The 3D Nucleon Structure

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Università di Pavia & INFN

Funded by:

3DSPIN MAPPING THE PROTON IN 3D

European Research Council

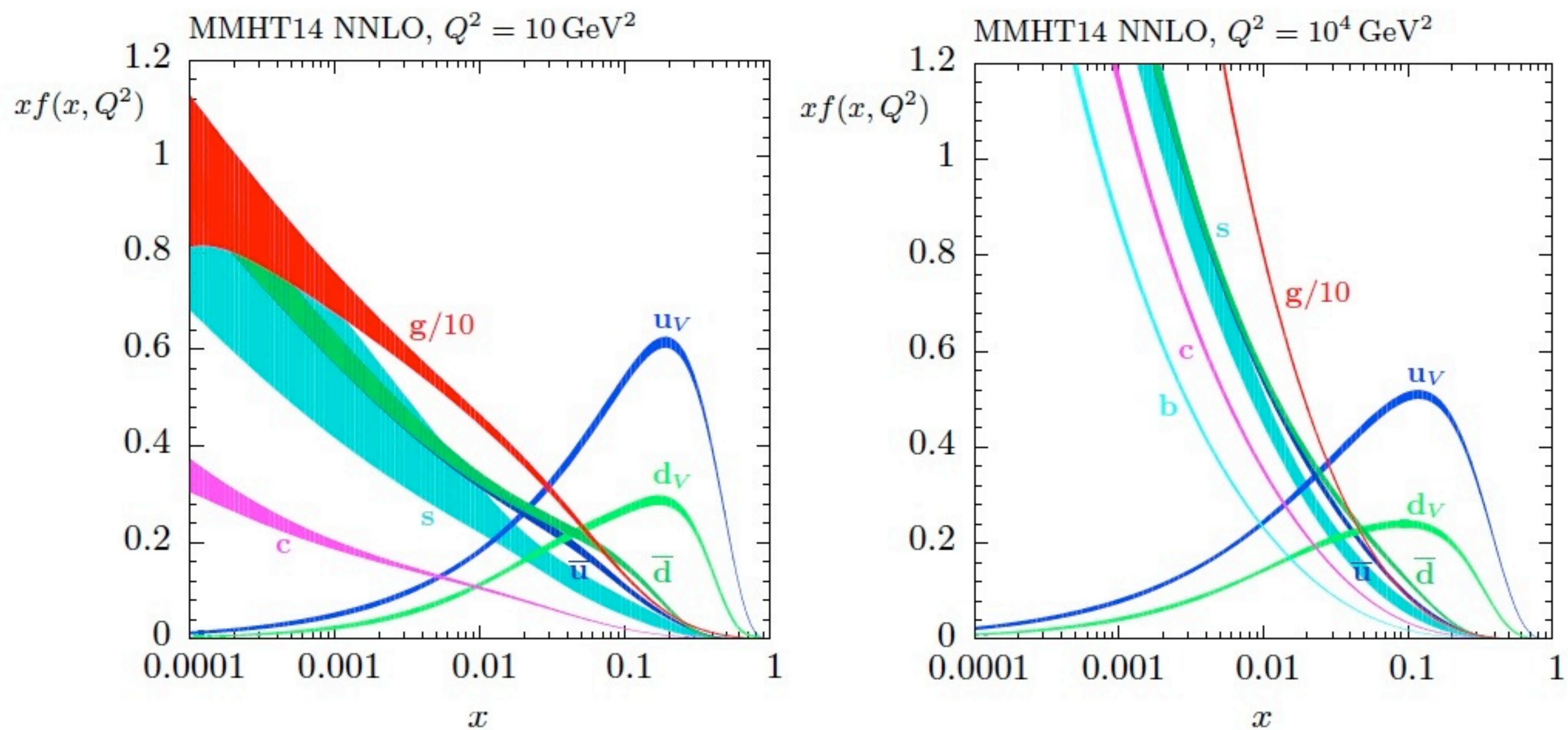
INFN Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DI PAVIA

Principal Investigator: A. Bacchetta

Available Maps: Parton Distribution Functions

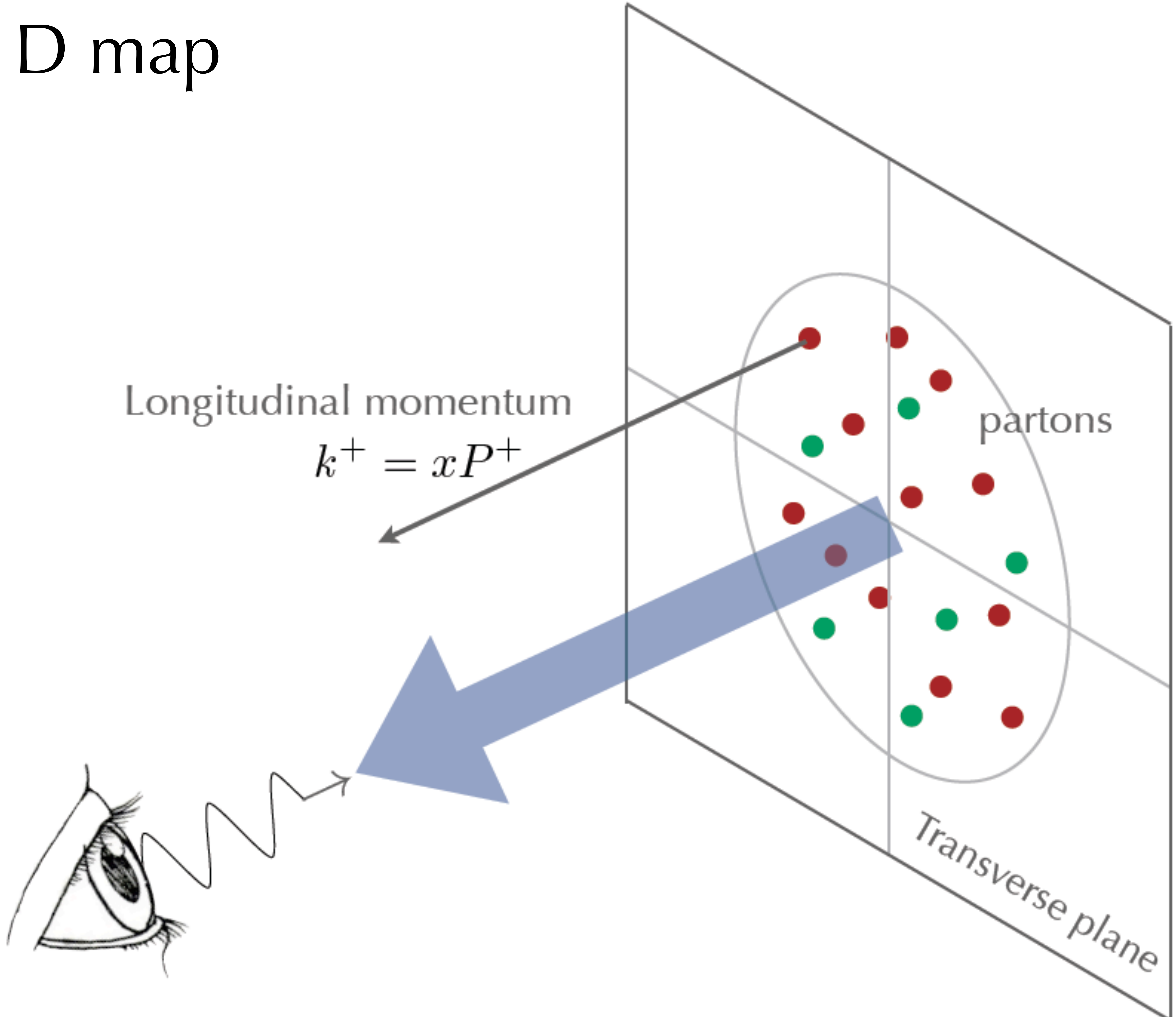
monodimensional (in momentum space)



MMHT2014 Eur. Phys. J. C75 (2015) 204

→ talk of M. Guzzi

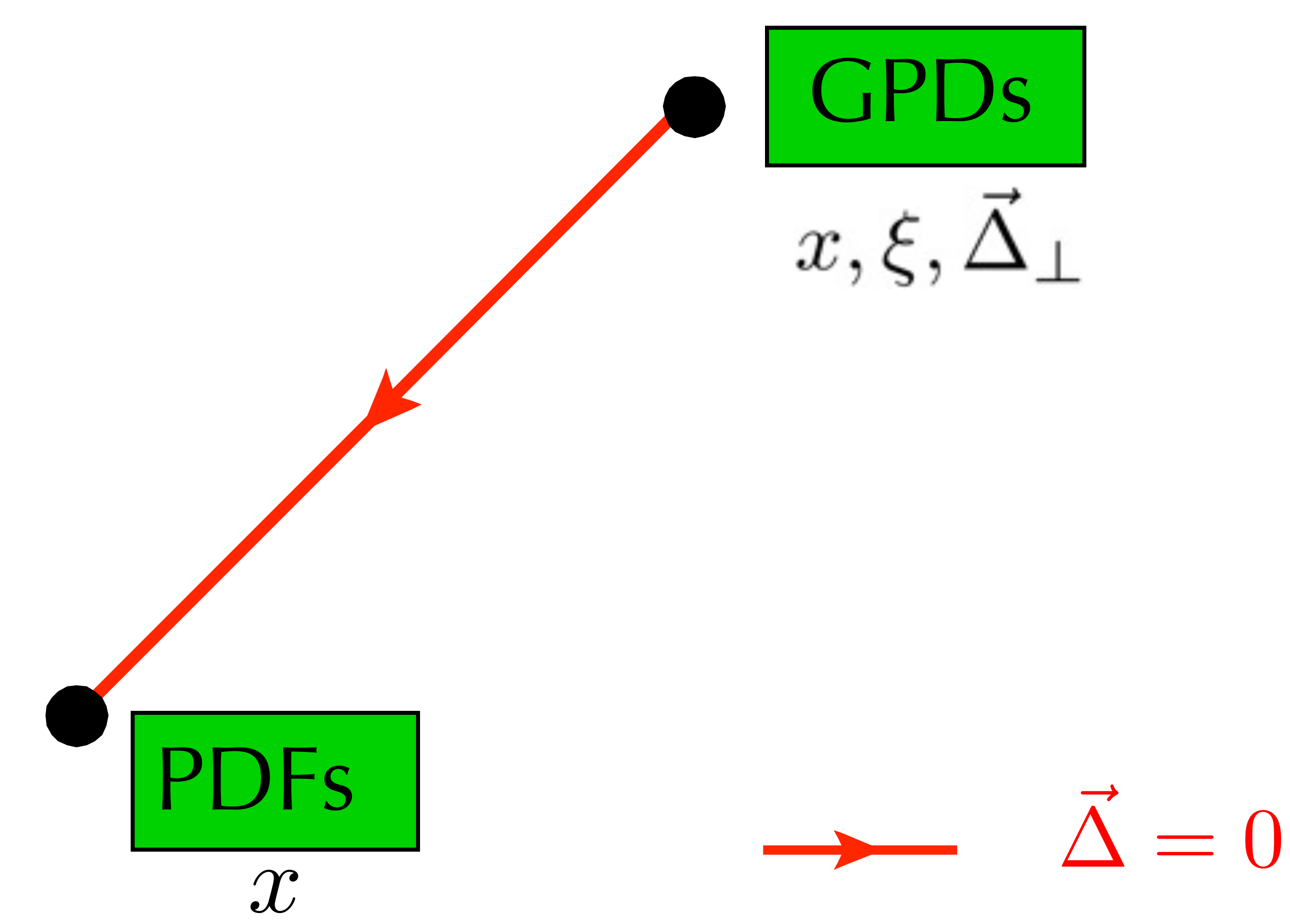
PDFs: 1D map



How can we built up
a multidimensional picture
of the nucleon?

Generalized Parton Distributions (GPDs)

$$\boxed{\frac{1}{2}\int \frac{\mathrm{d}z^-}{2\pi} e^{ik^+z^-} \langle p'^+,\, -\frac{\vec{\Delta}_\perp}{2},\, \Lambda' | \bar{\psi}(-\frac{z}{2})\, \Gamma\, \mathcal{W}\, \psi(\frac{z}{2}) | p^+,\, \frac{\vec{\Delta}_\perp}{2},\, \Lambda \rangle_{z^+=0, z_\perp=0}} \longrightarrow \text{non-diagonal matrix elements}$$



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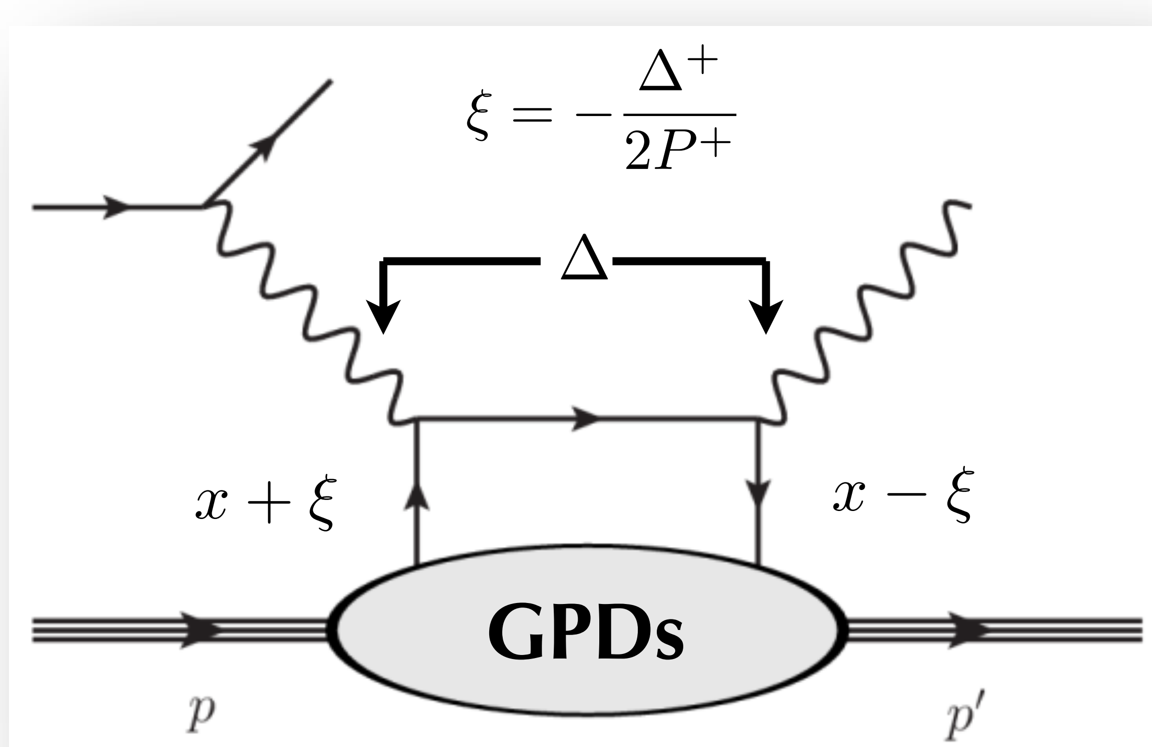
Depend on

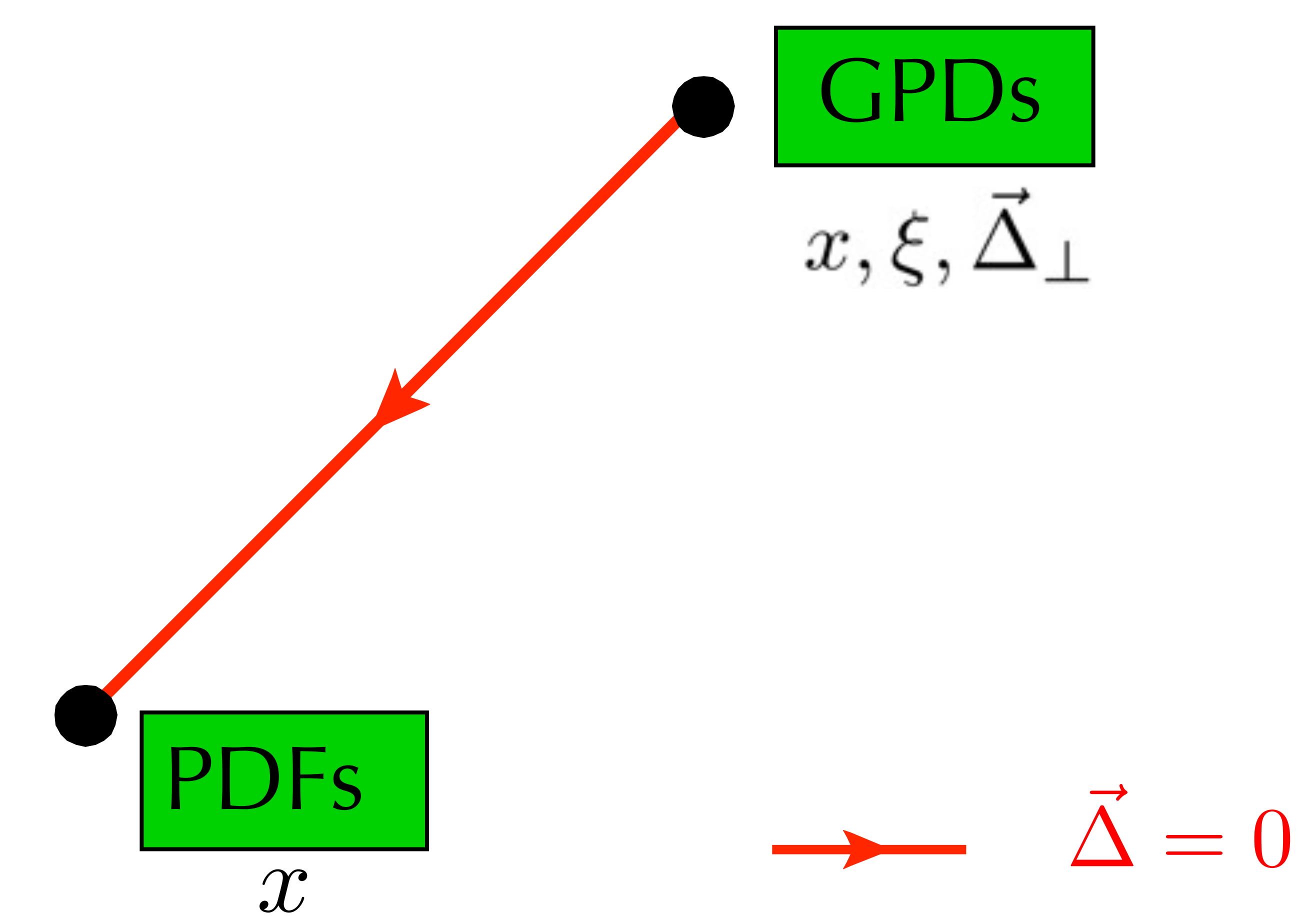
$x=\dfrac{k^+}{P^+}$: longitudinal momentum fraction

Δ : momentum transfer

$\Lambda,\ \Lambda',\ \Gamma$: nucleon and quark polarizations

Deeply Virtual Compton Scattering





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Δ : momentum transfer $\qquad \vec{\Delta}_\perp \xleftrightarrow{\text{FT}} \vec{b}_\perp$: impact parameter

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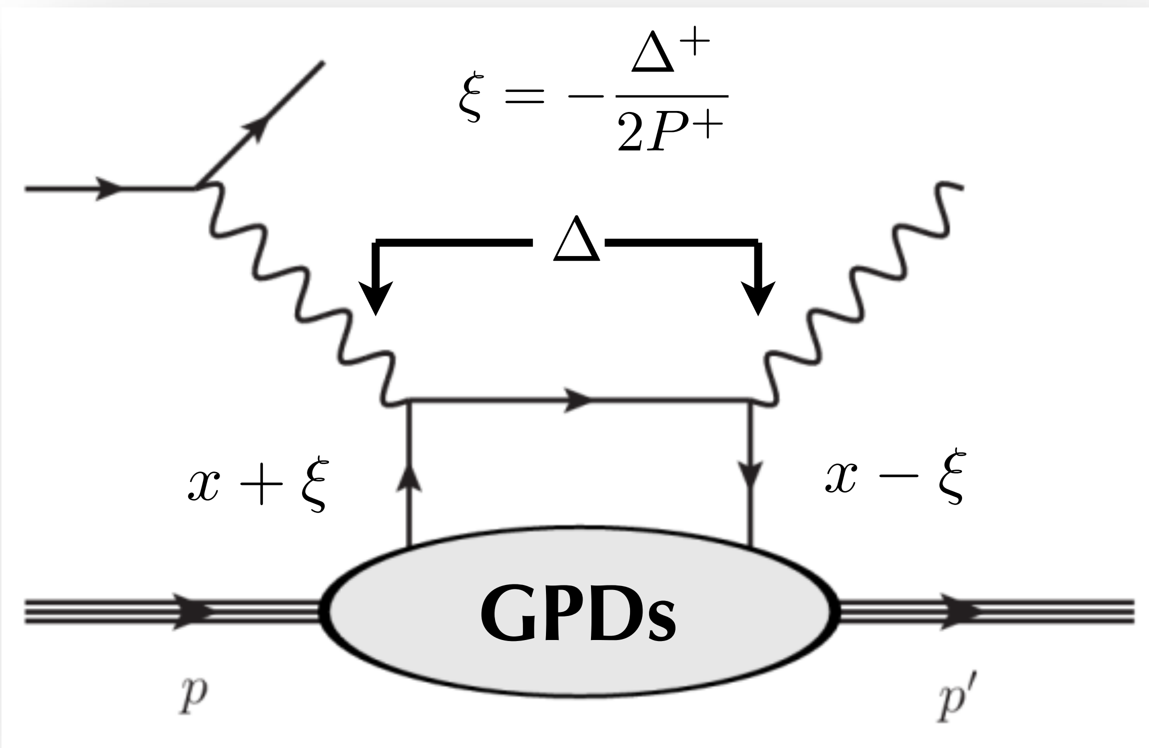
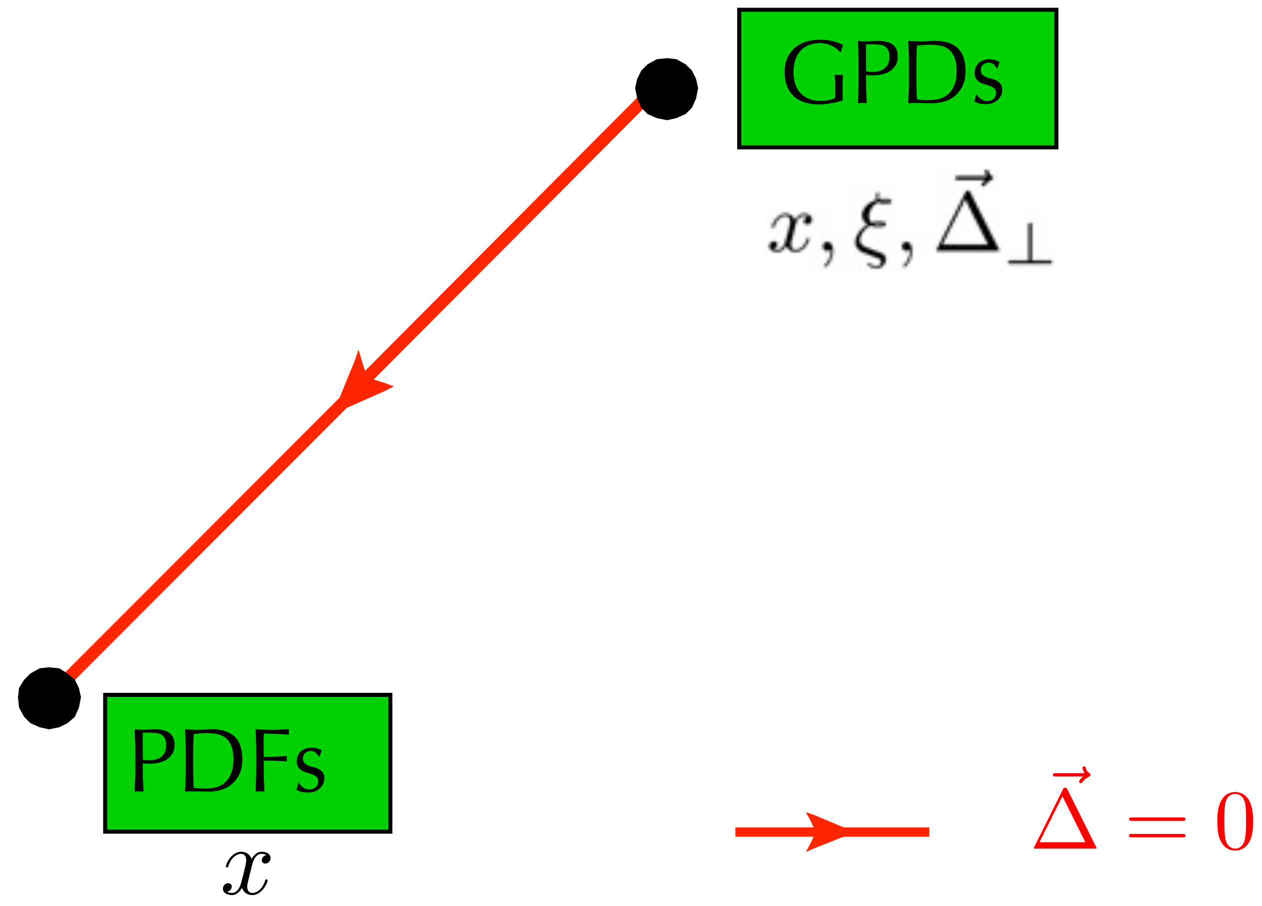
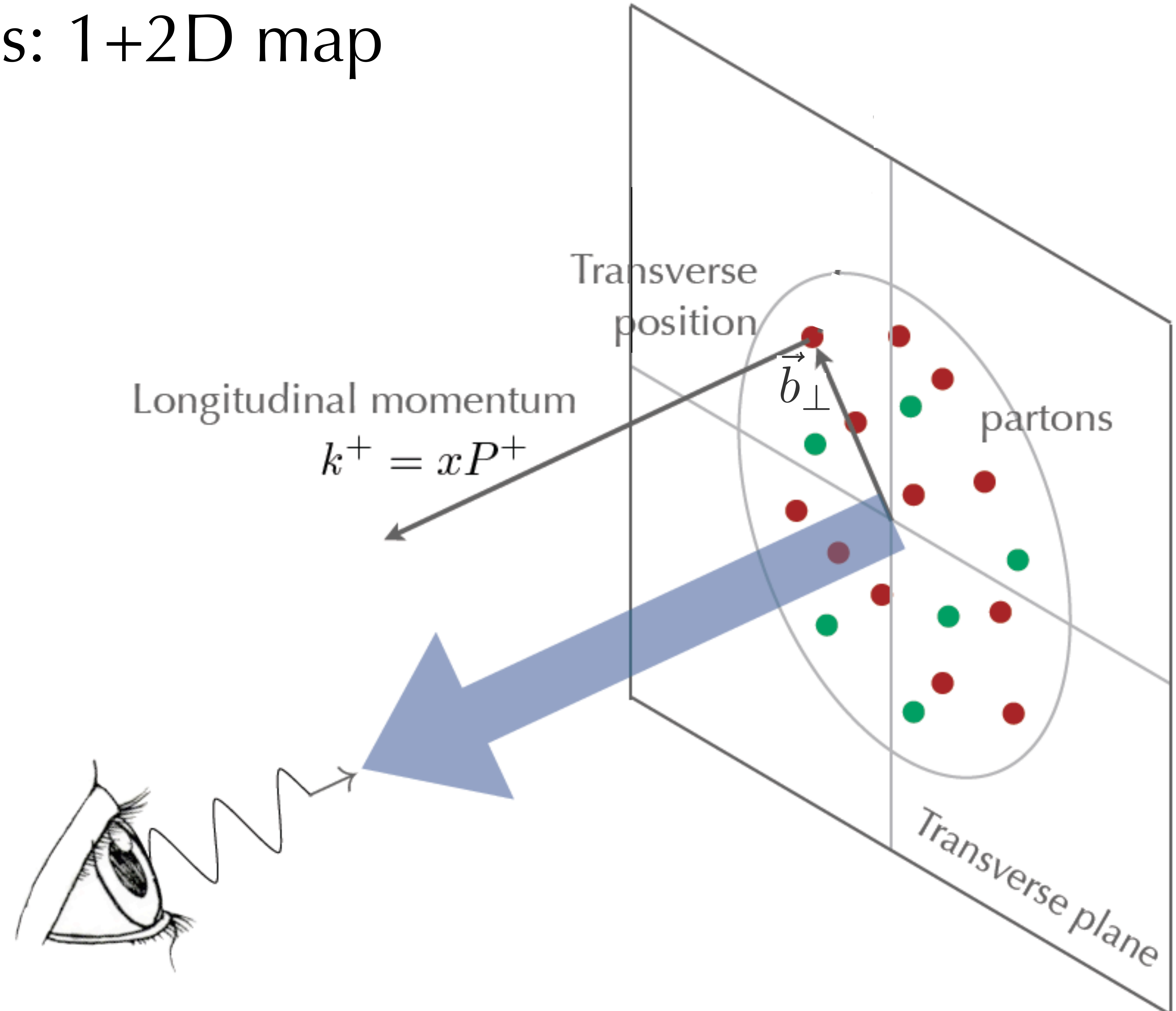




GPDs: 1+2D map



Transverse position
Longitudinal momentum
$k^+ = xP^+$
$\vec{b}_\perp$
partons
Transverse plane

Transverse Momentum PDFs (TMDs)

$$\boxed{\frac{1}{2}\int\frac{\mathrm{d}z^-\mathrm{d}^2z_\perp}{(2\pi)^3}e^{ik\cdot z}\langle p^+,\,\vec{0}_\perp,\,\Lambda'|\bar{\psi}(-\frac{z}{2})\,\Gamma\,\mathcal{W}\,\psi(\frac{z}{2})|p^+,\,\vec{0}_\perp,\,\Lambda\rangle_{z^+=0}}$$

