Nucleon 3D imaging

Alessandro Bacchetta

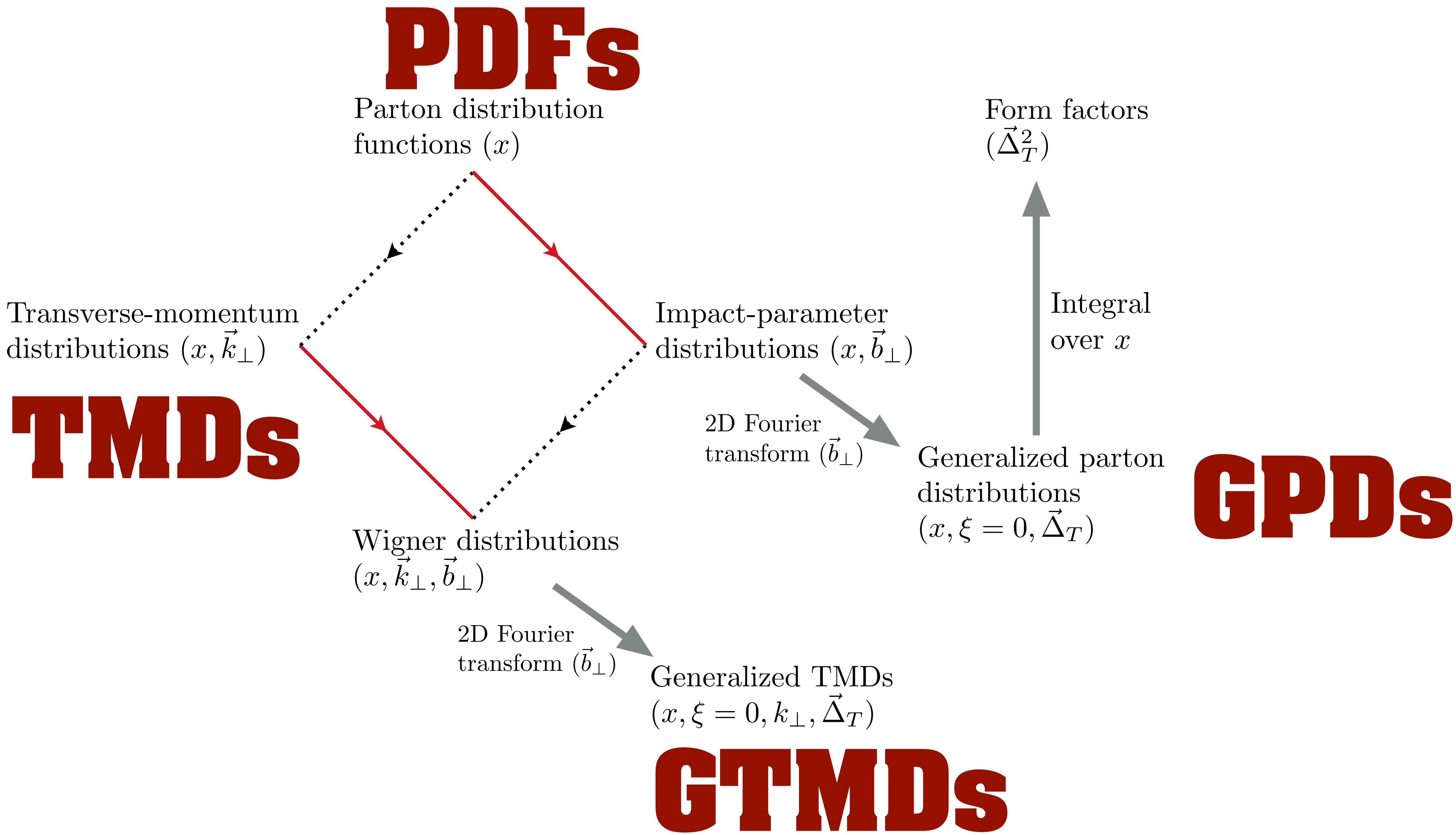
Funded by

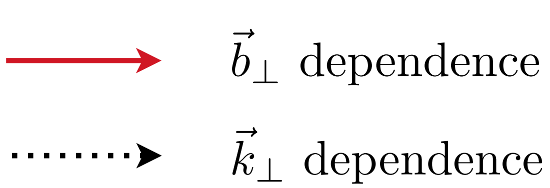
3DSPIN
MAPPING THE PROTON IN 3D

erc
European Research Council

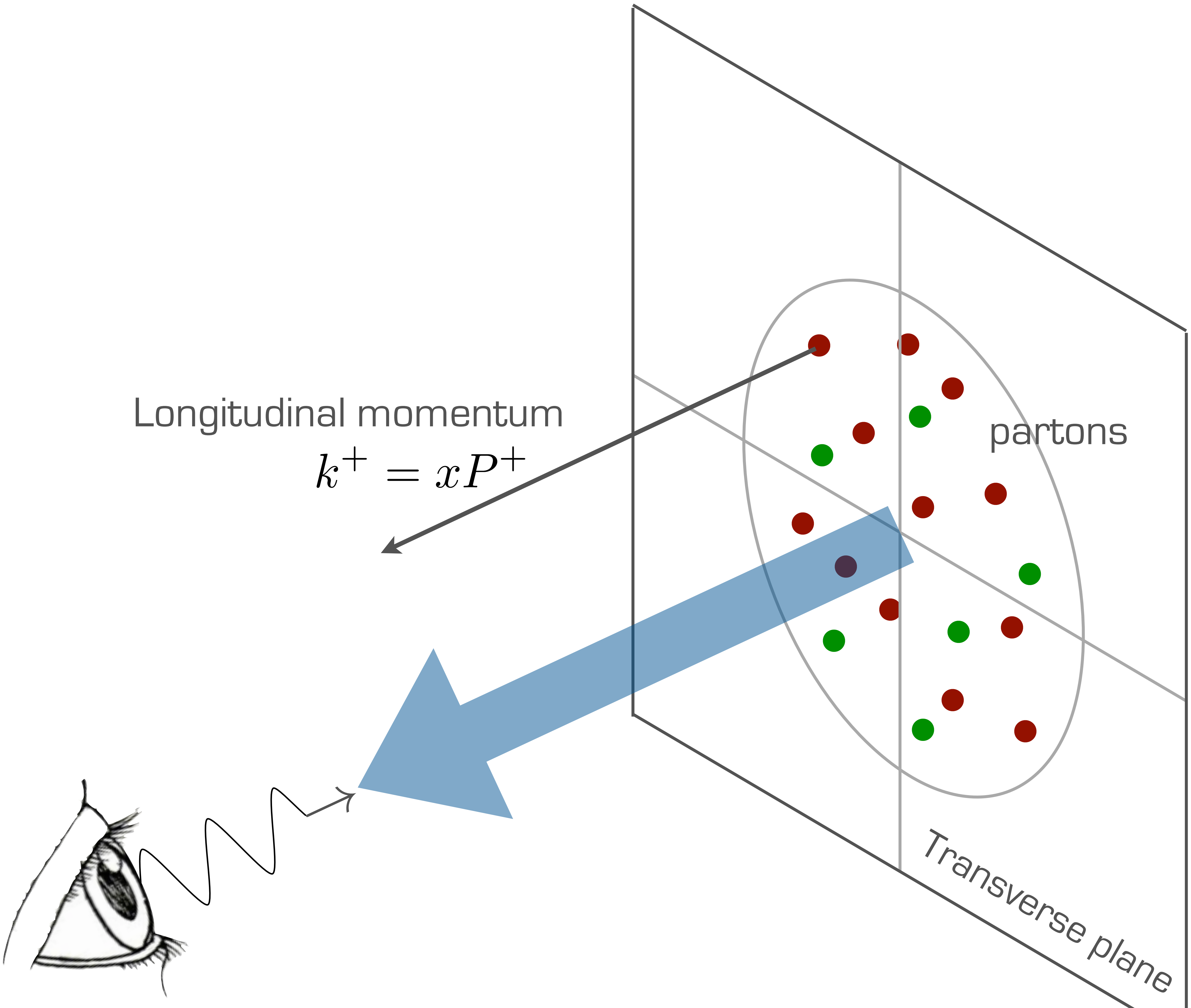
INFN
Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DI PAVIA



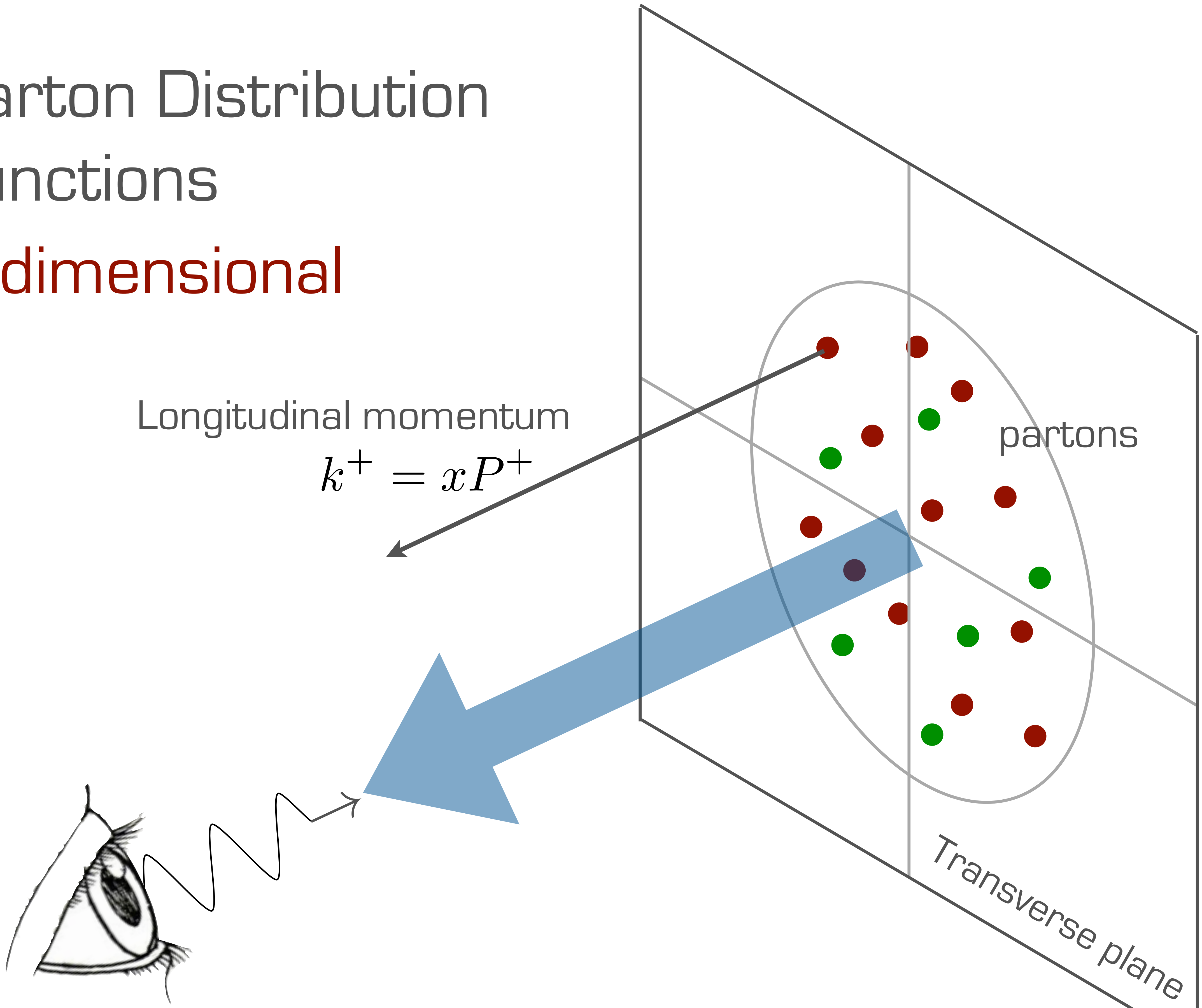


see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

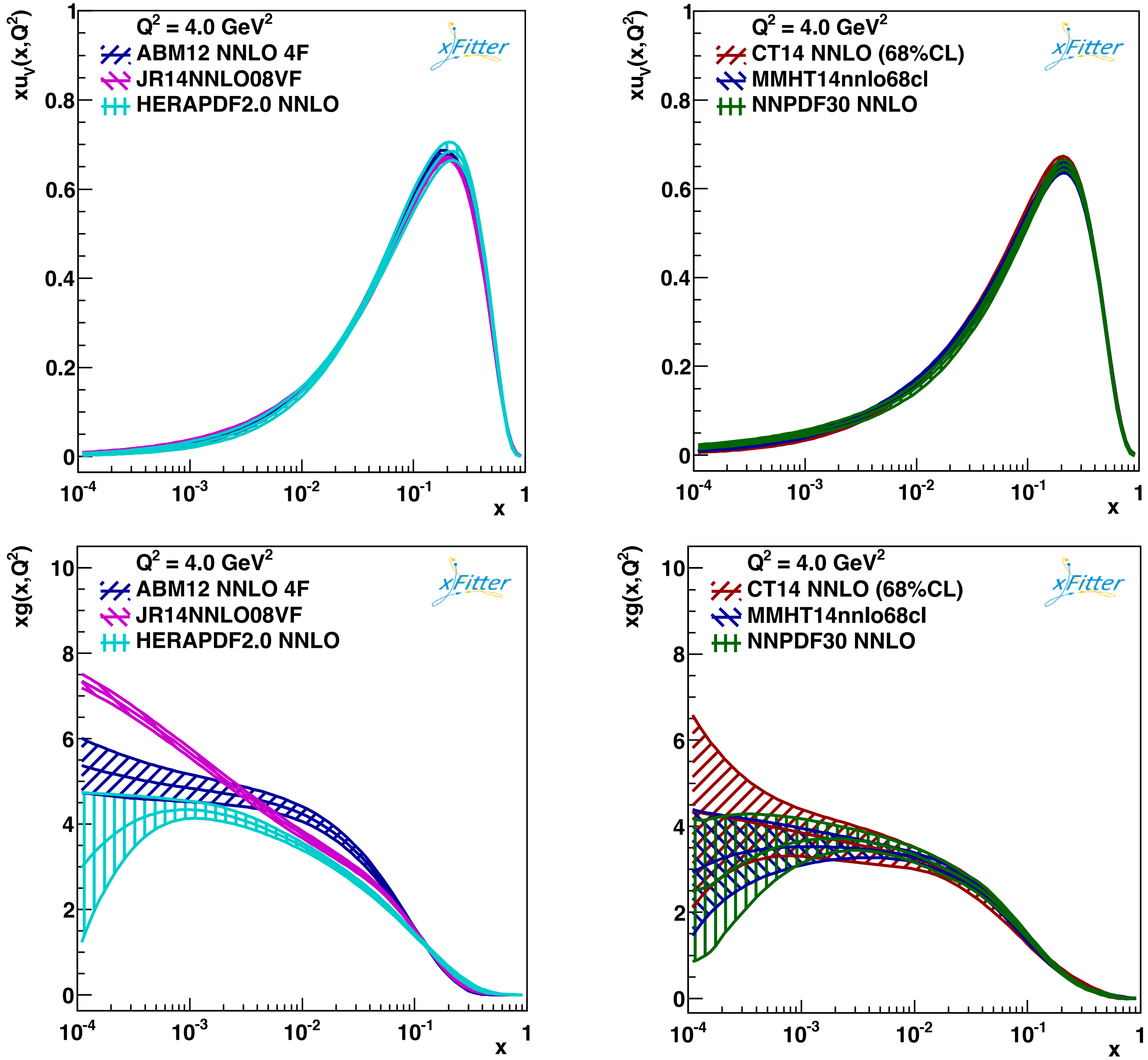

Longitudinal momentum
$k^+ = xP^+$
partons
Transverse plane

Parton Distribution Functions

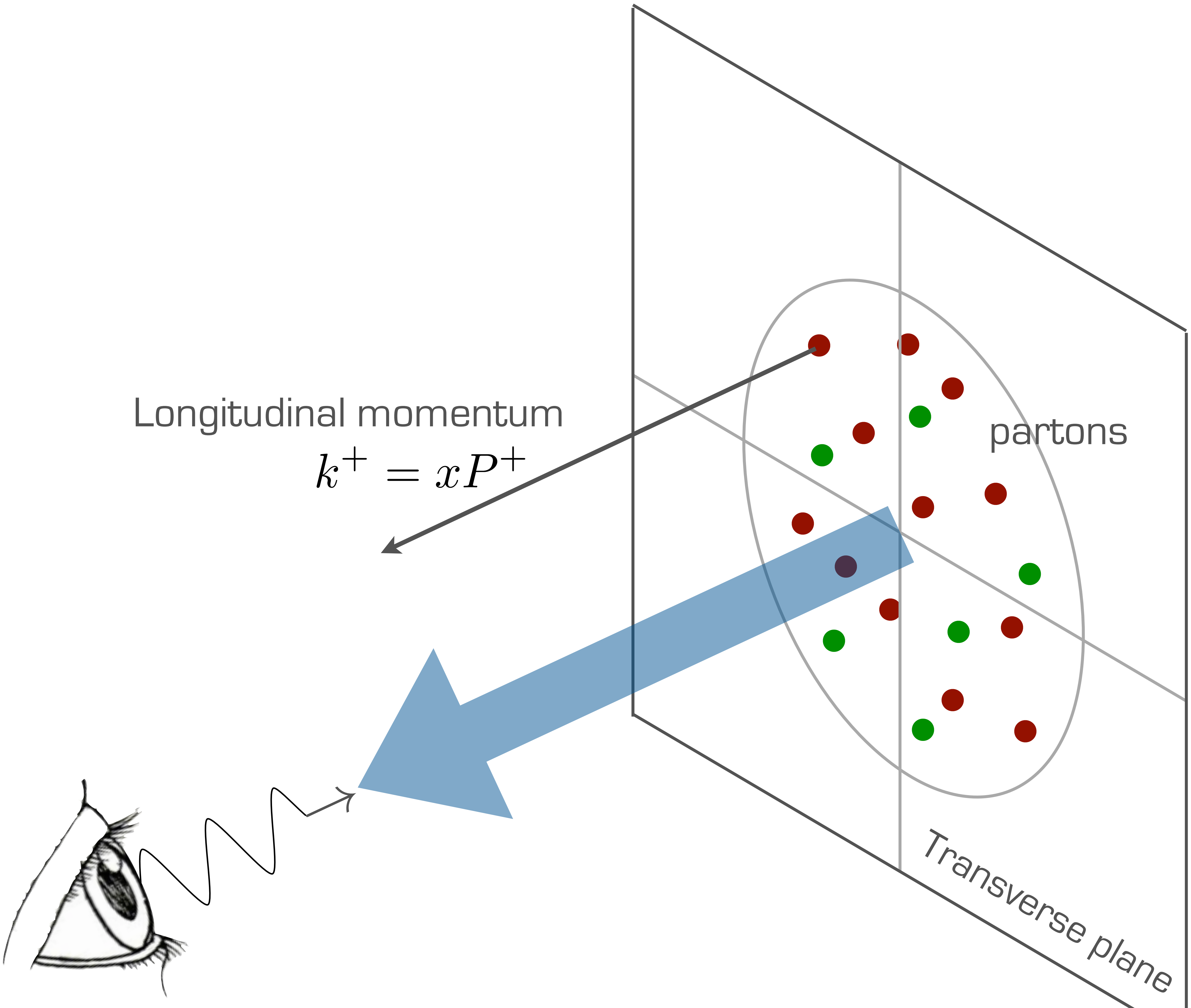
1 dimensional



Proton 1D "imaging"



Accardi et al., arXiv:1603.08906



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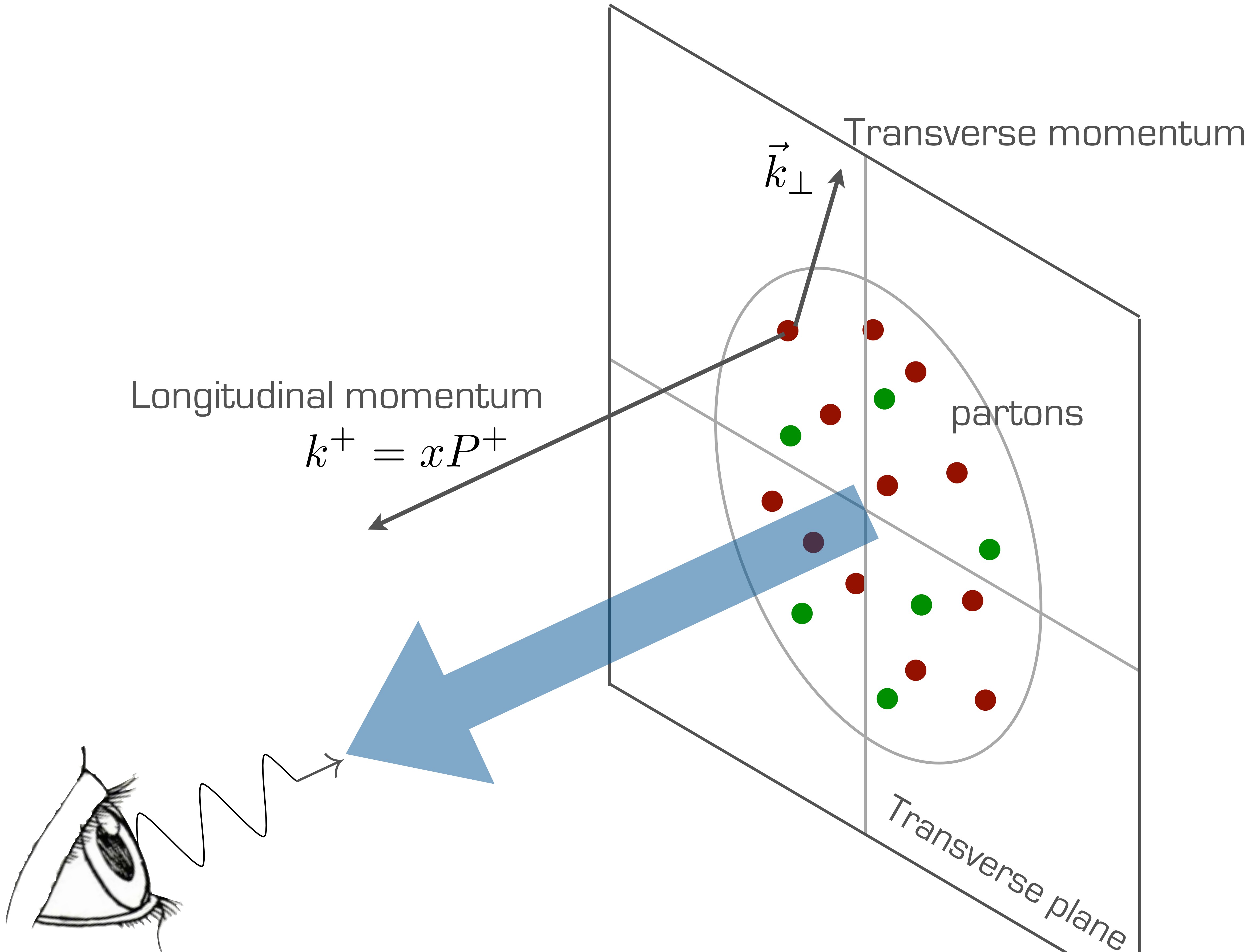
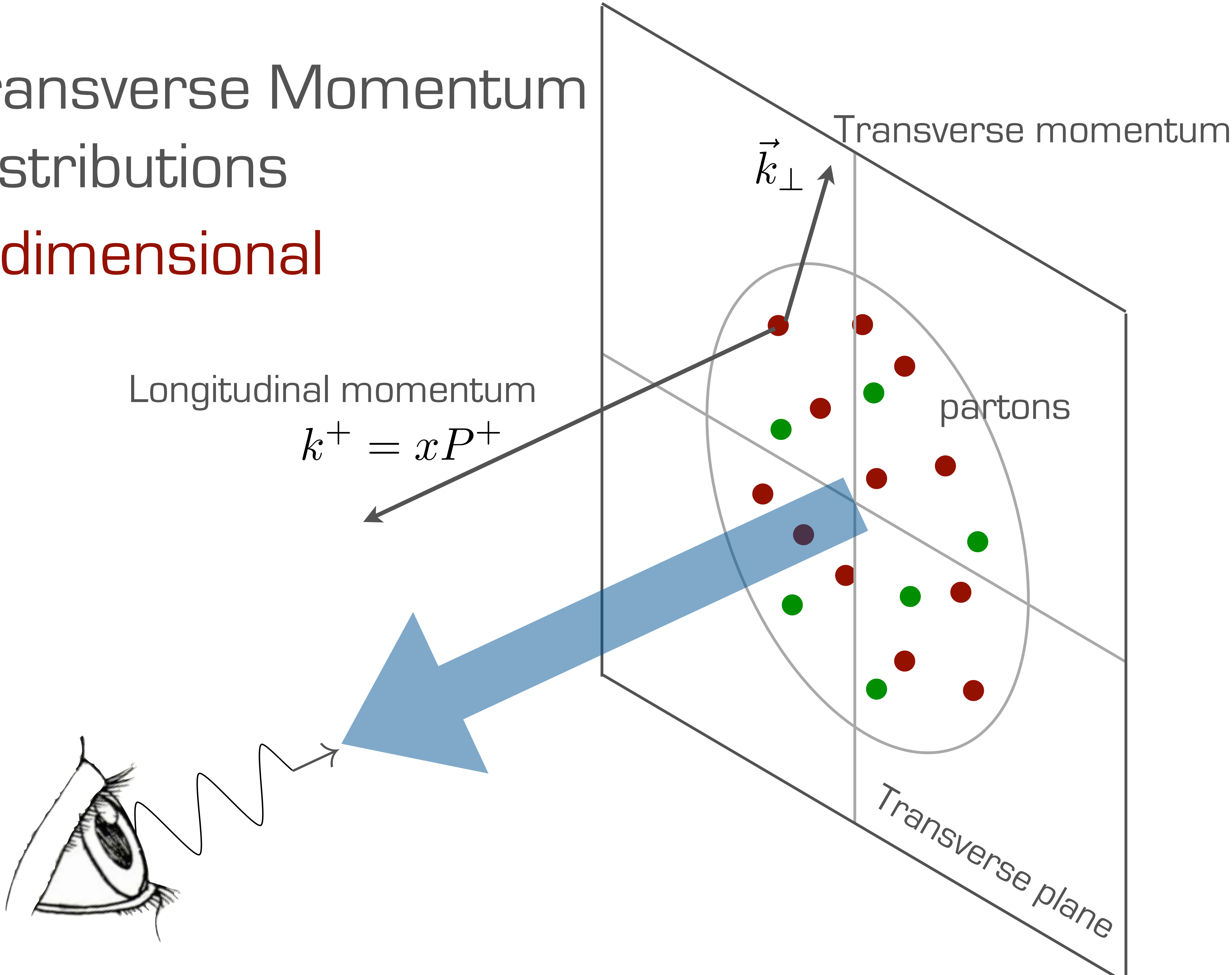
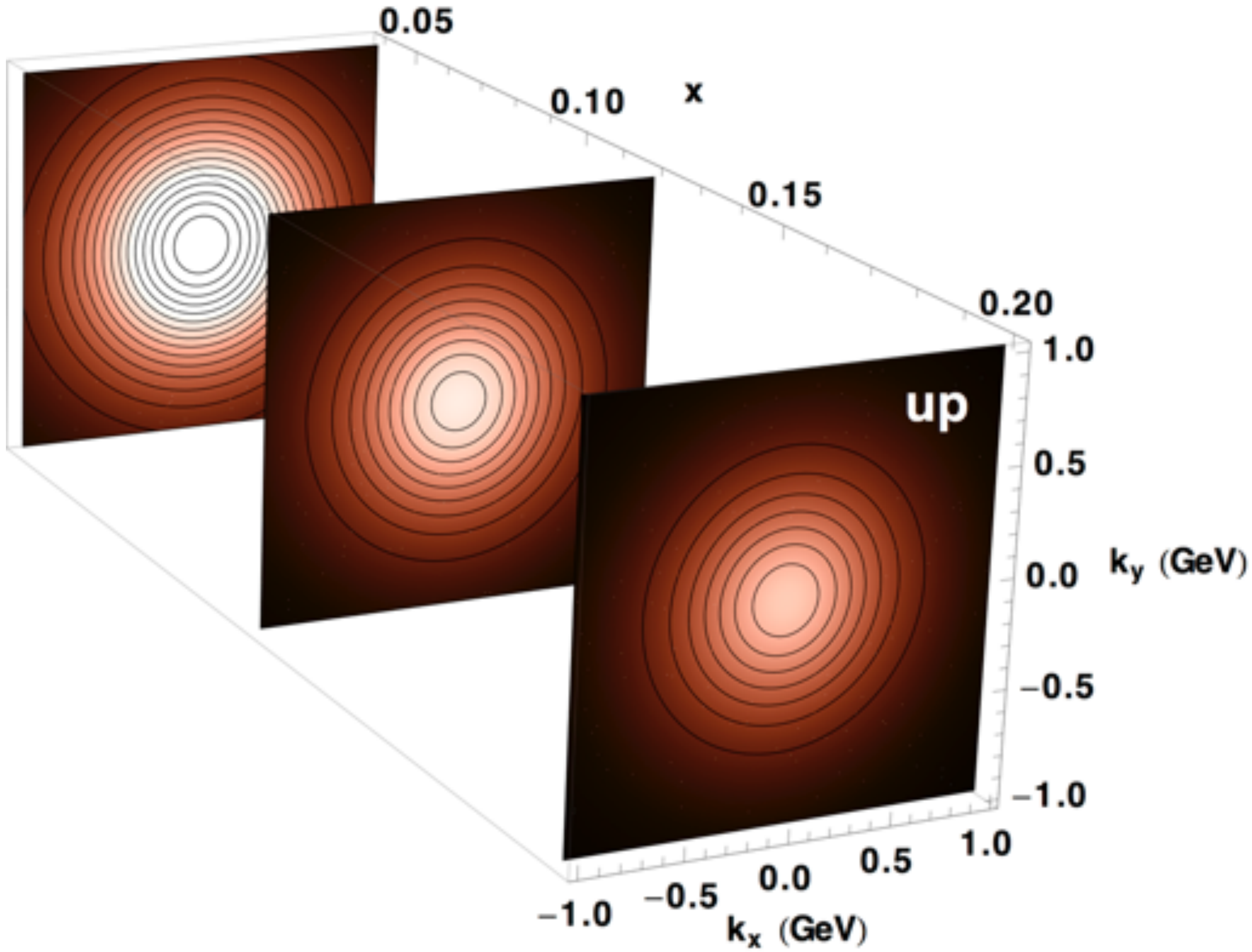

Transverse momentum
$\vec{k}_\perp$
Longitudinal momentum
$k^+ = xP^+$
partons
Transverse plane

Transverse Momentum Distributions

3 dimensional

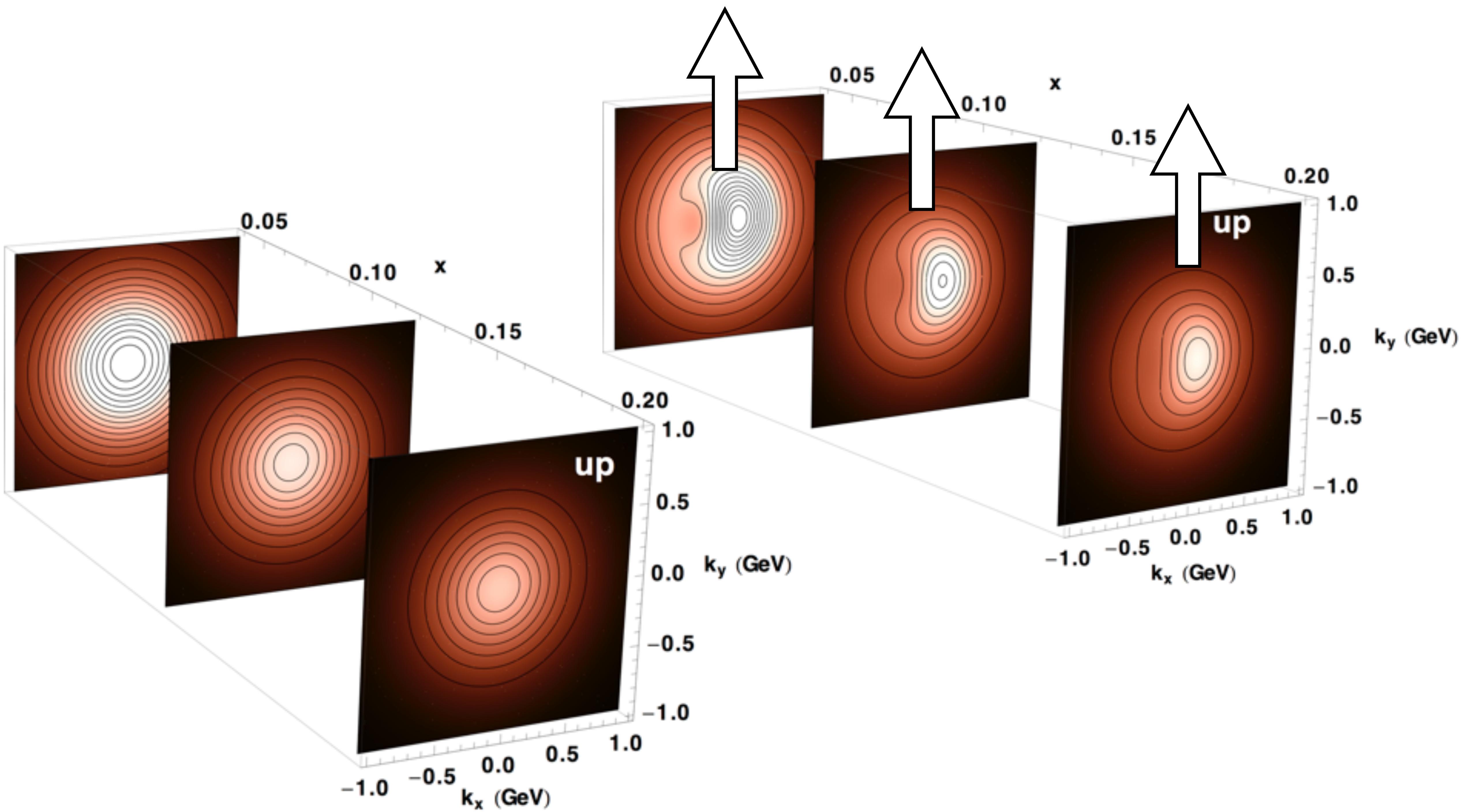


3D “imaging” in momentum space



Unpolarized TMD: cylindrically symmetric

3D "imaging" in momentum space



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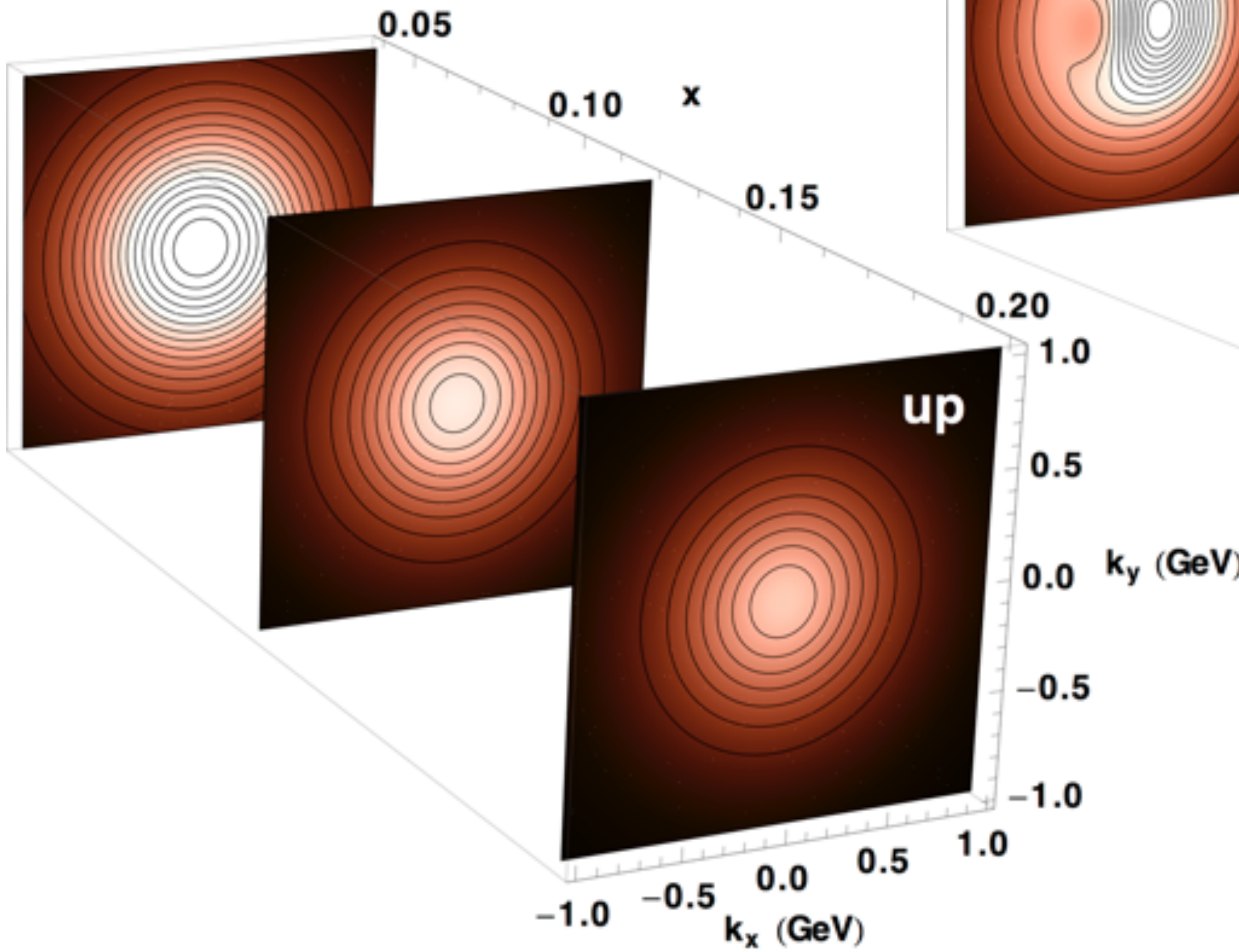
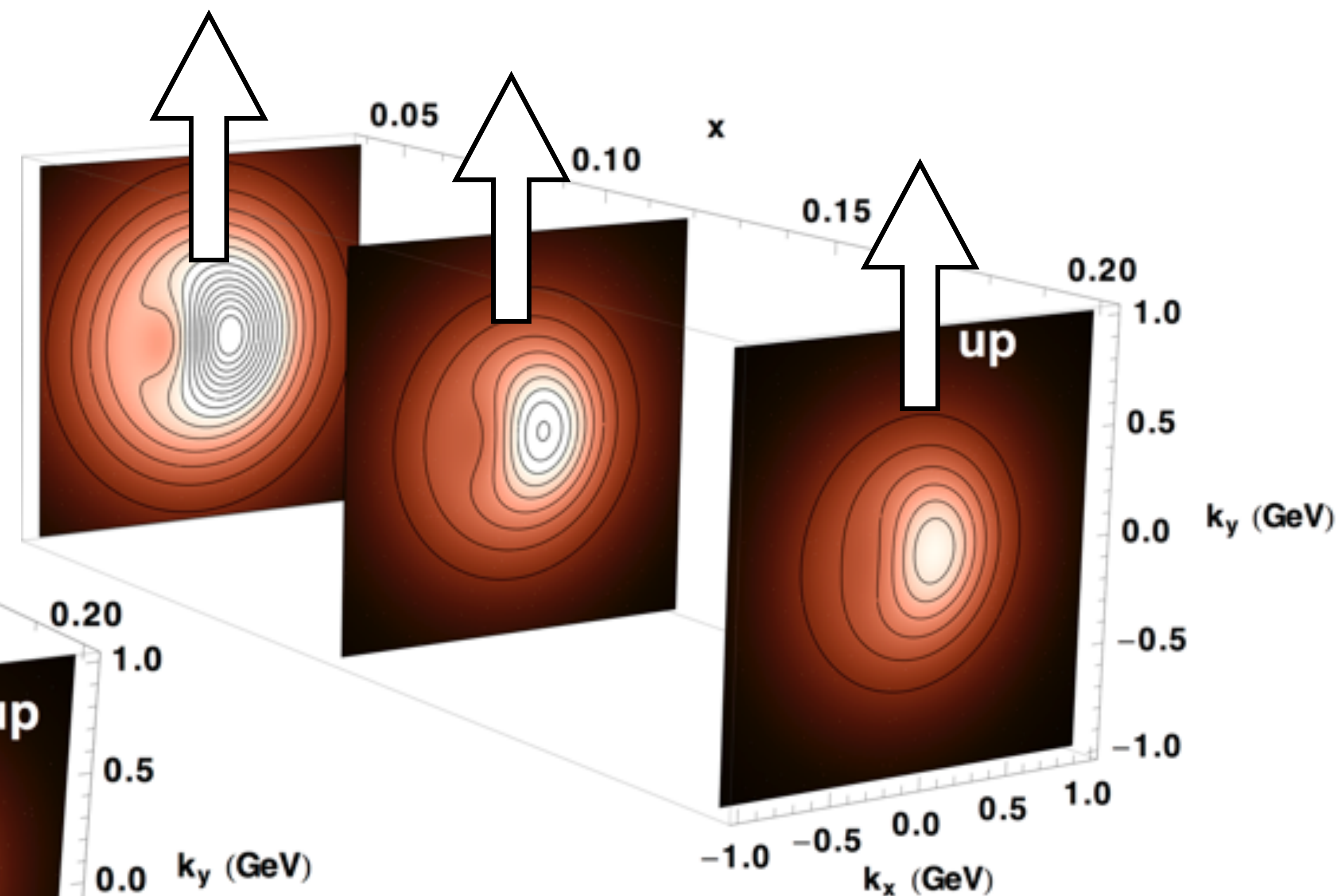
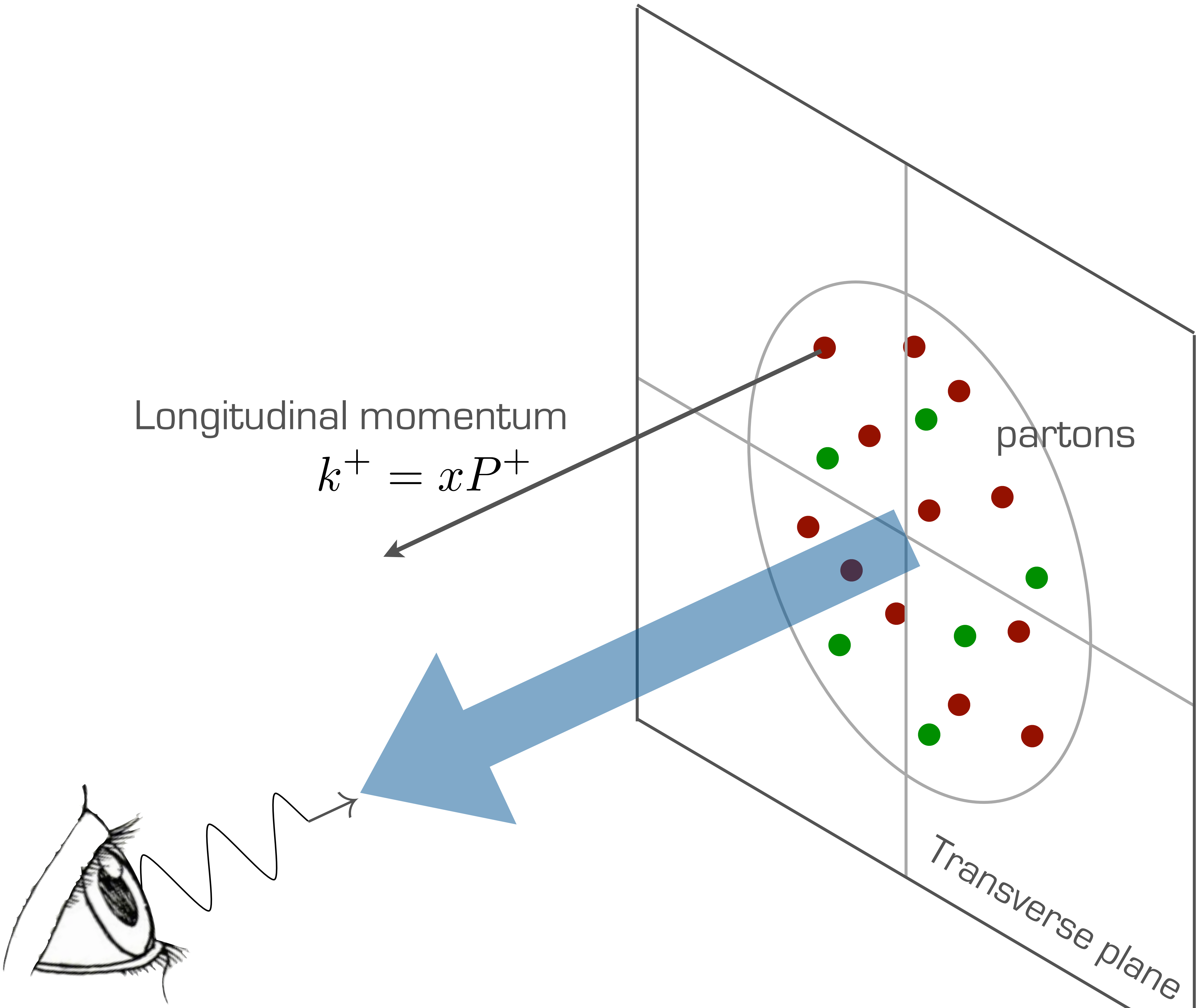




