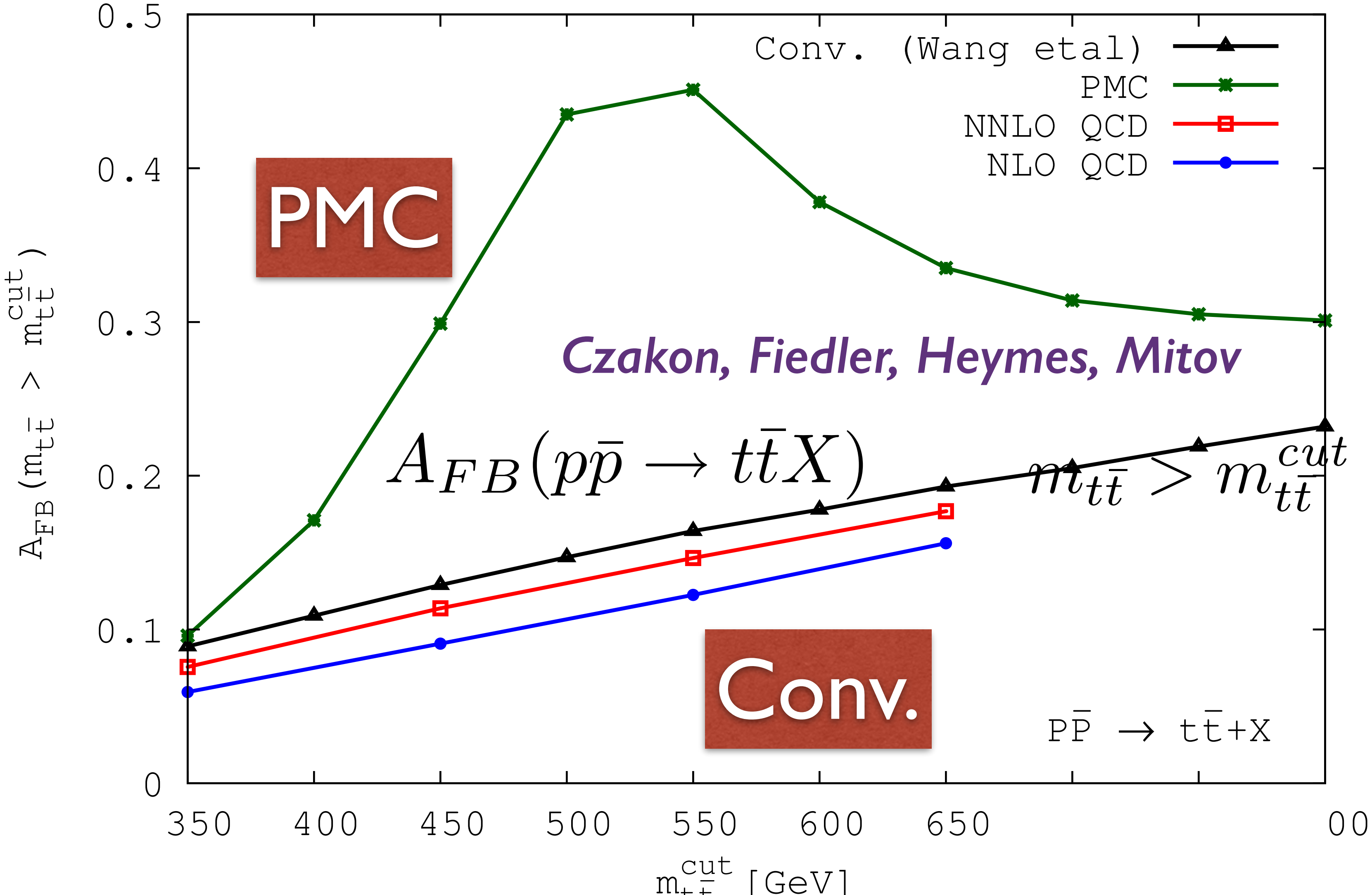
The QCD coupling at all scales and the elimination of renormalization scale uncertainties

The Principle of Maximum Conformality (PMC)



BLM: G. Peter Lepage
Paul Mackenzie

PMC: Leonardo di Giustin
Xing-Gang Wu
Matin Mojaza
Sheng-Quan Wang

LFHQCD: Alexandre Deur
H. Guenter Dosch,
G.de Tèramond

Stan Brodsky
SLAC
NATIONAL ACCELERATOR LABORATORY

GGI School

Frontiers in Nuclear and Hadronic Physics

February 25 - March 8, 2019

Goals

- **Test QCD to maximum precision**
- **Maximize sensitivity to new physics**
- **Obtain high precision determination of $\alpha_s(Q^2)$ and other parameters**
- **Determine renormalization scales without ambiguity**
- **Eliminate scheme dependence**

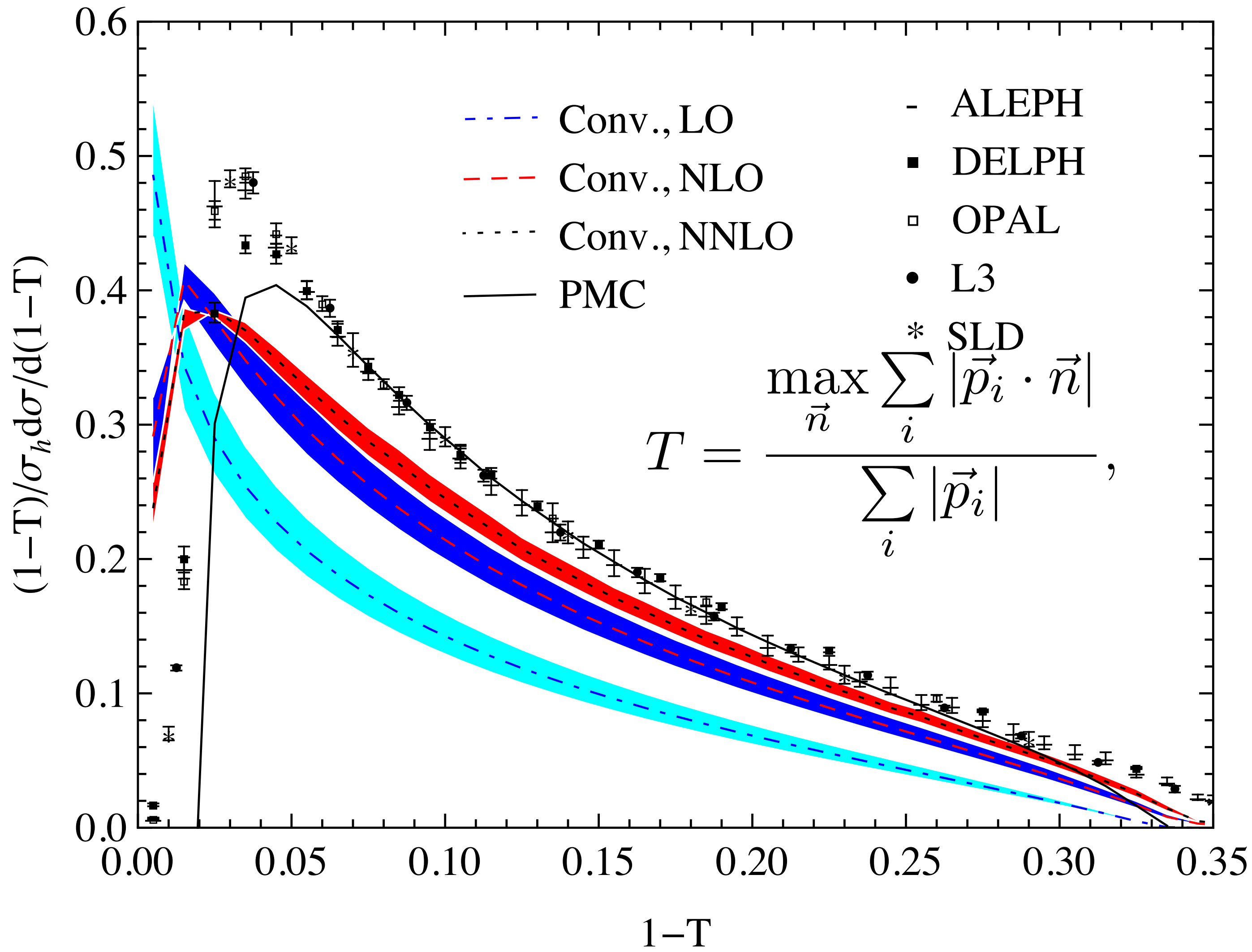
Predictions for physical observables cannot depend on theoretical conventions, such as the renormalization scheme or the initial scale choice

- *Principle of Maximum Conformality (PMC)*

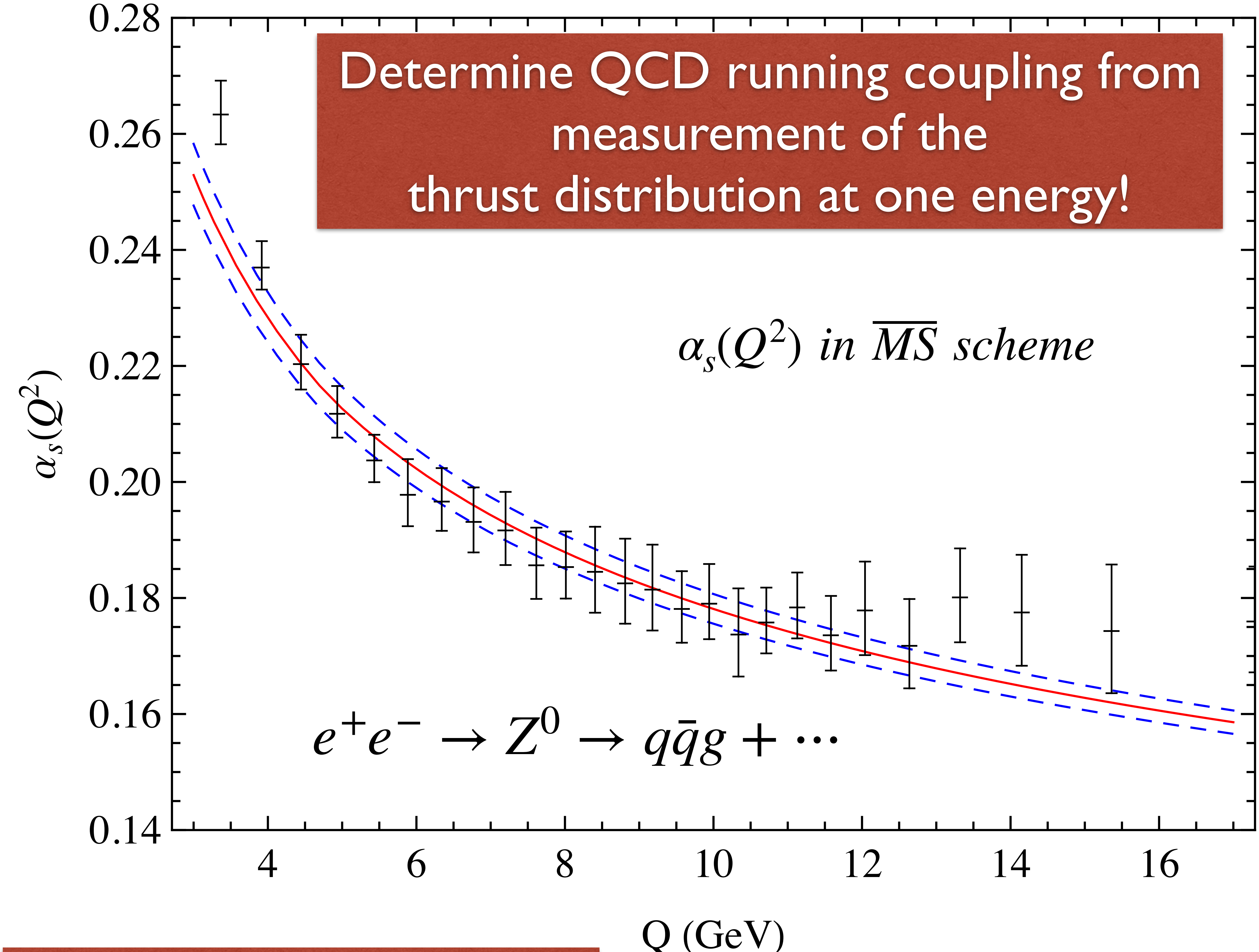
Invariance Principles of Quantum Field Theory

- *PoIncarè Invariance: Physical predictions must be independent of the observer's Lorentz frame: Front Form*
- *Causality: Information within causal horizon: Front Form*
- *Gauge Invariance: Physical predictions of gauge theories must be independent of the choice of gauge*
- *Scheme-Independence: Physical predictions of a renormalizable theory must be independent of the choice of the renormalization scheme —Principle of Maximum Conformality (PMC)*
- *Mass-Scale Invariance: Conformal Invariance of the Action (DAFF)*

S.-Q. Wang, L. Di Giustino, X.-G. Wu, SJB



The thrust $(1 - T)$ differential distributions using the conventional (Conv.) and PMC scale settings. The dot-dashed, dashed and dotted lines are the conventional results at LO, NLO and NNLO, respectively. The solid line is the PMC result. The bands for the theoretical predictions are obtained by varying $\mu_r \in [M_Z/2, 2M_Z]$. The PMC prediction eliminates the scale μ_r uncertainty. The experimental data points are taken from the ALEPH [2], DELPH [3], OPAL [4], L3 [5] and SLD [38] experiments.



S.-Q. Wang, L. Di Giustino, X.-G. Wu, SJB

PHYSICAL REVIEW D VOLUME 28, NUMBER 1 1 JULY 1983

On the elimination of scale ambiguities in perturbative quantum chromodynamics

Stanley J. Brodsky
Institute for Advanced Study, Princeton, New Jersey 08540
*and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305**

G. Peter Lepage
Institute for Advanced Study, Princeton, New Jersey 08540
*and Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853**

Paul B. Mackenzie
Fermilab, Batavia, Illinois 60510
(Received 23 November 1982)

We present a new method for resolving the scheme-scale ambiguity that has plagued perturbative analyses in quantum chromodynamics (QCD) and other gauge theories. For Abelian theories the method reduces to the standard criterion that only vacuum-polarization insertions contribute to the effective coupling constant. Given a scheme, our procedure automatically determines the coupling-constant scale appropriate to a particular process. This leads to a new criterion for the convergence of perturbative expansions in QCD. We examine a number of well known reactions in QCD, and find that perturbation theory converges well for all processes other than the gluonic width of the Υ. Our analysis calls into question recent determinations of the QCD coupling constant based upon Υ decay.

PRL 110, 192001 (2013) PHYSICAL REVIEW LETTERS week ending 10 MAY 2013

Systematic All-Orders Method to Eliminate Renormalization-Scale and Scheme Ambiguities in Perturbative QCD

Matin Mojaza*
CP3-Origins, Danish Institute for Advanced Studies, University of Southern Denmark, DK-5230 Odense, Denmark and SLAC National Accelerator Laboratory, Stanford University, Stanford, California 94039, USA

Stanley J. Brodsky†
SLAC National Accelerator Laboratory, Stanford University, Stanford, California 94039, USA

Xing-Gang Wu‡
Department of Physics, Chongqing University, Chongqing 401331, People's Republic of China

(Received 13 January 2013; published 10 May 2013)

We introduce a generalization of the conventional renormalization schemes used in dimensional regularization, which illuminates the renormalization scheme and scale ambiguities of perturbative QCD predictions, exposes the general pattern of nonconformal $\{\beta_i\}$ terms, and reveals a special degeneracy of the terms in the perturbative coefficients. It allows us to systematically determine the argument of the running coupling order by order in perturbative QCD in a form which can be readily automatized. The new method satisfies all of the principles of the renormalization group and eliminates an

Principle of Maximum Conformality (PMC)

Setting the Renormalization Scale in QCD: The Principle of Maximum Conformality

Stanley J. Brodsky (SLAC & Southern Denmark U., CP3-Origins), Leonardo Di Giustino (SLAC)..

Published in **Phys.Rev. D86 (2012) 085026**

Electron-Electron Scattering in QED

$$\mathcal{M}_{ee\to ee}(++;++) = \frac{8\pi s}{t}\,\alpha(t) + \frac{8\pi s}{u}\,\alpha(u)$$

$$\alpha(t) = \frac{\alpha(0)}{1-\Pi(t)}$$

Gell-Mann--Low Effective Charge

- **Dressed Photon Propagator sums all β (vacuum polarization) contributions, proper and improper**

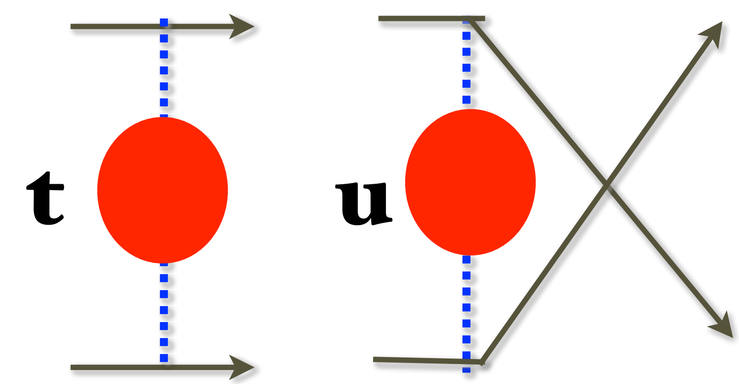
$$\alpha(t) = \frac{\alpha(t_0)}{1-\Pi(t,t_0)} \qquad \Pi(t,t_0) = \frac{\Pi(t)-\Pi(t_o)}{1-\Pi(t_0)}$$

- **Initial Scale Choice t_o is Arbitrary!**

- **Any renormalization scheme can be used** $\alpha(t) \to \alpha_{\overline{MS}}(e^{-\frac{5}{3}}t)$

Electron-Electron Scattering in QED

$$\mathcal{M}_{ee\to ee}(++;++) = \frac{8\pi s}{t}\,\alpha(t) + \frac{8\pi s}{u}\,\alpha(u)$$



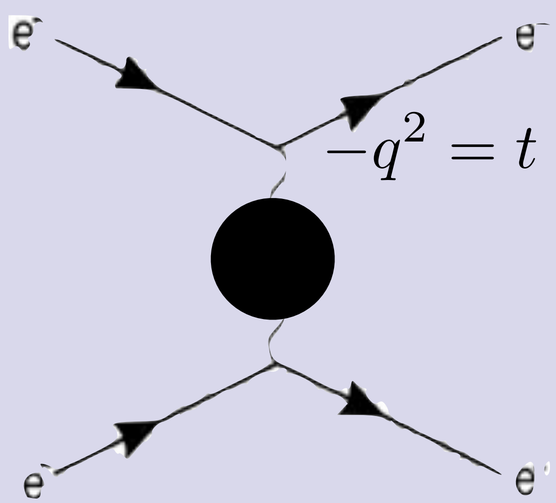
- **No renormalization scale ambiguity!**
- **Gauge Invariant. Dressed photon propagator**
- **Sums all vacuum polarization, non-zero beta terms into running coupling. This is the purpose of the running coupling!**
  - **Two separate physical scales: t, u = photon virtuality**
- **If one chooses a different initial scale, one must sum an infinite number of graphs -- but always recover same result!**
- **Number of active leptons correctly set**
- **Analytic: reproduces correct behavior at lepton mass thresholds**
- **No renormalization scale ambiguity!**

Lessons from QED

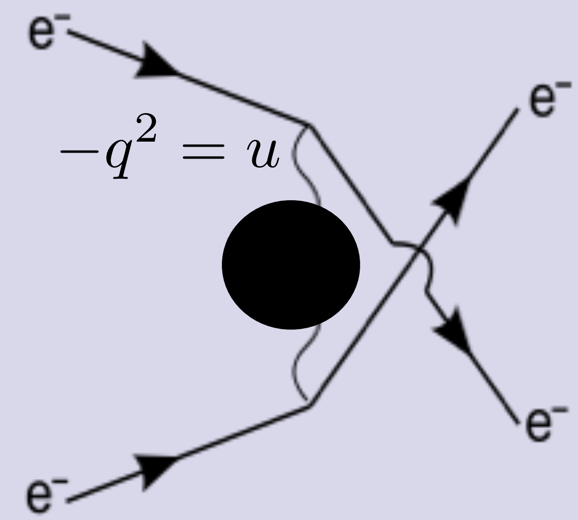
In the (physical) Gell Mann-Low scheme, the momentum scale of the running coupling is the virtuality of the exchanged photon; independent of initial scale.

$$\alpha(t) = \frac{\alpha(t_0)}{1-\Pi(t,t_0)} \qquad \Pi(t,t_0) = \frac{\Pi(t)-\Pi(t_0)}{1-\Pi(t_0)}$$

Example: ee-scattering



$$\mathcal{M}_{ee\to ee} = \frac{8\pi s}{t}\alpha(t) + \frac{8\pi s}{u}\alpha(u)$$



Two separate scales;
one for each skeleton graph.

For any other scale choice an infinite set of diagrams must be taken into account to obtain the correct result!

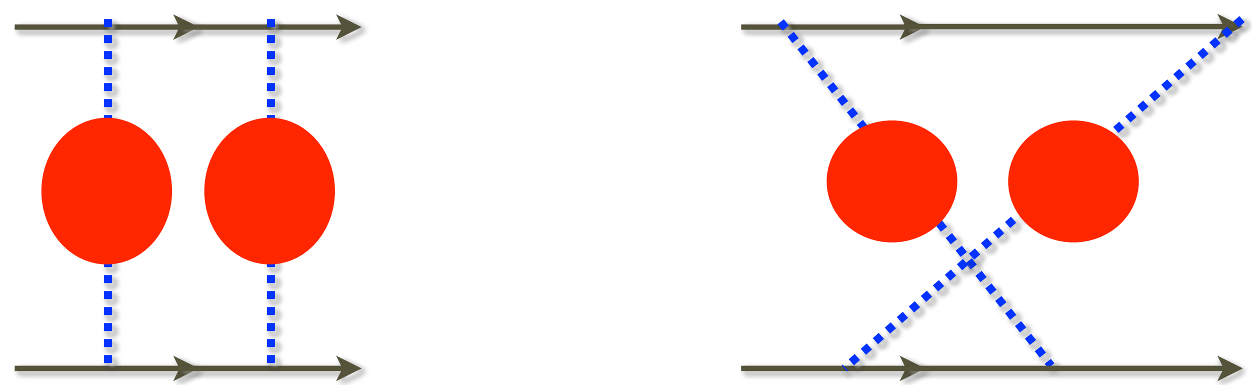
In any other scheme, the correct scale displacement must be used

$$\log\frac{\mu^2_{\overline{MS}}}{m_\ell^2} = 6\int_0^1 dx\, x(1-x)\log\frac{m_\ell^2 + Q^2 x(1-x)}{m_\ell^2}, \quad \xrightarrow{Q^2 \gg m_\ell^2} \log\frac{Q^2}{m_\ell^2} - \frac{5}{3}$$

$$\boxed{\alpha_{\overline{MS}}(e^{-5/3}q^2) = \alpha_{GM-L}(q^2).}$$

Electron-Electron Scattering in QED

New renormalization scale at each order of pQED



Each "skeleton" graph has its own renormalization scale

Renormalization scheme independent at each order

Independent of initial scale μ_0

Abelian theory is the analytic limit QCD at Nc = 0

Lessons from QED

- **No Renormalization Scale Ambiguity**
- **Dressed Photon Propagator sums all β terms**
- **New Scale at Every Order, Every Skeleton Graph**
- **effective number of flavors n_f determined**
- **Predictions are scheme independent**
- **QCD becomes Abelian QED in Zero Color Limit** $N_C \to 0$

Can use $\overline{MS}$ scheme in QED; answers are scheme independent
Analytic extension: coupling is complex for time-like argument

$$C_F = \frac{N_C^2 - 1}{2N_C}$$

Huet, sjb

$$\boxed{\lim N_C \to 0 \text{ at fixed } \alpha = C_F \alpha_s, n_\ell = n_F / C_F}$$

$$\boxed{\text{QCD} \to \text{Abelian Gauge Theory}}$$

Analytic Feature of SU(Nc) Gauge Theory

Scale-Setting procedure for QCD must be applicable to QED

All β (vacuum polarization) terms summed by the running coupling $\alpha(Q^2)$

BLM/PMC: Set Scales

$$a(Q) \equiv \frac{\alpha_s(Q)}{\pi}$$

such to absorb all 'renormalon-terms', i.e. non-conformal terms

$$\begin{aligned}\rho(Q^2) = r_{0,0} &+ r_{1,0}a(Q) + (\beta_0 a(Q)^2 + \beta_1 a(Q)^3 + \beta_2 a(Q)^4 + \underline{\cdots) r_{2,1}} \\ &+ (\beta_0^2 a(Q)^3 + \frac{5}{2}\beta_1\beta_0 a(Q)^4 + \underline{\cdots) r_{3,2}} + (\beta_0^3 + \cdots) r_{4,3} \\ &+ r_{2,0}a(Q)^2 + 2a(Q)(\beta_0 a(Q)^2 + \beta_1 a(Q)^3 + \underline{\cdots) r_{3,1}} \\ &+ \cdots\end{aligned}$$

$$r_{1,0}a(Q_1) = r_{1,0}a(Q) - \beta(a) r_{2,1} + \frac{1}{2}\beta(a)\frac{\partial\beta}{\partial a} r_{3,2} + \cdots + \frac{(-1)^n}{n!}\frac{d^{n-1}\beta}{(d\ln\mu^2)^{n-1}} r_{n+1,n}$$

$$r_{2,0}a(Q_2)^2 = r_{2,0}a(Q)^2 - 2a(Q)\beta(a) r_{3,1} + \cdots$$

How do we identify the β terms at all orders?

BLM: Use n_f dependence of β_0 and β_1

BLM-PMC Scale Setting

$$\beta_0 = 11 - \tfrac{2}{3} n_f$$

$$\rho = C_0 \alpha_{\overline{\rm MS}}(Q) \left[1 + \frac{\alpha_{\overline{\rm MS}}(Q)}{\pi} \left(-\tfrac{3}{2}\beta_0 A_{\rm VP} + \tfrac{33}{2} A_{\rm VP} + B \right) + \cdots \right]$$

n_f dependent coefficient identifies quark loop VP contribution

by

$$\rho = C_0 \alpha_{\overline{\rm MS}}(Q^*) \left[1 + \frac{\alpha_{\overline{\rm MS}}(Q^*)}{\pi} C_1^* + \cdots \right],$$

Conformal coefficient - independent of β

where

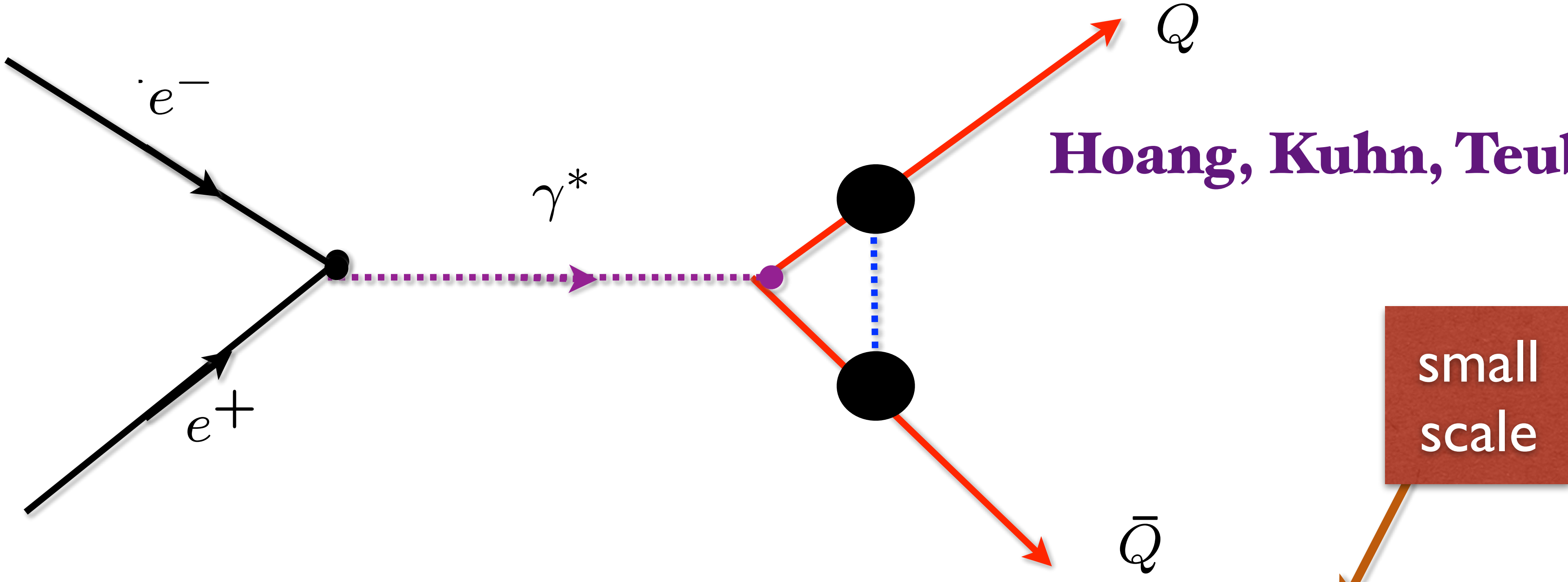
$$Q^* = Q \exp(3A_{\rm VP}),$$

$$C_1^* = \tfrac{33}{2} A_{\rm VP} + B .$$

The term $33A_{\rm VP}/2$ in C_1^* serves to remove that part of the constant B which renormalizes the leading-order coupling. The ratio of these gluonic corrections to the light-quark corrections is fixed by $\beta_0 = 11 - \frac{2}{3} n_f$.

Use skeleton expansion:

Gardi, Grunberg, Rathsman, sjb



Hoang, Kuhn, Teubner, sjb

$$F_1 + F_2 = [1 - 2\frac{\alpha_s(se^{3/4}/4)}{\pi}] \times [1 + \frac{\pi\alpha_s(sv^2)}{4v}]$$

Angular distributions of massive quarks close to threshold.

Example of Multiple BLM Scales

Need QCD coupling at small scales at low relative velocity v

Principle of Maximum Conformality (PMC)

- **Subtract extra constant δ in dimensional regularization. Defines new scheme R_δ**

$$\log 4\pi - \gamma_E - \delta \qquad \overline{MS} : \delta = 0$$

(δ: Arbitrary constant!)

- **$\boxed{\text{Coefficients of δ identify β terms !}}$**

- **Shift β terms to argument of running coupling $\alpha_s(Q_n^2)$ at each order n (analogous to all-orders vacuum polarization summation in QED)**

- **Resulting PQCD series matches β= 0 conformal series!**

- **scheme-independent predictions at each computed order!**

- **almost independent of initial scale μ_0**

M. Mojaza, L. di Giustino, Xing-Gang Wu, sjb

M. Mojaza, Xing-Gang Wu, sjb

Exposing the Renormalization Scheme Dependence

Observable in the $\mathcal{R}_\delta$ -scheme:

$$\rho_\delta(Q^2) = r_0 + r_1 a(\mu) + [r_2 + \beta_0 r_1 \delta] a(\mu)^2 + [r_3 + \beta_1 r_1 \delta + 2\beta_0 r_2 \delta + \beta_0^2 r_1 \delta^2] a(\mu)^3 + \cdots$$

$$\mathcal{R}_0 = \overline{\text{MS}}\ , \quad \mathcal{R}_{\ln 4\pi - \gamma_E} = \text{MS} \qquad \mu^2 = \mu^2_{\overline{\text{MS}}}\ \exp(\ln 4\pi - \gamma_E)\ , \quad \mu^2_{\delta_2} = \mu^2_{\delta_1}\ \exp(\delta_2 - \delta_1)$$

Note the divergent 'renormalon series' $n! \beta^n \alpha_s^n$

Renormalization Scheme Equation

$$\frac{d\rho}{d\delta} = -\beta(a) \frac{d\rho}{da} \stackrel{!}{=} 0 \quad \longrightarrow \text{PMC}$$

$$\rho_\delta(Q^2) = r_0 + r_1 a_1(\mu_1) + (r_2 + \beta_0 r_1 \delta_1) a_2(\mu_2)^2 + [r_3 + \beta_1 r_1 \delta_1 + 2\beta_0 r_2 \delta_2 + \beta_0^2 r_1 \delta_1^2] a_3(\mu_3)^3$$

The $\delta_k^p a^n$-term indicates the term associated to a diagram with $1/\epsilon^{n-k}$ divergence for any p. Grouping the different δ_k-terms, one recovers in the $N_c \to 0$ Abelian limit the dressed skeleton expansion.

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

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

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

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

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

order by order

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

$Conformal\ Series$

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

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

A robot can compute the PMC scales

Special Degeneracy in PQCD

There is nothing special about a particular value for δ, thus for any δ

General pattern of pQCD

$$\rho(Q^2) = r_{0,0} + r_{1,0}a(Q) + [r_{2,0} + \beta_0 \underline{r_{2,1}}]a(Q)^2 + [r_{3,0} + \beta_1 \underline{r_{2,1}} + 2\beta_0 \underline{r_{3,1}} + \beta_0^2 \underline{r_{3,2}}]a(Q)^3$$
$$+ [r_{4,0} + \beta_2 \underline{r_{2,1}} + 2\beta_1 \underline{r_{3,1}} + \frac{5}{2}\beta_1\beta_0 \underline{r_{3,2}} + 3\beta_0 r_{4,1} + 3\beta_0^2 r_{4,2} + \beta_0^3 r_{4,3}]a(Q)^4$$

According to the principal of maximum conformality we must set the scales such to absorb all 'renormalon-terms', i.e. non-conformal terms

$$\rho(Q^2) = r_{0,0} + r_{1,0}a(Q) + (\beta_0 a(Q)^2 + \beta_1 a(Q)^3 + \beta_2 a(Q)^4 + \underline{\cdots)r_{2,1}}$$
$$+ (\beta_0^2 a(Q)^3 + \frac{5}{2}\beta_1\beta_0 a(Q)^4 + \underline{\cdots)r_{3,2}} + (\beta_0^3 + \cdots)r_{4,3}$$
$$+ r_{2,0}a(Q)^2 + 2a(Q)(\beta_0 a(Q)^2 + \beta_1 a(Q)^3 + \underline{\cdots)r_{3,1}}$$
$$+ \cdots$$

PMC Scales Q_1 Q_2

$$r_{1,0}a(Q_1) = r_{1,0}a(Q) - \beta(a)r_{2,1} + \frac{1}{2}\beta(a)\frac{\partial\beta}{\partial a}r_{3,2} + \cdots + \frac{(-1)^n}{n!}\frac{d^{n-1}\beta}{(d\ln\mu^2)^{n-1}}r_{n+1,n}$$

$$r_{2,0}a(Q_2)^2 = r_{2,0}a(Q)^2 - 2a(Q)\beta(a)r_{3,1} + \cdots$$

M. Mojaza, Xing-Gang Wu, sjb

General result for an observable in any $\mathcal{R}_\delta$ renormalization scheme:

$$\begin{aligned}\rho(Q^2) =& r_{0,0} + r_{1,0}a(Q) + [r_{2,0} + \beta_0 r_{2,1}]a(Q)^2 \\ &+ [r_{3,0} + \beta_1 r_{2,1} + 2\beta_0 r_{3,1} + \beta_0^2 r_{3,2}]a(Q)^3 \\ &+ [r_{4,0} + \beta_2 r_{2,1} + 2\beta_1 r_{3,1} + \frac{5}{2}\beta_1\beta_0 r_{3,2} + 3\beta_0 r_{4,1} \\ &+ 3\beta_0^2 r_{4,2} + \beta_0^3 r_{4,3}]a(Q)^4 + \mathcal{O}(a^5) \qquad (19)\end{aligned}$$

PMC scales thus satisfy

$$r_{1,0}a(Q_1) = r_{1,0}a(Q) - \beta(a)r_{2,1}$$

$$r_{2,0}a(Q_2)^2 = r_{2,0}a(Q)^2 - 2a(Q)\beta(a)r_{3,1}$$

$$r_{3,0}a(Q_3)^3 = r_{3,0}a(Q)^3 - 3a(Q)^2\beta(a)r_{4,1}$$

$$\vdots$$

$$r_{k,0}a(Q_k)^k = r_{k,0}a(Q)^2 - k\ a(Q)^{k-1}\beta(a)r_{k+1,1}$$

number of flavors n_f depends on Q_k

Conformal symmetry: Template for QCD

- **Take conformal symmetry as initial approximation; then correct for non-zero beta function and quark masses**

- **Eigensolutions of ERBL evolution equation for distribution amplitudes**
  Frishman, Lepage, Mackenzie, Sachrajda, sjb, Gardi, Braun

- **Commensurate scale relations: relate observables at corresponding scales: Generalized Crewther Relation**
  H. J. Lu, sjb

- **Fix Renormalization Scale (BLM, Effective Charges)**
  J. Ellis, Gardi, Grunberg, Rathsman, Gabadadze, Kataev, Lepage, Lu, Mackenzie, sjb

- **The BFKL QCD Pomeron with Optimal Renormalization**
  Kim, Fadin, Lipatov, Pivovarov, sjb

- **IR Fixed Point -- A Conformal Domain**

- **Use AdS/CFT**

Since ρ is a physical observable, it must be independent of the arbitrary renormalization scheme and scale. That is,

initial

$$\boxed{\frac{\partial \rho_\delta}{\partial \mu_\delta} = 0\ , \qquad \frac{\partial \rho_\delta}{\partial \delta} = 0\ ,}$$

Generalization: use δ_n at n-loops.

$$\begin{aligned}\rho_\delta(Q^2) =& r_0 + r_1 a_1(Q) + (r_2 - \beta_0 r_1 \underline{\delta_1}) a_2(Q)^2 \\ &+ [r_3 - \beta_1 r_1 \underline{\delta_1} - 2\beta_0 r_2 \underline{\delta_2} + \beta_0^2 r_1 \underline{\delta_1^2}] a_3(Q)^3 \\ &+ [r_4 - \beta_2 r_1 \underline{\delta_1} - 2\beta_1 r_2 \underline{\delta_2} - 3\beta_0 r_3 \underline{\delta_3} + 3\beta_0^2 r_2 \underline{\delta_2^2} \\ &- \beta_0^3 r_1 \underline{\delta_1^3} + \frac{5}{2}\beta_1 \beta_0 r_1 \underline{\delta_1^2}] a(Q)^4 + \mathcal{O}(a^5)\end{aligned}$$

Shows the general way nonconformal terms enter an observable and the scheme dependence

$$\bar{R}_{e^+e^-}(s) = \frac{1}{2\pi i}\int_{-s-i\epsilon}^{-s+i\epsilon} \frac{\bar{D}(Q^2)}{Q^2} dQ^2 \qquad \bar{D}(Q^2) = \gamma(a) - \beta(a)\frac{d}{da}\Pi(Q^2, a)$$

Initial expression

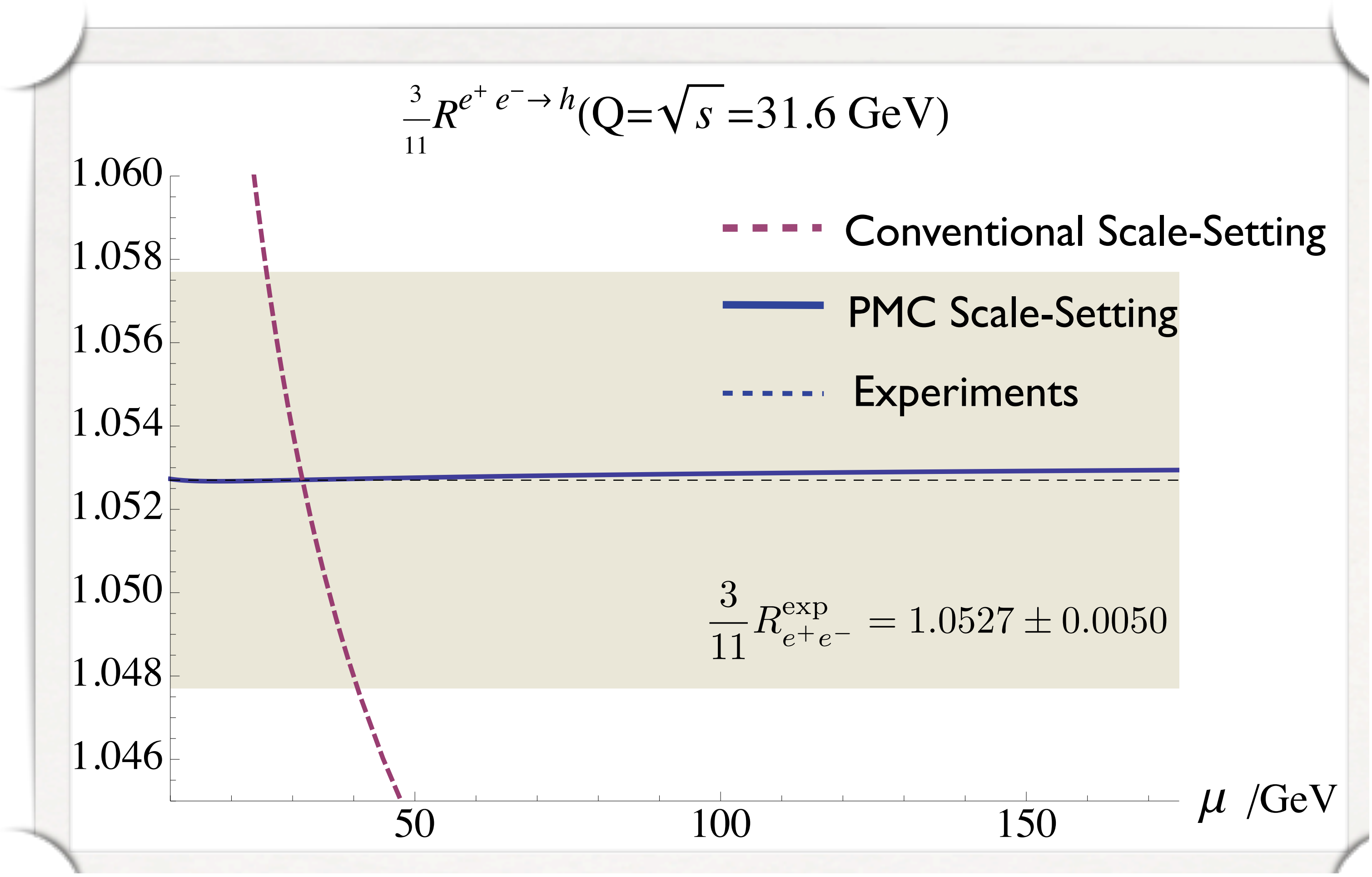
$$\bar{R}_{e^+e^-}(s) = \gamma_0 + \gamma_1 a(\mu) + [\gamma_2 + \beta_0 \underline{\Pi_1}]a(\mu)^2 + [\gamma_3 + \beta_1 \underline{\Pi_1} + 2\beta_0 \underline{\Pi_2} - \beta_0^2 \underline{\frac{\pi^2\gamma_1}{3}}]a(\mu)^3$$
$$+ [\gamma_4 + \beta_2 \underline{\Pi_1} + 2\beta_1 \underline{\Pi_2} + \beta_0 \Pi_3 - \frac{5}{2}\beta_0\beta_1 \underline{\frac{\pi^2\gamma_1}{3}} - 3\beta_0^2 \frac{\pi^2\gamma_2}{3} - \beta_0^3\pi^2\Pi_1]a(\mu)^4$$

Final expression

$$\bar{R}_{e^+e^-}(Q) = \gamma_0 + \gamma_1 a(Q_1) + \gamma_2 a(Q_2)^2 + \gamma_3 a(Q_3)^3 + \gamma_4 a(Q_4)^4$$

Final PMC Scales

$$Q_1 = 1.3\ Q,\ \ Q_2 = 1.2\ Q,$$
$$Q_3 = 5.3\ Q,\ \ Q_4 \sim Q$$

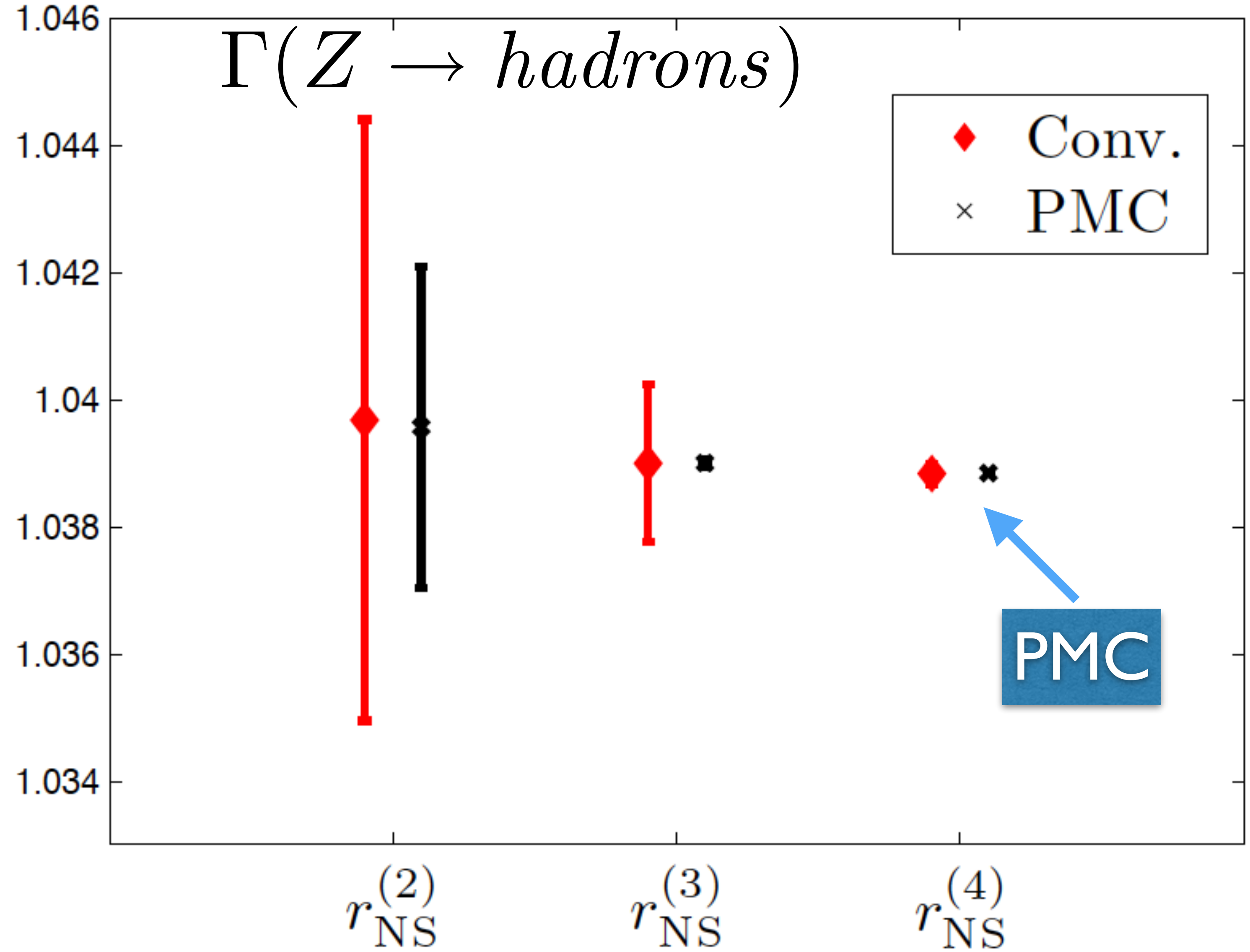


Dependence on initial scale μ

Reanalysis of the Higher Order Perturbative QCD corrections to Hadronic Z Decays using the Principle of Maximum Conformality

S-Q Wang, X-G Wu, sjb

P.A. Baikov, K.G. Chetyrkin, J.H. Kuhn, and J. Rittinger, Phys. Rev. Lett. 108, 222003 (2012).



The values of $r_{\rm NS}^{(n)} = 1 + \sum_{i=1}^{n} C_i^{\rm NS} a_s^i$ and their errors $\pm|C_n^{\rm NS} a_s^n|_{\rm MAX}$. The diamonds and the crosses are for conventional (Conv.) and PMC scale settings, respectively. The central values assume the initial scale choice $\mu_r^{\rm init} = M_Z$.

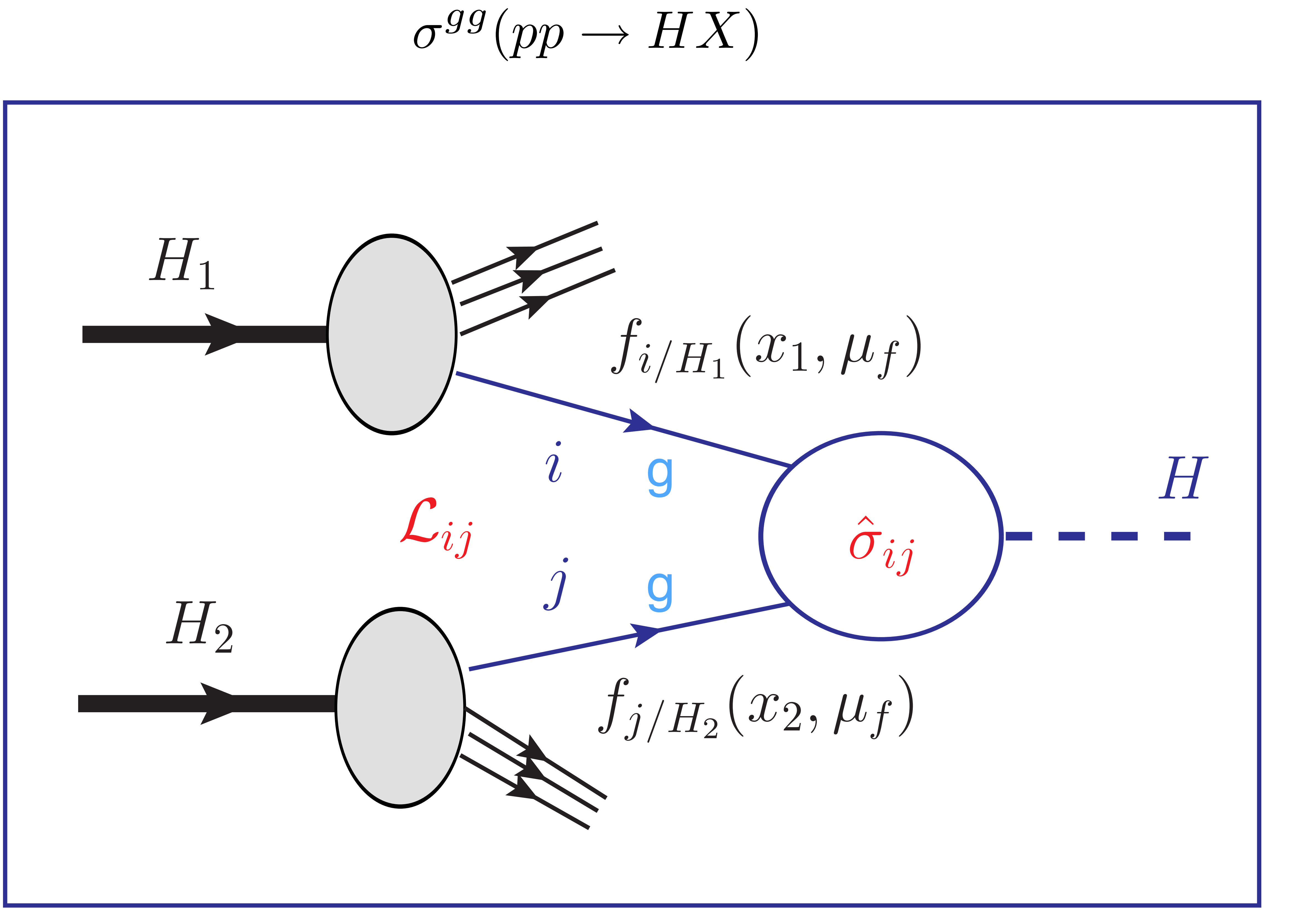
Features of BLM/PMC

- *Predictions are scheme-independent at every order*
- *Matches conformal series*
- *No n! Renormalon growth of pQCD series*
- *New scale appears at each order; n_F determined at each order - matches virtuality of quark loops!*
- *Multiple Physical Scales Incorporated (Hoang, Kuhn, Tuebner, sjb)*
- *Rigorous: Satisfies all Renormalization Group Principles*
- *Realistic Estimate of Higher-Order Terms*
- *Reduces to standard QED scale* $N_C \to 0$
- *GUT: Must use the same scale setting procedure for QED, QCD*
- *Eliminates unnecessary theory error*
- *Maximal sensitivity to new physics*
- *Commensurate Scale Relations between observables: Generalized Crewther Relation (Kataev, Lu, Rathsman, sjb)*
- *PMC Reduces to BLM at NLO: Example: BFKL intercept* (Fadin, Kim, Lipatov, Pivovarov, sjb)

Application of the Principle of Maximum Conformality to the Hadroproduction of the Higgs Boson at the LHC

Sheng-Quan Wang[1],* Xing-Gang Wu[2],† Stanley J. Brodsky[3],‡ and Matin Mojaza[4]§

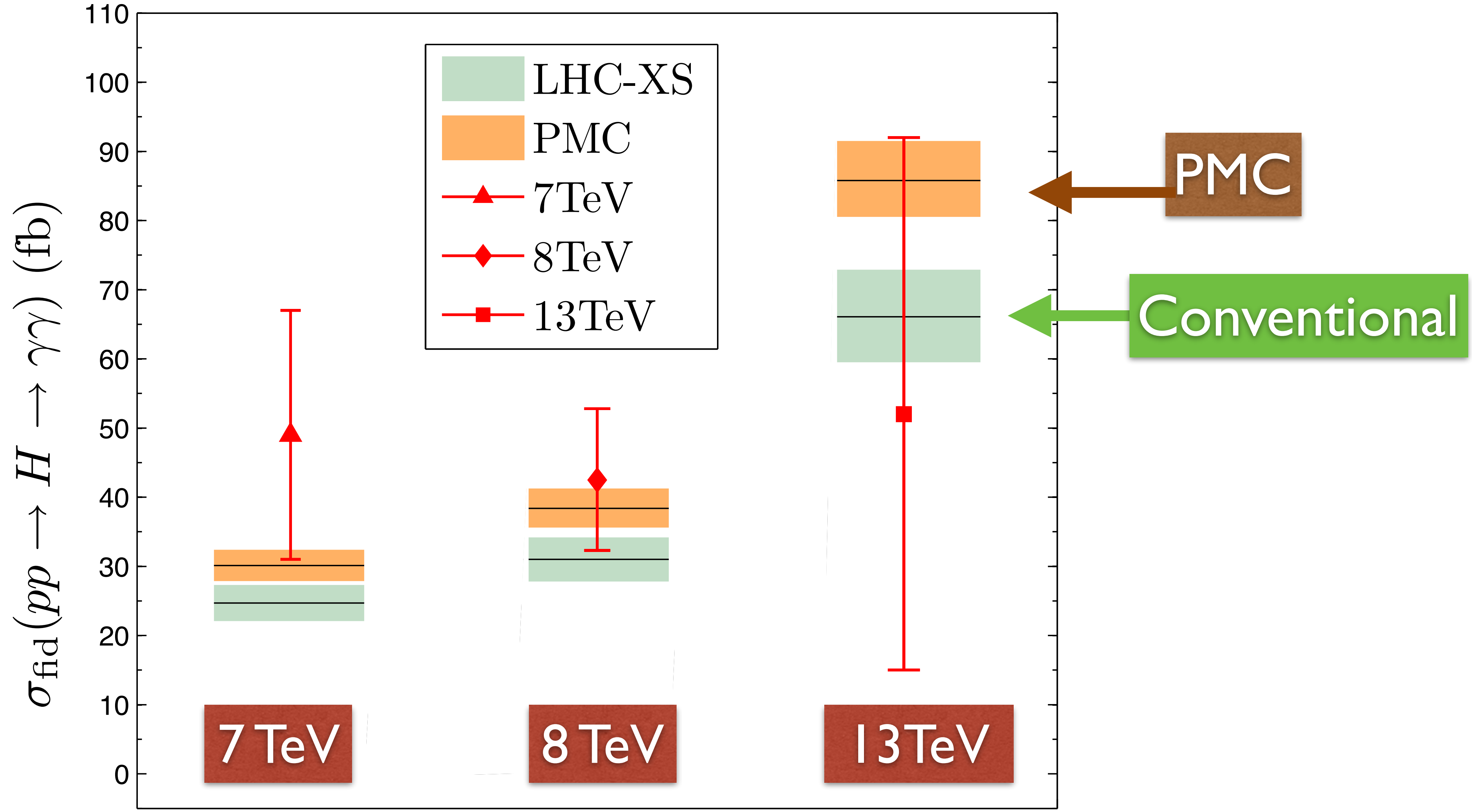
We present improved pQCD predictions for Higgs boson hadroproduction at the Large Hadronic Collider (LHC) by applying the Principle of Maximum Conformality (PMC), a procedure which resums the pQCD series using the renormalization group (RG), thereby eliminating the dependence of the predictions on the choice of the renormalization scheme while minimizing sensitivity to the initial choice of the renormalization scale. In previous pQCD predictions for Higgs boson hadroproduction, it has been conventional to assume that the renormalization scale μ_r of the QCD coupling $\alpha_s(\mu_r)$ is the Higgs mass, and then to vary this choice over the range $1/2m_H < \mu_r < 2m_H$ in order to estimate the theory uncertainty. However, this error estimate is only sensitive to the non-conformal β terms in the pQCD series, and thus it fails to correctly estimate the theory uncertainty in cases where pQCD series has large higher order contributions, as is the case for Higgs boson hadroproduction. Furthermore, this *ad hoc* choice of scale and range gives pQCD predictions which depend on the renormalization scheme being used, in contradiction to basic RG principles. In contrast, after applying the PMC, we obtain next-to-next-to-leading order RG resummed pQCD predictions for Higgs boson hadroproduction which are renormalization-scheme independent and have minimal sensitivity to the choice of the initial renormalization scale. Taking $m_H = 125$ GeV, the PMC predictions for the $pp \to HX$ Higgs inclusive hadroproduction cross-sections for various LHC center-of-mass energies are: $\sigma_{\rm Incl}|_{7\,{\rm TeV}} = 21.21^{+1.36}_{-1.32}$ pb, $\sigma_{\rm Incl}|_{8\,{\rm TeV}} = 27.37^{+1.65}_{-1.59}$ pb, and $\sigma_{\rm Incl}|_{13\,{\rm TeV}} = 65.72^{+3.46}_{-3.01}$ pb, respectively. We also predict the fiducial cross section $\sigma_{\rm fid}(pp \to H \to \gamma\gamma)$: $\sigma_{\rm fid}|_{7\,{\rm TeV}} = 30.1^{+2.3}_{-2.2}$ fb, $\sigma_{\rm fid}|_{8\,{\rm TeV}} = 38.3^{+2.9}_{-2.8}$ fb, and $\sigma_{\rm fid}|_{13\,{\rm TeV}} = 85.8^{+5.7}_{-5.3}$ fb. The error limits in these predictions include the small residual high-order renormalization-scale dependence, plus the uncertainty from the factorization-scale. The PMC predictions show better agreement with the ATLAS measurements than the LHC-XS predictions which are based on conventional renormalization scale-setting.