Depend on

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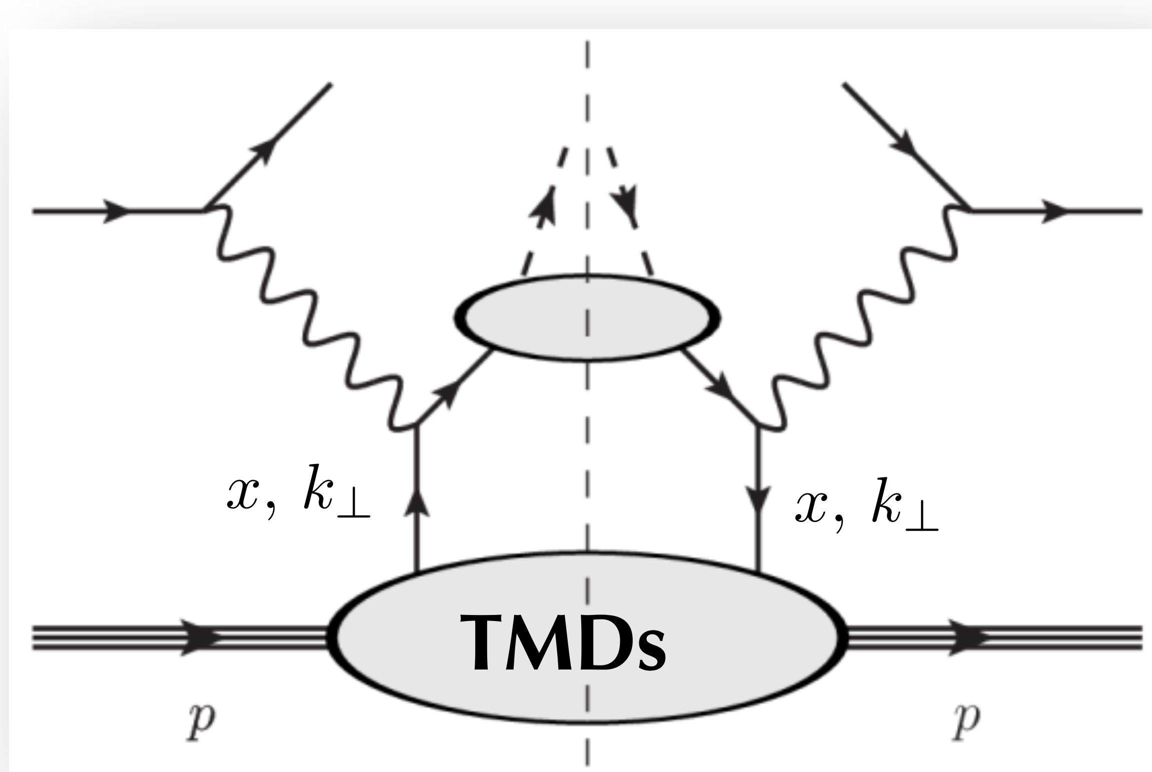
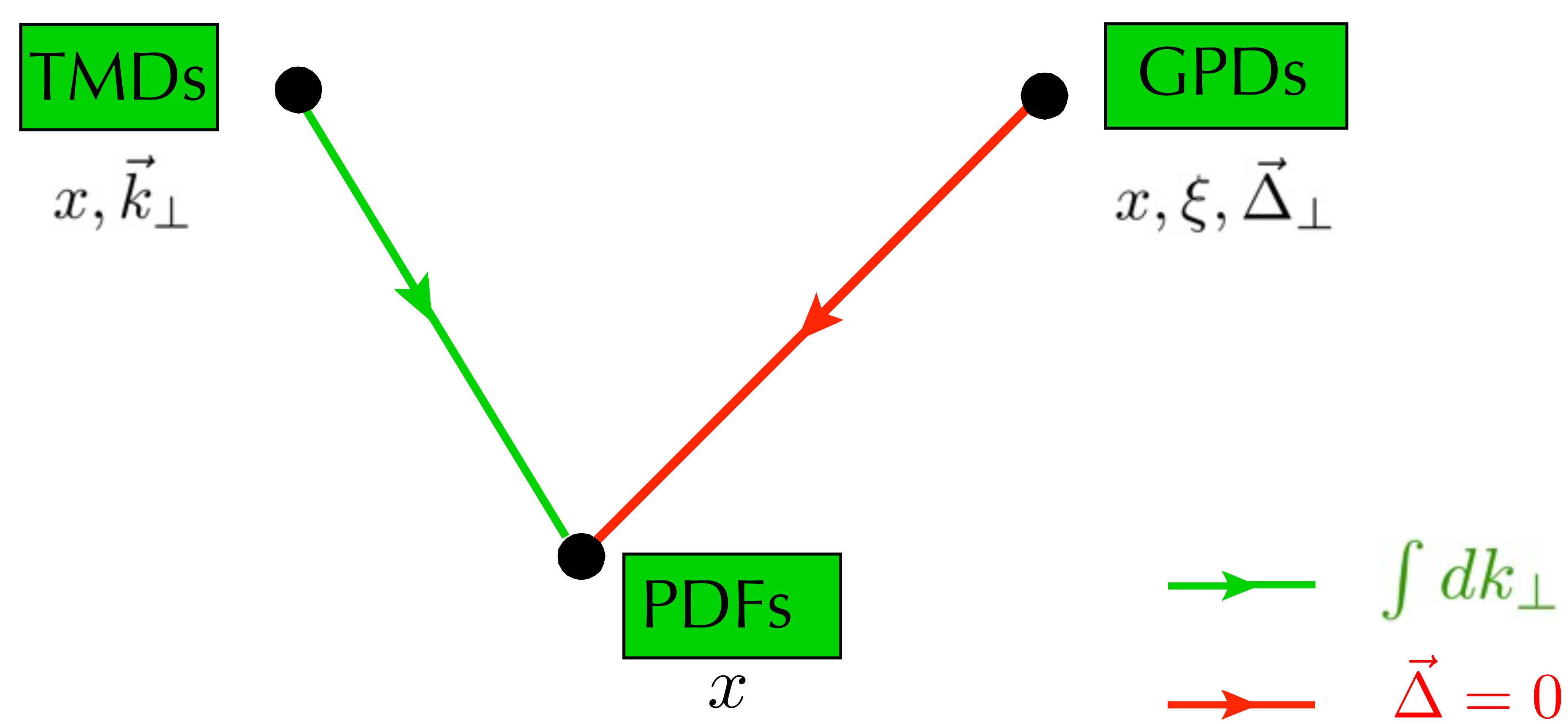
Semi-Inclusive
Deep Inelastic Scattering





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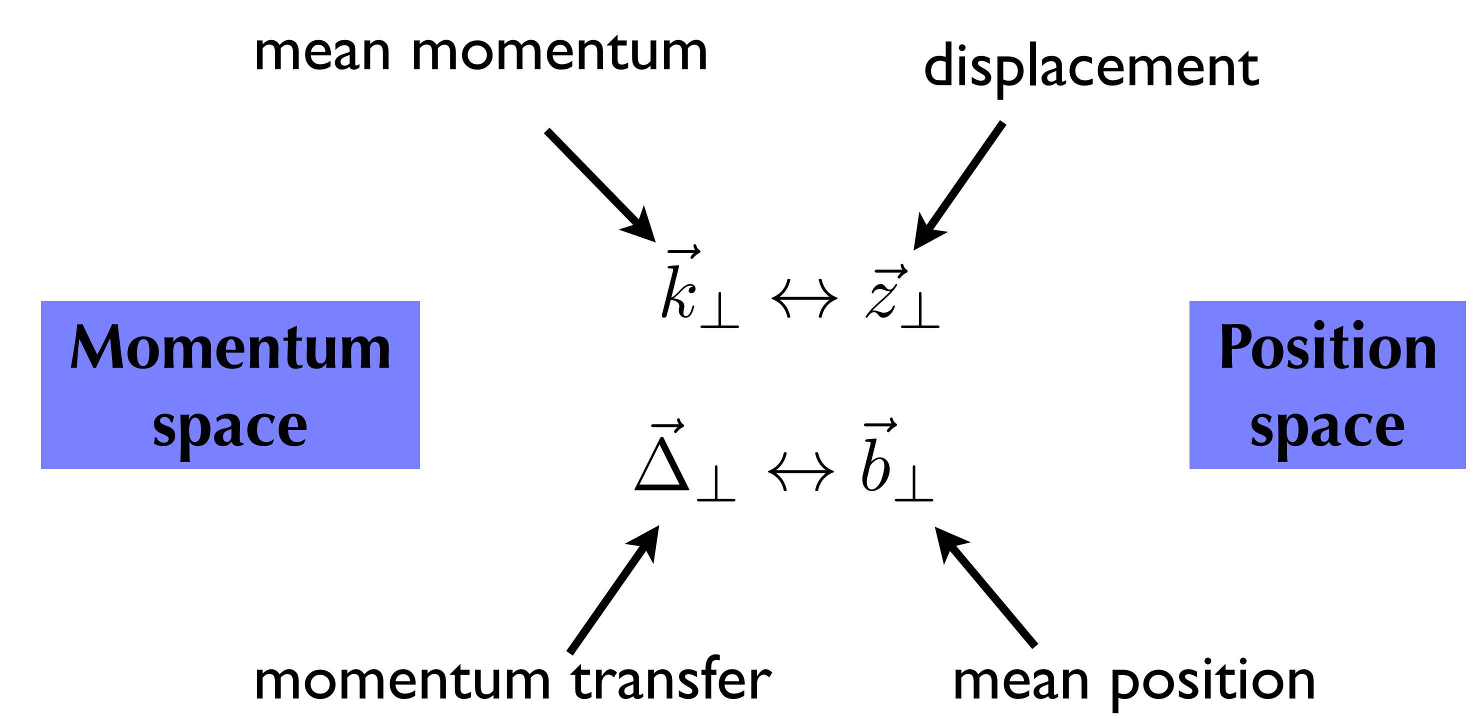
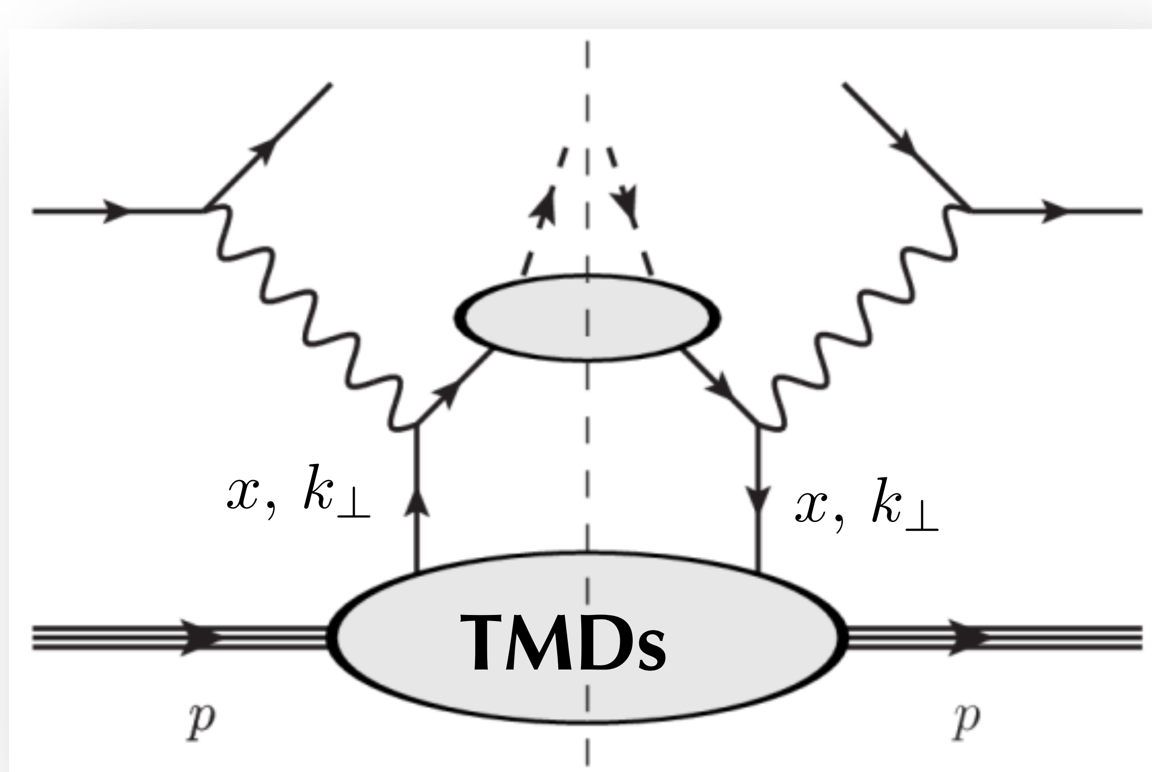
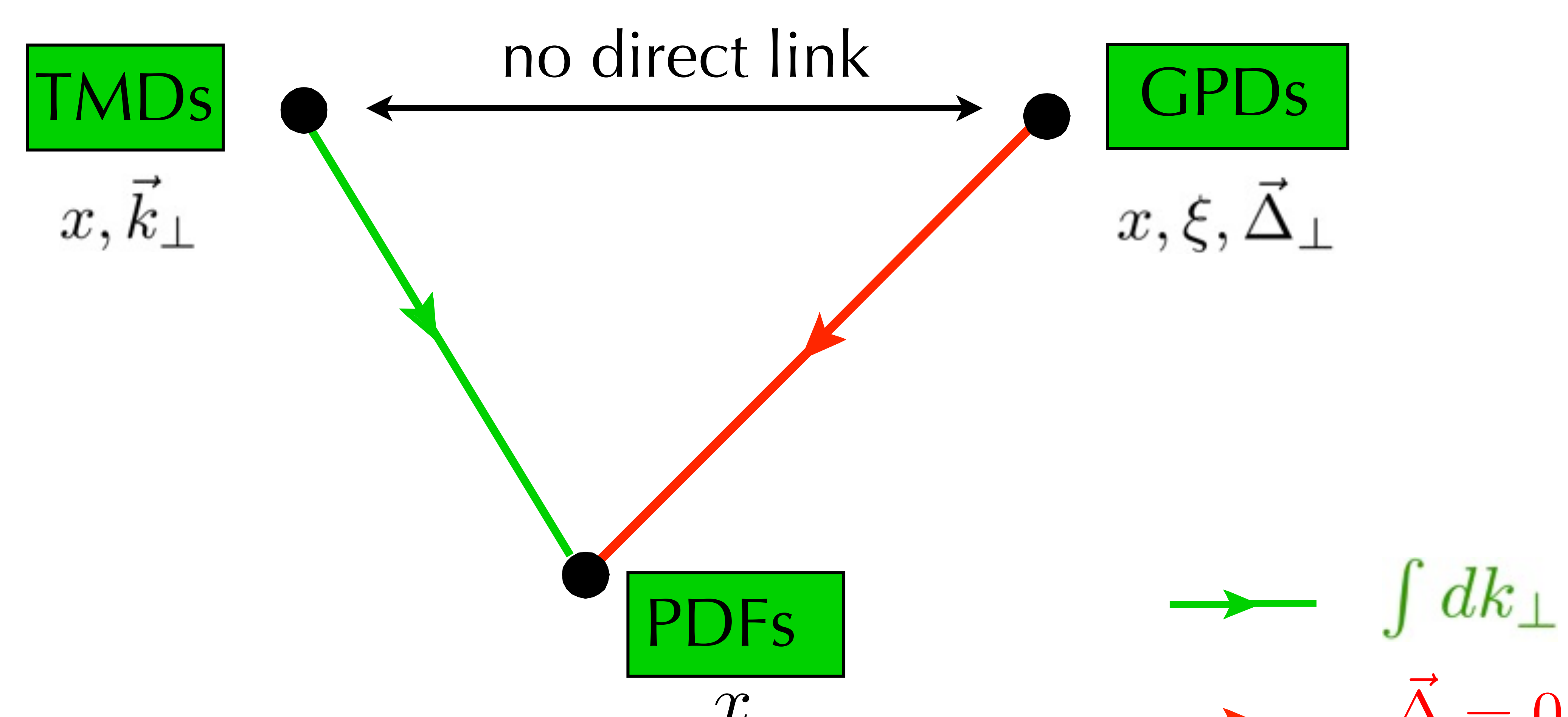
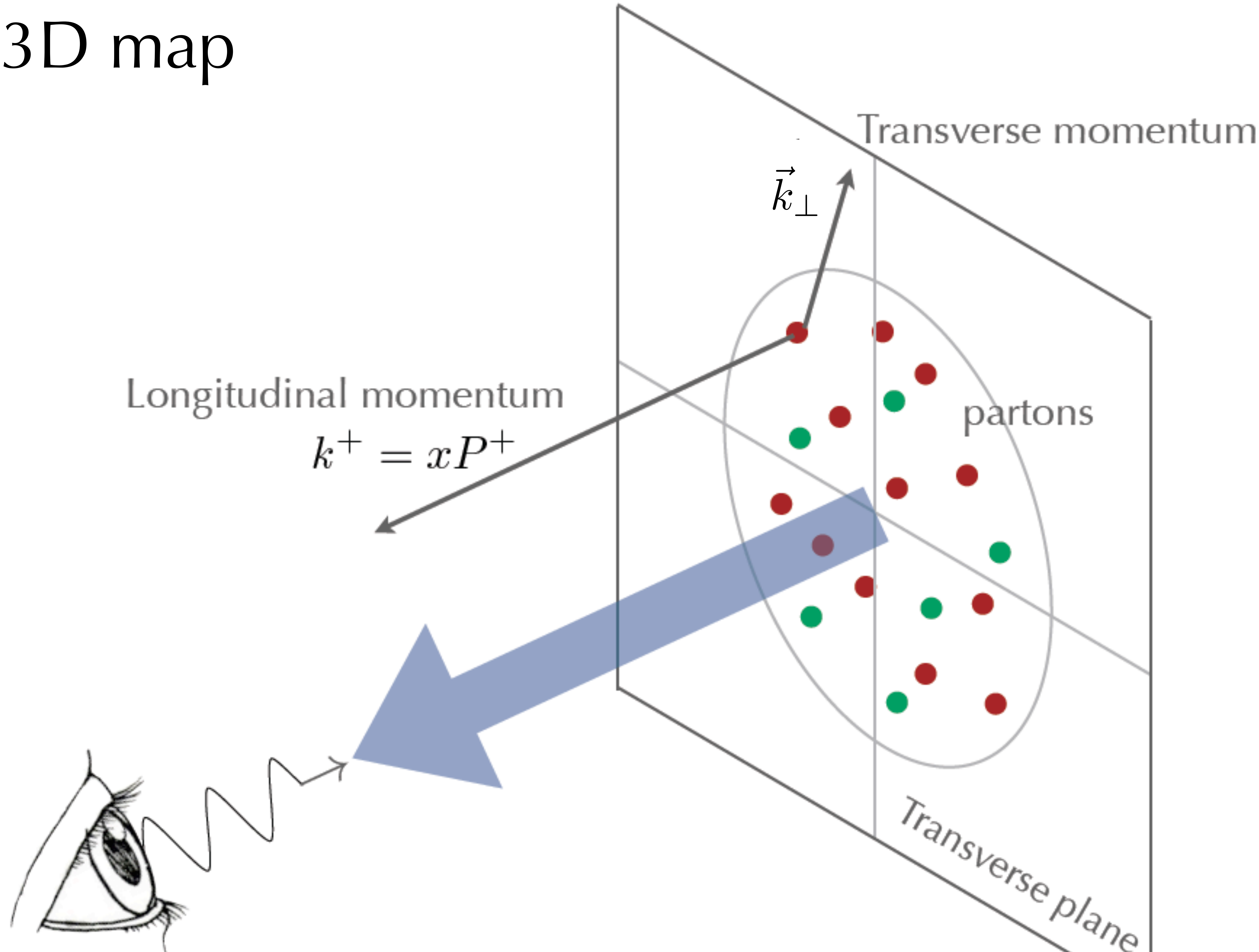


Semi-Inclusive Deep Inelastic Scattering





TMDs: 3D map



Transverse momentum
$\vec{k}_\perp$
Longitudinal momentum
$k^+ = xP^+$
partons
Transverse plane

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$k_\perp$: parton transverse momentum

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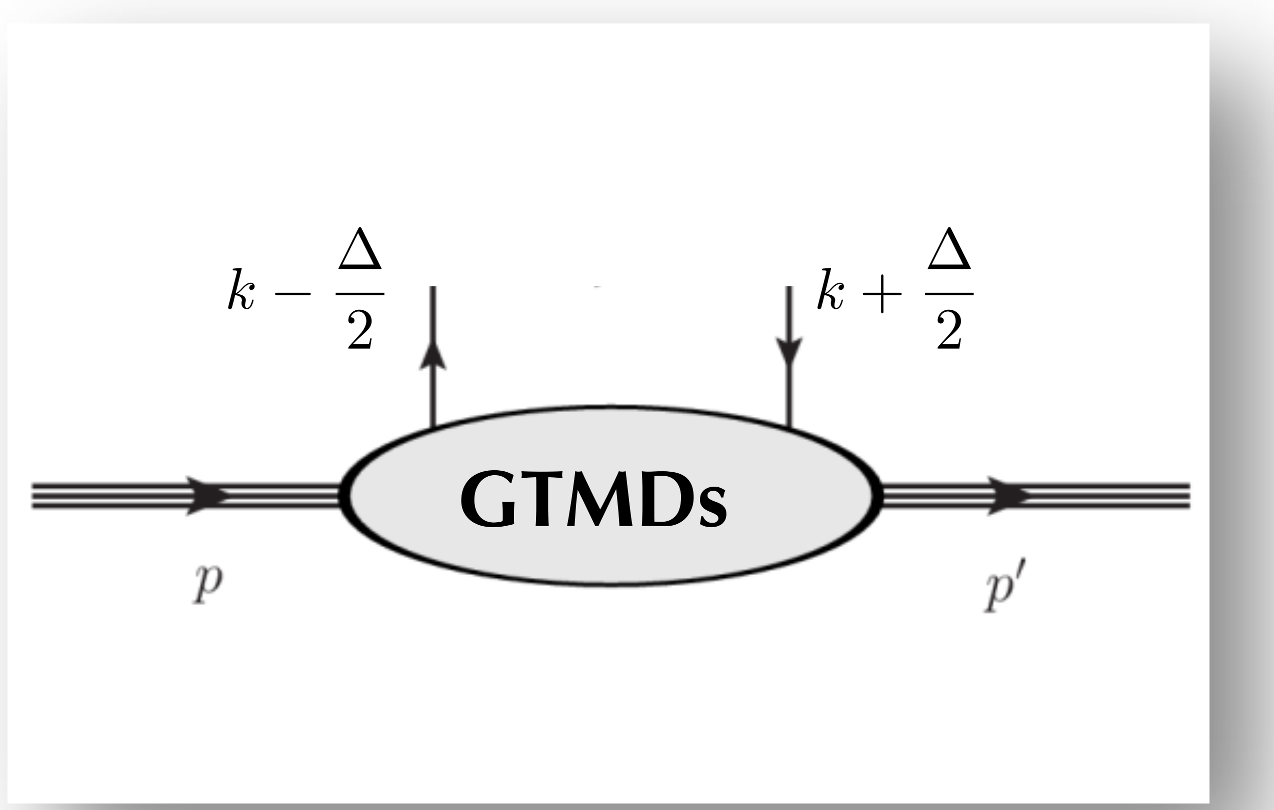

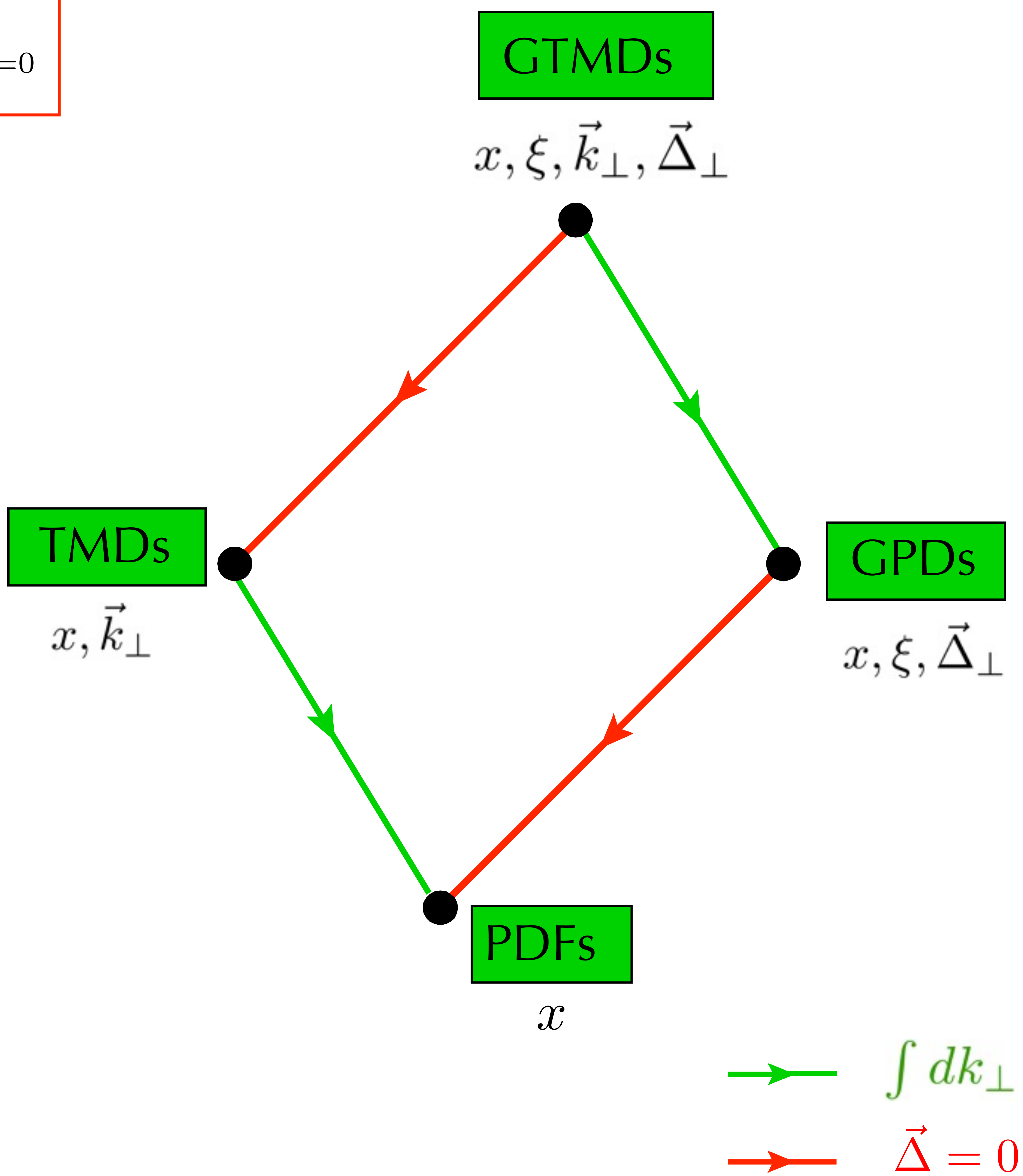

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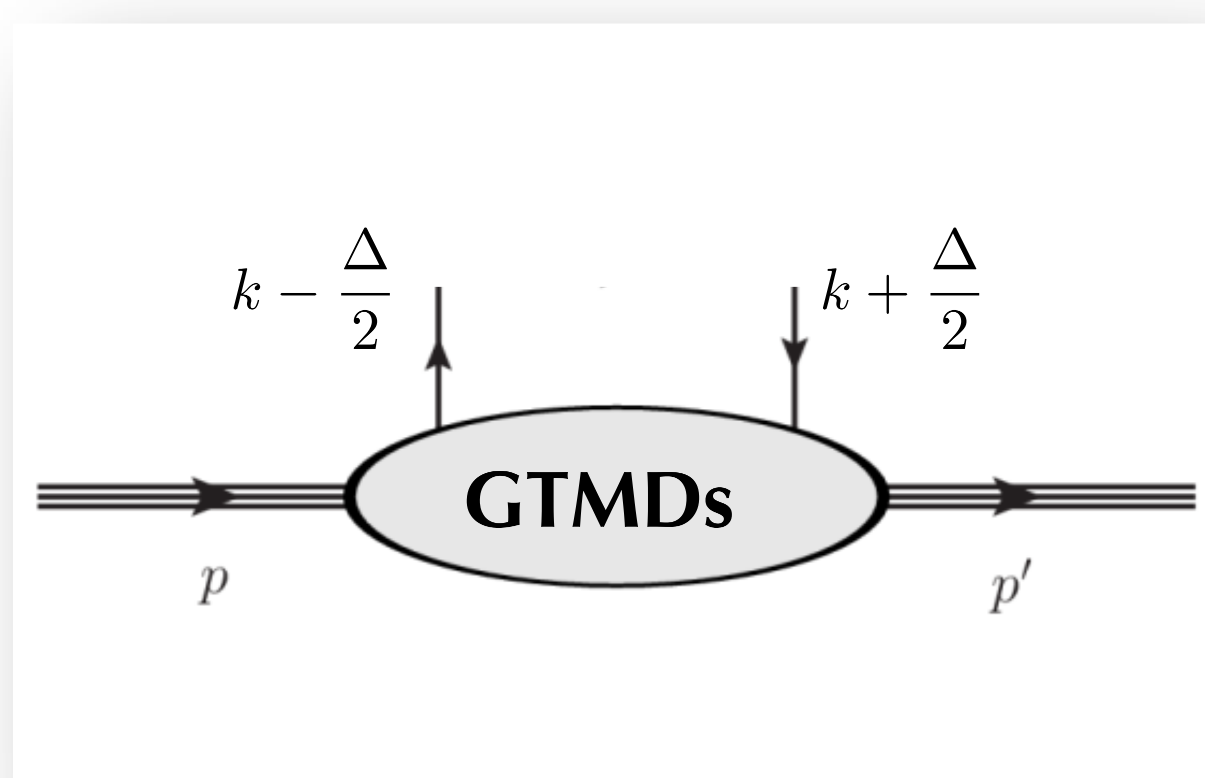
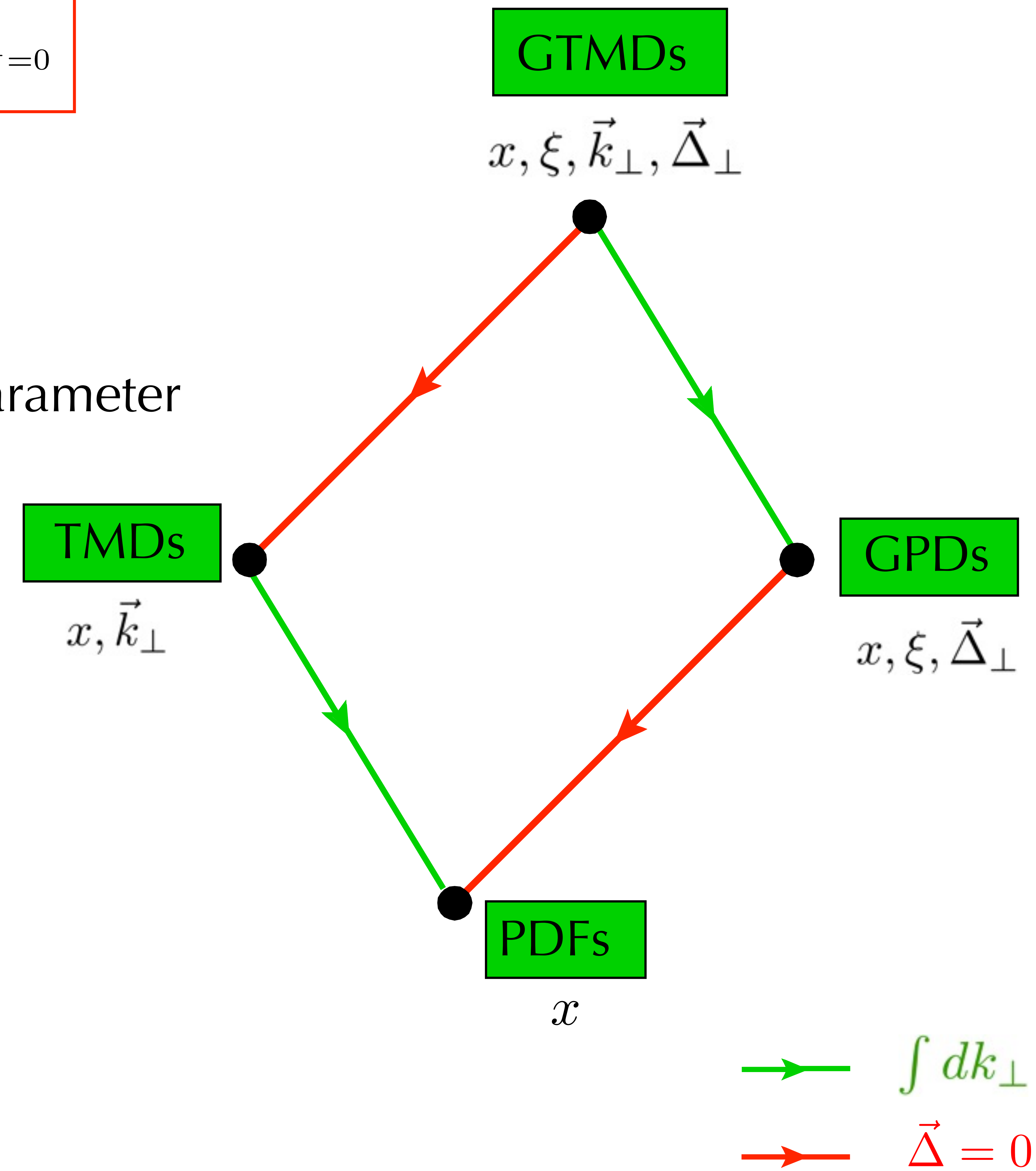
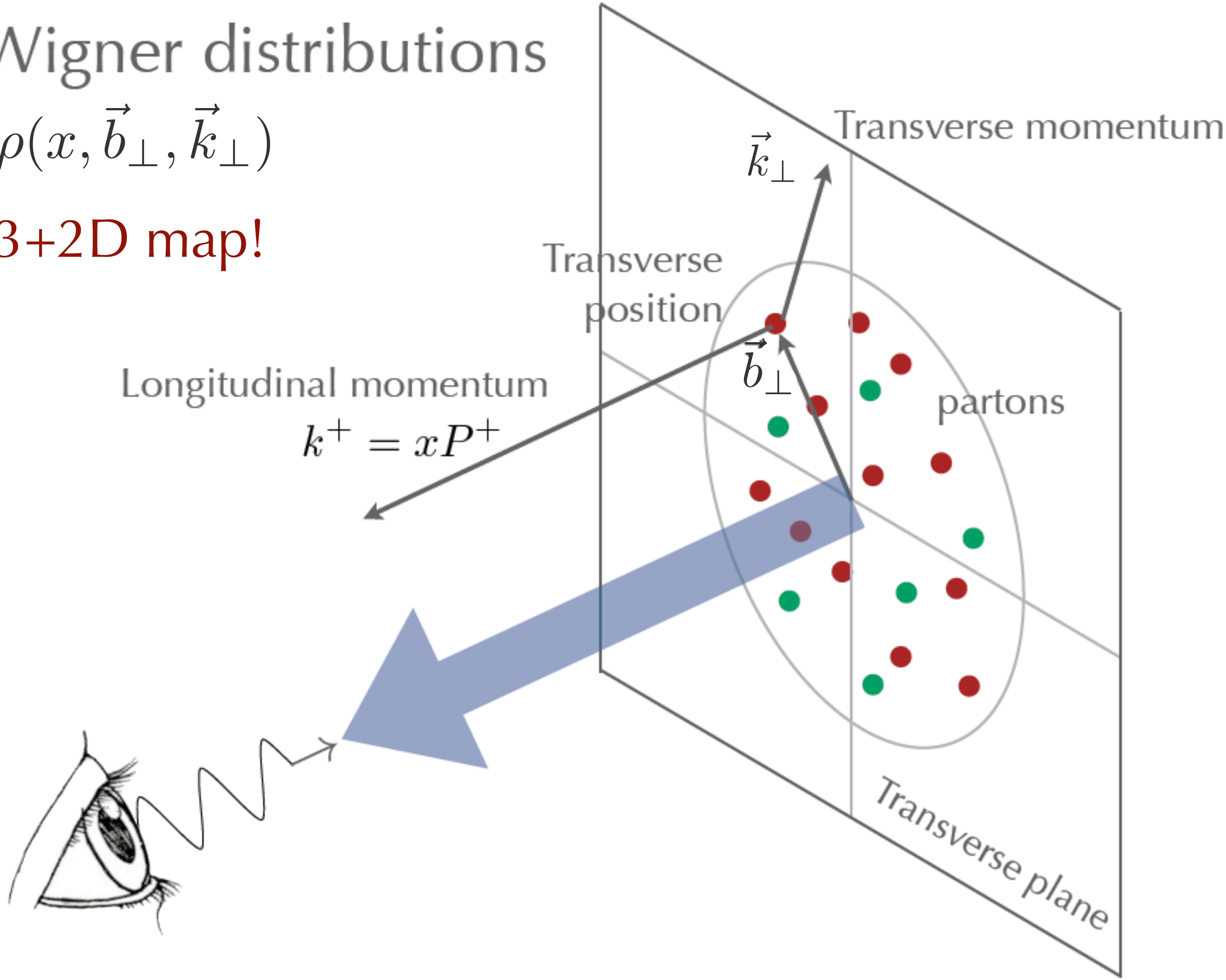