With transverse spin: distortions encoded in Sivers TMD

Requires presence of orbital angular momentum

Unpolarized TMD: cylindrically symmetric


Longitudinal momentum
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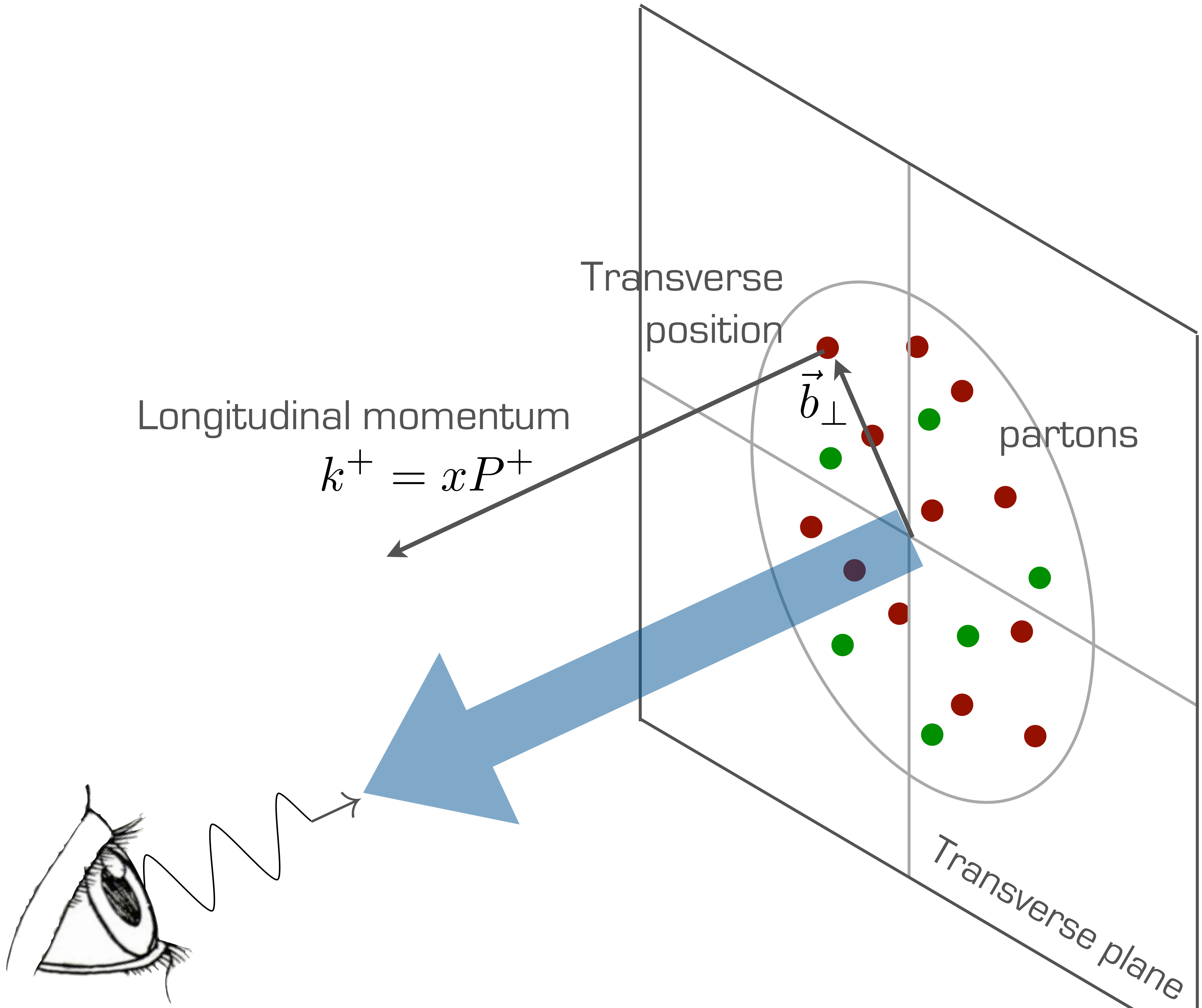
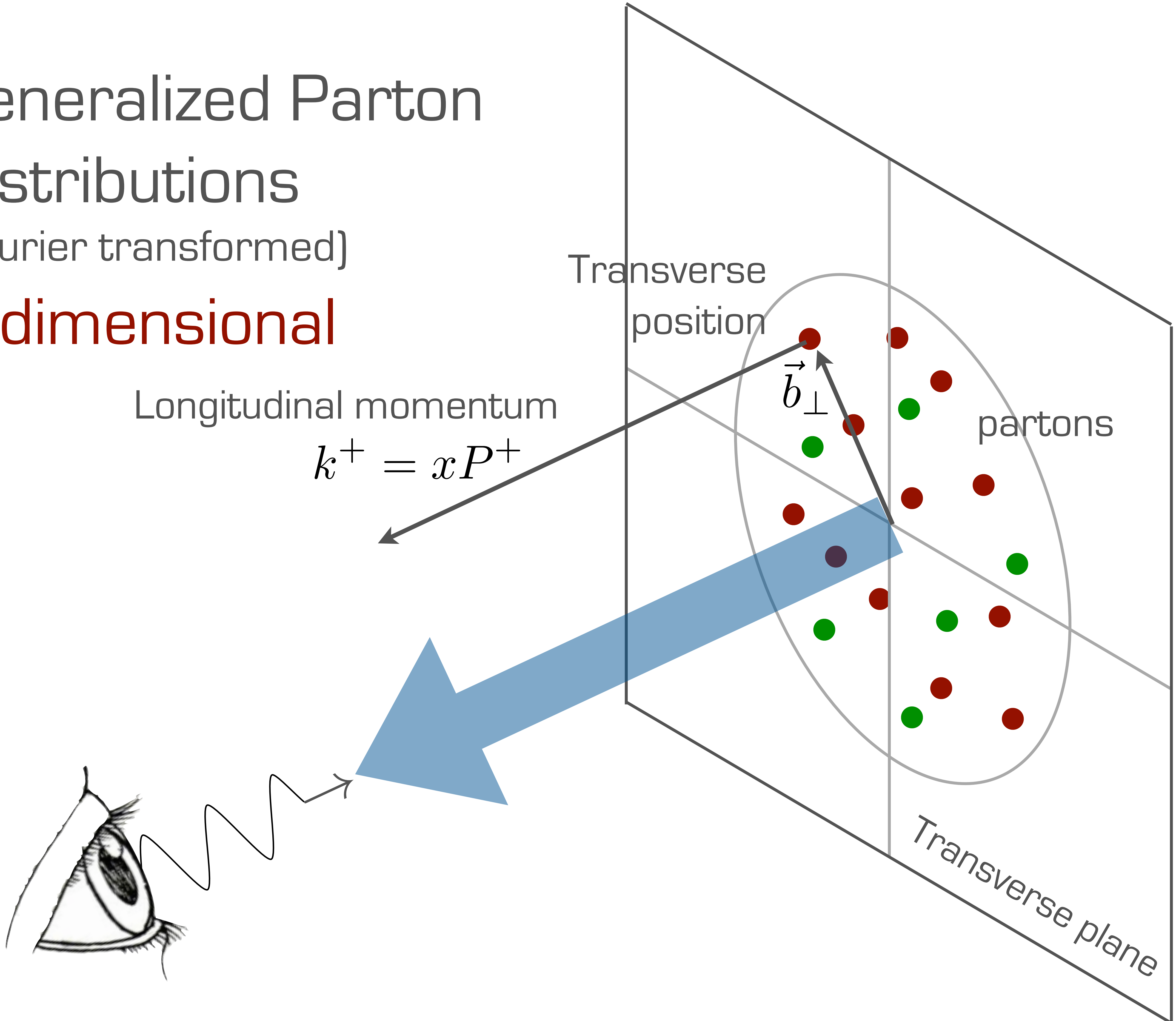


Transverse position
$\vec{b}_\perp$
partons
Longitudinal momentum
$k^+ = xP^+$
Transverse plane

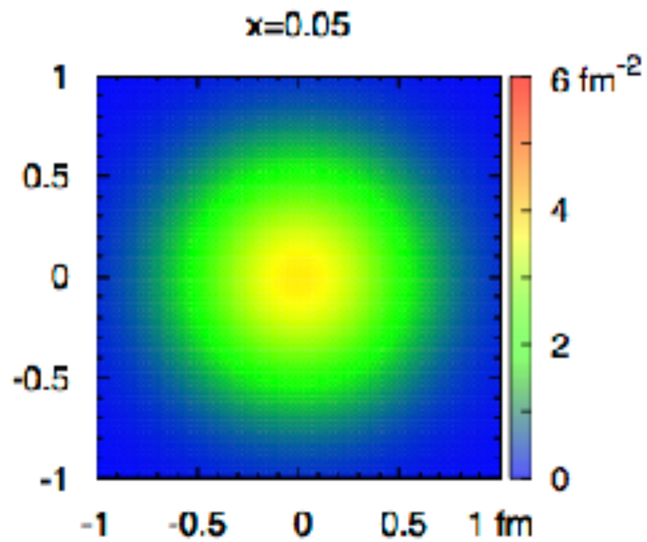
Generalized Parton Distributions

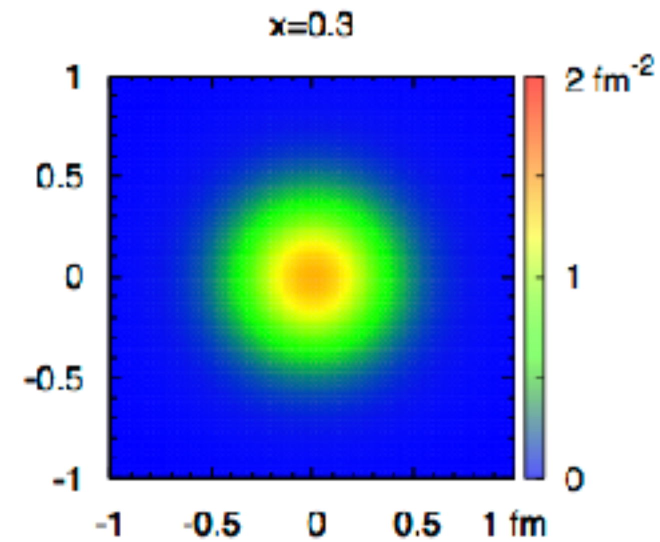
(Fourier transformed)

3 dimensional

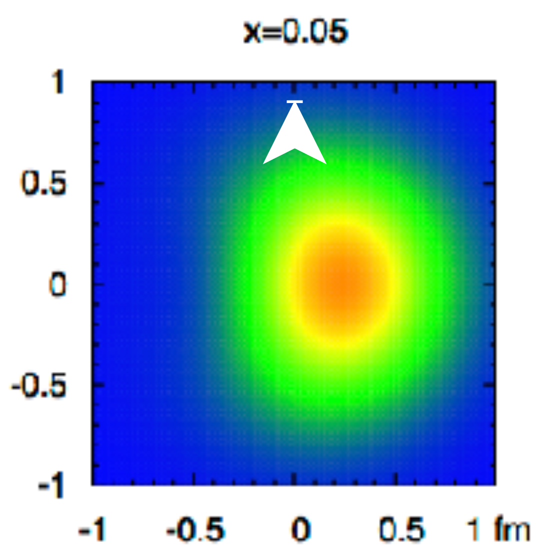


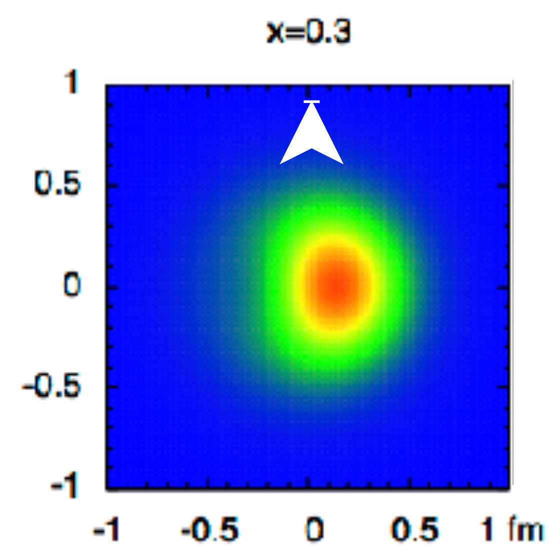
3D “imaging” in impact parameter space



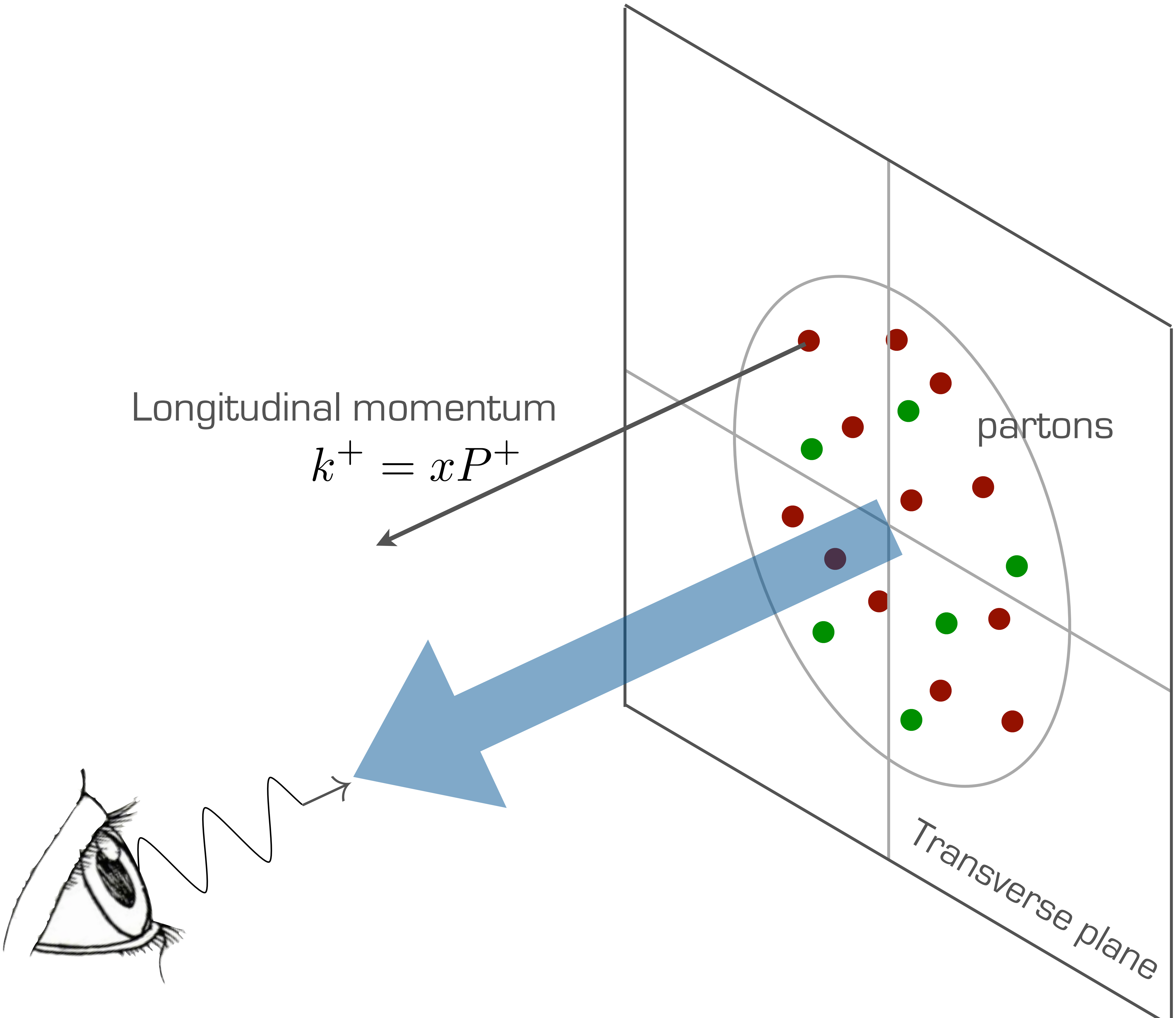


down valence





Diehl, Kroll, arXiv:1302.4604, and talk by M. Diehl at DIS 2013



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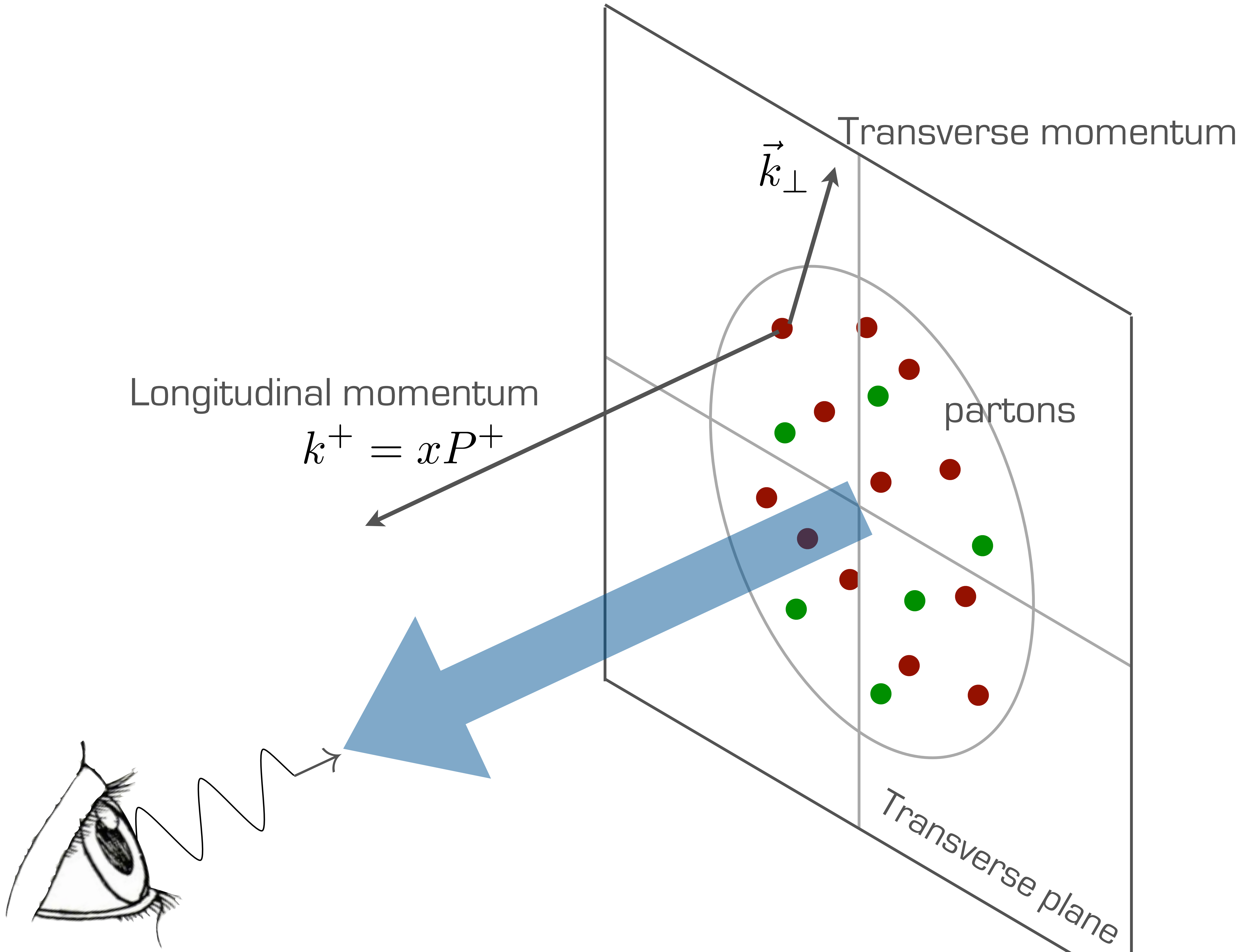
Transverse plane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$\vec{k}_\perp$
Longitudinal momentum
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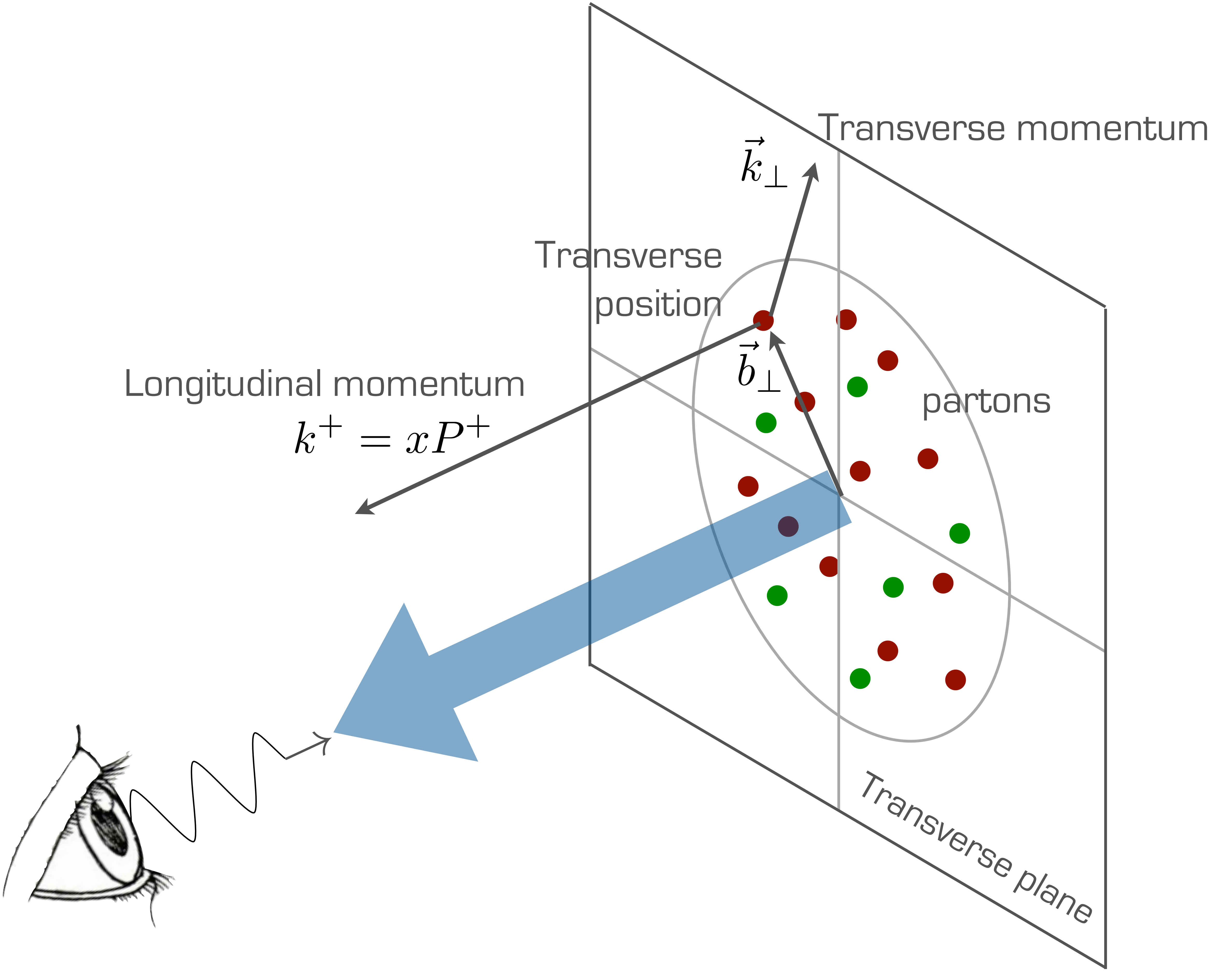
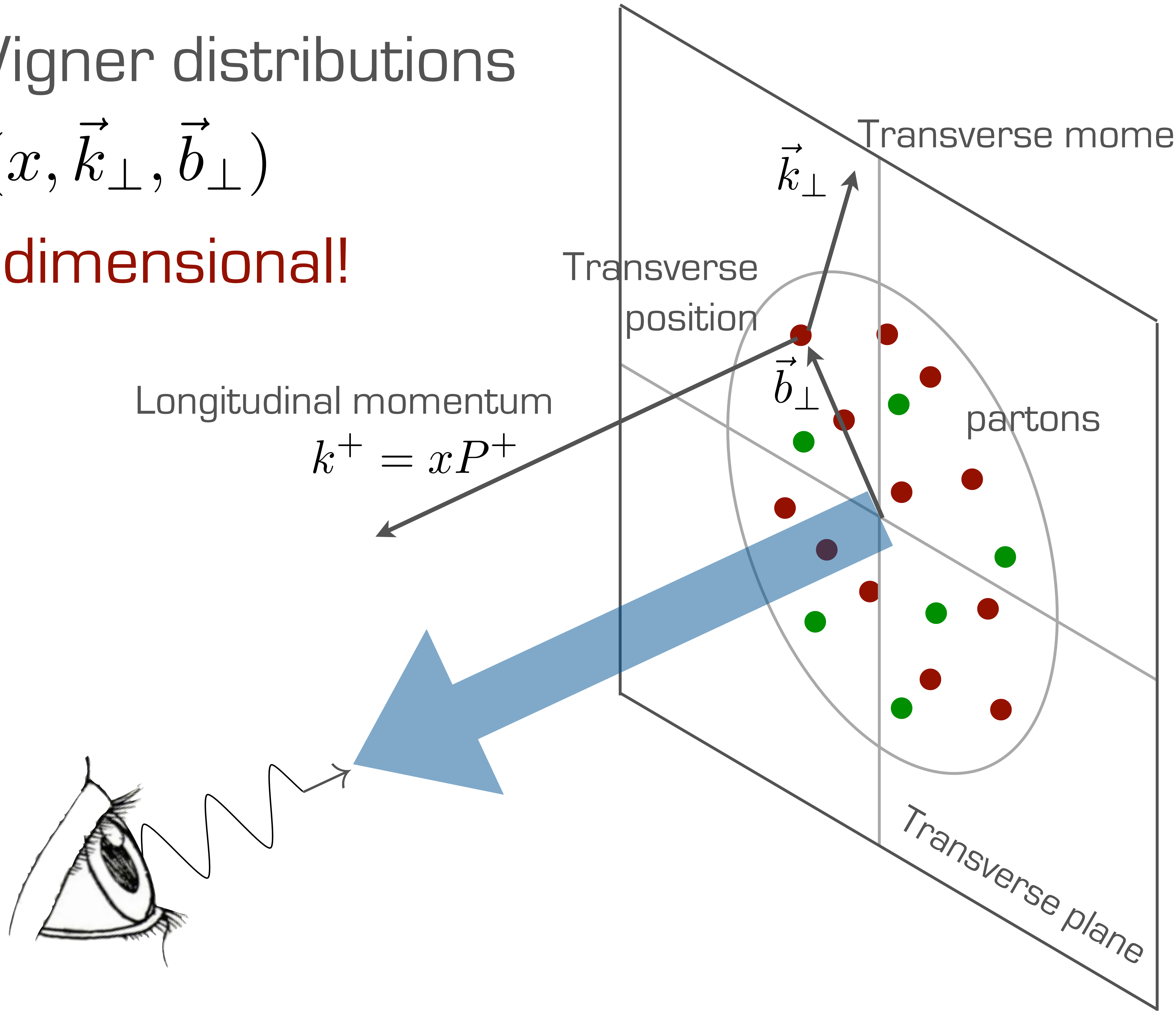
Transverse plane

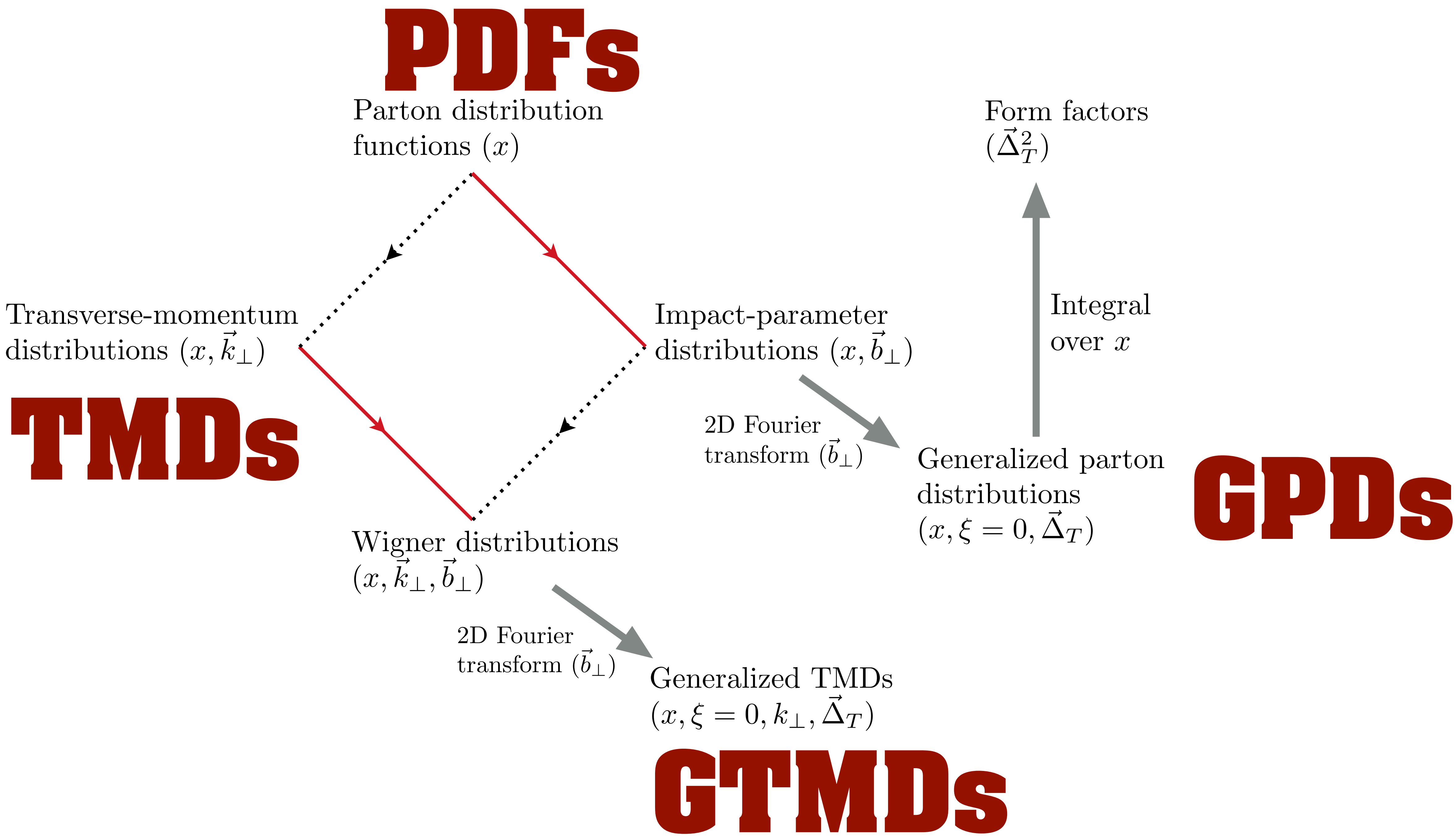

Transverse momentum
$\vec{k}_\perp$
Transverse
position
$\vec{b}_\perp$
partons
Longitudinal momentum
$k^+ = xP^+$
Transverse plane

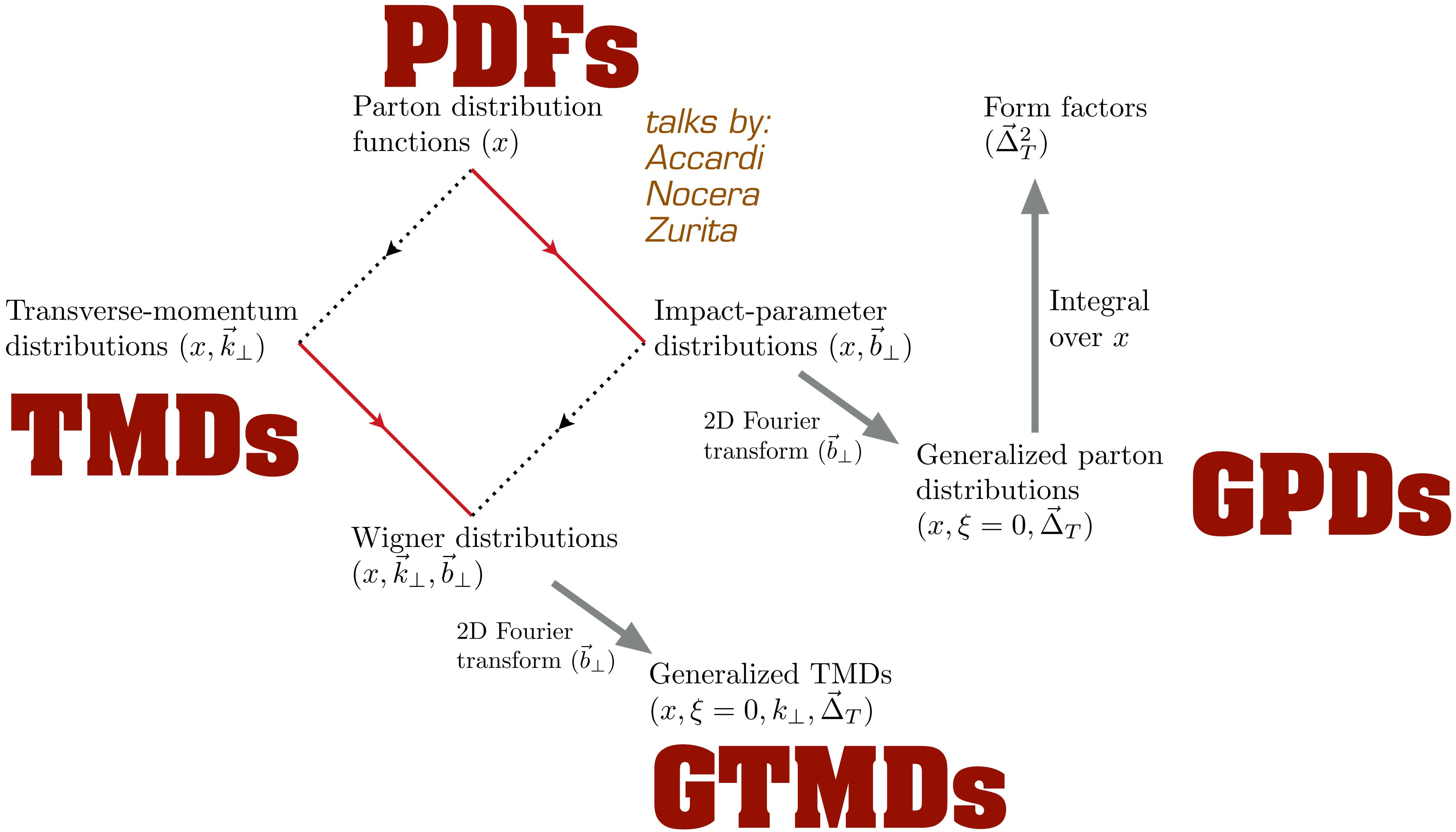
Wigner distributions

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

5 dimensional!




PDFs
Parton distribution functions (x)
Transverse-momentum distributions $(x, \vec{k}_\perp)$
TMDs
Impact-parameter distributions $(x, \vec{b}_\perp)$
Wigner distributions $(x, \vec{k}_\perp, \vec{b}_\perp)$
2D Fourier transform $(\vec{b}_\perp)$
Generalized TMDs $(x, \xi = 0, k_\perp, \vec{\Delta}_T)$
GTMDs
2D Fourier transform $(\vec{b}_\perp)$
Generalized parton distributions $(x, \xi = 0, \vec{\Delta}_T)$
GPDs
Integral over x
Form factors $(\vec{\Delta}_T^2)$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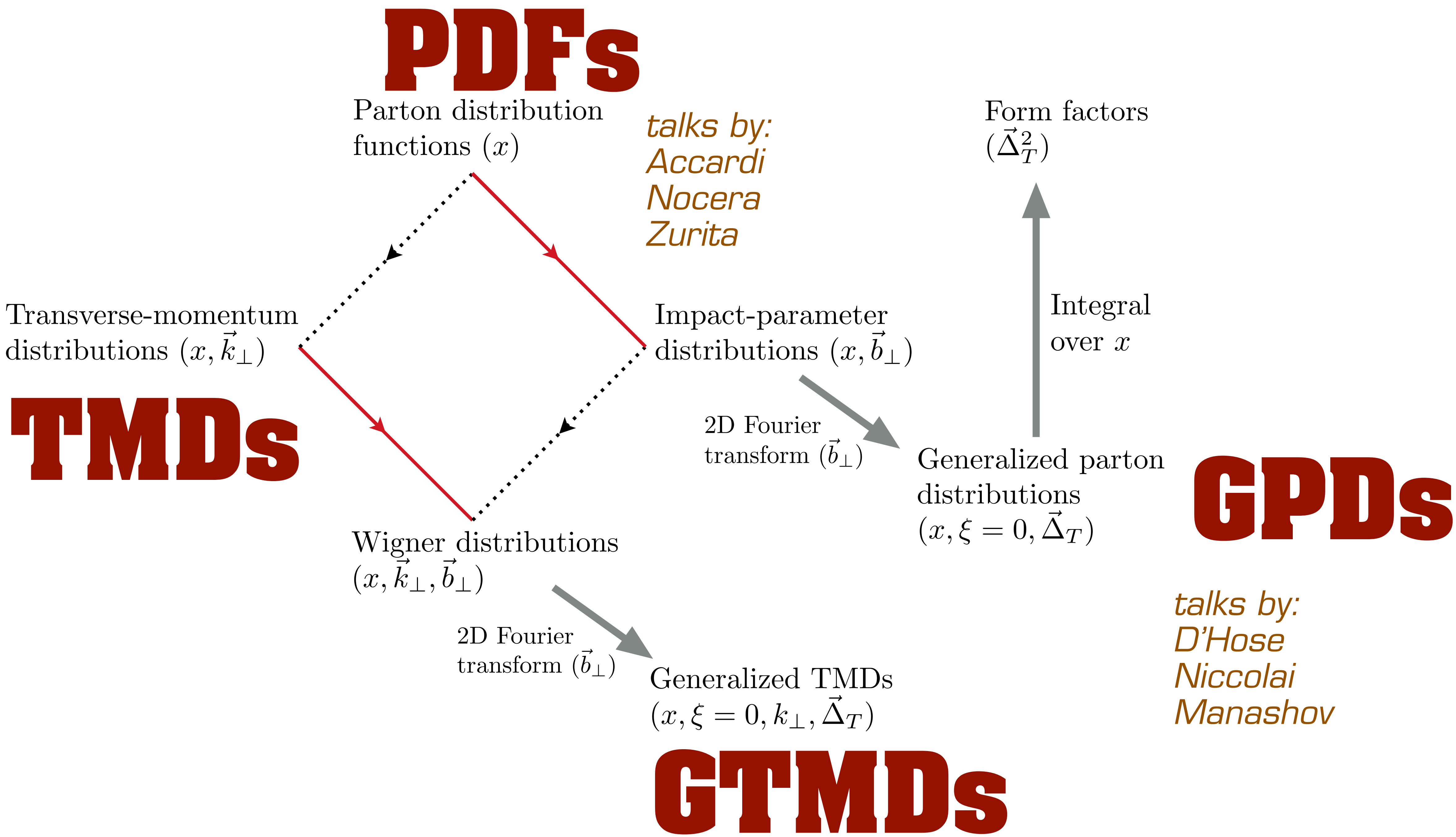
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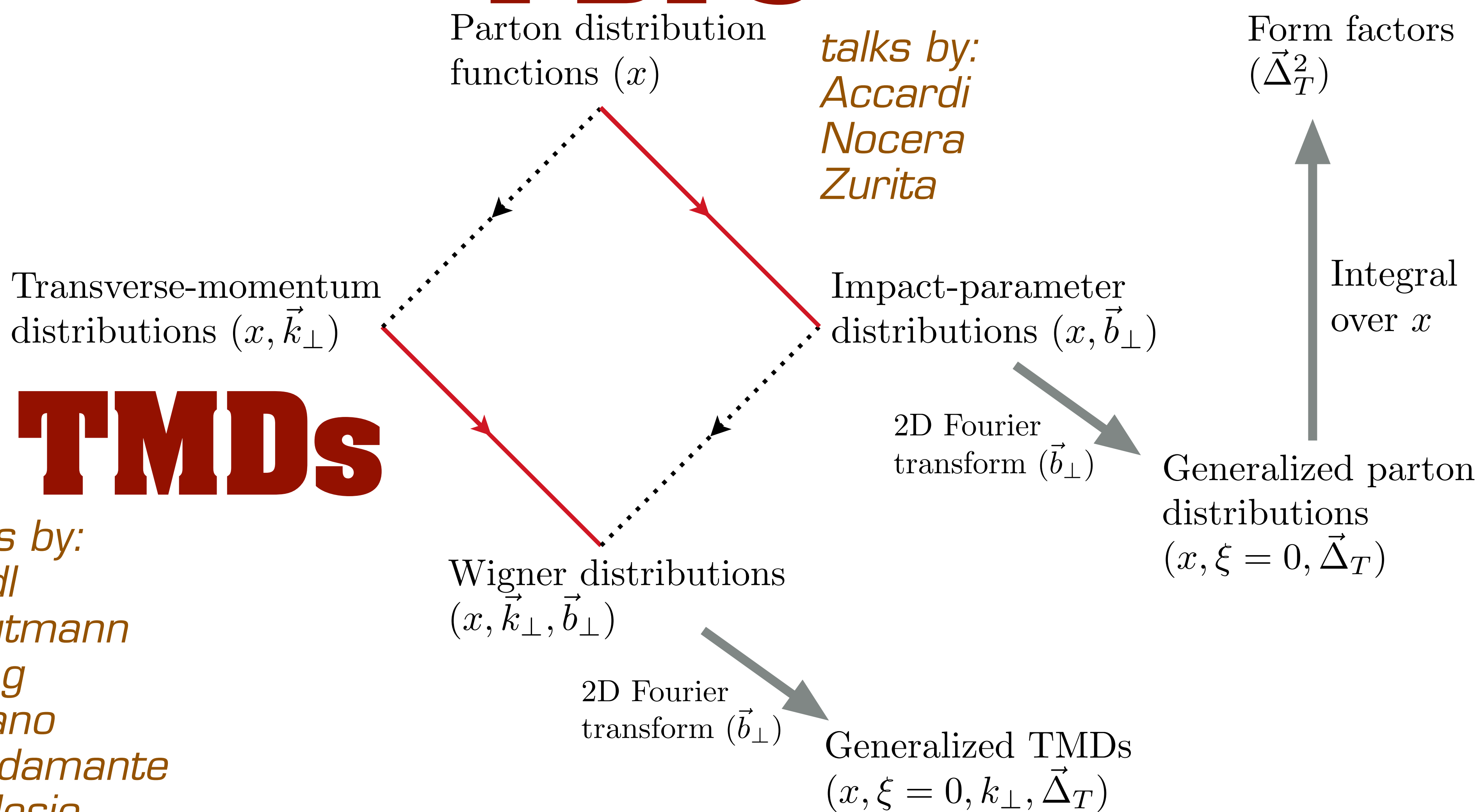

talks by:
Accardi
Nocera
Zurita

TMDs

talks by:
Seidl
Hautmann
Kang
Pisano
Bradamante
D'Alesio
Schaefer
Cloet
Kotzinian
Artru
Diefenthaler
Gonzalez
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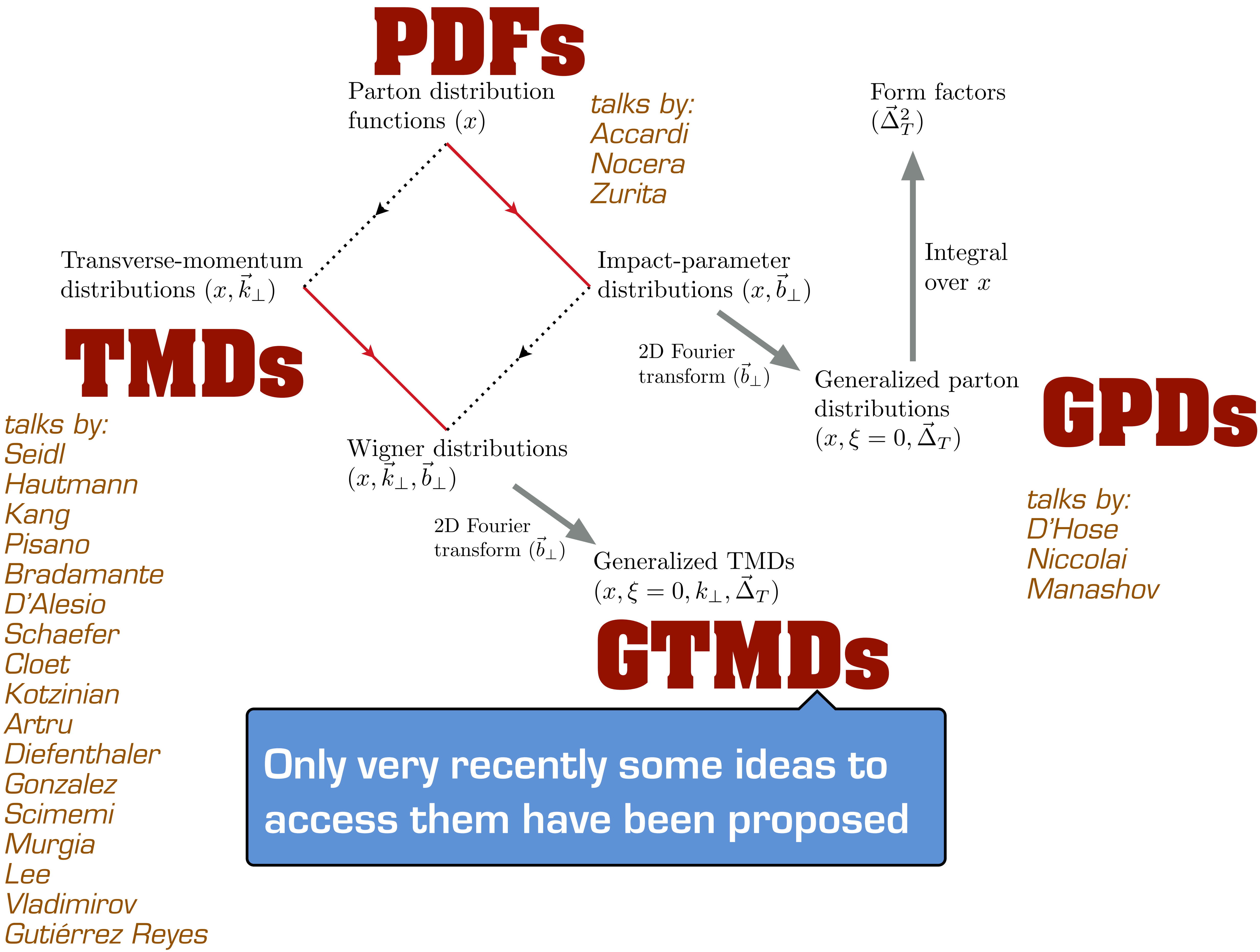
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Only very recently some ideas to access them have been proposed

Why do we do it?

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- To benefit society?

Example: impact on high-energy physics

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

ATLAS Collab. arXiv:1701.07240

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In other words, LHC needs us...