$\sigma^{gg}(pp \to HX)$
H_1
H_2
$f_{i/H_1}(x_1, \mu_f)$
$f_{j/H_2}(x_2, \mu_f)$
i
j
g
g
$\mathcal{L}_{ij}$
$\hat{\sigma}_{ij}$
H

S-Q Wang, X-G Wu, sjb

$$\sigma(pp \to HX \to \gamma\gamma X)$$

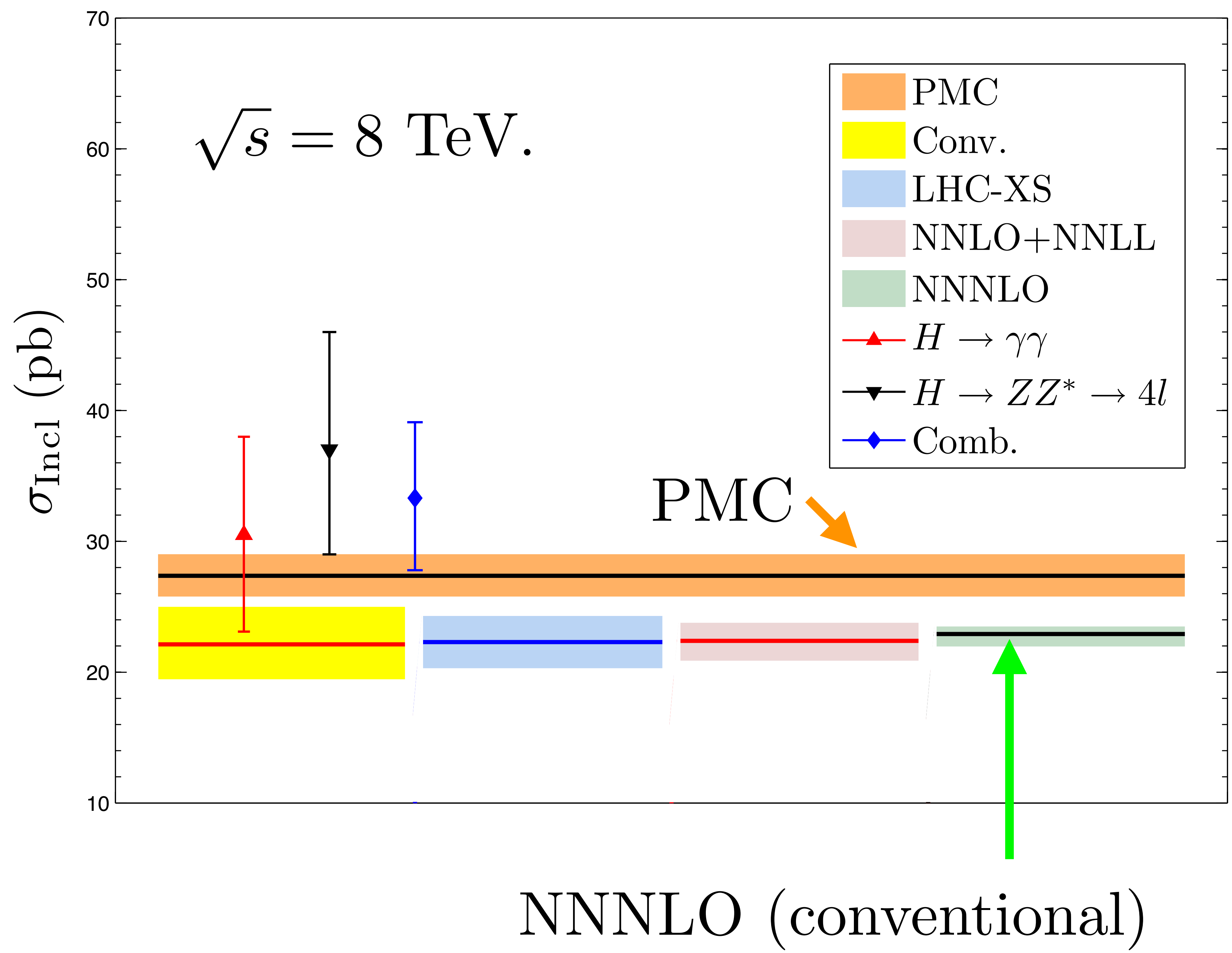


Comparison of the PMC predictions for the fiducial cross section $\sigma_{\rm fid}(pp \to H \to \gamma\gamma)$ with the ATLAS measurements at various collision energies. The LHC-XS predictions are presented as a comparison.

$\sigma_{\rm fid}(pp \to H \to \gamma\gamma)$	7 TeV	8 TeV	13 TeV
ATLAS data [48]	49 ± 18	$42.5^{+10.3}_{-10.2}$	52^{+40}_{-37}
LHC-XS [3]	24.7 ± 2.6	31.0 ± 3.2	$66.1^{+6.8}_{-6.6}$
PMC prediction	$30.1^{+2.3}_{-2.2}$	$38.4^{+2.9}_{-2.8}$	$85.8^{+5.7}_{-5.3}$

S-Q Wang, X-G Wu, sjb

$$\sigma^{gg}(pp \to HX)$$



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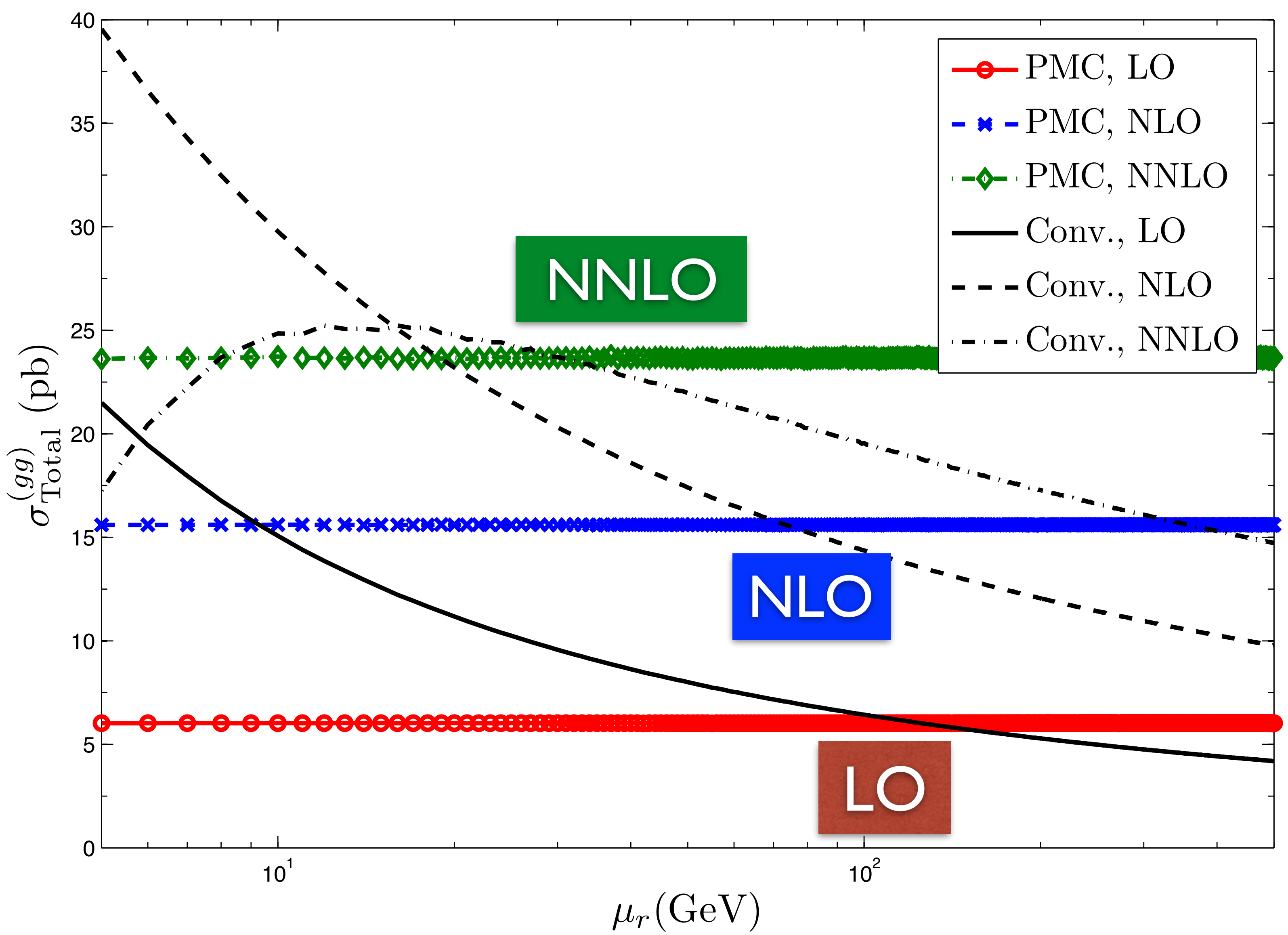
PMC insensitive to initial scale choice

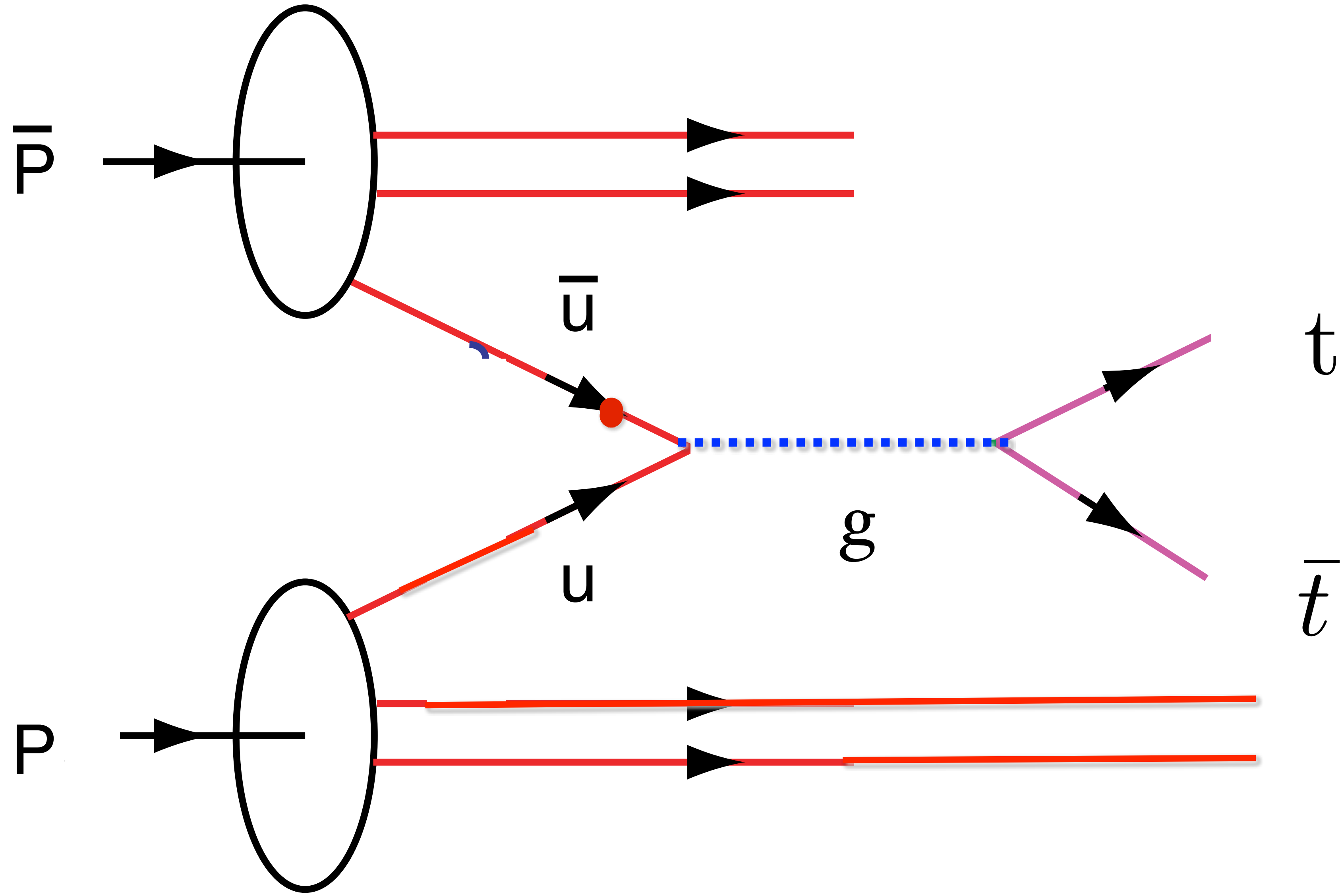
Different PMC scales at each order!

$$\sigma^{gg}(pp \to HX)$$



The gluon-fusion total cross-sections $\sigma^{(gg)}_{\rm Total}$ up to LO, NLO and NNLO levels versus the initial scale μ_r under conventional (Conv.) and PMC scale-settings with the collision energy $\sqrt{S} = 8$ TeV.

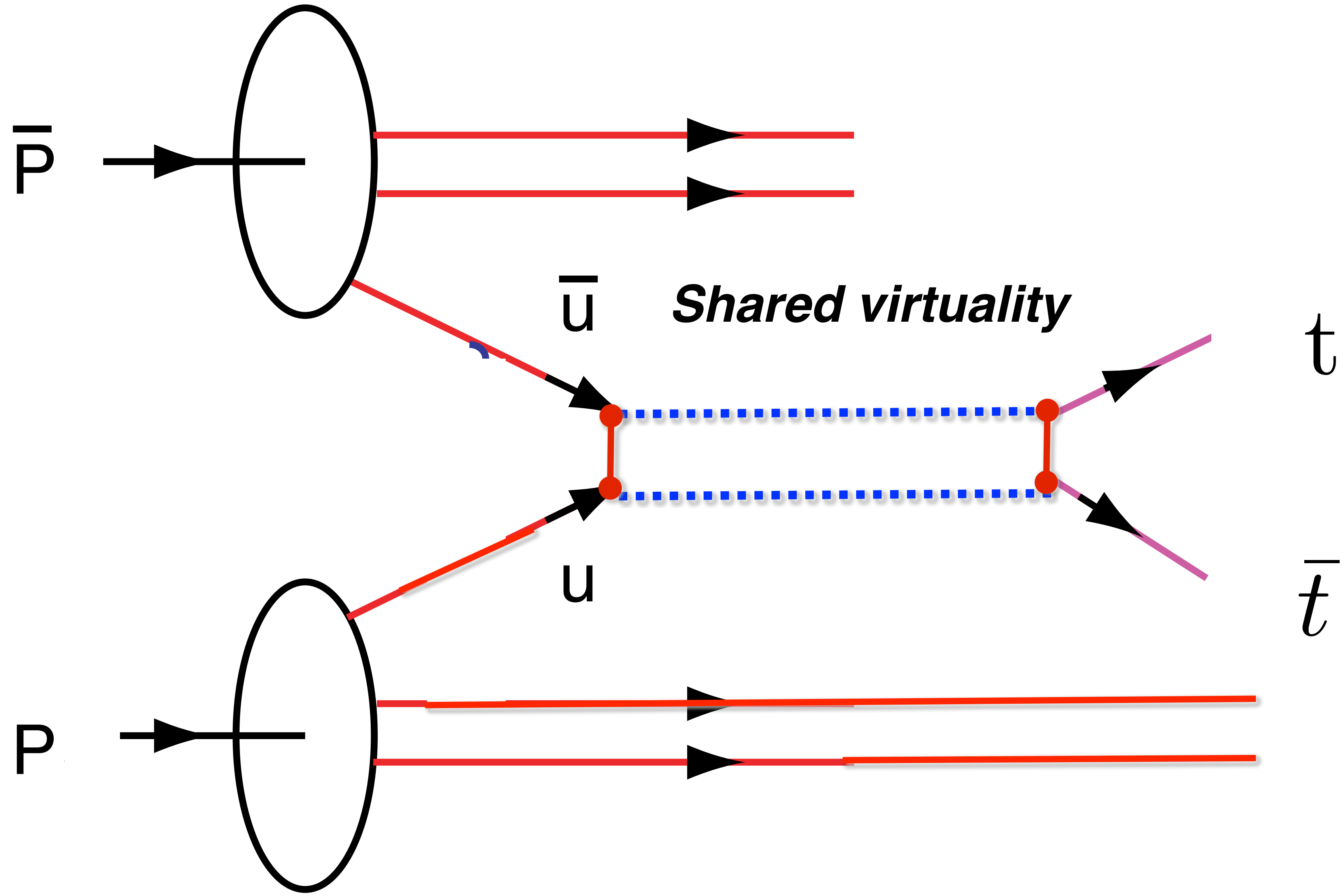
Implications for the $\bar{p}p \to t\bar{t}X$ asymmetry at the Tevatron



Born term.

Xing-Gang Wu, sjb

Implications for the $\bar{p}p \to t\bar{t}X$ asymmetry at the Tevatron



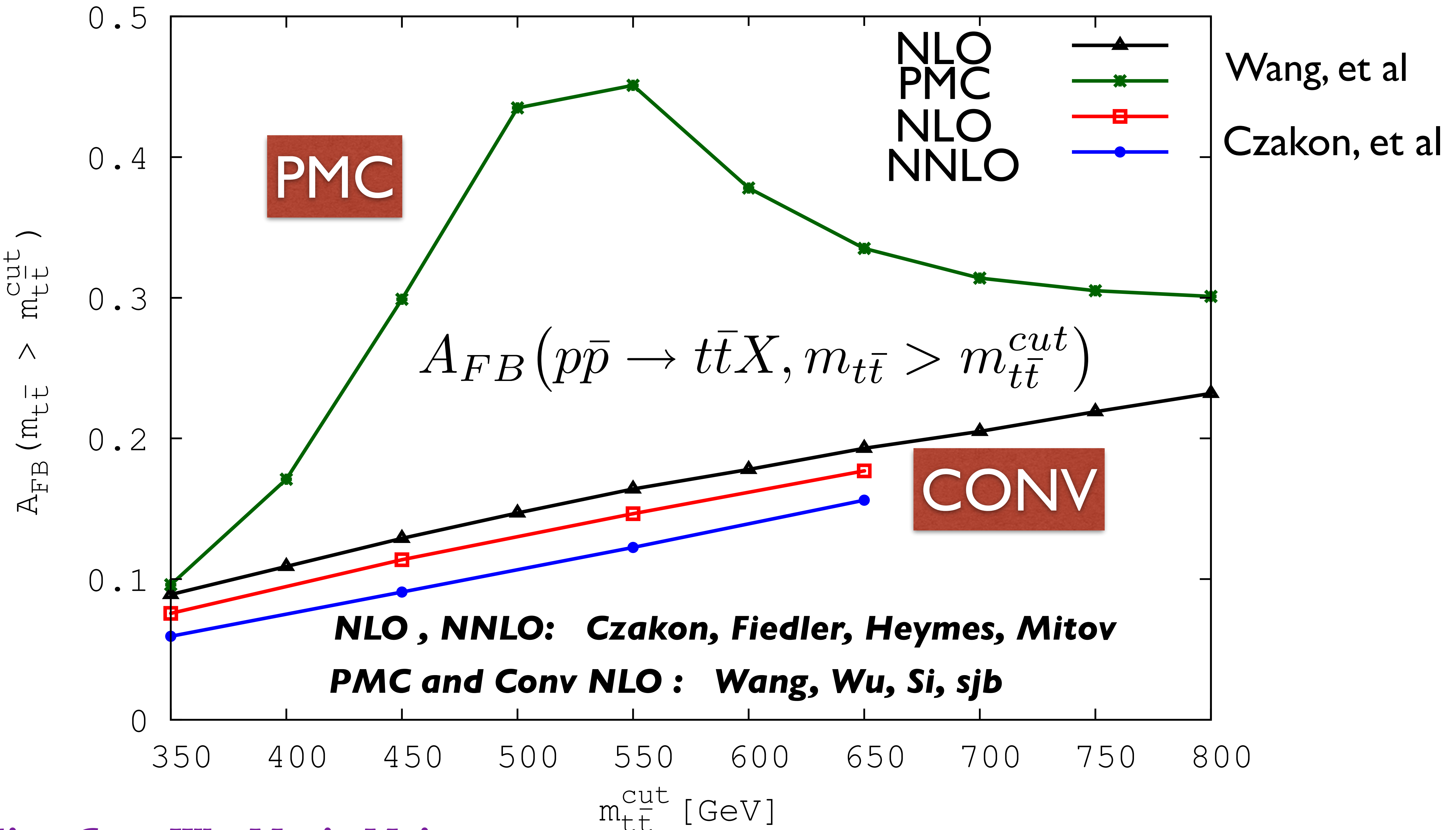
Interferes with Born term.

Small value of renormalization scale increases asymmetry, just as in QED!!

Xing-Gang Wu, sjb

NNLO QCD predictions for fully-differential top-quark pair production at the Tevatron arXiv:1601.05375

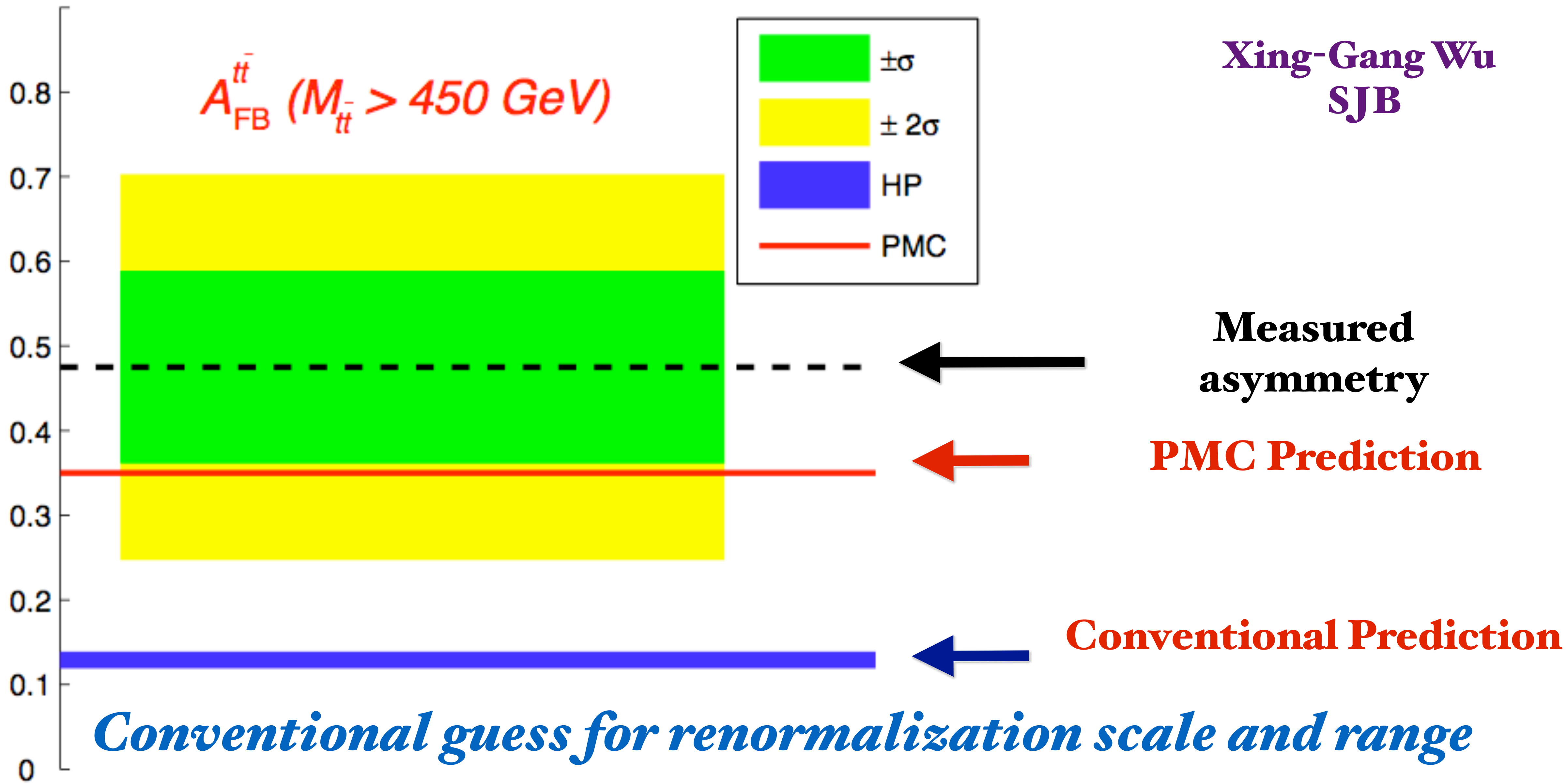
Michał Czakon,[a] Paul Fiedler,[a] David Heymes[b] and Alexander Mitov[b]



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

Predictions for the cumulative front-back asymmetry.

The Renormalization Scale Ambiguity for Top-Pair Production Eliminated Using the 'Principle of Maximum Conformality' (PMC)

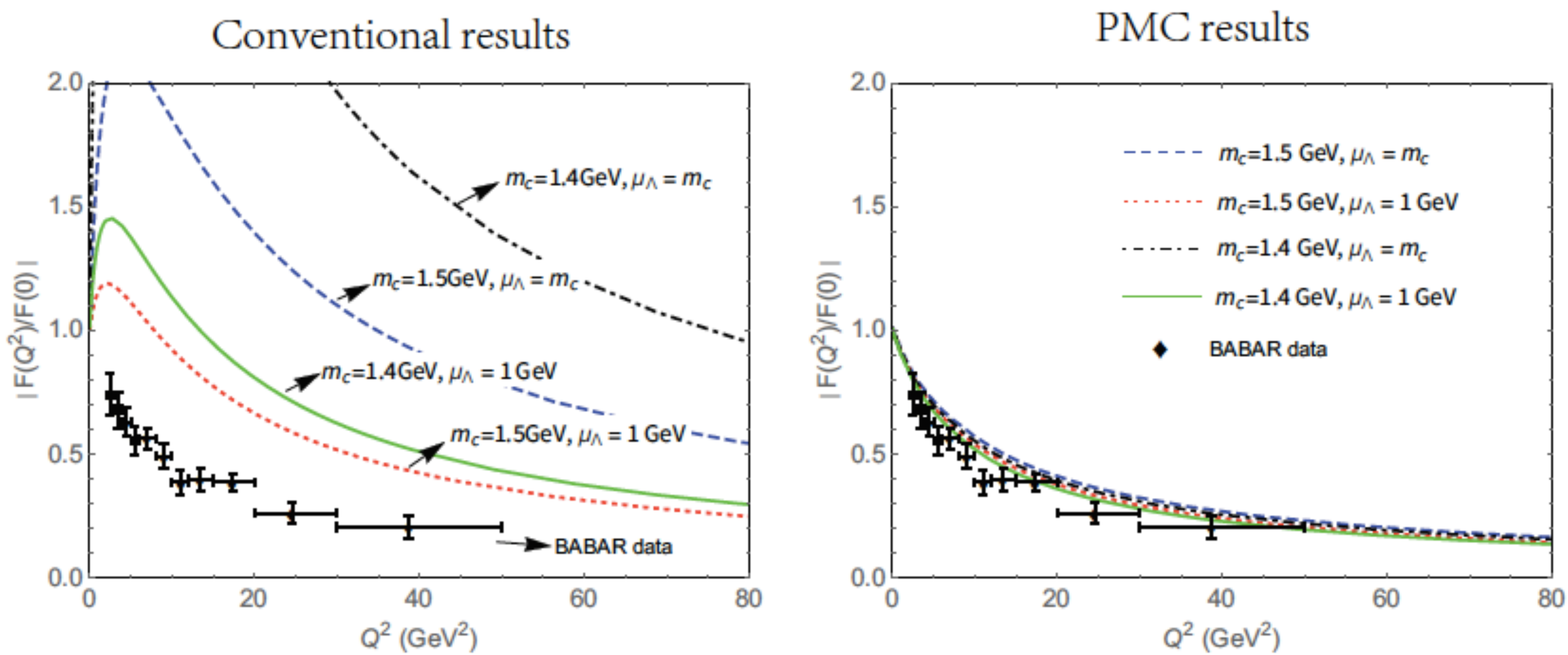


BLM/PMC: Scheme-Independent, same as Gell-Mann-Low in pQED

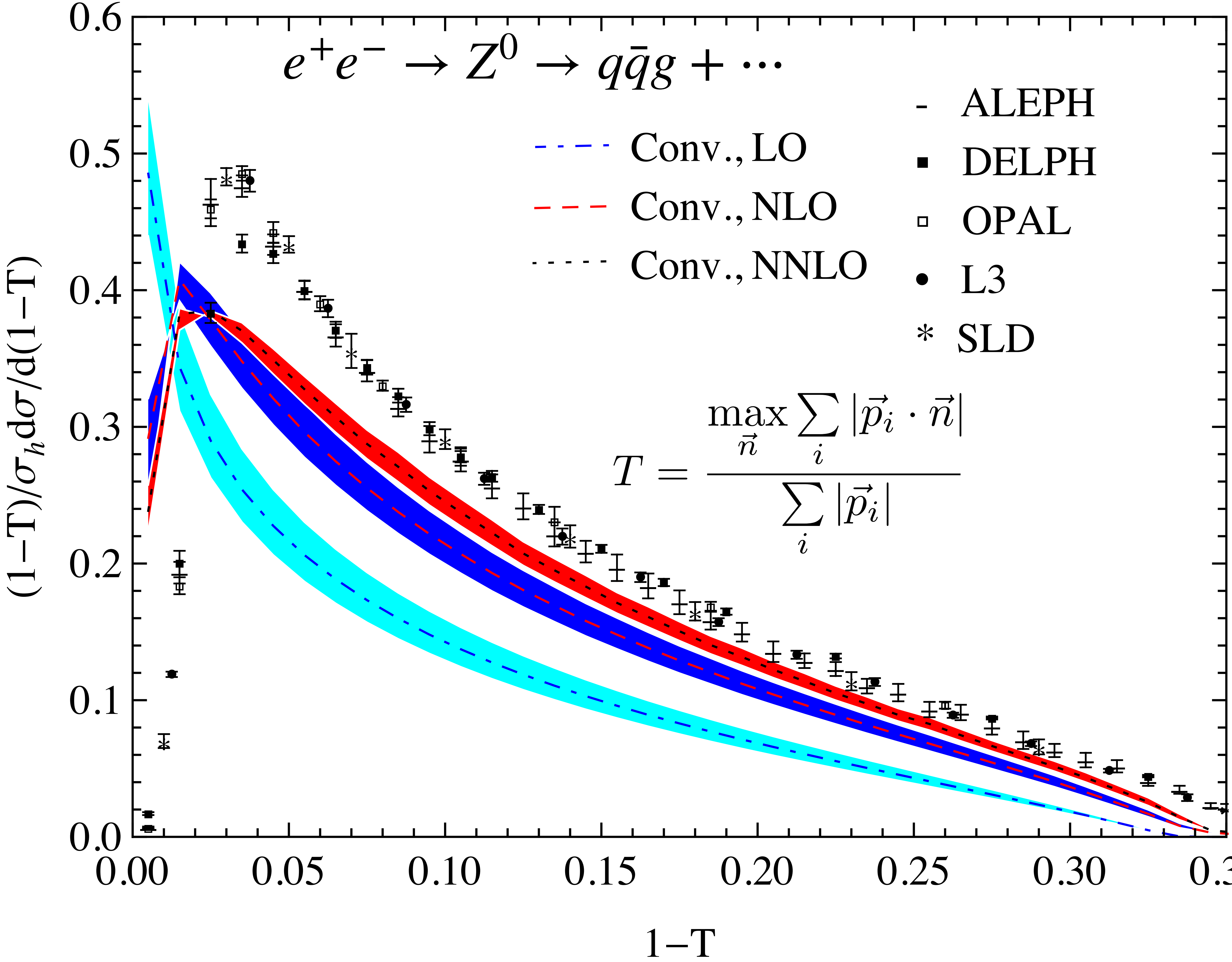
Top quark forward-backward asymmetry predicted by pQCD NNLO within 1 σ of CDF/D0 measurements using PMC/BLM scale setting

A solution to the $\gamma\gamma^* \to \eta_c$ puzzle using the Principle of Maximum Conformality

Sheng-Quan Wang[1,2],* Xing-Gang Wu[2],† Wen-Long Sang[3,4],‡ and Stanley J. Brodsky[5]§

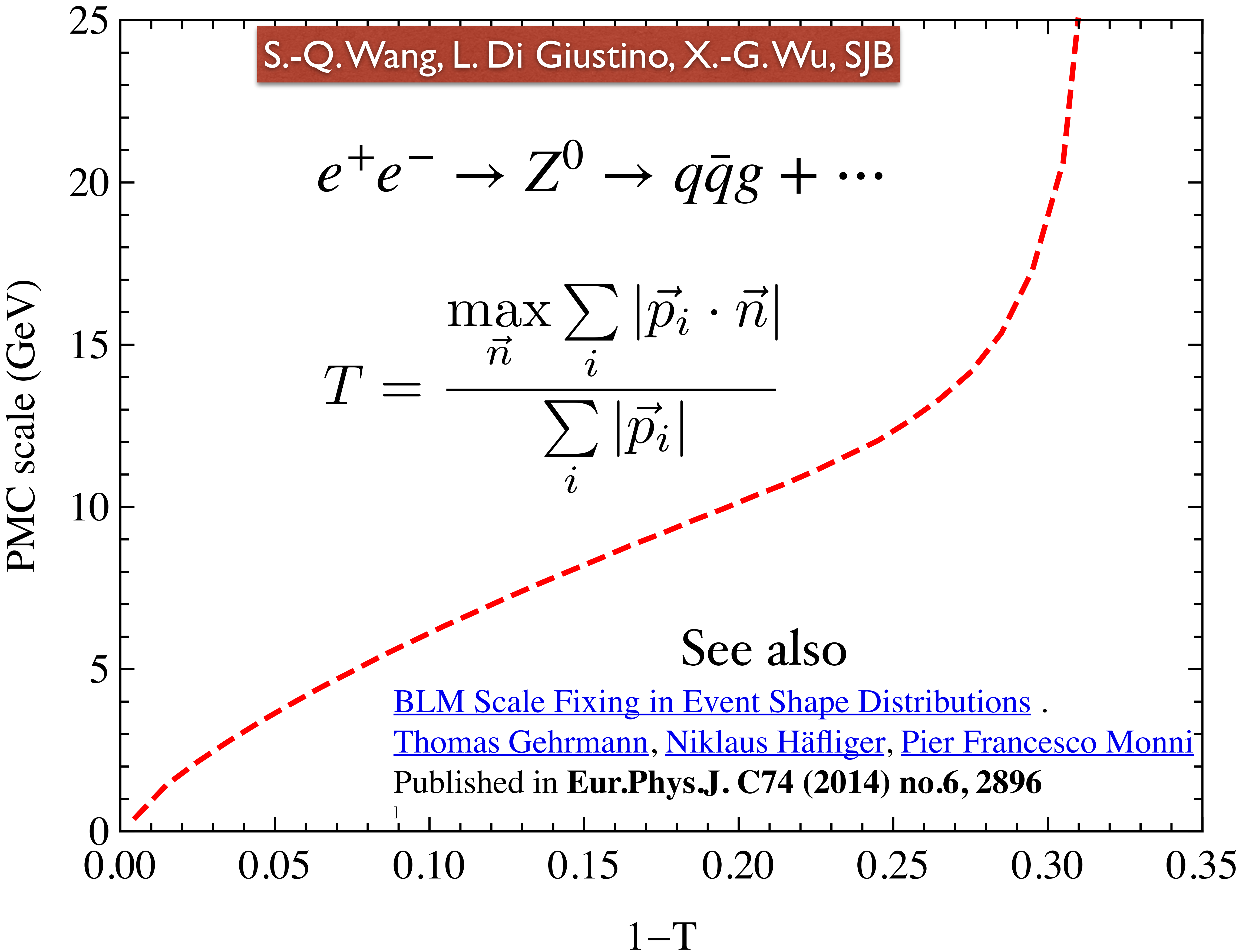


The transition form factor ratio $|F(Q^2)/F(0)|$ versus the momentum transfer squared Q^2 under conventional (Up) [3] and PMC (Down) scale setting. $m_c = 1.5$, 1.4 GeV.



$e^+e^- \to Z^0 \to q\bar{q}g + \cdots$
Conv., LO
Conv., NLO
Conv., NNLO
ALEPH
DELPH
OPAL
L3
SLD
$T = \frac{\max_{\vec{n}} \sum_i |\vec{p}_i \cdot \vec{n}|}{\sum_i |\vec{p}_i|}$
$(1-T)/\sigma_h d\sigma/d(1-T)$
1−T
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.00
0.05
0.10
0.15
0.20
0.25
0.30

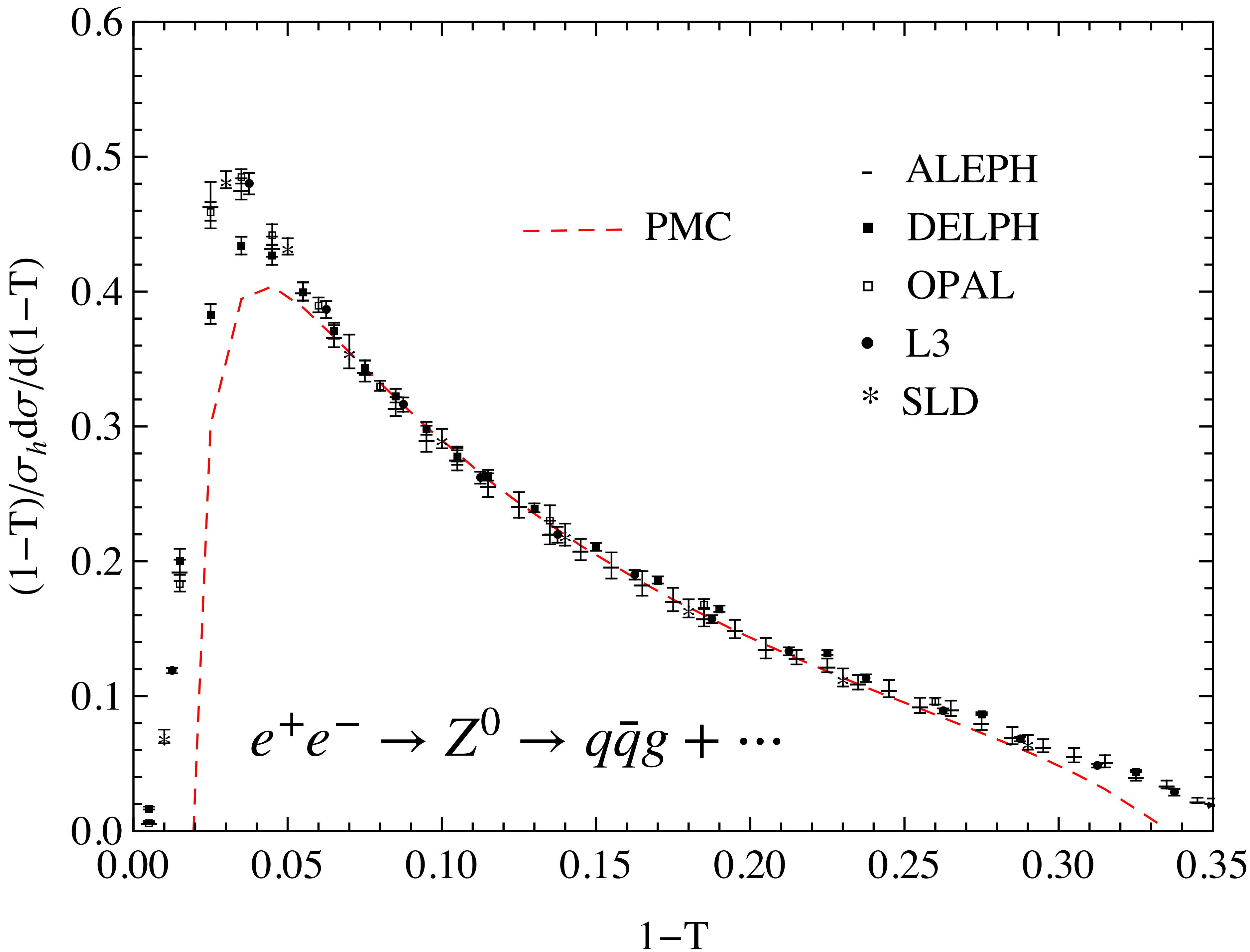
Renormalization scale depends on thrust T!



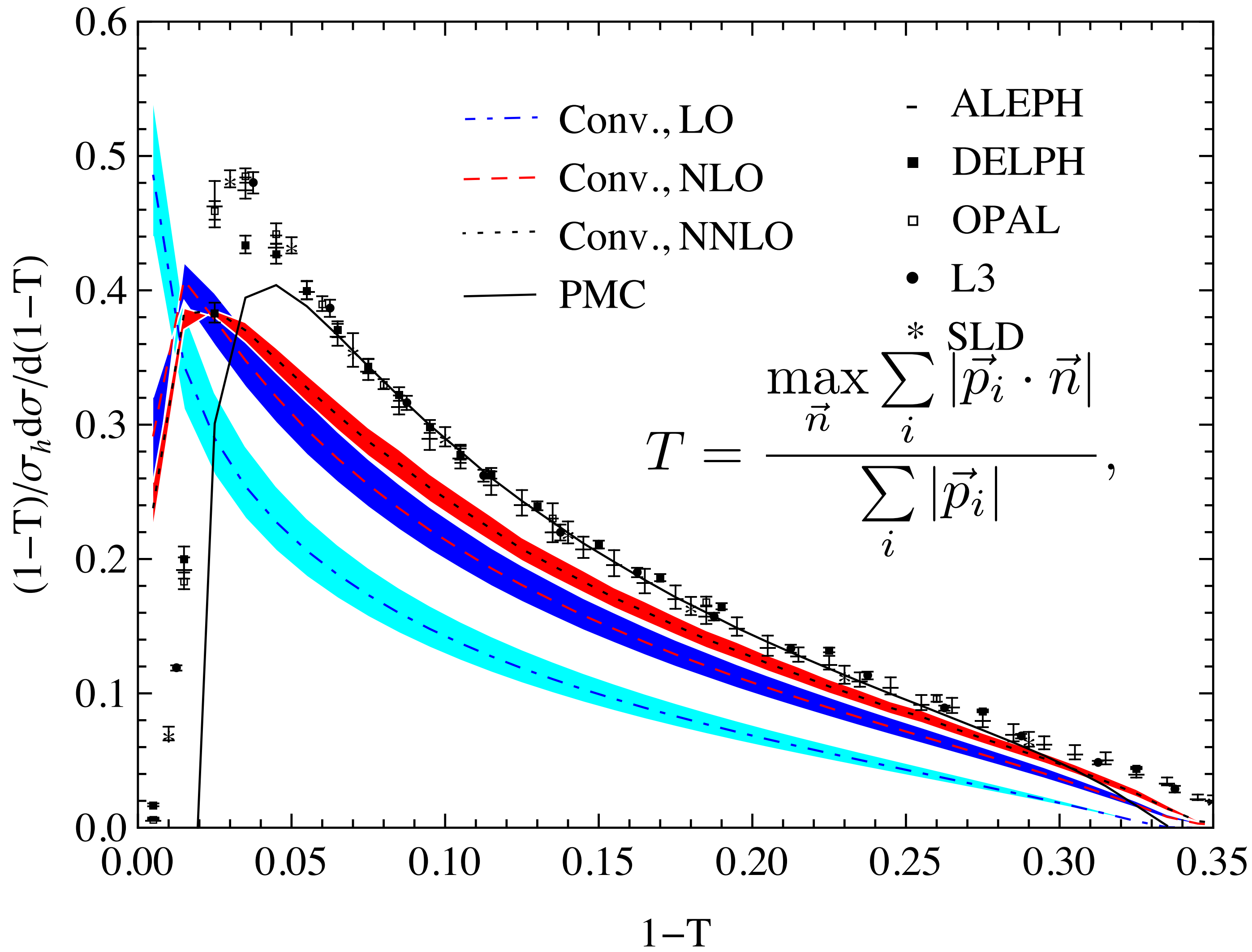
$\alpha_s(Q^2)$ *in* $\overline{MS}$ *scheme*

Thrust Distribution in Electron-Positron Annihilation using the Principle of Maximum Conformality

S.-Q. Wang, L. Di Giustino, X.-G. Wu, SJB



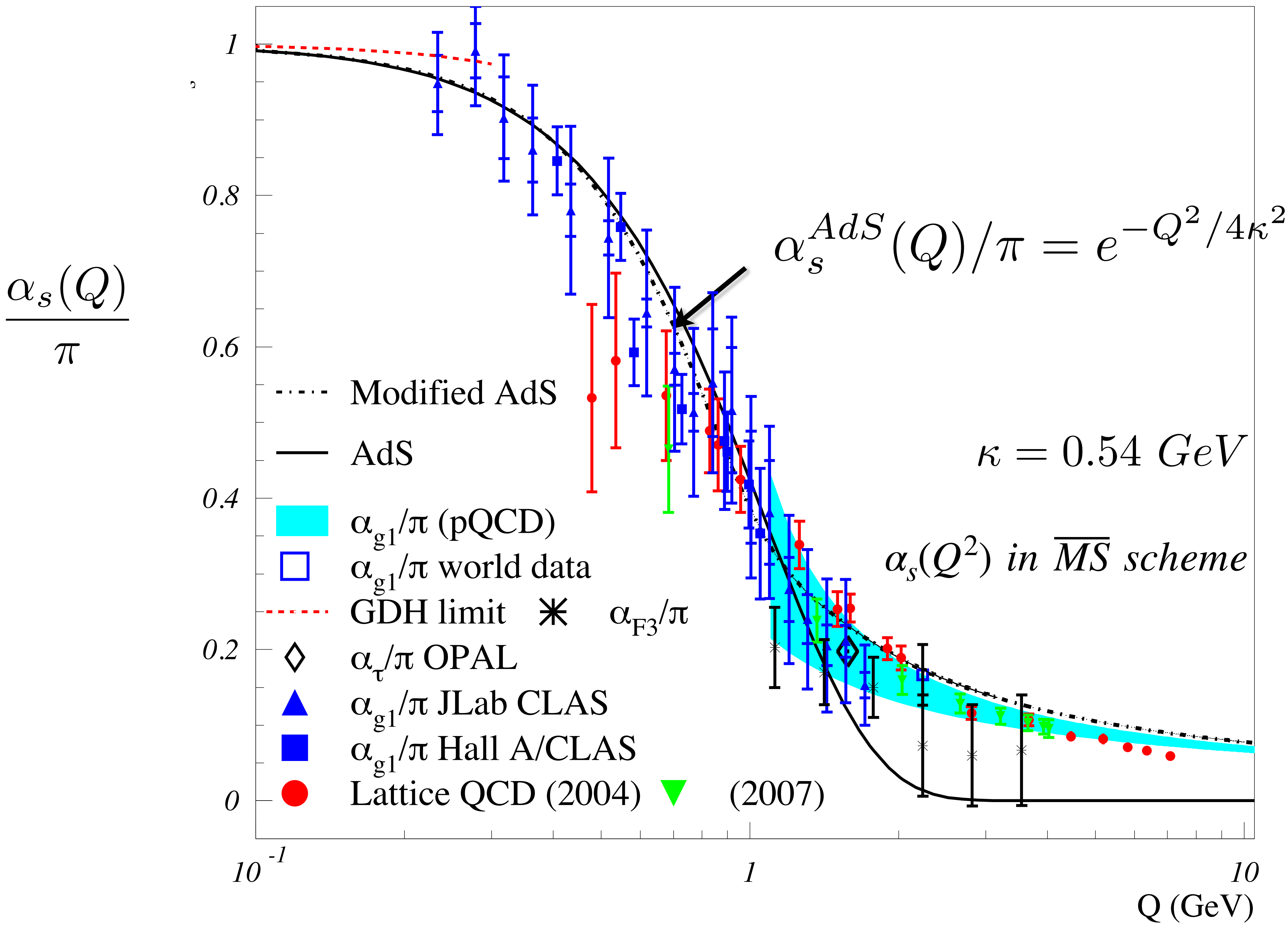
S.-Q. Wang, L. Di Giustino, X.-G. Wu, SJB



$$T = \frac{\max\limits_{\vec{n}} \sum\limits_i |\vec{p}_i \cdot \vec{n}|}{\sum\limits_i |\vec{p}_i|},$$

The thrust $(1-T)$ differential distributions using the conventional (Conv.) and PMC scale settings. The dot-dashed, dashed and dotted lines are the conventional results at LO, NLO and NNLO, respectively. The solid line is the PMC result. The bands for the theoretical predictions are obtained by varying $\mu_r \in [M_Z/2, 2M_Z]$. The PMC prediction eliminates the scale μ_r uncertainty. The experimental data points are taken from the ALEPH [2], DELPH [3], OPAL [4], L3 [5] and SLD [38] experiments.