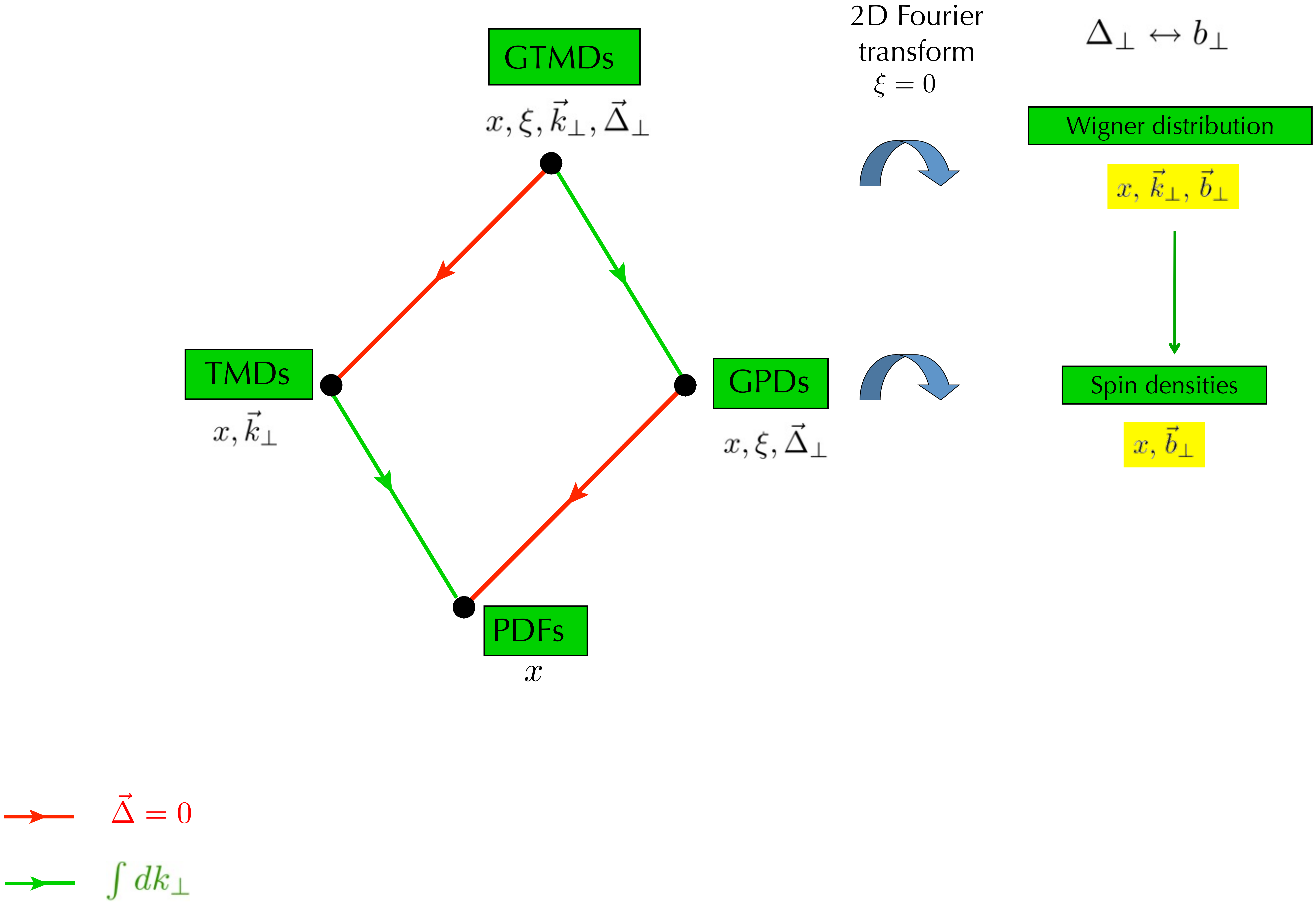


Wigner distributions

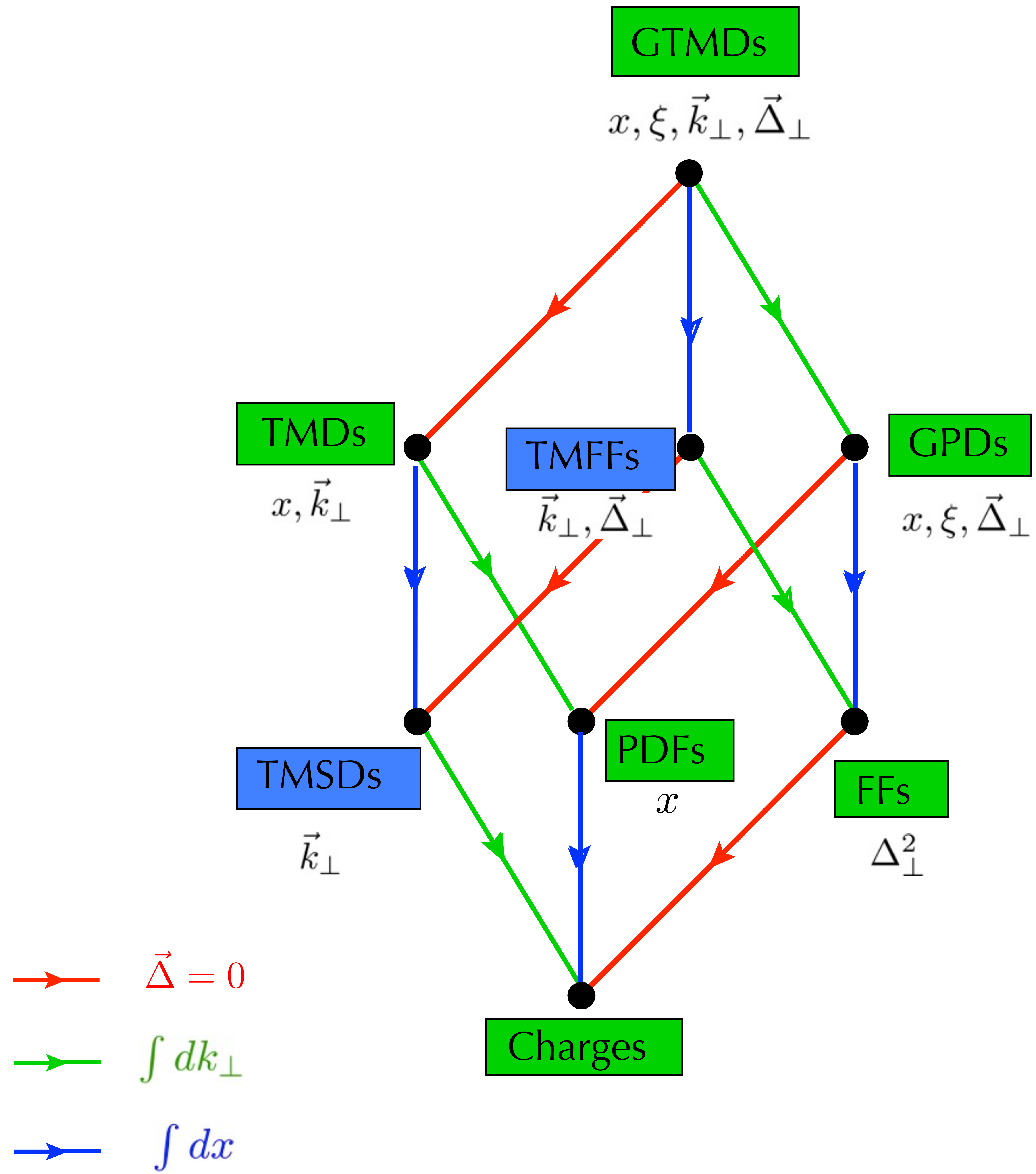
$$\rho(x, \vec{b}_\perp, \vec{k}_\perp)$$

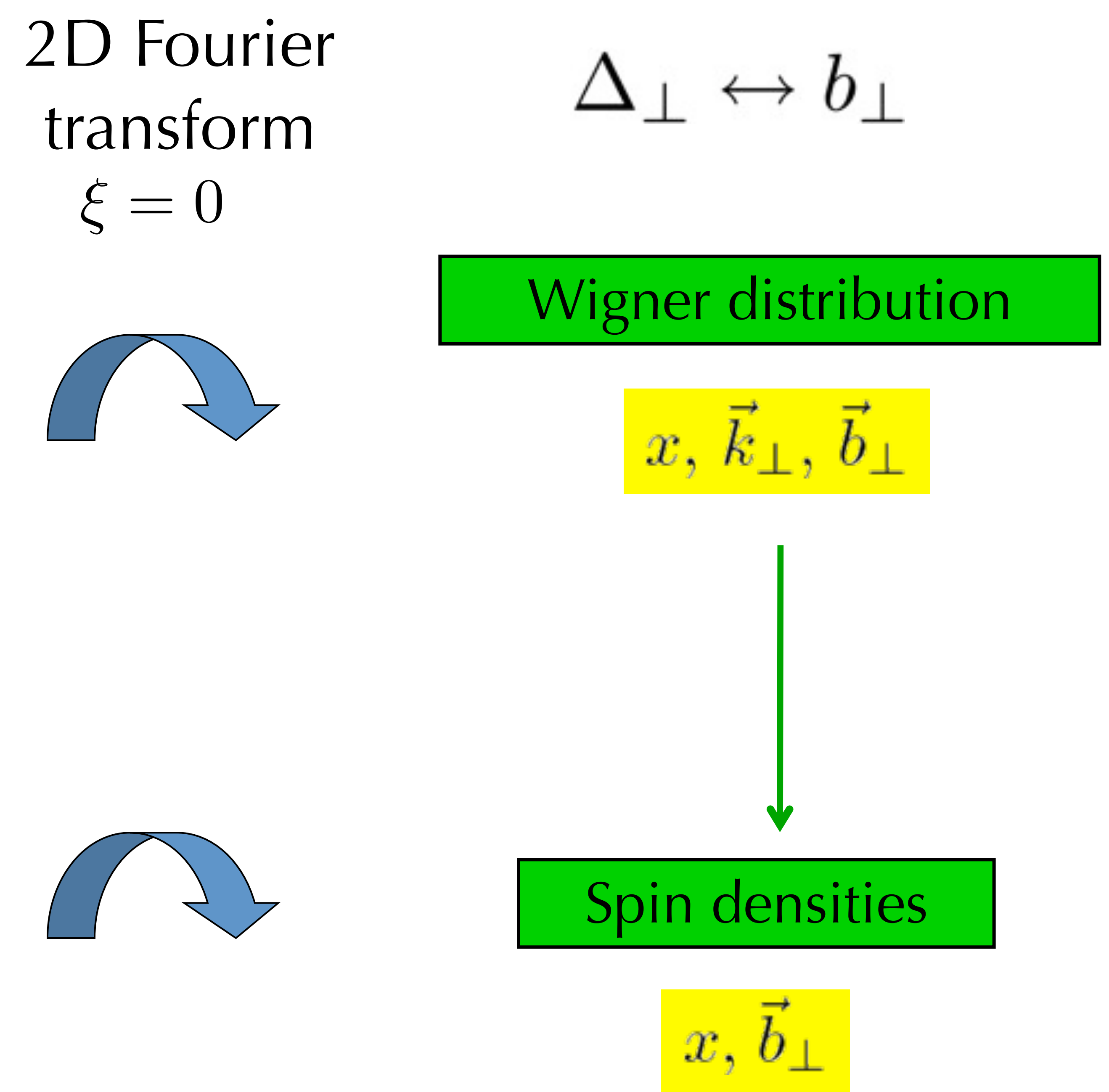
3+2D map!





Lorcé, BP, Vanderhaeghen, JHEP05 (2011) 041





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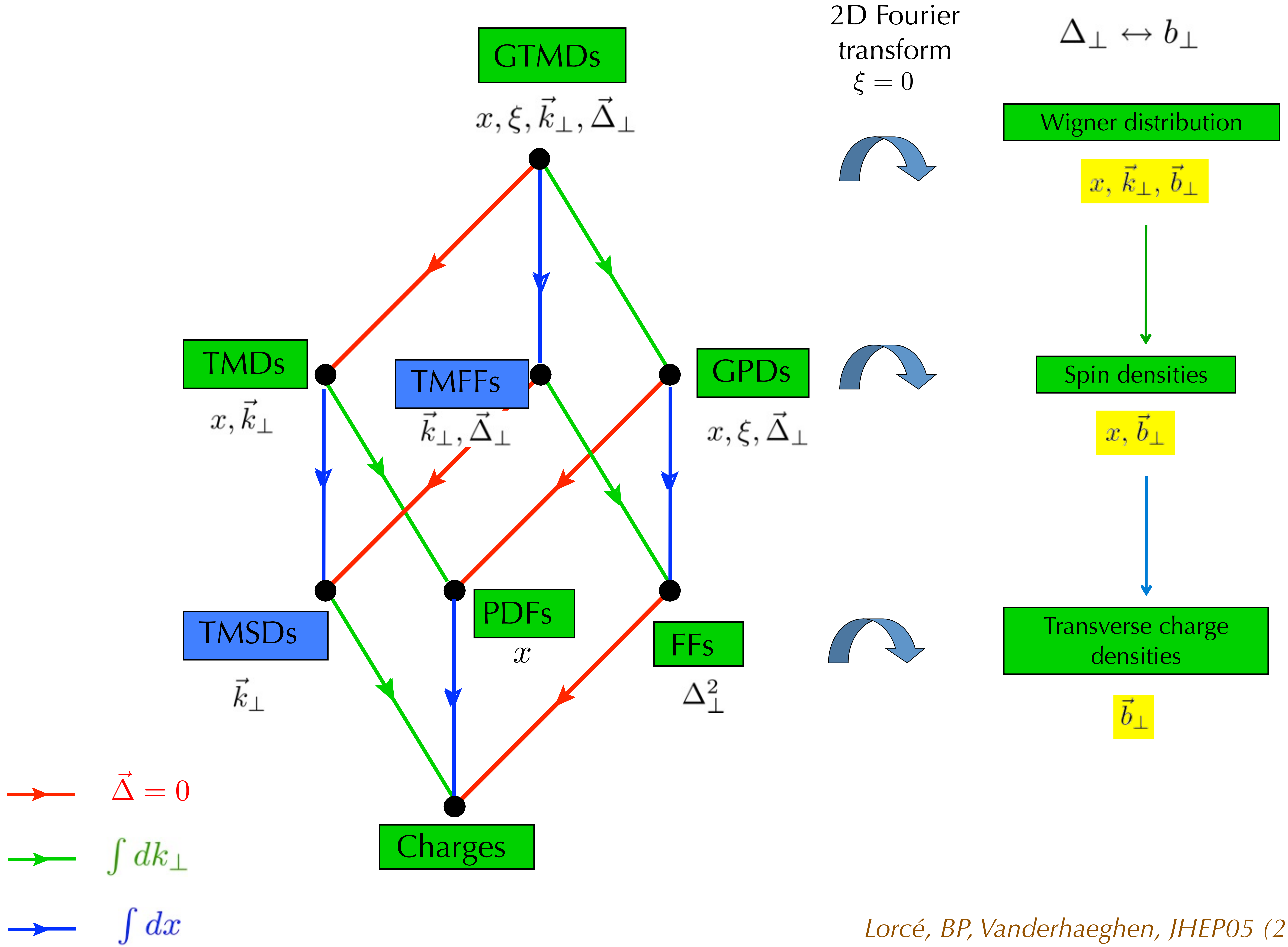

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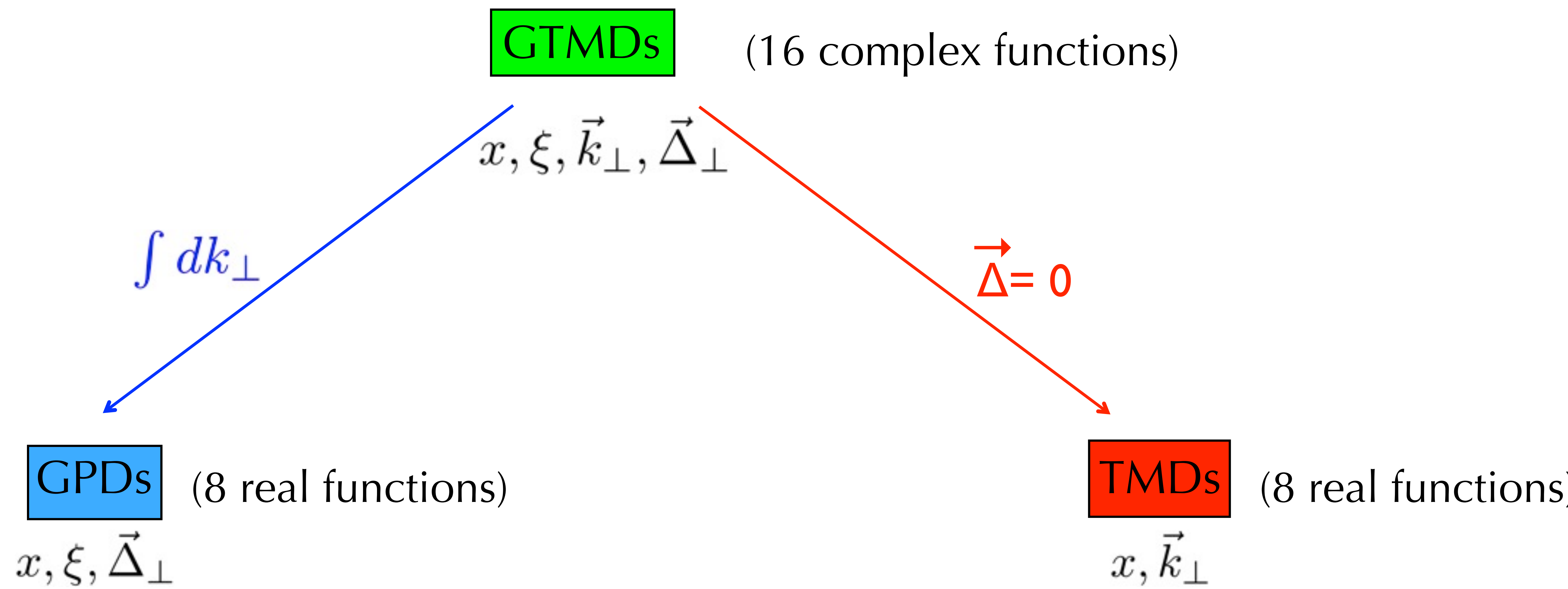


Quark polarization (columns), Nucleon polarization (rows)

	U	T	L
U	H	$\mathcal{E}_T$	
T	E	$H_T, \tilde{H}_T$	$\tilde{E}$
L		$\tilde{E}_T$	$\tilde{H}$

Quark polarization (columns), Nucleon polarization (rows)

	U	T	L
U	f_1	$h_1^\perp$	
T	$f_{1T}^\perp$	$h_1, \ h_{1T}^\perp$	g_{1T}
L		$h_{1L}^\perp$	g_{1L}

each distribution contains unique information

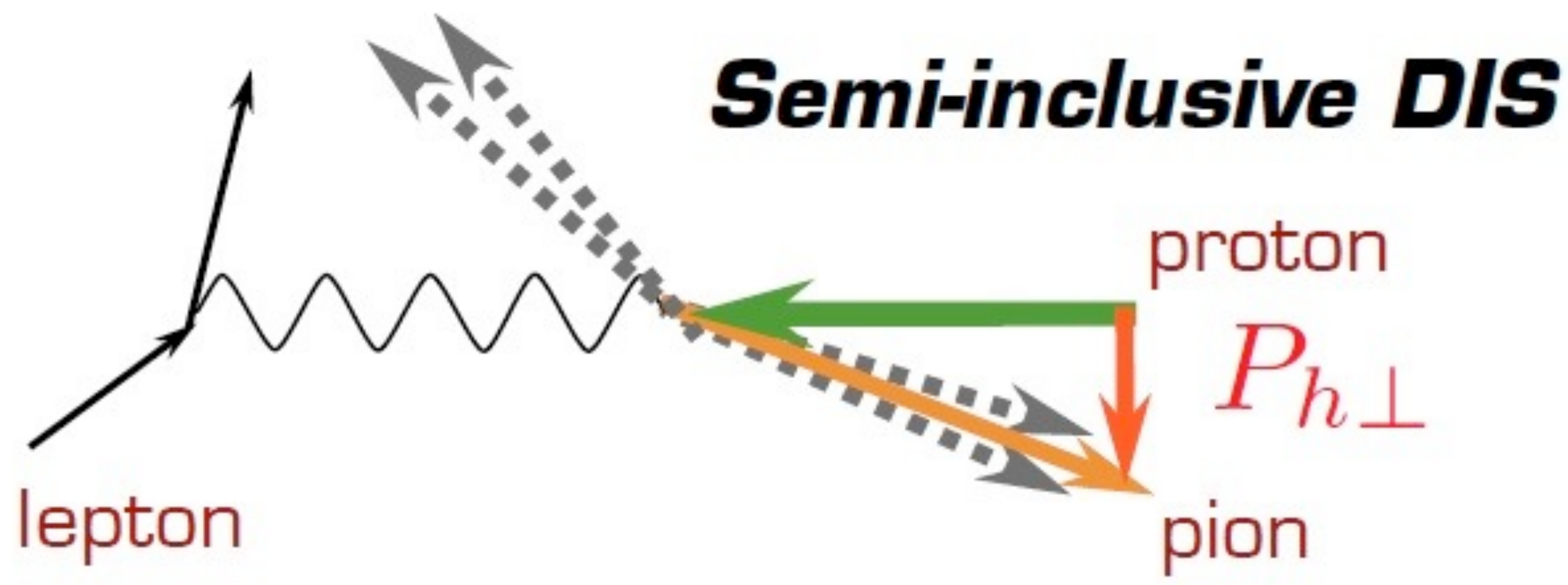
the distributions in red vanish if there is no quark orbital angular momentum

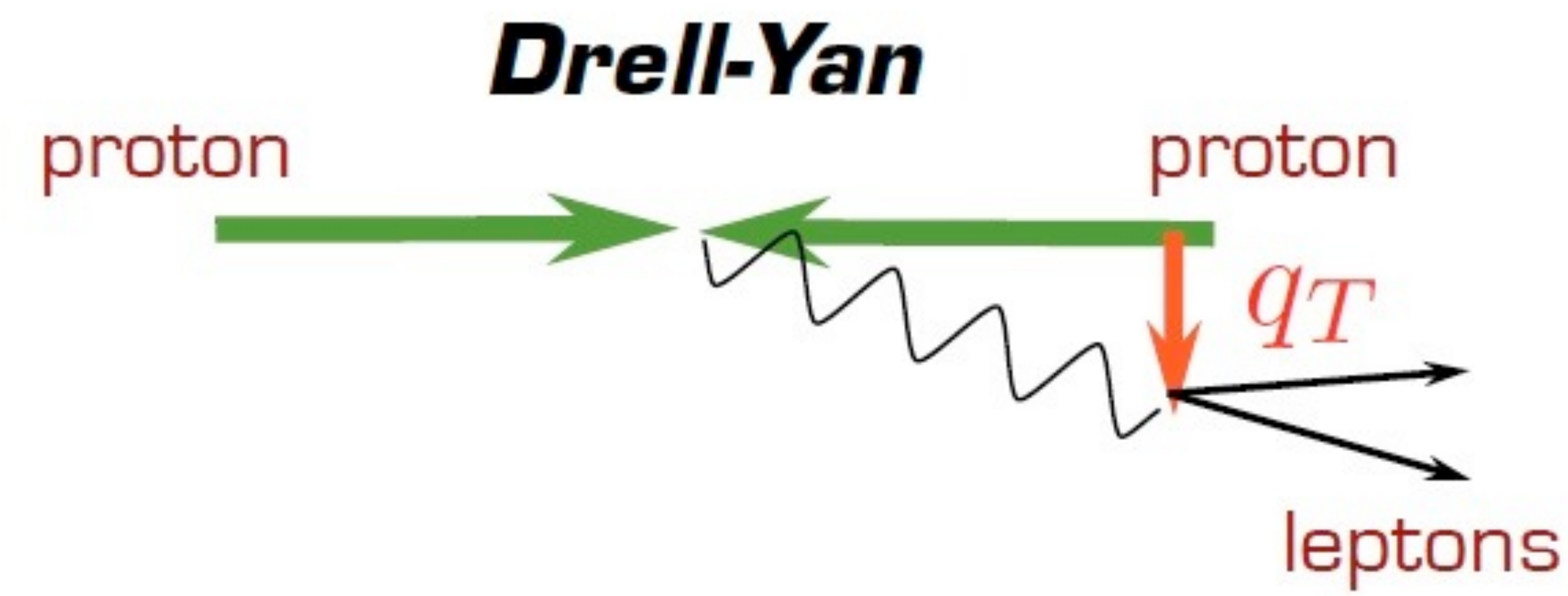
the distributions in black survive in the collinear limit

Key information from TMDs

- Spin-Spin and Spin-Orbit Correlations of partons
- Transverse momentum size
- Test what we can calculate with QCD (perturbative and lattice)
- Non-perturbative structure we cannot calculate with QCD

Where can we access TMDs?





we are interested
in the region of small transverse-momenta
sensitive to non-perturbative QCD effects

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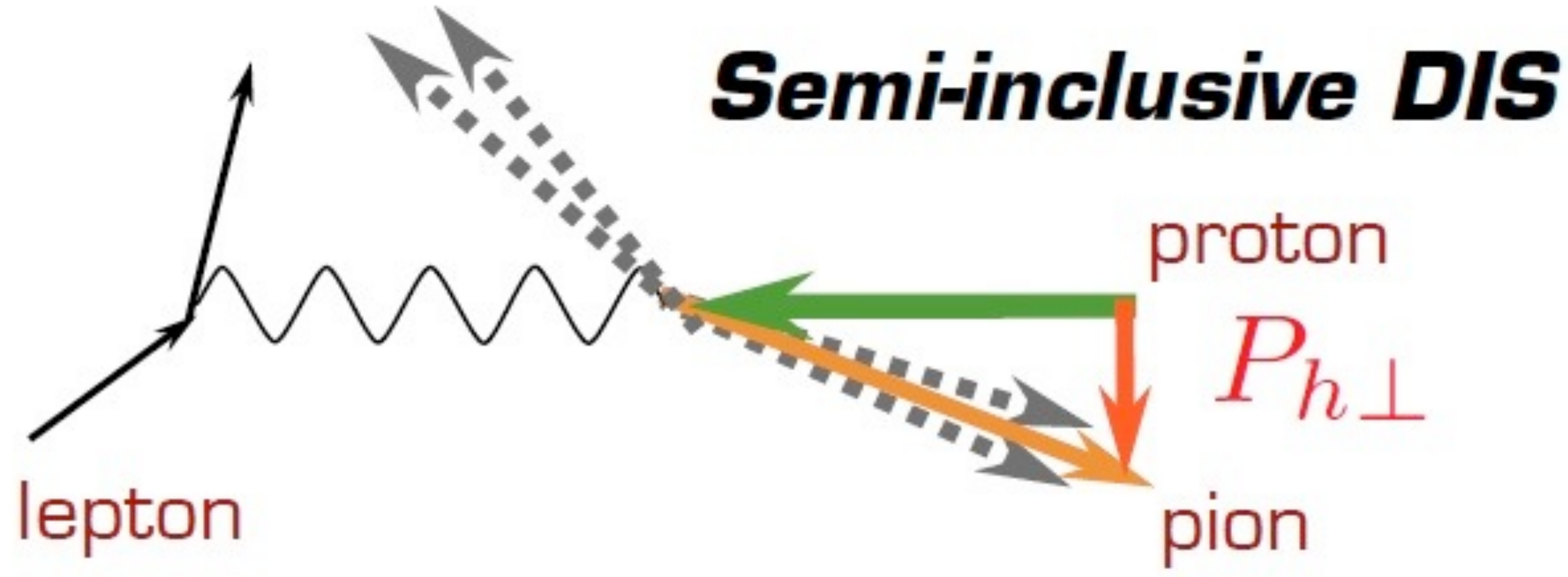