$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \overline{\psi}_q (i \not{\partial} - g \not{A} + m) \psi_q - \frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu}$$

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QCD is the most complex part of the Standard Model and at the same time the most useful, after QED

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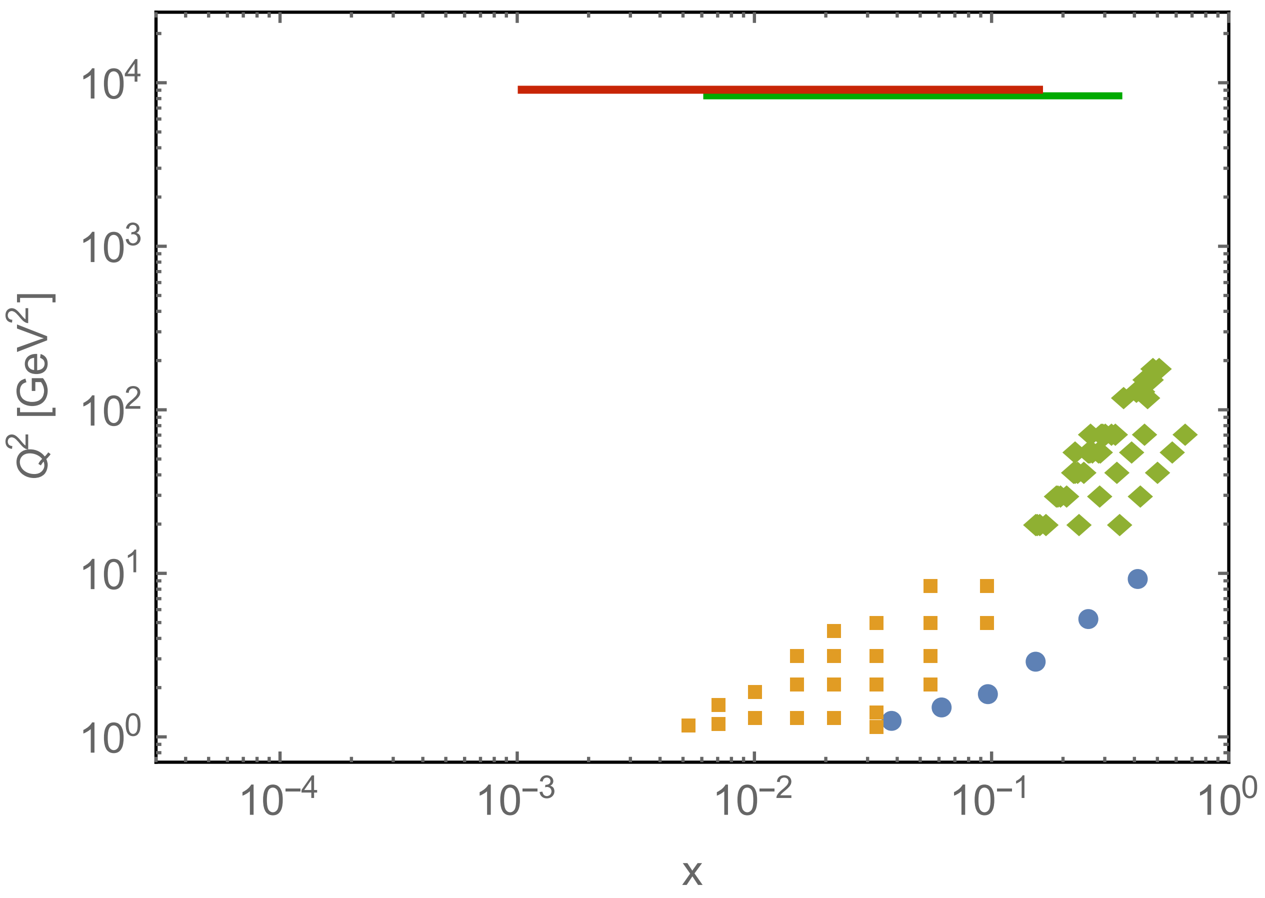
Either we build the EIC,
or we give up understanding QCD

TMDs

TMD Science Matrix


Deliverables	Observables	What we learn
Sivers & unpolarized TMD quarks and gluon	SIDIS with transverse polarization; di-hadron (di-jet)	Quantum interference & spin-orbital correlations 3D Imaging of quark's motion: valence + sea 3D Imaging of gluon's motion QCD dynamics in an unprecedented Q^2 (P_{hT}) range
Chiral-odd functions: transversity; Boer-Mulders	SIDIS with transverse polarization	3rd basic quark PDF: valence + sea, tensor charge Novel spin-dependent hadronization effect QCD dynamics in a chiral-odd sector with a wide Q^2 (P_{hT}) coverage

Quark unpol. TMD: measurements



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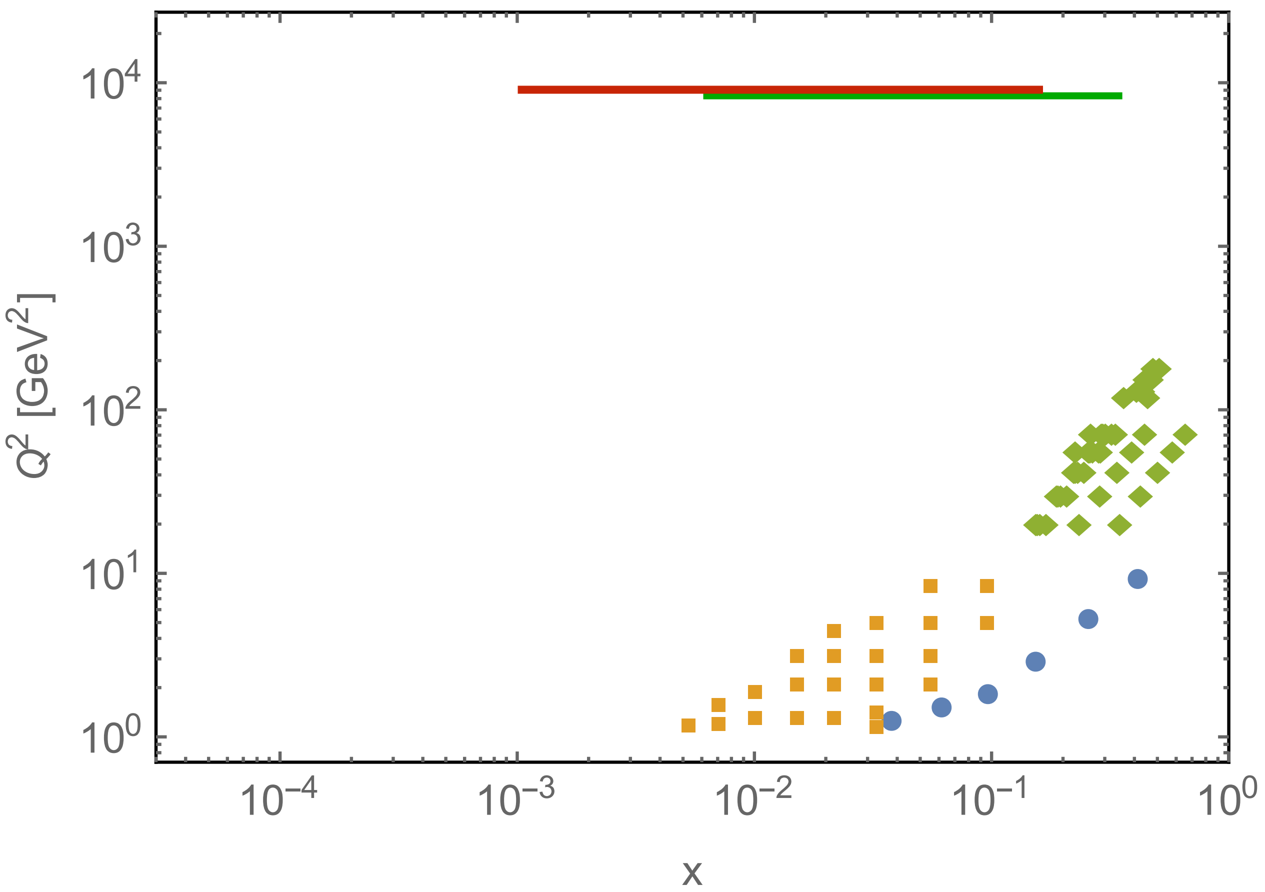

Drell-Yan@ Fermilab

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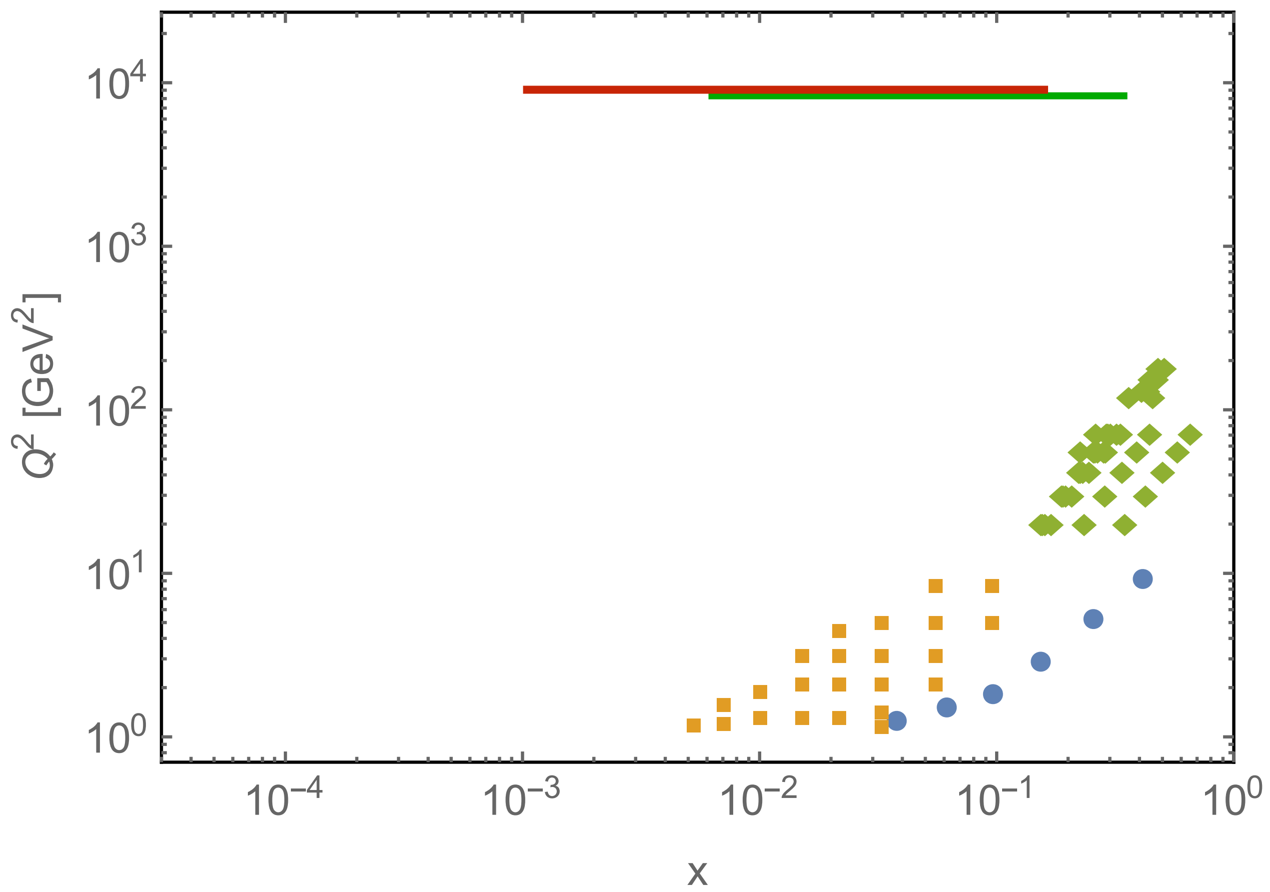

Z production@ Tevatron

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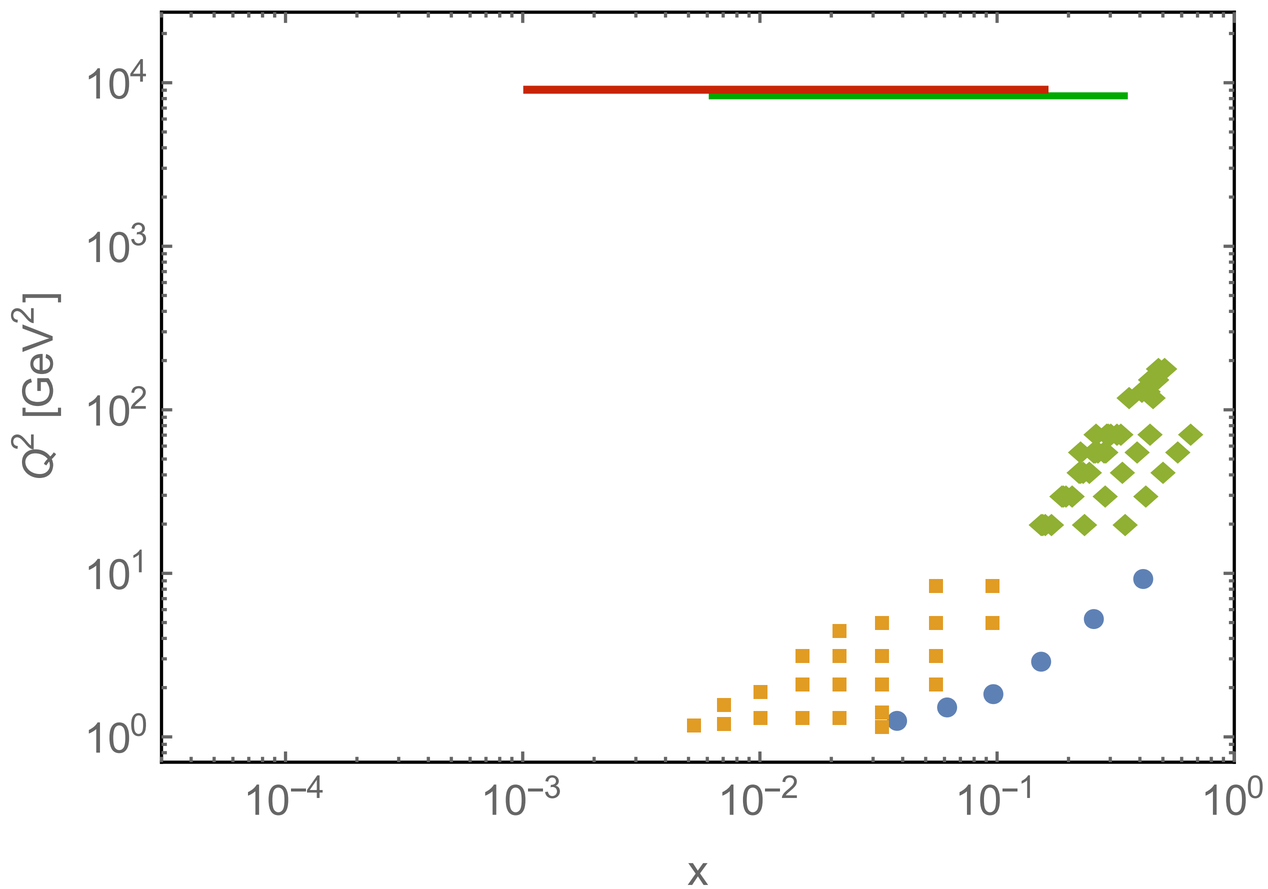

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SIDIS@ hermes

Quark unpol. TMD: measurements

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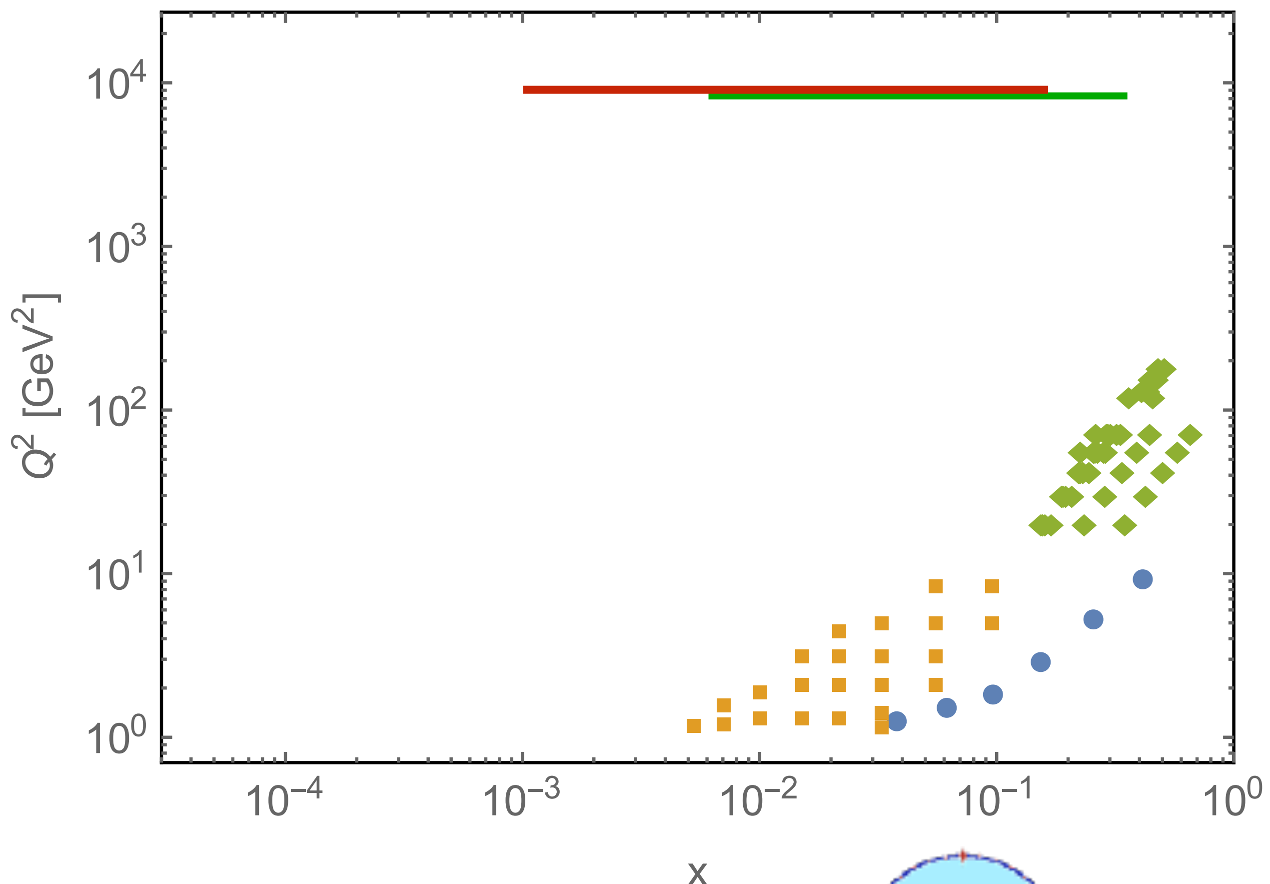
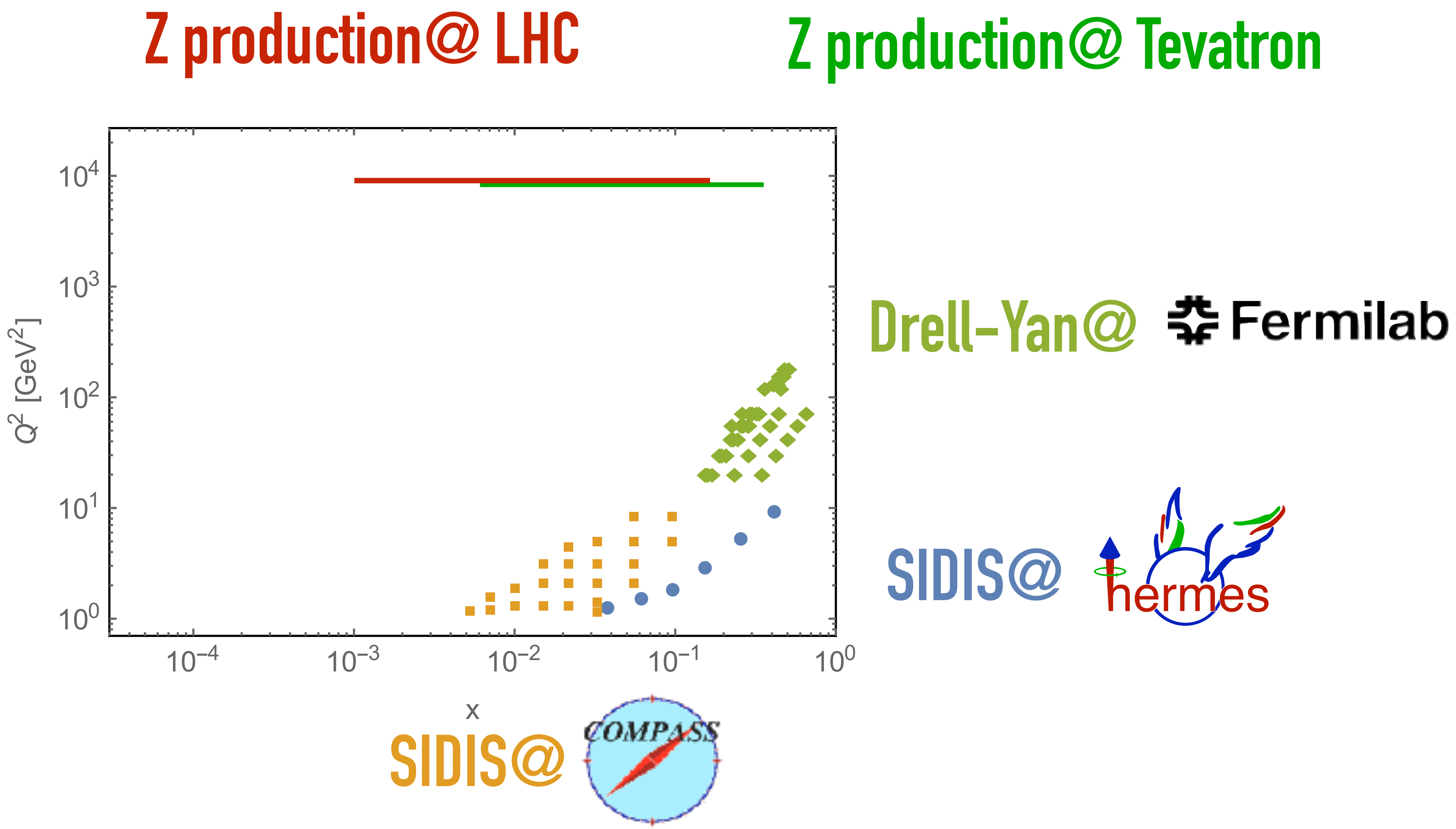


Drell-Yan@ Fermilab

SIDIS@ hermes

SIDIS@ COMPASS

Quark unpol. TMD: measurements

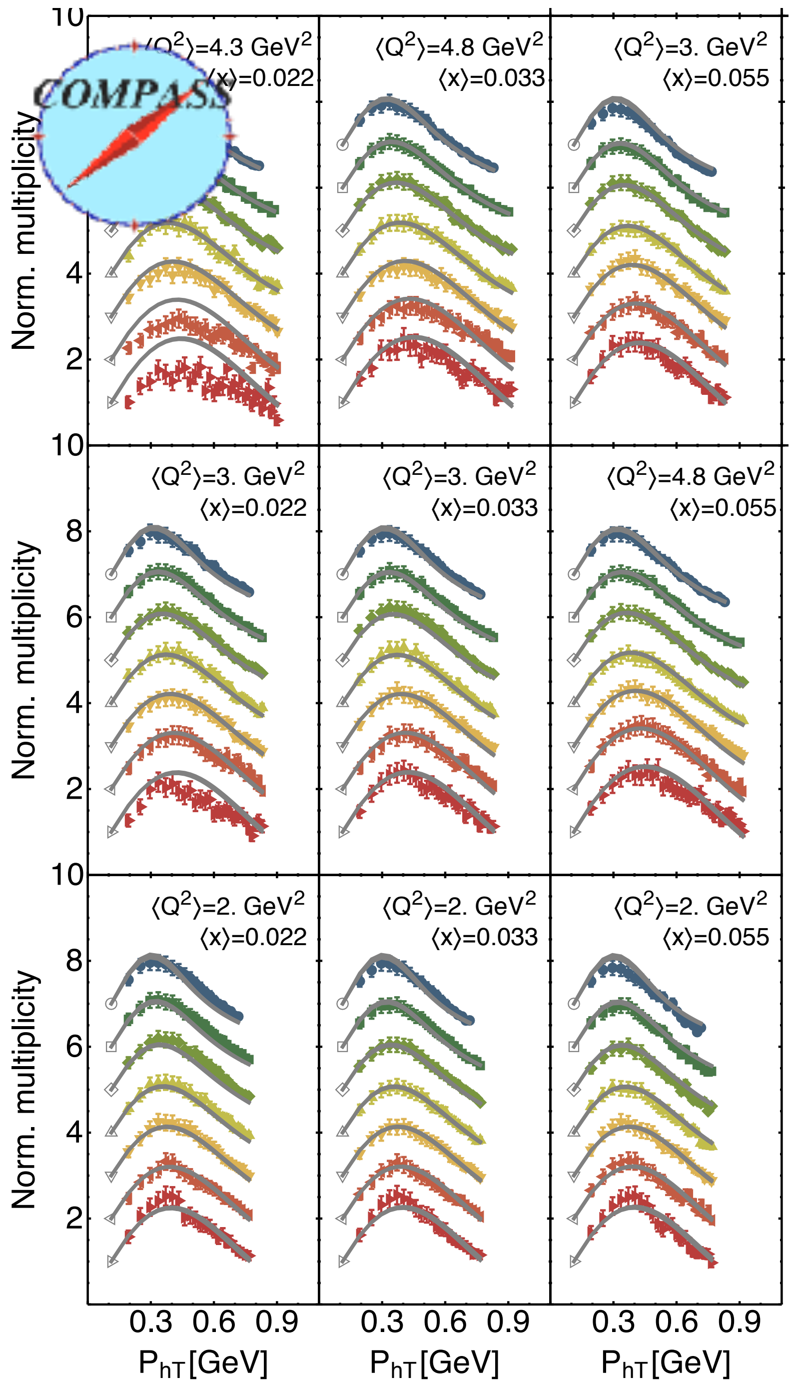


Quark unpol. TMD: extractions

	Framework	HERMES	COMPASS	DY	Z production	N of points
KN 2006 hep-ph/0506225	NLL/NLO	✘	✘	✔	✔	98
Pavia 2013 arXiv:1309.3507	No evo	✔	✘	✘	✘	1538
Torino 2014 arXiv:1312.6261	No evo	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NNLL/NLO	✘	✘	✔	✔	223
EIKV 2014 arXiv:1401.5078	NLL/LO	1 (x,Q^2) bin	1 (x,Q^2) bin	✔	✔	500 (?)
Pavia 2016 arXiv:1703.10157	NLL/LO	✔	✔	✔	✔	8059
SV 2017 arXiv:1706.01473	NNLL/ NNLO	✘	✘	✔	✔	309

First global fit of TMDs

SIDIS



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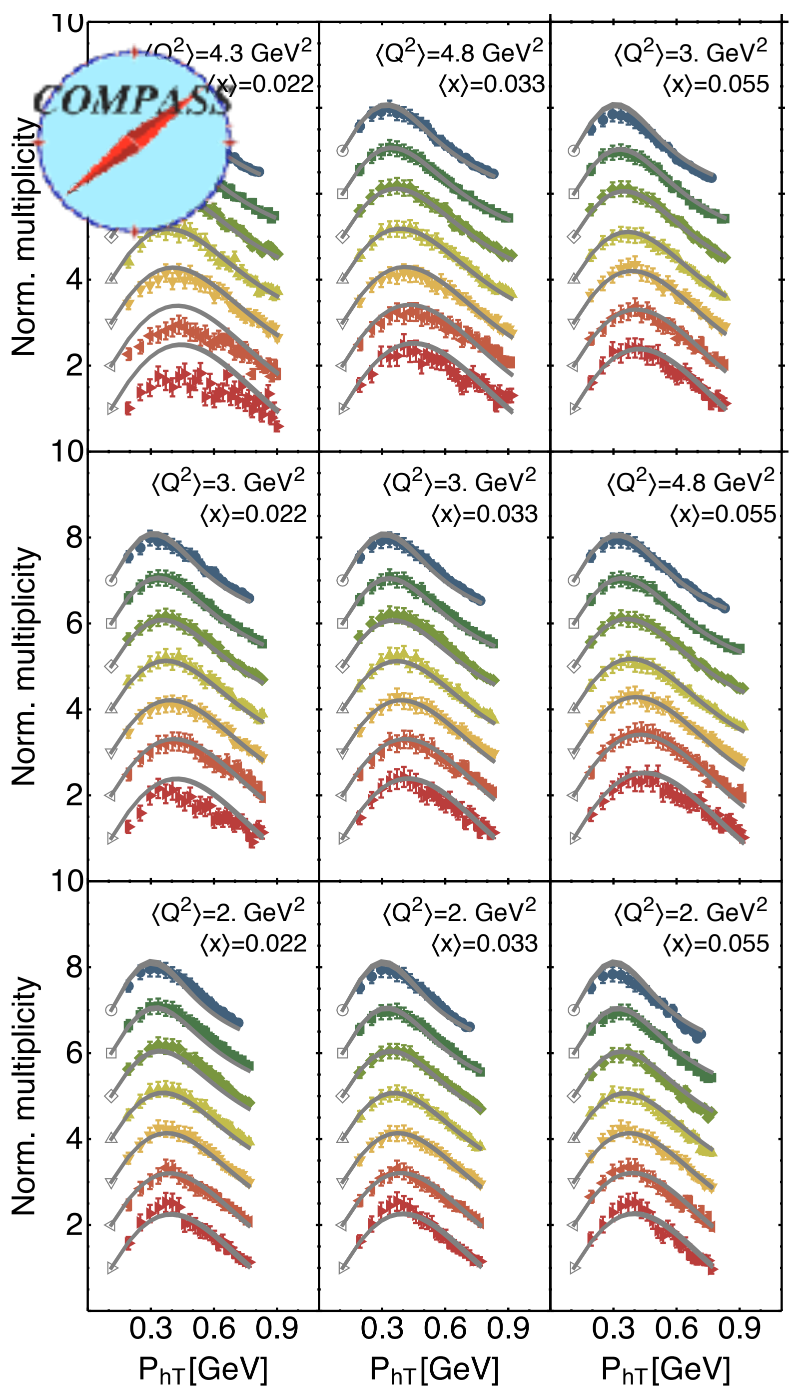

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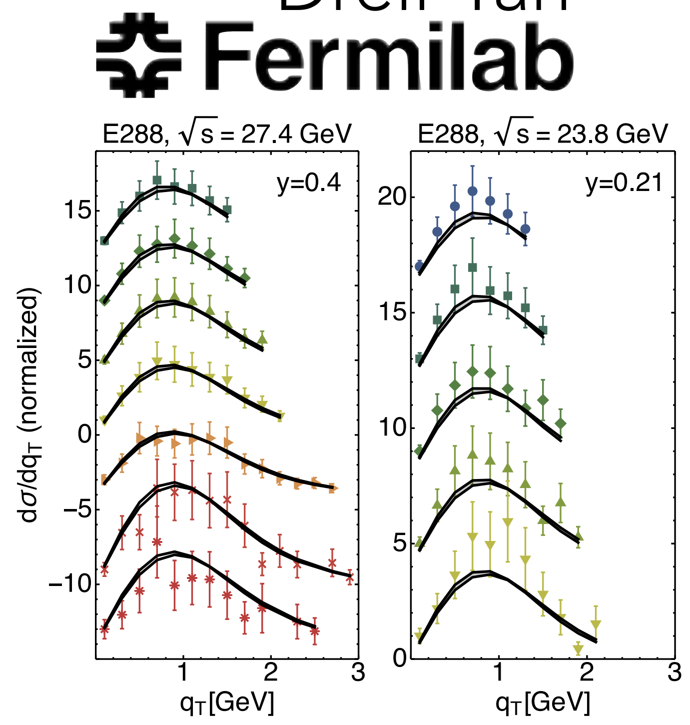

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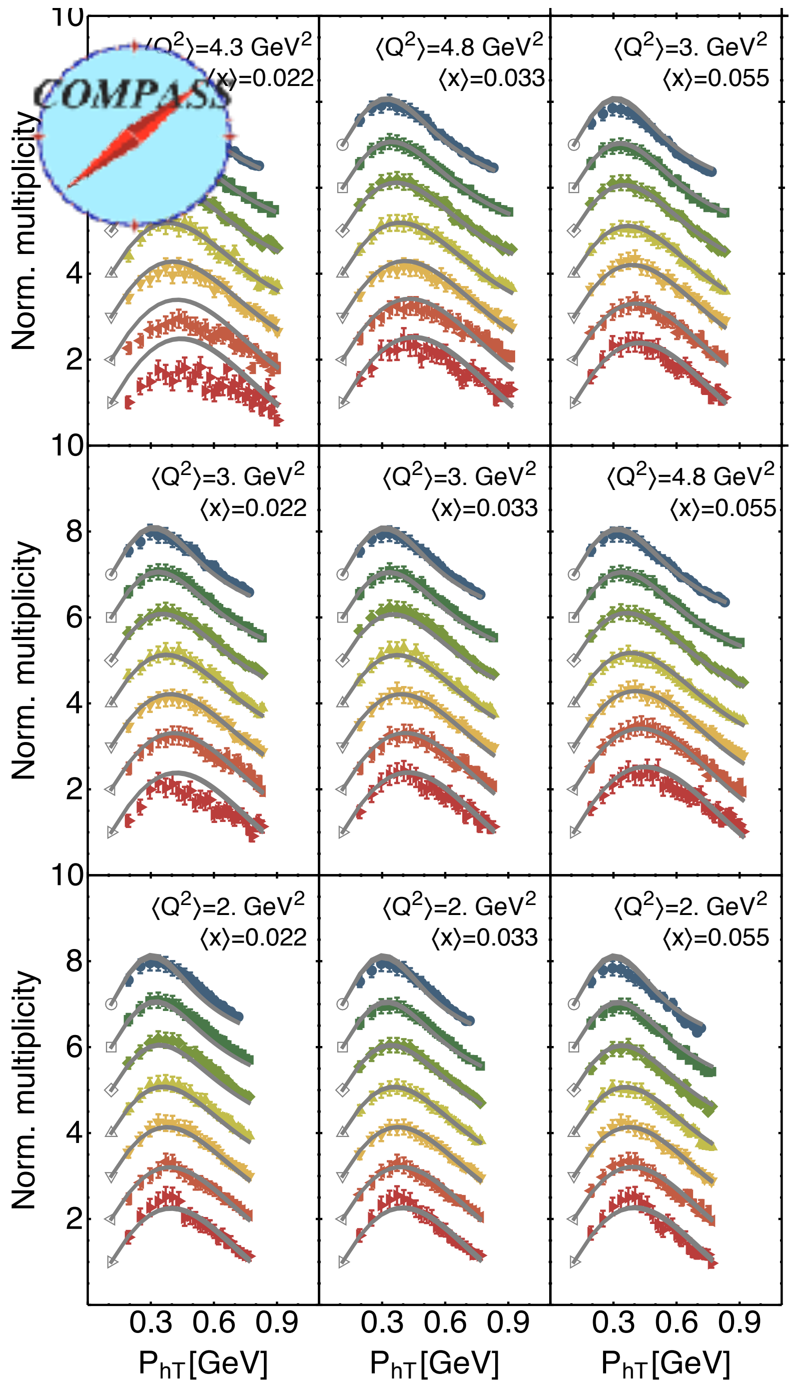
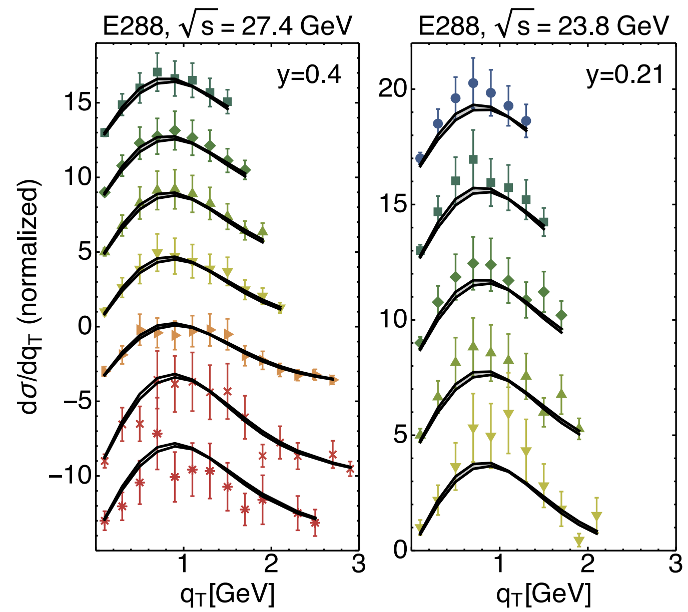
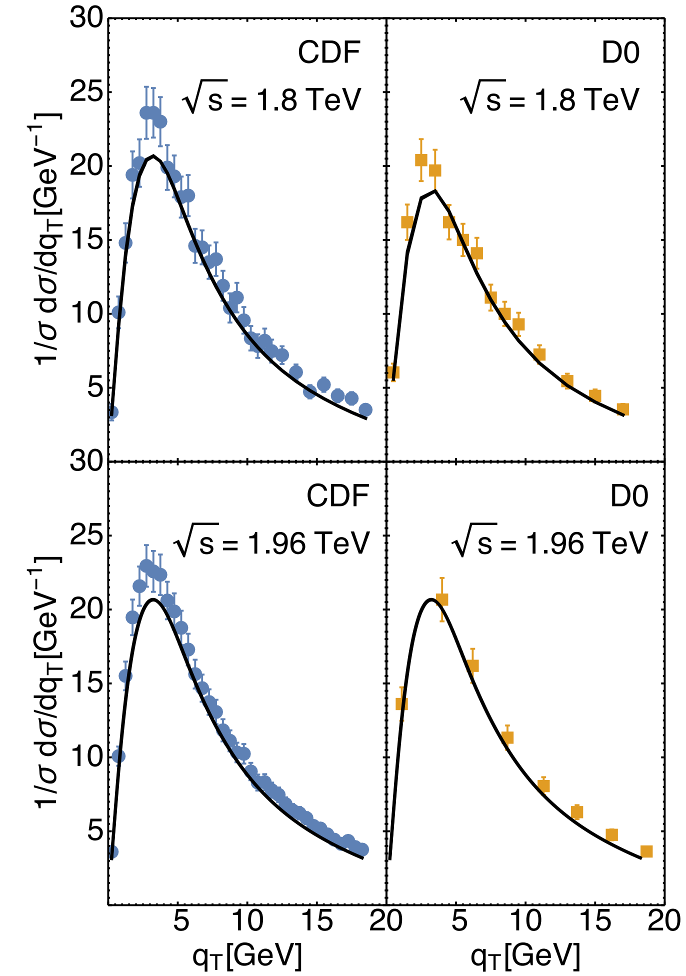


Drell-Yan

Fermilab

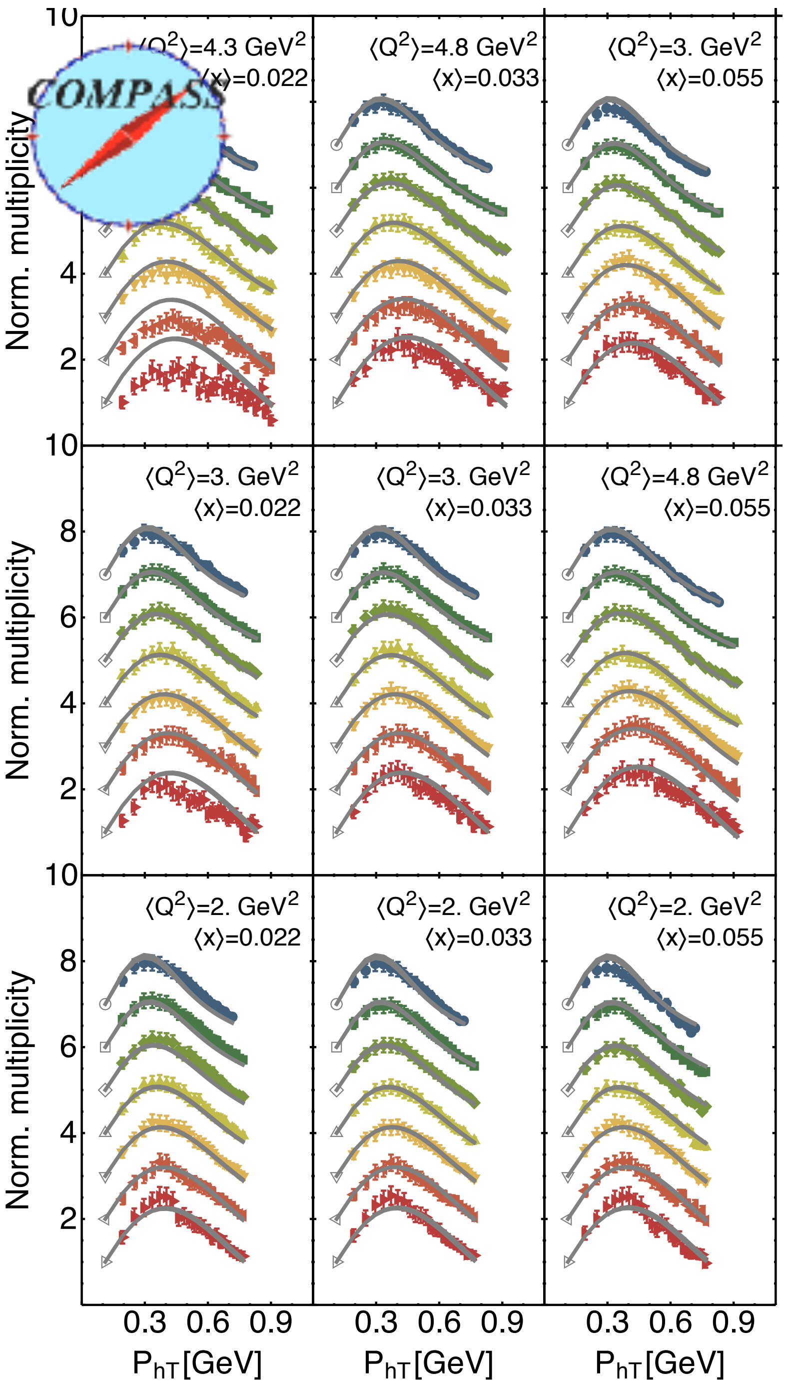


Z production

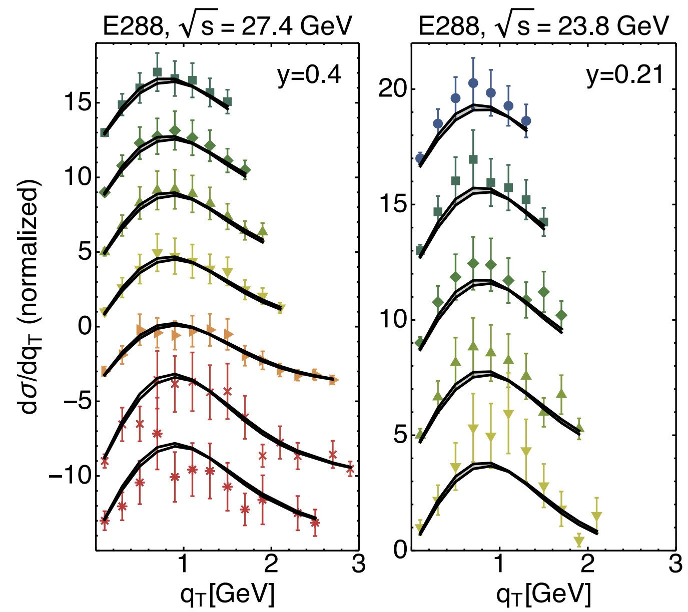


First global fit of TMDs

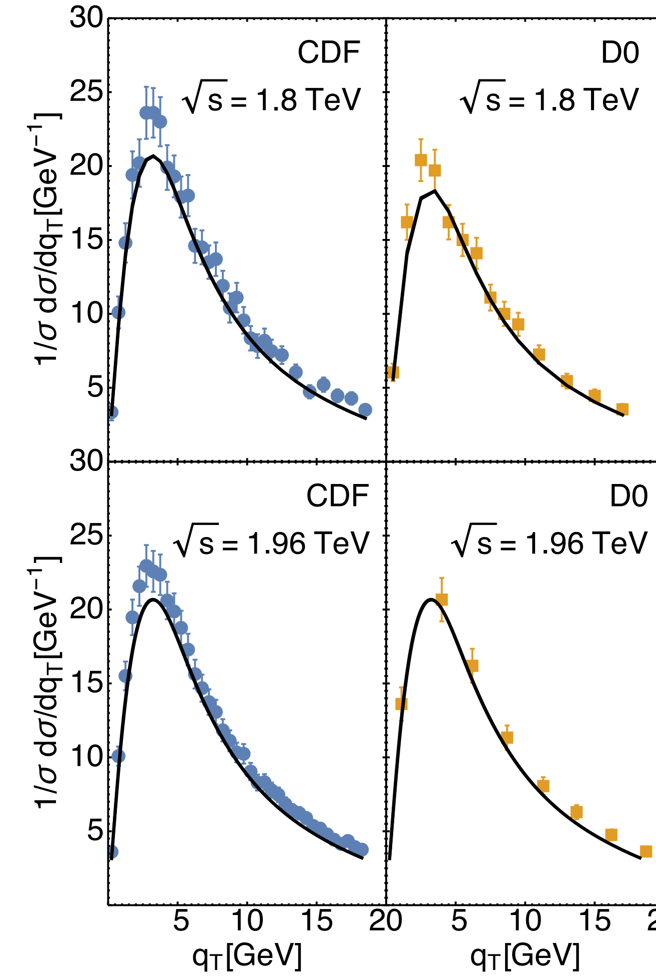
SIDIS



Drell-Yan



Z production



Number of data points: 8059

Global χ^2/dof = 1.52

Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

see talk by C. Pisano

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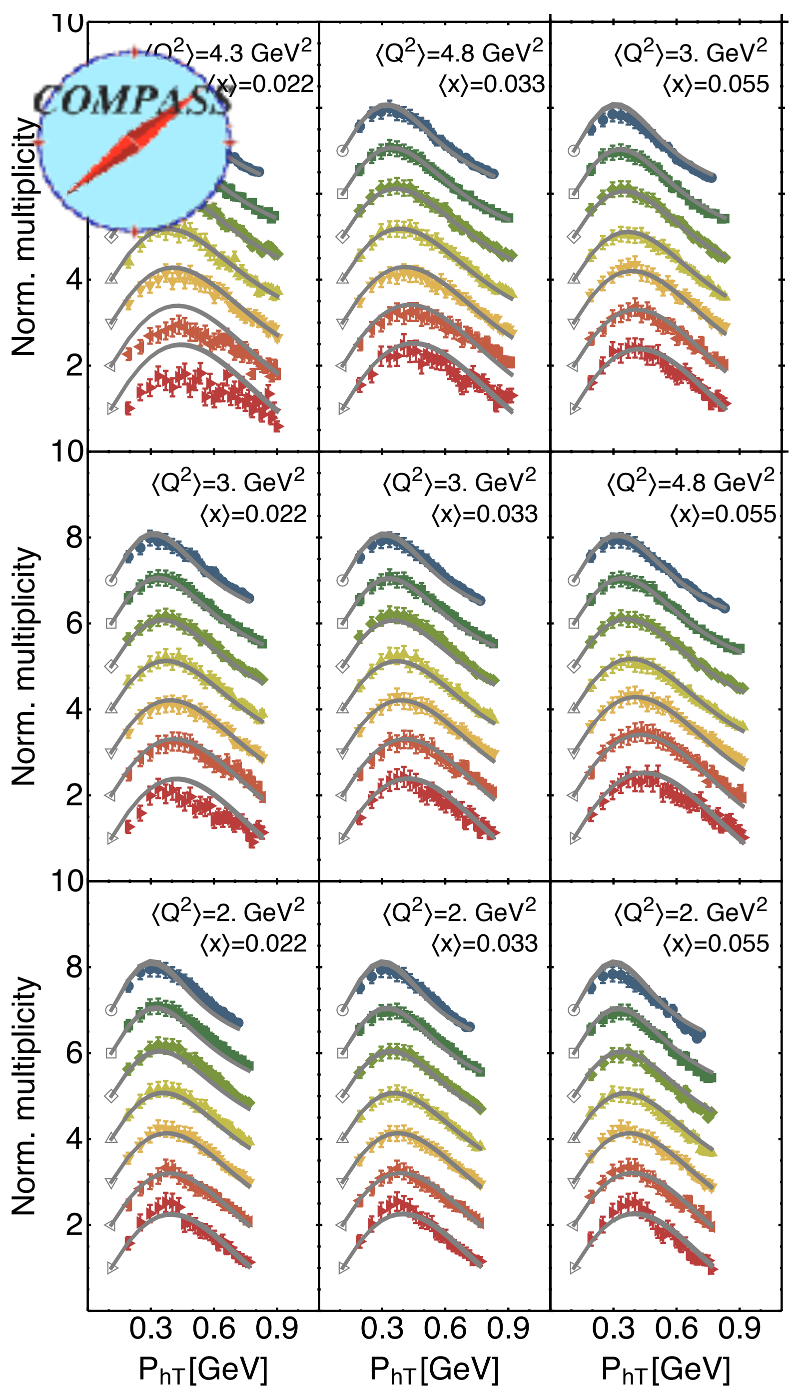
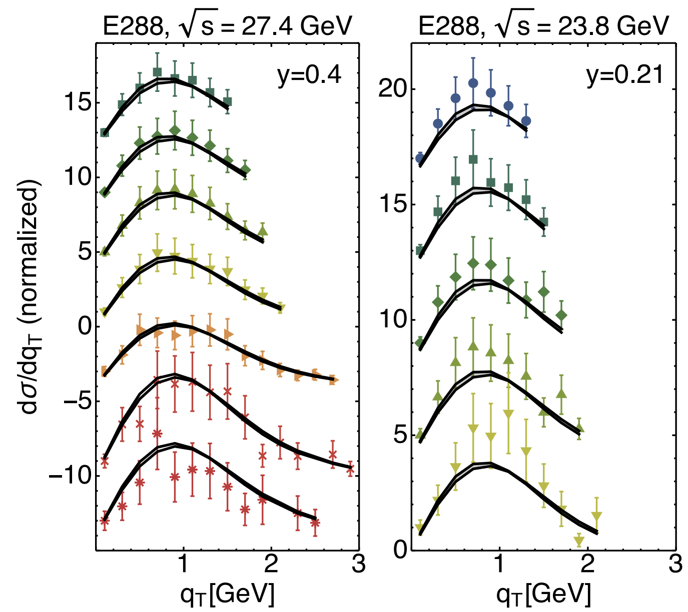


