Transverse Momentum-Dependent Parton Distributions

Alessandro Bacchetta

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3DSPIN
MAPPING
THE PROTON IN 3D

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TMDs at DIS

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- DIS 2000 in Liverpool (my first participation to DIS): about 5 talks, concentrated in Spin Physics WG

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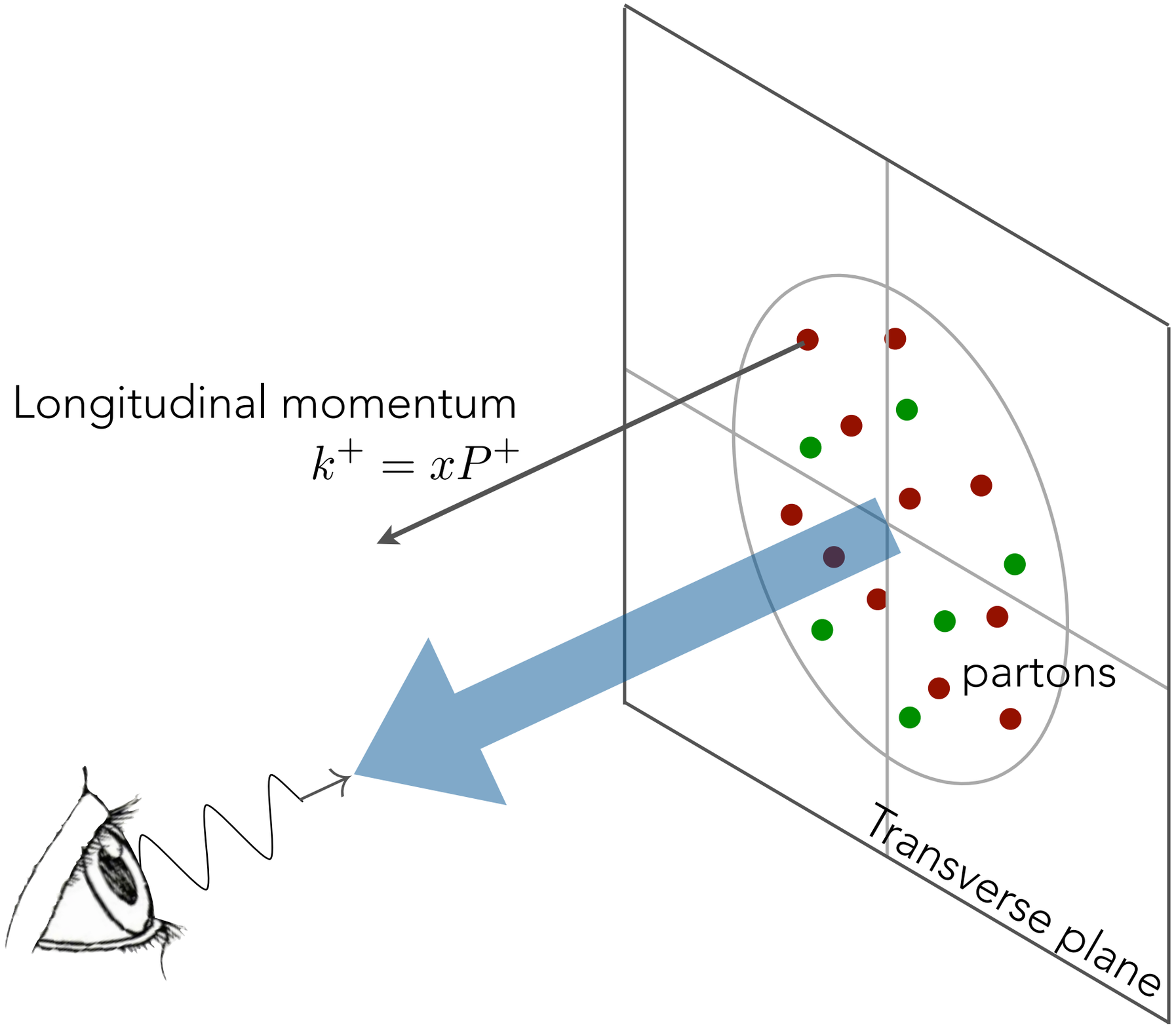
- DIS 2017 in Birmingham: about 5^2 talks, across several WGs