QCD Coupling defined at all scales, IR Fixed Point



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

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

Deur, de Teramond, sjb

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

$$m_p = 2\kappa$$

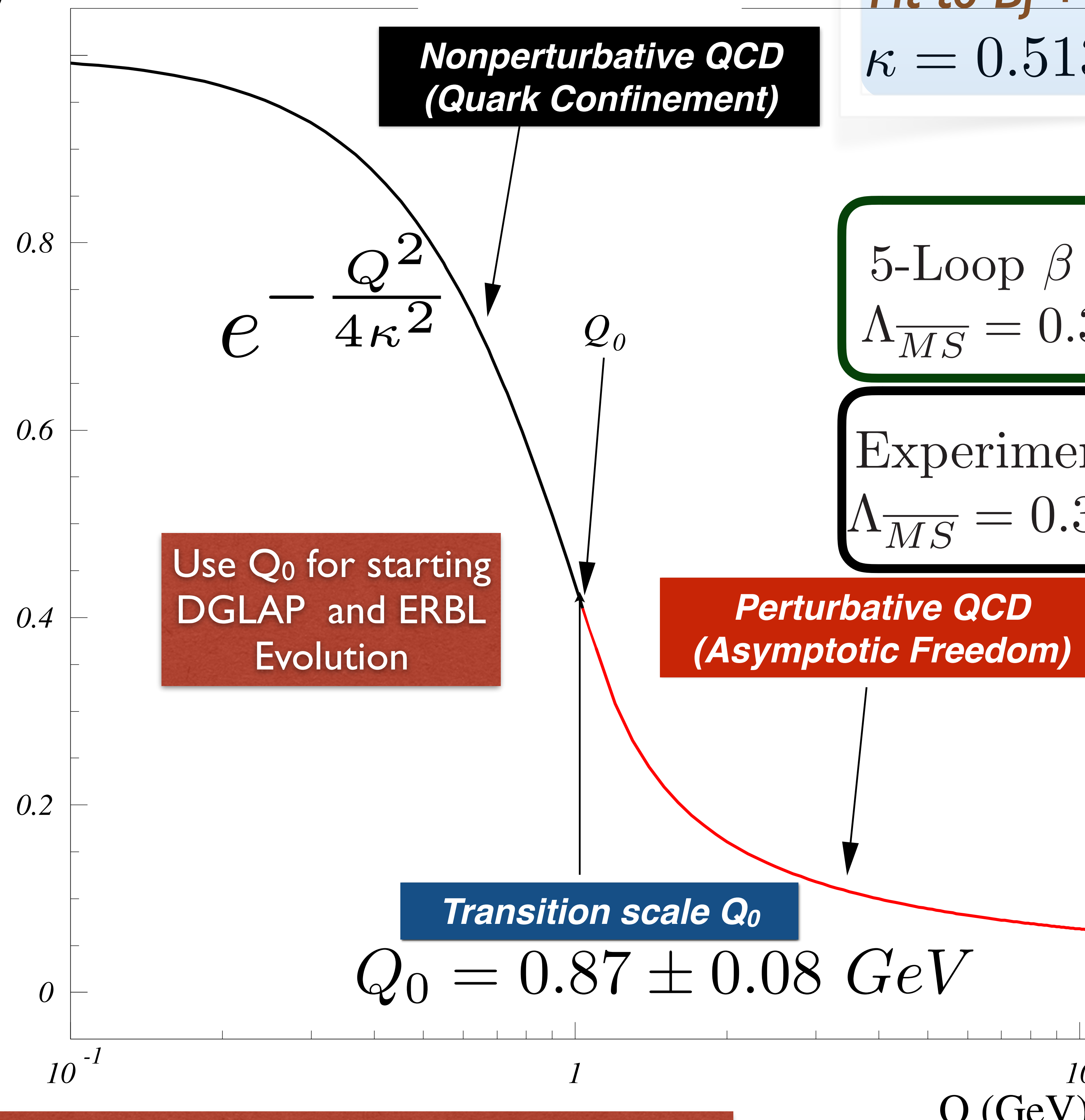
All-Scale QCD Coupling

Deur, de Tèramond, sjb

Fit to Bj + DHG Sum Rules:

$\kappa = 0.513 \pm 0.007\ GeV$

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



5-Loop β Prediction:

$\Lambda_{\overline{MS}} = 0.339 \pm 0.019\ GeV$

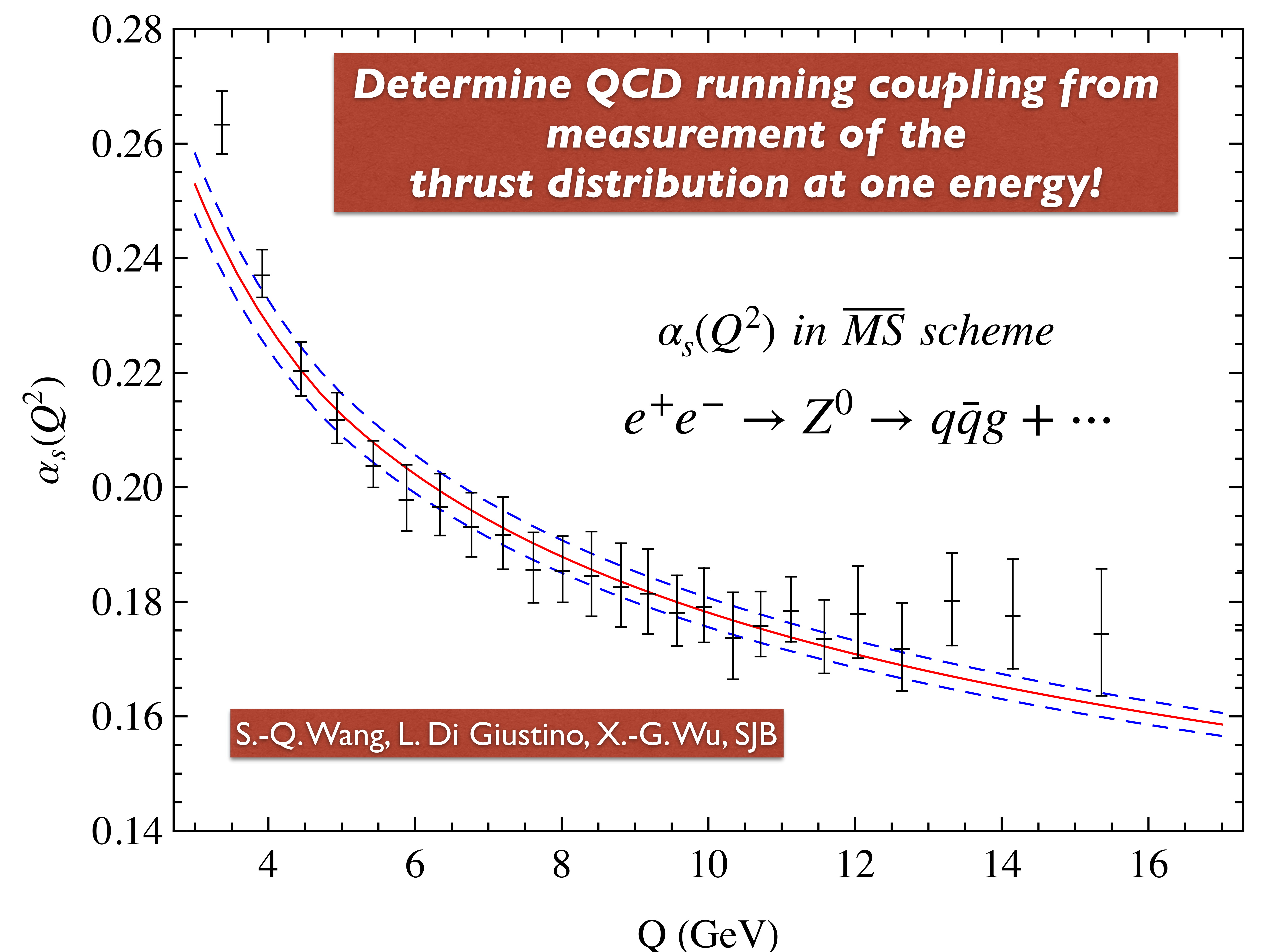
Experiment:

$\Lambda_{\overline{MS}} = 0.332 \pm 0.017\ GeV$

$\lambda \equiv \kappa^2$

Reverse Dimensional Transmutation!

$\overline{MS}$ *scheme*


Determine QCD running coupling from measurement of the thrust distribution at one energy!
$\alpha_s(Q^2)$ in $\overline{MS}$ scheme
$e^+e^- \to Z^0 \to q\bar{q}g + \cdots$
S.-Q. Wang, L. Di Giustino, X.-G. Wu, SJB
$\alpha_s(Q^2)$
Q (GeV)
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
4
6
8
10
12
14
16

Relate Observables to Each Other

- Eliminate intermediate scheme
- No scale ambiguity
- Transitive!
- Commensurate Scale Relations
- Conformal Template
- Example: Generalized Crewther Relation

$$R_{e^+e^-}(Q^2) \equiv 3 \sum_{\text{flavors}} e_q{}^2 \left[1 + \frac{\alpha_R(Q)}{\pi} \right] .$$

$$\int_0^1 dx \left[g_1^{ep}(x, Q^2) - g_1^{en}(x, Q^2) \right] \equiv \frac{1}{3} \left| \frac{g_A}{g_V} \right| \left[1 - \frac{\alpha_{g_1}(Q)}{\pi} \right]$$

$$
\begin{aligned}
\frac{\alpha_R(Q)}{\pi} = \frac{\alpha_{\overline{\rm MS}}(Q)}{\pi} &+ \left(\frac{\alpha_{\overline{\rm MS}}(Q)}{\pi}\right)^2 \left[\left(\frac{41}{8} - \frac{11}{3}\zeta_3\right) C_A - \frac{1}{8}C_F + \left(-\frac{11}{12} + \frac{2}{3}\zeta_3\right) f\right] \\
&+ \left(\frac{\alpha_{\overline{\rm MS}}(Q)}{\pi}\right)^3 \left\{\left(\frac{90445}{2592} - \frac{2737}{108}\zeta_3 - \frac{55}{18}\zeta_5 - \frac{121}{432}\pi^2\right) C_A^2 + \left(-\frac{127}{48} - \frac{143}{12}\zeta_3 + \frac{55}{3}\zeta_5\right) C_A C_F - \frac{23}{32}C_F^2 \right.\\
&+ \left[\left(-\frac{970}{81} + \frac{224}{27}\zeta_3 + \frac{5}{9}\zeta_5 + \frac{11}{108}\pi^2\right) C_A + \left(-\frac{29}{96} + \frac{19}{6}\zeta_3 - \frac{10}{3}\zeta_5\right) C_F\right] f \\
&\left. + \left(\frac{151}{162} - \frac{19}{27}\zeta_3 - \frac{1}{108}\pi^2\right) f^2 + \left(\frac{11}{144} - \frac{1}{6}\zeta_3\right) \frac{d^{abc}d^{abc}}{C_F d(R)} \frac{\left(\sum_f Q_f\right)^2}{\sum_f Q_f^2}\right\}.
\end{aligned}
$$

$$
\begin{aligned}
\frac{\alpha_{g_1}(Q)}{\pi} = \frac{\alpha_{\overline{\rm MS}}(Q)}{\pi} &+ \left(\frac{\alpha_{\overline{\rm MS}}(Q)}{\pi}\right)^2 \left[\frac{23}{12}C_A - \frac{7}{8}C_F - \frac{1}{3}f\right] \\
&+ \left(\frac{\alpha_{\overline{\rm MS}}(Q)}{\pi}\right)^3 \left\{\left(\frac{5437}{648} - \frac{55}{18}\zeta_5\right) C_A^2 + \left(-\frac{1241}{432} + \frac{11}{9}\zeta_3\right) C_A C_F + \frac{1}{32}C_F^2 \right.\\
&\left. + \left[\left(-\frac{3535}{1296} - \frac{1}{2}\zeta_3 + \frac{5}{9}\zeta_5\right) C_A + \left(\frac{133}{864} + \frac{5}{18}\zeta_3\right) C_F\right] f + \frac{115}{648} f^2\right\}.
\end{aligned}
$$

Eliminate $\overline{\text{MS}}$

Find Amazing Simplification

$$R_{e^+e^-}(Q^2) \equiv 3 \sum_{\text{flavors}} e_q{}^2 \left[1 + \frac{\alpha_R(Q)}{\pi} \right].$$

$$\int_0^1 dx \left[g_1^{ep}(x, Q^2) - g_1^{en}(x, Q^2) \right] \equiv \frac{1}{3} \left| \frac{g_A}{g_V} \right| \left[1 - \frac{\alpha_{g_1}(Q)}{\pi} \right]$$

$$\frac{\alpha_{g_1}(Q)}{\pi} = \frac{\alpha_R(Q^*)}{\pi} - \left(\frac{\alpha_R(Q^{**})}{\pi} \right)^2 + \left(\frac{\alpha_R(Q^{***})}{\pi} \right)^3$$

Geometric Series in Conformal QCD

Generalized Crewther Relation

Lu, Kataev, Gabadadze, Sjb

Lu, Kataev, Gabadadze, Sjb

Generalized Crewther Relation

$$[1+\frac{\alpha_R(s^*)}{\pi}][1-\frac{\alpha_{g_1}(q^2)}{\pi}]=1$$

$$\sqrt{s^*}\simeq 0.52Q$$

Conformal relation true to all orders in perturbation theory!

No radiative corrections to axial anomaly

Nonconformal terms set relative scales (BLM)

No renormalization scale ambiguity!

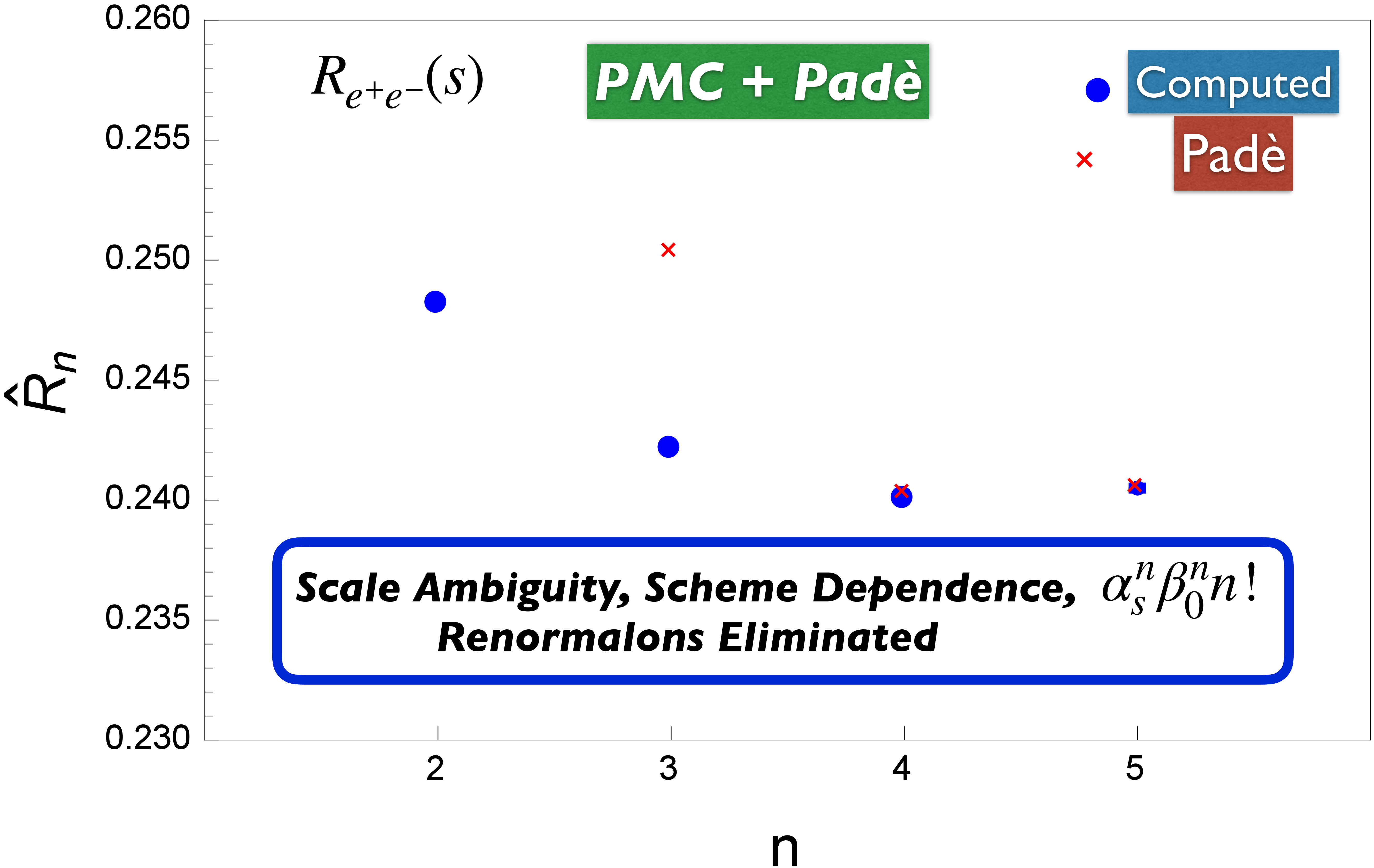
Both observables go through new quark thresholds at commensurate scales!

Renormalization Scales, and Momentum Flow in Feynman Diagrams

John Ellis, Einan Gardi, Marek Karliner, Mark Samuel, sjb

Abstract: We show that the Pade Approximant (PA) approach for resummation of perturbative series in QCD provides a systematic method for approximating the flow of momentum in Feynman diagrams. In the large-β_0 limit, diagonal PA's generalize the Brodsky-Lepage-Mackenzie (BLM) scale-setting method to higher orders in a renormalization scale- and scheme-invariant manner, using multiple scales that represent Neubert's concept of the distribution of momentum flow through a virtual gluon. If the distribution is non-negative, the PA's have only real roots, and approximate the distribution function by a sum of delta-functions, whose locations and weights are identical to the optimal choice provided by the Gaussian quadrature method for numerical integration. We show how the first few coefficients in a perturbative series can set rigorous bounds on the all-order momentum distribution function, if it is positive. We illustrate the method with the vacuum polarization function and the Bjorken sum rule computed in the large-β_0 limit.

Studies of higher-order perturbative QCD diagrams are often made by first de- composing them in a skeleton expansion, in which each term contains chains of vacuum polarization bubbles inserted in virtual-gluon propagators. These have been studied in the BLM approach, which seeks the optimal scale for evaluating each term in the skeleton expansion. The last step, the sum over skeleton graphs, is then similar to summation of perturbative contributions for a corresponding theory with β = 0, i.e., a conformal theory. We shall adopt a similar procedure here.



Extending the Predictive Power of pQCD

B-L Dun, X-G. Wu, J.M, Shen, sjb

Problems with traditional scale setting

- *Predictions are scheme-dependent! At every order! This fundamental flaw does not get repaired at high orders*
- *Fails to satisfy Renormalization Group Principles*
- *Guessing the renormalization scale and its range is heuristic*
- *Gives wrong predictions for QED*
- *GUT: Must use the same scale-setting procedure for QED, QCD*
- *n! Renormalon growth — no convergence of pQCD*
- *Uses the same scale at each order.*
- *guessed value for n_f does not correctly reflect quark loop virtuality*
- *Multiple Physical Scales cannot be Incorporated*
- *Unrealistic Estimate of Higher-Order Terms: Only β-terms exposed by scale variation*
- *Introduces an unnecessary theory error!*
- *Can give wrong predictions for pQCD observables*
- *Obscures sensitivity to new physics*

Essential Points

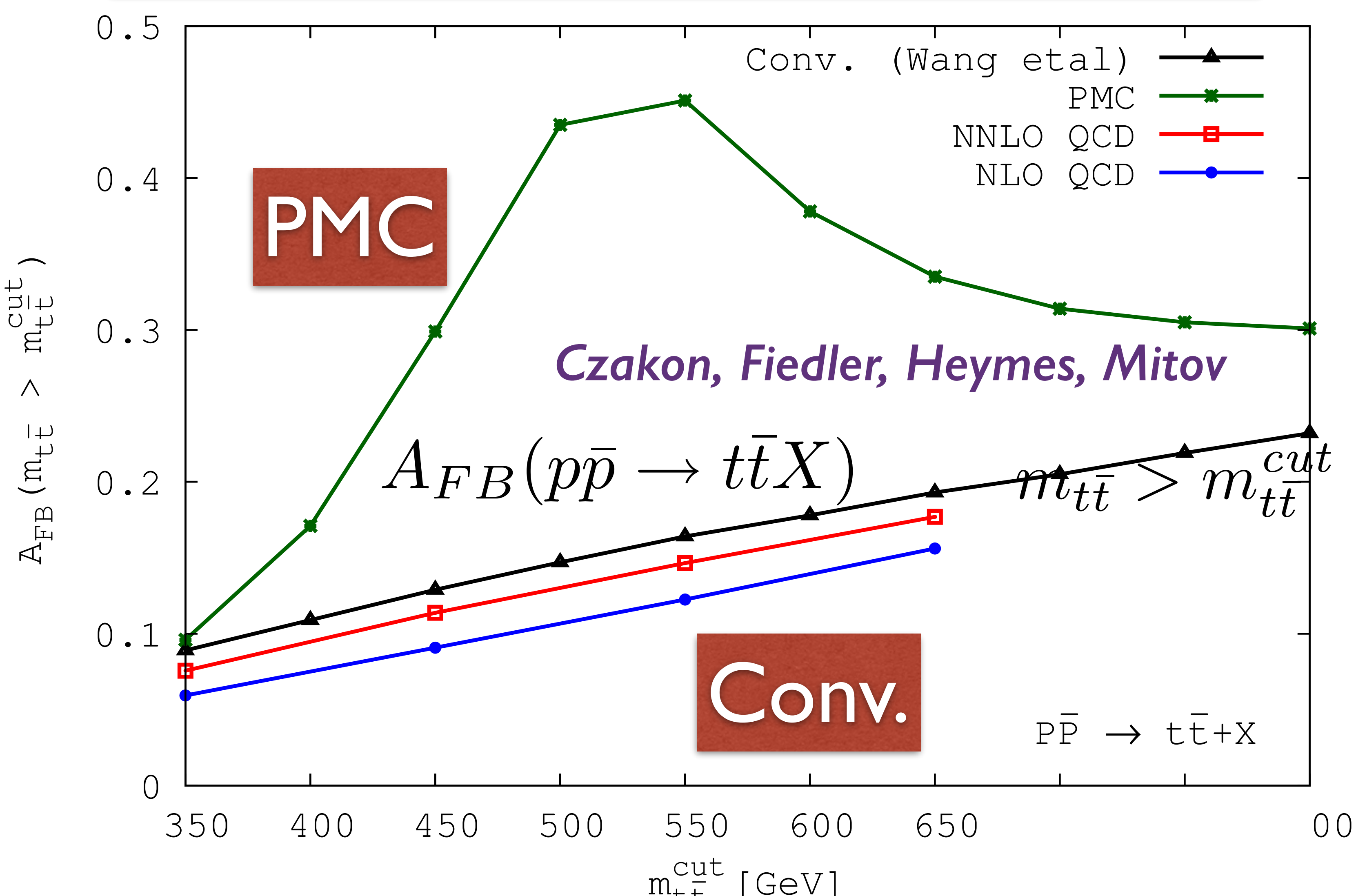
- ***Physical Results cannot depend on choice of Scheme***
- ***Different PMC scales at each order***
- ***No scale ambiguity!***
- ***Series identical to conformal theory***
- ***Relation between observables scheme independent, transitive***
- ***Choice of initial scale irrelevant even at finite order***
- ***Identify β terms using R_δ method***

Features of BLM/PMC

- *Predictions are scheme-independent at every order*
- *Matches conformal series*
- *No n! Renormalon growth of pQCD series*
- *New scale appears at each order; n_F determined at each order - matches virtuality of quark loops*
- *Multiple Physical Scales Incorporated (Hoang, Kuhn, Tuebner, sjb)*
- *Rigorous: Satisfies all Renormalization Group Principles*
- *Realistic Estimate of Higher-Order Terms*
- *Reduces to standard QED scale* $N_C \to 0$
- *GUT: Must use the same scale setting procedure for QED, QCD*
- *Eliminates unnecessary theory error*
- *Maximal sensitivity to new physics*
- *Commensurate Scale Relations between observables: Generalized Crewther Relation (Kataev, Lu, Rathsman, sjb)*
- *Reduces to BLM at NLO: Example: BFKL intercept* **(Fadin, Kim, Lipatov, Pivovarov, sjb)**

The QCD coupling at all scales and the elimination of renormalization scale uncertainties

The Principle of Maximum Conformality (PMC)



BLM: G. Peter Lepage
Paul Mackenzie

PMC: Leonardo di Giustino
Xing-Gang Wu
Matin Mojaza
Sheng-Quan Wang

LFHQCD: Alexandre Deur
H. Guenter Dosch,
G.de Tèramond

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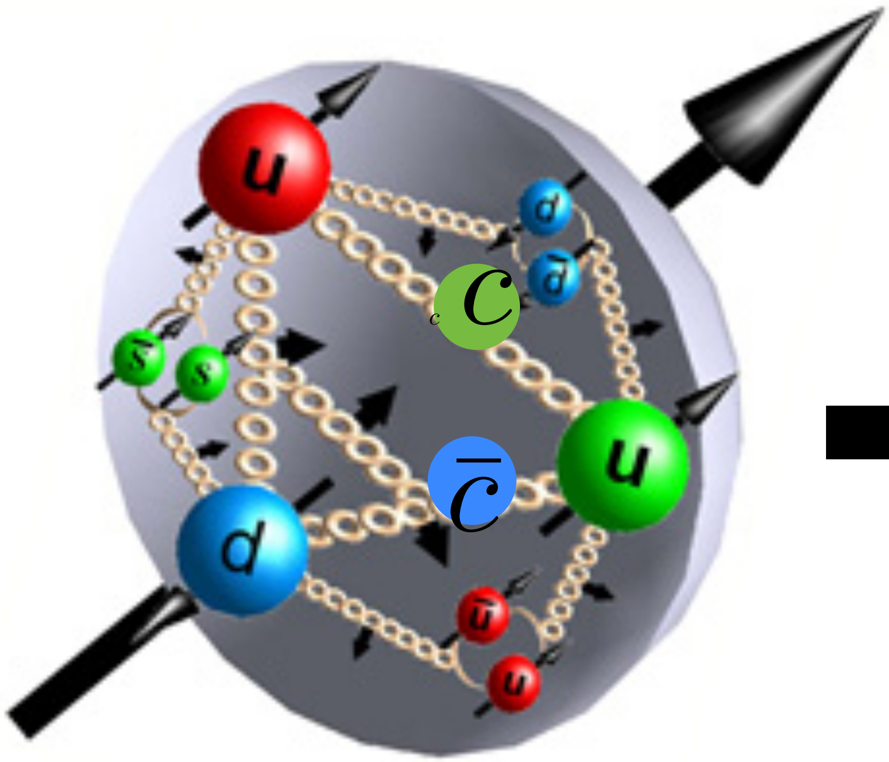
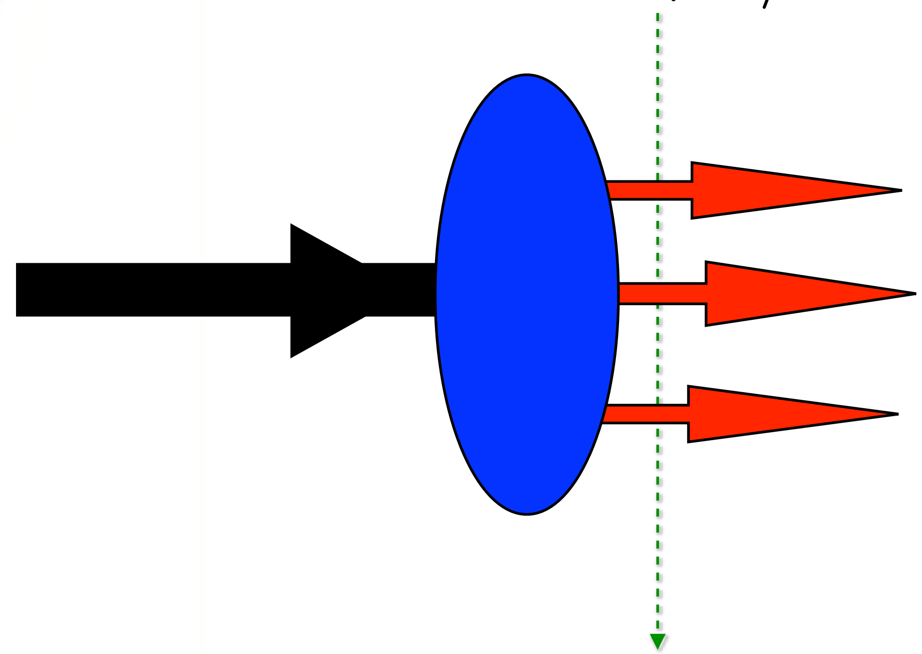
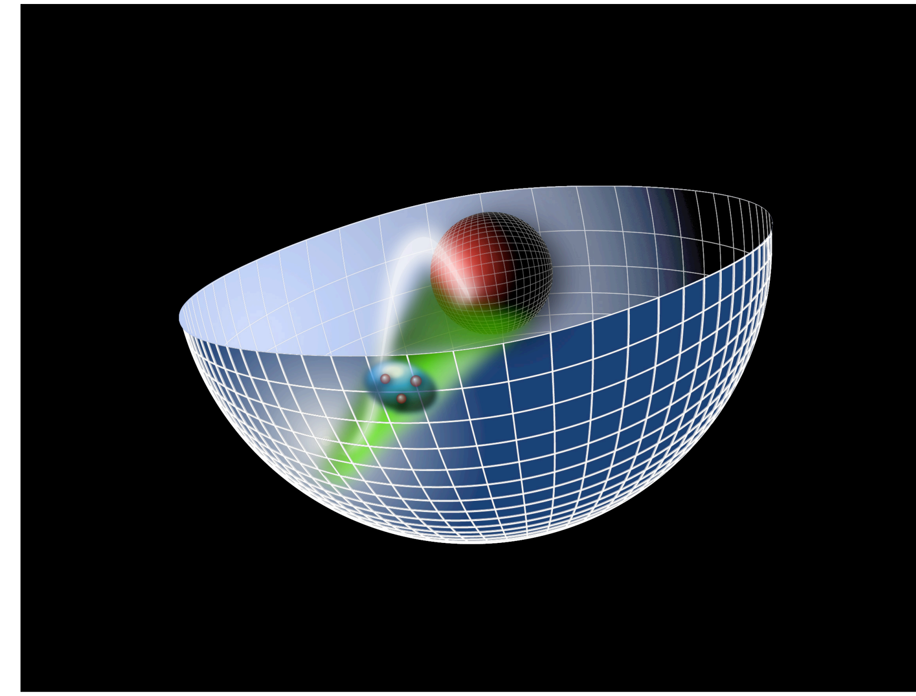
Novel QCD Features of Hadrons and Nuclei







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with Guy de Tèramond, Hans Günter Dosch, and Alexandre Deur

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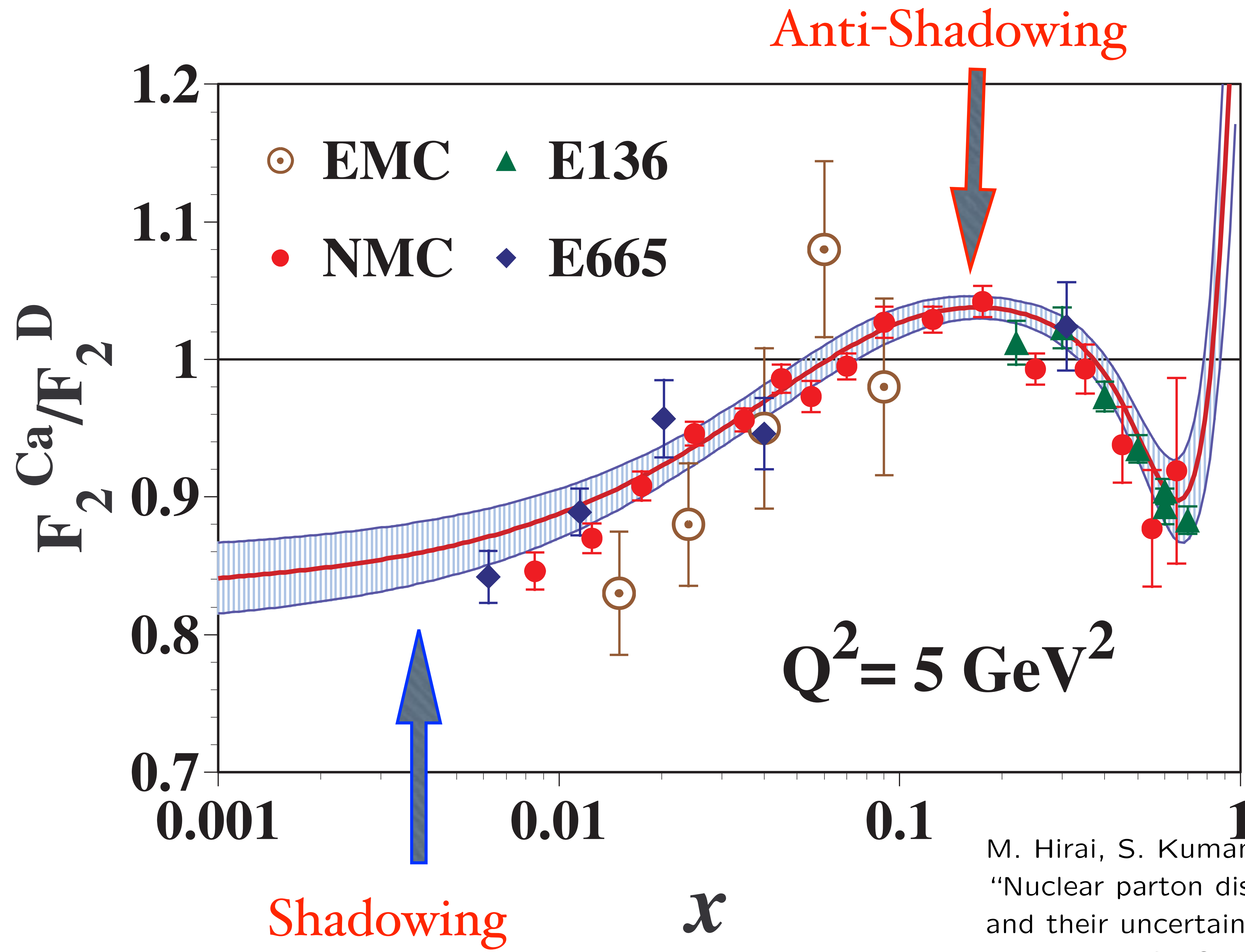
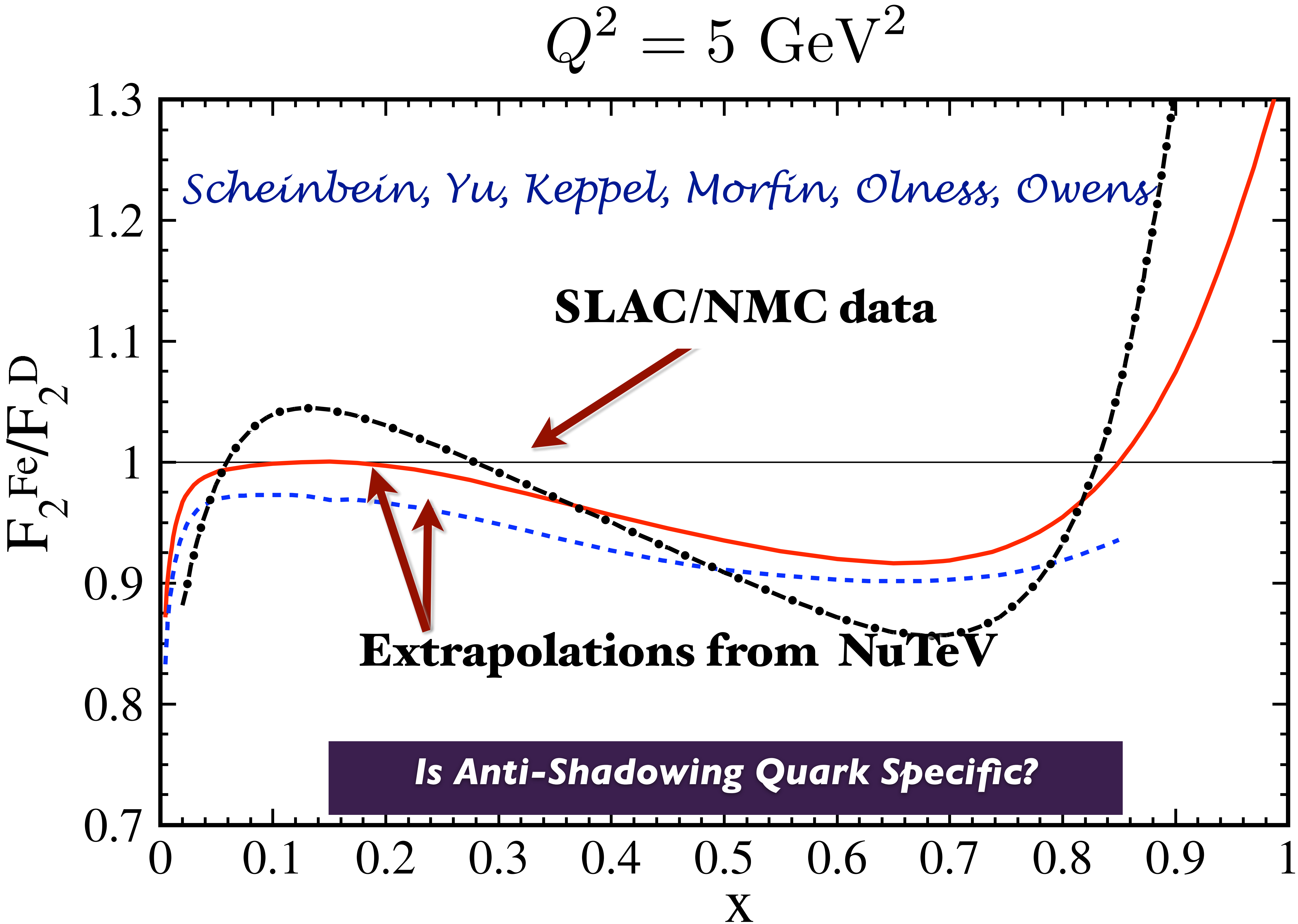
QCD Myths

- 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
- QCD Confinement and Mass Scale from $\Lambda_{\overline{MS}}$



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].



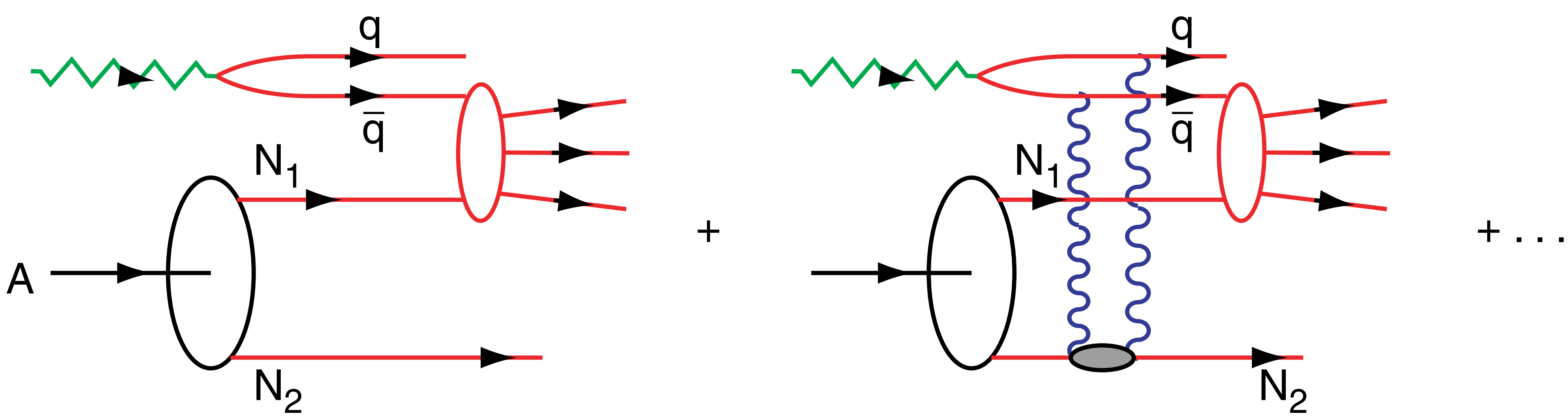
No anti-shadowing in deep inelastic neutrino scattering !

Is Antishadowing in DIS
Non-Universal, Flavor-Dependent?

Do Nuclear PDFS
Obey Momentum and other Sum Rules?

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

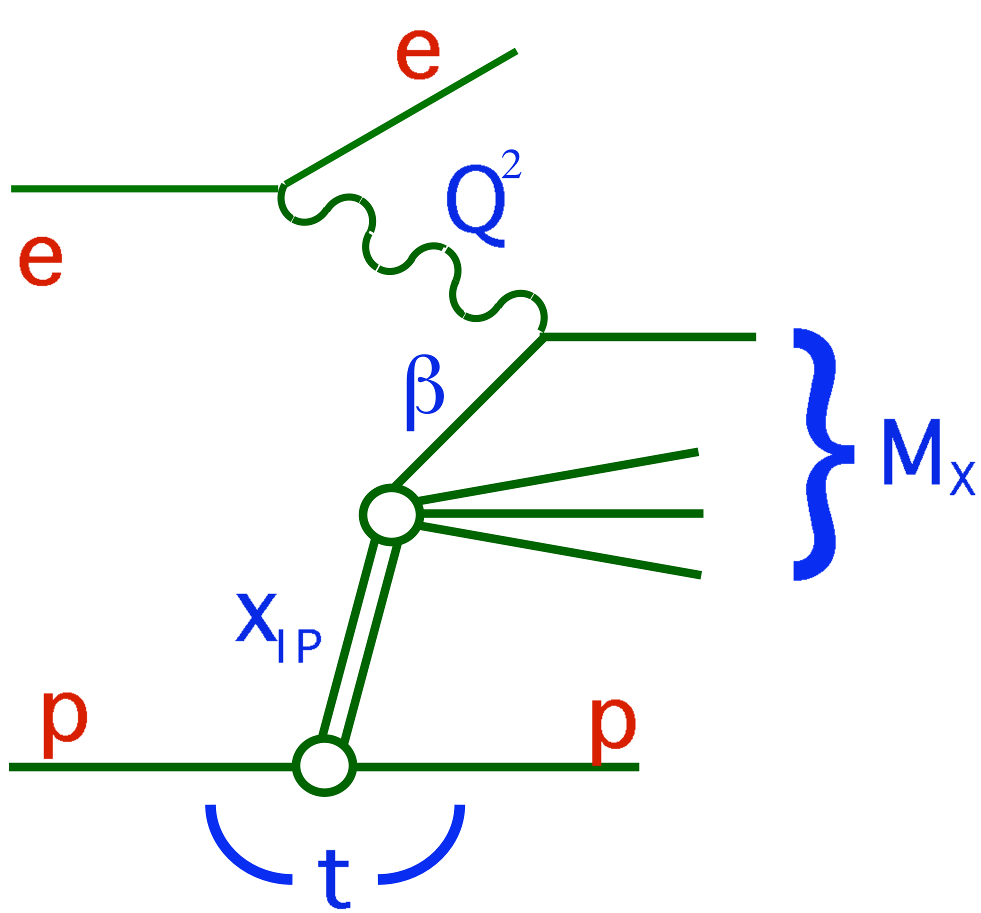
Diffraction via Reggeon gives constructive interference!

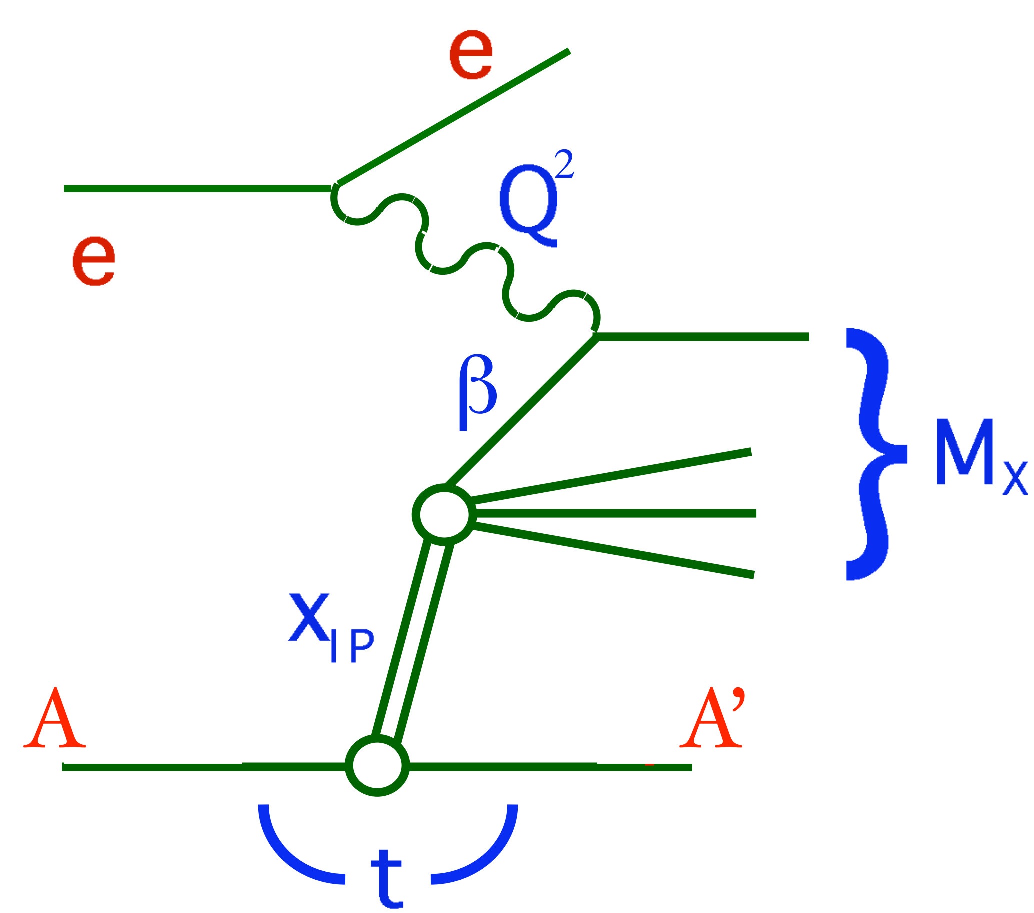
Anti-shadowing not universal

Diffractive Deep Inelastic Scattering

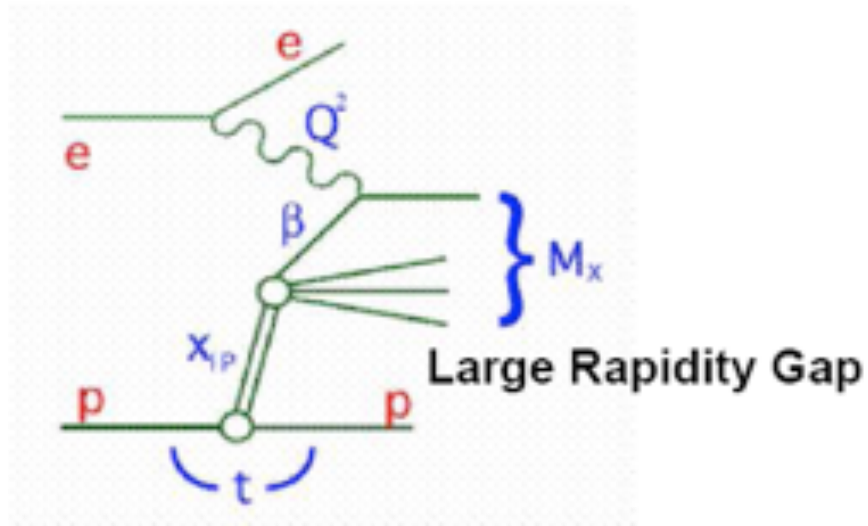
Diffractive DIS $ep \to epX$ where there is a large rapidity gap and the target nucleon remains intact probes the final state interaction of the scattered quark with the spectator system via gluon exchange.

Diffractive DIS on nuclei $eA \to e'AX$ and hard diffractive reactions such as $\gamma^* A \to VA$ can occur coherently leaving the nucleus intact.