Drell-Yan



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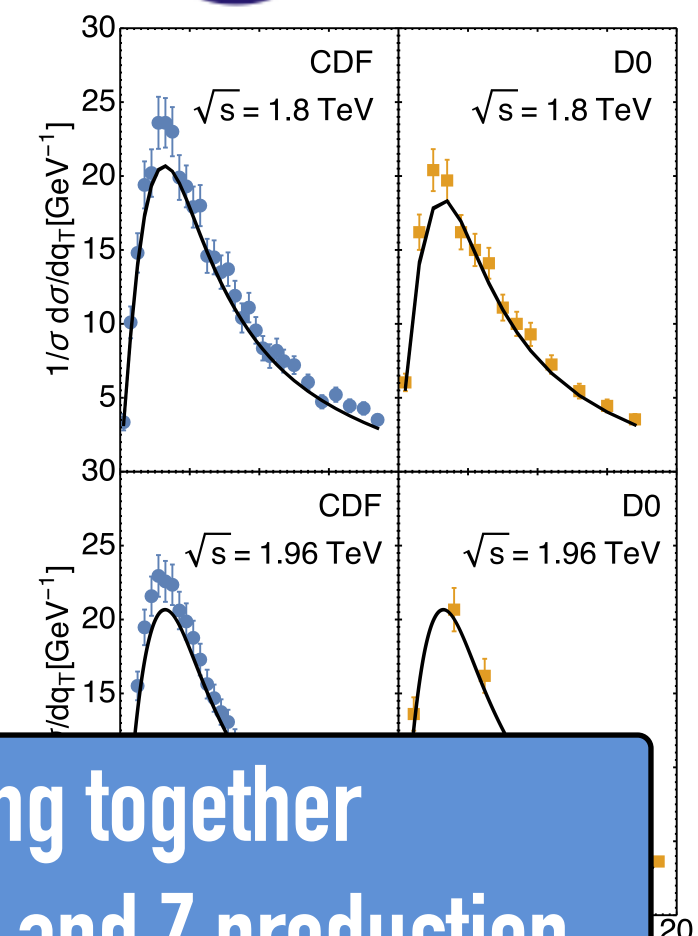

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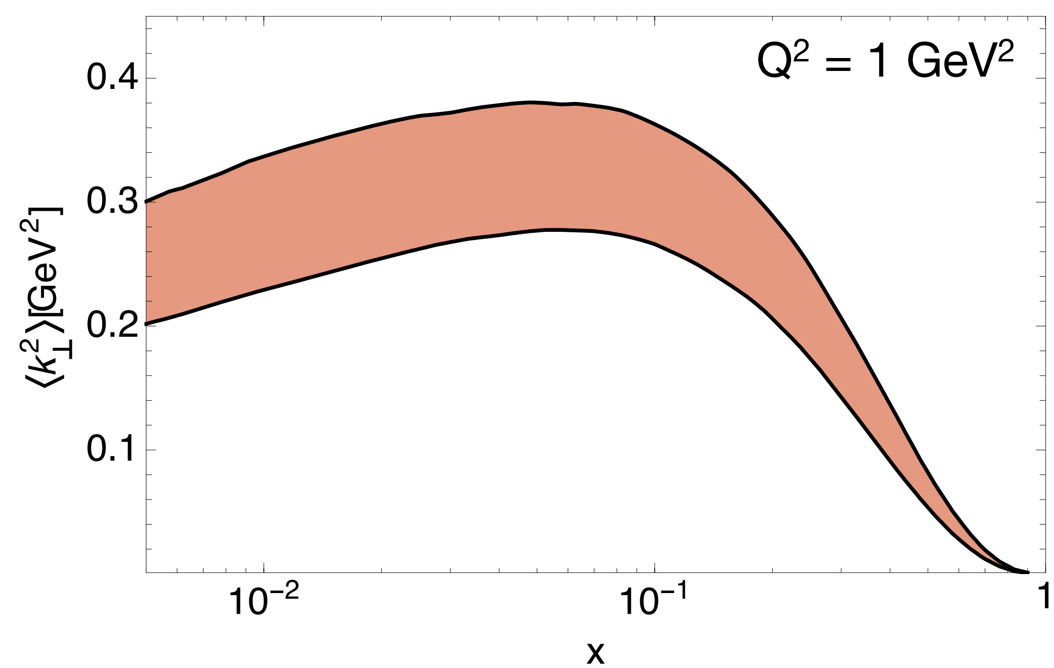
Pavia2016: first fit putting together semi-inclusive DIS, Drell-Yan and Z production

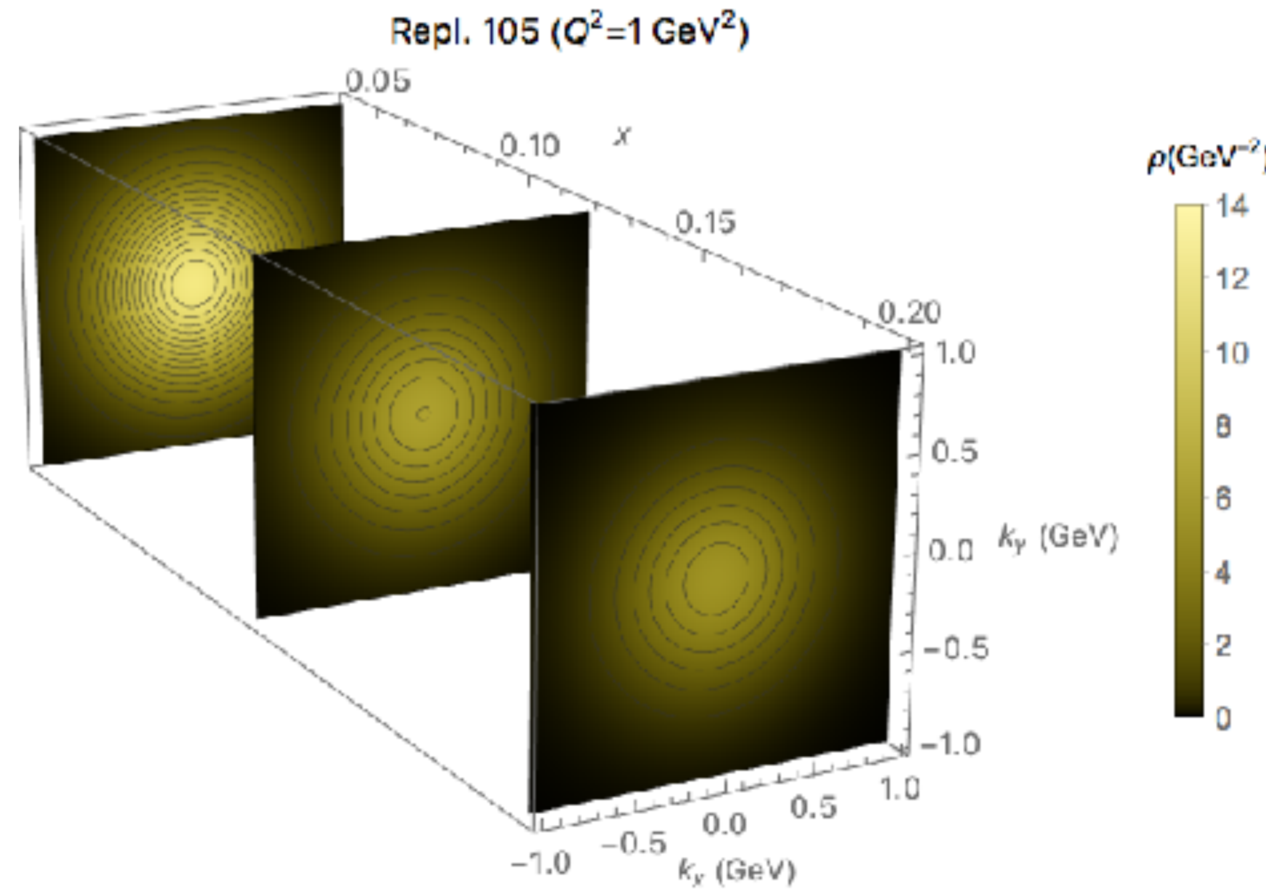
Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

see talk by C. Pisano

It's the dawn of TMD global fits era

Transverse size in momentum space





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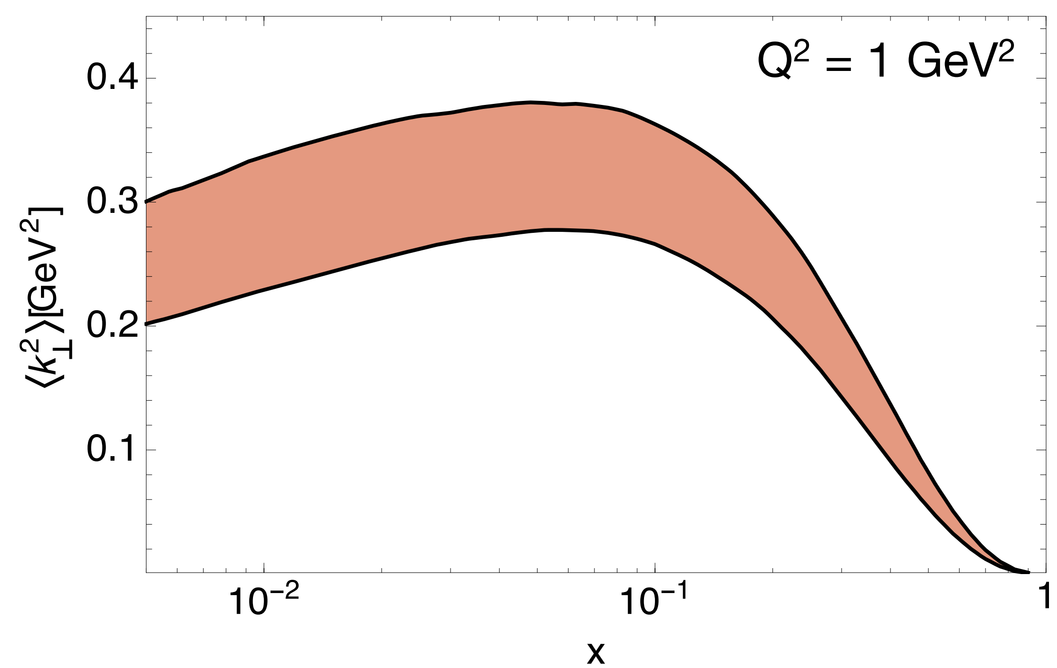
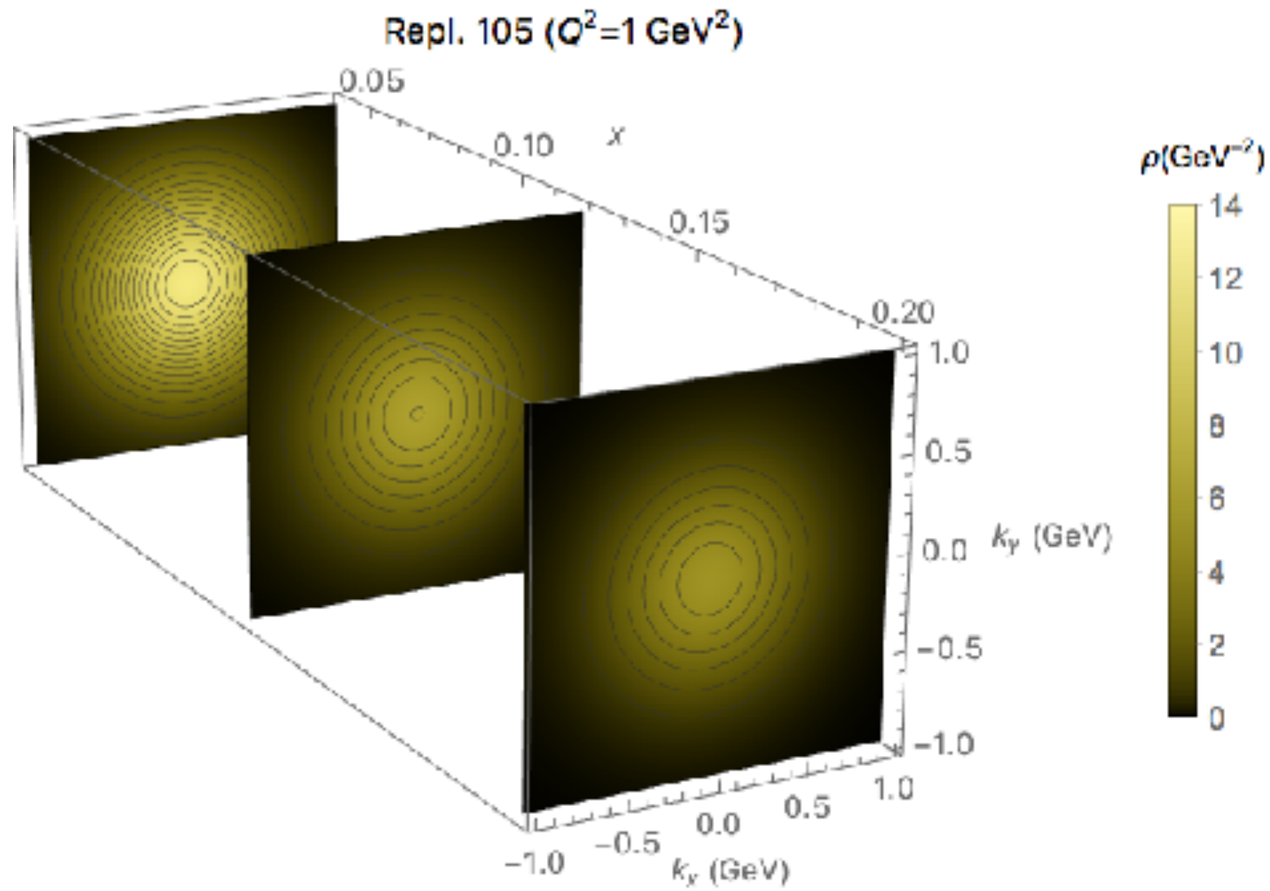
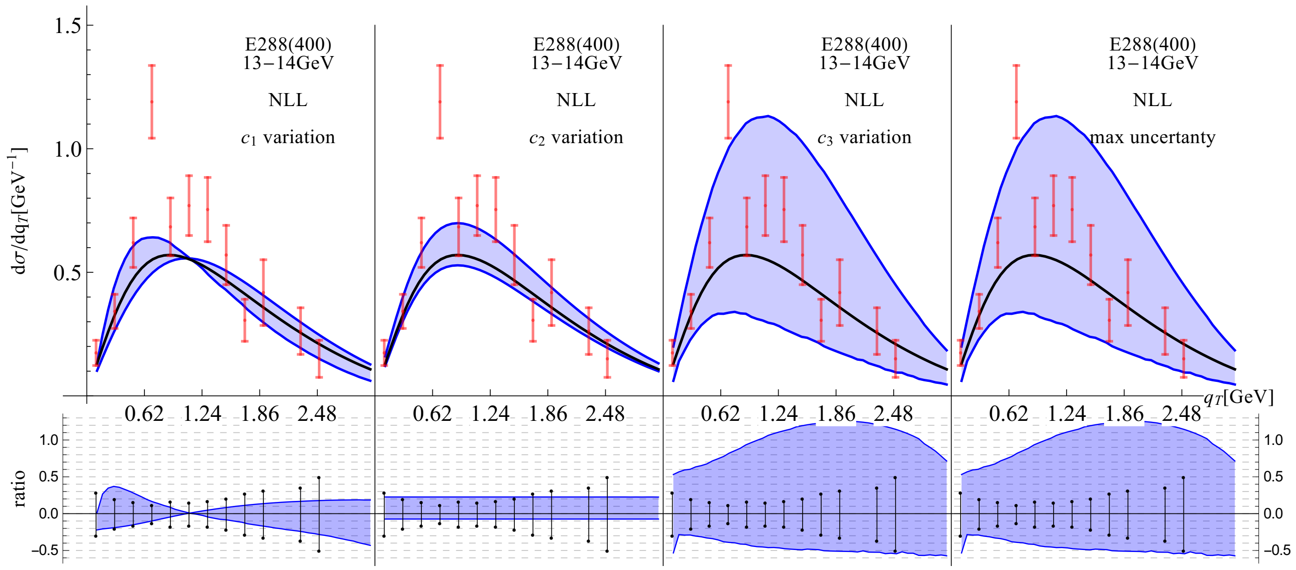




Improvement in perturbative accuracy

NLL/LO



see talk by A. Vladimirov

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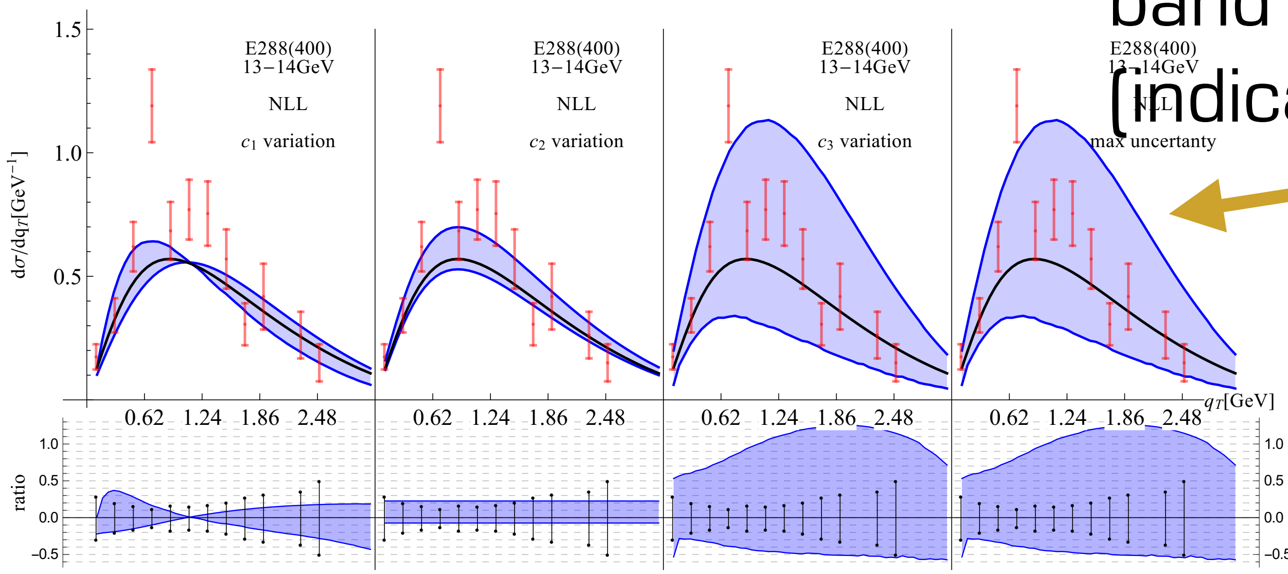

band due to scale variation
(indication of theory accuracy)

see talk by A. Vladimirov

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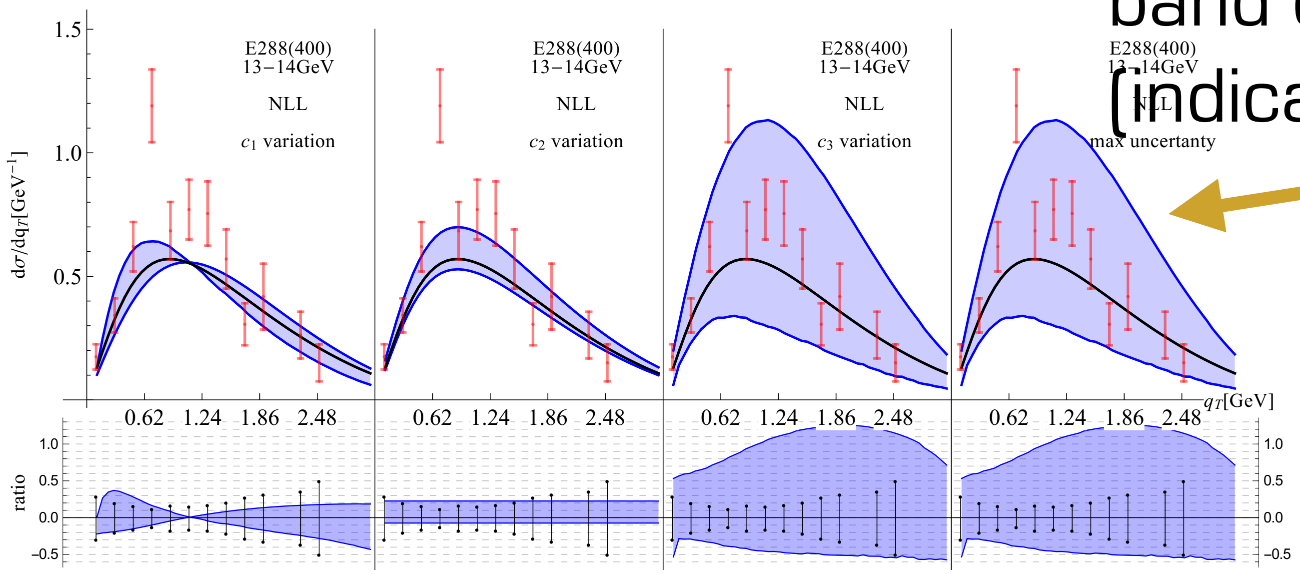
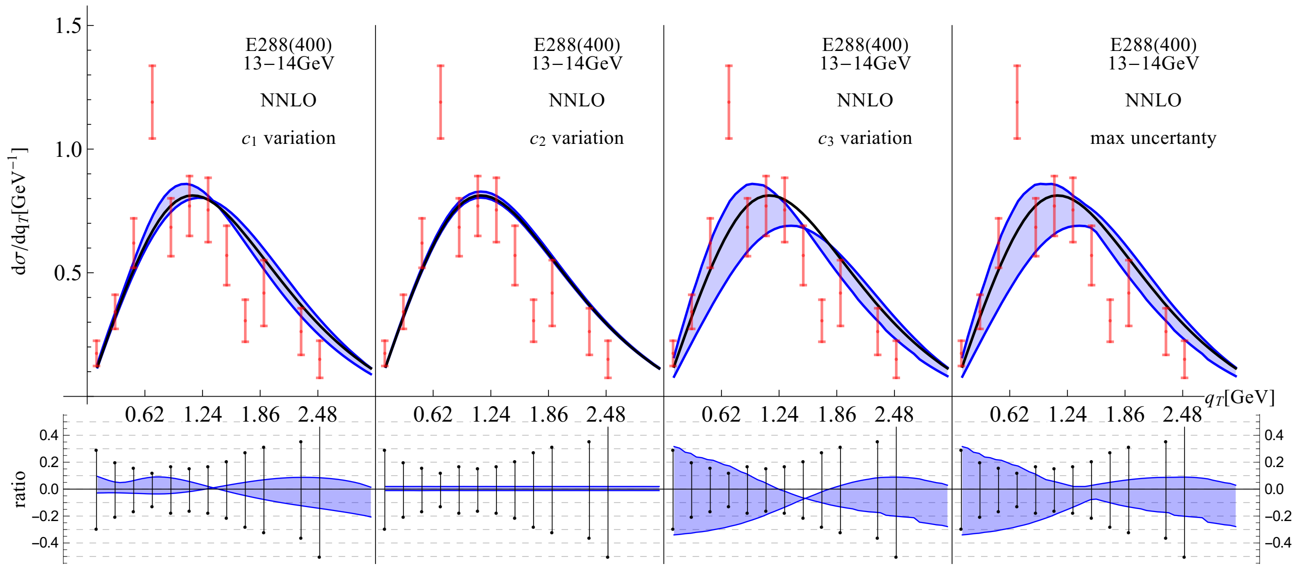


NNLL/NNLO



Huge improvement for low-energy experiments

see talk by A. Vladimirov

Unpolarized TMDs open issues

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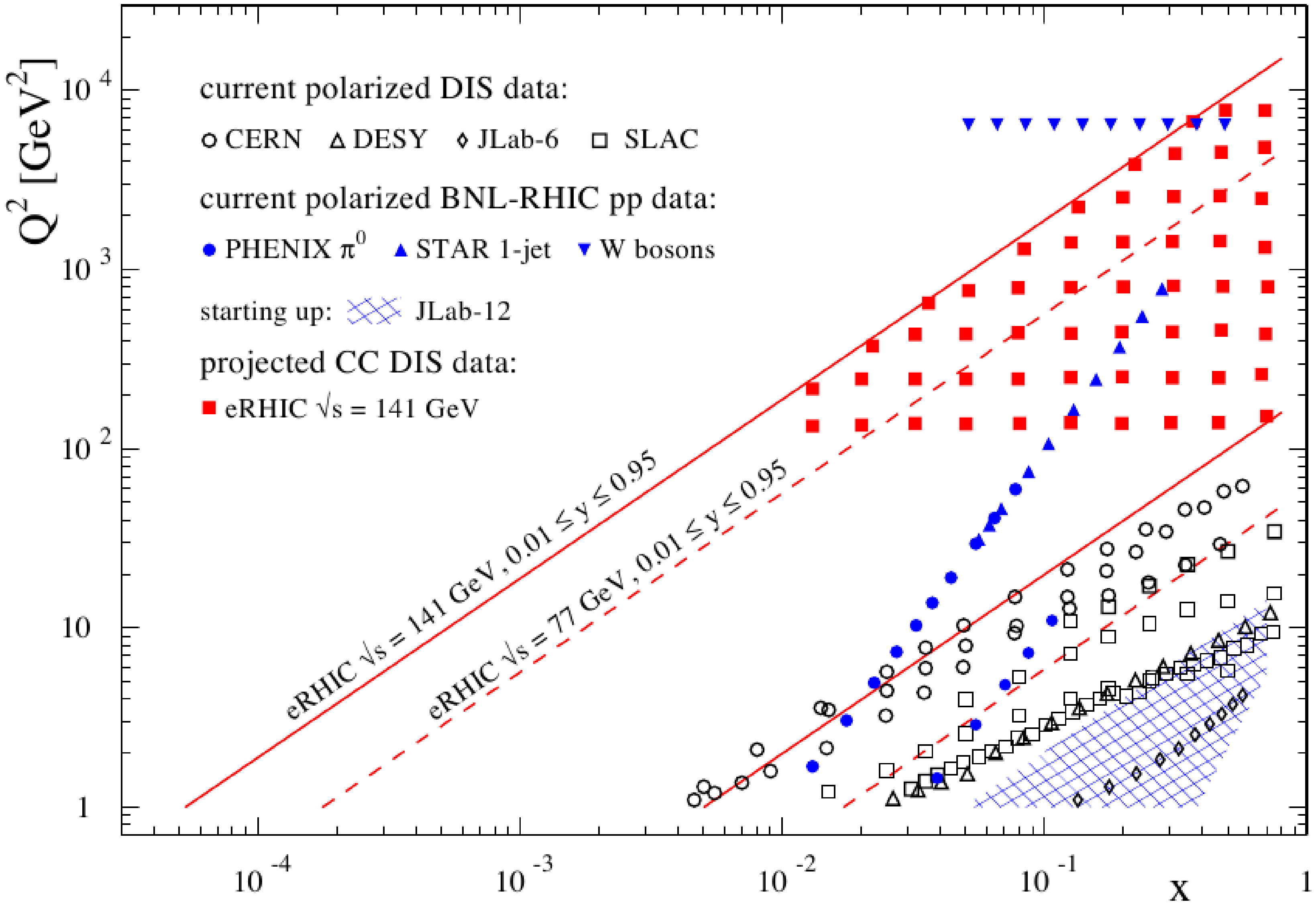
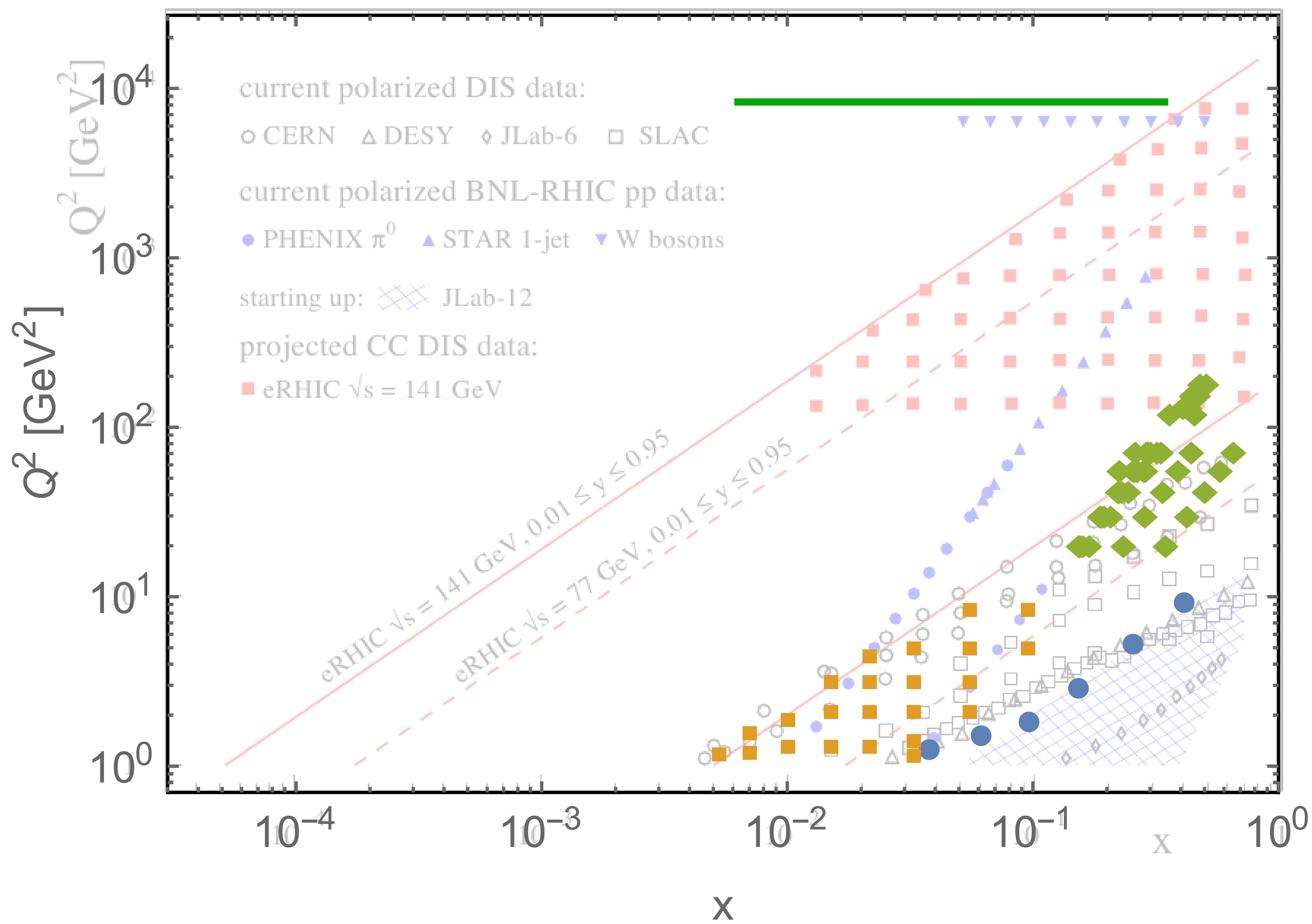
Future perspectives and EIC



from EIC white paper EPJA 52 (2016)

Future perspectives and EIC



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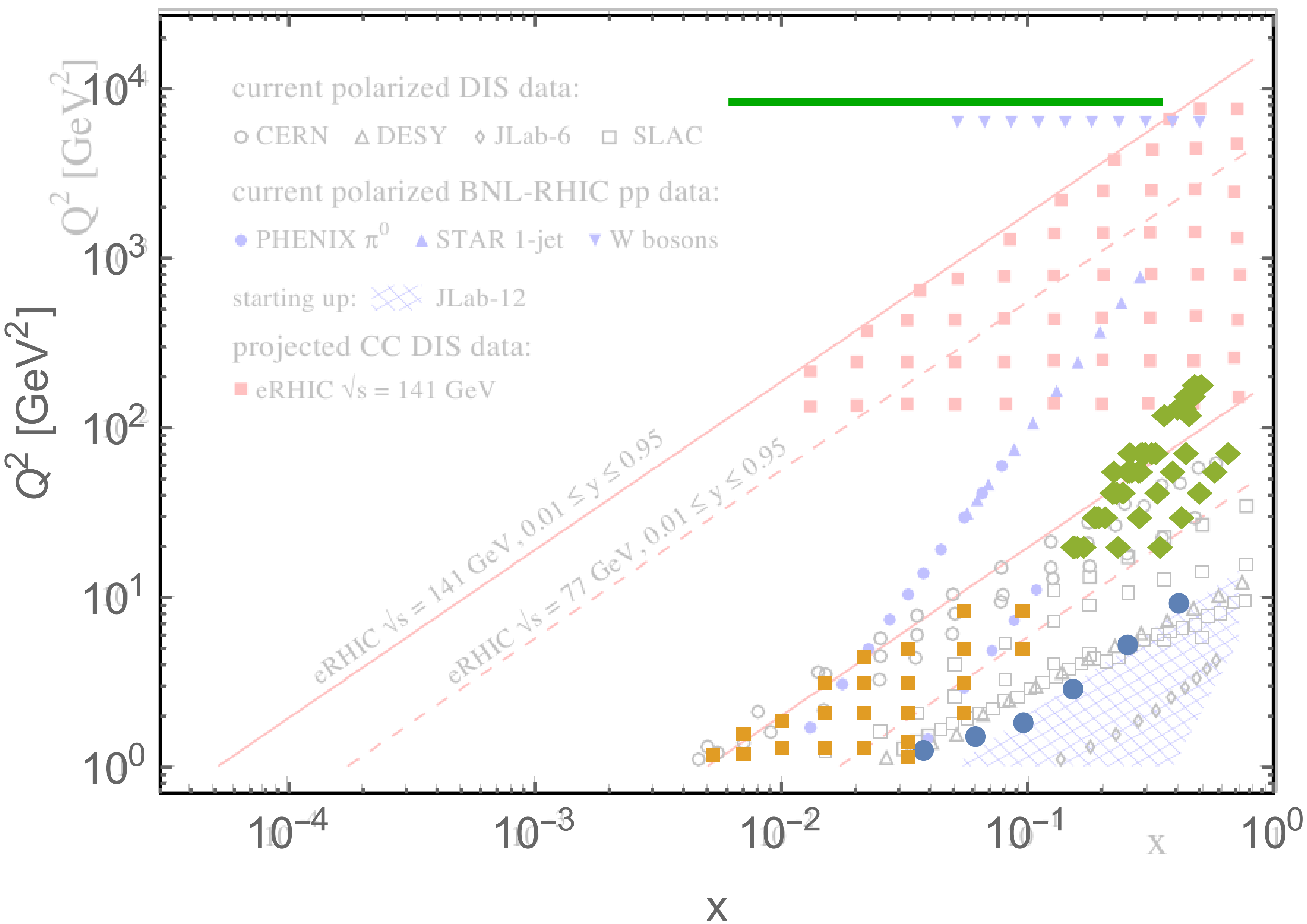

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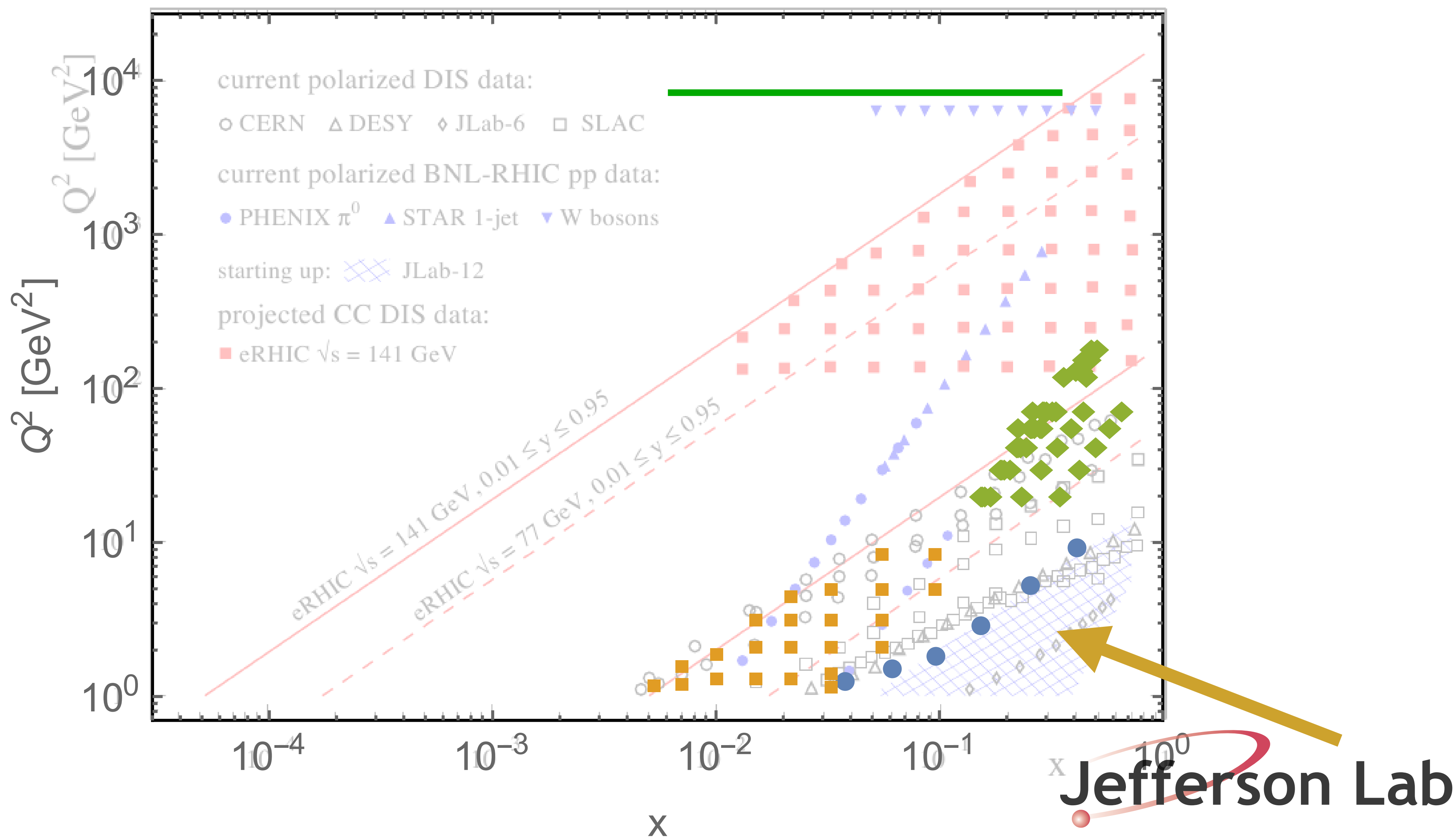

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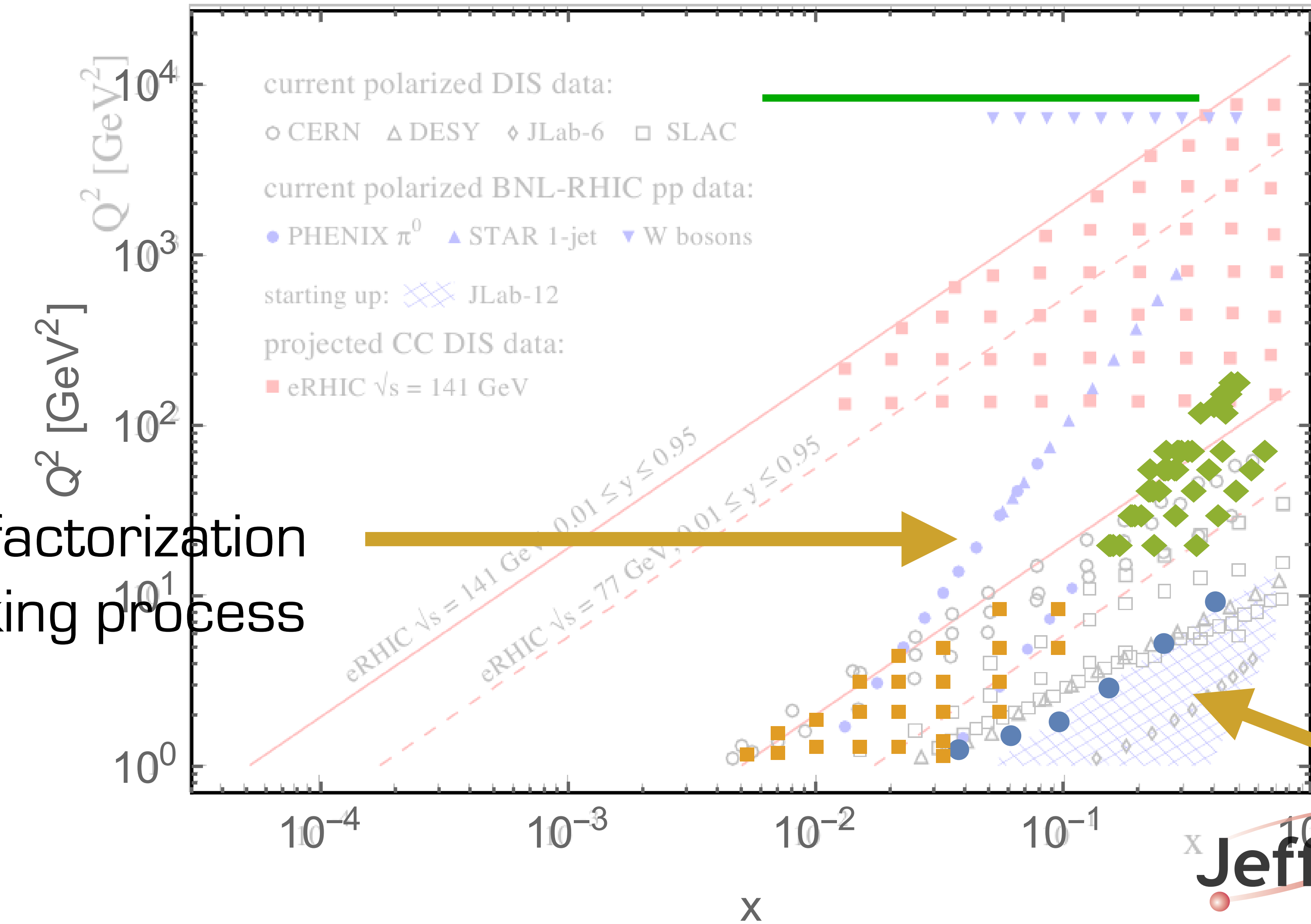

Jefferson Lab

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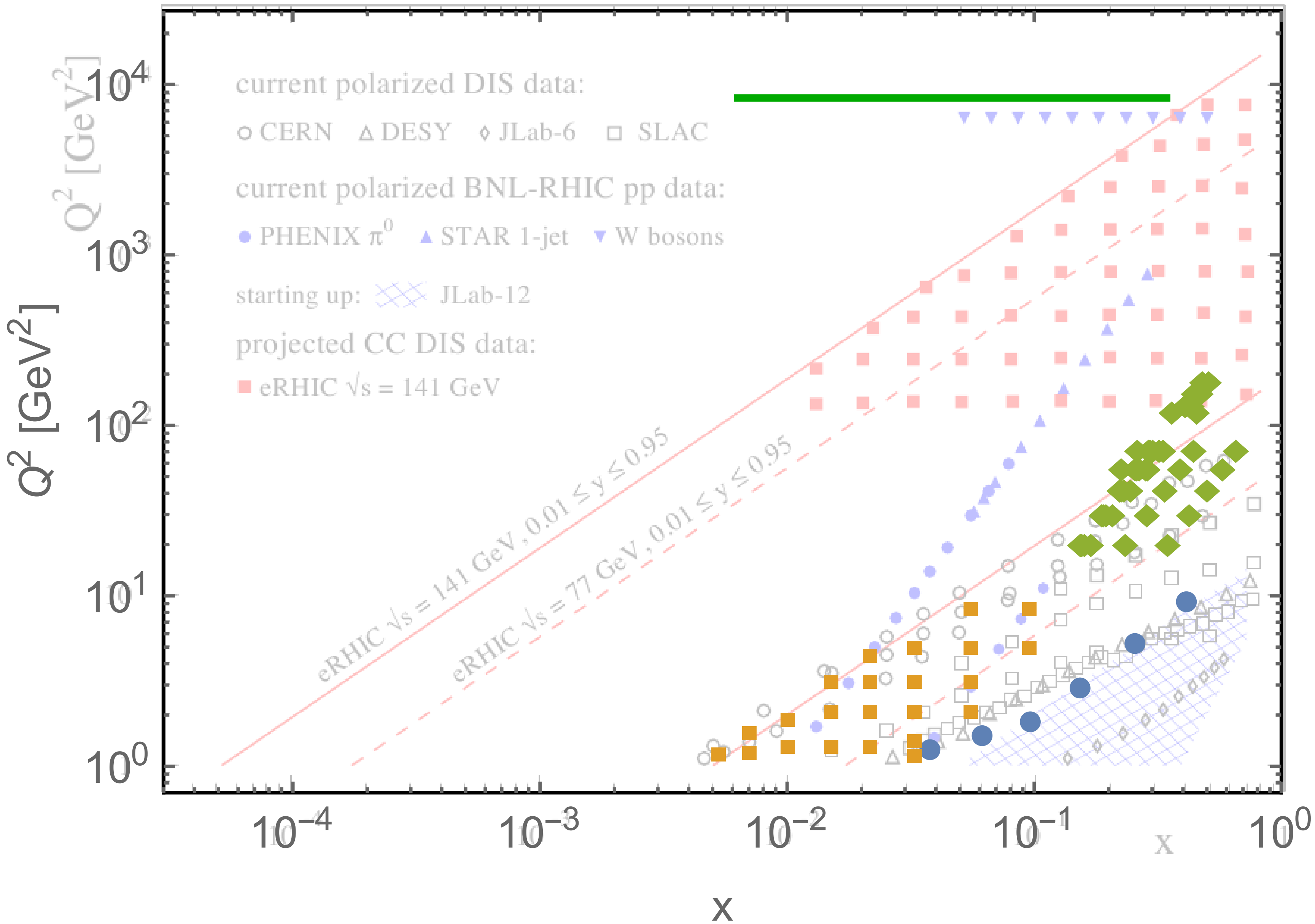

