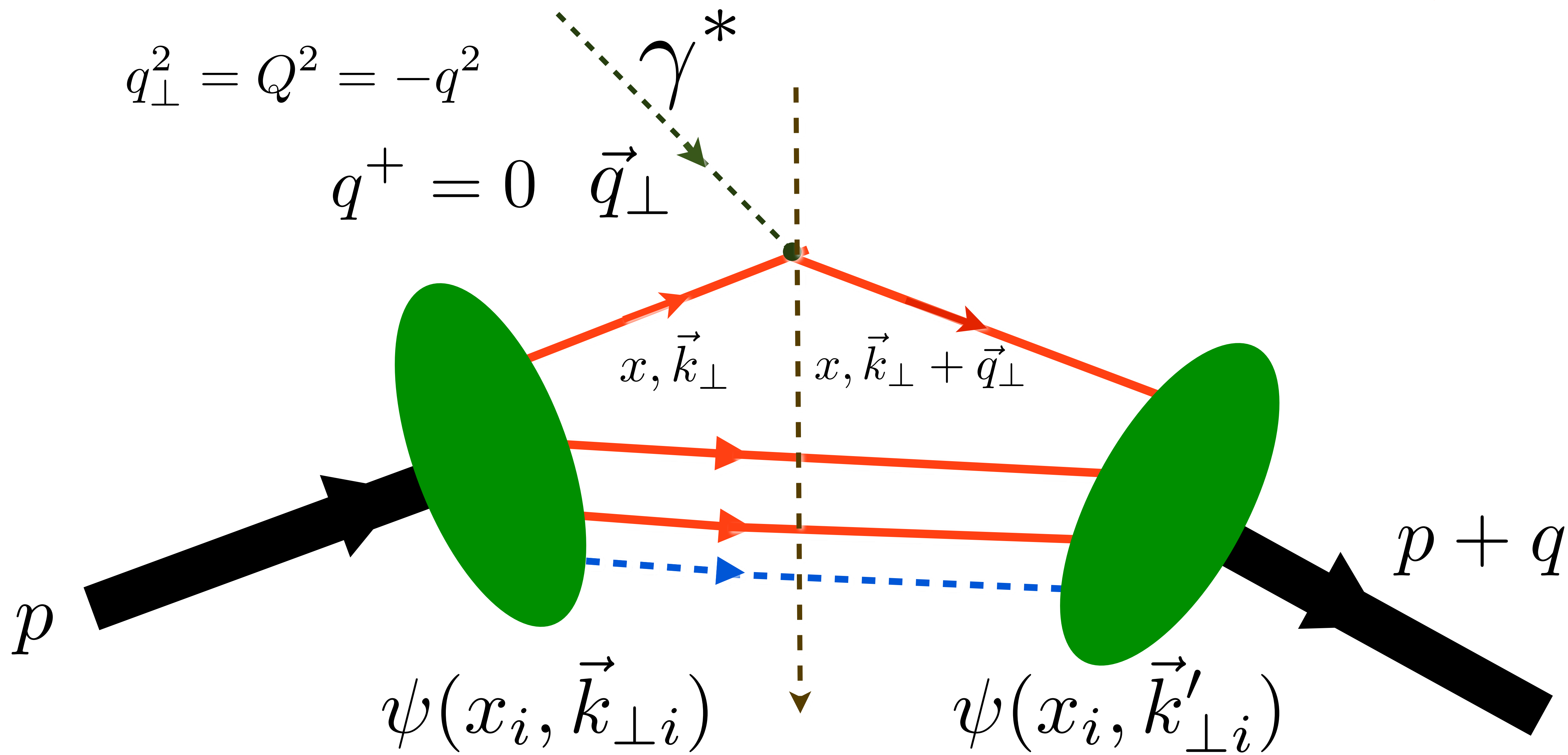

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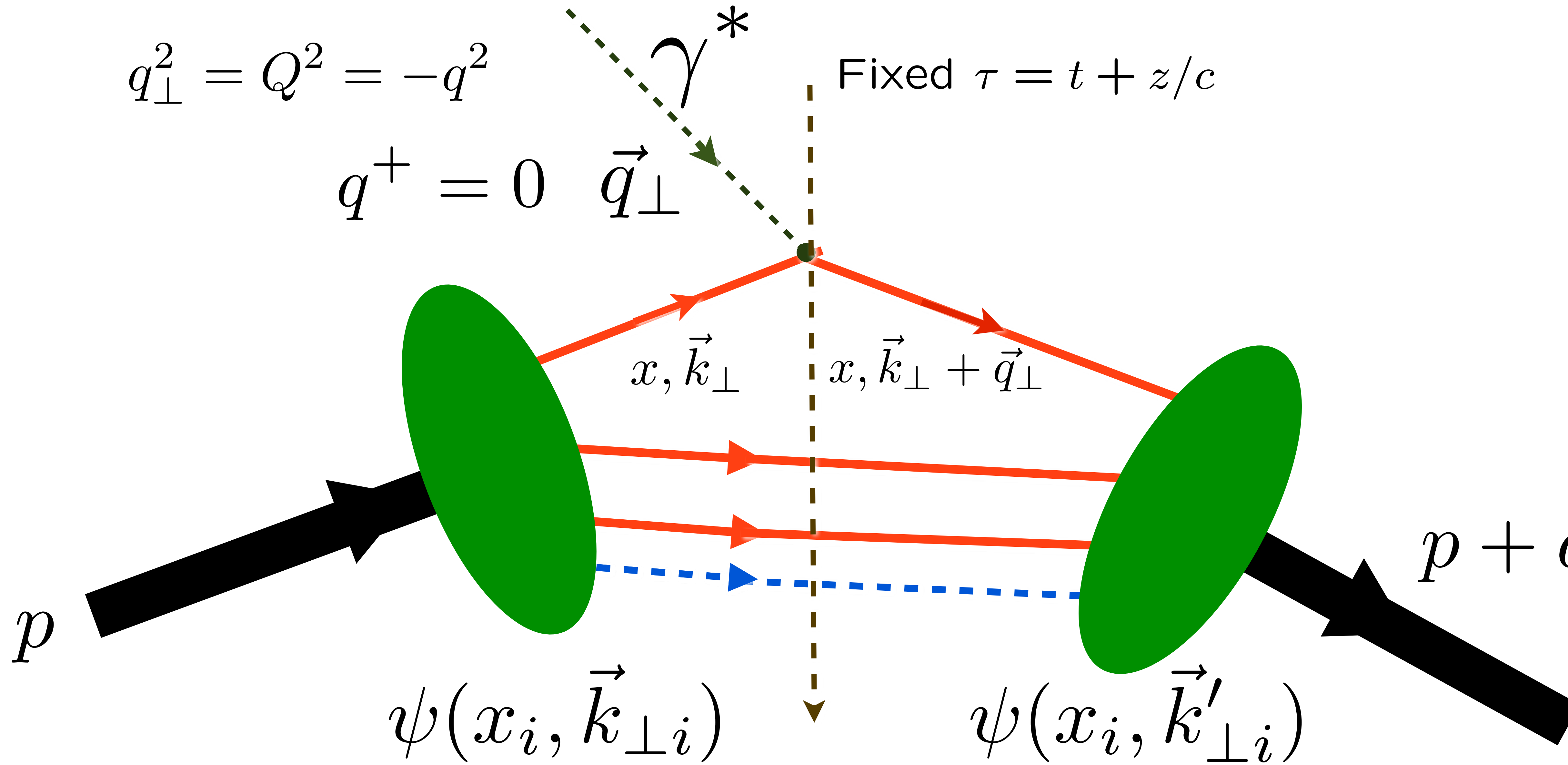

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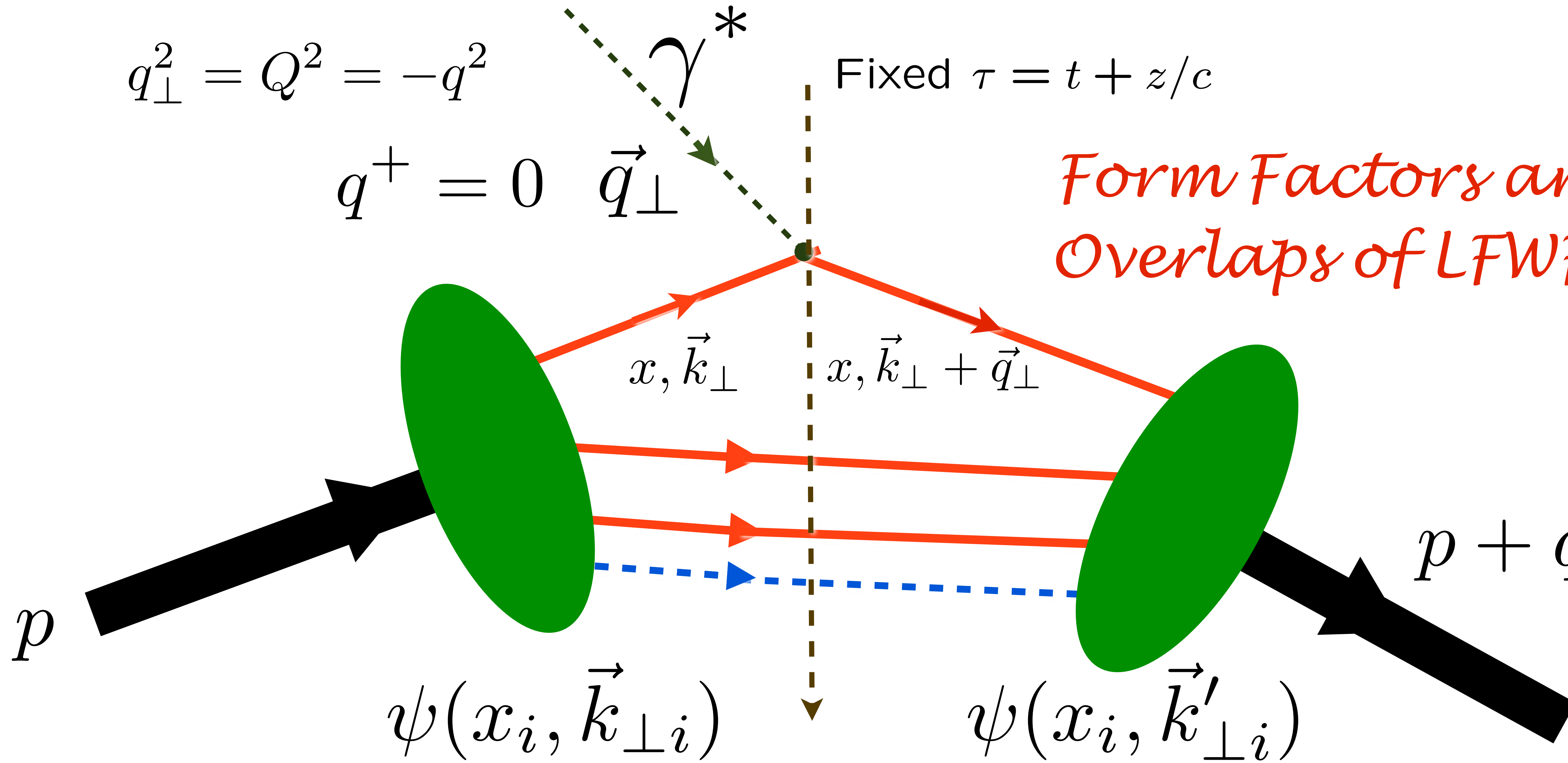

Form Factors are Overlaps of LFWFs

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Drell &Yan, West
Exact LF formula!

Exact LF Formula for Pauli Form Factor

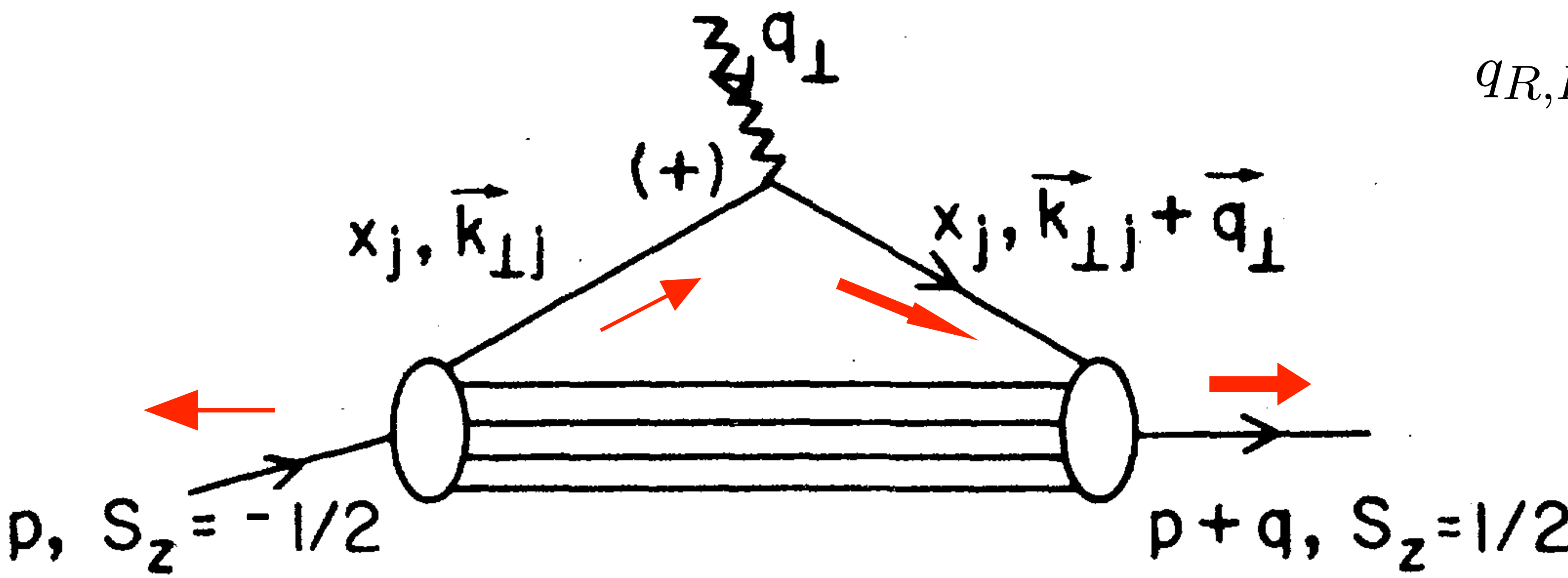
$$\frac{F_2(q^2)}{2M} = \sum_a \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp] \sum_j e_j \, \frac{1}{2} \times$$

Drell, sjb

$$\left[-\frac{1}{q^L}\psi_a^{\uparrow *}(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\, \psi_a^{\downarrow}(x_i, \mathbf{k}_{\perp i}, \lambda_i) + \frac{1}{q^R}\psi_a^{\downarrow *}(x_i, \mathbf{k}'_{\perp i}, \lambda_i)\, \psi_a^{\uparrow}(x_i, \mathbf{k}_{\perp i}, \lambda_i) \right]$$

$$\mathbf{k}'_{\perp i} = \mathbf{k}_{\perp i} - x_i \mathbf{q}_\perp \qquad \mathbf{k}'_{\perp j} = \mathbf{k}_{\perp j} + (1 - x_j)\mathbf{q}_\perp$$

$$q_{R,L} = q^x \pm i q^y$$

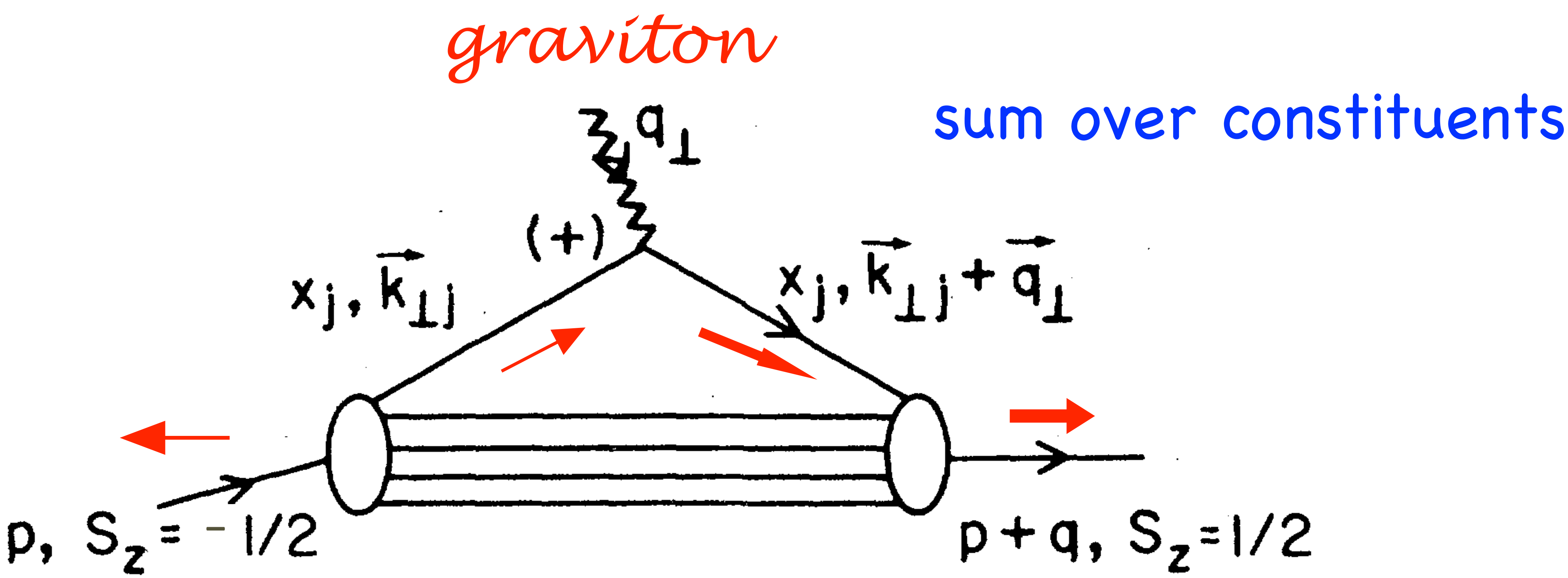


Must have $\Delta \ell_z = \pm 1$ to have nonzero $F_2(q^2)$

Nonzero Proton Anomalous Moment -->
Nonzero orbital quark angular momentum

Vanishing Anomalous gravitomagnetic moment B(0)

Terayev, Okun, et al: B(0) Must vanish because of Equivalence Theorem



Hwang, Schmidt, sjb;
Holstein et al

B(0) = 0

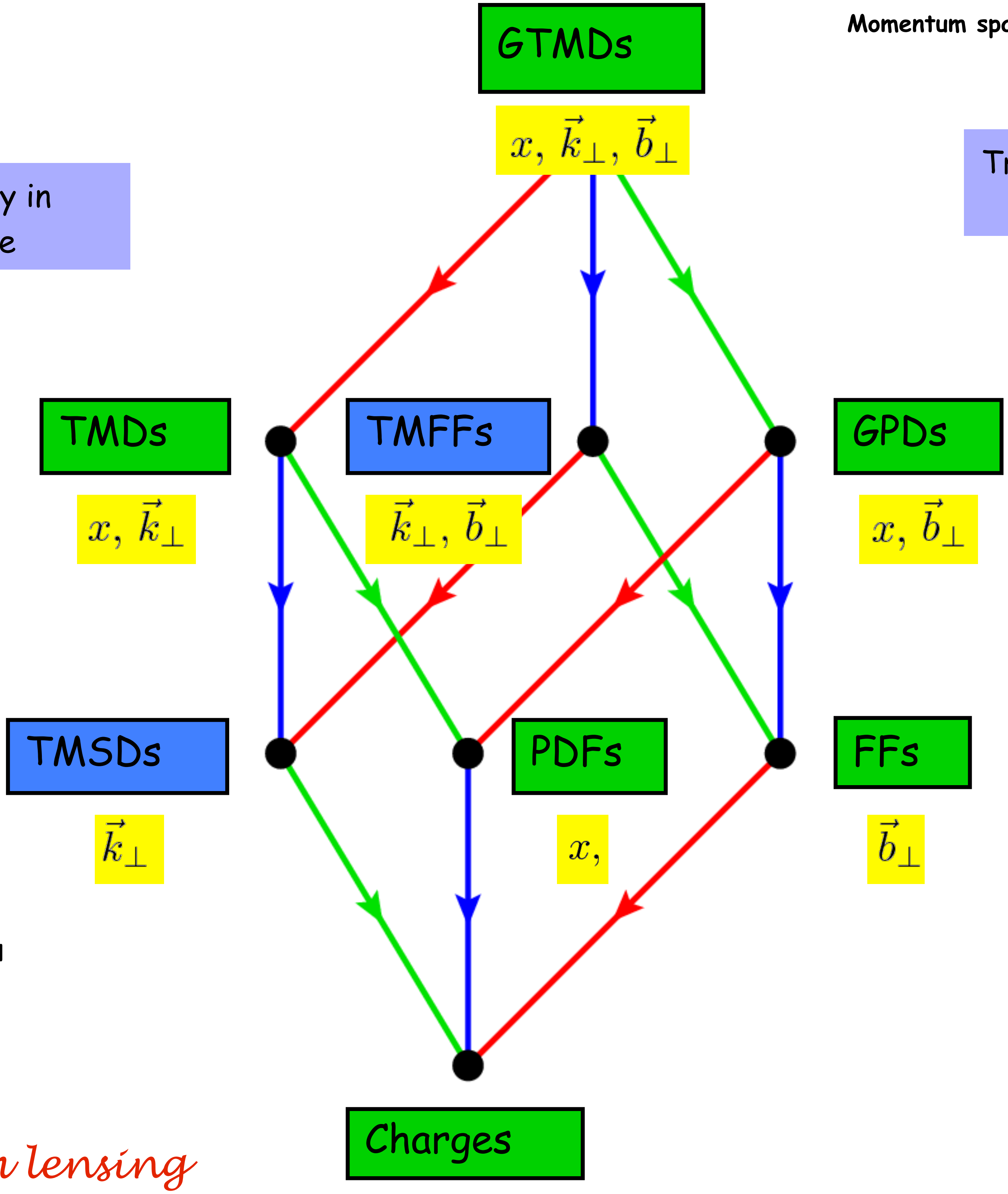
Each Fock State

Momentum space $\vec{k}_\perp \leftrightarrow \vec{z}_\perp$ Position space

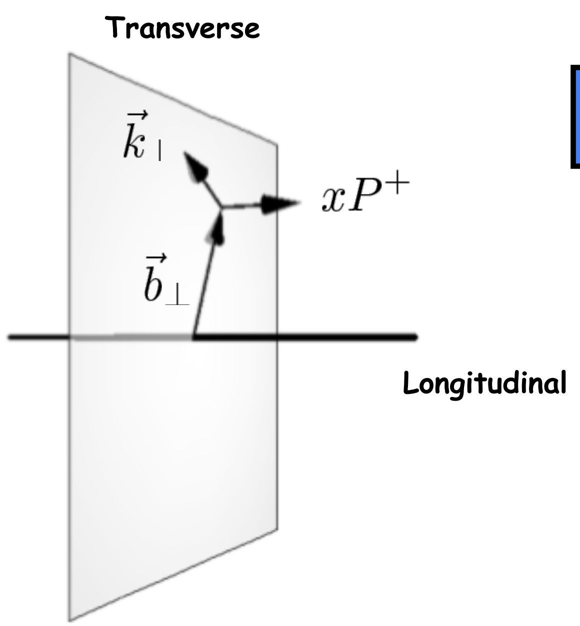
$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$

Transverse density in momentum space

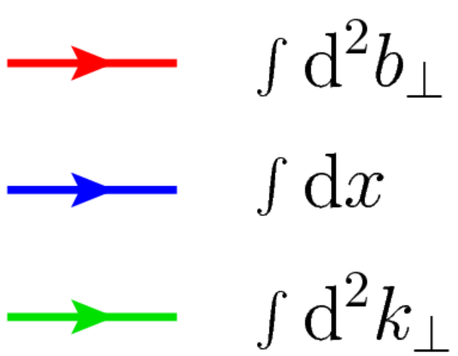
Transverse density in position space



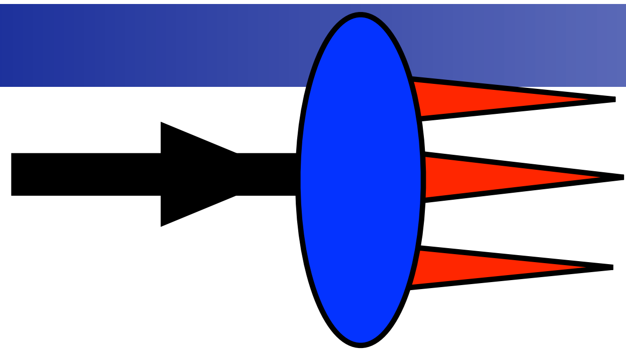
Lorce, Pasquini



Diehl, Hwang, sjb



Sivers, T-odd from lensing



$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

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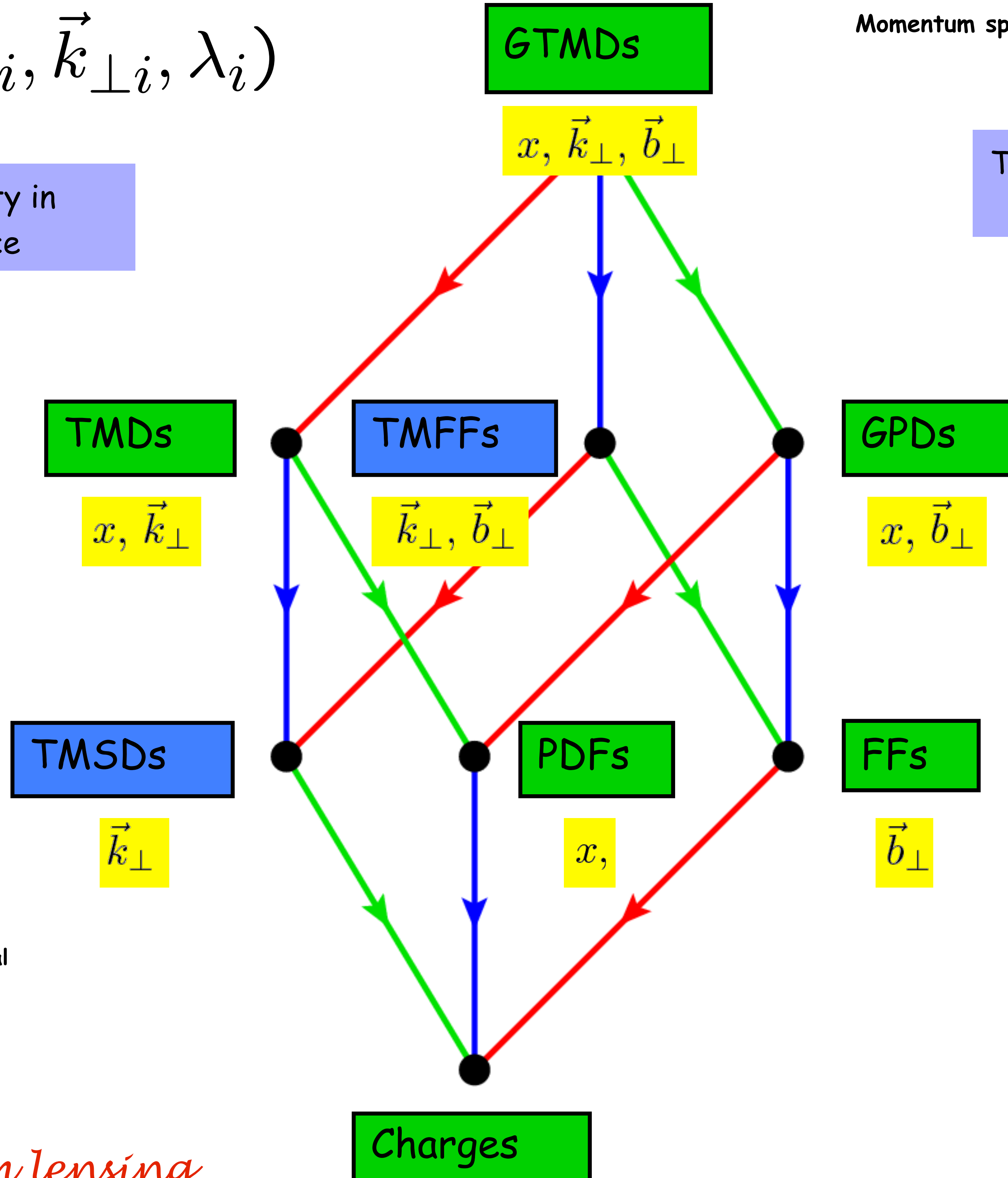
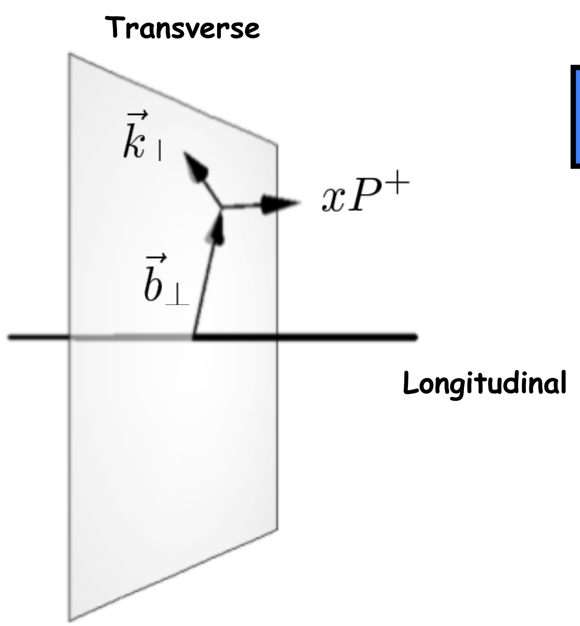


Lorce, Pasquini

Diehl, Hwang, sjb



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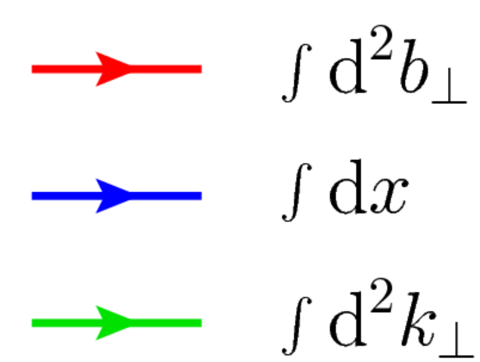
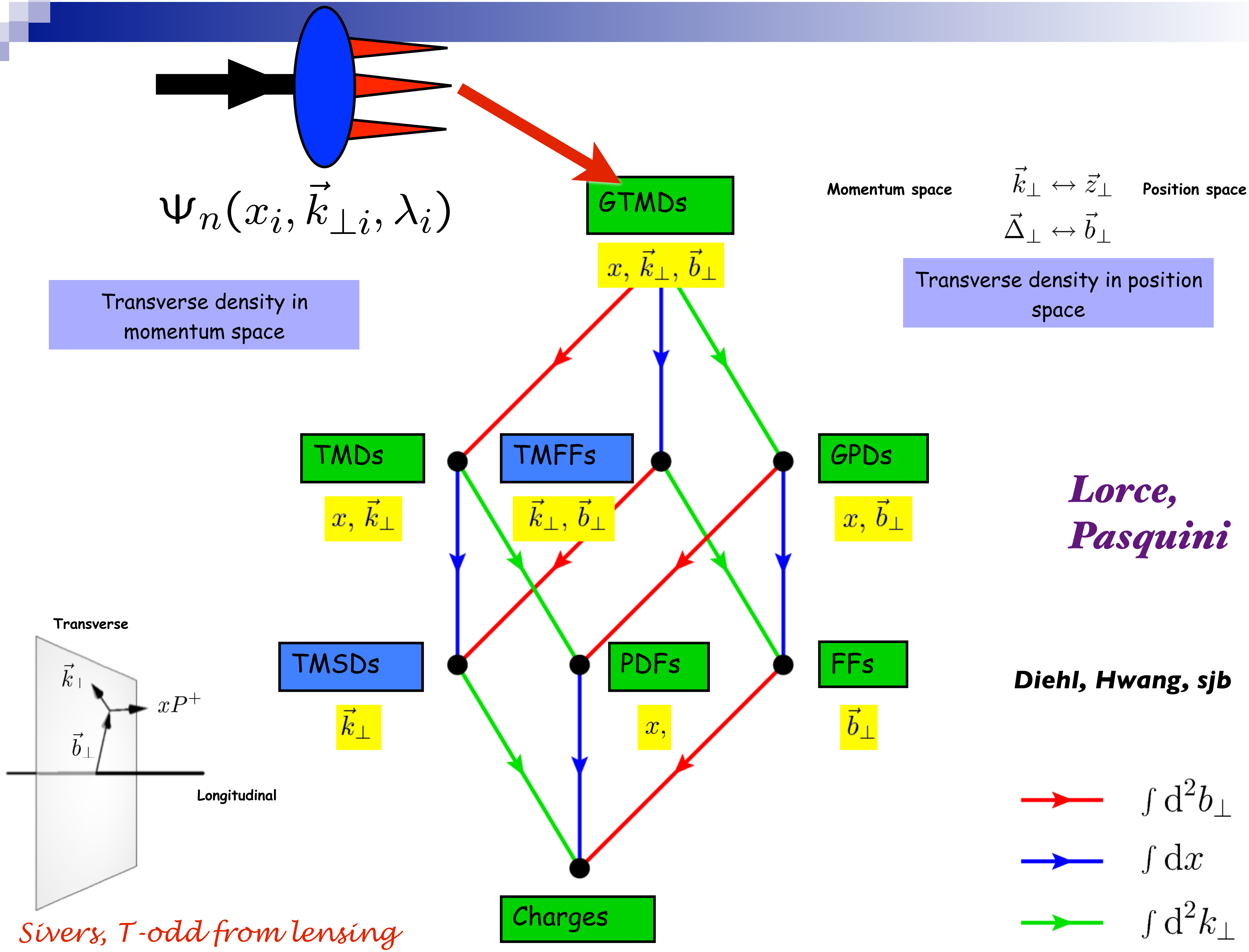
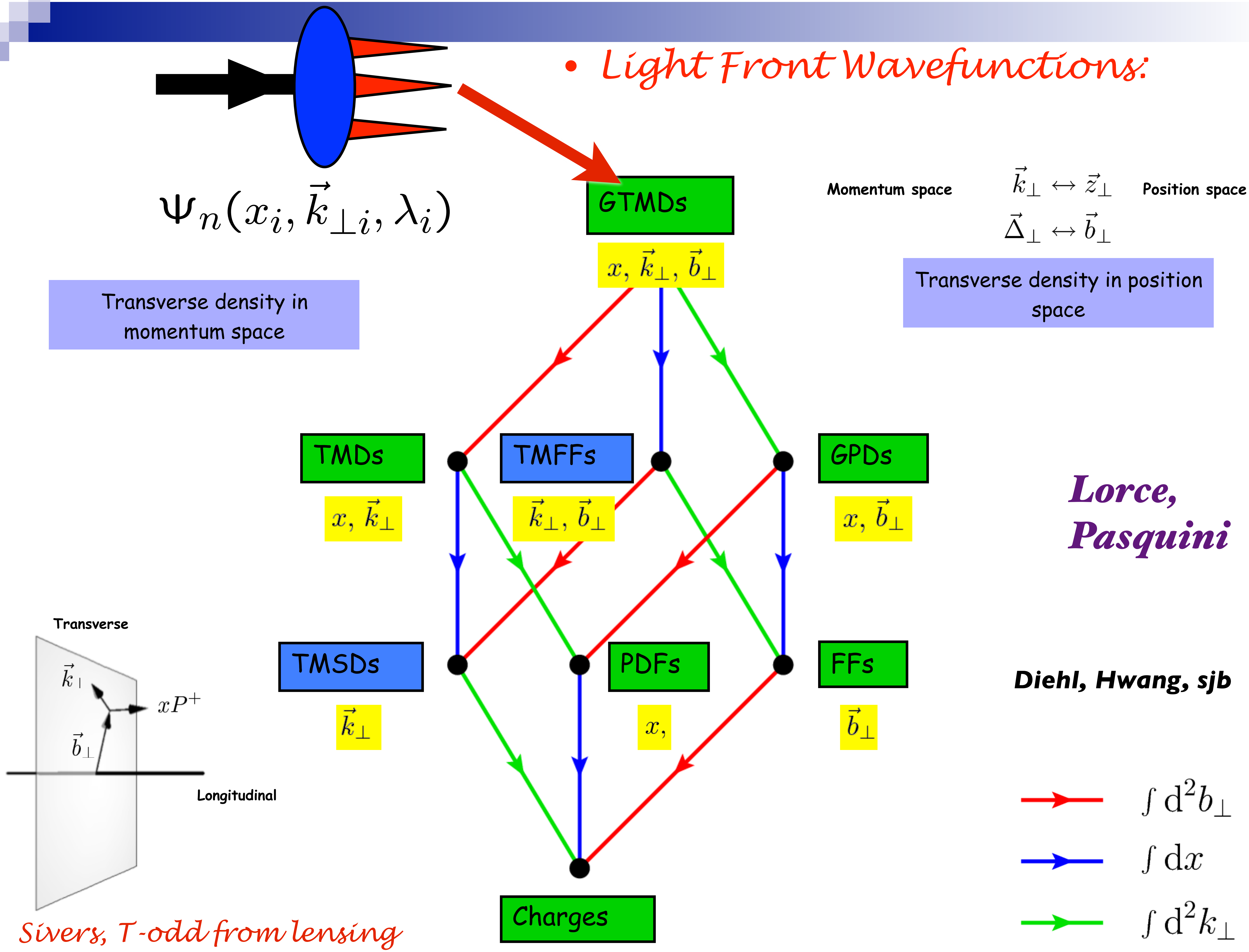




$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$
GTMDs
$x,\ \vec{k}_\perp,\ \vec{b}_\perp$
Momentum space
$\vec{k}_\perp \leftrightarrow \vec{z}_\perp$
Position space
$\vec{\Delta}_\perp \leftrightarrow \vec{b}_\perp$
Transverse density in momentum space
Transverse density in position space
TMDs
$x,\ \vec{k}_\perp$
TMFFs
$\vec{k}_\perp,\ \vec{b}_\perp$
GPDs
$x,\ \vec{b}_\perp$
Lorce, Pasquini
Transverse
$\vec{k}_\perp$
xP^+
$\vec{b}_\perp$
Longitudinal
TMSDs
$\vec{k}_\perp$
PDFs
$x,$
FFs
$\vec{b}_\perp$
Diehl, Hwang, sjb
$\int d^2 b_\perp$
$\int dx$
$\int d^2 k_\perp$
Charges
Sivers, T-odd from lensing

- *Light Front Wavefunctions:*



$$\left|\psi_p(P^+, \vec{P}_\perp)\right\rangle = \sum_n \prod_{i=1}^{n} \frac{\mathrm{d}x_i\, \mathrm{d}^2\vec{k}_{\perp i}}{\sqrt{x_i}\,16\pi^3} 16\pi^3 \delta\left(1 - \sum_{i=1}^{n} x_i\right) \delta^{(2)}\left(\sum_{i=1}^{n} \vec{k}_{\perp i}\right) \times \psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)\left|n;\, x_i P^+, x_i \vec{P}_\perp + \vec{k}_{\perp i}, \lambda_i\right\rangle.$$

$$q_{\lambda_q/\Lambda_p}(x, \Lambda) = \sum_{n, q_a} \int \prod_{j=1}^{n} \mathrm{d}x_j\, \mathrm{d}^2\vec{k}_{\perp j} \sum_{\lambda_i} \left|\psi^{(\Lambda)}_{n/H}(x_i, \vec{k}_{\perp i}, \lambda_i)\right|^2 \times \delta\left(1 - \sum_i^n x_i\right) \delta^{(2)}\left(\sum_i^n \vec{k}_{\perp i}\right) \delta(x - x_q) \delta_{\lambda_a \lambda_q} \Theta\left(\Lambda^2 - \mathcal{M}_n^2\right),$$

Obeys DGLAP Evolution *Defines quark distributions*

Connection to Bethe-Salpeter:

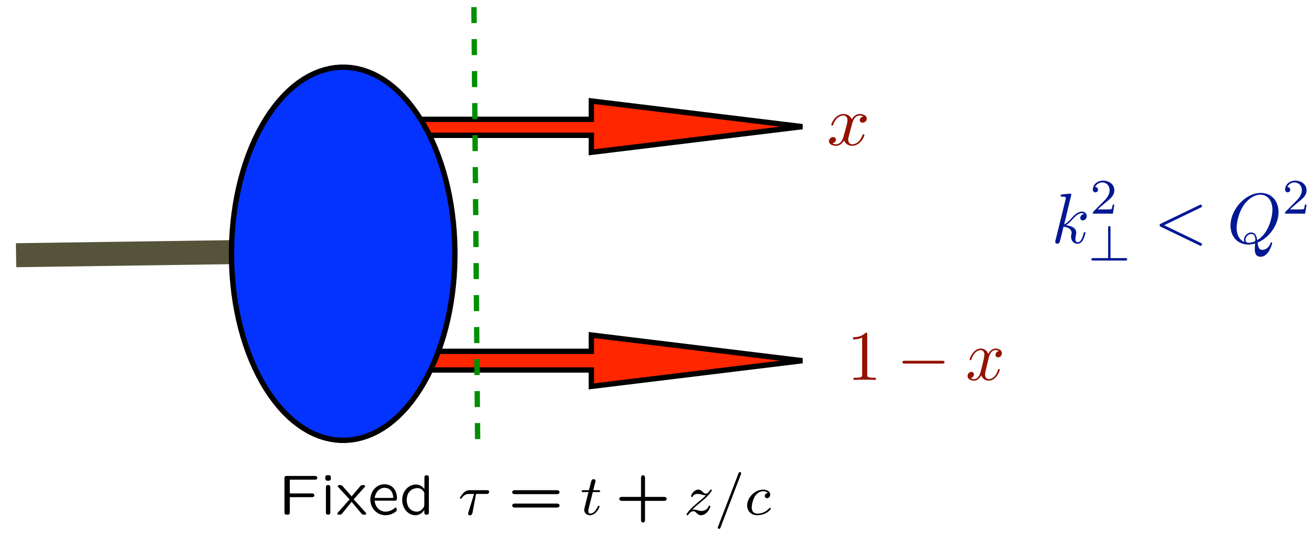
$$\int dk^- \Psi_{BS}(k, P) \rightarrow \psi_{LF}(x, \vec{k}_\perp) \qquad \Psi_{BS}(x, P)|_{x^+=0}$$

Hadron Distribution Amplitudes

$A^+ = 0$

$$\phi_M(x, Q) = \int^Q d^2\vec{k}\ \psi_{q\bar{q}}(x, \vec{k}_\perp)$$

$$\sum_i x_i = 1$$



- Fundamental gauge invariant non-perturbative input to hard exclusive processes, heavy hadron decays. Defined for Mesons, Baryons
- Evolution Equations from PQCD, OPE
- Conformal Expansions
- Compute from valence light-front wavefunction in light-cone gauge

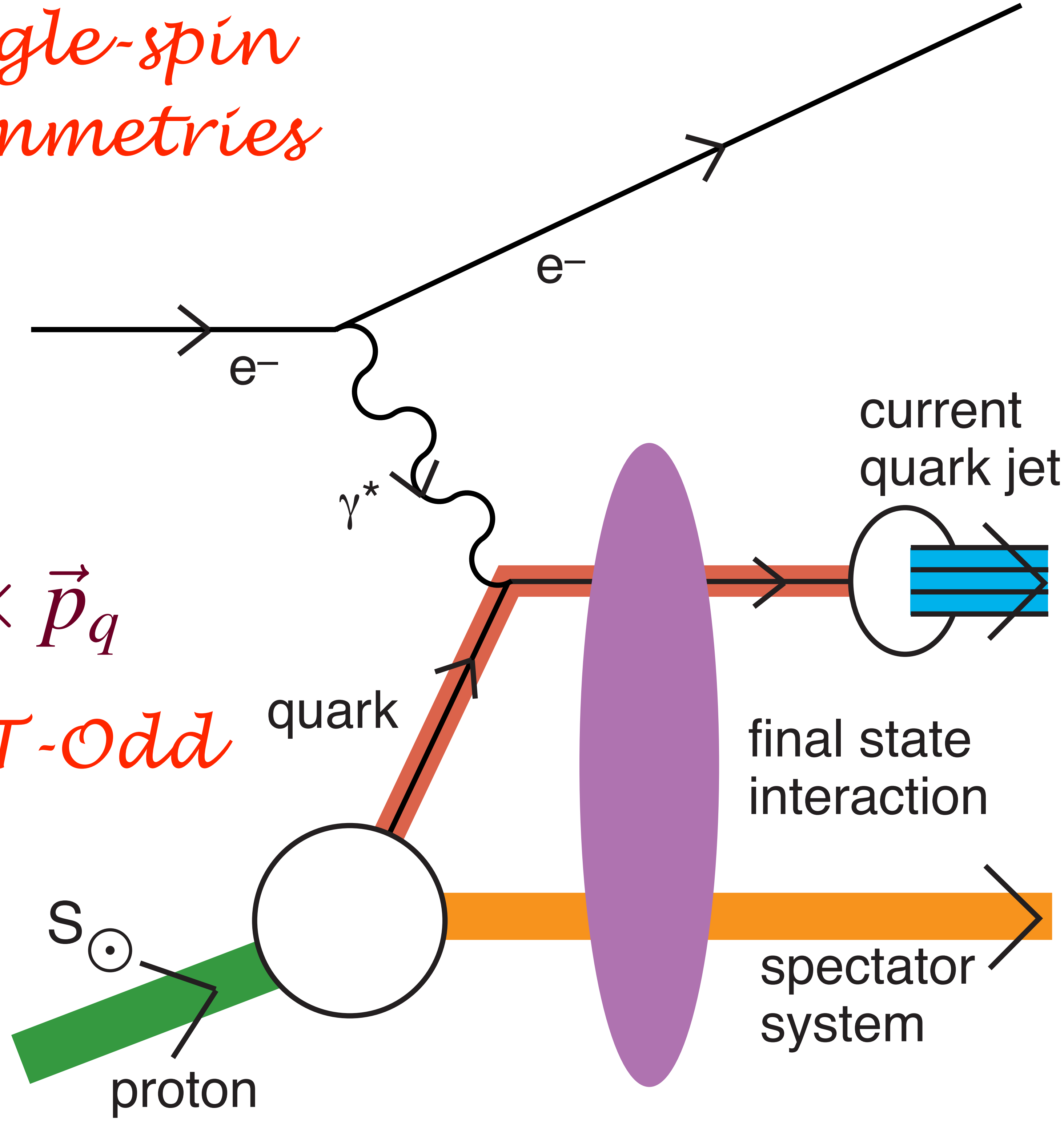
Lepage, sjb

Efremov, Radyushkin

Sachrajda, Frishman Lepage, sjb

Braun, Gardi

Single-spin asymmetries



$$\vec{S}_p \cdot \vec{q} \times \vec{p}_q$$

T-Odd

Hwang, Schmidt, sjb

Collins, Burkardt, Ji, Yuan. Pasquini, ...

Leading Twist Sivers Effect

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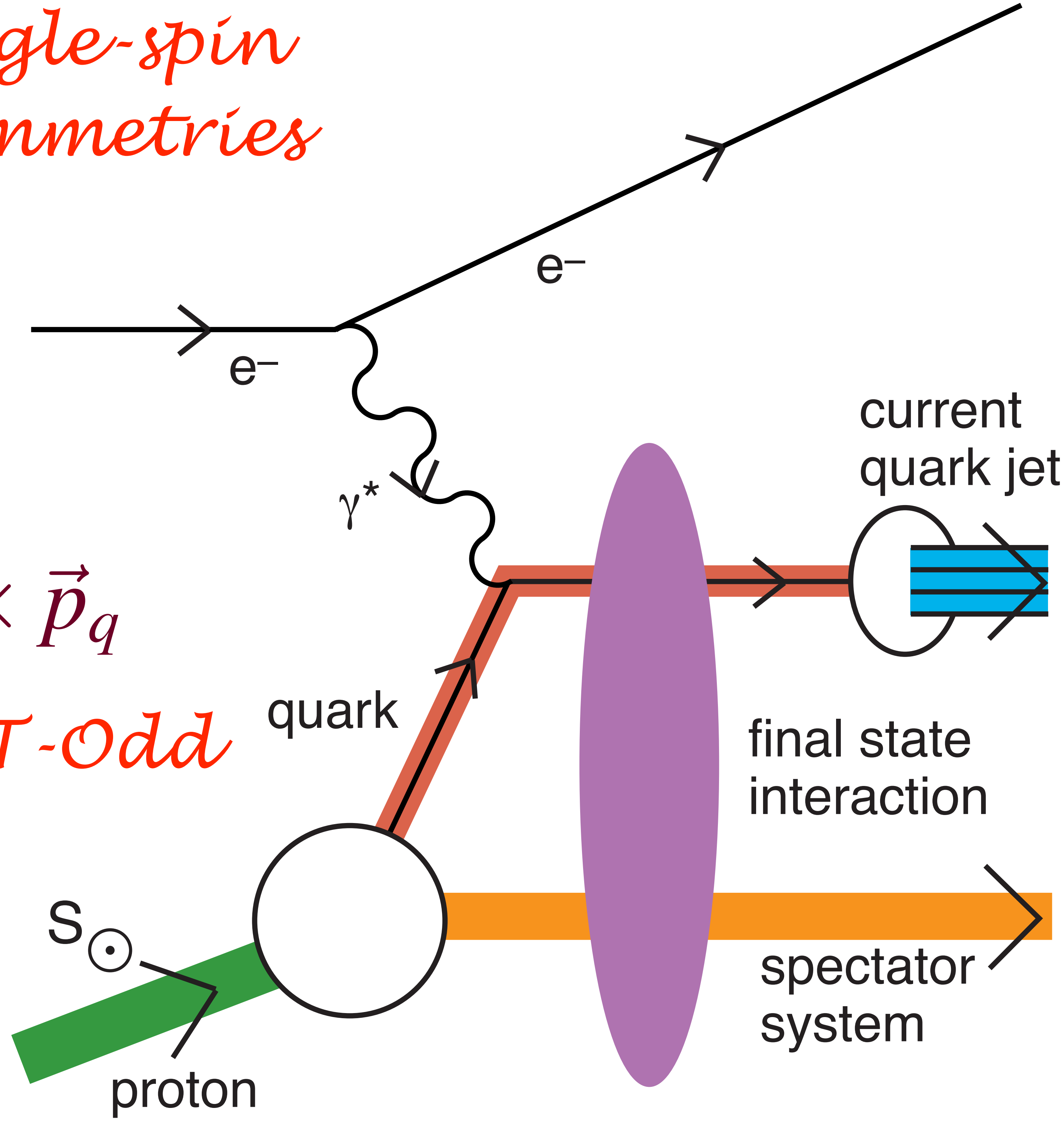

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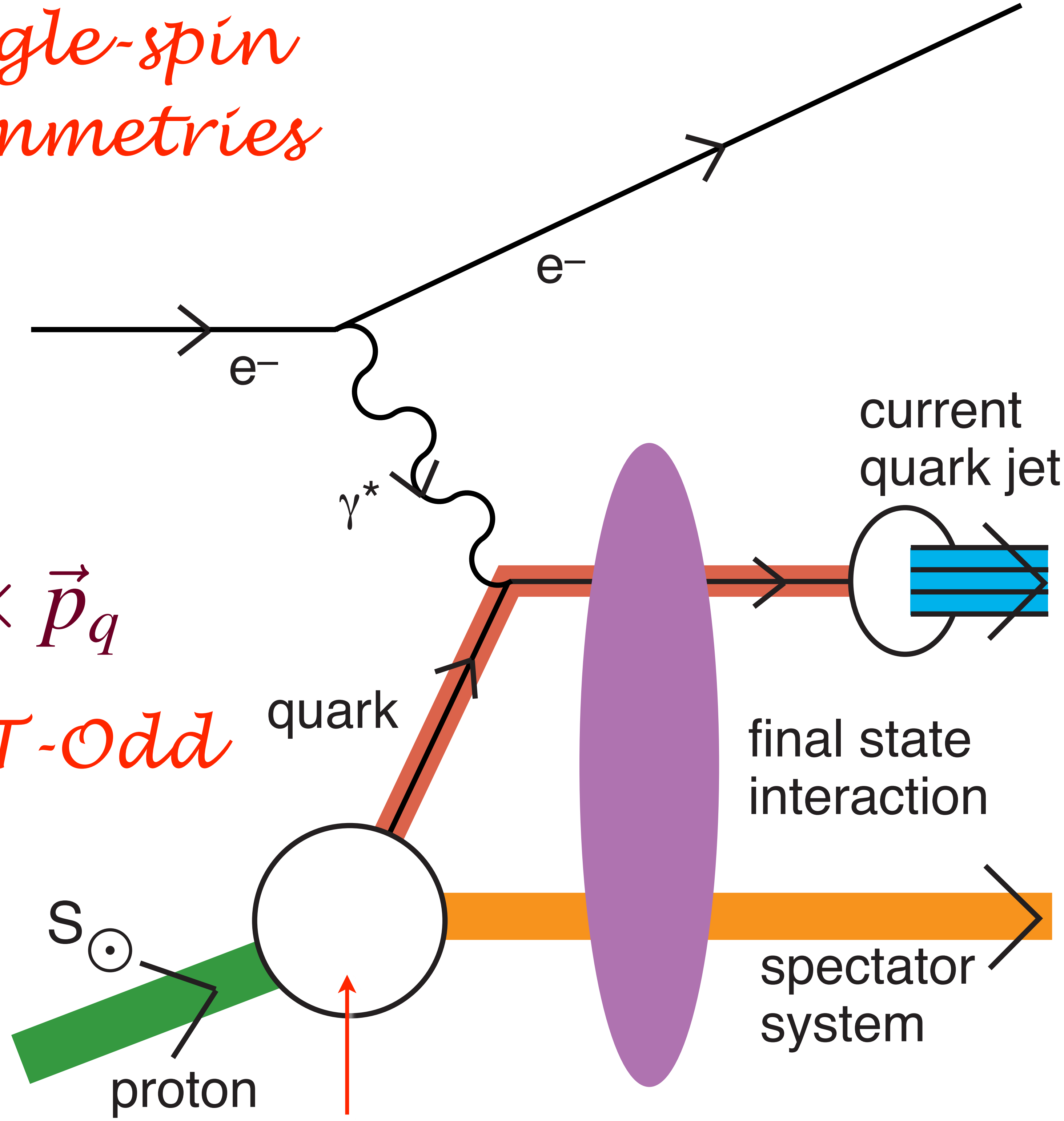

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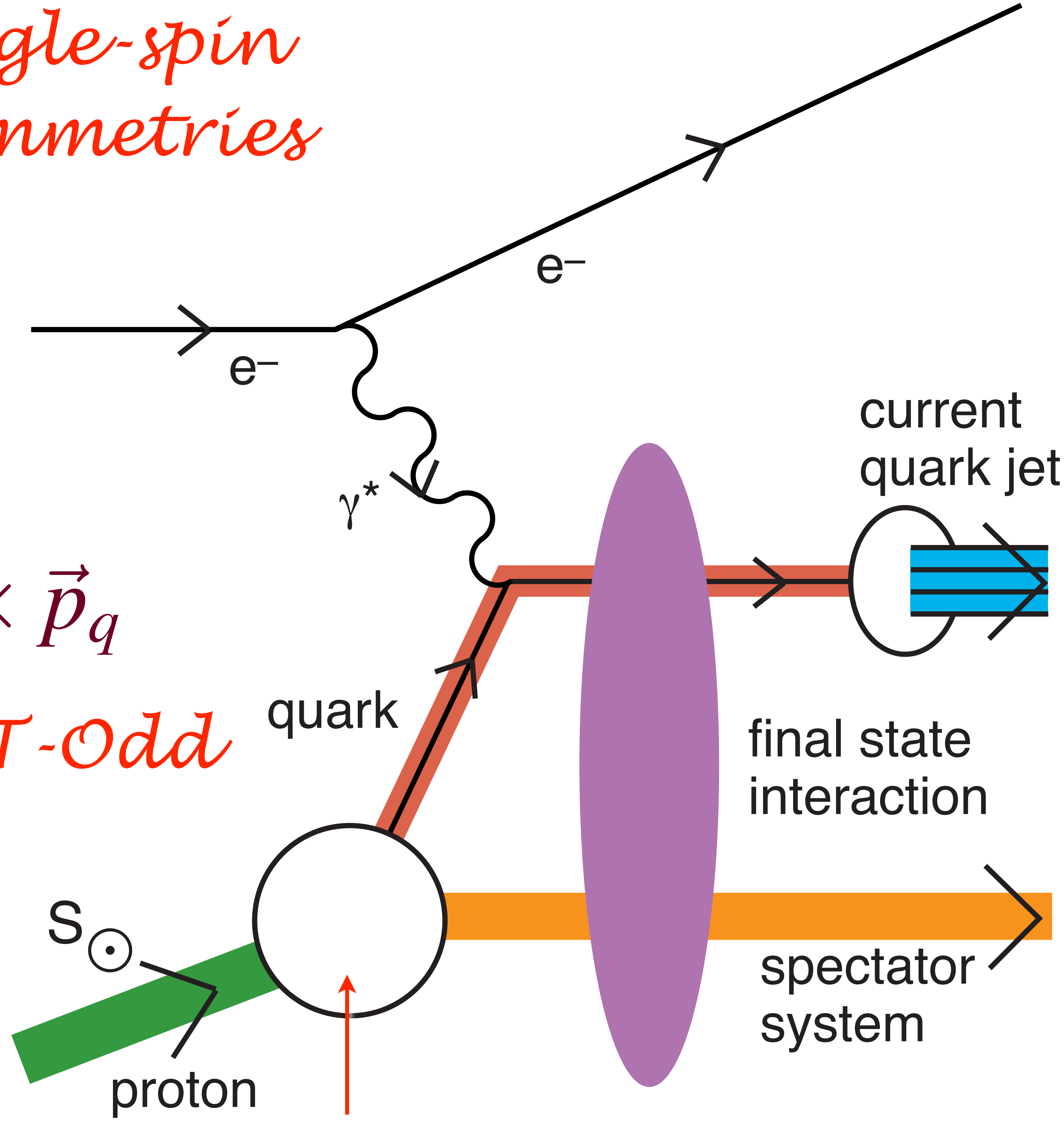

Light-Front Wavefunction
S and P- Waves!

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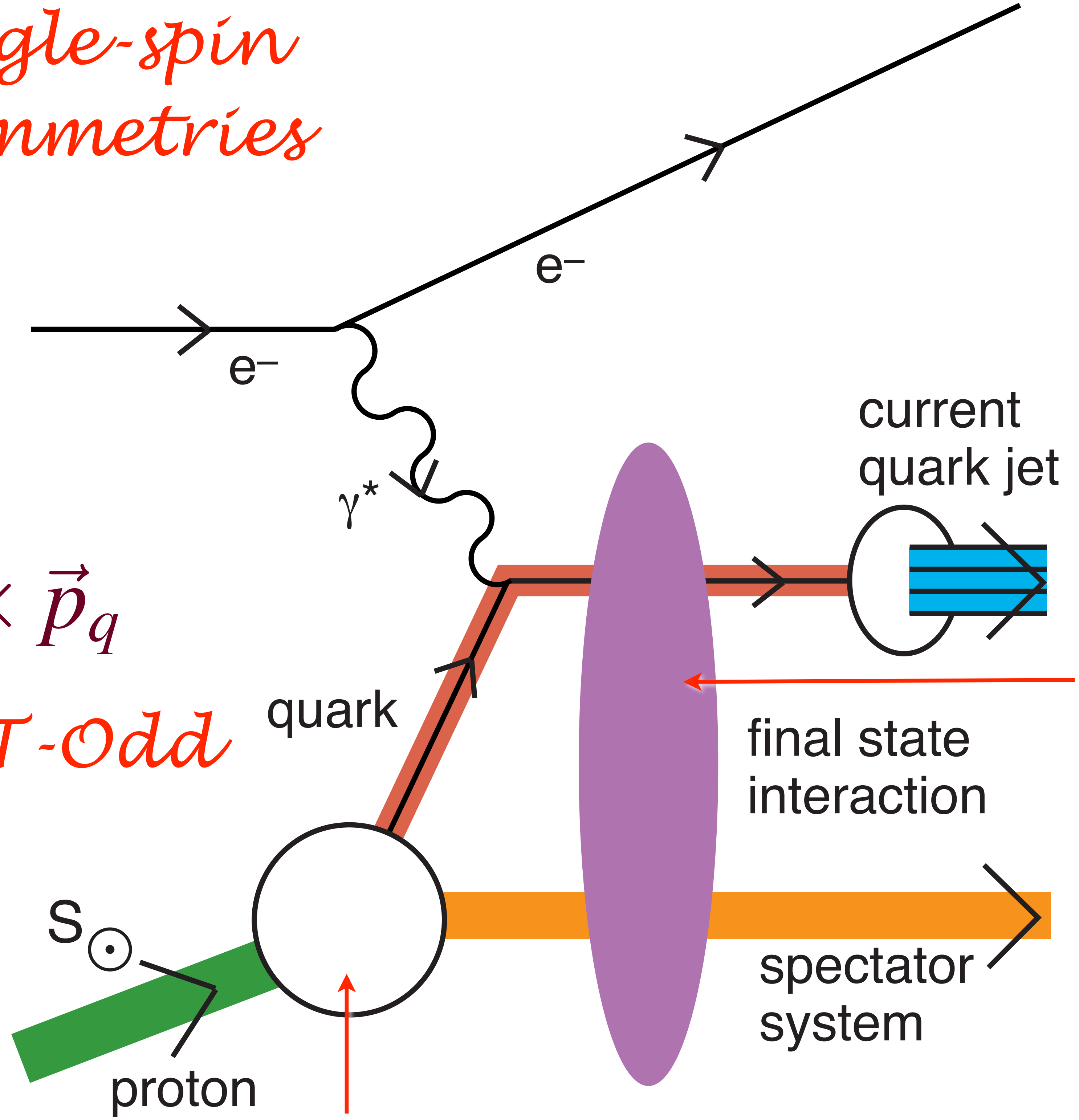

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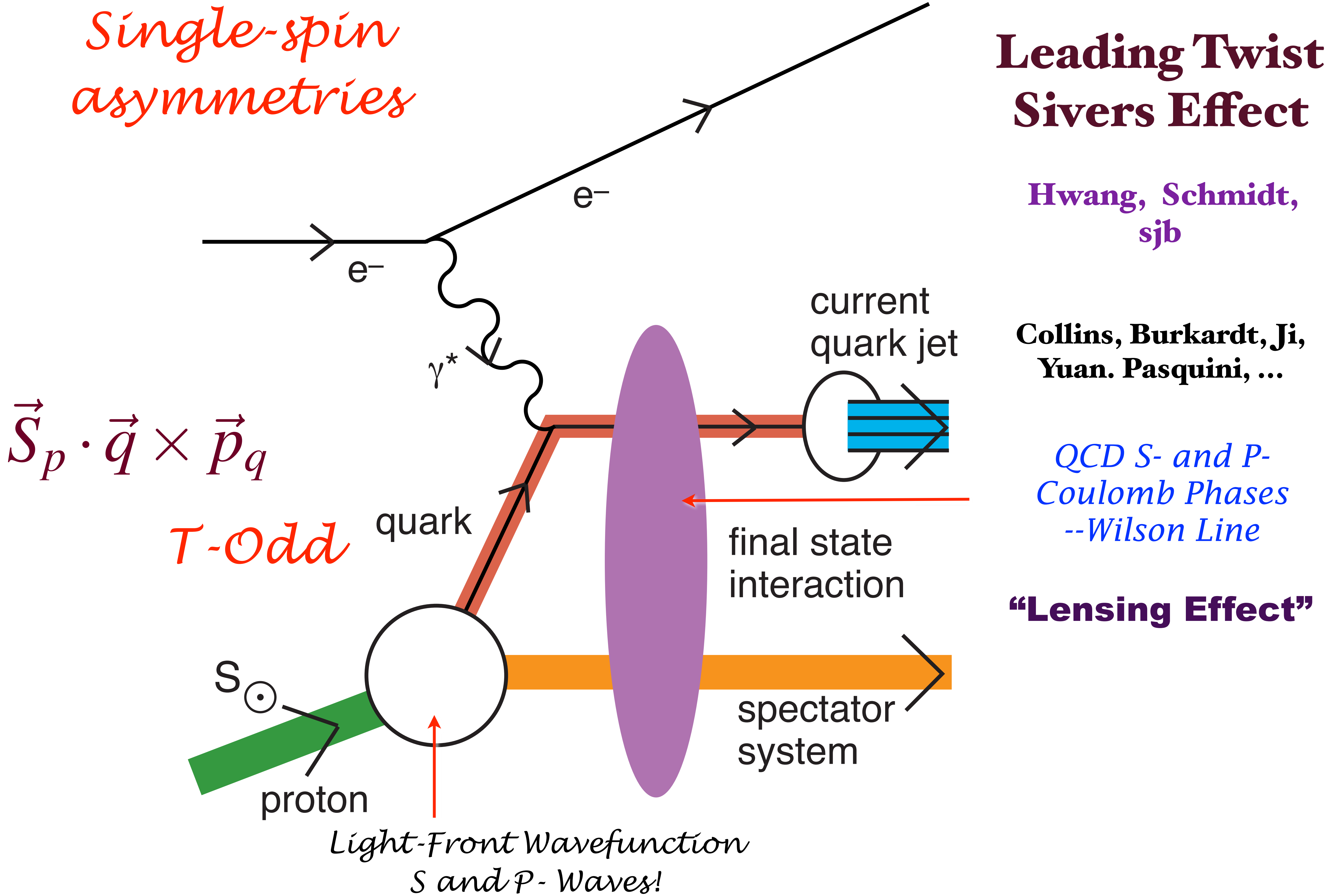

Single-spin asymmetries
Leading Twist Sivers Effect
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$\vec{S}_p \cdot \vec{q} \times \vec{p}_q$
T-Odd
e–
e–
γ*
current quark jet
quark
final state interaction
QCD S- and P- Coulomb Phases --Wilson Line
"Lensing Effect"
S
proton
spectator system
Light-Front Wavefunction S and P- Waves!