Diffractive Structure Function F_2^D



Diffractive inclusive cross section

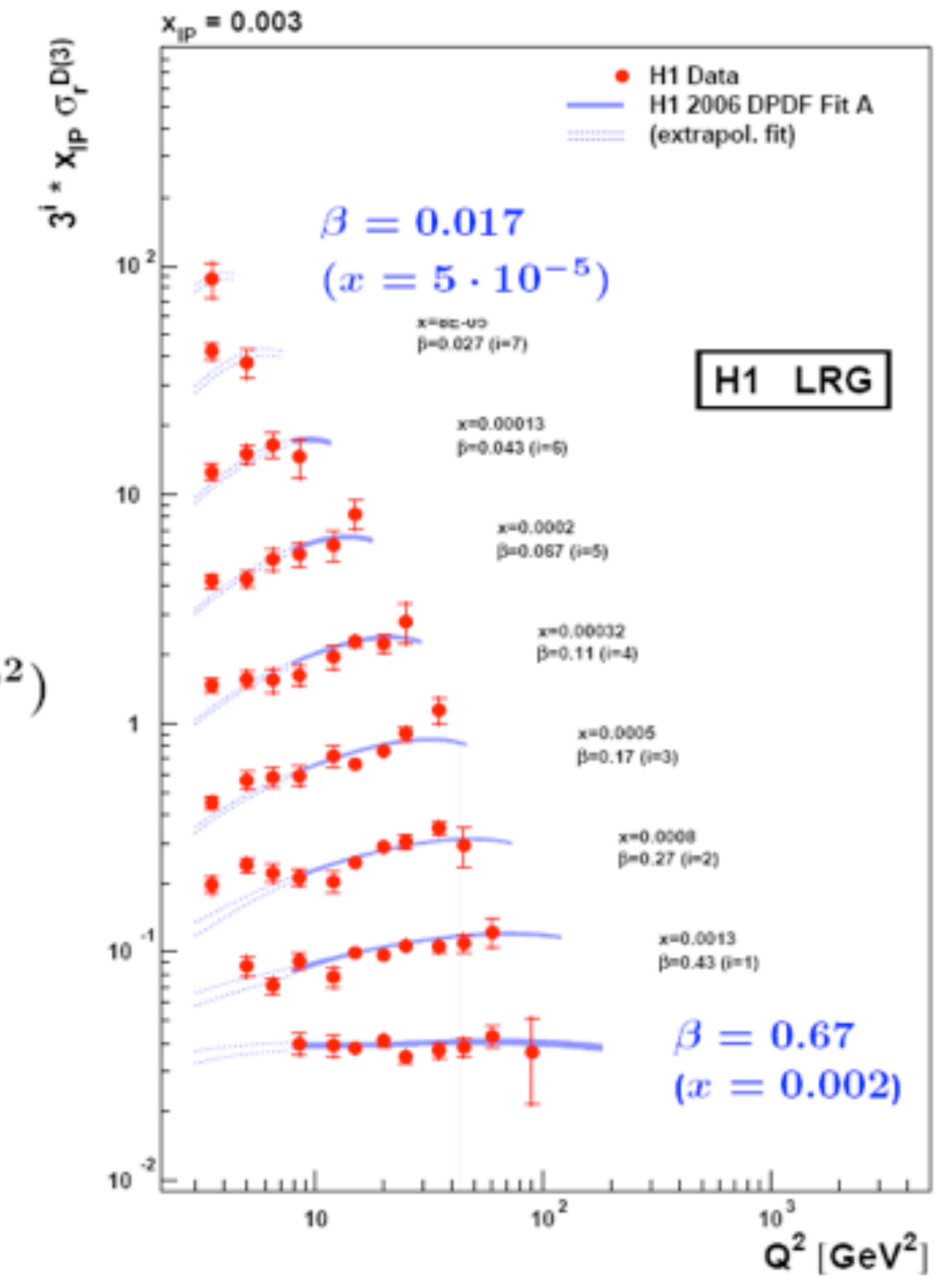
$$\frac{d^3\sigma_{NC}^{diff}}{dx_{I\!P}\, d\beta\, dQ^2} \propto \frac{2\pi\alpha^2}{xQ^4} F_2^{D(3)}(x_{I\!P}, \beta, Q^2)$$

$$F_2^D(x_{I\!P}, \beta, Q^2) = f(x_{I\!P}) \cdot F_2^{I\!P}(\beta, Q^2)$$

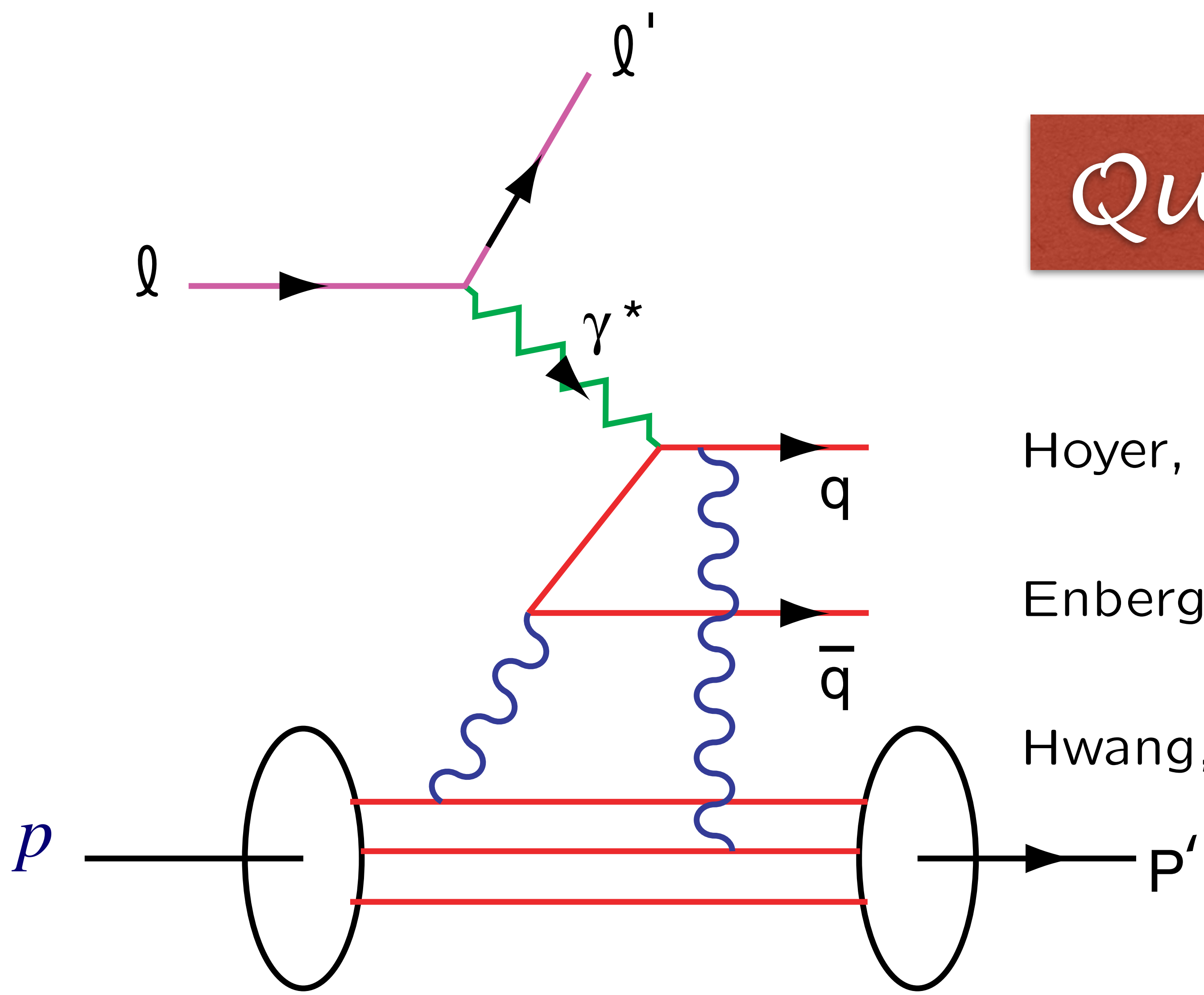
extract DPDF and $xg(x)$ from scaling violation

Large kinematic domain $3 < Q^2 < 1600\ \mathrm{GeV}^2$

Precise measurements *sys 5%, stat 5–20 %*



Quark Rescattering



Hoyer, Marchal, Peigne, Sannino, SJB (BHMPS)

Enberg, Hoyer, Ingelman, SJB

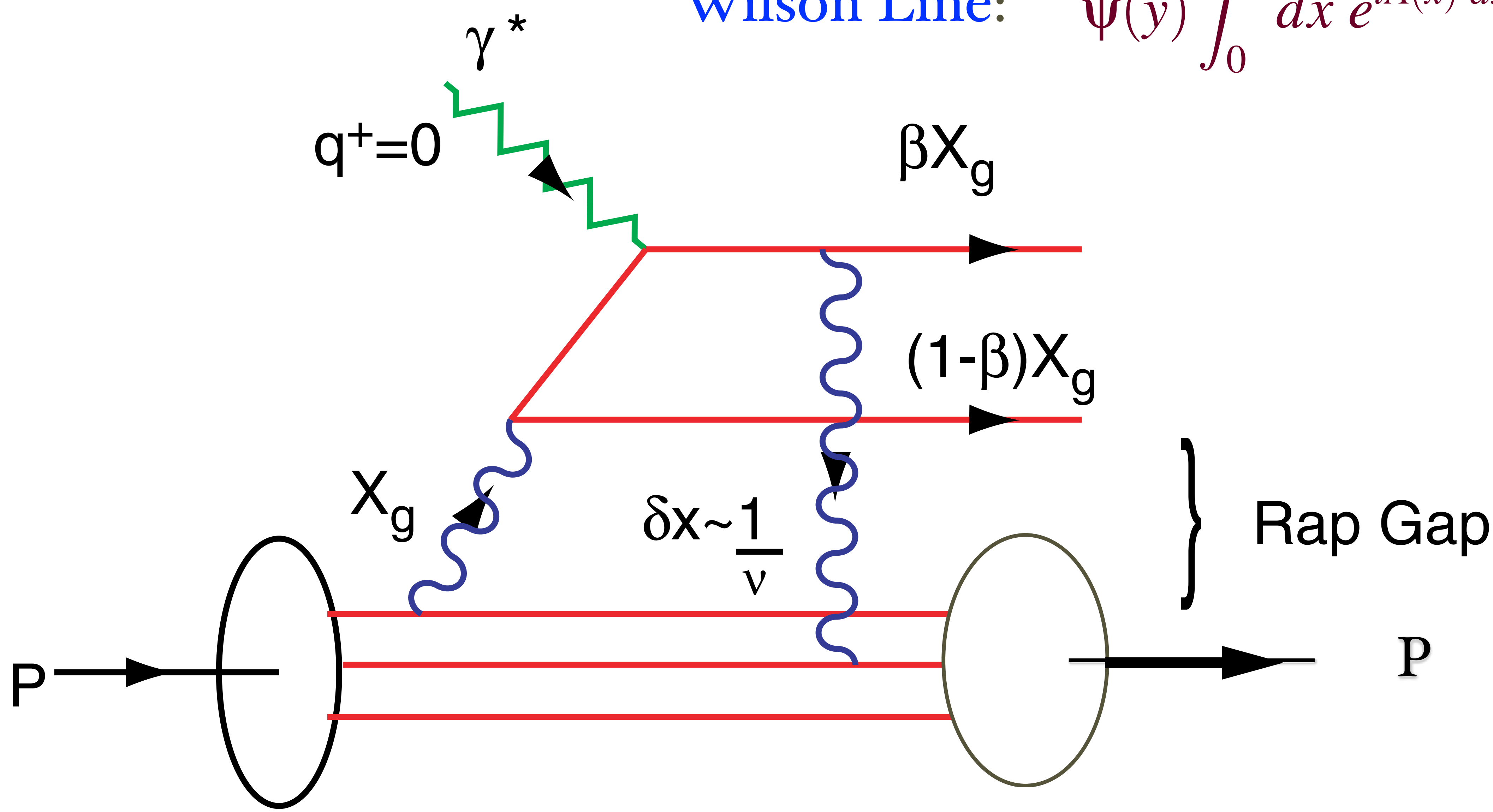
Hwang, Schmidt, SJB

Two-Gluon Exchange: Low-Nussinov model of Pomeron

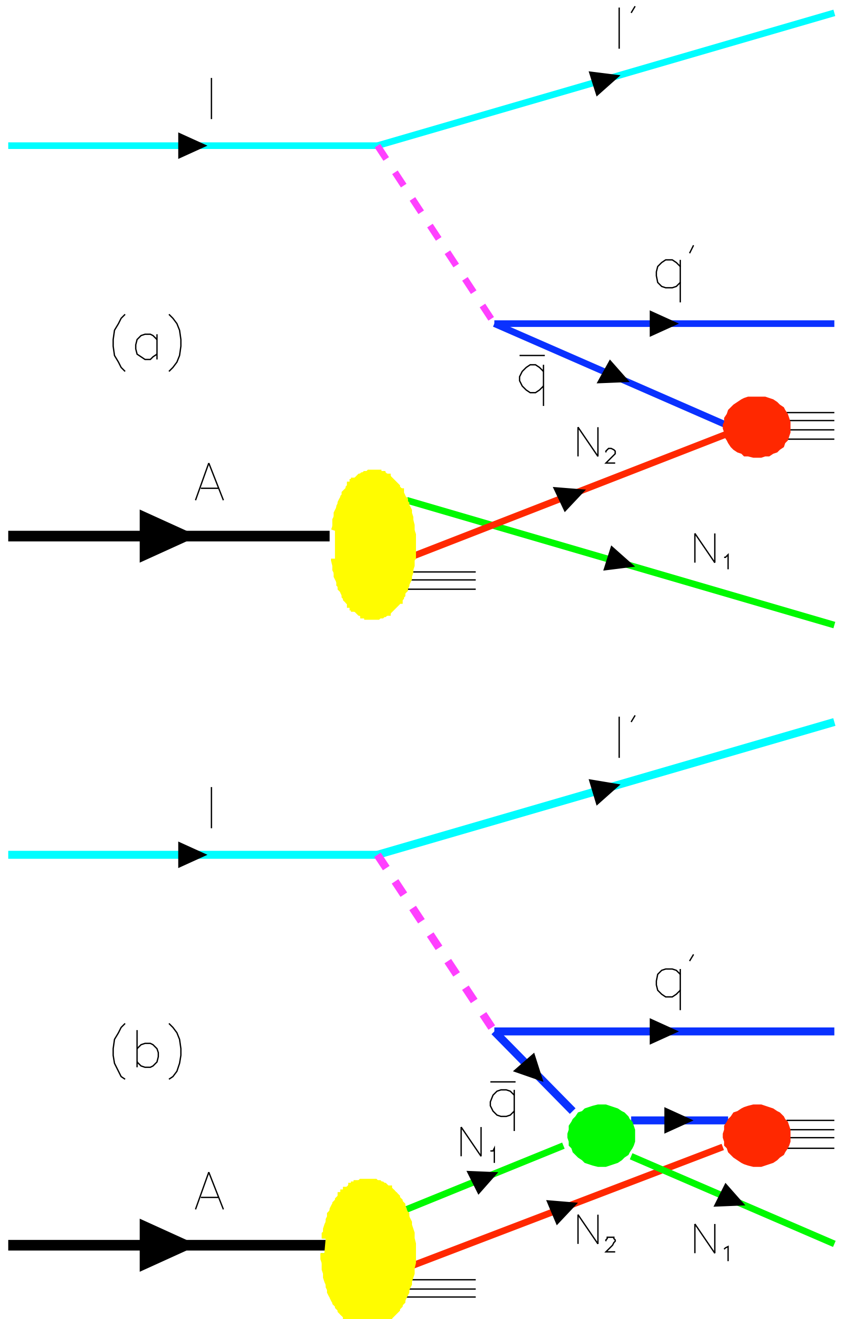
Hoyer, Marchal, Peigne, Sannino, sjb

QCD Mechanism for Rapidity Gaps

Wilson Line: $\overline{\psi}(y)\int_0^y dx\, e^{iA(x)\cdot dx}\,\psi(0)$



Reproduces lab-frame color dipole approach
DDIS: Input for leading twist nuclear shadowing



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

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

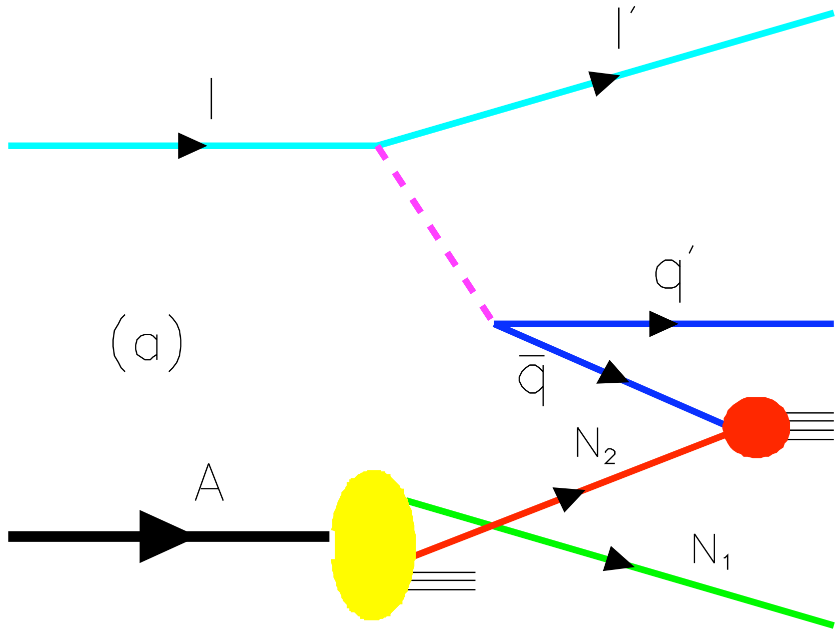
If the scattering on nucleon N_1 is via pomeron exchange, the one-step and two-step amplitudes are opposite in phase, thus diminishing the $\bar{q}$ flux reaching N_2.

Interior nucleons shadowed

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

Observed HERA DDIS produces nuclear shadowing

Schmidt, Lu, Yang, sjb



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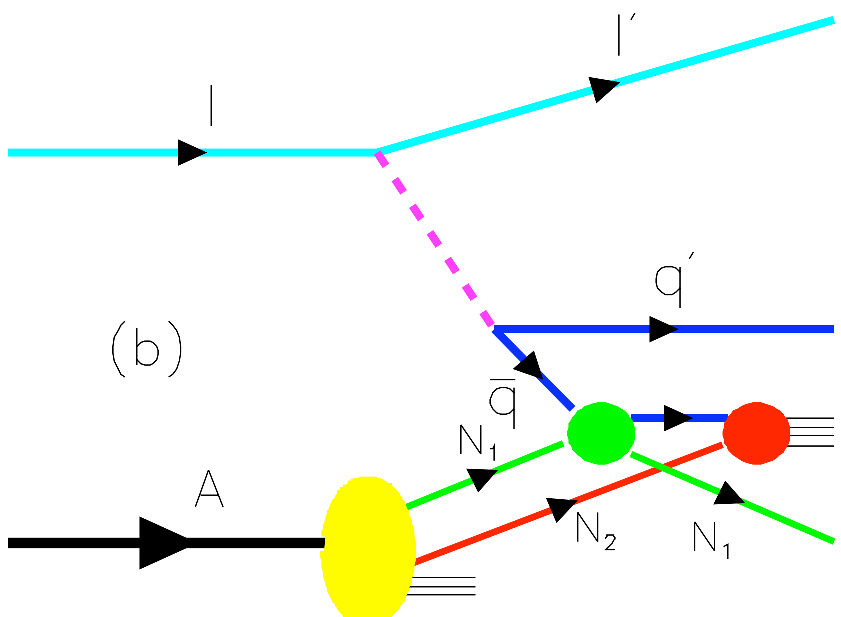


Regge

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.~~

constructive in phase

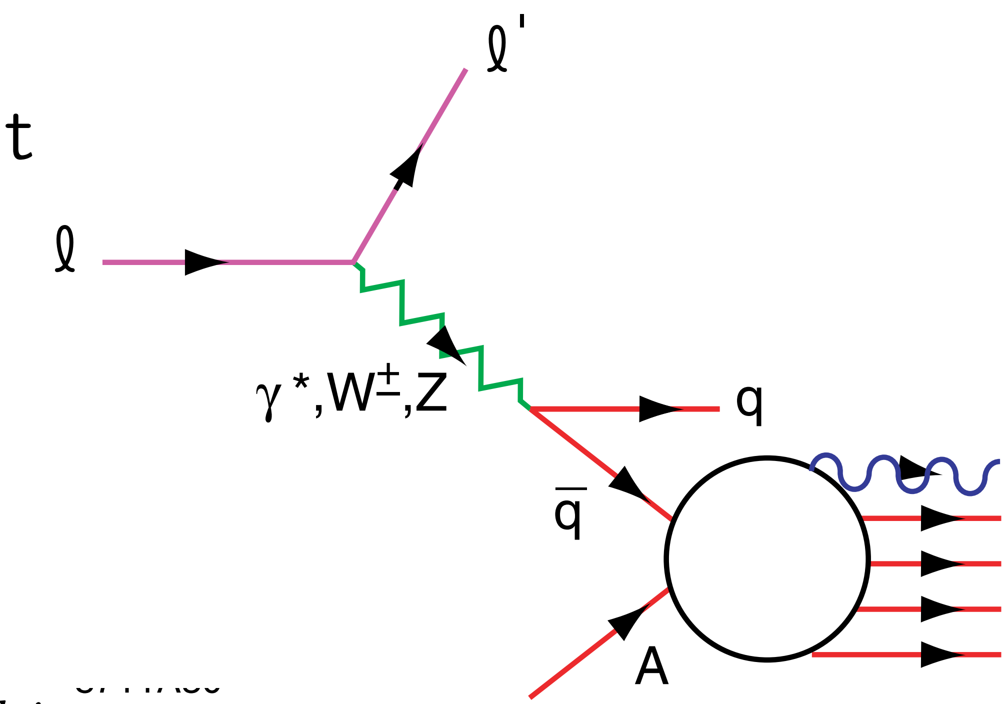
thus ***increasing*** the flux reaching N2

Interior nucleons anti-shadowed

Regge Exchange in DDIS produces nuclear anti-shadowing!

Origin of Regge Behavior of Deep Inelastic Structure Functions

$$F_{2p}(x) - F_{2n}(x) \propto x^{1/2}$$



Antiquark interacts with target nucleus at energy $\widehat{s} \propto \frac{1}{x_{bj}}$

Regge contribution: $\sigma_{\bar{q}N} \sim \widehat{s}^{\alpha_R - 1}$

Nonsinglet Kuti-Weisskoff $F_{2p} - F_{2n} \propto \sqrt{x_{bj}}$ at small x_{bj}.

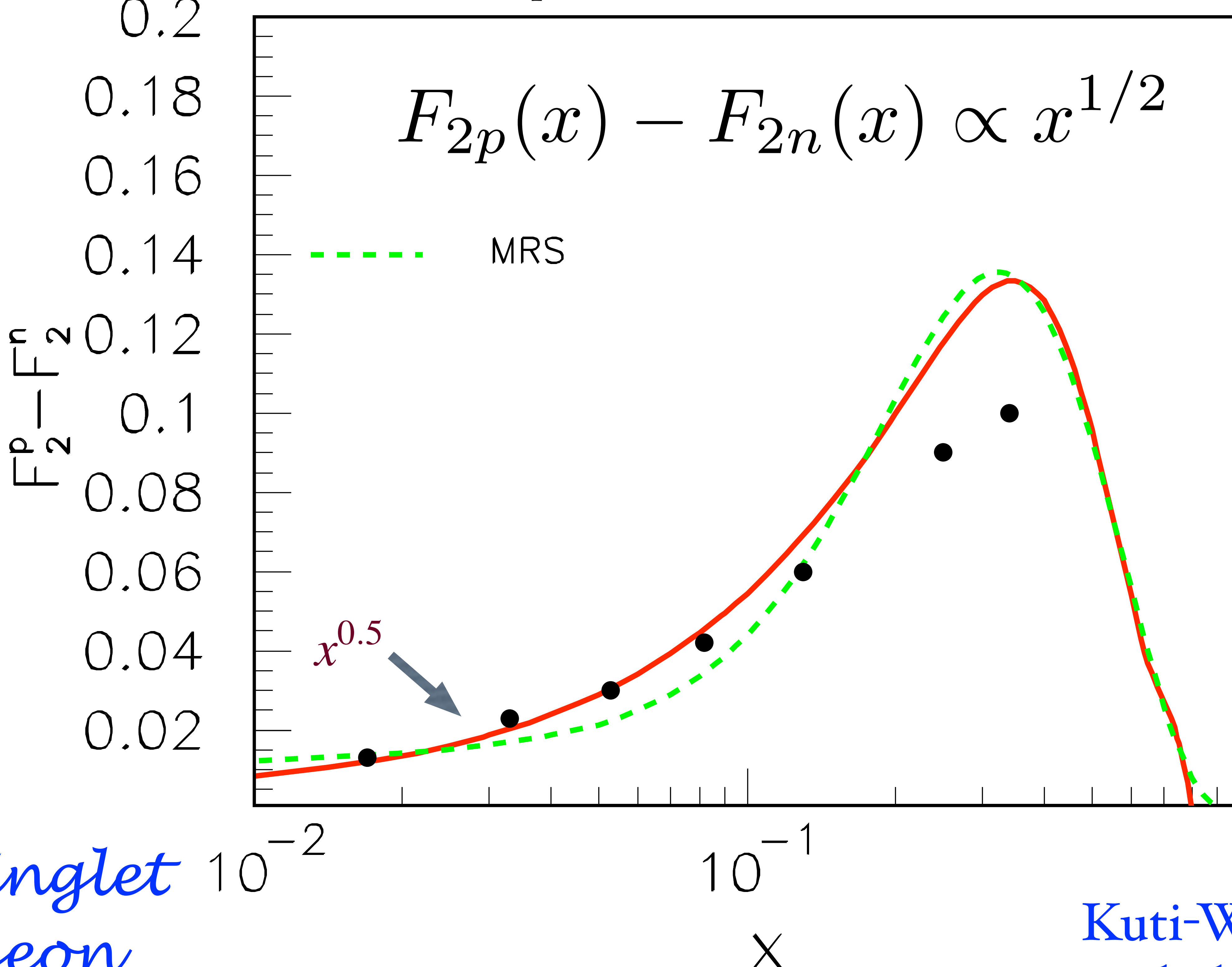
Shadowing of $\sigma_{\bar{q}M}$ produces shadowing of nuclear structure function.

Landshoff, Polkinghorne, Short

Close, Gunion, sjb

Schmidt, Yang, Lu, sjb

Regge contribution: $\sigma_{\bar{q}N} \sim \hat{s}^{\alpha_R - 1}$ $\alpha_R \simeq 1/2$

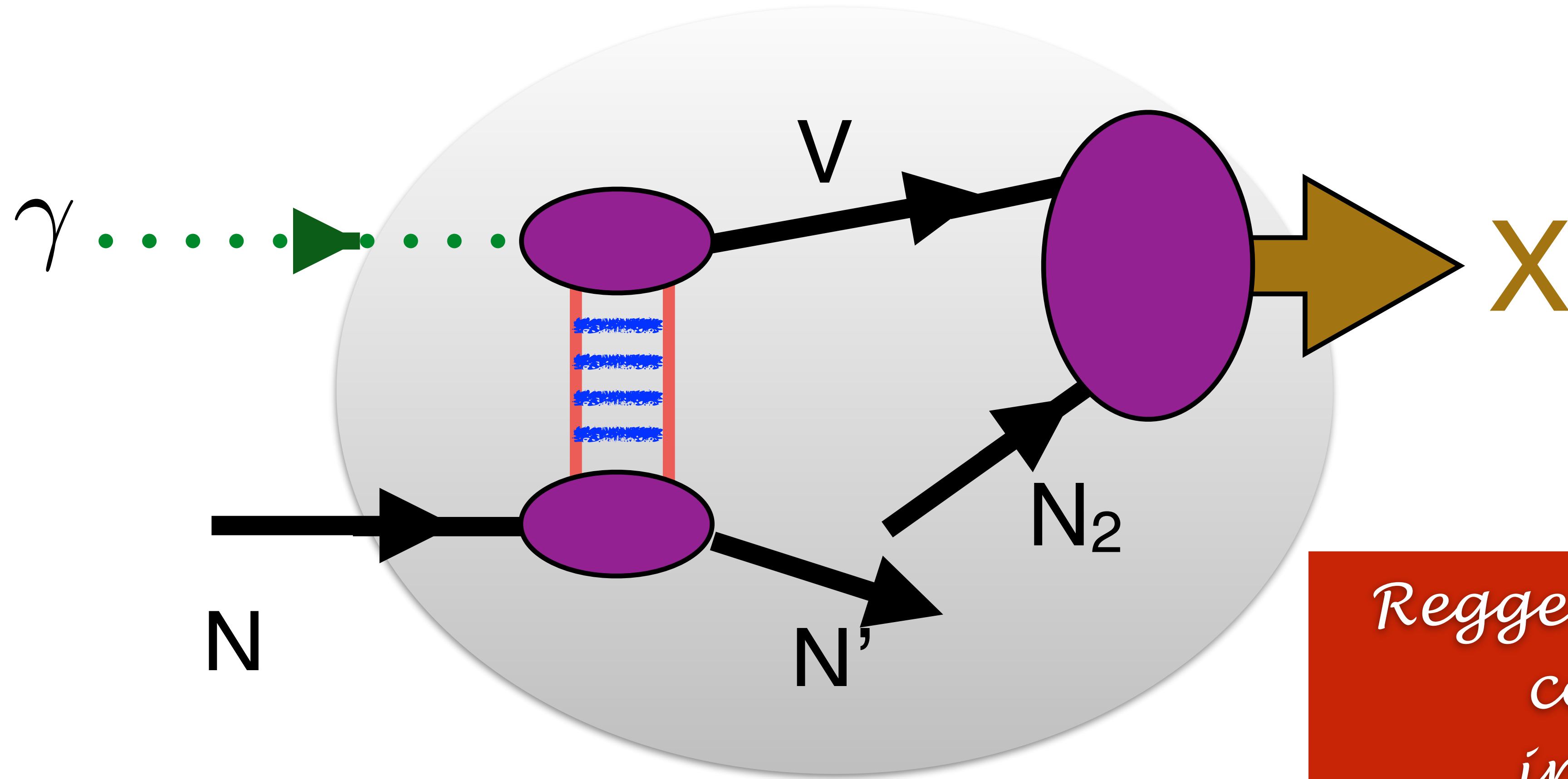


Non-singlet Reggeon Exchange

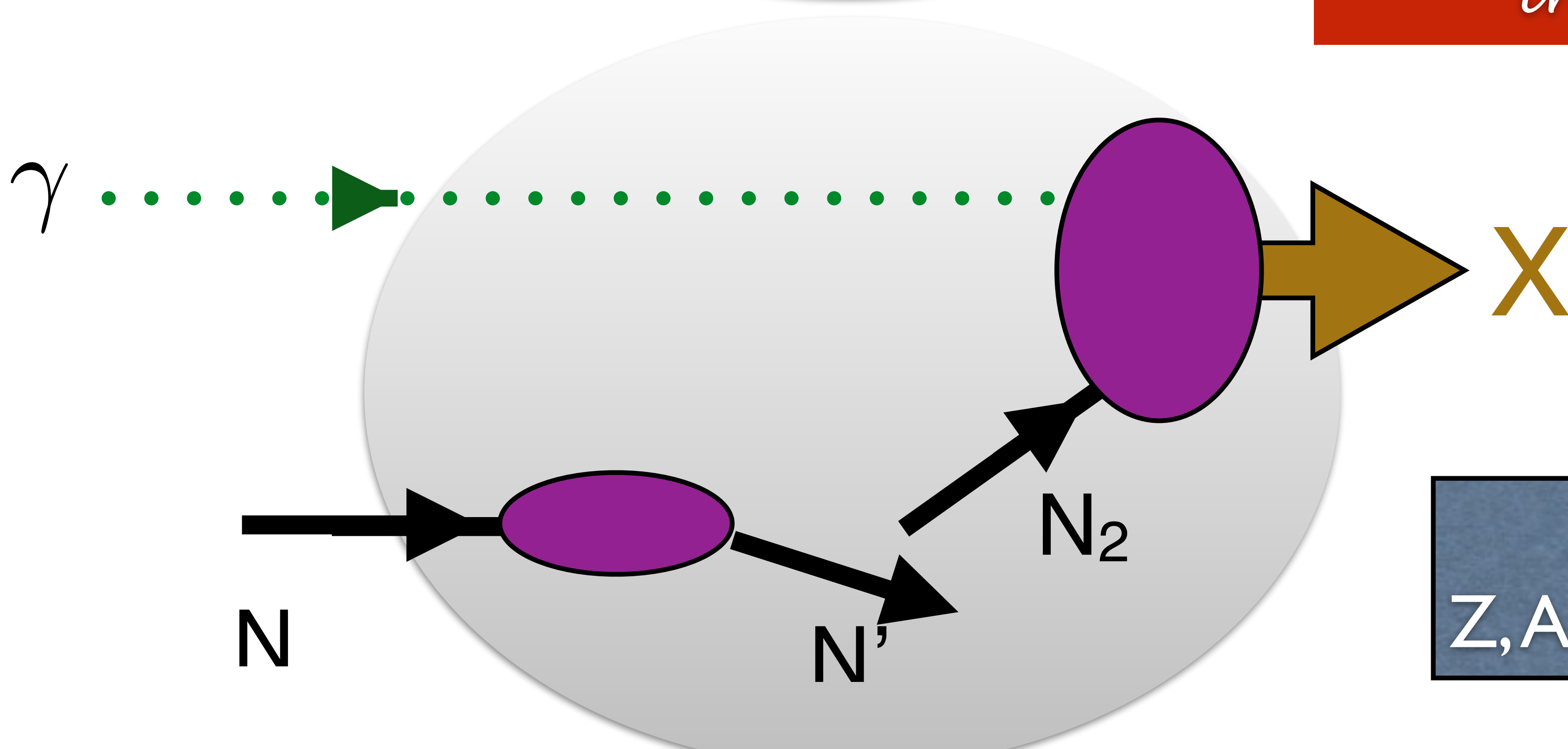
Kuti-Weisskopf behavior

Two-step and One-Step Glauber processes

I=1 Reggeon Exchange on N_1



Regge Phase can give constructive interference!



Anomalous Z,A-Z dependence

Reggeon Exchange

Regge contribution: $\sigma_{\bar{q}N} \sim \hat{s}^{\alpha_R - 1}$ $\alpha_R \simeq 1/2$

Phase of two-step amplitude relative to one step:

$$\frac{1}{\sqrt{2}}(1-i) \times i = \frac{1}{\sqrt{2}}(i+1)$$

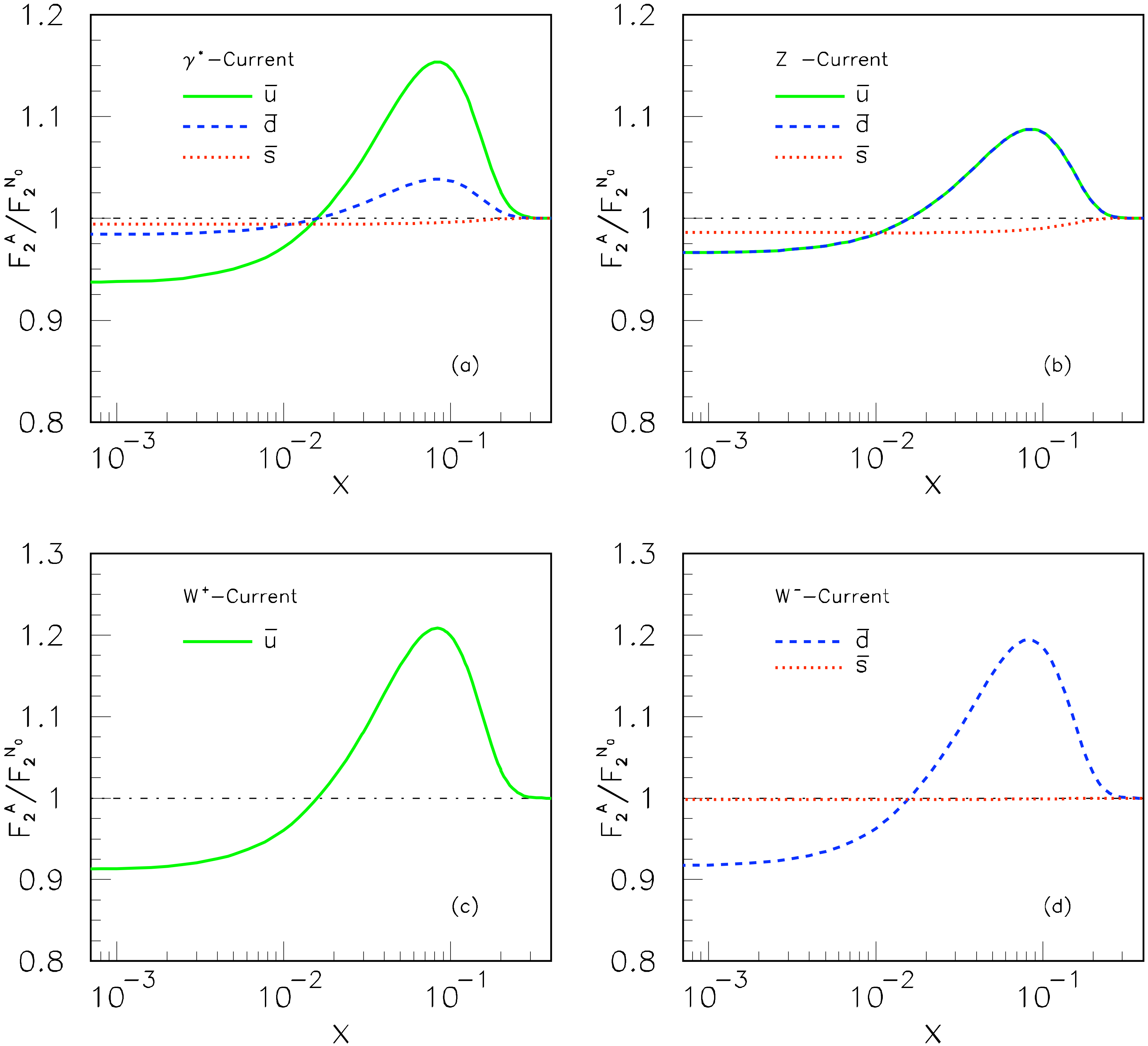
Constructive Interference

Depends on quark flavor!

Thus antishadowing is not universal

Different for couplings of $\gamma^*, Z^0, W^\pm$

Test: Tagged Drell-Yan



Lu, Schmidt, Yang; sjb

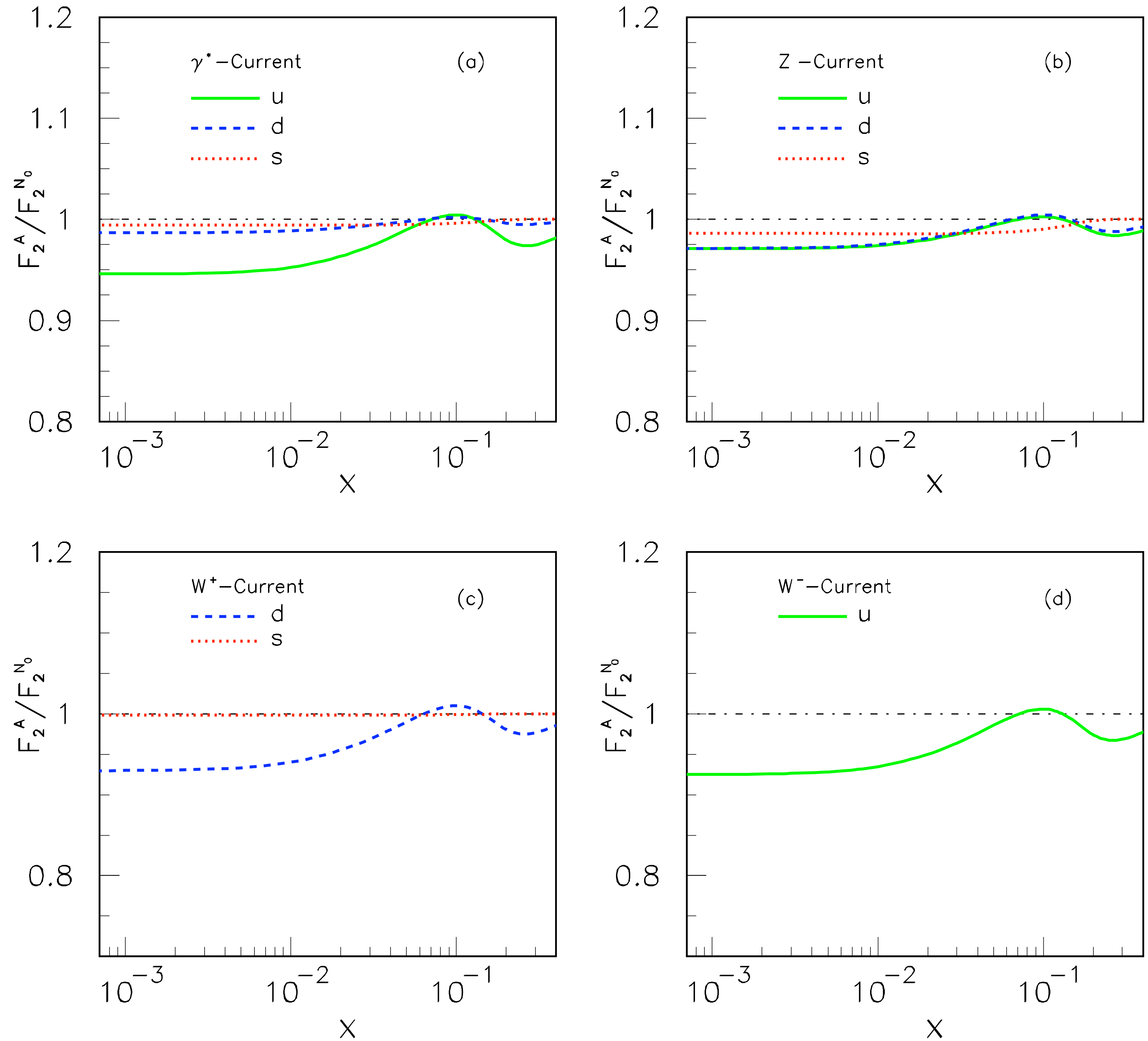
Modifies NuTeV extraction of

$\sin^2\theta_W$

Test in flavor-tagged DIS at the EIC

Nuclear Antishadowing not universal !

Shadowing and Antishadowing of DIS Structure Functions

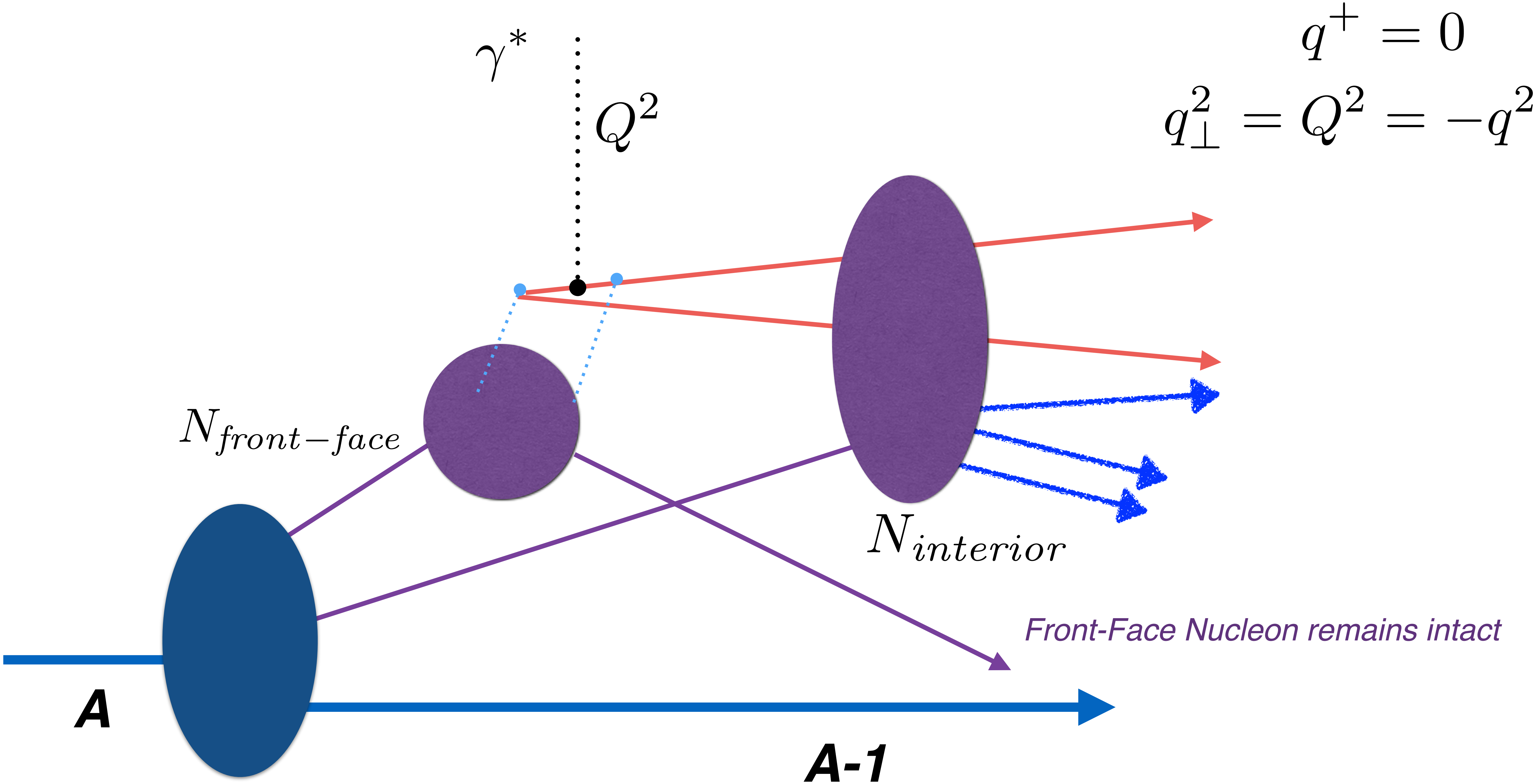


S. J. Brodsky, I. Schmidt and J. J. Yang, "Nuclear Antishadowing in Neutrino Deep Inelastic Scattering," Phys. Rev. D 70, 116003 (2004) [arXiv:hep-ph/0409279].

Modifies NuTeV extraction of

$$\sin^2\theta_W$$

Test in flavor-tagged lepton-nucleus collisions

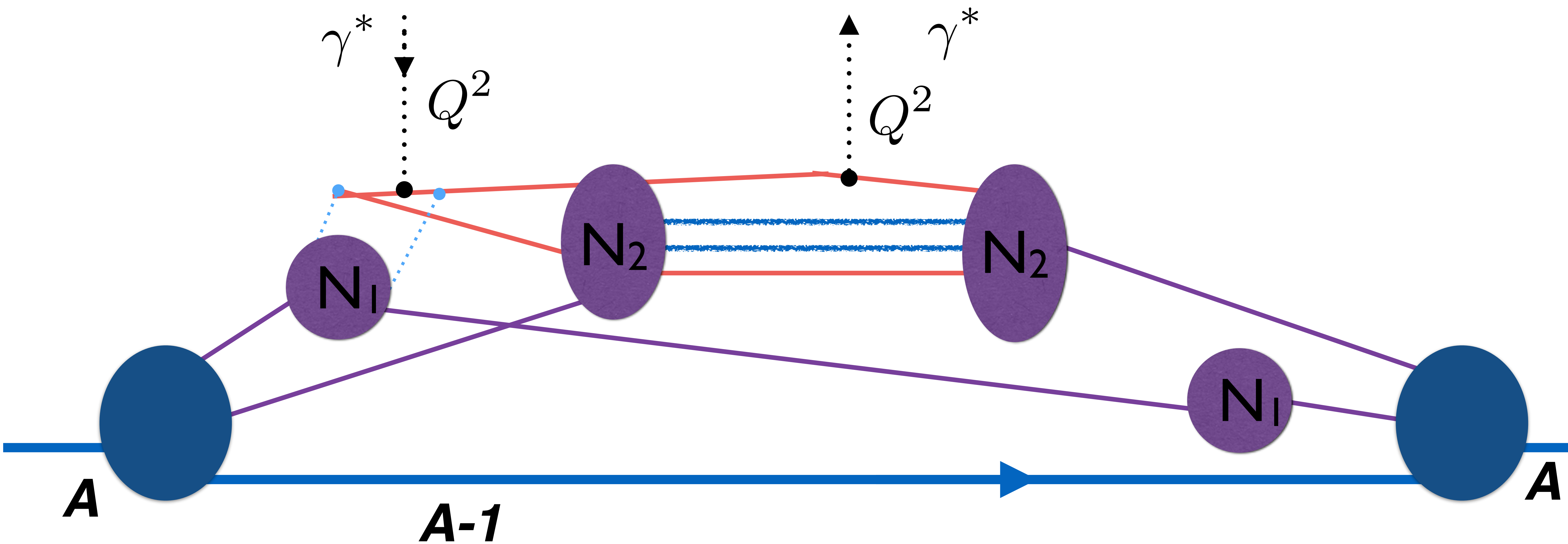


Two-Step Process in the $q^+=0$ Parton Model Frame

Illustrates the LF time sequence

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

Illustrates the LF time sequence



Front-Face Nucleon N_1 struck

Front-Face Nucleon N_1 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! No Sum Rules for Nuclear PDFs!

Liuti, sjb

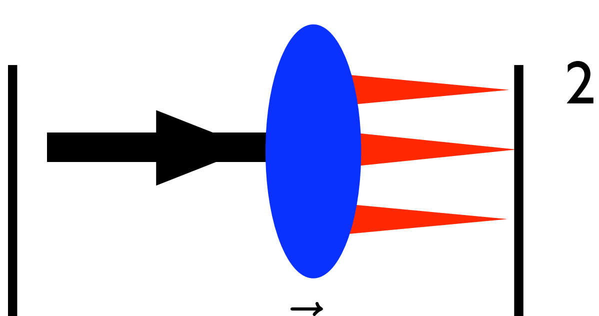
LFWFs are real for stable hadrons, nuclei

Crucial JLab Experiments

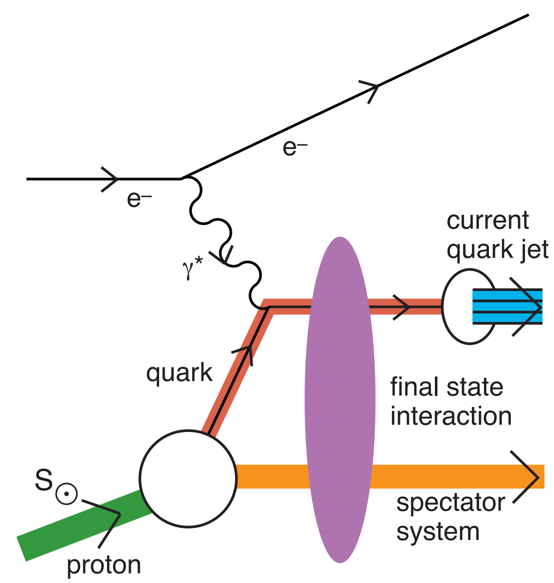
- *Measure Diffractive DIS: Agree with Shadowing of Nuclear Structure Functions?*
- *Isospin Dependence of Diffractive DIS — Reggeon Exchange -*
- *Use deuteron: see n to p*
- *Flavor Dependence of Antishadowing: Tagged Quark Distributions?*
- *Test for Odderon Exchange in DDIS*

What is measured!

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



$$\left|\Psi_n(x_i, \vec{k}_{\perp i}, \lambda_i)\right|^2$$

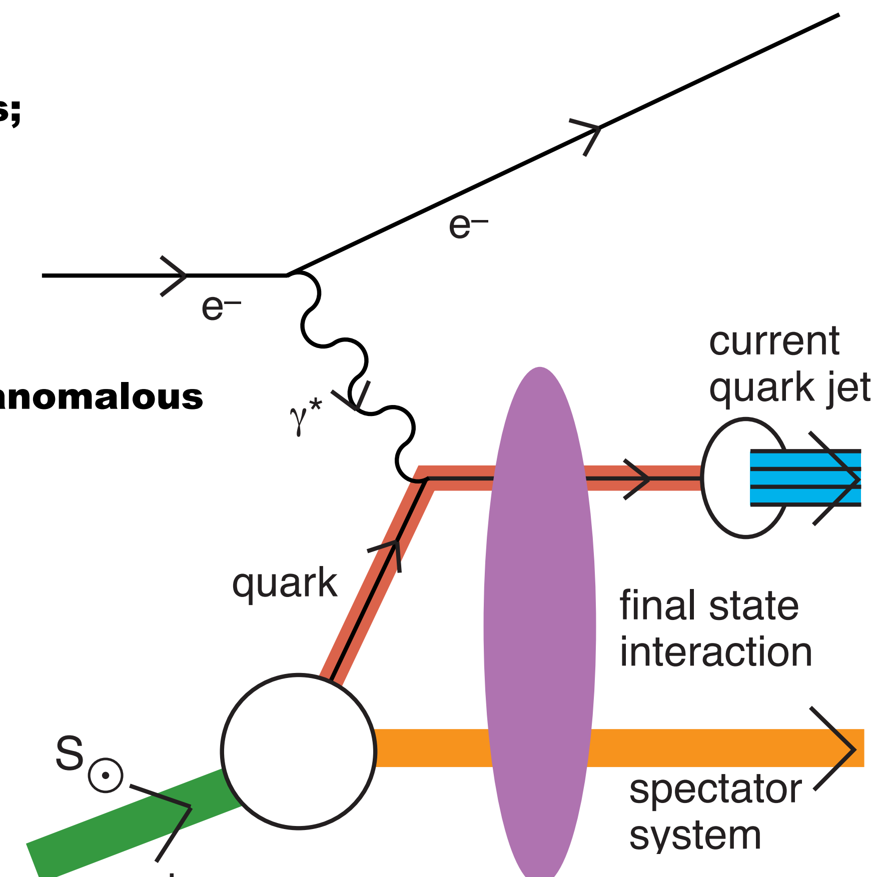


Final-State Interactions Produce Pseudo T-Odd (Sivers Effect)

Hwang, Schmidt, sjb
Collins

$$\mathbf{i}\ \vec{S} \cdot \vec{p}_{jet} \times \vec{q}$$

- **Leading-Twist Bjorken Scaling!**
- **Requires nonzero orbital angular momentum of quark**
- **Arises from the interference of Final-State QCD Coulomb phases in S- and P- waves;**
- **Wilson line effect -- lc gauge prescription**
- **Relate to the quark contribution to the target proton anomalous magnetic moment and final-state QCD phases**
- **QCD phase at soft scale!**
- **New window to QCD coupling and running gluon mass in the IR**
- **QED S and P Coulomb phases infinite -- difference of phases finite!**
- **Alternate: Retarded and Advanced Gauge: Augmented LFWFs**



Dae Sung Hwang, Yuri V. Kovchegov, Ivan Schmidt, Matthew D. Sievert, sjb

Pasquini, Xiao, Yuan, sjb

Mulders, Boer **Qiu, Sterman**

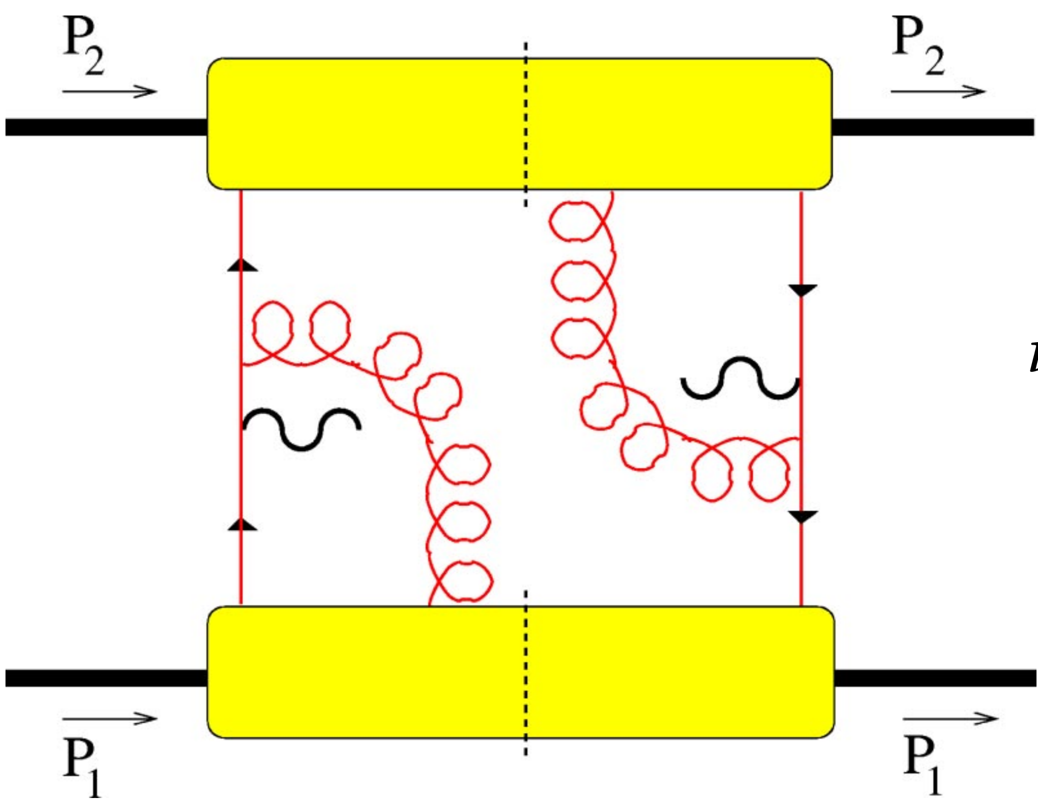
Double Initial-State Interactions generate anomalous $\cos 2\phi$

Drell-Yan planar correlations

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda \cos^2\theta + \mu \sin 2\theta\ \cos\phi + \frac{\nu}{2}\sin^2\theta \cos 2\phi\right)$$

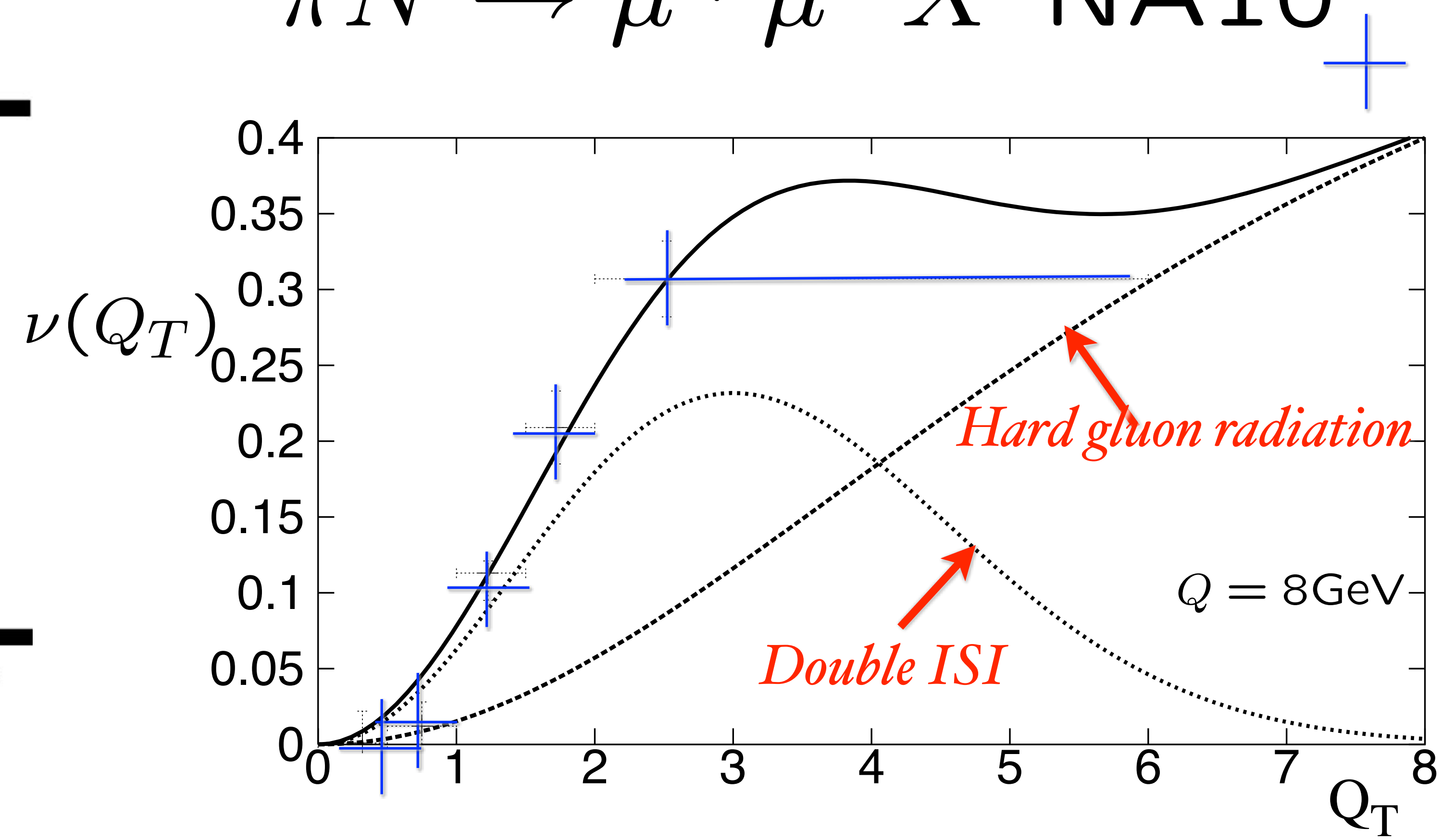
PQCD Factorization (Lam Tung): $1 - \lambda - 2\nu = 0$

$$\frac{\nu}{2} \quad \propto \quad h_1^{\perp}(\pi)\, h_1^{\perp}(N)$$



Violates Lam-Tung relation!