Longitudinal momentum

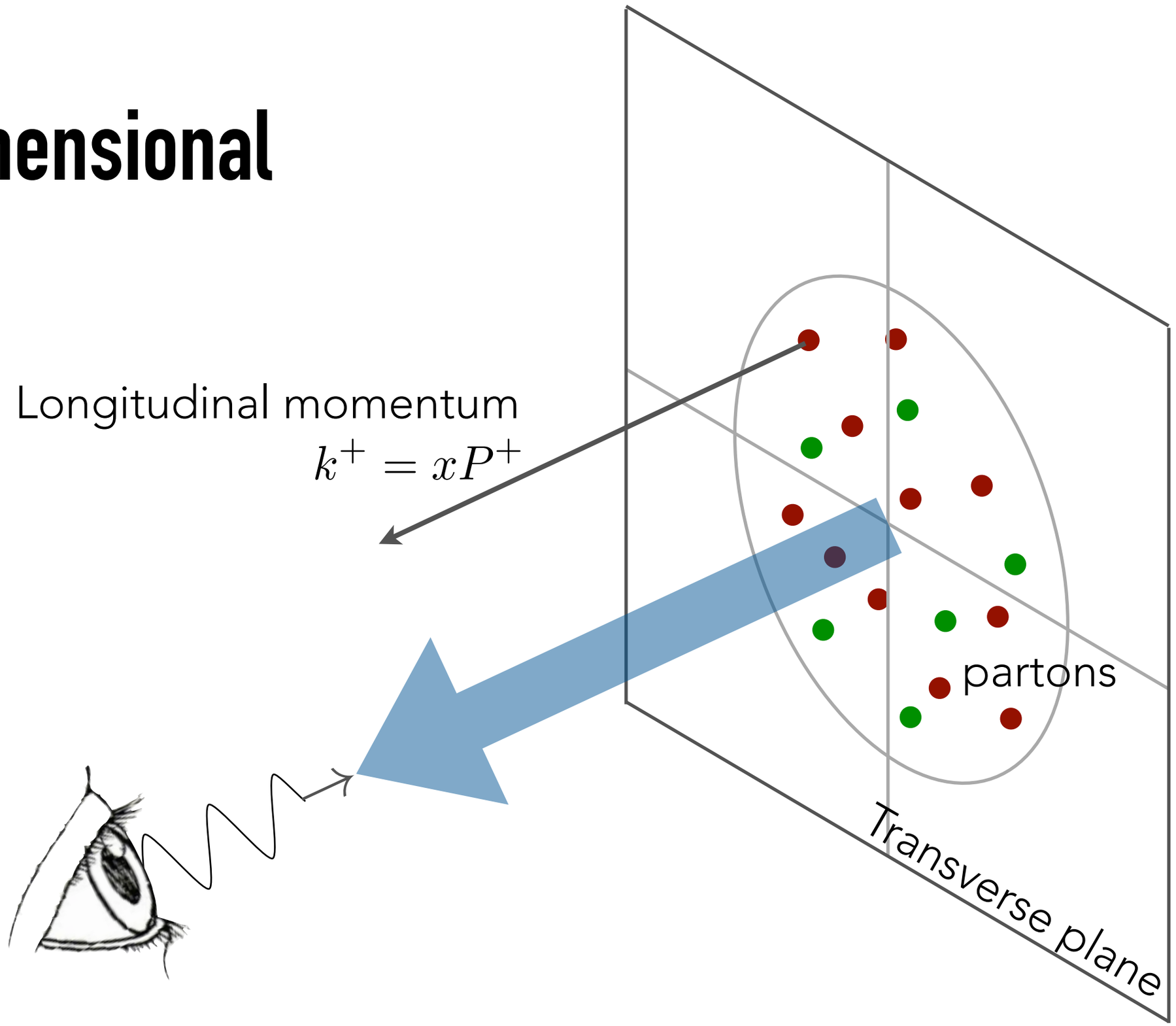
$k^+ = xP^+$



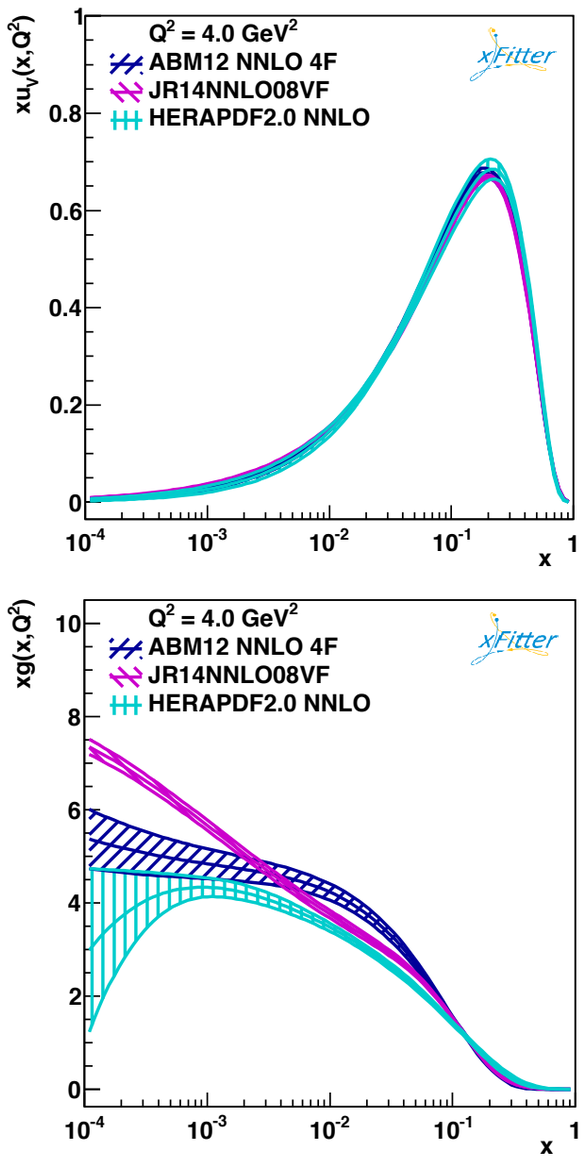
Parton Distribution Functions

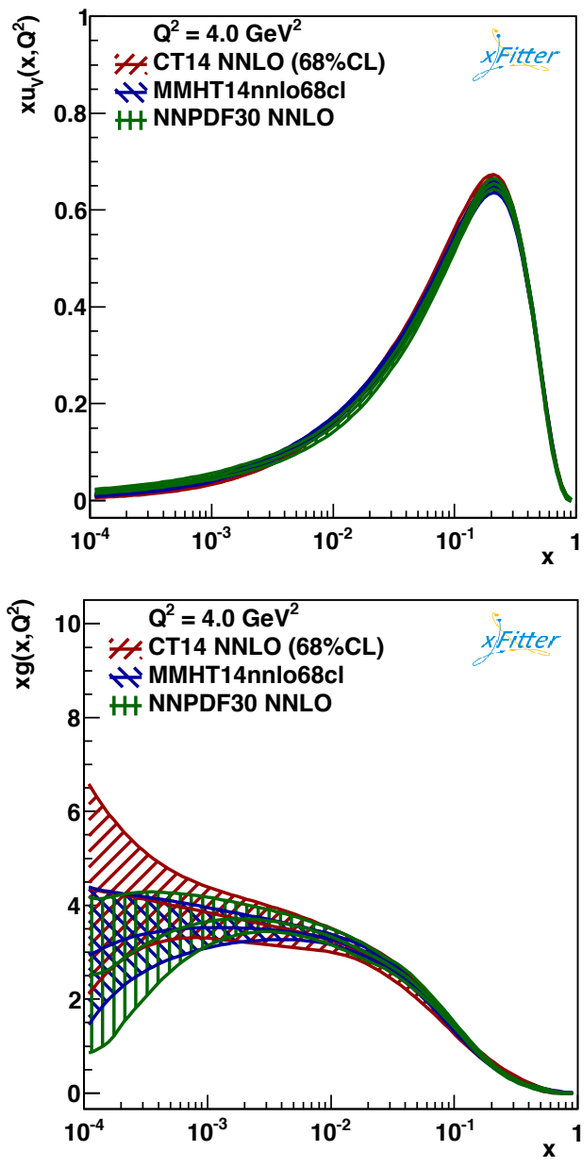
$f(x)$

1 dimensional



1D maps of partonic distribution





Accardi et al., arXiv:1603.08906
see talk by M. Ubiali

Longitudinal momentum

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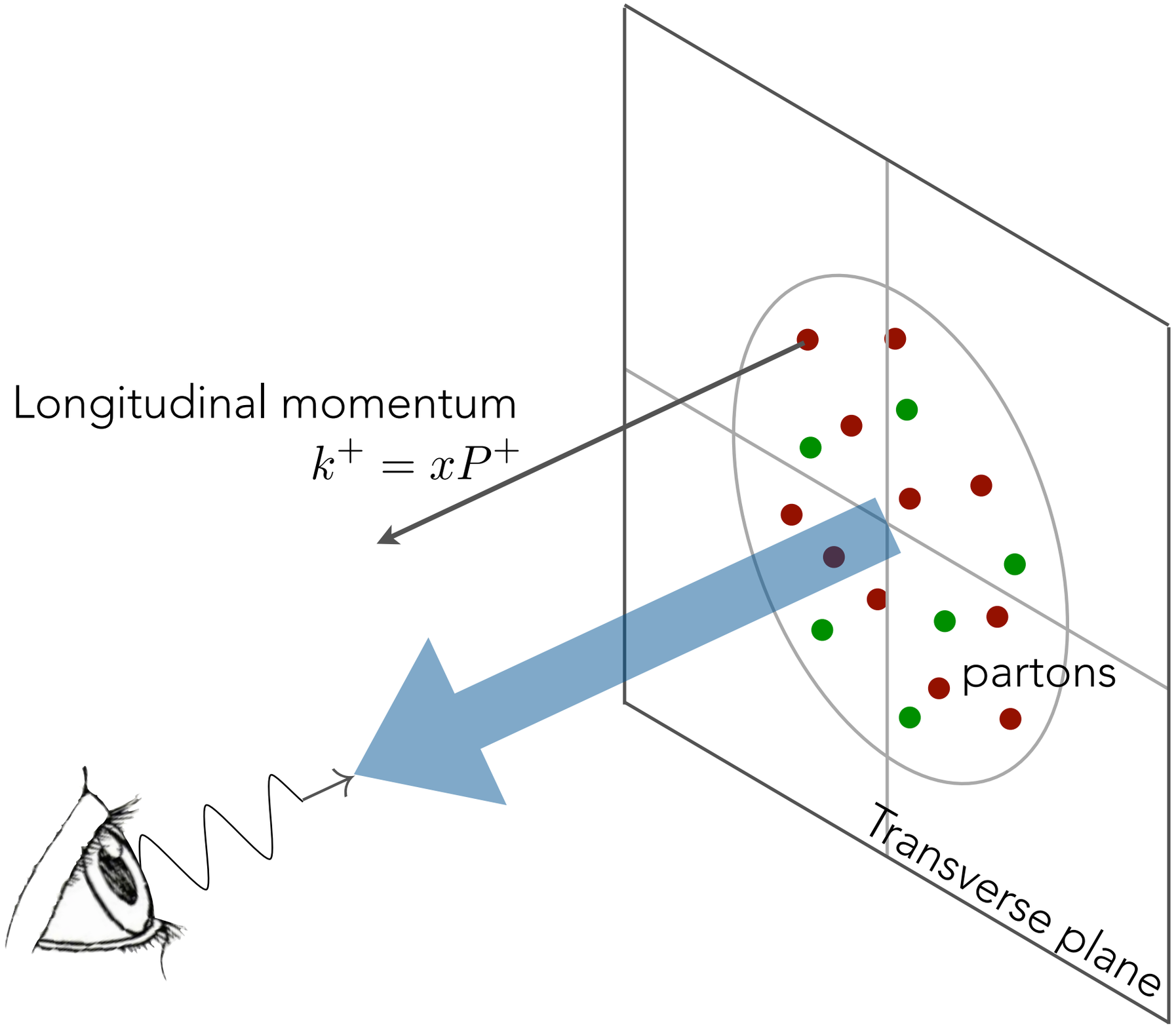
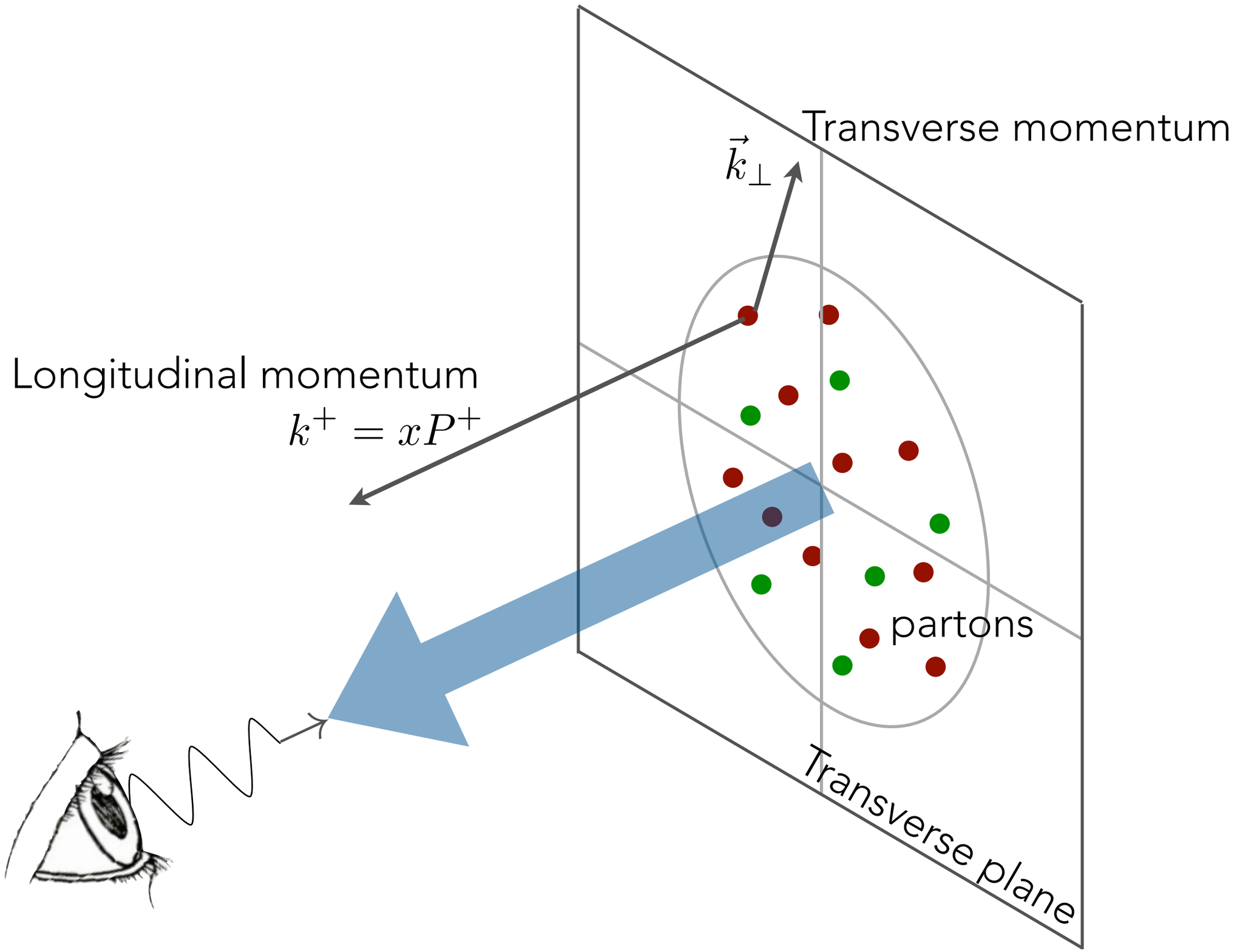
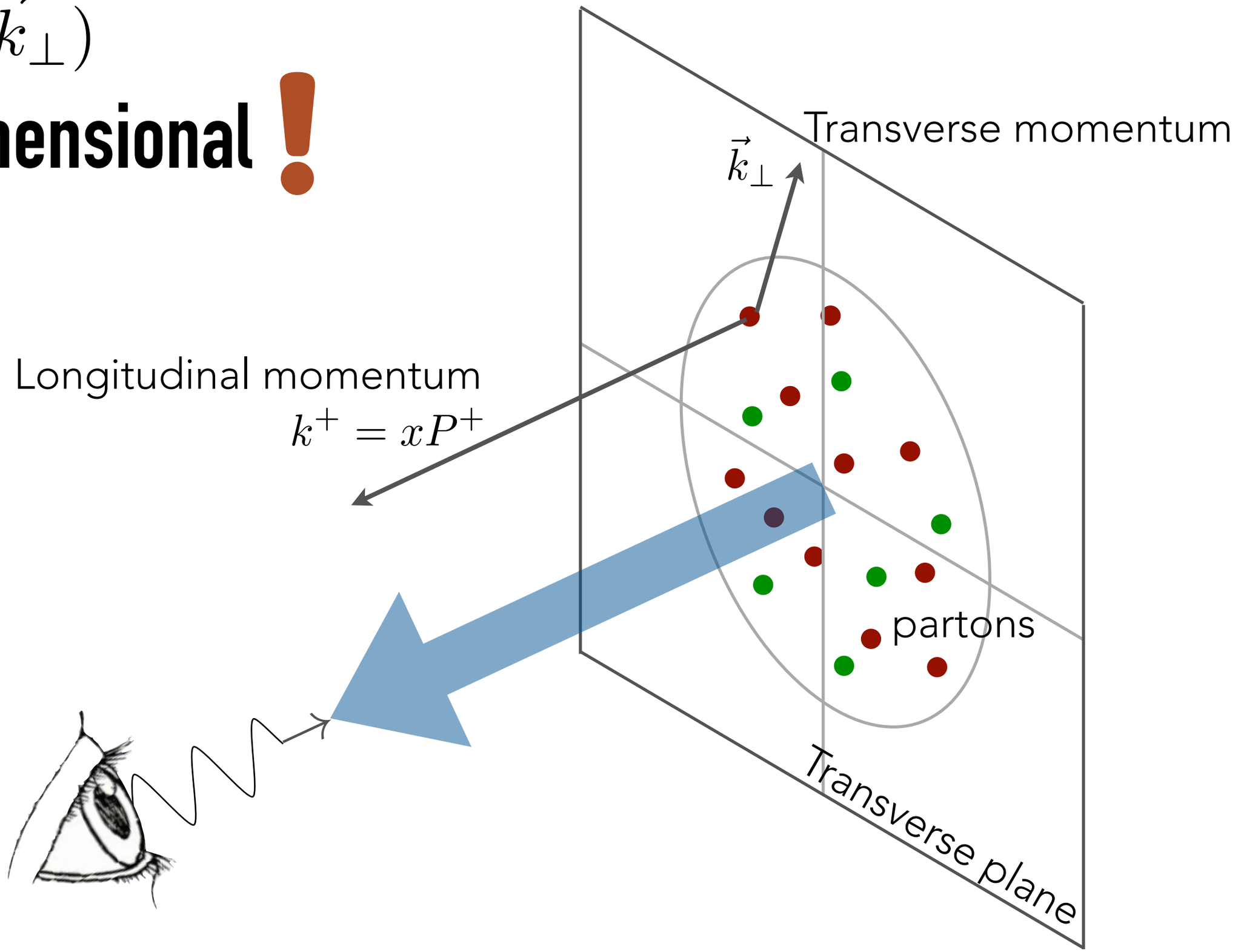



Transverse momentum
$\vec{k}_\perp$
Longitudinal momentum
$k^+ = xP^+$
partons
Transverse plane

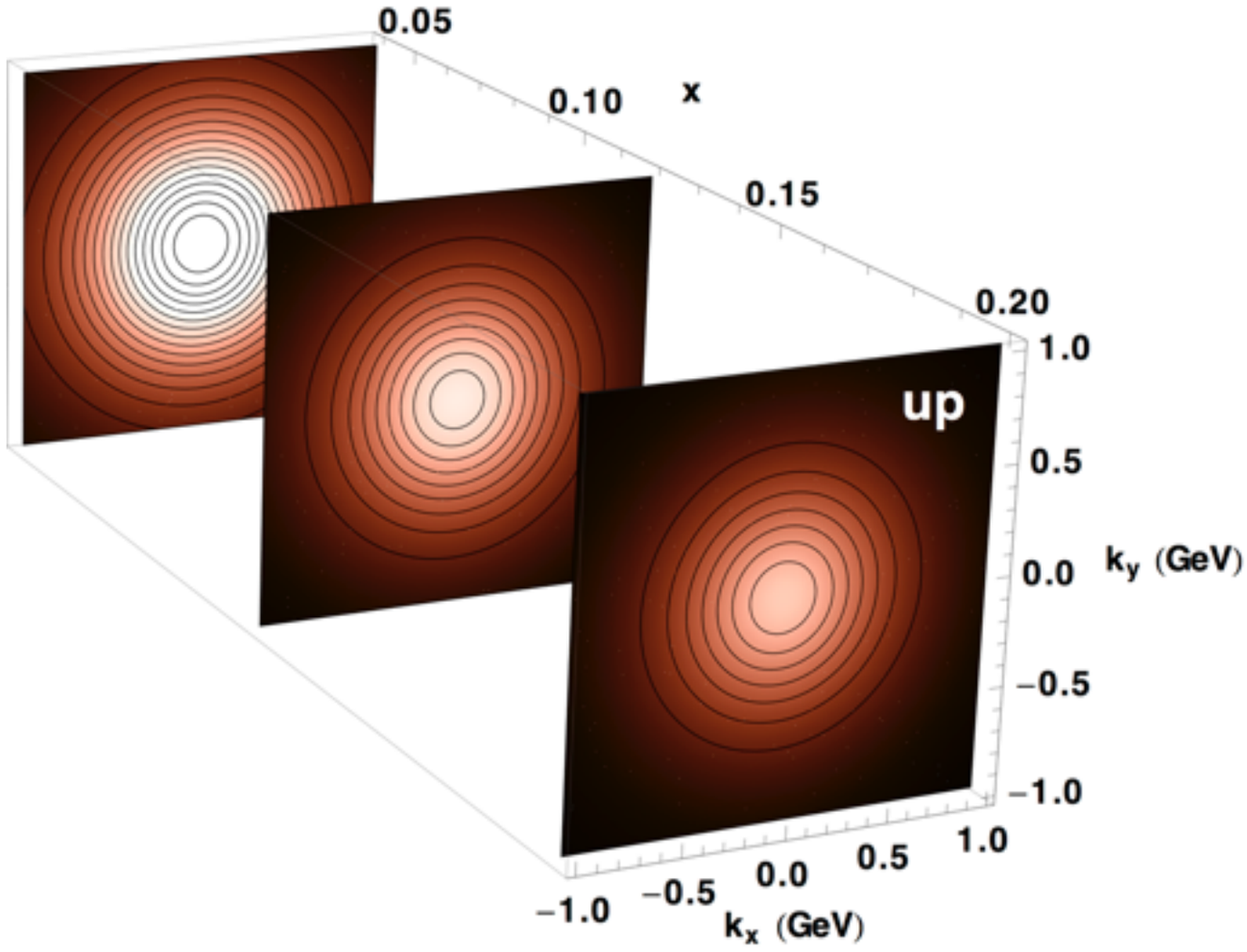
Transverse-Momentum Distributions

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

3 dimensional !