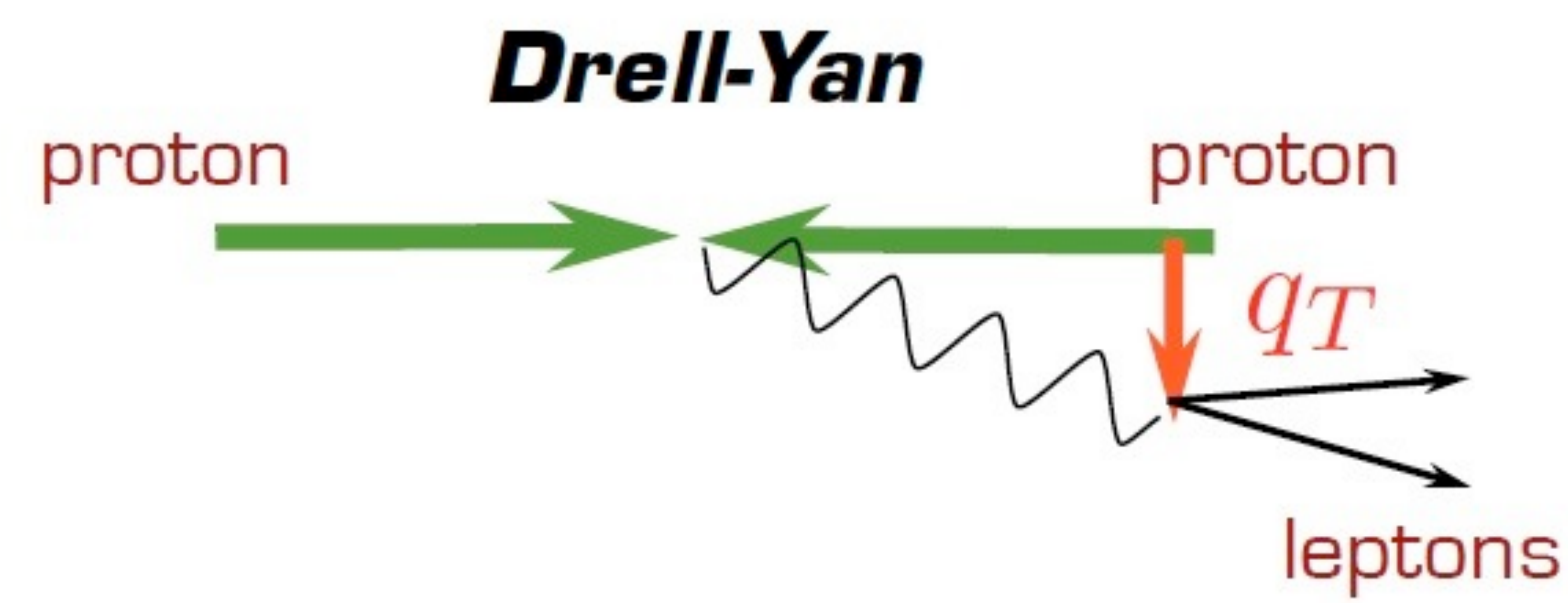

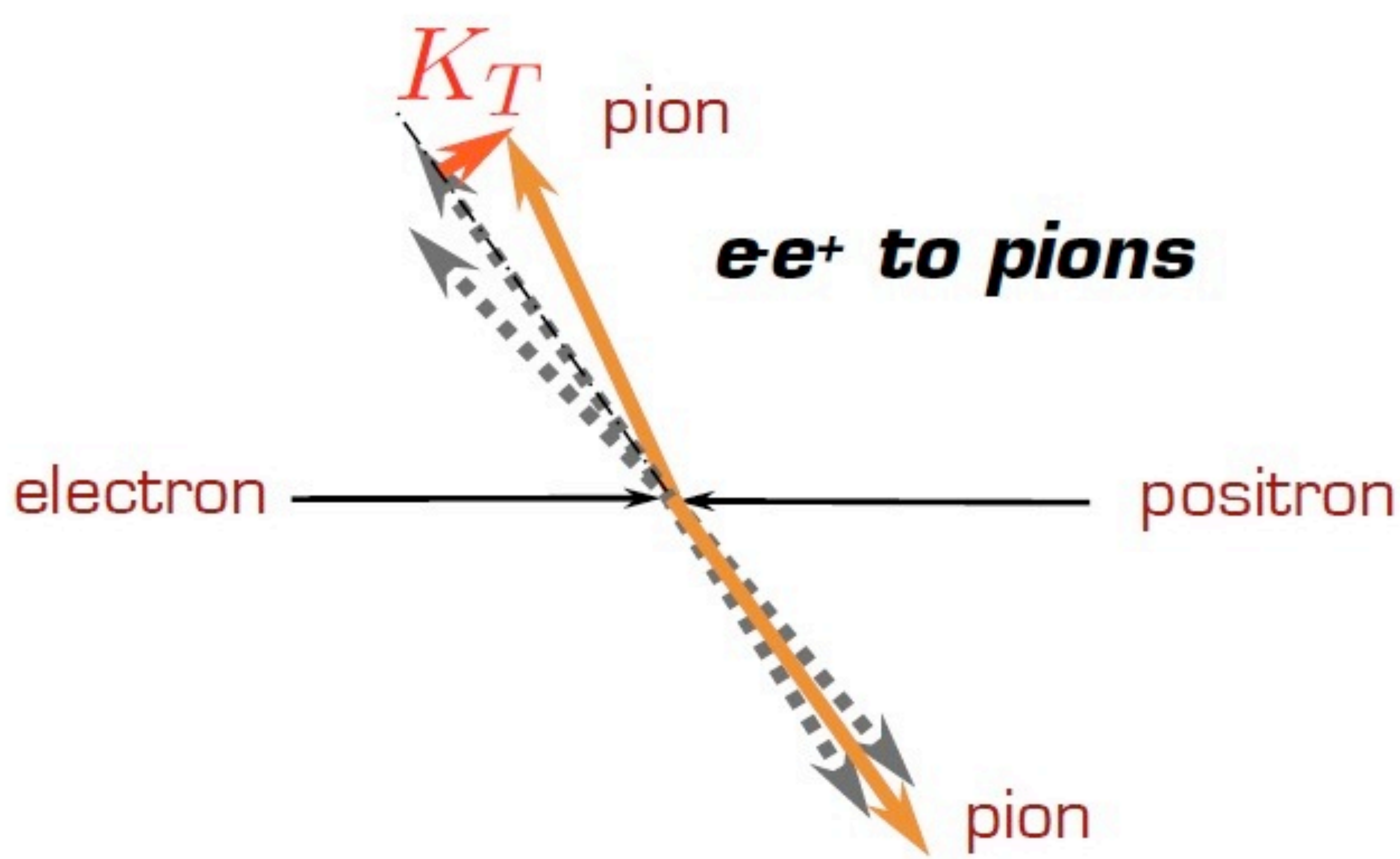

we are interested
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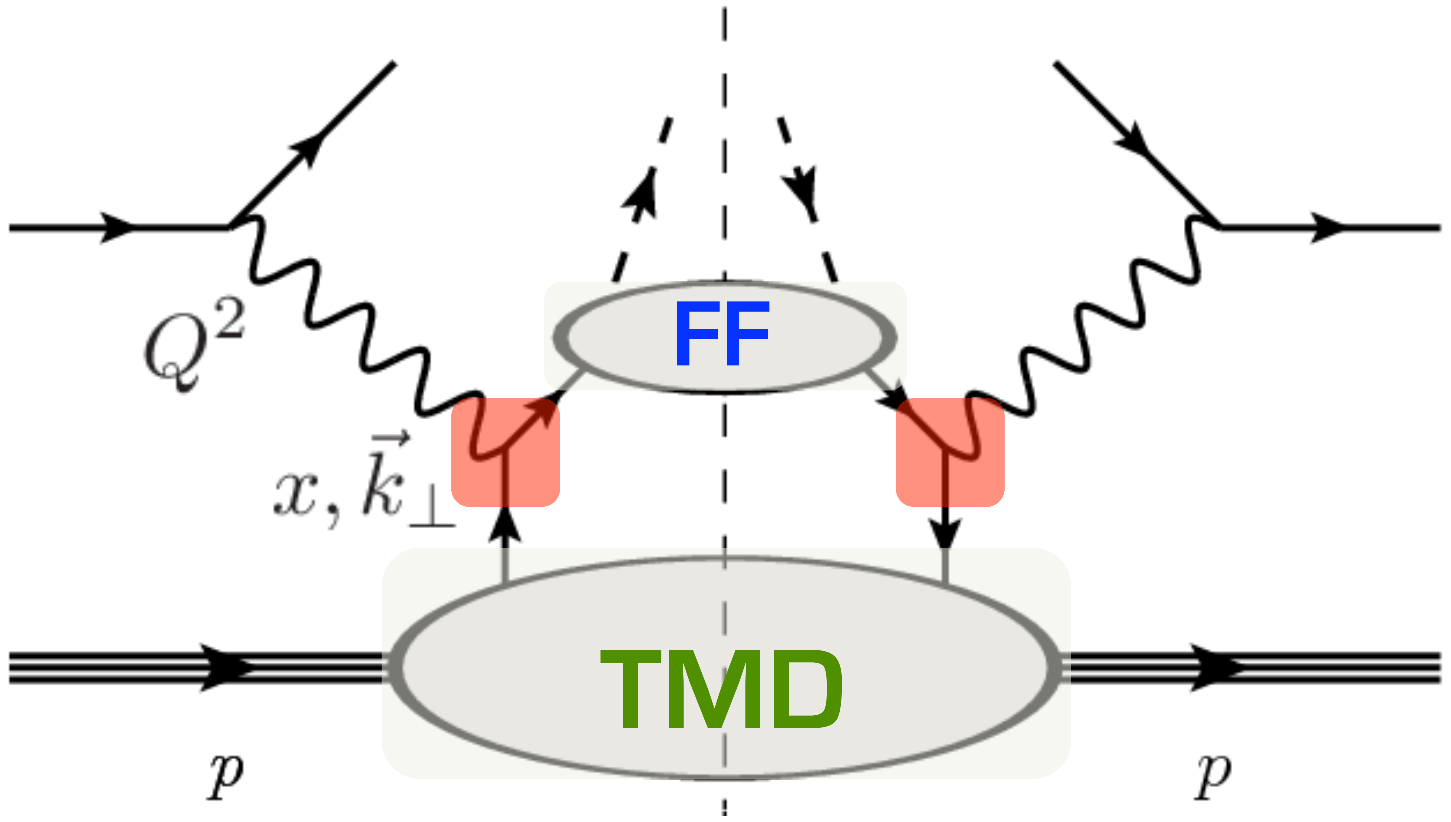
How to measure the TMDs

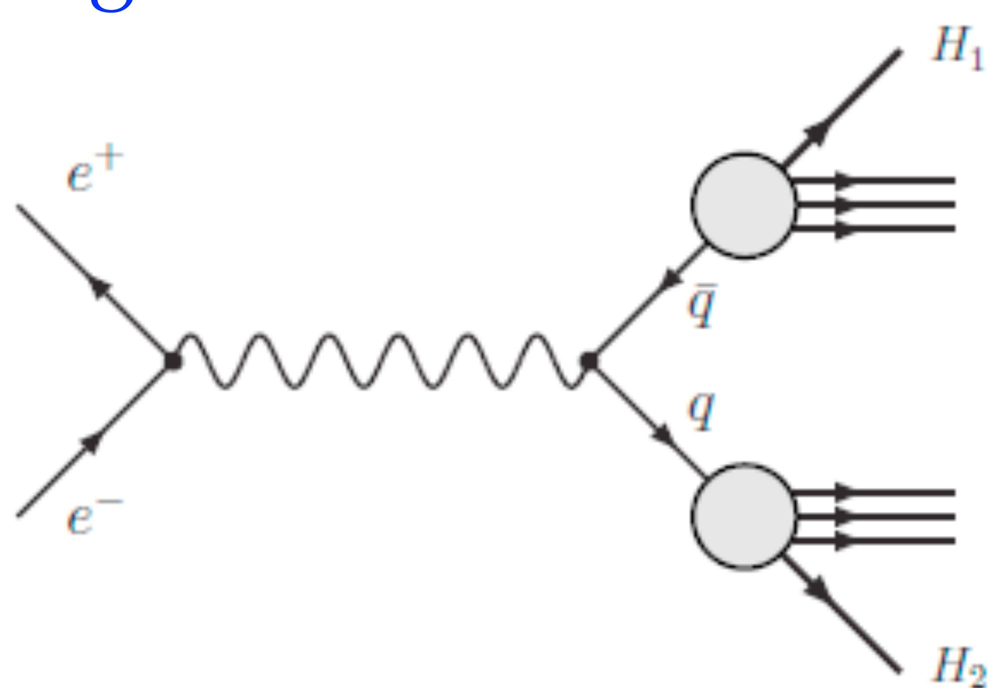
$$\ell(l) + N(P) \to \ell(l') + h(P_h) + X$$



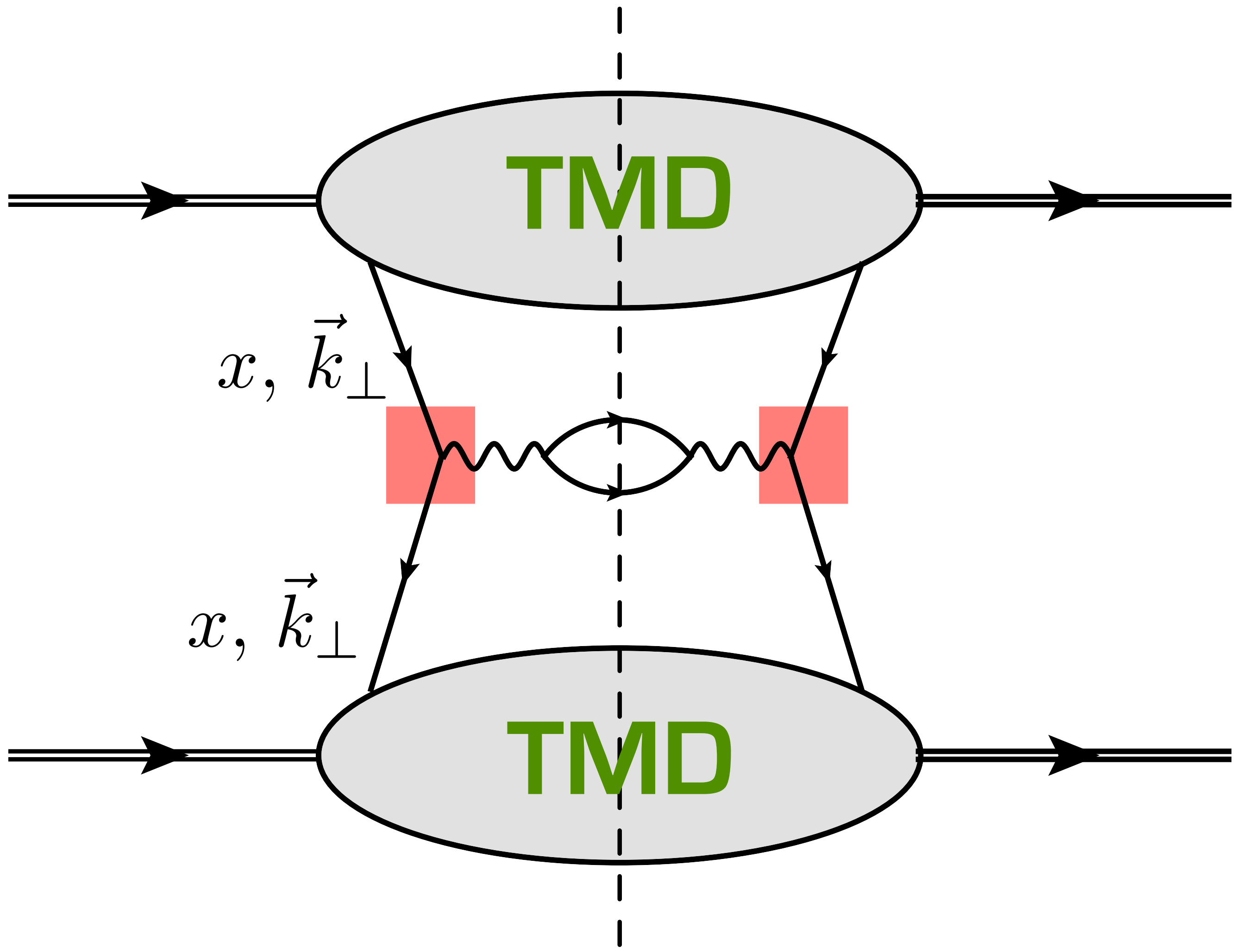
$$d\sigma \sim \sum \mathrm{TMD}(x, \vec{k}_\perp) \otimes d\hat{\sigma}_{hard} \otimes \mathrm{FF}(z, \vec{p}_\perp) + \mathcal{O}(\frac{P_T}{Q})$$

Fragmentation Functions

$$e^+e^- \to hh'X$$



$$h(P_1) + h(P_2) \to \ell^+(l) + \ell^-(l')$$



$$d\sigma \sim \sum \mathrm{TMD}(x, \vec{k}_\perp) \otimes \overline{\mathrm{TMD}}(x, \vec{k}_\perp) \otimes d\hat{\sigma}_{hard}$$

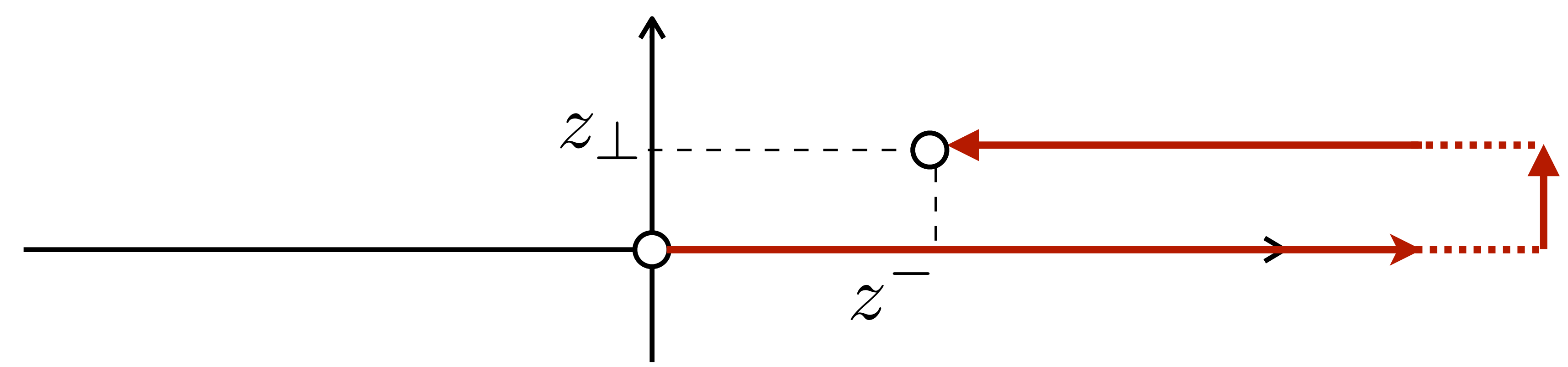
✓Factorization

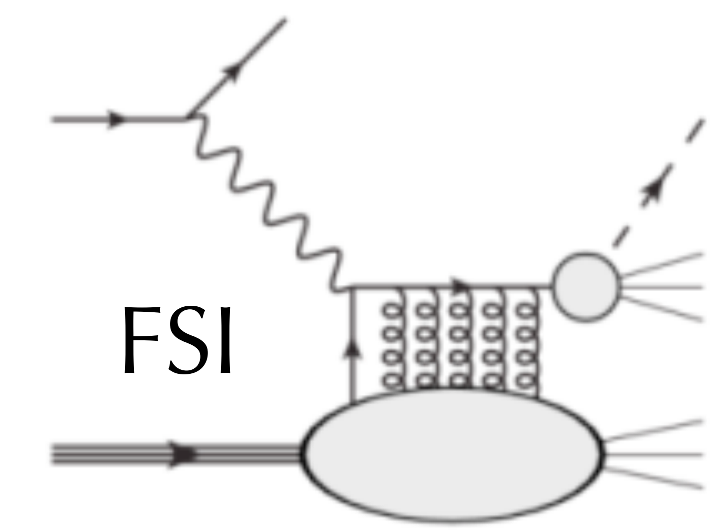
✓Universality

Gauge link dependence of TMDs

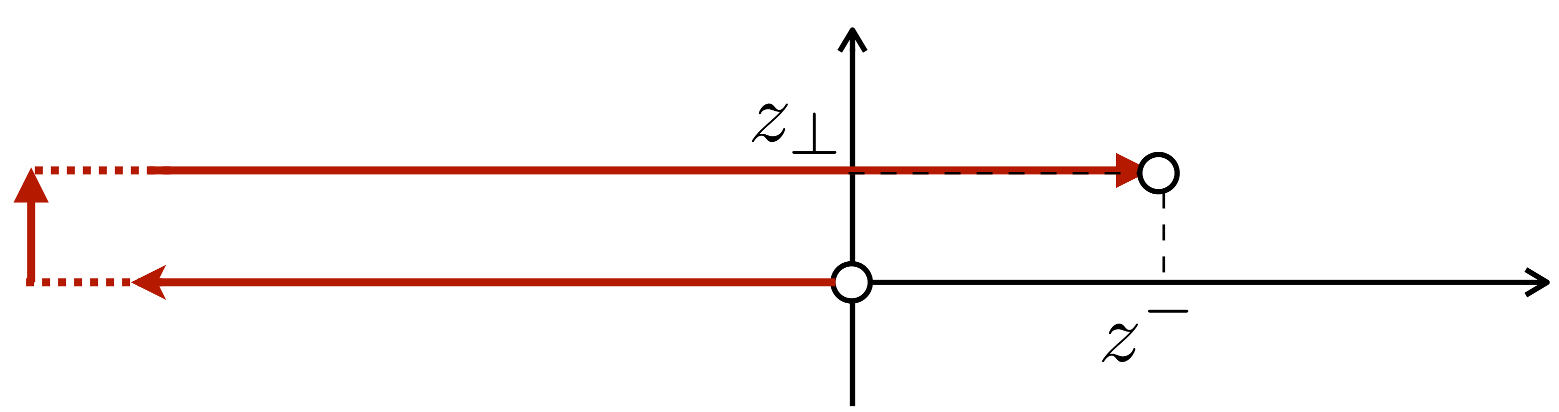
$$\frac{1}{2}\int \frac{\mathrm{d}z^-\mathrm{d}^2 z_\perp}{(2\pi)^3} e^{i(k^+ z^- - \vec{k}_\perp\cdot\vec{z}_\perp)} \langle p^+,\, 0_\perp,\, \Lambda' | \bar{\psi}(0)\, \gamma^+ \boxed{\mathrm{GaugeLink}} \psi(0, z^-, z_\perp) | p^+,\, 0_\perp,\, \Lambda\rangle$$

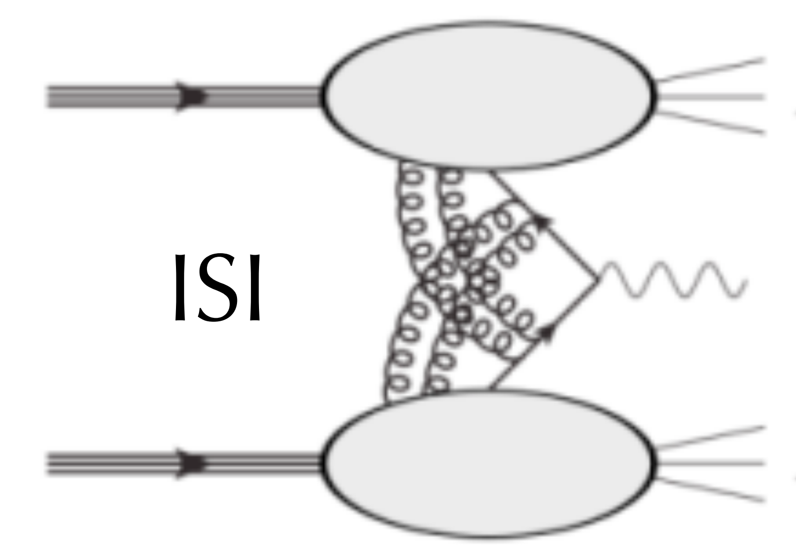
SIDIS





Drell-Yan





Gauge link dependence of TMDs

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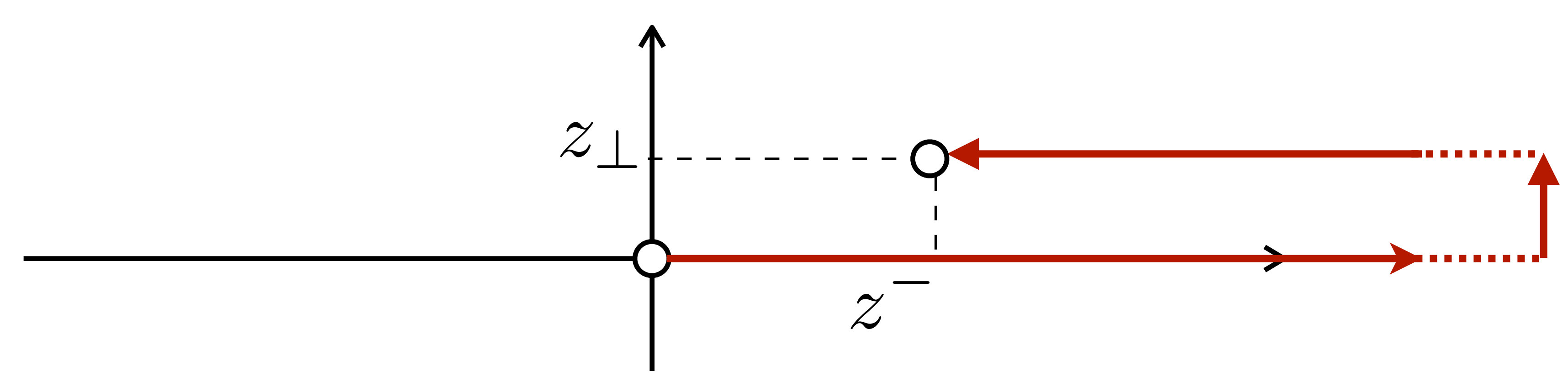
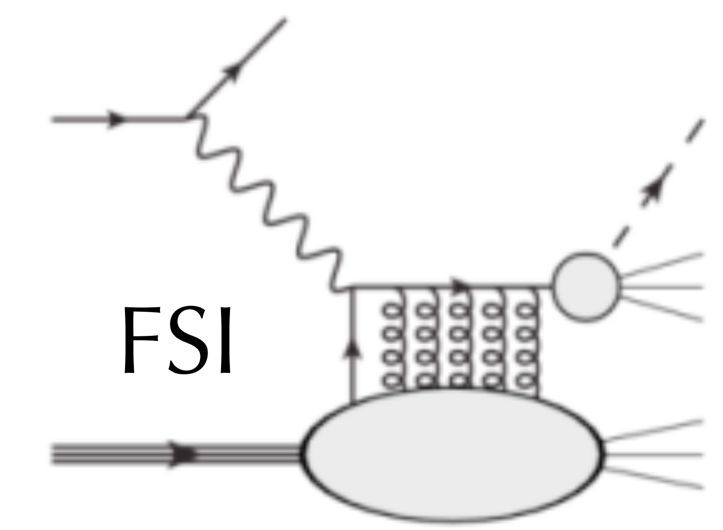
SIDIS





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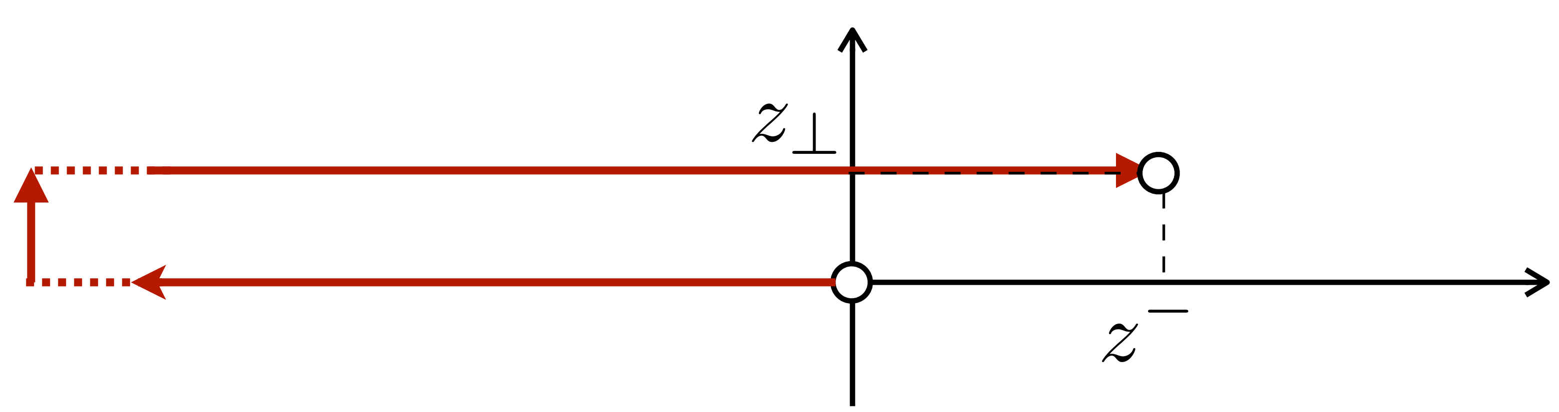
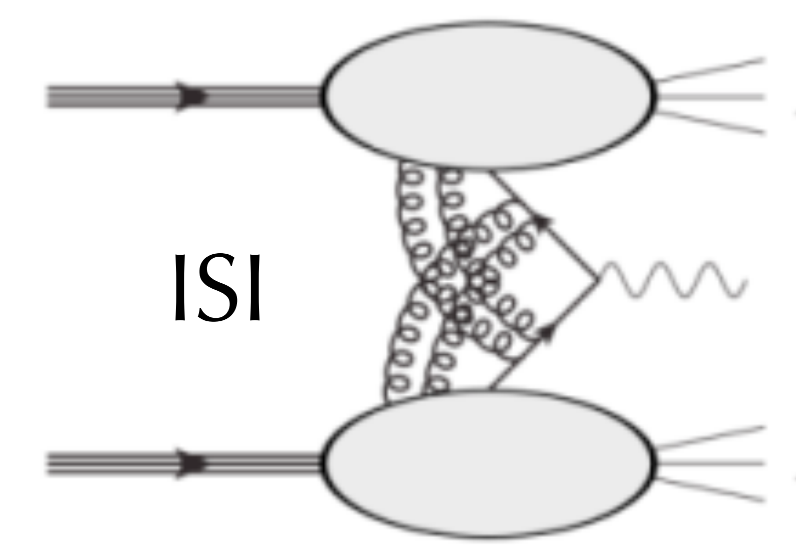




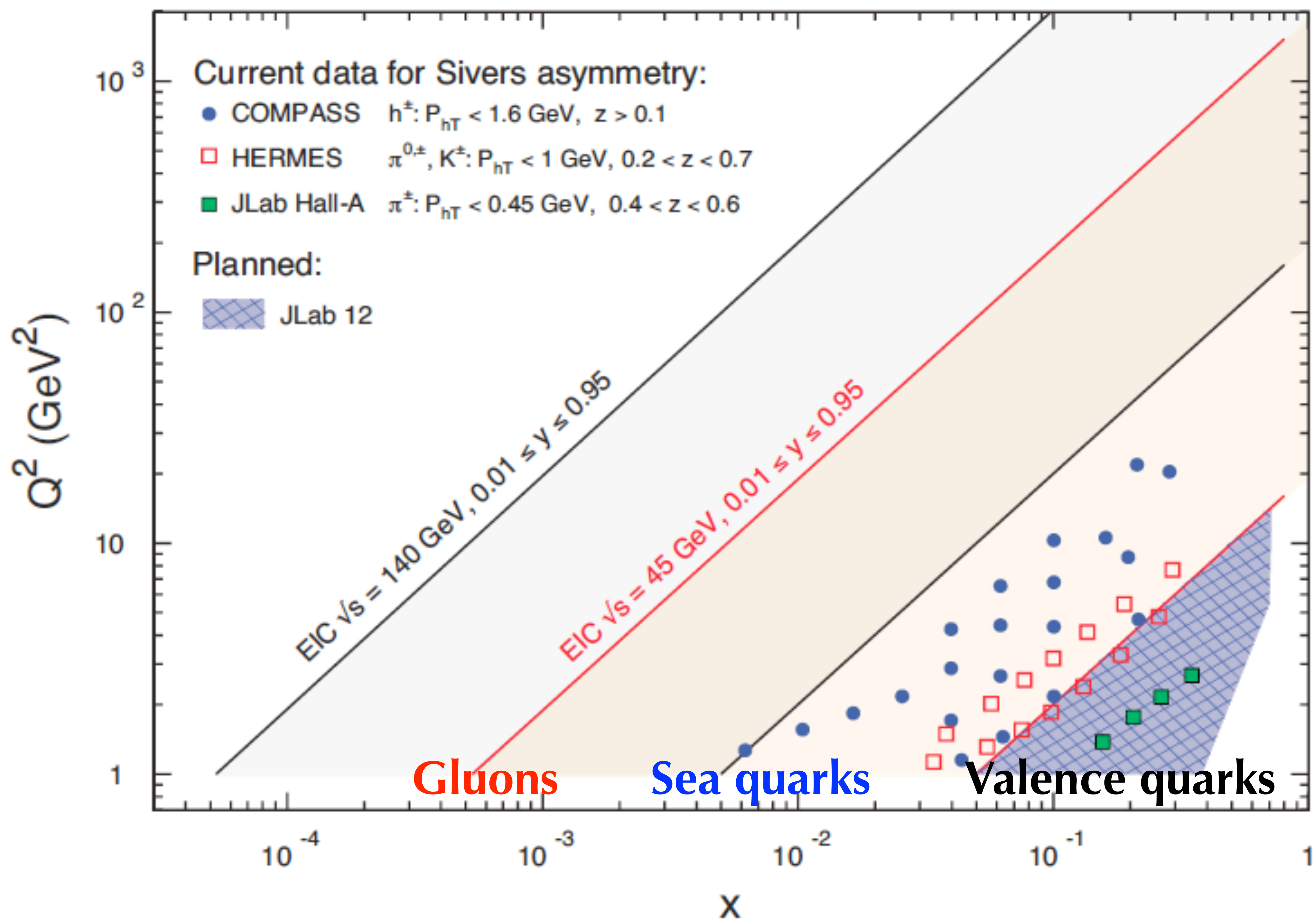
Sivers function $_{\text{SIDIS}}$ = – Sivers function $_{\text{Drell-Yan}}$

Boer-Mulders function $_{\text{SIDIS}}$ = – Boer-Mulders function $_{\text{Drell-Yan}}$

Strong QCD prediction. Needs to be tested.