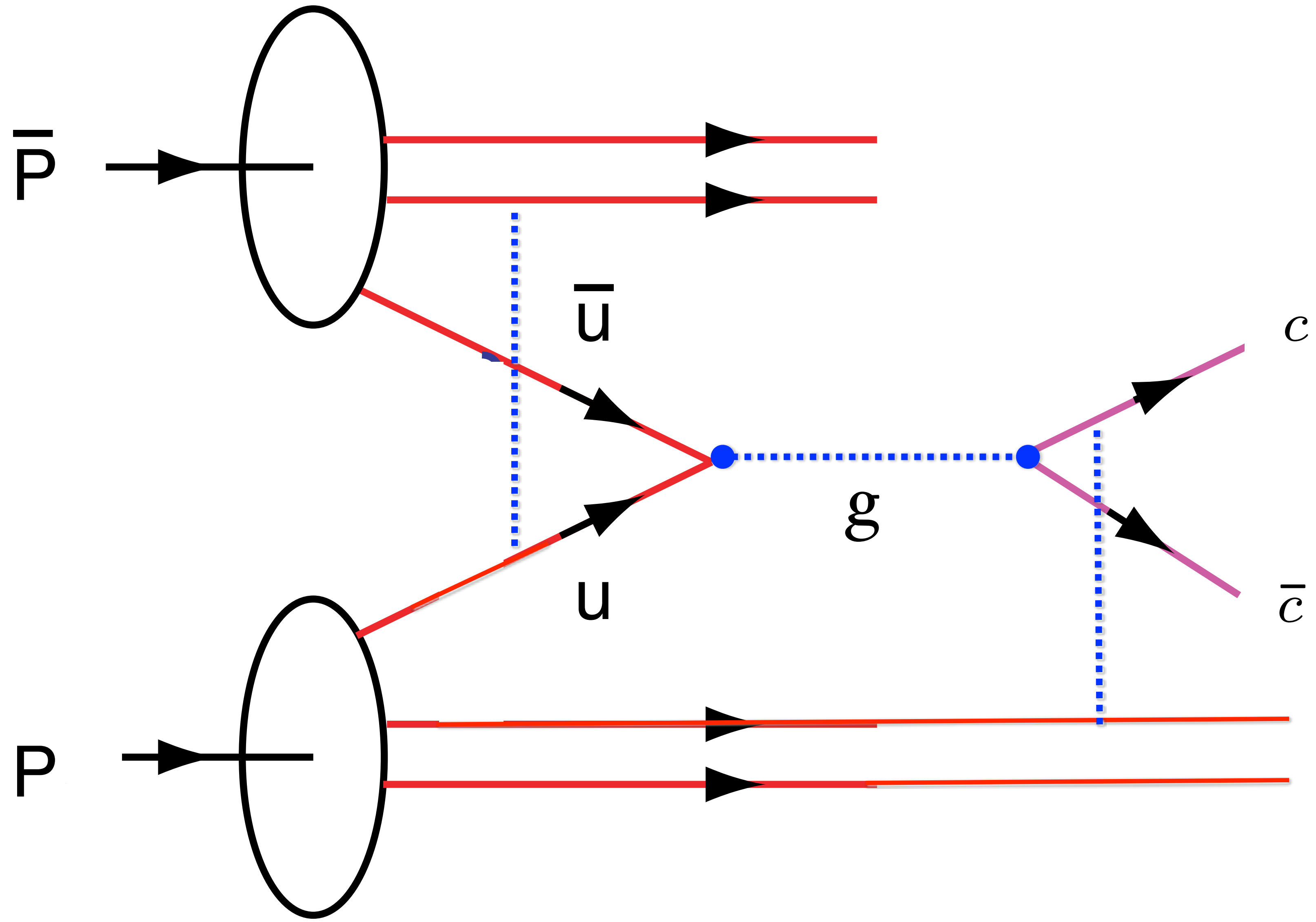
$\pi N \to \mu^+\mu^- X$ NA10



Double Boer-Mulders Effect

Boer, Hwang, sjb

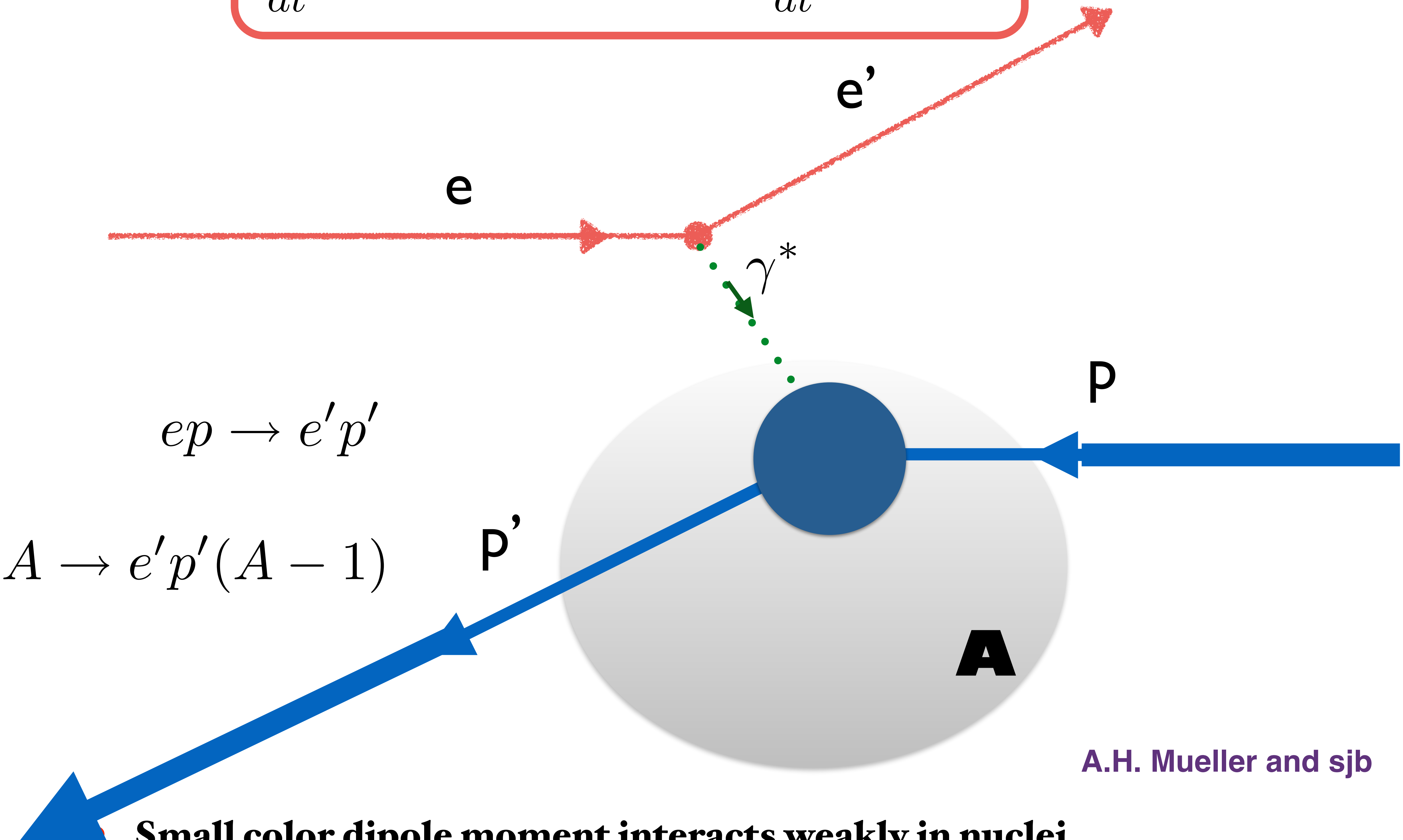
Collins and Qiu



Problem for factorization when both ISI and FSI occur

Color Transparency

$$\boxed{\frac{d\sigma}{dt}(eA \to ep(A-1)) = Z\frac{d\sigma}{dt}(ep \to ep)}$$



$$ep \to e'p'$$

$$eA \to e'p'(A-1)$$

A.H. Mueller and sjb

Small color dipole moment interacts weakly in nuclei

Color Transparency

Bertsch, Gunion, Goldhaber, sjb

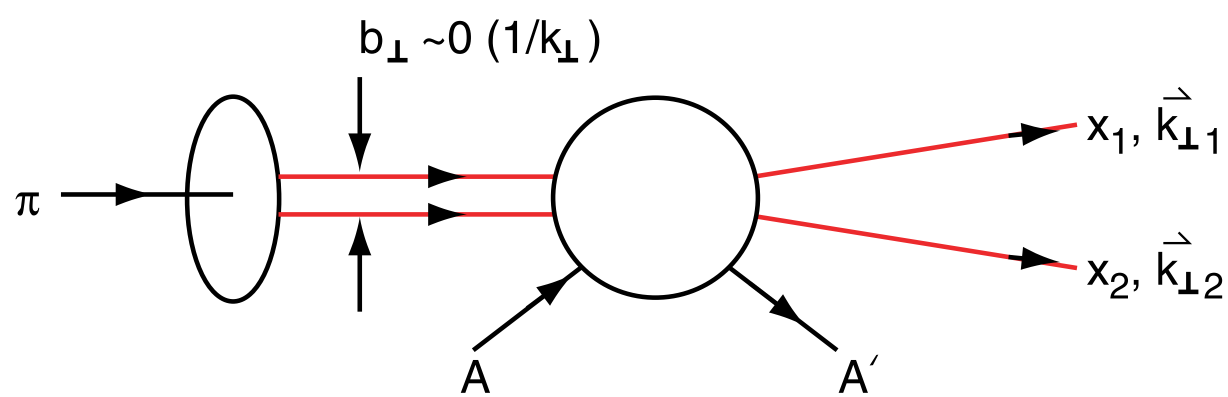
Mueller, sjb

Frankfurt, Strikman, Miller

$$\frac{d\sigma}{dt}(eA \to ep(A-1)) = Z\frac{d\sigma}{dt}(ep \to ep)$$ at high momentum transfer

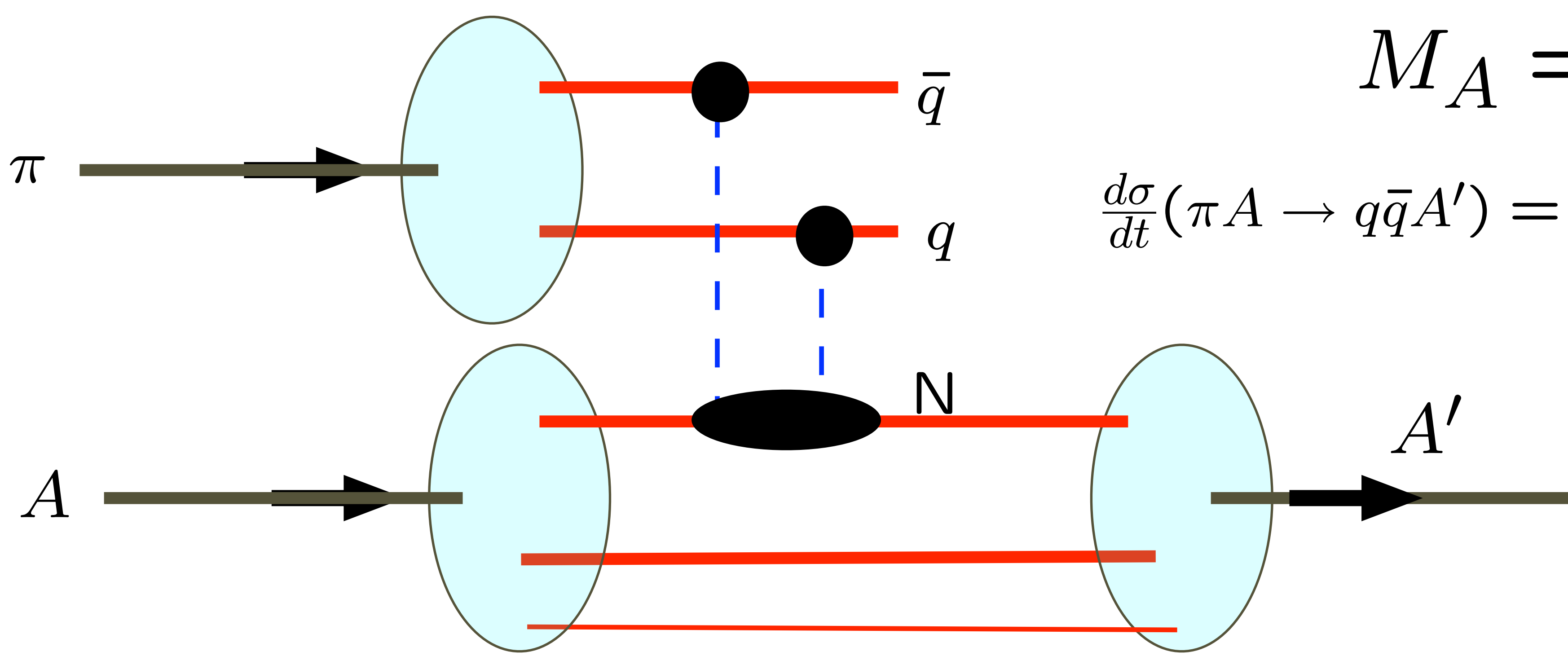
- **Fundamental test of gauge theory in hadron physics**
- **Small color dipole moment interacts weakly in nuclei**
- **Complete coherence at high energies**
- **Many tests in hard exclusive processes**
- **Clear Demonstration of CT from Diffractive Di-Jets**
- **Explains Baryon Anomaly at RHIC**

Fermilab E791 Experiment, Ashery et al.



large $k_\perp$, small $b_\perp$

Small color-dipole moment pion not absorbed;
interacts with each nucleon coherently
QCD COLOR Transparency



$$M_A = A\ M_N$$

$$\frac{d\sigma}{dt}(\pi A \to q\bar{q}A') = A^2\ \frac{d\sigma}{dt}(\pi N \to q\bar{q}N')\ F_A^2(t)$$

Target left intact

Diffraction, Rapidity gap

Frankfurt Miller Strikman

Mueller, sjb; Bertsch et al;
Frankfurt, Miller, Strikman

Measure pion LFWF in diffractive dijet production
Confirmation of color transparency

A-Dependence results: $\sigma \propto A^{\alpha}$

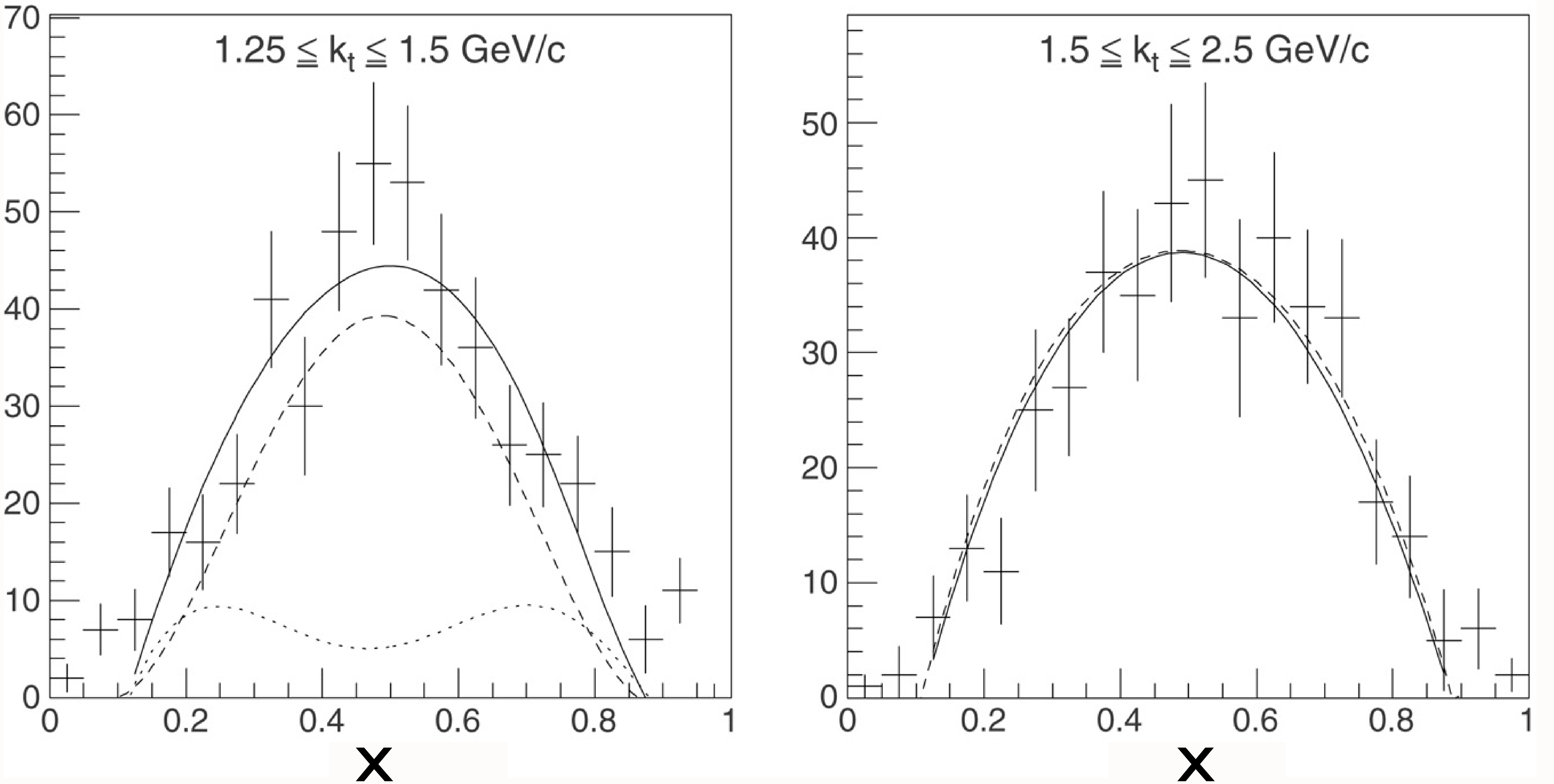
$\mathbf{k}_t$ **range (GeV/c)**	α	α **(CT)**
$1.25 < k_t < 1.5$	$1.64\ {+0.06}\ {-0.12}$	1.25
$1.5 < k_t < 2.0$	1.52 ± 0.12	1.45
$2.0 < k_t < 2.5$	1.55 ± 0.16	1.60

Ashery E791

$$\alpha(Conventional) = 0.70 \pm 0.10$$

Conventional Glauber Theory Ruled Out !

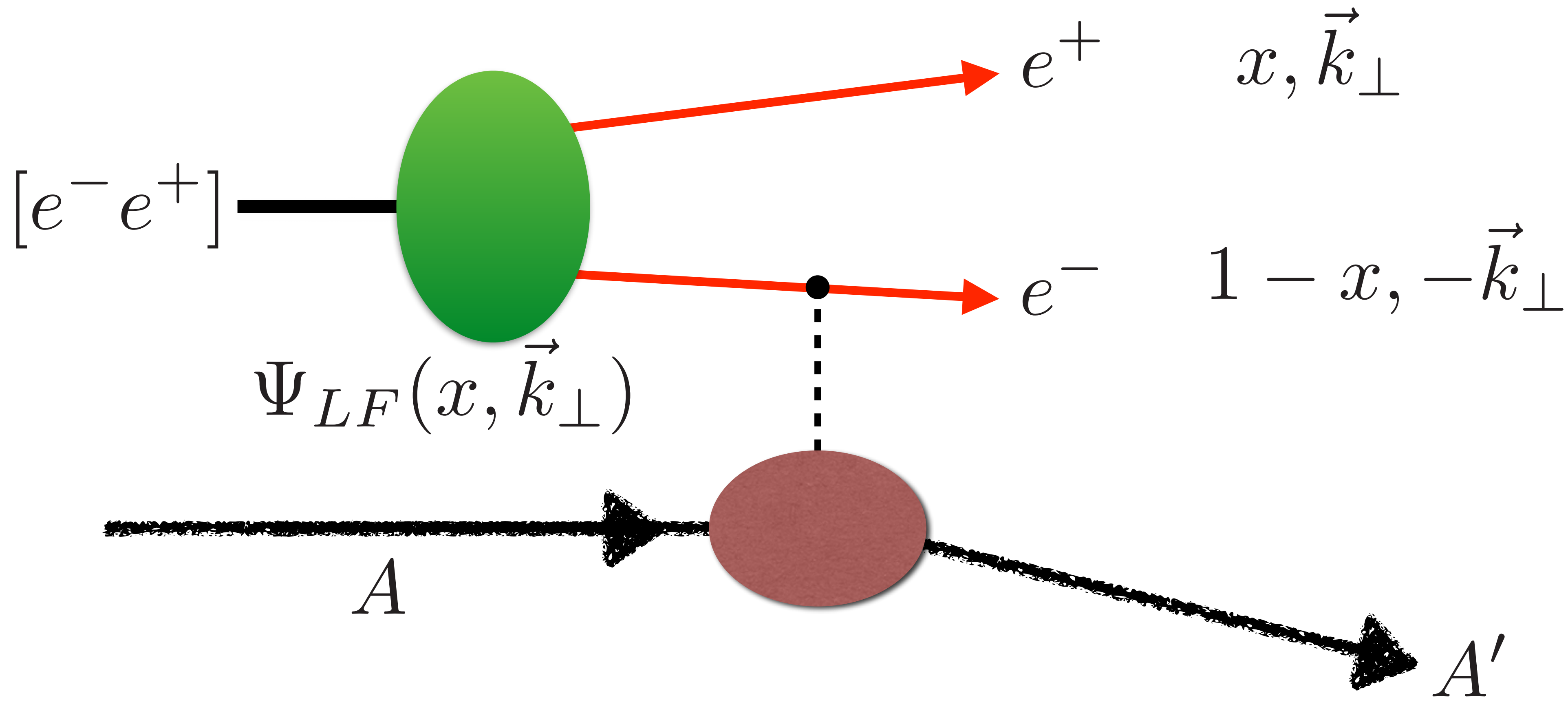
Factor of 7



The x distribution of diffractive dijets from the platinum target for $1.25 \leq k_t \leq 1.5$ GeV$/c$ (left) and for $1.5 \leq k_t \leq 2.5$ GeV$/c$ (right). The solid line is a fit to a combination of the asymptotic and CZ distribution amplitudes. The dashed line shows the contribution from the asymptotic function and the dotted line that of the CZ function.

$$Measures\ \frac{d^2}{dk_\perp^2}\psi_\pi^{LF}(x, k_\perp)$$

Coherent dissociation of positronium



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

$$\text{Measures } \frac{\partial}{\partial \vec{k}_\perp} \psi^{LF}_{[e^+ e^-]}(x, \vec{k}_\perp)$$

Diffractive Dissociation of Atoms and Nuclei

- Measure LFWFs of atoms

- See transitions from nonrelativistic to relativistic domain

$$\psi_{[e^+e^-]}(x, \overrightarrow{k}_\perp) \sim \frac{(\alpha m_e)^4}{\overrightarrow{k}^4} \to \frac{f(x)}{k_\perp^2}$$

- Higher Fock states of positronium such as

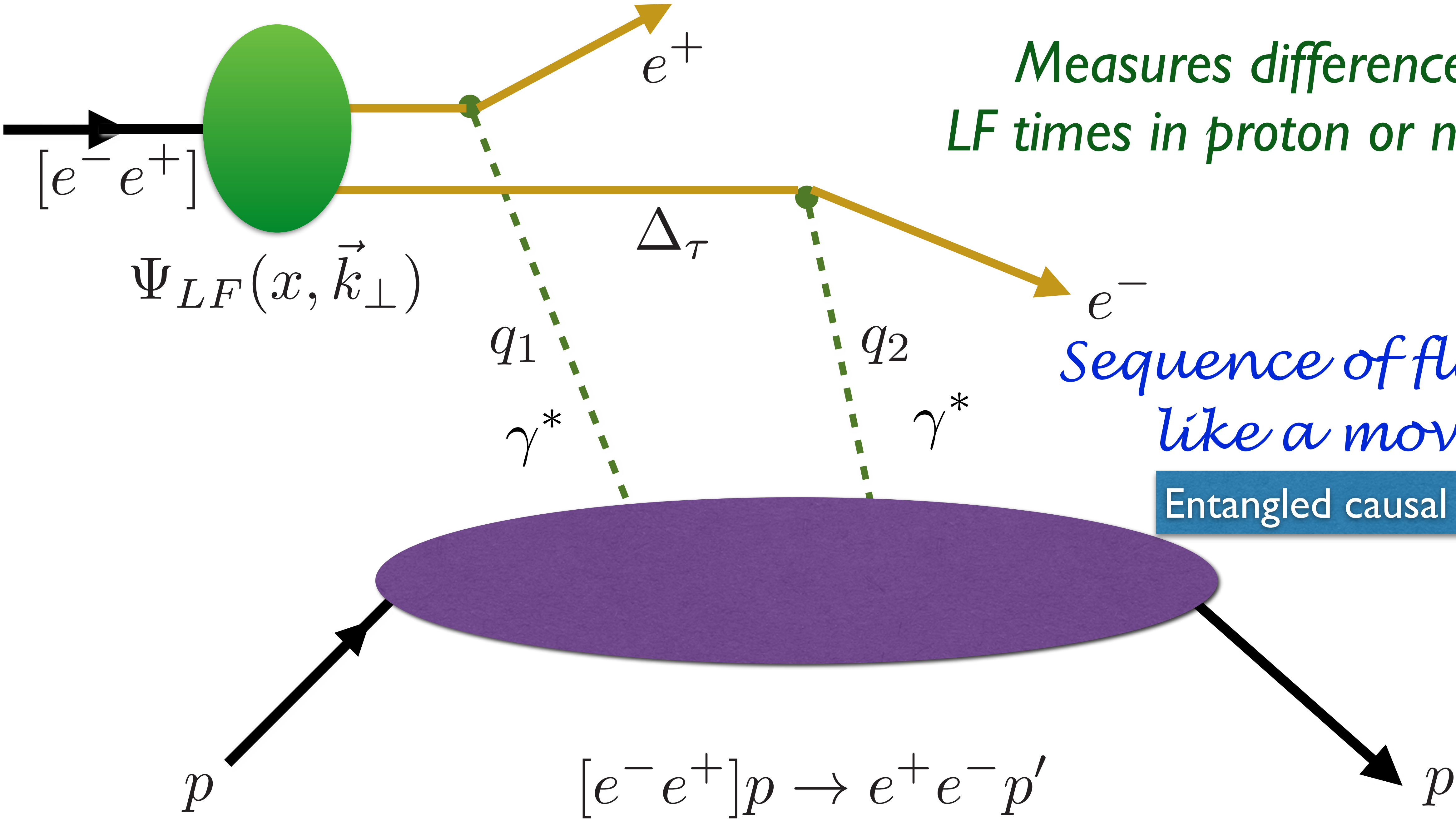
- Measure LFWF of nuclei

$$|\, e^+e^-\gamma >, |\, e^+e^-e^+e^- >, |\, e^+e^-\mu^+\mu^- >,$$

- "Hidden-Color" Fock states of deuteron such as

$$|\, np >, |\, \Delta^+ + \Delta^- >, six\ quark\ jets\ |\, uuuddd >, three\ \bar{3}_C\ diquarks\ |\, (ud)[ud][ud] >$$

Measure Deeply Virtual Compton Scattering Using Positronium - Proton Scattering



$$[e^- e^+]p \to e^+ e^- p'$$

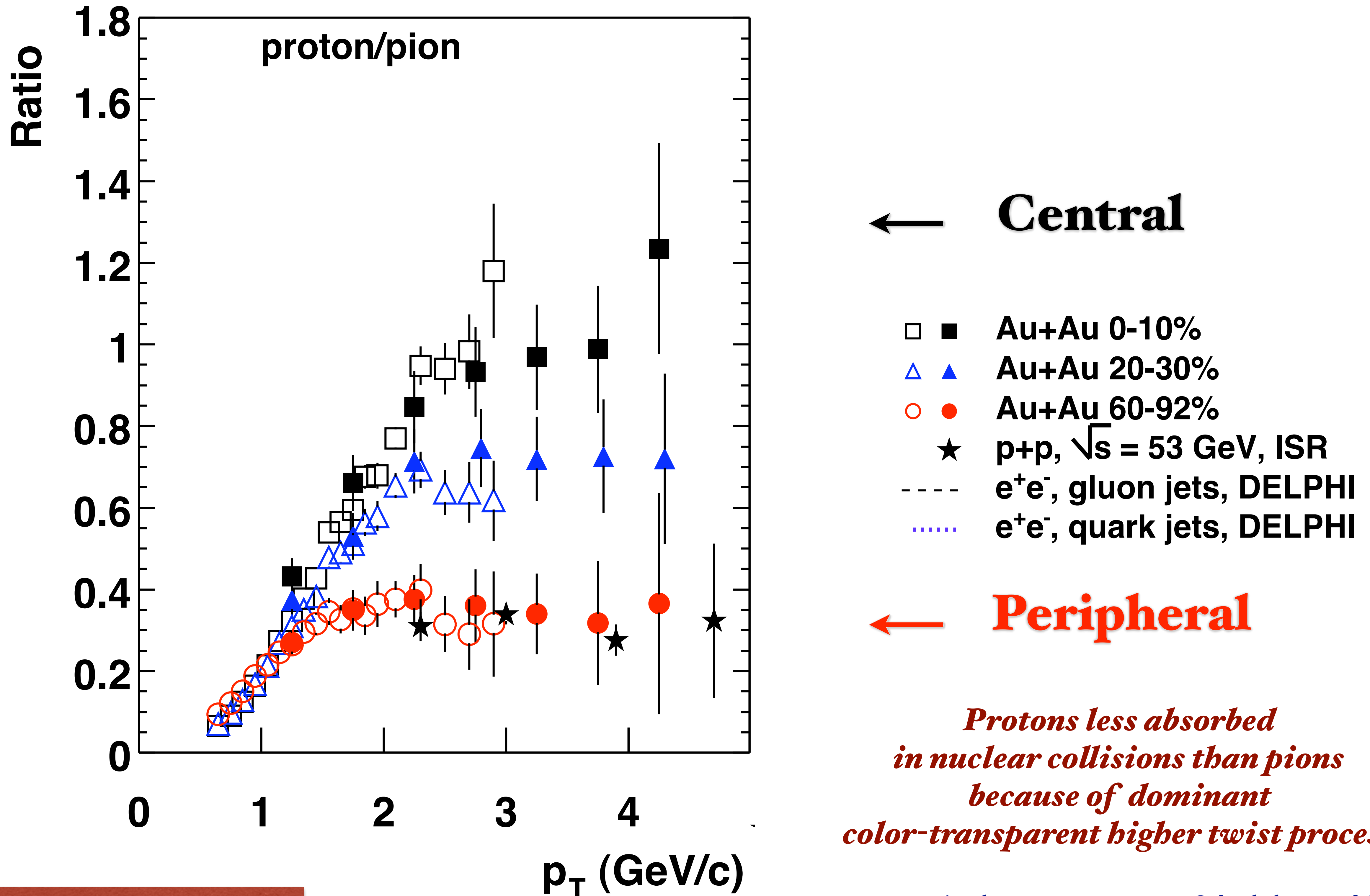
$$< p' | J^\mu(x) J^\nu(y) | p >$$

Both virtual photons are spacelike

$$q_1^2 < 0$$
$$q_2^2 < 0$$

S. S. Adler *et al*. PHENIX Collaboration *Phys. Rev. Lett*. **91**, 172301 (2003).

Particle ratio changes with centrality!



Protons less absorbed in nuclear collisions than pions because of dominant color-transparent higher twist process

Arleo, Hwang, Sickles, sjb

Tannenbaum: "Baryon Anomaly"

Evidence for Direct, Higher-Twist, Color Transparent Subprocesses at RHIC

- *Anomalous power behavior at fixed x_T*
- *Protons more likely to come from direct subprocess than pions*
- *protons not from jets! No same-side hadrons*
- *Protons less absorbed than pions in "central" nuclear collisions because of color transparency*
- *Predicts increasing proton to pion ratio in "central" collisions*
- *Exclusive-inclusive connection at $x_T = 1$*

EIC: Resolve complex physics signals at hadron and ion colliders

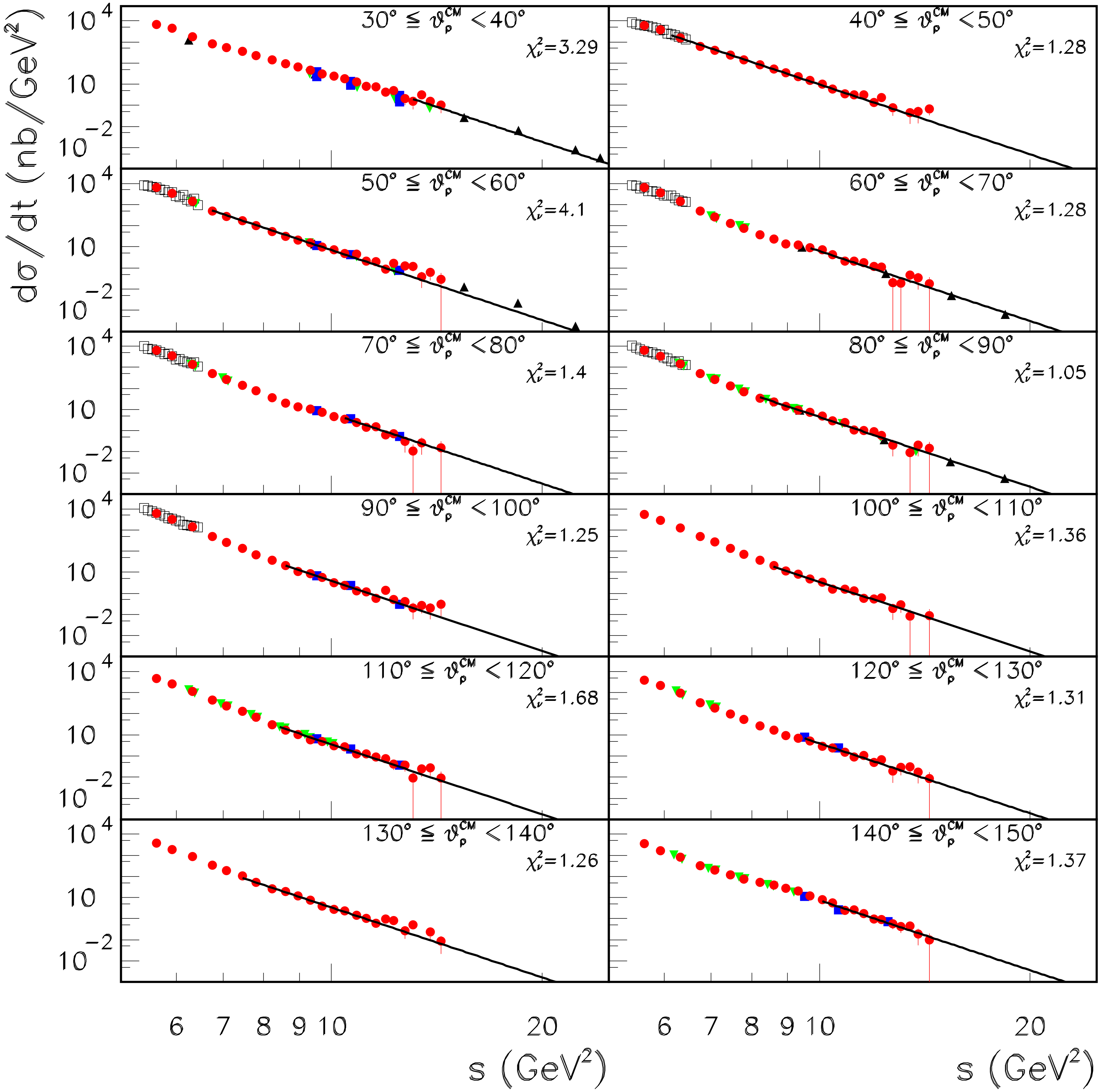
Hidden Color in QCD

Lepage, Ji, sjb

- Deuteron six-quark wavefunction:
- 5 color-singlet combinations of six color-triplets --
- Only one of the five states is |n p>
- Components evolve towards equality at short distances
- Hidden color states dominate deuteron form factor and photodisintegration at high momentum transfer
- Dominates x > 1 domain of deep inelastic scattering on nuclei: quark carries momentum of more than one nucleus!

$$\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-}) \simeq \frac{d\sigma}{dt}(\gamma d \to pn) \text{ at high } Q^2$$

Deuteron Photodisintegration



PQCD and AdS/CFT:

$$s^{n_{tot}-2}\frac{d\sigma}{dt}(A+B\to C+D) = F_{A+B\to C+D}(\theta_{CM})$$

$$s^{11}\frac{d\sigma}{dt}(\gamma d\to np) = F(\theta_{CM})$$

$$n_{tot}-2 = (1+6+3+3)-2 = 11$$

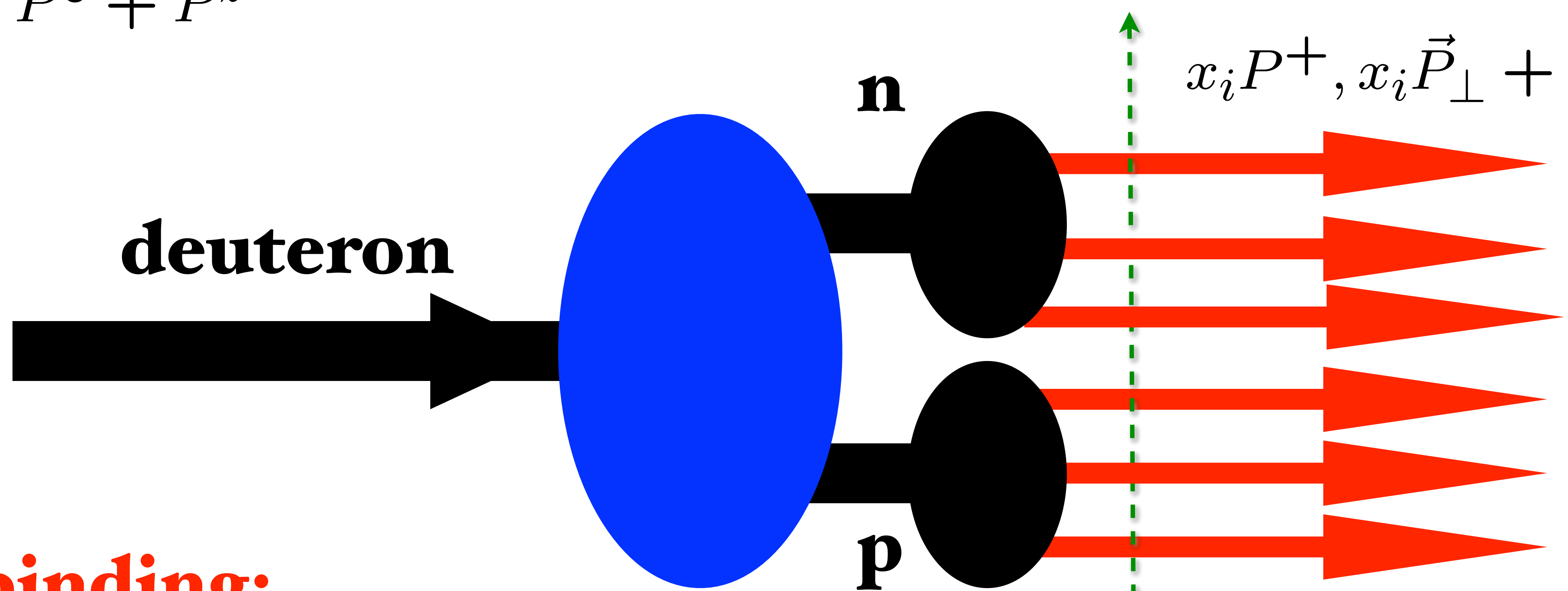
Reflects conformal invariance

$P^+ = P^0 + P^z$

Fixed $\tau = t + z/c$

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

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



Weak binding:

$$\psi_d(x_i, \vec{k}_{\perp i}) = \psi_d^{body} \times \psi_n \times \psi_p$$

$\sum_i^n x_i = 1$

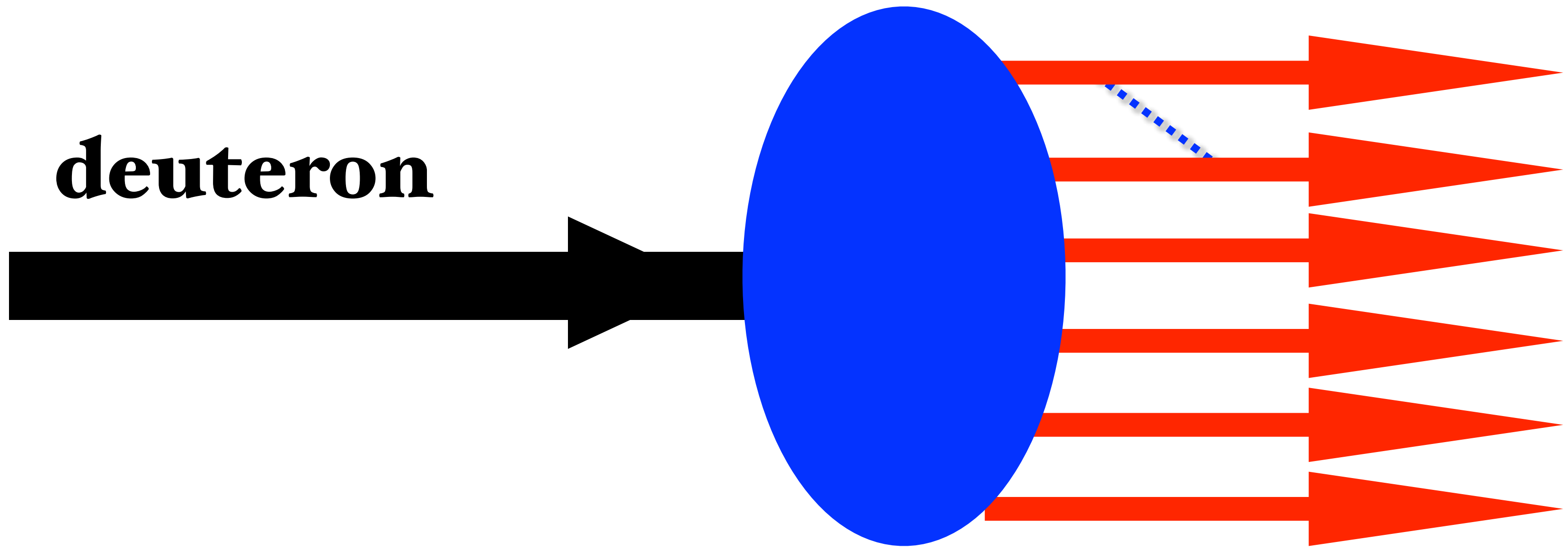
$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

Nuclear Physics:
Two color-singlet combinations of three 3_C

pQCD Evolution of 5 color-singlet Fock states

Lepage, Ji, sjb

$$\Psi^{\mathbf{d}}_n(x_i, \vec{k}_{\perp i}, \lambda_i)$$



$\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

$\sum_i^n x_i = 1$

$$\Phi_n(x_i, Q) = \int^{k^2_{\perp i} < Q^2} \Pi' d^2 k_{\perp j} \psi_n(x_i, \vec{k}_{\perp j})$$

5 X 5 Matrix Evolution Equation for deuteron distribution amplitude

Lepage, Ji, sjb

Hidden Color in QCD

Study the Deuteron as a QCD Object

- Deuteron six-quark wavefunction
- 5 color-singlet combinations of 6 color-triplets -- only one state is |n p>
- Components evolve towards equality at short distances
- Hidden color states dominate deuteron form factor and photodisintegration at high momentum transfer
- Expense Dominance at x > 1
- Predict $\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{-}) \simeq \frac{d\sigma}{dt}(\gamma d \to pn)$ at high Q^2

Hidden Color of Deuteron

Deuteron six-quark state has five color-singlet configurations, only one of which is n-p.

Asymptotic Solution has Expansion

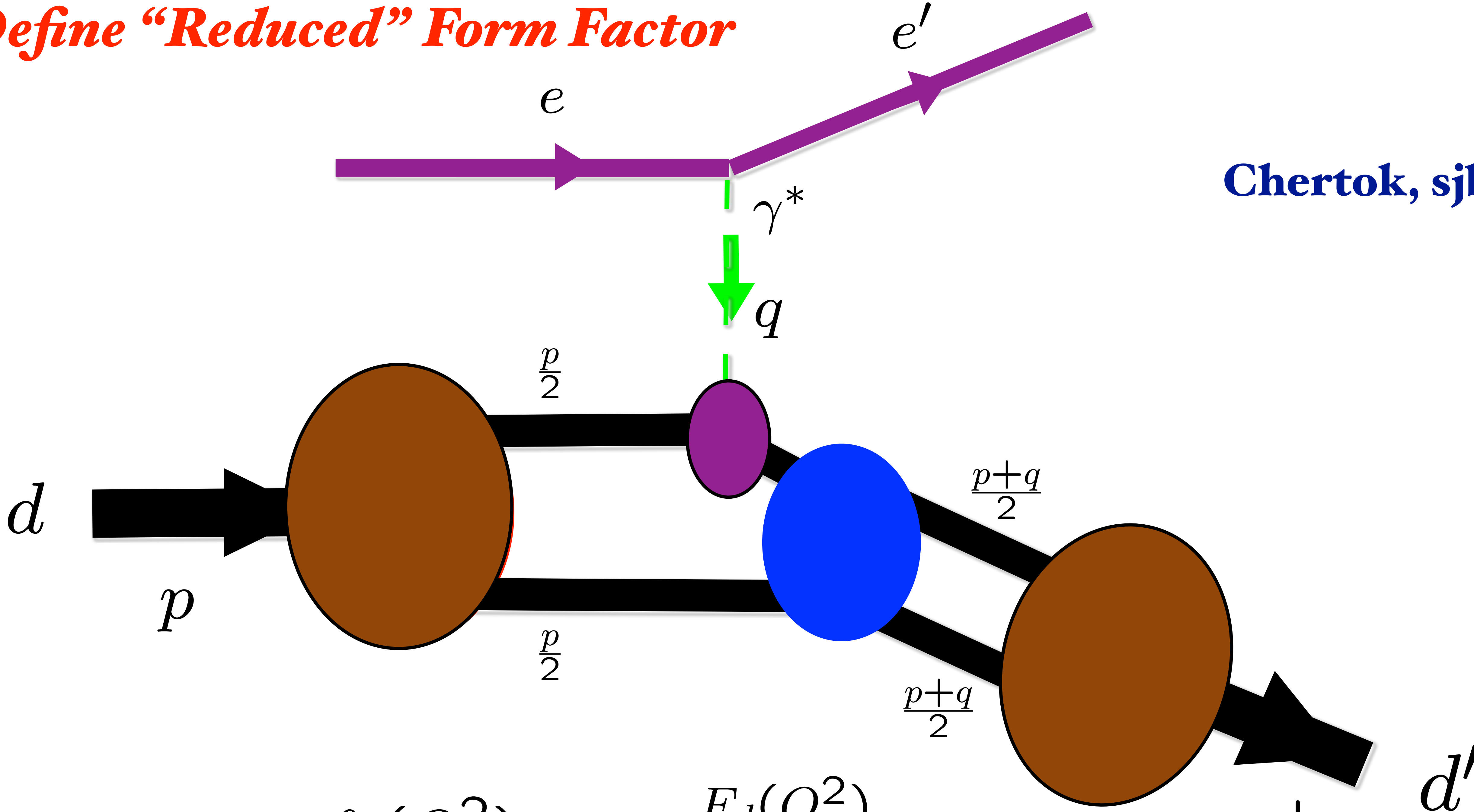
$$\psi_{[6]\{33\}} = \left(\frac{1}{9}\right)^{1/2} \psi_{NN} + \left(\frac{4}{45}\right)^{1/2} \psi_{\Delta\Delta} + \left(\frac{4}{5}\right)^{1/2} \psi_{CC}$$

ERBL Evolution: Transition to Delta-Delta

Lepage, Ji, sjb

Define "Reduced" Form Factor

Chertok, sjb



$$f_d(Q^2) \equiv \frac{F_d(Q^2)}{F_p(\frac{Q^2}{4})F_n(\frac{Q^2}{4})}$$

Elastic electron-deuteron scattering

QCD Prediction for Deuteron Form Factor

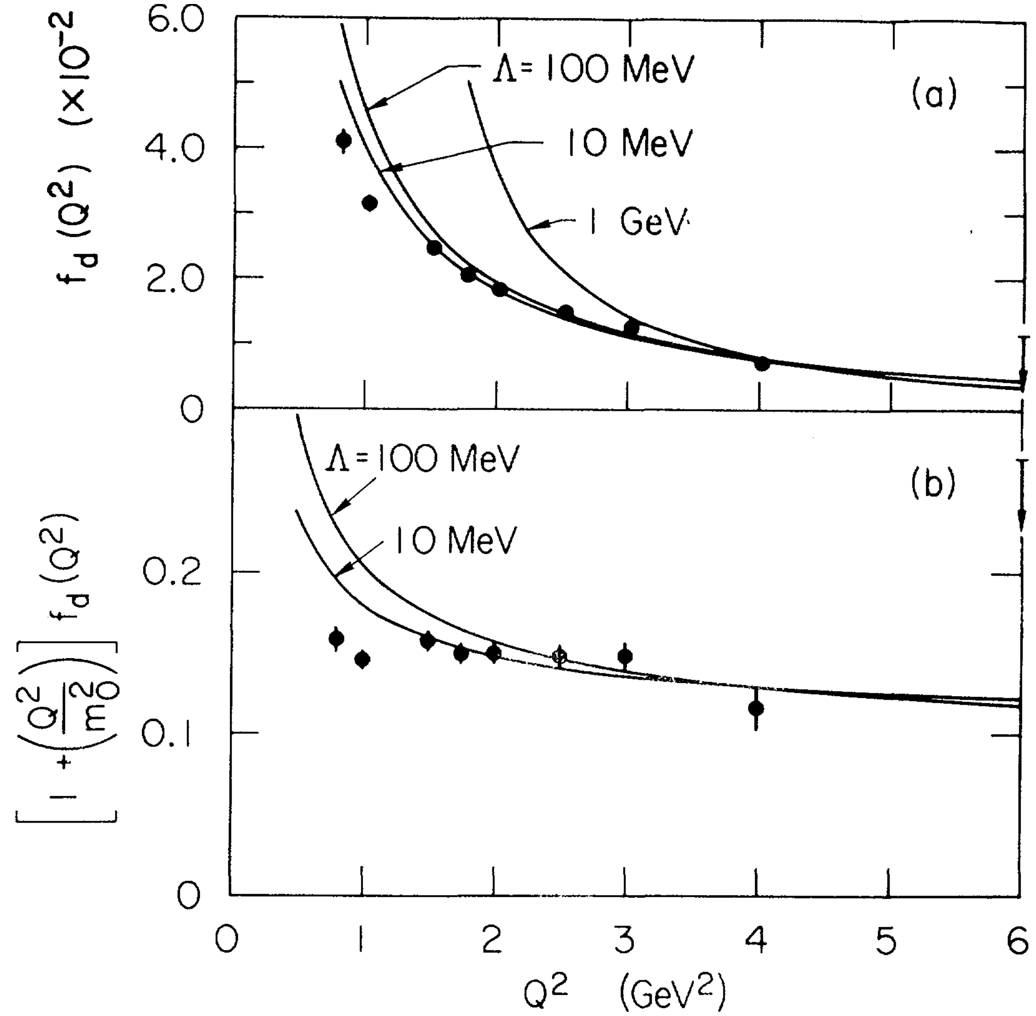
Lepage, Ji, sjb

$$F_d(Q^2) = \left[\frac{\alpha_s(Q^2)}{Q^2}\right]^5 \sum_{m,n} d_{mn} \left(\ln \frac{Q^2}{\Lambda^2}\right)^{-\gamma_n^d - \gamma_m^d} \left[1 + O\left(\alpha_s(Q^2), \frac{m}{Q}\right)\right]$$

Define "Reduced" Form Factor

$$f_d(Q^2) \equiv \frac{F_d(Q^2)}{F_N^{\,2}(Q^2/4)} .$$

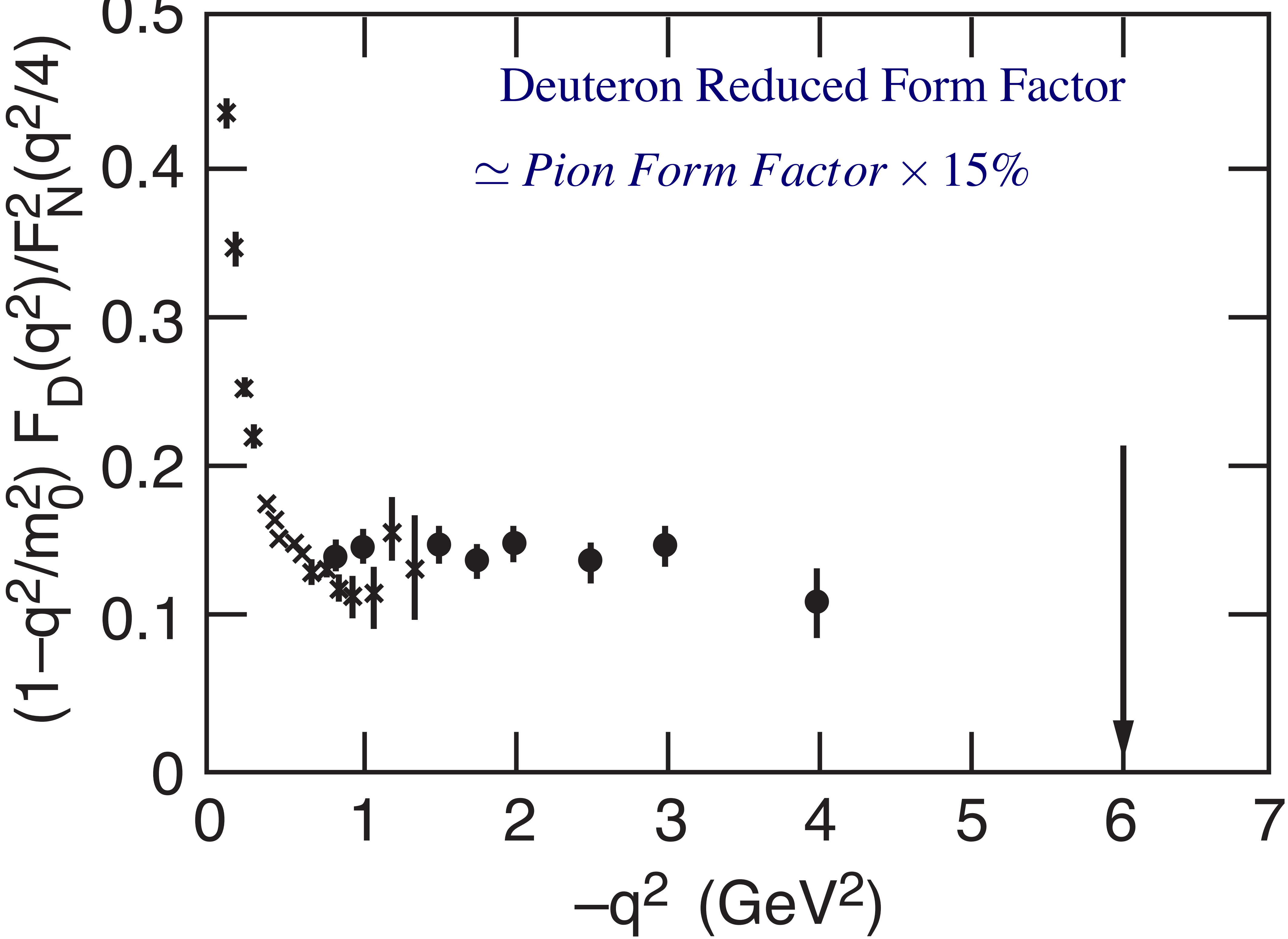
$$f_d(Q^2) \sim \frac{\alpha_s(Q^2)}{Q^2} \left(\ln \frac{Q^2}{\Lambda^2}\right)^{-(2/5)\, C_F/\beta}$$



(a) Comparison of the asymptotic QCD prediction $f_d(Q^2) \propto (1/Q^2)[\ln(Q^2/\Lambda^2)]^{-1-(2/5)C_F/\beta}$ with final data of Ref. 10 for the reduced deuteron form factor, where $F_N(Q^2) = [1 + Q^2/(0.71\ \mathrm{GeV}^2)]^{-2}$. The normalization is fixed at the $Q^2 = 4\ \mathrm{GeV}^2$ data point. (b) Comparison of the prediction $[1 + (Q^2/m_0^{\,2})]\, f_d(Q^2) \propto [\ln(Q^2/\Lambda^2)]^{-1-(2/5)\,C_F/\beta}$ with the above data. The value $m_0^{\,2} = 0.28\ \mathrm{GeV}^2$ is used

Same large momentum transfer behavior as pion form factor

Chertok, sjb



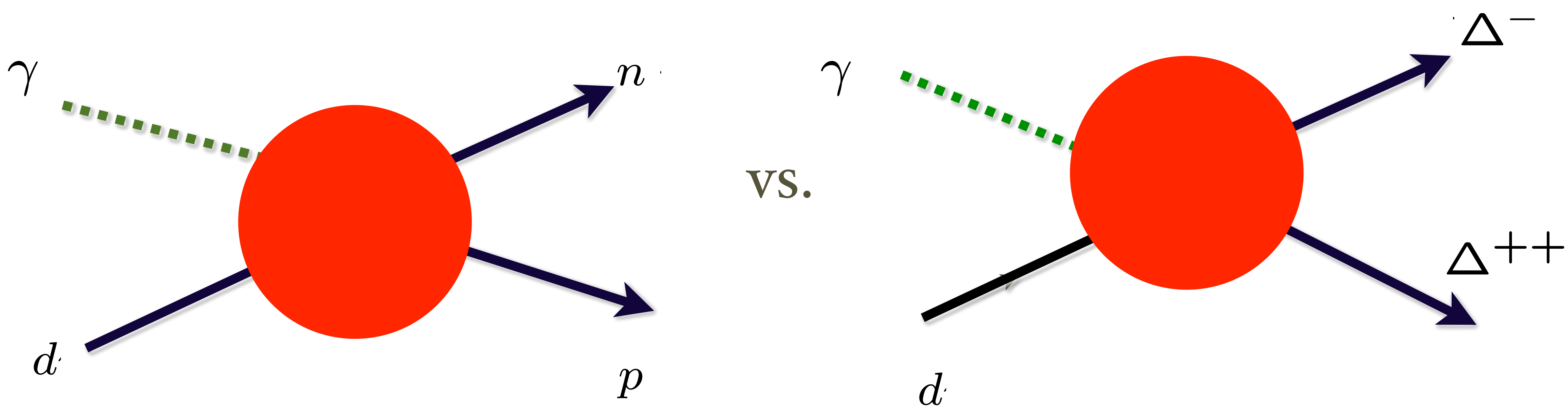
Deuteron Reduced Form Factor
$\simeq$ Pion Form Factor $\times$ 15%
$(1-q^2/m_0^2)\ F_D(q^2)/F_N^2(q^2/4)$
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
6
7
$-q^2\ (\mathrm{GeV}^2)$

Test of Hidden Color in Deuteron Photodisintegration

$$R = \frac{\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^{--})}{\frac{d\sigma}{dt}(\gamma d \to pn)}$$

Ratio predicted to approach 2:5

Ratio should grow with transverse momentum as the hidden color component of the deuteron grows in strength.