3D maps of partonic distribution



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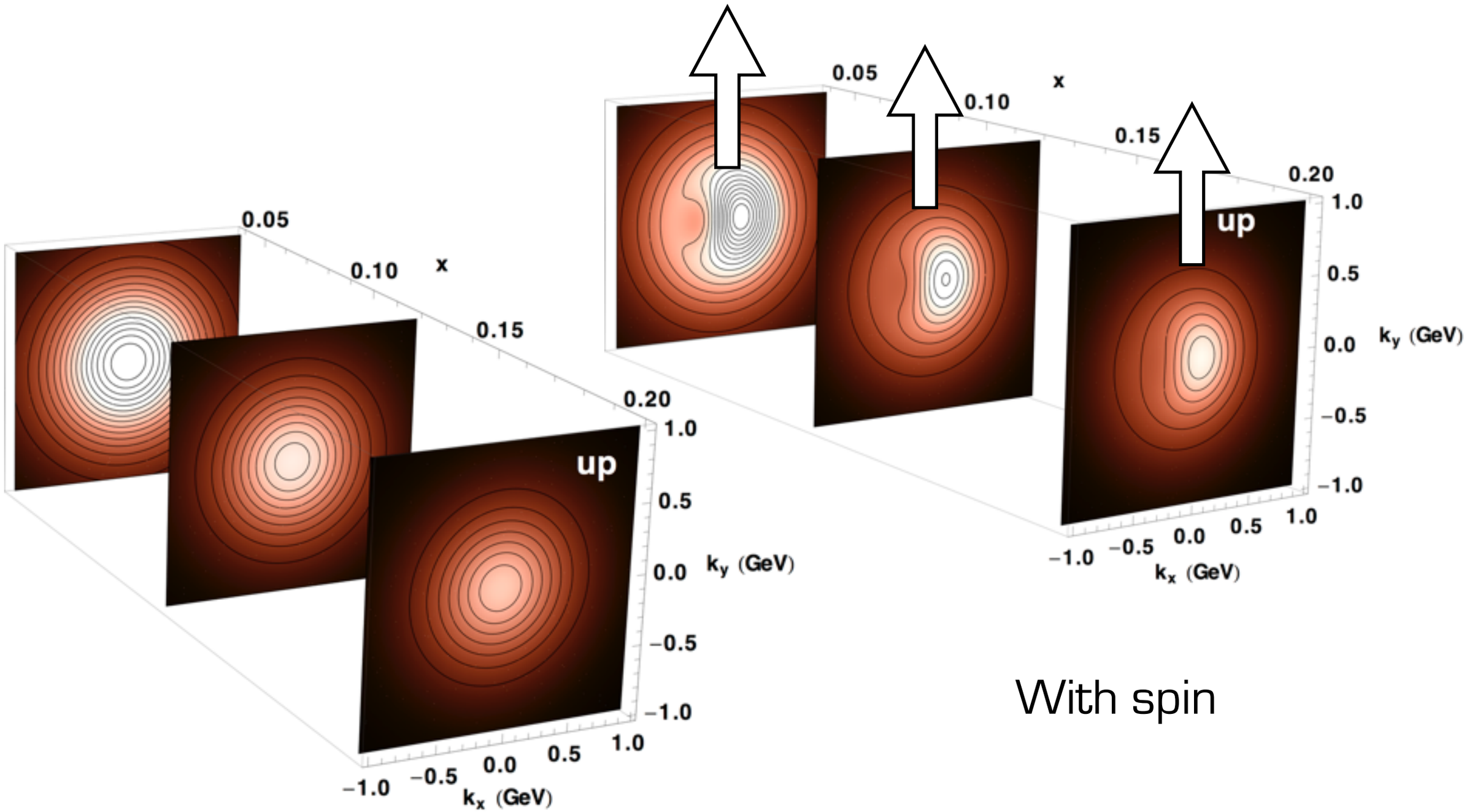

With spin

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All Volumes & Issues

The 3-D Structure of the Nucleon

ISSN: 1434-6001 (Print) 1434-601X (Online)

In this topical collection (17 articles)

Why do we map partonic distributions?

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- Test things we can calculate with QCD (perturbative and lattice)

Why do we map partonic distributions?

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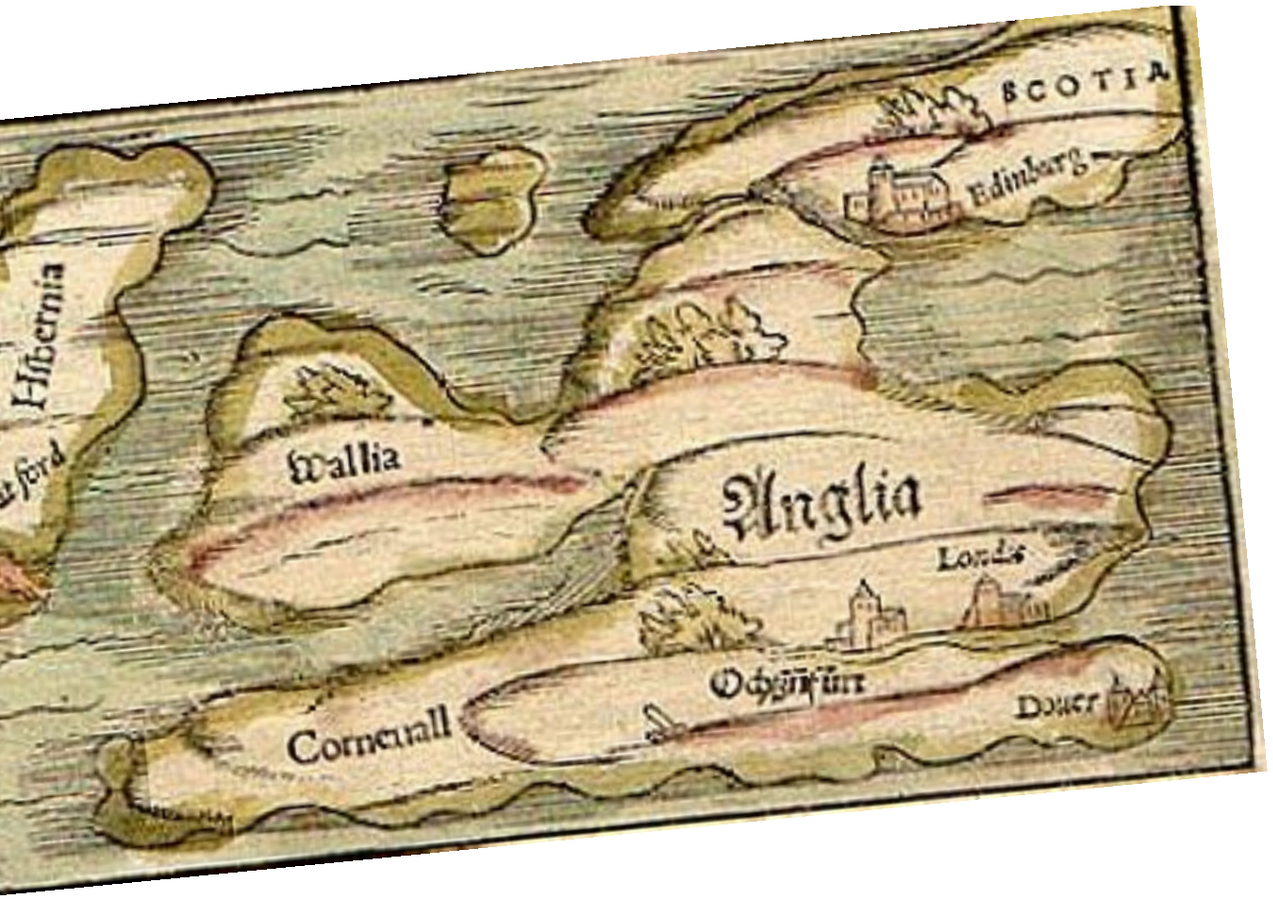
- Measure things that we cannot calculate with QCD

- Test things we can calculate with QCD (perturbative and lattice)

- Use to make predictions in hadronic collisions and look for new interesting physics

What did we achieve so far?



1. Exploration phase

First measurements

Parton model interpretation

Last decade

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2. Consolidation phase

Measurements from several experiments

First global fits, validation of TMD factorisation and evolution

Next decade

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Electron Ion Collider

Global fits, to a level comparable to standard PDFs

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YOU ARE HERE

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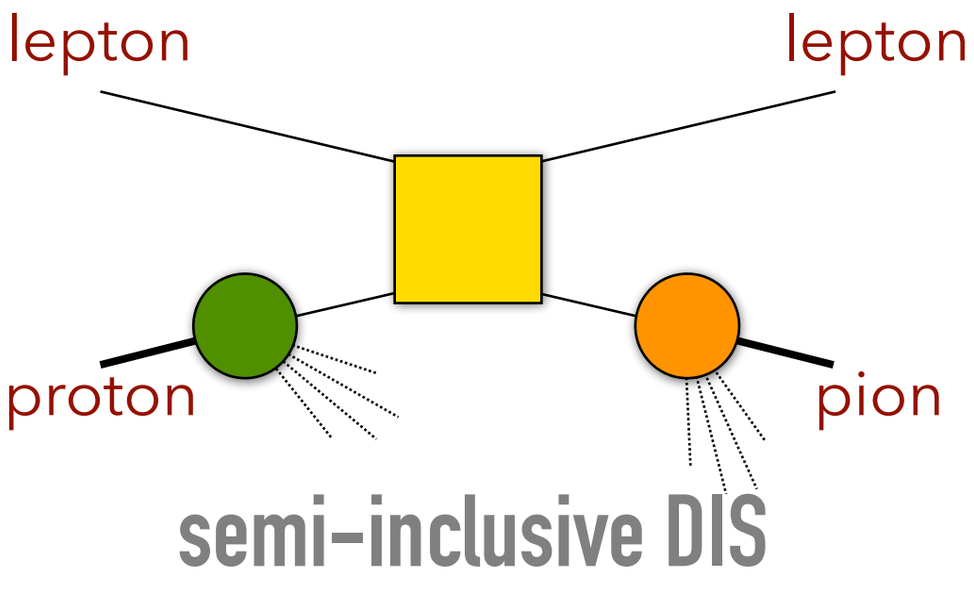
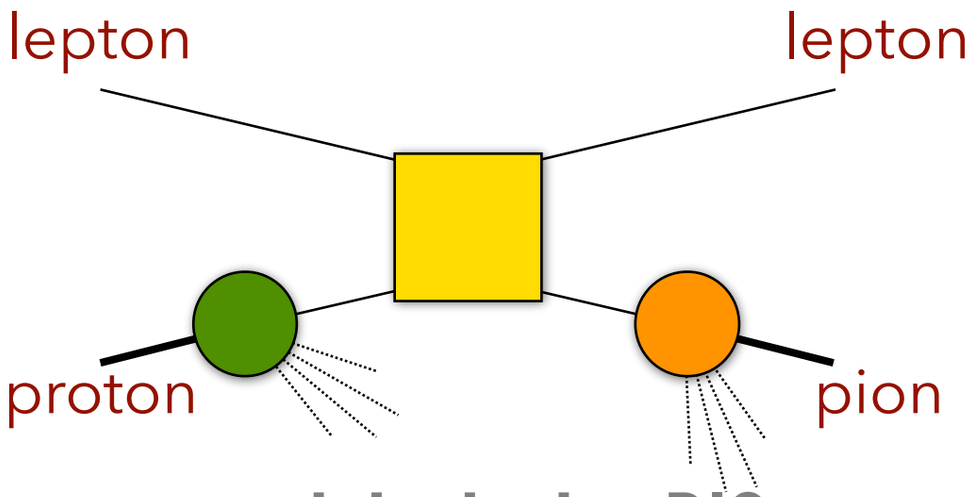
Factorization and universality



semi-inclusive DIS

Factorization and universality



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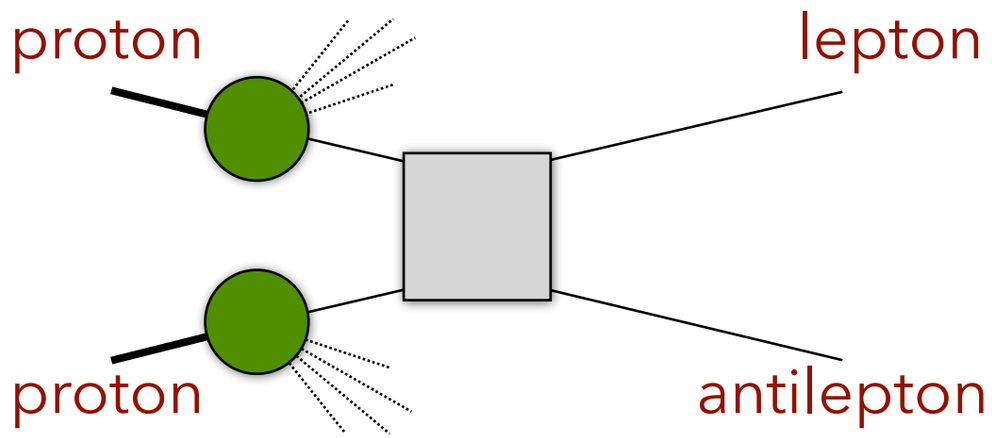
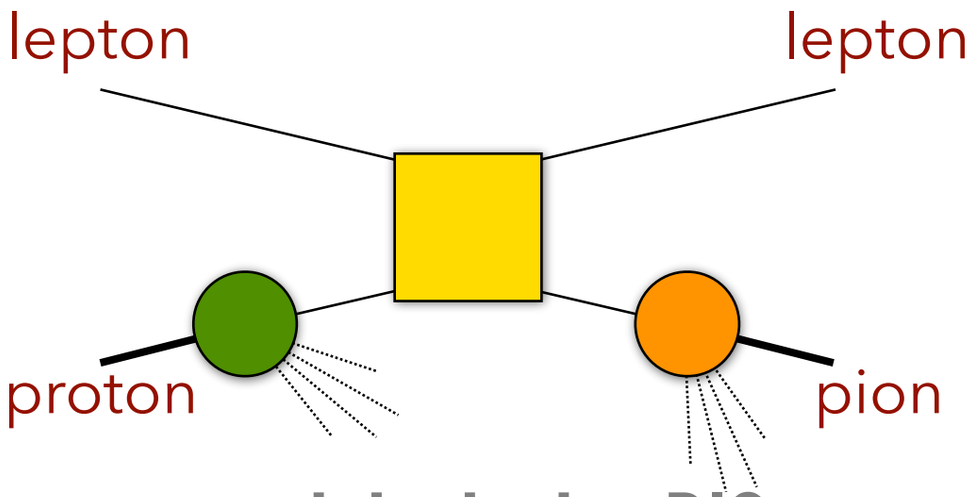