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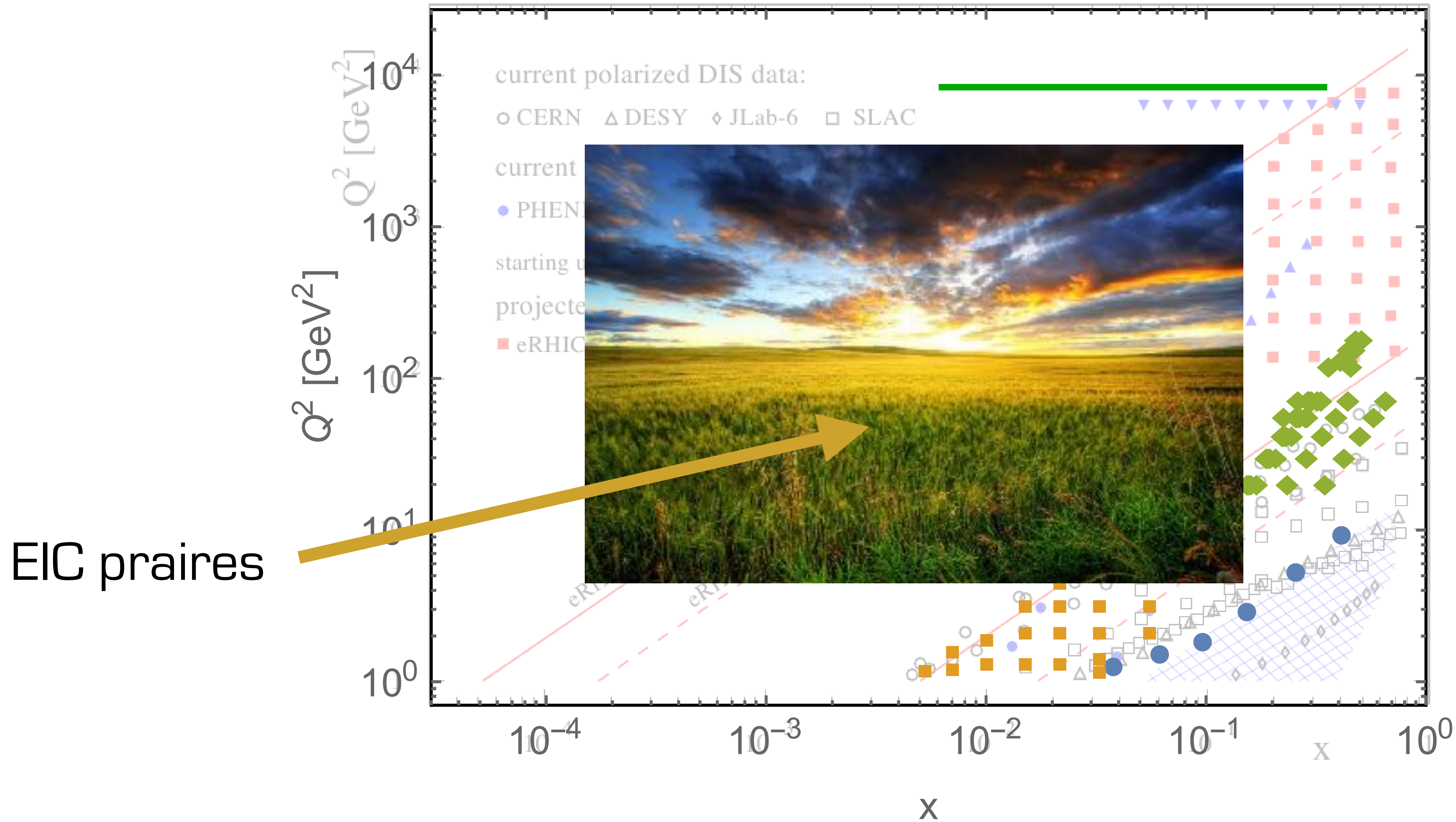

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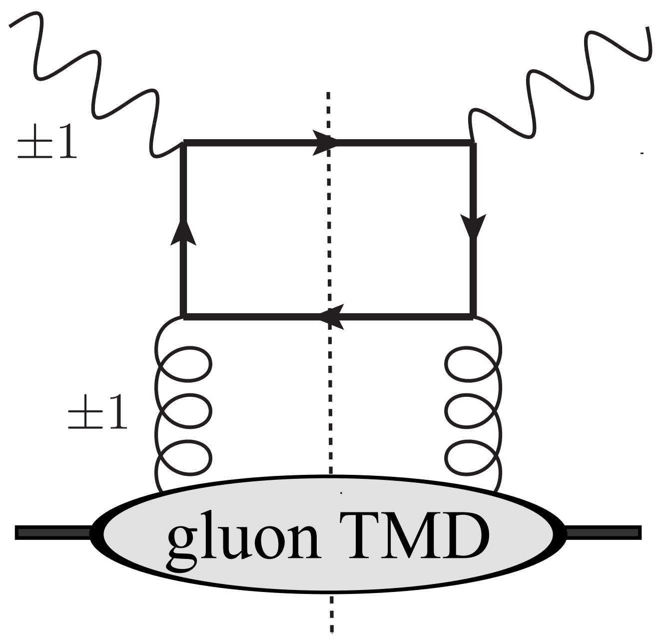
Gluon TMDs

$e\,p \to e \text{ jet jet } X$



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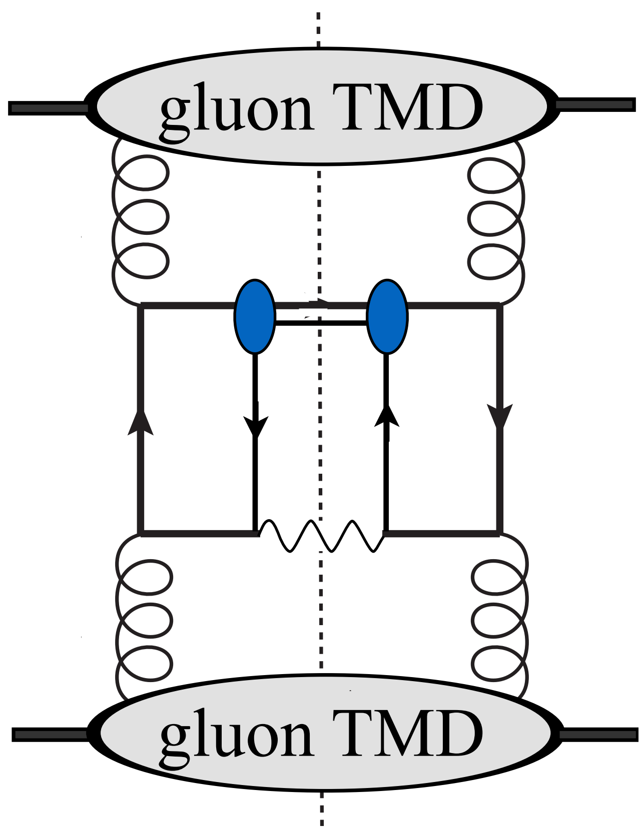

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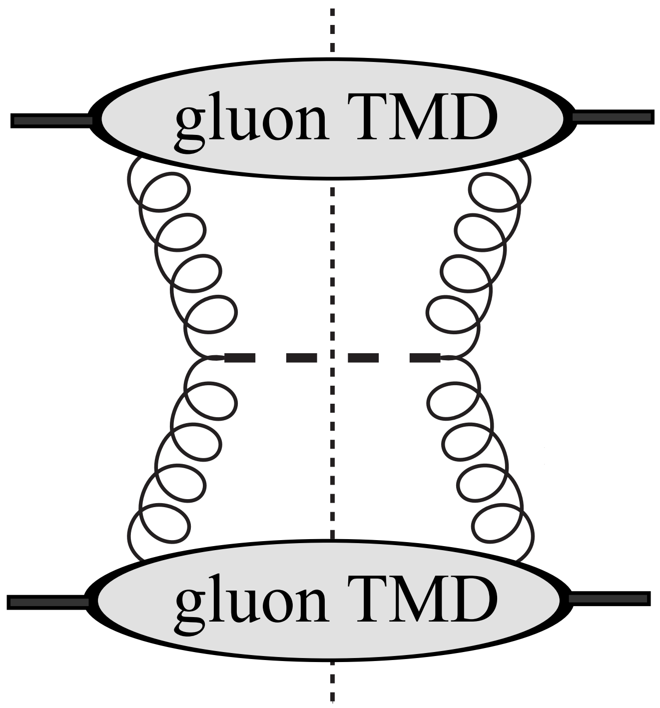
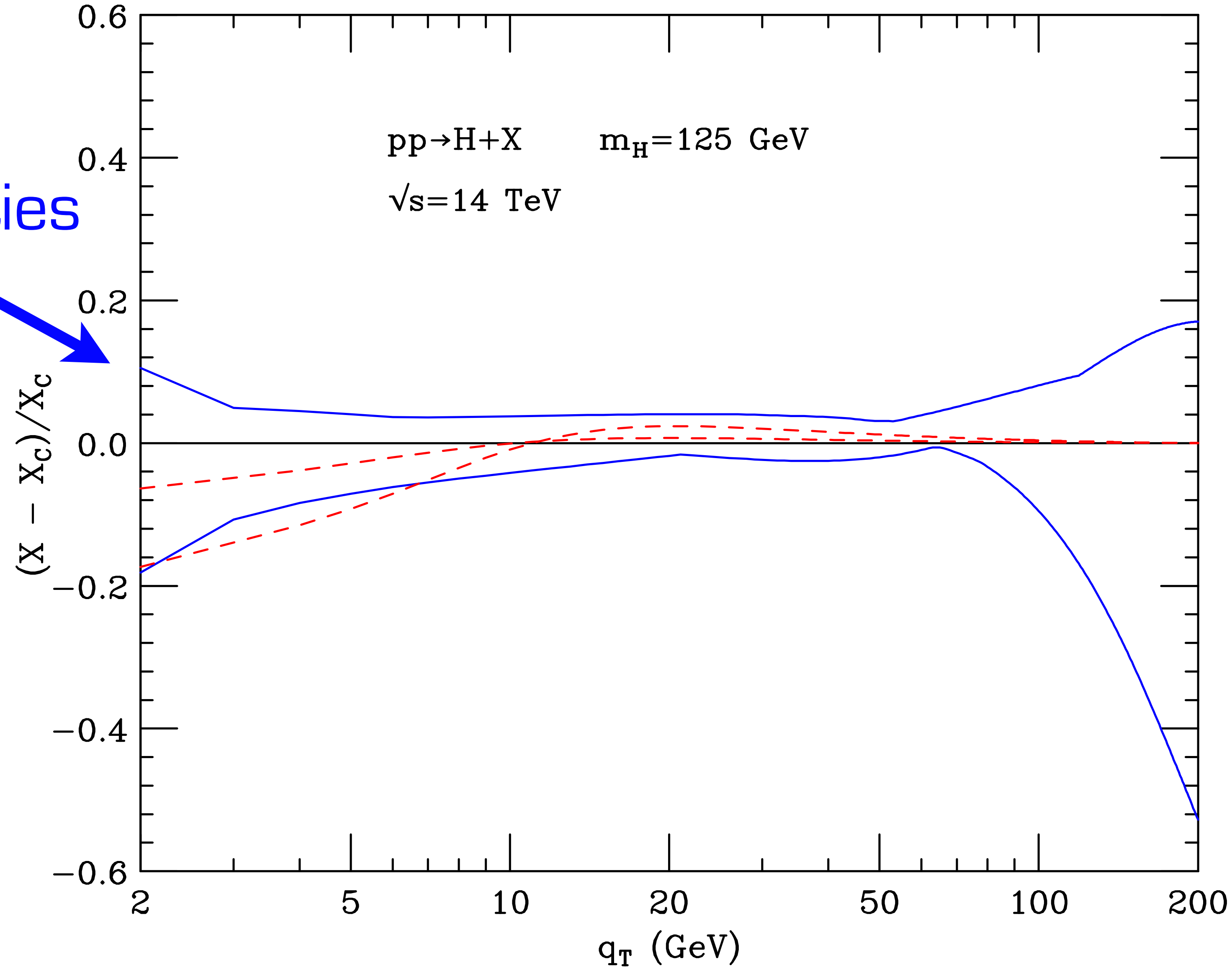


see, e.g., Boer, den Dunnen, Pisano, Schlegel, Vogelsang, PRL108 (12)
den Dunnen, Lansberg, Pisano, Schlegel, PRL 112 (14)
see talks by C. Pisano, F. Murgia, J.H. Lee

Higgs transverse momentum

PDF uncertainties



G. Ferrera, talk at REF 2014, Antwerp, https://indico.cern.ch/event/330428/

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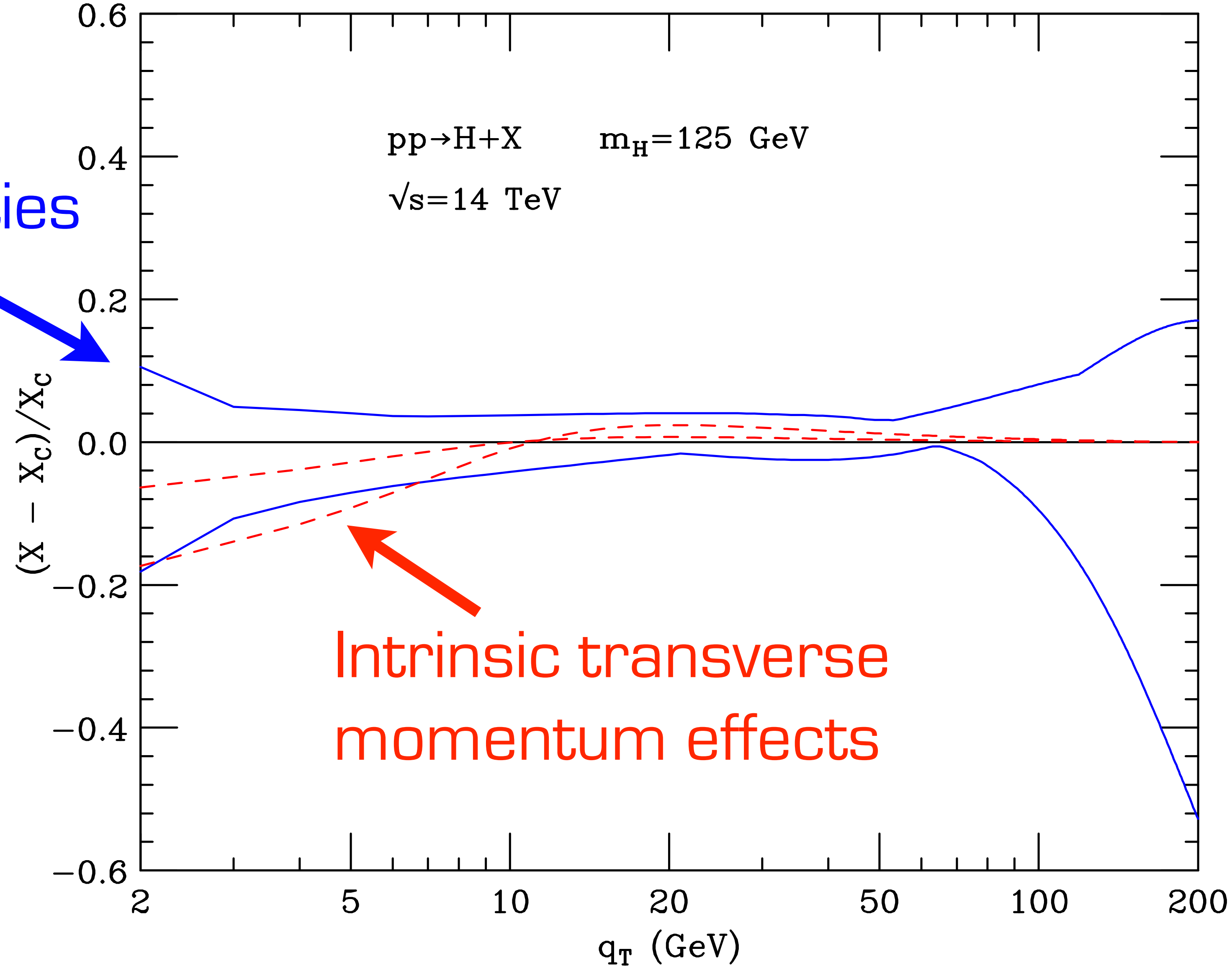

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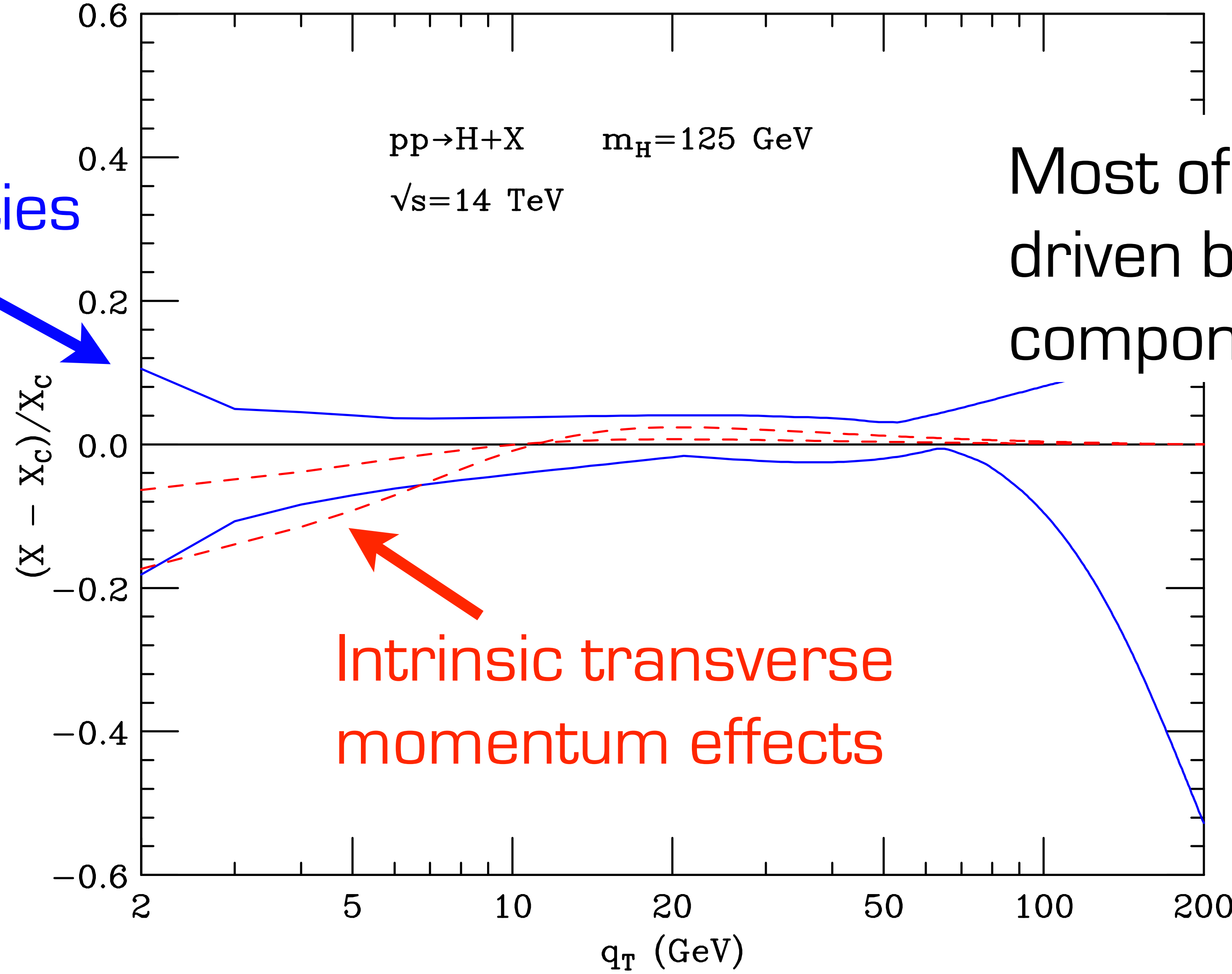

Most of the spectrum is driven by the perturbative components of TMDs

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G. Ferrera, talk at REF 2014, Antwerp, https://indico.cern.ch/event/330428/

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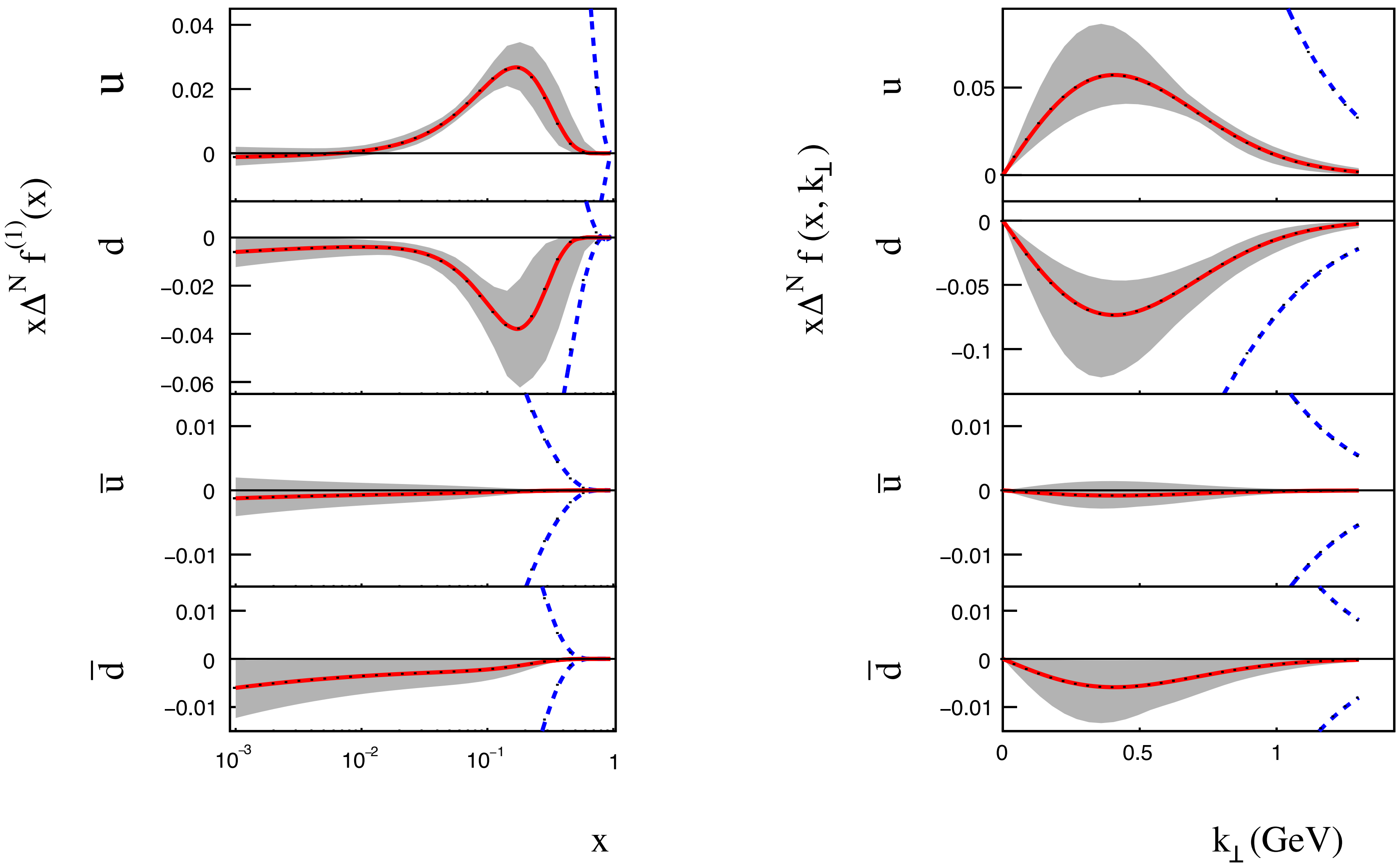
talk by F. Hautmann

Sivers function



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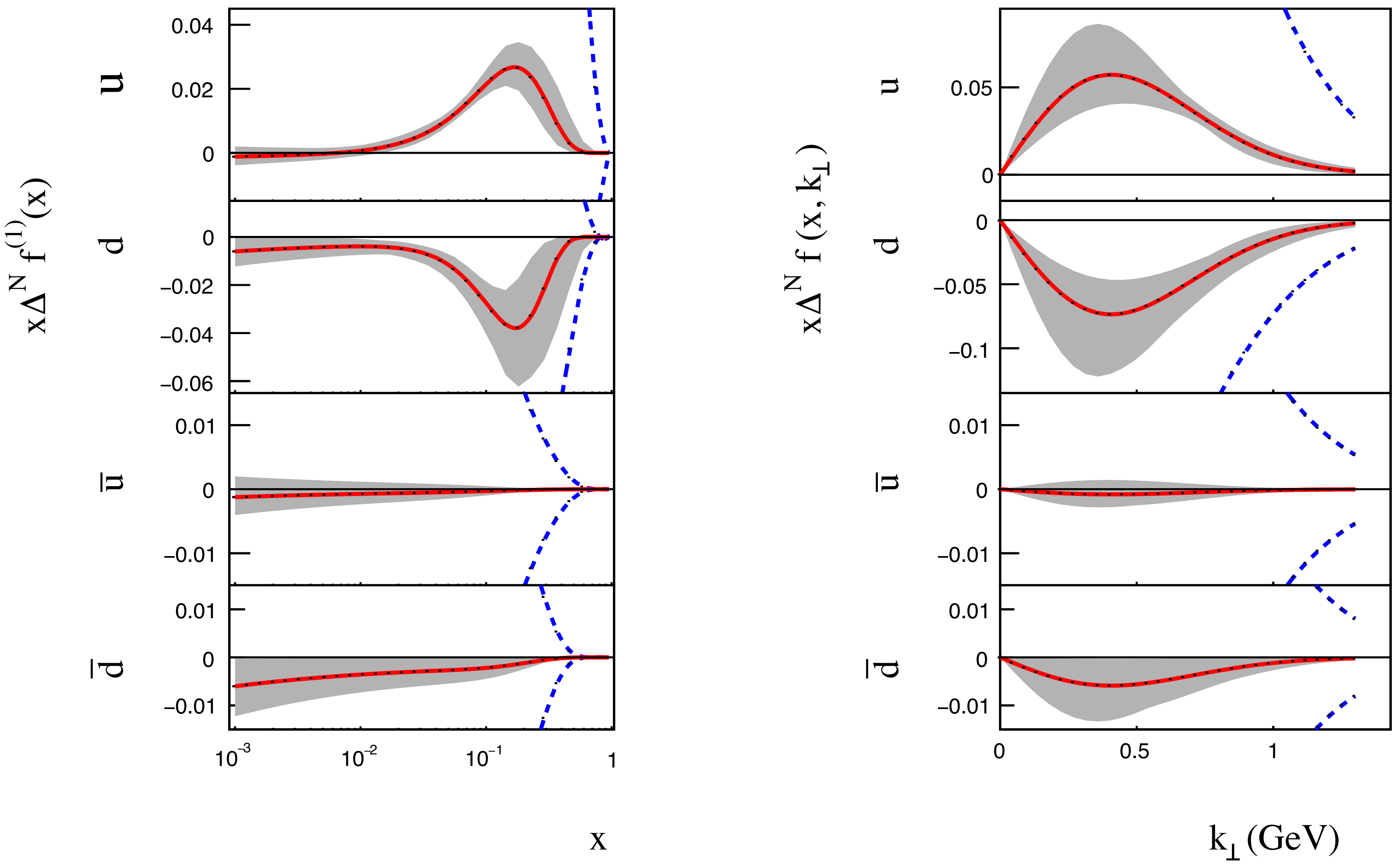

Anselmino, Boglione, D'Alesio, Murgia, Prokudin, [arXiv:1612.06413]()

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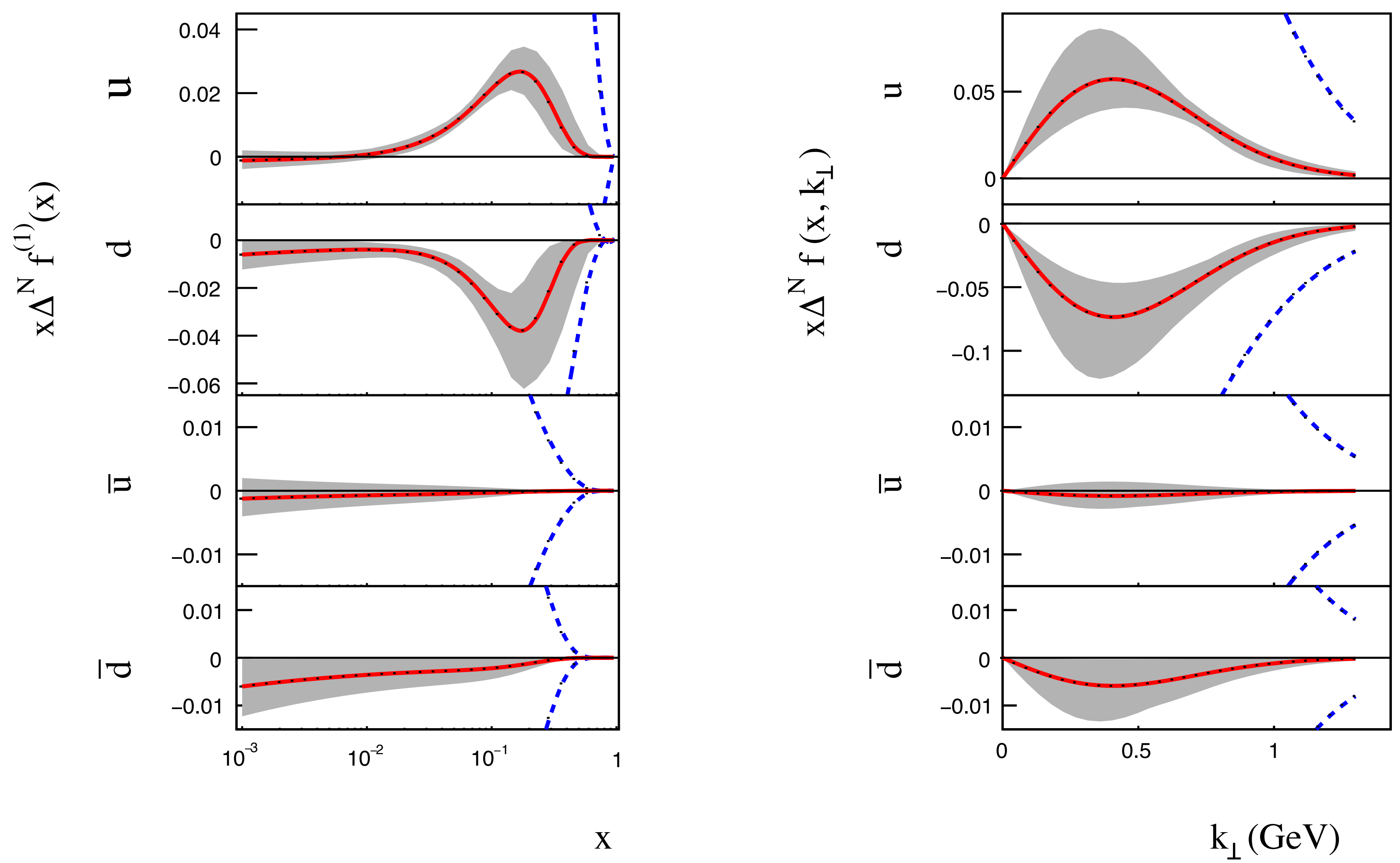

Anselmino, Boglione, D'Alesio, Murgia, Prokudin, [arXiv:1612.06413]

Most recent extraction, no TMD evolution. It is probably not a big problem for fixed-target DIS, but it will play a major role at EIC

Nontrivial universality of Sivers TMD

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Sivers function SIDIS = − Sivers function Drell-Yan

Collins, PLB 536 (02)

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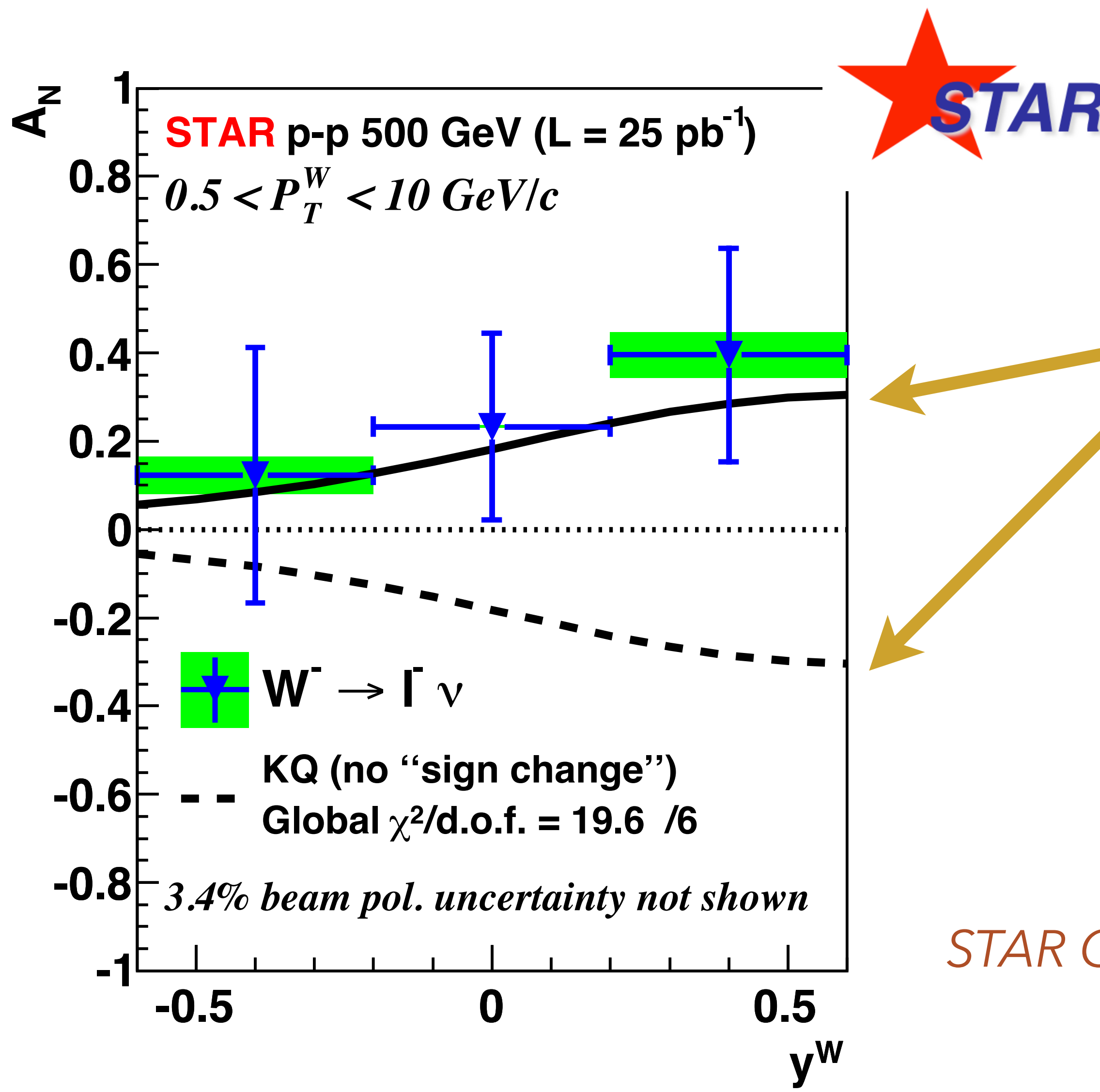

first evidence
of sign change?

STAR Collab. arXiv:1511.06003

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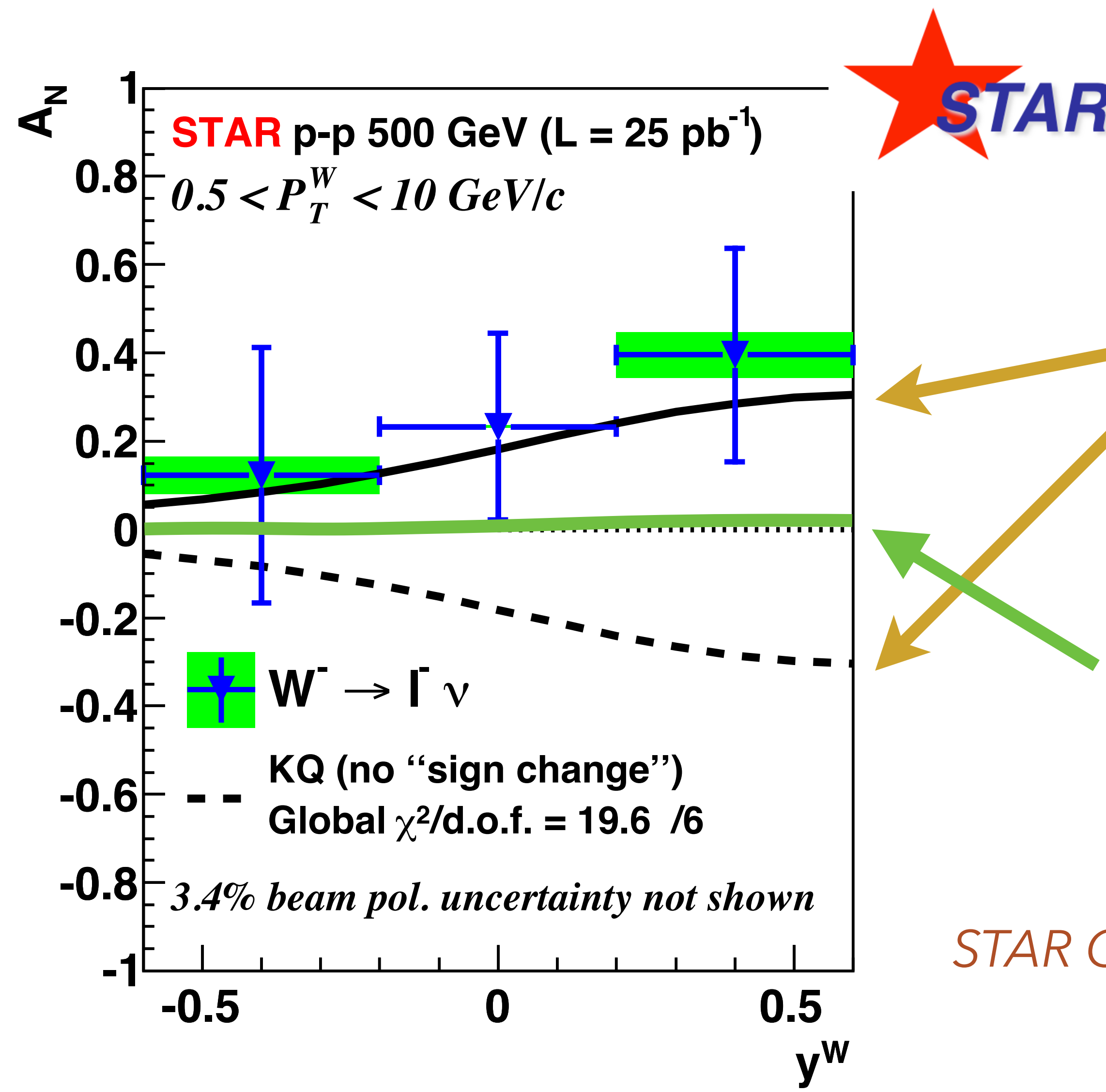
Collins, PLB 536 (02)



first evidence
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prediction with TMD
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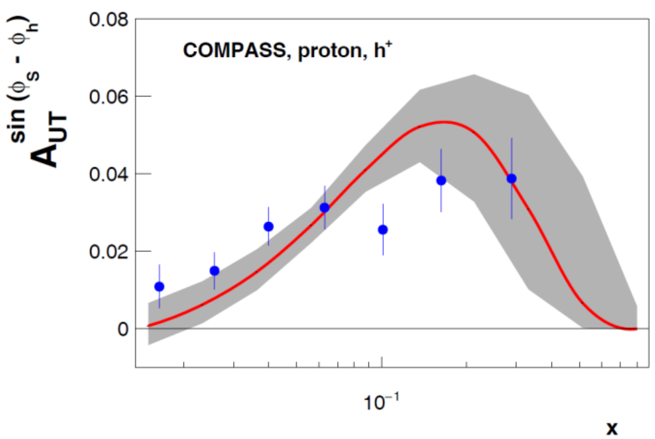
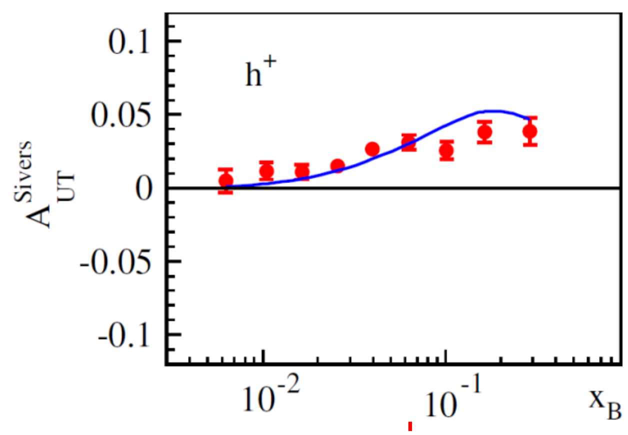
Compass measurement

talk by B. Parsamyan at DIS 2017

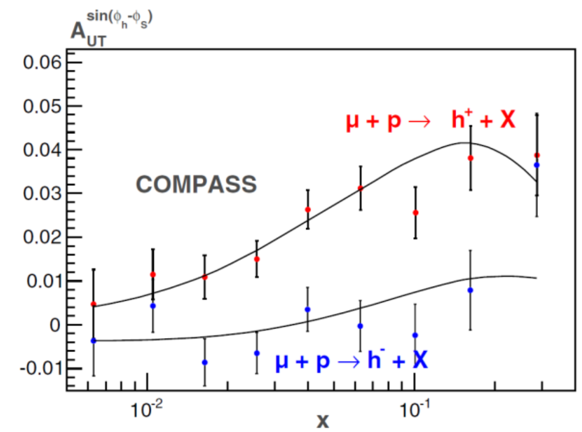
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**



TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**



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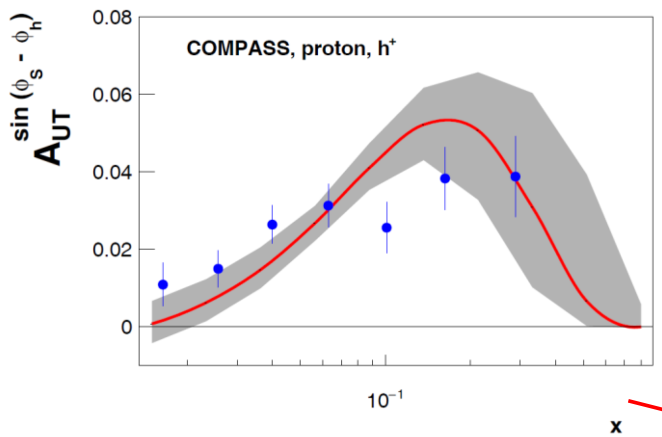

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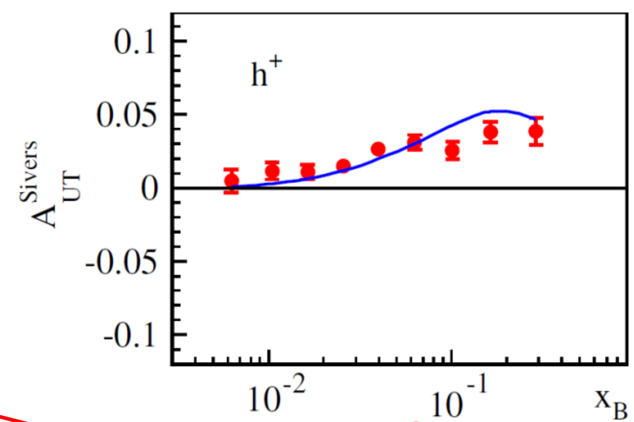

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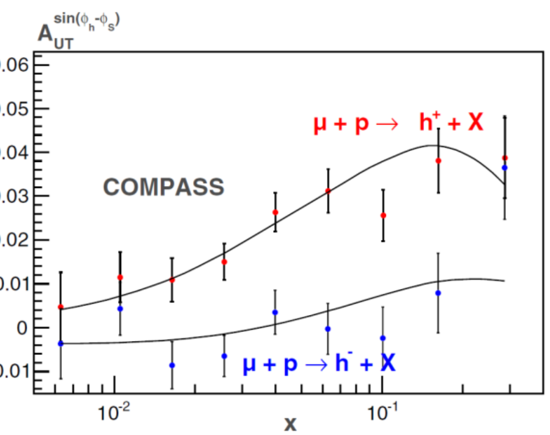
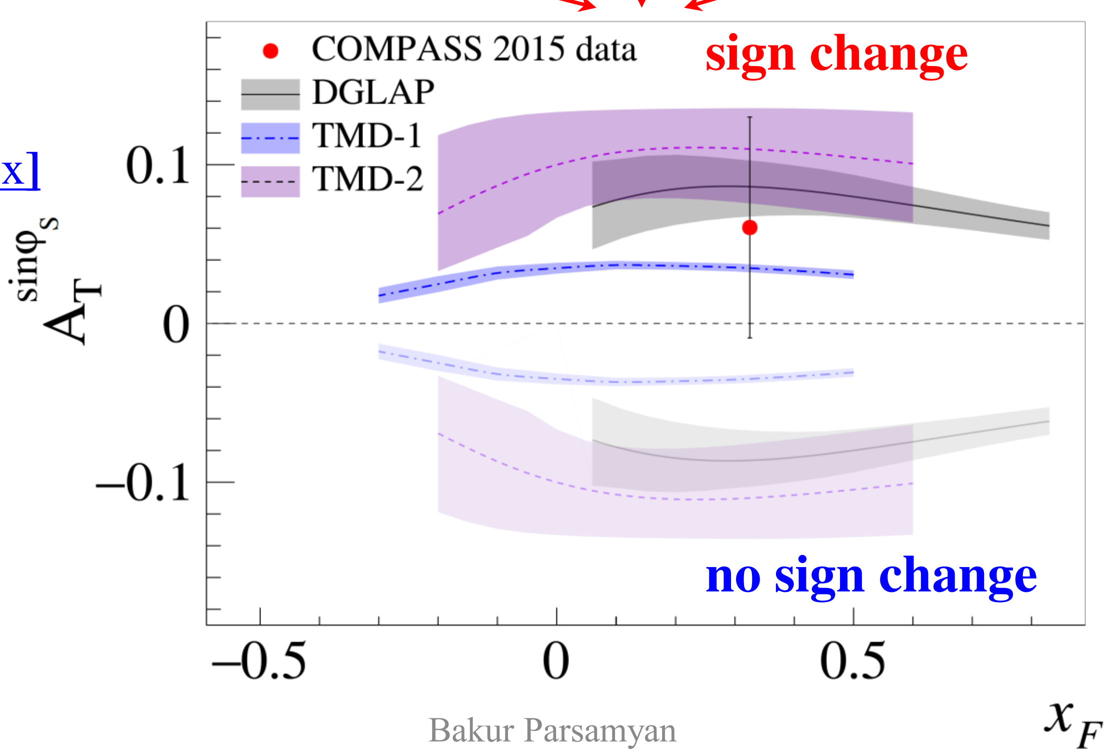


New! **03 April 2017**
COMPASS
[CERN-EP-2017-059](#)
[arXiv:1704.00488[hep-ex]](#)



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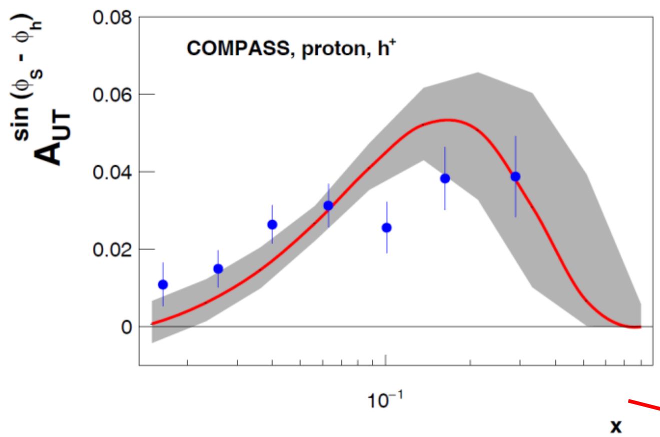

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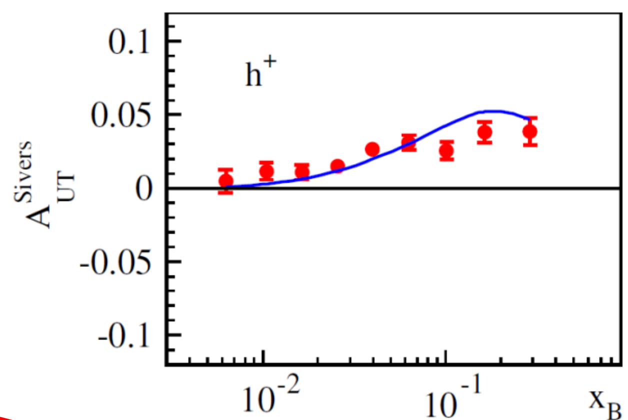

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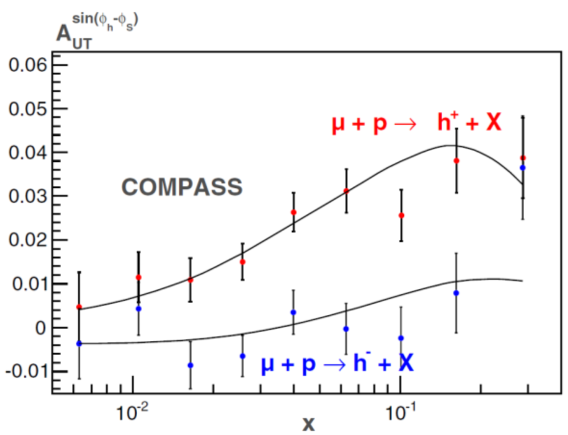

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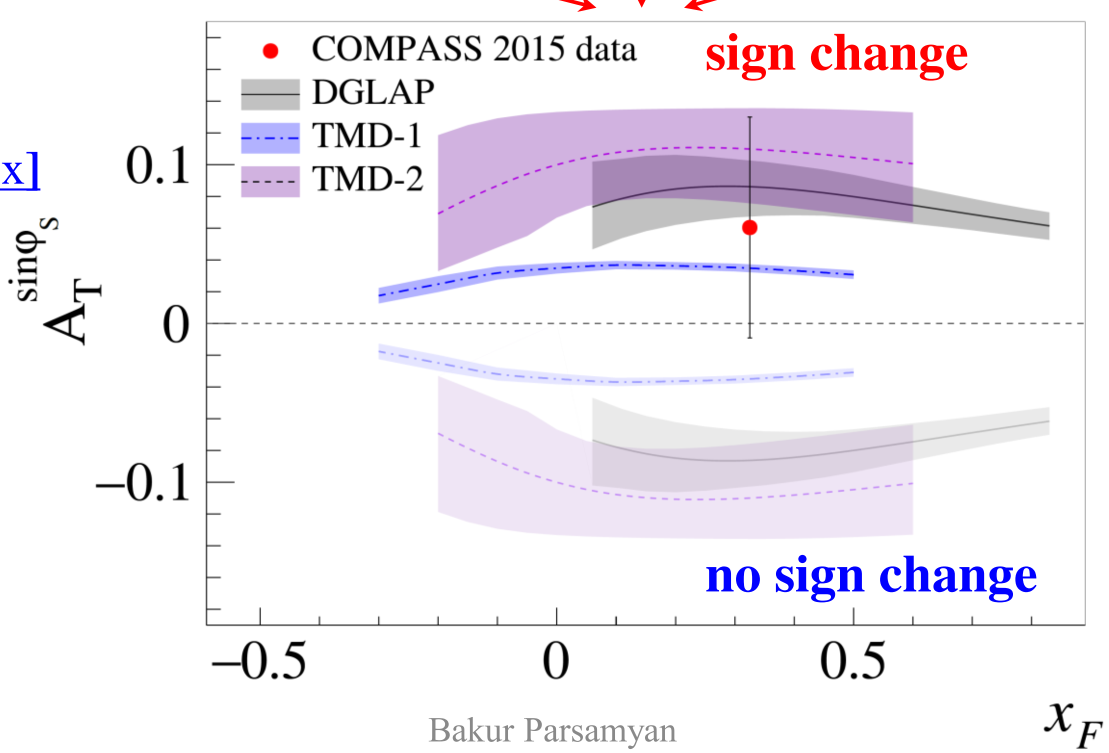
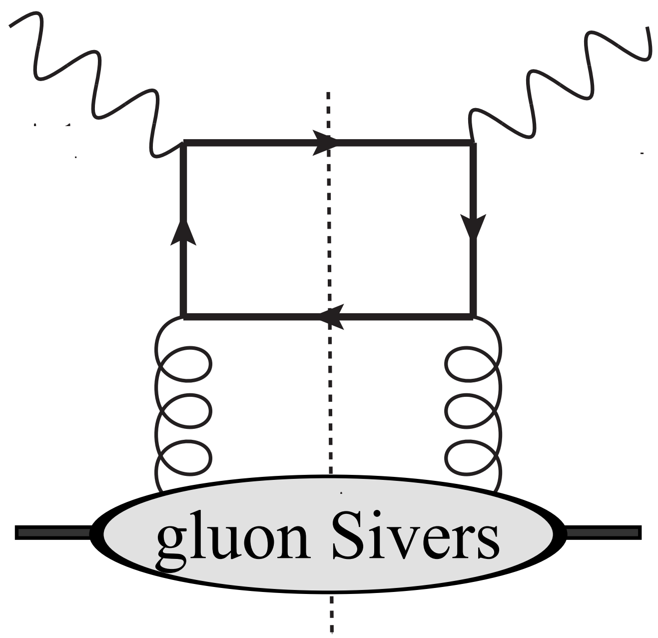


Most of the uncertainty is due to evolution.
EIC can fix this.