Possible contribution from pion charge exchange at small t.

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

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

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

The Light Front Fock State Wavefunctions

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

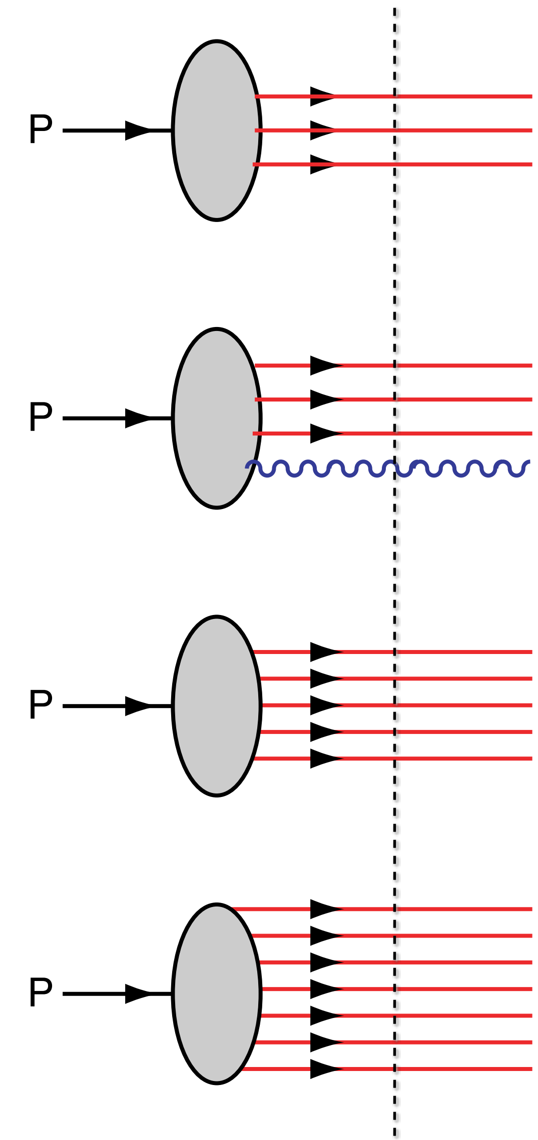
are boost invariant; they are independent of the hadron's energy and momentum P^μ.

The light-cone momentum fractions

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

are boost invariant.

$$\sum_i^n k_i^+ = P^+, \sum_i^n x_i = 1, \sum_i^n \vec{k}_i^\perp = \vec{0}^\perp.$$



Fixed LF time

Intrinsic heavy quarks

s(x), c(x), b(x) at high x !

$\bar{s}(x) \neq s(x)$

$\bar{u}(x) \neq \bar{d}(x)$

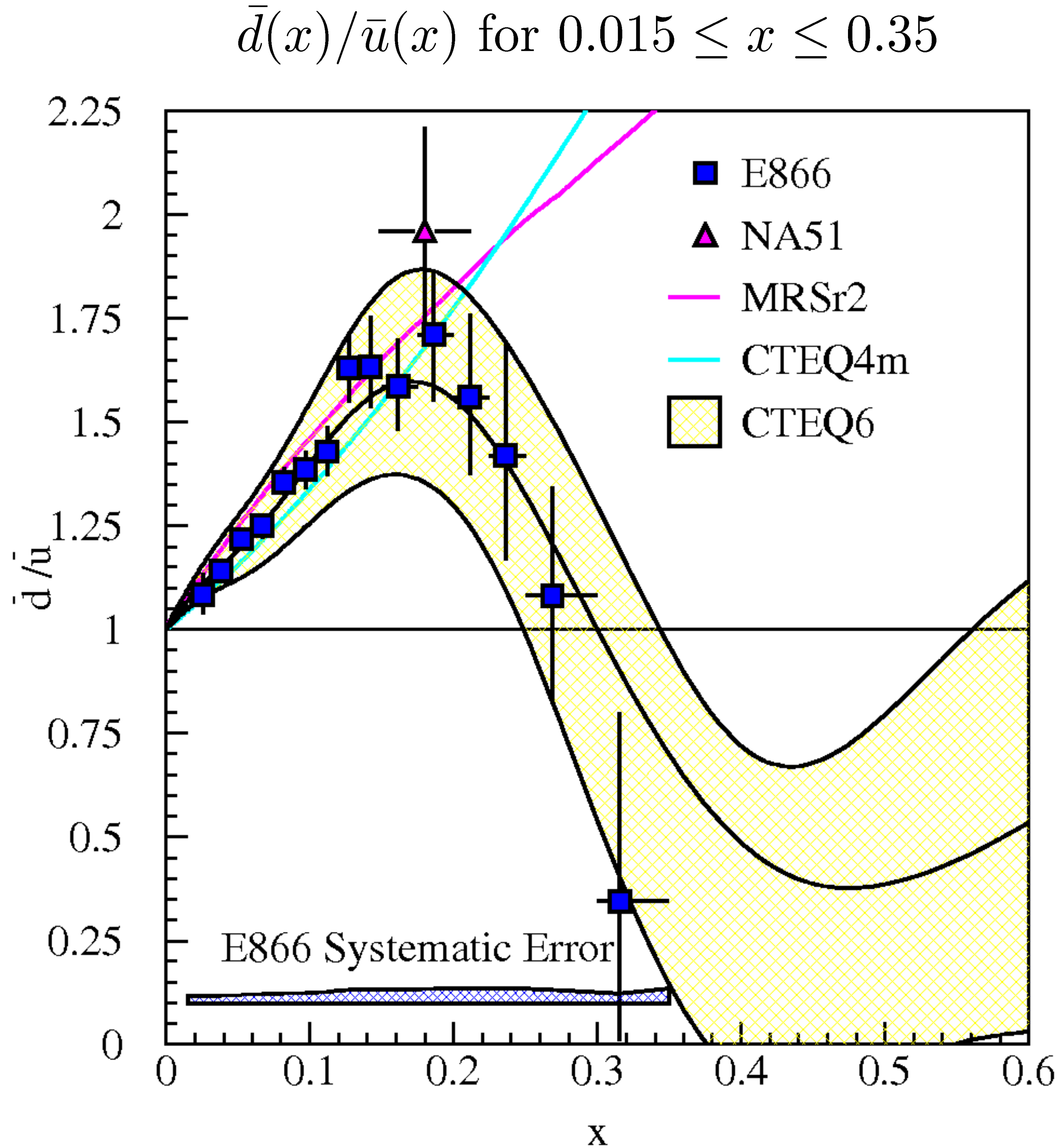
Hidden Color

- E866/NuSea (Drell-Yan)

$$\bar{d}(x) \neq \bar{u}(x)$$

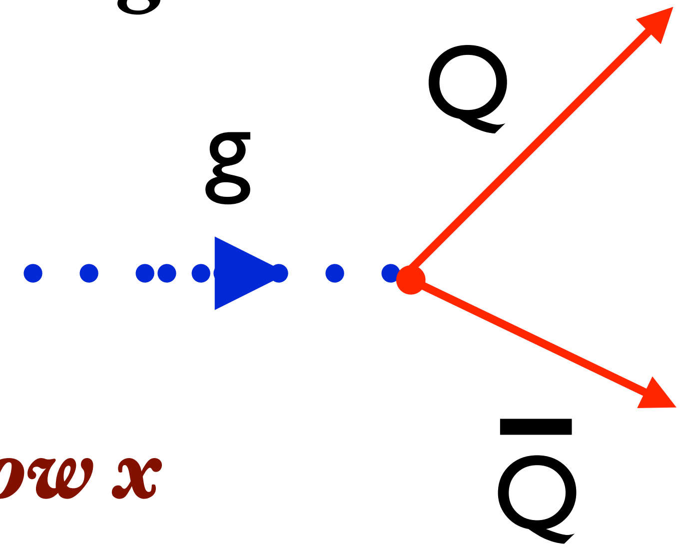
Interactions of quarks at same rapidity in 5-quark Fock state

Intrinsic sea quarks



Do heavy quarks exist in the proton at high x?

Conventional wisdom: gluon splitting



Heavy quarks generated only at low x via DGLAP evolution from gluon splitting

Maximally off-shell - requires low x, high W^2

$$s(x, \mu_F^2) = c(x, \mu_F^2) = b(x, \mu_F^2) \equiv 0$$

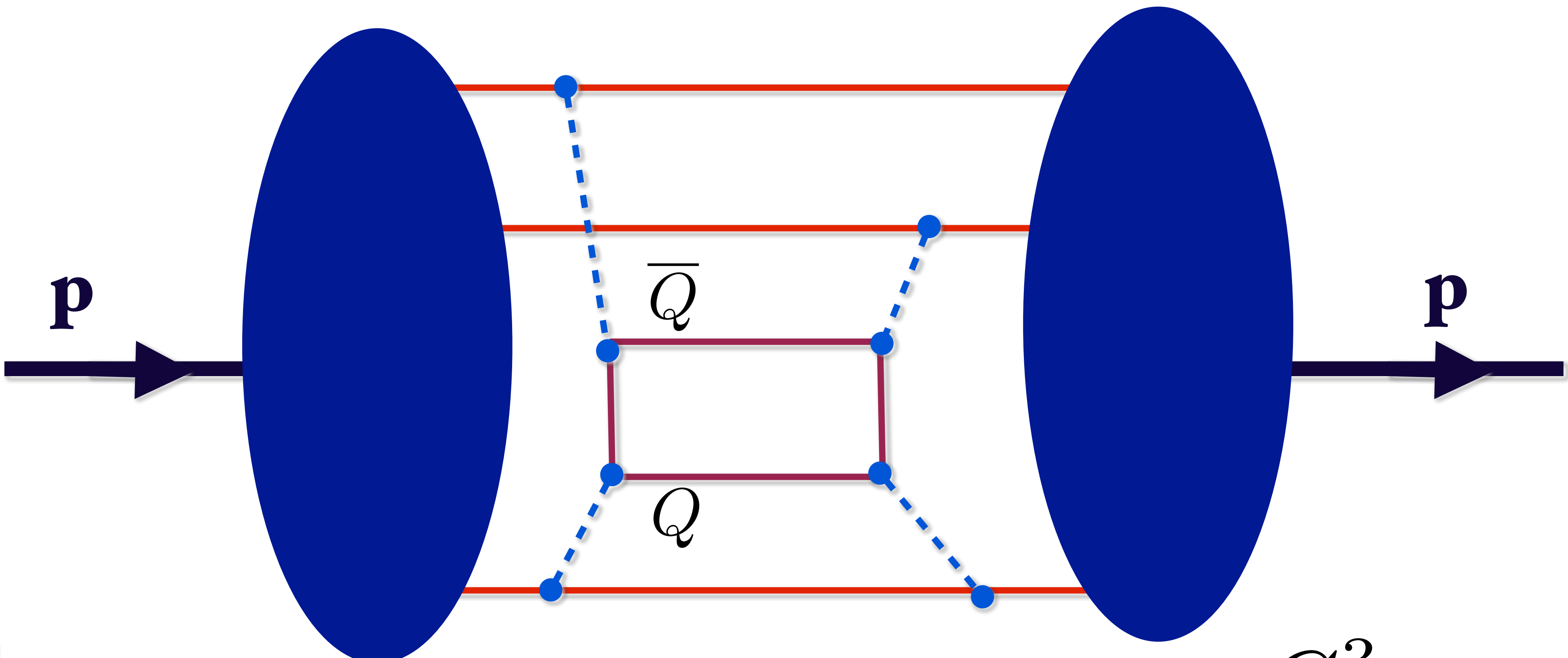
$$\text{at starting scale } Q_0^2 = \mu_F^2$$

Conventional wisdom is wrong even in QED!

Proton Self Energy from g g to gg scattering

QCD predicts Intrinsic Heavy Quarks!

$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$



$$\frac{F_{\mu\nu}^4}{M_\ell^2}$$

$$\frac{G_{\mu\nu}^3}{M_Q^2}$$

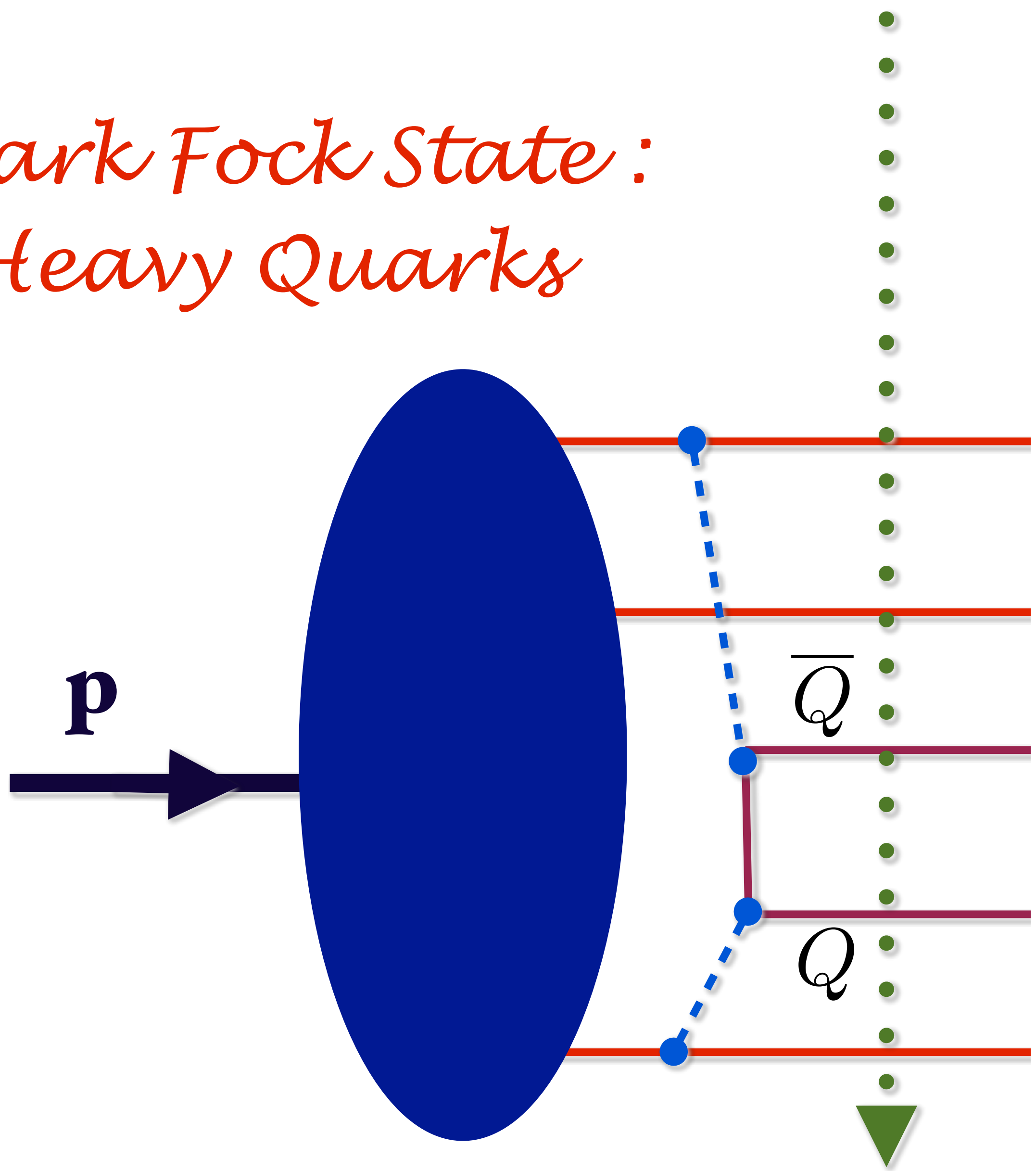
Probability (QED) $\propto \frac{1}{M_\ell^4}$

Probability (QCD) $\propto \frac{1}{M_Q^2}$

Collins, Ellis, Gunion, Mueller, sjb
M. Polyakov, et al.

Fixed LF time

Proton 5-quark Fock State :
Intrinsic Heavy Quarks



QCD predicts Intrinsic Heavy Quarks at high x!

Minimal off-shellness

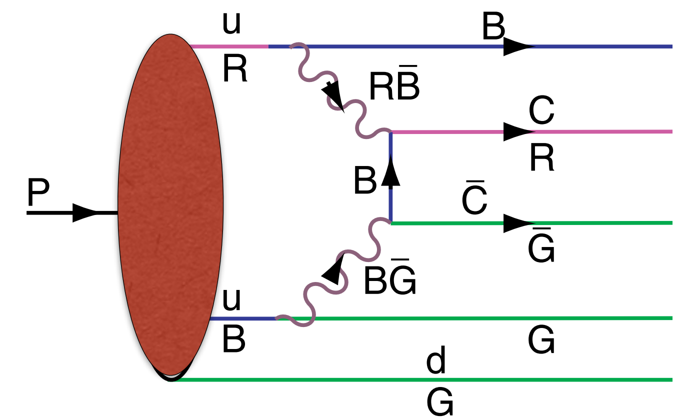
$$x_Q \propto (m_Q^2 + k_\perp^2)^{1/2}$$

$\text{Probability (QED)} \propto \frac{1}{M_\ell^4}$ $\text{Probability (QCD)} \propto \frac{1}{M_Q^2}$

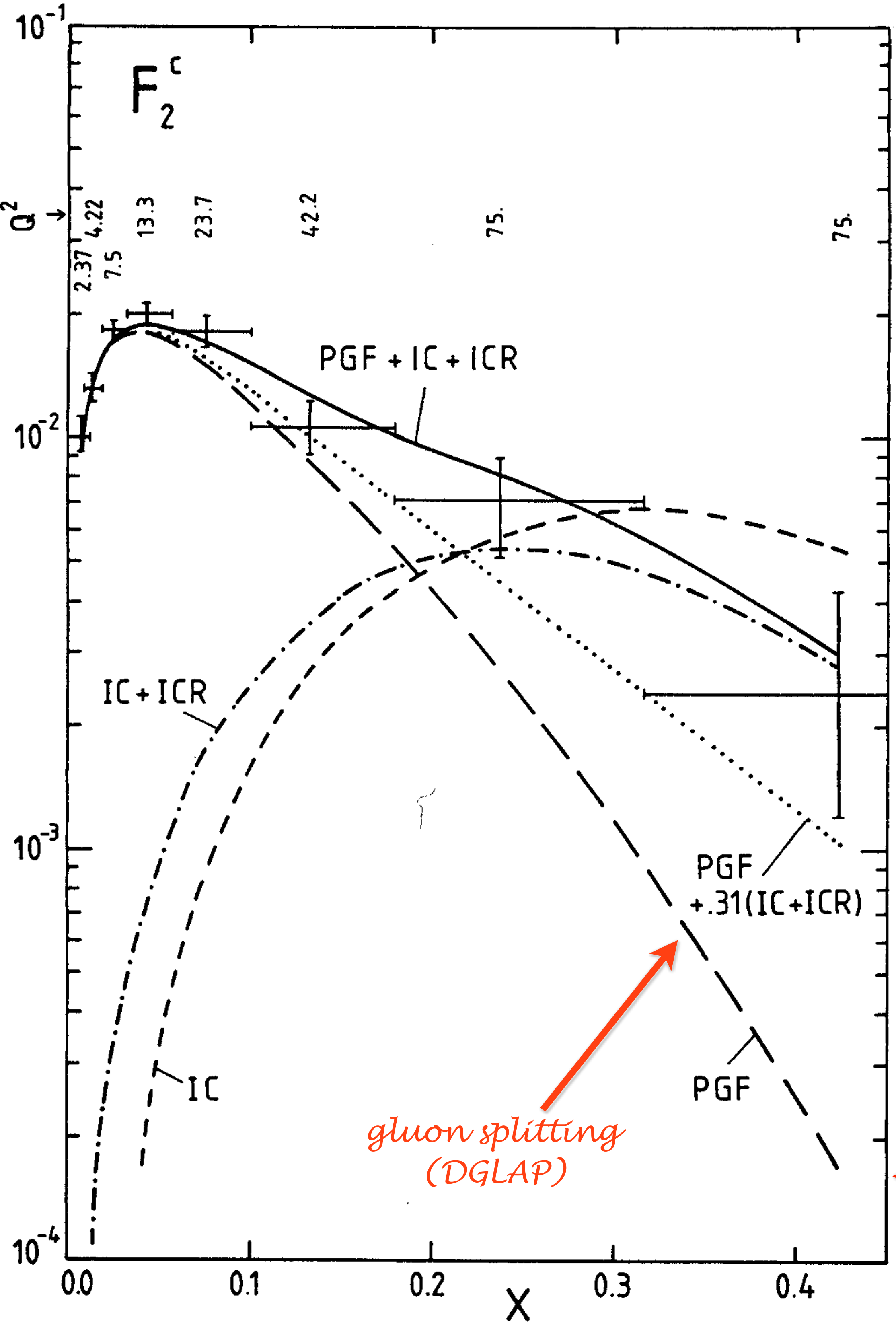
Collins, Ellis, Gunion, Mueller, sjb
M. Polyakov

Hoyer, Peterson, Sakai, sjb

Intrinsic Heavy-Quark Fock States



- **Rigorous prediction of QCD, OPE**
- **Color-Octet Color-Octet Fock State**
- **Probability** $P_{Q\bar{Q}} \propto \frac{1}{M_Q^2}$ $P_{Q\bar{Q}Q\bar{Q}} \sim \alpha_s^2 P_{Q\bar{Q}}$ $P_{c\bar{c}/p} \simeq 1\%$
- **Large Effect at high x**
- **Greatly increases kinematics of colliders such as Higgs production (Kopeliovich, Schmidt, Soffer, sjb)**
- **Underestimated in conventional parameterizations of heavy quark distributions (Pumplin, Tung)**

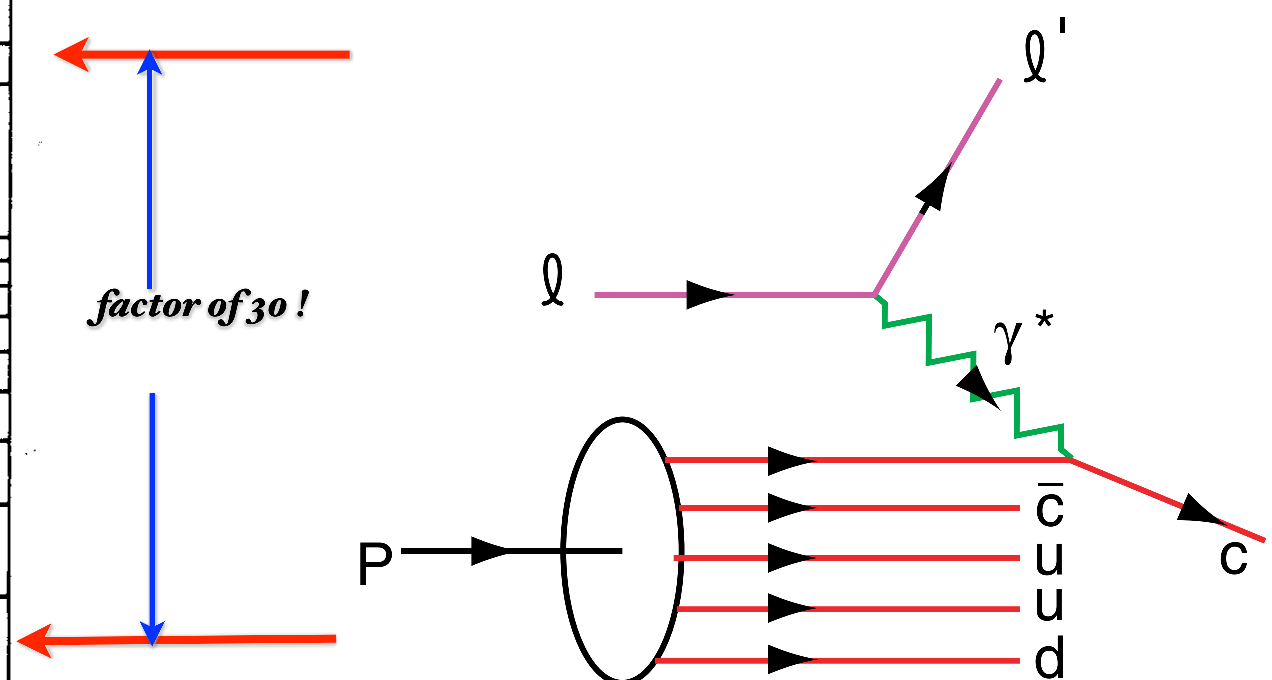


Measurement of Charm Structure Function!

J. J. Aubert et al. [European Muon Collaboration], "Production Of Charmed Particles In 250-Gev Mu+ - Iron Interactions," Nucl. Phys. B 213, 31 (1983).

First Evidence for Intrinsic Charm

Hoyer, Peterson, Sakai, sjb



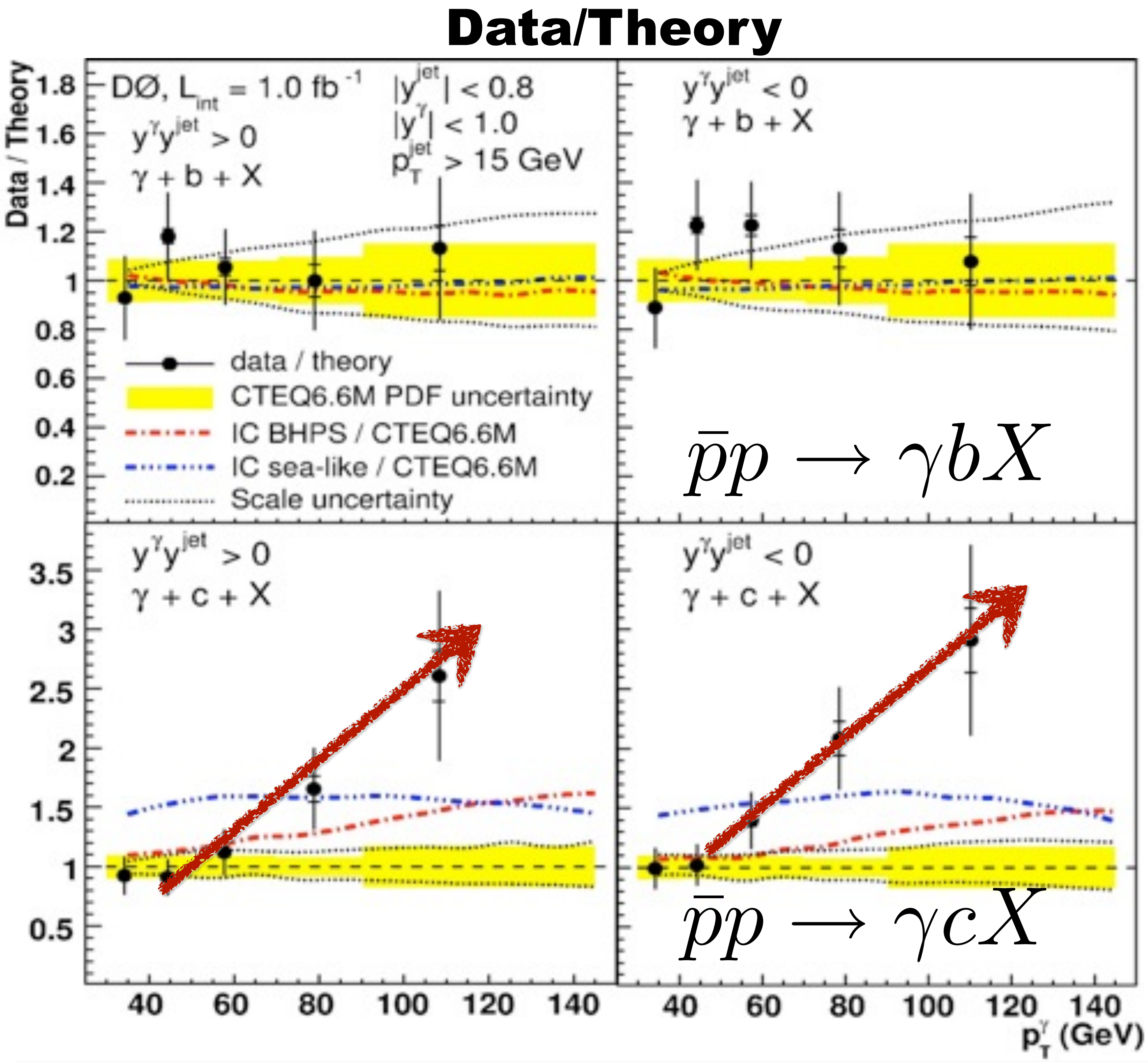
DGLAP / Photon-Gluon Fusion: factor of 30 too small

Two Components (separate evolution):

$$c(x,Q^2) = c(x,Q^2)_{\text{extrinsic}} + c(x,Q^2)_{\text{intrinsic}}$$

PRL 102, 192002 (2009) PHYSICAL REVIEW LETTERS week ending 15 MAY 2009

Measurement of $\gamma + b + X$ and $\gamma + c + X$ Production Cross Sections in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

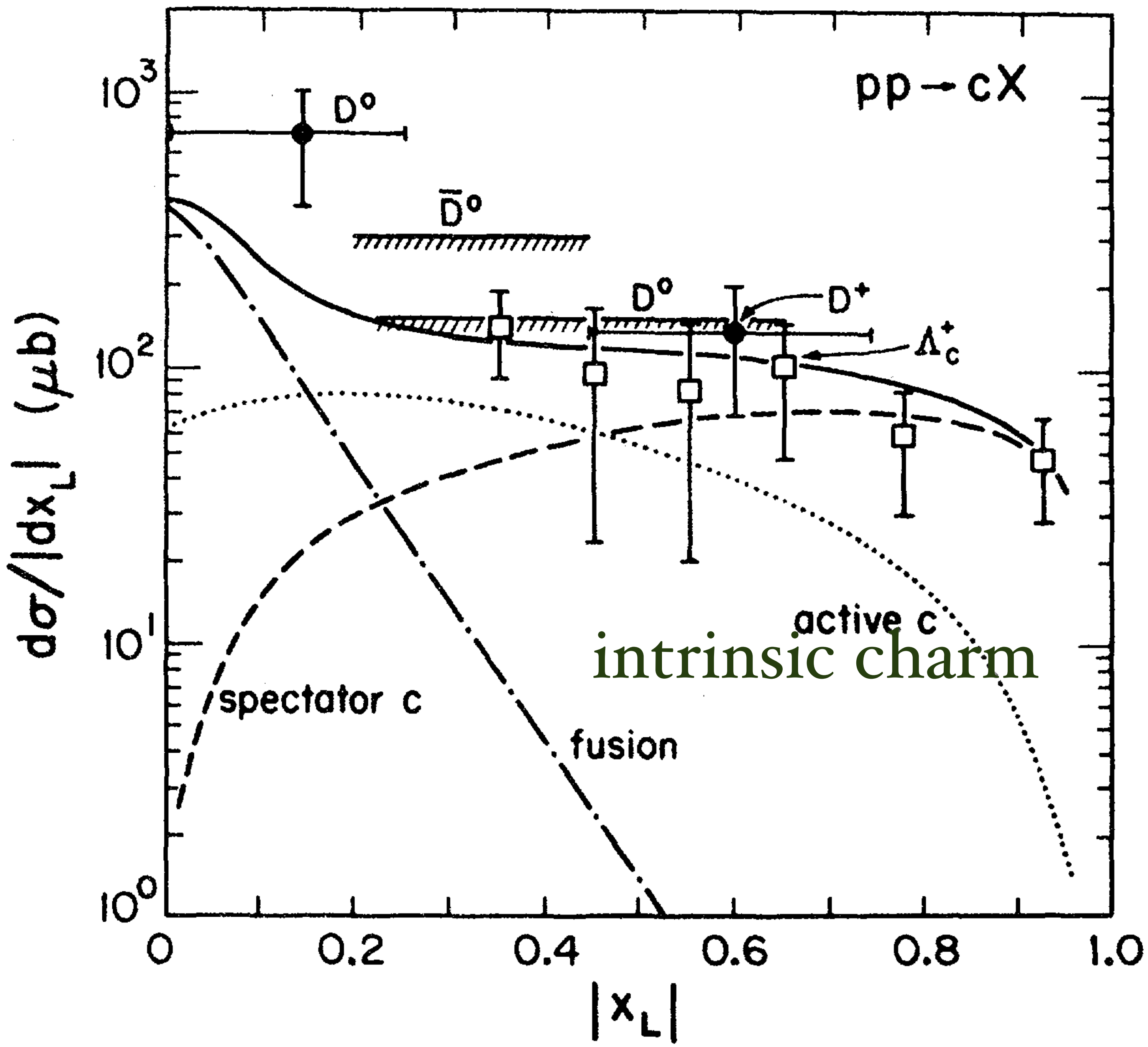


$$\frac{\Delta\sigma(\bar{p}p \to \gamma c X)}{\Delta\sigma(\bar{p}p \to \gamma b X)}$$

Ratio insensitive to gluon PDF, scales

Signal for significant IC at x > 0.1

Consistent with EMC measurement of charm structure function at high x



Barger, Halzen, Keung

Evidence for charm at large x

- EMC data: $c(x,Q^2) > 30 \times$ DGLAP
  $Q^2 = 75$ GeV^2, $x = 0.42$

- High x_F $pp \to J/\psi X$

- High x_F $pp \to J/\psi J/\psi X$

- High x_F $pp \to \Lambda_c X$

- High x_F $pp \to \Lambda_b X$

- High x_F $pp \to \Xi(ccd) X$ (SELEX)

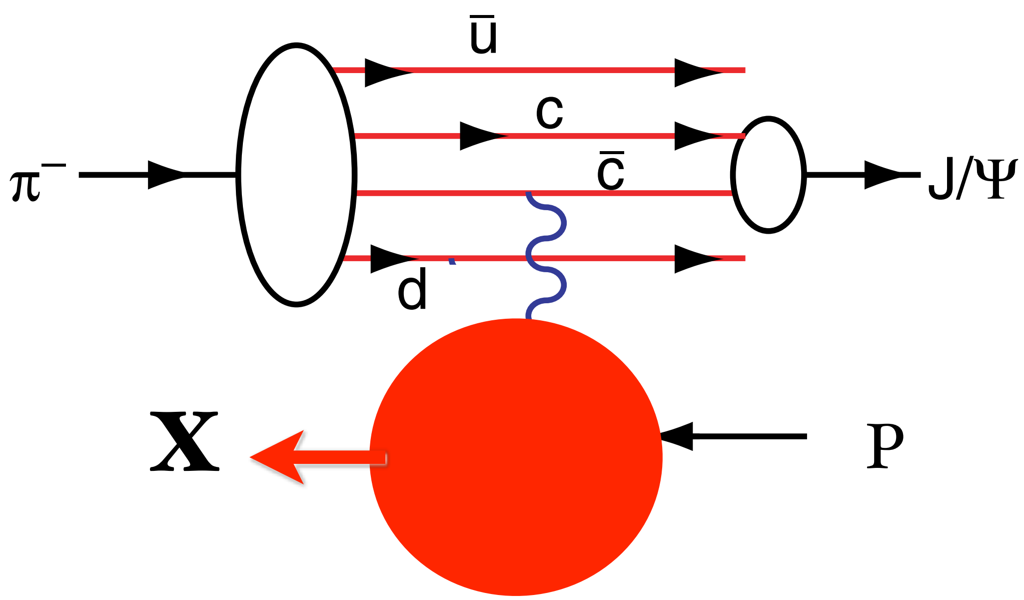
Critical Measurements at threshold for JLab, PANDA

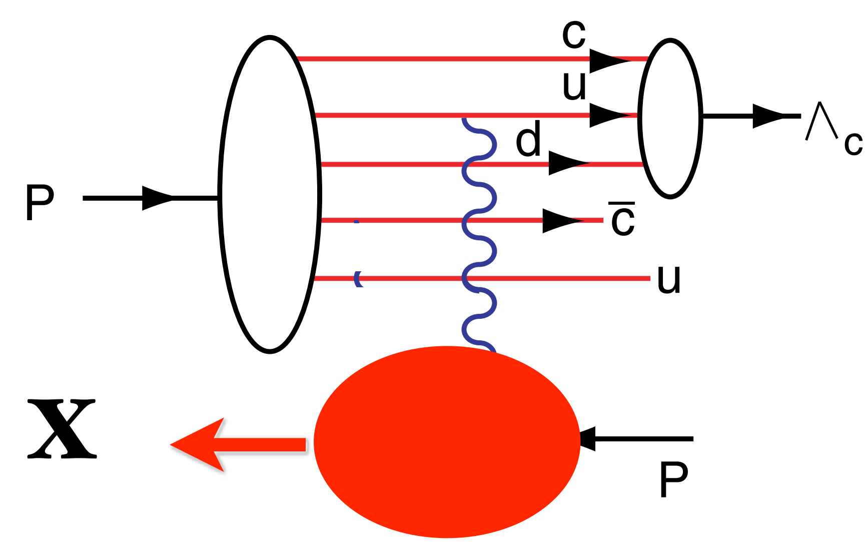
Interesting spin, charge asymmetry, threshold, spectator effects

Important corrections to B decays; Quarkonium decays

Gardner, Karliner, sjb

Leading Hadron Production from Intrinsic Charm



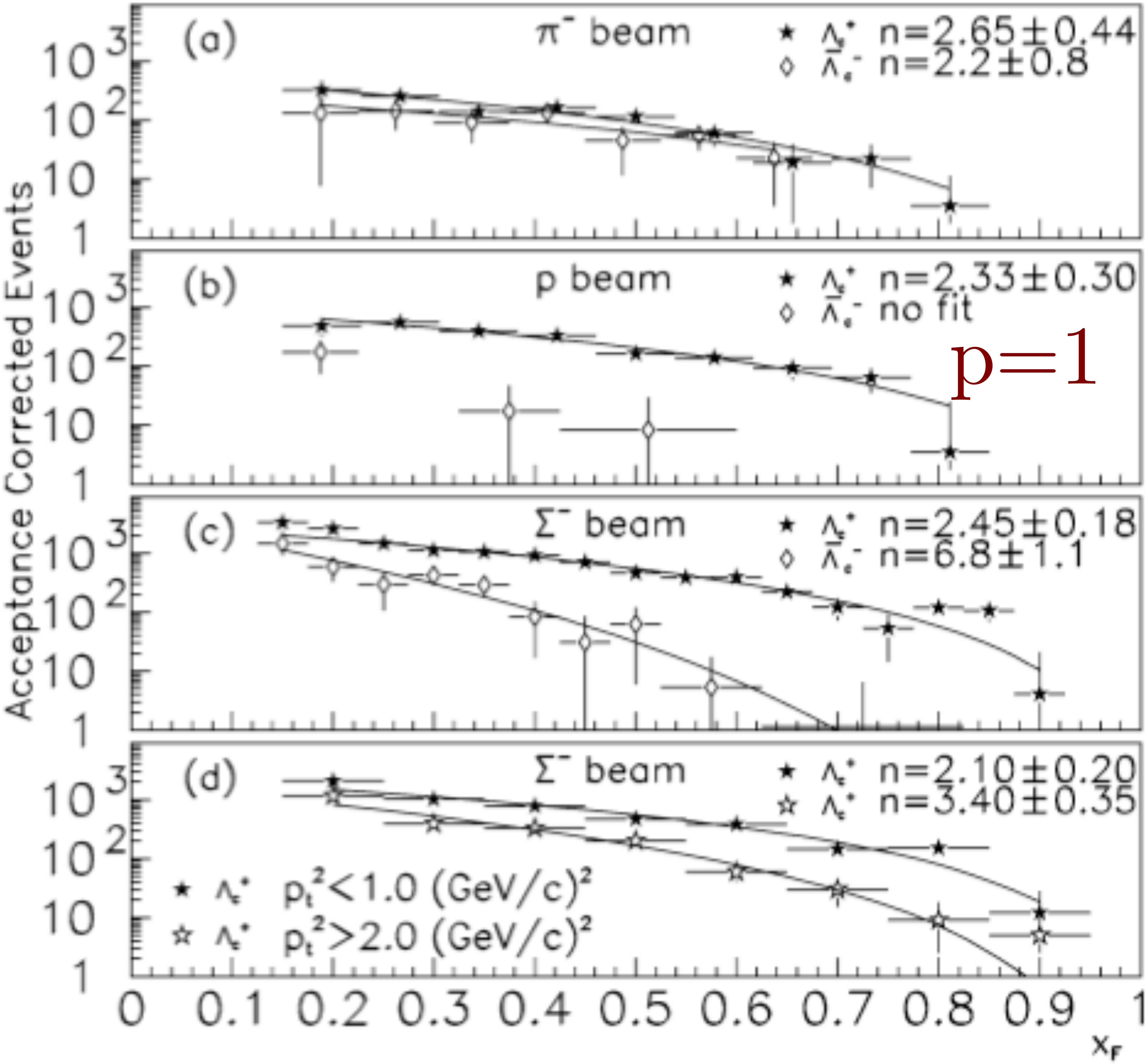


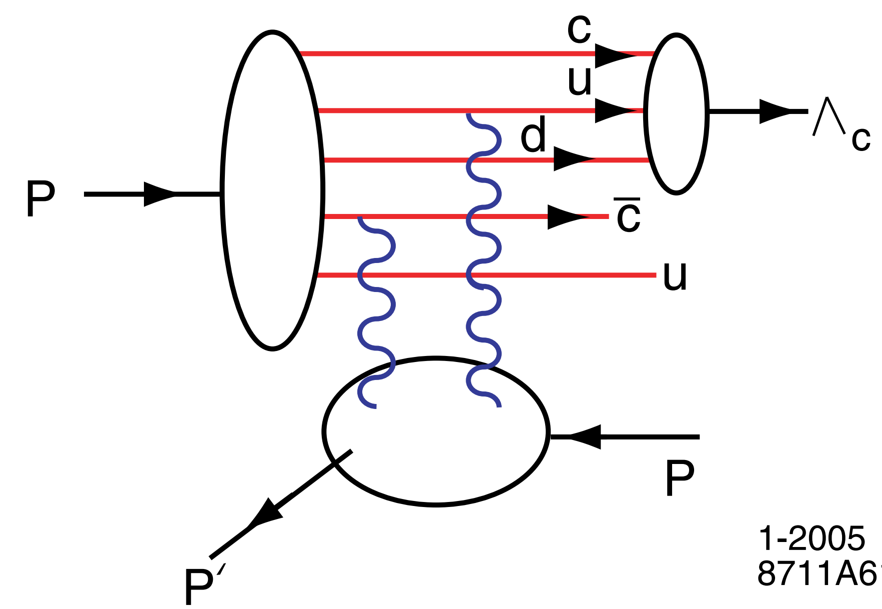
Spectator counting rules

$$\frac{dN}{dx_F} \propto (1 - x_F)^{2n_{spect}-1}$$

Coalescence of Comoving Charm and Valence Quarks
Produce J/ψ, Λ_c and other Charm Hadrons at High x_F

SELEX





$$p(uudc\bar{c}) \rightarrow \Lambda_c(cud)$$

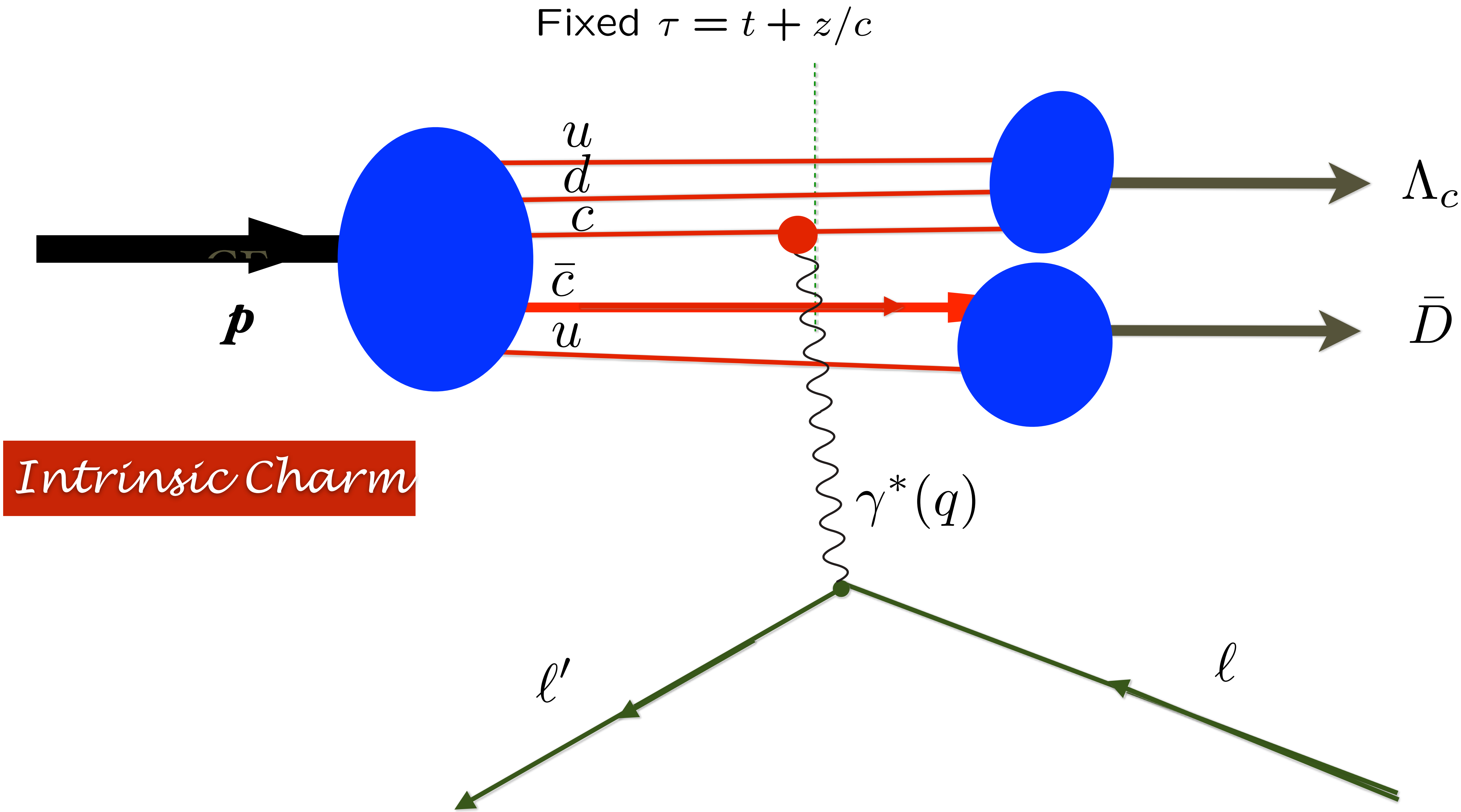
$$n_s = 2$$

Phase space alone gives minimum power

$$(1 - x_F)^p, p = n_s - 1$$

Maximum fraction of projectile momentum carried by charm quarks!

Light-Front Wavefunctions and Heavy-Quark Electroproduction

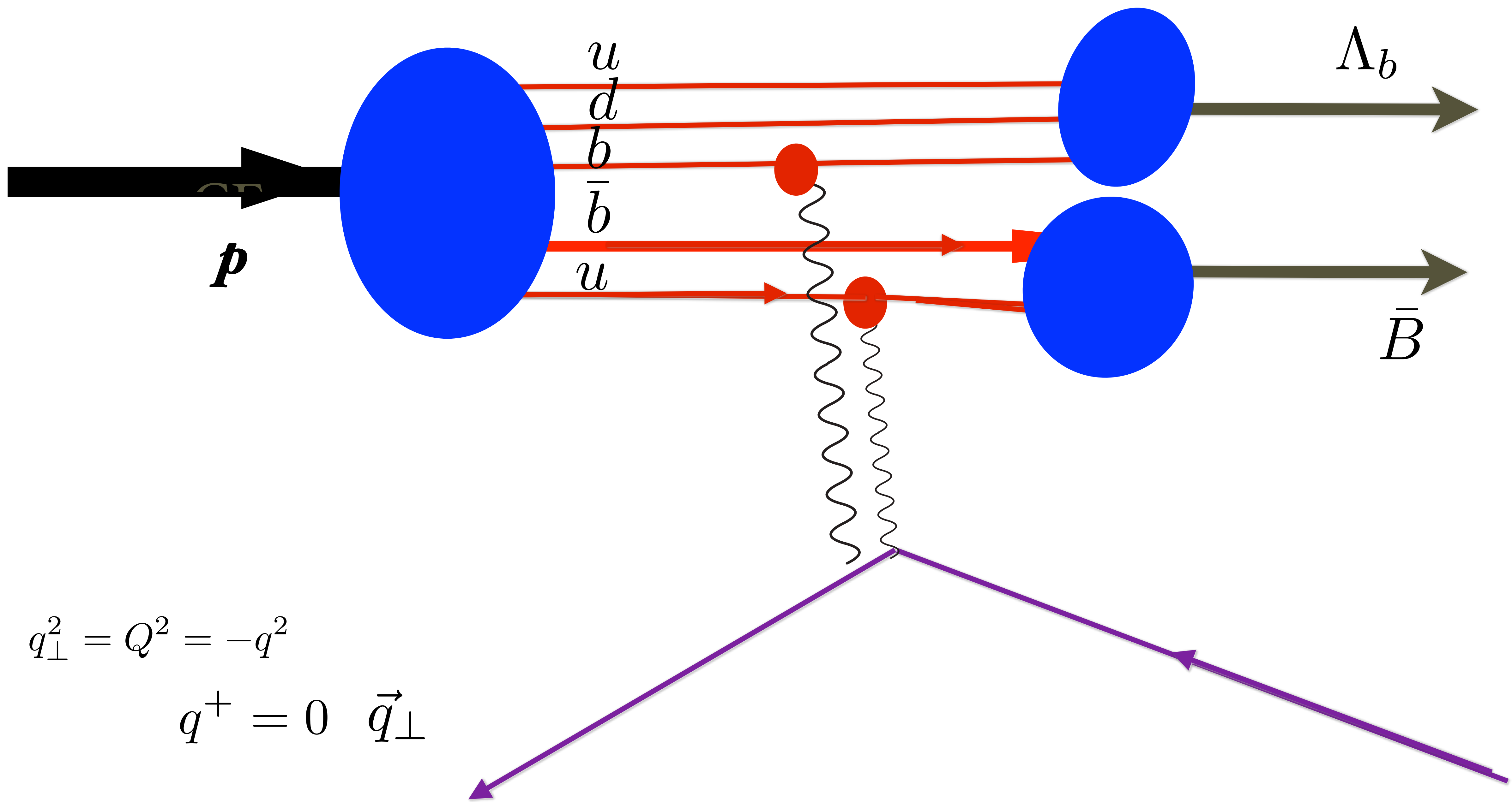


Threshold Production at JLab!