Drell-Yan

Factorization and universality



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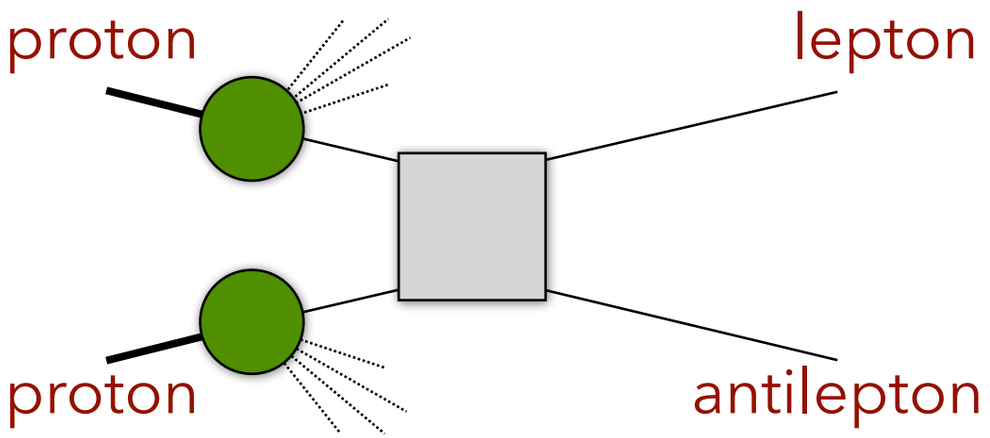

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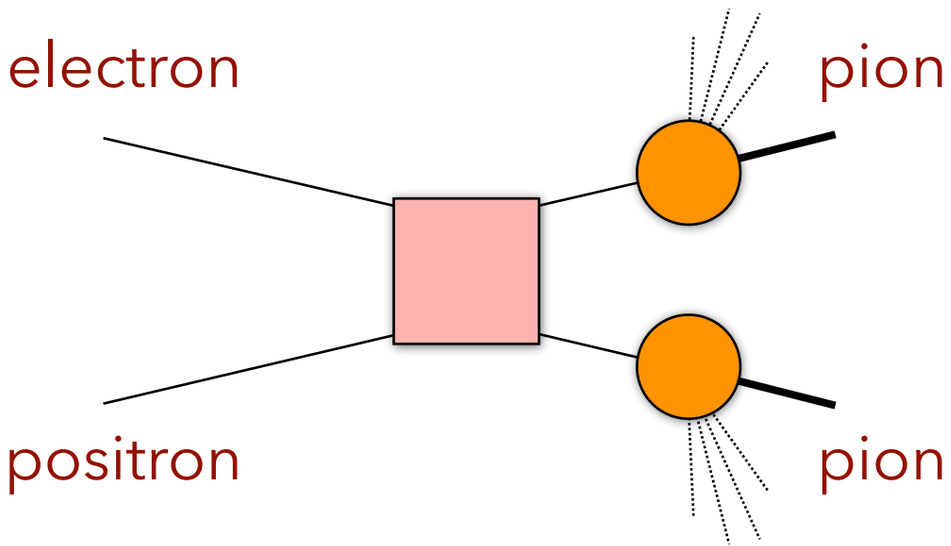
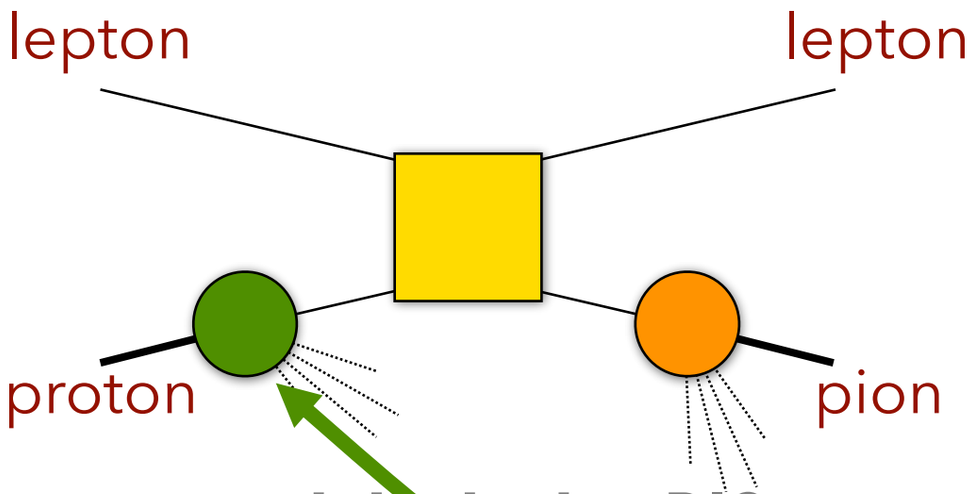


$e^- e^+$ to pions

Factorization and universality



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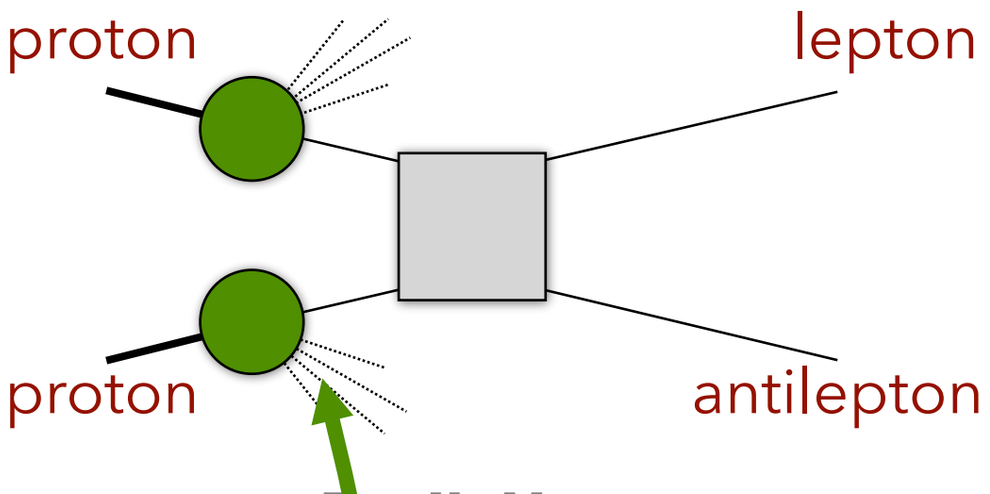

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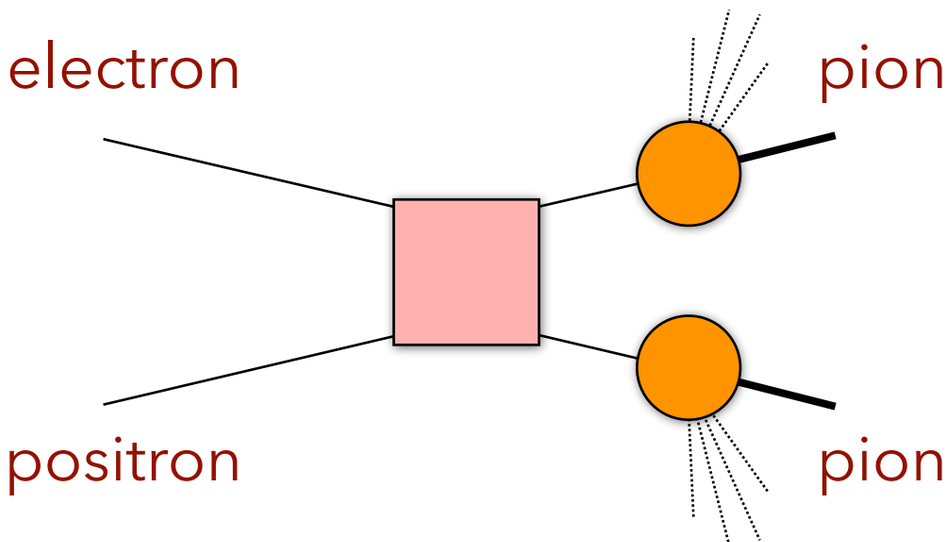

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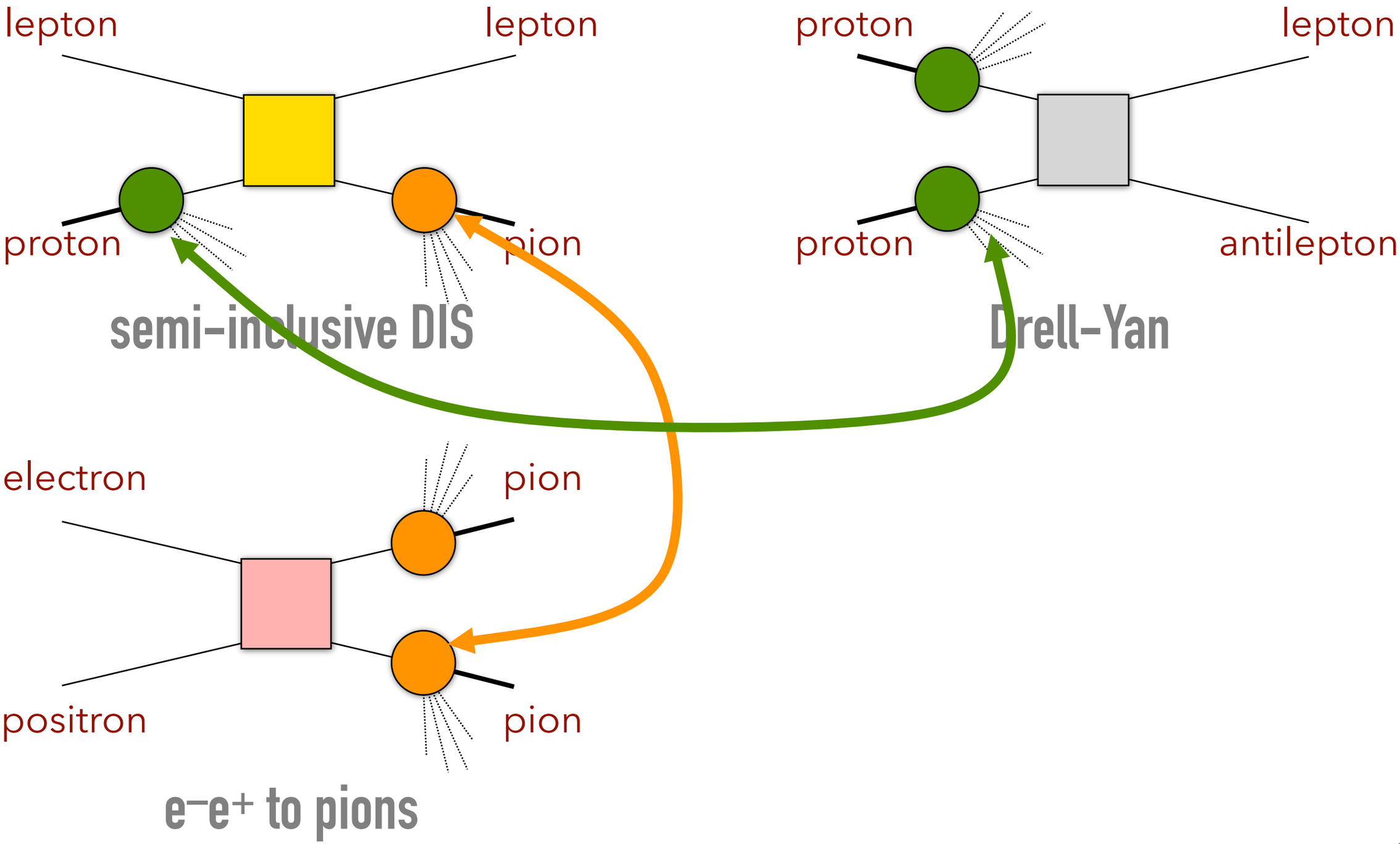