Gluon Sivers TMD

$e\, p \to e\, h\, h\, X$



Gluon Sivers TMD

COMPASS, 1701.02453

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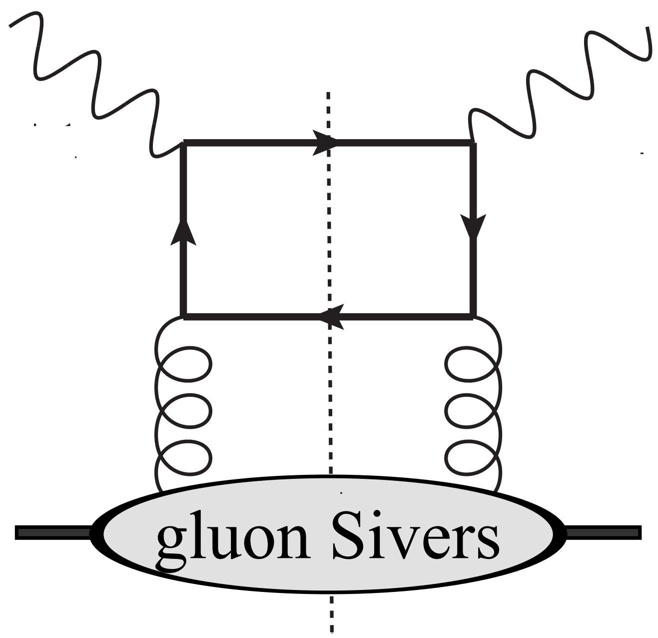

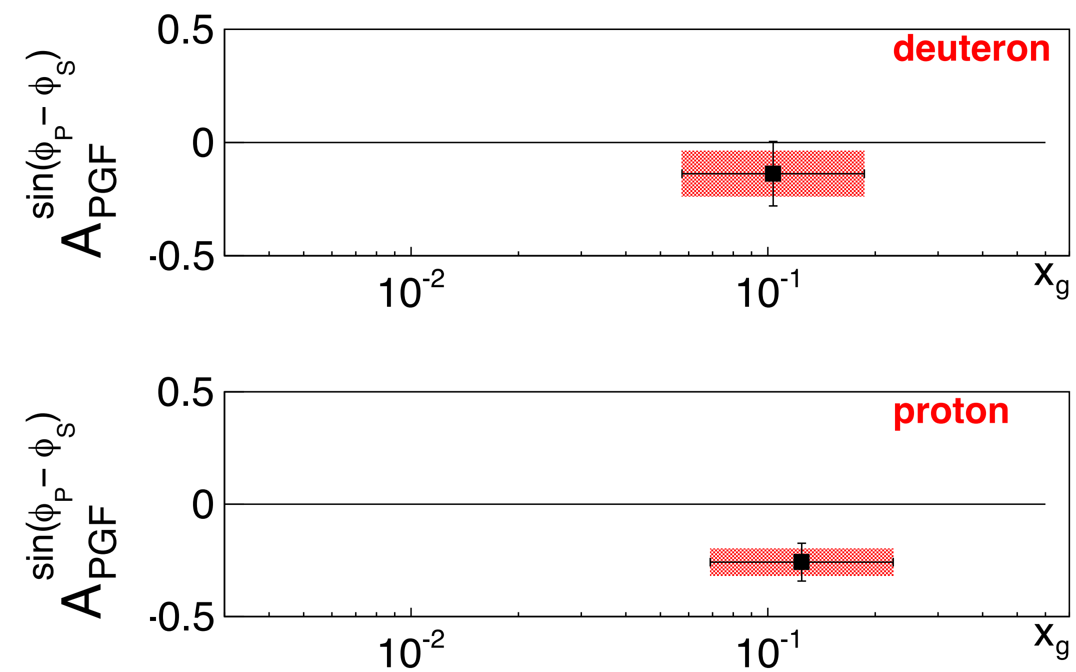

Estimate of asymmetry related to gluon Sivers TMD. Based also on Monte Carlo input.

Gluon Sivers TMD

COMPASS, 1701.02453

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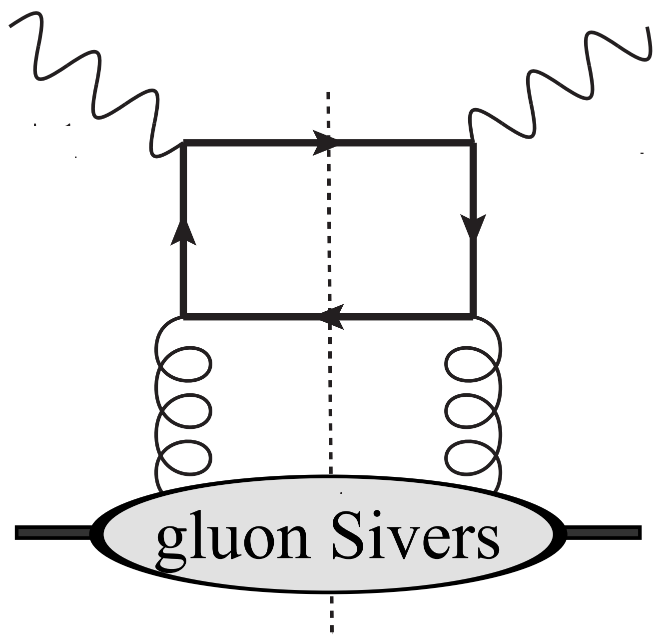
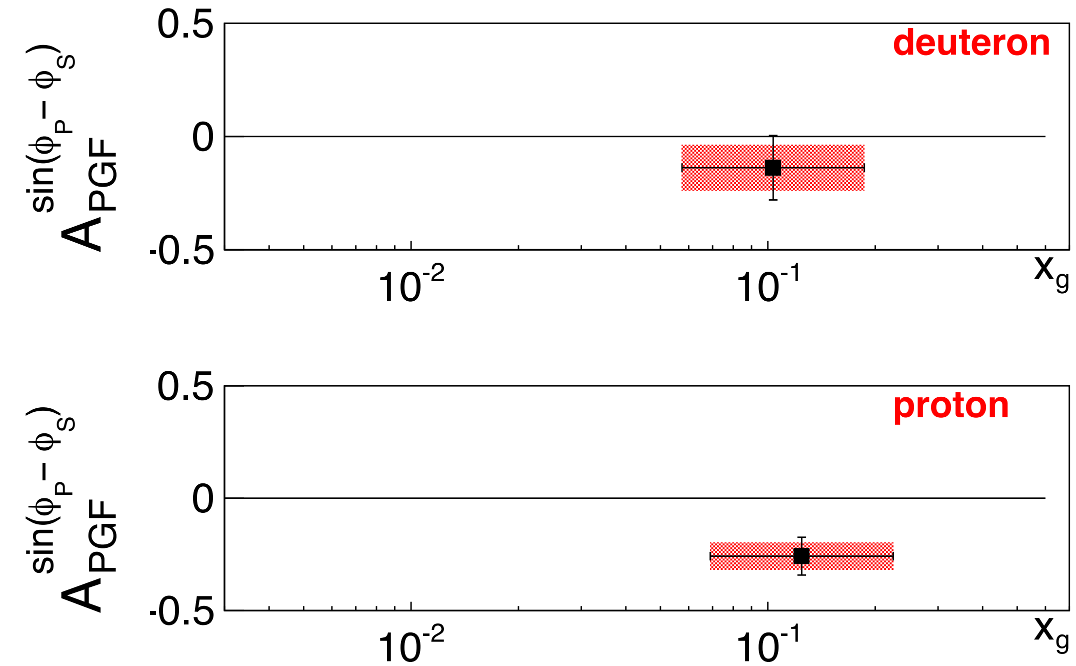




Estimate of asymmetry related to gluon Sivers TMD. Based also on Monte Carlo input.

see also talks by F. Murgia for J/ψ production and Lee for EIC

Transversity

Torino 2015
(no TMD evolution)

Anselmino et al., arXiv:1510.05389

Kang et al. 2015
(with TMD evolution)

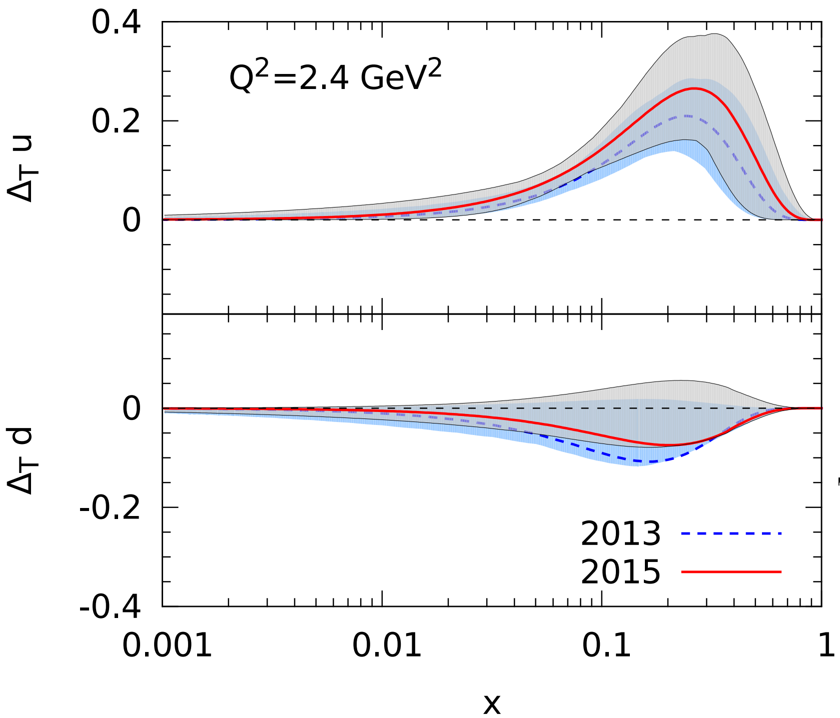
arXiv:1505.05589

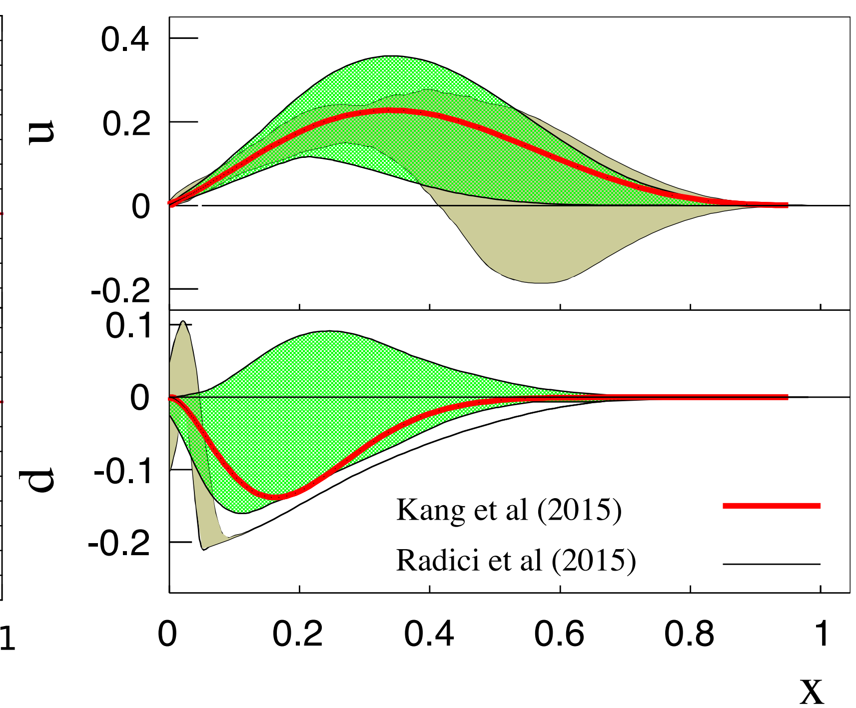
Pavia 2015
(dihadron collinear)

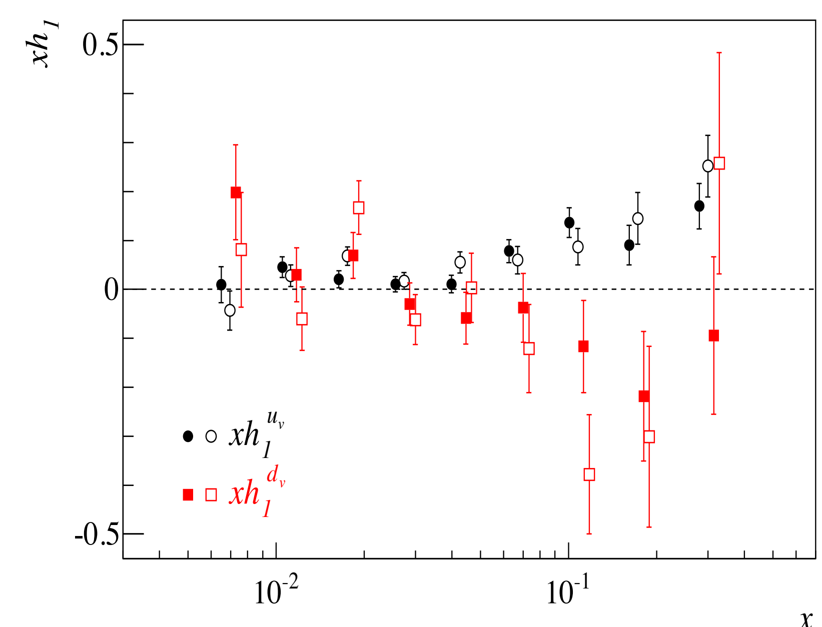
Radici et al., arXiv:1503.03495

Martin et al. 2015
(point-by-point)

arXiv:1412.5946





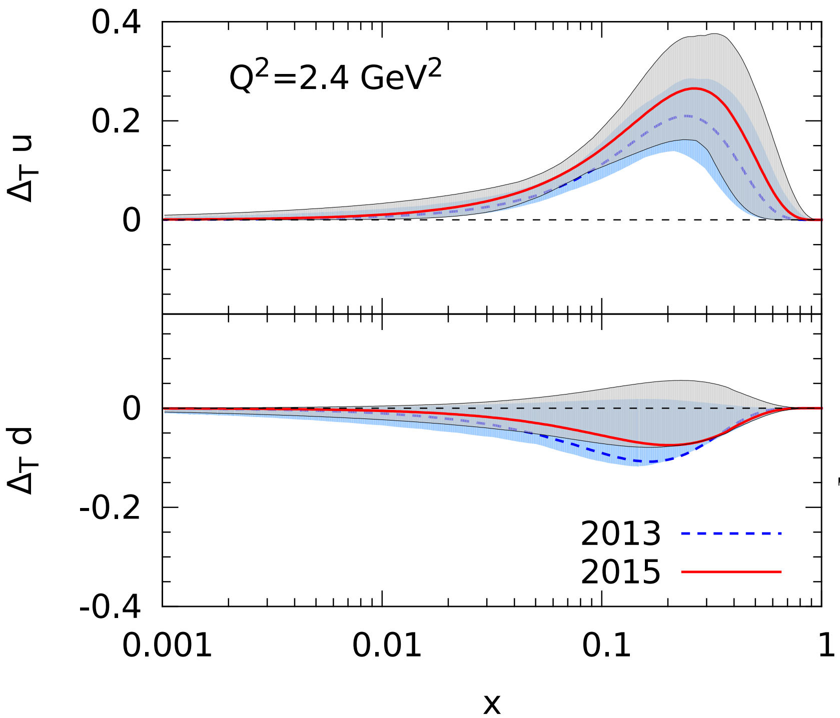


talk by F. Bradamante

Transversity

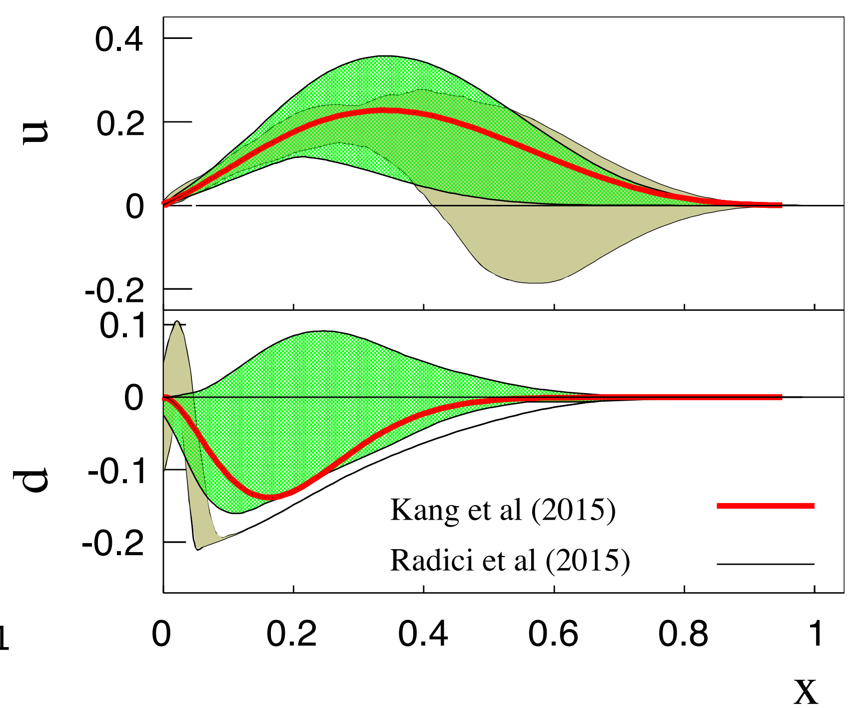
Torino 2015
(no TMD evolution)

Anselmino et al., arXiv:1510.05389



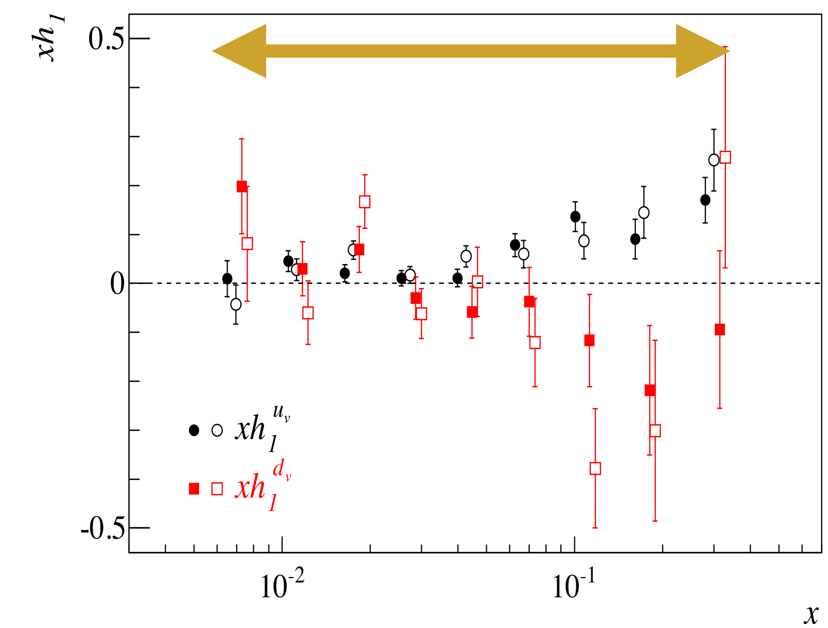
Kang et al. 2015
(with TMD evolution)
arXiv:1505.05589

Pavia 2015
(dihadron collinear)
Radici et al., arXiv:1503.03495



Martin et al. 2015
(point-by-point)
arXiv:1412.5946

clearly shows
data range



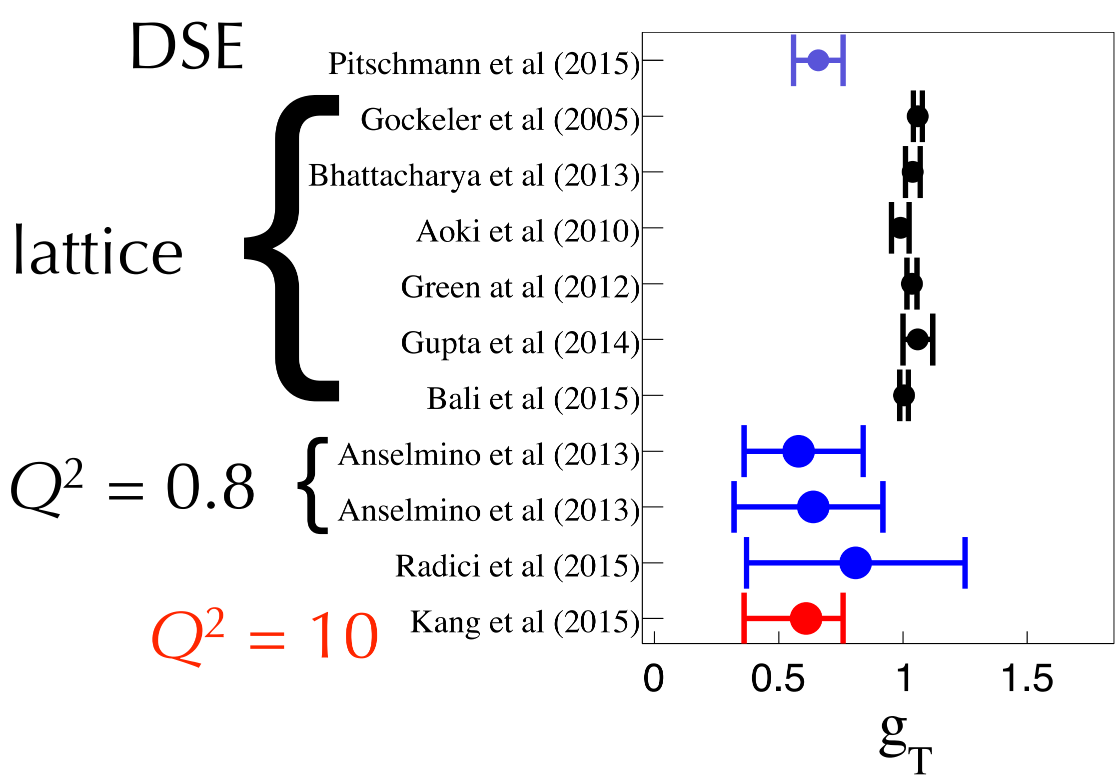
talk by F. Bradamante

Tensor charge

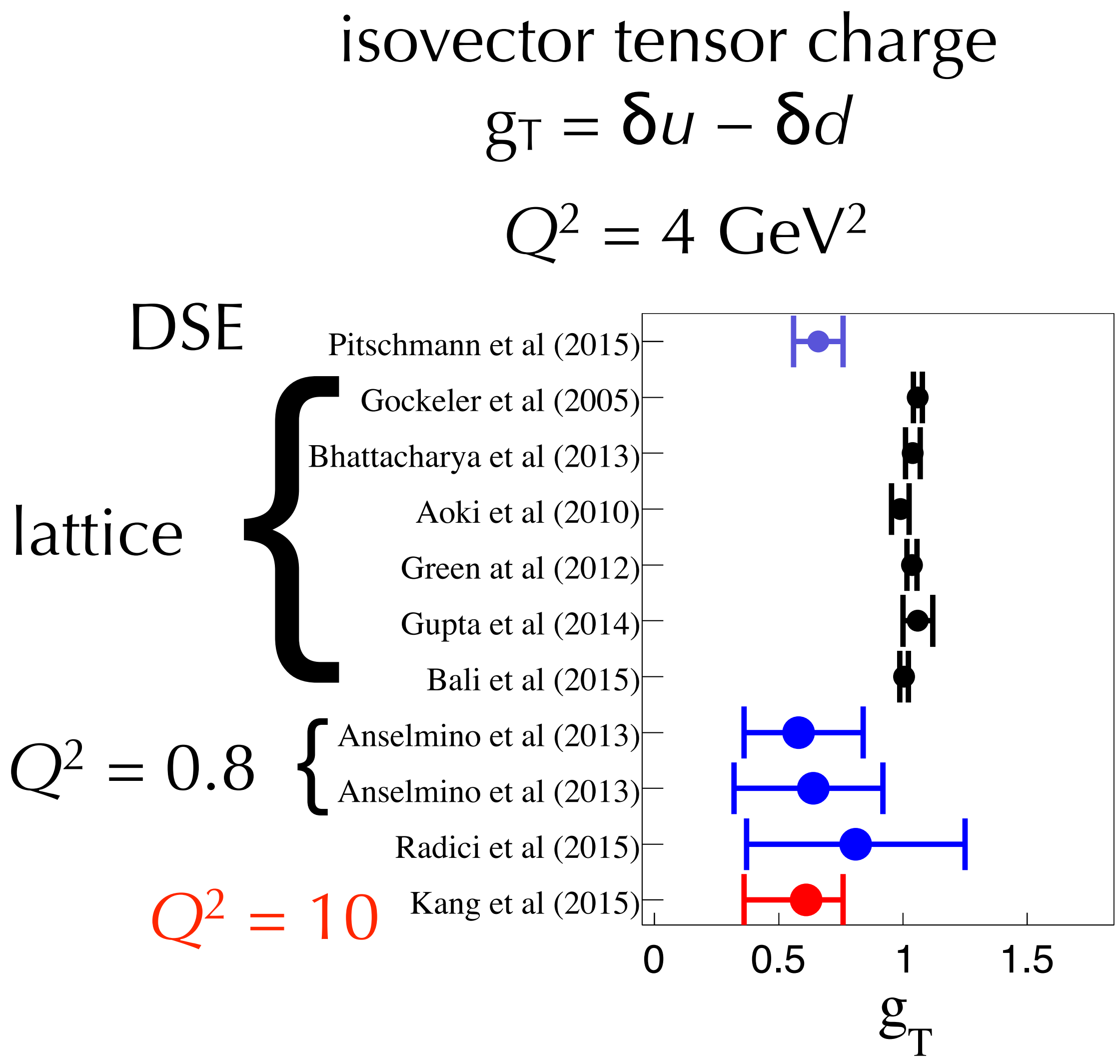
isovector tensor charge

$g_T = \delta u - \delta d$

$Q^2 = 4\ \text{GeV}^2$

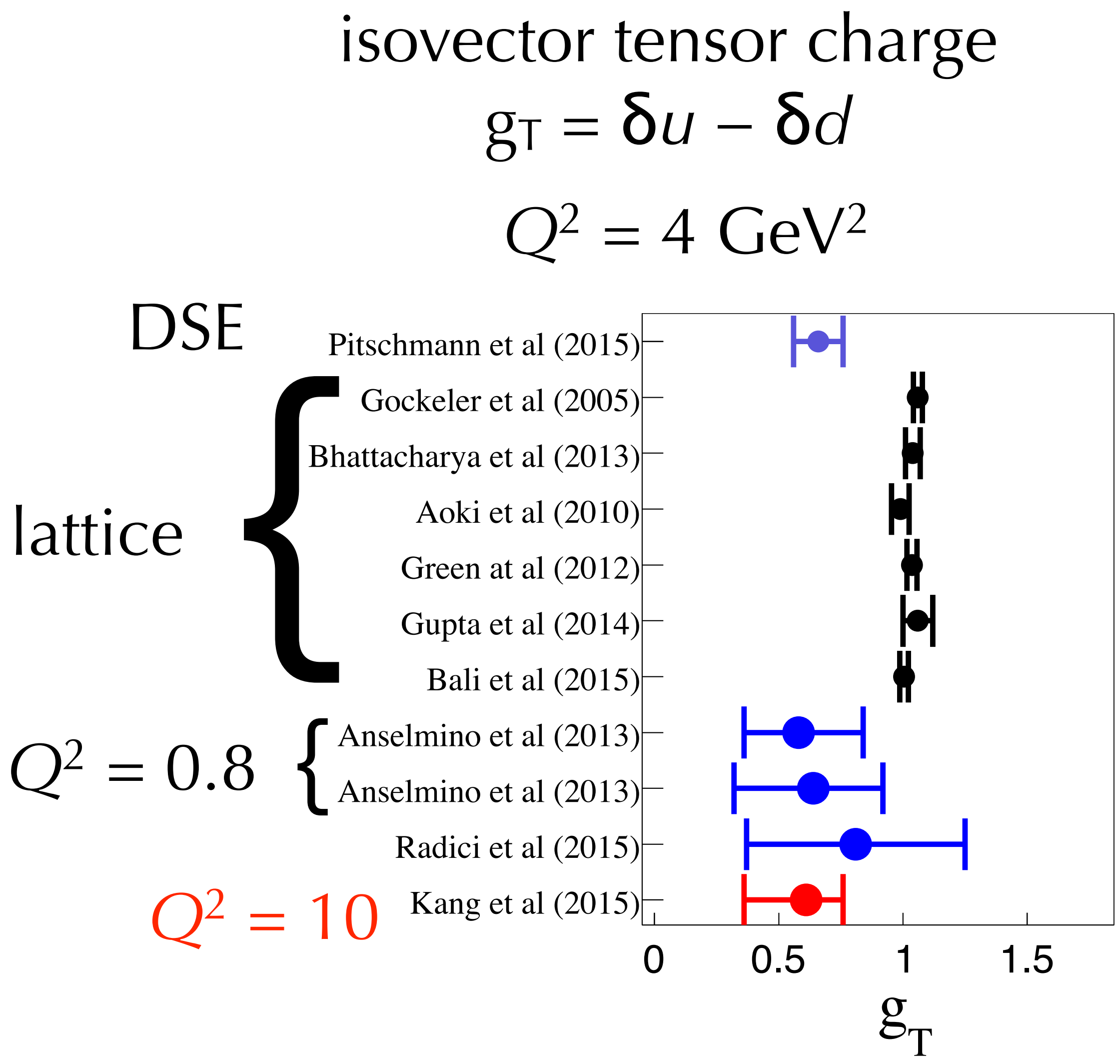


Tensor charge



Tensor charge is an ideal quantity to compare to lattice QCD

Tensor charge



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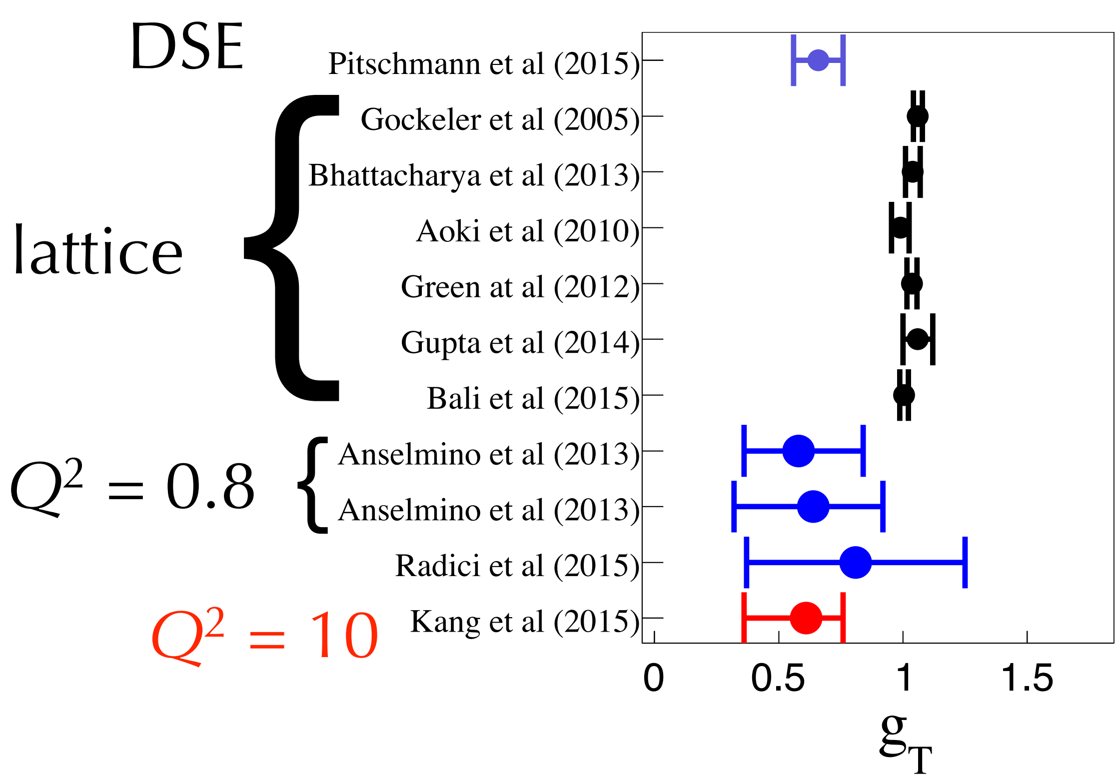

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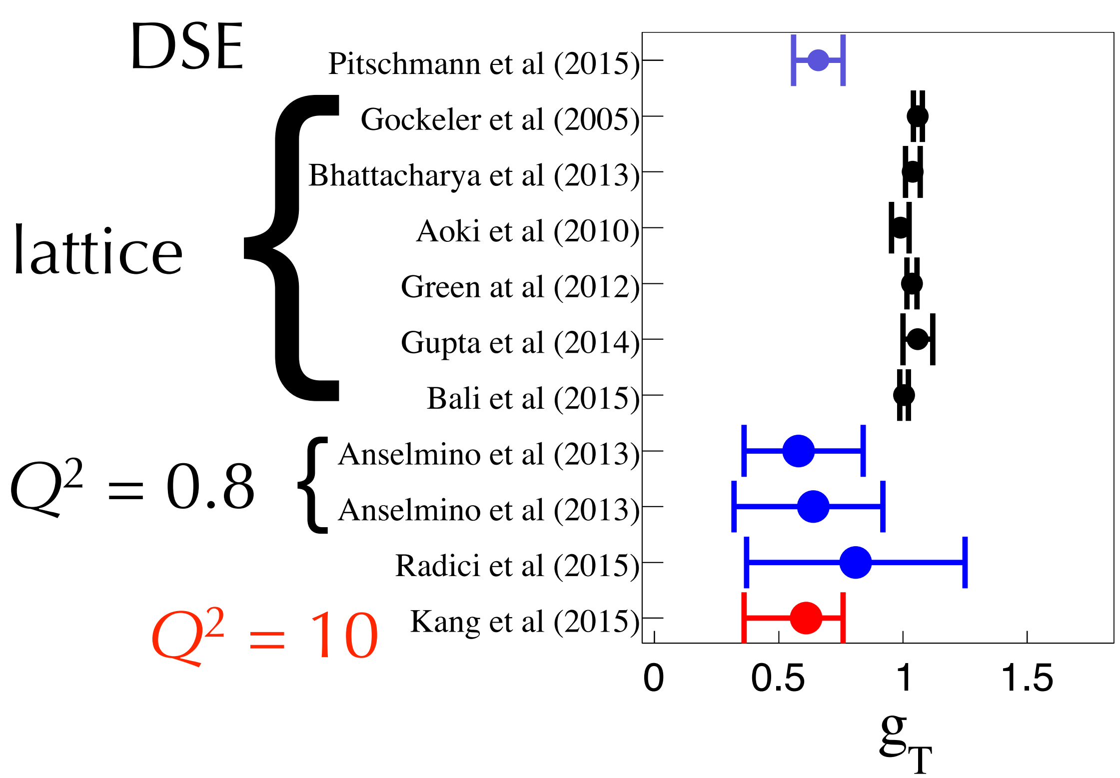

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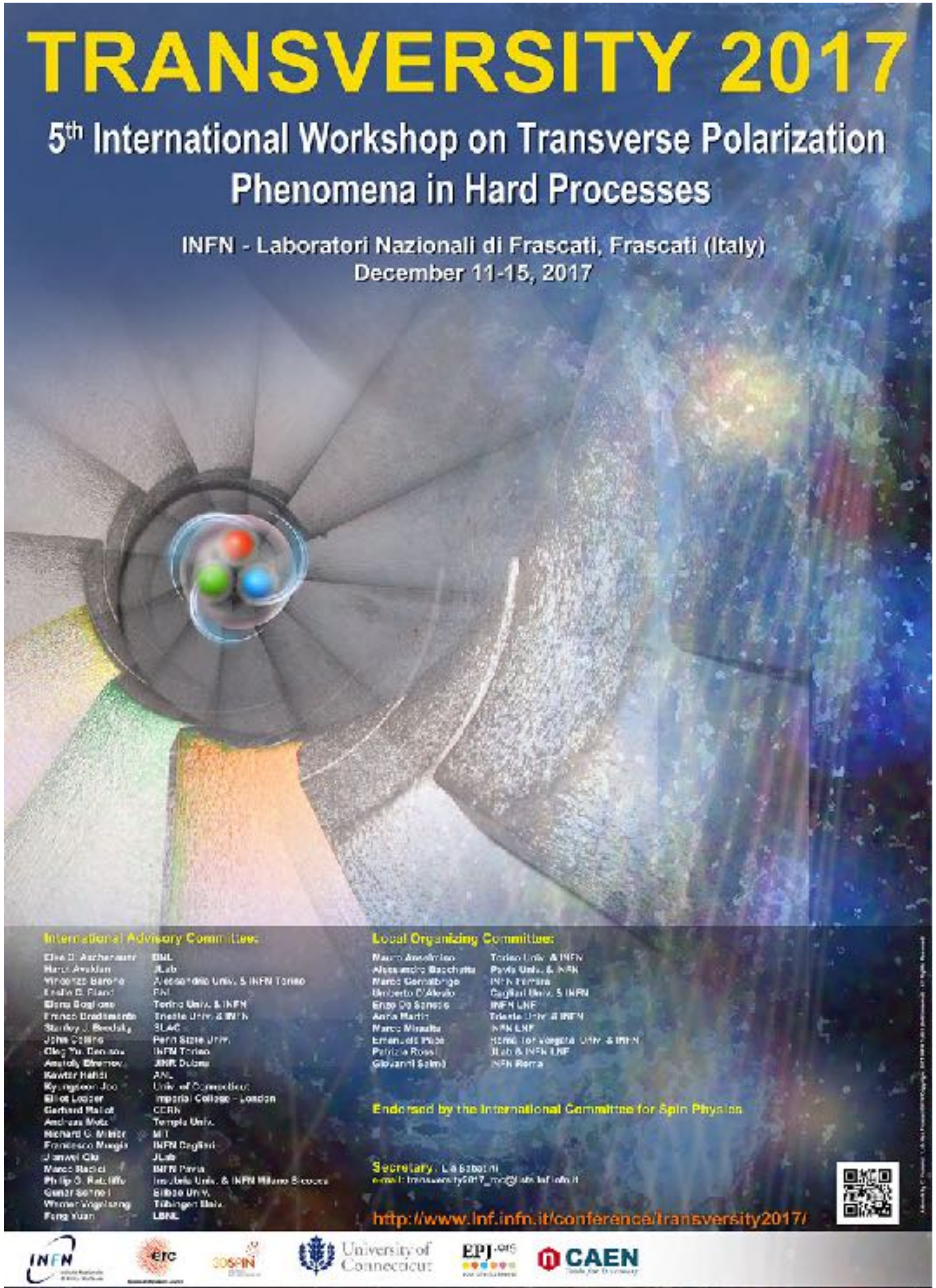
talk by S. Liuti

see also talk by A. Accardi for a way to access tensor charge in inclusive DIS

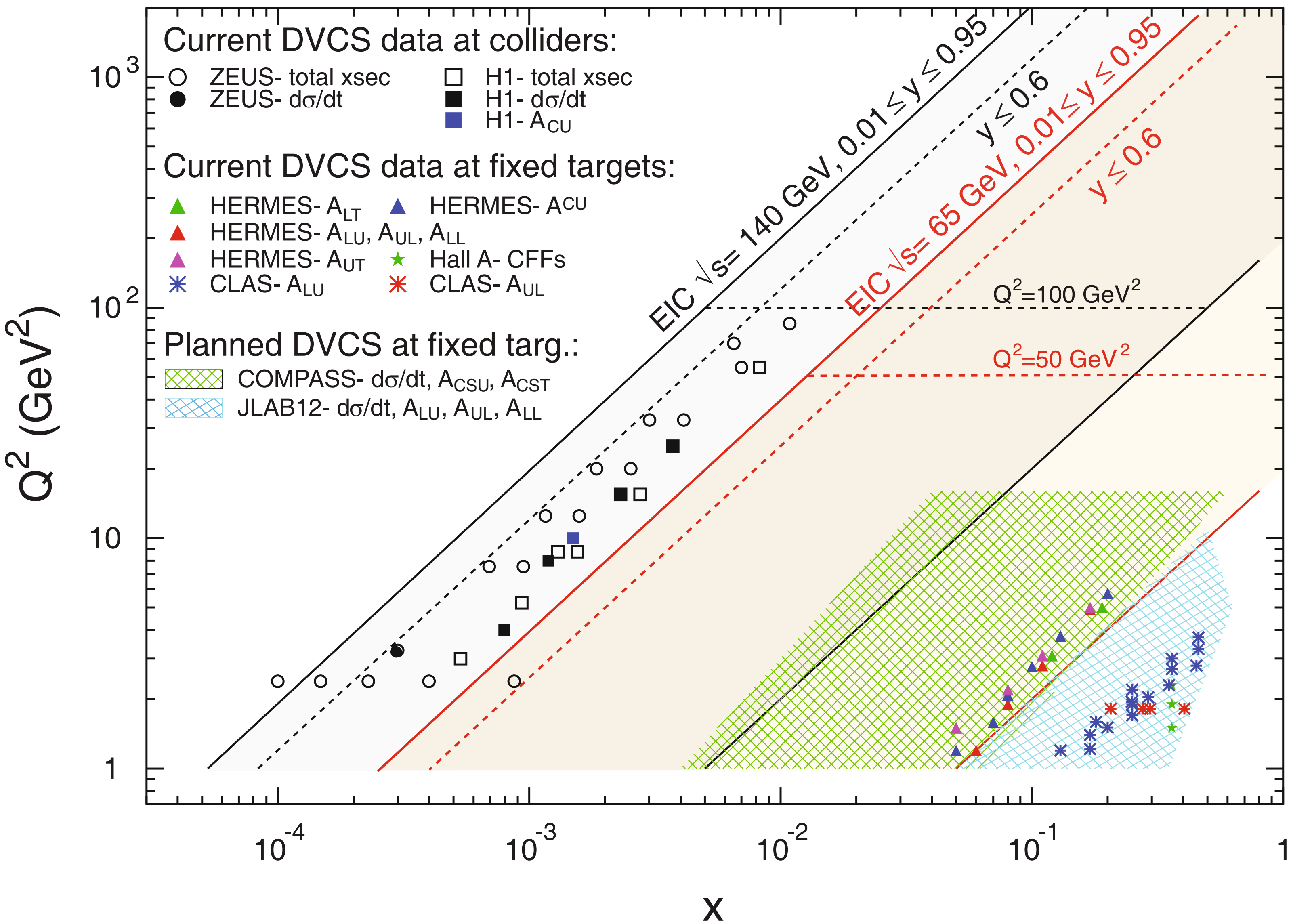

TRANSVERSITY 2017
5th International Workshop on Transverse Polarization Phenomena in Hard Processes
INFN - Laboratori Nazionali di Frascati, Frascati (Italy)
December 11-15, 2017
International Advisory Committee:
Local Organizing Committee:
Endorsed by the International Committee for Spin Physics
http://www.lnf.infn.it/conference/transversity2017/
University of Connecticut
CAEN