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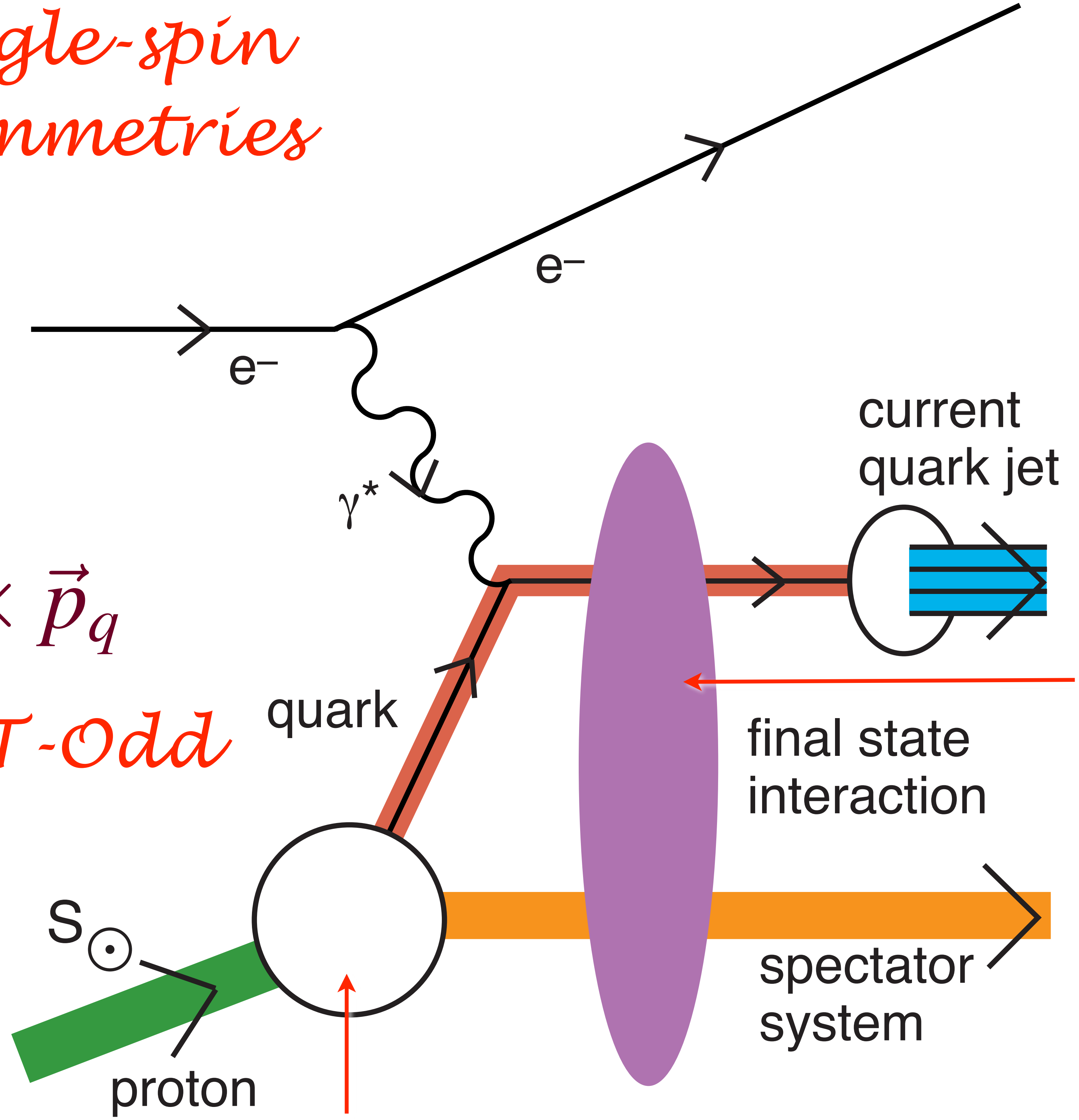

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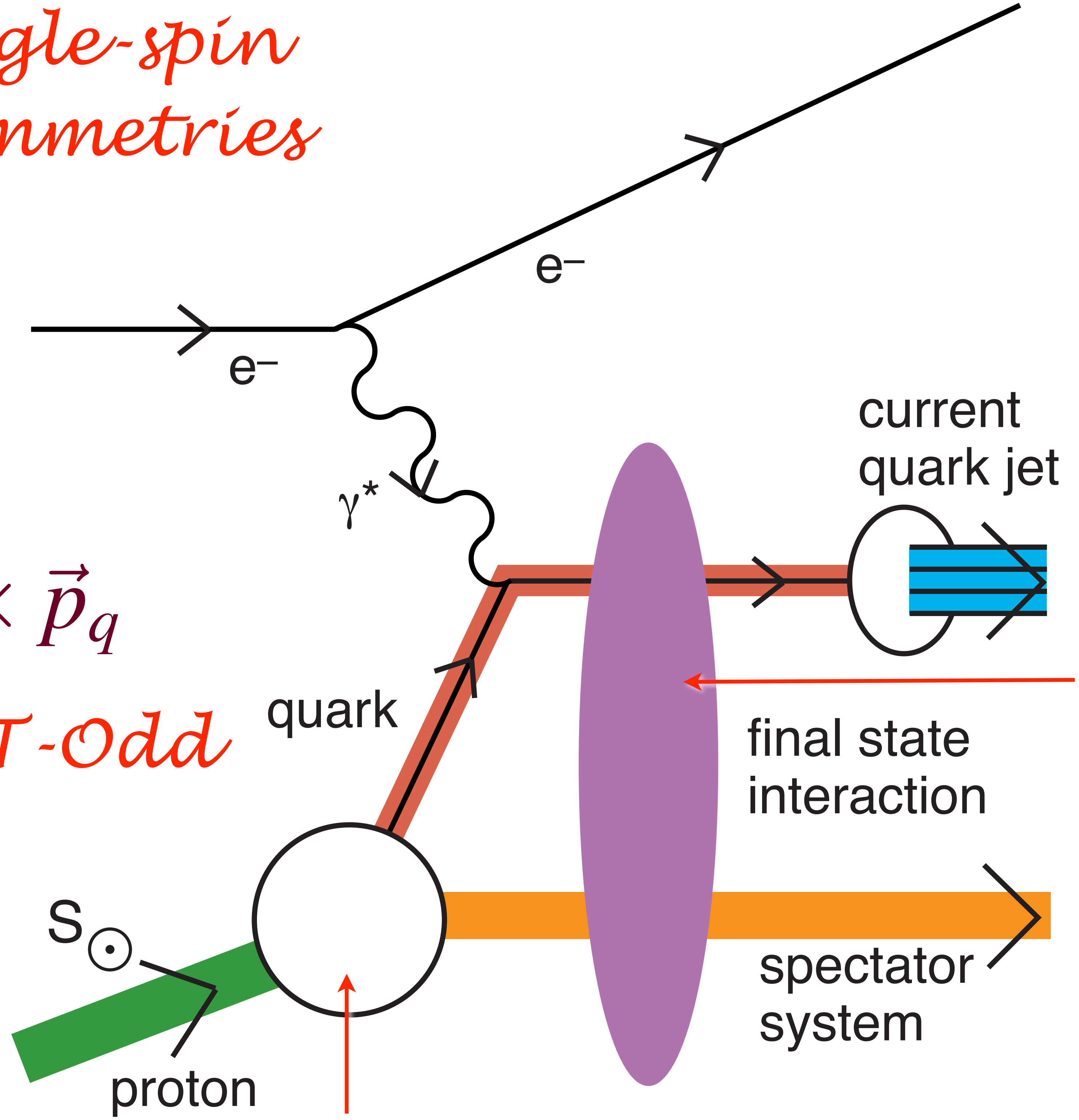
Pseudo- T-Odd



QCD S- and P- Coulomb Phases --Wilson Line

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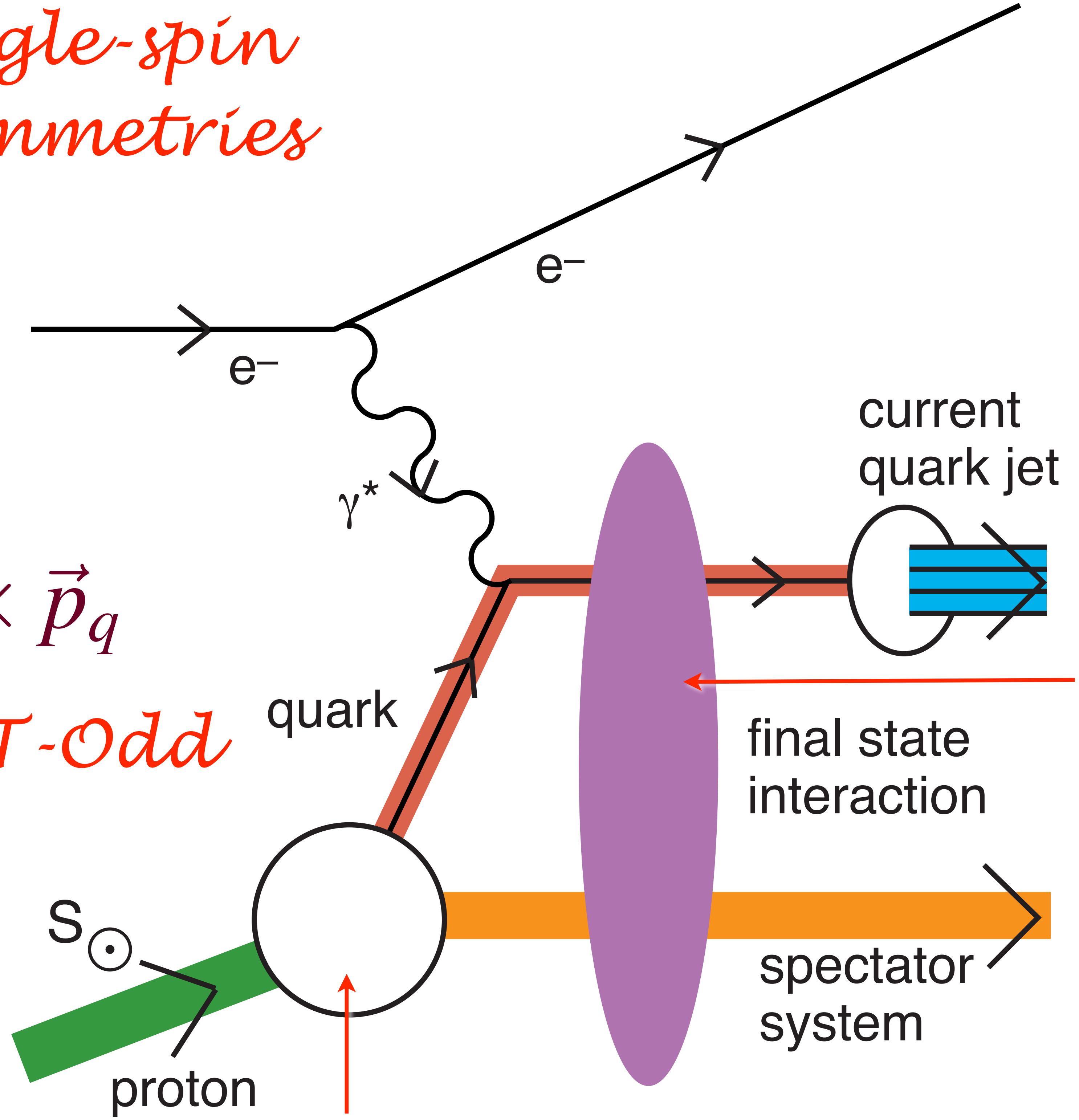

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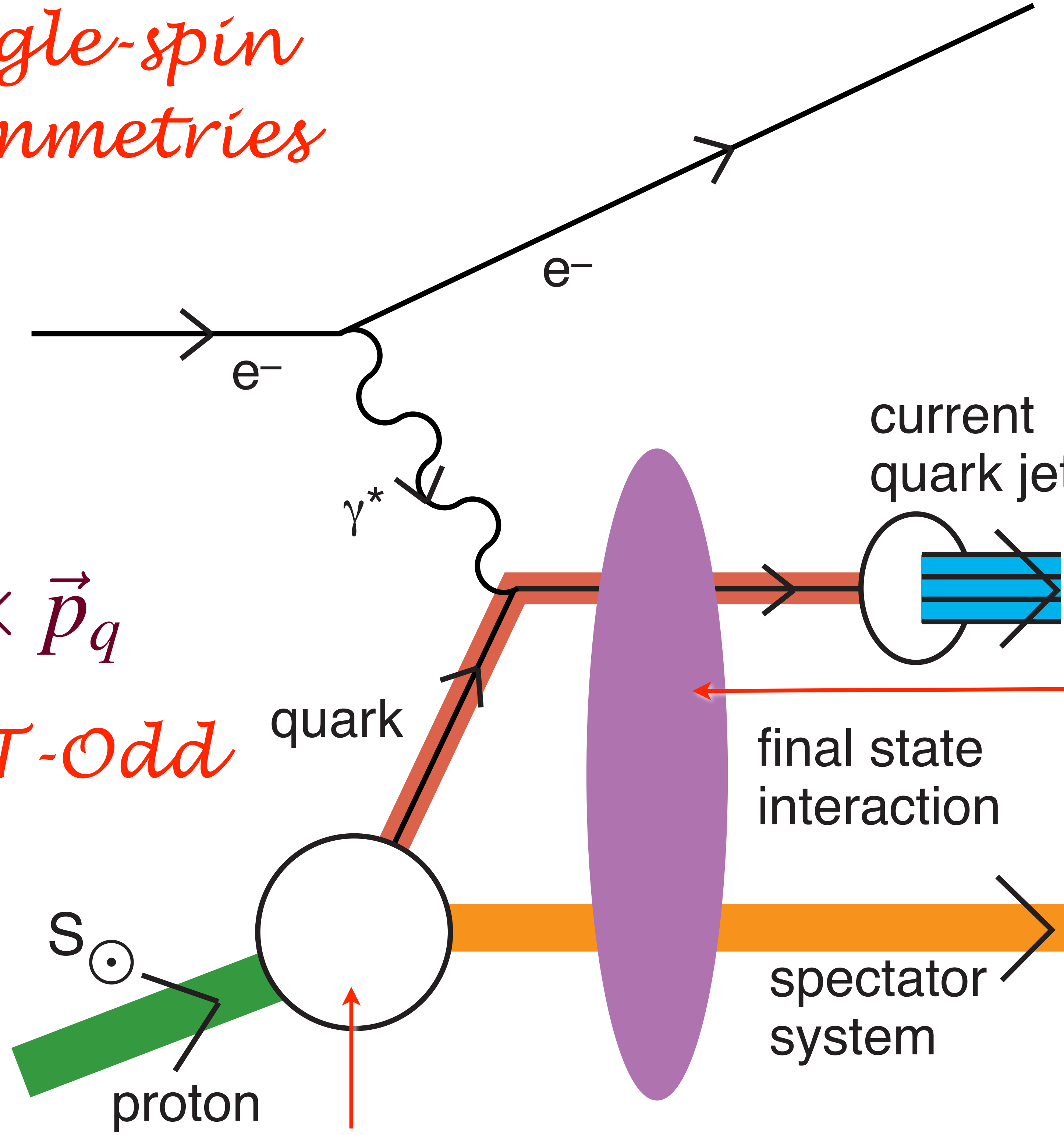

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Sign reversal in DY!

Leading-Twist Rescattering Violates pQCD Factorization!

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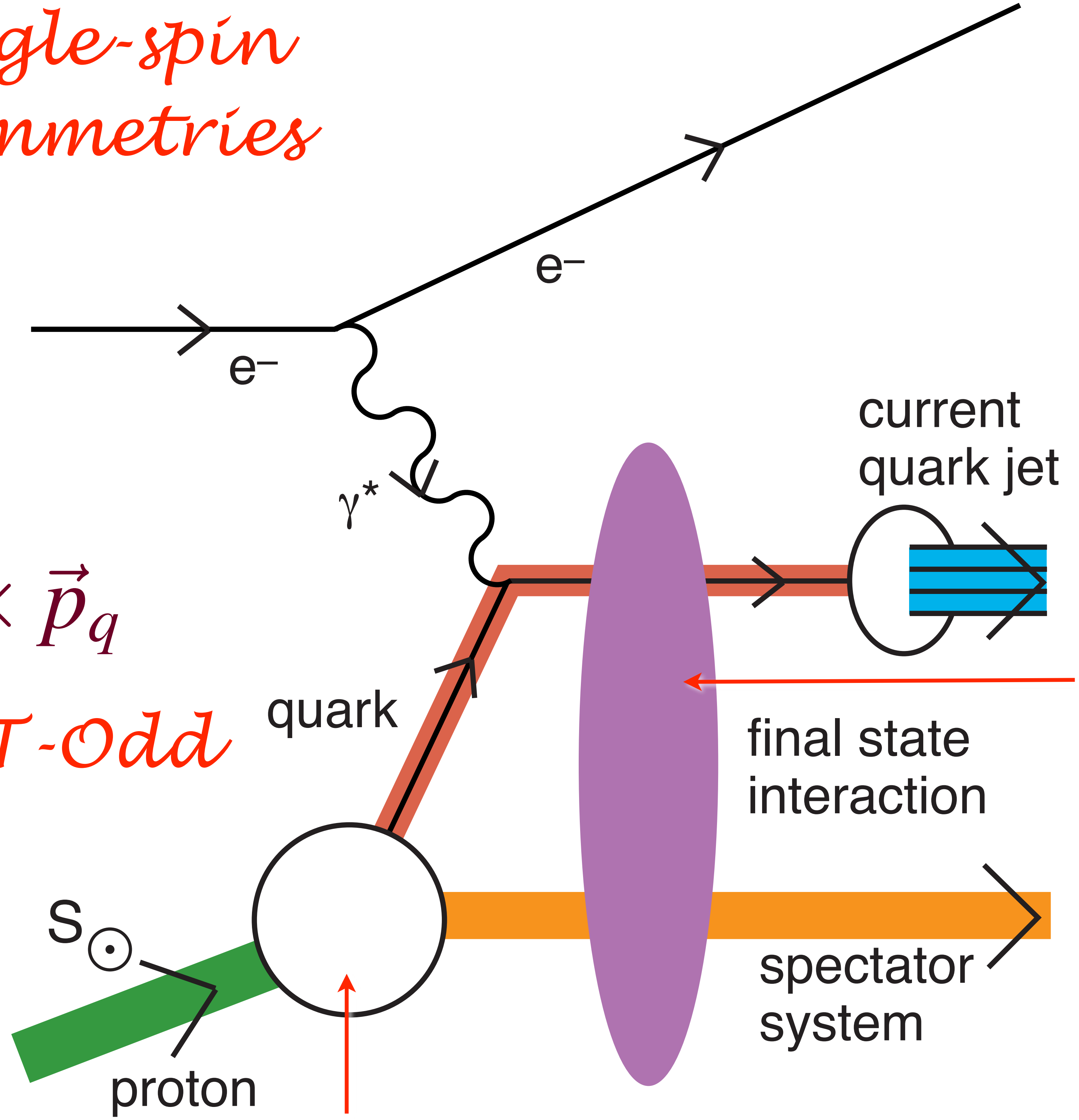

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QCD S- and P- Coulomb Phases --Wilson Line

"Lensing Effect"

QED: Lensing involves soft scales

Leading-Twist Rescattering Violates pQCD Factorization!

Sign reversal in DY!

Static	Dynamic
Square of Target LFWFs	Modified by Rescattering: ISI & FSI
No Wilson Line	Contains Wilson Line, Phases
Probability Distributions	No Probabilistic Interpretation
Process-Independent	Process-Dependent - From Collision
T-even Observables	T-Odd (Sivers, Boer-Mulders, etc.)
No Shadowing, Anti-Shadowing	Shadowing, Anti-Shadowing, Saturation
Sum Rules: Momentum and J^z	Sum Rules Not Proven
DGLAP Evolution; mod. at large x	DGLAP Evolution
No Diffractive DIS	Hard Pomeron and Odderon Diffractive DIS

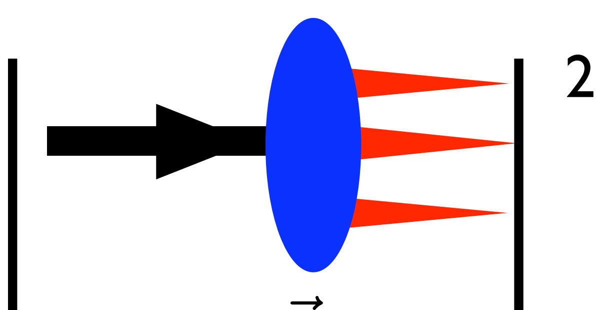
Hwang, Schmidt, sjb,

Mulders, Boer

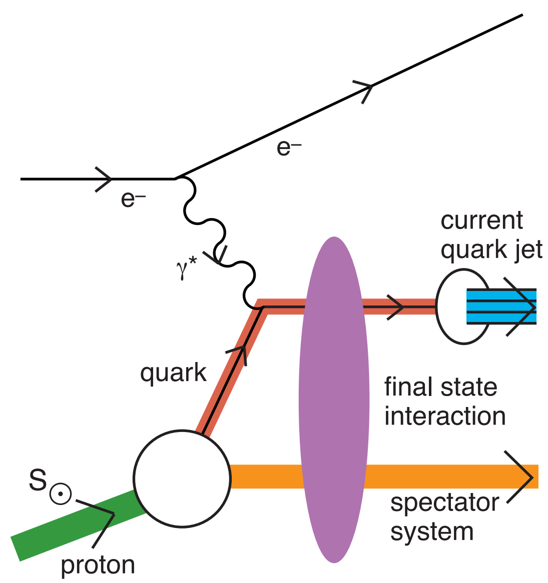
Qiu, Sterman

Collins, Qiu

Pasquini, Lorce, Xi
Yuan, sjb



$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



- **LF wavefunctions play the role of Schrödinger wavefunctions in Atomic Physics**
- **LFWFs=Hadron Eigensolutions: Direct Connection to QCD Lagrangian**
- **Relativistic, frame-independent: no boosts, no disc contraction, Melosh built into LF spinors**
- **Hadronic observables computed from LFWFs: Form factors, Structure Functions, Distribution Amplitudes, GPDs, TMDs, Weak Decays, ... modulo `lensing' from ISIs, FSIs**
- **Cannot compute current matrix elements using instant form from eigensolutions alone -- need to include vacuum currents!**
- **Hadron Physics without LFWFs is like Biology without DNA!**

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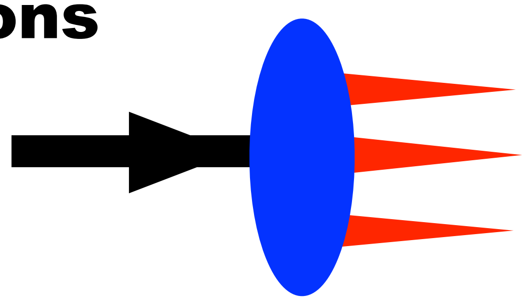

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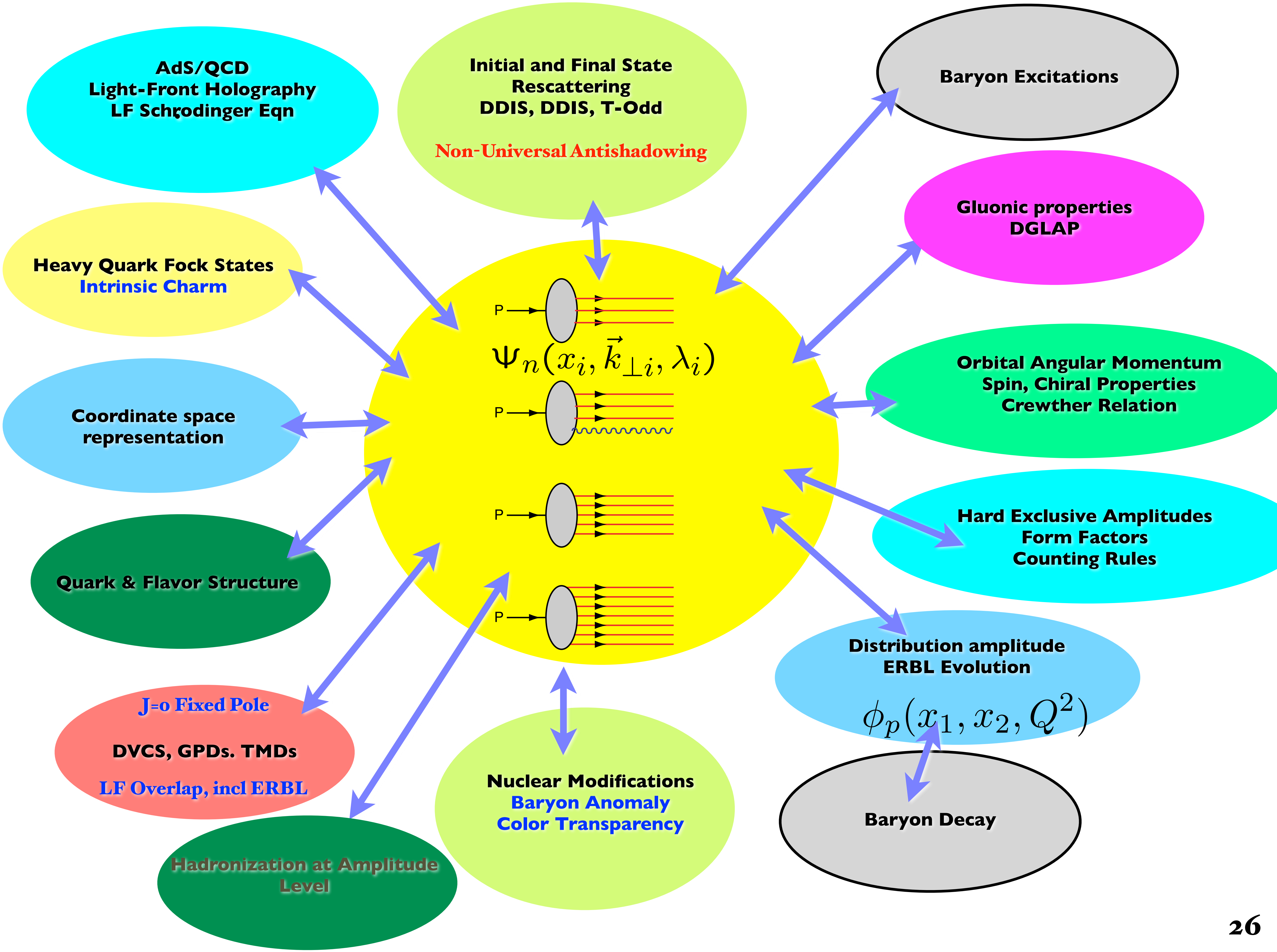
QCD and the LF Hadron Wavefunctions



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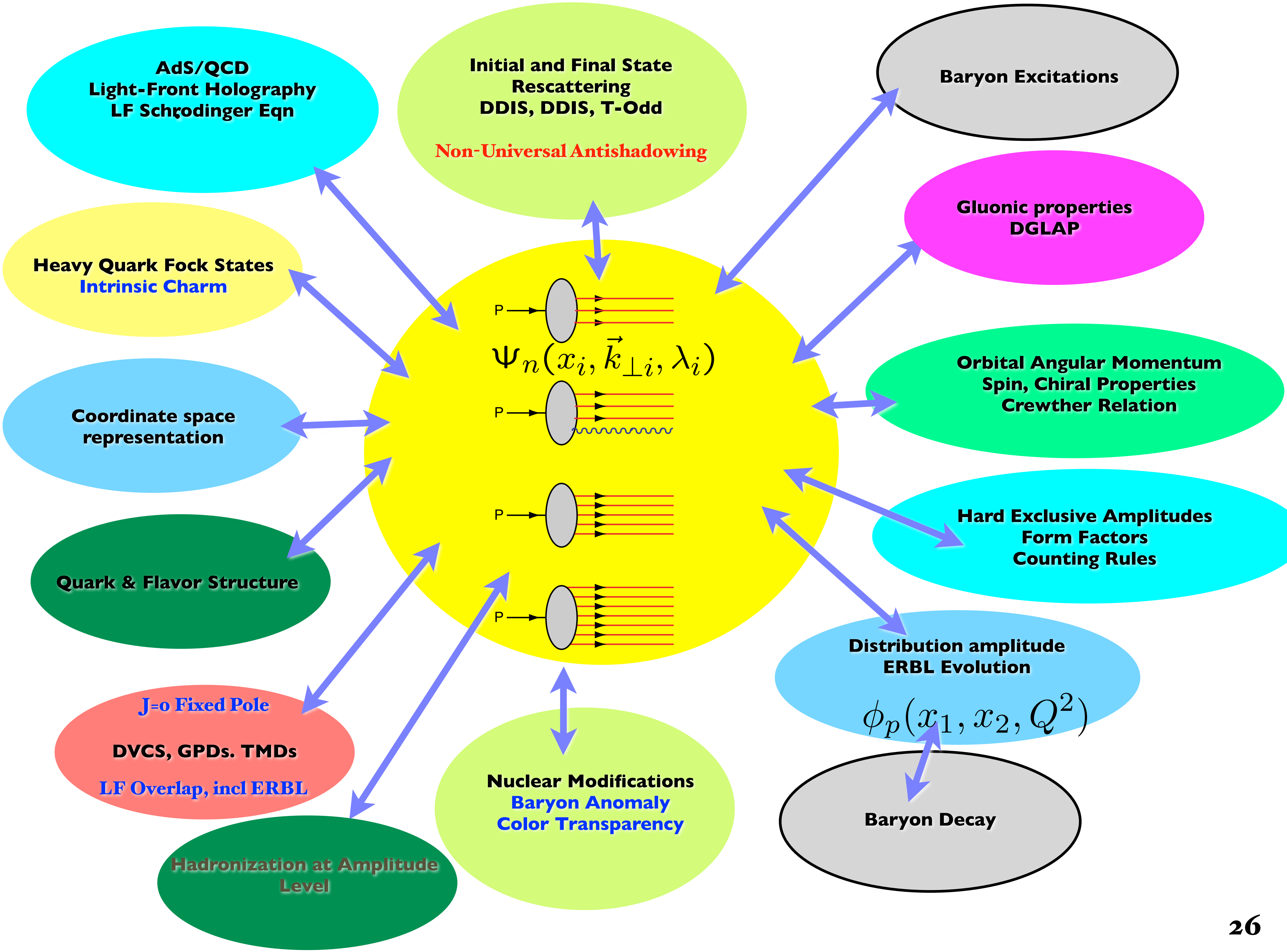

QCD Lagrangian

gluon dynamics

quark kinetic energy + quark-gluon dynamics

quark mass term

$$\mathcal{L}_{QCD} = -\frac{1}{4}Tr(G^{\mu\nu}G_{\mu\nu}) + \sum_{f=1}^{n_f} i\bar{\Psi}_f D_\mu \gamma^\mu \Psi_f + \sum_{f=1}^{n_f} m_f \bar{\Psi}_f \Psi_f$$

$$iD^\mu = i\partial^\mu - gA^\mu \quad G^{\mu\nu} = \partial^\mu A^\mu - \partial^\nu A^\mu - g[A^\mu, A^\nu]$$

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Fundamental Theory of Hadron and Nuclear Physics

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Yang Mills Gauge Principle: Color Rotation and Phase Invariance at Every Point of Space and Time

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Scale-Invariant Coupling
Renormalizable
Asymptotic Freedom
Color Confinement

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QCD Mass Scale from Confinement not Explicit

Atomic Physics from First Principles

$\mathcal{L}_{QED} \rightarrow$ H_{QED}

QED atoms: positronium and muonium

$$(H_0 + H_{int})\ |\Psi>= E\ |\Psi>$$

$$[-\frac{\Delta^2}{2m_{\rm red}} + V_{\rm eff}(\vec{S},\vec{r})]\ \psi(\vec{r}) = E\ \psi(\vec{r})$$

Effective two-particle equation

Includes Lamb Shift, quantum corrections

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Spherical Basis r, θ, ϕ

$$V_{eff} \rightarrow V_C(r) = -\frac{\alpha}{r}$$

Coulomb potential

Semiclassical first approximation to QED --> **Bohr Spectrum**

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Light-Front QCD

$\mathcal{L}_{QCD}$ → H^{LF}_{QCD}

$$(H^0_{LF} + H^I_{LF})|\Psi> = M^2|\Psi>$$

Coupled Fock states

$$[\frac{\vec{k}^2_\perp + m^2}{x(1-x)} + V^{LF}_{\text{eff}}]\ \psi_{LF}(x, \vec{k}_\perp) = M^2\ \psi_{LF}(x, \vec{k}_\perp)$$

Effective two-particle equation

$$[-\frac{d^2}{d\zeta^2} + \frac{m^2}{x(1-x)} + \frac{-1+4L^2}{4\zeta^2} + U(\zeta, S, L)]\ \psi_{LF}(\zeta) = M^2\ \psi_{LF}(\zeta)$$

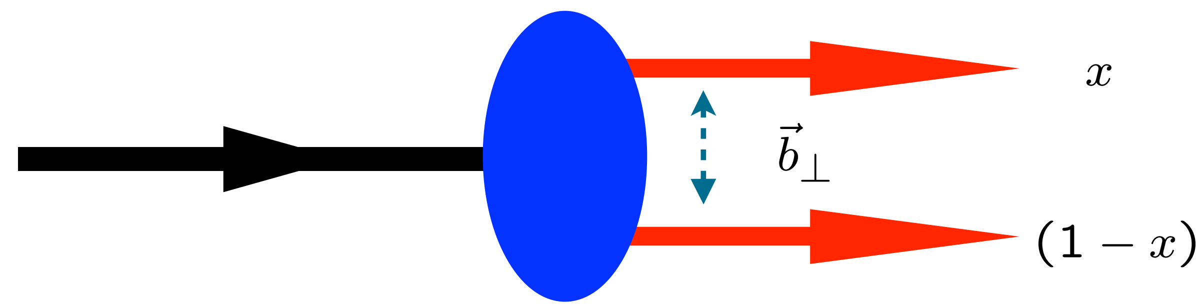
Azimuthal Basis

ζ, ϕ

de Tèramond, Dosch, sjb

Light-Front QCD

Fixed $\tau = t + z/c$



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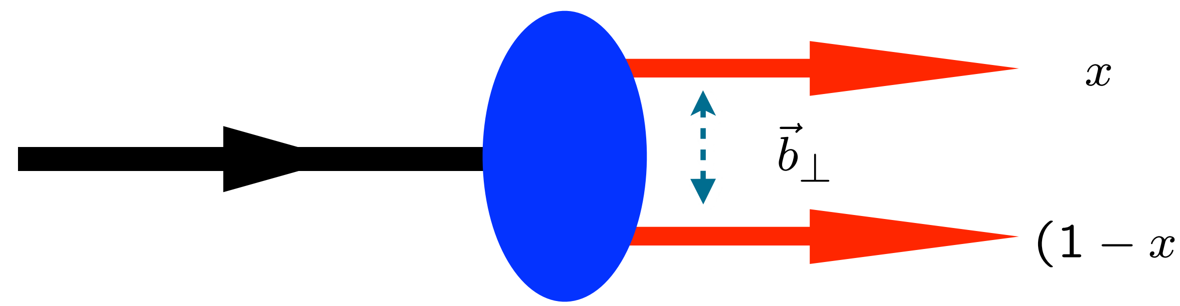

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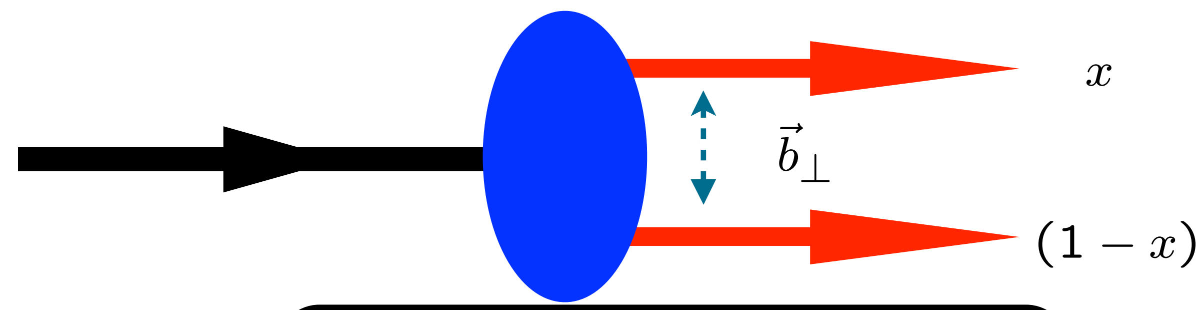

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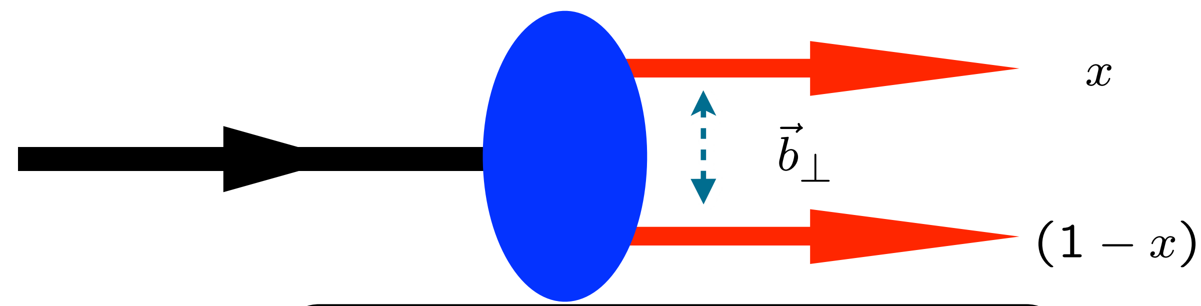
ζ, ϕ

de Tèramond, Dosch, sjb

Light-Front QCD

Fixed $\tau = t + z/c$

$\mathcal{L}_{QCD} \rightarrow H^{LF}_{QCD}$



$$\zeta^2 = x(1-x) b^2_\perp$$

$$(H^0_{LF} + H^I_{LF})|\Psi> = M^2|\Psi>$$

Coupled Fock states

$$\left[\frac{\vec{k}^2_\perp + m^2}{x(1-x)} + V^{LF}_{\text{eff}}\right] \psi_{LF}(x, \vec{k}_\perp) = M^2 \ \psi_{LF}(x, \vec{k}_\perp)$$

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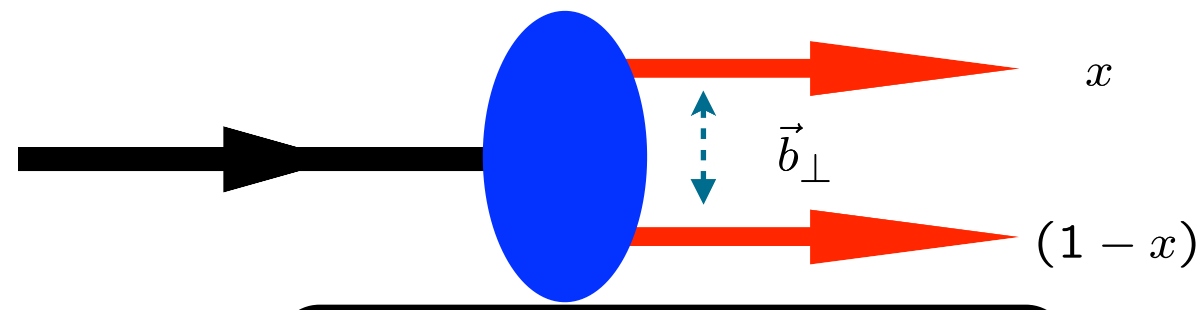

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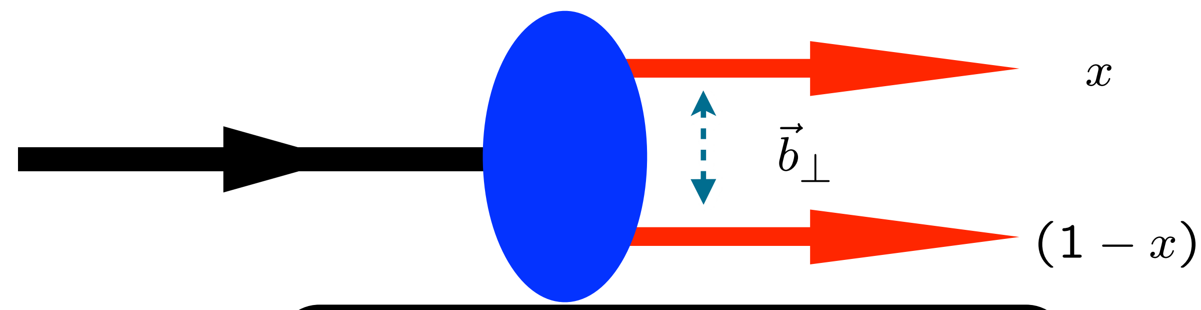

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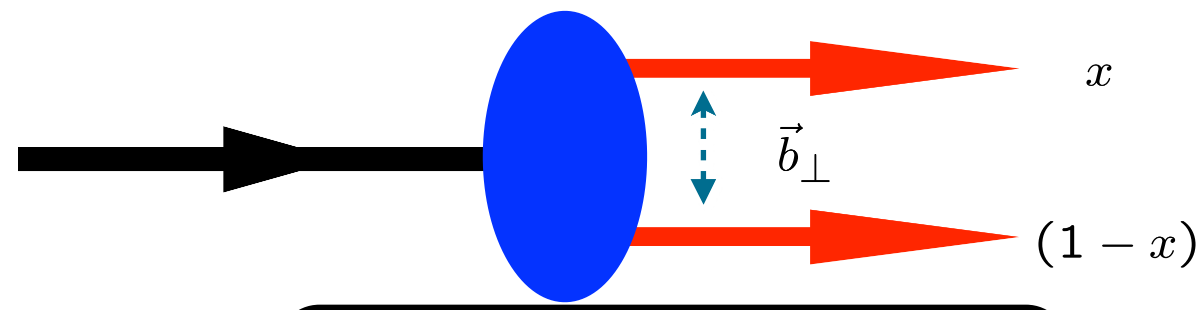

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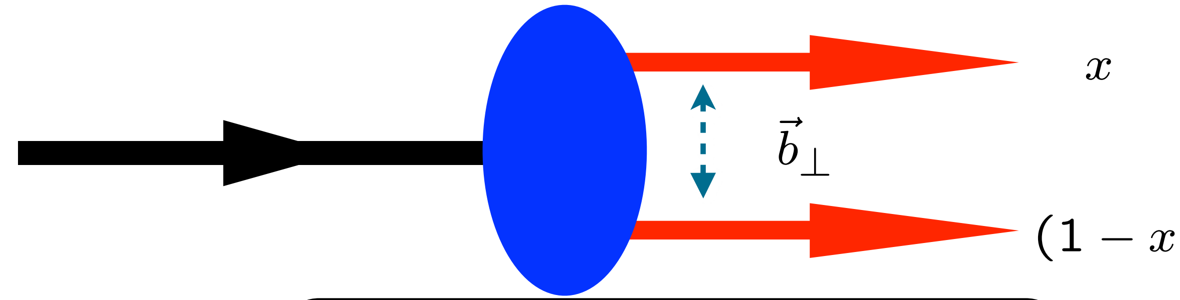

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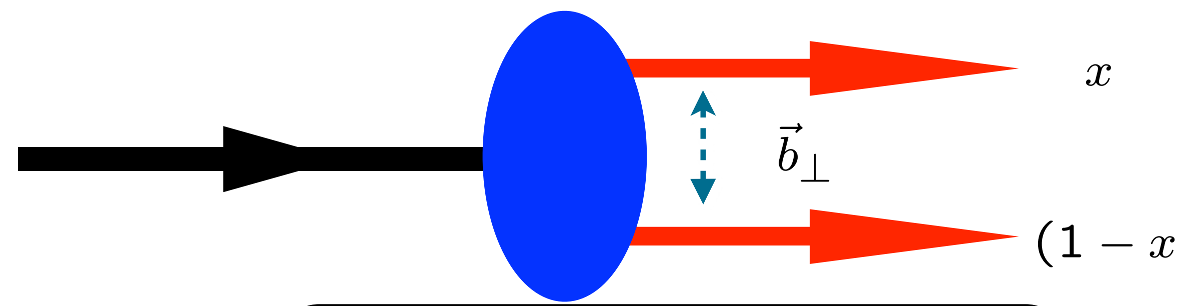

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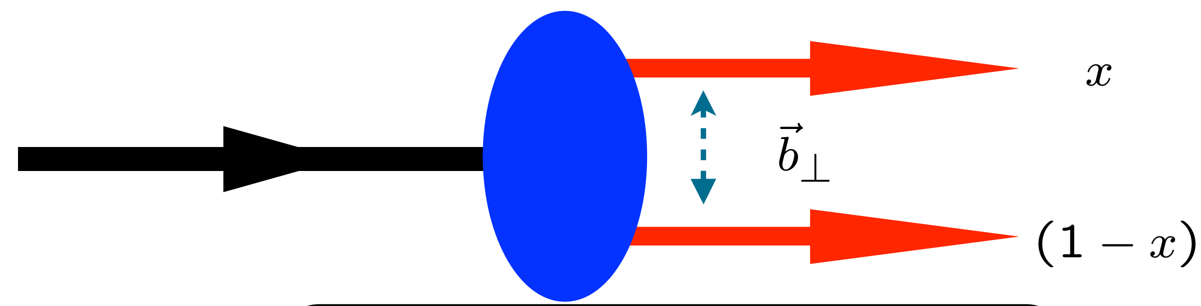

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Eliminate higher Fock states and retarded interactions

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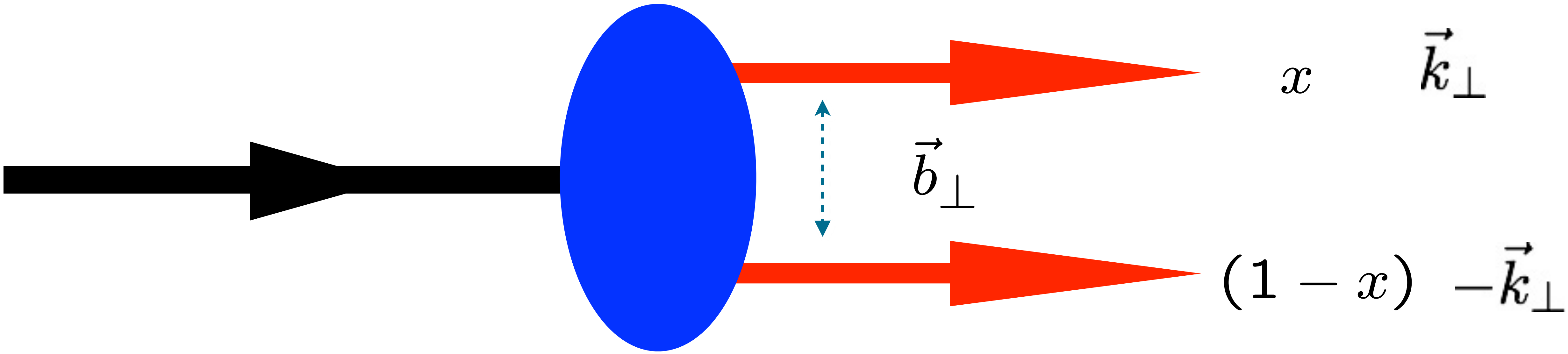

$$\zeta^2 \equiv b_\perp^2 x(1-x)$$

Invariant transverse separation

$$\zeta^2 \text{ conjugate to } \frac{k_\perp^2}{x(1-x)} = (p_q + p_{\bar{q}})^2 = \mathcal{M}^2_{q+\bar{q}}$$

$$\int dk^- \Psi_{BS}(P,k) \to \psi_{LF}(x, \vec{k}_\perp)$$

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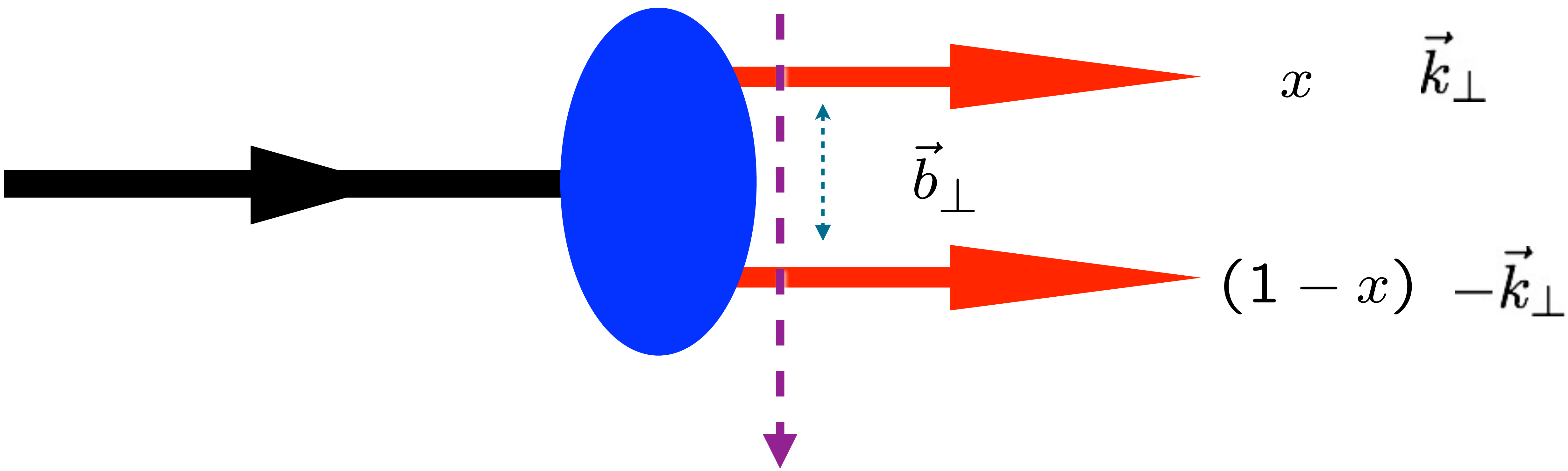

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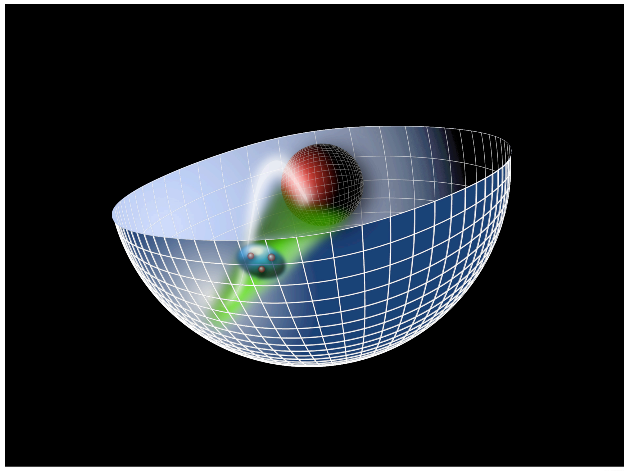
$$e^{\varphi(z)} = e^{+\kappa^2 z^2}$$



Light-Front Holography

$$\left[-\frac{d^2}{d\zeta^2} + \frac{1-4L^2}{4\zeta^2} + U(\zeta)\right]\psi(\zeta) = \mathcal{M}^2\psi(\zeta)$$

Light-Front Schrödinger Equation

Confinement scale:

$$\kappa \simeq 0.5 \text{ GeV}$$

$$1/\kappa \simeq 1/3 \ fm$$

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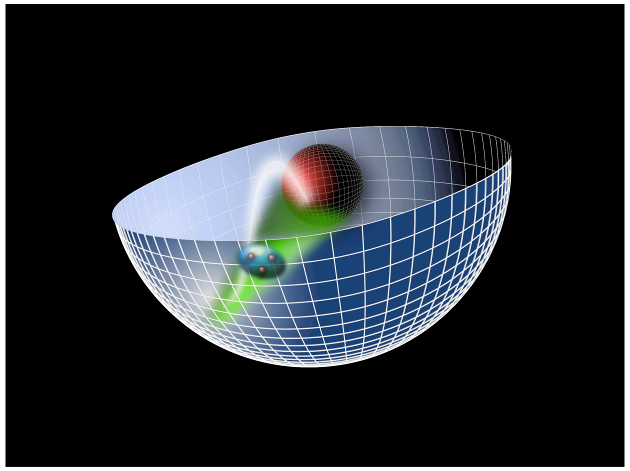

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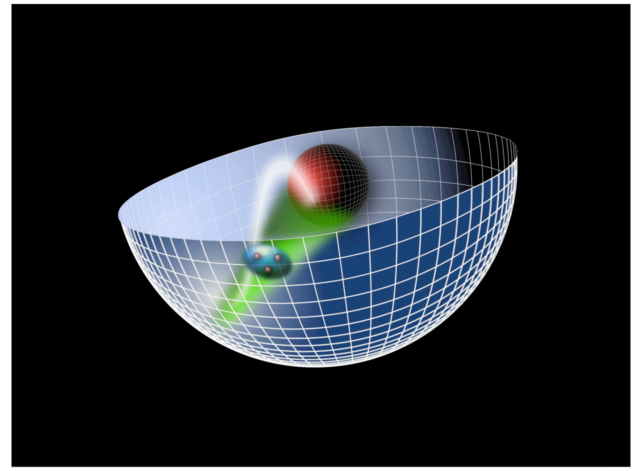

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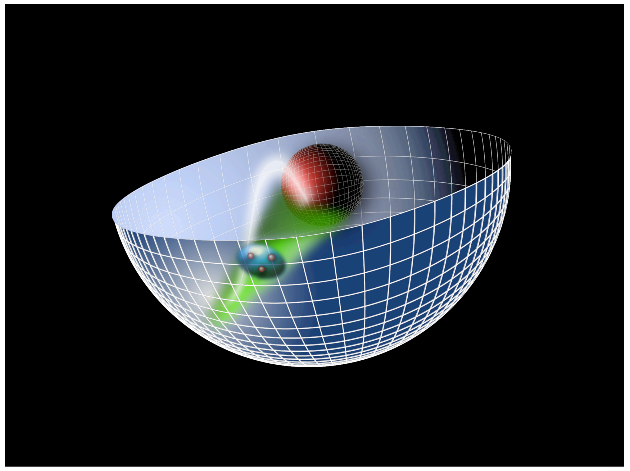

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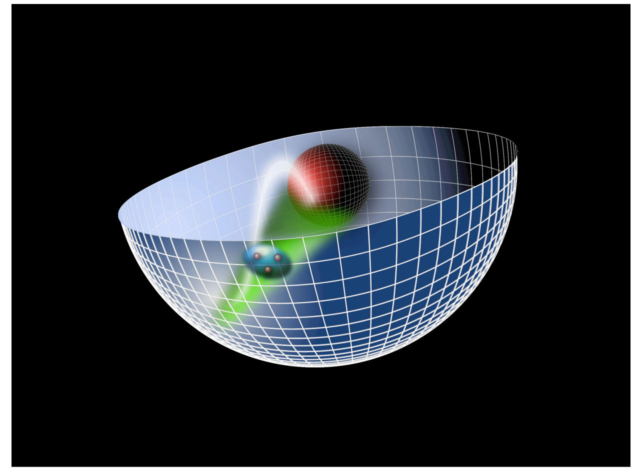

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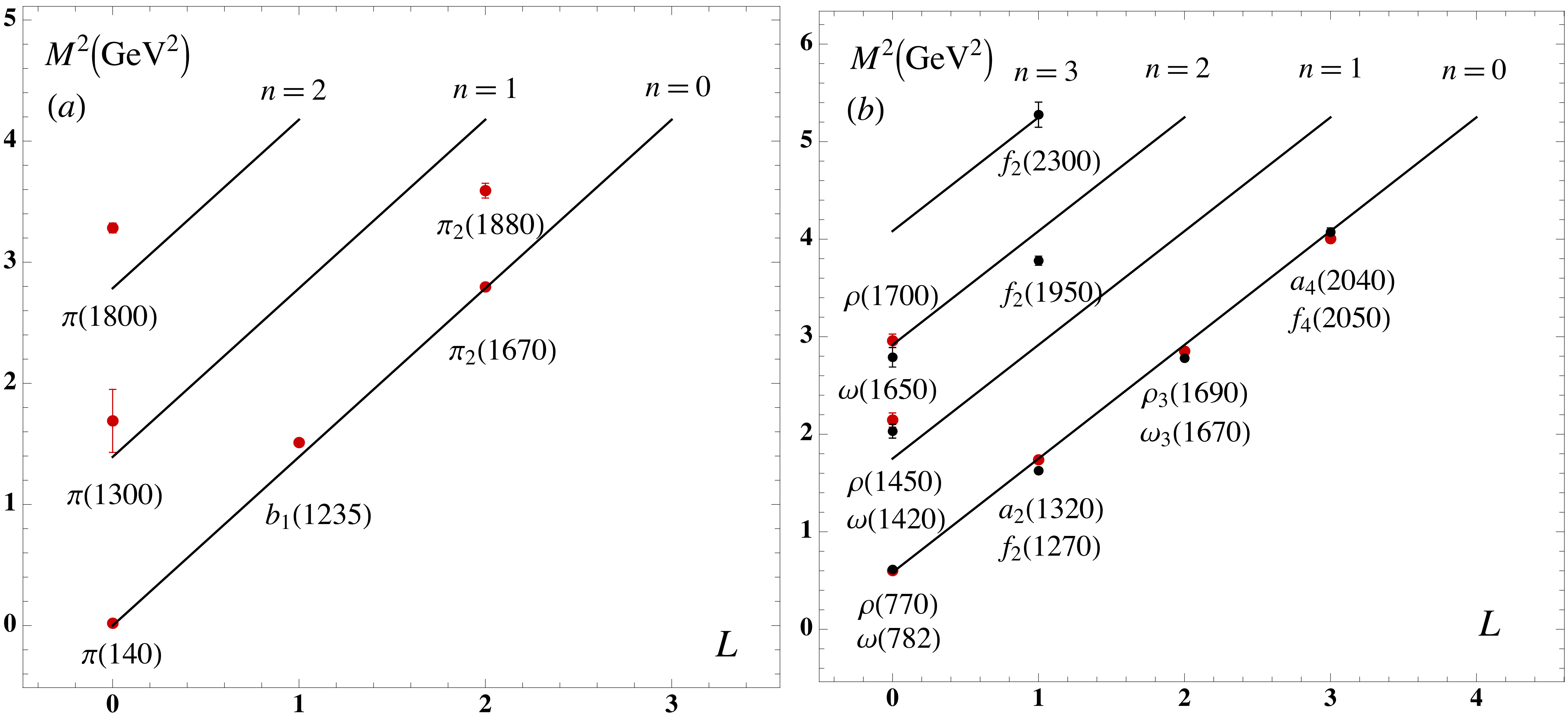
- **de Alfaro, Fubini, Furlan:**
- **Fubini, Rabinovici:**

Scale can appear in Hamiltonian and EQM without affecting conformal invariance of action!

$m_u = m_d = 0$

de Tèramond, Dosch, sjb



$$M^2(n, L, S) = 4\kappa^2(n + L + S/2)$$

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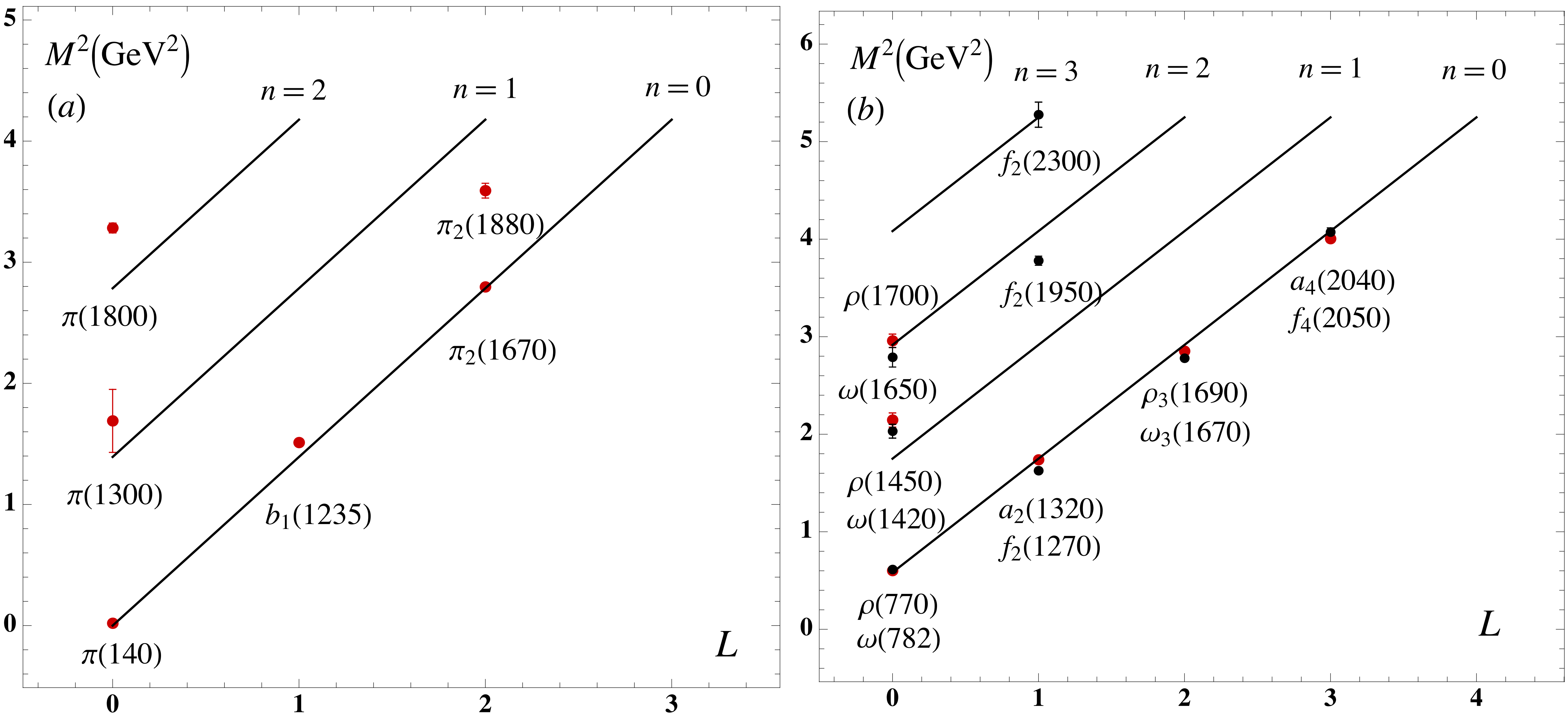

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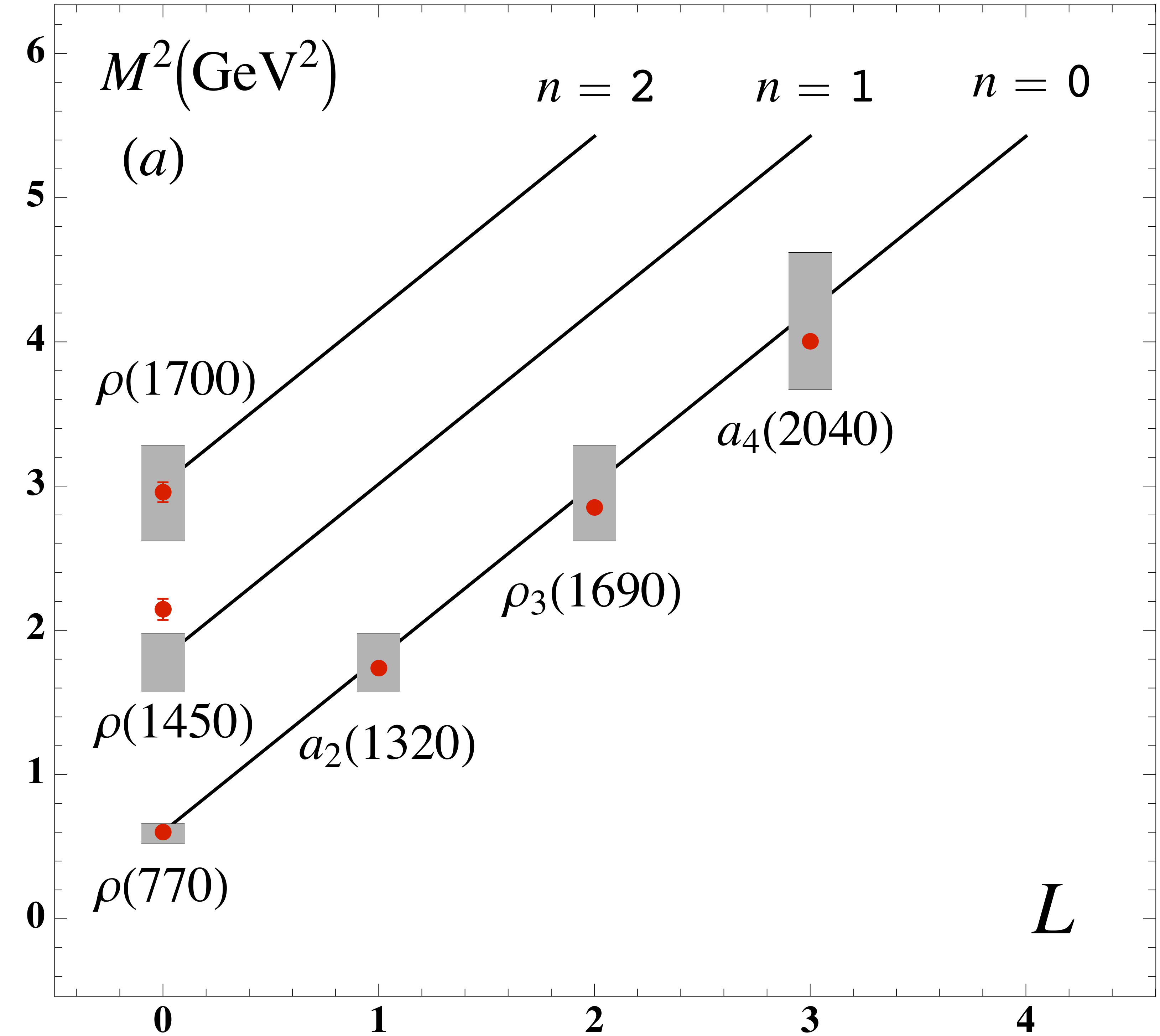

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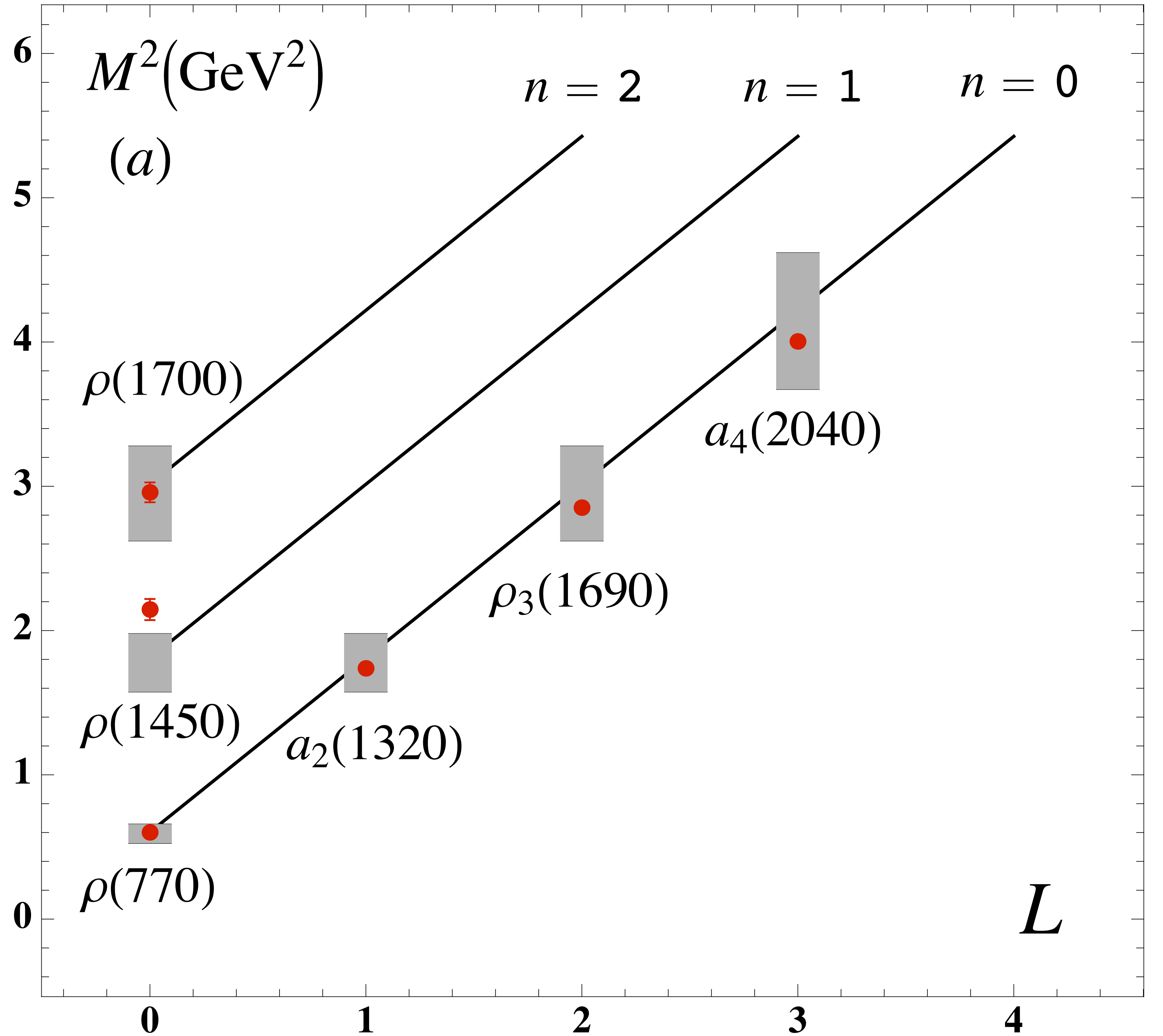

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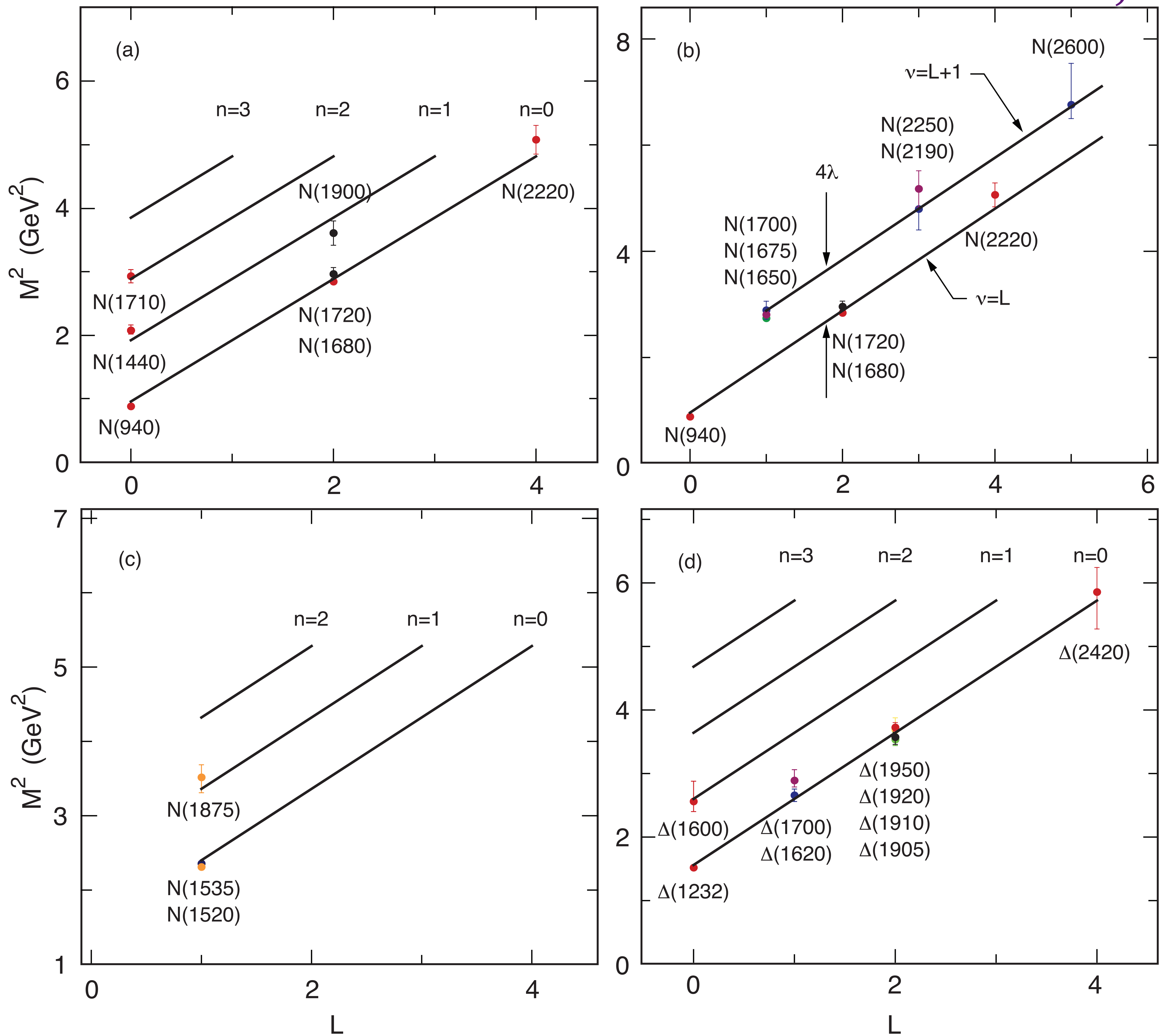
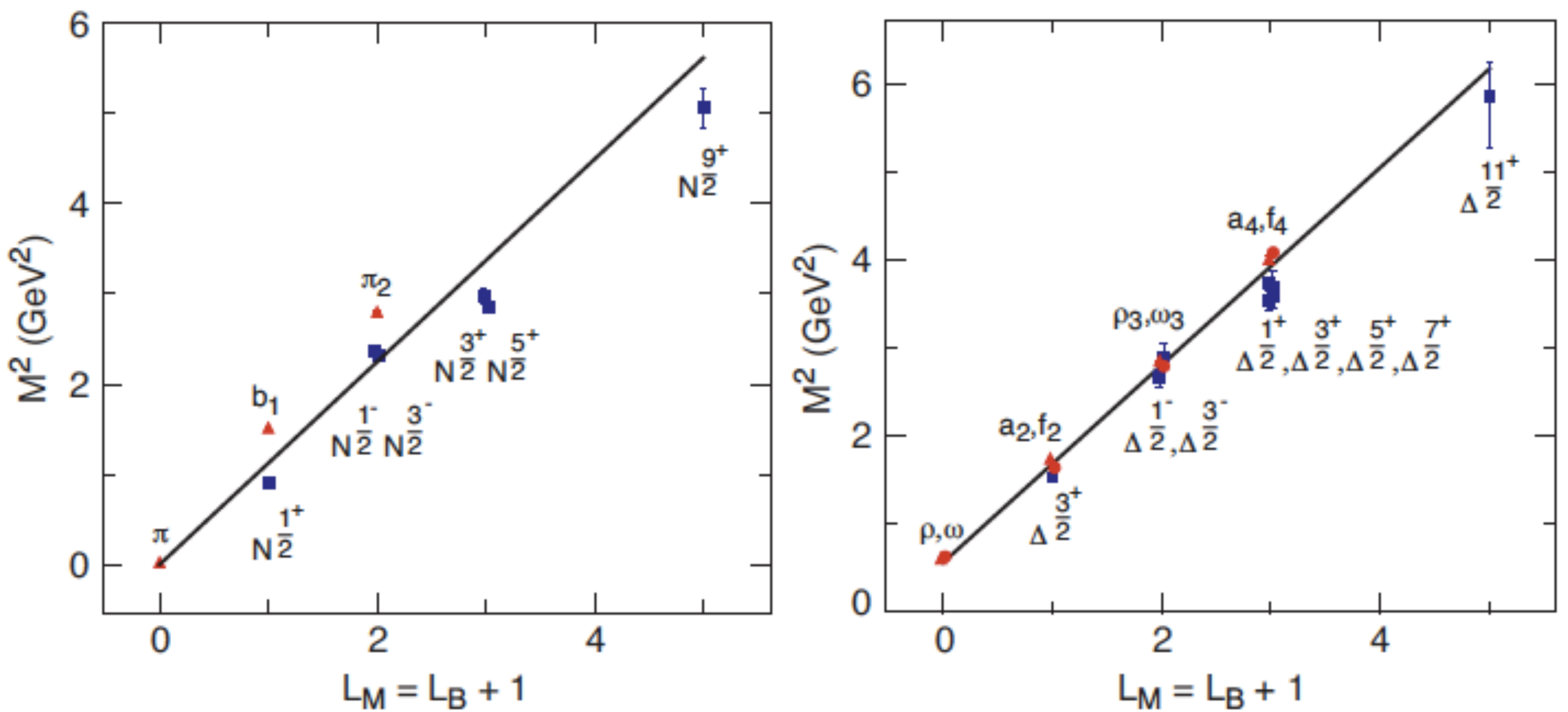


Baryon orbital and radial excitations for $\kappa = 0.49$ GeV (nucleons) and 0.51 GeV (Deltas)

de Tèramond, Dosch, sjb



Superconformal Meson-Nucleon Partners

$$\kappa = 530 \text{ MeV}$$

AdS/QCD and Light-Front Holography

- Single Scale κ; Only ratios predicted
- Spectroscopy, LFWFs, and Dynamics
- LF Schrödinger Equation — Analogous to Schrödinger Equation for Atomic Physics
- QCD Running Couplings
- Matching Scale Q_0

Some Features of AdS/QCD

- ***Regge spectroscopy—same slope in n,L for mesons, baryons***
- ***Chiral features for m_q=0: m_π=0, chiral-invariant proton***
- ***Hadronic LFWFs***
- ***Counting Rules***
- ***Connection between hadron masses and*** $\Lambda_{\overline{MS}}$

Superconformal AdS Light-Front Holographic QCD (LFHQCD)

Meson-Baryon Mass Degeneracy for L_M=L_B+1

Need a First Approximation to QCD

Comparable in simplicity to Schrödinger Theory in Atomic Physics

Relativistic, Frame-Independent, Color-Confining

Goal: An analytic first approximation to QCD

- As Simple as Schrödinger Theory in Atomic Physics
- Relativistic, Frame-Independent, Color-Confining
- Confinement in QCD -- What is the analytic form of the confining interaction?
- What sets the QCD mass scale?
- QCD Running Coupling at all scales
- Hadron Spectroscopy-Regge Trajectories
- Light-Front Wavefunctions
- Form Factors, Structure Functions, Hadronic Observables
- Constituent Counting Rules
- Hadronization at the Amplitude Level
- Insights into QCD Condensates
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- Systematically improvable

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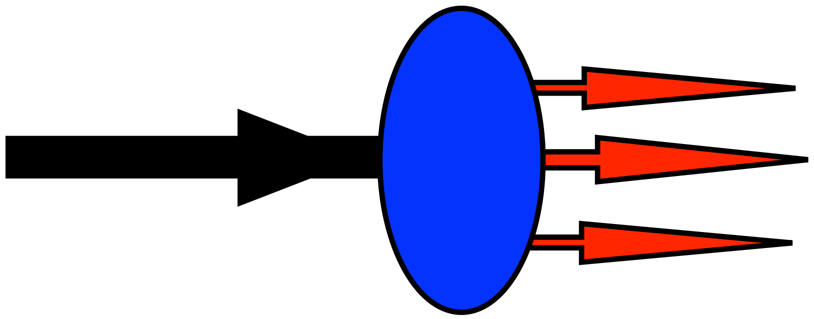
Bound States in Relativistic Quantum Field Theory:

Light-Front Wavefunctions

Dirac's Front Form: Fixed $\tau = t + z/c$



$$\psi(x_i, \vec{k}_{\perp i}, \lambda_i)$$

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Invariant under boosts. Independent of P^μ

$$\mathrm{H}_{LF}^{QCD} |\psi> = M^2 |\psi>$$

Direct connection to QCD Lagrangian

Off-shell in invariant mass

Remarkable new insights from AdS/CFT, the duality between conformal field theory and Anti-de Sitter Space

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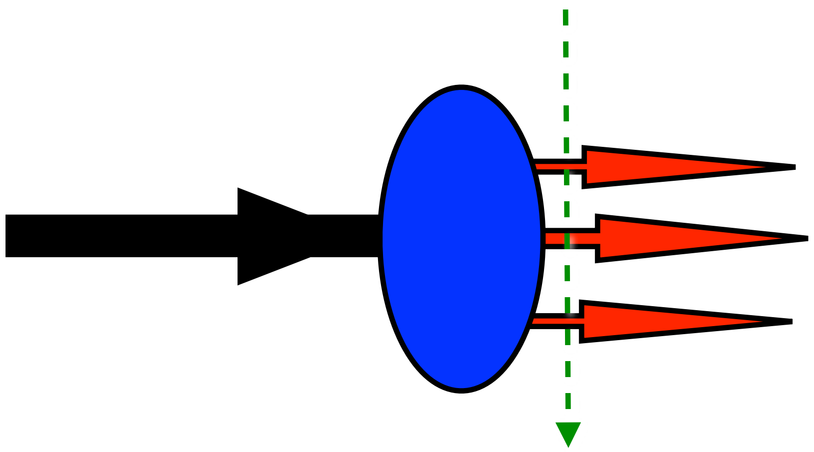

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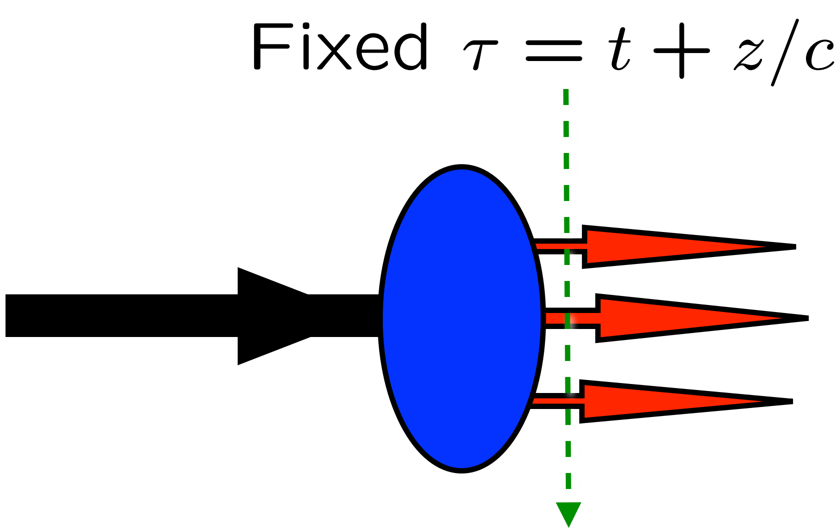

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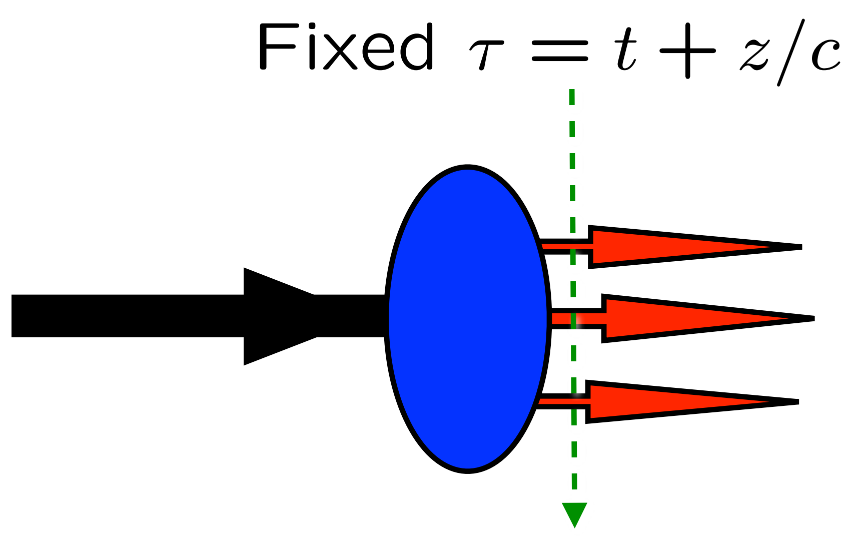

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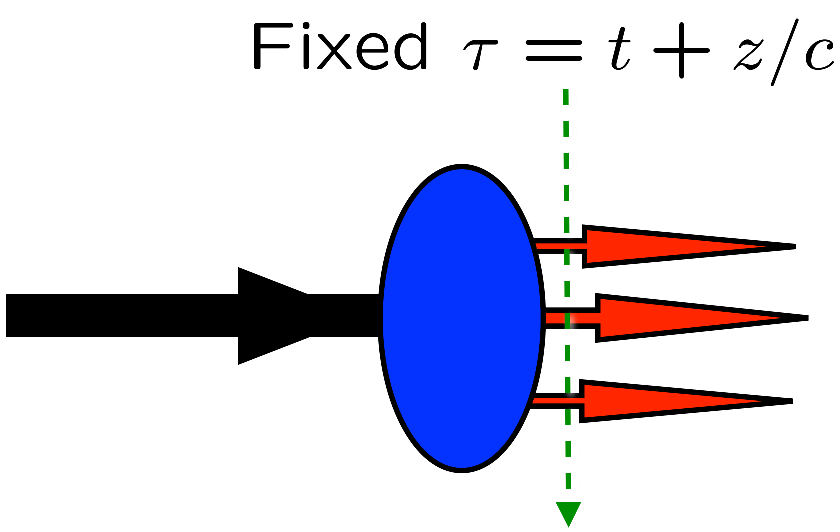

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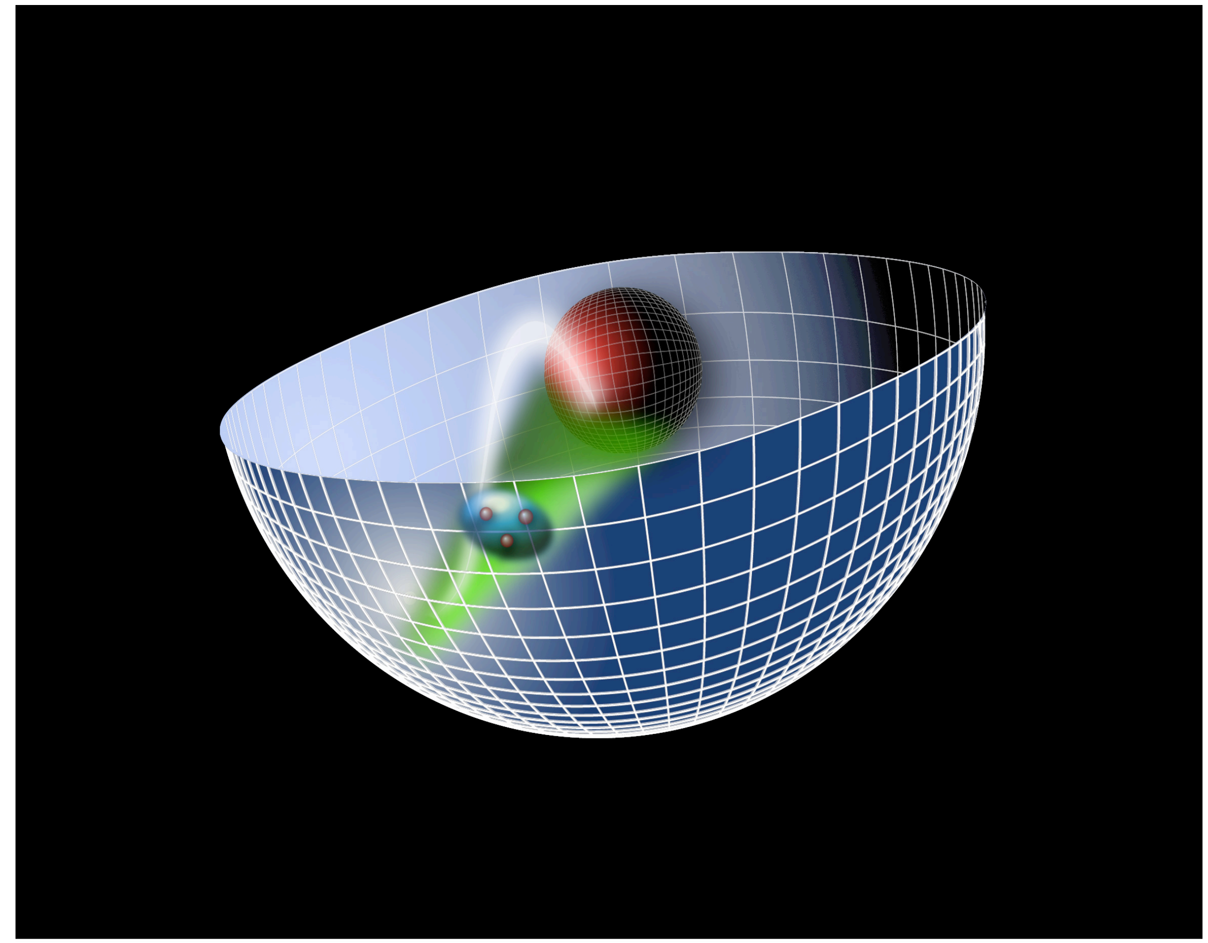
Light-Front Holography and Non-Perturbative QCD

Goal:
Use AdS/QCD duality to construct a first approximation to QCD

Hadron Spectrum
Light-Front Wavefunctions,
Form Factors, DVCS, etc



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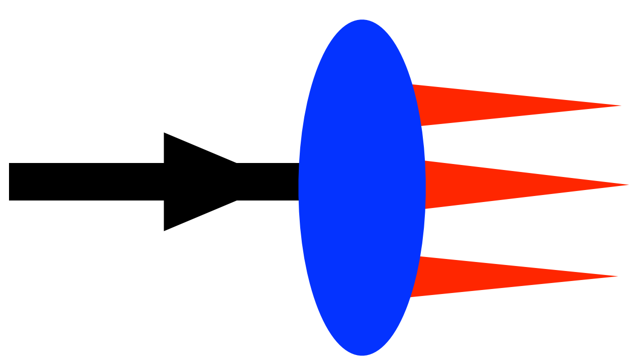
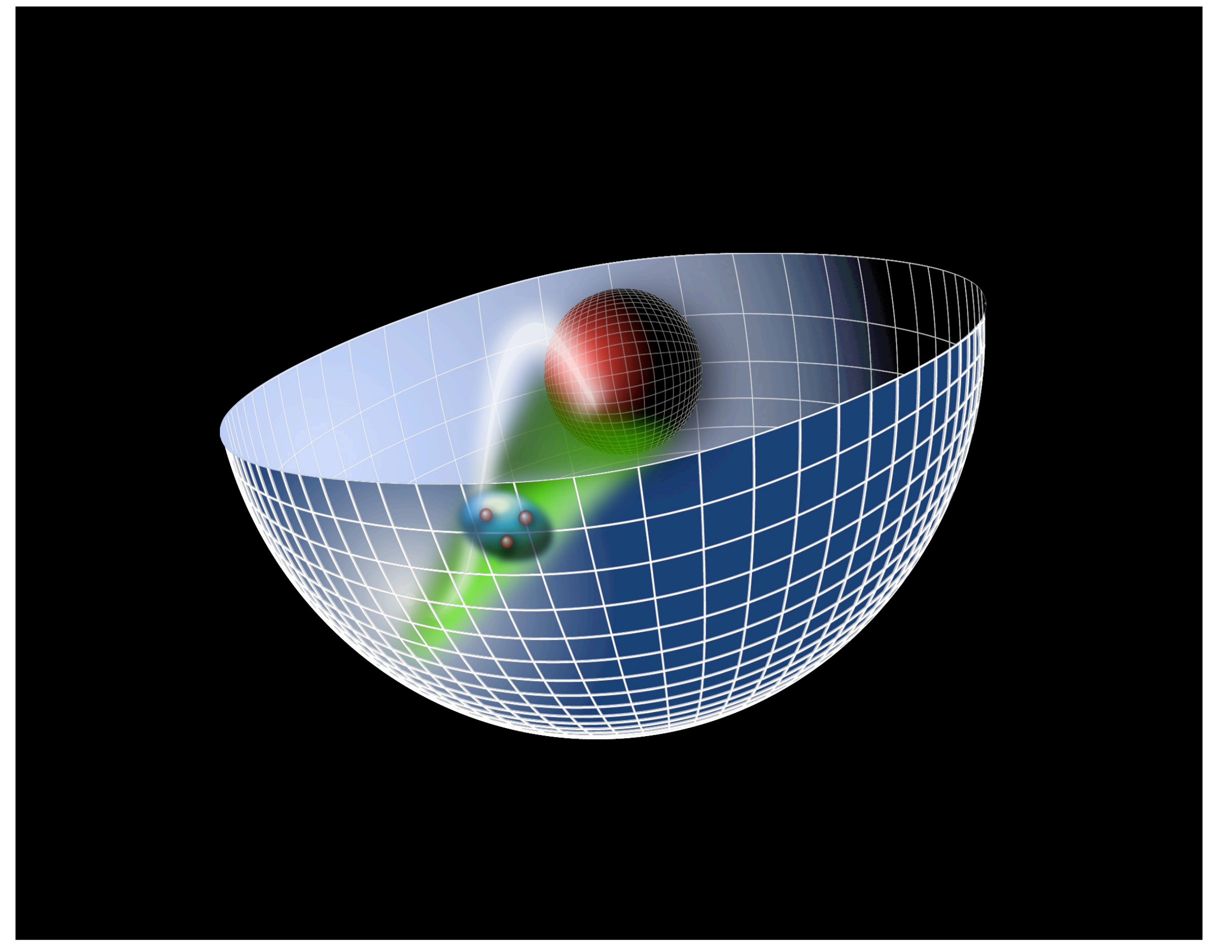


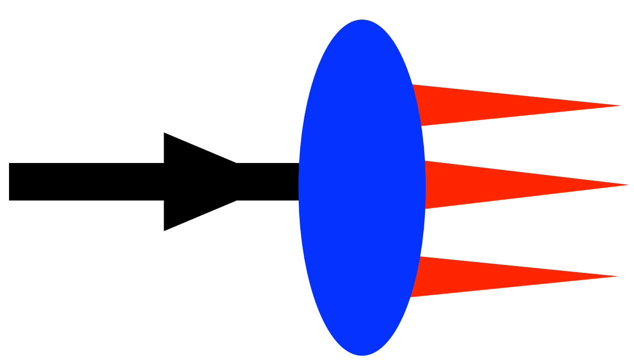
$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



Light-Front Holography and Non-Perturbative QCD

Goal:
Use AdS/QCD duality to construct a first approximation to QCD

Hadron Spectrum
Light-Front Wavefunctions,
Form Factors, DVCS, etc



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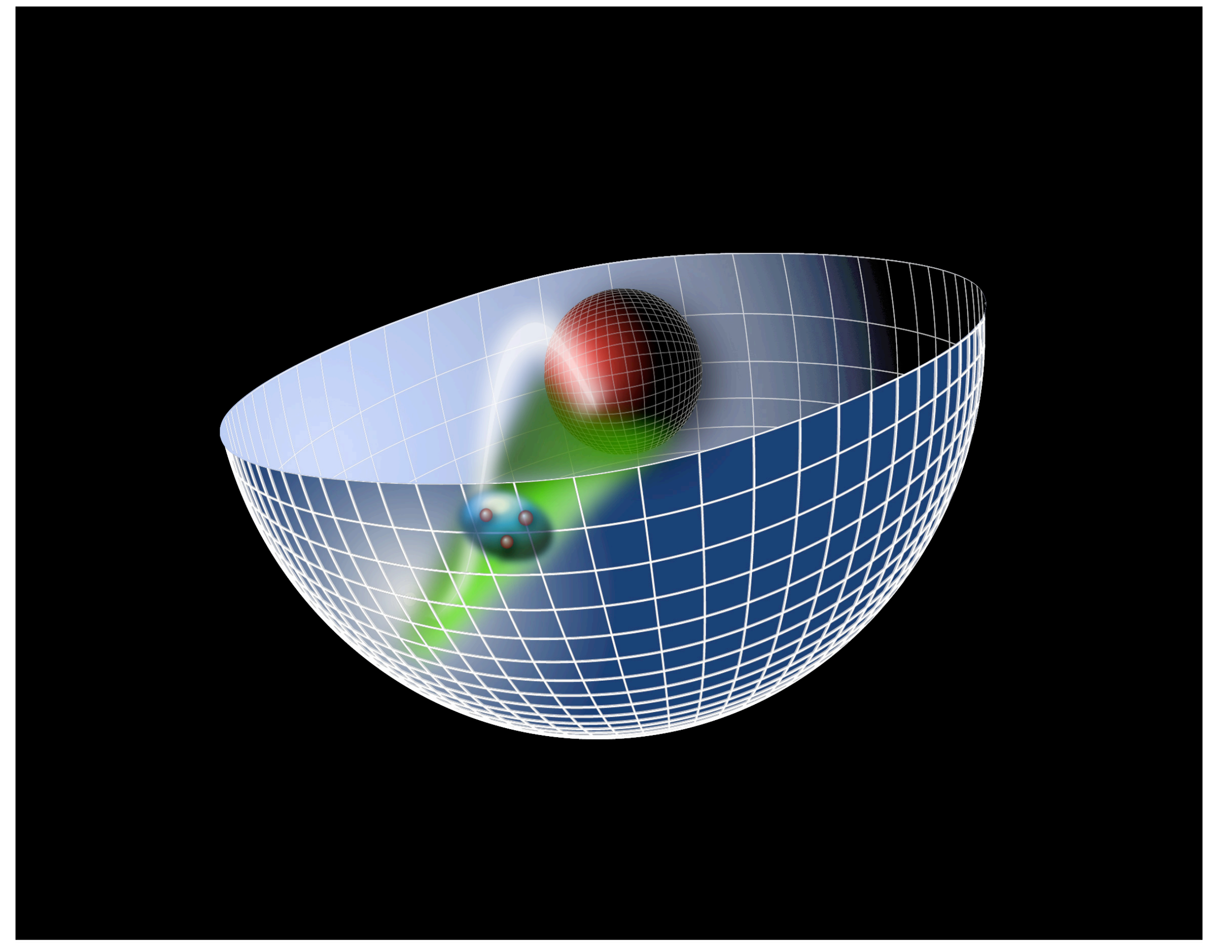
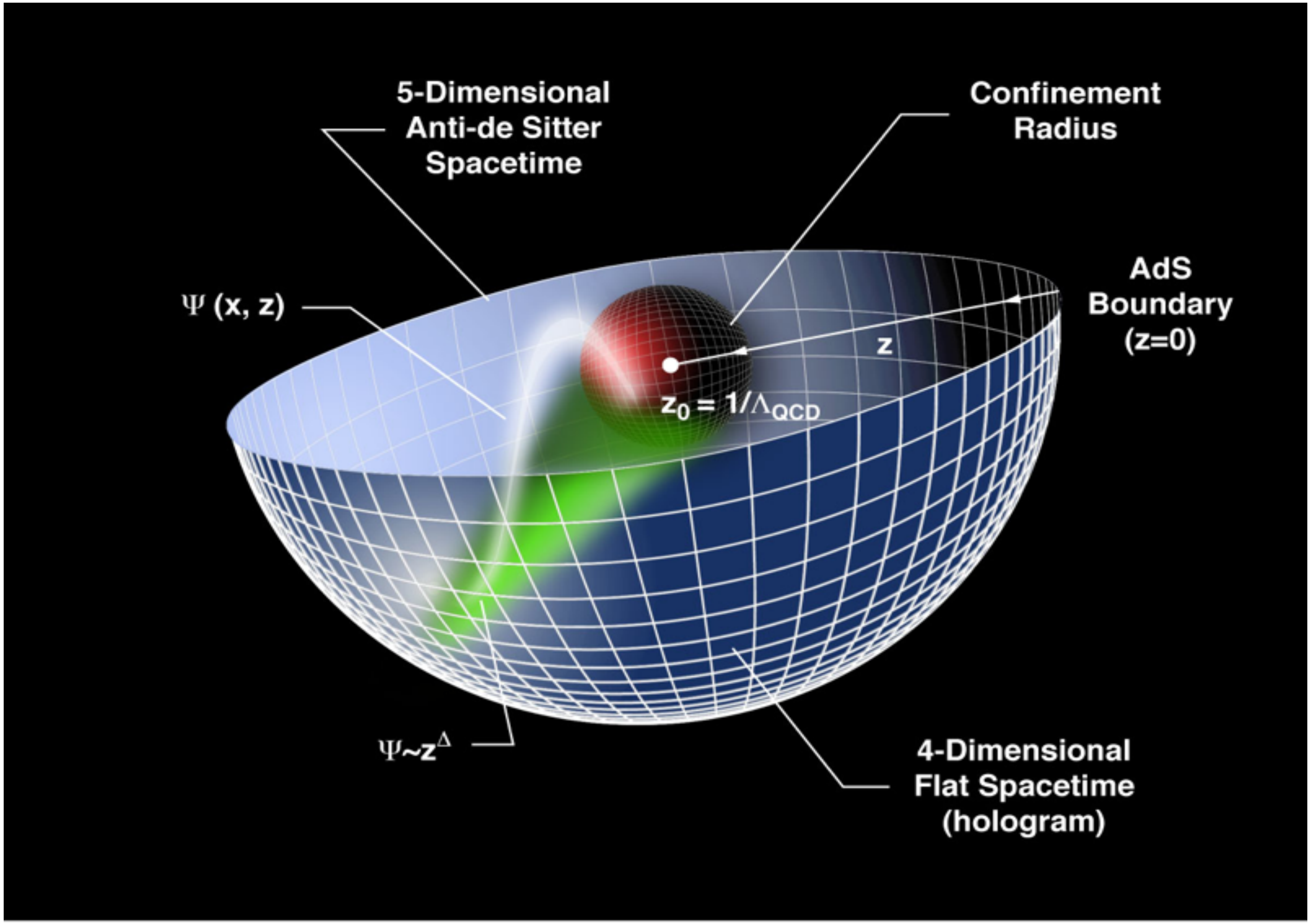


in collaboration with Guy de Teramond and H. Guenter Dosch

Applications of AdS/CFT to QCD



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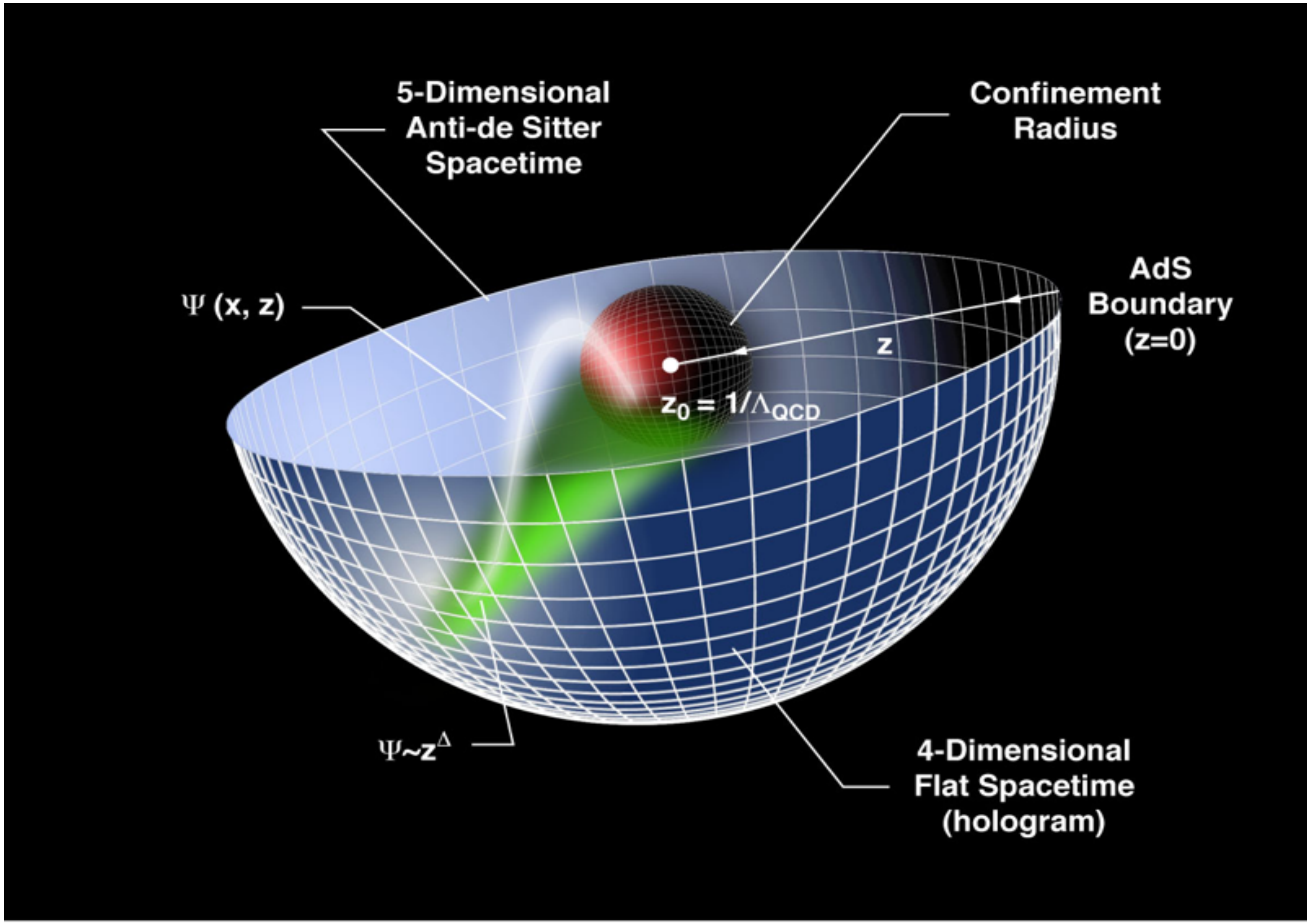

Changes in physical length scale mapped to evolution in the 5th dimension z

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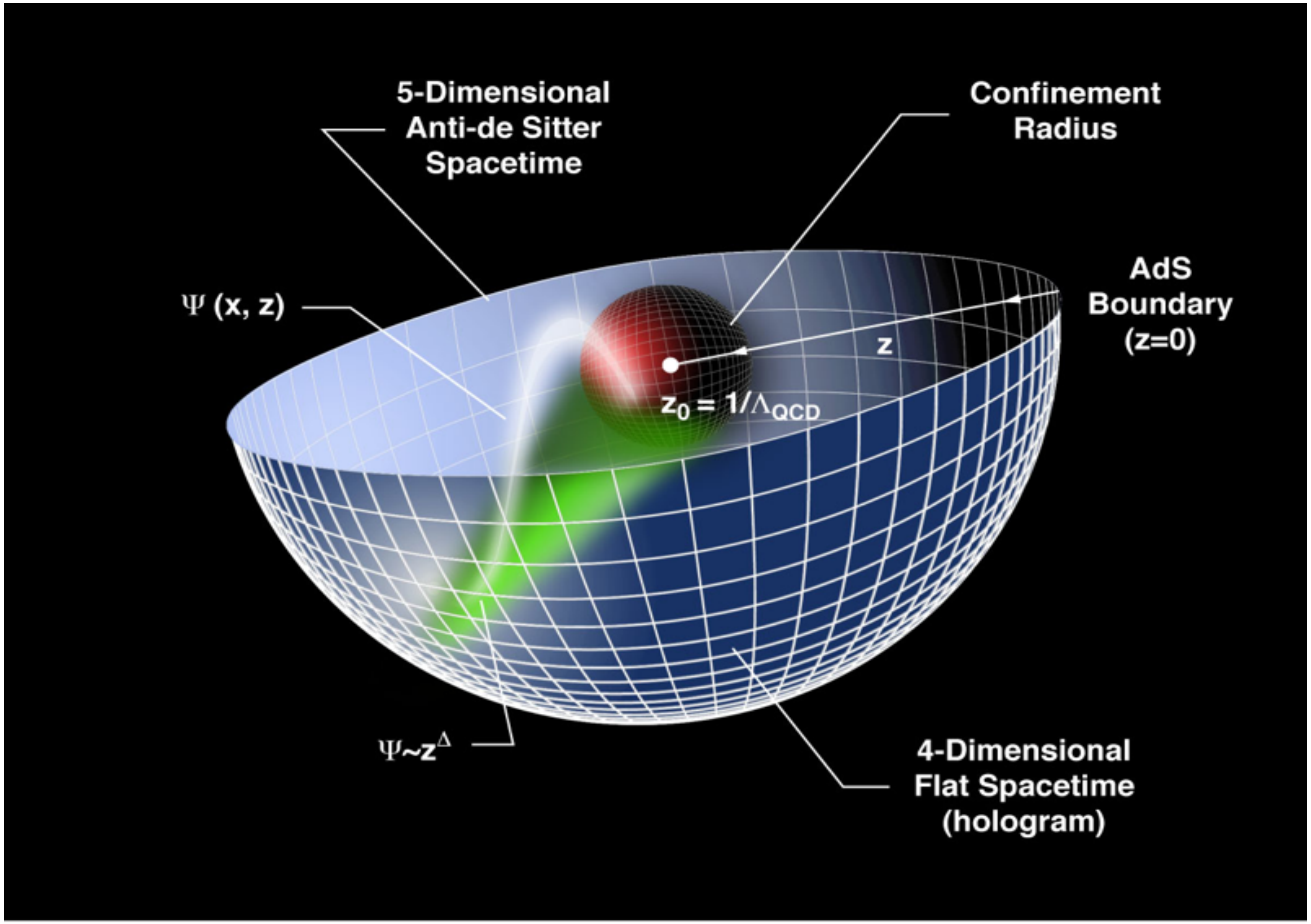

Changes in physical length scale mapped to evolution in the 5th dimension z

in collaboration with Guy de Teramond and H. Guenter Dosch

AdS/CFT

- Isomorphism of $SO(4,2)$ of conformal QCD with the group of isometries of AdS space

$$ds^2 = \frac{R^2}{z^2}(\eta_{\mu\nu}dx^\mu dx^\nu - dz^2),$$

$x^\mu \rightarrow \lambda x^\mu, \; z \rightarrow \lambda z$, maps scale transformations into the holographic coordinate z.

- AdS mode in z is the extension of the hadron wf into the fifth dimension.

- Different values of z correspond to different scales at which the hadron is examined.

$$x^2 \rightarrow \lambda^2 x^2, \quad z \rightarrow \lambda z.$$

$x^2 = x_\mu x^\mu$: invariant separation between quarks

- The AdS boundary at $z \rightarrow 0$ correspond to the $Q \rightarrow \infty$, UV zero separation limit.

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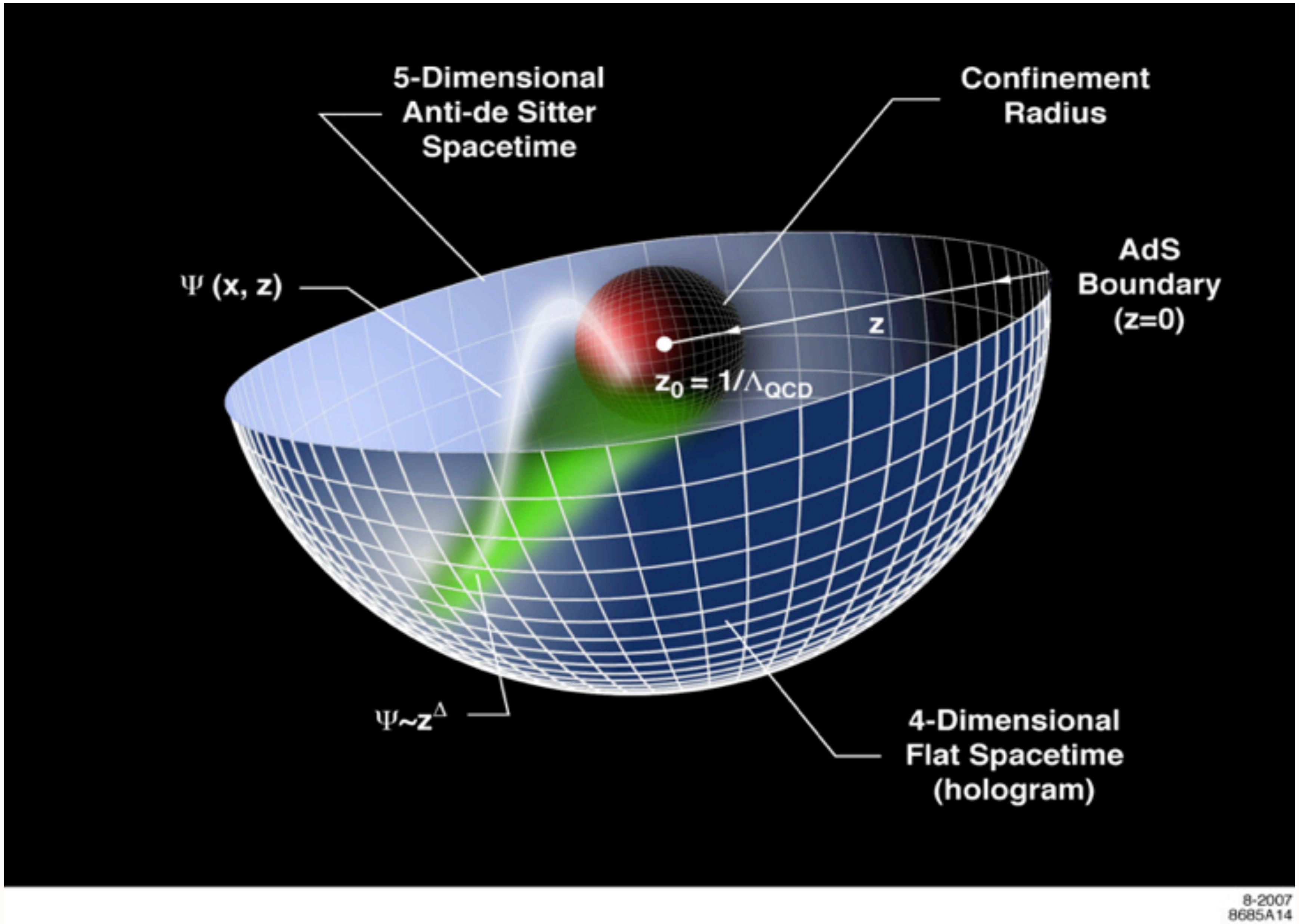

Changes in physical length scale mapped to evolution in the 5th dimension z

- Truncated AdS/CFT (Hard-Wall) model: cut-off at $z_0 = 1/\Lambda_{\rm QCD}$ breaks conformal invariance and allows the introduction of the QCD scale (Hard-Wall Model) Polchinski and Strassler (2001).
- Smooth cutoff: introduction of a background dilaton field $\varphi(z)$ – usual linear Regge dependence can be obtained (Soft-Wall Model) Karch, Katz, Son and Stephanov (2006).

Dilaton-Modified AdS/QCD

$$ds^2 = e^{\varphi(z)} \frac{R^2}{z^2}(\eta_{\mu\nu} x^\mu x^\nu - dz^2)$$

- **Soft-wall dilaton profile breaks conformal invariance** $e^{\varphi(z)} = e^{+\kappa^2 z^2}$
- **Color Confinement**
- **Introduces confinement scale** κ
- **Uses AdS_5 as template for conformal theory**

$$e^{\varphi(z)} = e^{+\kappa^2 z^2}$$

- Dosch, de Teramond, sjb

AdS Soft-Wall Schrodinger Equation for bound state of two scalar constituents:

$$[-\frac{d^2}{dz^2} - \frac{1-4L^2}{4z^2} + U(z)]\Phi(z) = \mathcal{M}^2\Phi(z)$$

$$U(z) = \kappa^4 z^2 + 2\kappa^2(L+S-1)$$

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Positive-sign dilaton

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Derived from variation of Action for Dilaton-Modified AdS_5

Identical to Light-Front Bound State Equation!

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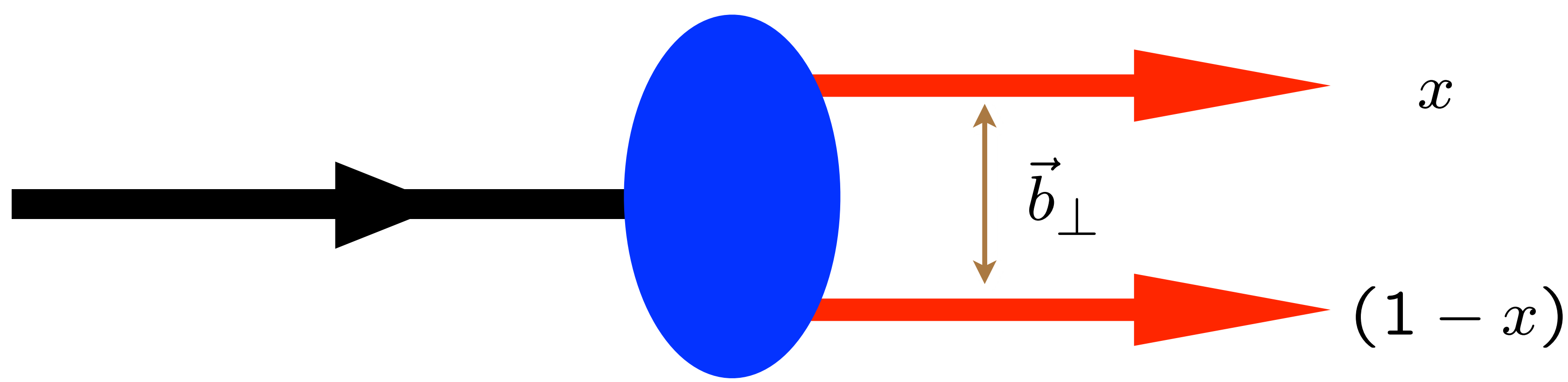
$$z \longleftrightarrow \zeta = \sqrt{x(1-x)\vec{b}_\perp^2}$$

LF(3+1) ⟷ AdS_5

de Teramond, sjb

Light-Front Holographic Dictionary



$$(\mu R)^2 = L^2 - (J-2)^2$$

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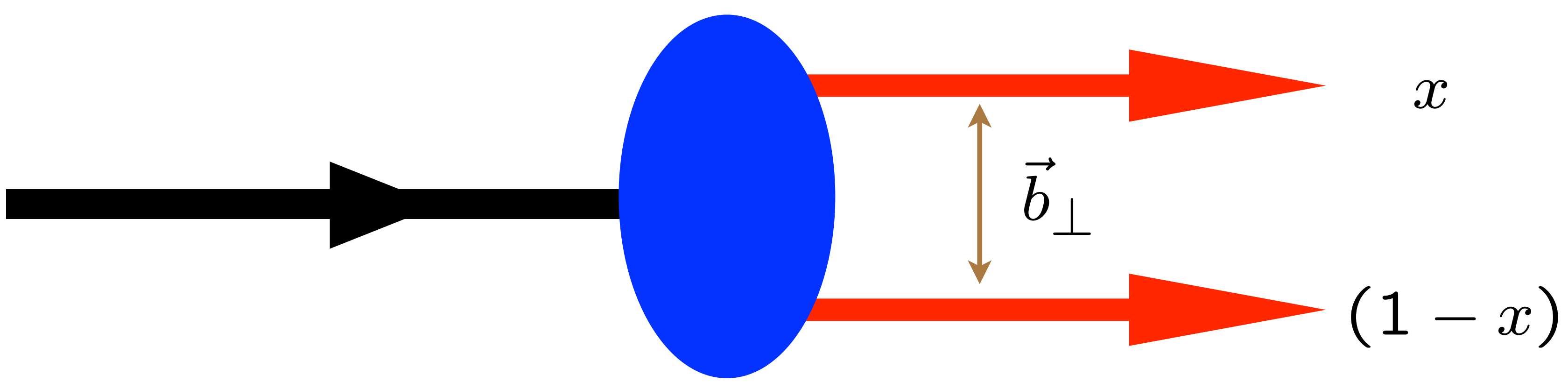
Light-Front Holographic Dictionary

$$\psi(x, \vec{b}_\perp)$$



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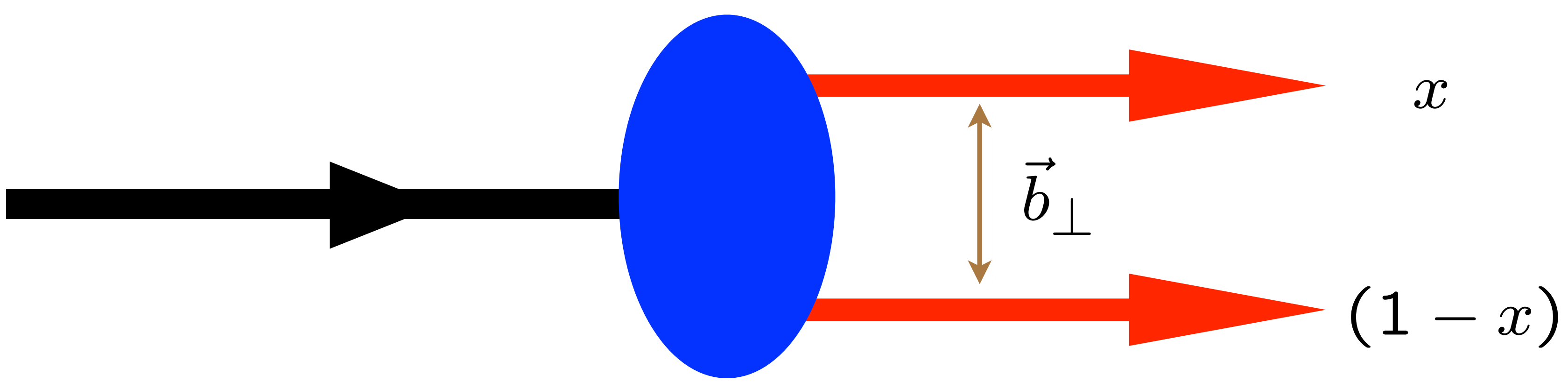

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LF(3+1) ⟷ AdS_5

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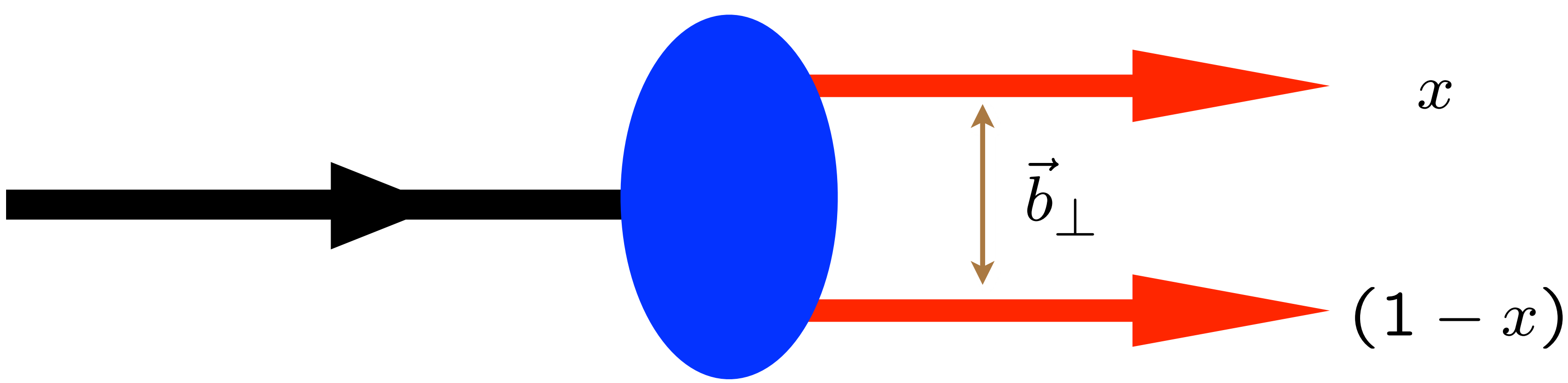
$$\psi(x, \vec{b}_\perp) \longleftrightarrow \phi(z)$$



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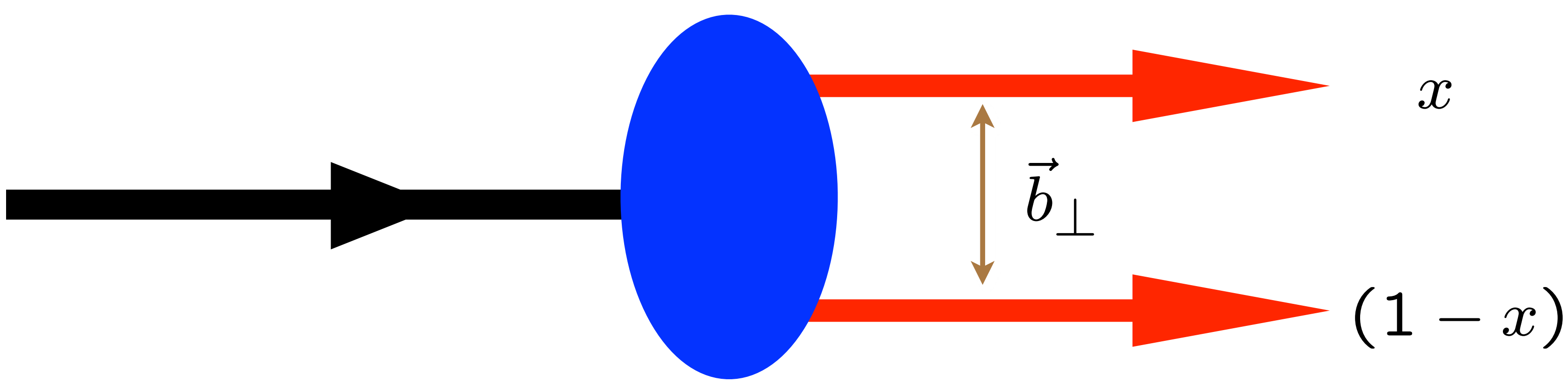

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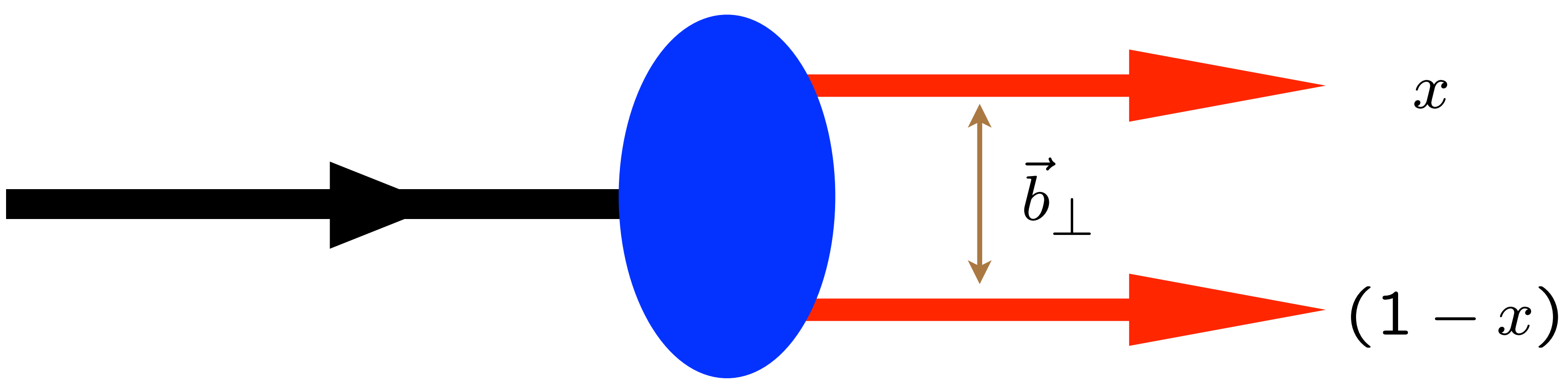

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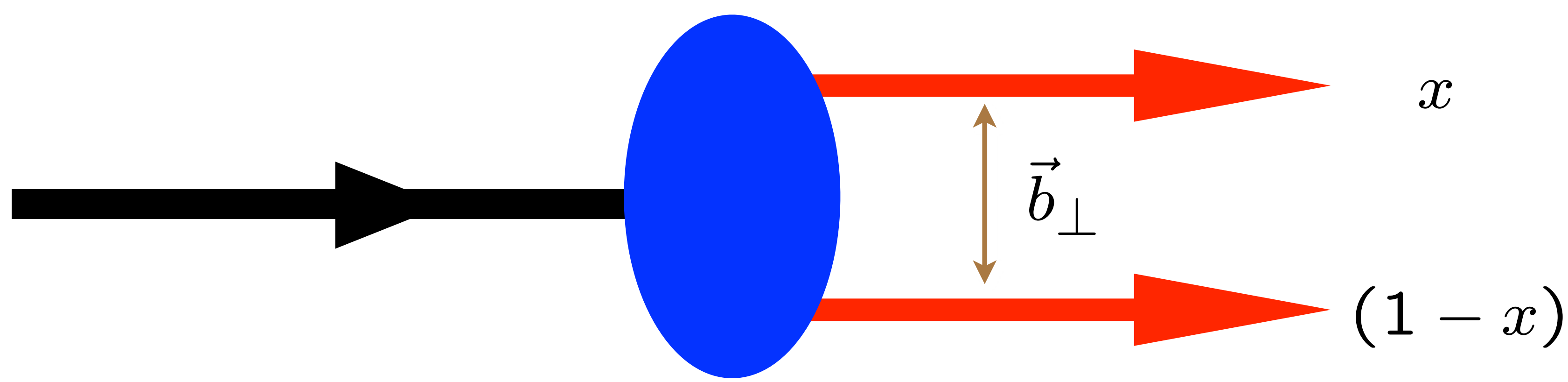

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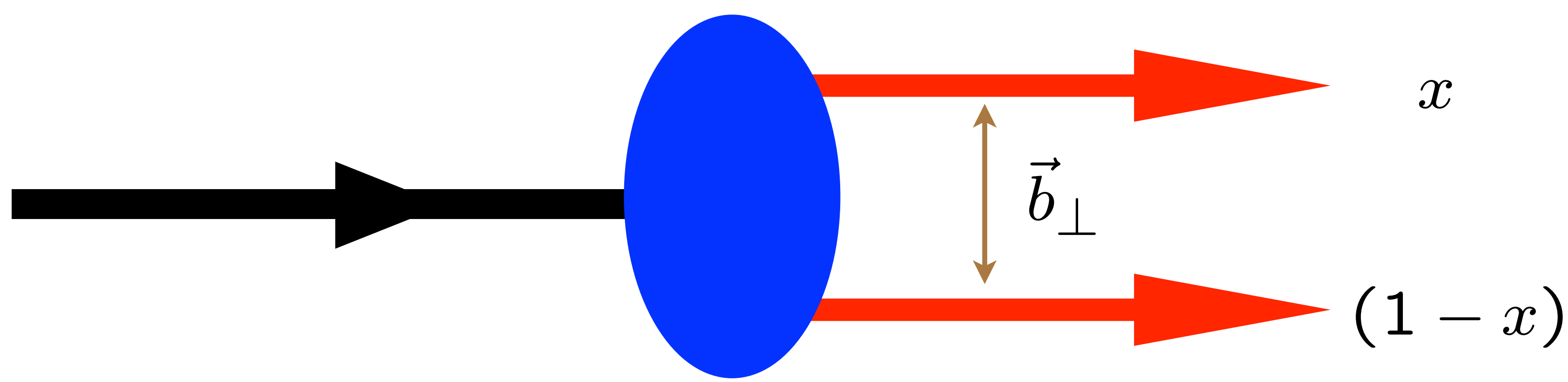

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Light-Front Holography: *Unique mapping derived from equality of LF and AdS formula for EM and gravitational current matrix elements and identical equations of motion*

de Teramond, sjb

LF(3+1) ↔ AdS_5

Light-Front Holographic Dictionary

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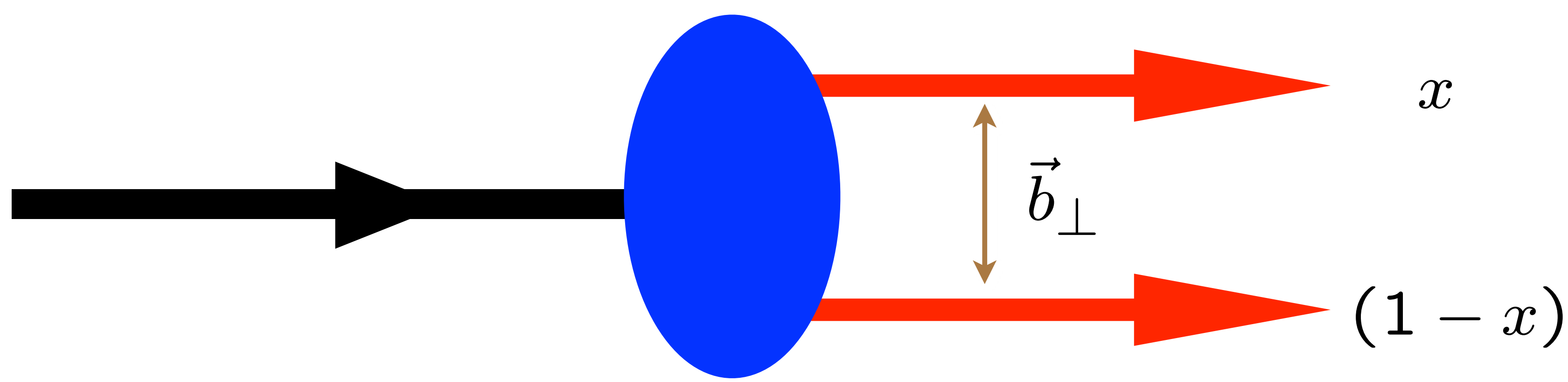

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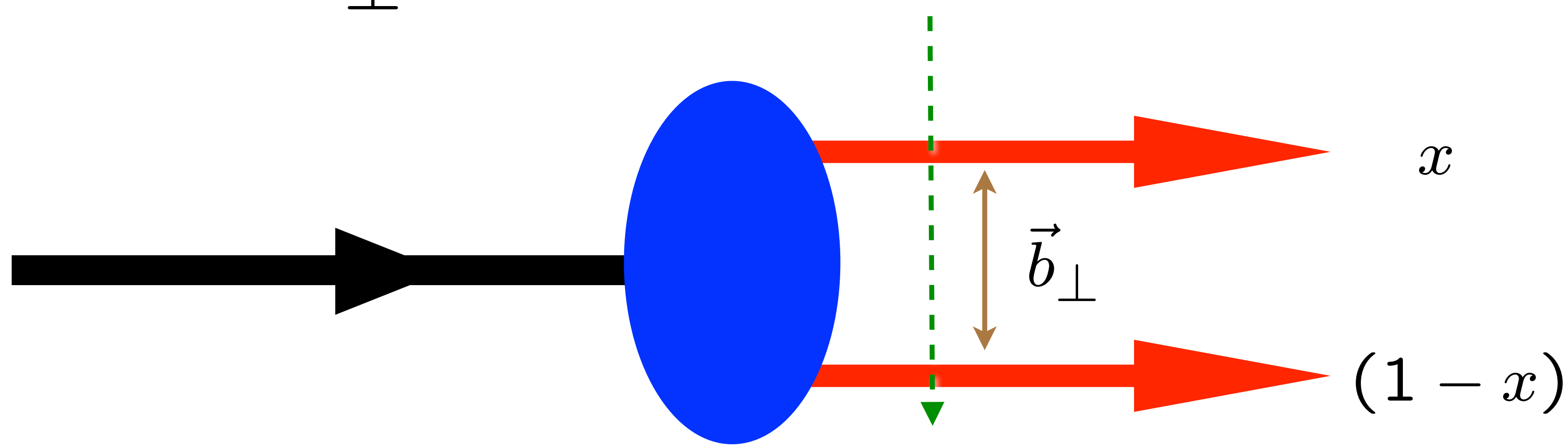

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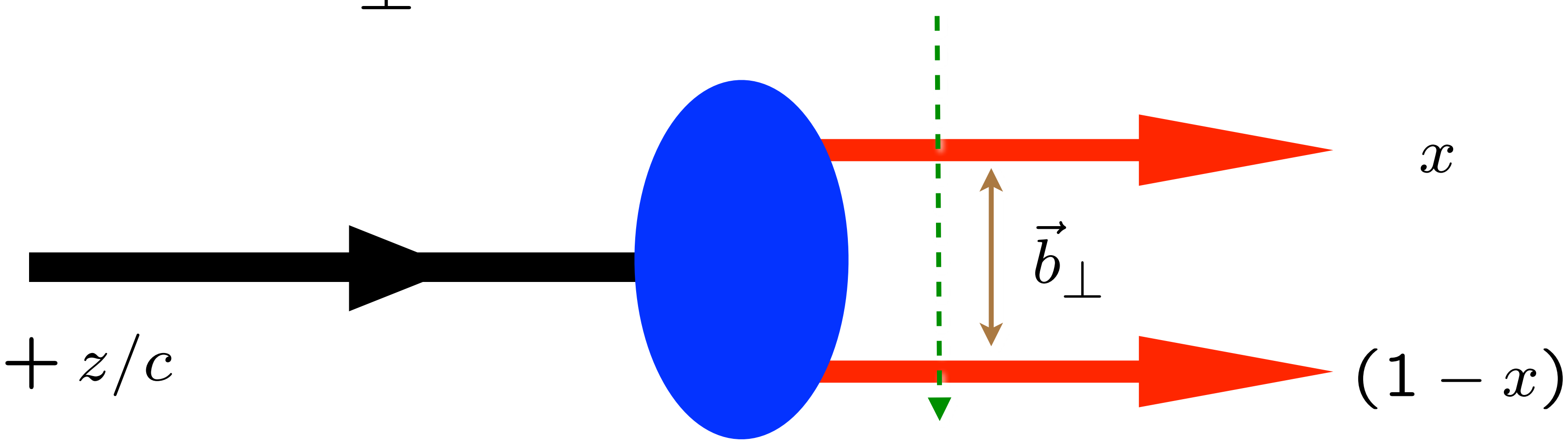

Fixed $\tau = t + z/c$

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Light-Front Holography: *Unique mapping derived from equality of LF and AdS formula for EM and gravitational current matrix elements and identical equations of motion*

de Tèramond, Dosch, sjb

General-Spin Hadrons

- Obtain spin-J mode $\Phi_{\mu_1 \cdots \mu_J}$ with all indices along 3+1 coordinates from Φ by shifting dimensions

$$\Phi_J(z) = \left(\frac{z}{R}\right)^{-J} \Phi(z)$$

$$e^{\varphi(z)} = e^{+\kappa^2 z^2}$$

- Substituting in the AdS scalar wave equation for Φ

$$\left[z^2 \partial_z^2 - \left(3 - 2J - 2\kappa^2 z^2\right) z\, \partial_z + z^2 \mathcal{M}^2 - (\mu R)^2\right] \Phi_J = 0$$

- Upon substitution $z \rightarrow \zeta$

$$\phi_J(\zeta) \sim \zeta^{-3/2+J} e^{\kappa^2 \zeta^2/2}\, \Phi_J(\zeta)$$

we find the LF wave equation

$$\boxed{\left(-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + \kappa^4 \zeta^2 + 2\kappa^2 (L+S-1)\right) \phi_{\mu_1 \cdots \mu_J} = \mathcal{M}^2 \phi_{\mu_1 \cdots \mu_J}}$$

with $(\mu R)^2 = -(2-J)^2 + L^2$

de Tèramond, Dosch, sjb

AdS/QCD
Soft-Wall Model

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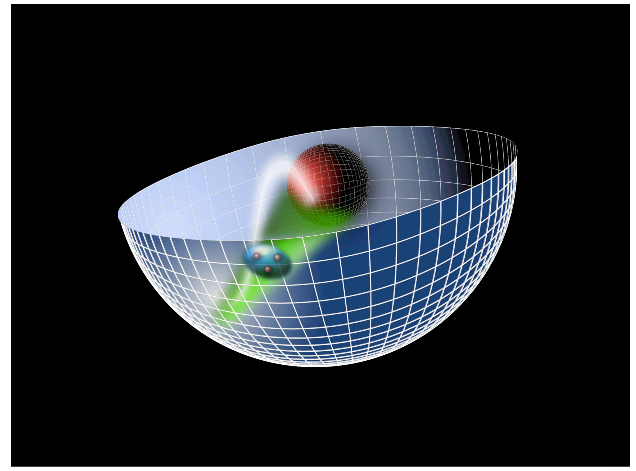

Light-Front Holography

$$\left[-\frac{d^2}{d\zeta^2} + \frac{1-4L^2}{4\zeta^2} + U(\zeta)\right]\psi(\zeta) = \mathcal{M}^2\psi(\zeta)$$

Light-Front Schrödinger Equation

Confinement scale:

$$\kappa \simeq 0.6 \ GeV$$

$$1/\kappa \simeq 1/3 \ fm$$

- **Fubini, Rabinovici:**

de Tèramond, Dosch, sjb

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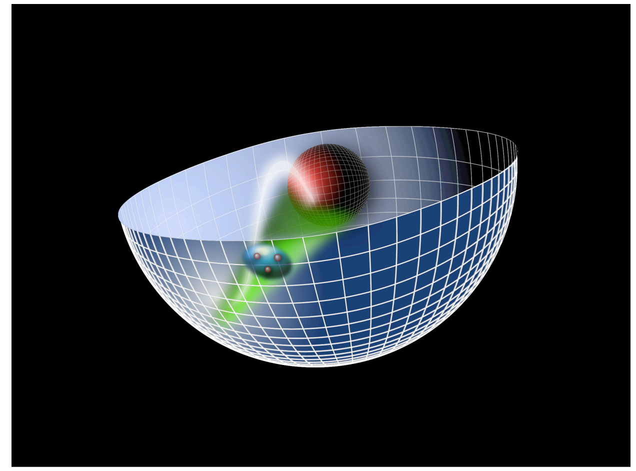

$$\zeta^2 = x(1-x)\mathbf{b}_\perp^2.$$

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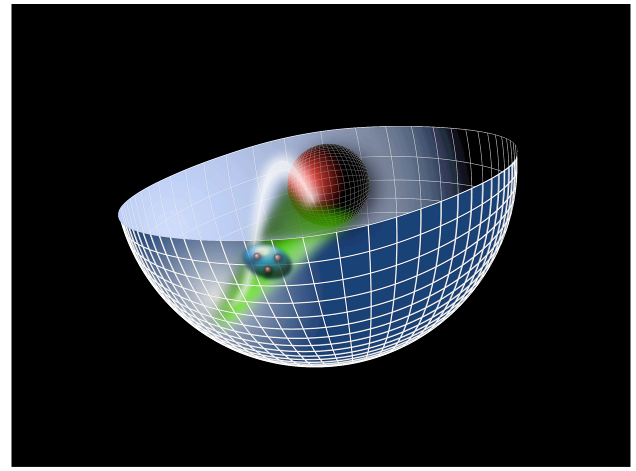

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$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L+S-1)$$

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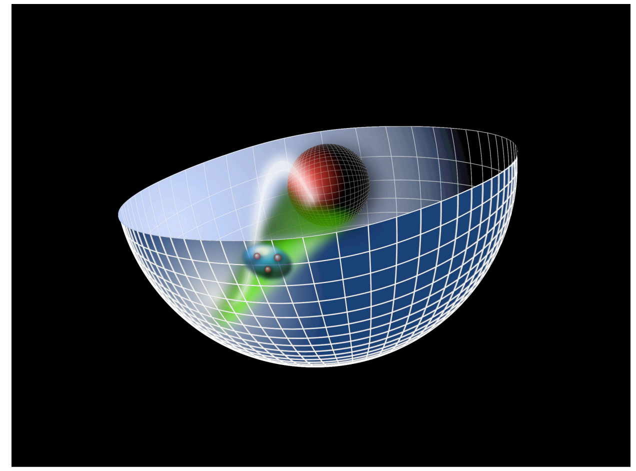

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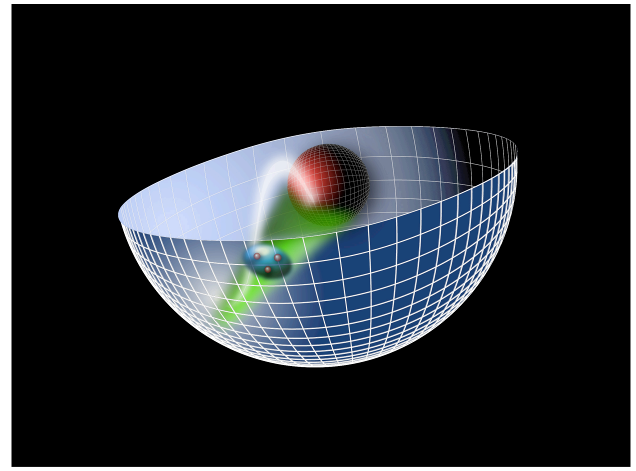

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- **de Alfaro, Fubini, Furlan:**
- **Fubini, Rabinovici:**

Scale can appear in Hamiltonian and EQM without affecting conformal invariance of action!

Meson Spectrum in Soft Wall Model

- Effective potential: $U(\zeta^2) = \kappa^4 \zeta^2 + 2\kappa^2(J-1)$
- LF WE

$$\left(-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + \kappa^4\zeta^2 + 2\kappa^2(J-1)\right)\phi_J(\zeta) = M^2\phi_J(\zeta)$$

- Normalized eigenfunctions $\langle\phi|\phi\rangle = \int d\zeta\, \phi^2(z)^2 = 1$

$$\phi_{n,L}(\zeta) = \kappa^{1+L}\sqrt{\frac{2n!}{(n+L)!}}\,\zeta^{1/2+L}e^{-\kappa^2\zeta^2/2}L_n^L(\kappa^2\zeta^2)$$

- Eigenvalues

$$\mathcal{M}^2_{n,J,L} = 4\kappa^2\left(n + \frac{J+L}{2}\right)$$

G. de Teramond, H. G. Dosch, sjb

Meson Spectrum in Soft Wall Model

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Meson Spectrum in Soft Wall Model

Pion: Negative term for J=0 cancels positive terms from LFKE and potential

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$$\left(-\frac{d^2}{d\zeta^2} - \frac{1-4L^2}{4\zeta^2} + \kappa^4\zeta^2 + 2\kappa^2(J-1)\right)\phi_J(\zeta) = M^2 \phi_J(\zeta)$$

- Normalized eigenfunctions $\langle\phi|\phi\rangle = \int d\zeta\, \phi^2(z)^2 = 1$

$$\phi_{n,L}(\zeta) = \kappa^{1+L}\sqrt{\frac{2n!}{(n+L)!}}\,\zeta^{1/2+L} e^{-\kappa^2\zeta^2/2} L_n^L(\kappa^2\zeta^2)$$

- Eigenvalues

$$\mathcal{M}^2_{n,J,L} = 4\kappa^2\left(n + \frac{J+L}{2}\right)$$

G. de Teramond, H. G. Dosch, sjb

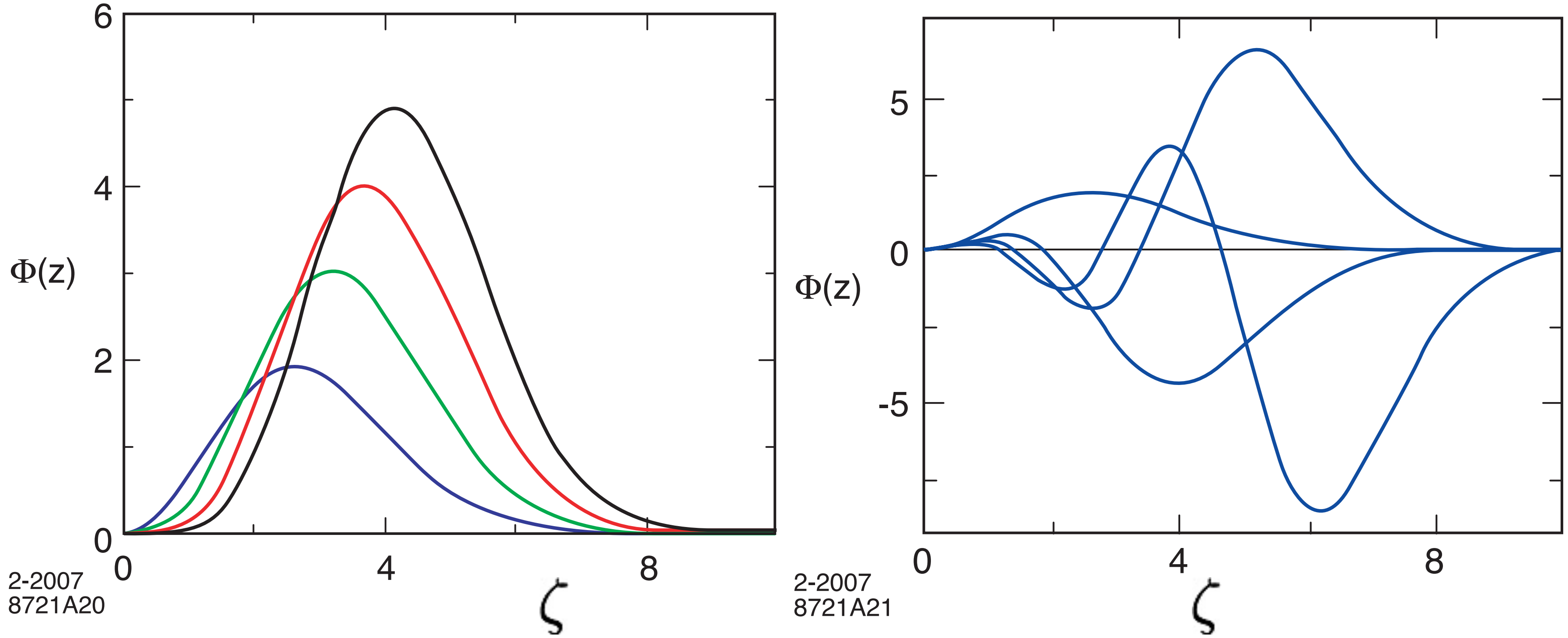
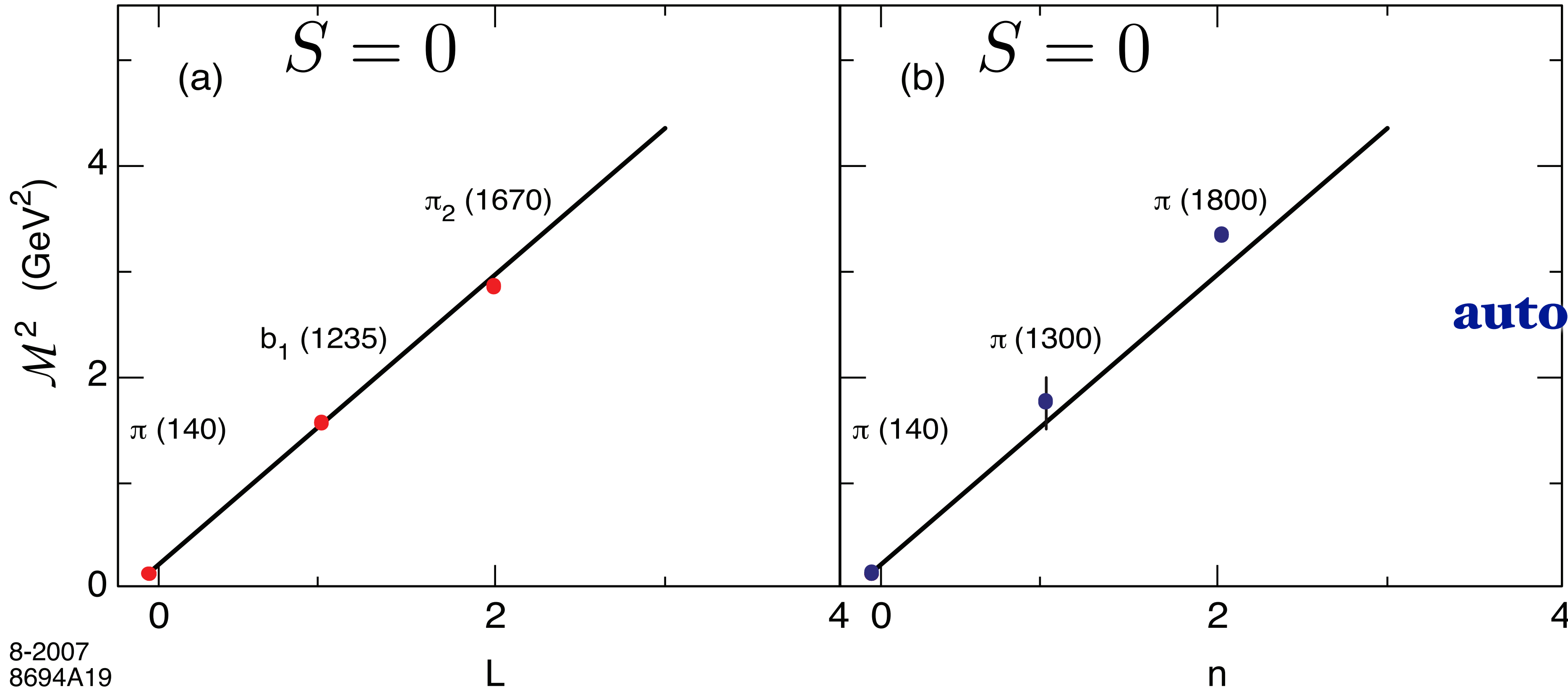


Fig: Orbital and radial AdS modes in the soft wall model for κ = 0.6 GeV .