Coalescence of comovers produces $|F>=|\Lambda_c \bar{D}>$ Final State

Charm Produced in Target-Rapidity Domain

Light-Front Wavefunctions and Heavy Quark Hadroproduction



Coalescence of comovers produces $|F> = |\Lambda_b \bar{B}>$ Final State

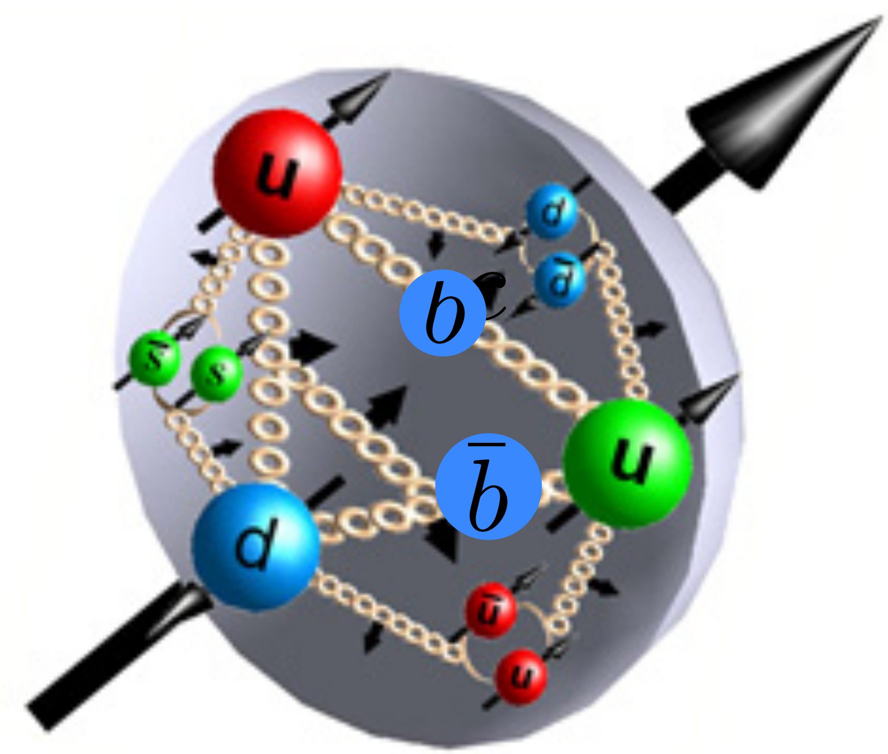
27 May 1991

CM-P00063074

THE Λ_b^o BEAUTY BARYON PRODUCTION IN PROTON-PROTON INTERACTIONS AT $\sqrt{s}$=62 GeV: A SECOND OBSERVATION

G. Bari, M. Basile, G. Bruni, G. Cara Romeo, R. Casaccia, L. Cifarelli, F. Cindolo, A. Contin, G. D'Alì, C. Del Papa, S. De Pasquale, P. Giusti, G. Iacobucci, G. Maccarrone, T. Massam, R. Nania, F. Palmonari, G. Sartorelli, G. Susinno, L. Votano and A. Zichichi

CERN, Geneva, Switzerland
Dipartimento di Fisica dell'Università, Bologna, Italy
Dipartimento di Fisica dell'Università, Cosenza, Italy
Istituto di Fisica dell'Università, Palermo, Italy
Istituto Nazionale di Fisica Nucleare, Bologna, Italy
Istituto Nazionale di Fisica Nucleare, LNF, Frascati, Italy



Abstract

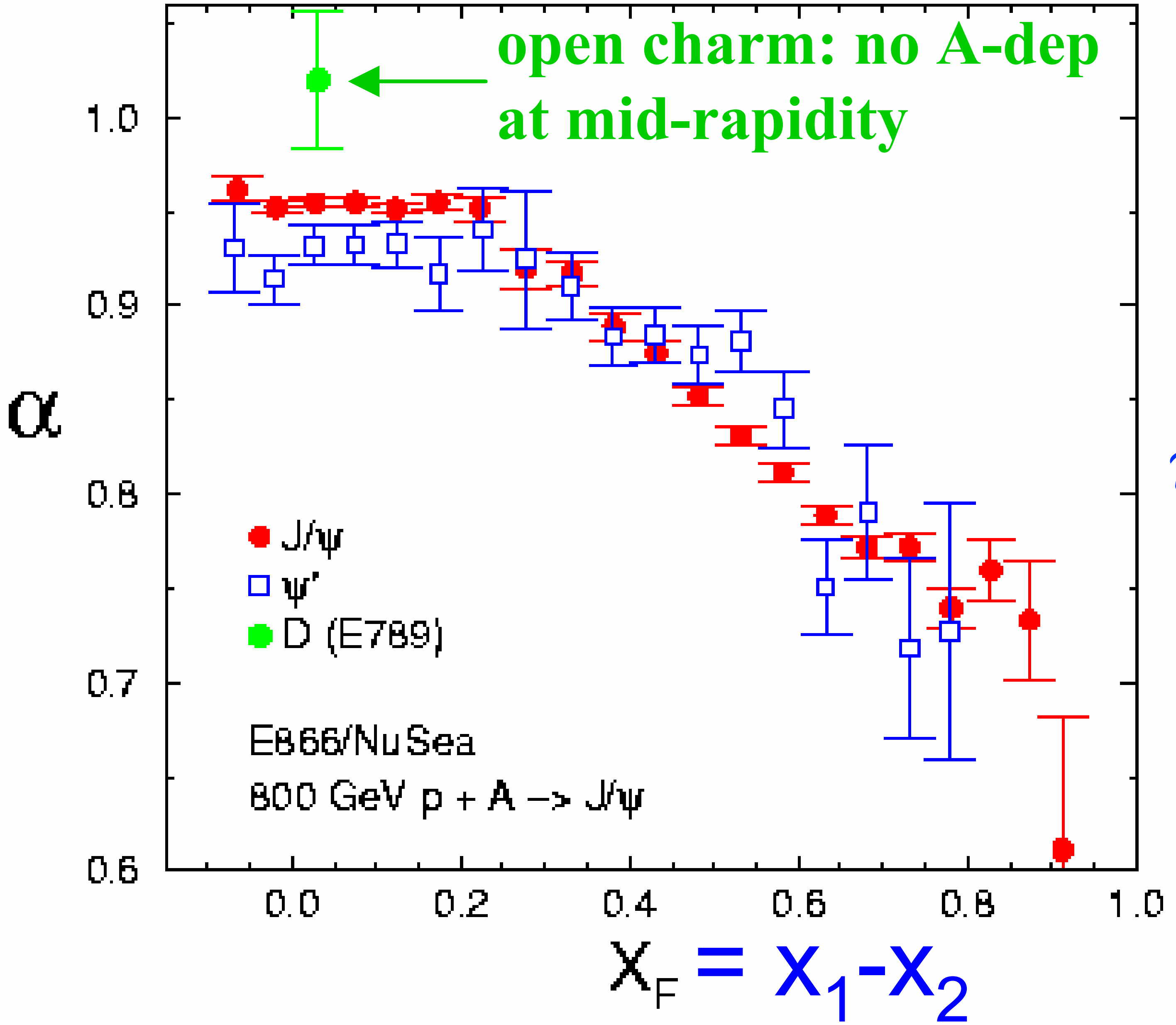
Another decay mode of the Λ_b^o (open-beauty baryon) state has been observed: $\Lambda_b^o \to \Lambda_c^+\pi^+\pi^-\pi^-$. In addition, new results on the previously observed decay channel, $\Lambda_b^o \to pD^o\pi^-$, are reported. These results confirm our previous findings on Λ_b^o production at the ISR. The mass value (5.6 GeV/c^2) is found to be in good agreement with theoretical predictions. The production mechanism is found to be "leading".

Evidence for Intrinsic Bottom!

800 GeV p-A (FNAL) $\sigma_A = \sigma_p * A^\alpha$

PRL 84, 3256 (2000); PRL 72, 2542 (1994)

M. Leitch



$$\frac{d\sigma}{dx_F}(pA \to J/\psi X)$$

Remarkably Strong Nuclear Dependence for Fast Charmonium

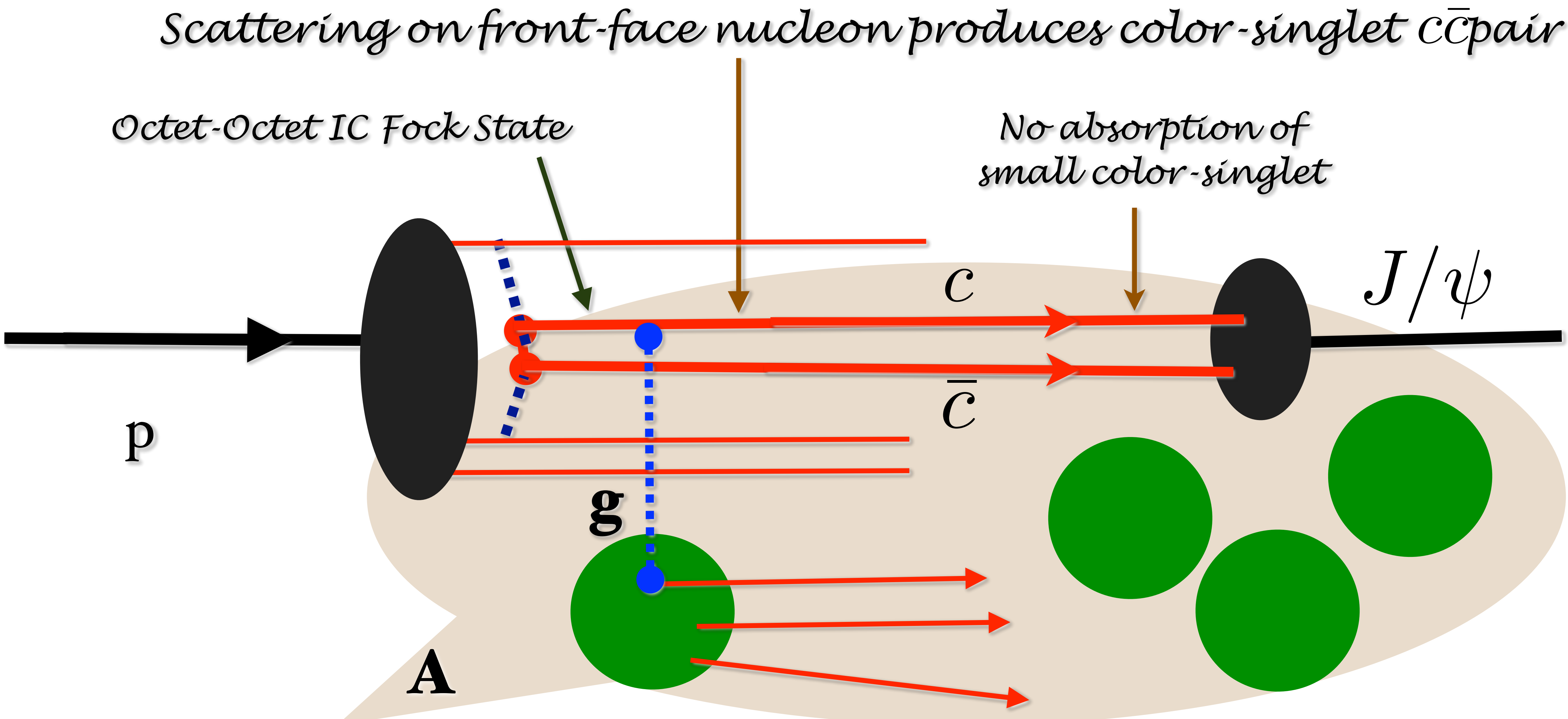
Violation of PQCD Factorization

Violation of factorization in charm hadroproduction.
P. Hoyer, M. Vanttinen (Helsinki U.) , U. Sukhatme (Illinois U., Chicago) . HU-TFT-90-14, May 1990. 7pp.
Published in Phys.Lett.B246:217-220,1990

IC Explains large excess of quarkonia at large x_F, A-dependence

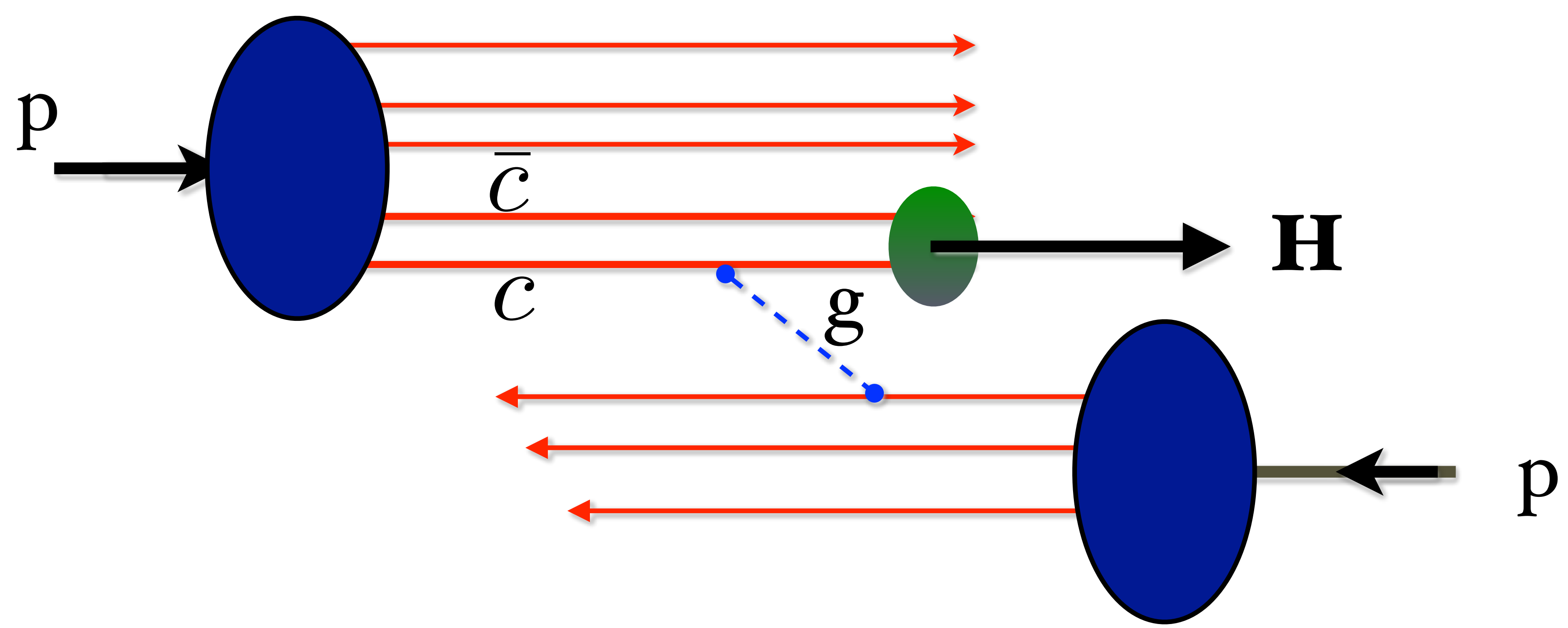
Color-Opaque IC Fock state interacts on nuclear front surface

Kopeliovich, Schmidt, Soffer, sjb



$$\frac{d\sigma}{dx_F}(pA \to J/\psi X) = A^{2/3} \times \frac{d\sigma}{dx_F}(pN \to J/\psi X)$$

Intrinsic Charm Mechanism for Inclusive High-X_F Higgs Production



$$pp \to HX$$

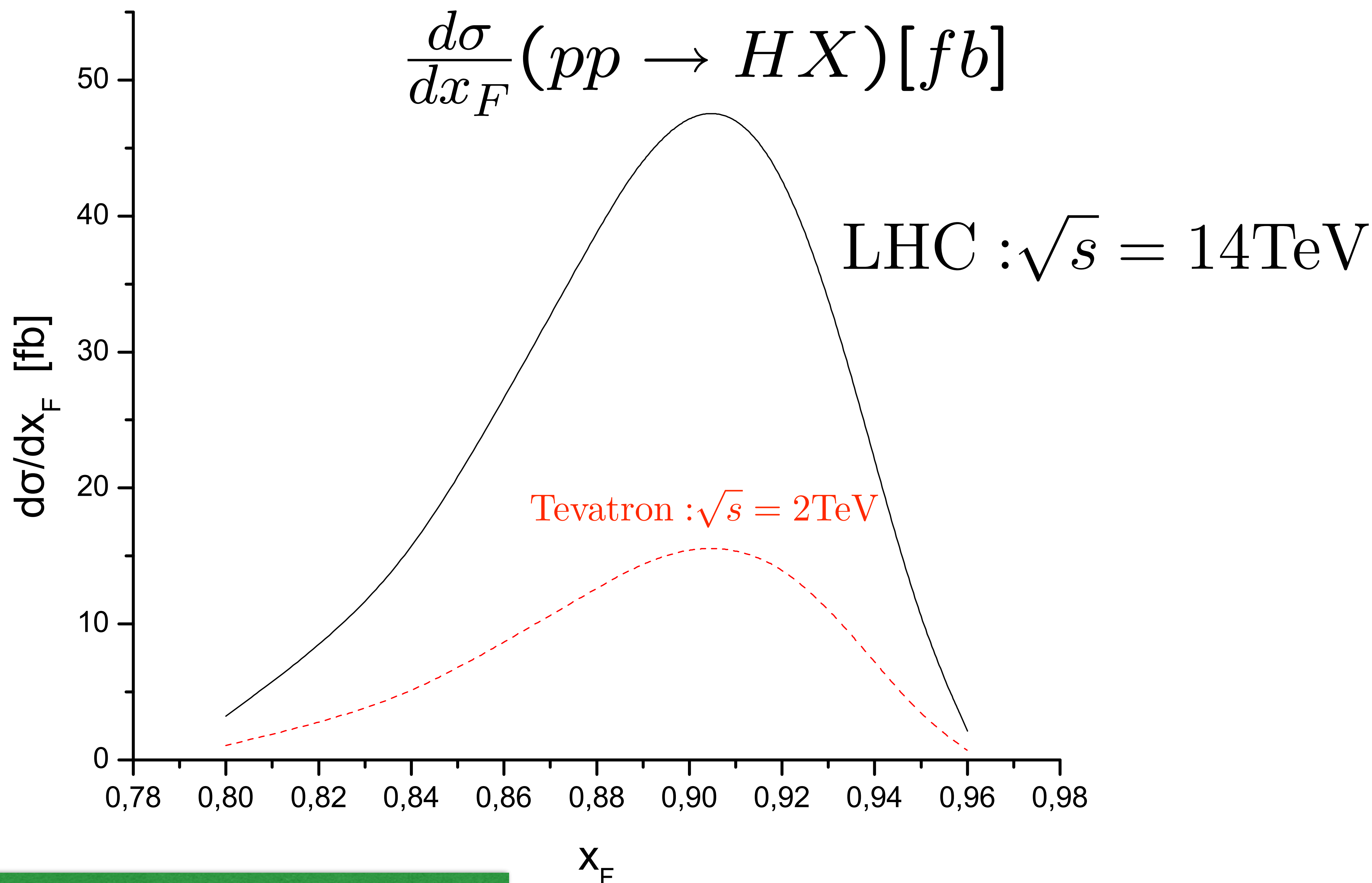
Goldhaber, Soffer, Kopeliovich, Schmidt, sjb

Also: intrinsic bottom, top

Higgs can have 80% of Proton Momentum!

New search strategy for Higgs

AFTER: Higgs production at threshold!



Need High x_F Acceptance

Most practical: Higgs to 2 or 4 muons

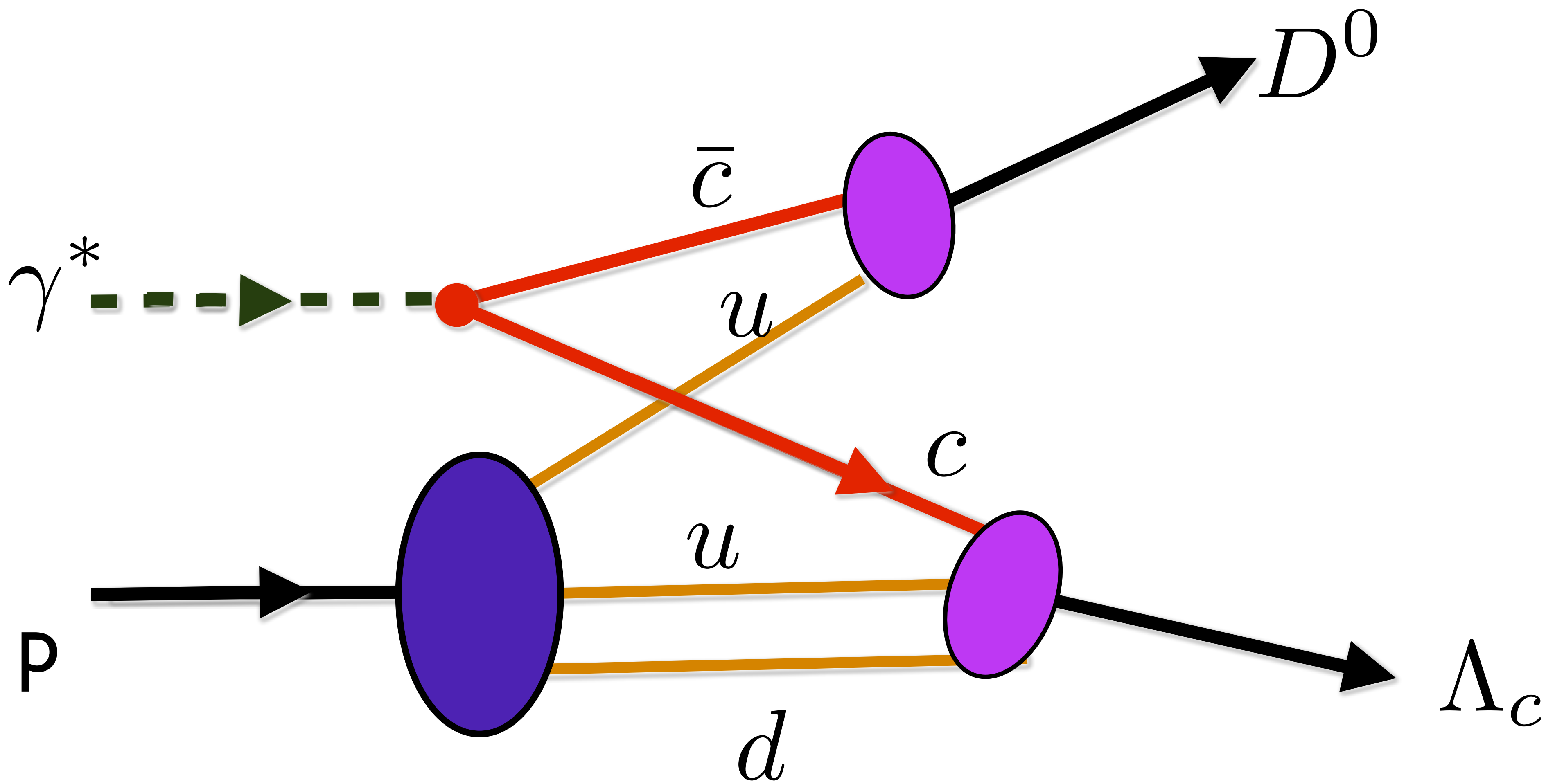
Goldhaber, Kopeliovich, Schmidt, Soffer, sjb

Some Key QCD Issues in Electroproduction

- **Intrinsic Heavy Quarks at high x;** $s(x) \neq \bar{s}(x)$
- **Role of Color Confinement in DIS**
- **Hadronization at the Amplitude Level**
- **Leading-Twist Lensing: Sivers Effect**
- **Diffractive DIS**
- **Static versus Dynamic Structure Functions**
- **Origin of Shadowing and Anti-Shadowing**
- **Is Anti-Shadowing Non-Universal: Flavor Specific?**
- **Nuclear Correlations and Effects**

Open Charm Production at Threshold!

JLab 12 GeV: A Charm Factory!

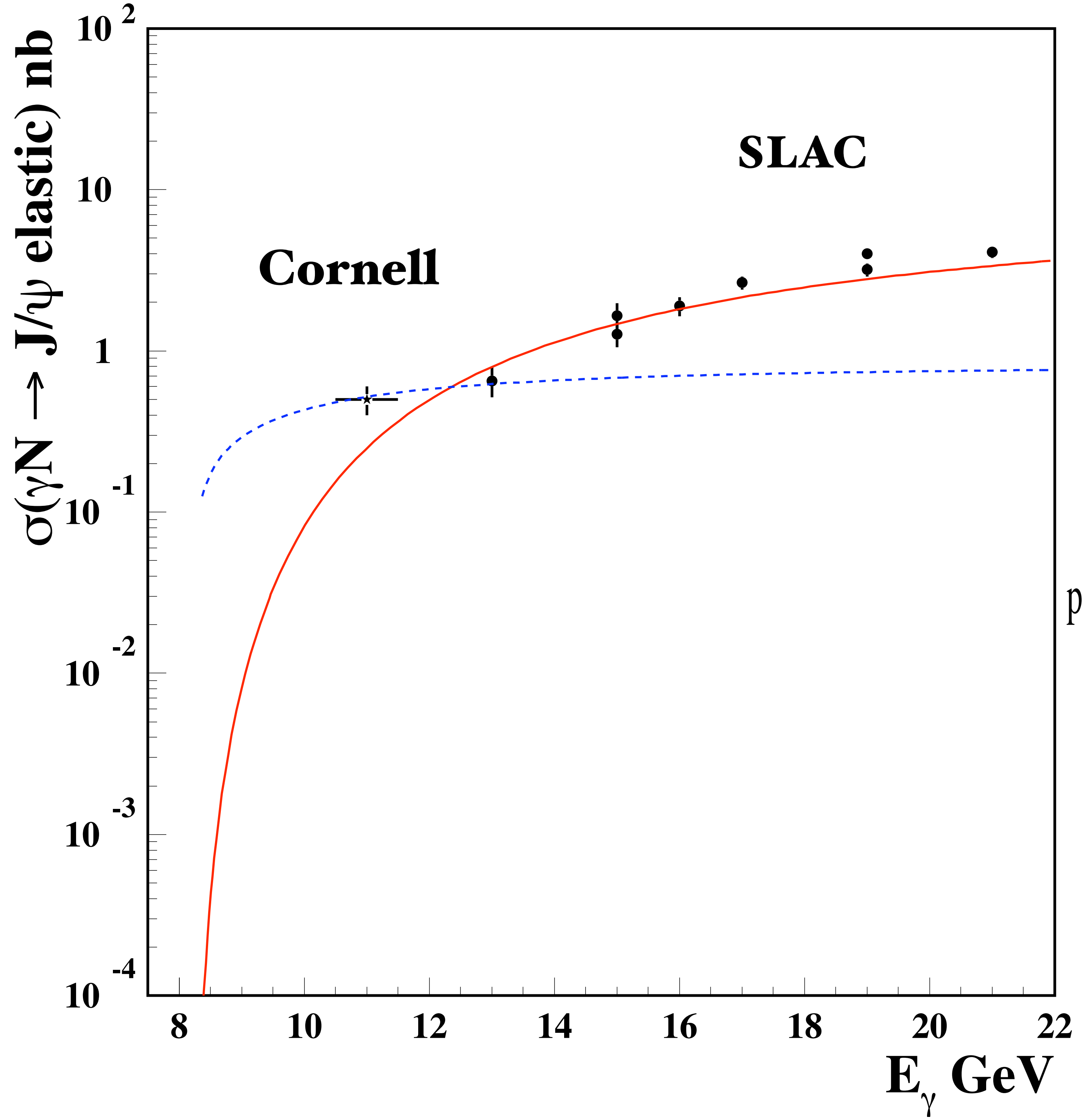


$$\gamma^* p \to \overline{D}^0(\bar{c}u)\Lambda_c(cud)$$

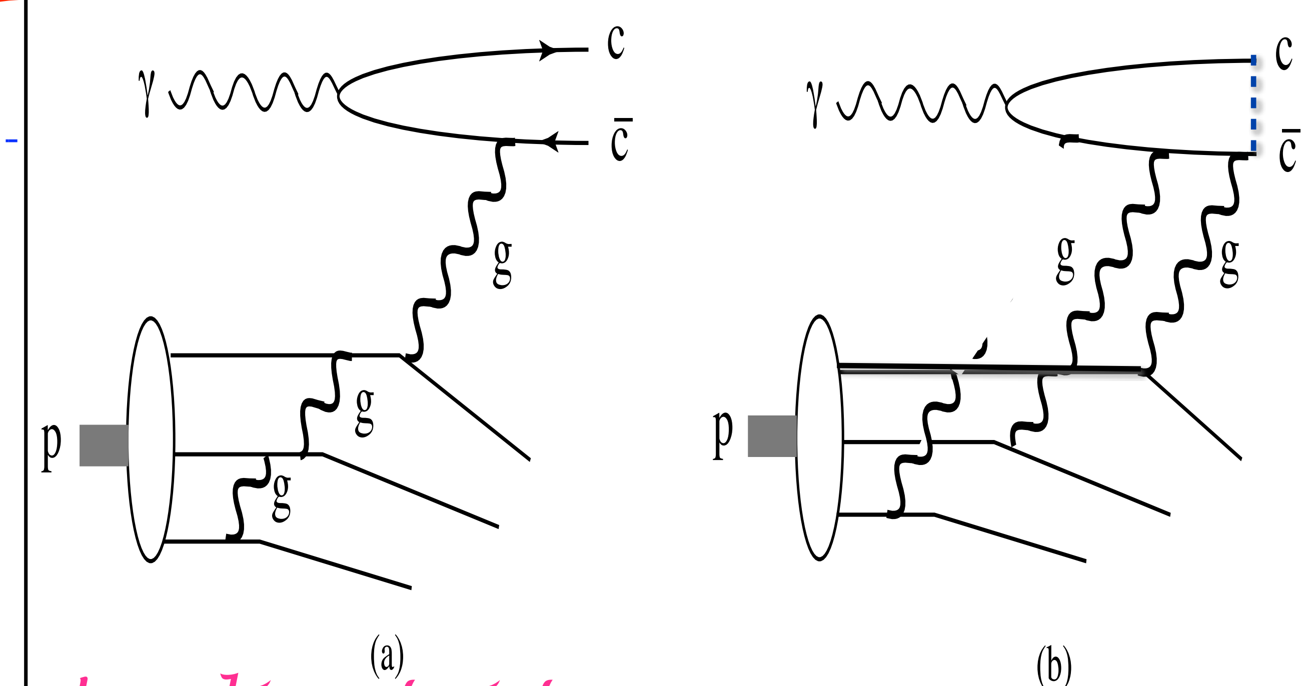
c and u quark interchange

$$\gamma p \to J/\psi p$$

Chudakov, Hoyer, Laget, sjb



cross section: 1 nb



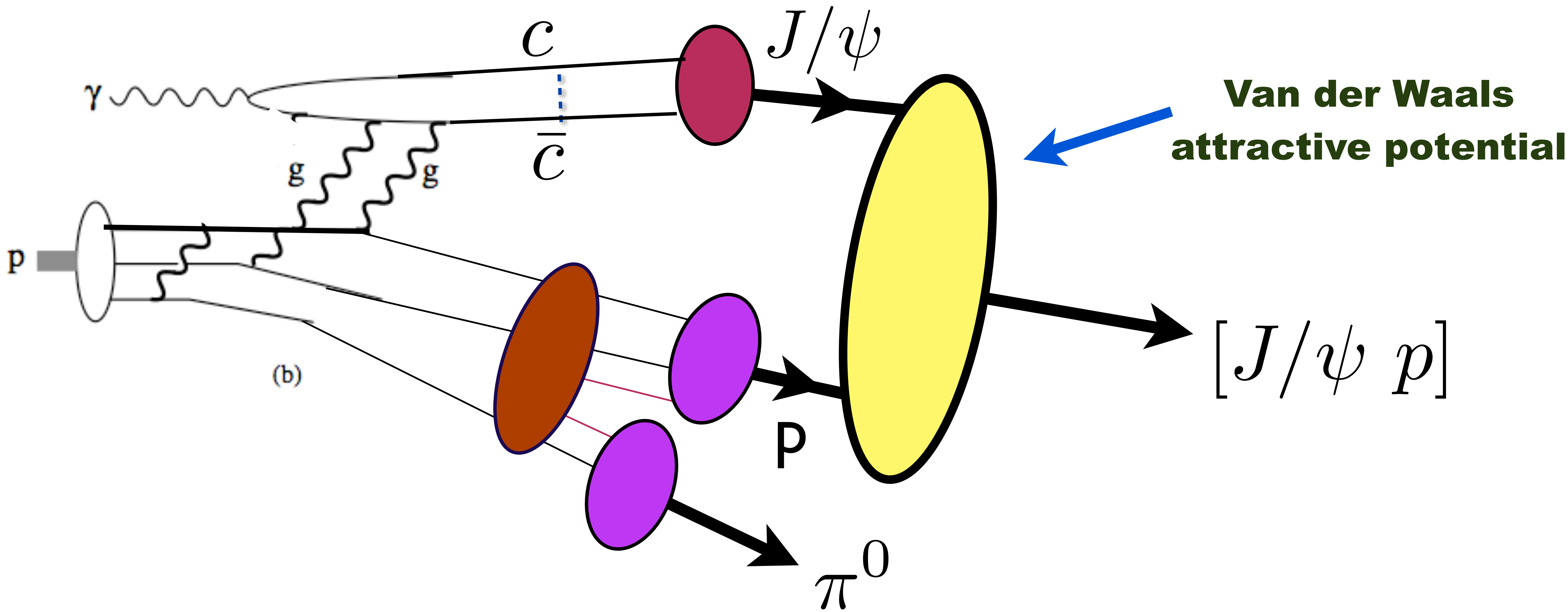
Leading twist contribution

Dominant near threshold

Phase space factor β cancelled by gluonic final-state interactions

Sommerfeld-Schwinger-Sakharov Effect

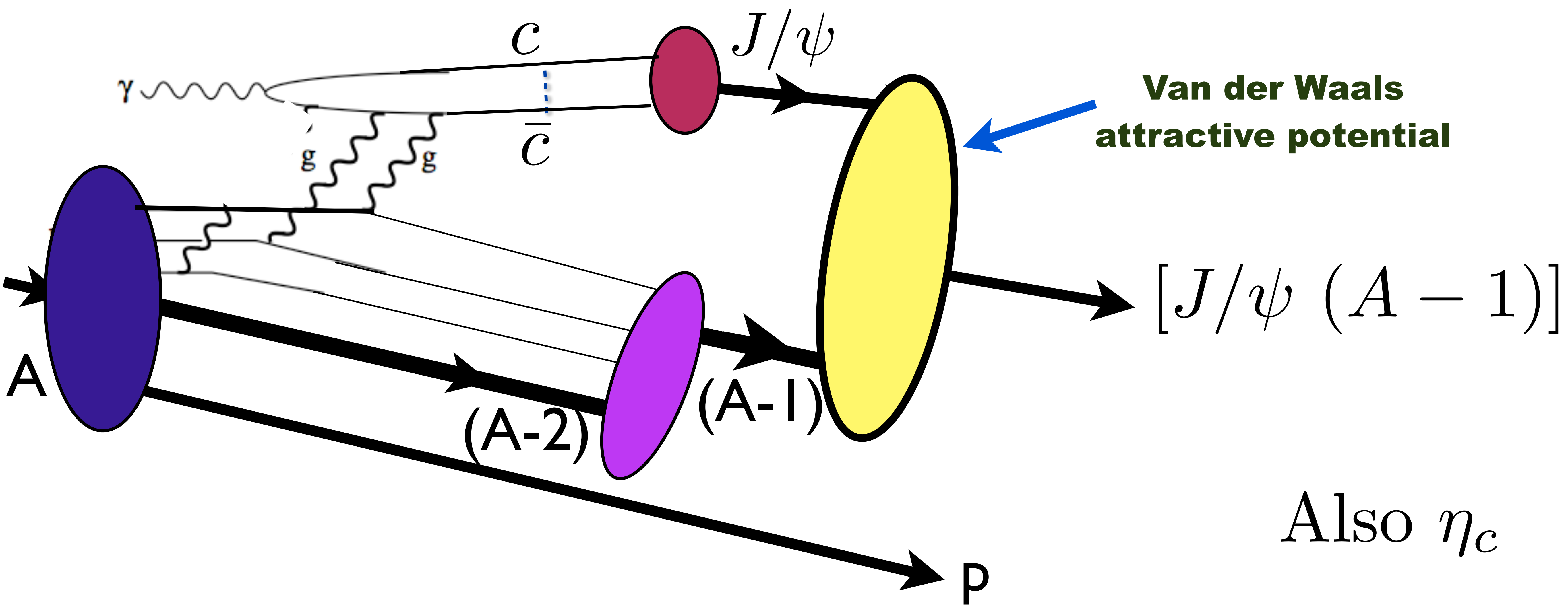
Charmonium Production at Threshold



$$\gamma\ p \to [J/\psi\ p]\ \pi^0 \qquad \gamma\ p \to [J/\psi\ n]\ \pi^+$$

Form proton-charmonium bound state! $|uudc\bar{c}>$

Charmonium Production on Nuclei at Threshold



Also η_c

$$\gamma\ A \to [J/\psi\ (A-1)]\ p$$

Form "nuclear-bound" charmonium bound-states!

JLab 12 GeV: An Exotic Charm Factory!

$$\gamma^* p \to J/\psi + p \text{ threshold}$$

$$\text{at } \sqrt{s} \simeq 4 \text{ GeV}, \; E^{\gamma^*}_{\text{lab}} \simeq 7.5 \text{ GeV}.$$

$$\gamma^* p \to X(3872) + p'$$

$|c\bar{c}q\bar{q}>$ *tetraquark*

$$\text{Produce } [J/\psi + p] \text{ bound state}$$

$|uudc\bar{c}>$ *pentaquark*

$$\gamma^* d \to J/\psi + d \text{ threshold}$$

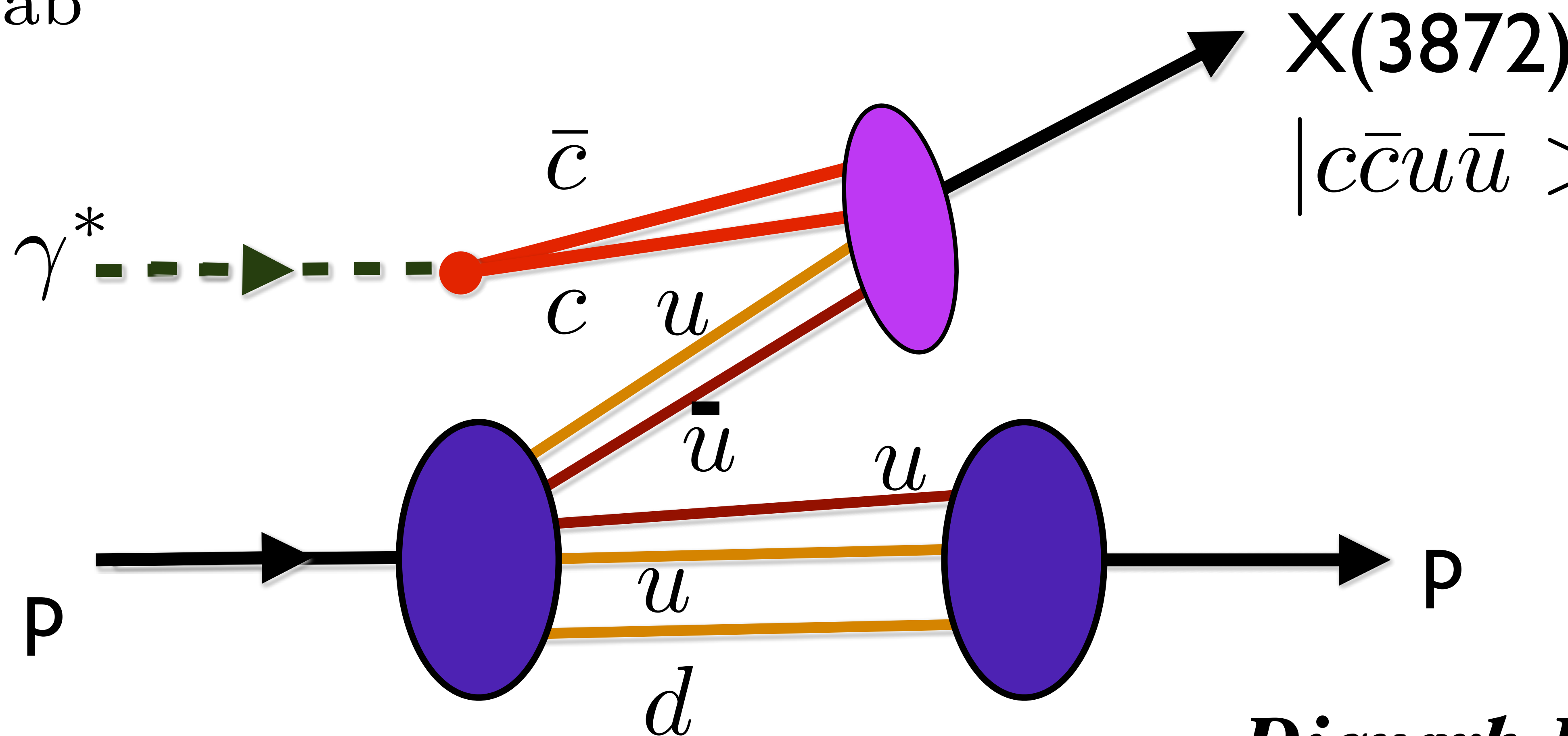
$$\text{at } \sqrt{s} \simeq 5 \text{ GeV}, \; E^{\gamma^*}_{\text{lab}} \simeq 6 \text{ GeV}.$$

Produce $[J/\psi + d]$ nuclear-bound quarkonium state

$|uuddduc\bar{c}>$ *octoquark!*

Tetraquark Production at Threshold

$$E^{\gamma}_{\rm lab} > 11.9 \text{ GeV}$$



Diquark-Diquark vs Molecular State?

$$\gamma^* p \to X(3872) + p'$$

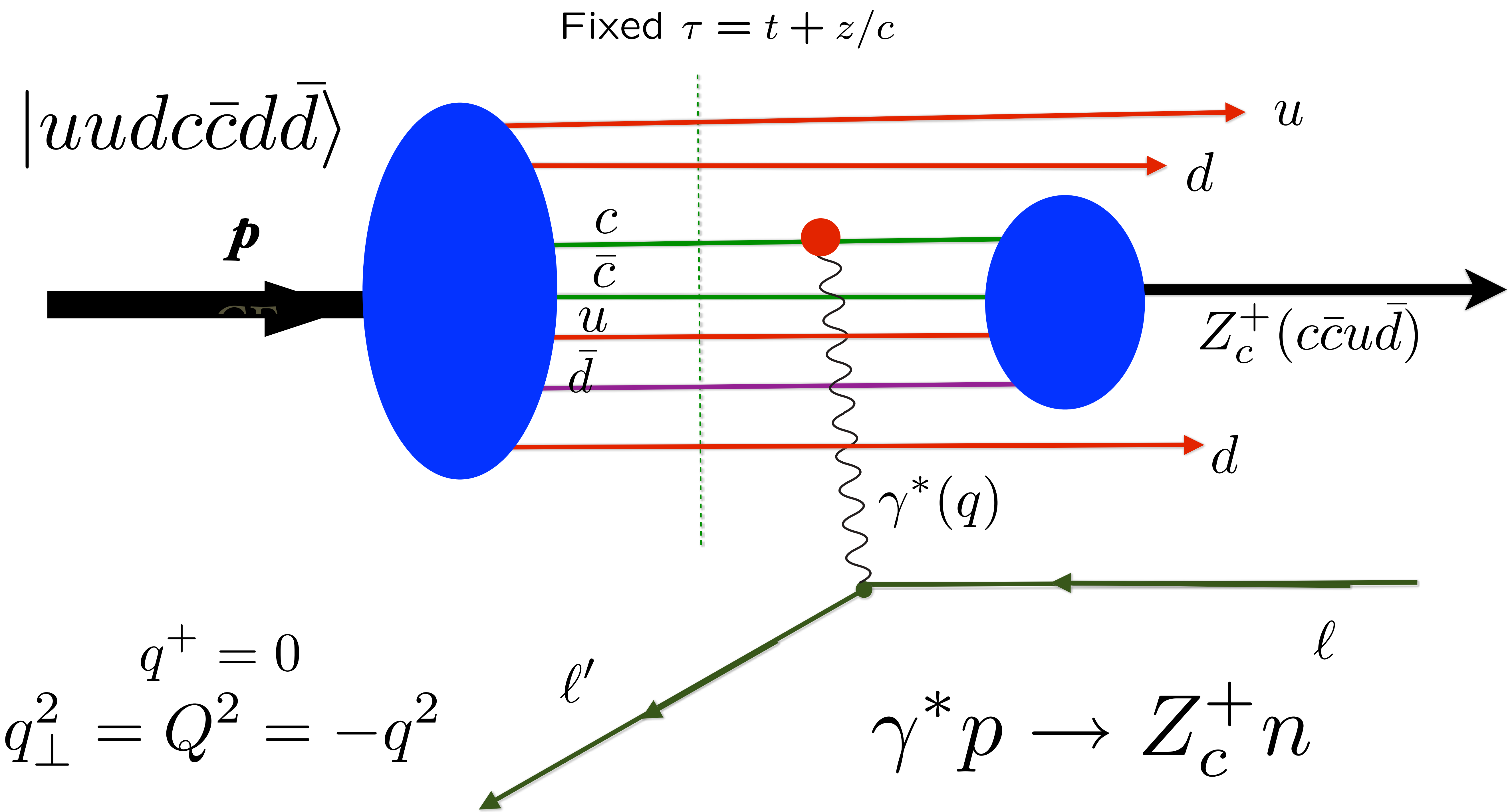
$$|c\bar{c}q\bar{q}>$$

New approach to hadronic decays

Dominance of Ψ' vs J/Ψ decays

Lebed, Hwang, sjb

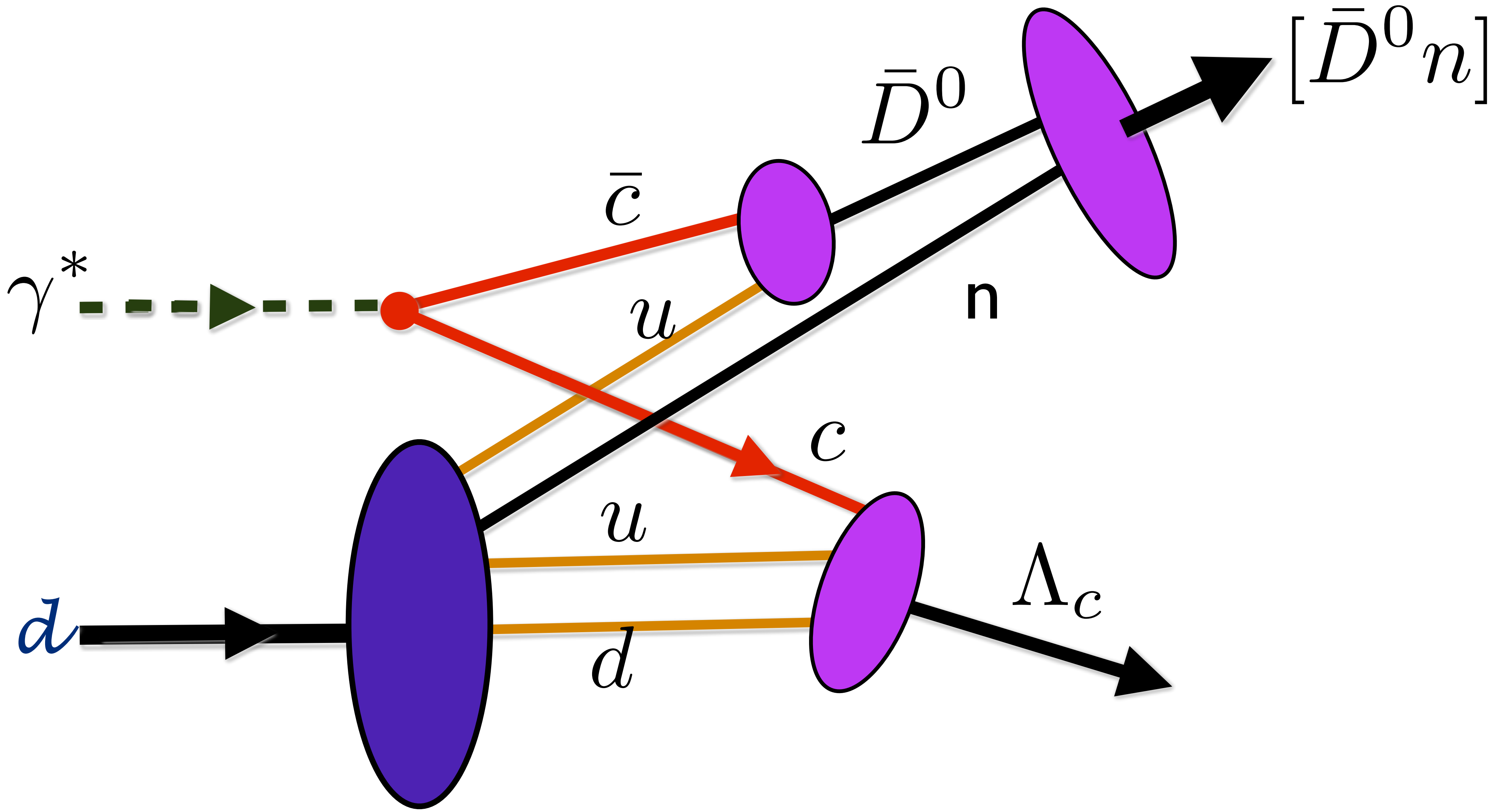
Light-Front Wavefunctions and Heavy-Quark Electroproduction



Produce Charged Tetraquarks at JLab!

Coalescence of comovers at threshold produces Z_c^+ tetraquark resonance

Open Charm Production at Threshold

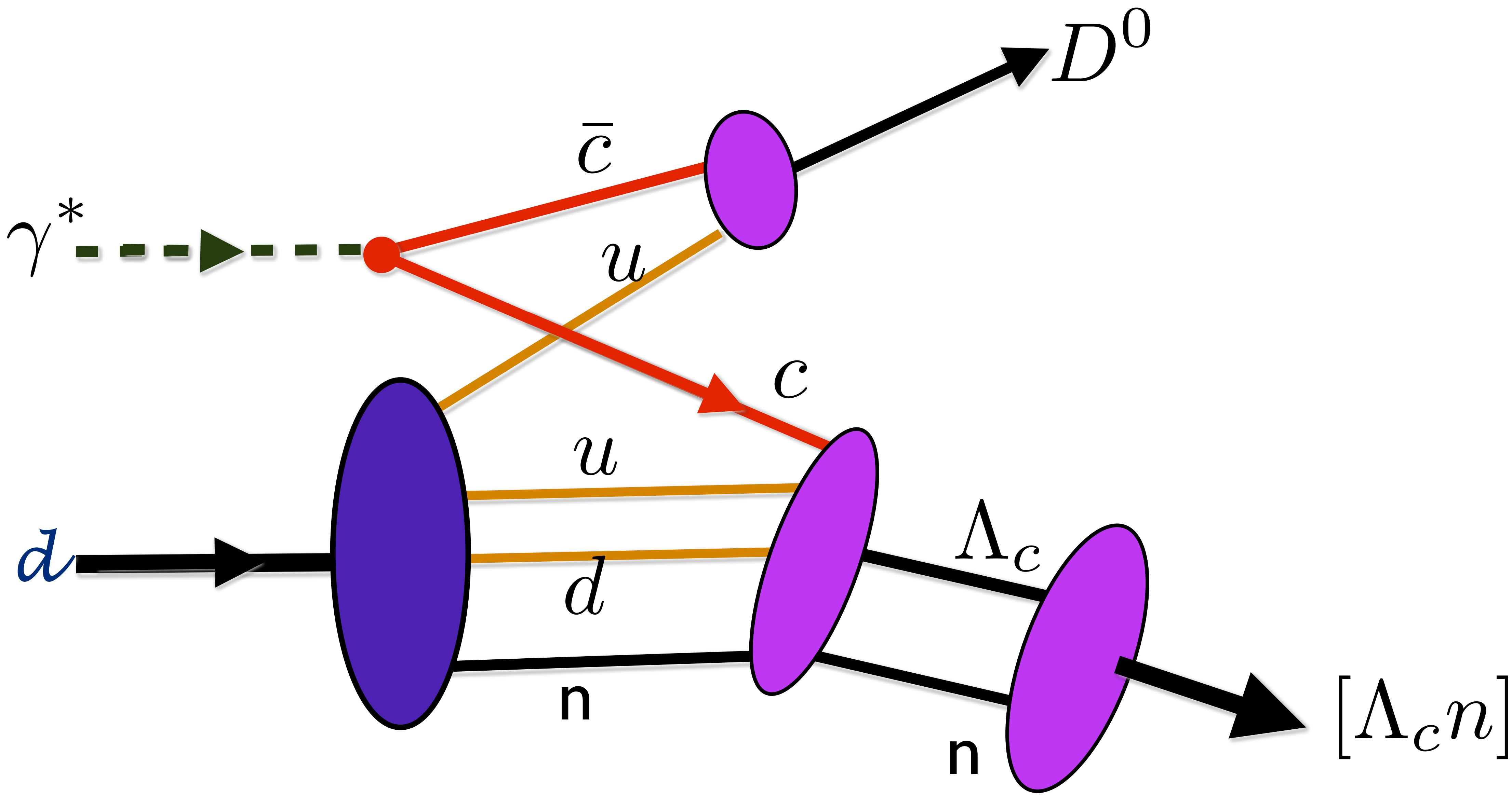


$$\gamma^* d \to \Lambda_c + [\overline{D}^0(\bar{c}u)n](\bar{c}uudd)$$

Create pentaquark on deuteron at low relative velocity

Open Charm Production at Threshold

Nuclear binding at low relative velocity

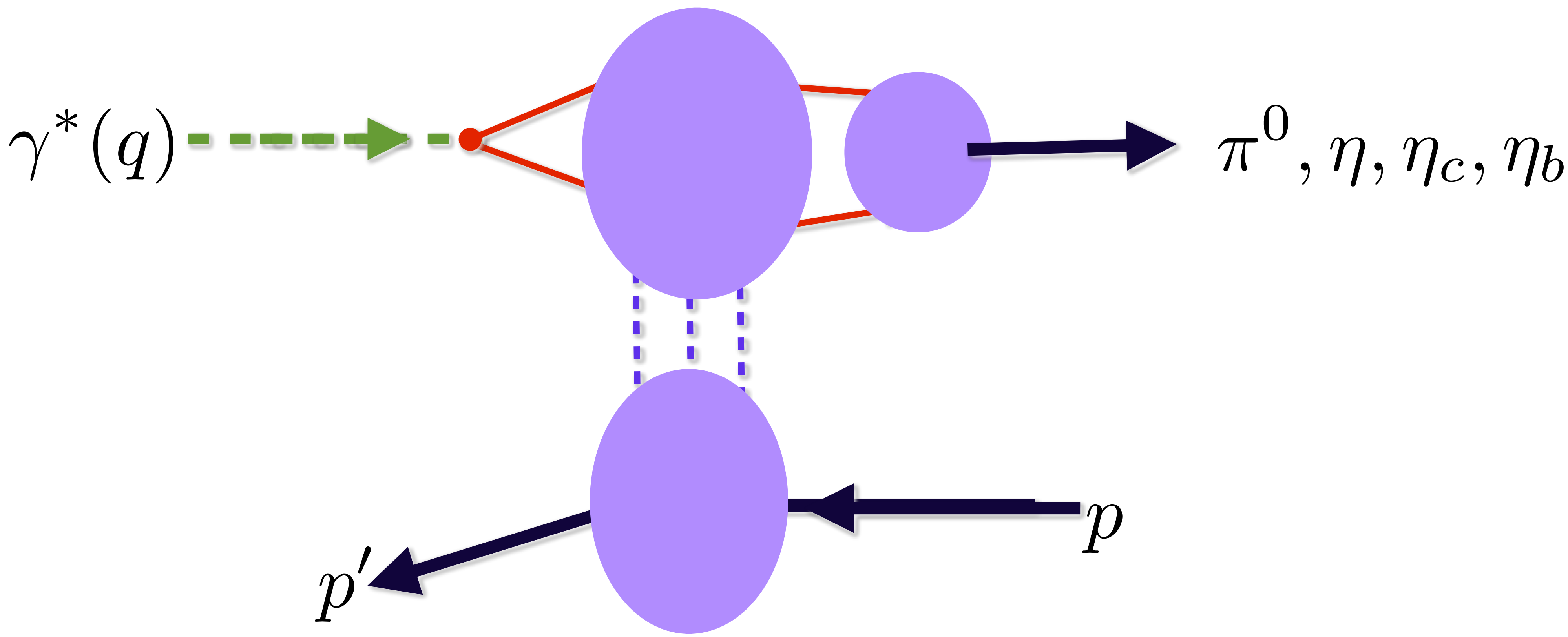


$$\gamma^* d \to \overline{D}^0(\bar{c}u)[\Lambda_c n](cududd)$$

Possible charmed B= 2 nucleus

JLab 12 GeV: An Exotic Charm Factory!