GPDs

GPDs Science Matrix

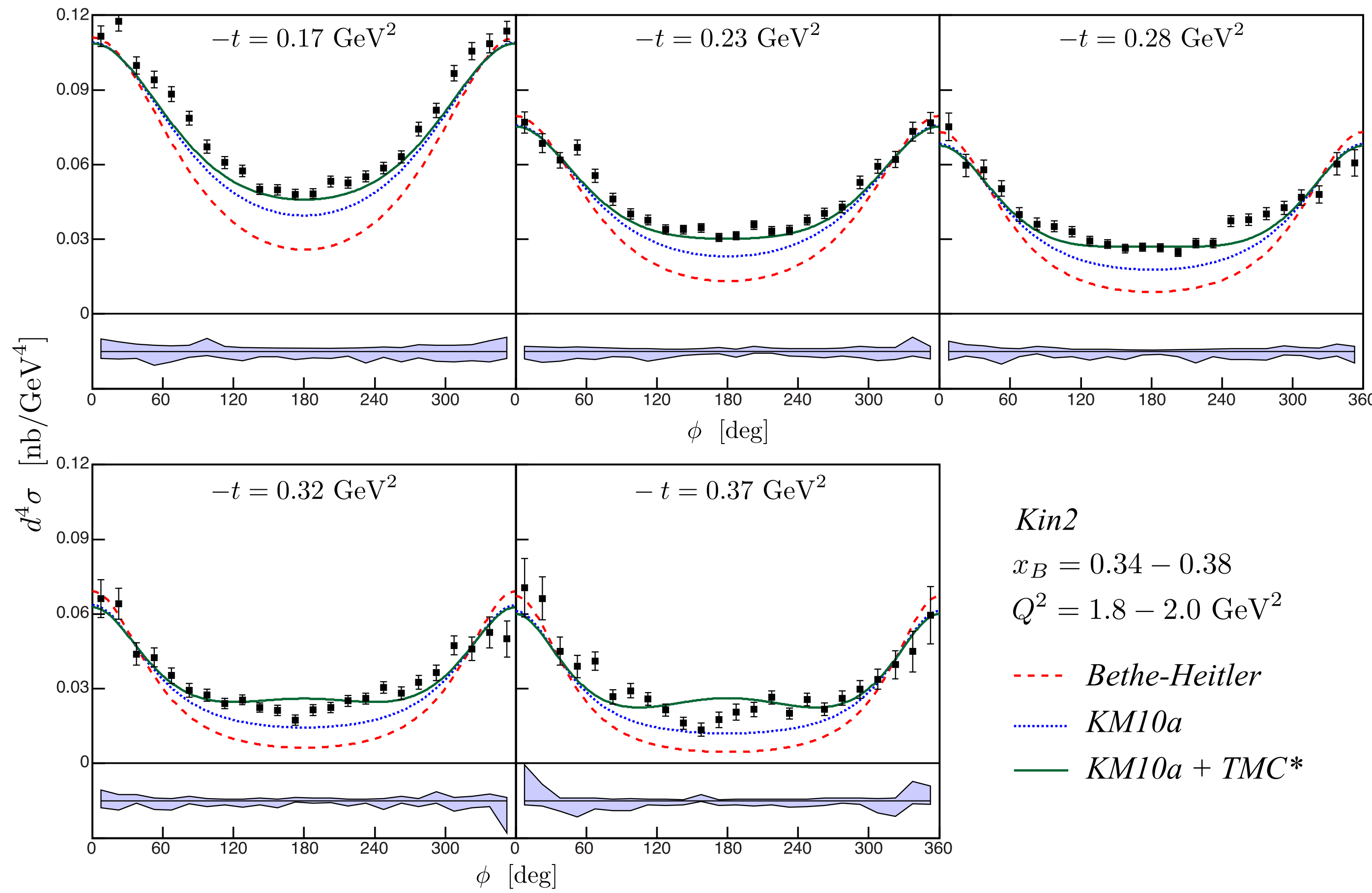
Deliverables	Observables	What we learn
GPDs of sea quarks and gluons	DVCS and J/ψ, ρ^0, ϕ production cross-section and polarization asymmetries	transverse spatial distrib. of sea quarks and gluons; total angular momentum and spin-orbit correlations
GPDs of valence and sea quarks	electro-production of π^+, K and ρ^+, K^*	dependence on quark flavor and polarization

Existing and future data



Example of data and parametrizations

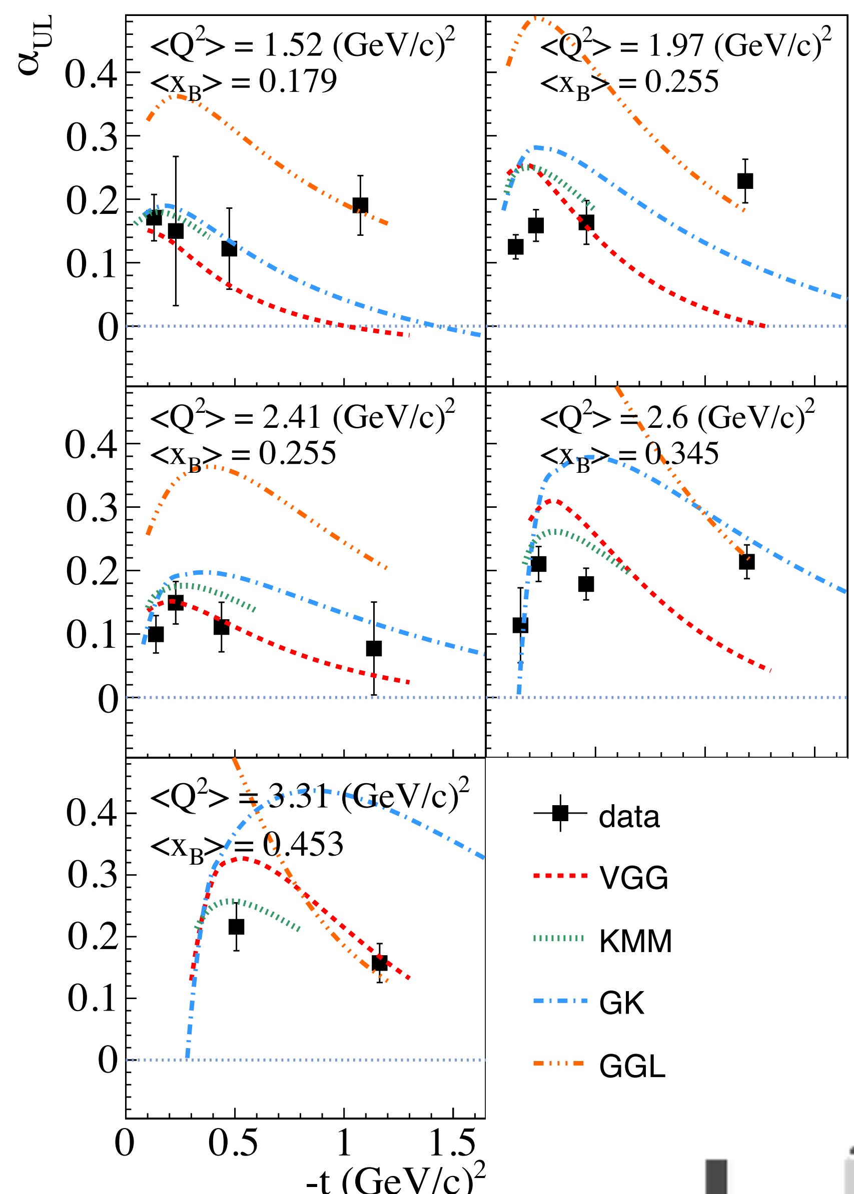
Defurne et al. arXiv:1504.05453



Jefferson Lab

Hall-A E00-110

Pisano et al., arXiv:1501.07052



CEBAF Large Acceptance Spectrometer

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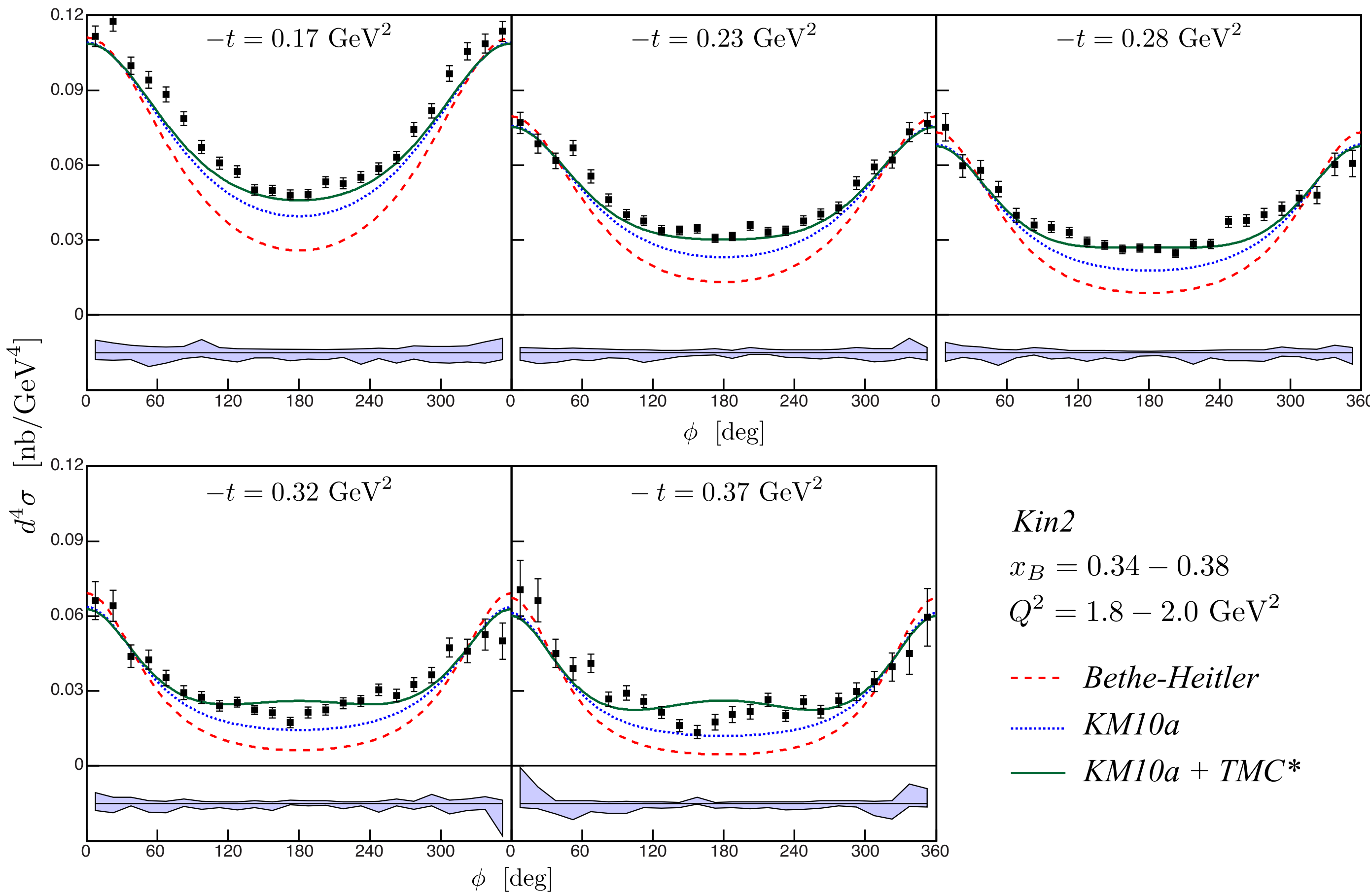

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Hall-A E00-110

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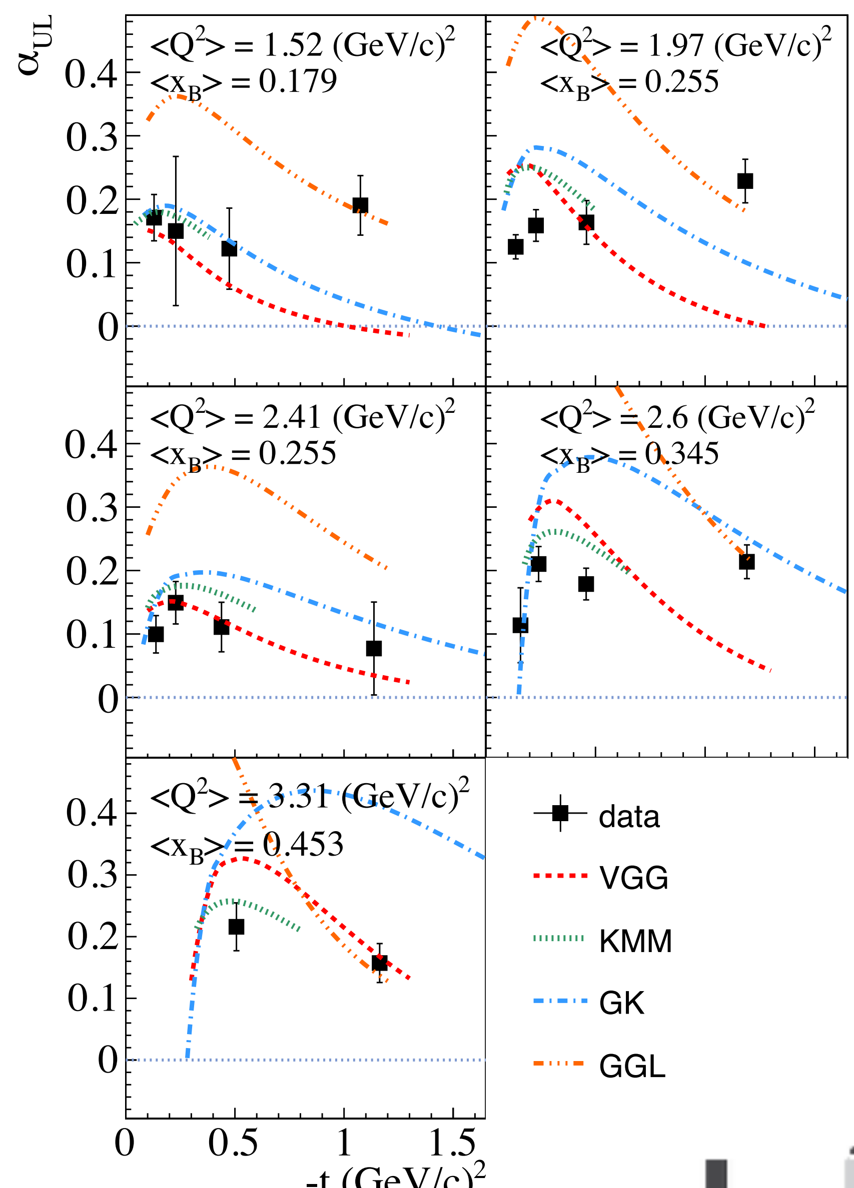


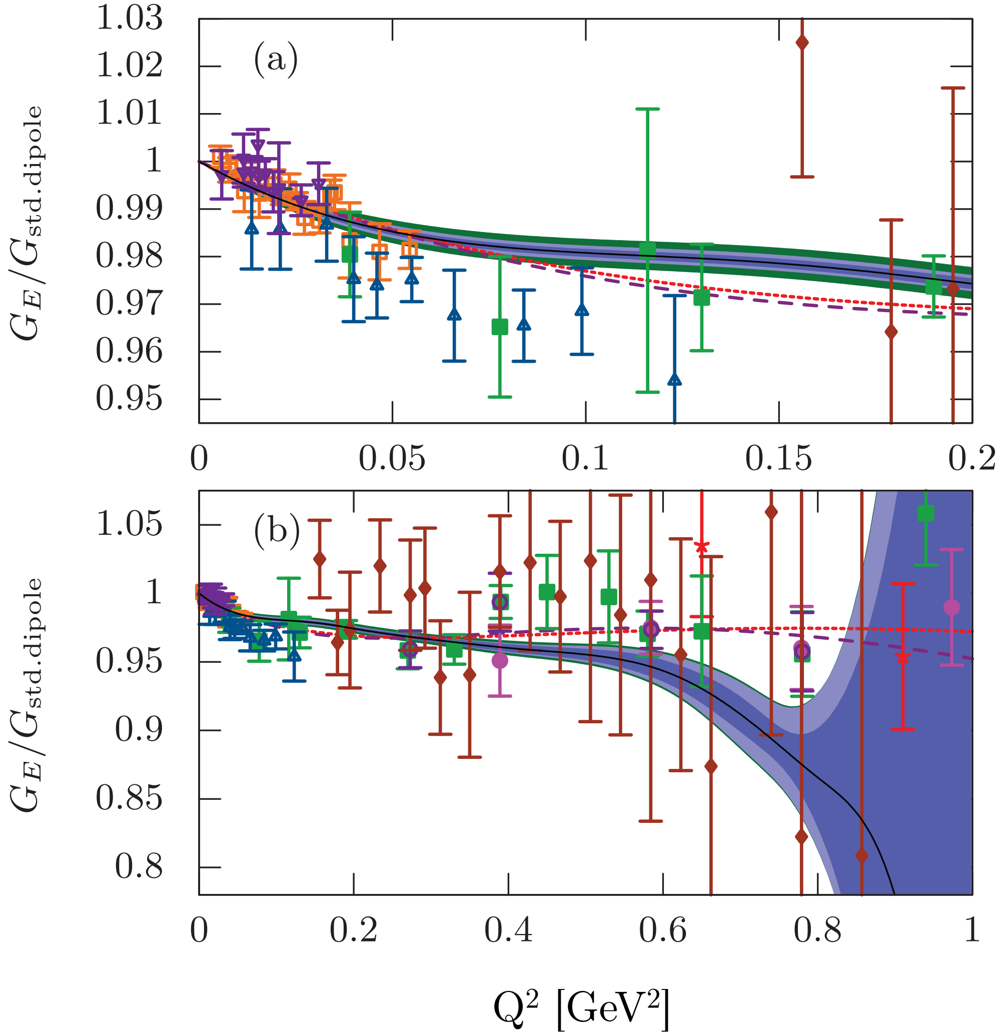
CEBAF Large Acceptance Spectrometer

Steady progress in data collection and parametrizations.

Not all data are well reproduced, yet

Imaging: let's start from 2D...

Bernauer et al., arXiv:1307.6227



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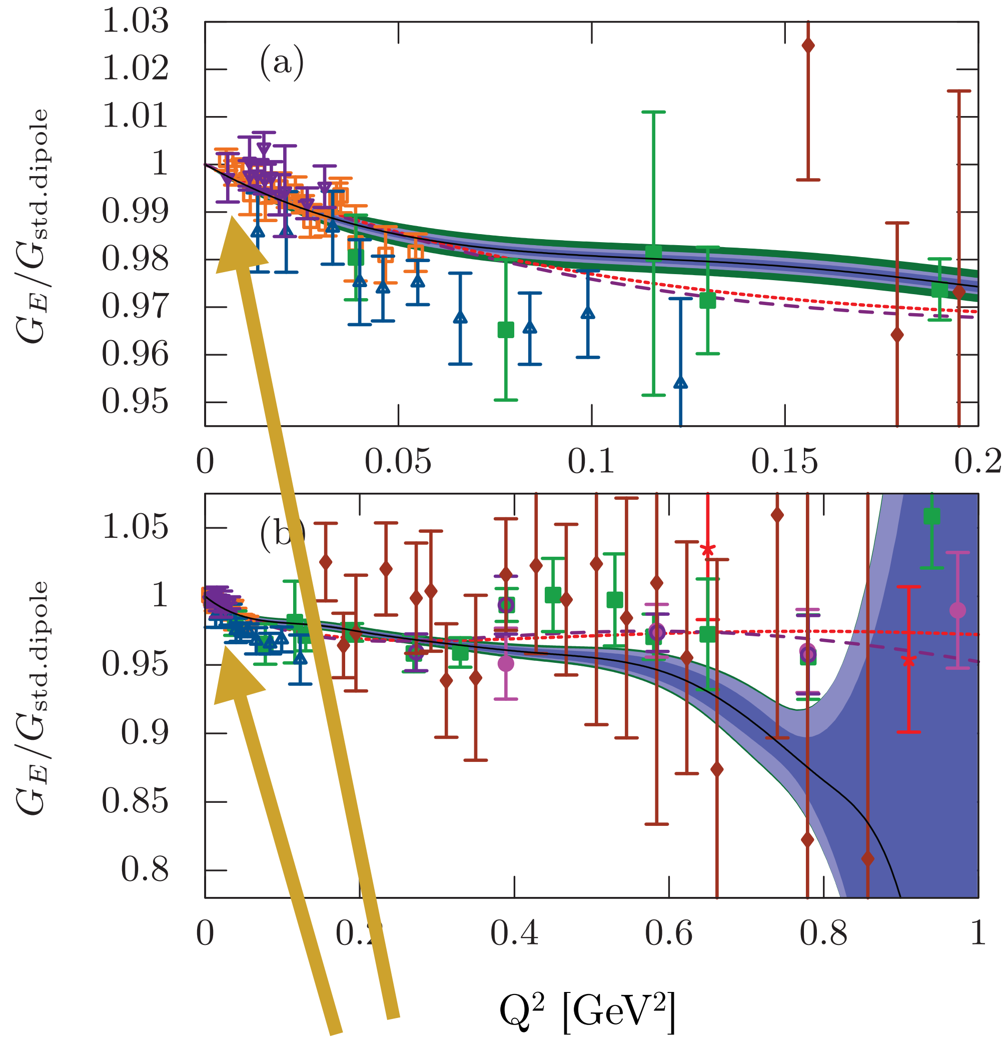

Form Factors are extracted, fitted, and slope at Q^2=0 is determined.

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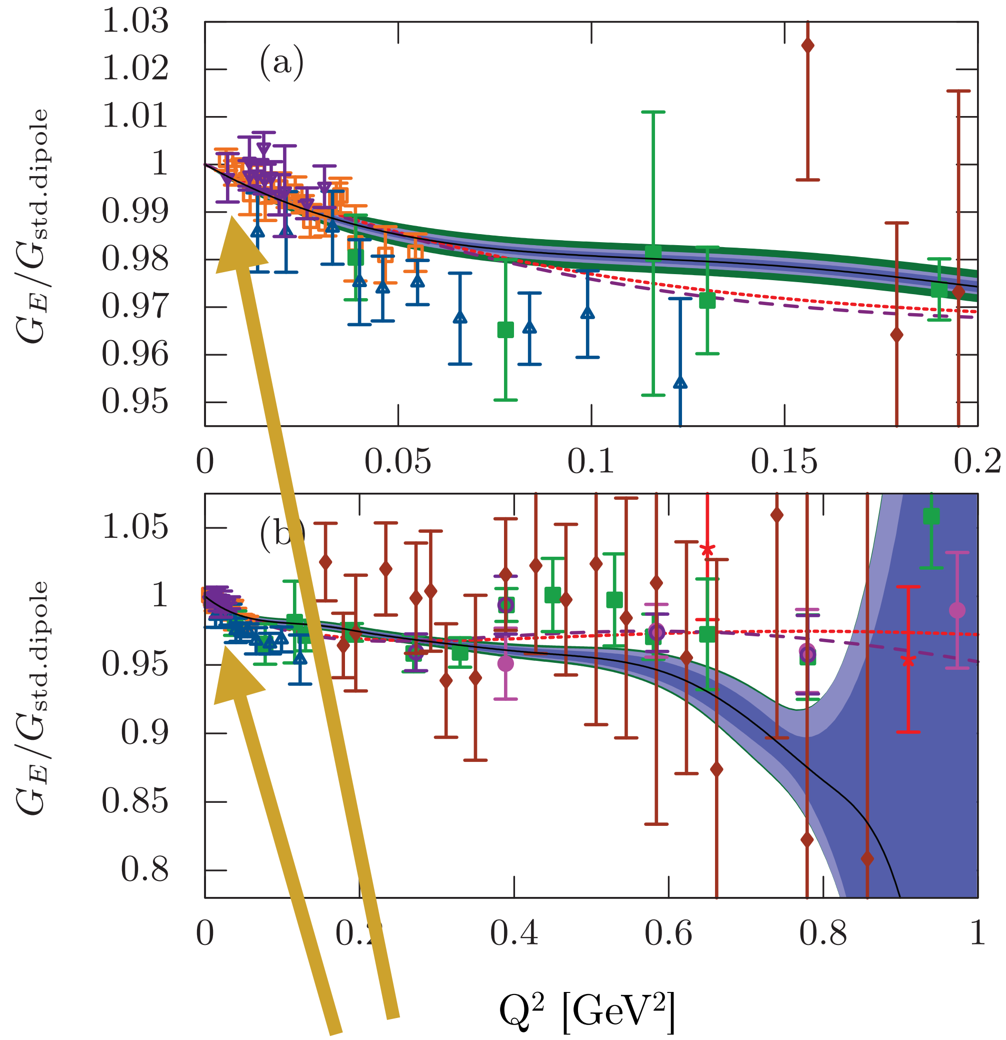
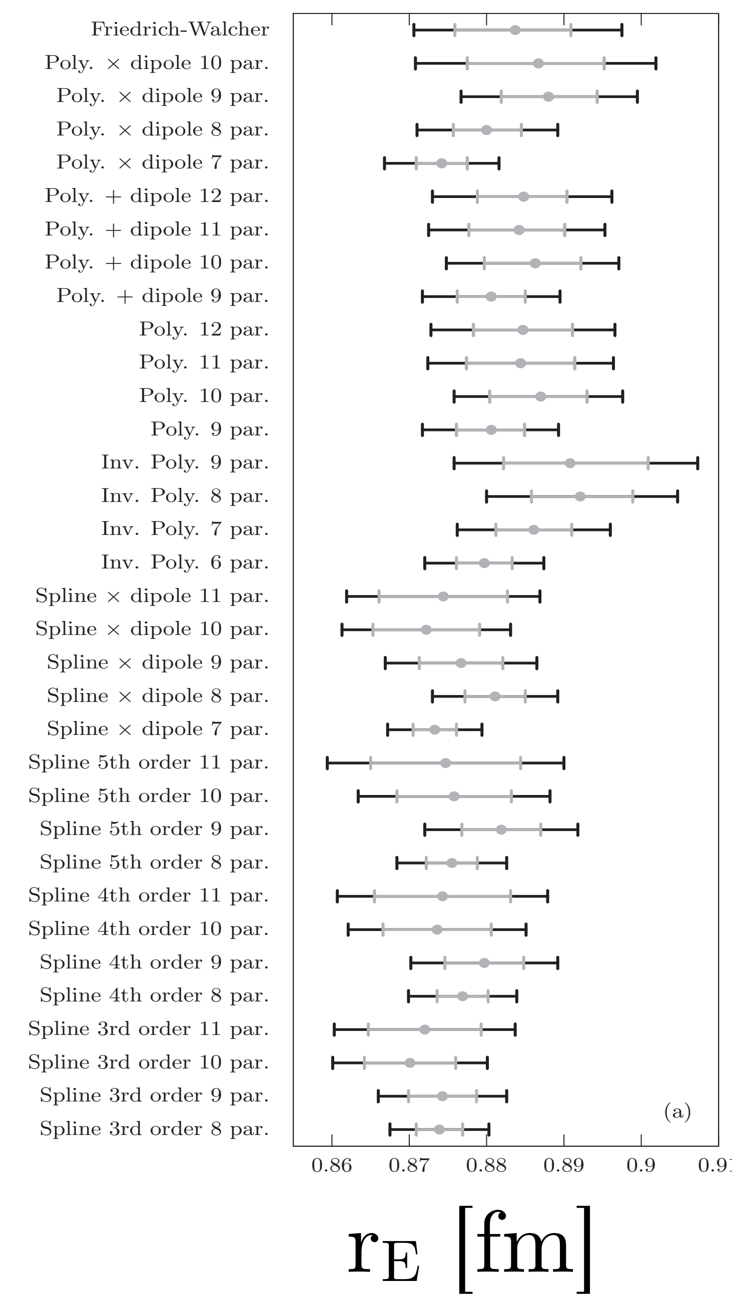
Bernauer et al., [arXiv:1307.6227]()





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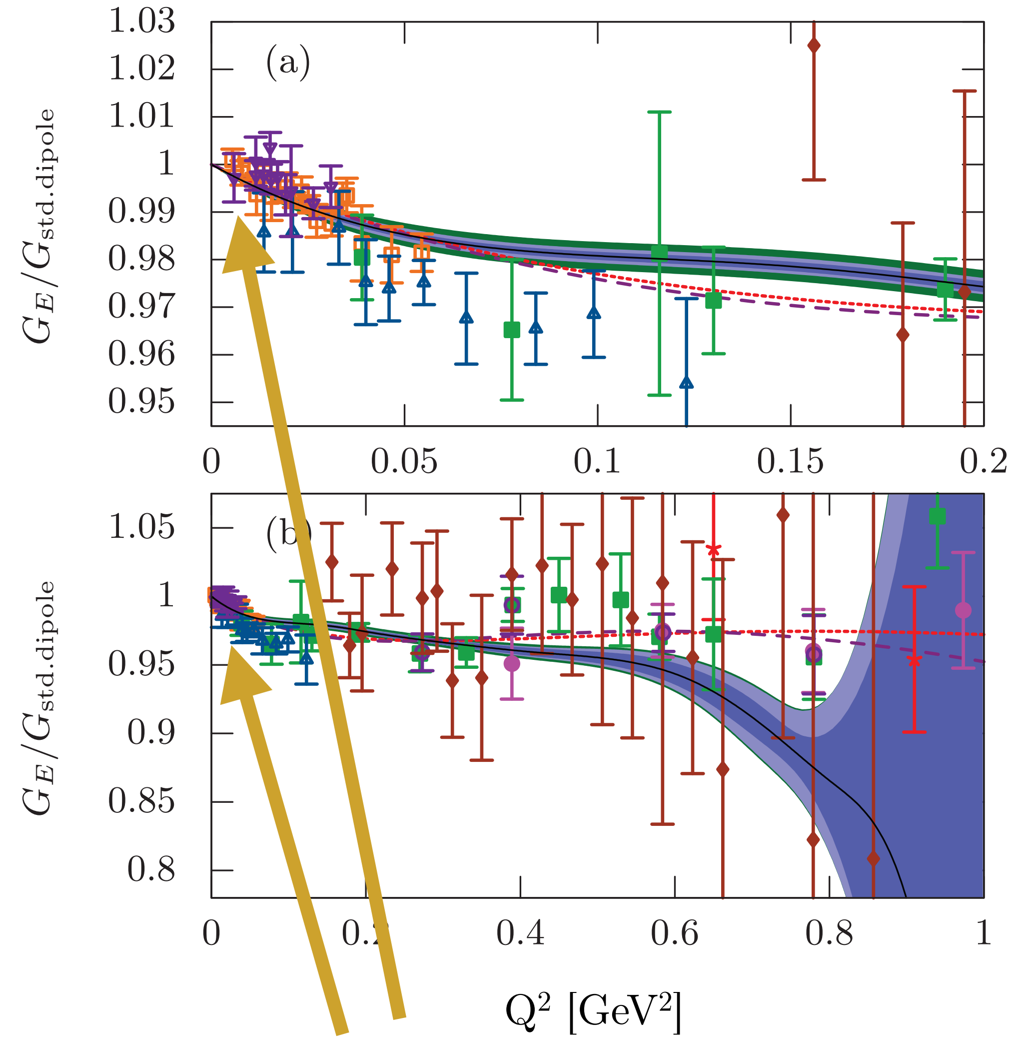

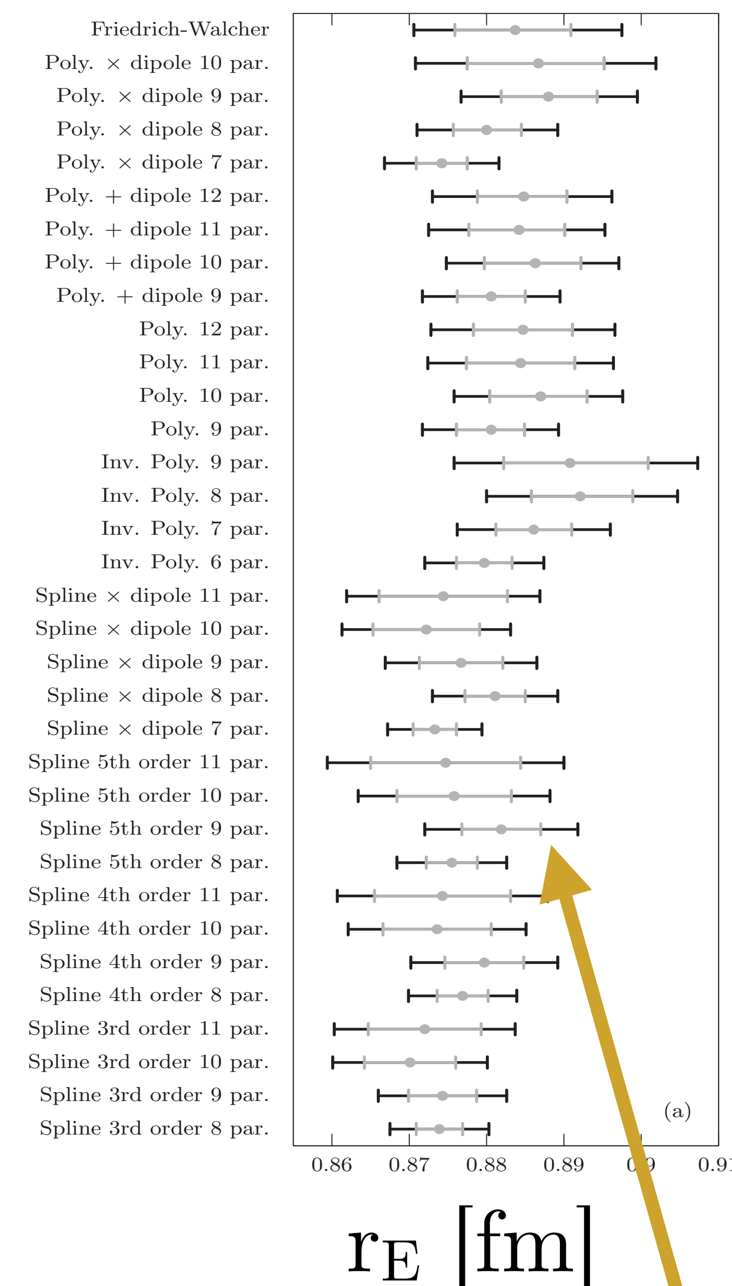

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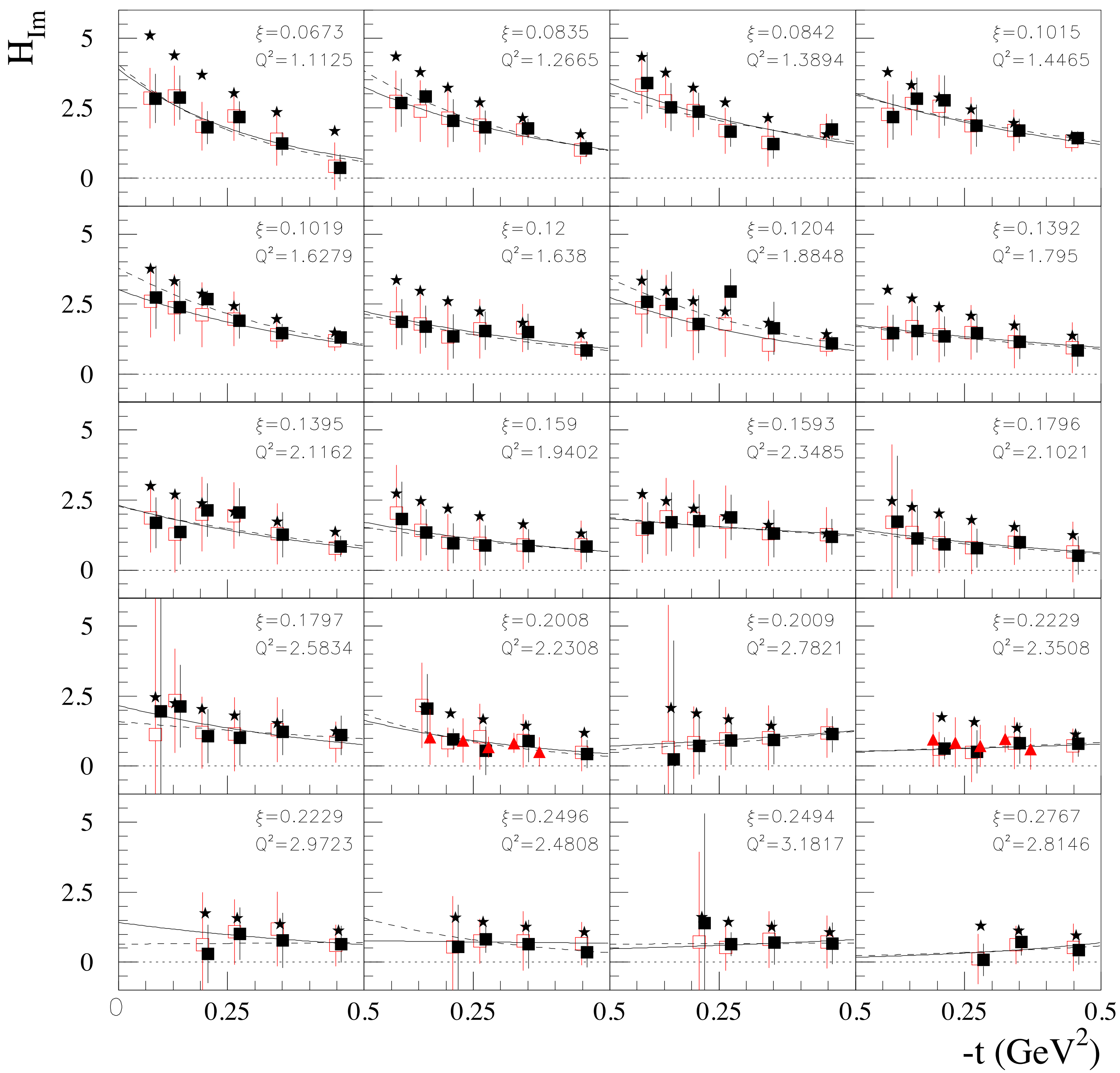
Thanks to the wealth of data, the extraction is mildly sensitive to extrapolation.

The way to 3D imaging

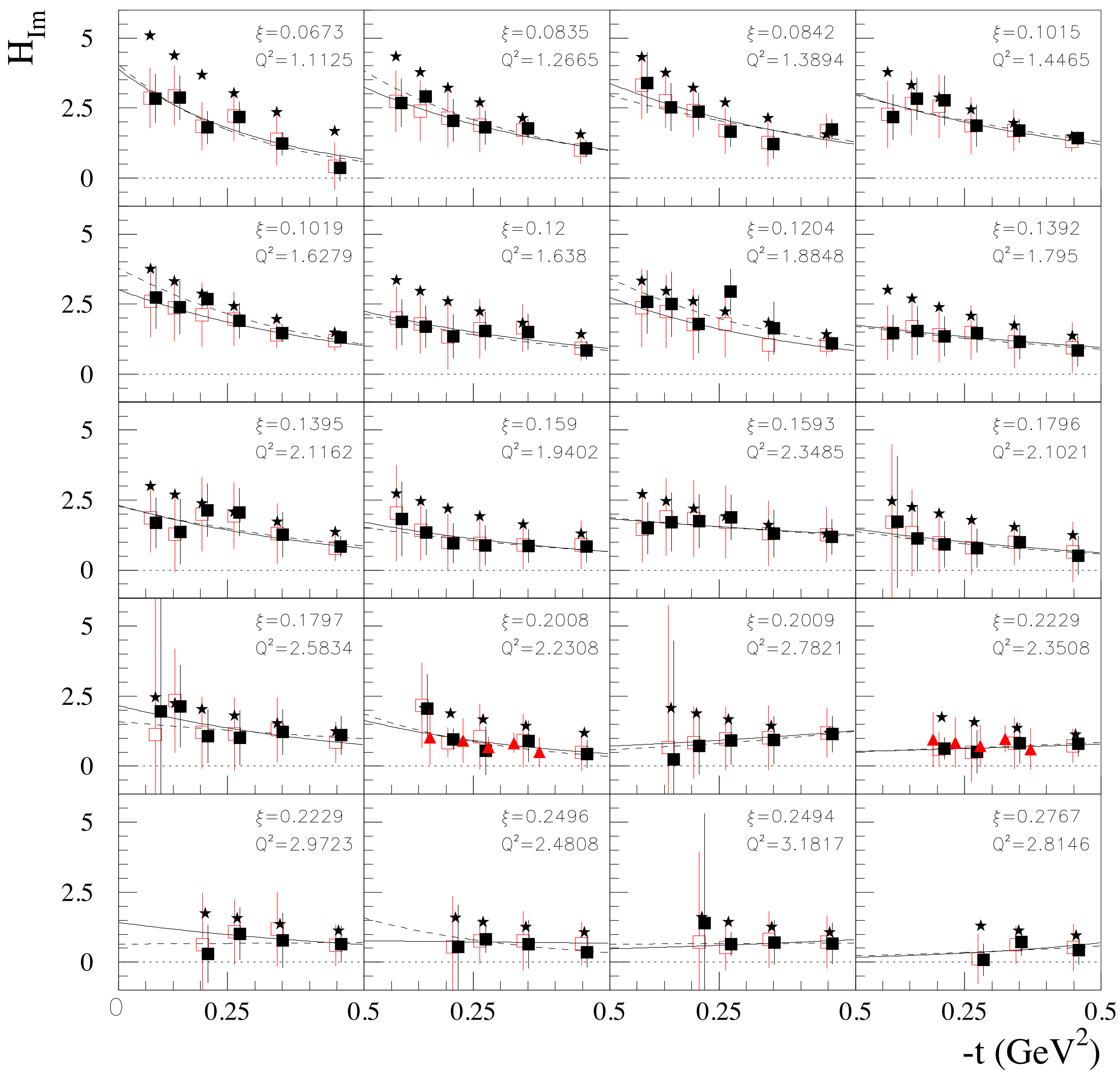


Compton Form Factors are extracted from data

Jefferson Lab

Dupré, Guidal, Niccolai, Vanderhaeghen, arXiv:1704.07330

The way to 3D imaging



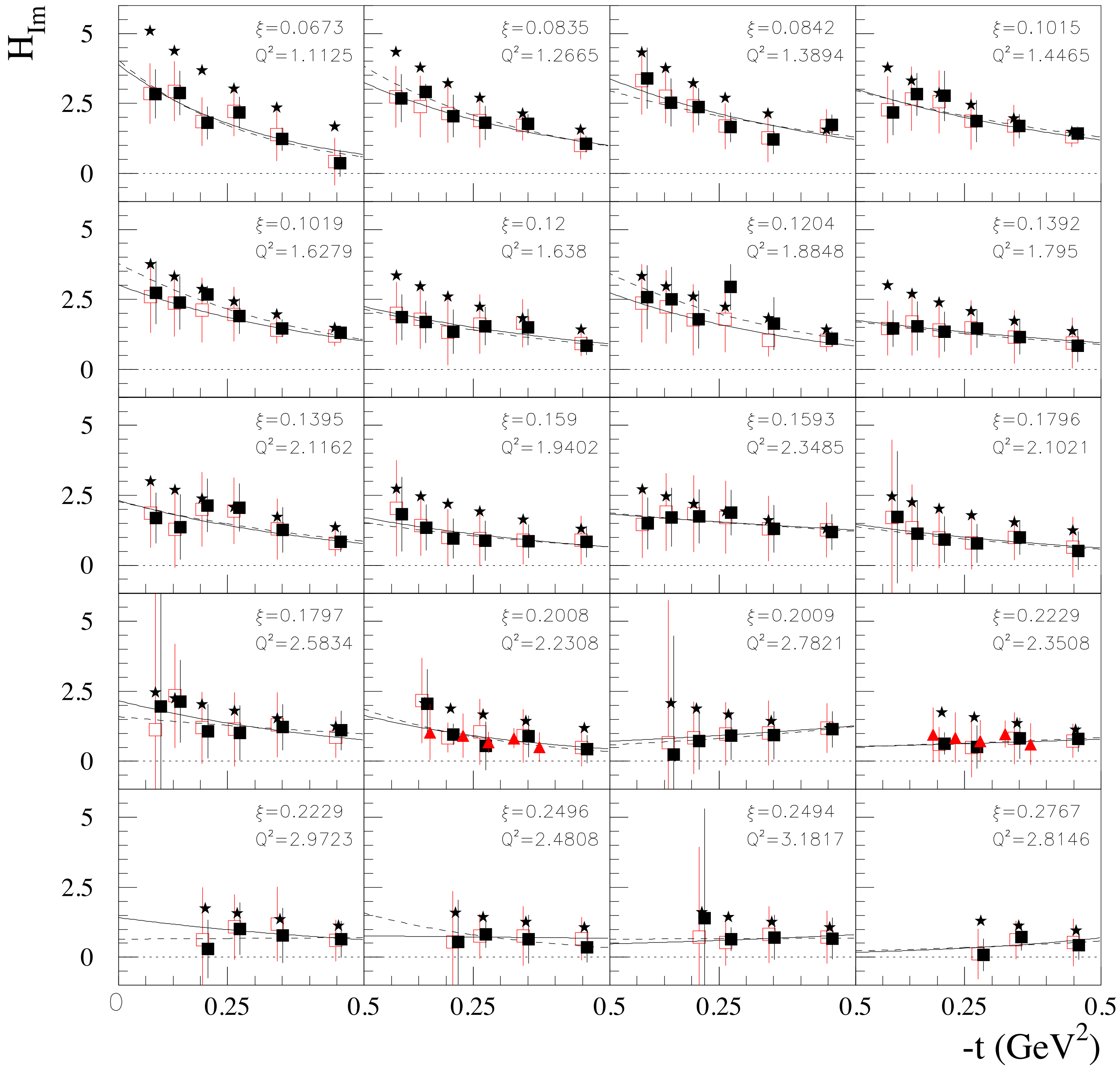
Compton Form Factors are extracted from data

Jefferson Lab

hermes

Dupré, Guidal, Niccolai, Vanderhaeghen, [*arXiv:1704.07330*]

The way to 3D imaging



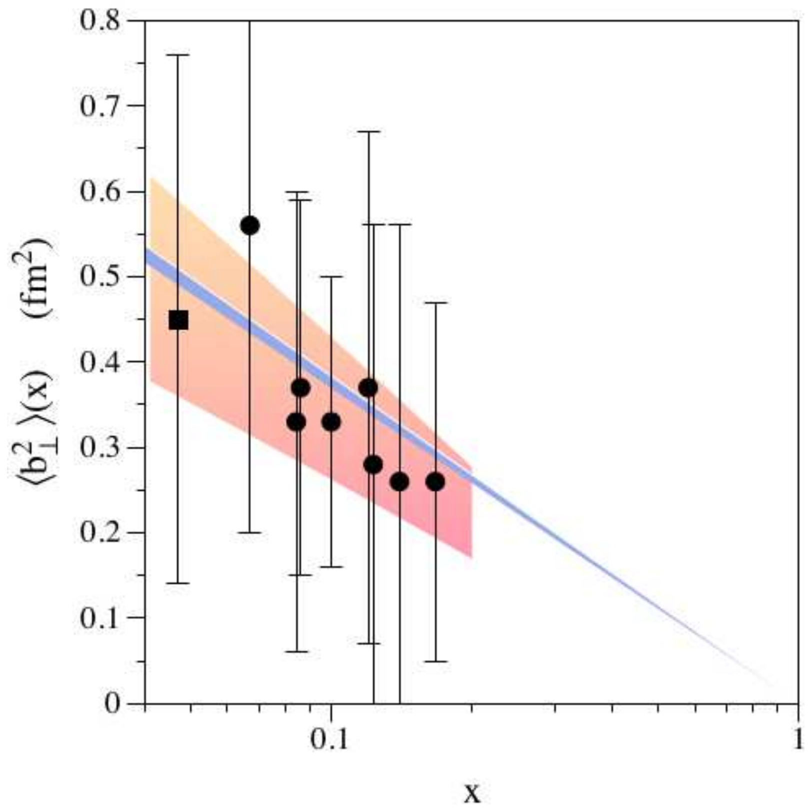
Compton Form Factors are extracted from data