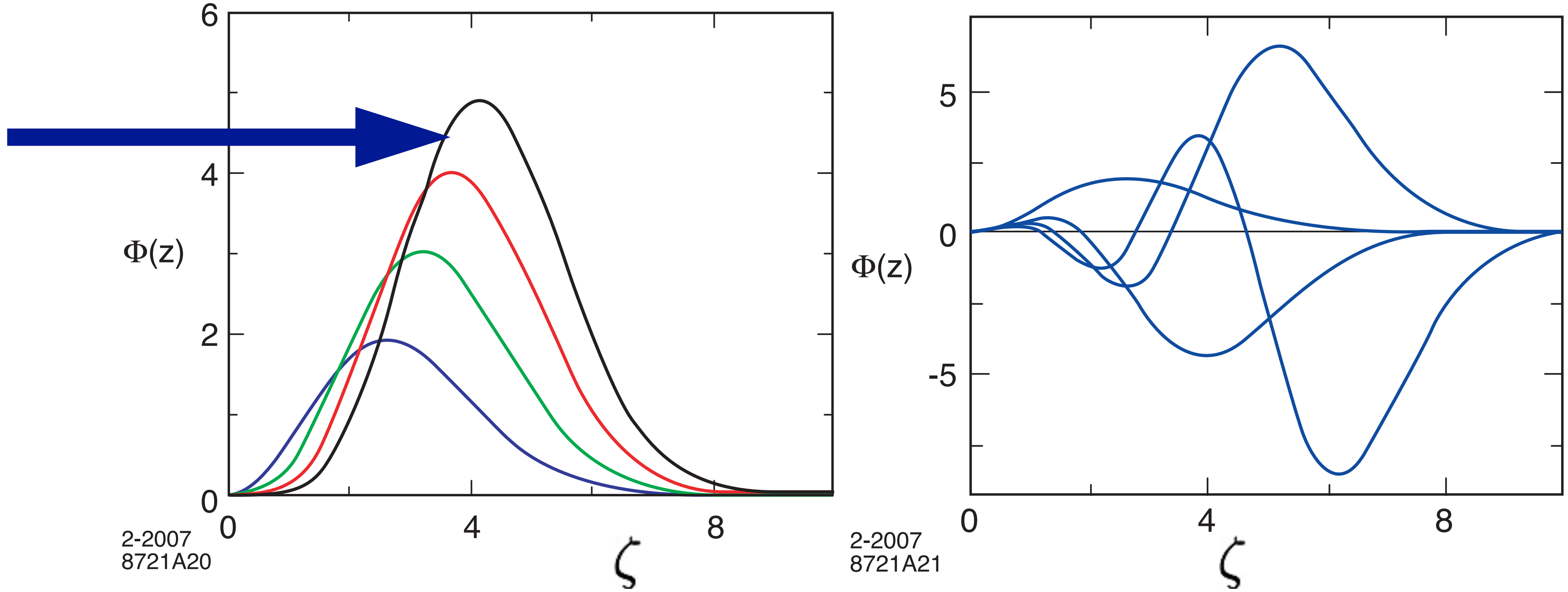
Soft Wall Model



Pion mass automatically zero!

$$m_q = 0$$

Light meson orbital (a) and radial (b) spectrum for $\kappa = 0.6$ GeV.



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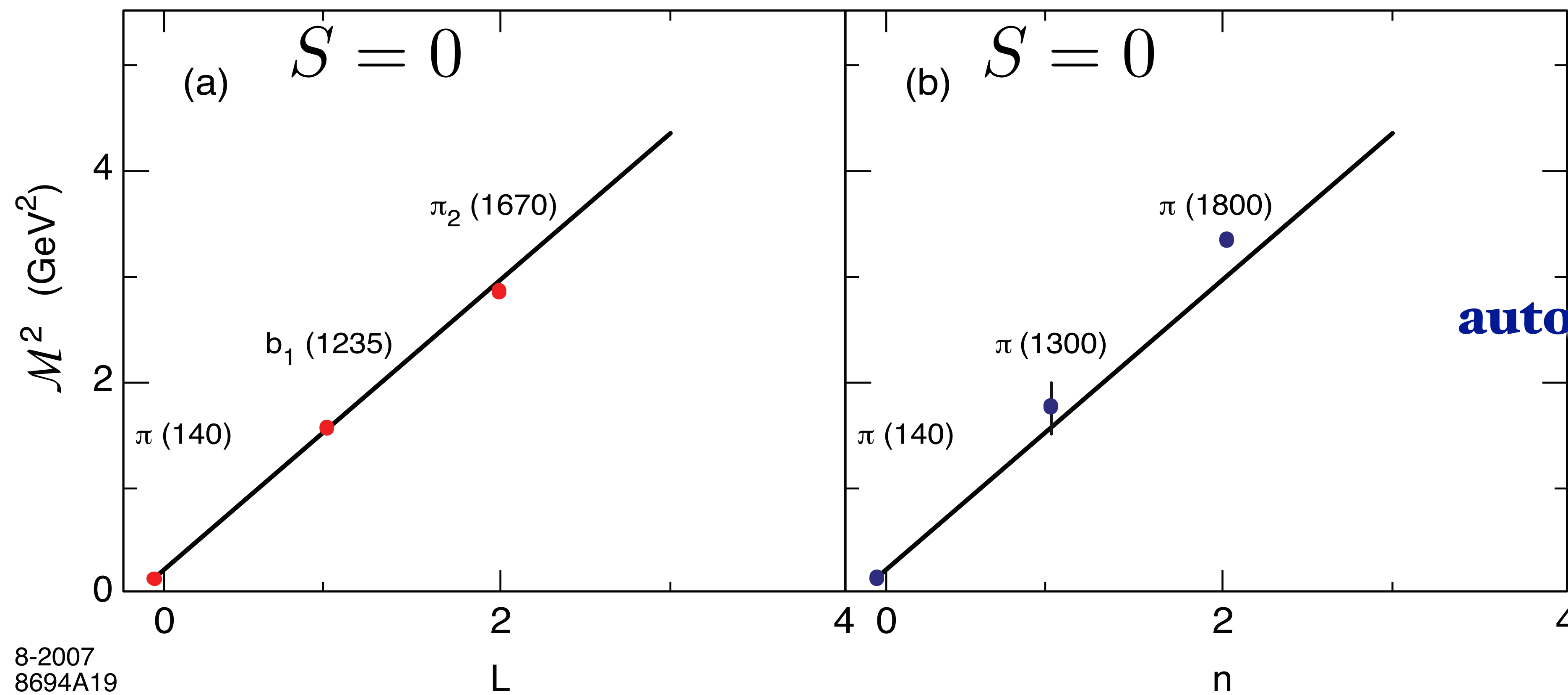

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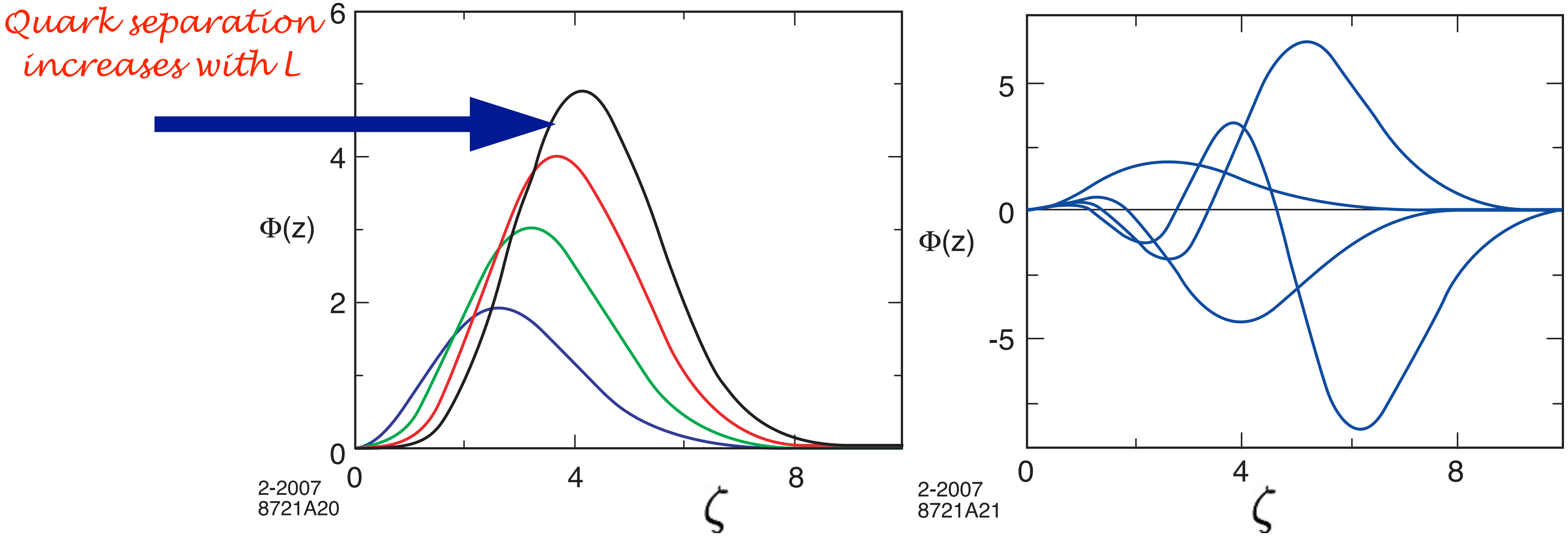

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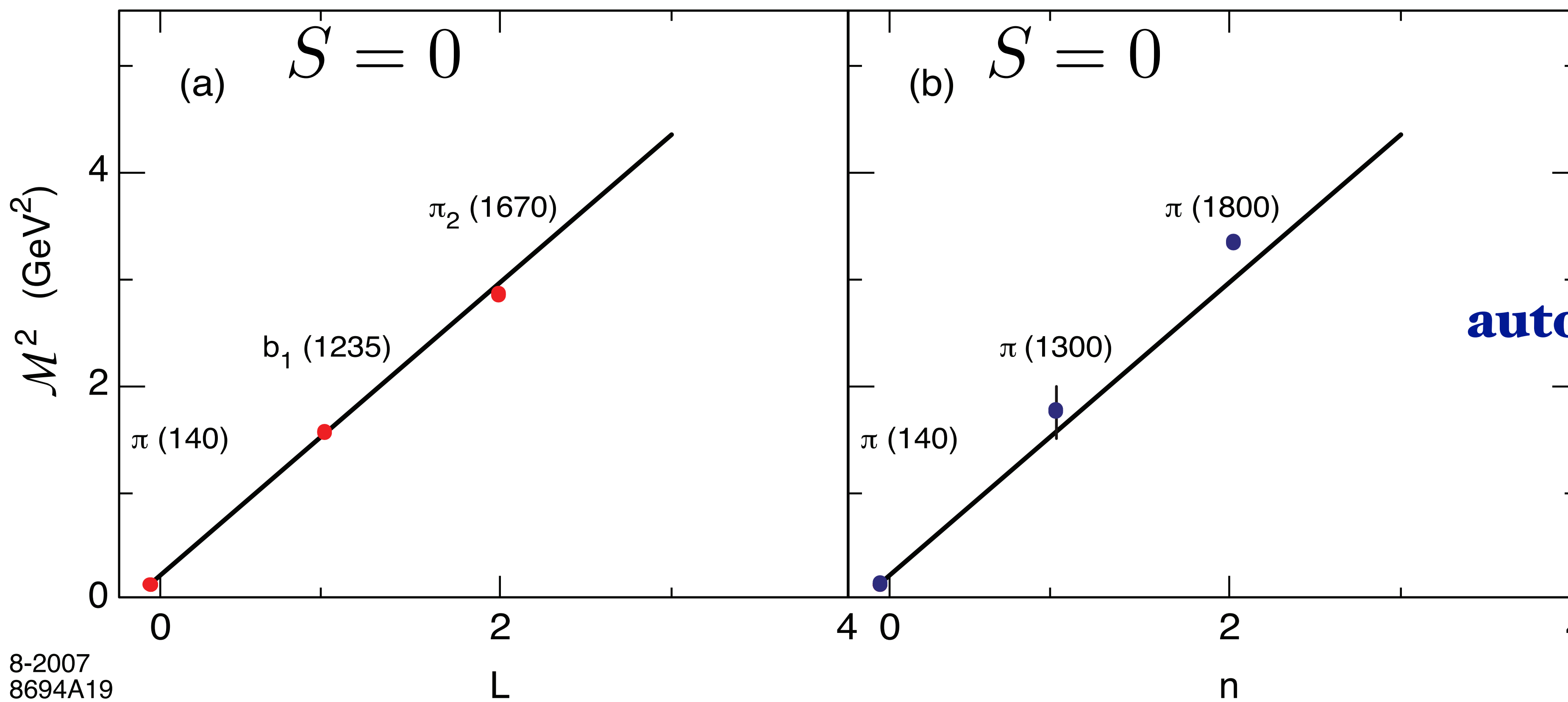

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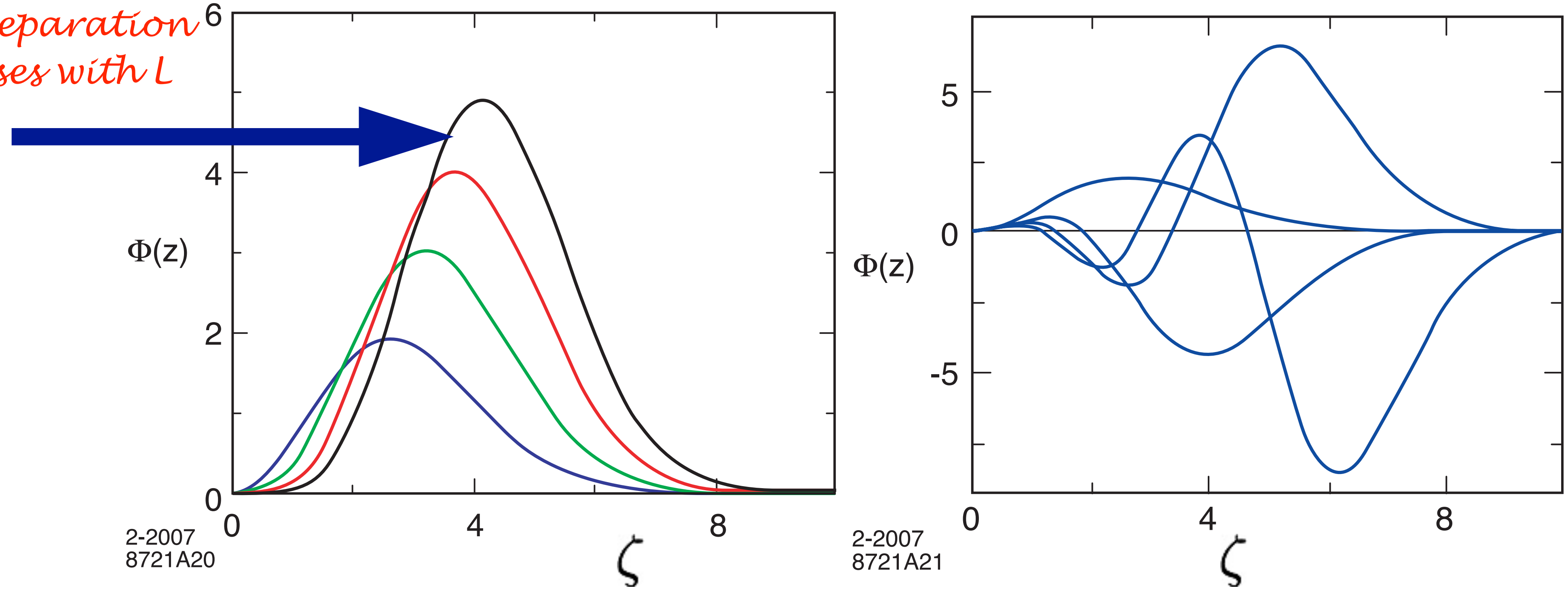

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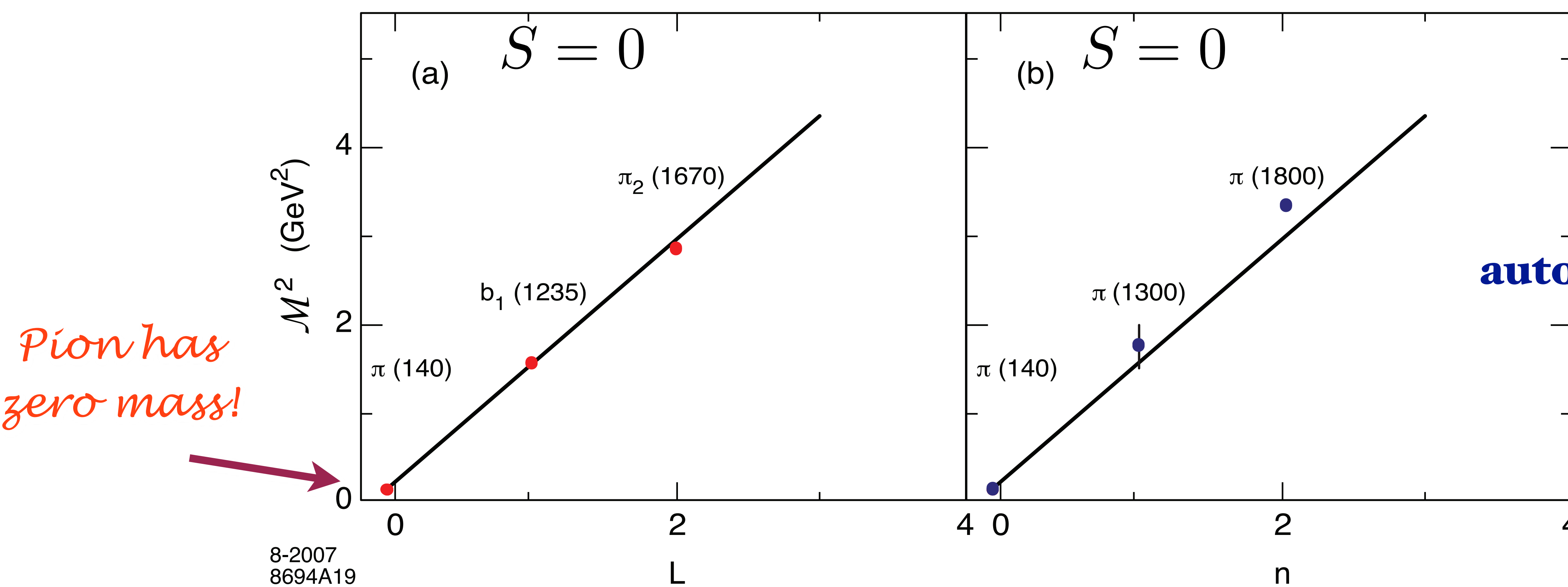

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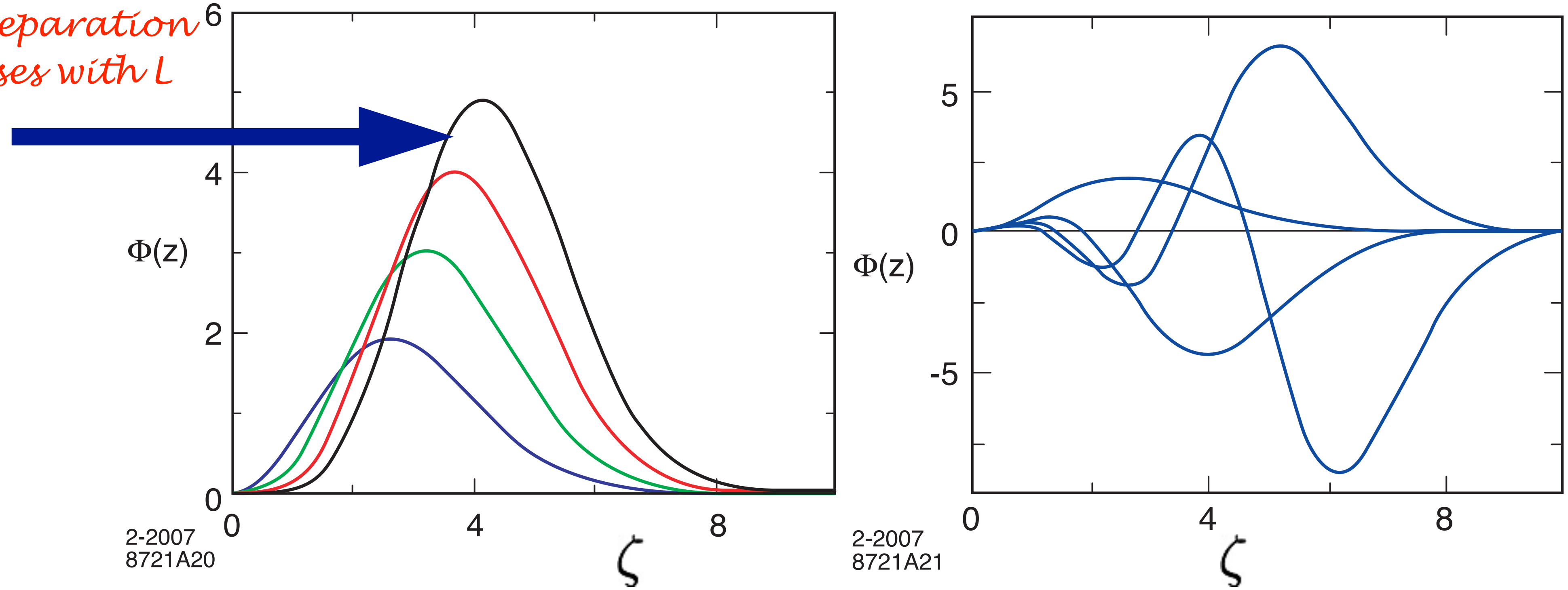

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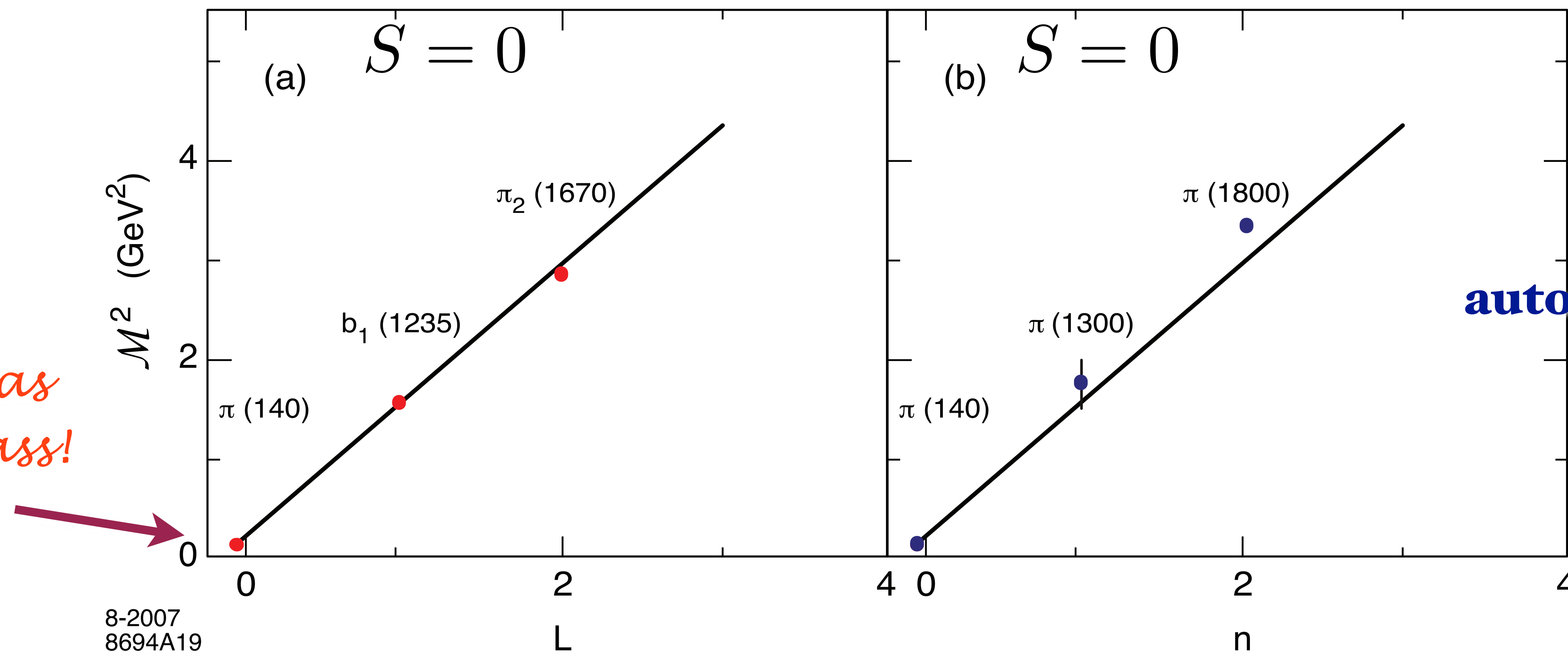
Same slope in n and L!



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Light meson orbital (a) and radial (b) spectrum for $\kappa = 0.6$ GeV.

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$4\kappa^2$ for $\Delta n = 1$
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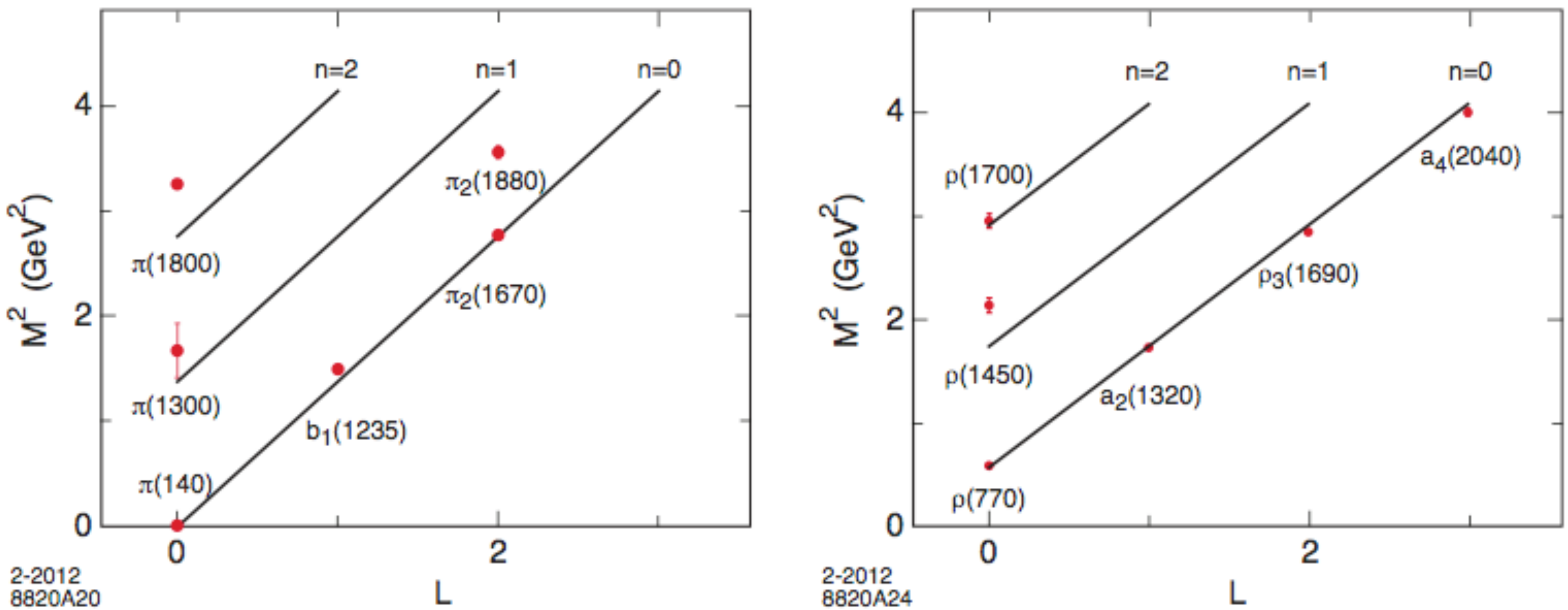

I=1 orbital and radial excitations for the π ($\kappa = 0.59$ GeV) and the ρ-meson families ($\kappa = 0.54$ GeV)

- Triplet splitting for the $I = 1, L = 1, J = 0, 1, 2$, vector meson a-states

$$\mathcal{M}_{a_2(1320)} > \mathcal{M}_{a_1(1260)} > \mathcal{M}_{a_0(980)}$$

Mass ratio of the ρ and the a_1 mesons: coincides with Weinberg sum rules

G. de Teramond, H. G. Dosch, sjb

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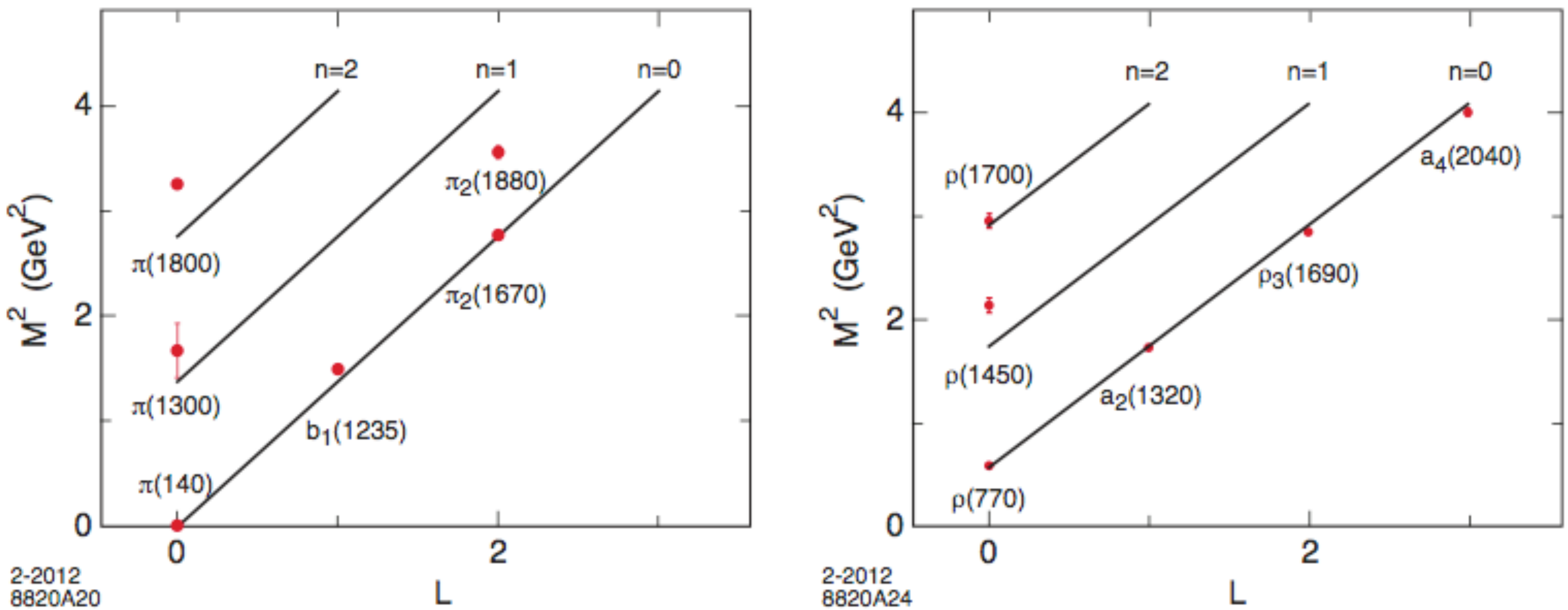

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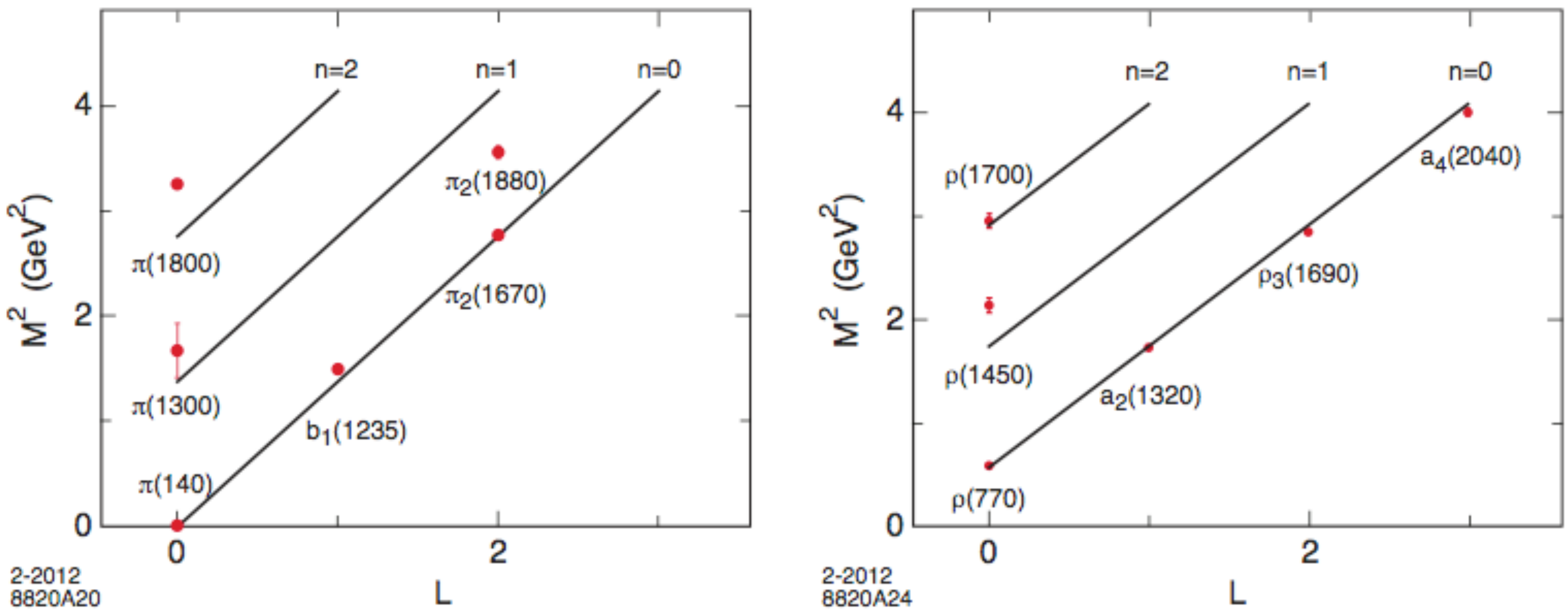

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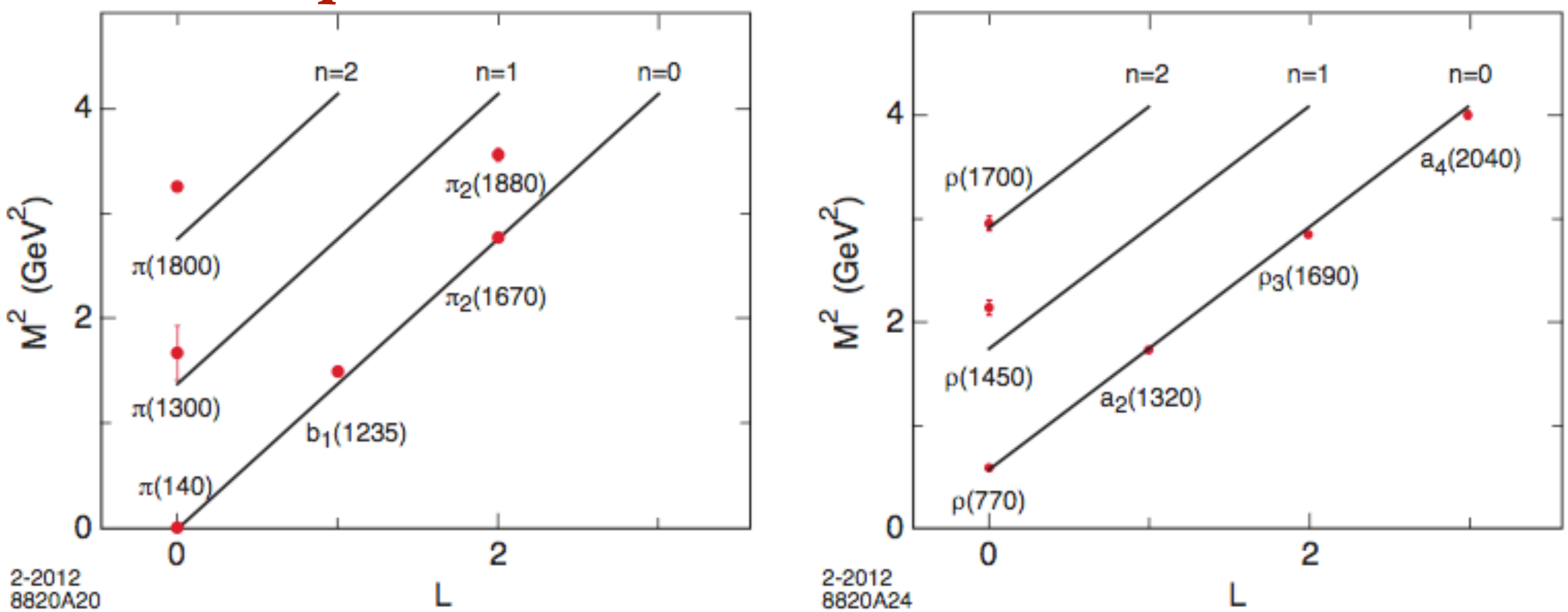
Massless pion in Chiral Limit!



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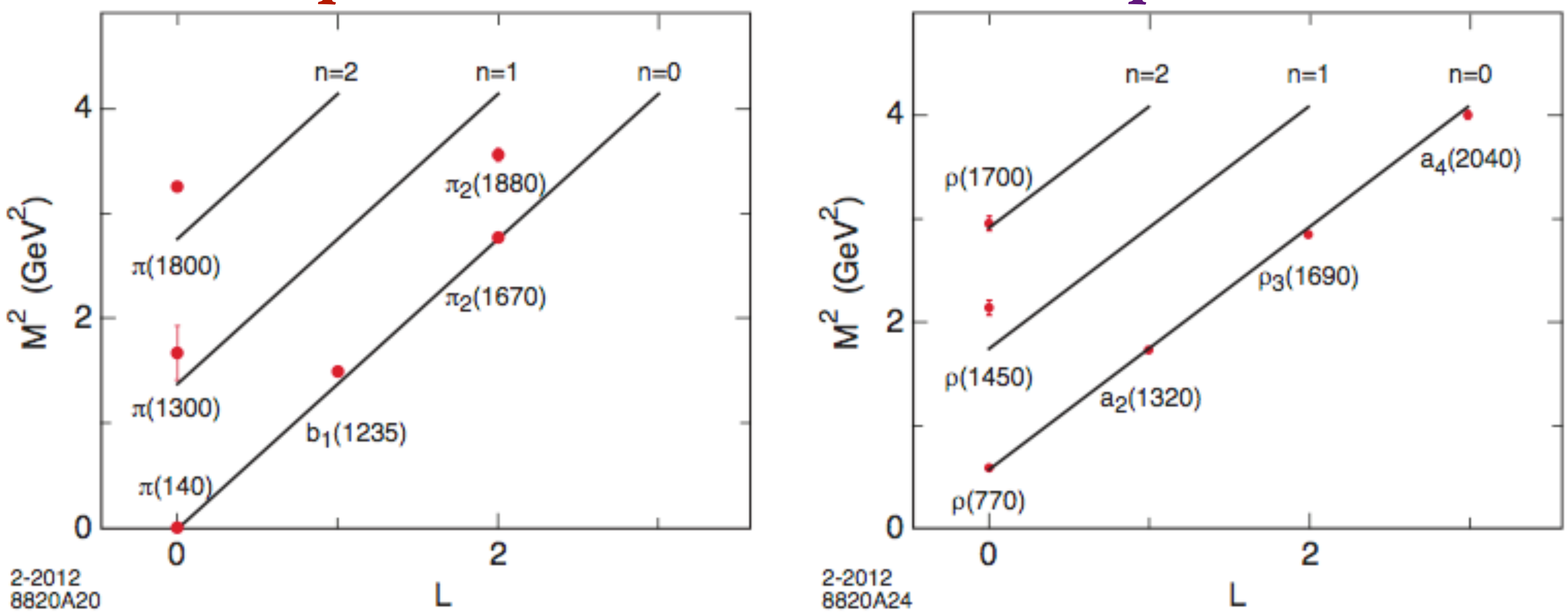

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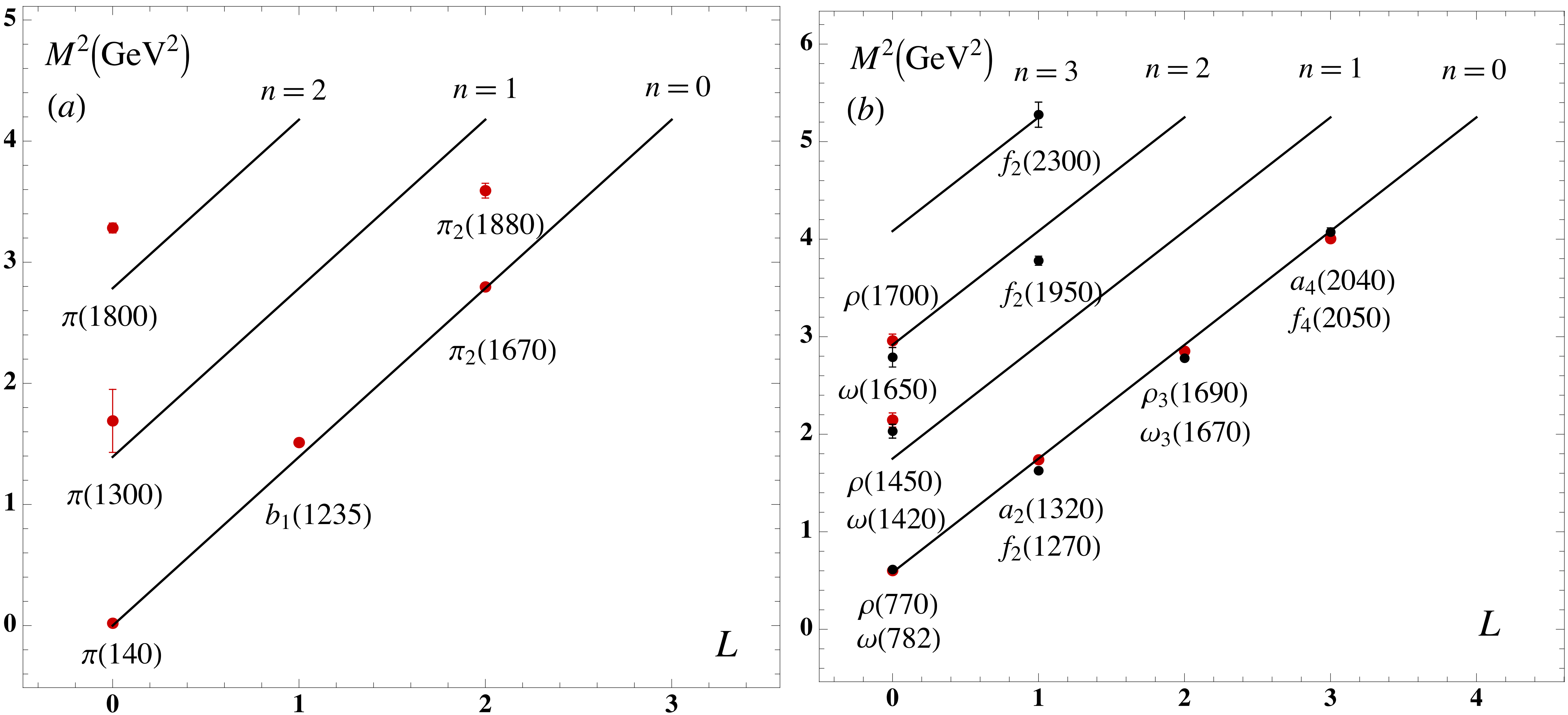
$$m_u = m_d = 0$$

de Tèramond, Dosch, sjb



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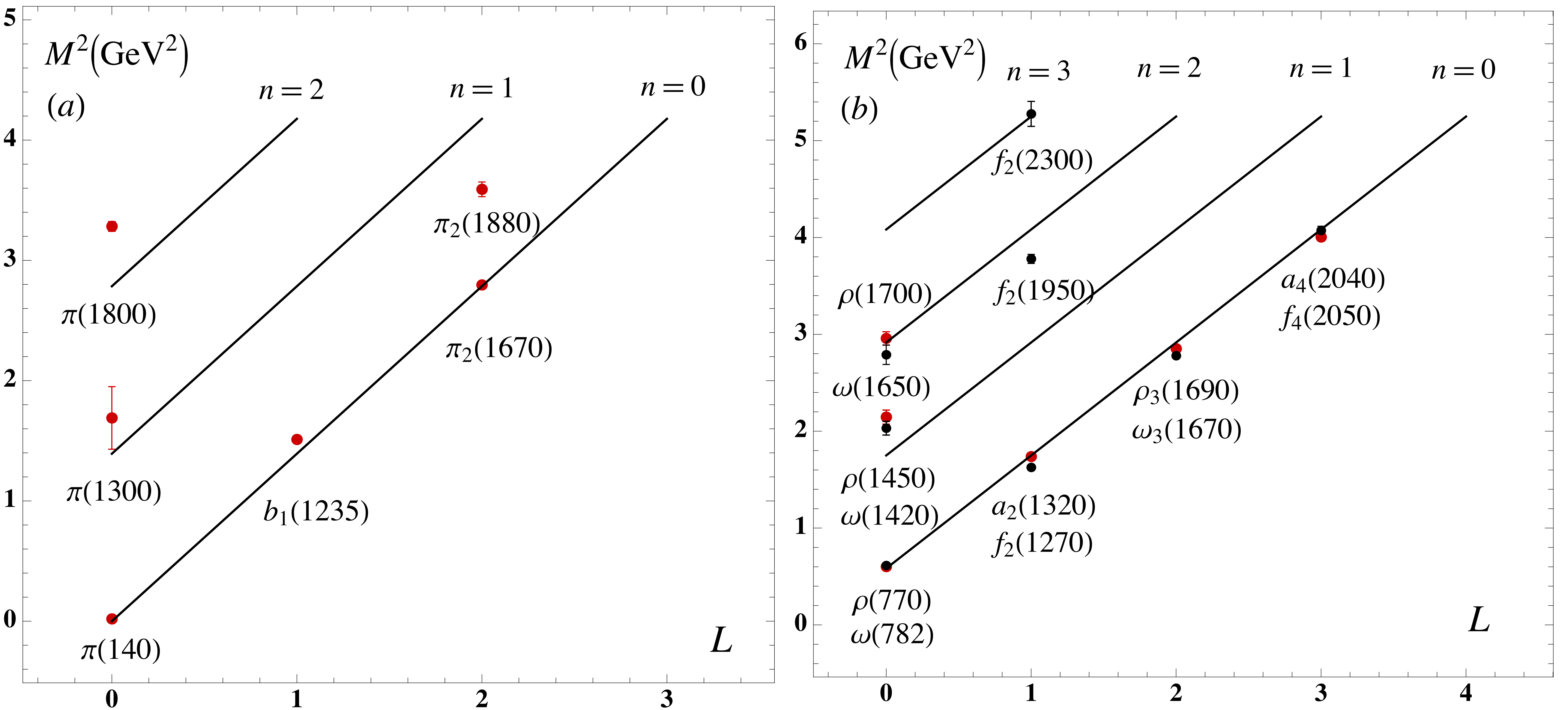

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De Teramond, Dosch, sjb

- Results easily extended to light quarks masses (Ex: K-mesons)

- First order perturbation in the quark masses

$$\Delta M^2 = \langle \psi | \sum_a m_a^2 / x_a | \psi \rangle$$

- Holographic LFWF with quark masses

$$\lambda \equiv \kappa^2$$

$$\psi(x, \zeta) \sim \sqrt{x(1-x)}\, e^{-\frac{1}{2\lambda}\left(\frac{m_q^2}{x} + \frac{m_q^2}{1-x}\right)} e^{-\frac{1}{2}\lambda \zeta^2}$$

- Ex: Description of diffractive vector meson production at HERA

  [J. R. Forshaw and R. Sandapen, PRL **109**, 081601 (2012)]

- For the K^*

$$M_{n,L,S}^2 = M_{K^\pm}^2 + 4\lambda \left(n + \frac{J+L}{2}\right)$$

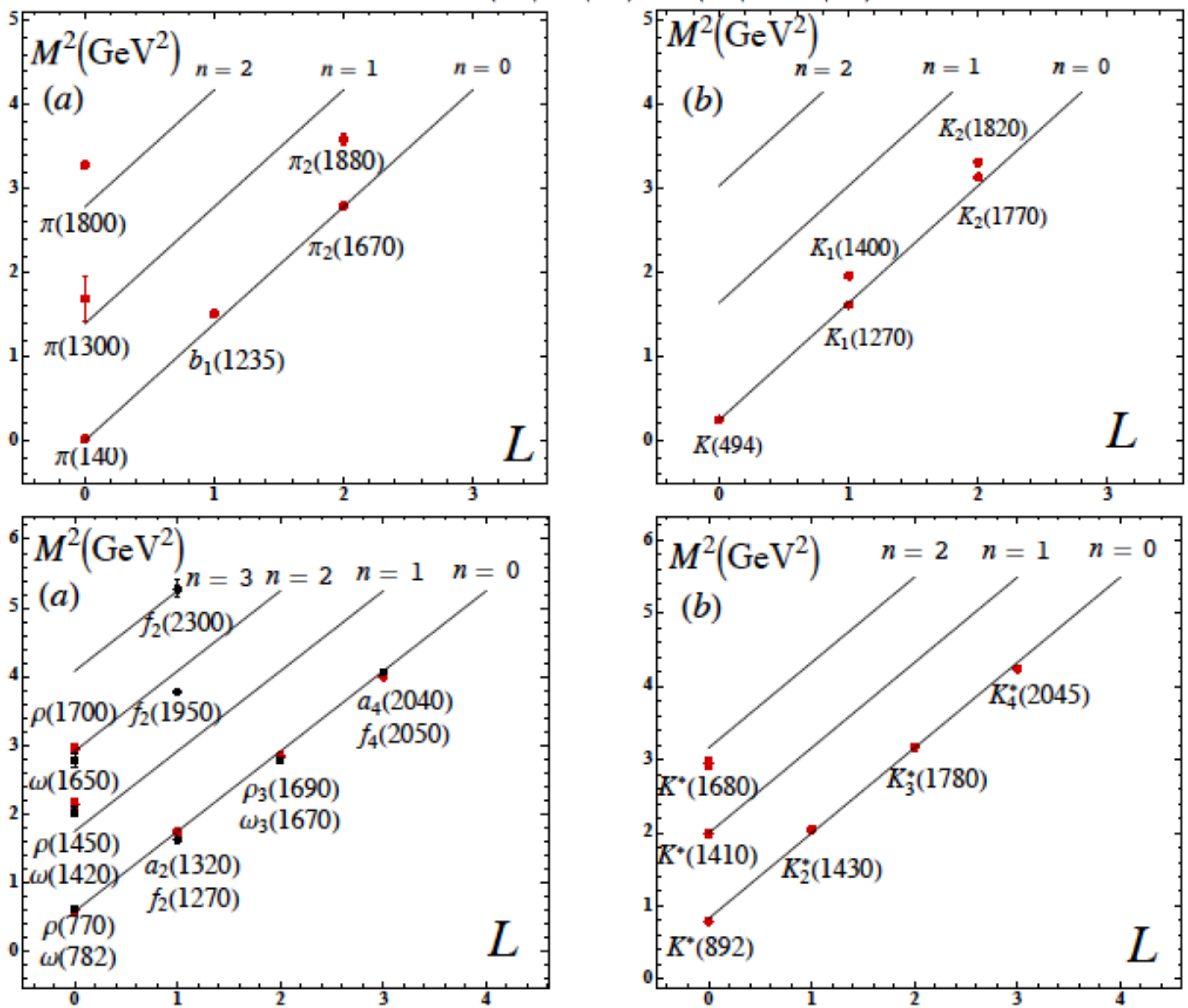
- Effective quark masses from reduction of higher Fock states as functionals of the valence state:

$$m_u = m_d = 46 \text{ MeV}, \quad m_s = 357 \text{ MeV}$$

De Tèramond, Dosch, sjb

$$m_u = m_d = 46 \text{ MeV}, \quad m_s = 357 \text{ MeV}$$

$$M^2 = M_0^2 + \left\langle X \left| \frac{m_q^2}{x} \right| X \right\rangle + \left\langle X \left| \frac{m_{\bar{q}}^2}{1-x} \right| X \right\rangle$$

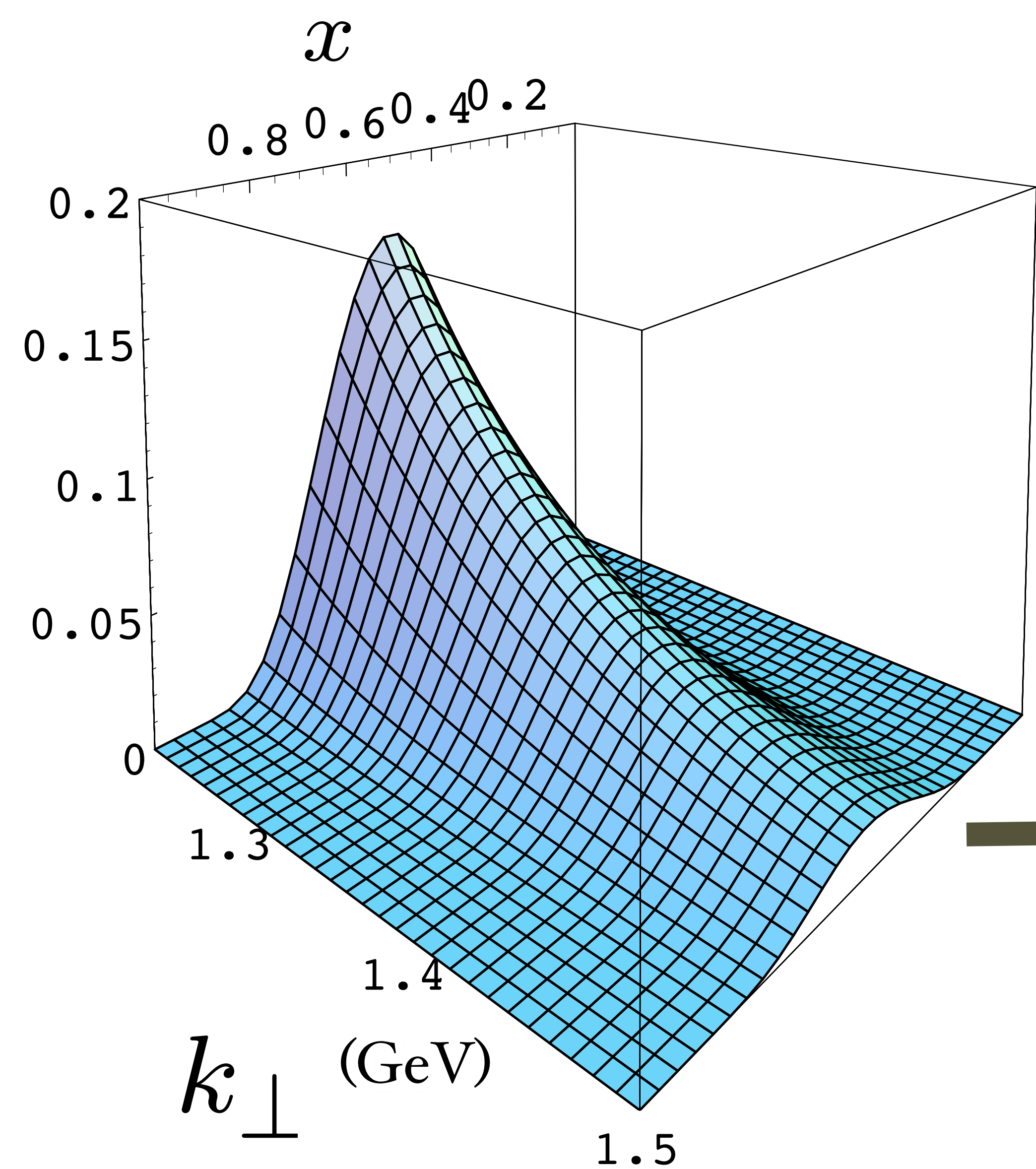


Prediction from AdS/QCD: Meson LFWF

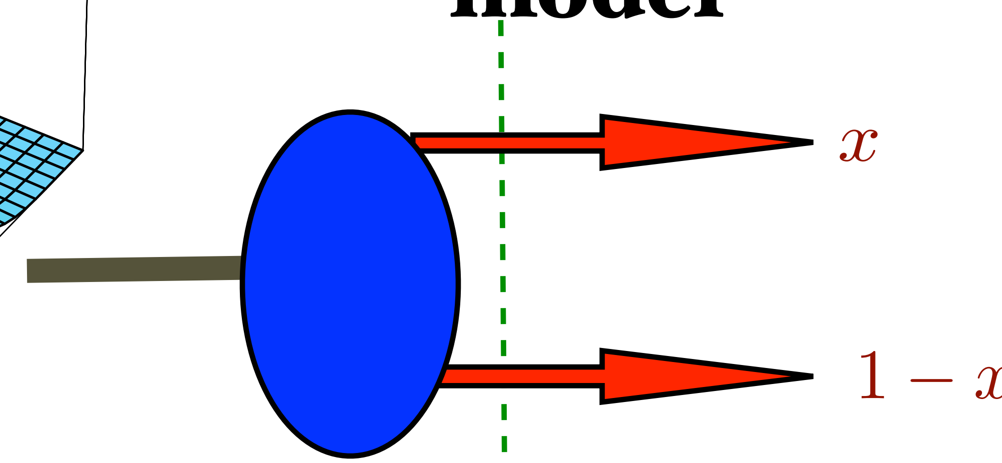
$$e^{\varphi(z)} = e^{+\kappa^2 z}$$

de Teramond, Cao, sjb

$$\psi_M(x, k_\perp^2)$$



"Soft Wall" model



massless quarks

$$\psi_M(x, k_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}} e^{-\frac{k_\perp^2}{2\kappa^2 x(1-x)}}$$

$$\phi_\pi(x) = \frac{4}{\sqrt{3}\pi} f_\pi \sqrt{x(1-x)}$$

$$f_\pi = \sqrt{P_{q\bar{q}}} \frac{\sqrt{3}}{8} \kappa = 92.4 \text{ MeV}$$

Same as DSE!

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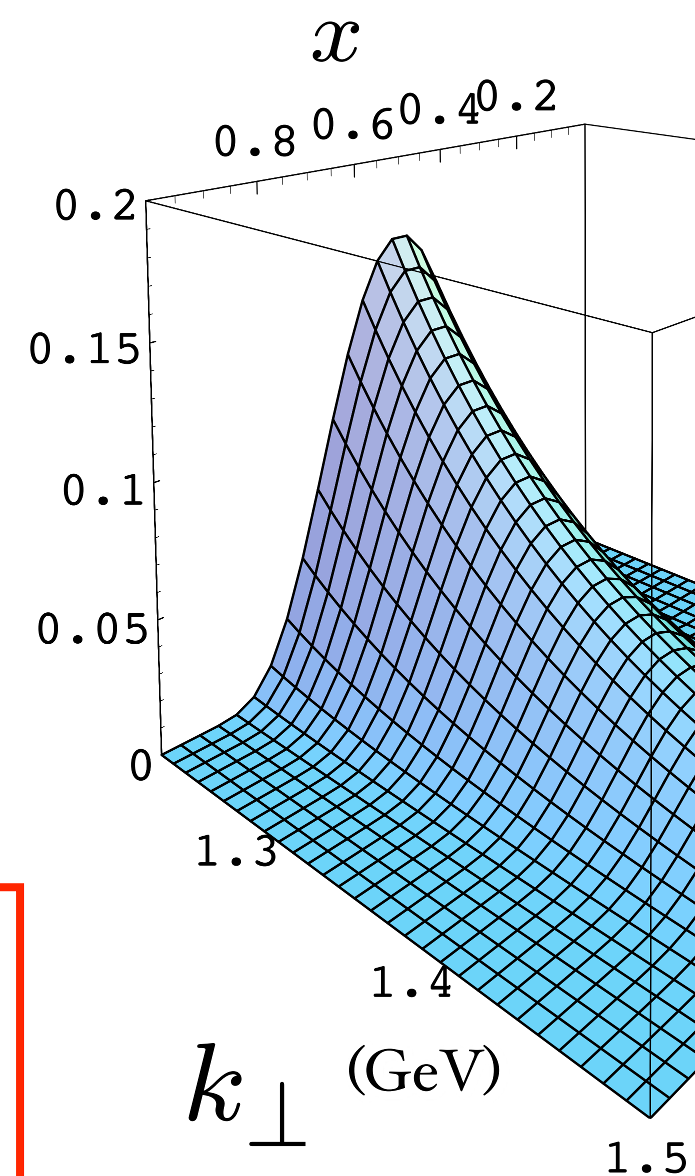

de Teramond, Cao, sjb

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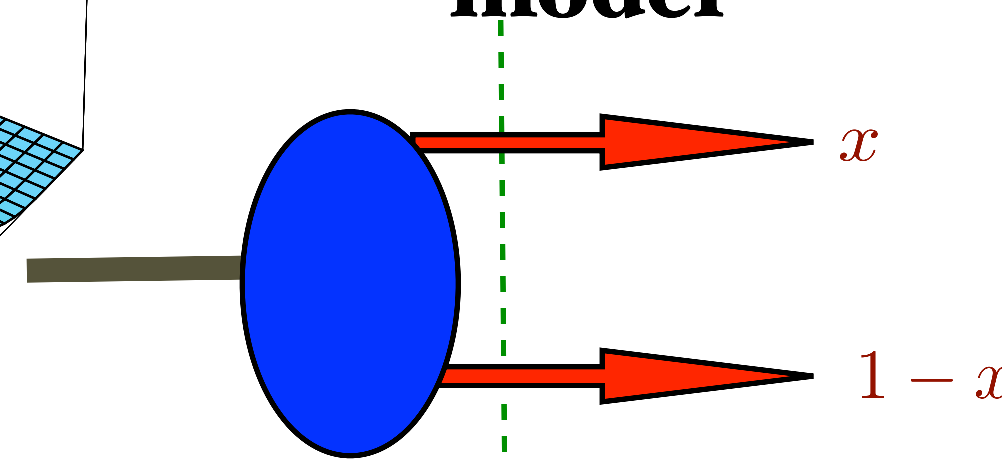

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Note coupling

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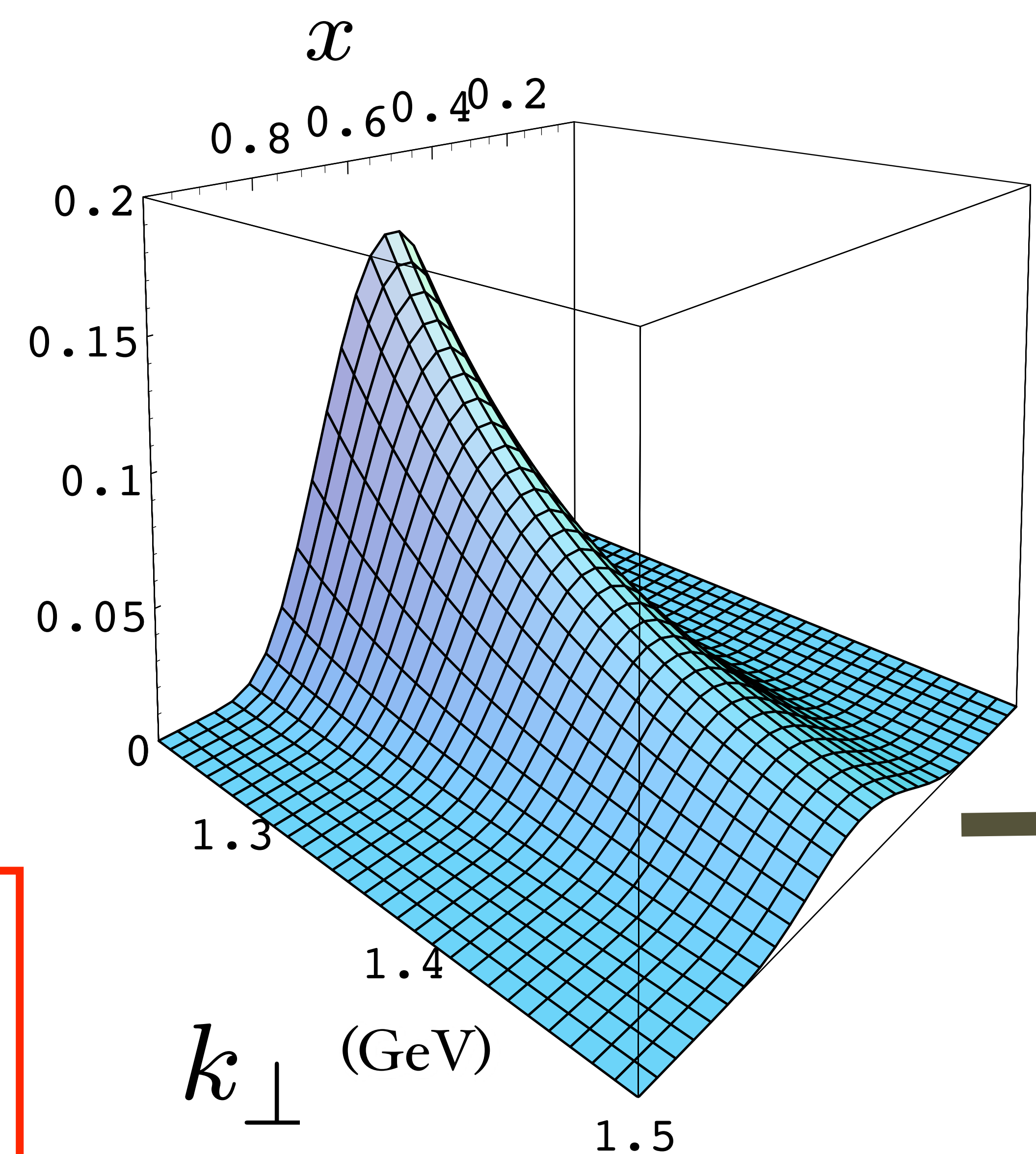

de Teramond, Cao, sjb

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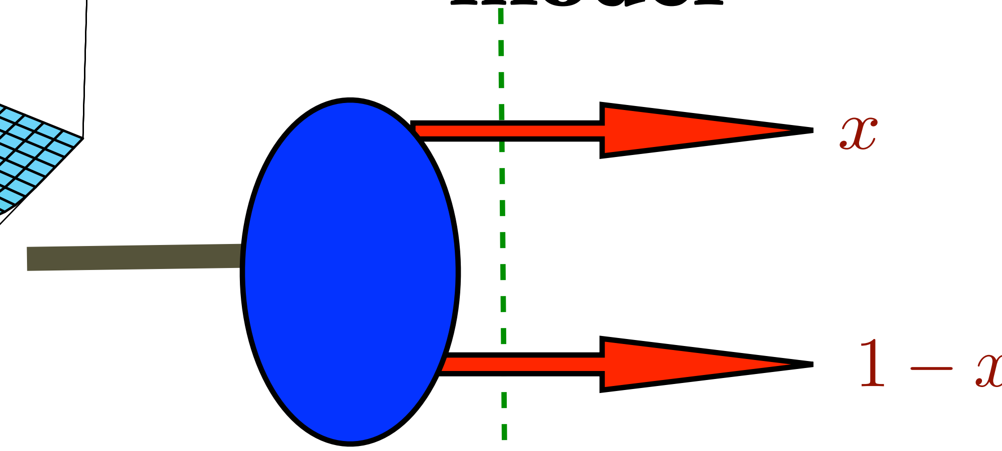

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Provides Connection of Confinement to Hadron Structure

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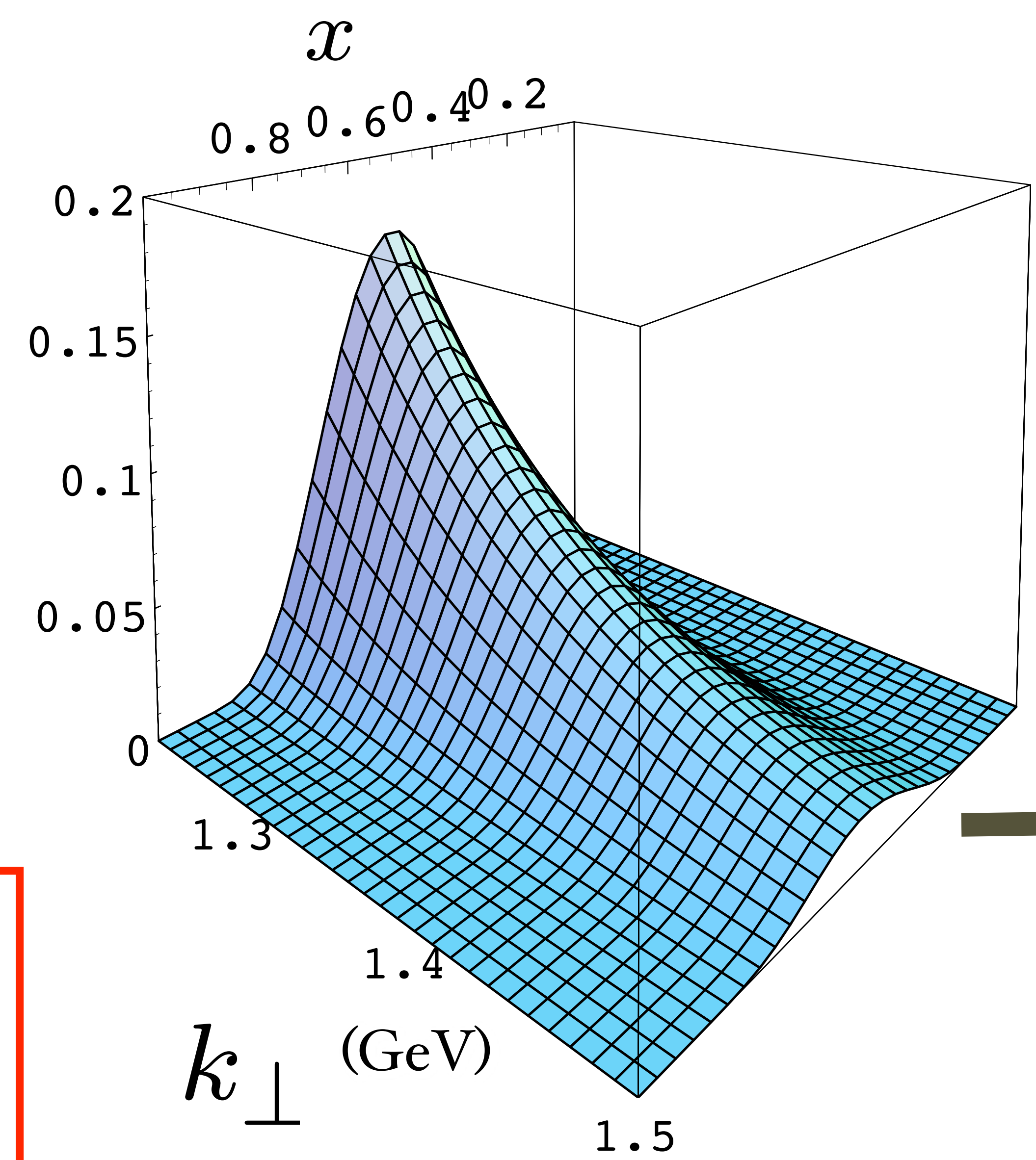

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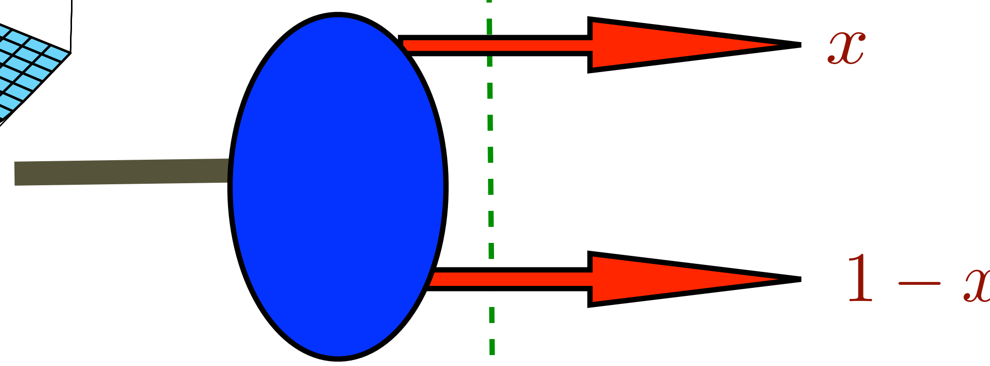