Collins, PLB 536 (2002) 43

Paste, present and future TMD measurements



hermes

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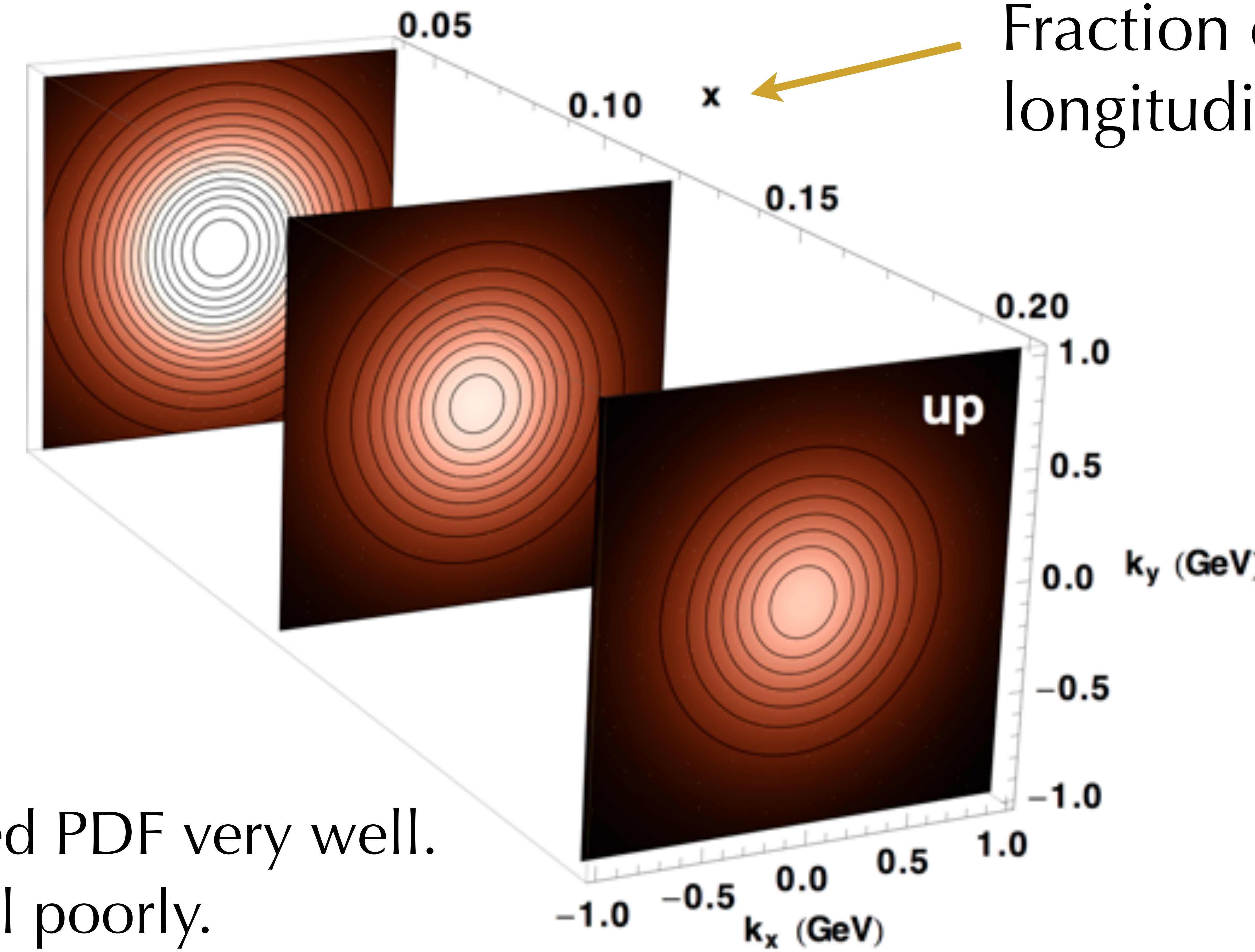
COMPASS

EIC

Accardi et al., The Electron Ion Collider: the next QCD Frontier
arXiv:1212.1701

The unpolarized TMD f_1



Fraction of longitudinal momentum

Transverse momentum

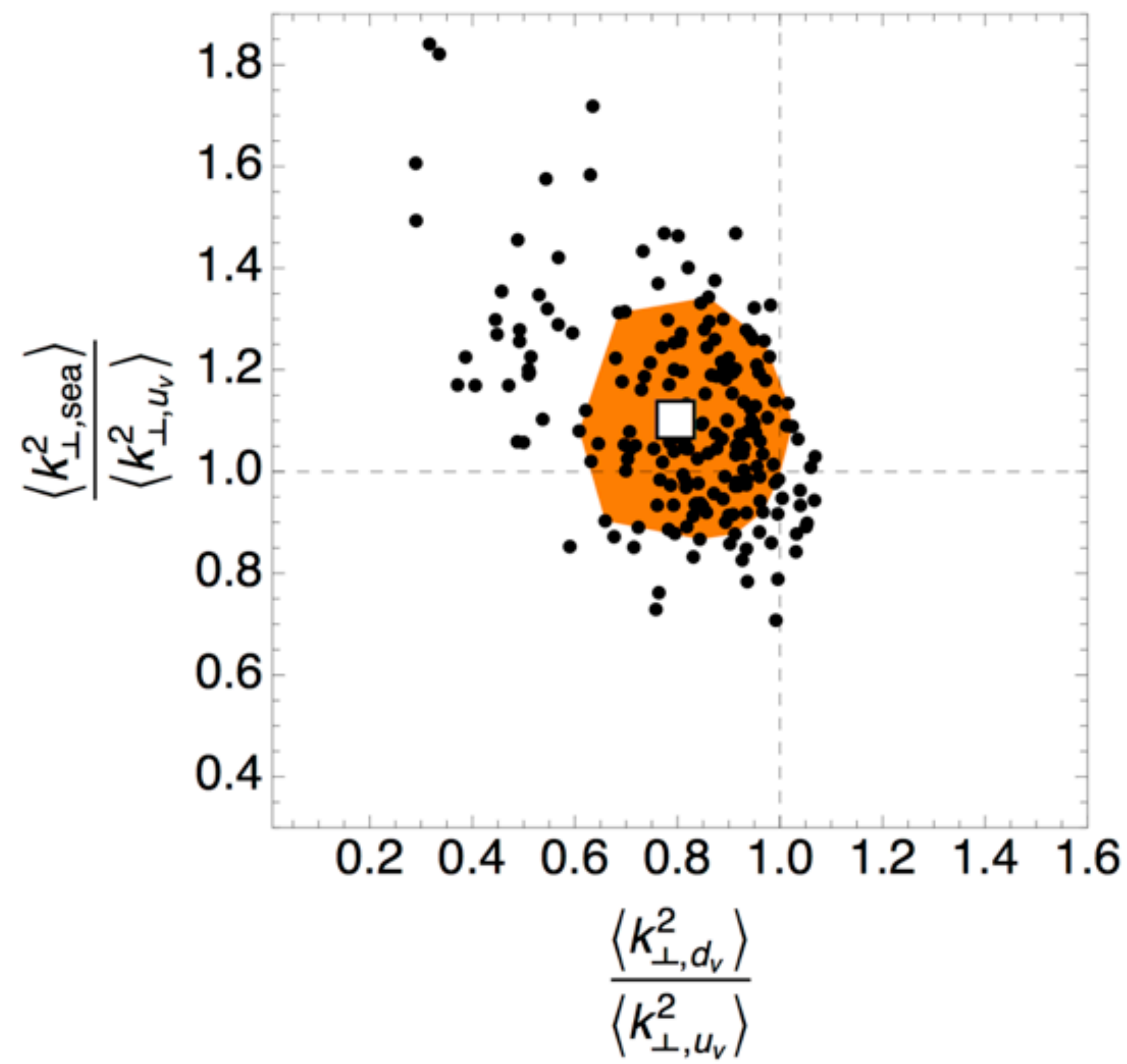
We know the integrated PDF very well.
We know the TMD still poorly.

Correlation between x and $k_\perp$
Flavor dependence of TMDs

?

Flavor structure of TMDs: indications from data

Ratio of width of sea / width of up valence



Ratio width of down valence/ width of up valence

fit to SIDIS multiplicities from HERMES:

$$\langle k^2_{\perp,d_v}\rangle < \langle k^2_{\perp,u_v}\rangle < \langle k^2_{\perp,sea}\rangle$$

Signori,et.al., JHEP 1311 (13)

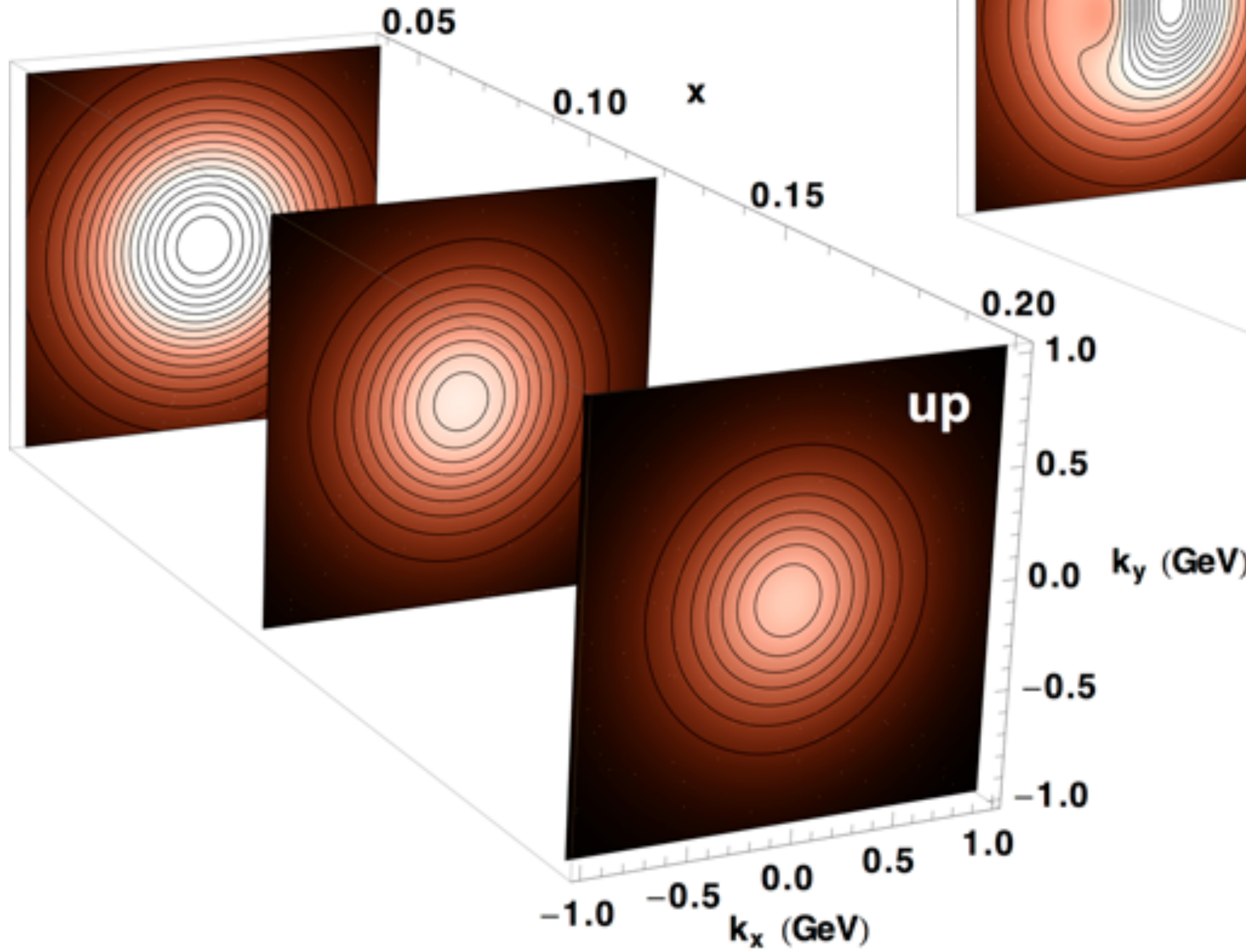
Flavor-inpependence is not ruled out:

$$0.4 < \langle k_\perp^2\rangle < 0.8\,\mathrm{GeV}^2$$

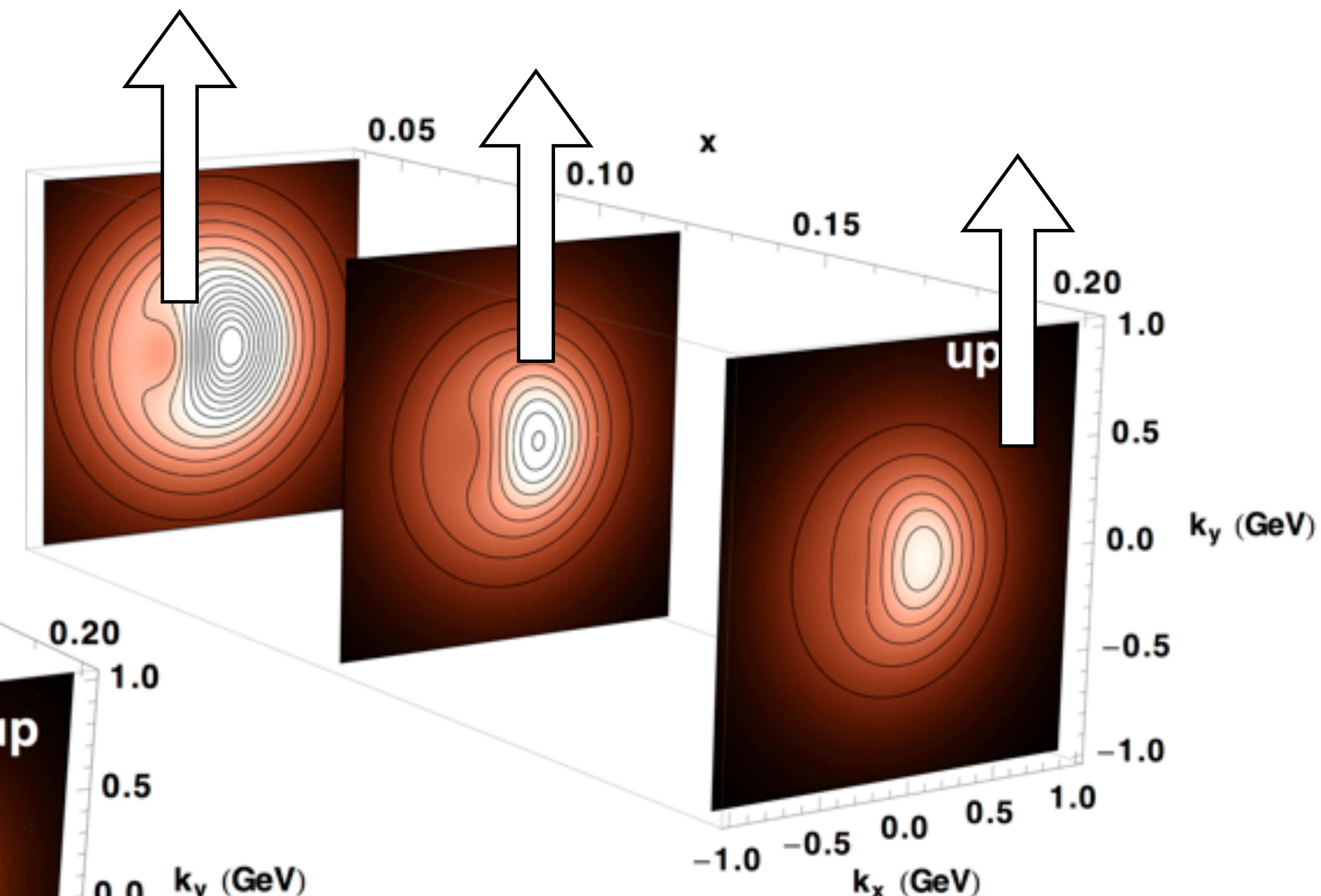
fit to SIDIS multiplicities from HERMES and COMPASS

Anselmino,et.al., JHEP 1404 (14)

Adding the spin

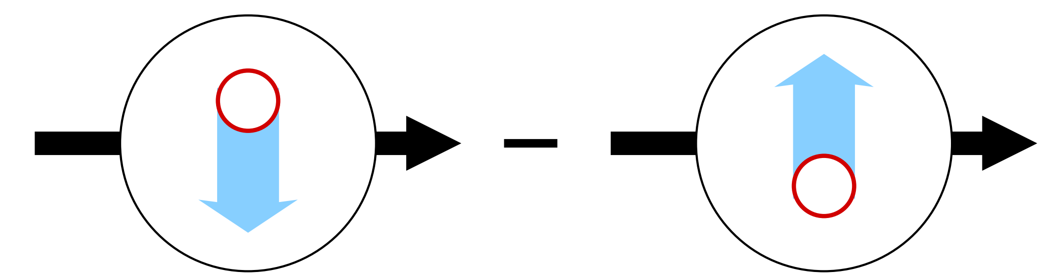


correlation between x and $k_\perp$

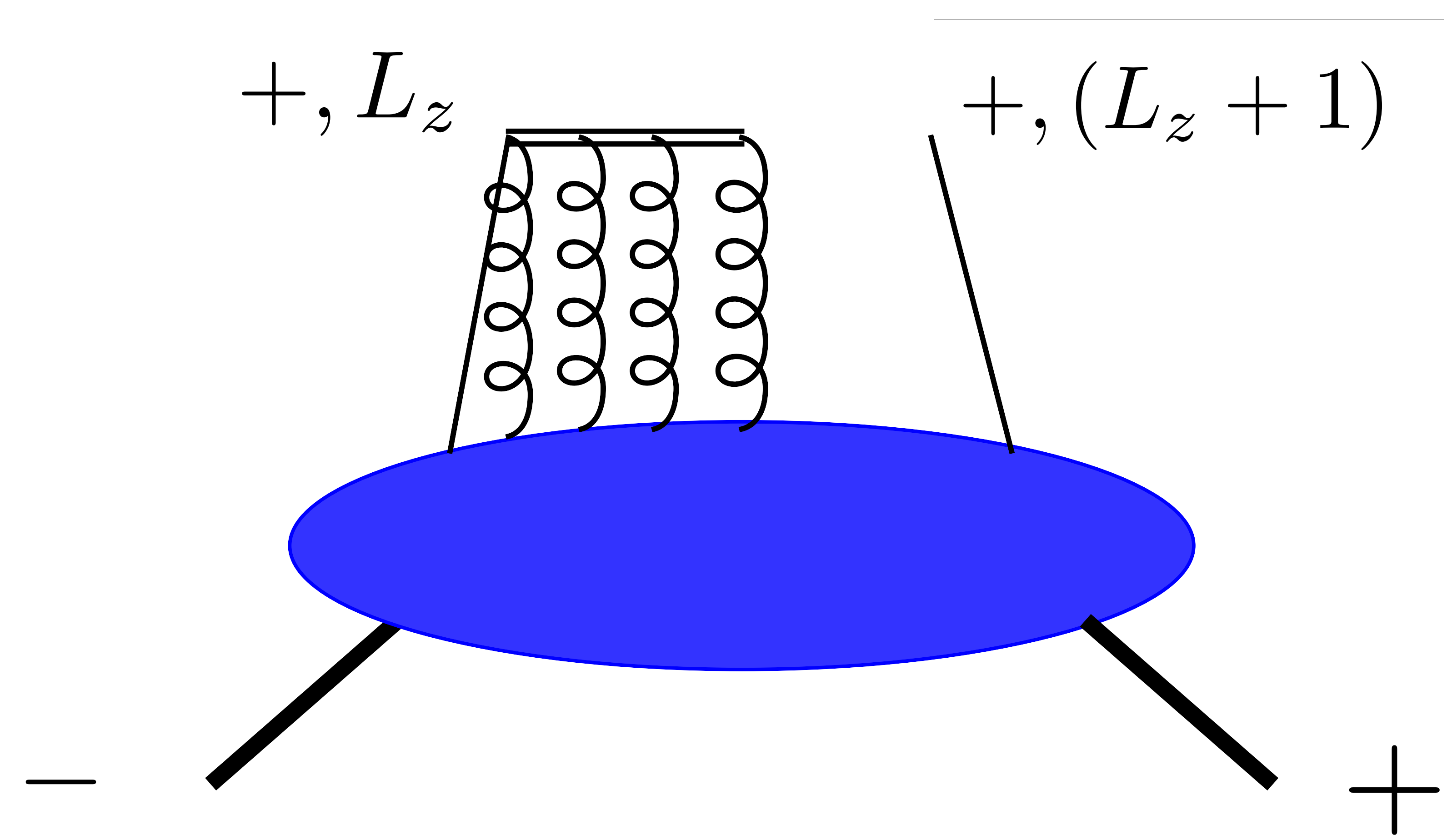


correlation between x, $k_\perp$ and spin

Sivers function

$f_{1T}^{\perp} =$ 

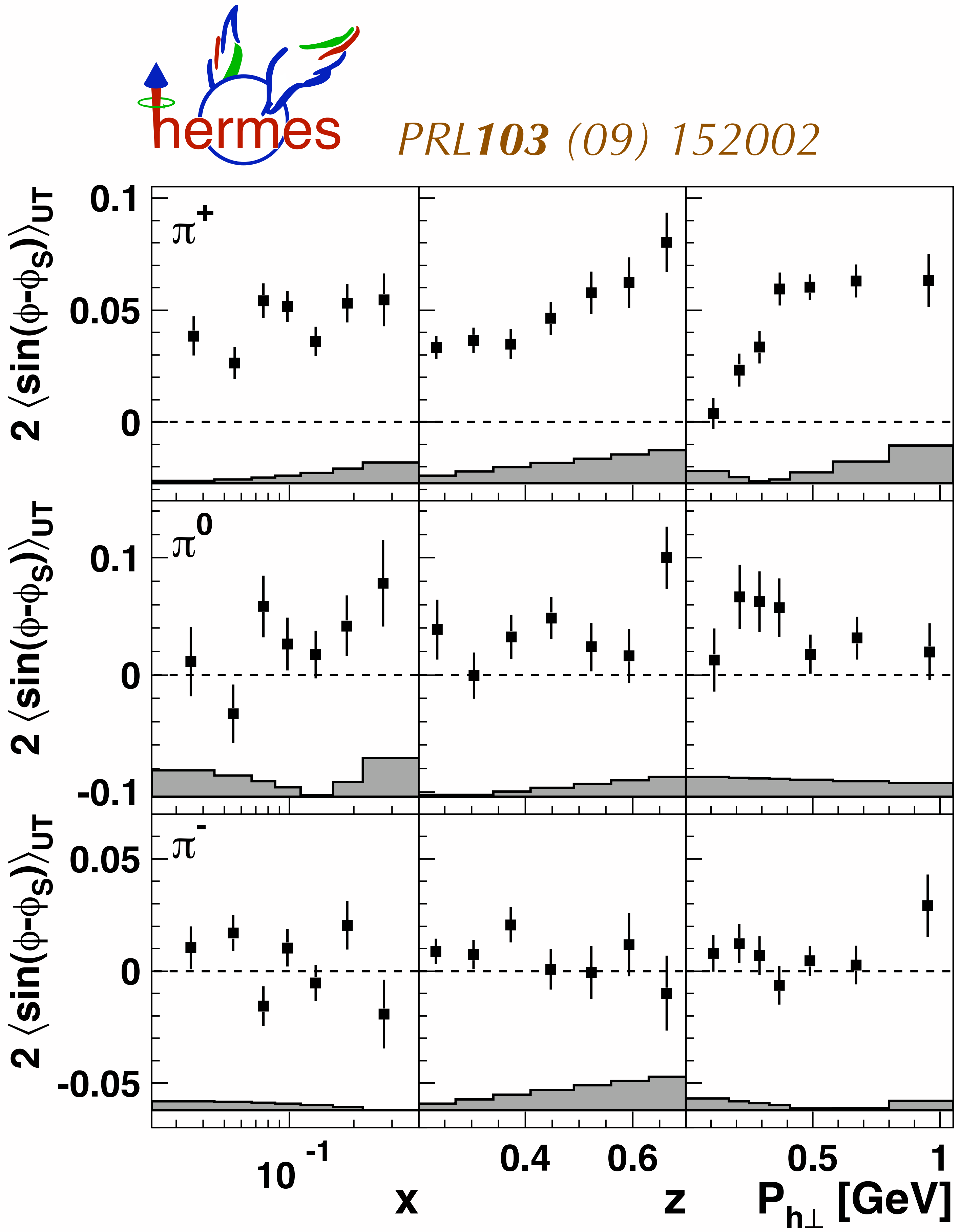
unpolarized quarks in $\perp$ pol. nucleon

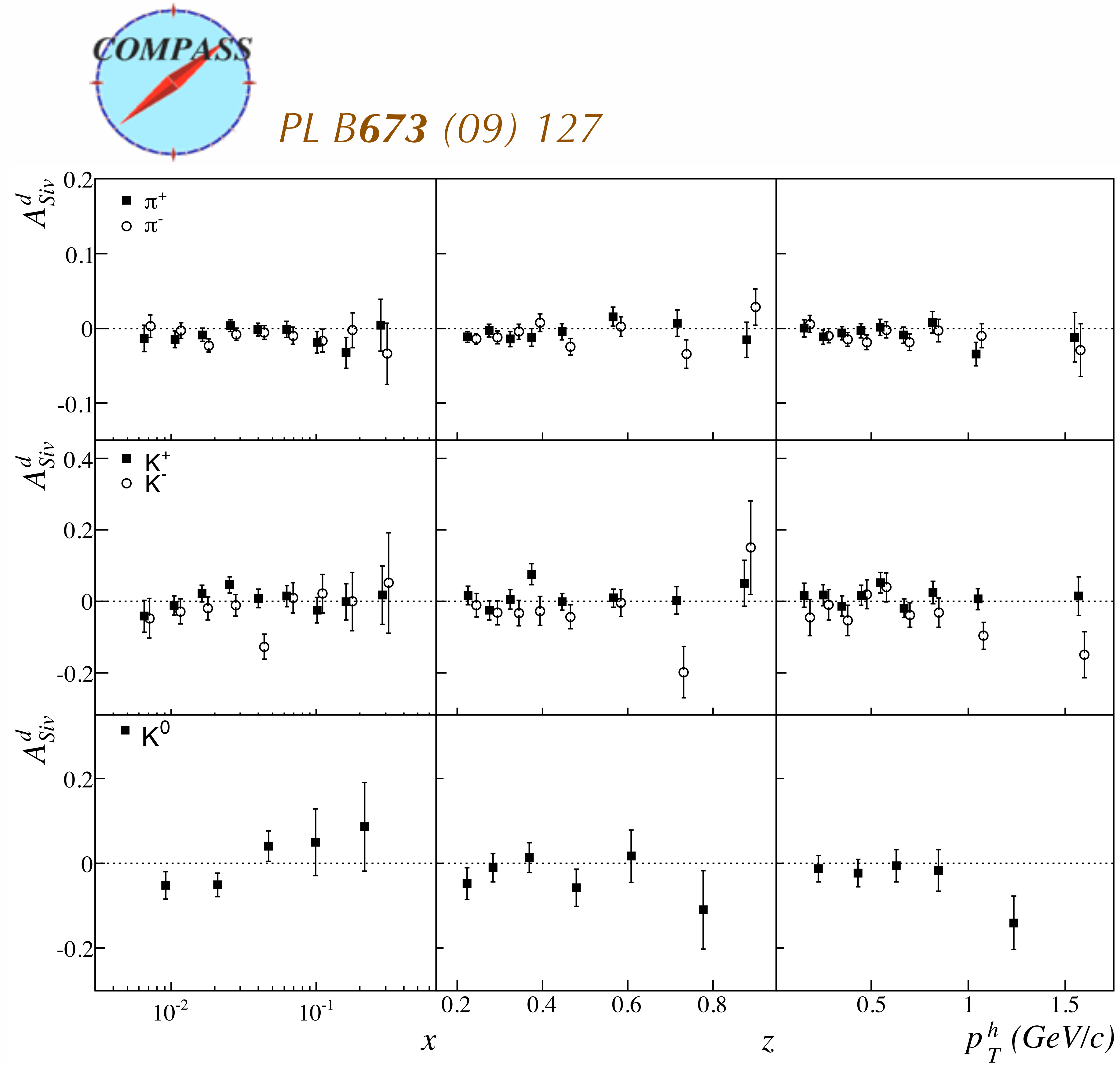


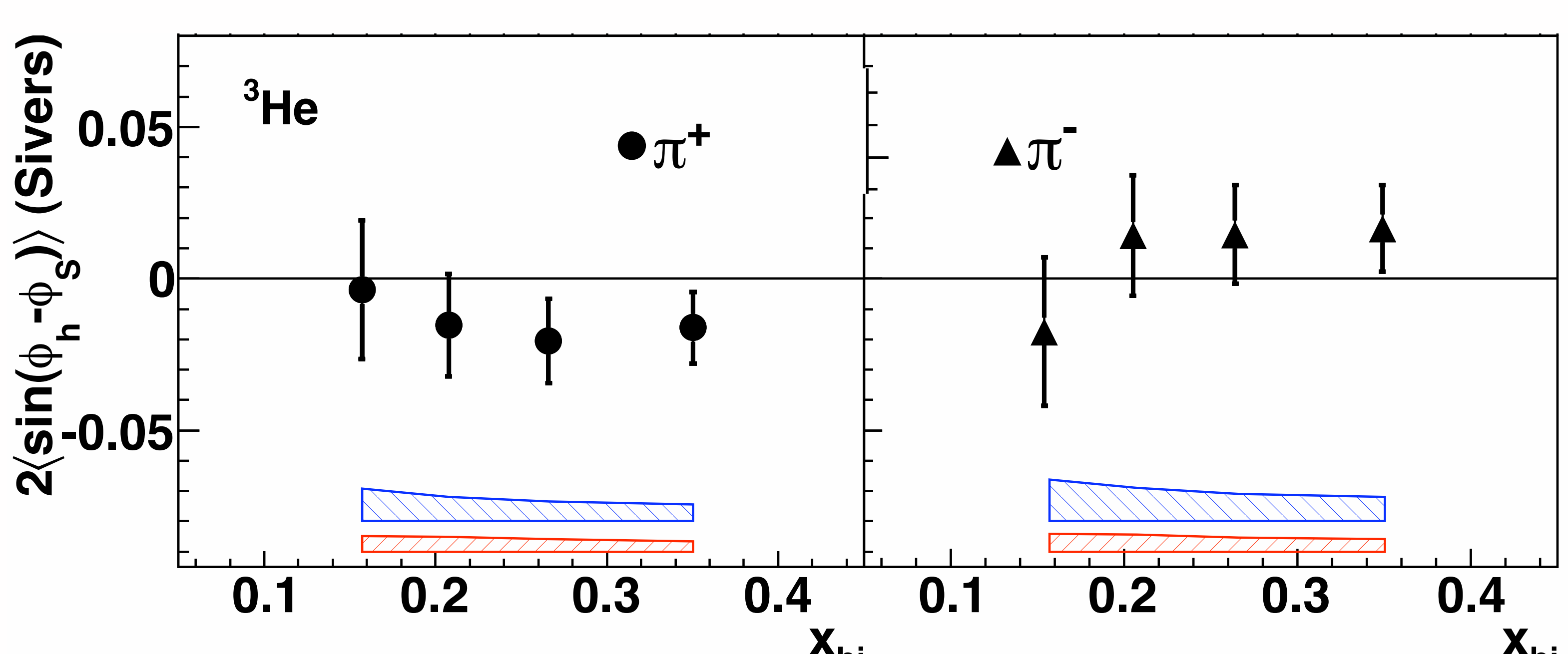
$$f_{1T}^{\perp}|_{\mathrm{SIDIS}} = -f_{1T}^{\perp}|_{\mathrm{DY}}$$

non-zero ONLY with final-state interaction

the helicity mismatch requires orbital angular momentum







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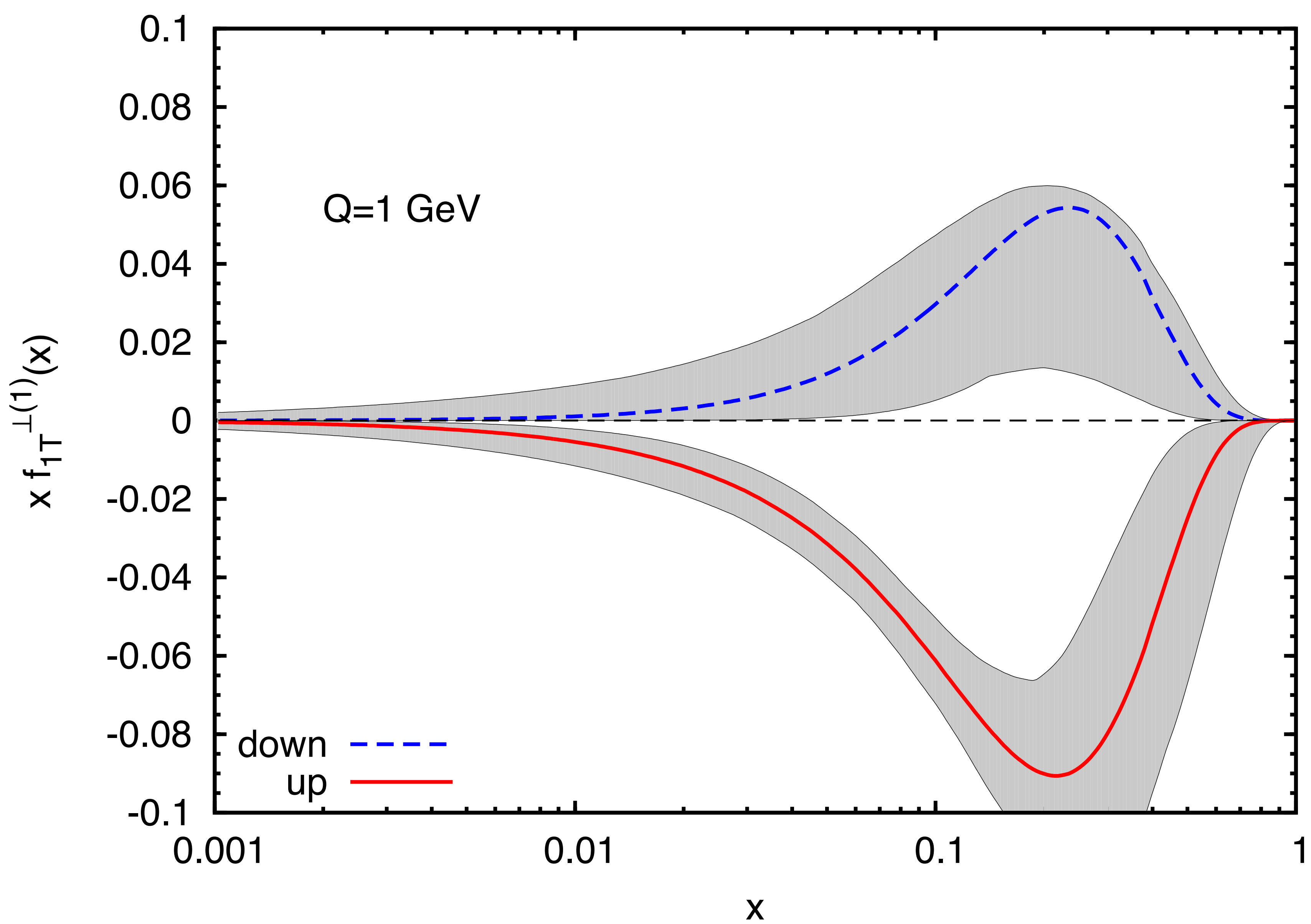
Hall A