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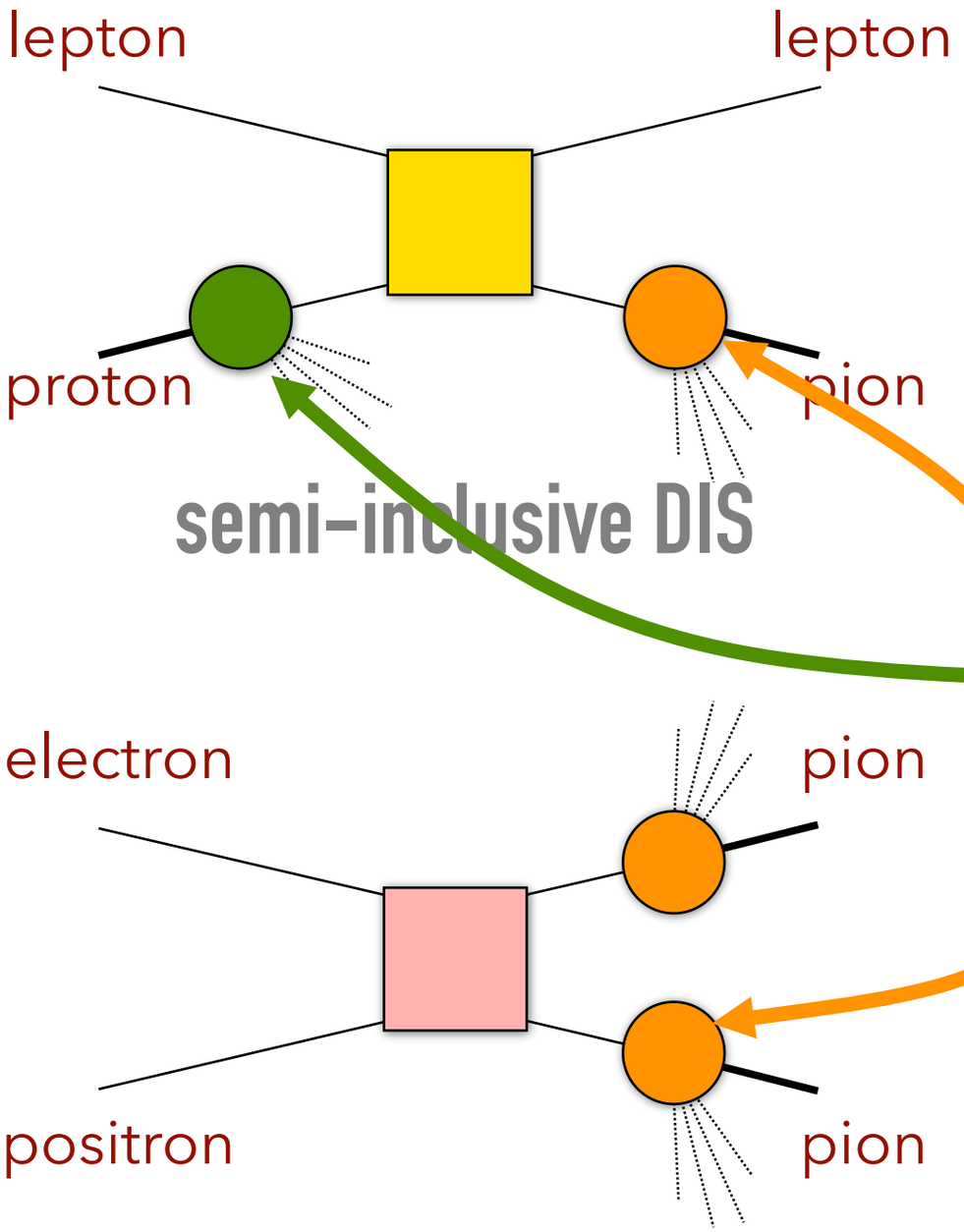
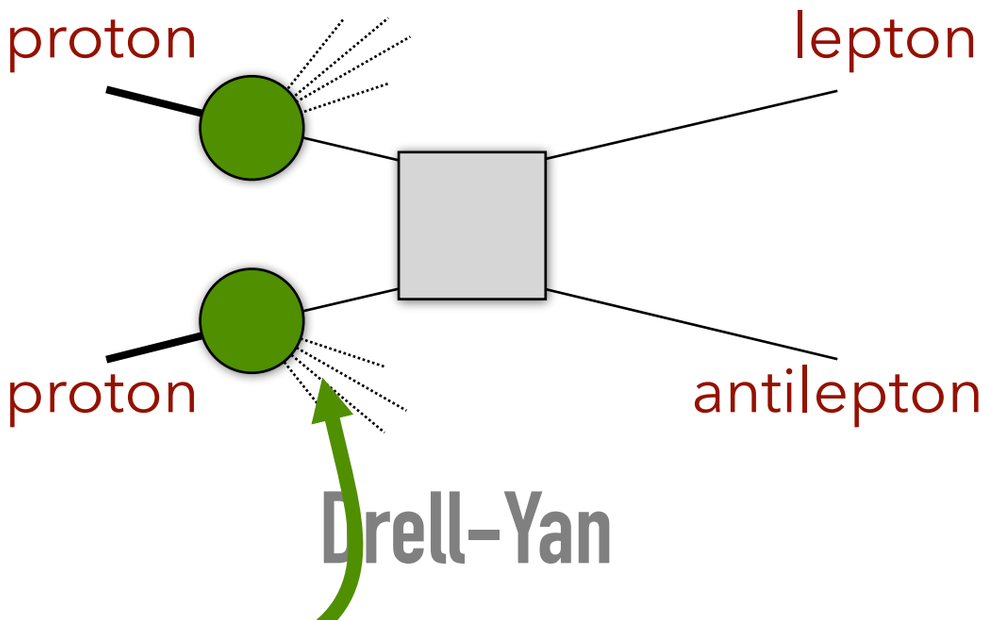
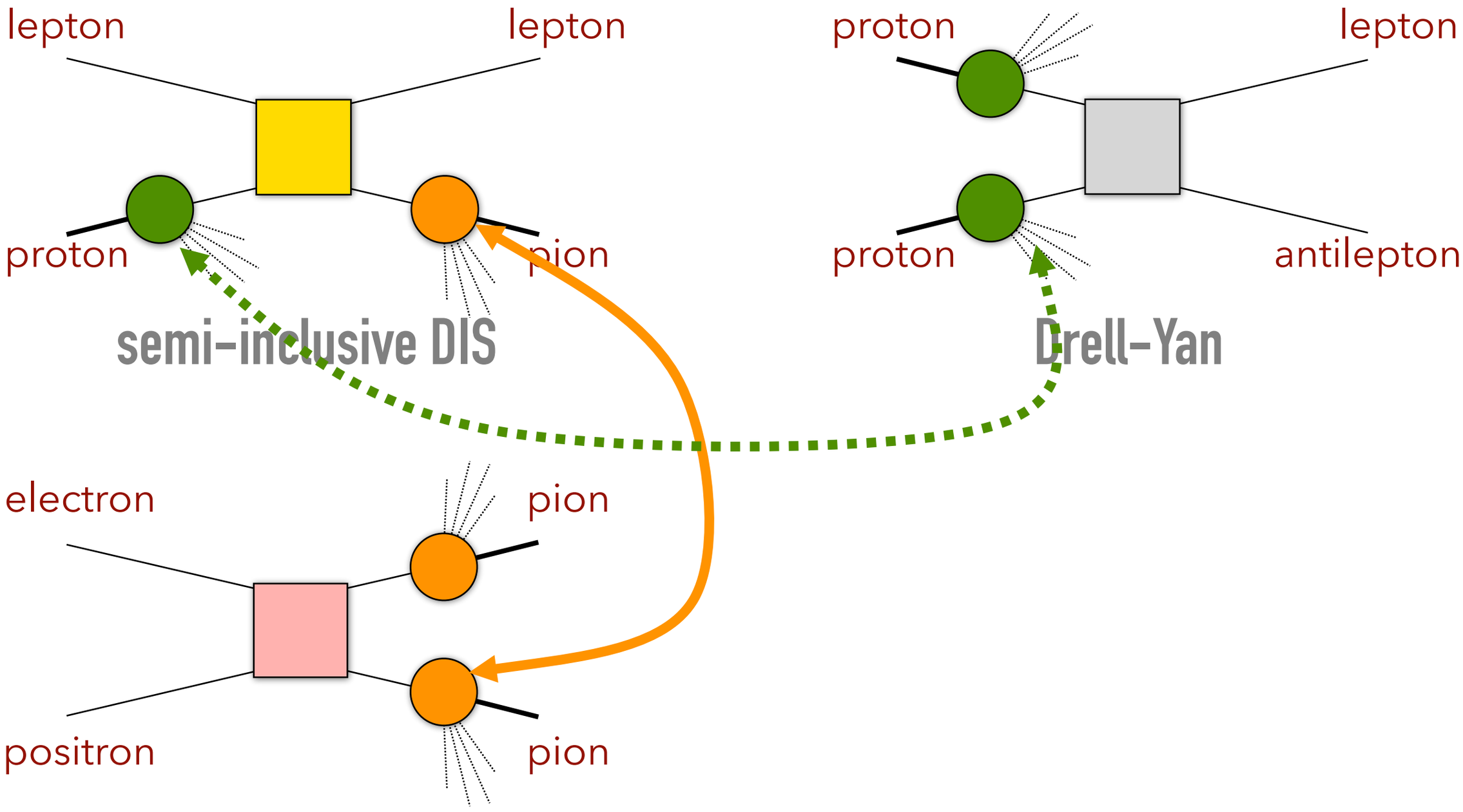




TMD factorization well understood

see, e.g., Ji, Ma, Yuan, PRD 71 (05)
Collins, "Foundations of Perturbative QCD" (11)
Rogers, Aybat, PRD 83 (11)
Echevarria, Idilbi, Scimemi JHEP 1207 (12)

Factorization and universality



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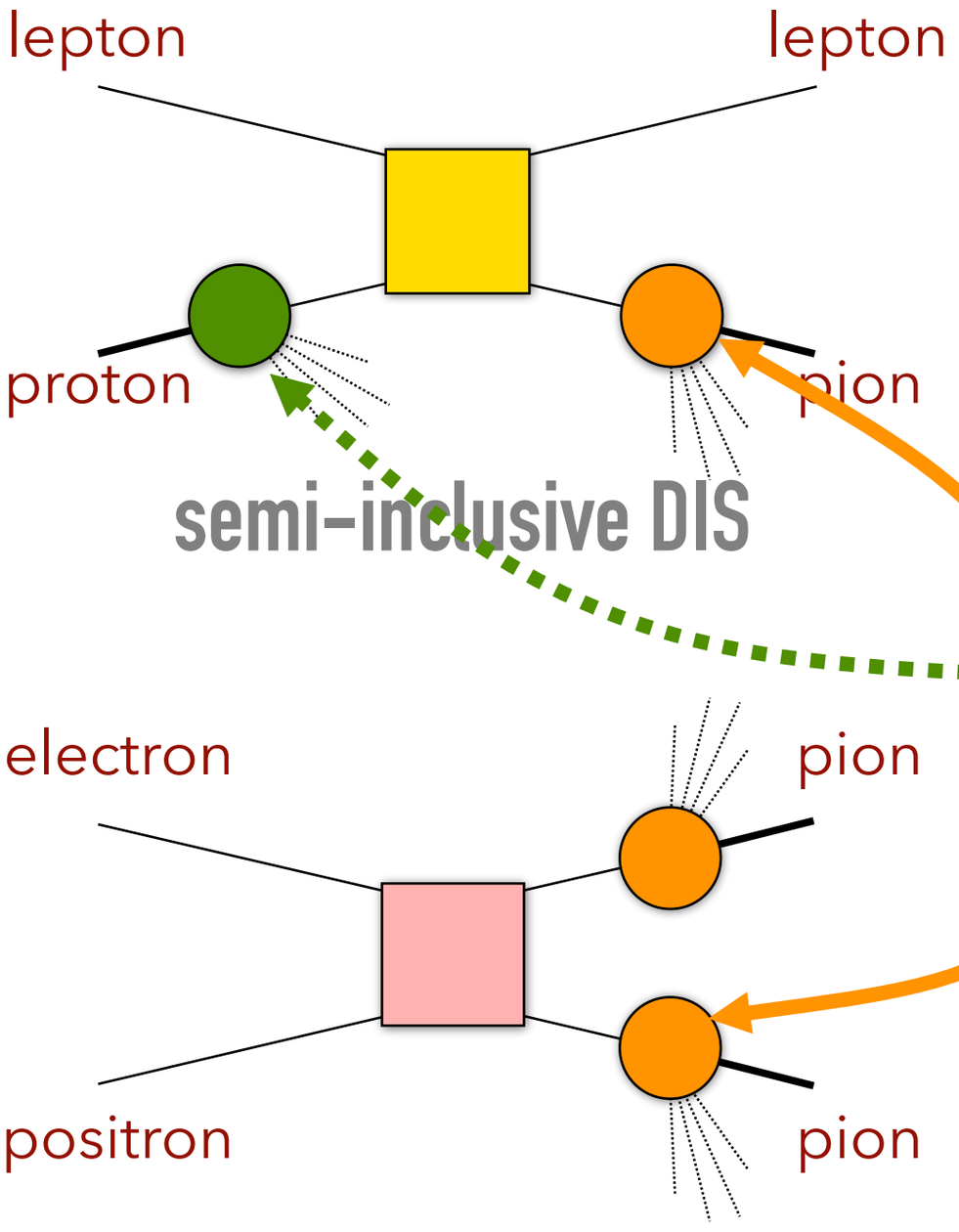
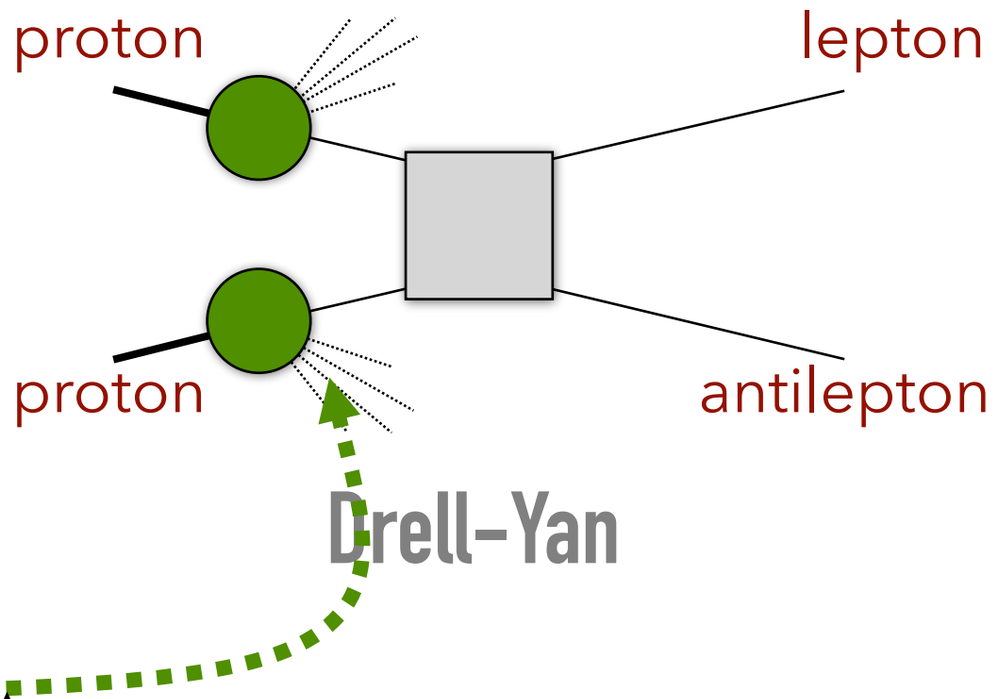
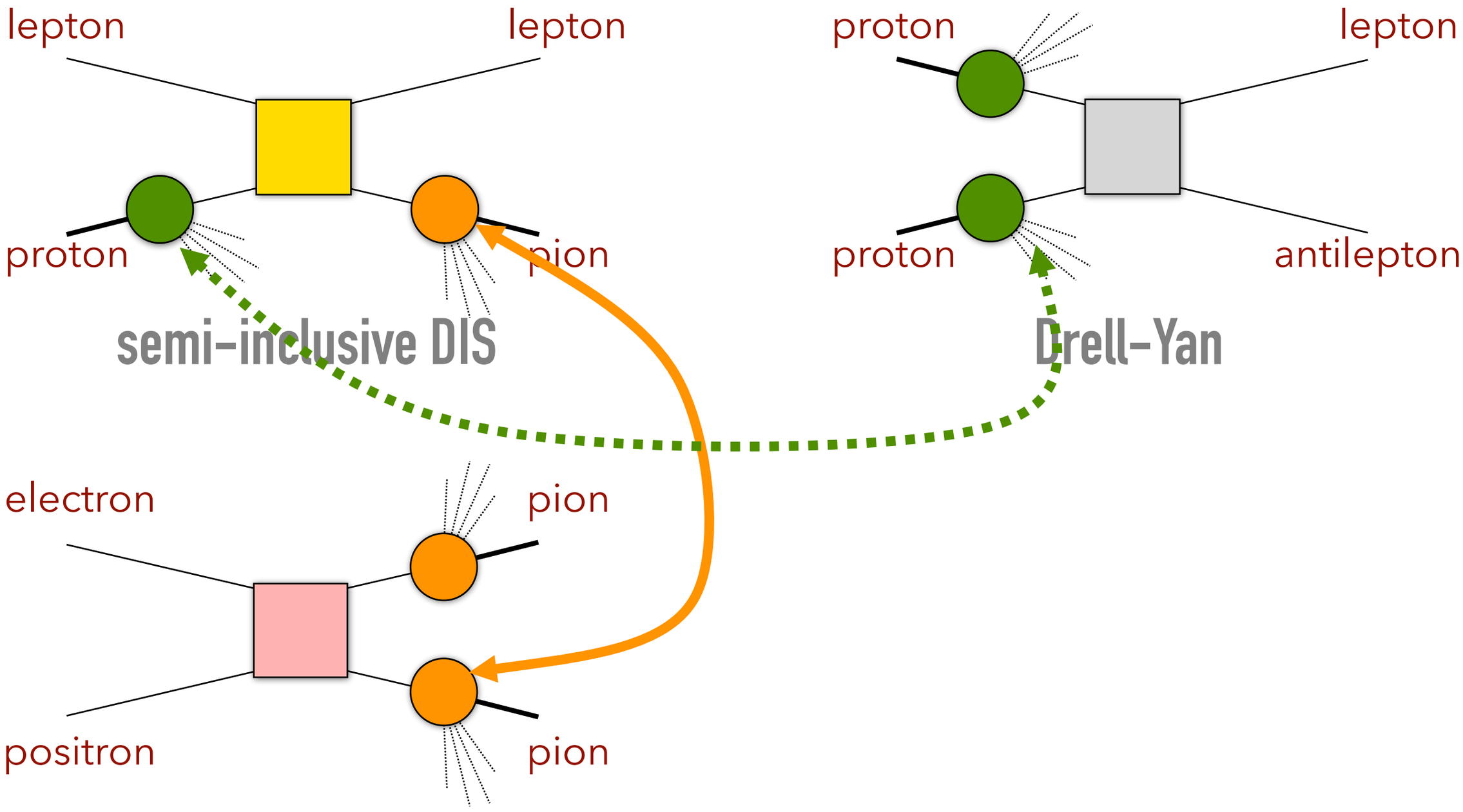