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Provides Connection of Confinement to Hadron Structure

AdS/QCD Holographic Wave Function for the ρ Meson and Diffractive ρ Meson Electroproduction

J. R. Forshaw*
Consortium for Fundamental Physics, School of Physics and Astronomy, University of Manchester, Oxford Road, Manchester M13 9PL, United Kingdom

R. Sandapen†
Département de Physique et d'Astronomie, Université de Moncton, Moncton, New Brunswick E1A3E9, Canada
(Received 5 April 2012; published 20 August 2012)

We show that anti–de Sitter/quantum chromodynamics generates predictions for the rate of diffractive ρ-meson electroproduction that are in agreement with data collected at the Hadron Electron Ring Accelerator electron–proton collider.

$$\psi_M(x, k_\perp) = \frac{4\pi}{\kappa\sqrt{x(1-x)}} e^{-\frac{k_\perp^2}{2\kappa^2 x(1-x)}}$$

See also Ferreira and Dosch

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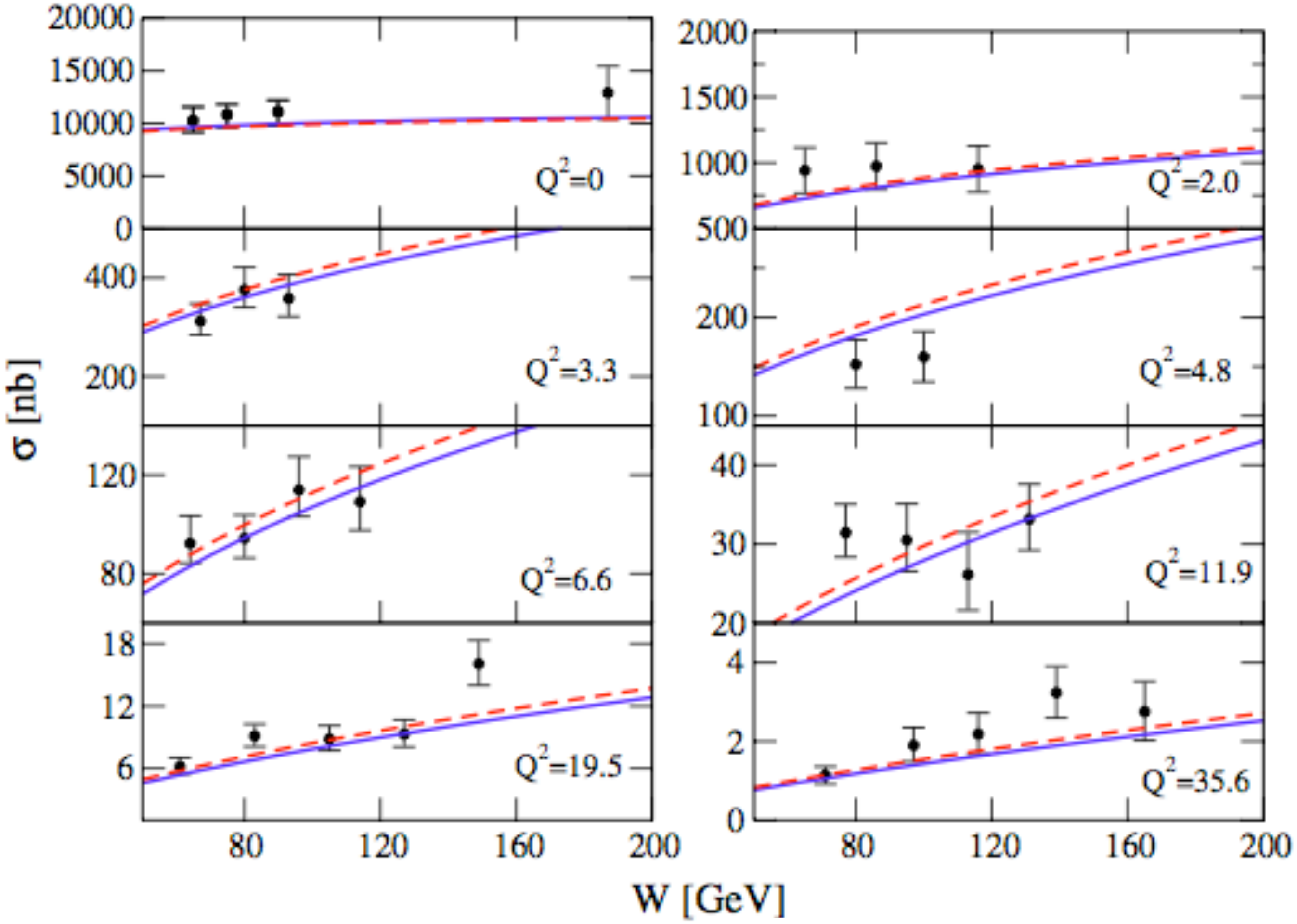
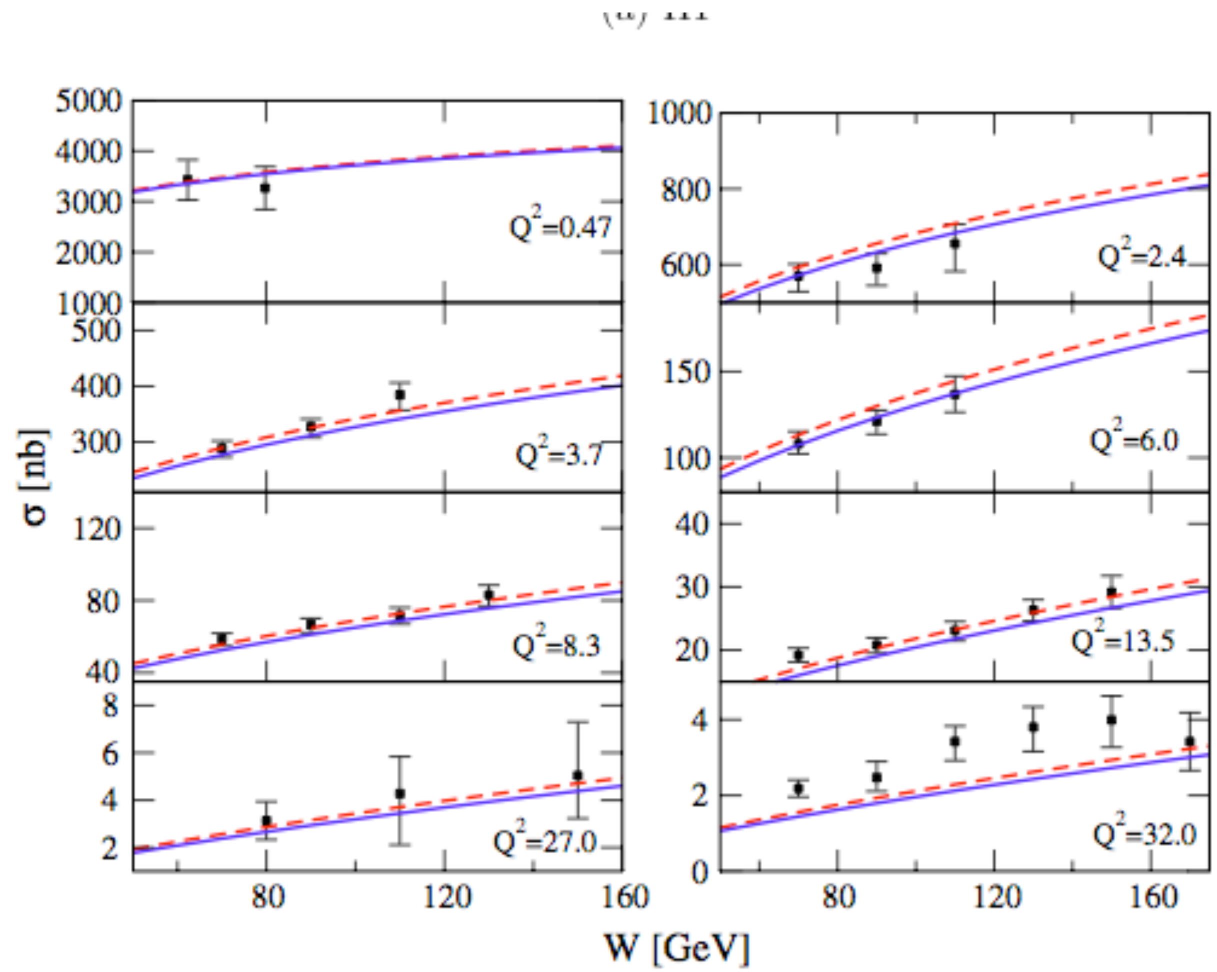


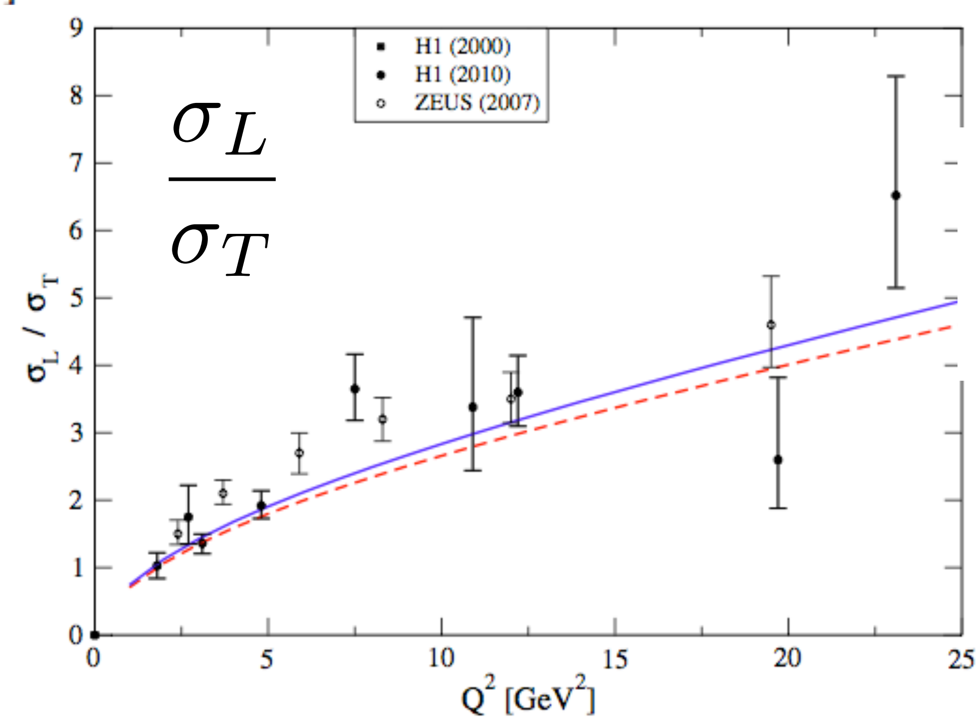
(a) H



(b) ZEUS

J. R. Forshaw, R. Sandapen

$$\gamma^* p \to \rho^0 p'$$



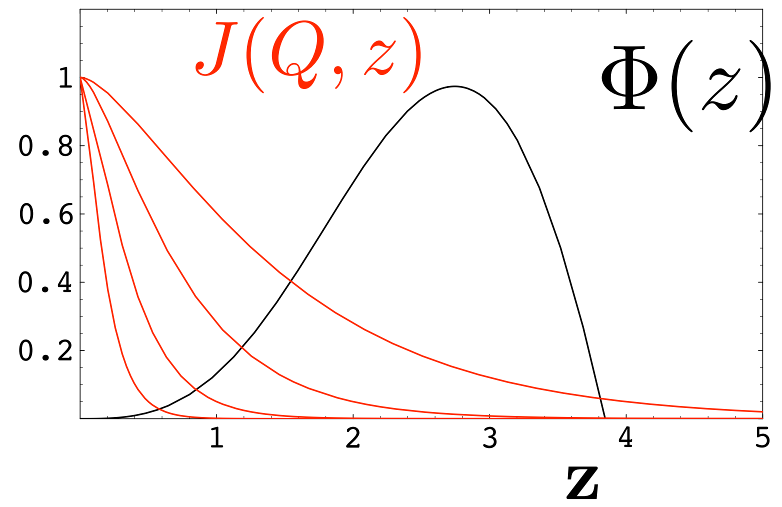
$$\tilde{\phi}(x, k) \propto \frac{1}{\sqrt{x(1-x)}} \exp\left(-\frac{M_{q\bar{q}}^2}{2\kappa^2}\right),$$

See also Ferreira and Dosch

Hadron Form Factors from AdS/QCD

Propagation of external perturbation suppressed inside AdS.

$$F(Q^2)_{I\to F} = \int \frac{dz}{z^3}\Phi_F(z)J(Q,z)\Phi_I(z)$$



Polchinski, Strassler
de Teramond, sjb

Consider a specific AdS mode $\Phi^{(n)}$ dual to an n partonic Fock state $|n\rangle$. At small z, $\Phi^{(n)}$ scales as $\Phi^{(n)} \sim z^{\Delta_n}$. Thus:

$$F(Q^2) \to \left[\frac{1}{Q^2}\right]^{\tau-1},$$

where $\tau = \Delta_n - \sigma_n$, $\sigma_n = \sum_{i=1}^{n} \sigma_i$.

Dimensional Quark Counting Rules: General result from AdS/CFT and Conformal Invariance

Twist $\tau = n + L$

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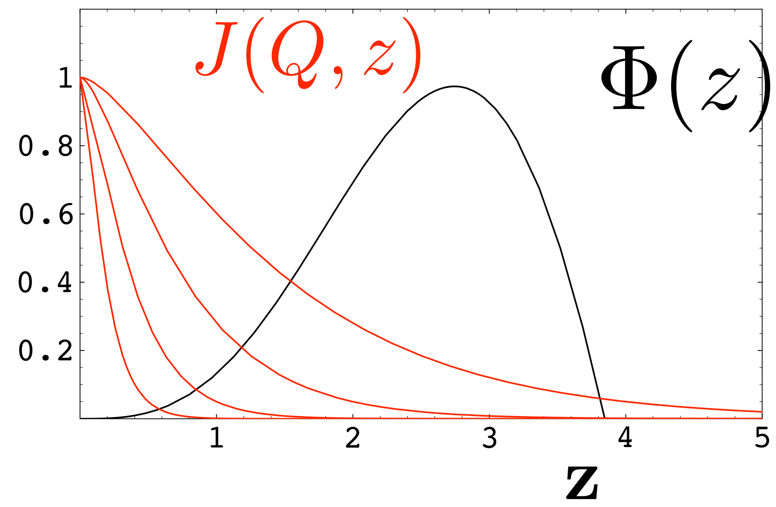

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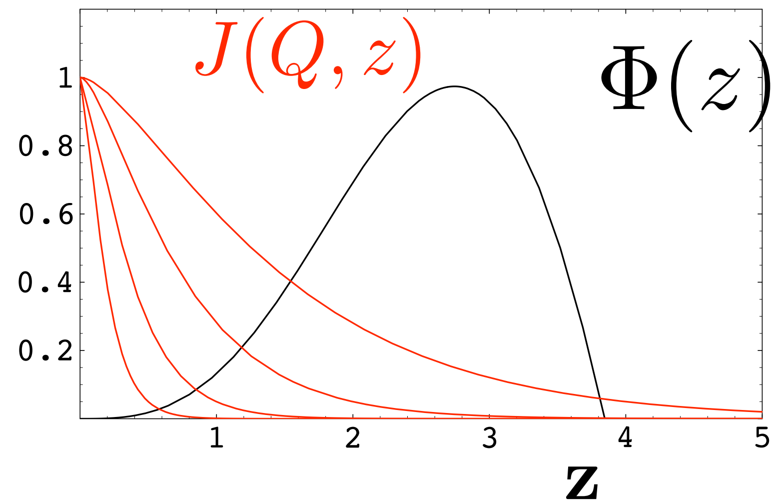
High Q^2
from
small z ~ 1/Q



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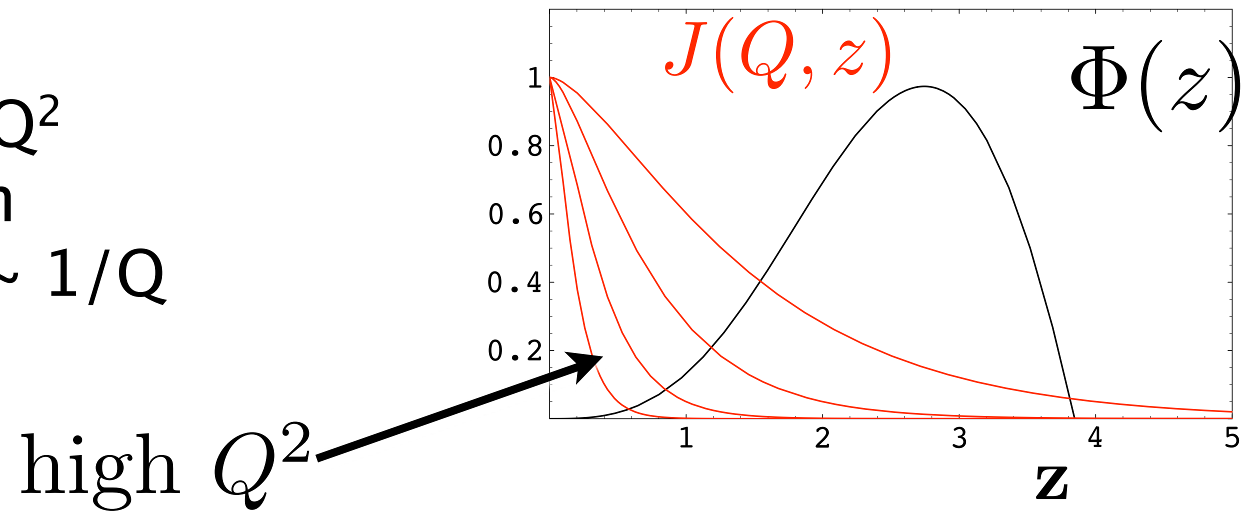

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Holographic Mapping of AdS Modes to QCD LFWFs

Drell-Yan-West: Form Factors are Convolution of LFWFs

- Integrate Soper formula over angles:

$$F(q^2) = 2\pi \int_0^1 dx \, \frac{(1-x)}{x} \int \zeta d\zeta J_0\left(\zeta q \sqrt{\frac{1-x}{x}}\right) \tilde{\rho}(x,\zeta),$$

with $\widetilde{\rho}(x,\zeta)$ QCD effective transverse charge density.

- Transversality variable

$$\zeta = \sqrt{x(1-x)\vec{b}_\perp^2}$$

- Compare AdS and QCD expressions of FFs for arbitrary Q using identity:

$$\int_0^1 dx J_0\left(\zeta Q \sqrt{\frac{1-x}{x}}\right) = \zeta Q K_1(\zeta Q),$$

the solution for $J(Q,\zeta) = \zeta Q K_1(\zeta Q)$!

de Teramond, sjb

Identical to Polchinski-Strassler Convolution of AdS Amplitudes

Holographic Mapping of AdS Modes to QCD LFWFs

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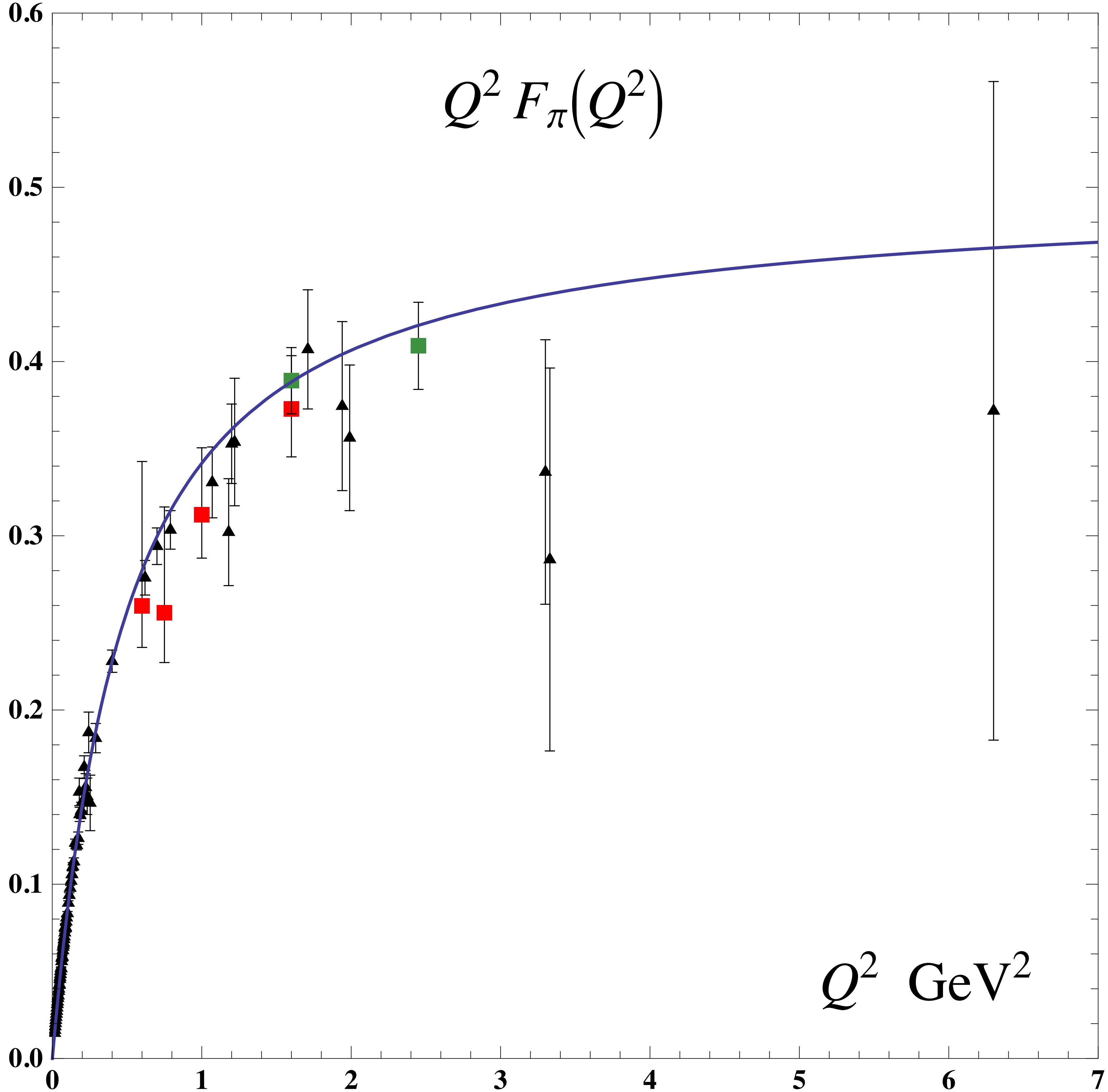


$Q^2 F_\pi(Q^2)$
Q^2 GeV^2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0
1
2
3
4
5
6
7

Uniqueness

de Tèramond, Dosch, sjb

$$U(\zeta) = \kappa^4 \zeta^2 + 2\kappa^2(L+S-1) \qquad e^{\varphi(z)} = e^{+\kappa^2 z^2}$$

- **ζ^2 confinement potential and dilaton profile unique!**

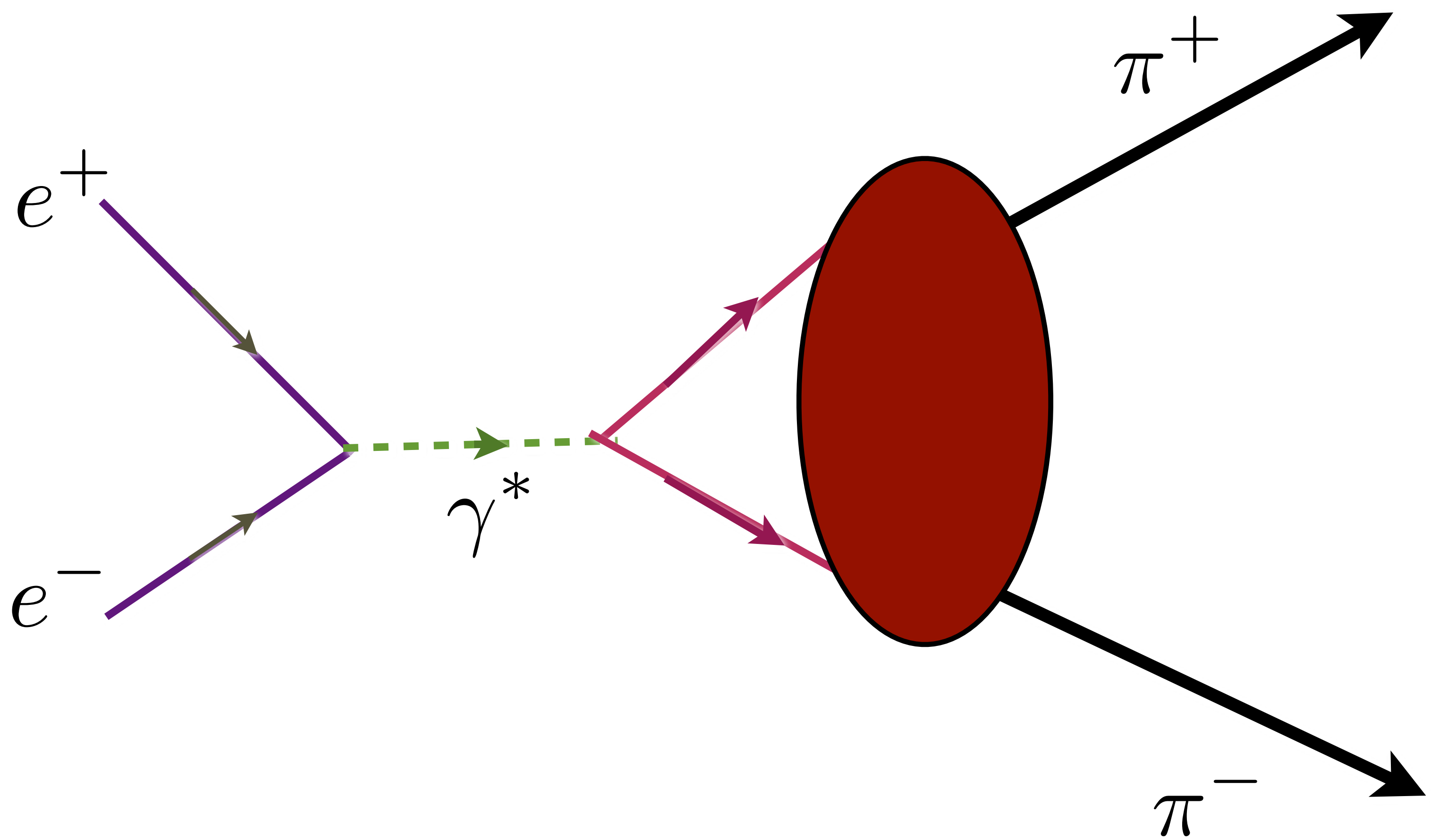
- **Linear Regge trajectories in n and L: same slope!**

- **Massless pion in chiral limit! No vacuum condensate!**

- **Conformally invariant action for massless quarks retained despite mass scale**

- **Same principle, equation of motion as de Alfaro, Furlan, Fubini, <u>Conformal Invariance in Quantum Mechanics</u> Nuovo Cim. A34 (1976) 569**

Dressed soft-wall current brings in higher Fock states and more vector meson poles



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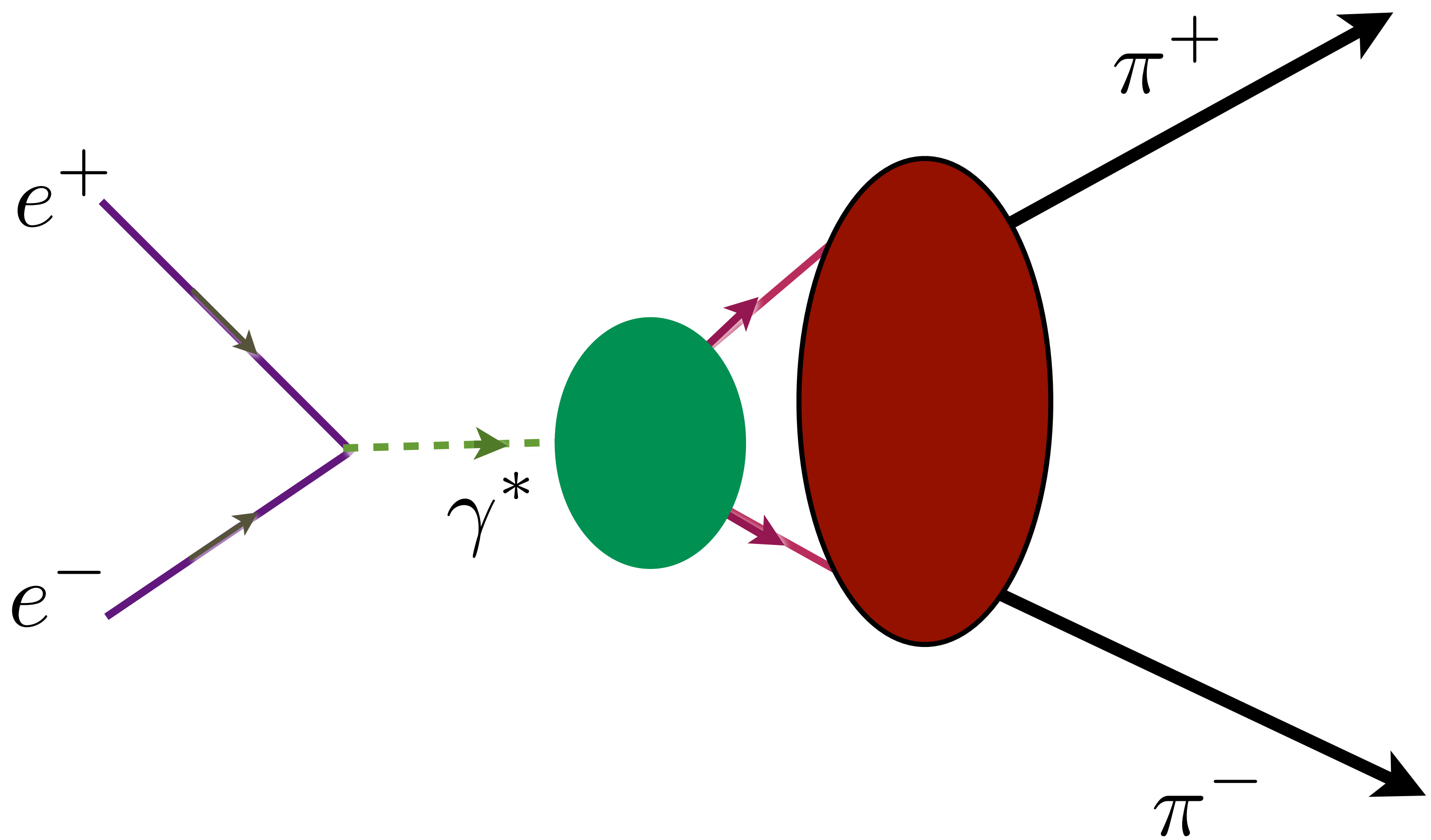

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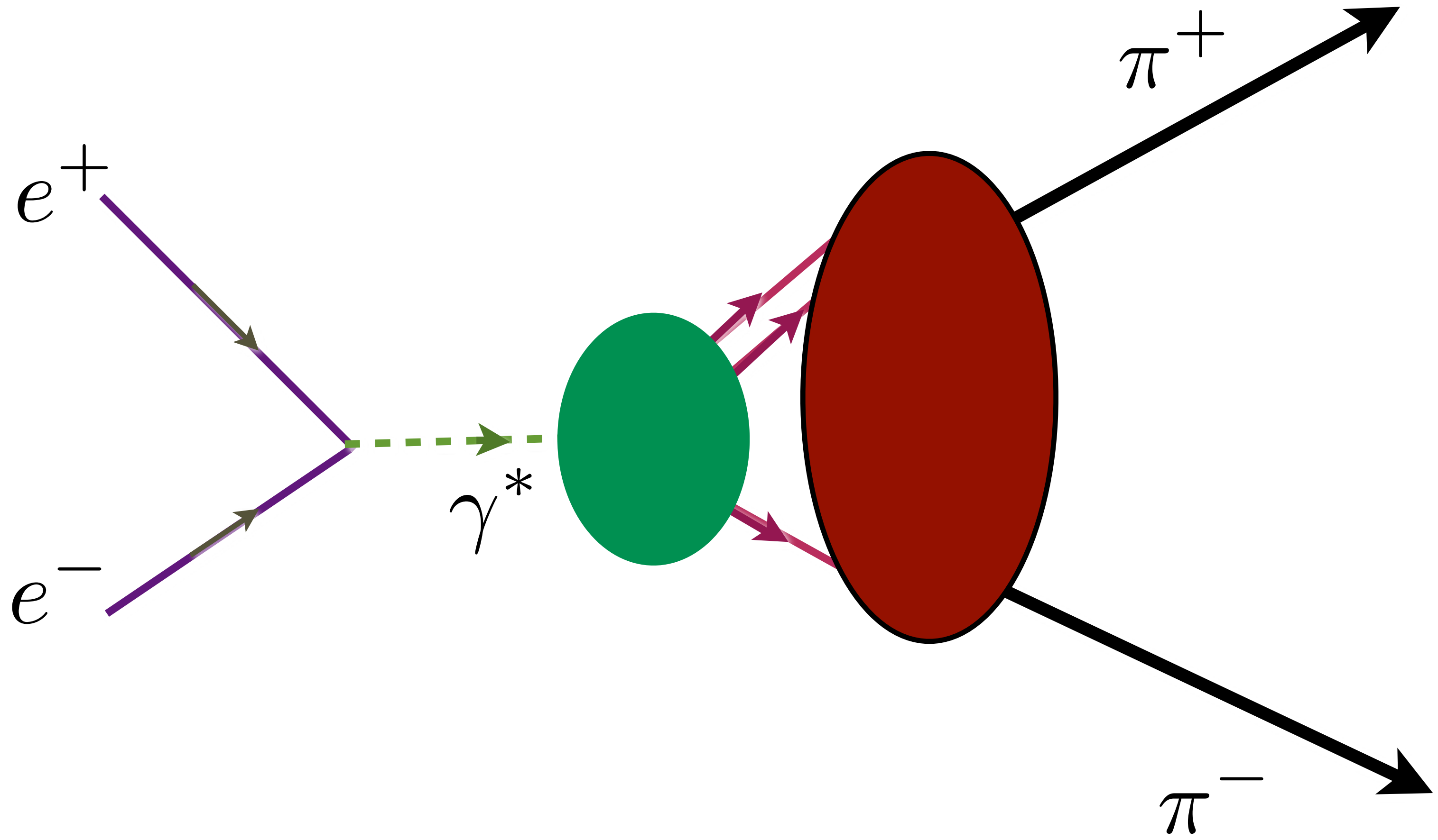

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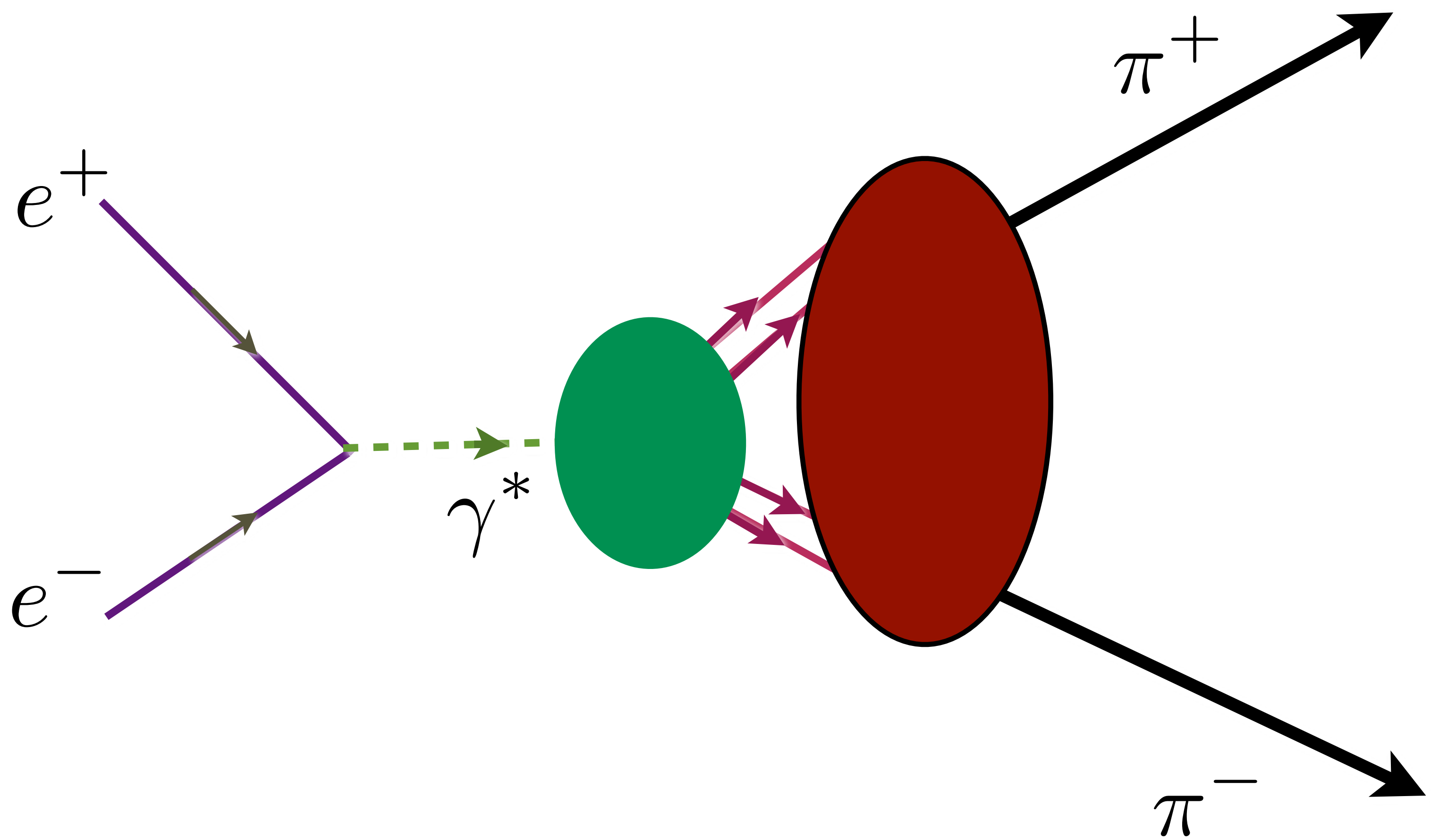
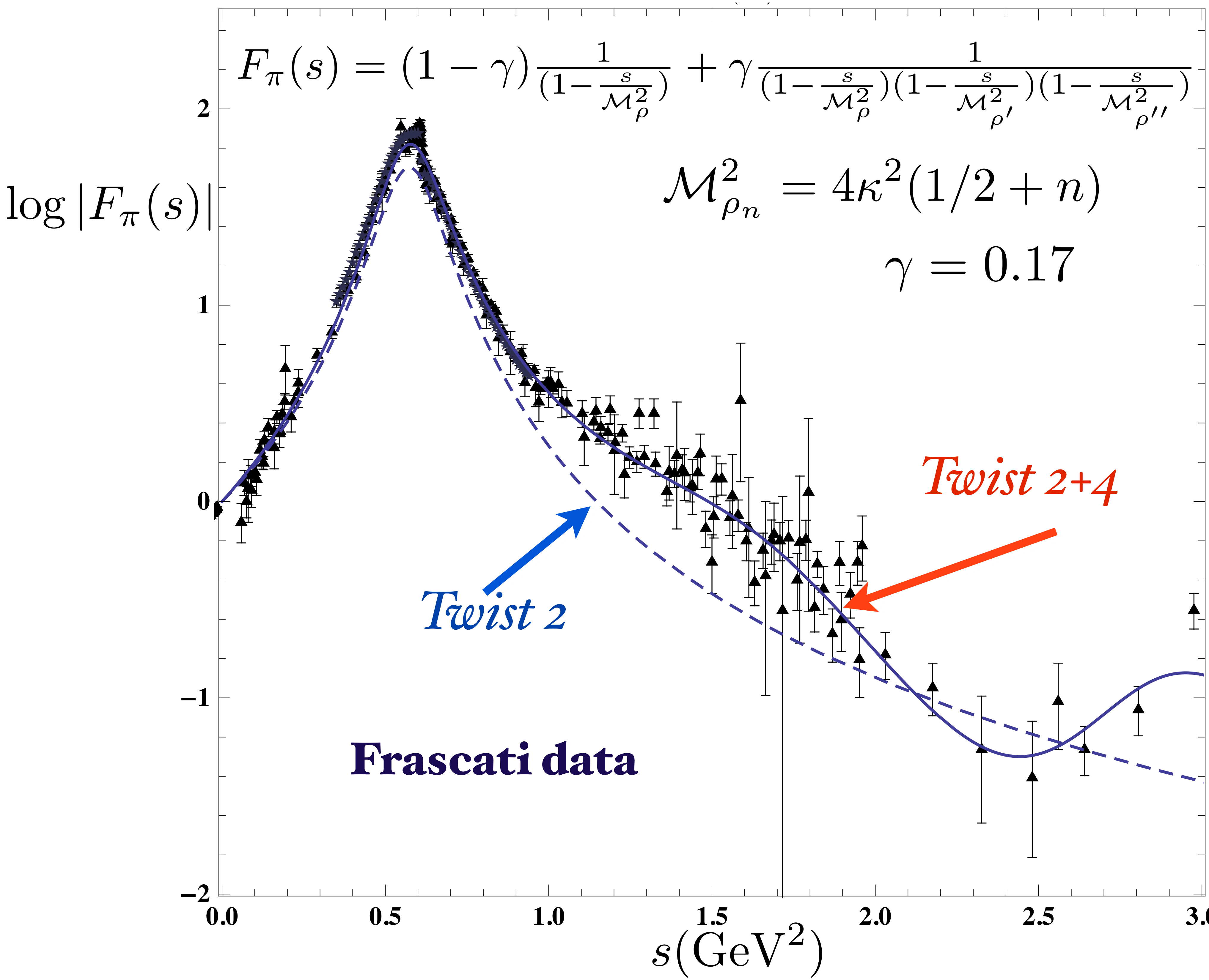


Timelike Pion Form Factor from AdS/QCD and Light-Front Holography



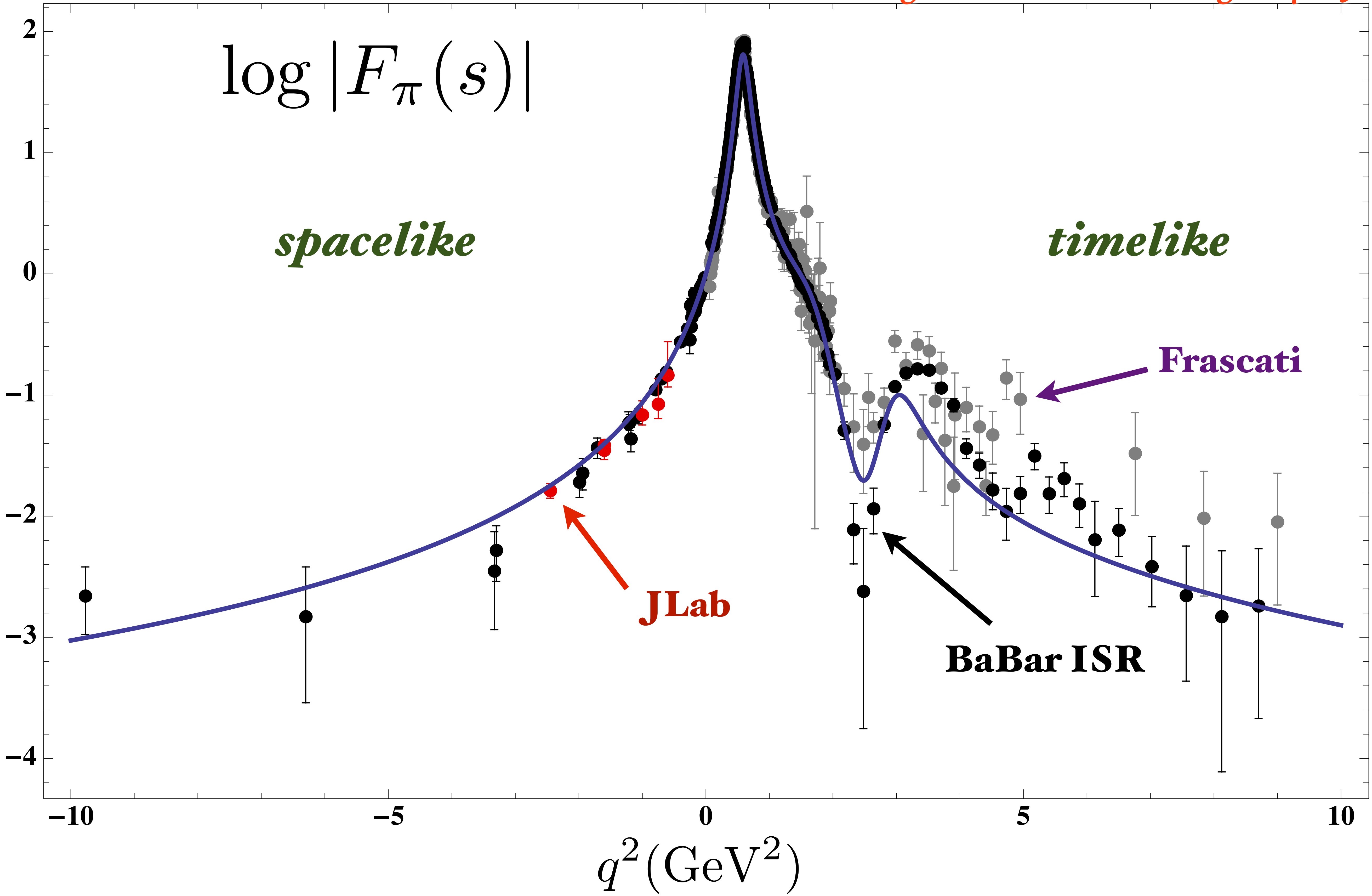
Prescription for Timelike poles :

$$\frac{1}{s - M^2 + i\sqrt{s}\Gamma}$$

14% four-quark probability

G. de Teramond & sjb

Pion Form Factor from AdS/QCD and Light-Front Holography



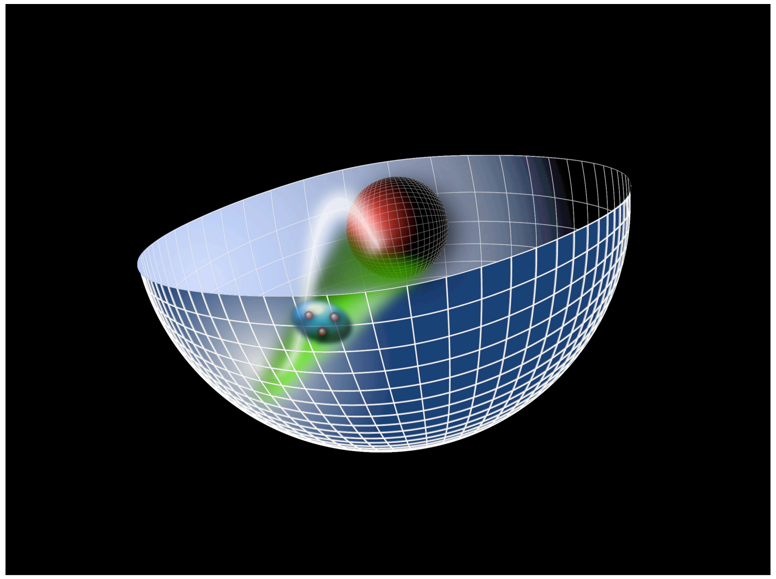
Remarkable Features of Light-Front Schrödinger Equation

- **Relativistic, frame-independent**
- **QCD scale appears - unique LF potential**
- **Reproduces spectroscopy and dynamics of light-quark hadrons with one parameter**
- **Zero-mass pion for zero mass quarks!**
- **Regge slope same for n and L -- not usual HO**
- **Splitting in L persists to high mass -- contradicts conventional wisdom based on breakdown of chiral symmetry**
- **Phenomenology: LFWFs, Form factors, electroproduction**
- **Extension to heavy quarks**

$$U(\zeta) = \kappa^4 \zeta^2 + 2\kappa^2 (L + S - 1)$$

$\phi(z)$

AdS5: Conformal Template for QCD



- *Light-Front Holography*

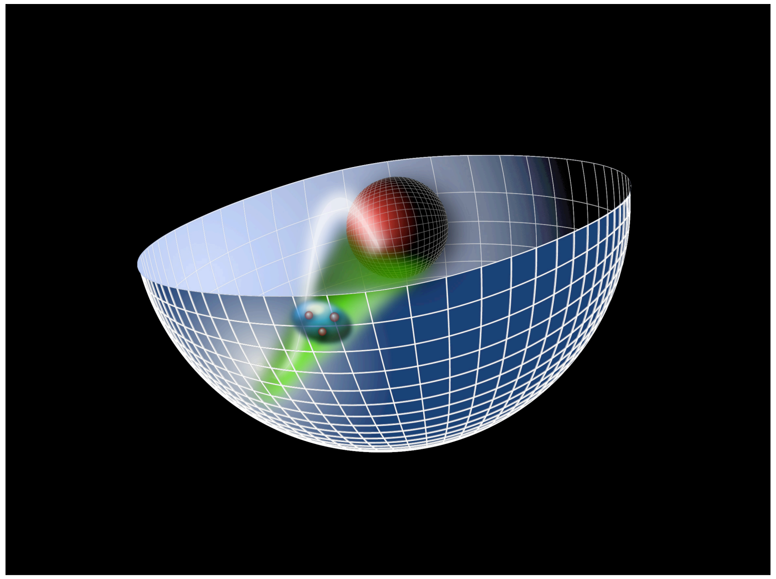
Duality of AdS_5 with LF Hamiltonian Theory

- *Light Front Wavefunctions:*

Light-Front Schrödinger Equation

Spectroscopy and Dynamics

$\phi(z)$



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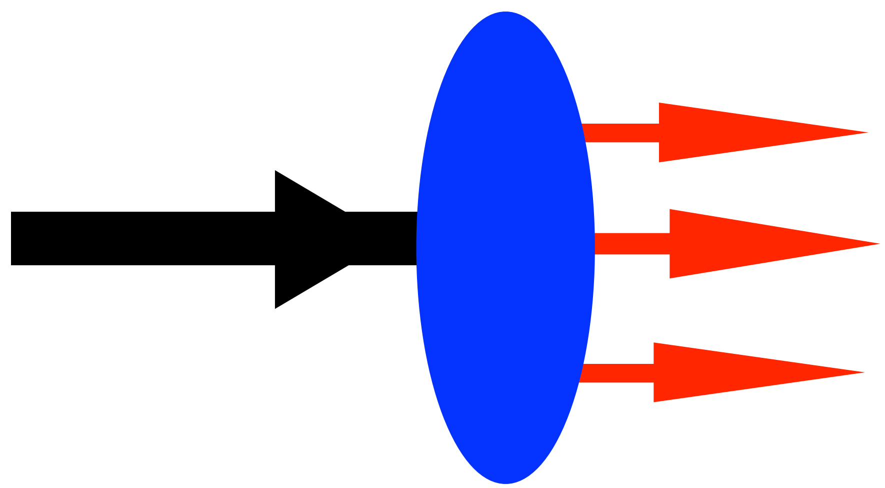

$$\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$

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Light-Front Schrödinger Equation
Spectroscopy and Dynamics

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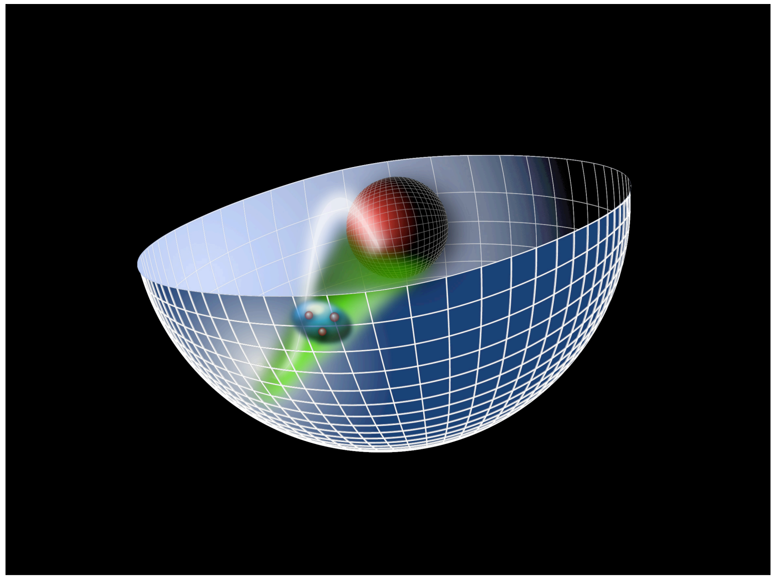

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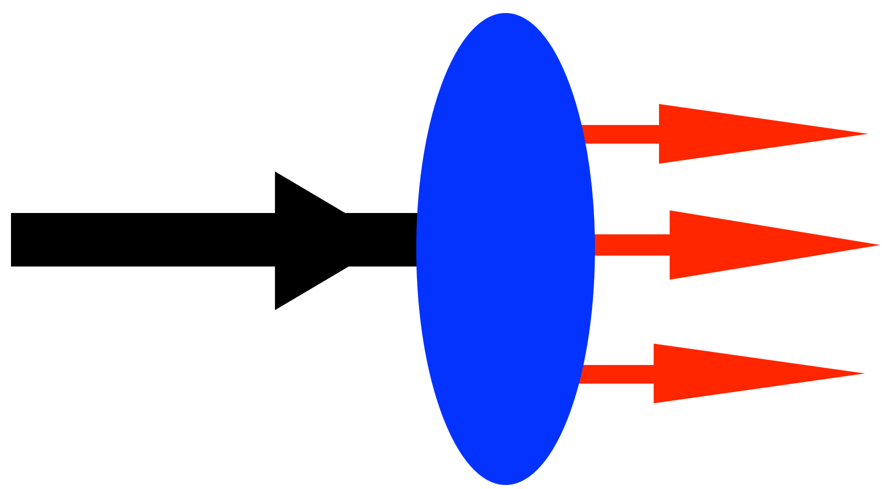

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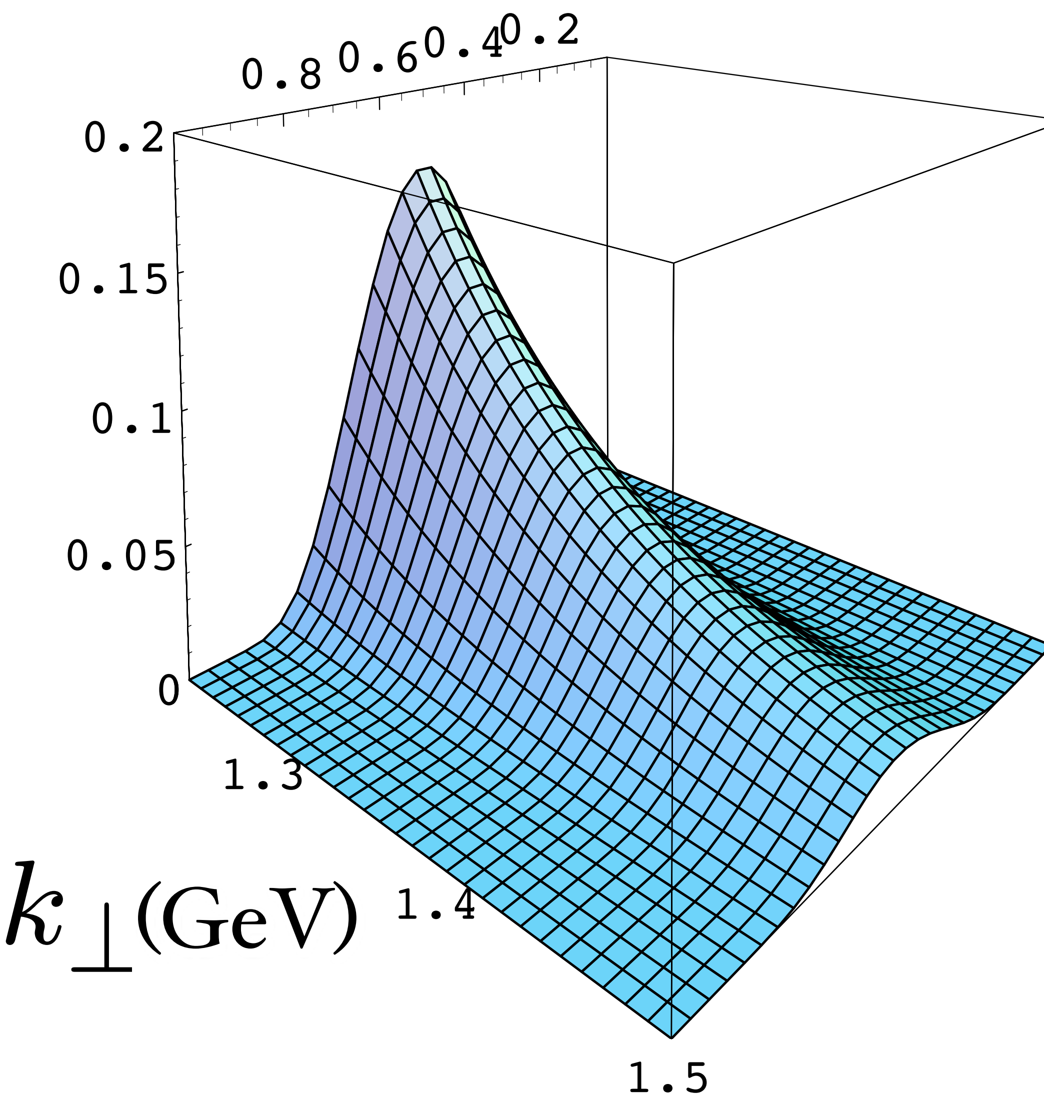

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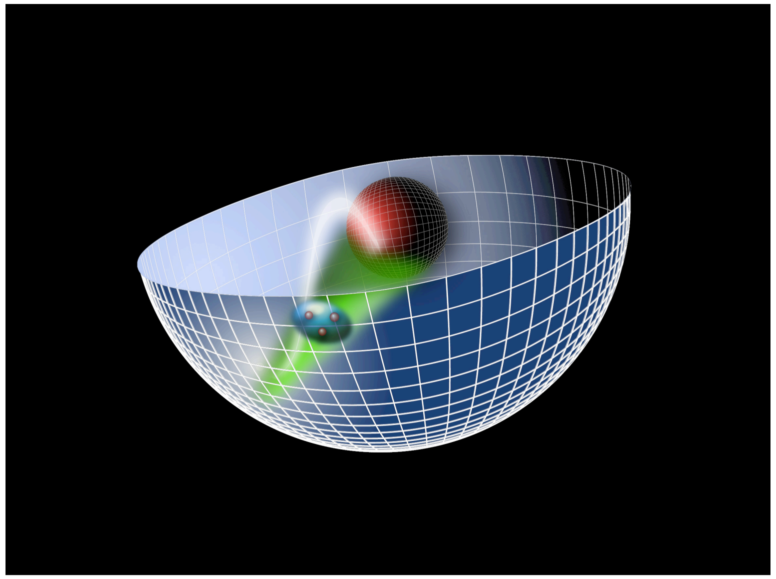

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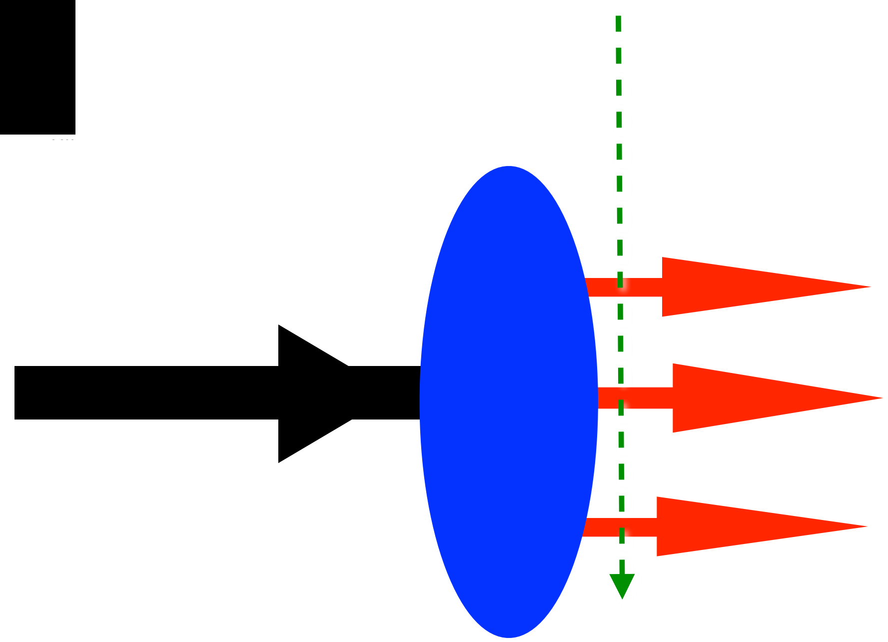

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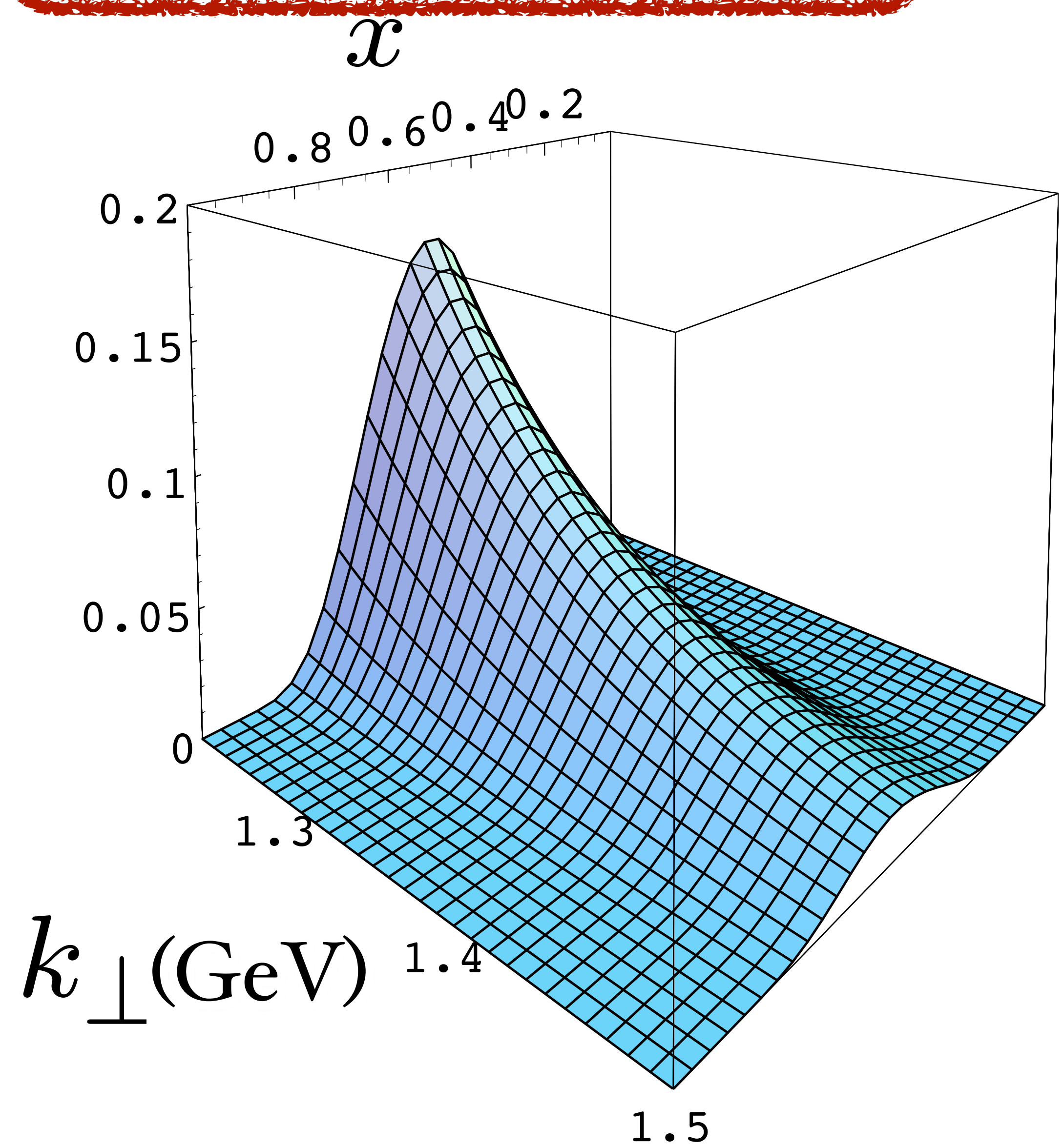

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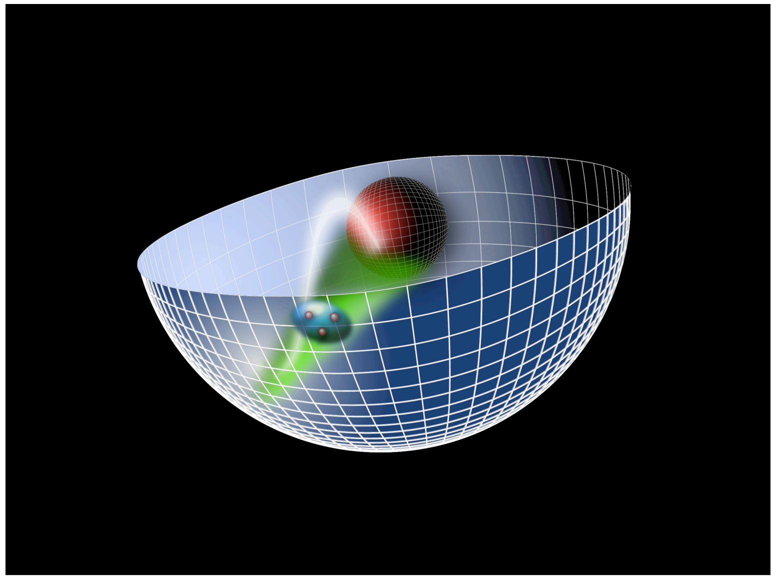

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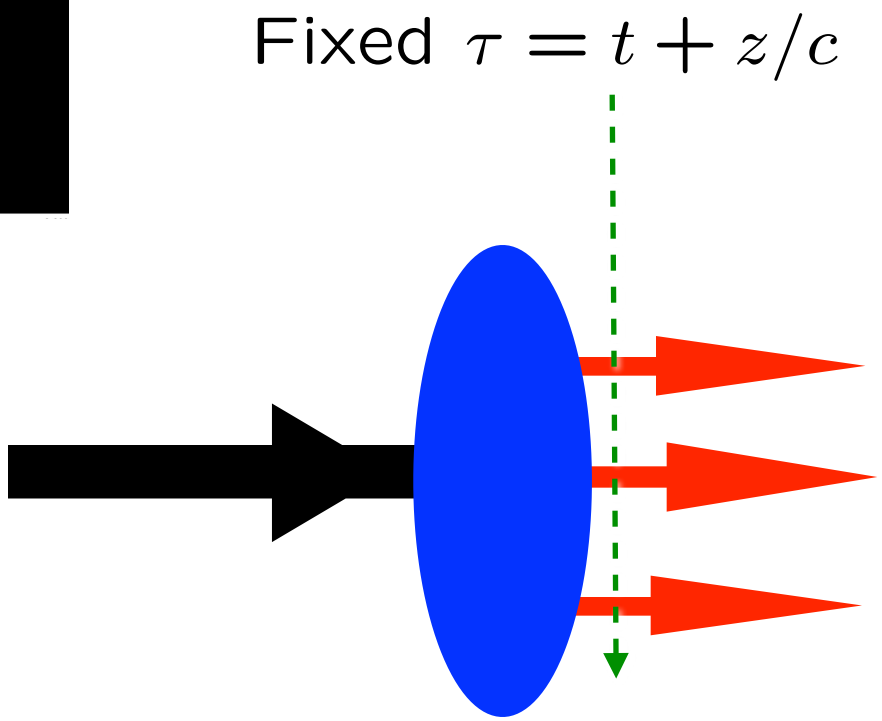

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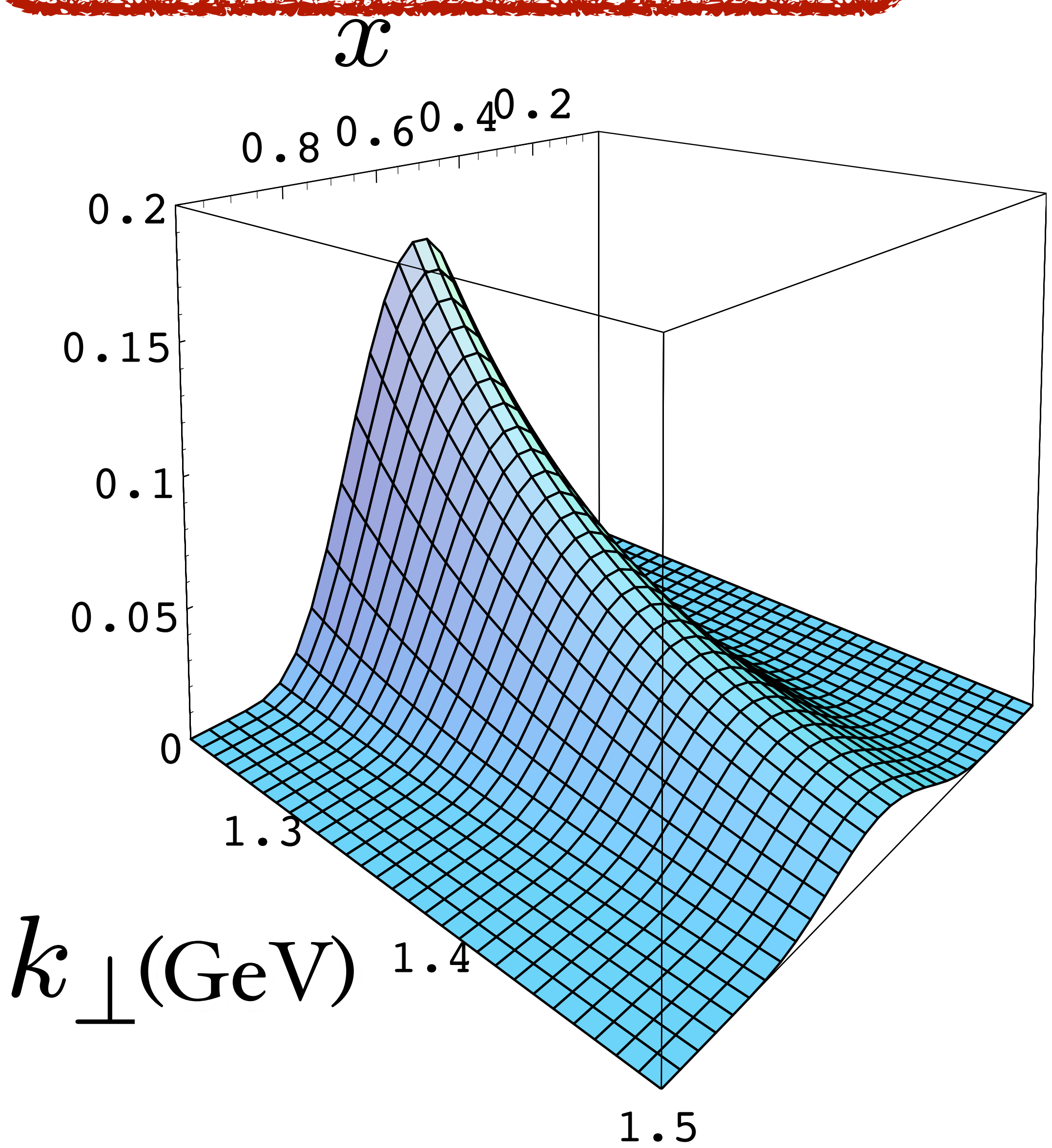

- *Light Front Wavefunctions:*

Light-Front Schrödinger Equation
Spectroscopy and Dynamics

QCD Lagrangian

$$\mathcal{L}_{QCD} = -\frac{1}{4}Tr(G^{\mu\nu}G_{\mu\nu}) + \sum_{f=1}^{n_f} i\bar{\Psi}_f D_\mu \gamma^\mu \Psi_f + \sum_{f=1}^{n_f} m_f \bar{\Psi}_f \Psi_f$$

$$iD^\mu = i\partial^\mu - gA^\mu \qquad G^{\mu\nu} = \partial^\mu A^\mu - \partial^\nu A^\mu - g[A^\mu, A^\nu]$$

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Classical Chiral Lagrangian is Conformally Invariant

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Where does the QCD Mass Scale Λ_{QCD} come from?