*PRL**107** (2011) 072003*

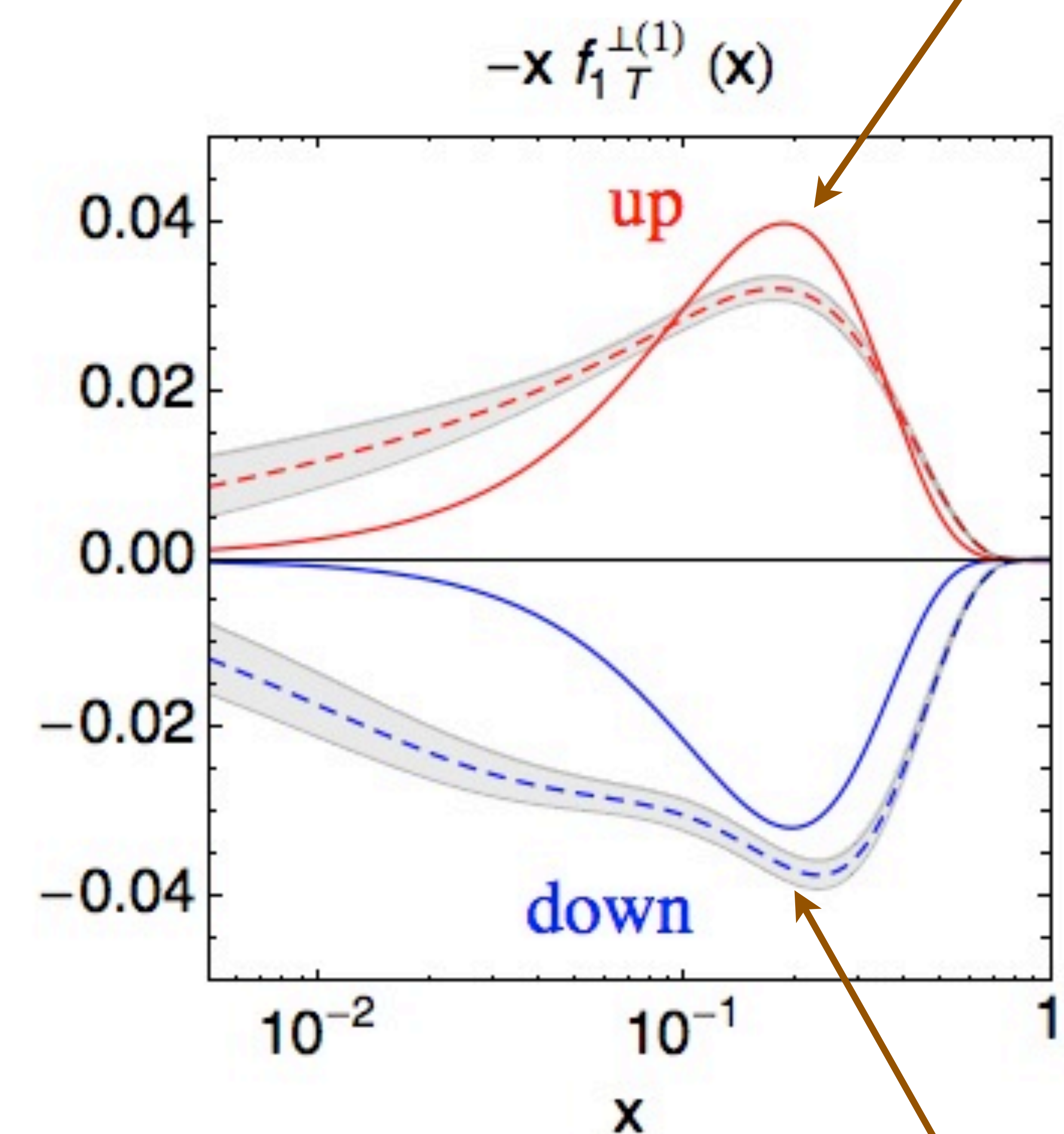
Sivers effect has been measured!

Sivers function has been extracted

*Anselmino et al., PRD**86** (2012) 014028*
[no TMD evo]



Echevarria, Idilbi, Kang, Vitev, PRD 89 (14)
[with TMD evo]



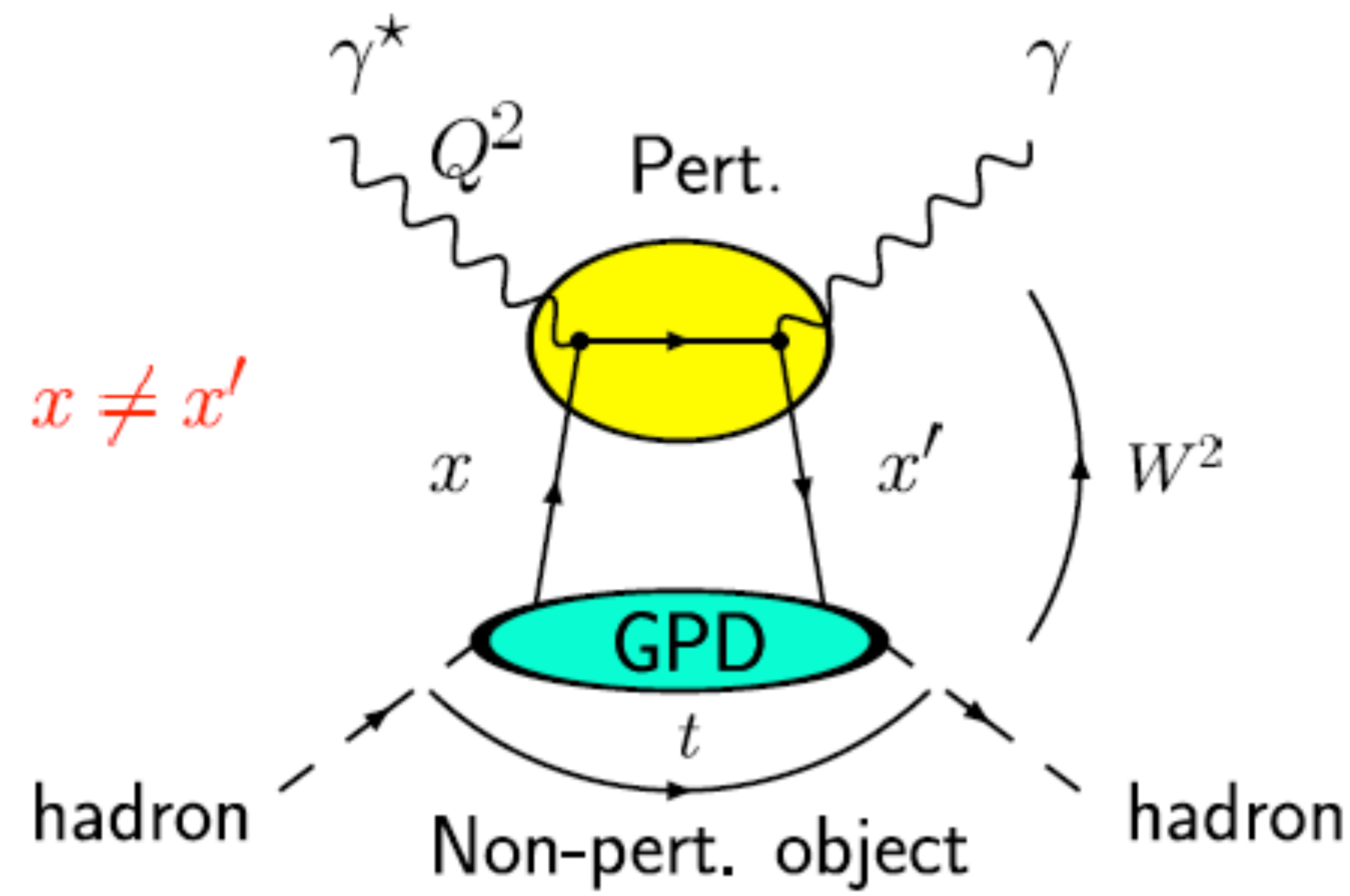
Bacchetta, Radici, PRL 107 (11)
[no TMD evo]

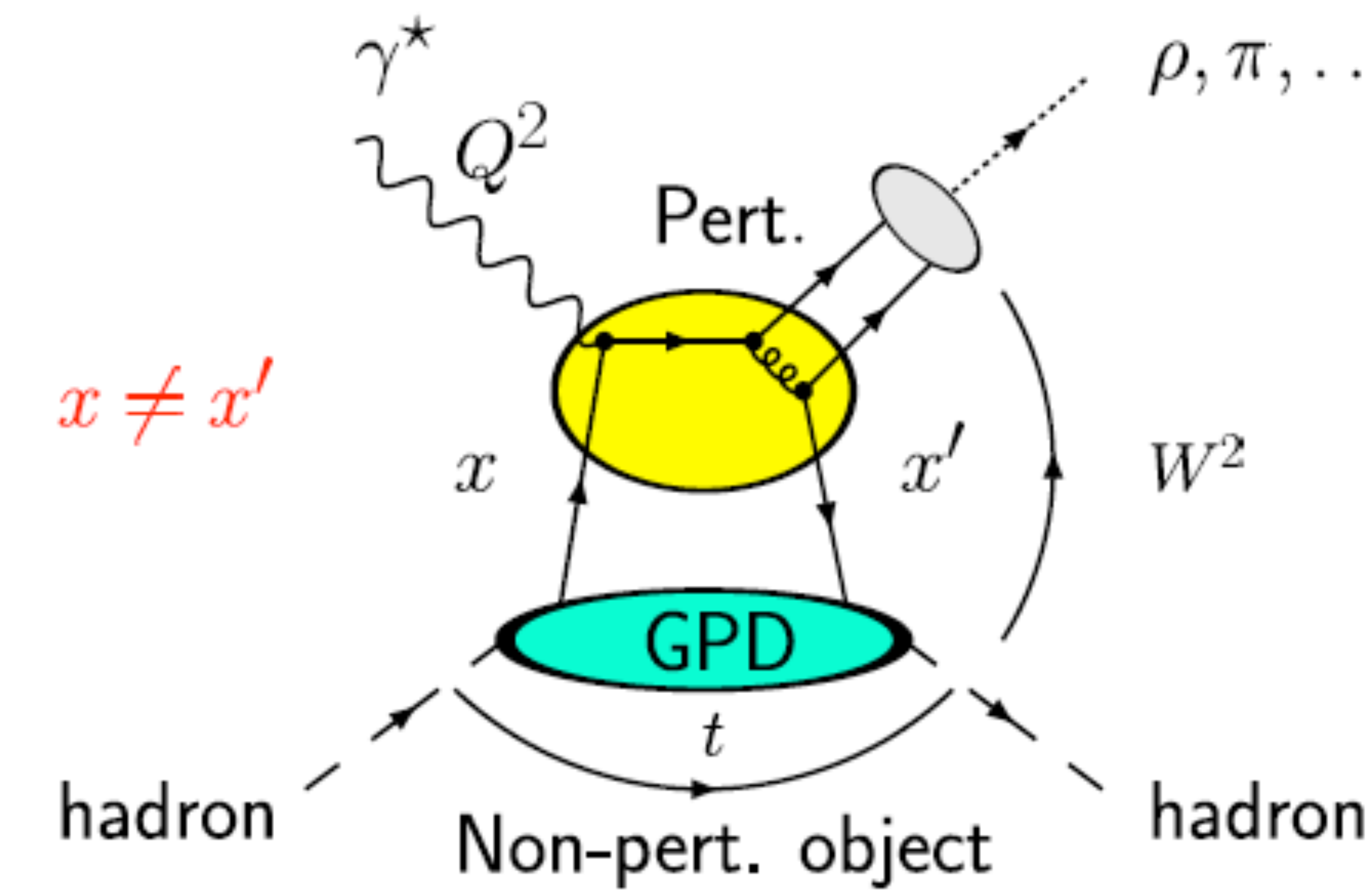
Key information from GPDs

- Transverse position size
- Decomposition of Form Factors w.r.t. x
- Sum rule for Angular Momentum
- Access to Form Factors of Energy Momentum Tensor

$\longrightarrow$ "mechanical" properties of the nucleon

How to measure the GPDs

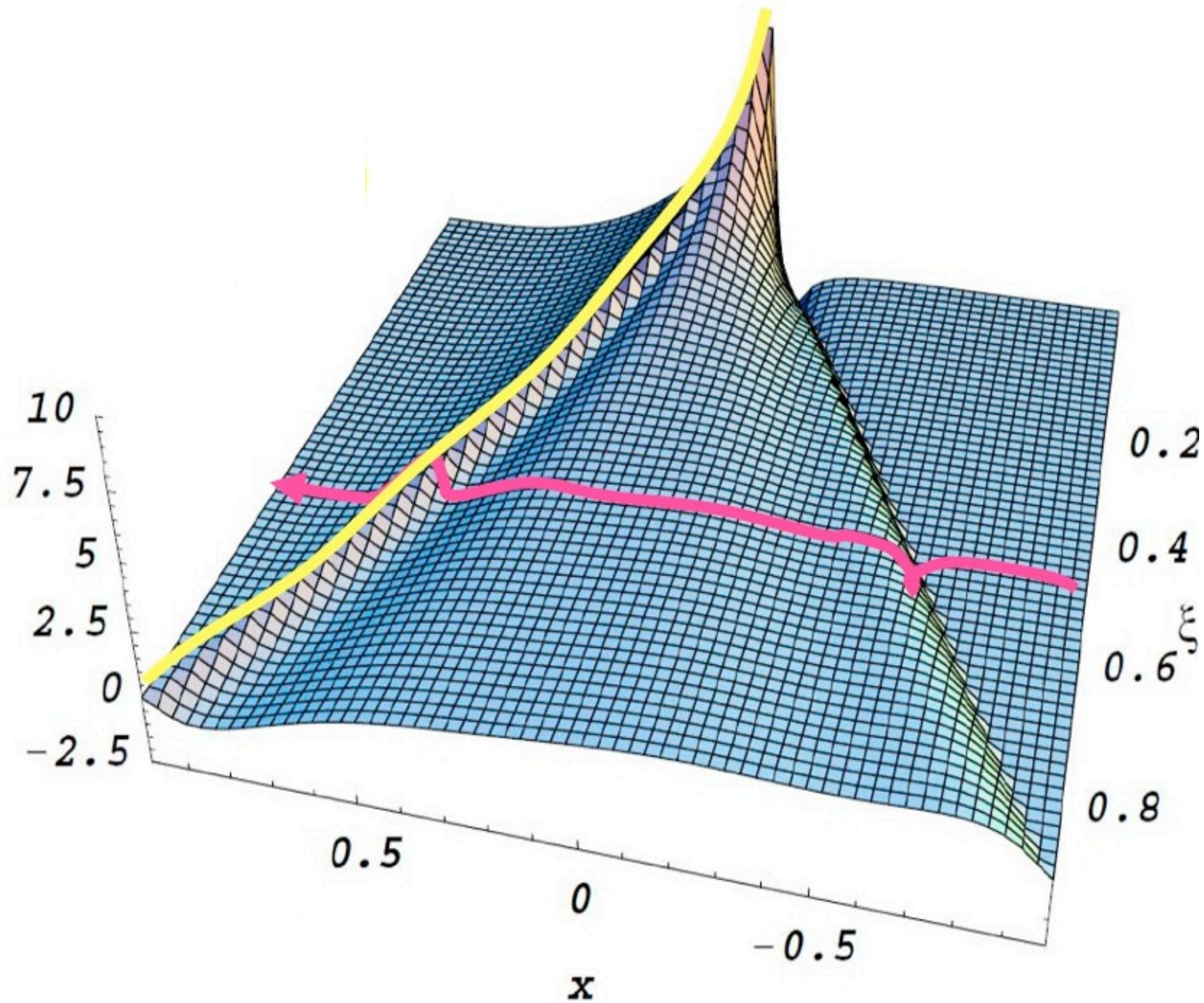




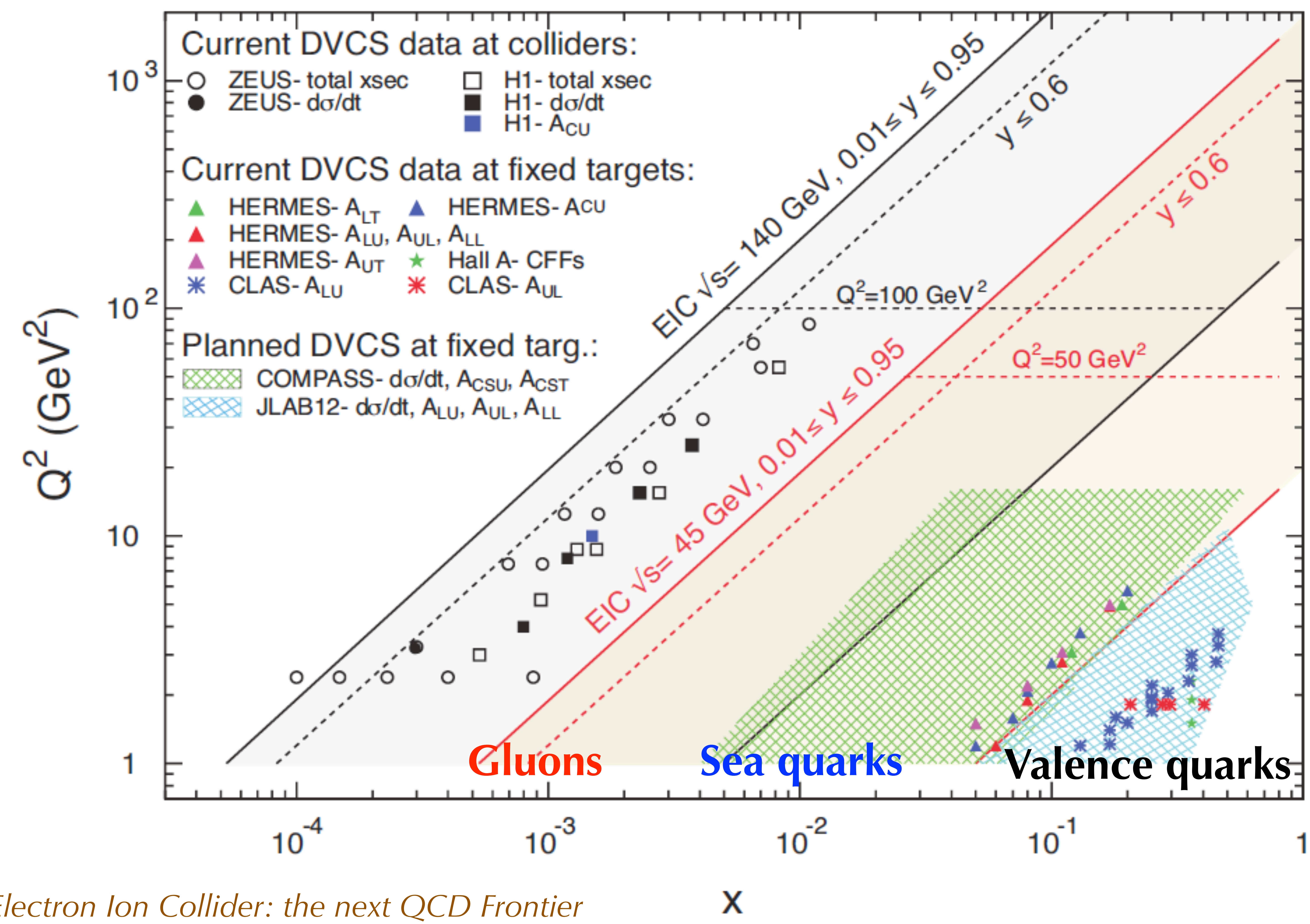
- accessible in exclusive reactions
- factorization for large Q^2, $|t| << Q^2$, W^2
- depend on 3 variables: x, ξ, t

Compton form factors

$$\int_{-1}^{+1} \mathrm{d}x \frac{H(x,\xi,t)}{x-\xi+i\epsilon} = \mathcal{P}\int_{-1}^{+1} \mathrm{d}x \frac{H(x,\xi,t)}{x-\xi} - i\pi H(\xi,\xi,t)$$



Paste, present and future DVCS experiments



DESY

hermes

Jefferson Lab

COMPASS

EIC

Accardi et al., The Electron Ion Collider: the next QCD Frontier
arXiv:1212.1701

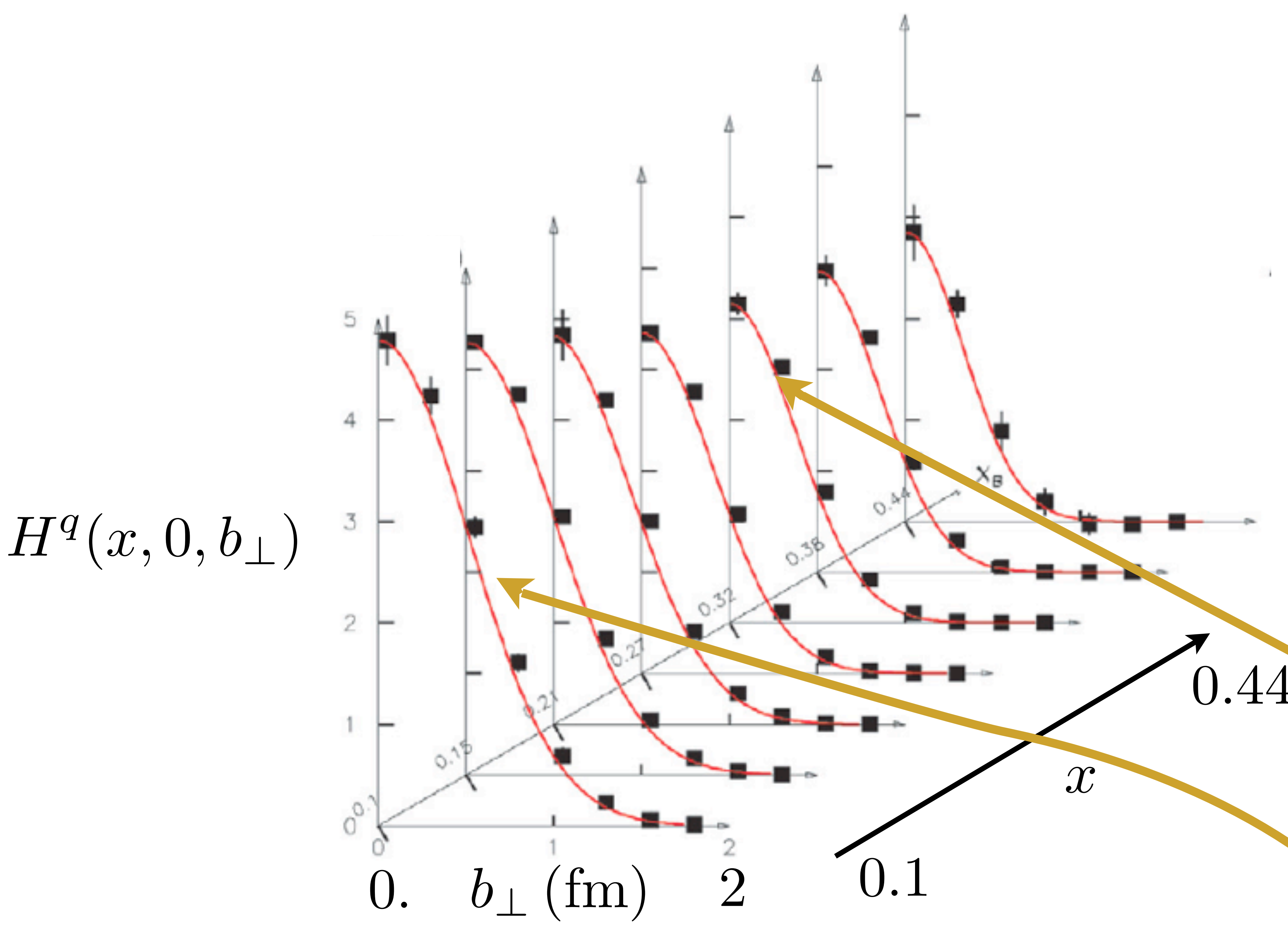
The unpolarized GPD H

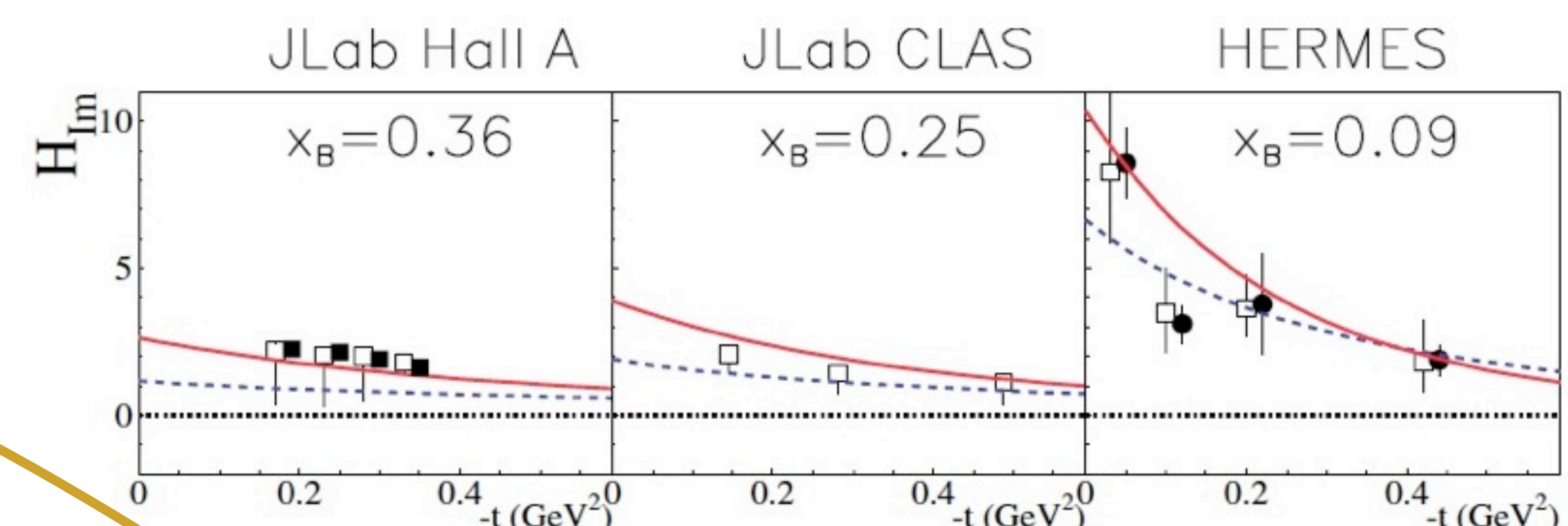
$$F_1(t) = \int \mathrm{d}x\, H(x,0,t)$$

$$H(x,0,\vec{b}_\perp) = \int \mathrm{d}^2\Delta_\perp\, H(x,0,t)\, e^{-i\vec{\Delta}_\perp\cdot\vec{b}_\perp}$$

extrapolation from data

$$t = -\vec{\Delta}_\perp^2$$





flat in t
narrow in $b_\perp$

steep in t
wide in $b_\perp$

Guidal et al., Rep. Prog. Phys. ***76*** *(2013) 066202*

The unpolarized GPD H

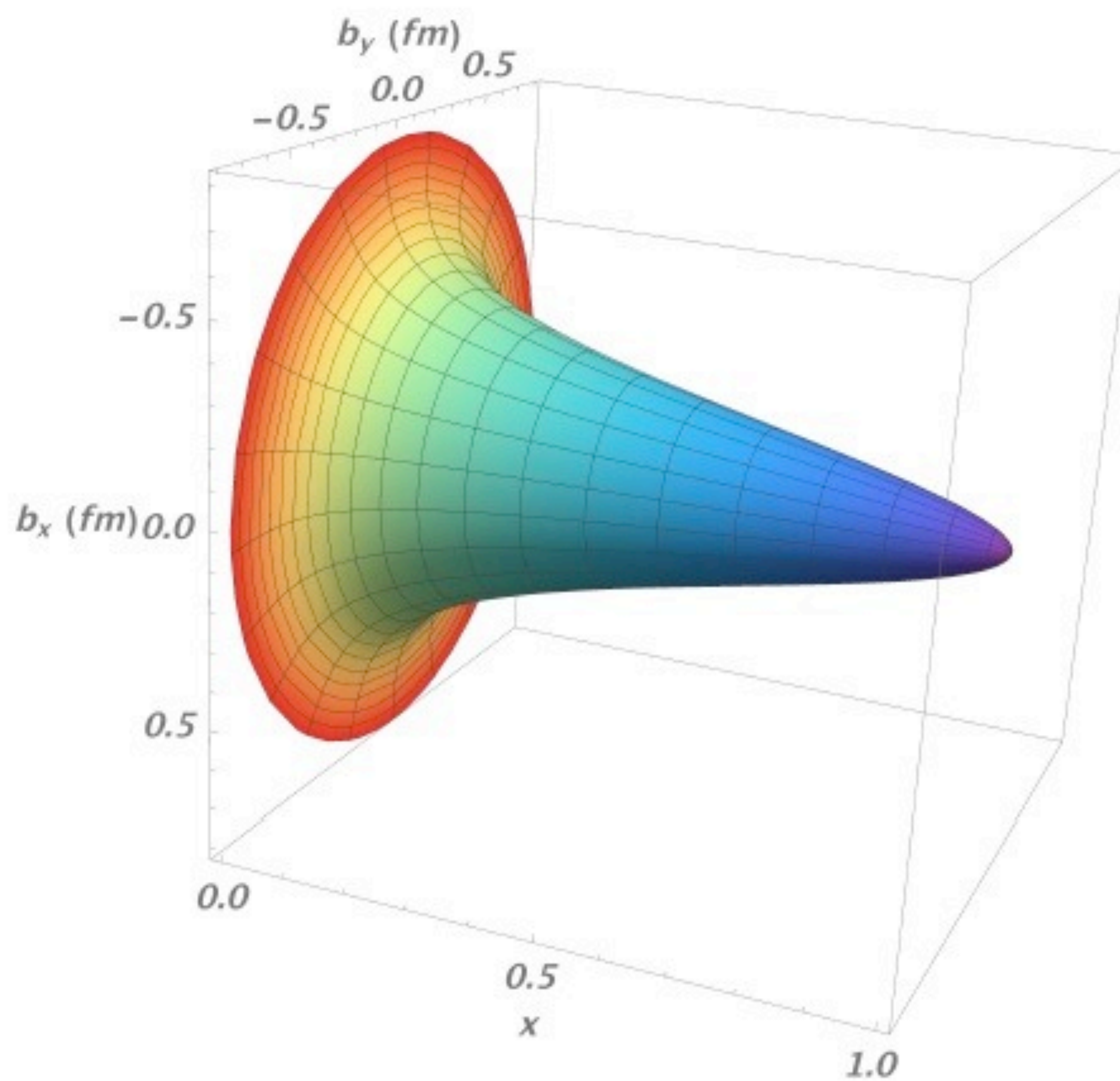
$$F_1(t) = \int \mathrm{d}x \, H(x,0,t)$$

$$H(x,0,\vec{b}_\perp) = \int \mathrm{d}^2\Delta_\perp \, H(x,0,t) \, e^{-i\vec{\Delta}_\perp \cdot \vec{b}_\perp}$$

$$t = -\vec{\Delta}_\perp^2$$

As x $\longrightarrow$ 1, the active parton carries all the momentum and represents the transverse centre of momentum

$$\langle \vec{b}_\perp^2(x) \rangle = \frac{\int \mathrm{d}^2\vec{b}_\perp \, \vec{b}_\perp^2 \, H(x,0,b_\perp)}{\int \mathrm{d}^2\vec{b}_\perp H(x,0,b_\perp)}$$