TMD universality is not trivial

see, e.g., Collins, PLB 536 (02)
Collins, Metz, PRL 93 (04)
Buffing, Mukherjee, Mulders, PRD 86 (12)

Factorization and universality



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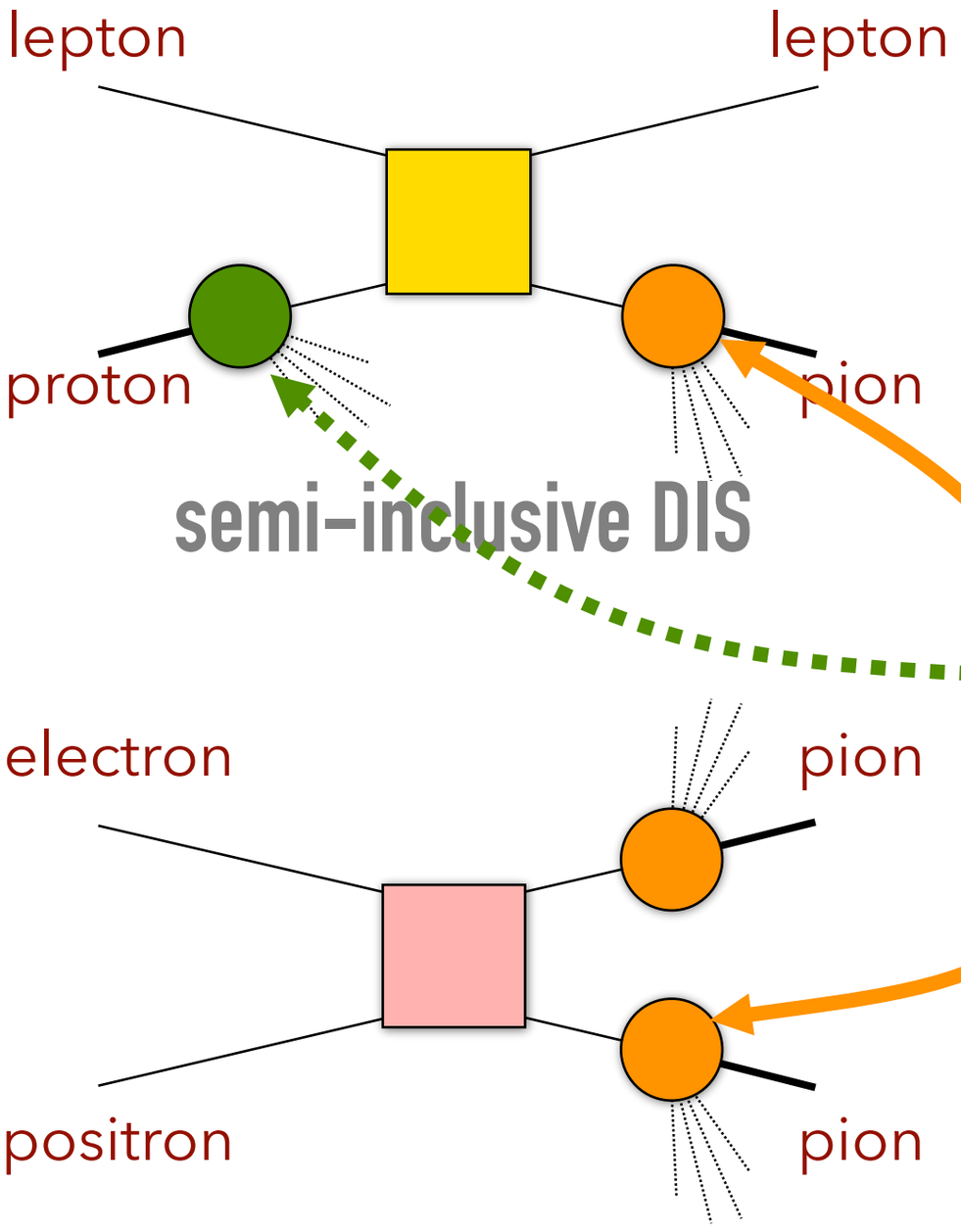

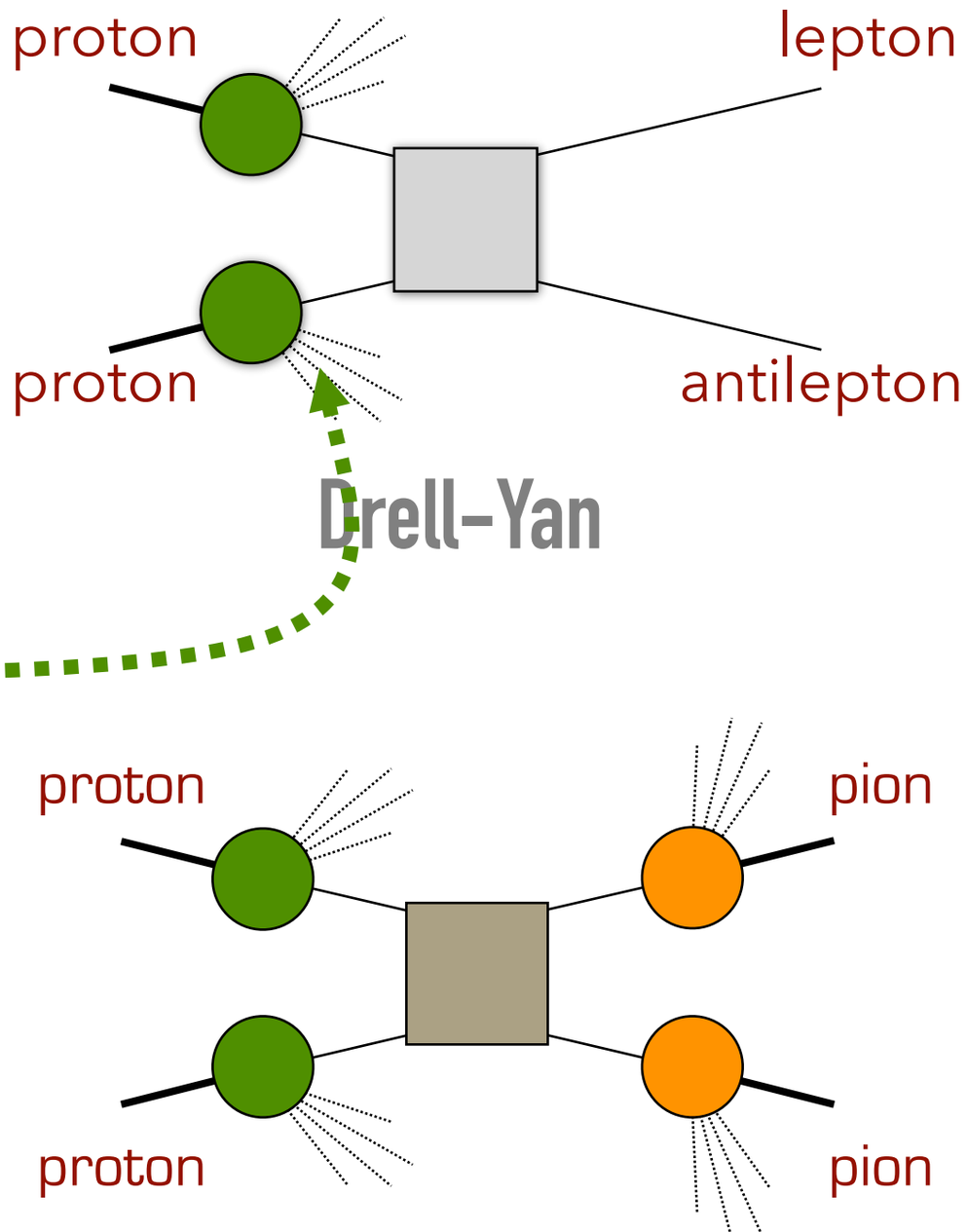

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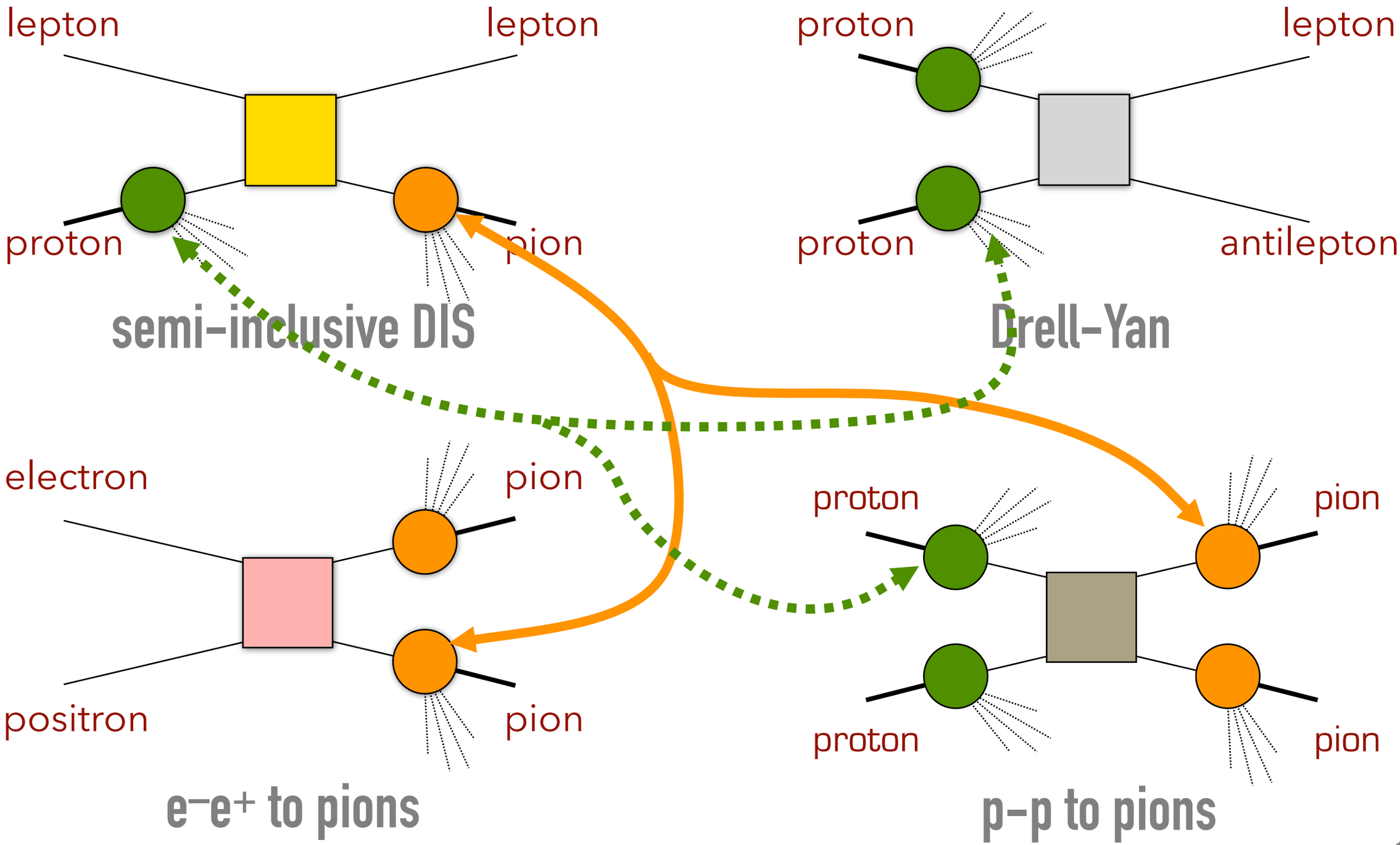