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How does color confinement arise?

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Unique confinement potential!

- **de Alfaro, Fubini, Furlan**

$$G|\psi(\tau)>= i\frac{\partial}{\partial\tau}|\psi(\tau)>$$

$$G = uH + vD + wK$$

New term

$$G = H_\tau = \frac{1}{2}\left(-\frac{d^2}{dx^2} + \frac{g}{x^2} + \frac{4uw - v^2}{4}x^2\right)$$

Retains conformal invariance of action despite mass scale!

$$4uw - v^2 = \kappa^4 = [M]^4$$

Identical to LF Hamiltonian with unique potential and dilaton!

- **Dosch, de Teramond, sjb**

$$\left[-\frac{d^2}{d\zeta^2} + \frac{1-4L^2}{4\zeta^2} + U(\zeta)\right]\psi(\zeta) = \mathcal{M}^2\psi(\zeta)$$

$$U(\zeta) = \kappa^4\zeta^2 + 2\kappa^2(L+S-1)$$

What determines the QCD mass scale Λ_{QCD}?

- Mass scale does not appear in the QCD Lagrangian (massless quarks)

- Dimensional Transmutation? Requires external constraint such as $\alpha_s(M_Z)$

- dAFF: Confinement Scale κ appears spontaneously via the Hamiltonian: $G = uH + vD + wK$ $\quad 4uw - v^2 = \kappa^4 = [M]^4$

- The confinement scale regulates infrared divergences, connects Λ_{QCD} to the confinement scale κ

- Only dimensionless mass ratios (and M times R) predicted

- Mass and time units [GeV] and [sec] from physics external to QCD

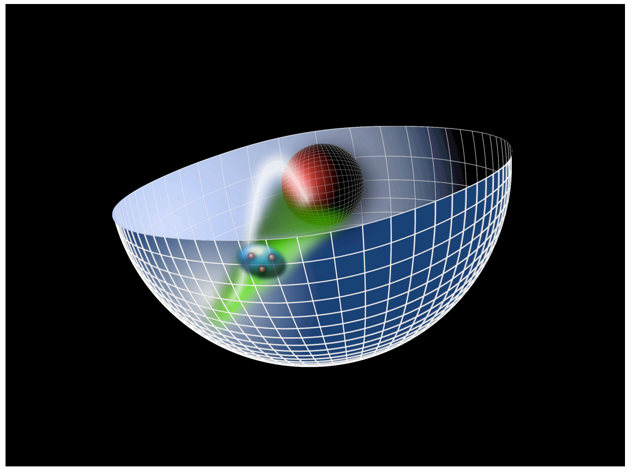
- New feature: bounded frame-independent relative time between constituents

dAFF: New Time Variable

$$\tau = \frac{2}{\sqrt{4uw - v^2}} \arctan\left(\frac{2tw + v}{\sqrt{4uw - v^2}}\right),$$

- Identify with difference of LF time $\Delta x^+/P^+$ between constituents
- Finite range
- Measure in Double-Parton Processes

de Tèramond, Dosch, sjb



AdS/QCD
Soft-Wall Model

Light-Front Holography

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Light-Front Schrödinger Equation

Confinement scale:

$$\kappa \simeq 0.6 \ GeV$$

$$1/\kappa \simeq 1/3 \ fm$$

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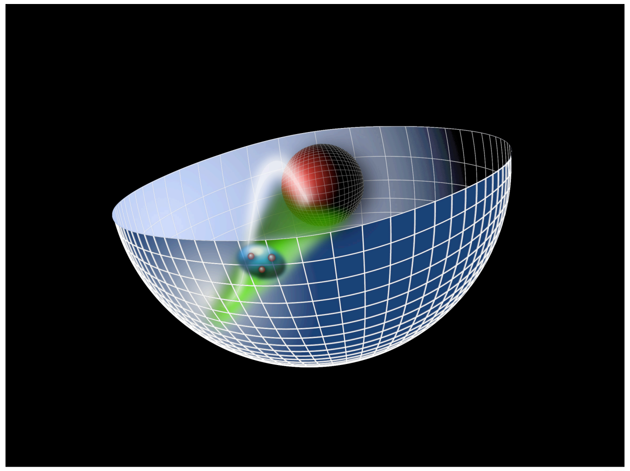

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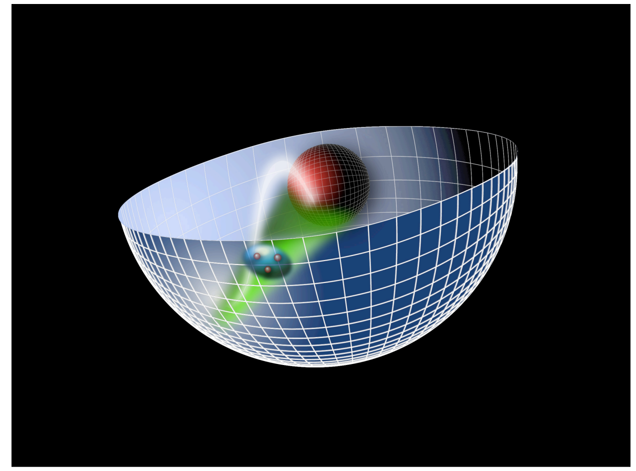

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Conformal Symmetry
of the action

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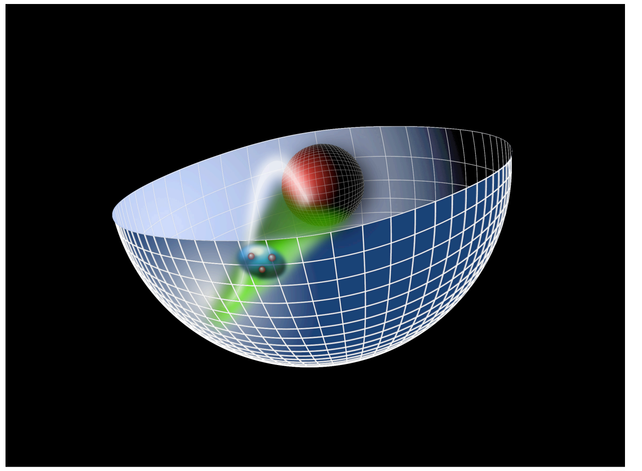

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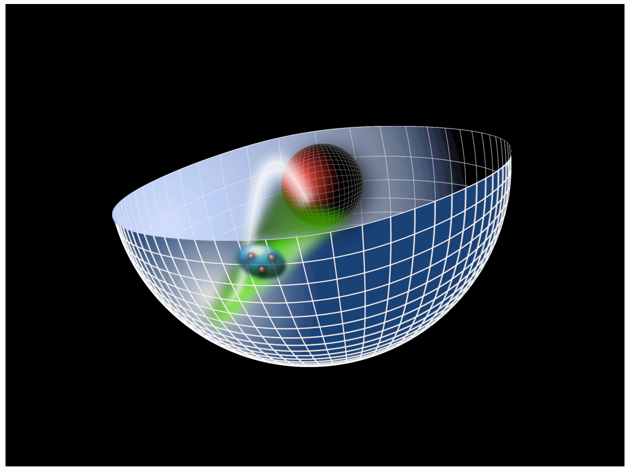

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Interpretation of Mass Scale κ

- Does not affect conformal symmetry of QCD action
- Self-consistent regularization of IR divergences
- Determines all mass and length scales for zero quark mass
- Compute scheme-dependent $\Lambda_{\overline{MS}}$ determined in terms of κ
- Value of κ itself not determined -- place holder
- Need external constraint such as f_π
- "Zero-Parameter" Model

Fubini and Rabinovici

Superconformal Algebra

de Teramond Dosch and SJB

1+1

$$\{\psi, \psi^+\} = 1$$

two anti-commuting fermionic operators

$$\psi = \frac{1}{2}(\sigma_1 - i\sigma_2), \quad \psi^+ = \frac{1}{2}(\sigma_1 + i\sigma_2)$$

Realization as Pauli Matrices

$$Q = \psi^+[-\partial_x + W(x)], \quad Q^+ = \psi[\partial_x + W(x)], \qquad W(x) = \frac{f}{x}$$

(Conformal)

$$S = \psi^+ x, \quad S^+ = \psi x$$

Introduce new spinor operators

$$\{Q, Q^+\} = 2H, \quad \{S, S^+\} = 2K \qquad Q \simeq \sqrt{H}, \quad S \simeq \sqrt{K}$$

$$\{Q, Q\} = \{Q^+, Q^+\} = 0, \quad [Q, H] = [Q^+, H] = 0$$

Fubini and Rabinovici

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Superconformal Algebra

Baryon Equation

Consider $R_w = Q + wS;$ $\quad$ w: dimensions of mass squared

$$G = \{R_w, R_w^+\} = 2H + 2w^2 K + 2wfI - 2wB \qquad 2B = \sigma_3$$

Retains Conformal Invariance of Action $\quad$ ***Fubini and Rabinovici***

New Extended Hamiltonian G is diagonal:

$$G_{11} = \left(-\partial_x^2 + w^2 x^2 + 2wf - w + \frac{4(f+\frac{1}{2})^2 - 1}{4x^2} \right)$$

$$G_{22} = \left(-\partial_x^2 + w^2 x^2 + 2wf + w + \frac{4(f-\frac{1}{2})^2 - 1}{4x^2} \right)$$

Identify $f - \frac{1}{2} = L_B \;, \quad w = \kappa^2$

Eigenvalue of G: $M^2(n, L) = 4\kappa^2(n + L_B + 1)$

LF Holography

Baryon Equation

Superconformal Algebra

$$\Big(-\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2(L_B+1) + \frac{4L_B^2-1}{4\zeta^2}\Big)\psi_J^+ = M^2\psi_J^+$$

$$\Big(-\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2 L_B + \frac{4(L_B+1)^2-1}{4\zeta^2}\Big)\psi_J^- = M^2\psi_J^-$$

$$M^2(n, L_B) = 4\kappa^2(n + L_B + 1)$$

S=1/2, P=+

both chiralities

Meson Equation

$$\Big(-\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2(J-1) + \frac{4L_M^2-1}{4\zeta^2}\Big)\phi_J = M^2\phi_J$$

$$M^2(n, L_M) = 4\kappa^2(n + L_M)$$

LF Holography

Baryon Equation

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Meson Equation

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$$M^2(n,L_M)=4\kappa^2(n+L_M)$$

Same κ *!*

LF Holography

Baryon Equation

Superconformal Algebra

$$\left(-\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2(L_B+1) + \frac{4L_B^2-1}{4\zeta^2}\right)\psi_J^+ = M^2\psi_J^+$$

$$\left(-\partial_\zeta^2 + \kappa^4\zeta^2 + 2\kappa^2 L_B + \frac{4(L_B+1)^2-1}{4\zeta^2}\right)\psi_J^- = M^2\psi_J^-$$

$$M^2(n, L_B) = 4\kappa^2(n + L_B + 1)$$

S=1/2, P=+

both chiralities

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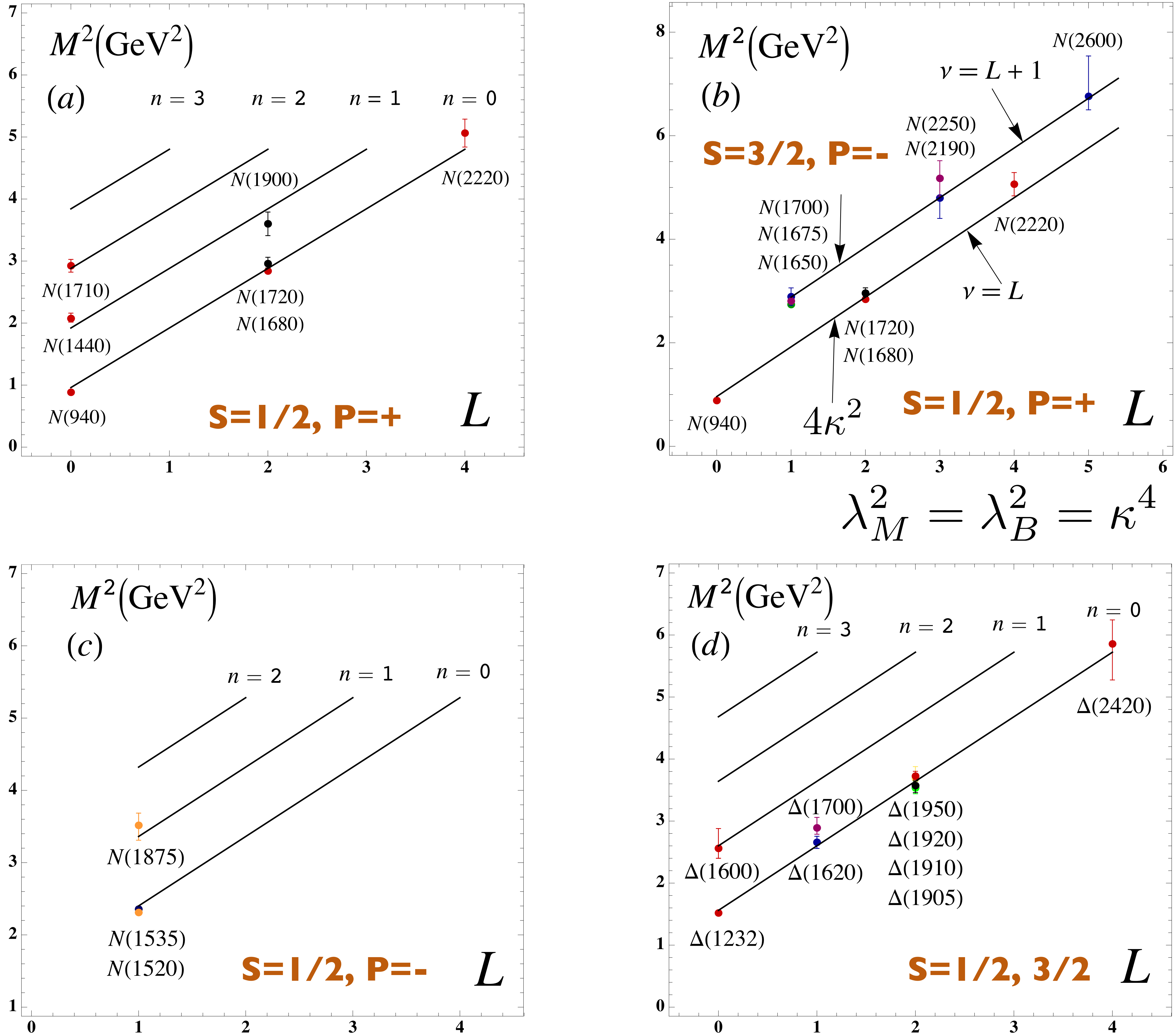
Meson-Baryon Degeneracy for $L_M = L_B + 1$



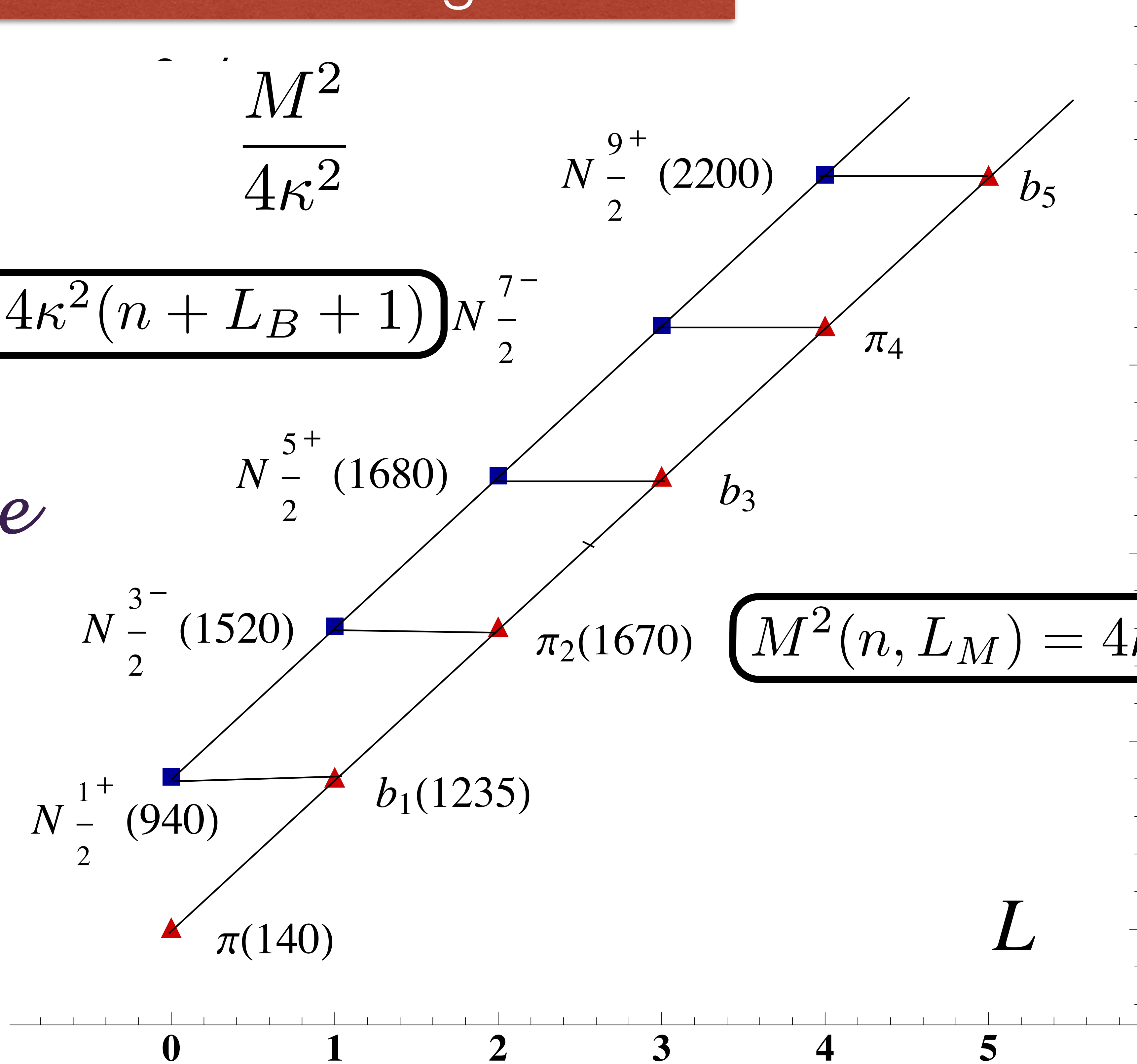
$M^2(\mathrm{GeV}^2)$
(a)
n = 3
n = 2
n = 1
n = 0
N(2220)
N(1900)
N(1710)
N(1440)
N(1720)
N(1680)
N(940)
S=1/2, P=+
L
$M^2(\mathrm{GeV}^2)$
(b)
N(2600)
ν = L + 1
N(2250)
N(2190)
S=3/2, P=-
N(1700)
N(1675)
N(1650)
N(2220)
ν = L
N(1720)
N(1680)
N(940)
$4\kappa^2$
S=1/2, P=+
L
$\lambda_M^2 = \lambda_B^2 = \kappa^4$
$M^2(\mathrm{GeV}^2)$
(c)
n = 2
n = 1
n = 0
N(1875)
N(1535)
N(1520)
S=1/2, P=-
L
$M^2(\mathrm{GeV}^2)$
(d)
n = 0
n = 3
n = 2
n = 1
Δ(2420)
Δ(1700)
Δ(1950)
Δ(1920)
Δ(1910)
Δ(1905)
Δ(1600)
Δ(1620)
Δ(1232)
S=1/2, 3/2
L

Superconformal Algebra

de Tèramond, Dosch, sjb

$$M^2(n, L_B) = 4\kappa^2(n + L_B + 1)$$

Same slope



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Superconformal Algebra

de Tèramond, Dosch, sjb

$$\frac{M^2}{4\kappa^2}$$

$$M^2(n, L_B) = 4\kappa^2(n + L_B + 1)$$

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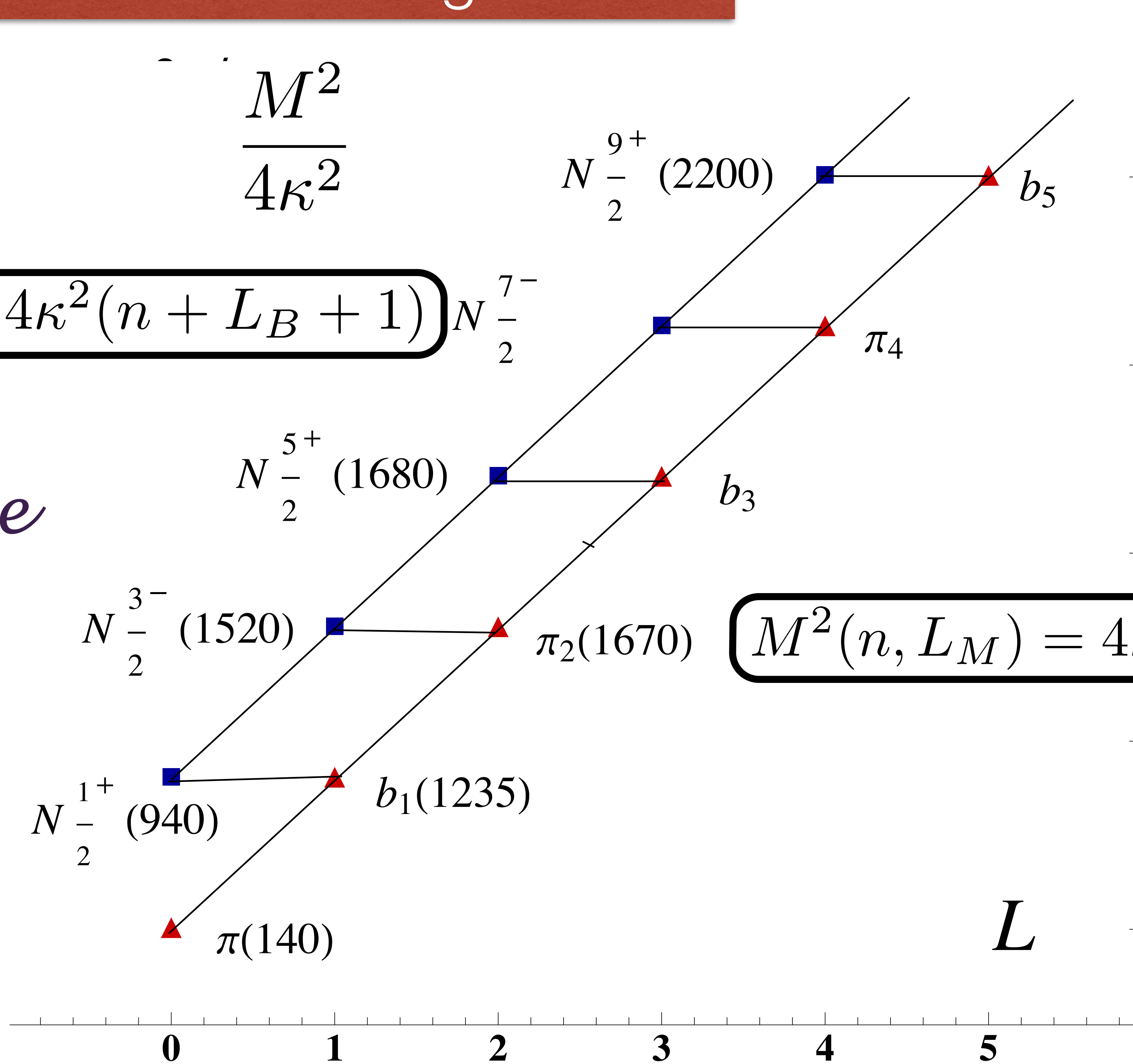
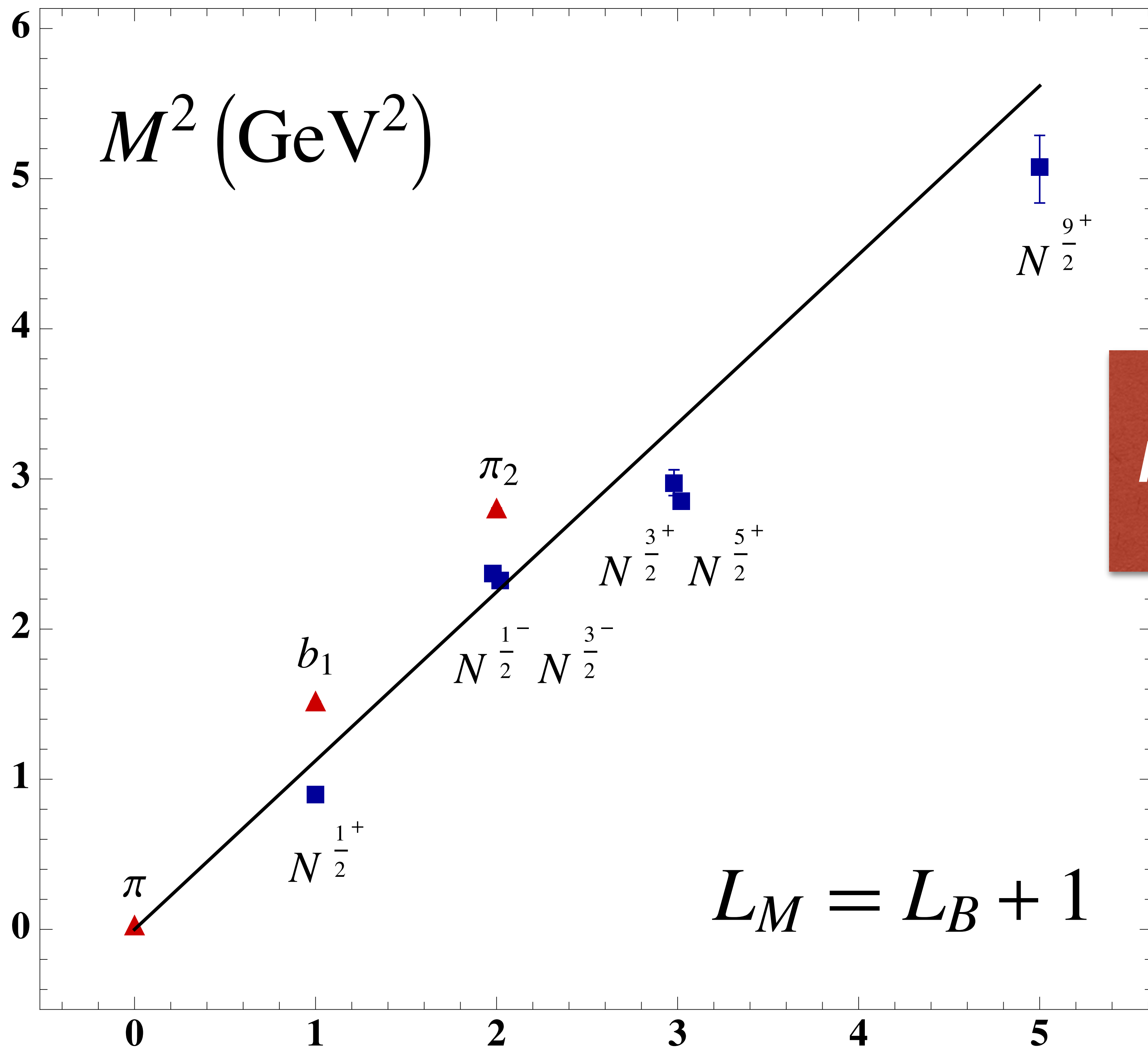


$$M^2(n, L_M) = 4\kappa^2(n + L_M)$$

$$\frac{M^2_{meson}}{M^2_{nucleon}} = \frac{n + L_M}{n + L_B + 1}$$

Meson-Baryon Mass Degeneracy for $L_M = L_B + 1$

Superconformal AdS Light-Front Holographic QCD (LFHQCD): Identical meson and baryon spectra!



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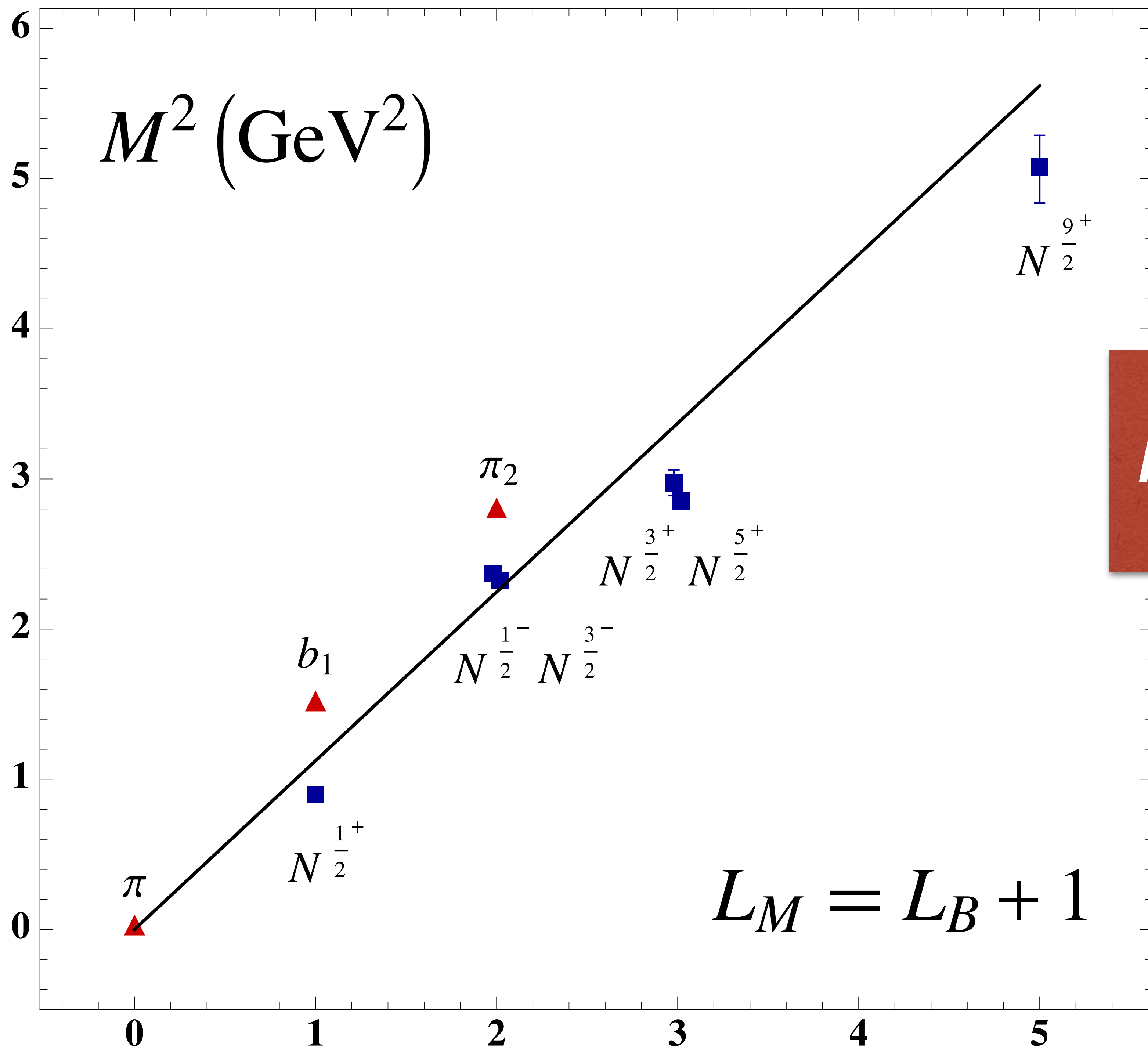

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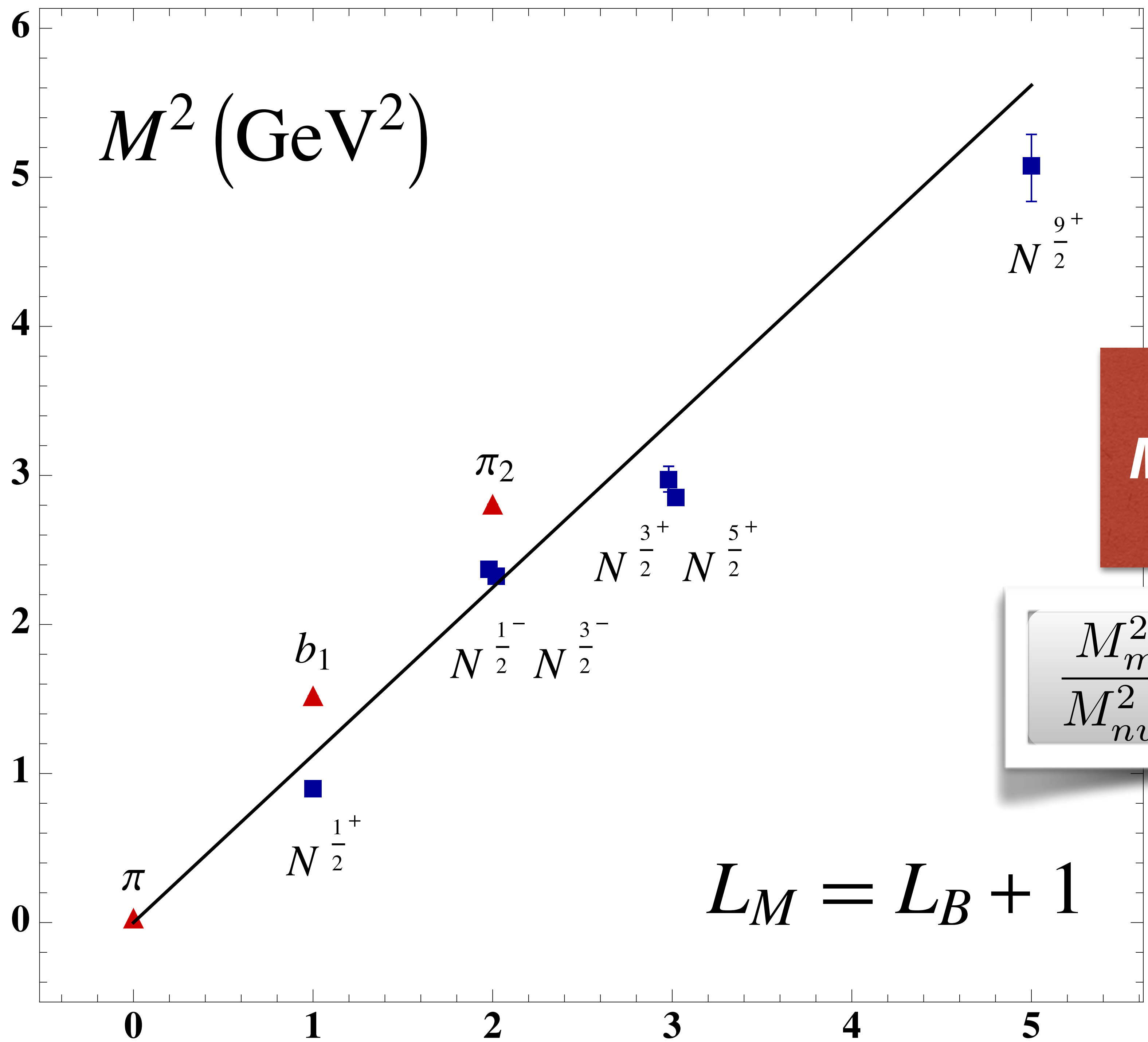

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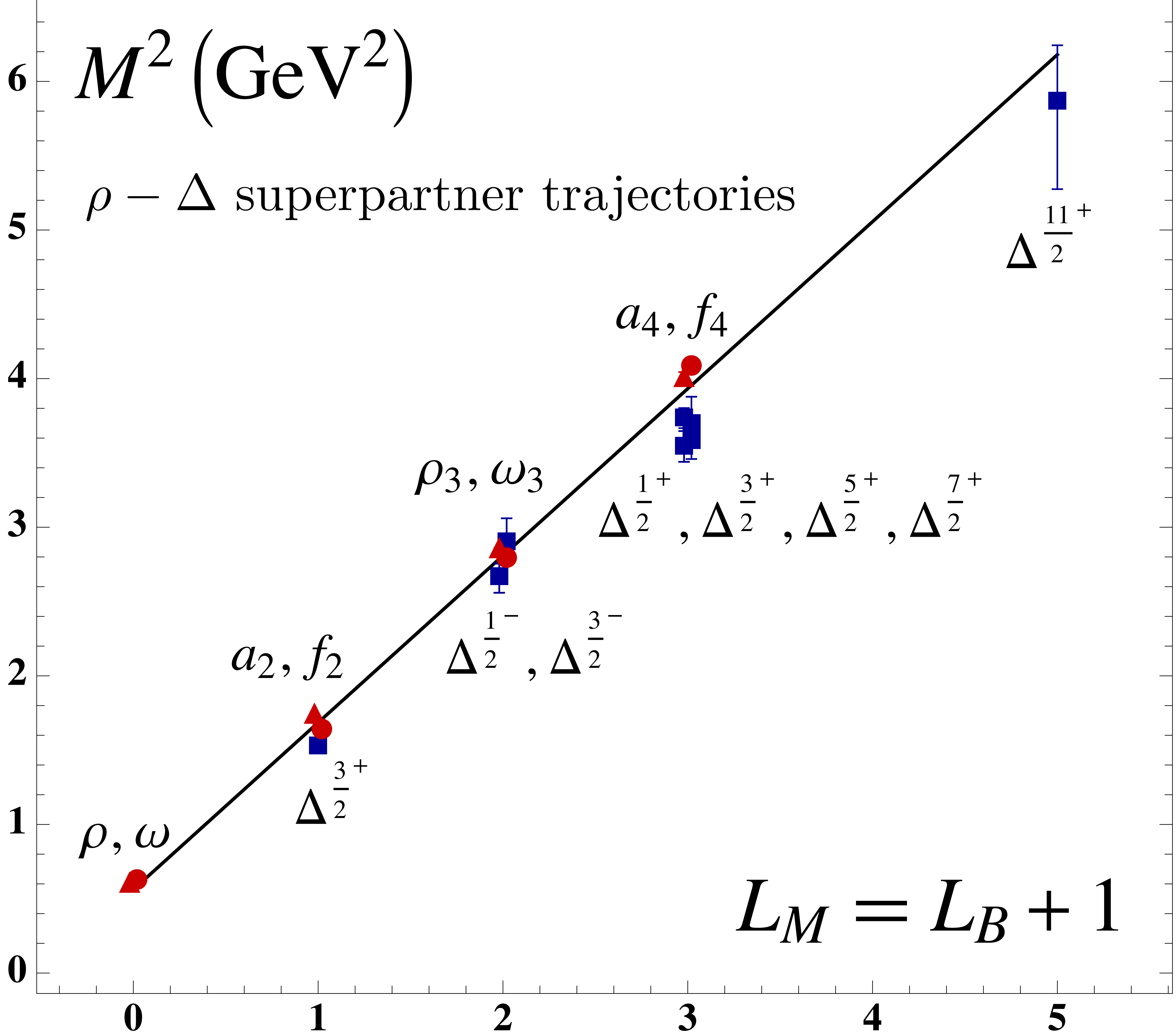


Dosch, de Teramond, sjb

Features of Supersymmetric Equations

- J =L+S baryon simultaneously satisfies both equations of G with L , L+1 for same mass eigenvalue

- $J^z = L^z + 1/2 = (L^z + 1) - 1/2$ $\quad S^z = \pm 1/2$

- Baryon spin carried by quark orbital angular momentum: $\langle J^z \rangle = L^z + 1/2$

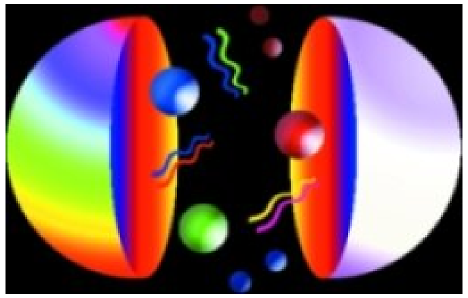
- Mass-degenerate meson "superpartner" with $L_M = L_B + 1$. *"Shifted meson-baryon Duality"*

Meson and baryon have same κ !

Fermionic Modes and Baryon Spectrum

[Hard wall model: GdT and S. J. Brodsky, PRL **94**, 201601 (2005)]

[Soft wall model: GdT and S. J. Brodsky, (2005), arXiv:1001.5193]



From Nick Evans

- Nucleon LF modes

$$\psi_+(\zeta)_{n,L} = \kappa^{2+L}\sqrt{\frac{2n!}{(n+L)!}}\zeta^{3/2+L}e^{-\kappa^2\zeta^2/2}L_n^{L+1}\left(\kappa^2\zeta^2\right)$$

$$\psi_-(\zeta)_{n,L} = \kappa^{3+L}\frac{1}{\sqrt{n+L+2}}\sqrt{\frac{2n!}{(n+L)!}}\zeta^{5/2+L}e^{-\kappa^2\zeta^2/2}L_n^{L+2}\left(\kappa^2\zeta^2\right)$$

- Normalization

$$\int d\zeta\, \psi_+^2(\zeta) = \int d\zeta\, \psi_-^2(\zeta) = 1$$

- Eigenvalues

$$\mathcal{M}^2_{n,L,S=1/2} = 4\kappa^2\left(n+L+1\right)$$

- "Chiral partners"

$$\frac{\mathcal{M}_{N(1535)}}{\mathcal{M}_{N(940)}} = \sqrt{2}$$

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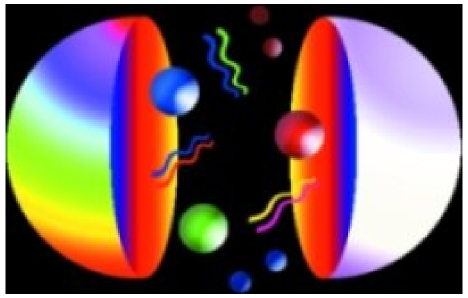

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- Normalization

$$\int d\zeta\, \psi_+^2(\zeta) = \int d\zeta\, \psi_-^2(\zeta) = 1$$

Chiral Symmetry of Eigenstate!

- Eigenvalues

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- "Chiral partners"

$$\frac{\mathcal{M}_{N(1535)}}{\mathcal{M}_{N(940)}} = \sqrt{2}$$

Chiral Features of Soft-Wall AdS/QCD Model

- **Boost Invariant**
- **Trivial LF vacuum! No condensate, but consistent with GMOR**
- **Massless Pion**
- **Hadron Eigenstates (even the pion) have LF Fock components of different L^z**
- **Proton: equal probability** $S^z = +1/2, L^z = 0; S^z = -1/2, L^z = +1$

$$J^z = +1/2 :< L^z >= 1/2, < S_q^z >= 0$$

- **Self-Dual Massive Eigenstates: Proton is its own chiral partner.**
- **Label State by minimum L as in Atomic Physics**
- **Minimum L dominates at short distances**
- **AdS/QCD Dictionary: Match to Interpolating Operator Twist at z=0.**

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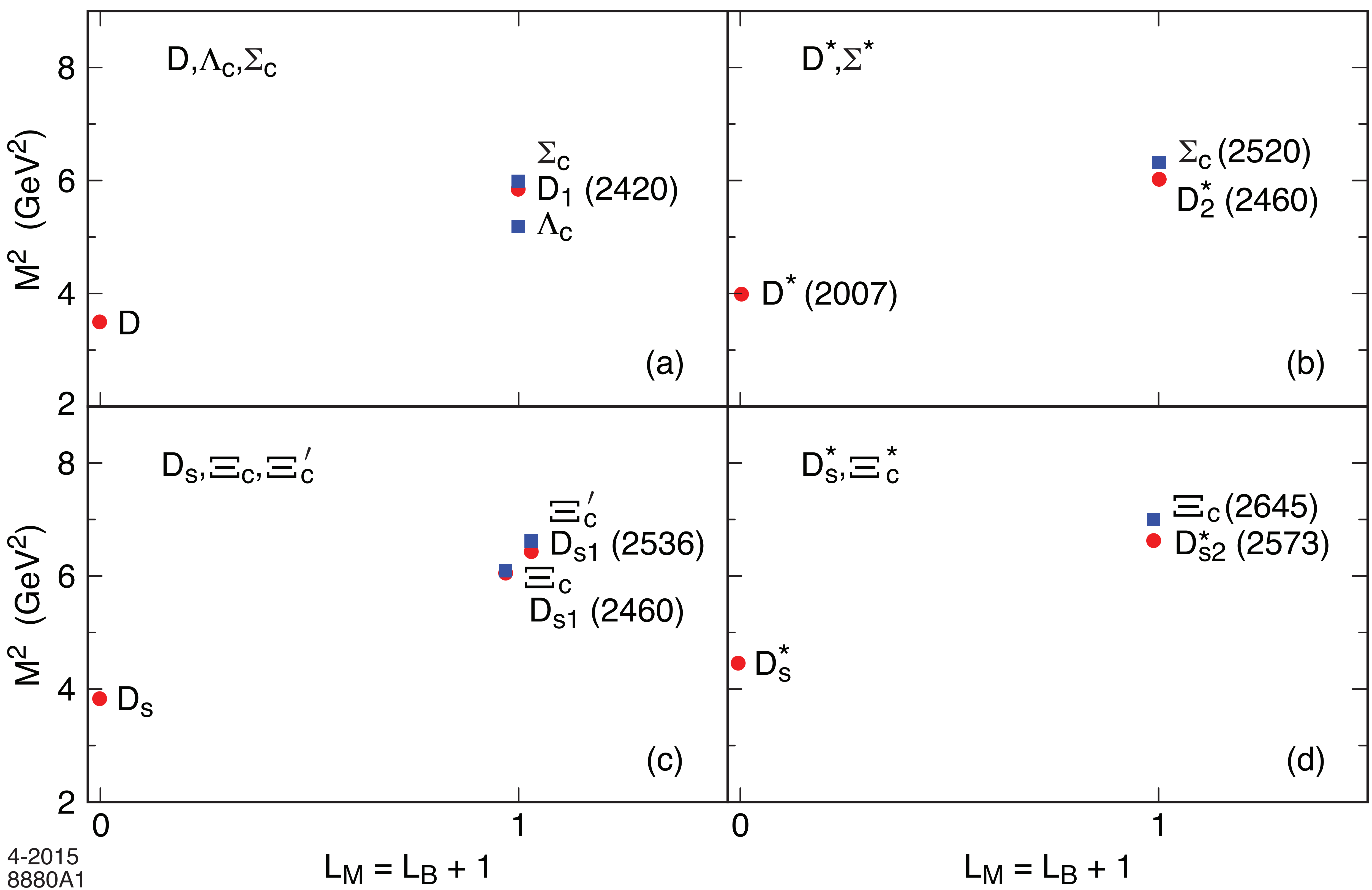
No mass -degenerate parity partners!

Supersymmetry Across the Light and Heavy-Light Hadronic Spectrum

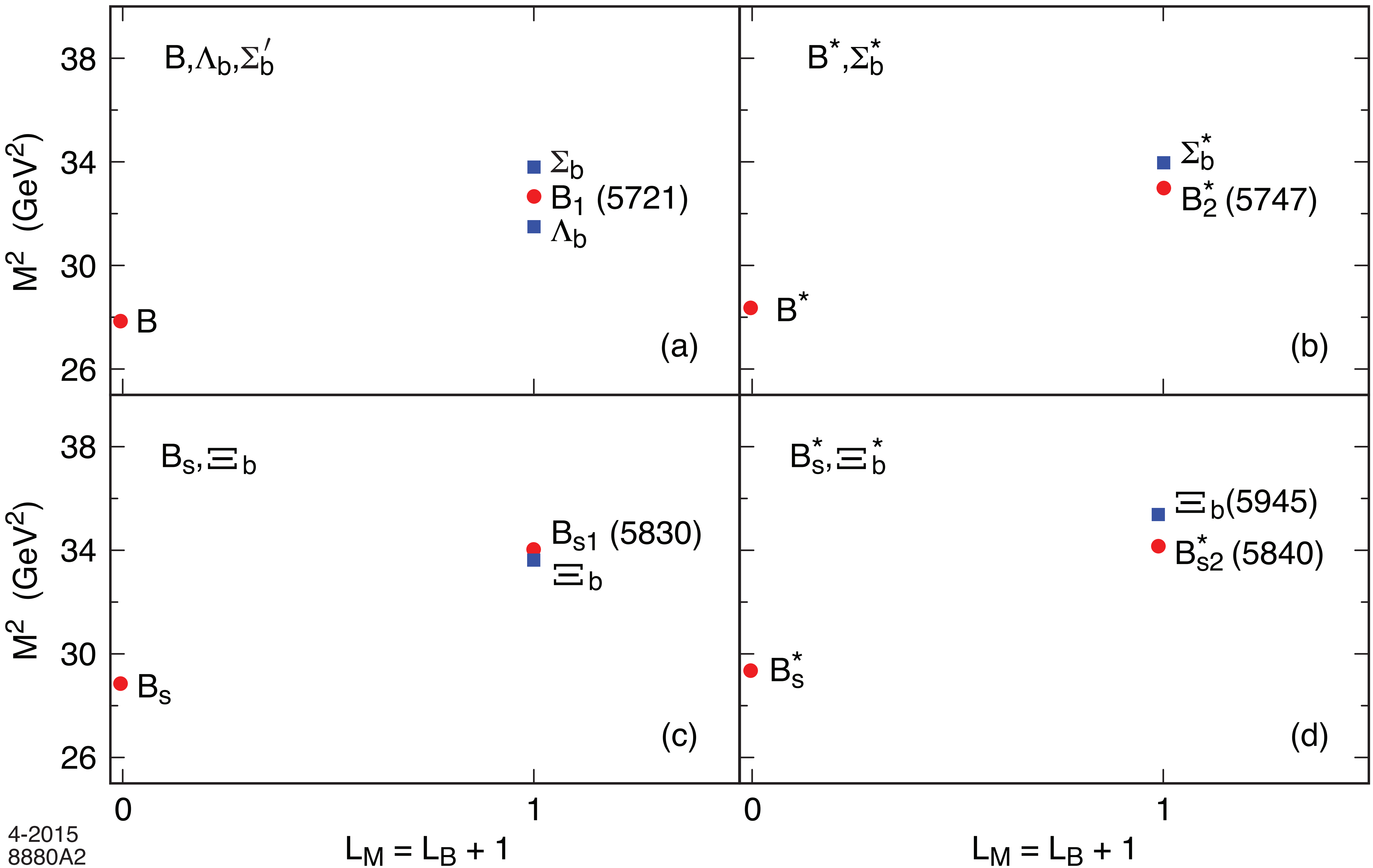
Dosch, de Teramond, sjb

Relativistic light-front bound-state equations for mesons and baryons can be constructed in the chiral limit from the supercharges of a superconformal algebra which connect baryon and meson spectra. Quark masses break the conformal invariance, but the basic underlying supersymmetric mechanism, which transforms meson and baryon wave functions into each other, still holds and gives remarkable connections across the entire spectrum of light and heavy-light hadrons. We also briefly examine the consequences of extending the supersymmetric relations to double-heavy mesons and baryons.

Dosch, de Teramond, sjb



Dosch, de Teramond, sjb



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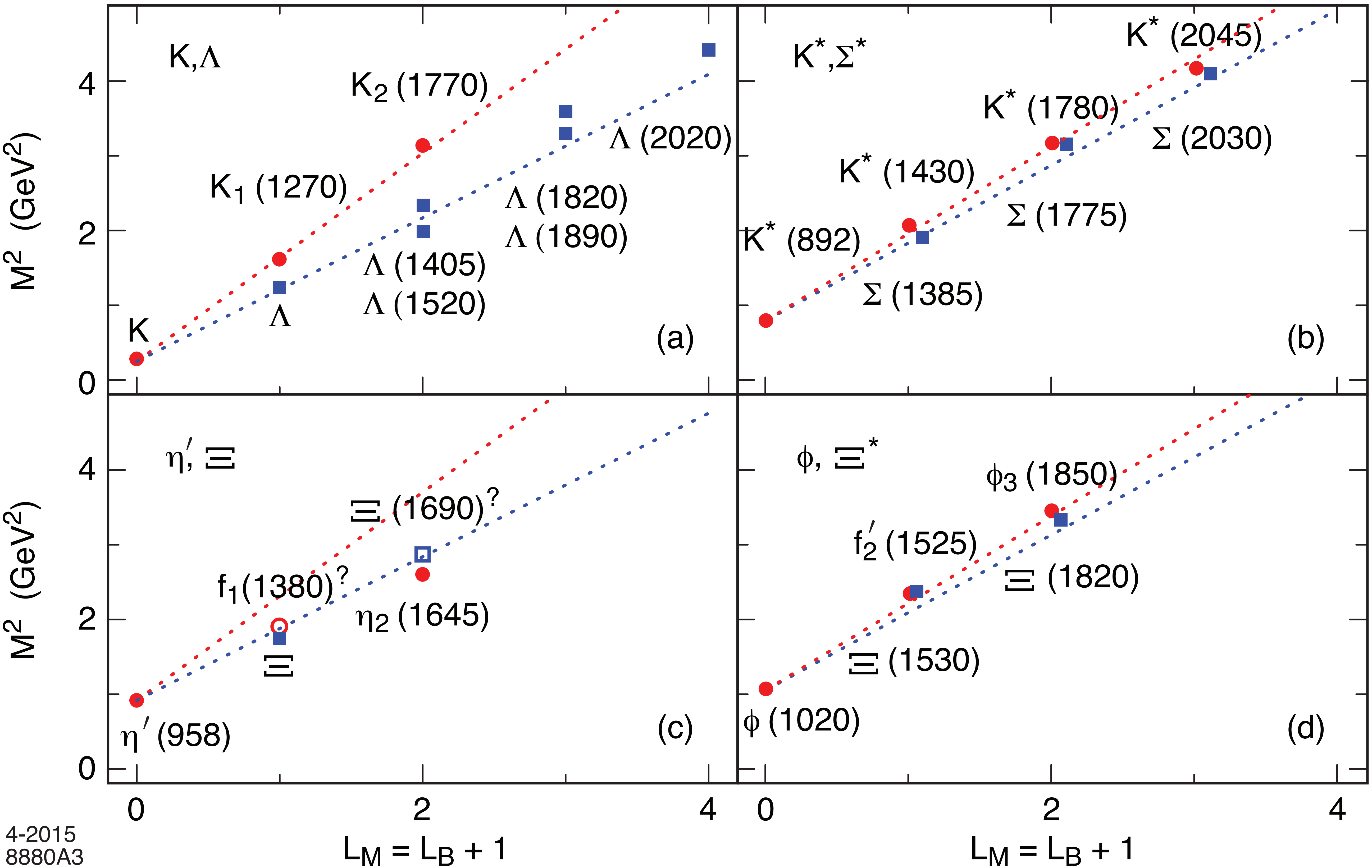


Space-Like Dirac Proton Form Factor

- Consider the spin non-flip form factors

$$F_+(Q^2) = g_+ \int d\zeta\, J(Q,\zeta) |\psi_+(\zeta)|^2,$$
$$F_-(Q^2) = g_- \int d\zeta\, J(Q,\zeta) |\psi_-(\zeta)|^2,$$

where the effective charges g_+ and g_- are determined from the spin-flavor structure of the theory.

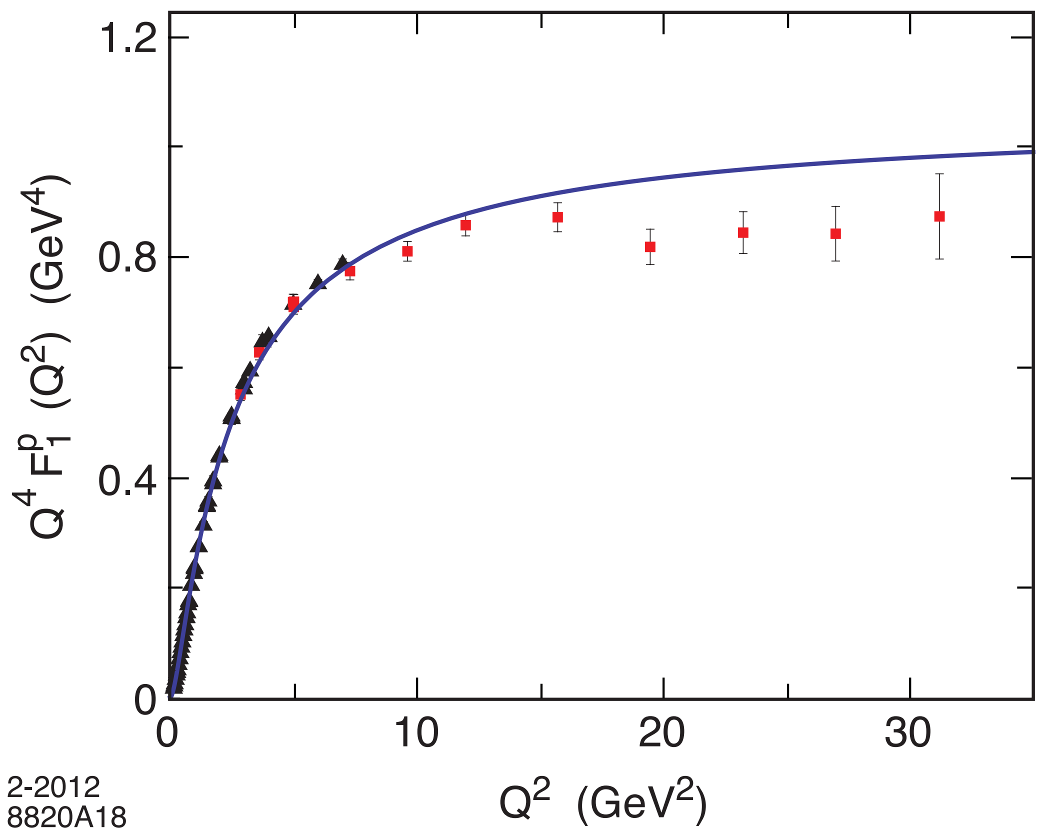
- Choose the struck quark to have $S^z = +1/2$. The two AdS solutions $\psi_+(\zeta)$ and $\psi_-(\zeta)$ correspond to nucleons with $J^z = +1/2$ and $-1/2$.

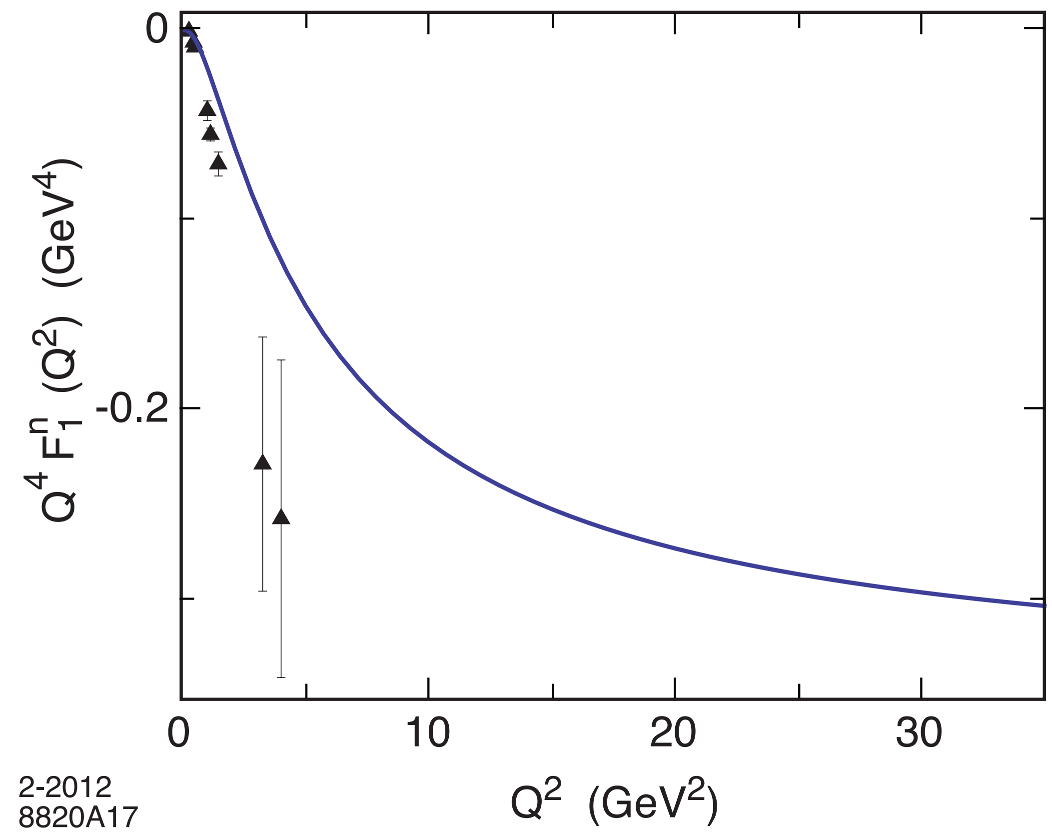
- For $SU(6)$ spin-flavor symmetry

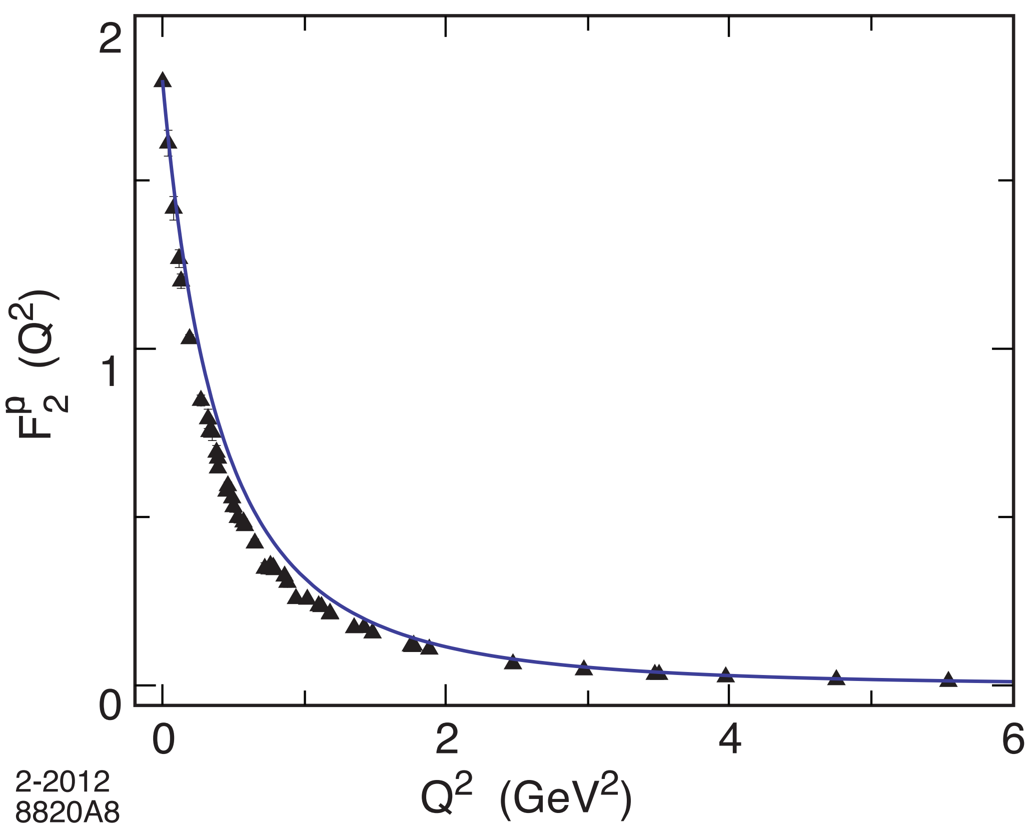
$$F_1^p(Q^2) = \int d\zeta\, J(Q,\zeta) |\psi_+(\zeta)|^2,$$
$$F_1^n(Q^2) = -\frac{1}{3} \int d\zeta\, J(Q,\zeta) \left[|\psi_+(\zeta)|^2 - |\psi_-(\zeta)|^2 \right],$$

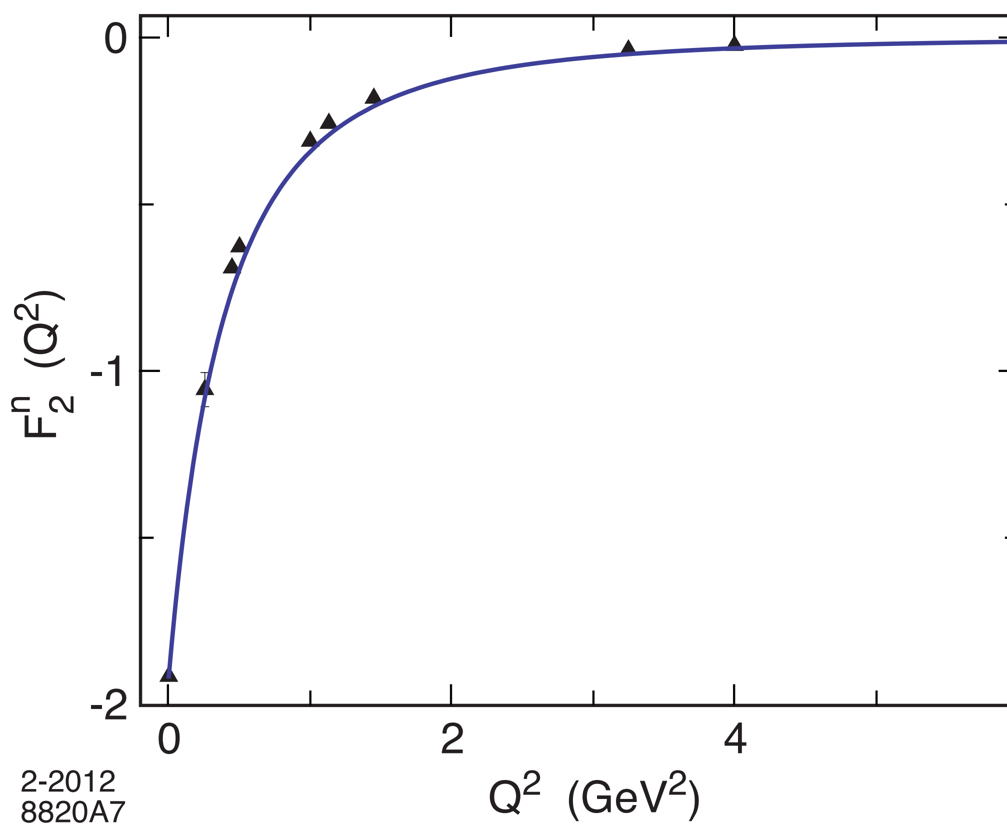
where $F_1^p(0) = 1,\ F_1^n(0) = 0$.