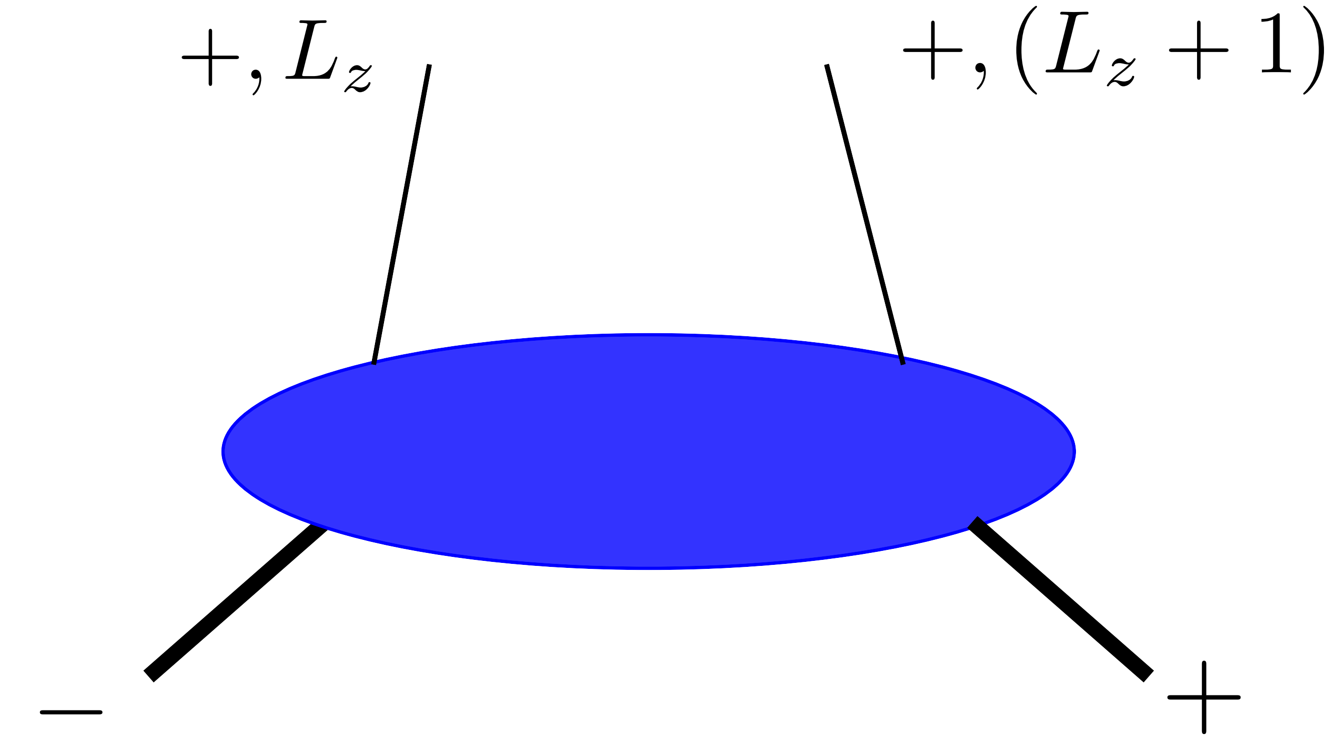
Dupré et al., arXiv:1606.07821

Unpolarized quarks in transversely pol. nucleon

"Helicity mismatch" requires orbital angular momentum

- $F_2(t) = \int \mathrm{d}x \, E(x, \xi, t)$
- no-forward limit to PDF

GPD E



unpolarized quarks in $\perp$ pol. nucleon

↓

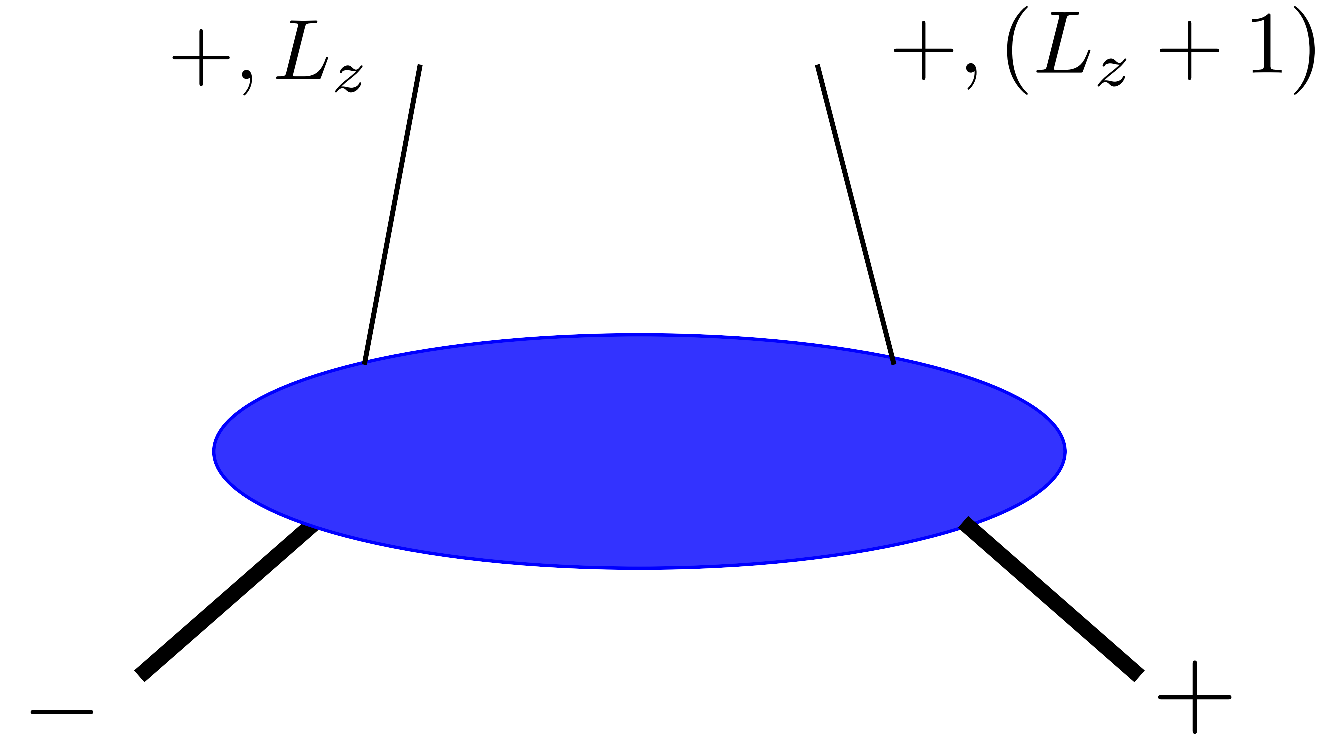
"partner" of Sivers function

Unpolarized quarks in transversely pol. nucleon

"Helicity mismatch" requires orbital angular momentum

- $F_2(t) = \int \mathrm{d}x\, E(x,\xi,t)$
- no-forward limit to PDF

GPD E



unpolarized quarks in $\perp$ pol. nucleon

↓

"partner" of Sivers function

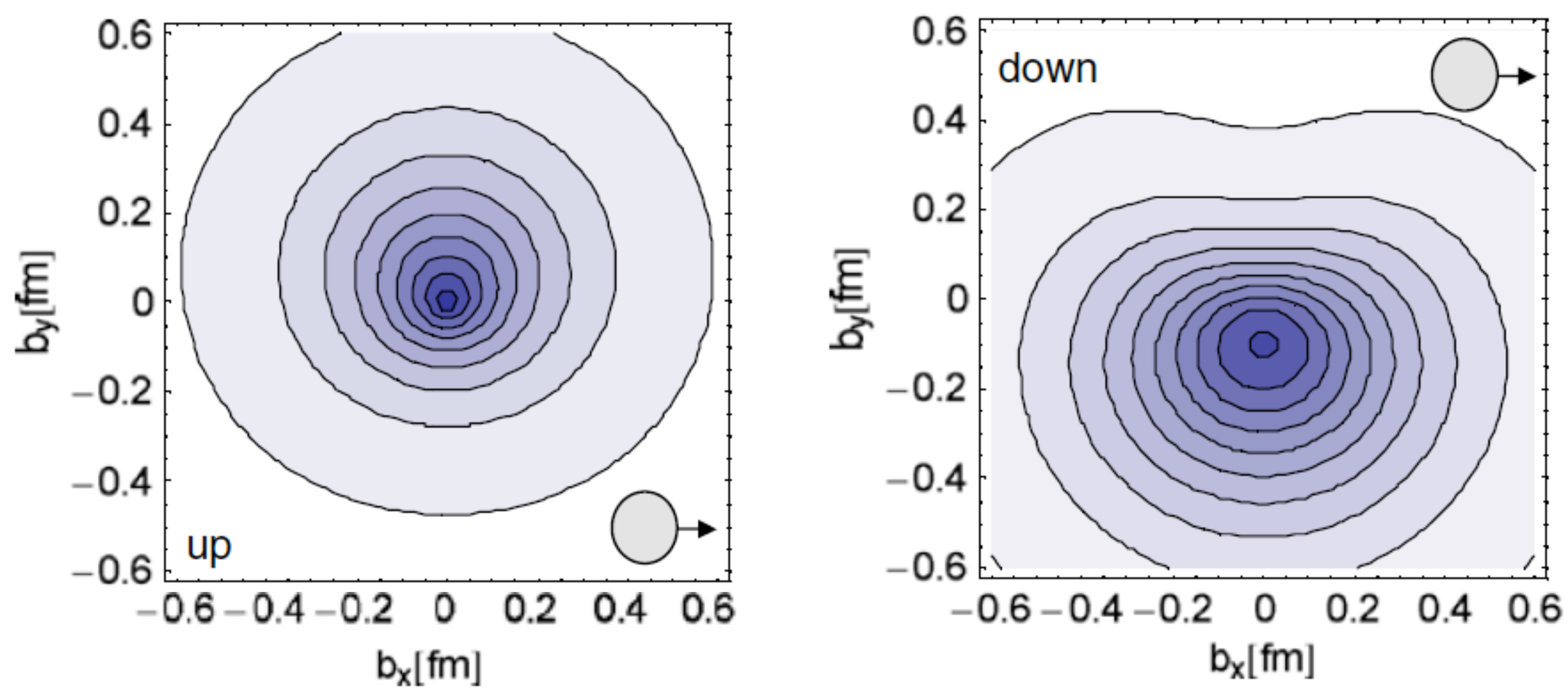
Lattice calculation

Transverse dipole moment:

$$d_y^q = \frac{\kappa^q}{2M}$$

$$\kappa^u = 1.86 \quad \kappa^d = -1.57$$

quark contribution to proton anomalous magnetic moment



Goeckeler et al., Phys. Rev. Lett. ***98*** *(2007) 222001*

Angular Momentum Relation ("Ji's Sum Rule")

*X. Ji, PRL **78** (1997) 610*

quark and gluon contribution to the nucleon spin

$$J^{q,g} = \frac{1}{2}\int_{-1}^{1} \mathrm{d}x\, x \left(H^{q,g}(x,0,0) + E^{q,g}(x,0,0) \right)$$

unpolarized PDF

not directly accessible

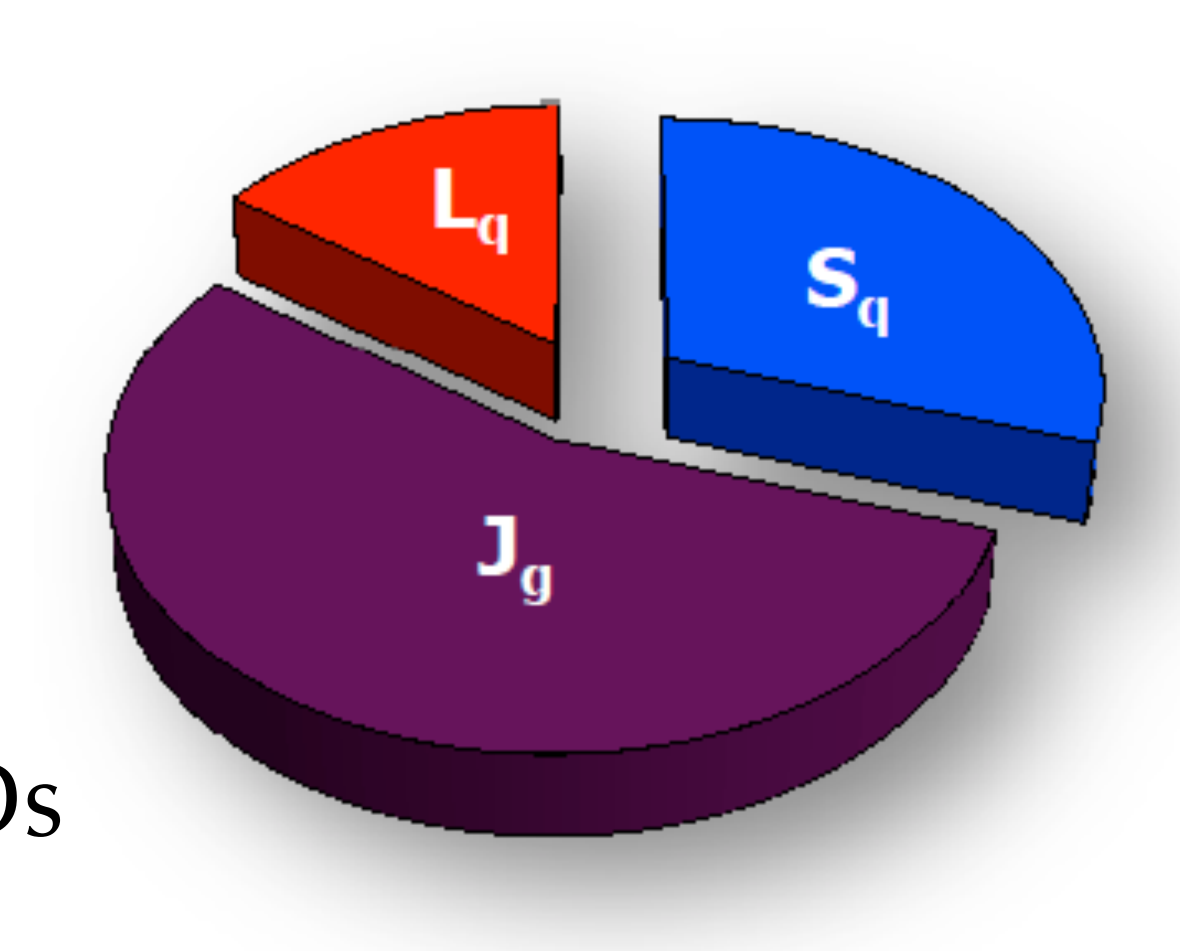
Proton spin decomposition

$\frac{1}{2}\Delta\Sigma$ from DIS

$J^q = L^q + S^q$

gauge invariant decomposition

sum rule for L^q from twist-3 GPDs



J^g

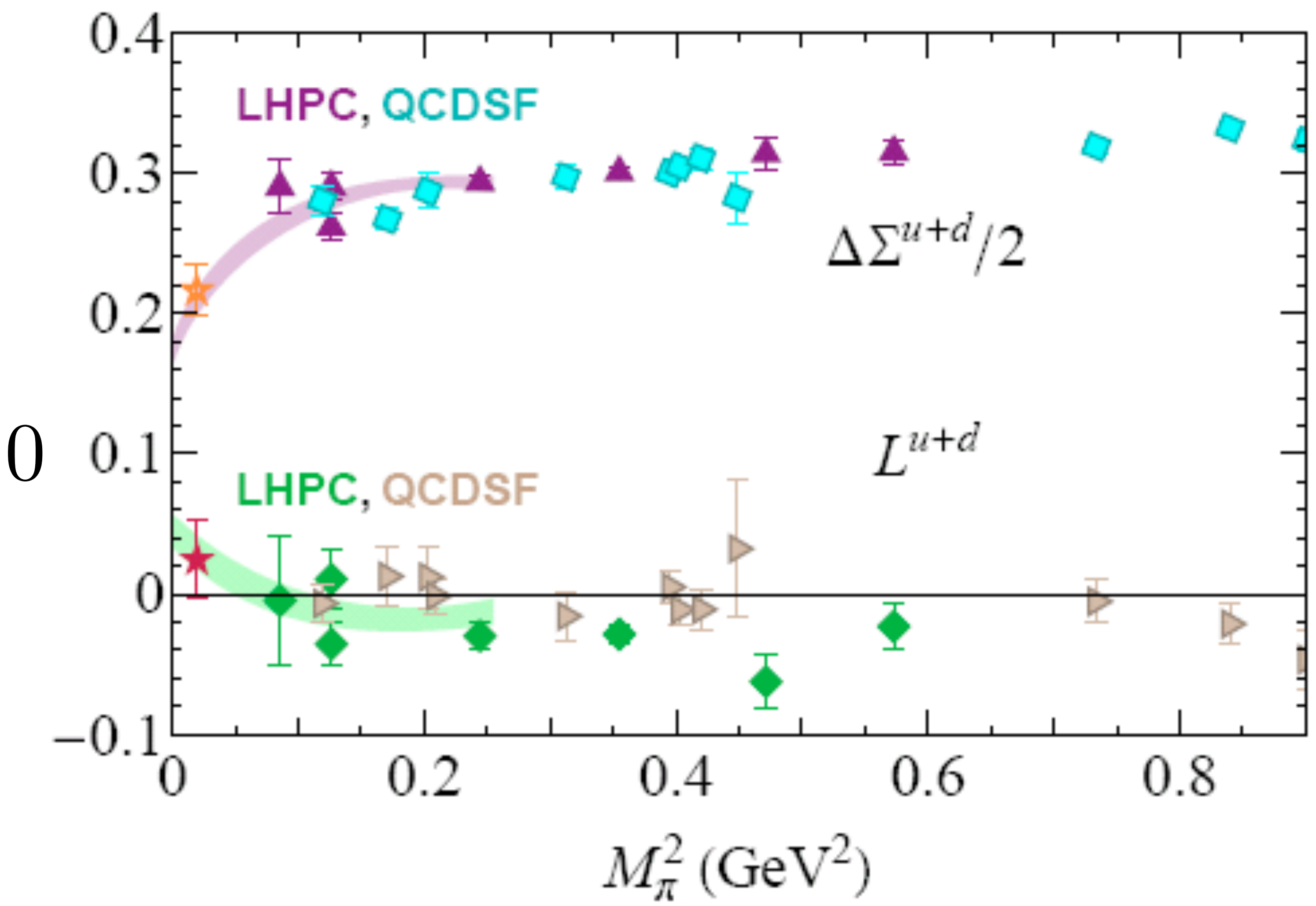
no further gauge-invariant decomposition

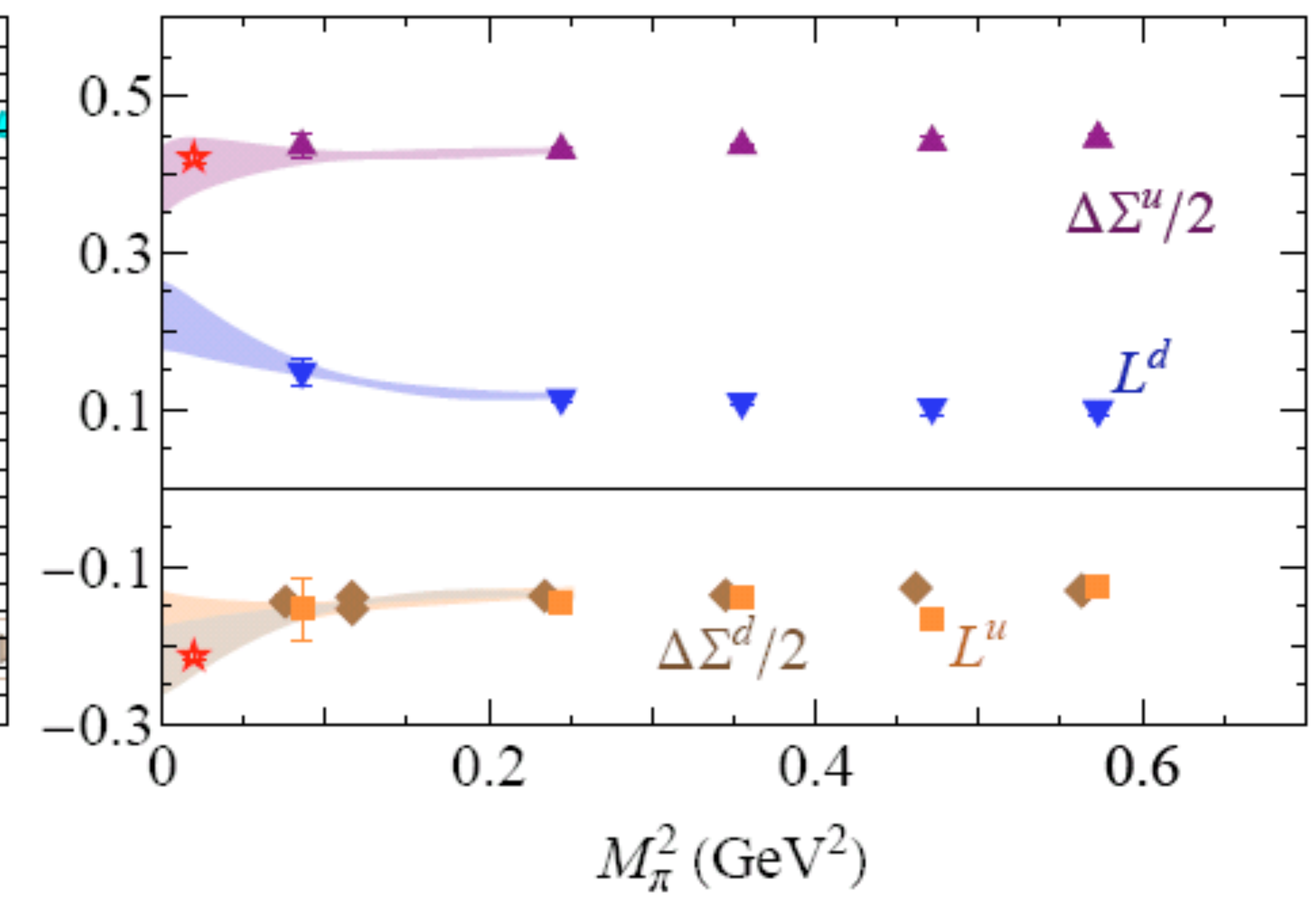
Lattice Calculations of Angular Momentum

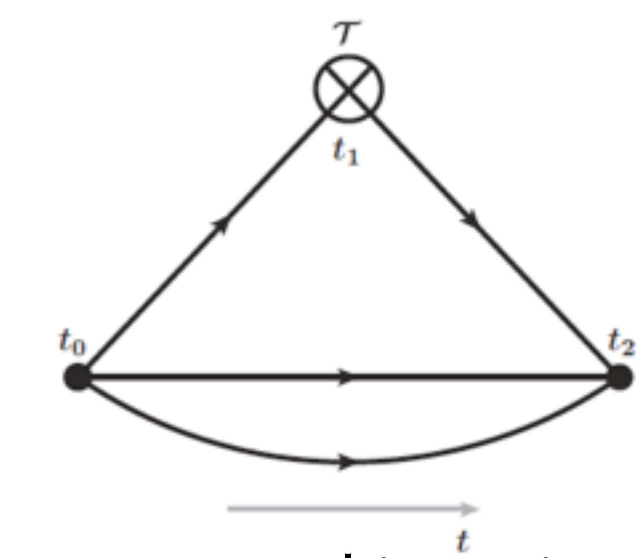
$$L^u + L^d \approx 0$$

$$J^u > 0, \quad J^d \approx 0$$

without disconnected insertion







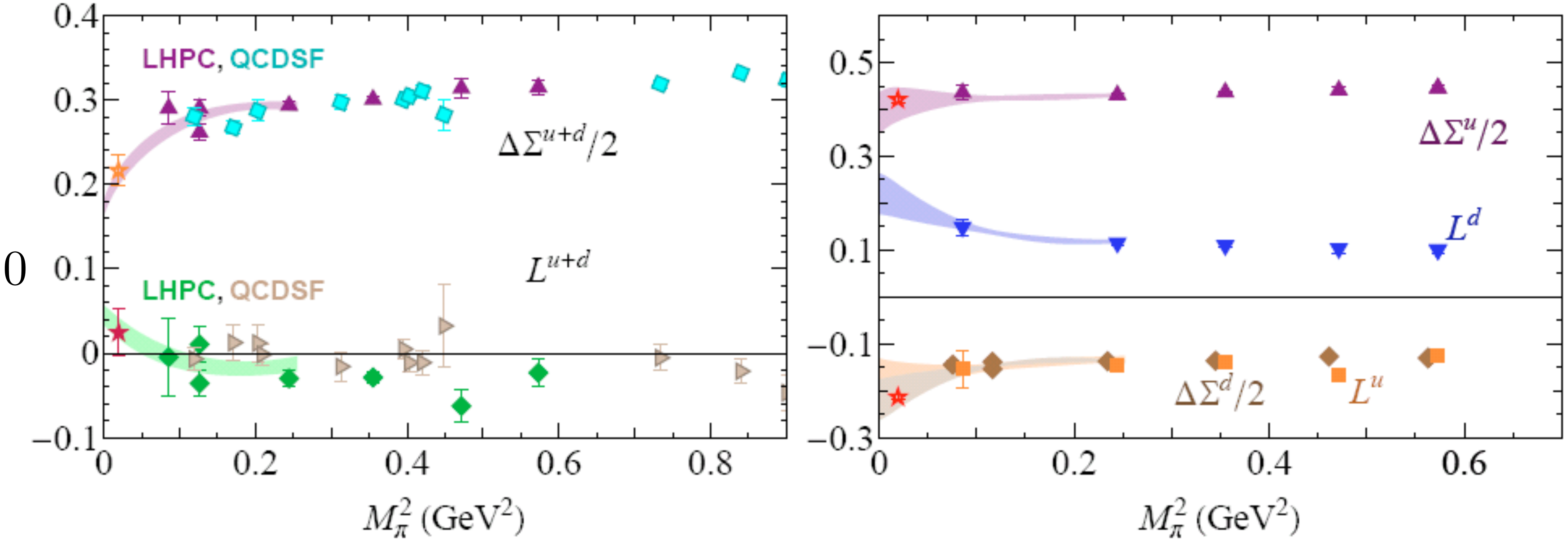
connected insertions (CI)

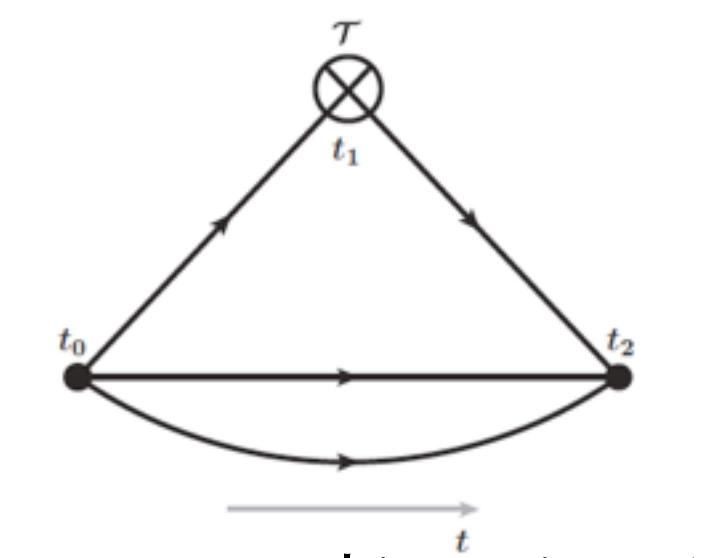
Lattice Calculations of Angular Momentum

without disconnected insertion

$L^u + L^d \approx 0$

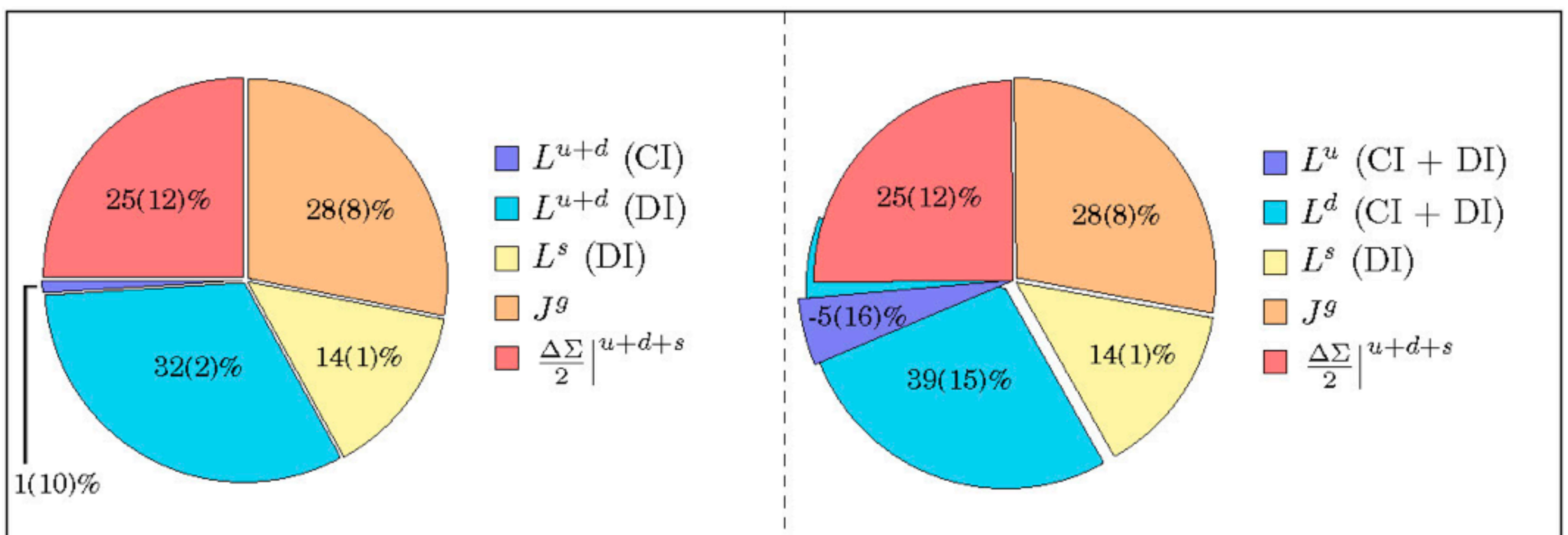
$J^u > 0, \quad J^d \approx 0$

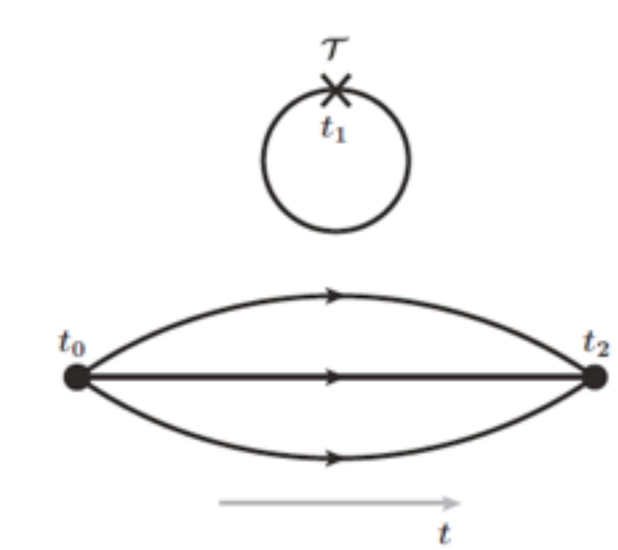




with disconnected insertion

$L^u + L^d \approx 33\%$

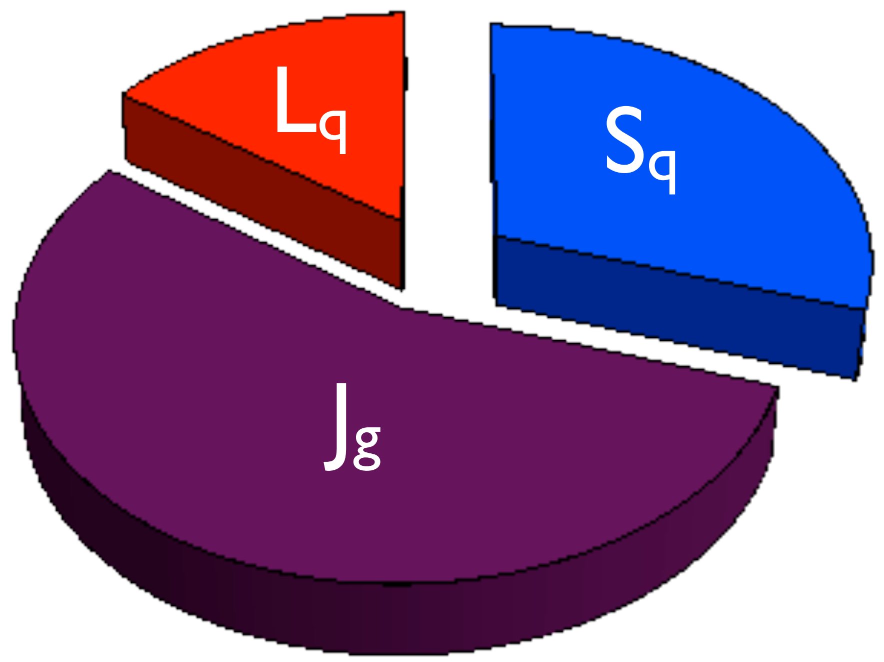




*Deka et al., PRD **91** (2015) 014505*

Different definitions of OAM

Ji's sum rule



Pros:

- Each term is gauge invariant
- Accessible in DIS and DVCS
- Can be calculated in Lattice QCD

Cons:

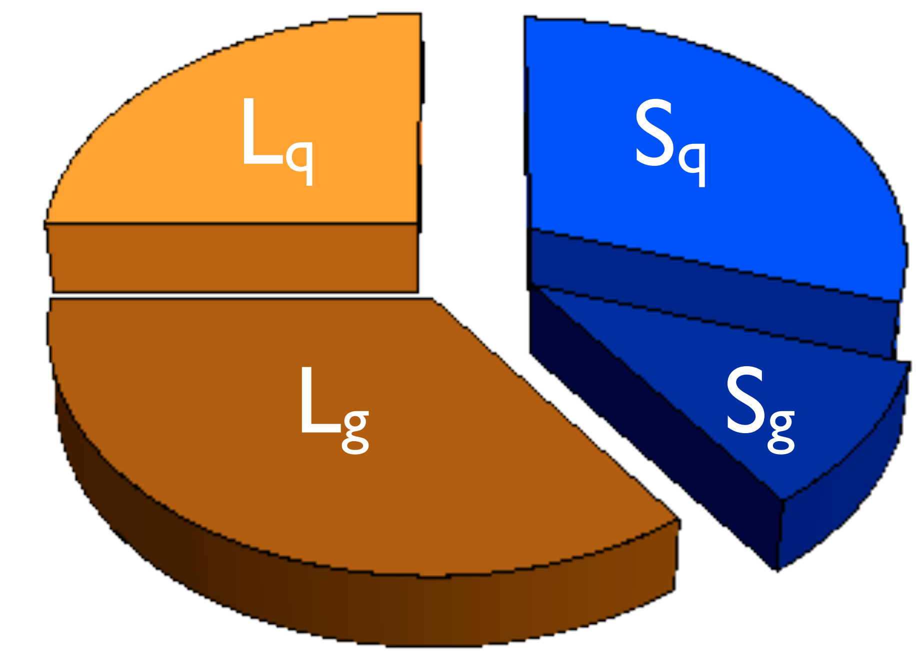
- Does not satisfy canonical commutation relations
- No decomposition of J_g in spin and orbital part

Improvements:

- Complete decomposition

$$J^g = L^g + \Delta g$$

Jaffe-Manohar



Pros:

- Satisfies canonical relations
- Complete decomposition

Cons:

- Gauge-variant decomposition
- Missing observables for the OAM

(Δg and $\Delta\Sigma$ measured by COMPASS, HERMES , RHIC)

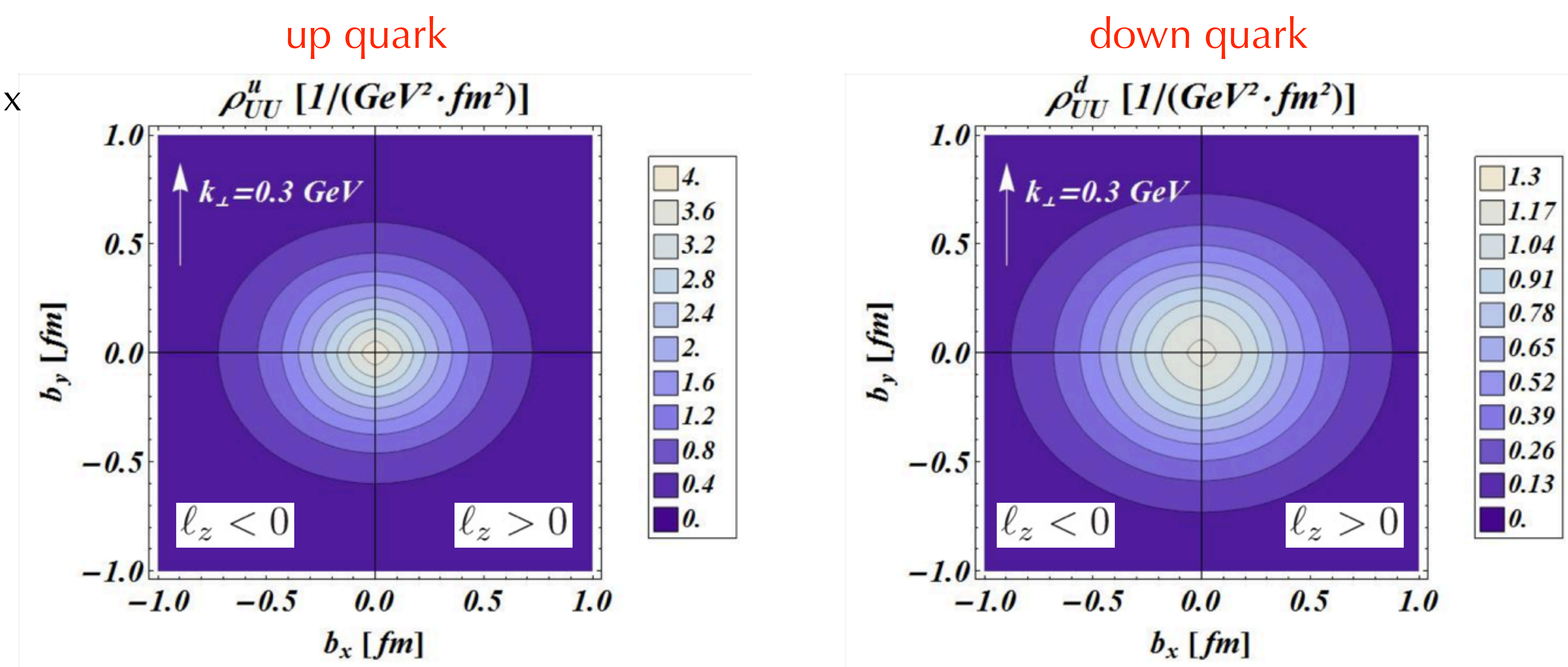
Improvements:

- OAM accessible via Wigner distributions and it can be calculated on the lattice

Lorcé, Leader, Phys. Rep. ***541*** *(2014) 163*

Unpolarized quarks in unpolarized proton

fixed $\vec{k}_\perp \uparrow$
integrated over x



Heisenberg uncertainty principle → not probabilistic interpretation

Distortion due to correlations between $\vec{k}_\perp$ and $\vec{b}_\perp$

↳ absent in GPD and TMD !

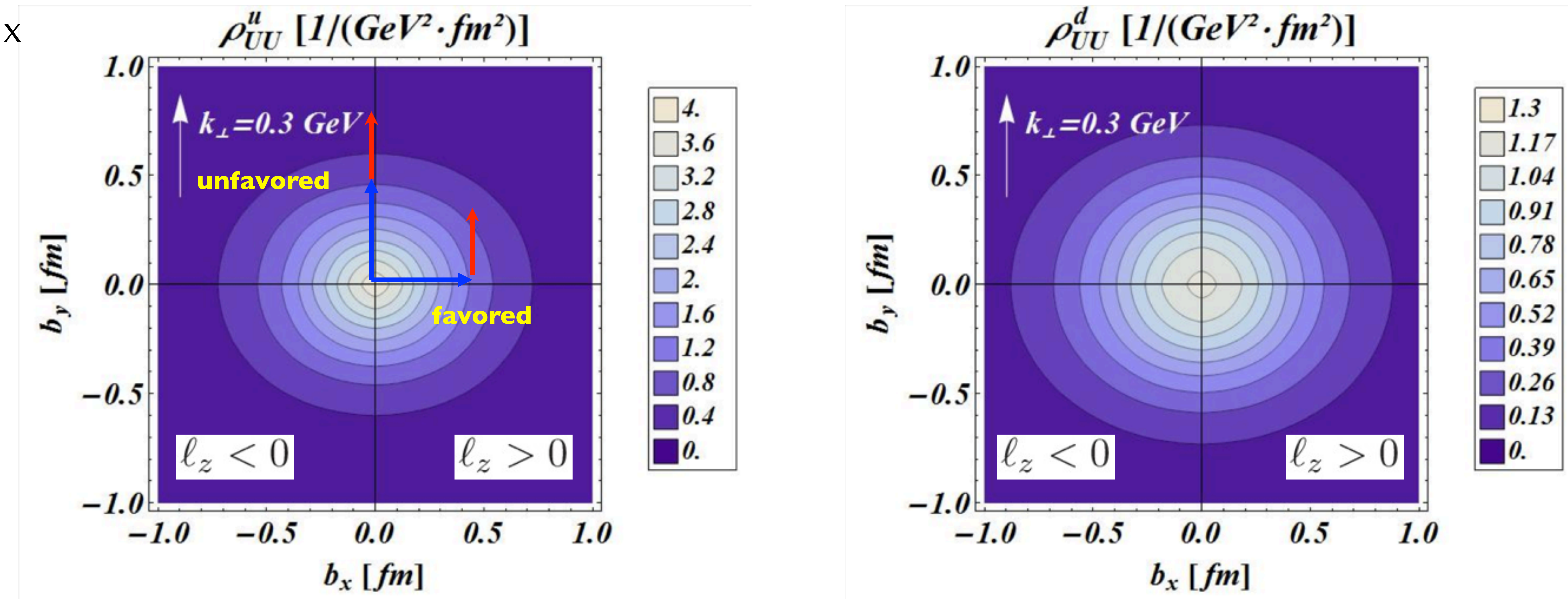
Left-right symmetry → no net quark OAM

Lorcé, Pasquini (2011)

Unpolarized quarks in unpolarized proton

fixed $\vec{k}_\perp \uparrow$
integrated over x

up quark down quark



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↳ absent in GPD and TMD !

Left-right symmetry → no net quark OAM

Lorcé, Pasquini (2011)

Quark Orbital Angular Momentum

$$\ell_z^q = \int \mathrm{d}x\, \mathrm{d}^2\vec{k}_\perp \mathrm{d}^2\vec{b}_\perp (\vec{b}_\perp \times \vec{k}_\perp)\rho^q_{LU}(\vec{b}_\perp, \vec{k}_\perp, x)$$

Wigner distribution for
Unpolarized quark in a Longitudinally pol. nucleon

Lorcé, BP, PRD ***84*** *(2011) 014015*

Lorcé, BP, Xiong, Yuan, PRD ***85*** *(2012) 114006*

Quark Orbital Angular Momentum

$$\ell_z^q = \int \mathrm{d}x\, \mathrm{d}^2\vec{k}_\perp \mathrm{d}^2\vec{b}_\perp (\vec{b}_\perp \times \vec{k}_\perp) \rho^q_{LU}(\vec{b}_\perp, \vec{k}_\perp, x)$$

$$= \int \mathrm{d}^2\vec{b}_\perp \vec{b}_\perp \times \langle \vec{k}^q_\perp \rangle \longrightarrow \langle \vec{k}^q_\perp \rangle = \int \mathrm{d}x\, \mathrm{d}\vec{k}_\perp\, \vec{k}_\perp \rho^q_{LU}(\vec{b}_\perp, \vec{k}_\perp, x)$$

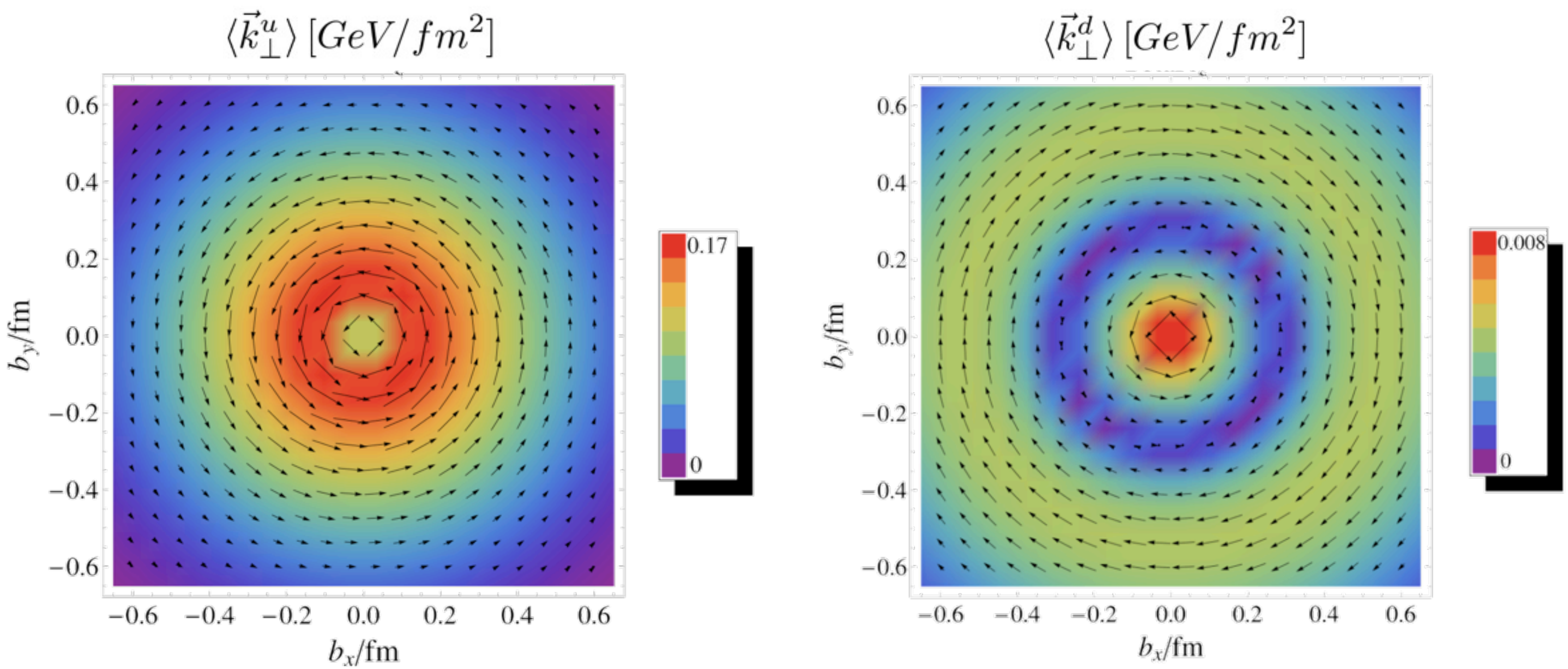
*Lorcé, BP, PRD **84** (2011) 014015*

*Lorcé, BP, Xiong, Yuan, PRD **85** (2012) 114006*

Quark Orbital Angular Momentum

$$\ell_z^q = \int \mathrm{d}x\, \mathrm{d}^2\vec{k}_\perp \mathrm{d}^2\vec{b}_\perp (\vec{b}_\perp \times \vec{k}_\perp) \rho^q_{LU}(\vec{b}_\perp, \vec{k}_\perp, x)$$

$$= \int \mathrm{d}^2\vec{b}_\perp \vec{b}_\perp \times \langle \vec{k}^q_\perp \rangle \longrightarrow \langle \vec{k}^q_\perp \rangle = \int \mathrm{d}x\, \mathrm{d}\vec{k}_\perp\, \vec{k}_\perp \rho^q_{LU}(\vec{b}_\perp, \vec{k}_\perp, x)$$



Results in a light-front constituent quark model:

*Lorcé, BP, PRD **84** (2011) 014015*

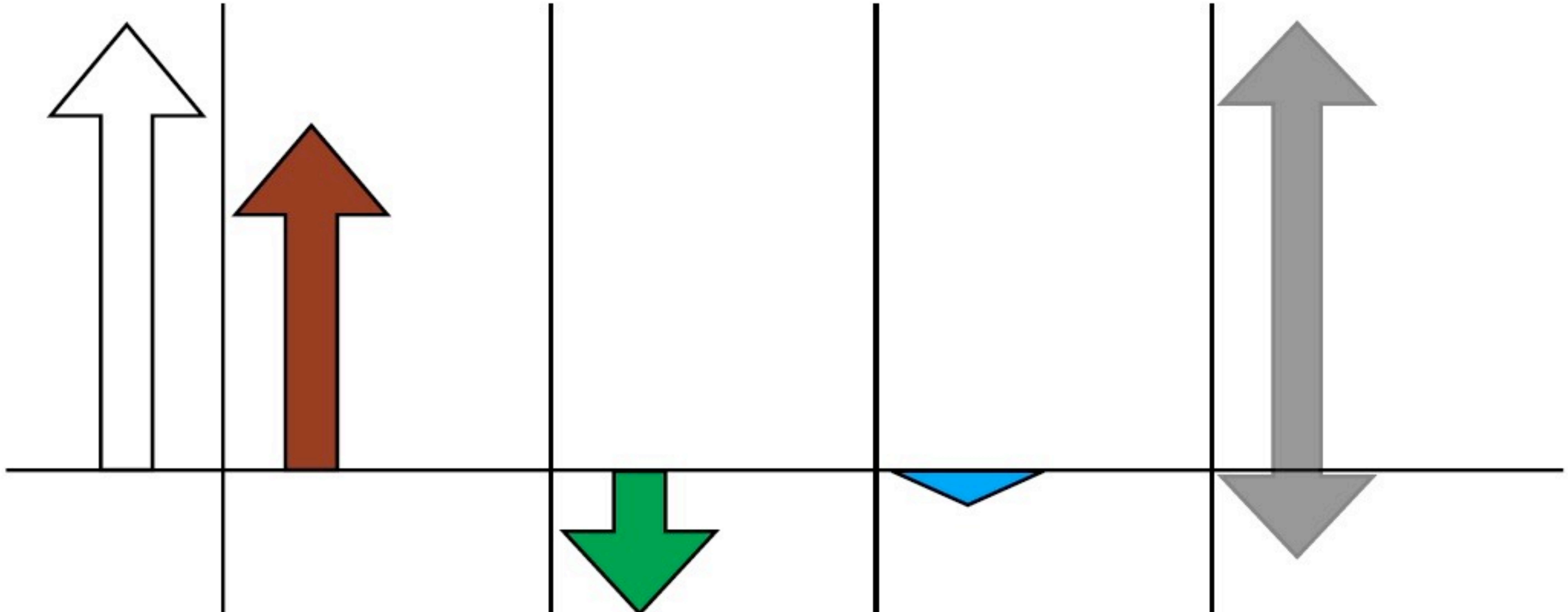
*Lorcé, BP, Xiong, Yuan, PRD **85** (2012) 114006*

Proton spin

u-quark OAM

d-quark OAM

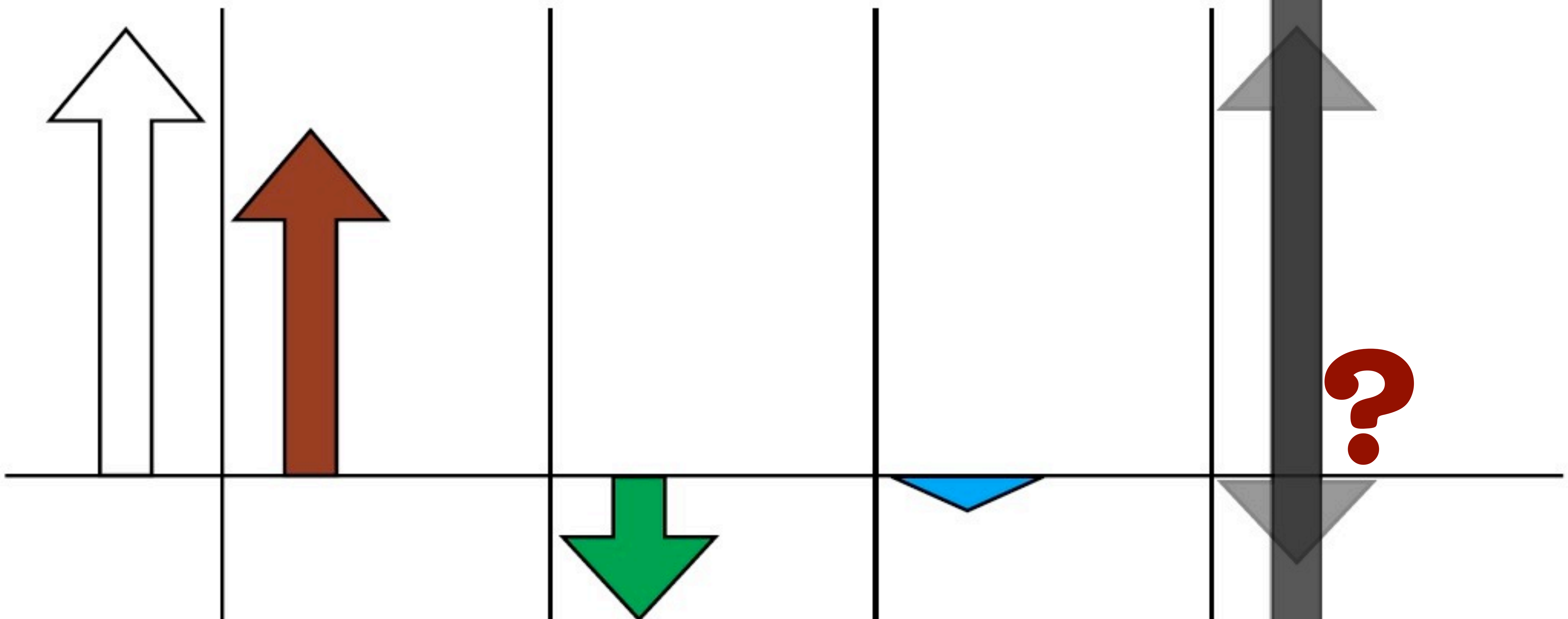
Status of spin sum rule



Proton spin	$u+\bar{u}$		$d+\bar{d}$		$s+\bar{s}$		g		
	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	
	82 ± 2		-45 ± 4		-11 ± 10		40 ± 60		DSSV

de Florian, Sassot, Stratmann, Vogelsang, PRL 113 (14)
NNPDF, Ball... Nocera... NPB 887 (14), Tab. 12, 13

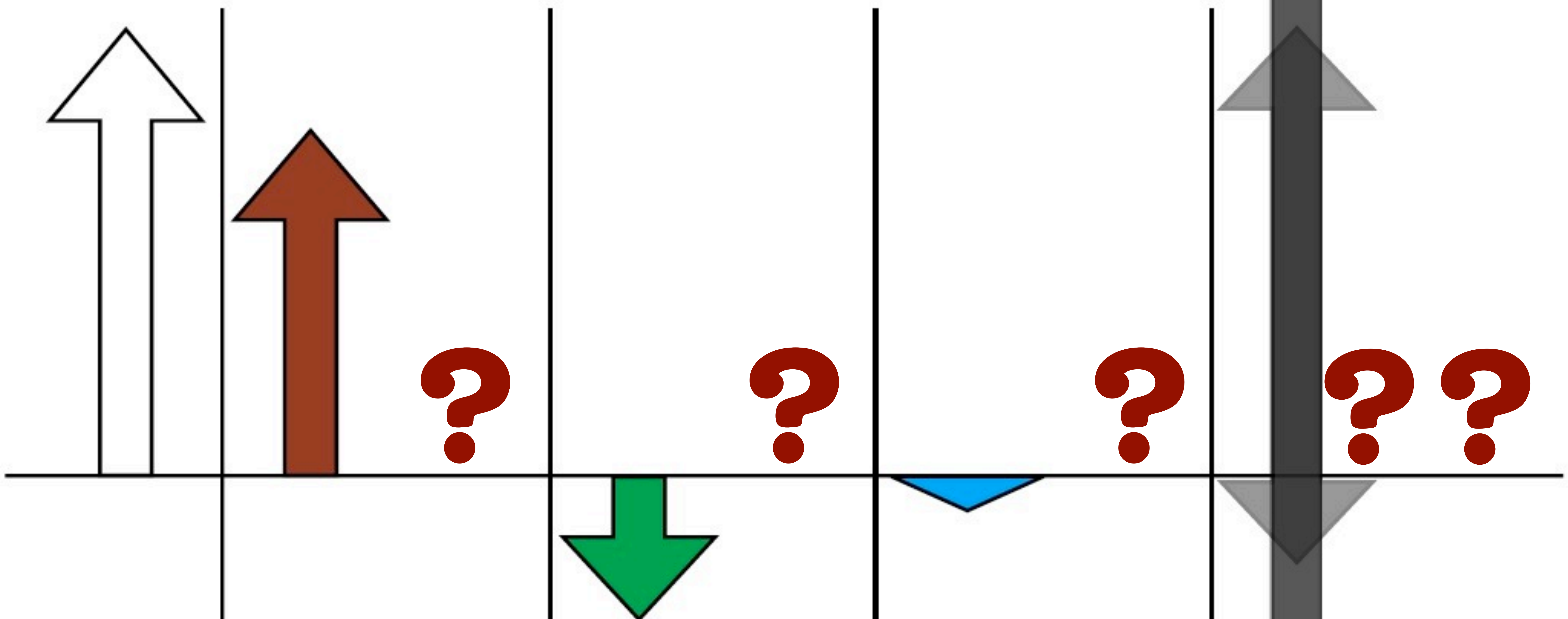
Status of spin sum rule



Proton spin	$u+\bar{u}$		$d+\bar{d}$		$s+\bar{s}$		g		
	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	
	82 ± 2		-45 ± 4		-11 ± 10		40 ± 60		DSSV
	79 ± 7		-47 ± 7		-12 ± 10		3 ± 324		NNPDF

de Florian, Sassot, Stratmann, Vogelsang, PRL 113 (14)
NNPDF, Ball... Nocera... NPB 887 (14), Tab. 12, 13

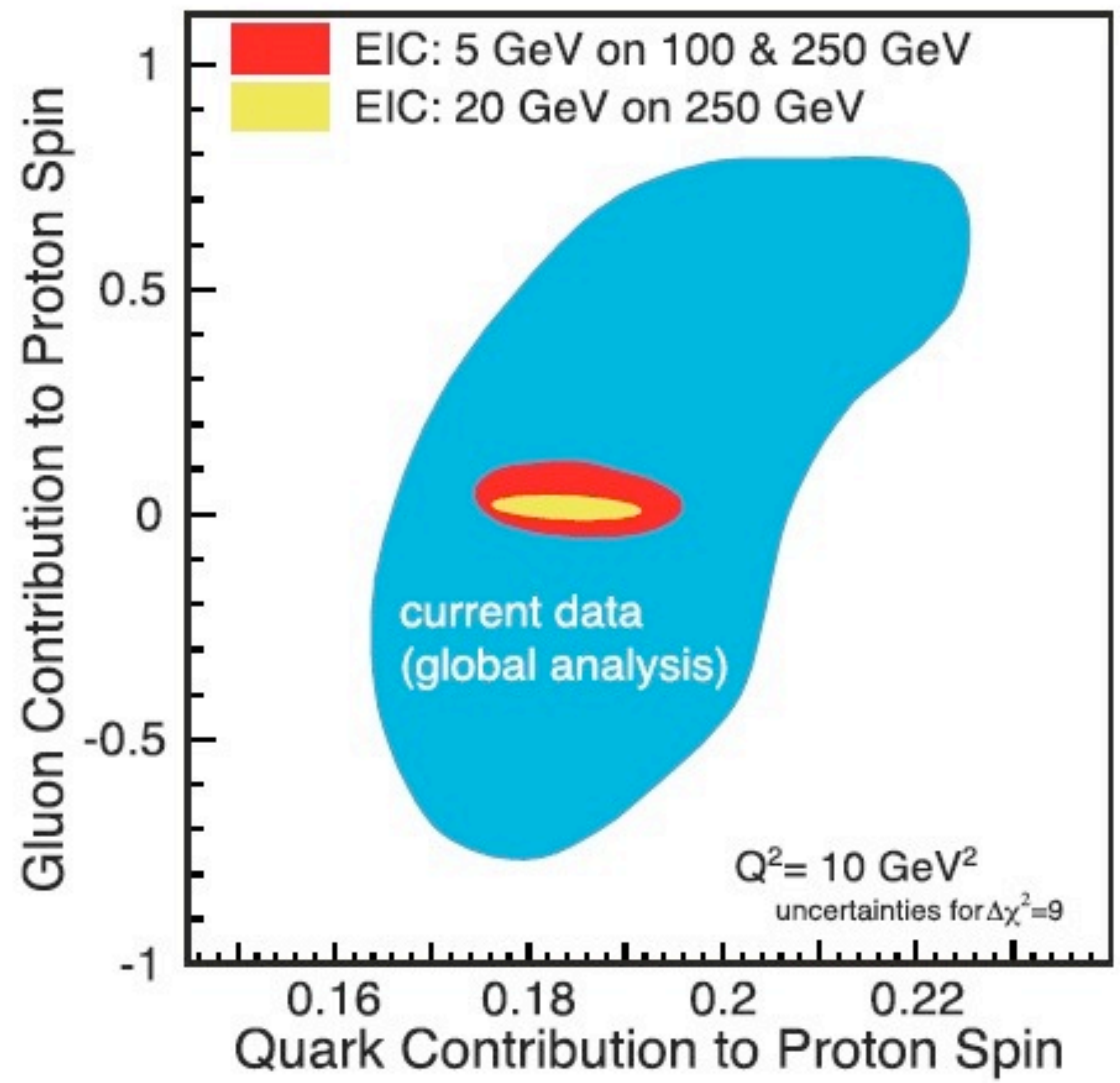
Status of spin sum rule



Proton spin	$u+\bar{u}$		$d+\bar{d}$		$s+\bar{s}$		g		
	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	
	82 ± 2		-45 ± 4		-11 ± 10		40 ± 60		DSSV
	79 ± 7		-47 ± 7		-12 ± 10		3 ± 324		NNPDF

de Florian, Sassot, Stratmann, Vogelsang, PRL 113 (14)
NNPDF, Ball... Nocera... NPB 887 (14), Tab. 12, 13

Impact of EIC on proton spin



Aschenauer, Stratmann, Sassot,PRD86 (2012)

Geesaman, et al., Reaching for the horizon: The 2015 long range plan for nuclear science (2015)

Conclusions

- TMDs and GPDs extend the concept of standard PDFs and provide a 3D description of the partonic structure of the nucleon

- TMDs and GPDs provide complementary information and allow us to investigate aspects of nucleon structure that are not accessible to standard collinear PDFs

- A lot of data is already available, but we expect more from e+e−, SIDIS at higher energies, Drell-Yan, DVCS, ...

- Some parametrizations of TMDs and GPDs are available, but we are a long way from anything similar to PDF global fits