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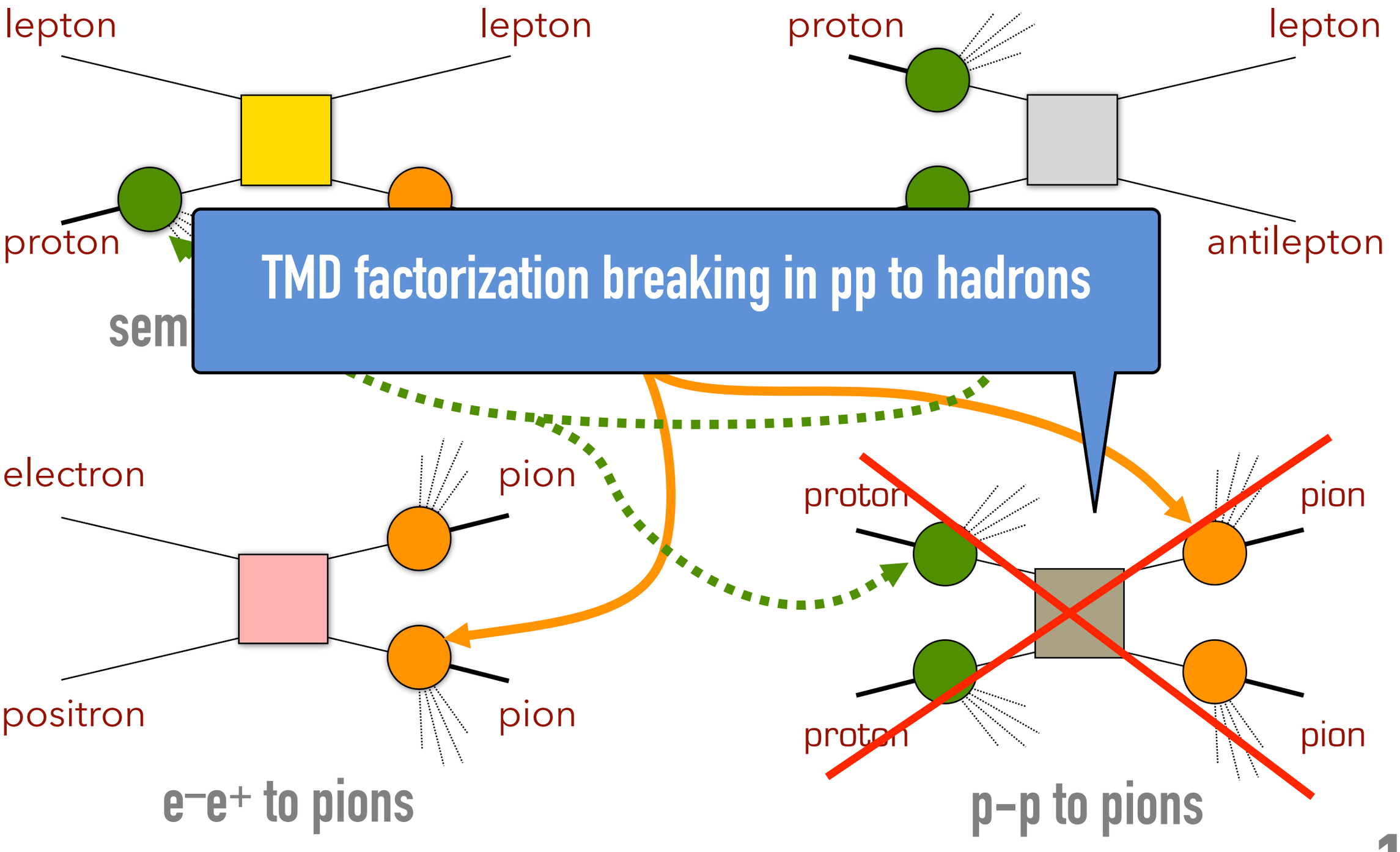

see, e.g., Rogers, Mulders, PRD81 (10)

see talks by M. Skoby (Wednesday, WG6)

TMD evolution

$$f_1^a(x, k_\perp; \mu^2) = \frac{1}{2\pi} \int d^2 b_\perp e^{-i b_\perp \cdot k_\perp} \widetilde{f}_1^a(x, b_\perp; \mu^2)$$

Rogers, Aybat, PRD 83 (11)
Collins, "Foundations of Perturbative QCD" (11)

possible schemes, e.g.,
Collins, Soper, Sterman, NPB250 (85)
Laenen, Sterman, Vogelsang, PRL 84 (00)
Echevarria, Idilbi, Schaefer, Scimemi, EPJ C73 (13)

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collinear PDF

pQCD

nonperturbative part of evolution

nonperturbative part of TMD

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Choice Choice Choice Choice

collinear PDF

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collinear PDF

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Collins–Soper–Sterman 2.0

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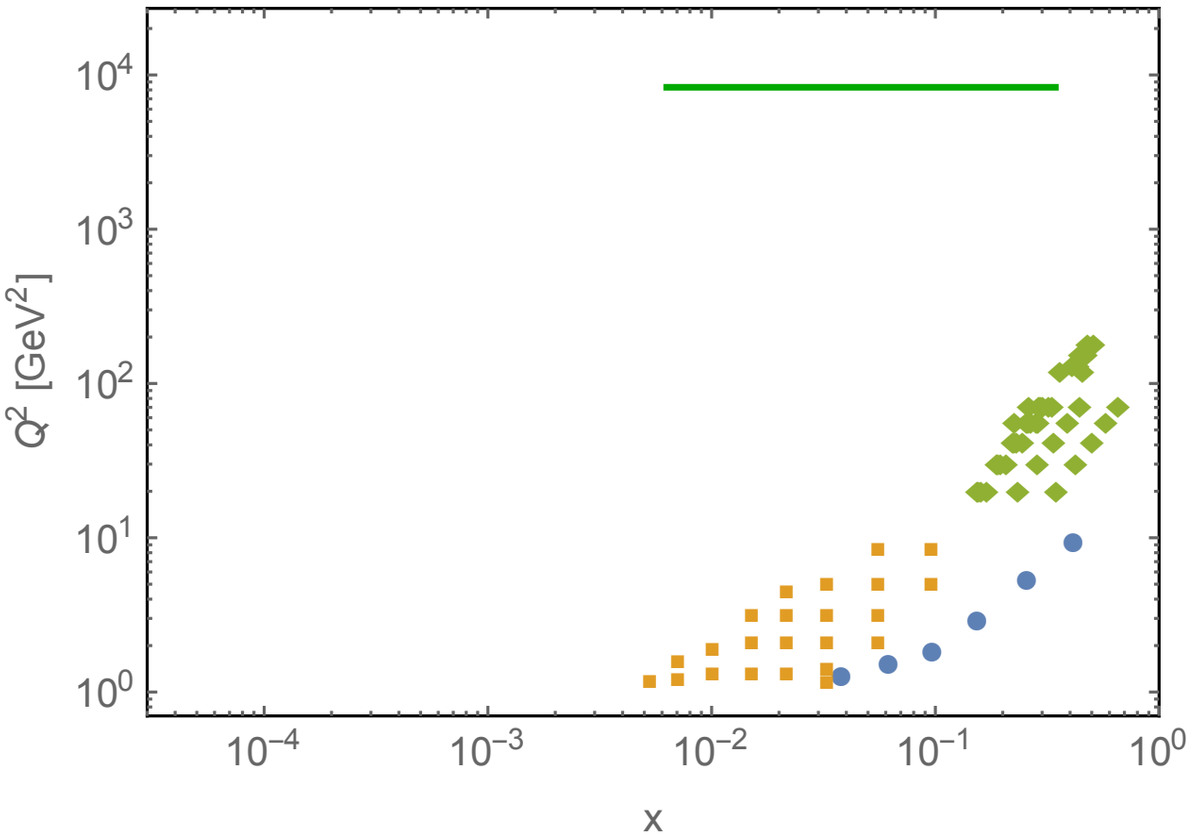
Experimental measurements



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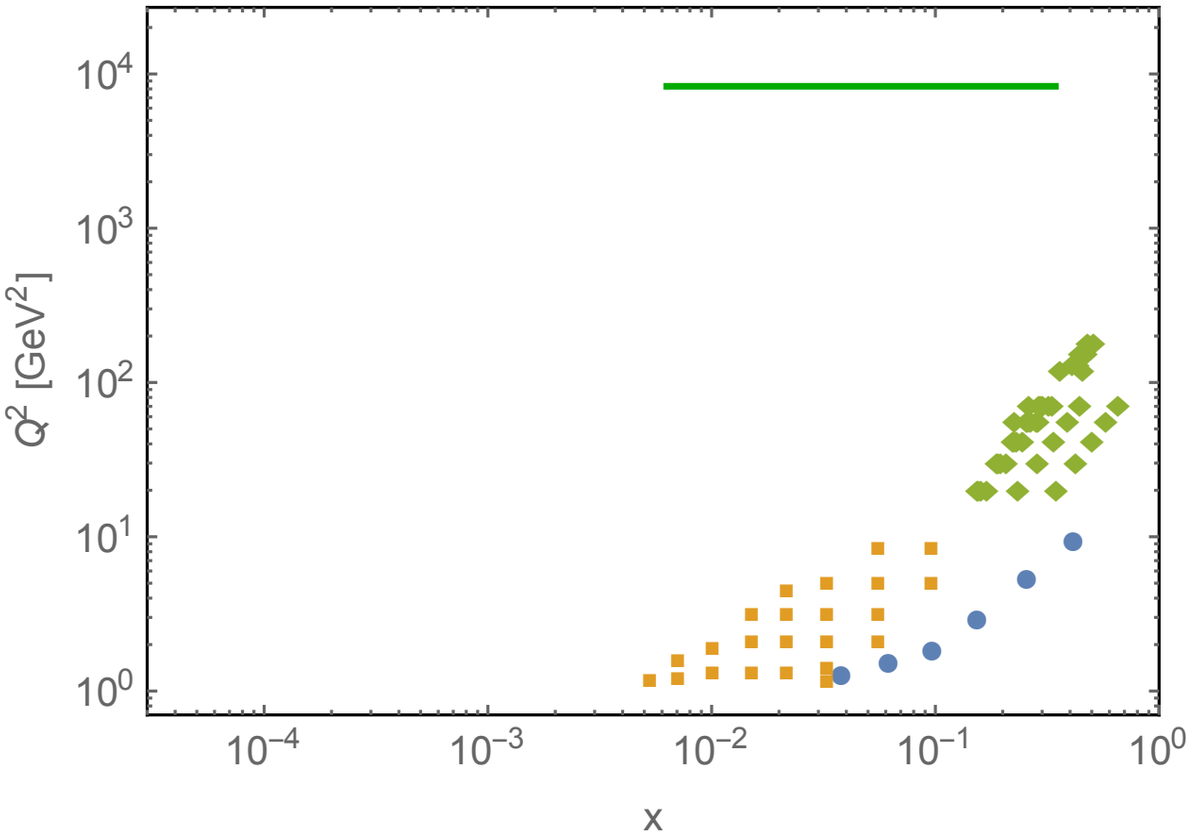

Drell-Yan@ Fermilab

Ito et al., PRD93 (81)
Moreno et al. PRD 43 (91)
Antreyan et al. PRL47 (81)

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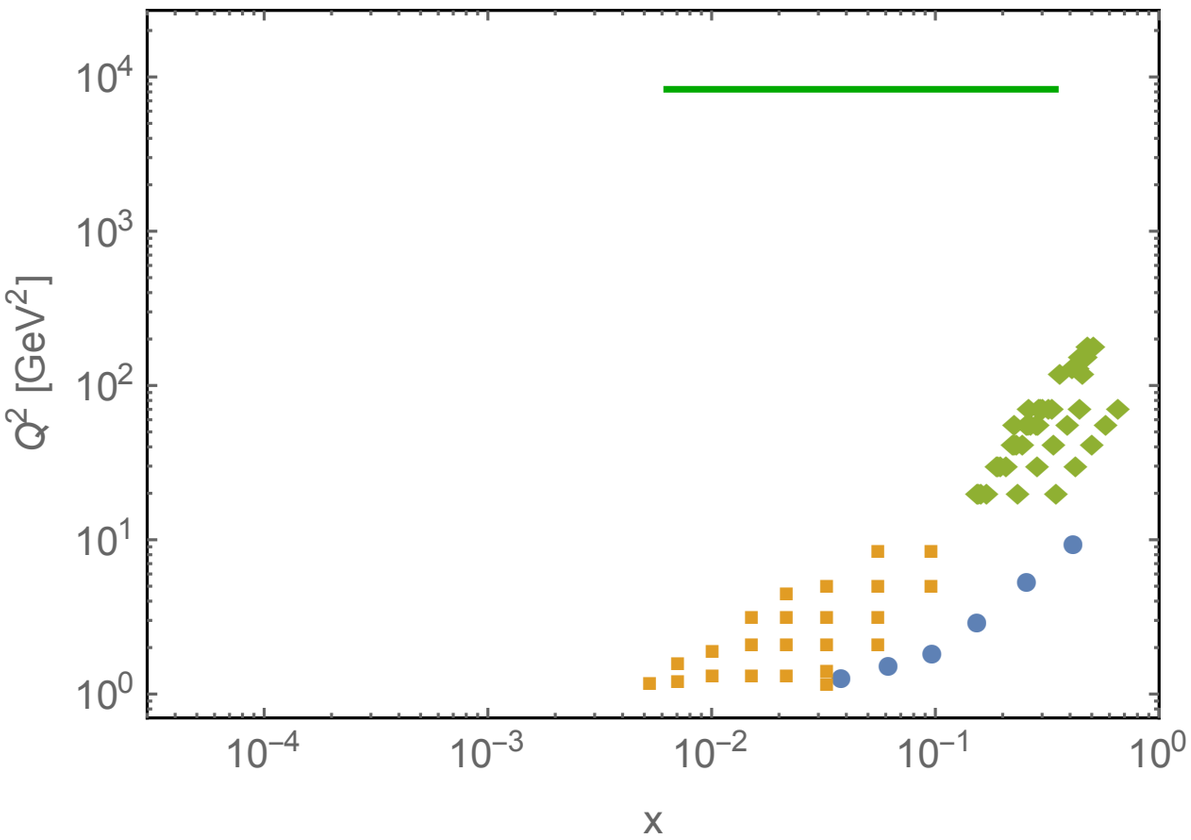