Using $SU(6)$ flavor symmetry and normalization to static quantities



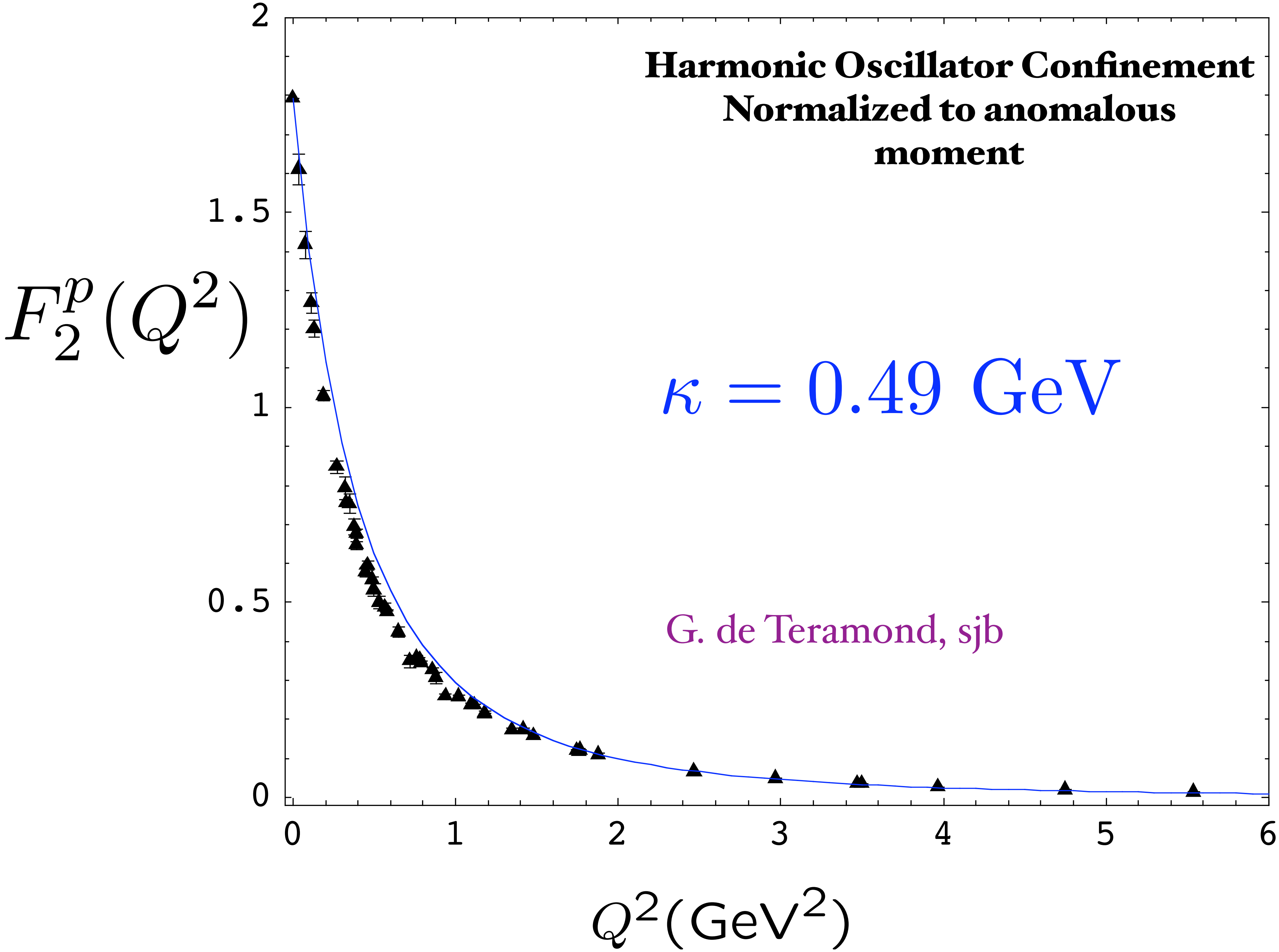






Spacelike Pauli Form Factor

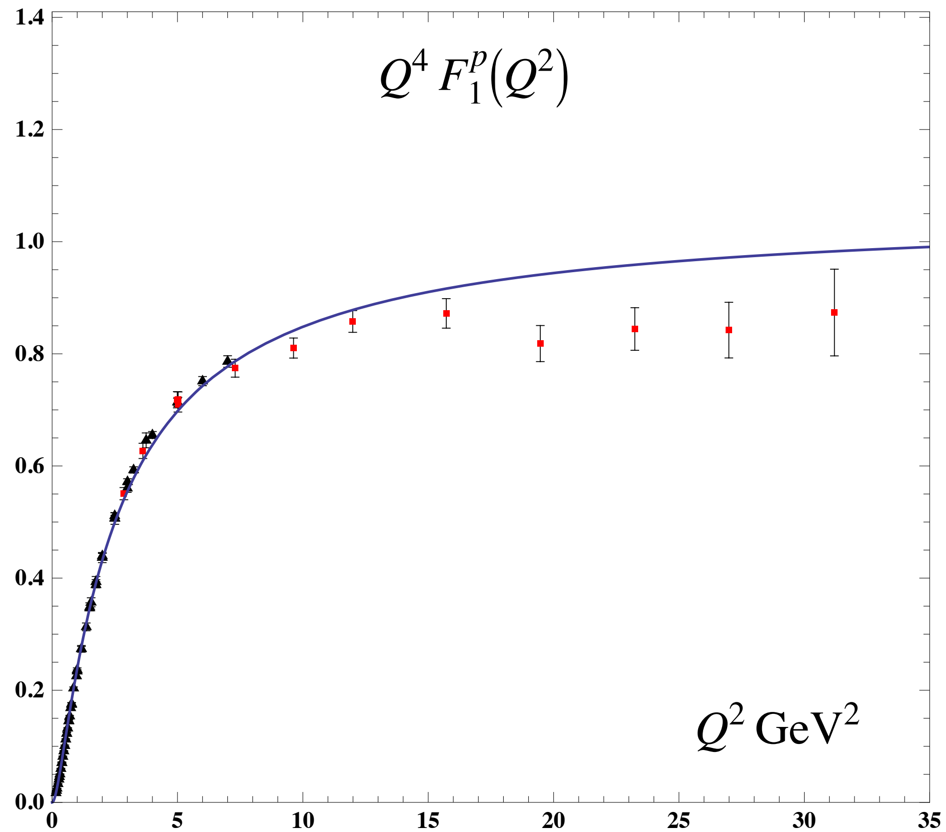
From overlap of $L = 1$ and $L = 0$ LFWFs

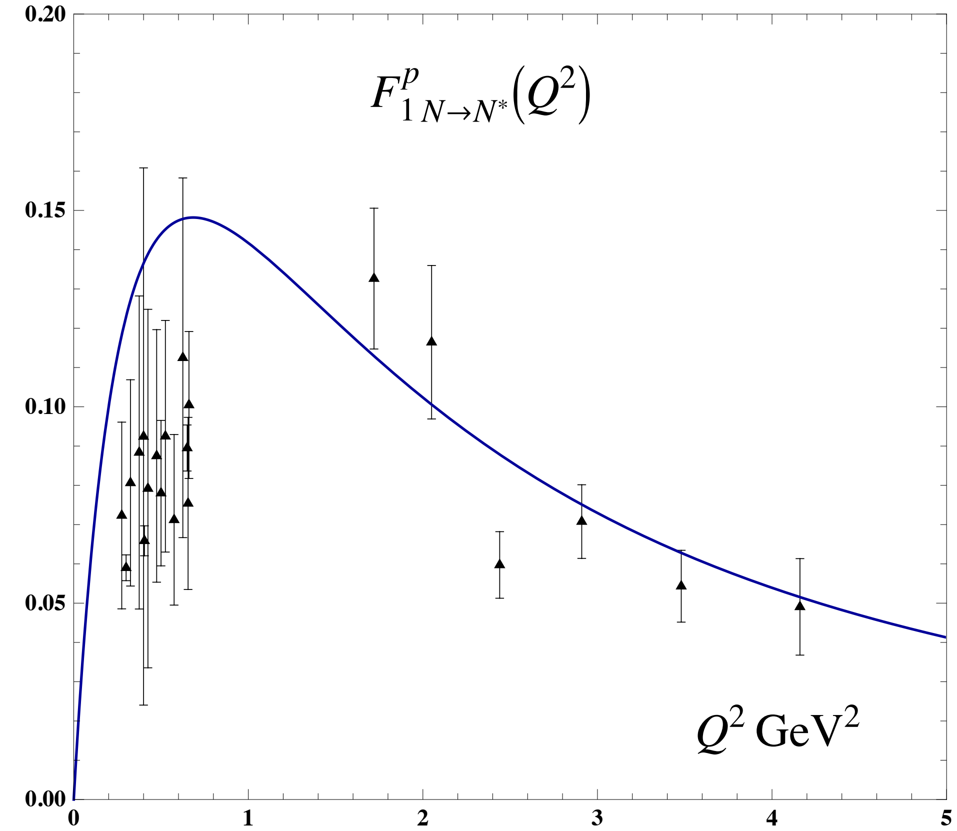


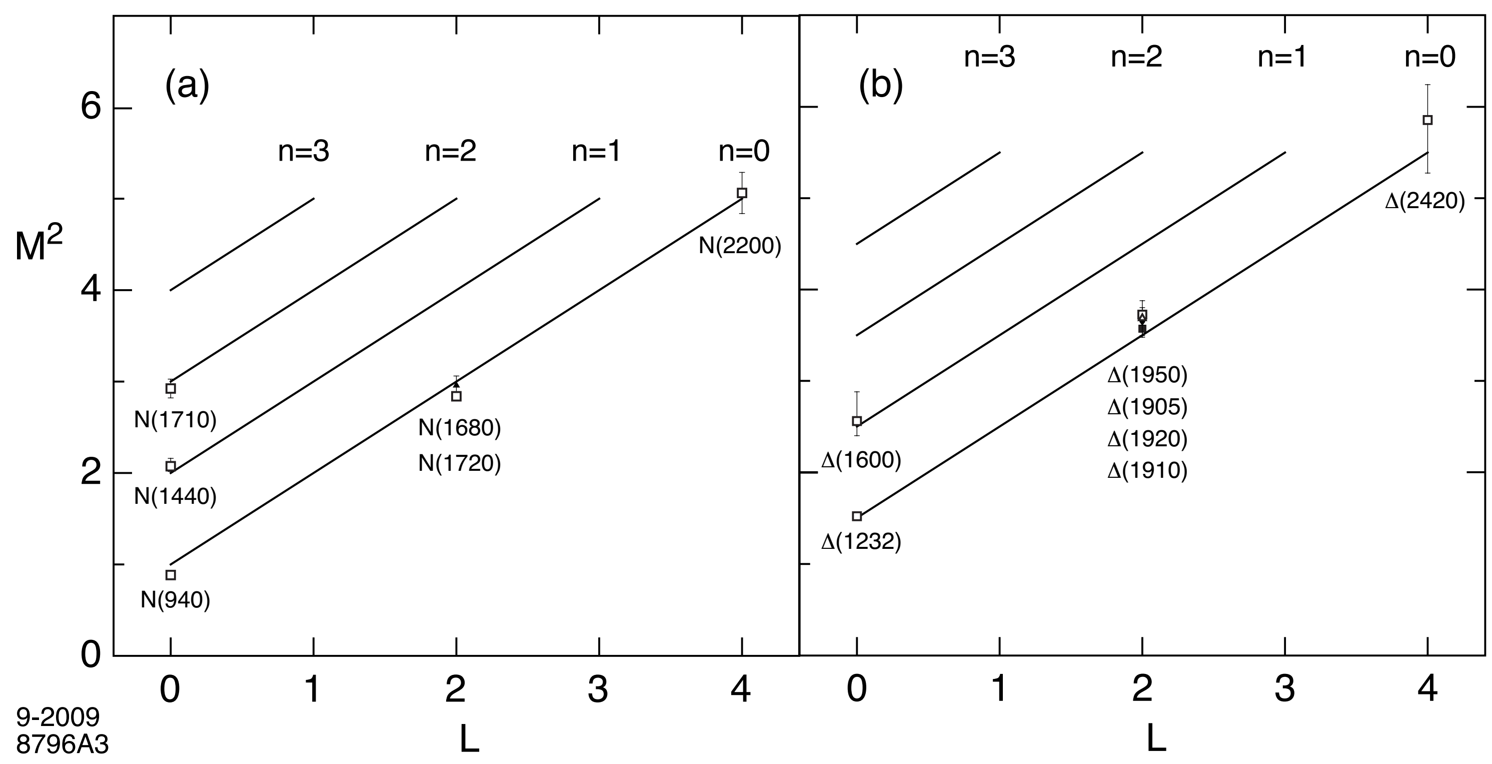
Predict hadron spectroscopy and dynamics

Excited Baryons in Holographic QCD

G. de Teramond & sjb







Nucleon Transition Form Factors

- Compute spin non-flip EM transition $N(940) \to N^*(1440)$: $\Psi_+^{n=0,L=0} \to \Psi_+^{n=1,L=0}$
- Transition form factor

$$F_{1\,N\to N^*}^{\,p}(Q^2) = R^4 \int \frac{dz}{z^4}\, \Psi_+^{n=1,L=0}(z) V(Q,z) \Psi_+^{n=0,L=0}(z)$$

- Orthonormality of Laguerre functions $\left(F_{1\,N\to N^*}^{\,p}(0) = 0, \quad V(Q=0,z) = 1\right)$

$$R^4 \int \frac{dz}{z^4}\, \Psi_+^{n',L}(z) \Psi_+^{n,L}(z) = \delta_{n,n'}$$

- Find

$$F_{1\,N\to N^*}^{\,p}(Q^2) = \frac{2\sqrt{2}}{3} \frac{\frac{Q^2}{M_P^2}}{\left(1 + \frac{Q^2}{\mathcal{M}_\rho^2}\right)\left(1 + \frac{Q^2}{\mathcal{M}_{\rho'}^2}\right)\left(1 + \frac{Q^2}{\mathcal{M}_{\rho''}^2}\right)}$$

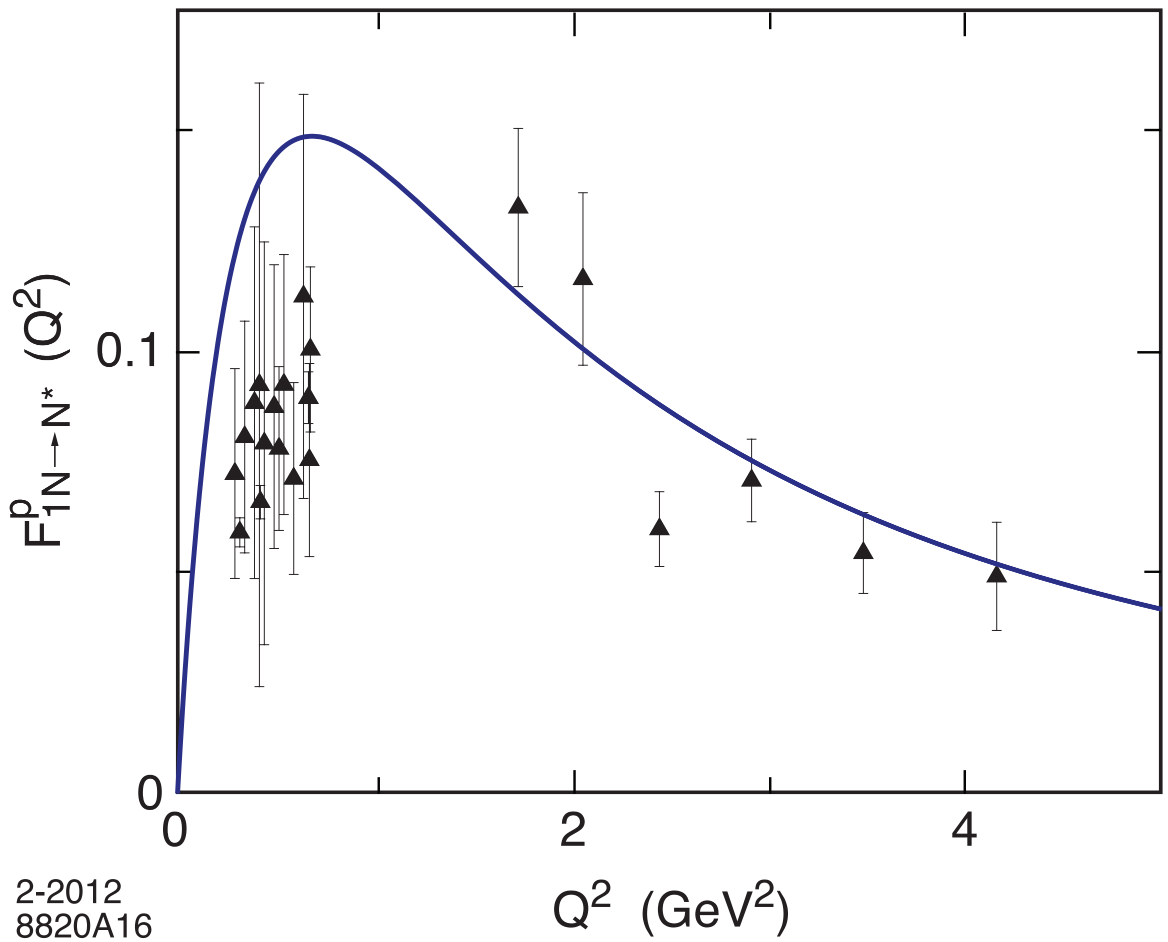
with ${\mathcal{M}_{\rho_n}}^2 \to 4\kappa^2(n + 1/2)$

de Teramond, sjb

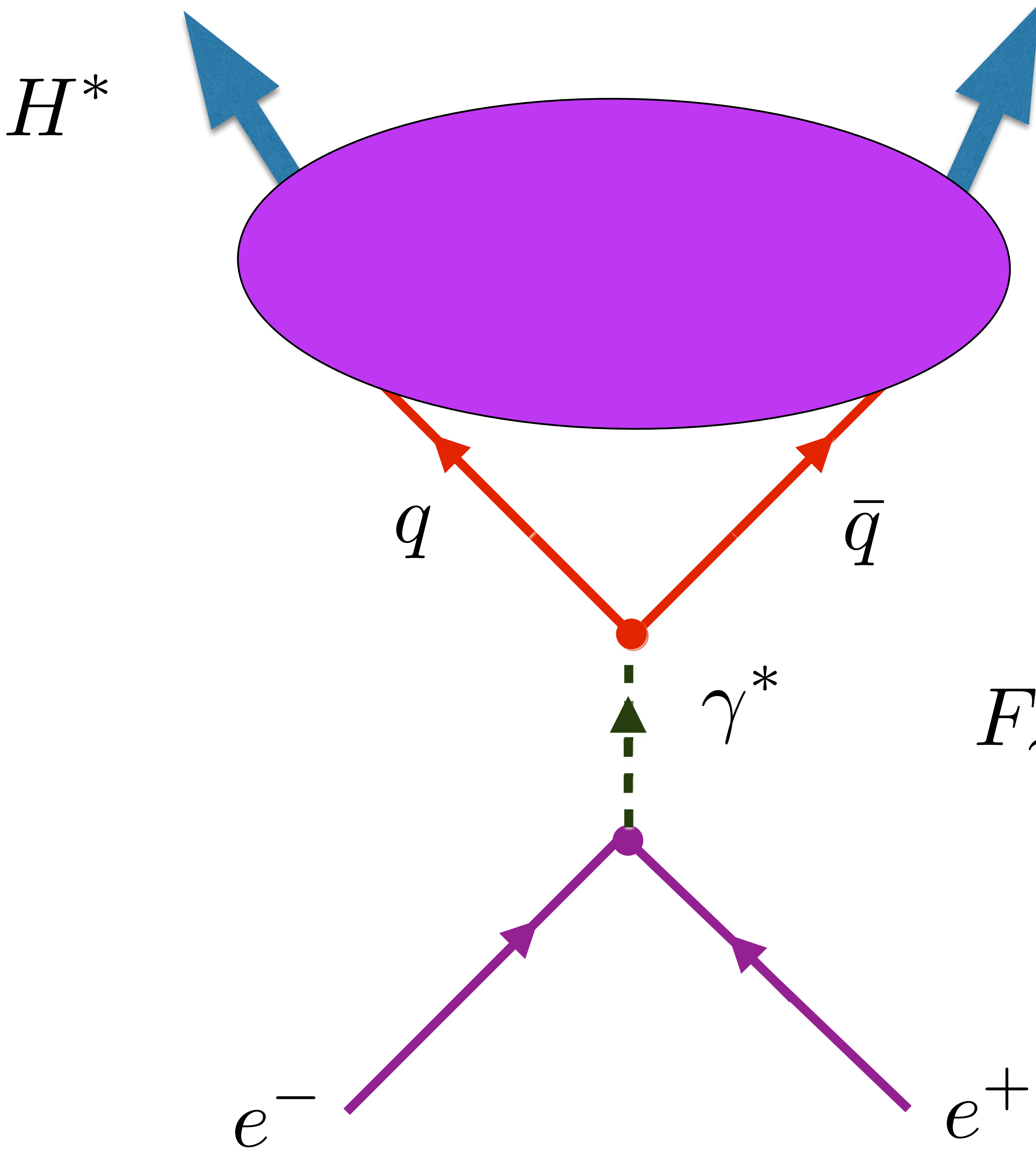
Consistent with counting rule, twist 3

Nucleon Transition Form Factors

$$F^p_{1\,N\to N^*}(Q^2) = \frac{\sqrt{2}}{3}\frac{\frac{Q^2}{\mathcal{M}^2_\rho}}{\left(1+\frac{Q^2}{\mathcal{M}^2_\rho}\right)\left(1+\frac{Q^2}{\mathcal{M}^2_{\rho'}}\right)\left(1+\frac{Q^2}{\mathcal{M}^2_{\rho''}}\right)}.$$



Proton transition form factor to the first radial excited state. Data from JLab



Dosch, de Teramond, sjb

$$F_{\gamma^* \to H^* \bar{H}}(s)$$

Prediction from Super Conformal AdS/QCD:
Same Form Factors for H= M and H=B if $L_M = L_B + 1$

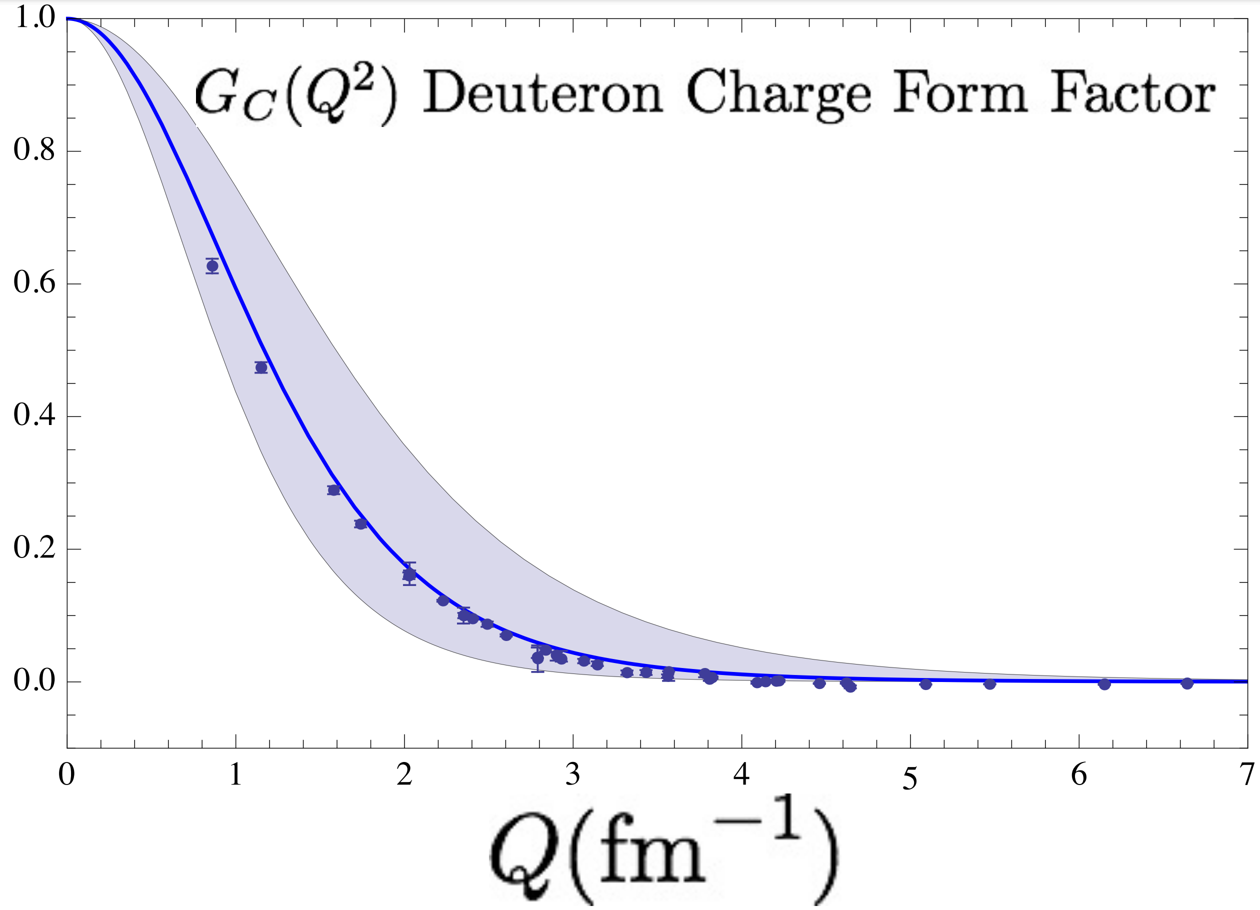
Nuclear physics in soft-wall AdS/QCD: Deuteron electromagnetic form factors

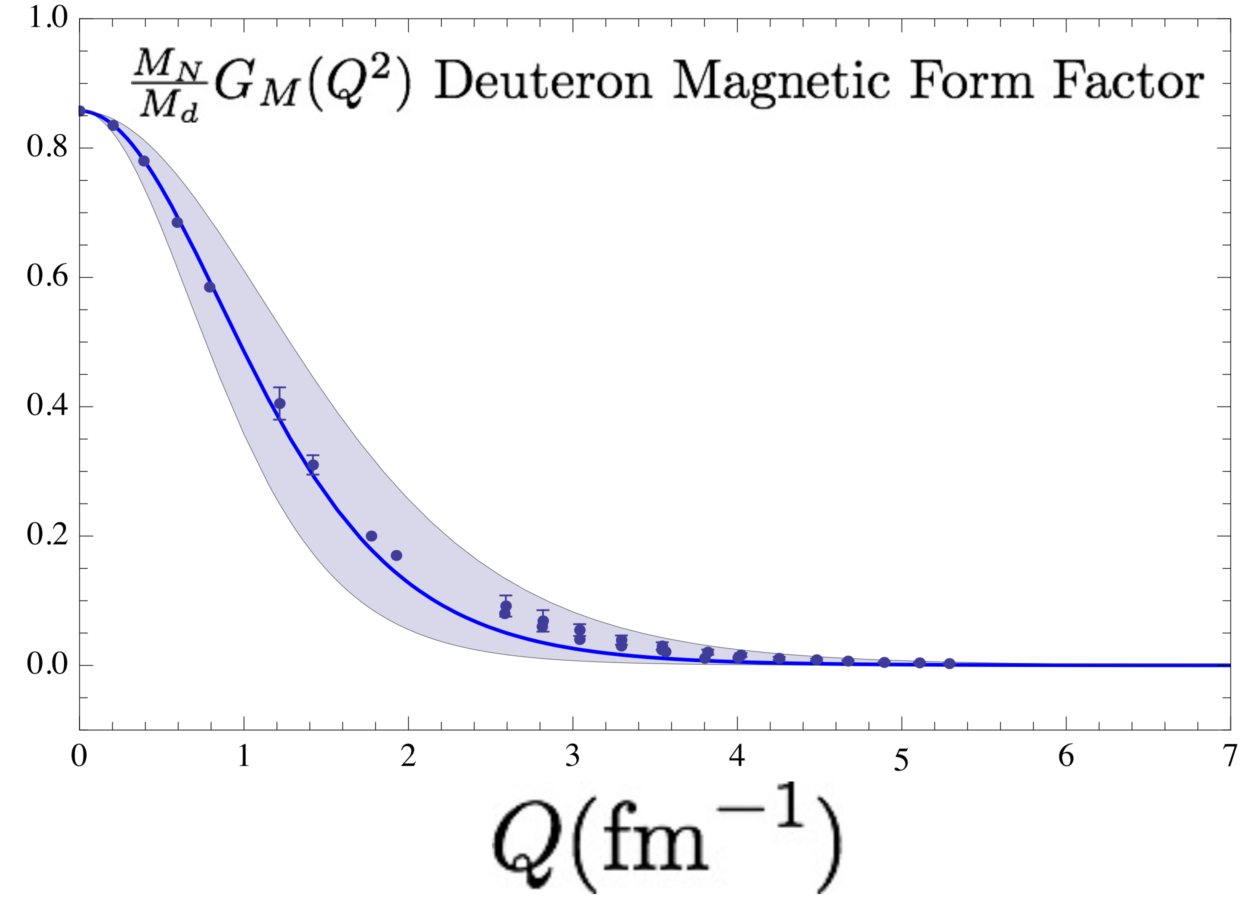
Thomas Gutsche, Valery E. Lyubovitskij, Ivan Schmidt, Alfredo Vega

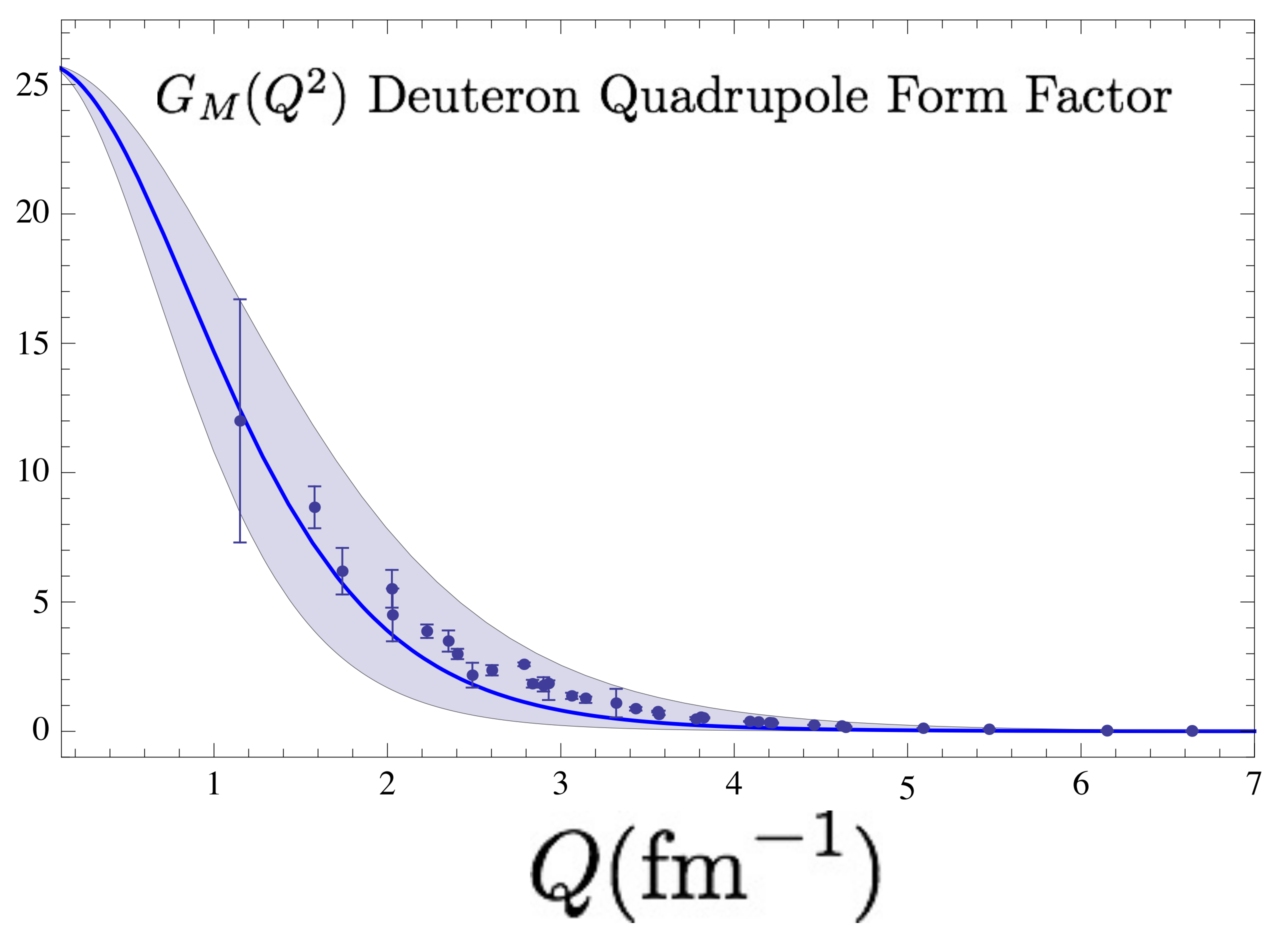
We present a high-quality description of the deuteron electromagnetic form factors in a soft-wall AdS/QCD approach. We first propose an effective action describing the dynamics of the deuteron in the presence of an external vector field. Based on this action the deuteron electromagnetic form factors are calculated, displaying the correct $1/Q^{10}$ power scaling for large Q^2 values. This finding is consistent with quark counting rules and the earlier observation that this result holds in confining gauge/gravity duals. The Q^2 dependence of the deuteron form factors is defined by a single and universal scale parameter κ, which is fixed from data.

arXiv:1501.02738 [hep-ph]

Application of Light-Front Holography to the Deuteron Form Factors







Thomas Gutsche, Valery E. Lyubovitskij, Ivan Schmidt, and Alfredo Vega

http://arxiv.org/abs/1501.02738v3

Consistent with quark counting rules
Ji, Lepage, sjb

Bjorken sum rule defines effective charge $\alpha_{g1}(Q^2)$

$$\int_0^1 dx[g_1^{ep}(x,Q^2) - g_1^{en}(x,Q^2)] \equiv \frac{g_a}{6}[1 - \frac{\alpha_{g1}(Q^2)}{\pi}]$$

- ***Can be used as standard QCD coupling***
- ***Well measured***
- ***Asymptotic freedom at large Q^2***
- ***Computable at large Q^2 in any pQCD scheme***
- ***Universal β_0, β_1***

Running Coupling from Modified AdS/QCD

Deur, de Teramond, sjb

- Consider five-dim gauge fields propagating in AdS_5 space in dilaton background $\varphi(z) = \kappa^2 z^2$

$$S = -\frac{1}{4}\int d^4x\, dz\, \sqrt{g}\, e^{\varphi(z)}\, \frac{1}{g_5^2}\, G^2$$

- Flow equation

$$\frac{1}{g_5^2(z)} = e^{\varphi(z)} \frac{1}{g_5^2(0)} \quad \text{or} \quad g_5^2(z) = e^{-\kappa^2 z^2} g_5^2(0)$$

where the coupling $g_5(z)$ incorporates the non-conformal dynamics of confinement

- YM coupling $\alpha_s(\zeta) = g_{YM}^2(\zeta)/4\pi$ is the five dim coupling up to a factor: $g_5(z) \to g_{YM}(\zeta)$
- Coupling measured at momentum scale Q

$$\alpha_s^{AdS}(Q) \sim \int_0^\infty \zeta d\zeta\, J_0(\zeta Q)\, \alpha_s^{AdS}(\zeta)$$

- Solution

$$\alpha_s^{AdS}(Q^2) = \alpha_s^{AdS}(0)\, e^{-Q^2/4\kappa^2}.$$

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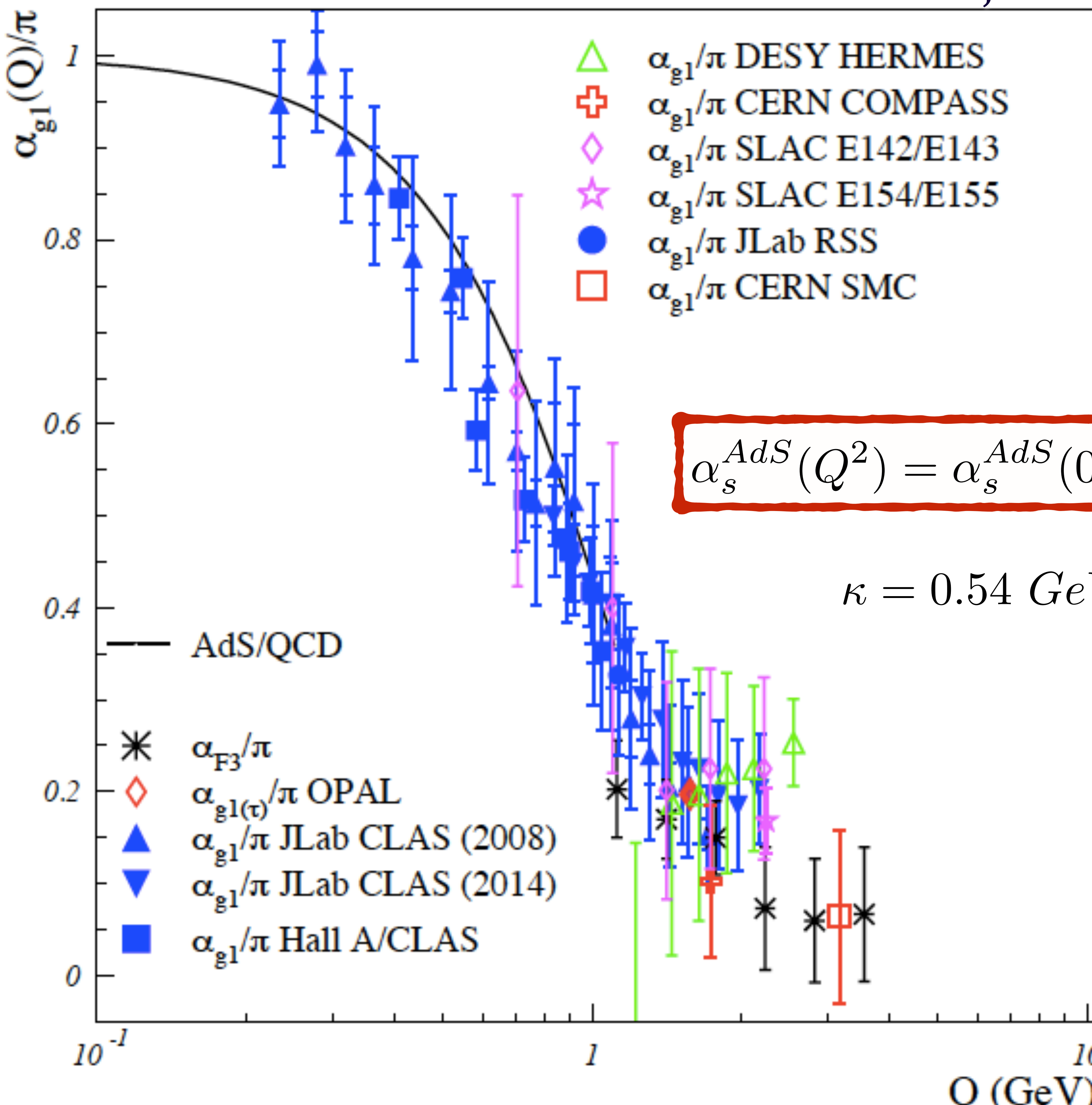
Deur, de Teramond, sjb



$$\alpha_s^{AdS}(Q^2) = \alpha_s^{AdS}(0) e^{-Q^2/4\kappa^2}$$

$$\kappa = 0.54\ GeV$$

$$e^{\varphi} = e^{+\kappa^2 z^2}$$

AdS/QCD dilaton captures the higher twist corrections to effective charges for Q < 1 GeV

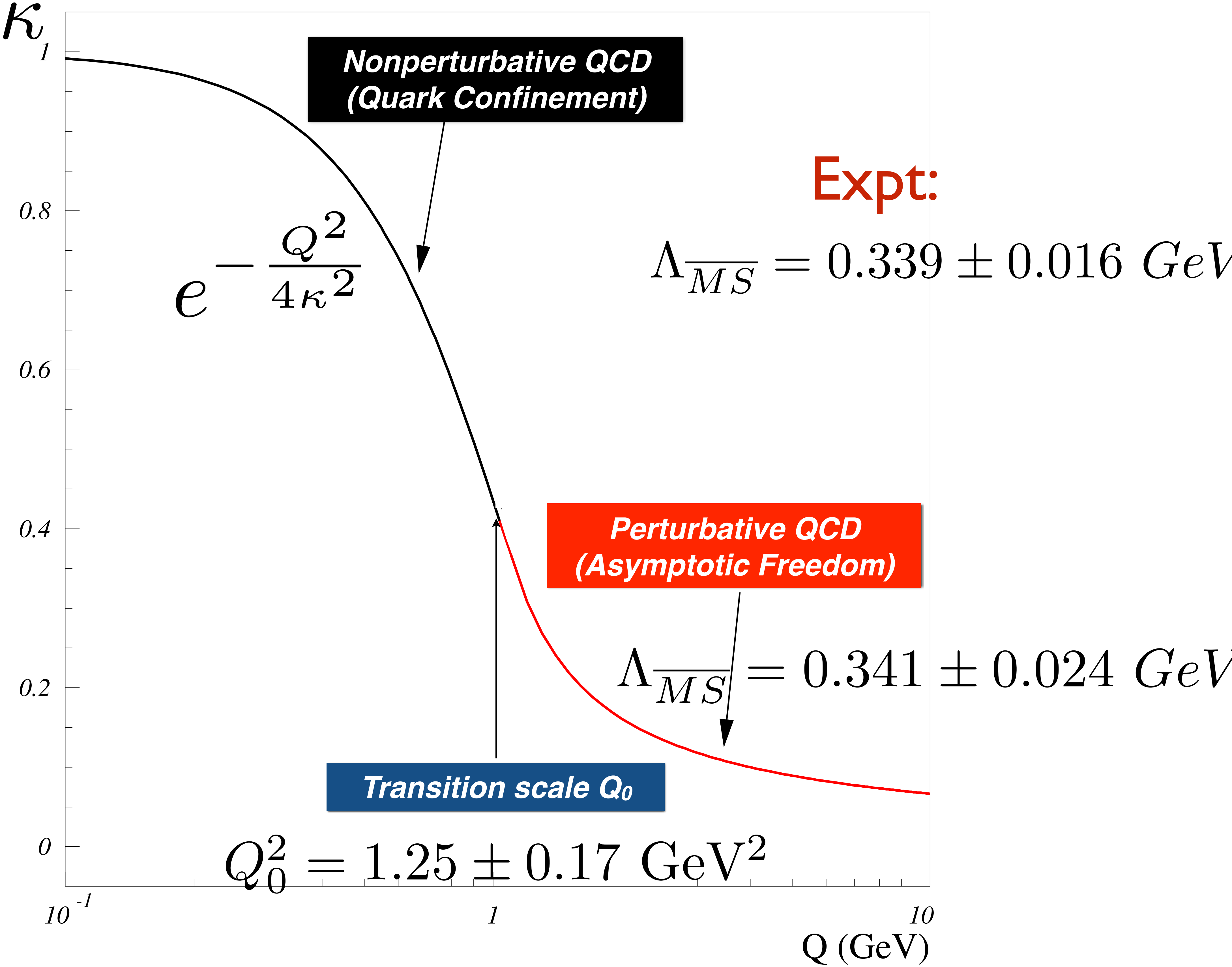
$$m_\rho = \sqrt{2}\kappa$$

$$m_p = 2\kappa$$

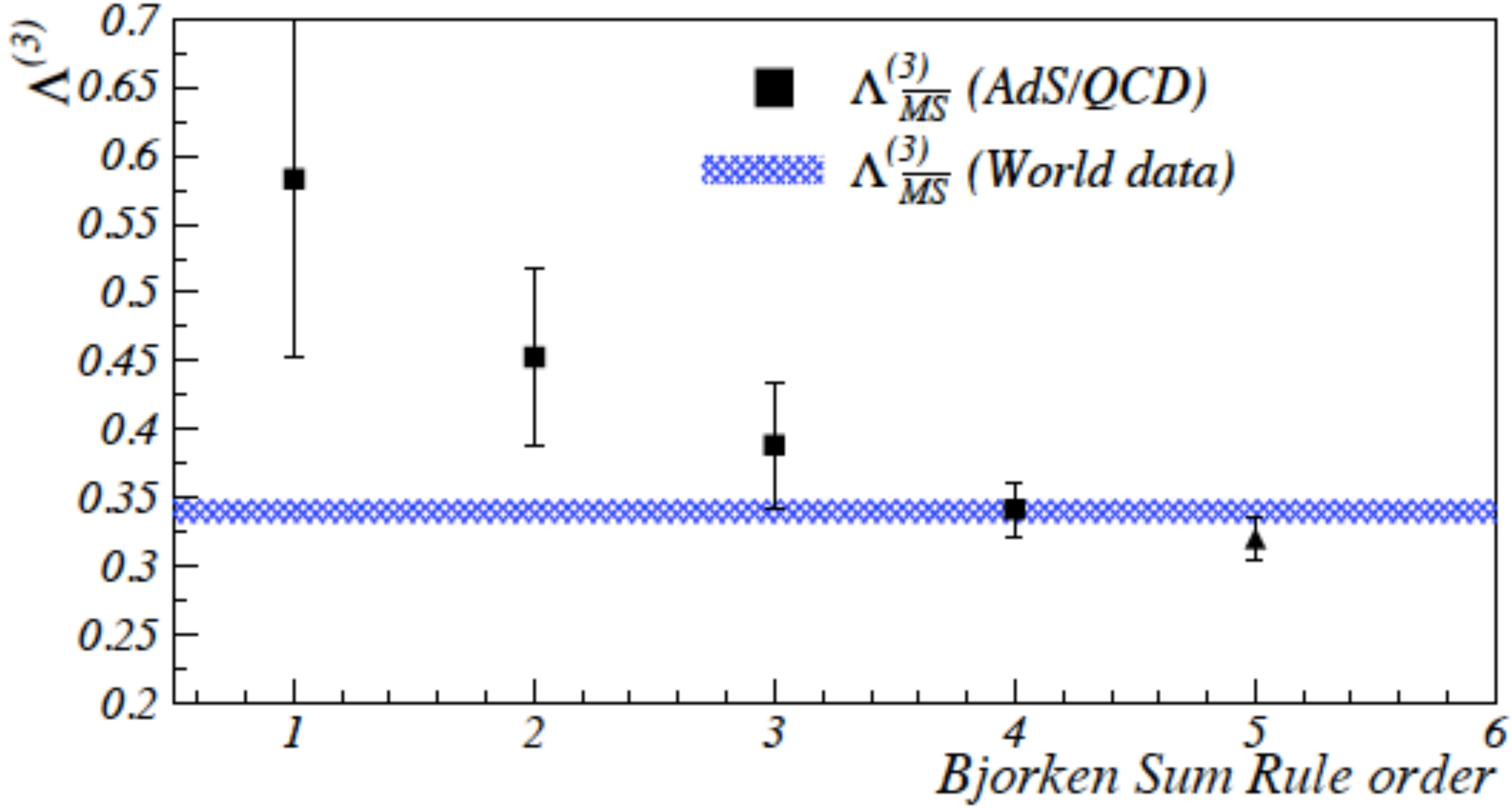
All-Scale QCD Coupling

Deur, de Teramond, sjb

$$\frac{\alpha^s_{g_1}(Q^2)}{\pi}$$



$$\lambda \equiv \kappa^2$$

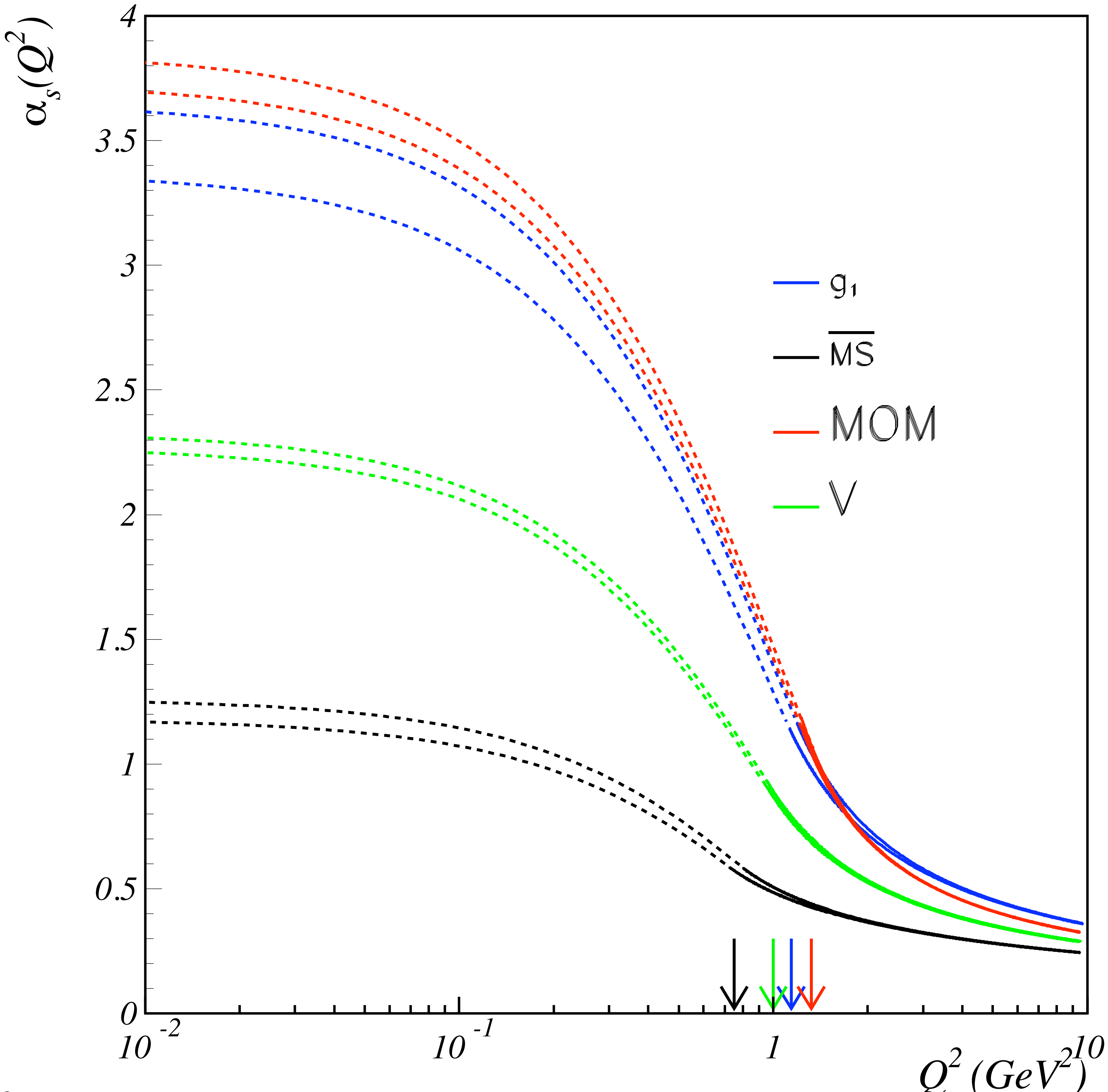


$$\Lambda_{\overline{MS}} = 0.341\ GeV = 0.440 m_\rho = 0.622 \kappa$$

Connect $\Lambda_{\overline{MS}}$ to hadron masses!

Experiment: $M_\rho = 0.7753 \pm 0.0003\ GeV$

Unification Predictions in Various Schemes



Preliminary

Deur,
de Teramond, sjb

Unification Scale Q_0

- *Matches perturbative to nonperturbative QCD*
- *Use for ERBL, DGLAP*
- *Hadronization at amplitude level*
- *BLFQ transition scale*
- *Use Principle of Maximum Conformality (PMC) to make scheme-indepedent predictions without renormalization scale ambiguity*

Set multiple renormalization scales -- Lensing, DGLAP, ERBL Evolution ...

$Choose\ renormalization\ scheme;\ e.g.\ \alpha_s^R(\mu_R^{\rm init})$

↓

$Choose\ \mu_R^{init};\ arbitrary\ initial\ renormalization\ scale$

↓

$Identify\ \{\beta_i^R\} - terms\ using\ n_f - terms$

$through\ the\ PMC - BLM\ correspondence\ principle$

↓

$Shift\ scale\ of\ \alpha_s\ to\ \mu_R^{\rm PMC}\ to\ eliminate\ \{\beta_i^R\} - terms$

↓

$Conformal\ Series$

$Result\ is\ independent\ of\ \mu_R^{\rm init}\ and\ scheme\ at\ fixed\ order$

PMC/BLM

No renormalization scale ambiguity!

Result is independent of Renormalization scheme and initial scale!

QED Scale Setting at N_C=0

Eliminates unnecessary systematic uncertainty

Scale fixed at each order

δ-Scheme automatically identifies β-terms!

Principle of Maximum Conformality

Xing-Gang Wu, Matin Mojaza
Leonardo di Giustino, SJB

Interpretation of Mass Scale κ

- Does not affect conformal symmetry of QCD action
- Self-consistent regularization of IR divergences
- Determines all mass and length scales for zero quark mass
- Compute scheme-dependent $\Lambda_{\overline{MS}}$ determined in terms of κ
- Value of κ itself not determined -- place holder
- Need external constraint such as f_π

Tony Zee

"Quantum Field Theory in a Nutshell"

Dreams of Exact Solvability

"In other words, if you manage to calculate m_P it better come out proportional to Λ_{QCD} since Λ_{QCD} is the only quantity with dimension of mass around.

Similarly for m_ρ.

Put in precise terms, if you publish a paper with a formula giving m_ρ/m_P in terms of pure numbers such as 2 and π, the field theory community will hail you as a conquering hero who has solved QCD exactly."

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$$m_\pi = 0$$

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$$\frac{\Lambda_{\overline{MS}}}{m_\rho} = 0.455 \pm 0.031$$

Remarkable Features of Light-Front Schrödinger Equation

- *Relativistic, frame-independent*
- *QCD scale appears - unique LF potential*
- *Reproduces spectroscopy and dynamics of light-quark hadrons with one parameter*
- *Zero-mass pion for zero mass quarks!*
- *Regge slope same for n and L -- not usual HO*
- *Splitting in L persists to high mass -- contradicts conventional wisdom based on breakdown of chiral symmetry*
- *Phenomenology: LFWFs, Form factors, electroproduction*
- *Extension to heavy quarks*

$$U(\zeta) = \kappa^4 \zeta^2 + 2\kappa^2(L + S - 1)$$

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Dynamics + Spectroscopy!

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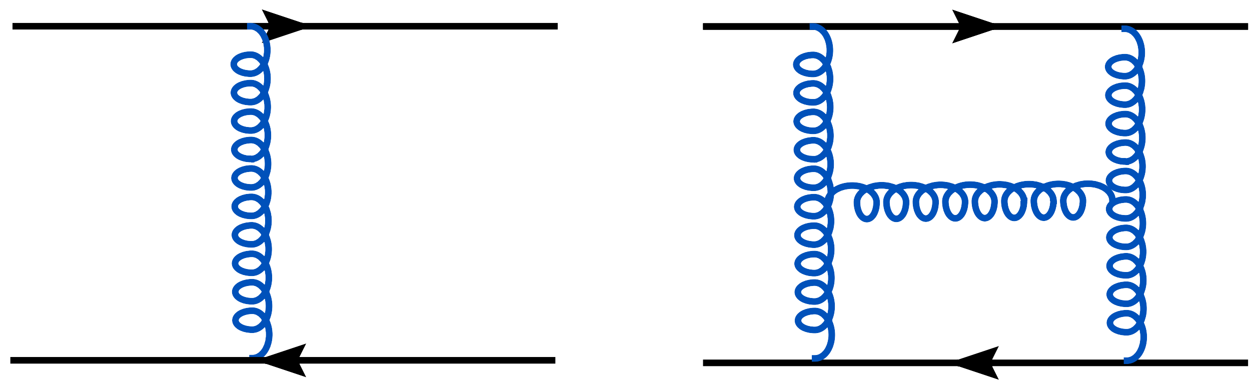
Heavy Quark Potential is IR Divergent in QCD

$$V(Q^2) = -\frac{(4\pi)^2 C_F}{Q^2} a(Q^2) \Big[1 + (c_{2,0} + c_{2,1} N_f) a(Q^2) + (c_{3,0} + c_{3,1} N_f + c_{3,2} N_f^2) a(Q^2)^2$$
$$+ (c_{4,0} + c_{4,1} N_f + c_{4,2} N_f^2 + c_{4,3} N_f^3) a(Q^2)^3 + 8\pi^2 C_A^3 \ln \frac{\mu_{IR}^2}{Q^2} a(Q^2)^3 \Big]$$

Smirnov, Smirnov, Steinhauser, 2010



Confinement eliminates IR divergences

Self-consistent mass scale κ

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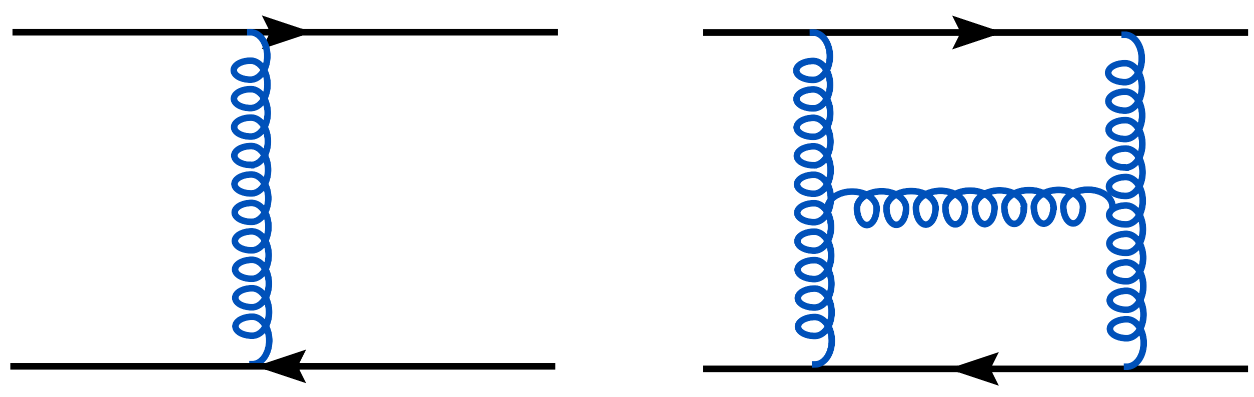

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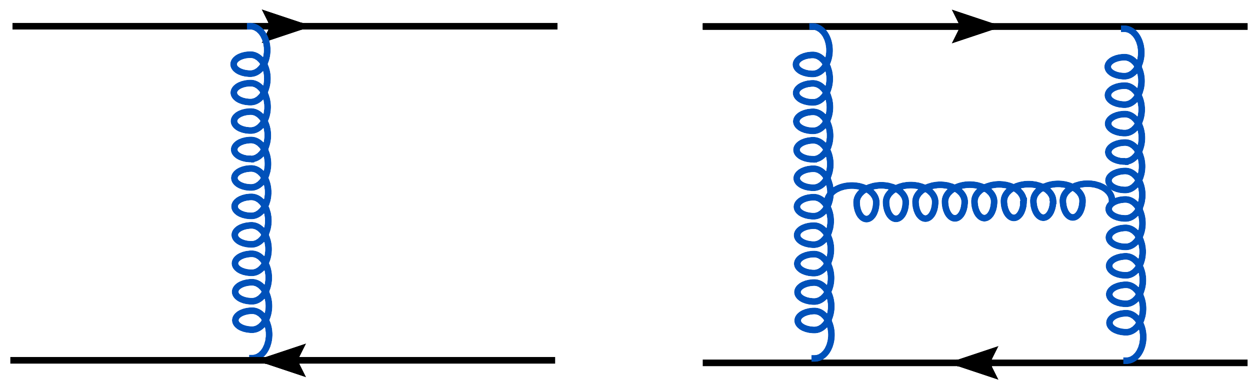

$\log \kappa^2 \zeta^2$

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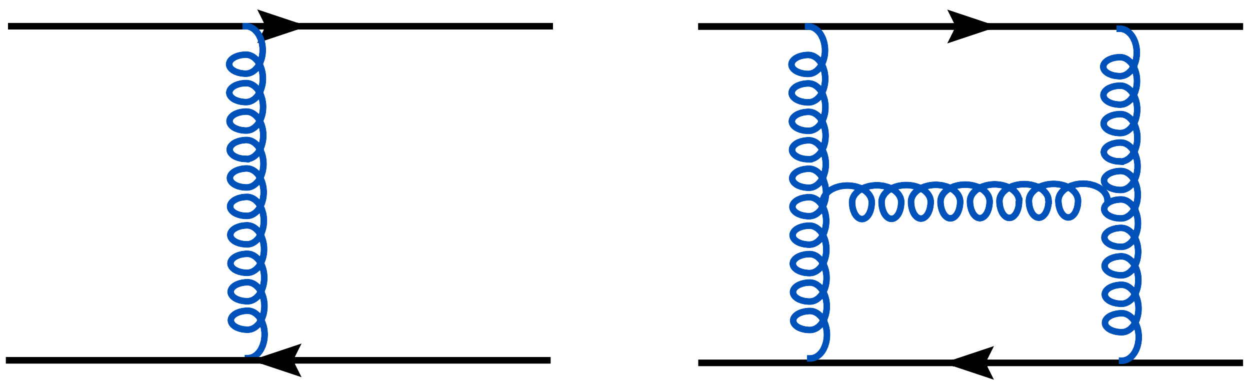

$\log \kappa^2 \zeta^2$

Summation of H graphs: confining potential

Confinement eliminates IR divergences

Self-consistent mass scale κ

Connection to the Linear Instant-Form Potential

Linear instant nonrelativistic form $V(r) = Cr$ for heavy quarks

↕

Harmonic Oscillator $U(\zeta) = \kappa^4 \zeta^2$ LF Potential for relativistic light quarks

A.P. Trawinski, S.D. Glazek, H. D. Dosch, G. de Teramond, sjb

Connection to the Linear Instant-Form Potential

- Compare invariant mass in the instant-form in the hadron center-of-mass system $\mathbf{P} = 0$,

$$M^2_{q\bar{q}} = 4\,m_q^2 + 4\mathbf{p}^2$$

with the invariant mass in the front-form in the constituent rest frame, $\mathbf{k}_q + \mathbf{k}_{\bar{q}} = 0$

$$M^2_{q\bar{q}} = \frac{\mathbf{k}^2_\perp + m_q^2}{x(1-x)}$$

obtain

$$U = V^2 + 2\sqrt{\mathbf{p}^2 + m_q^2}\,V + 2\,V\sqrt{\mathbf{p}^2 + m_q^2}$$

where $\mathbf{p}^2_\perp = \frac{\mathbf{k}^2_\perp}{4x(1-x)}$, $p_3 = \frac{m_q(x-1/2)}{\sqrt{x(1-x)}}$, and V is the effective potential in the instant-form

- For small quark masses a linear instant-form potential V implies a harmonic front-form potential U and thus linear Regge trajectories

A.P. Trawinski, S.D. Glazek, H. D. Dosch, G. de Teramond, sjb

An analytic first approximation to QCD

AdS/QCD + Light-Front Holography

- **As Simple as Schrödinger Theory in Atomic Physics**
- **LF radial variable ζ conjugate to invariant mass squared**
- **Relativistic, Frame-Independent, Color-Confining**
- **Unique confining potential!**
- **QCD Coupling at all scales: Essential for Gauge Link phenomena**
- **Hadron Spectroscopy and Dynamics from one parameter**
- **Wave Functions, Form Factors, Hadronic Observables, Constituent Counting Rules**
- **Insight into QCD Condensates: Zero cosmological constant!**
- **Systematically improvable with DLCQ-BLFQ Methods**

AdS/QCD and Light-Front Holography

$$\mathcal{M}^2_{n,J,L} = 4\kappa^2\left(n + \frac{J+L}{2}\right)$$

- **Zero mass pion for m_q =0 (n=J=L=0)**
- **Regge trajectories: equal slope in n and L**
- **Form Factors at high Q^2: Dimensional counting** $[Q^2]^{n-1}F(Q^2) \to \text{const}$
- **Space-like and Time-like Meson and Baryon Form Factors**
- **Running Coupling for NPQCD** $\alpha_s(Q^2) \propto e^{-\frac{Q^2}{4\kappa^2}}$
- **Meson Distribution Amplitude** $\phi_\pi(x) \propto f_\pi\sqrt{x(1-x)}$

Features of AdS/QCD

de Tèramond, Dosch, Deur, sjb

- **Color confining potential $\kappa^4 \zeta^2$ and universal mass scale from dilaton**

$$e^{\phi(z)} = e^{\kappa^2 z^2} \qquad \alpha_s(Q^2) \propto \exp -Q^2/4\kappa^2$$

- **Dimensional transmutation** $\Lambda_{\overline{MS}} \leftrightarrow \kappa \leftrightarrow m_H$

- **Chiral Action remains conformally invariant despite mass scale** *DAFF*

- **Light-Front Holography: Duality of AdS and frame-independent LF QCD**

- **Reproduces observed Regge spectroscopy — same slope in n, L, and J for mesons and baryons**

- **Massless pion for massless quark**

- **Supersymmetric meson-baryon dynamics and spectroscopy: $L_M = L_B + 1$**

Superconformal Algebra
Fubini and Rabinovici

- **Dynamics: LFWFs, Form Factors, GPDs**

Light and heavy mesons in a soft-wall holographic model

Valery E. Lyubovitskij[*1†], **Tanja Branz**[1], **Thomas Gutsche**[1], **Ivan Schmidt**[2], **Alfredo Vega**[2]

[1] *Institut für Theoretische Physik, Universität Tübingen,*
Kepler Center for Astro and Particle Physics,
Auf der Morgenstelle 14, D–72076 Tübingen, Germany

[2]*Departamento de Física y Centro Científico Tecnológico de Valparaíso (CCTVal),*
Universidad Técnica Federico Santa María, Casilla 110-V, Valparaíso, Chile

We study the spectrum and decay constants of light and heavy mesons in a soft-wall holographic approach, using the correspondence of string theory in Anti-de Sitter space and conformal field theory in physical space-time.

de Tèramond, Dosch, Lorce, sjb

Future Directions for AdS/QCD

- **Hadronization at the Amplitude Level**
- **Diffractive dissociation of pion and proton to jets**
- **Identify the factorization Scale for ERBL, DGLAP evolution: Q_0**
- **Compute Tetraquark Spectroscopy Sequentially**
- **Update SU(6) spin-flavor symmetry**
- **Heavy Quark States: Supersymmetry, not conformal**
- **Compute higher Fock states; e.g. Intrinsic Heavy Quarks**
- **Nuclear States — Hidden Color**
- **Basis LF Quantization**

We view the universe as light reaches us along the light-front at fixed

$$\tau = t + z/c$$

Front Form Vacuum Describes the Empty, Causal Universe

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“One of the gravest puzzles of theoretical physics”

DARK ENERGY AND THE COSMOLOGICAL CONSTANT PARADOX

A. ZEE

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Kavil Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA
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$$(\Omega_\Lambda)_{QCD} \sim 10^{45}$$

$$(\Omega_\Lambda)_{EW} \sim 10^{56}$$

$$\Omega_\Lambda = 0.76(expt)$$

Extraordinary conflict between the conventional definition of the vacuum in quantum field theory and cosmology

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Elements of the solution:

(A) Light-Front Quantization: causal, frame-independent vacuum

(B) New understanding of QCD “Condensates”

(C) Higgs Light-Front Zero Mode

Two Definitions of Vacuum State

Instant Form: Lowest Energy Eigenstate of Instant-Form Hamiltonian

$$H|\psi_0>= E_0|\psi_0>, E_0 = min\{E_i\}$$

Eigenstate defined at one time t over all space; Acausal! Frame-Dependent

Front Form: Lowest Invariant Mass Eigenstate of Light-Front Hamiltonian

$$H_{LF}|\psi_0>_{LF}= M_0^2|\psi_0>_{LF}, M_0^2 = 0.$$

Frame-independent eigenstate at fixed LF time τ = t+z/c within causal horizon

Frame-independent description of the causal physical universe!

Light-Front vacuum can simulate empty universe

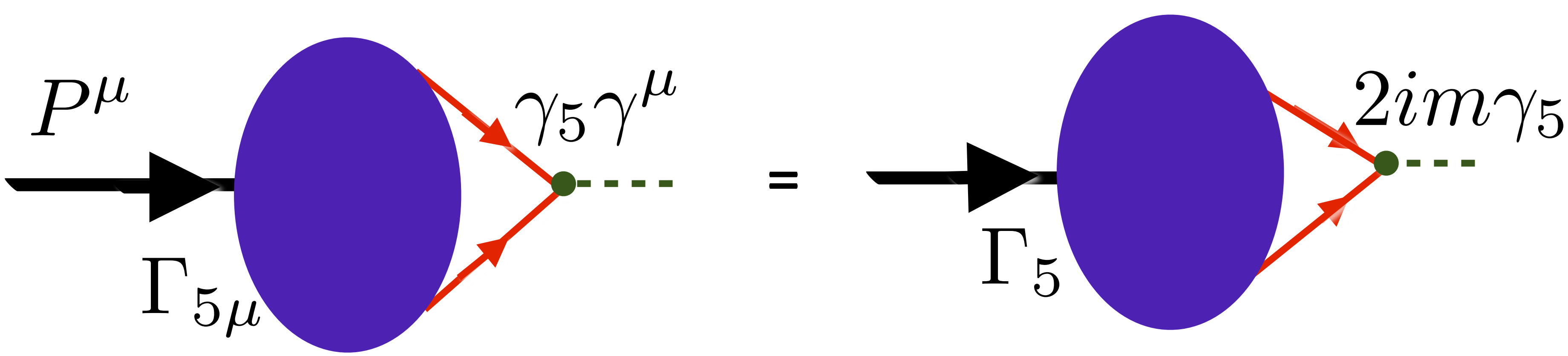
Shrock, Tandy, Roberts, sjb

- **Independent of observer frame**
- **Causal**
- **Lowest invariant mass state M= 0.**
- **Trivial up to k^+=0 zero modes-- already normal-ordering**
- **Higgs theory consistent with trivial LF vacuum (Srivastava, sjb)**
- **QCD and AdS/QCD: "In-hadron"condensates (Maris, Tandy Roberts) -- GMOR satisfied.**
- **QED vacuum; no loops**
- **Zero cosmological constant from QED, QCD**

Ward-Takahashi Identity for axial current

$$P^{\mu}\Gamma_{5\mu}(k,P) + 2im\Gamma_5(k,P) = S^{-1}(k+P/2)i\gamma_5 + i\gamma_5 S^{-1}(k-P/2)$$

$$S^{-1}(\ell) = i\gamma\cdot\ell A(\ell^2) + B(\ell^2) \qquad m(\ell^2) = \frac{B(\ell^2)}{A(\ell^2)}$$



plus non-pole

Identify pion pole at $P^2 = m_{\pi}^2$

$$P^{\mu} < 0|\bar{q}\gamma_5\gamma^{\mu}q|\pi >= 2m < 0|\bar{q}i\gamma_5 q|\pi >$$

$$f_{\pi}m_{\pi}^2 = -(m_u+m_d)\rho_{\pi}$$

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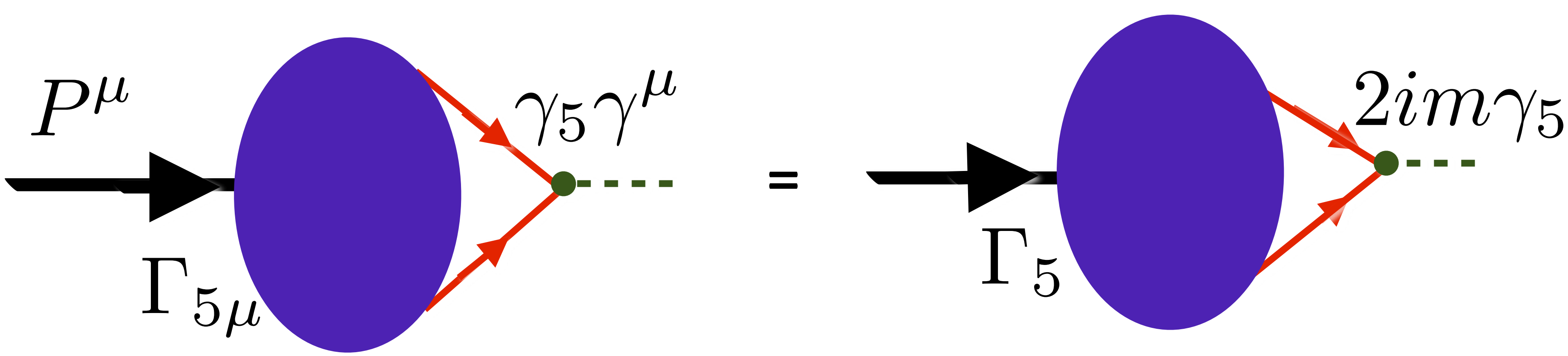

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PHYSICAL REVIEW D **66**, 045019 (2002)

Light-front formulation of the standard model

Prem P. Srivastava*
Instituto de Física, Universidade do Estado de Rio de Janeiro, RJ 20550, Brazil,
Theoretical Physics Department, Fermilab, Batavia, Illinois 60510,
and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

Stanley J. Brodsky†
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309
(Received 20 February 2002; published 20 August 2002)

Light-front (LF) quantization in the light-cone (LC) gauge is used to construct a renormalizable theory of the standard model. The framework derived earlier for QCD is extended to the Glashow-Weinberg-Salam (GWS) model of electroweak interaction theory. The Lorentz condition is automatically satisfied in LF-quantized QCD in the LC gauge for the free massless gauge field. In the GWS model, with the spontaneous symmetry breaking present, we find that the 't Hooft condition accompanies the LC gauge condition corresponding to the massive vector boson. The two transverse polarization vectors for the massive vector boson may be chosen to be the same as found in QCD. The nontransverse and linearly independent third polarization vector is found to be parallel to the gauge direction. The corresponding sum over polarizations in the standard model, indicated by $K_{\mu\nu}(k)$, has several simplifying properties similar to the polarization sum $D_{\mu\nu}(k)$ in QCD. The framework is unitary and ghost free (except for the ghosts at $k^{+}=0$ associated with the light-cone gauge prescription). The massive gauge field propagator has well-behaved asymptotic behavior. The interaction Hamiltonian of electroweak theory can be expressed in a form resembling that of covariant theory, plus additional instantaneous interactions which can be treated systematically. The LF formulation also provides a transparent discussion of the Goldstone boson (or electroweak) equivalence theorem, as the illustrations show.