They are fitted with some ansatz and the slope at t=0 for each value of ξ is extracted

$$H_{Im}(\xi, t) = A(\xi)e^{B(\xi)t}$$

Dupré, Guidal, Niccolai, Vanderhaeghen, arXiv:1704.07330

Transverse size of proton



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[arXiv:1704.07330]()

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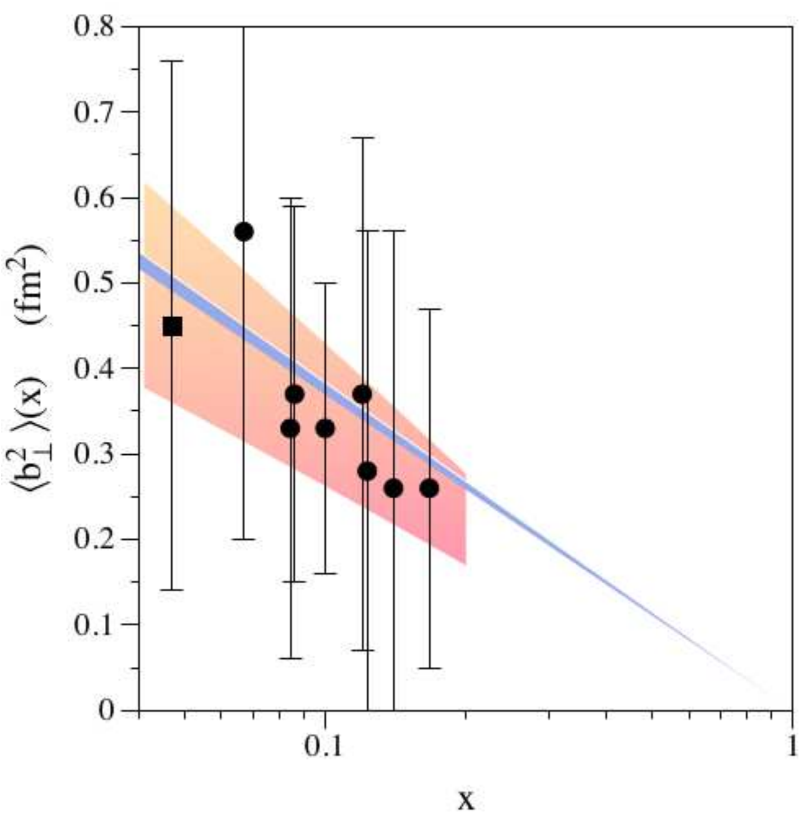
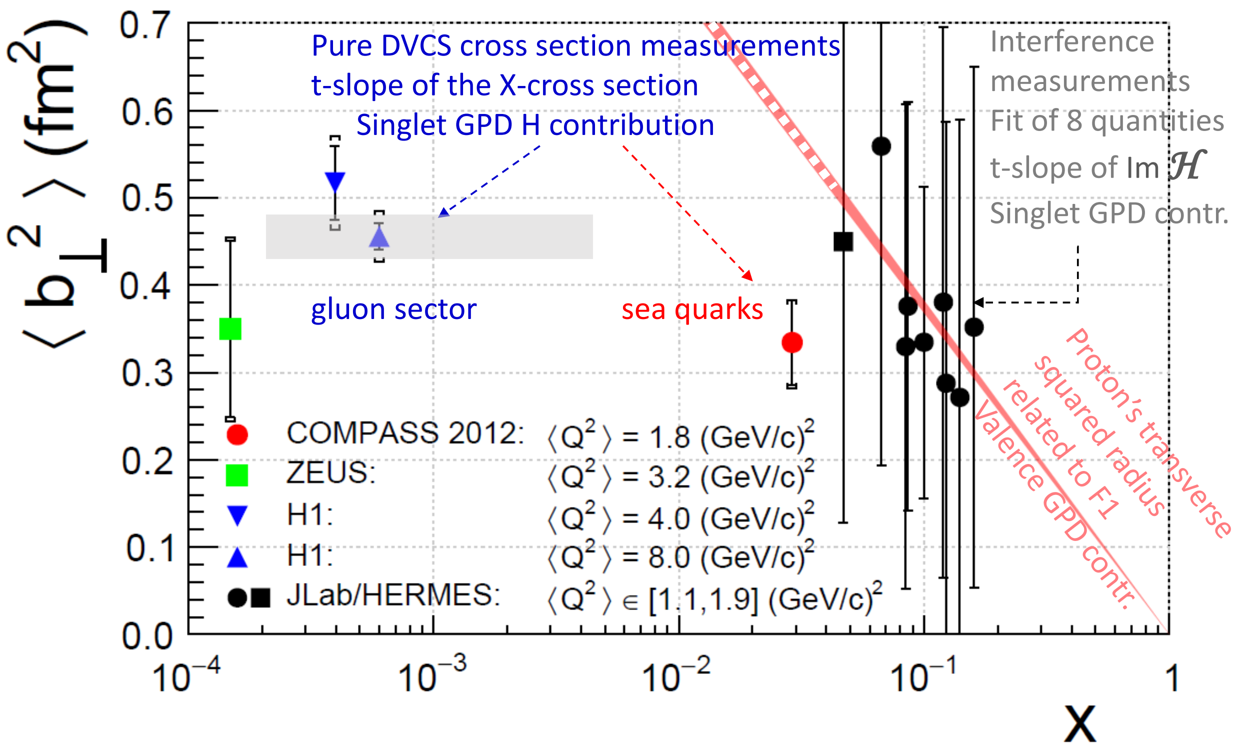


Dupré, Guidal, Niccolai, Vanderhaeghen, arXiv:1704.07330



talk by E. M. Kabuss at DIS2017 and Jörg arXiv:1702.06315

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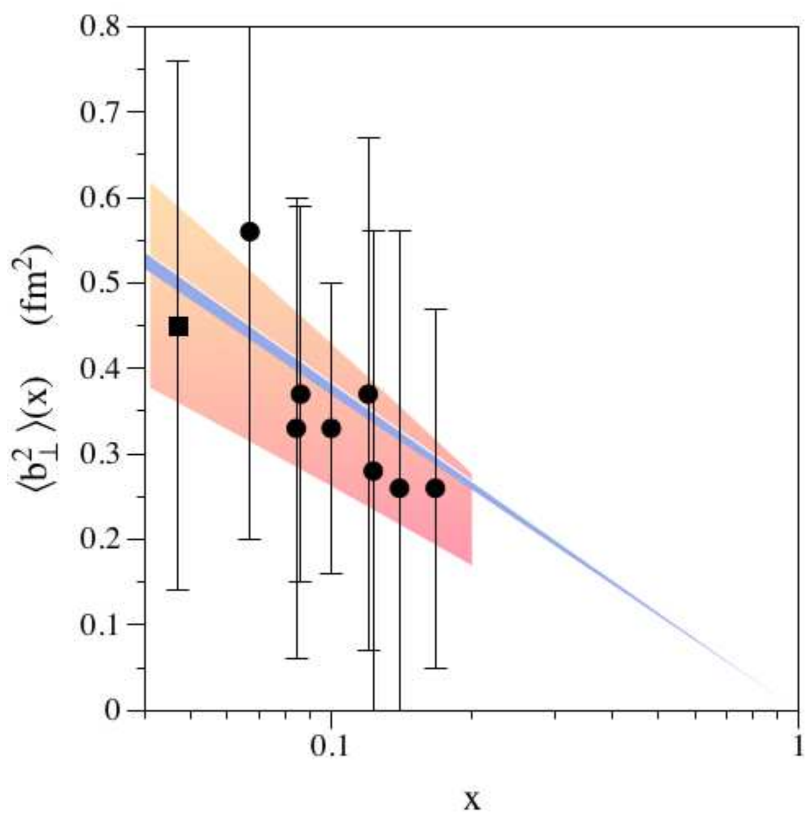
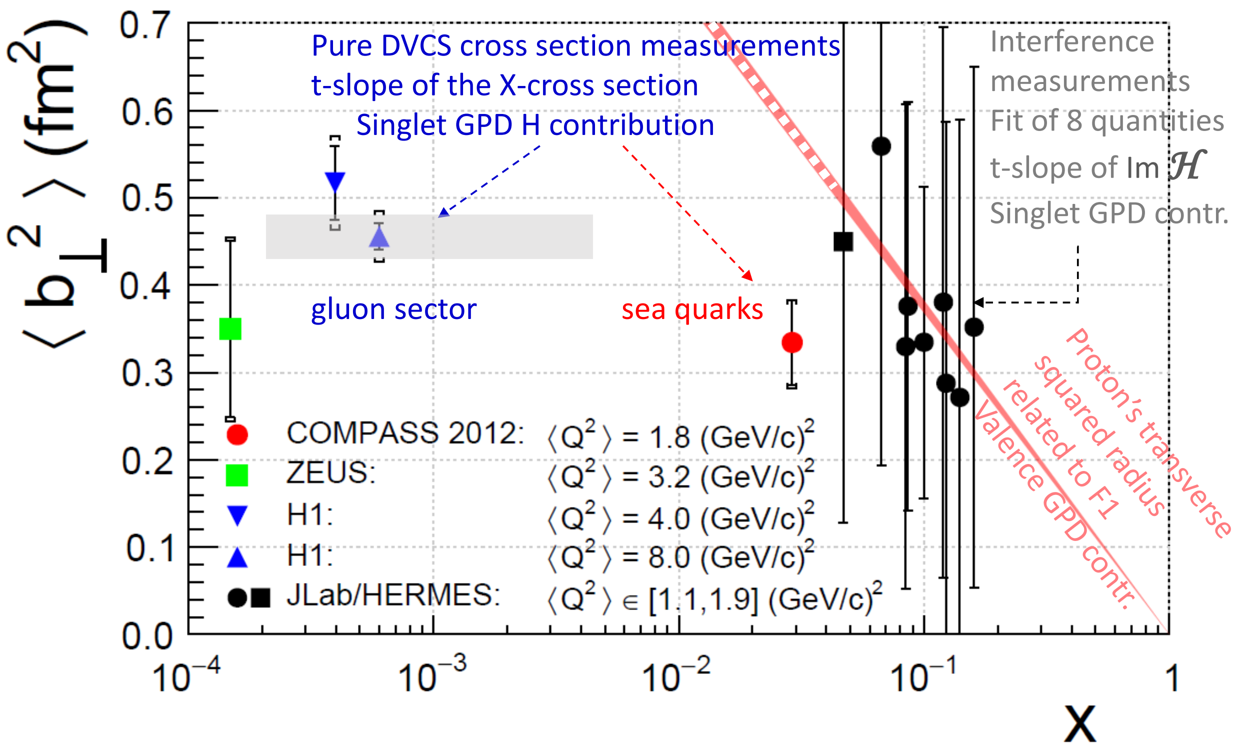
The errors are large, but slowly we are getting some 3D information. Even if we do not get 3D imaging, GPDs are still gold mines of information about QCD!





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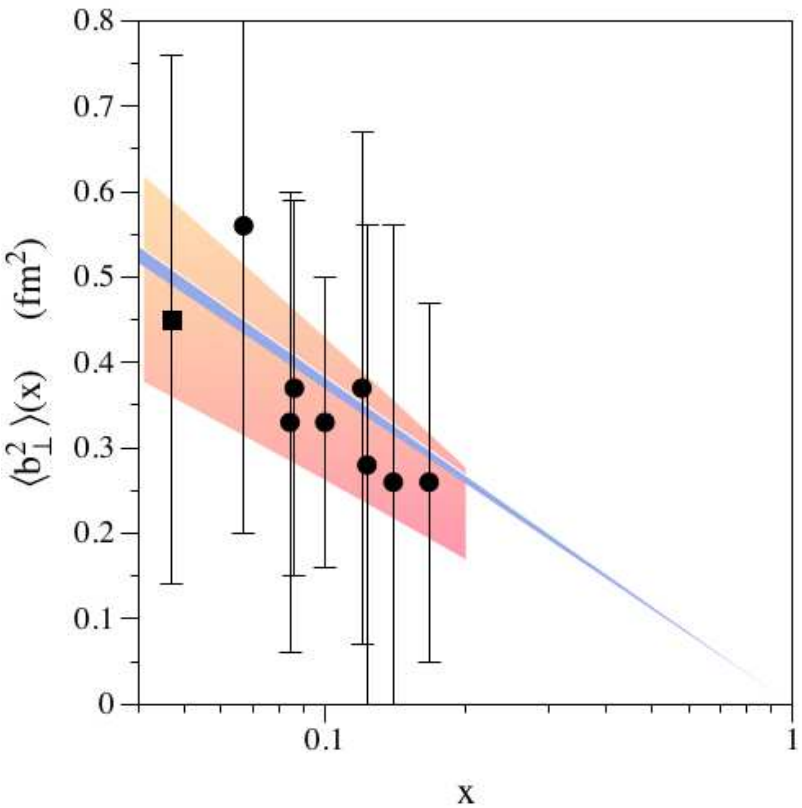
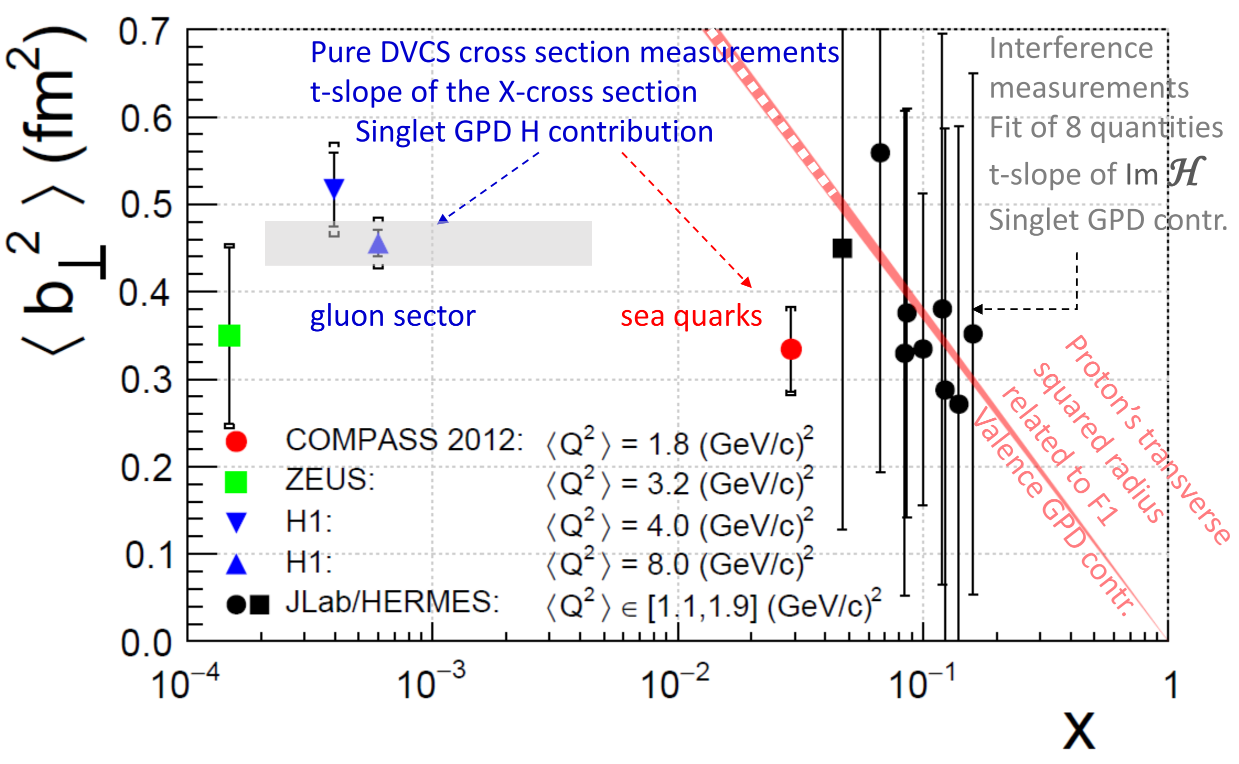


Dupré, Guidal, Niccolai, Vanderhaeghen, [arXiv:1704.07330]



talk by E. M. Kabuss at DIS2017 and Jörg arXiv:1702.06315

talks by S. Niccolai and N. D'Hose

What about angular momentum?

Ji's sum rule

$$J^q = \frac{1}{2}\int_0^1 dx\, x\left(H^q(x,0,0) + E^q(x,0,0)\right)$$

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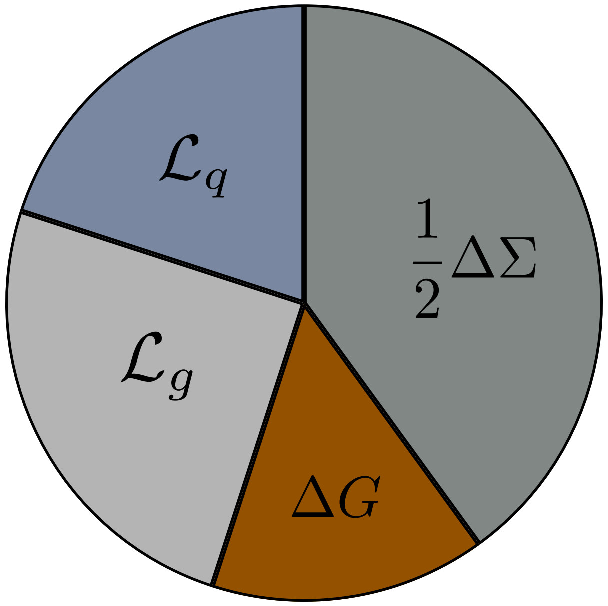
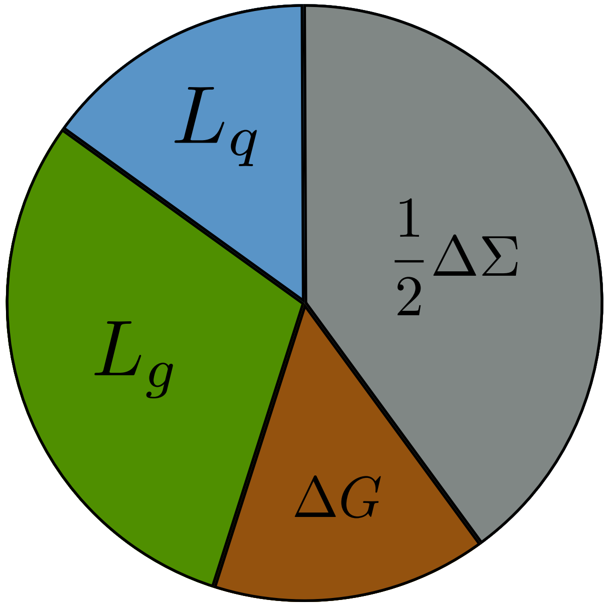
- Requires spanning x at fixed values of ξ (ξ=0 is the most convenient)
- Does not have an interpretation as angular momentum density as a function of x

Possibility to access angular momentum



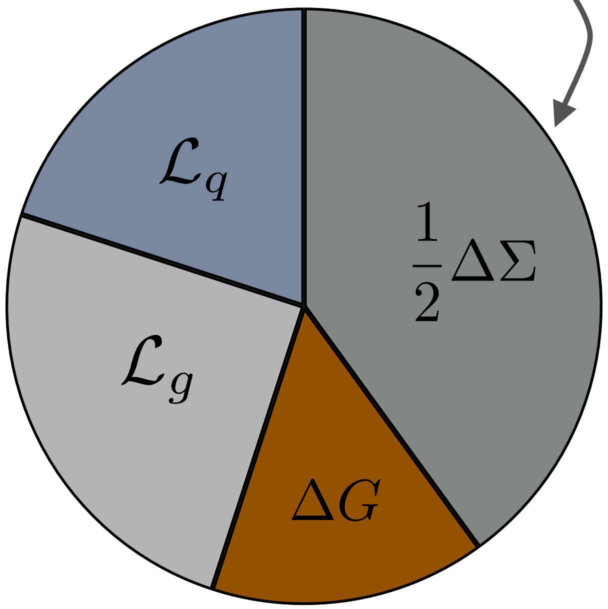


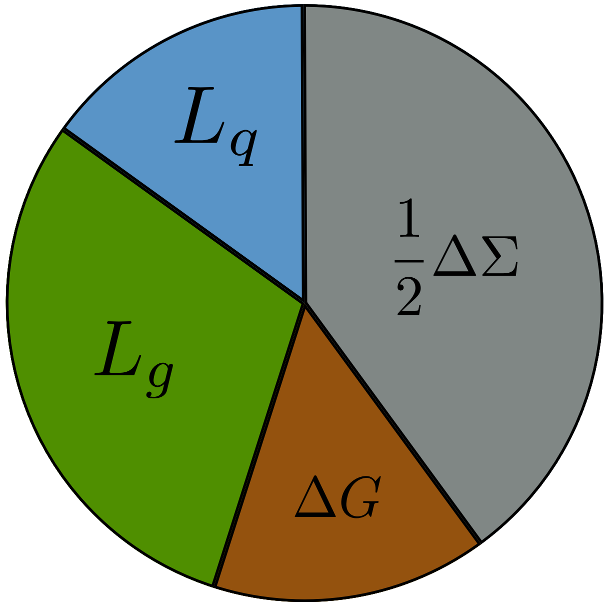
Canonical

Kinetic

Possibility to access angular momentum

Collinear quark helicity PDFs





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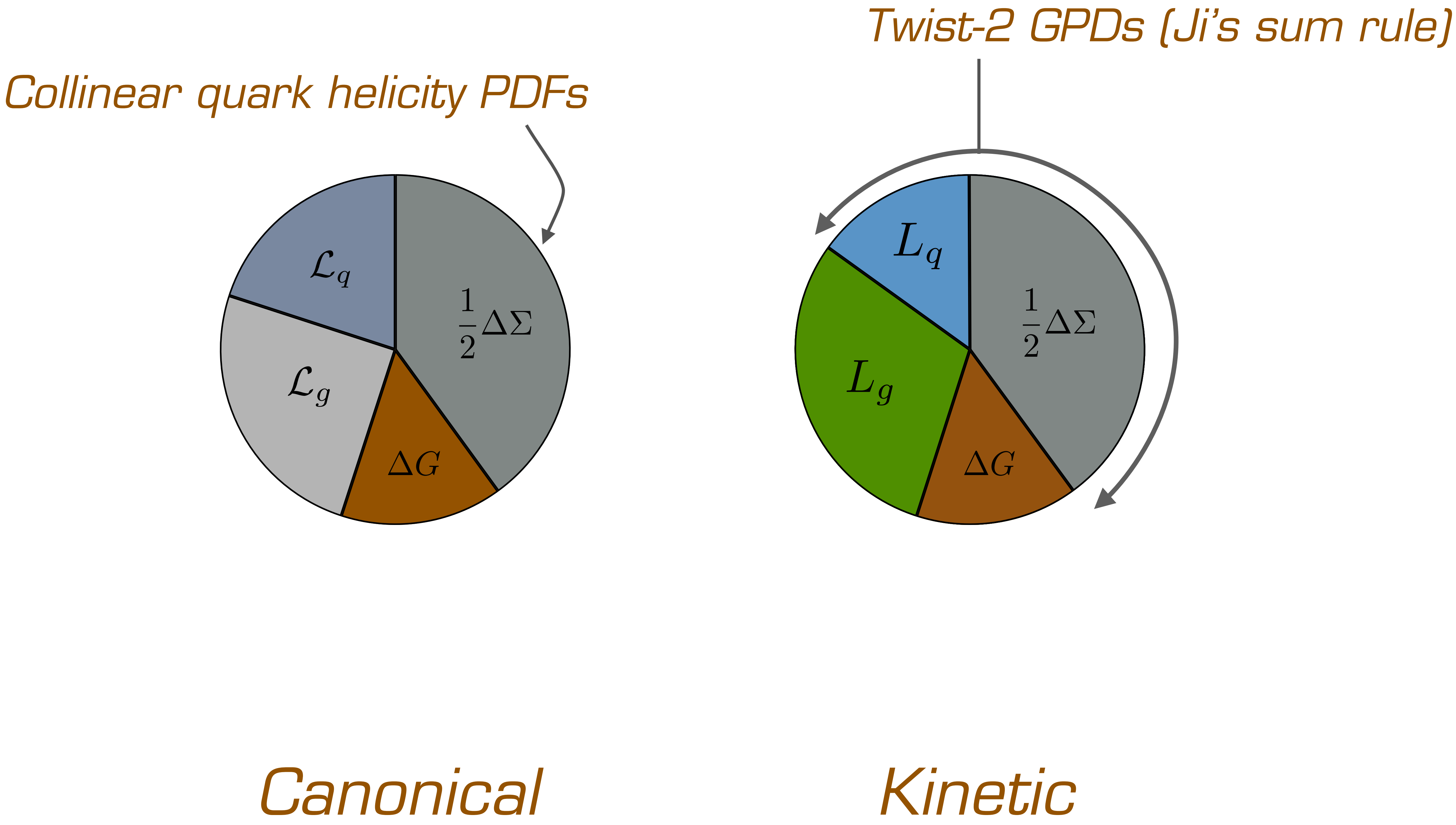

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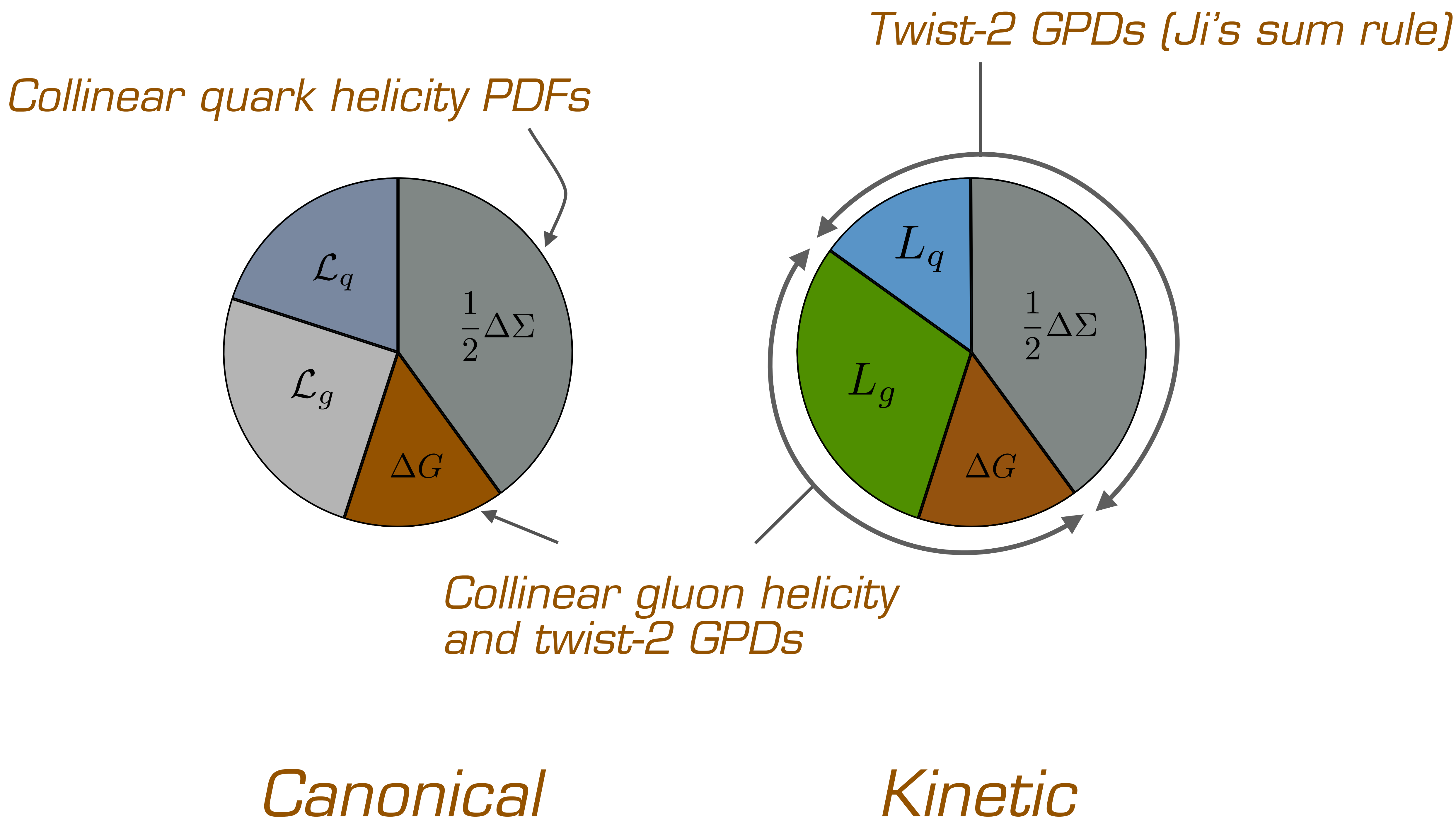

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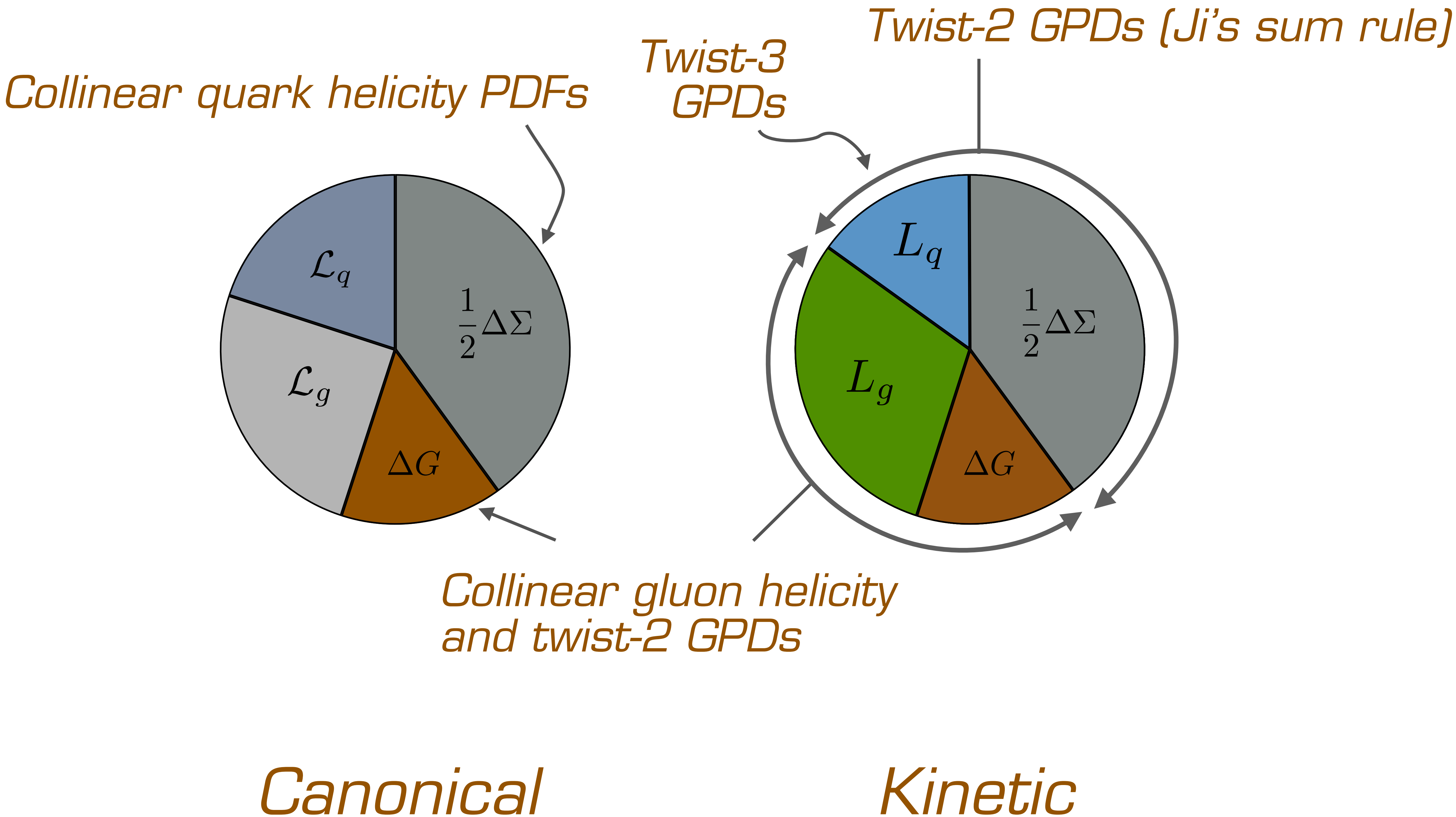

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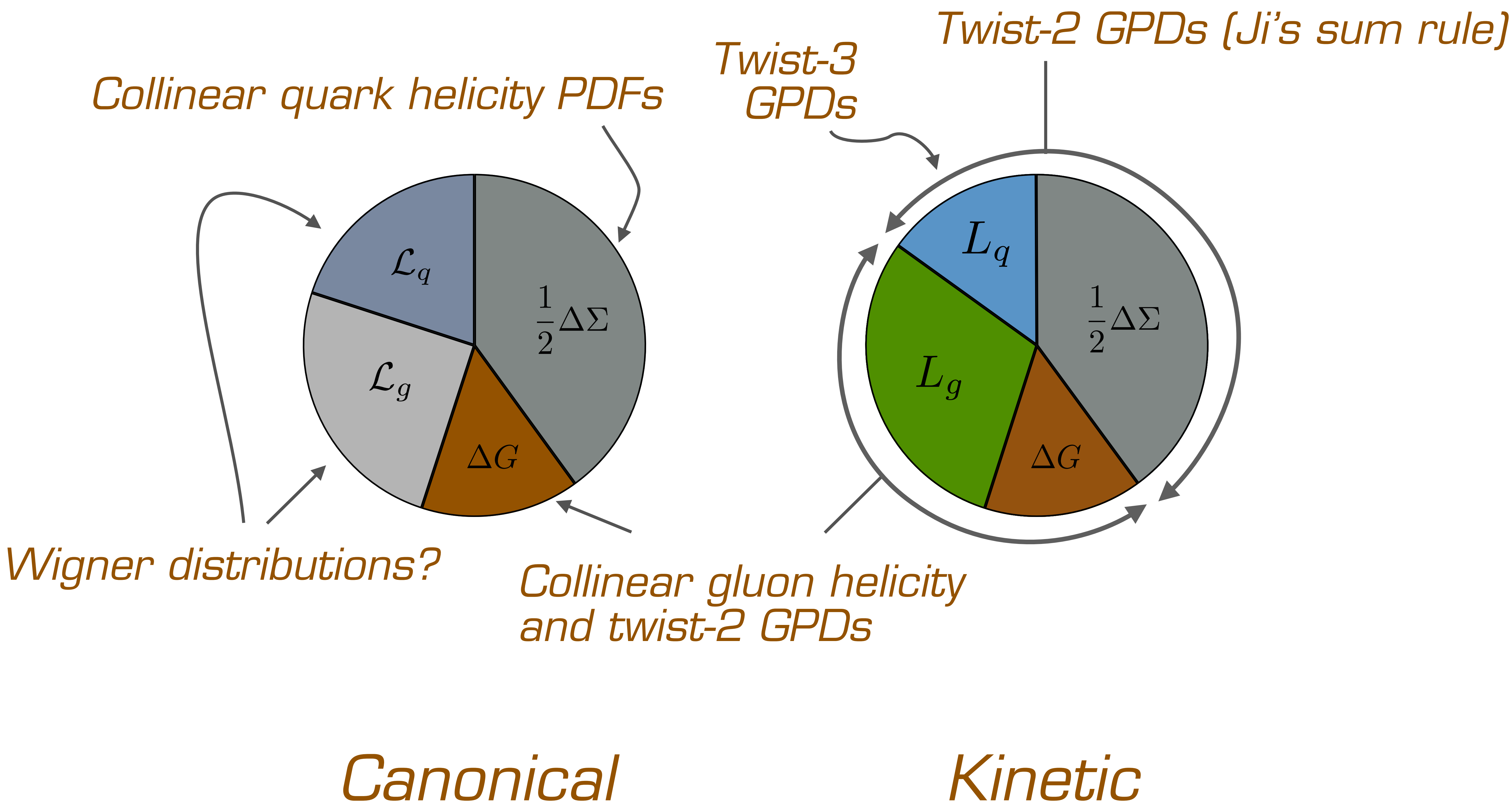
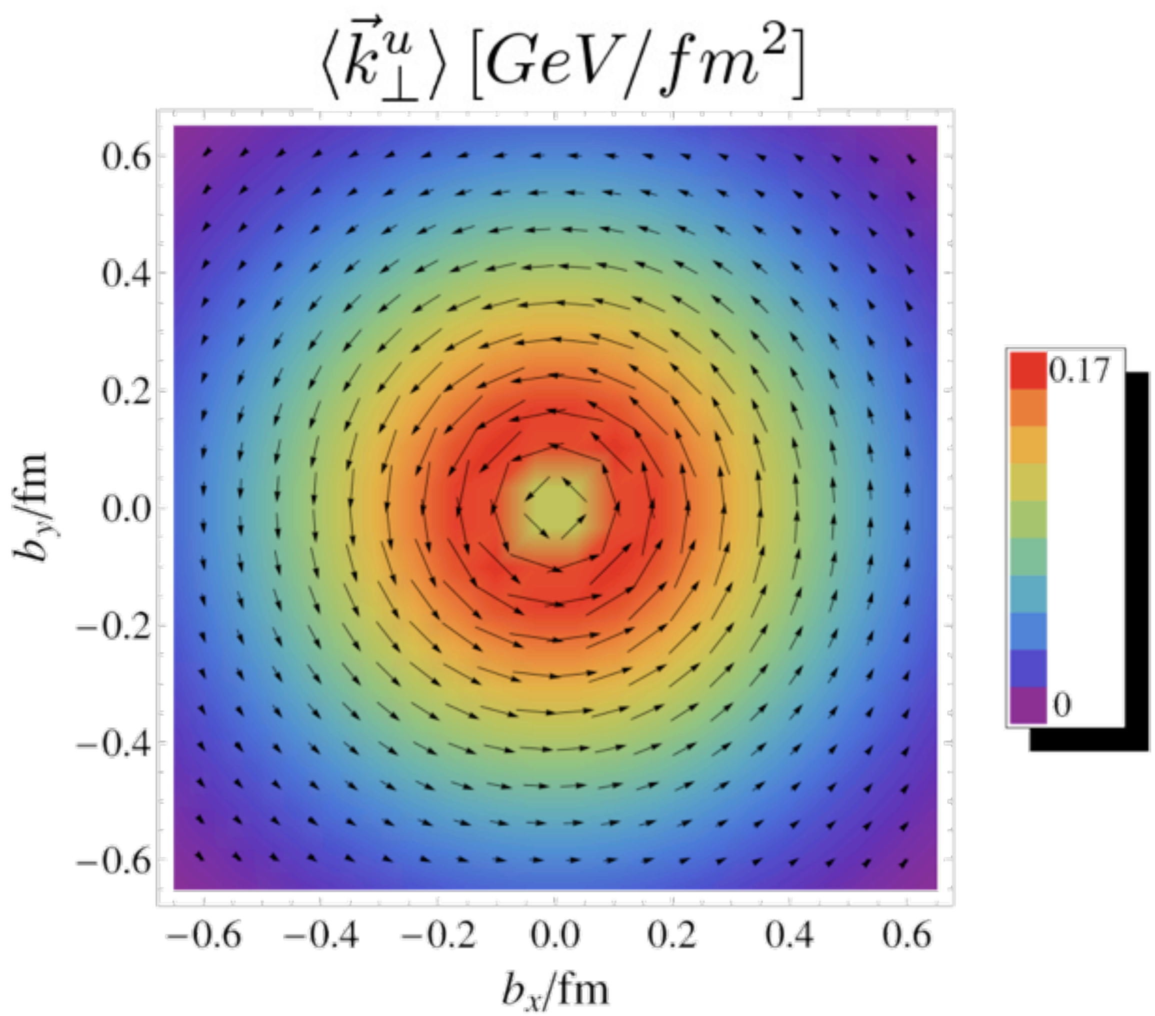


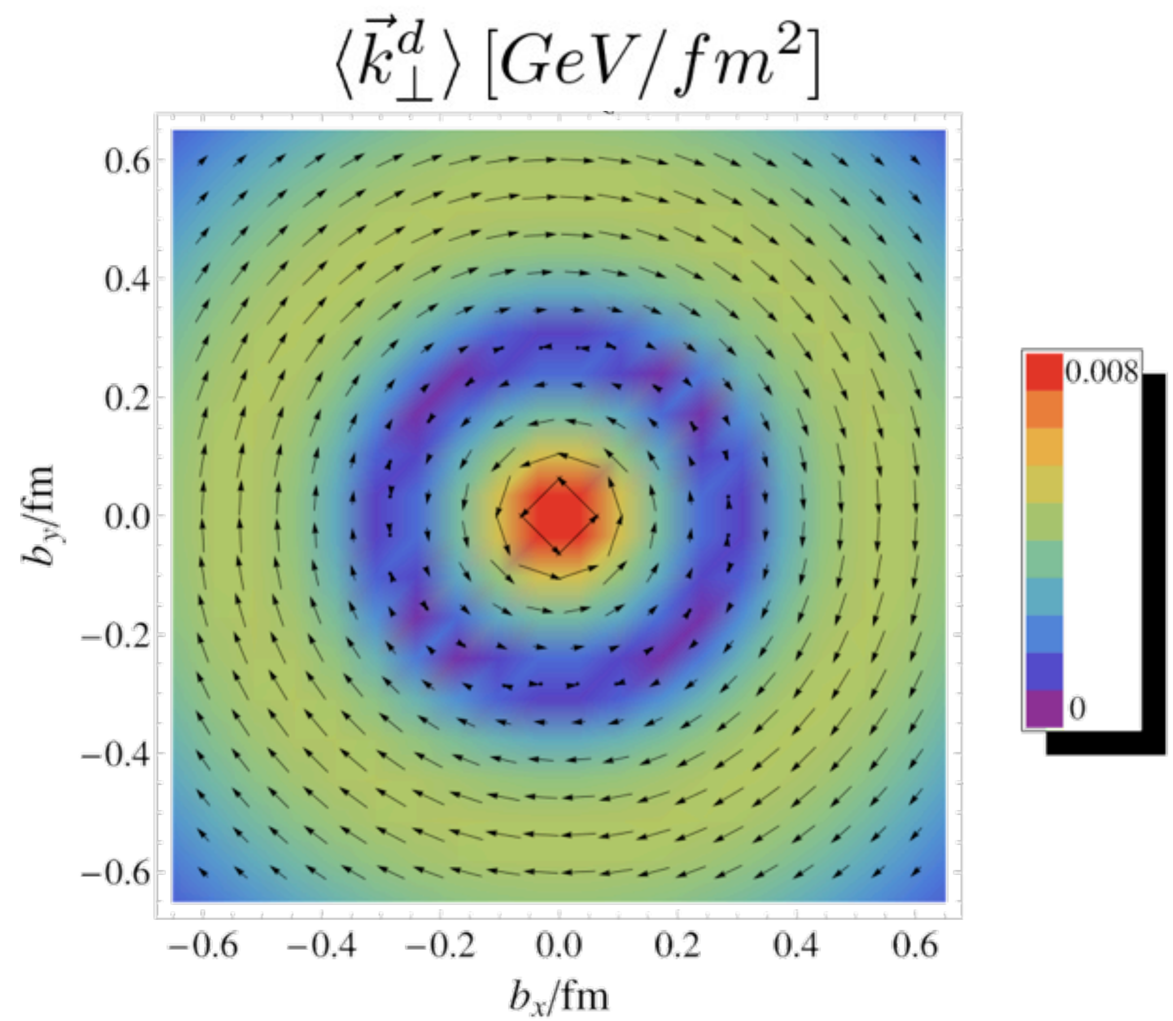
GTMDs

Generalized TMDs and Wigner

Only way to provide direct access to partonic orbital angular momentum

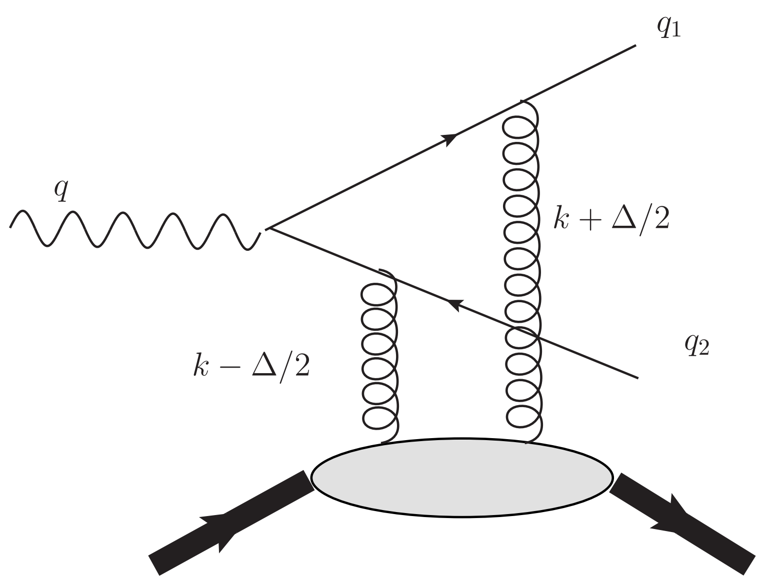
$$\mathcal{L}_z^q = \int \mathrm{d}x \mathrm{d}^2\vec{k}_\perp \mathrm{d}^2\vec{b}_\perp (\vec{b}_\perp \times \vec{k}_\perp) \rho^q_{LU}(\vec{b}_\perp, \vec{k}_\perp, x)$$





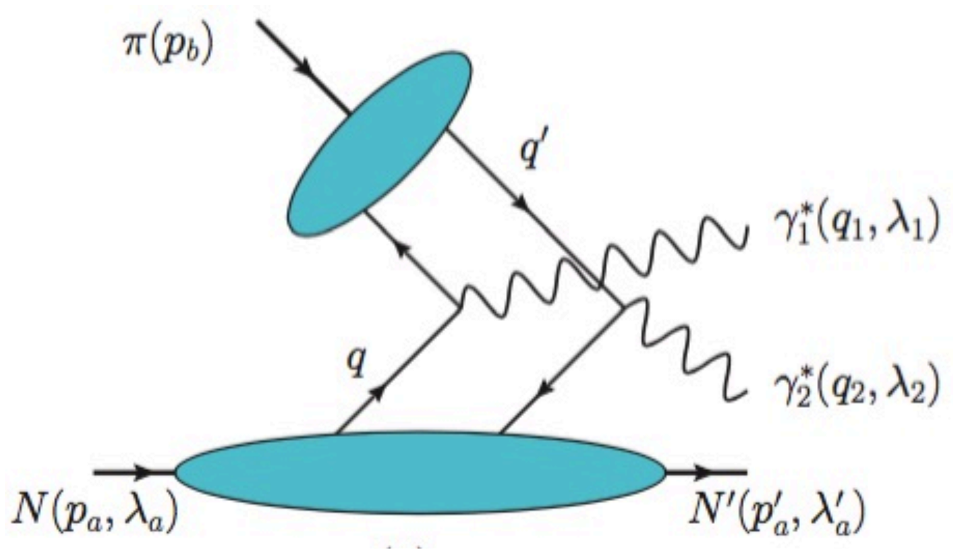
based on Pasquini, Lorcé, Xiong, Yuan, PRD 85 (12)

Wigner distributions and GTMDs



Exclusive dijet production

Hatta, Xiao, Yuan, arXiv:1601.01585
Hatta, Nakagawa, Xiao, Yuan, Zhao, arXiv:1612.02445
Ji, Yuan, Zhao, arXiv:1612.02438



Exclusive double Drell-Yan

Bhattacharya, Metz, Zhou, arXiv:1702.04387

Conclusions

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- Uninterrupted progress in the field of 3D “imaging” in the last decade
- The EIC will be our dream machine.
  Without the EIC, we will have a very limited view of the inner structure of the proton.
- Apart from mainstream activity (golden and silver), a lot of other interesting topics can be addressed (many other polarized objects, higher twist, jets, nuclear corrections, TMD factorization breaking...)