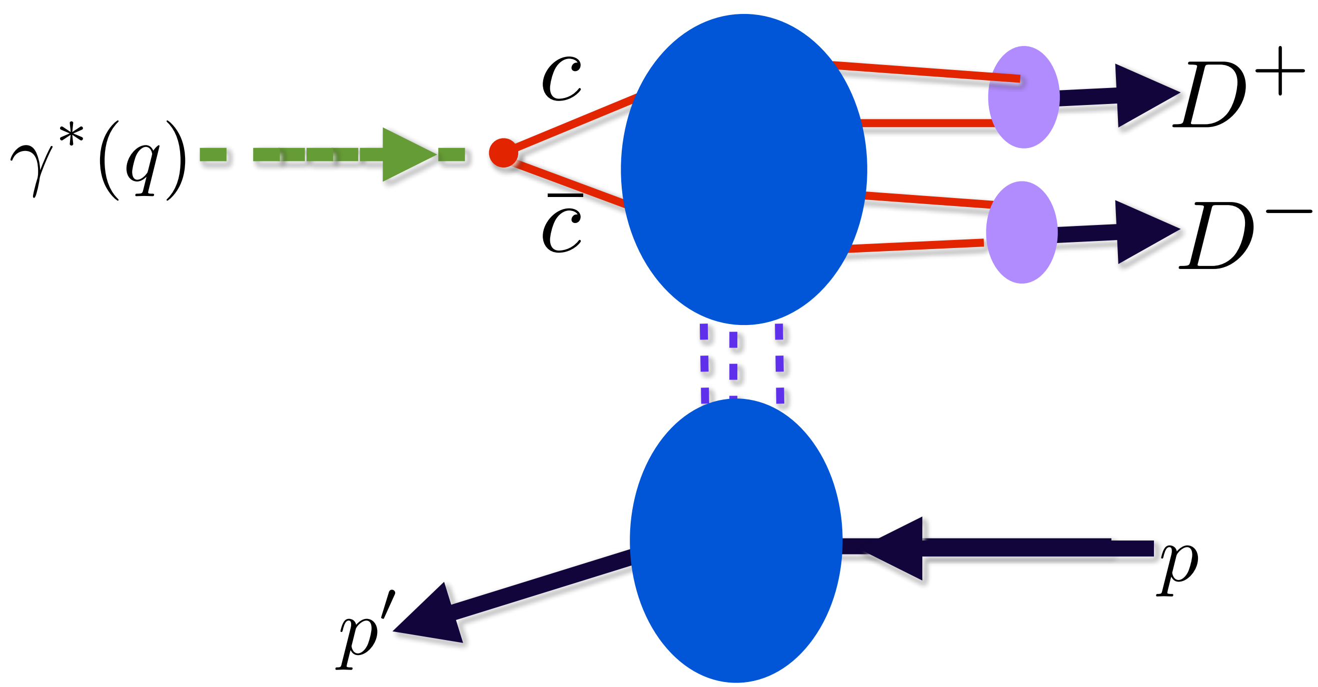
- **Charm quarks at high x -- allows charm states to be produced with minimal energy**
- **Charm produced at low velocities in the target -- the target rapidity domain** $x_F \sim -1$
- **Charm at threshold -- maximal domain for producing exotic states containing charm quarks**
- **Attractive QCD Van der Waals interaction -- "nuclear-bound quarkonium"**
  Miller, sjb; de Teramond,sjb
- **Dramatic Spin Correlations in the threshold Domain** σ_L vs. σ_T, A_{NN}
- **Strong SSS Threshold Enhancement**



Odderon has never been observed!

Look for Charge Asymmetries from Odderon-Pomeron Interference

Merino, Rathsman, sjb



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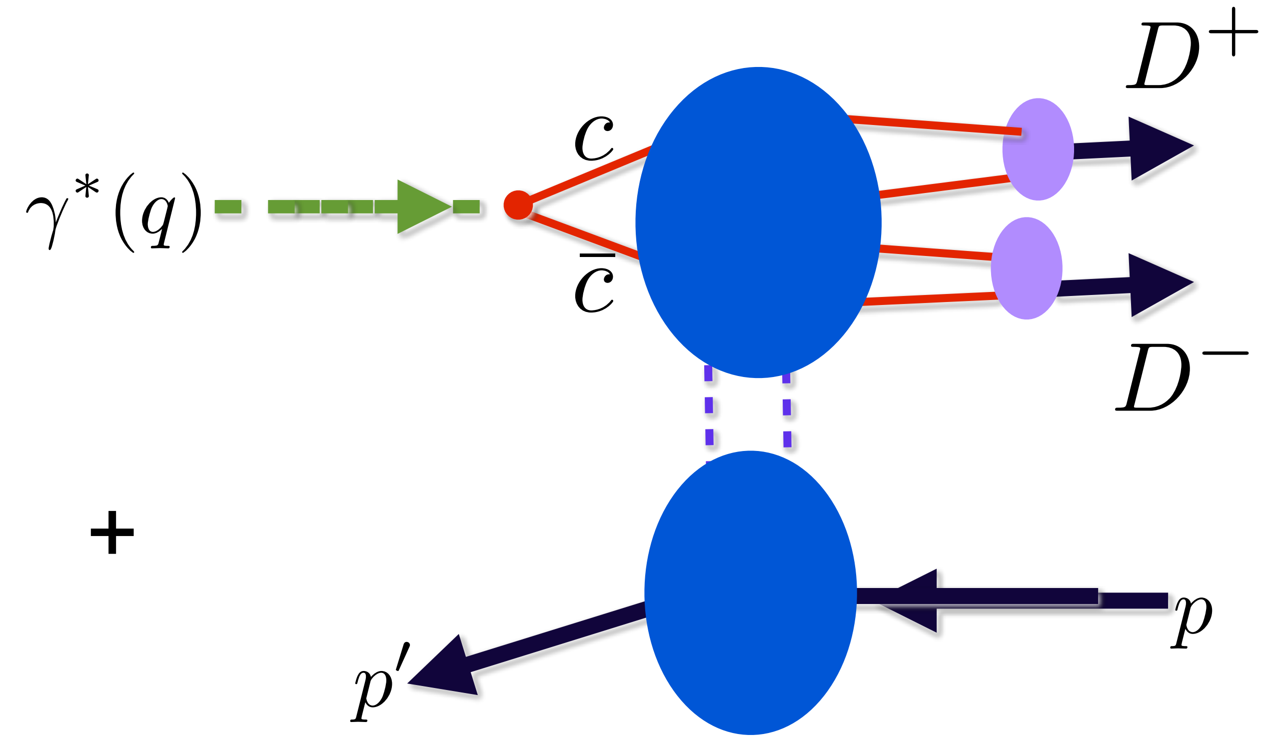


Odderon-Pomeron Interference leads to $K^+ K^-$, $D^+ D^-$ and $B^+ B^-$ charge and angular asymmetries

Odderon at amplitude level

Merino, Rathsman, sjb

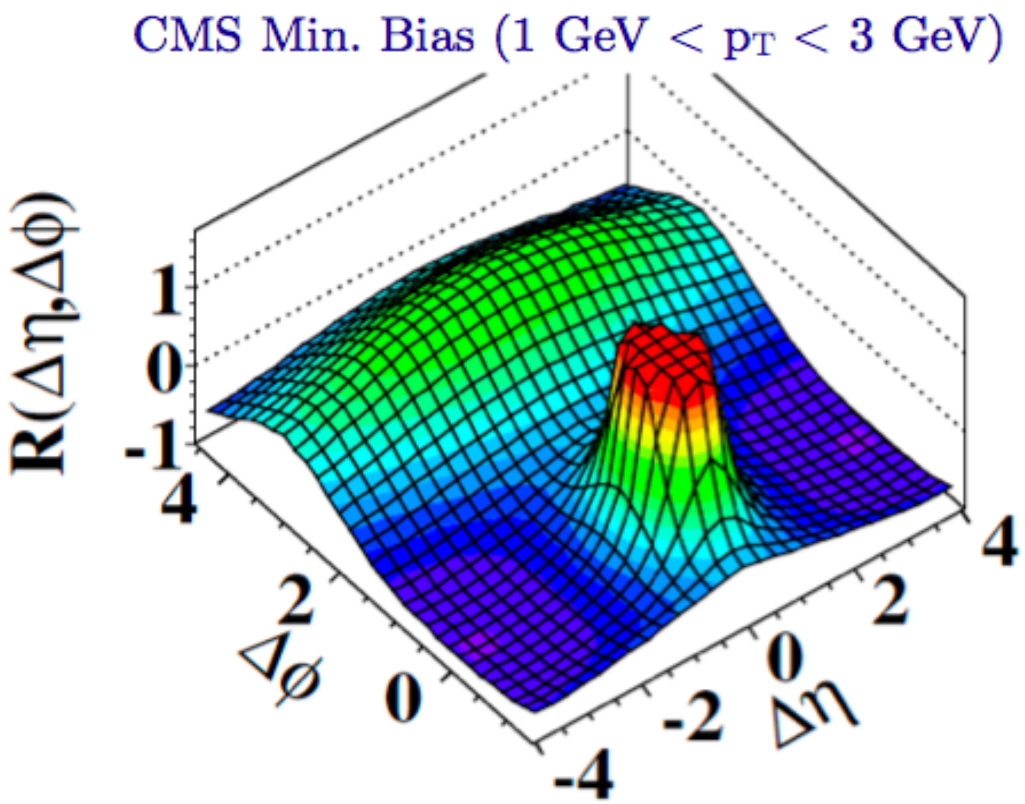
Strong enhancement at heavy-quark pair threshold from QCD Sakharov-Schwinger-Sommerfeld effect

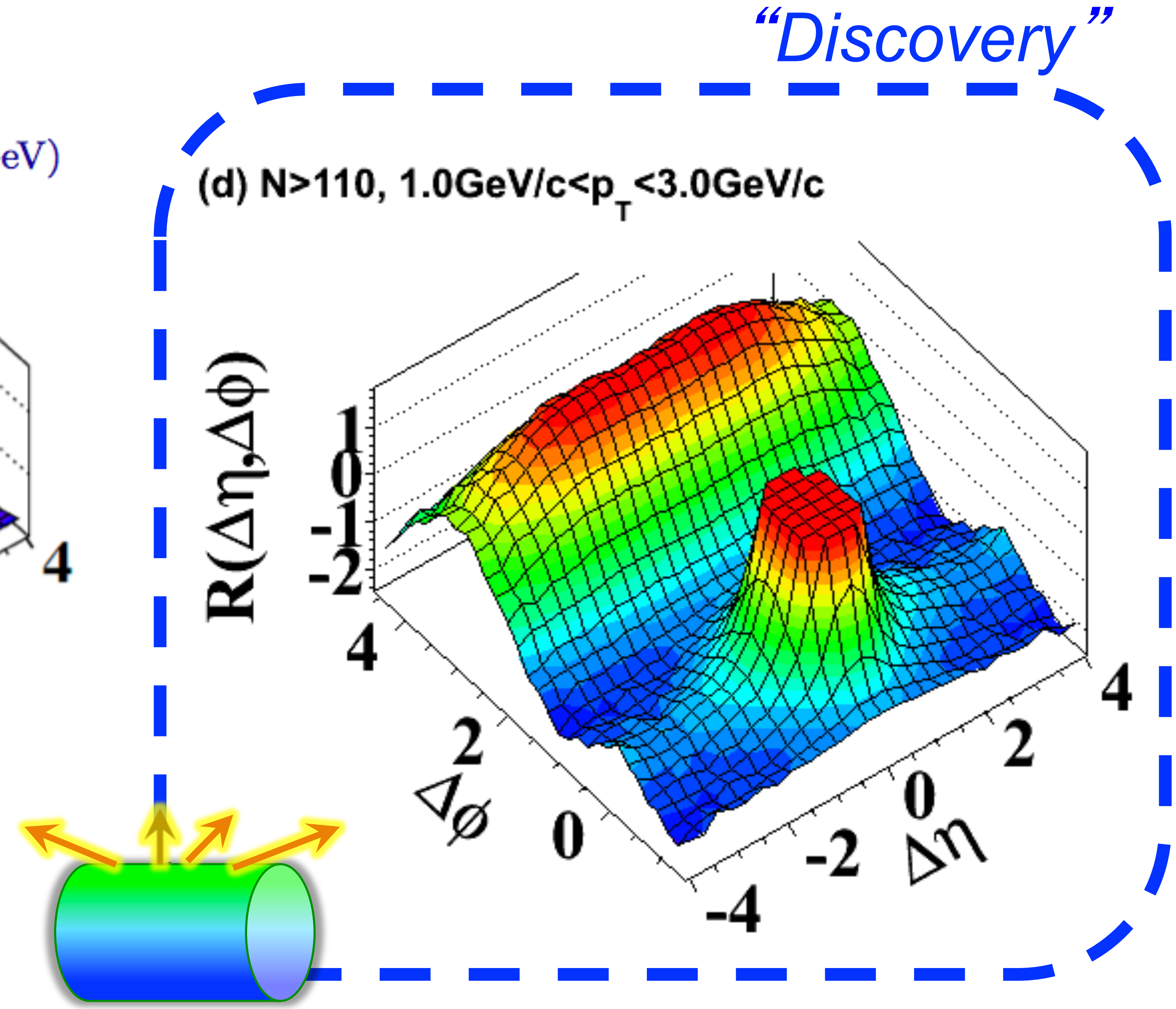
$$\frac{\pi \alpha_s(\beta^2 s)}{\beta}$$

Hoang, Kuhn, sjb

Ridge in high-multiplicity p p collisions

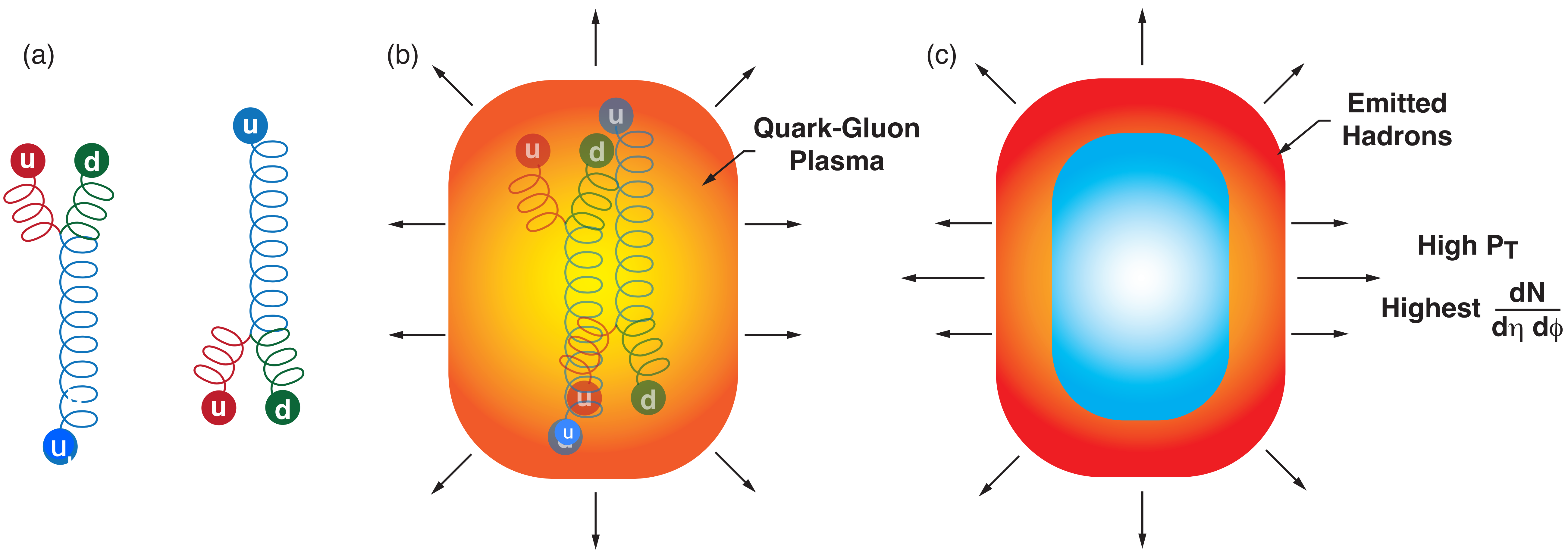
Two-particle correlations: CMS results





- Ridge: Distinct long range correlation in η collimated around ΔΦ≈ 0 for two hadrons in the intermediate 1 < p_T, q_T < 3 GeV

Ridge may reflect collision of aligned flux tubes



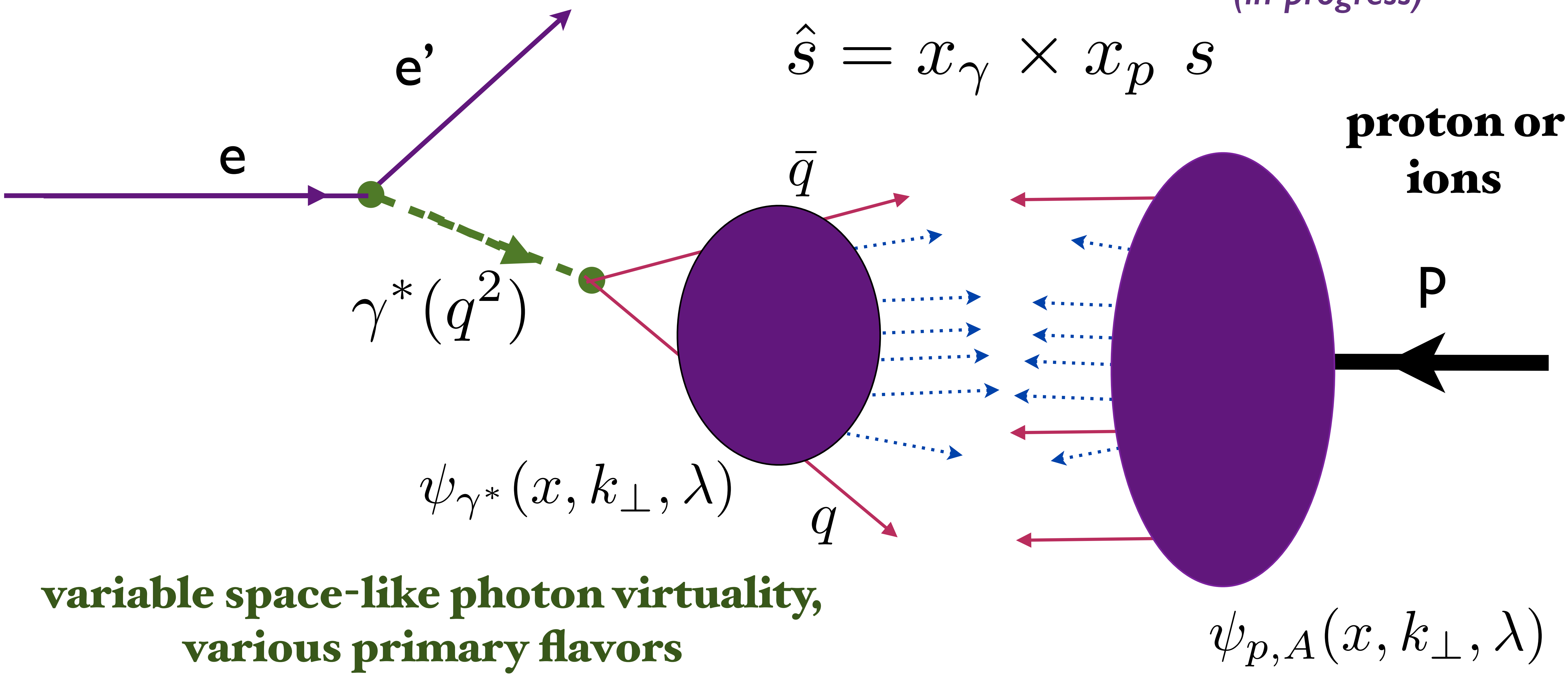
Bjorken, Goldhaber, sjb

Electron-Ion Collider:
Virtual Photon-Ion Collider

Perspective from the e-p collider frame

S. Glazek, P. Kubiczek, sjb
(in progress)

$$\hat{s} = x_\gamma \times x_p \; s$$



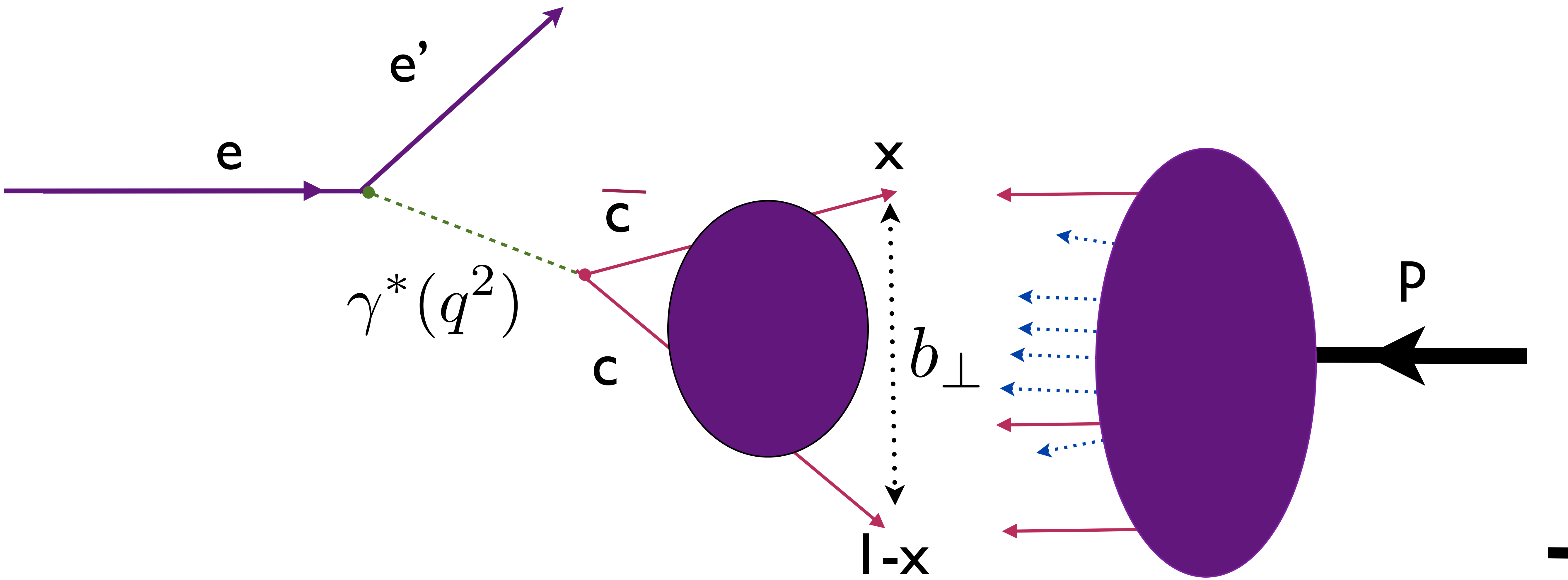
variable space-like photon virtuality,
various primary flavors

$\bar{q}$ q plane aligned with lepton scattering plane ~ $\cos^2\phi$

Front-surface dynamics: shadowing/antishadowing

$\bar{c}$ c acts as a 'drill'

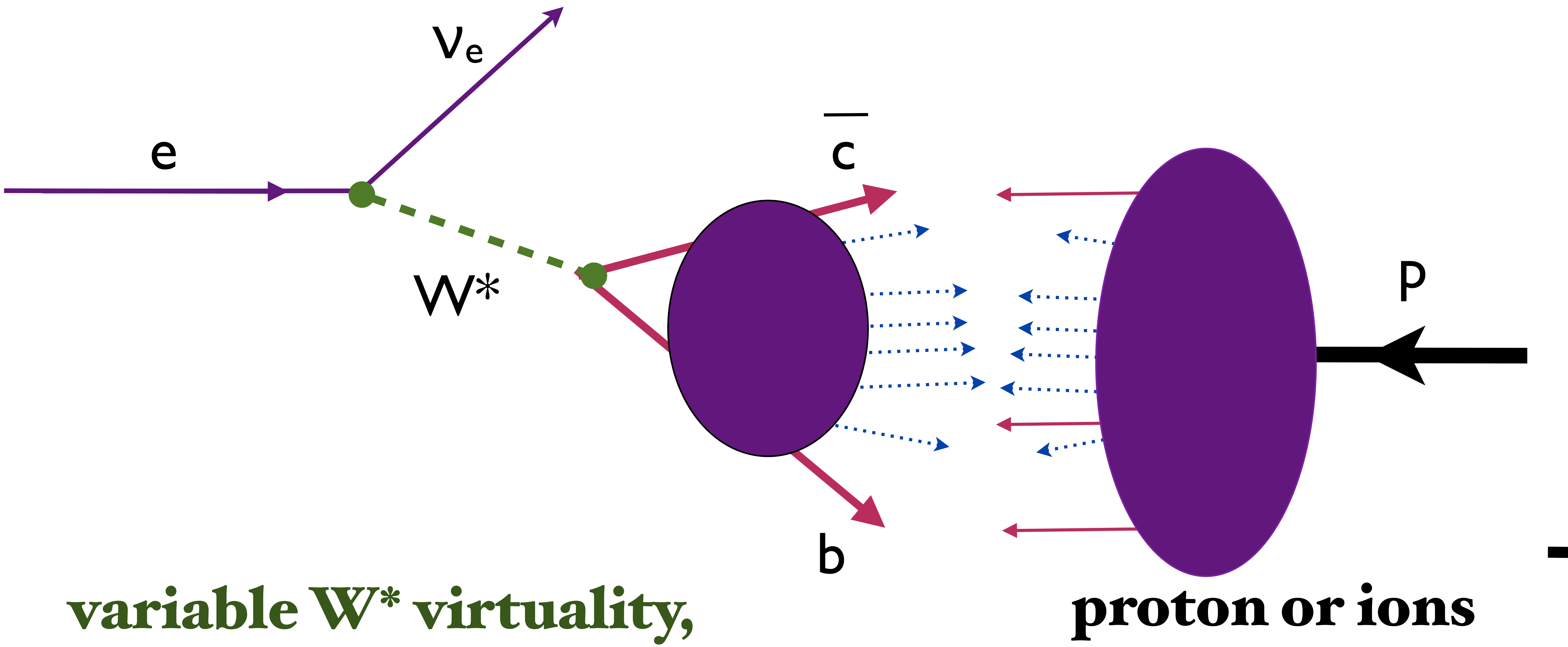
$$< b_\perp^2 > \sim \frac{1}{Q^2 x(1-x) + m_c^2}$$



High Q² virtual photon at an EIC acts as a precision, small bore, linearly oriented, flavor-dependent probe acting on a proton or nuclear target.

tudy final-state hadron multiplicity distributions, ridge, nuclear dependence, etc.

EIC: Virtual Weak Boson-Proton Collider



variable W* virtuality, variable flavors

"One of the gravest puzzles of theoretical physics"

DARK ENERGY AND THE COSMOLOGICAL CONSTANT PARADOX

A. ZEE

Department of Physics, University of California, Santa Barbara, CA 93106, USA
Kavil Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA
zee@kitp.ucsb.edu

$$(\Omega_\Lambda)_{QCD} \sim 10^{45}$$

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

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

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

Elements of the solution:

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

(B) New understanding of QCD "Condensates"

(C) Higgs Light-Front Zero Mode

“ Most embarrassing observation in physics – that’s the only quick thing I can say about dark energy that’s also true.” **-- Edward Witten**

Two general problems:

- Why is the cosmological constant so small, $\Lambda < 10^{-120}$ in Planck density units ?
- Why $\Lambda \sim \rho_{\mathrm{matter}}$?

  Coincidence problem.

addressed by anthropic principle, Weinberg 1987

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

Front Form Vacuum Describes the Empty, Causal Universe

- $P^+ = \sum_i p_i^+,\ p_i^+ > 0$: LF vacuum is the state with $P^+ = 0$ and contains no particles: all other states have $P^+ > 0$ (usual vacuum bubbles are kinematically forbidden in the front form !)

- Frame independent definition of the vacuum within the causal horizon

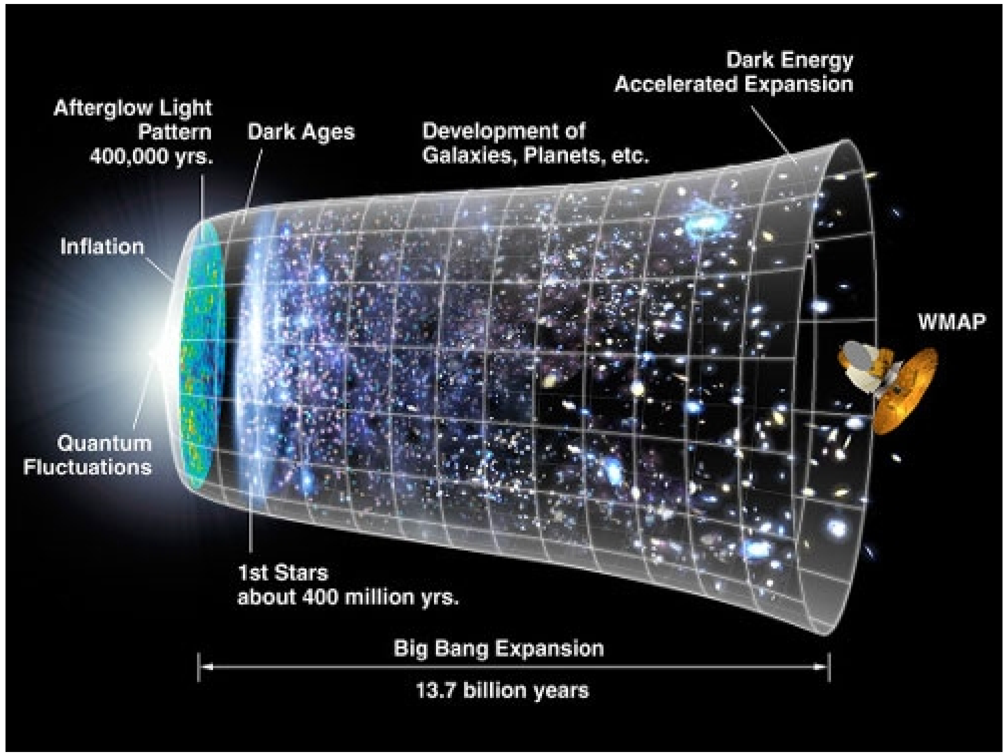
$$\boxed{P^2|0\rangle = 0}$$

(LF vacuum also has zero quantum numbers and $P^+ = 0$)

- LF vacuum is defined at fixed LF time $x^+ = x^0 + x^3$ over all $x^- = x^0 - x^3$ and $\mathbf{x}_\perp$, the expanse of space that can be observed within the speed of light

- Causality is maintained since LF vacuum only requires information within the causal horizon

- The front form is a natural basis for cosmology: universe observed along the front of a light wave



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

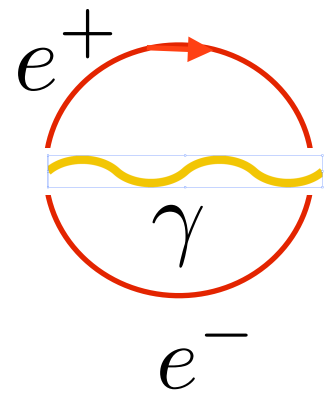
$$H_{LF}|\psi_0>_{LF}= M_0^2|\psi_0>_{LF}, M_0^2 = 0.$$

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

Frame-independent description of the causal physical universe!

Front-Form Vacuum in QED

$$P^+ = 0$$



$$\sum_i k_i^+ \neq P^+ = 0$$

$$k_i^+ > 0$$

- **All Light-Front Vacuum Graphs Vanish!**
- **Light-Front Vacuum is trivial since all plus momenta are positive and conserved.**
- **Zero modes (k^+=0) in vacuum allowed in some theories with massless fermions.**
- **Zero contribution to Λ from QED LF Vacuum**
- **Instant Form gives zero result if one normal orders.**

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

Profound Questions for Hadron Physics

- *Color Confinement*
- *Origin of QCD Mass Scale*
- *Spectroscopy: Tetraquarks, Pentaquarks, Gluonium, Exotic States*
- *Universal Regge Slopes: n, L, both Mesons and Baryons*
- *Massless Pion: Bound State*
- *Dynamics and Spectroscopy*
- *QCD Coupling at all Scales*
- *QCD Vacuum —Do Condensates Exist?*

QCD Principles

$$\boxed{\kappa \to C\kappa}$$

- Extended Conformal Invariance: AdS/QCD
- Chiral QCD only predicts mass ratios
- Supersymmetric Features of QCD: Superconformal algebra
- Unique Confinement Potential, Nonperturbative Running Coupling
- Physics Independent of Observer Frame: LF!
- Physics Independent of Conventions such as MSbar: PMC
- Zero Cosmological Constant for Causal Frame-Independent LF Vacuum
- Leading Twist Factorization-Breaking Corrections from ISI, FSI
- Nuclear Shadowing and Antishadowing not in nuclear LFWF
- Nuclear PDFS do not obey sum rules

Applications to Collider Physics

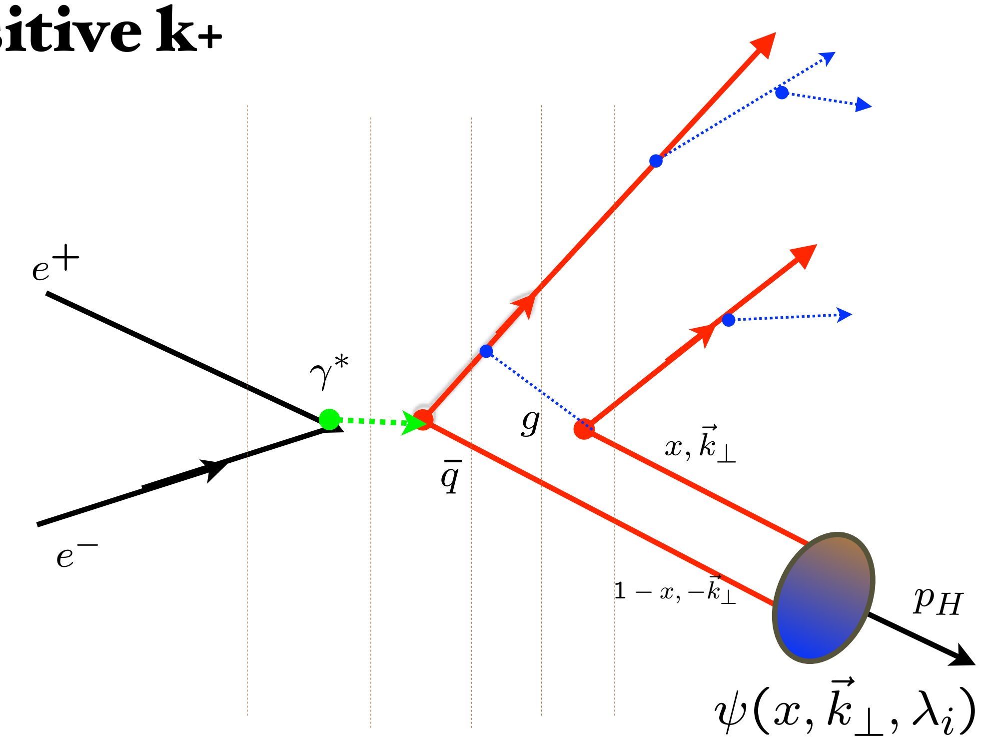
- **Non-Perturbative Structure Functions**
- **Fundamental understanding of angular momentum**
- **Higher Fock States: Intrinsic Heavy Quarks**
- **Higgs at High x_F**
- **Hadronization at the Amplitude Level**
- **Direct Higher-Twist Processes: Violation of leading twist scaling**
- **Collisions of Flux-Tubes: Ridge effect in p-p scattering**
- **Multiparton amplitudes: Cluster decomposition, Jz conservation, Parke-Taylor**
- **Multi-gluon initiated processes: Novel nuclear effects**
- **Non-Universal Anti-shadowing**
- **Hadronization from first principles -- at the Amplitude Level**
- **Principle of Maximum Conformality**
- **Connection to Pomeron**

Event amplitude generator

- **Quarks and Gluons Off-Shell**
- **LFPth: Minimal Time-Ordering Diagrams-Only positive k+**
- **J^z Conservation at every vertex**
- **Frame-Independent**
- **Cluster Decomposition**

Ji, sjb

- **"History"-Numerator structure universal**
- **Renormalization- alternate denominators**
- **LFWF takes Off-shell to On-shell**
- **Tested in QED: g-2 to three loops**

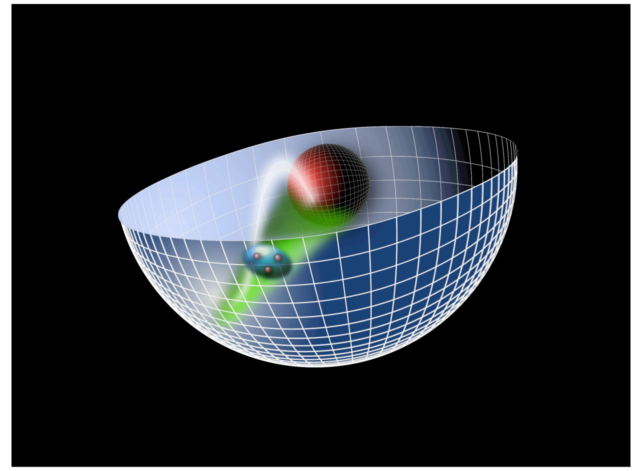


Roskies, Suaya, sjb

de Tèramond, Dosch, Lorcè, sjb

AdS/QCD
Soft-Wall Model

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



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

Light-Front Holography

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

Light-Front Schrödinger Equation

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

Unique Confinement Potential!

Conformal Symmetry
of the action

Single variable ζ

Confinement scale: $\kappa \simeq 0.5\ GeV$

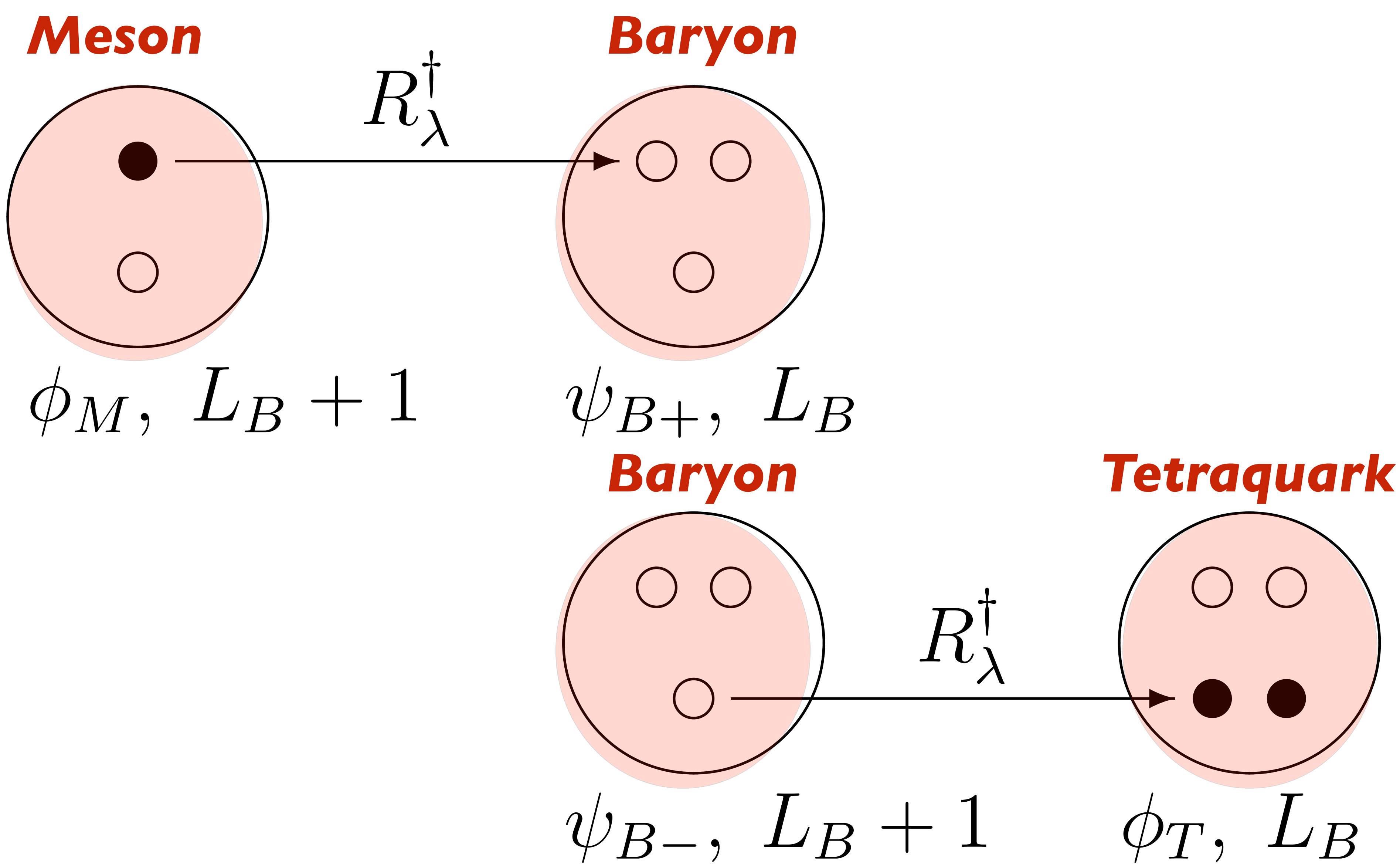
Scale can appear in Hamiltonian and EQM without affecting conformal invariance of action!

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

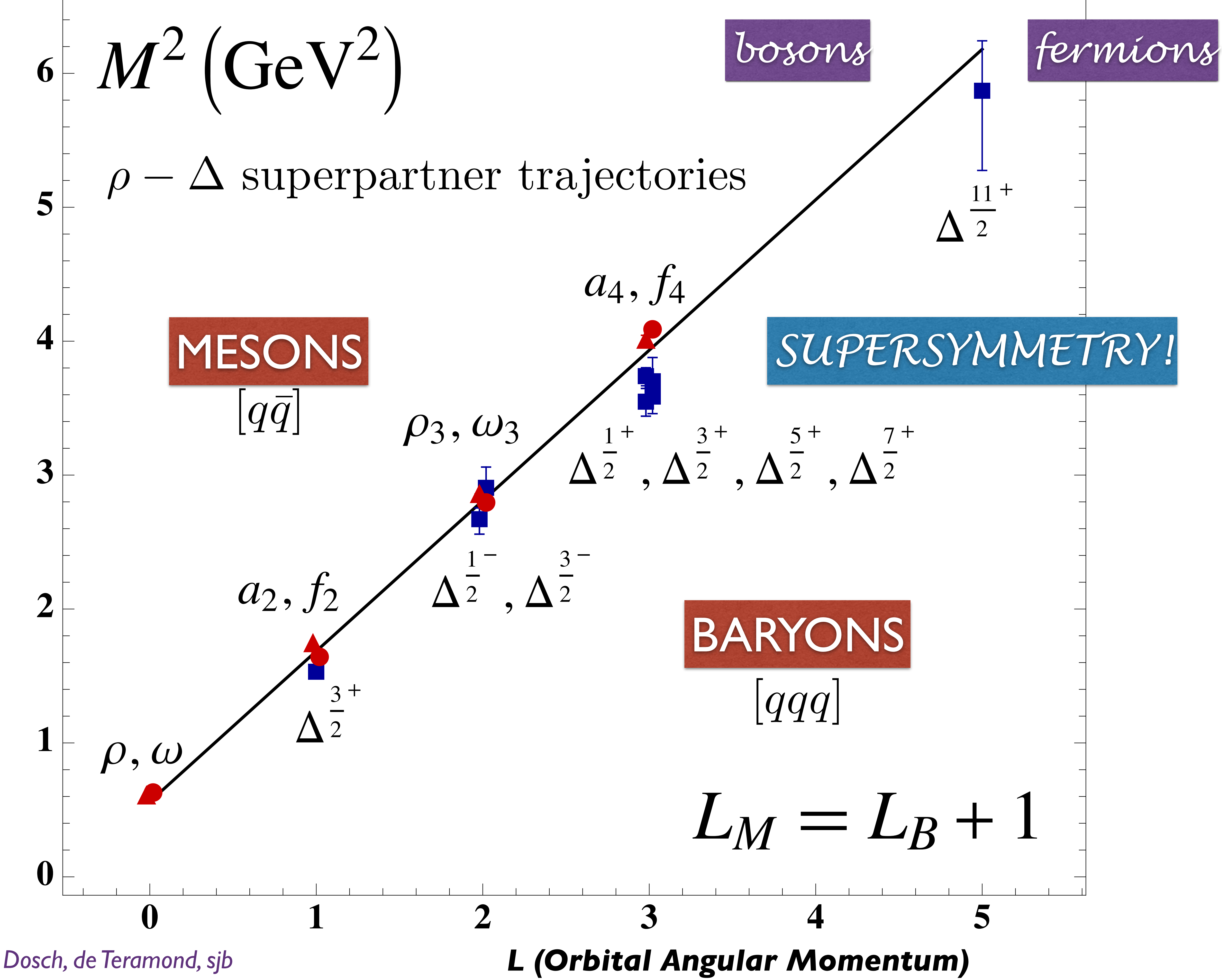
Superconformal Algebra

2X2 Hadronic Multiplets

Bosons, Fermions with Equal Mass!



Proton: quark + scalar diquark $|q(qq)>$
(Equal weight: $L = 0, L = 1$)



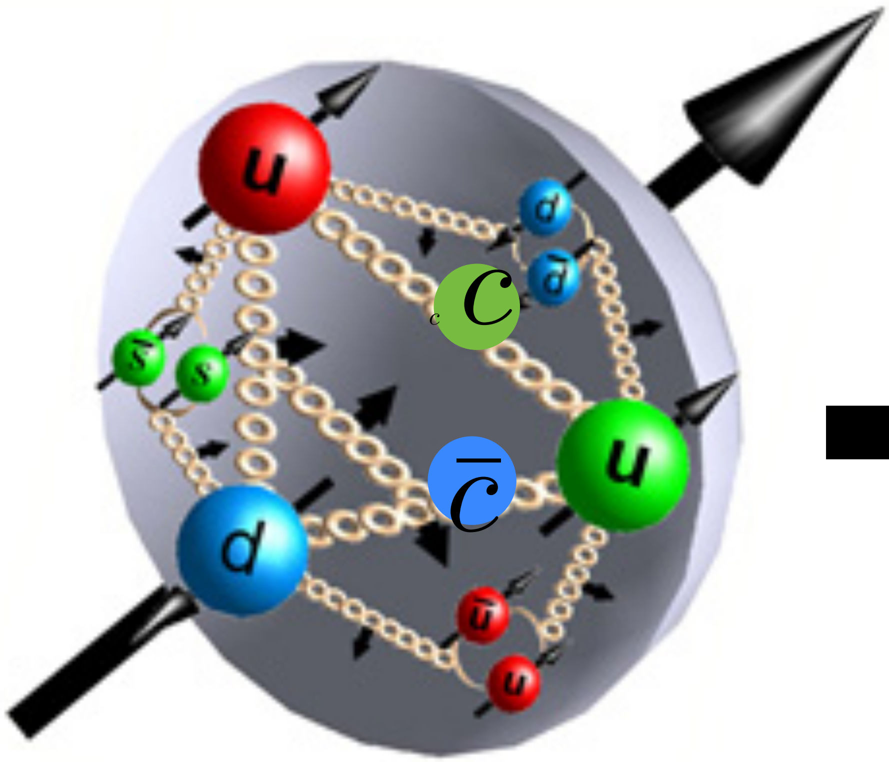
$M^2\,(\mathrm{GeV}^2)$
bosons
fermions
$\rho - \Delta$ superpartner trajectories
MESONS
$[q\bar{q}]$
SUPERSYMMETRY!
BARYONS
$[qqq]$
ρ, ω
a_2, f_2
ρ_3, ω_3
a_4, f_4
$\Delta \frac{3}{2}^+$
$\Delta \frac{1}{2}^-, \Delta \frac{3}{2}^-$
$\Delta \frac{1}{2}^+, \Delta \frac{3}{2}^+, \Delta \frac{5}{2}^+, \Delta \frac{7}{2}^+$
$\Delta \frac{11}{2}^+$
$L_M = L_B + 1$
L (Orbital Angular Momentum)
Dosch, de Teramond, sjb

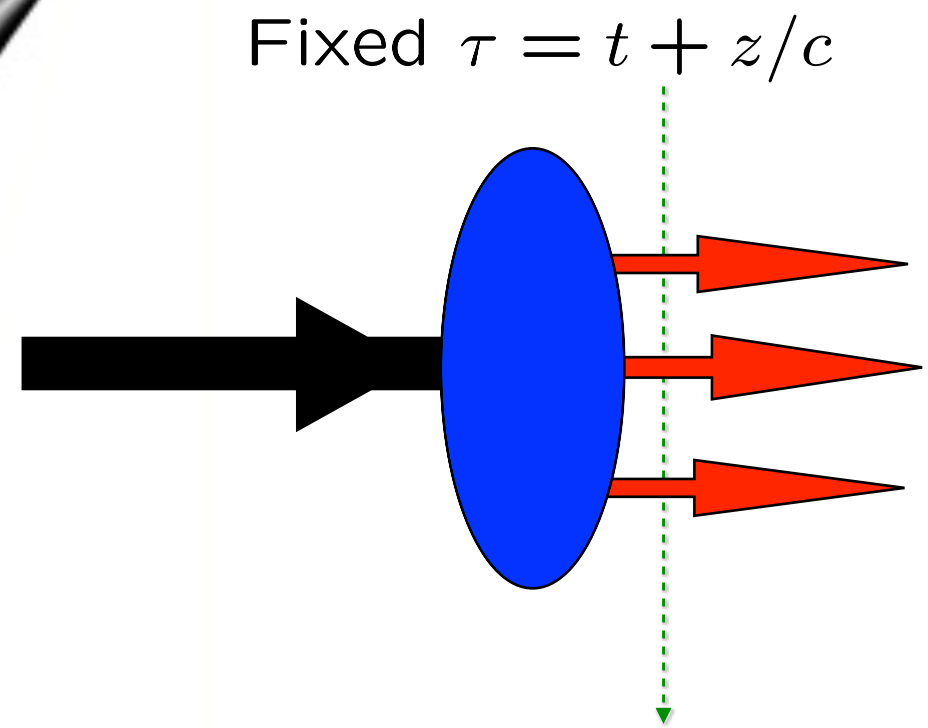
An analytic first approximation to QCD

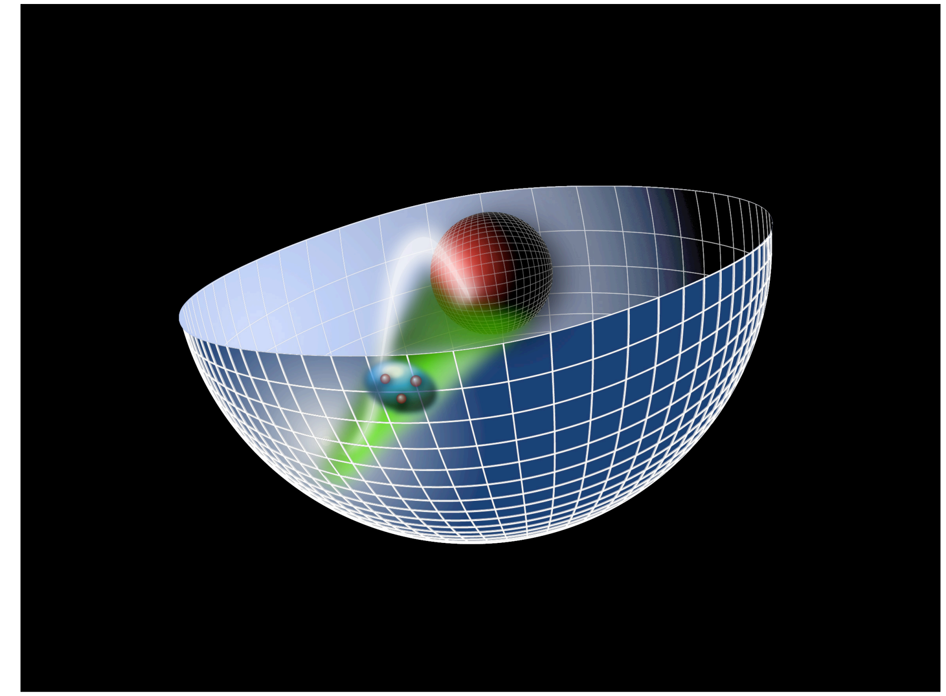
AdS/QCD + Light-Front Holography

- 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

Novel QCD Features of Hadrons and Nuclei







Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

with Guy de Tèramond, Hans Günter Dosch, and Alexandre Deur

GGI School

Frontiers in Nuclear and Hadronic Physics

February 25 - March 8, 2019