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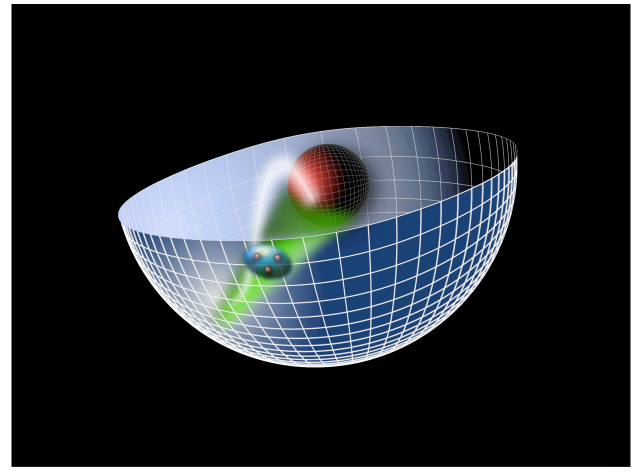
P. Srivastava, sjb

Standard Model on the Light-Front

- **Same phenomenological predictions**
- **Higgs field has three components**
- **Real part creates Higgs particle**
- **Imaginary part (Goldstone) become longitudinal components of W, Z**
- ***Higgs VEV of instant form becomes $k^+=0$ LF zero mode!***
- **Analogous to a background static classical Zeeman or Stark Fields**
- **Zero contribution to $T^\mu{}_\mu$; zero coupling to gravity**

de Tèramond, Dosch, sjb



AdS/QCD
Soft-Wall Model

$$e^{\varphi(z)} = e^{+\kappa^2 z^2}$$

Light-Front Holography

$$\Big[-\frac{d^2}{d\zeta^2} + \frac{1-4L^2}{4\zeta^2} + U(\zeta)\Big]\psi(\zeta) = \mathcal{M}^2\psi(\zeta)$$

Light-Front Schrödinger Equation

Confinement scale:

$$\kappa \simeq 0.6\ GeV$$

$$1/\kappa \simeq 1/3\ fm$$

- **Fubini, Rabinovici:**

de Tèramond, Dosch, sjb

AdS/QCD
Soft-Wall Model

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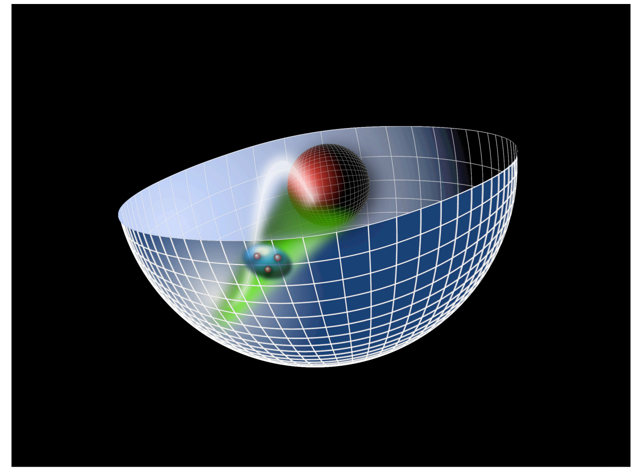


$$\zeta^2 = x(1-x)\mathbf{b}^2_\perp.$$

Light-Front Holography

$$\left[-\frac{d^2}{d\zeta^2} + \frac{1-4L^2}{4\zeta^2} + U(\zeta)\right]\psi(\zeta) = \mathcal{M}^2\psi(\zeta)$$

Light-Front Schrödinger Equation

Confinement scale:

$$\kappa \simeq 0.6\ GeV$$

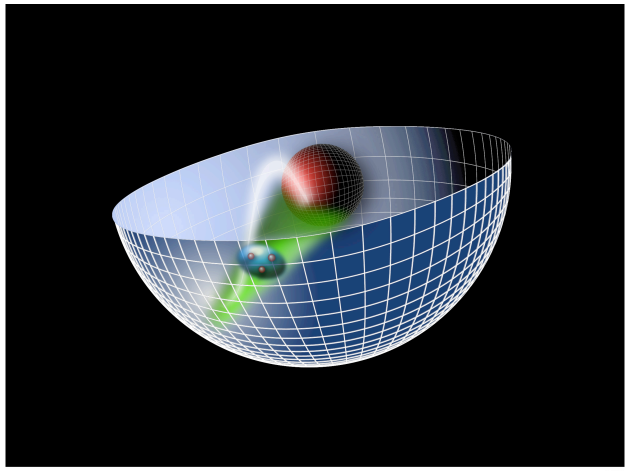
$$1/\kappa \simeq 1/3\ fm$$

- **Fubini, Rabinovici:**

de Tèramond, Dosch, sjb

AdS/QCD
Soft-Wall Model

$$e^{\varphi(z)} = e^{+\kappa^2 z^2}$$



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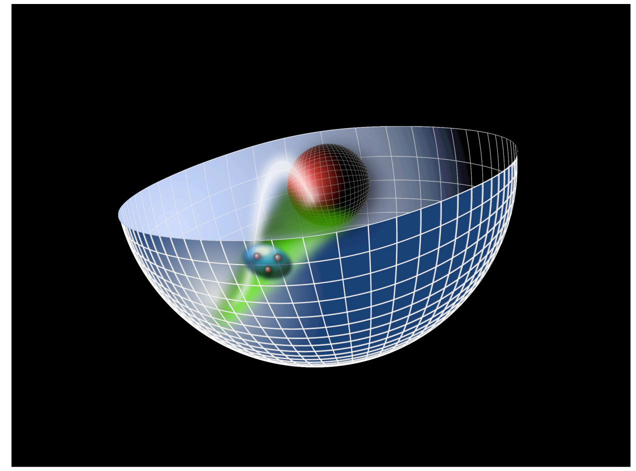

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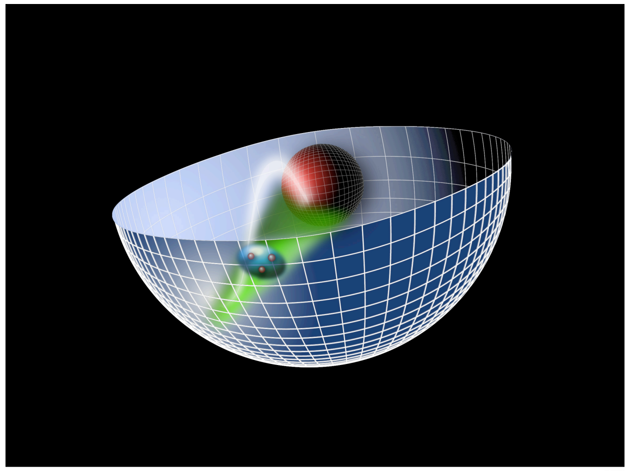

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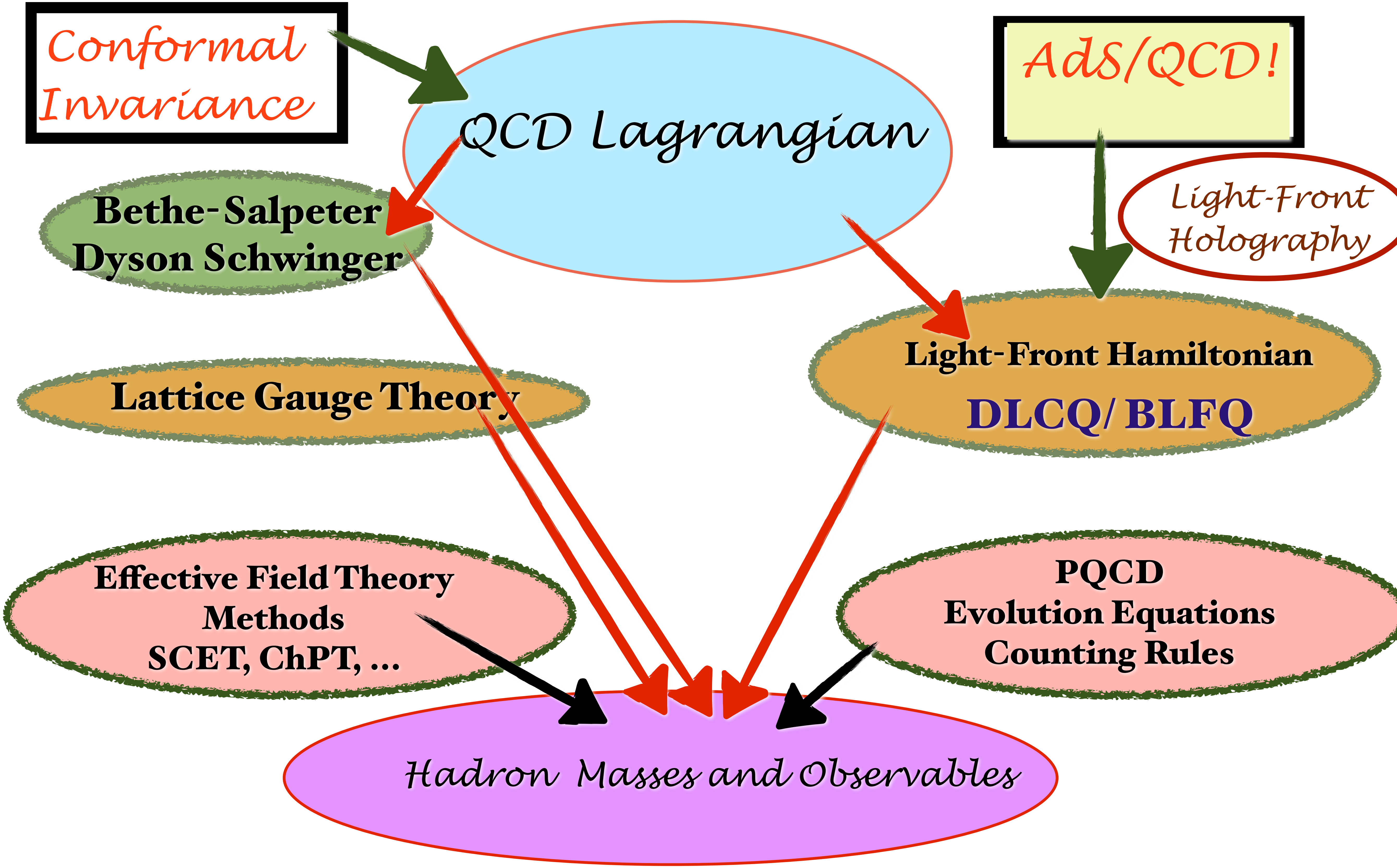
- **de Alfaro, Fubini, Furlan:**
  - **Fubini, Rabinovici:**

Scale can appear in Hamiltonian and EQM without affecting conformal invariance of action!

Predict Hadron Properties from First Principles!



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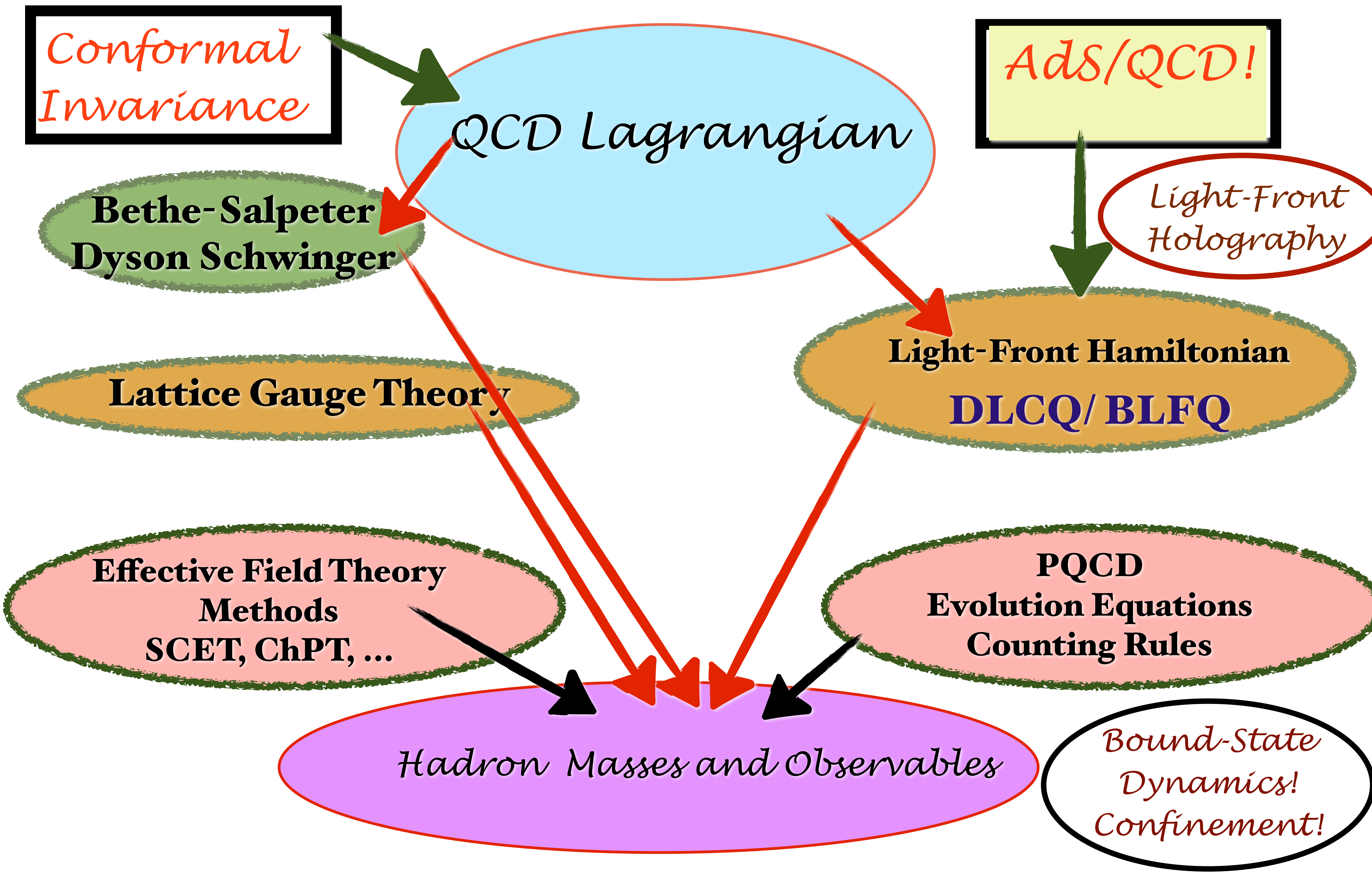
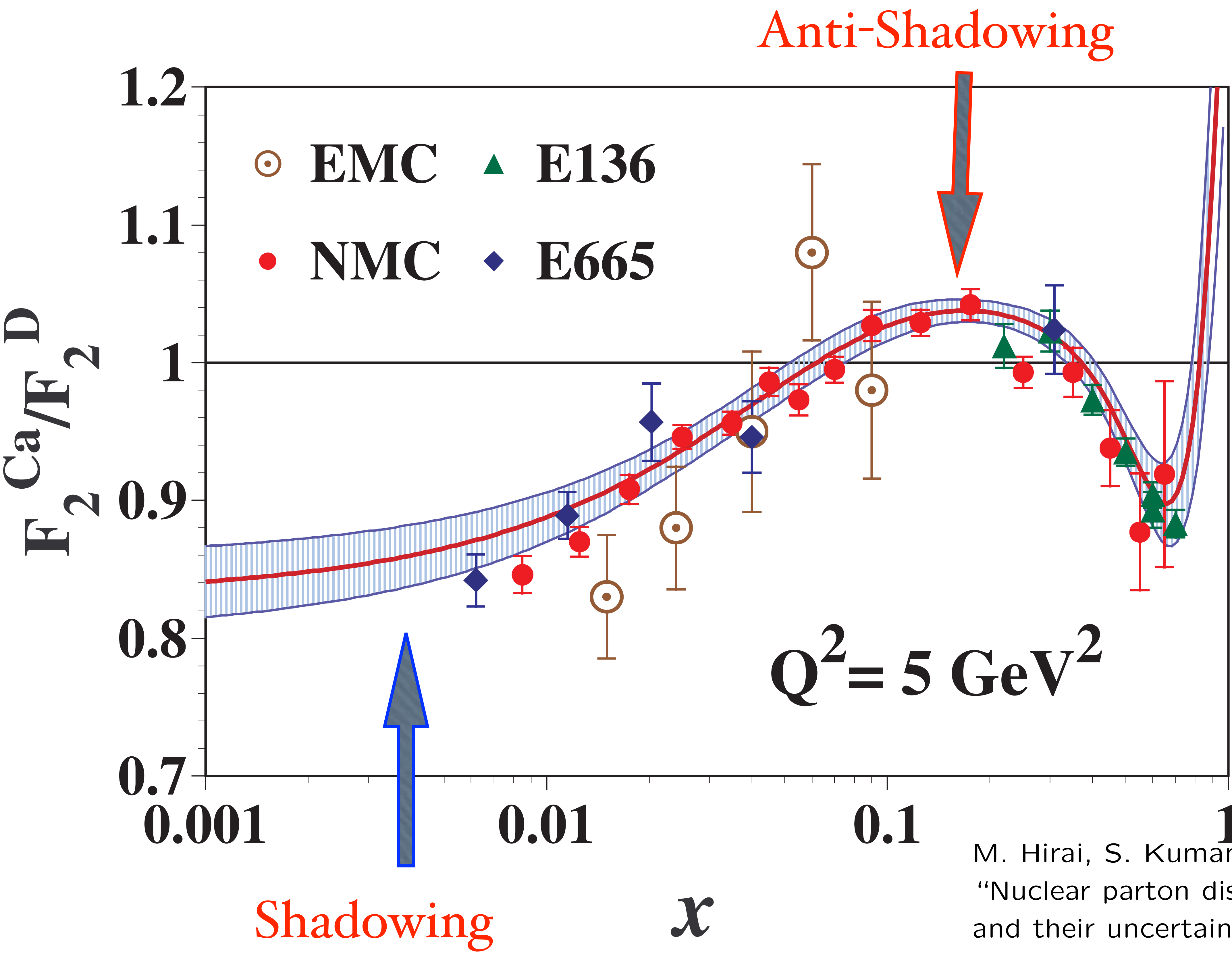
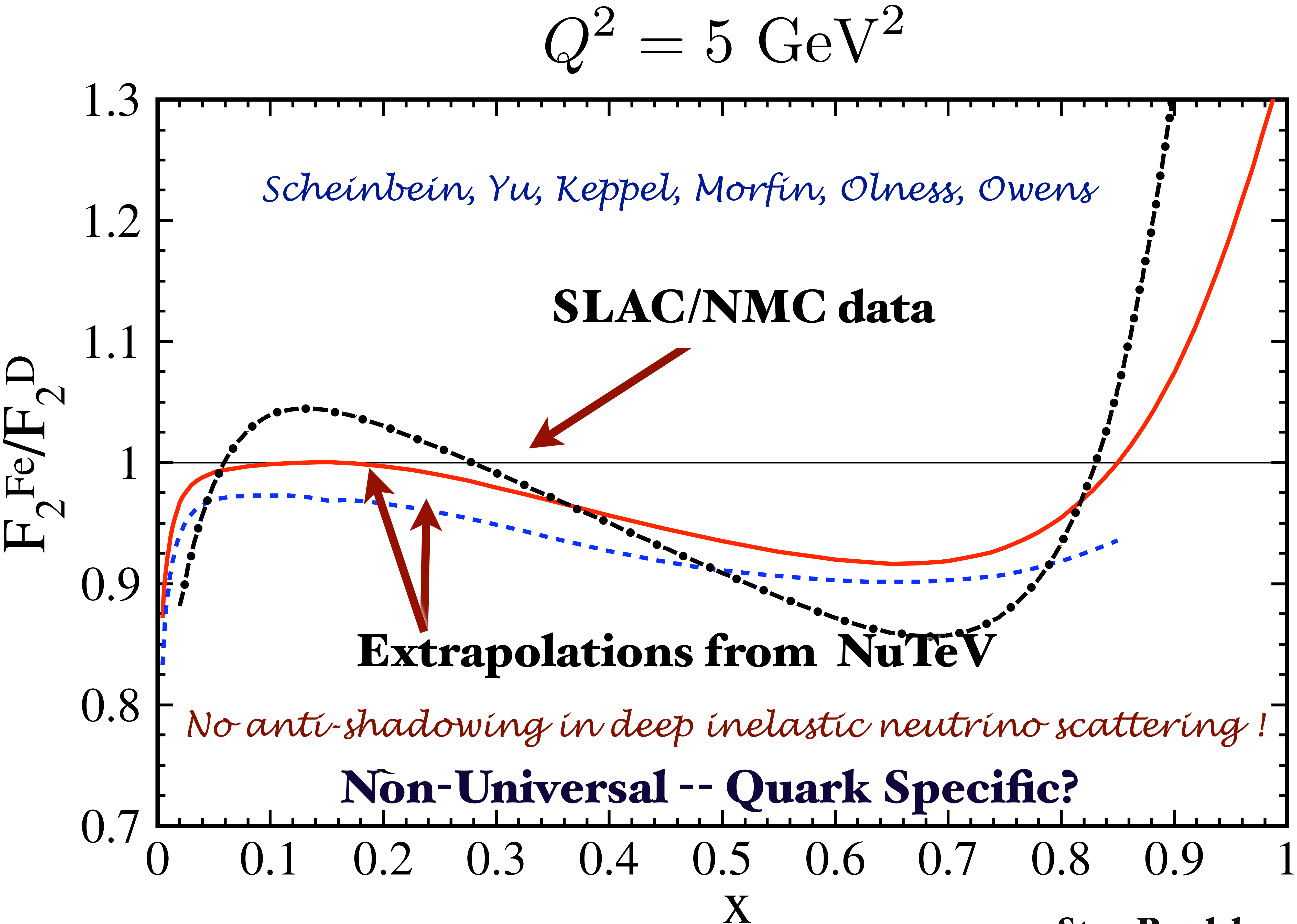


QCD Myths

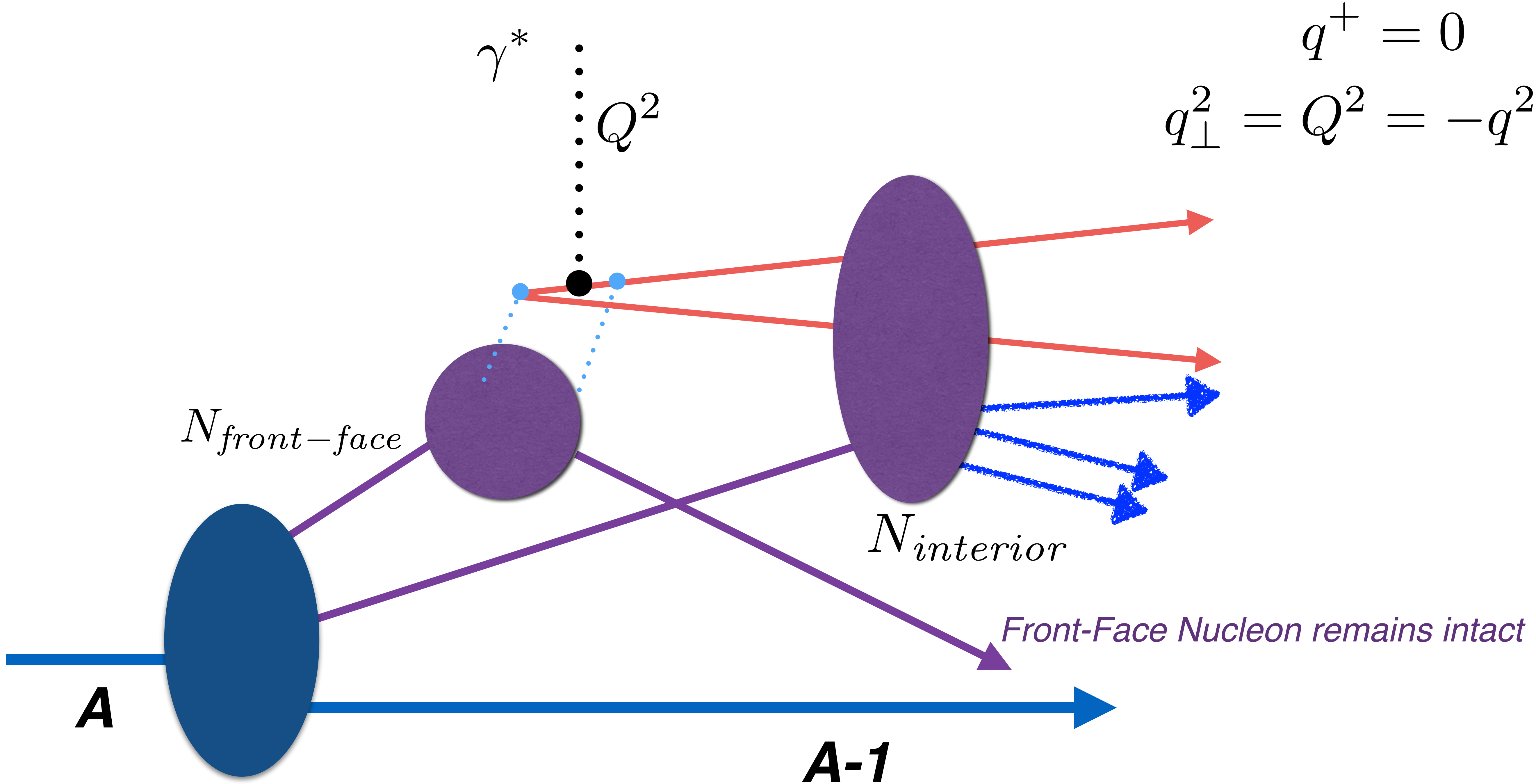
- **Anti-Shadowing is Universal**
- **ISI and FSI are higher twist effects and universal**
- **High transverse momentum hadrons arise only from jet fragmentation -- baryon anomaly!**
- **Heavy quarks only from gluon splitting**
- **Renormalization scale cannot be fixed**
- **QCD condensates are vacuum effects**
- **QCD gives 10^{42} to the cosmological constant**



M. Hirai, S. Kumano and T. H. Nagai, "Nuclear parton distribution functions and their uncertainties," Phys. Rev. C **70**, 044905 (2004) [arXiv:hep-ph/0404093]

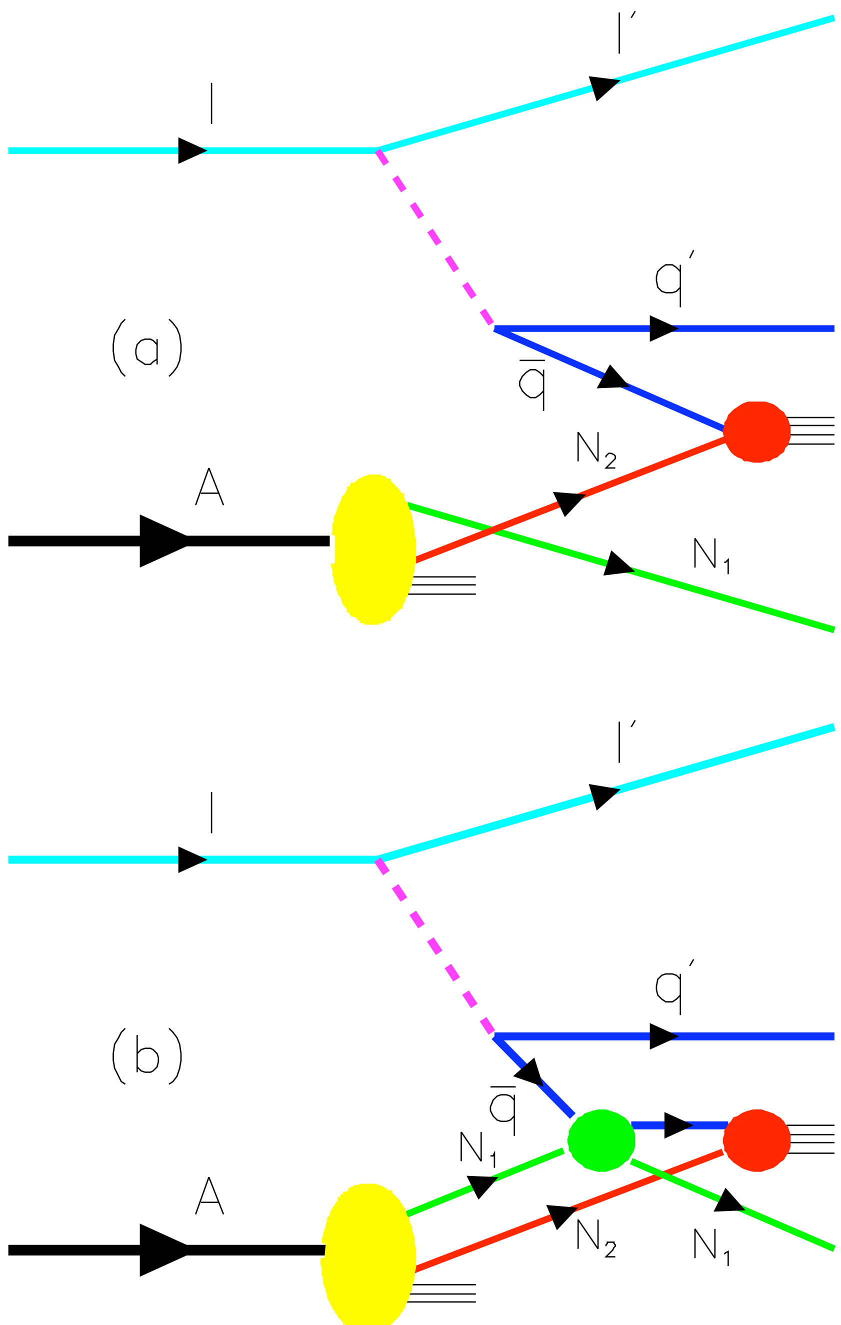


$Q^2 = 5\ \mathrm{GeV}^2$
Scheinbein, Yu, Keppel, Morfin, Olness, Owens
SLAC/NMC data
Extrapolations from NuTeV
No anti-shadowing in deep inelastic neutrino scattering !
Non-Universal -- Quark Specific?
F_2^{Fe}/F_2^D
X
1.3
1.2
1.1
1
0.9
0.8
0.7
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1



Two-Step Process in the $q^+=0$ Parton Model Frame

Illustrates the LF time sequence



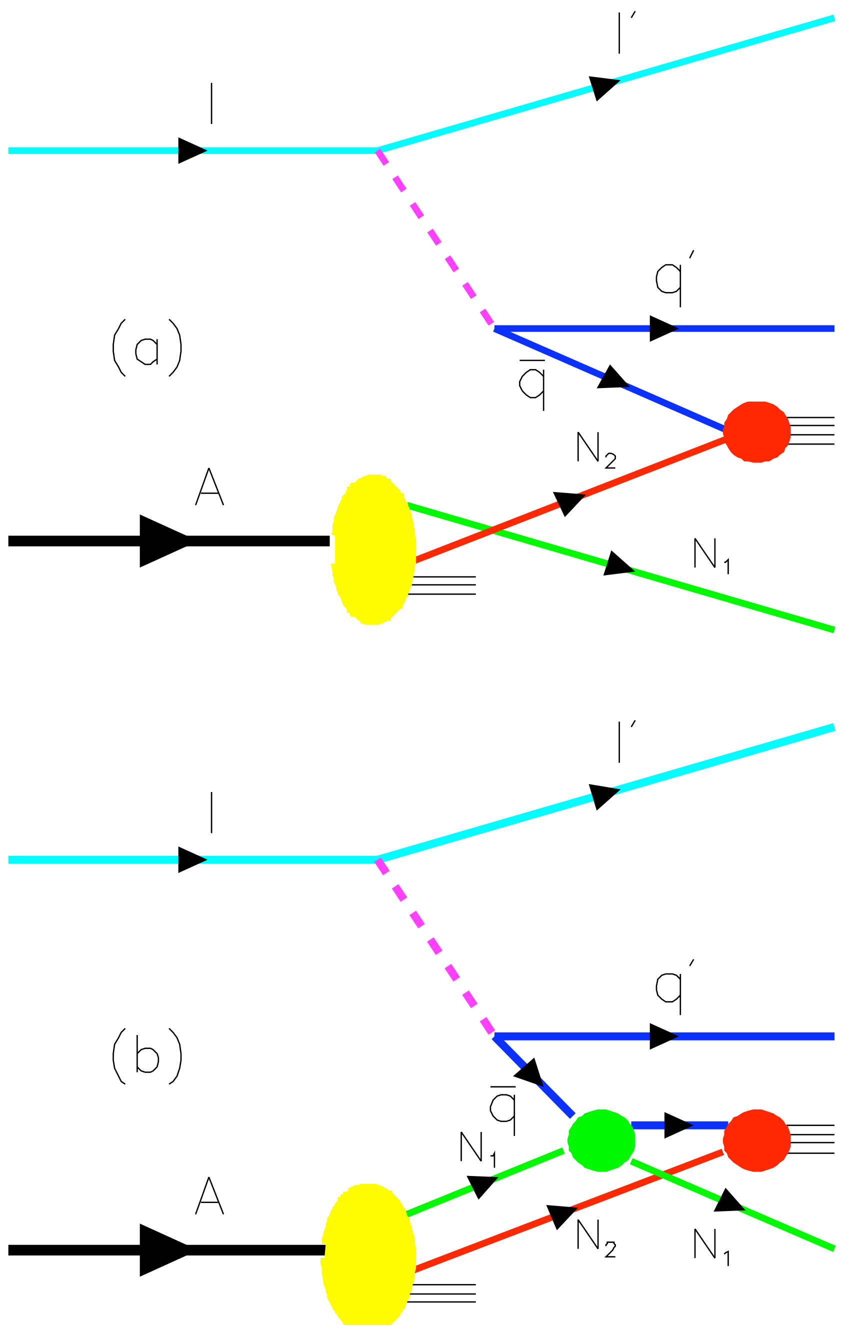
The one-step and two-step processes in DIS on a nucleus.

Coherence at small Bjorken x_B :
$1/Mx_B = 2\nu/Q^2 \geq L_A$.

If the scattering on nucleon N_1 is via pomeron exchange, the one-step and two-step amplitudes are opposite in phase, thus diminishing the $\bar{q}$ flux reaching N_2.

Diffraction via Pomeron gives destructive interference!

Shadowing



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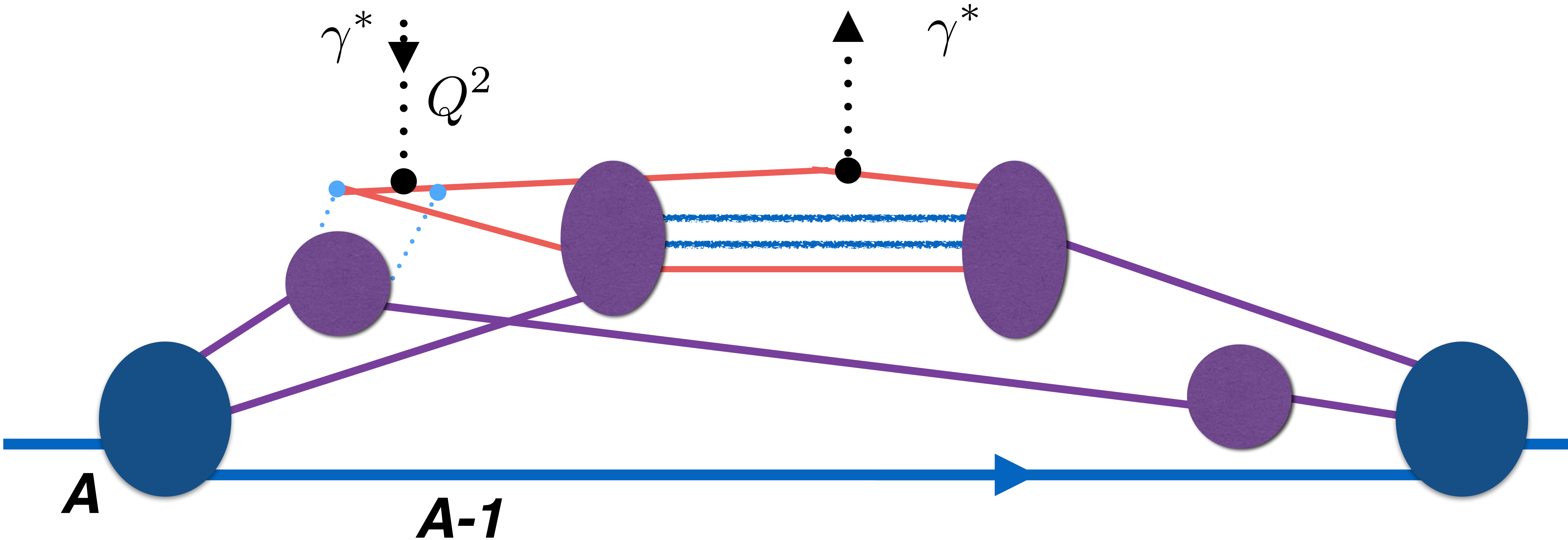
$\rightarrow$ Shadowing of the DIS nuclear structure functions.

Diffraction via Pomeron gives destructive interference!

Shadowing

$$q^+ = 0 \quad q_\perp^2 = Q^2 = -q^2$$

Illustrates the LF time sequence



Front-Face Nucleon struck

Front-Face Nucleon not struck

One-Step / Two-Step Interference

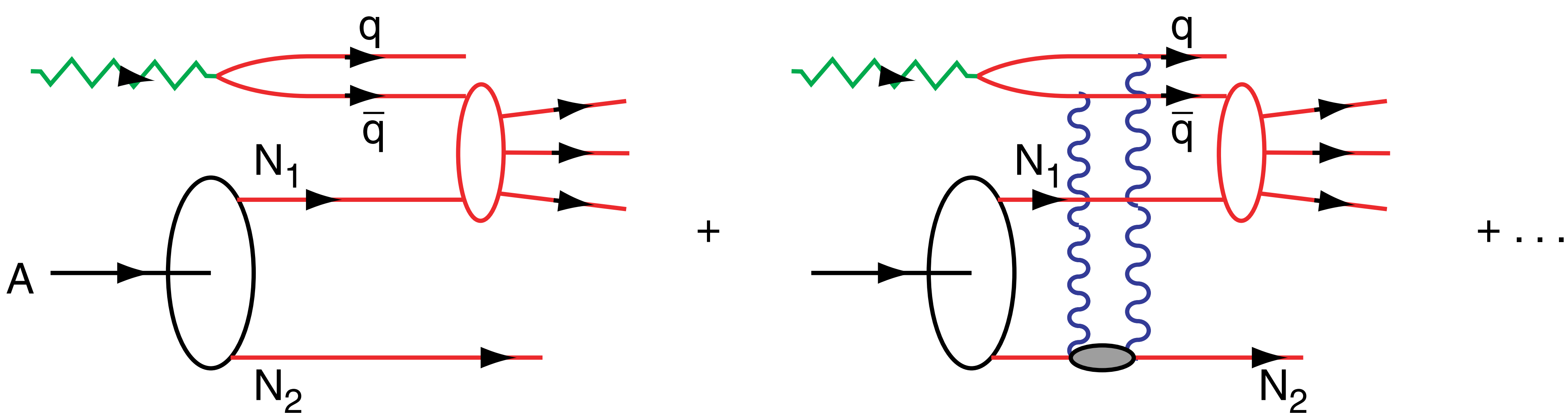
Study Double Virtual Compton Scattering $\gamma^* A \to \gamma^* A$

Cannot reduce to matrix element of local operator

Sum Rules not proven

Stodolsky
Pumplin, sjb
Gribov

Nuclear Shadowing in QCD



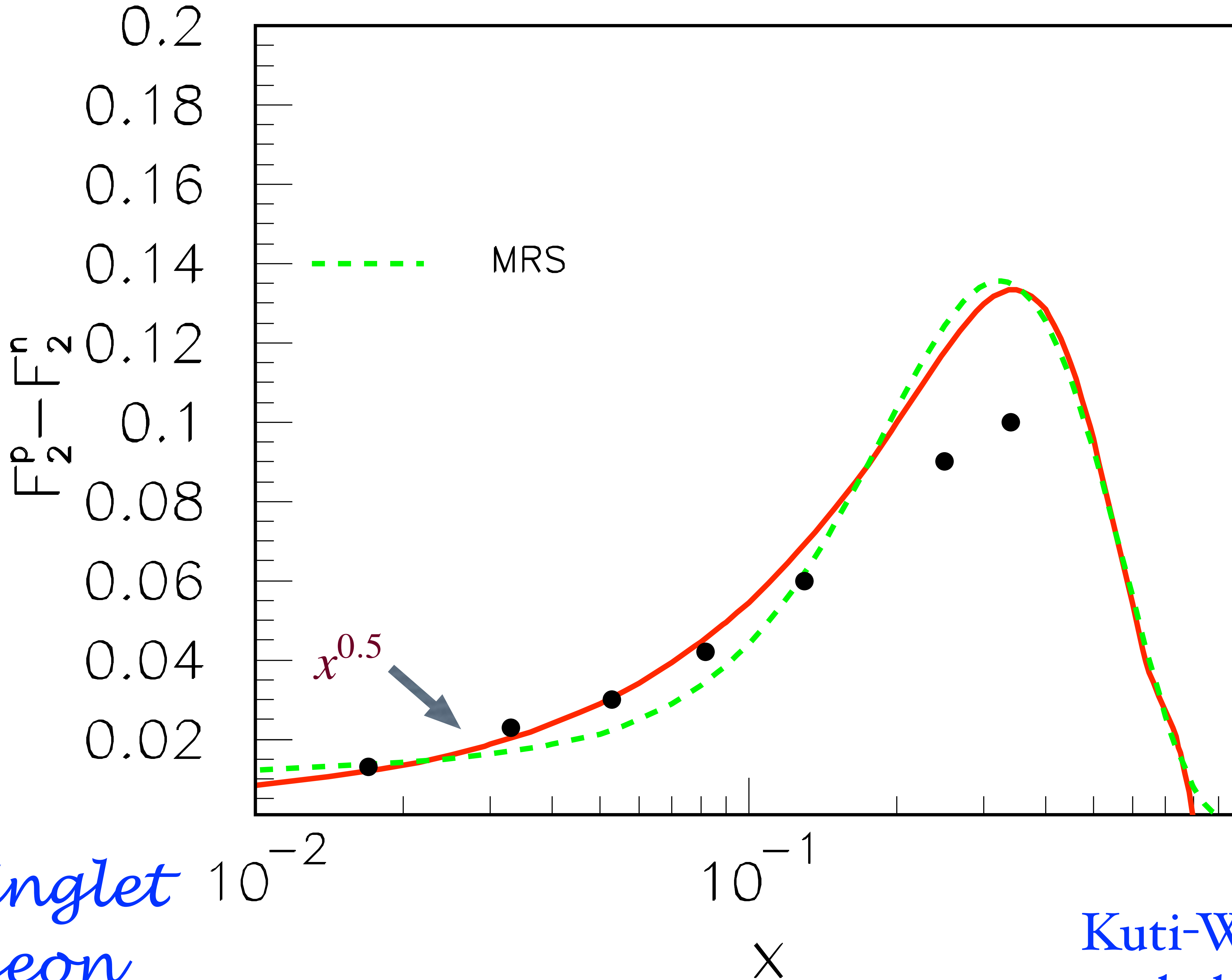
Shadowing depends on understanding leading twist-diffraction in DIS

Nuclear Shadowing not included in nuclear LFWF !

Dynamical effect due to virtual photon interacting in nucleus

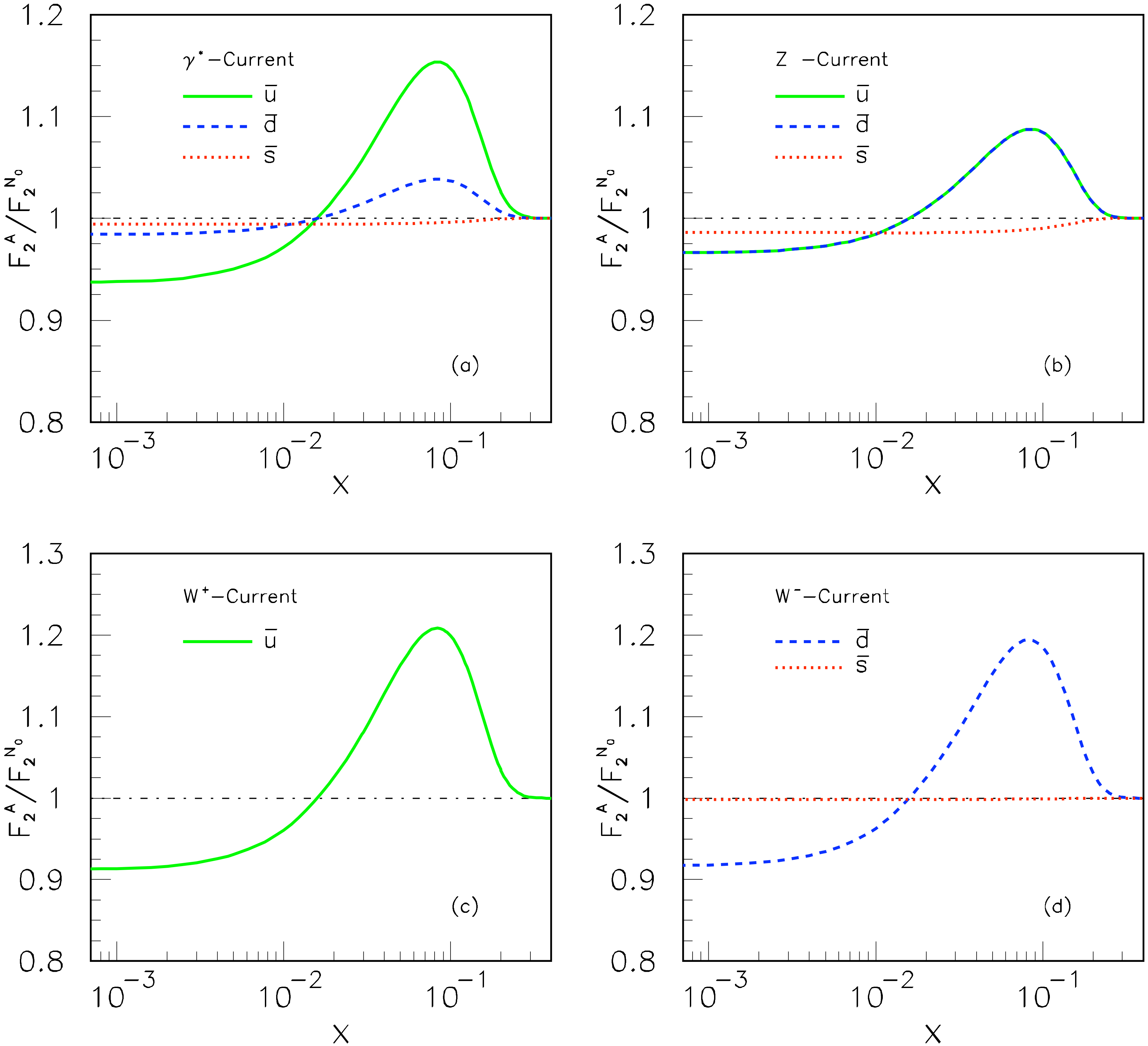
Diffraction via Reggeon gives constructive interference!

Anti-shadowing not universal



Non-singlet Reggeon Exchange

Kuti-Weisskopf behavior



Schmidt, Yang; sjb

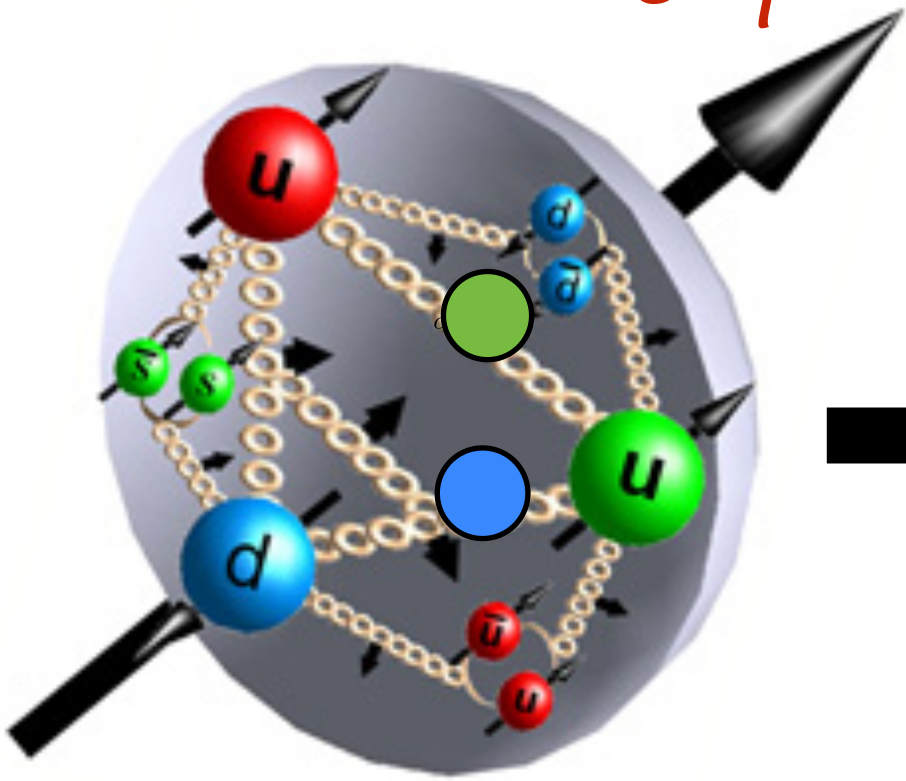
Modifies NuTeV extraction of

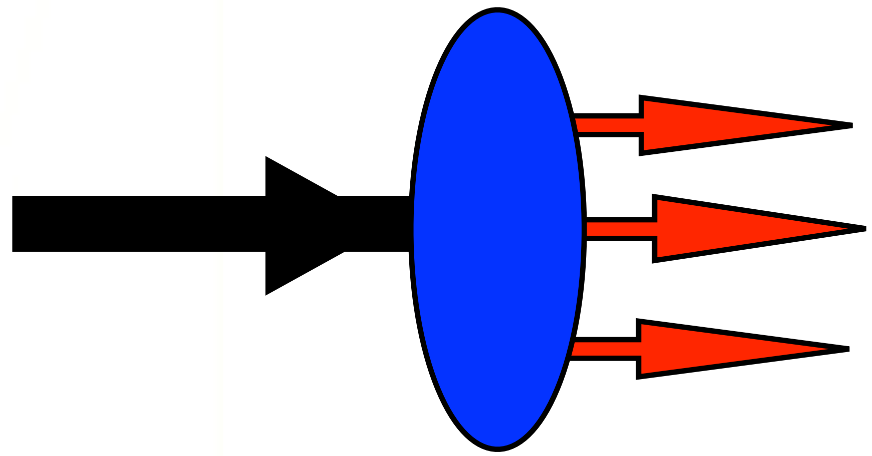
$\sin^2\theta_W$

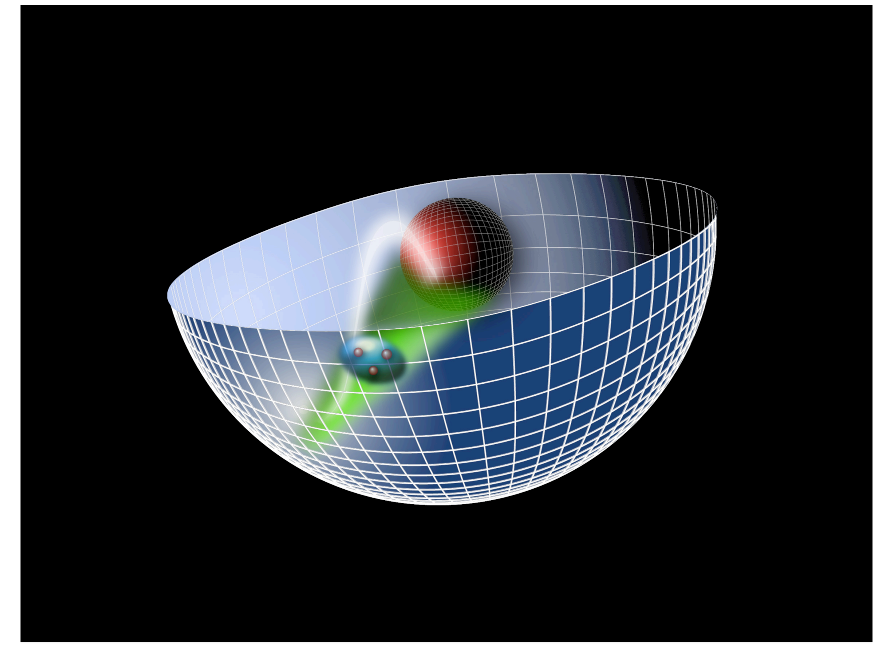
Test in flavor-tagged DIS at the EIC

Nuclear Antishadowing not universal !

Light-Front Holographic QCD, Color Confinement, and Supersymmetric Features of QCD







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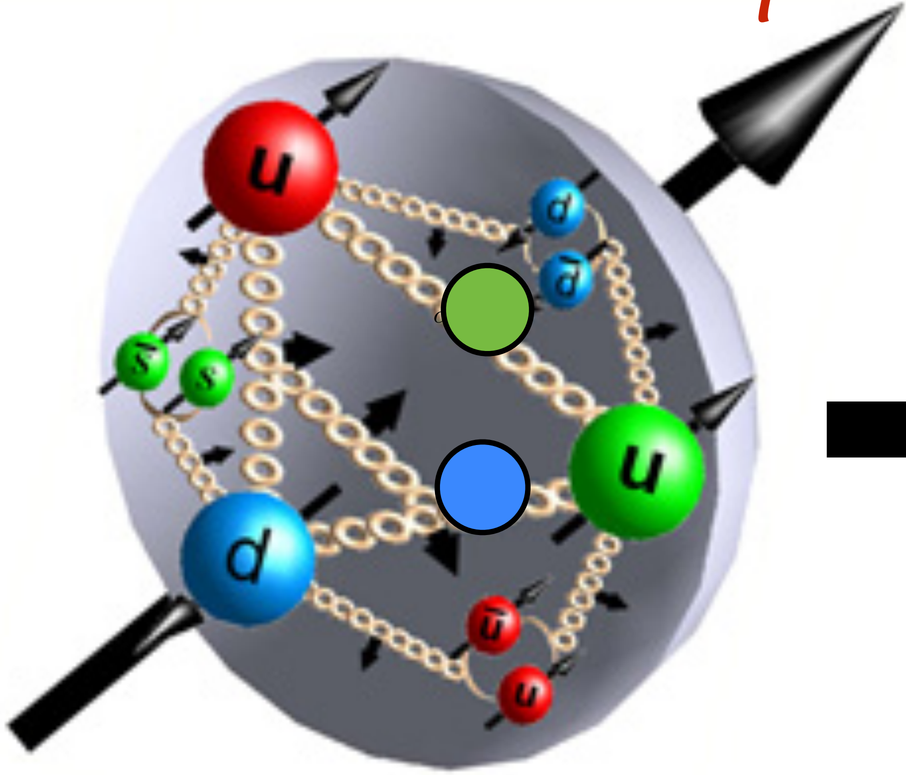
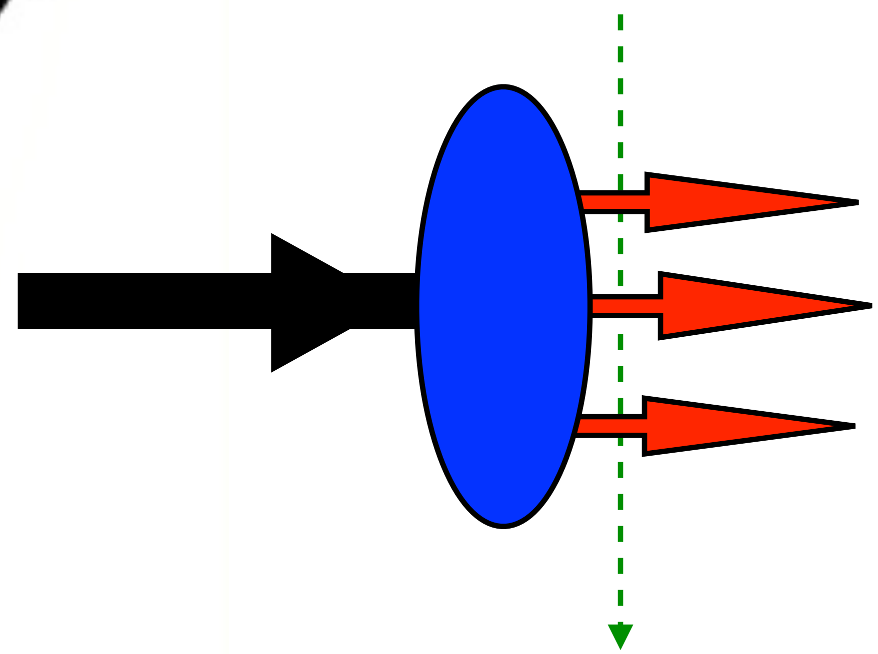
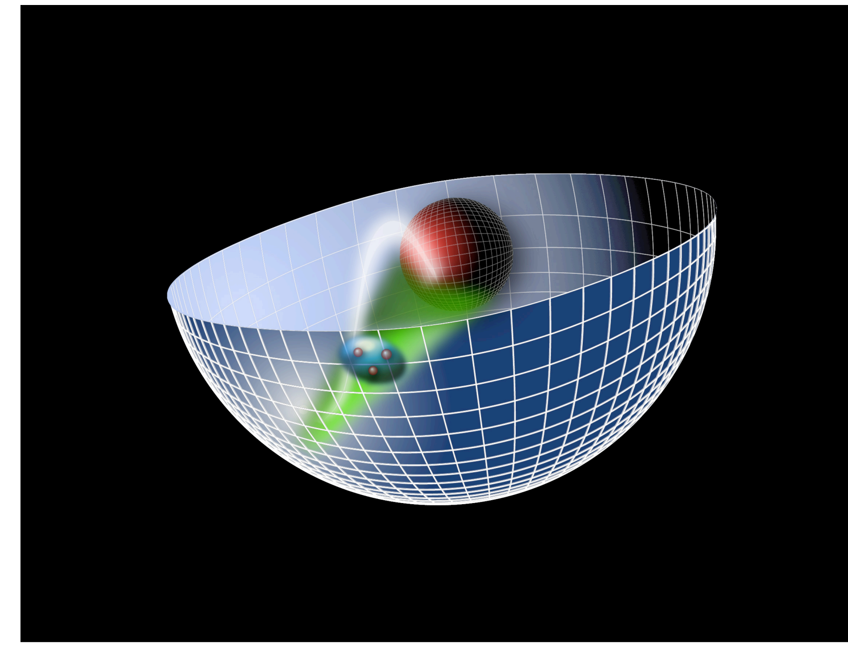


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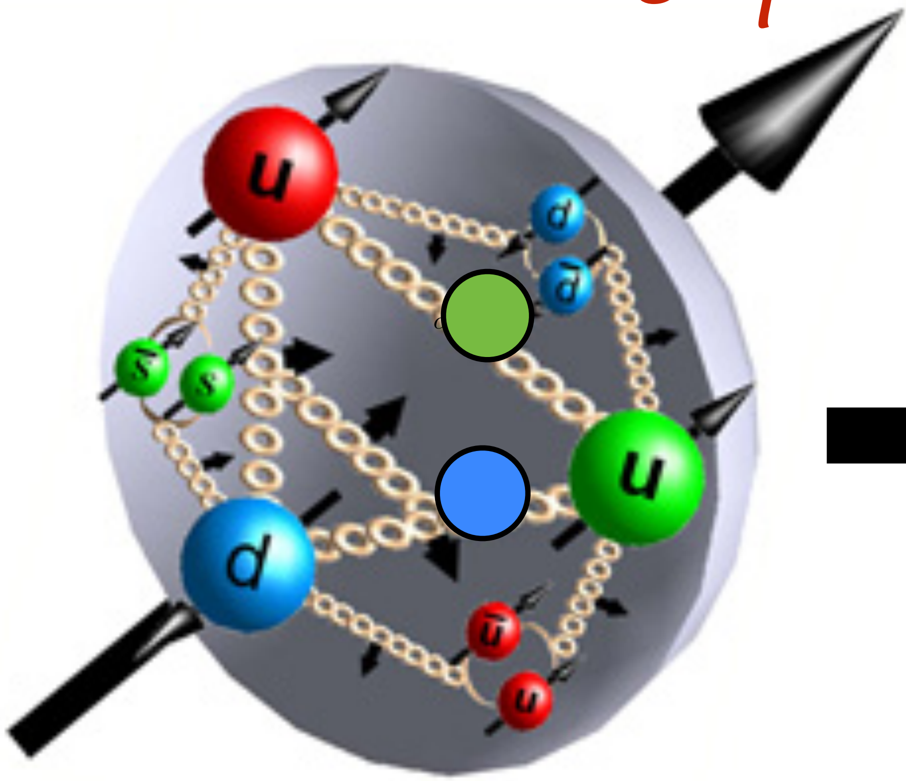

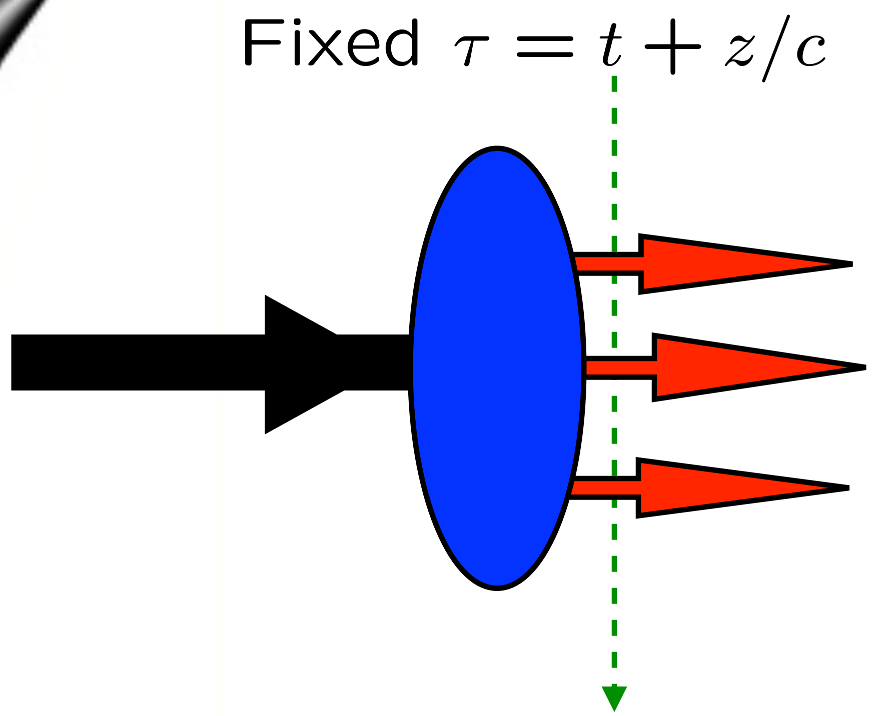

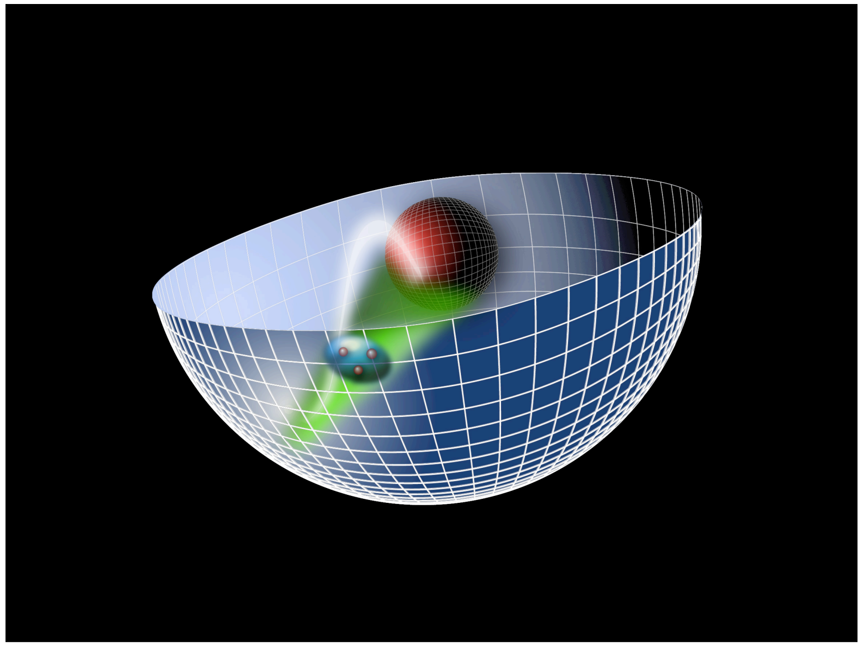

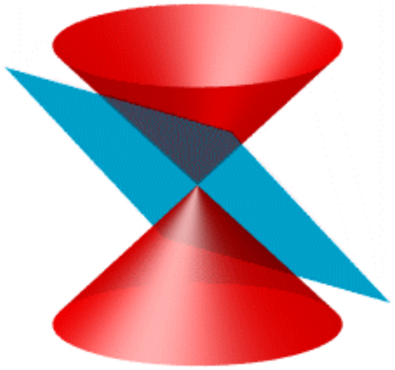

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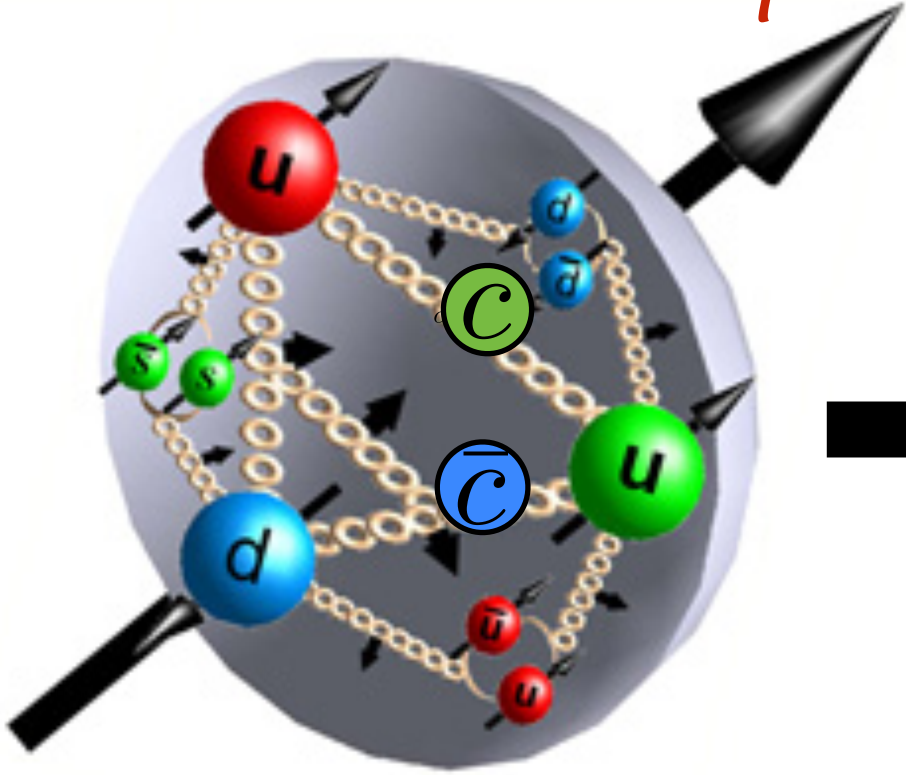

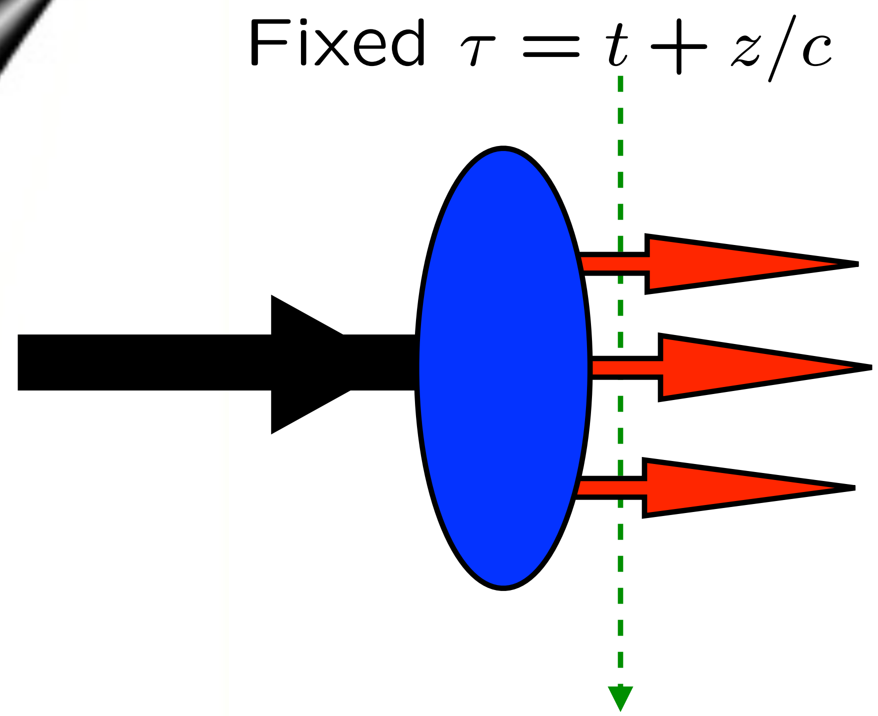

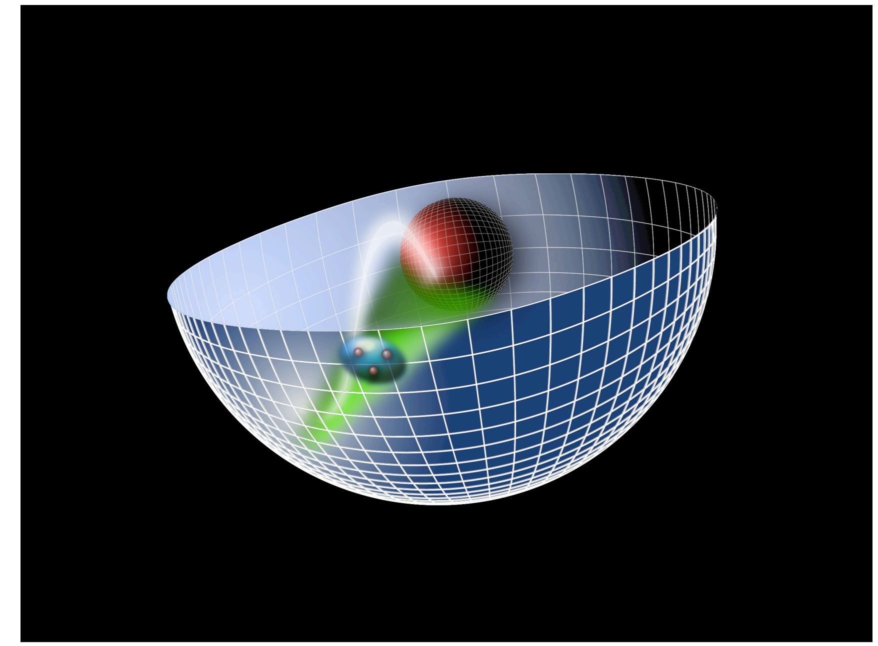

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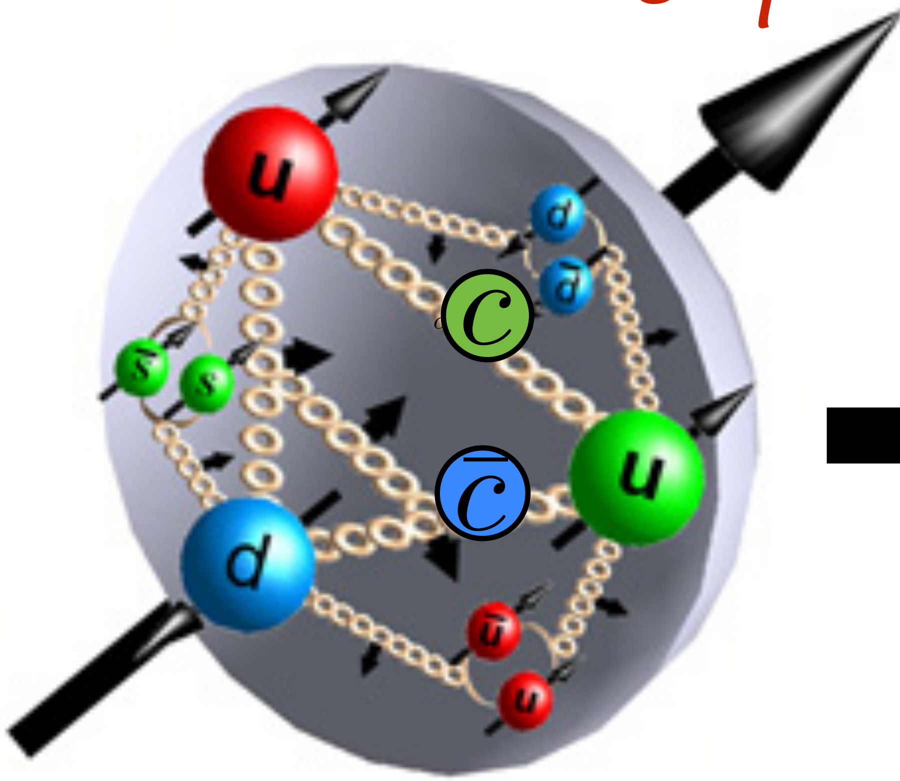

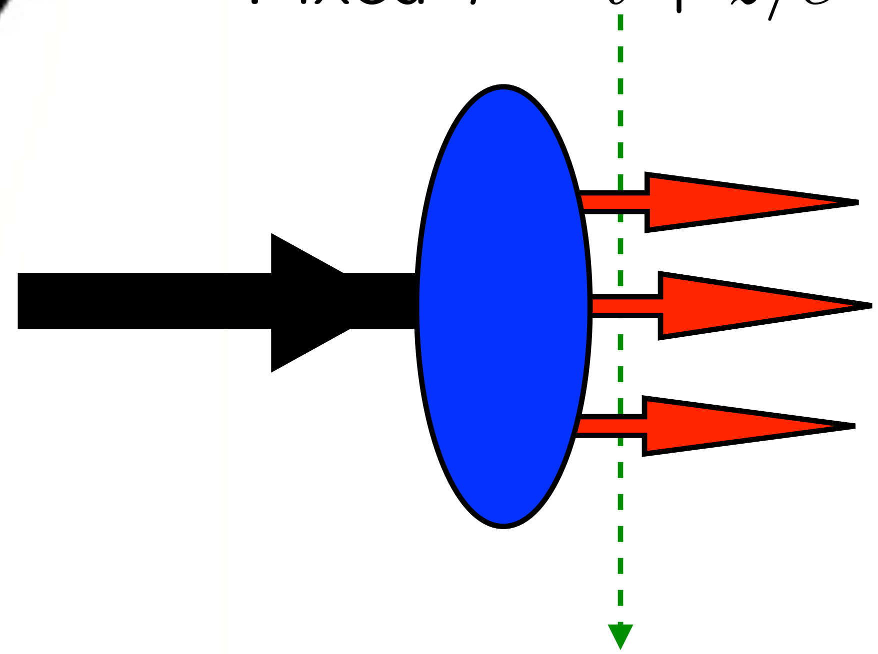

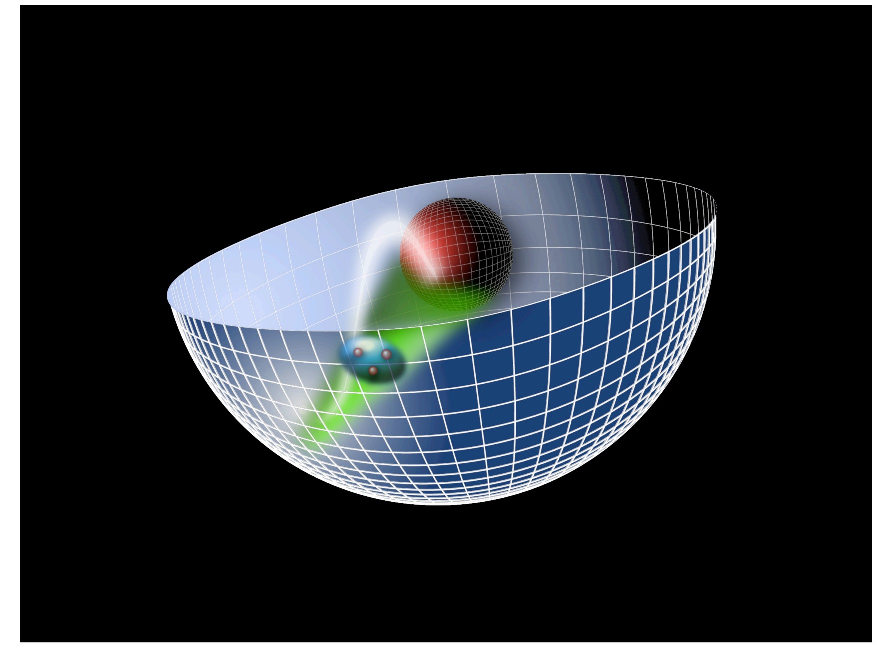

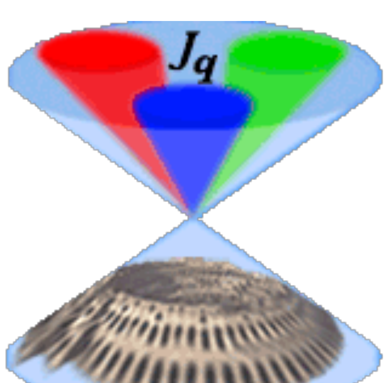

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Thanks for a Wonderful LC2015!

Barbara Pasquini

Giovanni Salmé

INFN Frascati National Laboratories

LC2016: Lisbon, Portugal