Z production@ Fermilab

Abbot et al. hep-ex/9909020
Affolder et al. hep-ex/0001021
Abazov et al. arXiv:0712.0803

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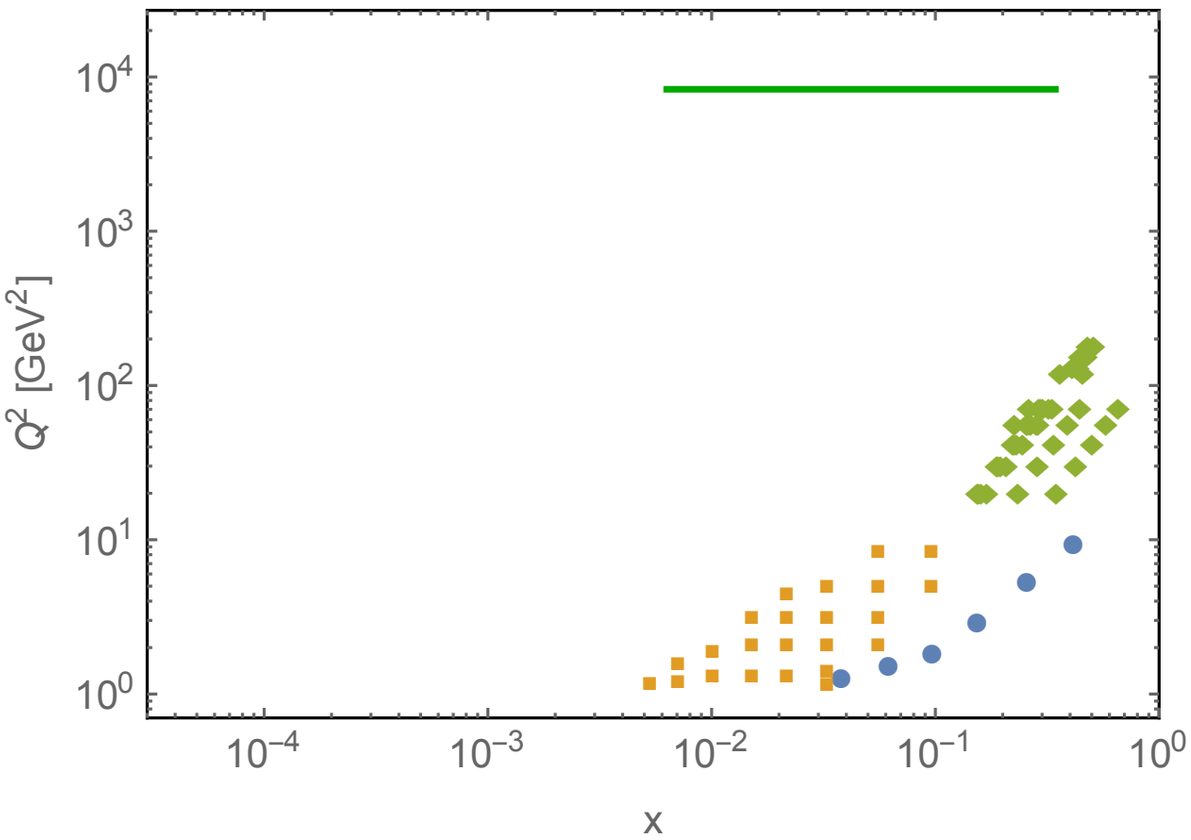

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SIDIS@ hermes

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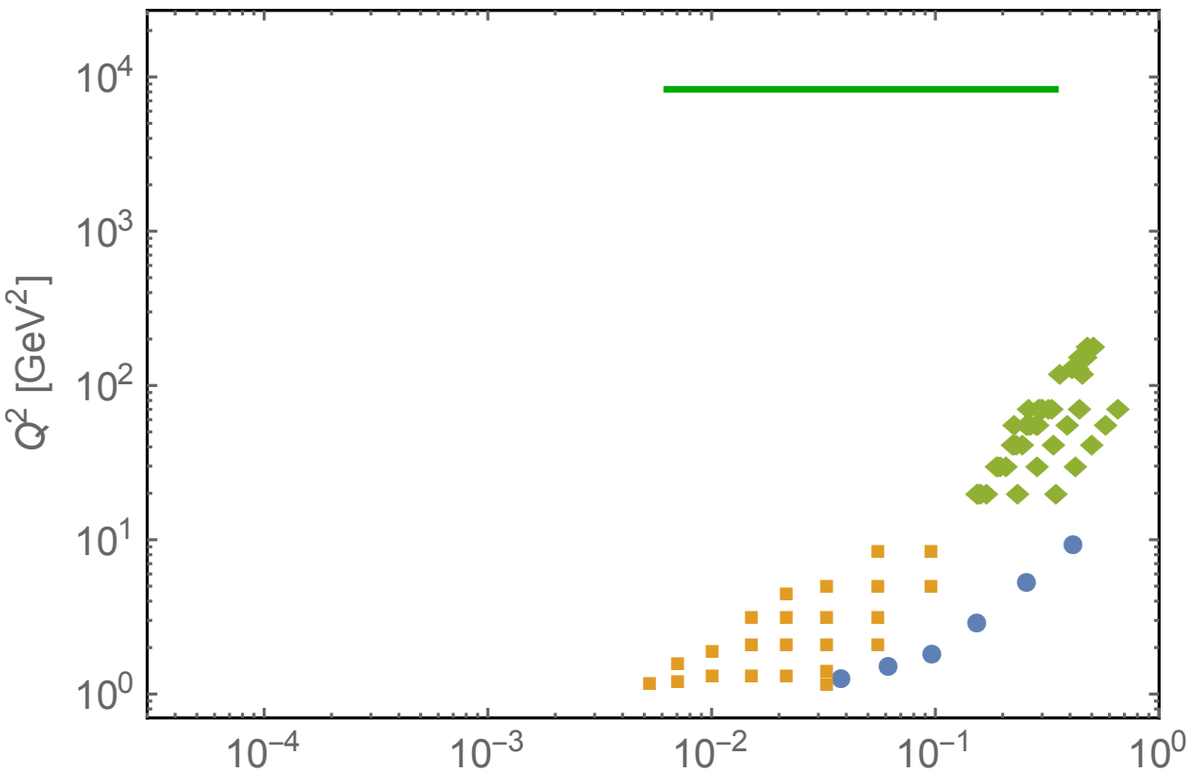

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SIDIS@ COMPASS

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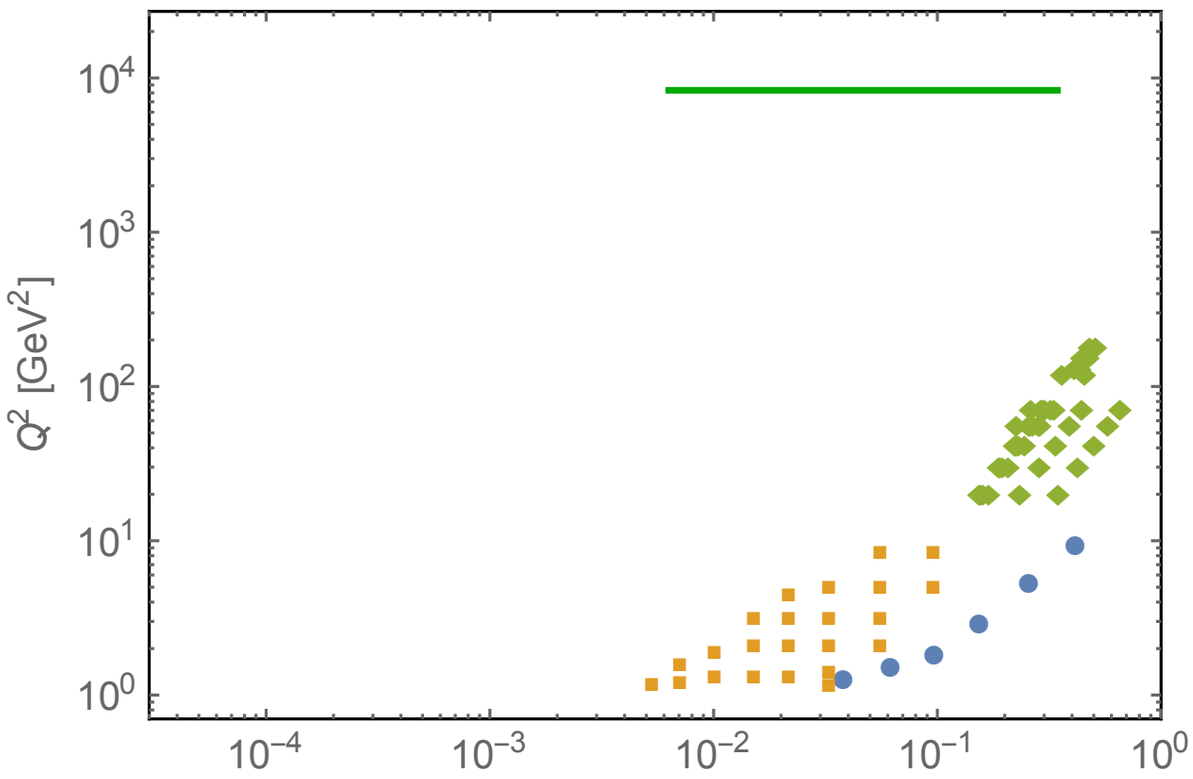

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SIDIS@ hermes

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x

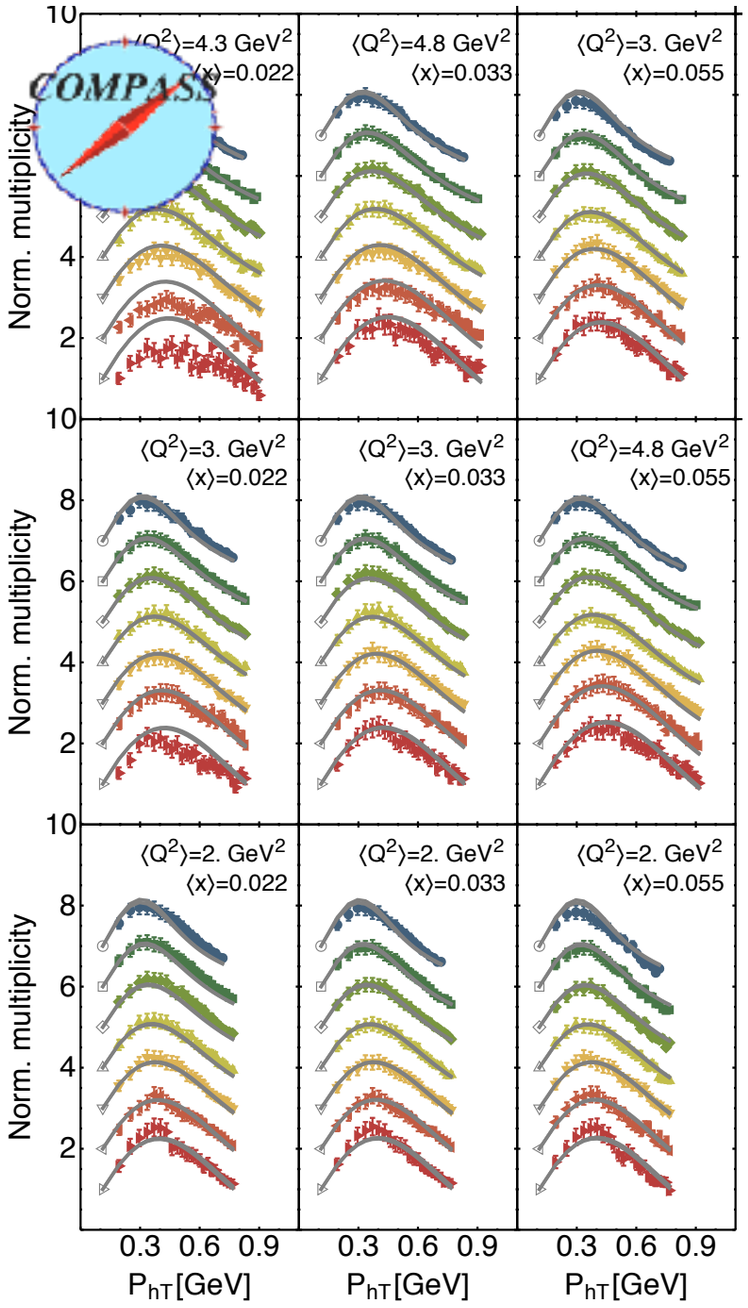
SIDIS@ COMPASS

Adolph et al., EPJ C73 (13)

Electron-positron annihilation data are still missing (only some azimuthal asymmetries are available)

First global fit of TMDs

SIDIS



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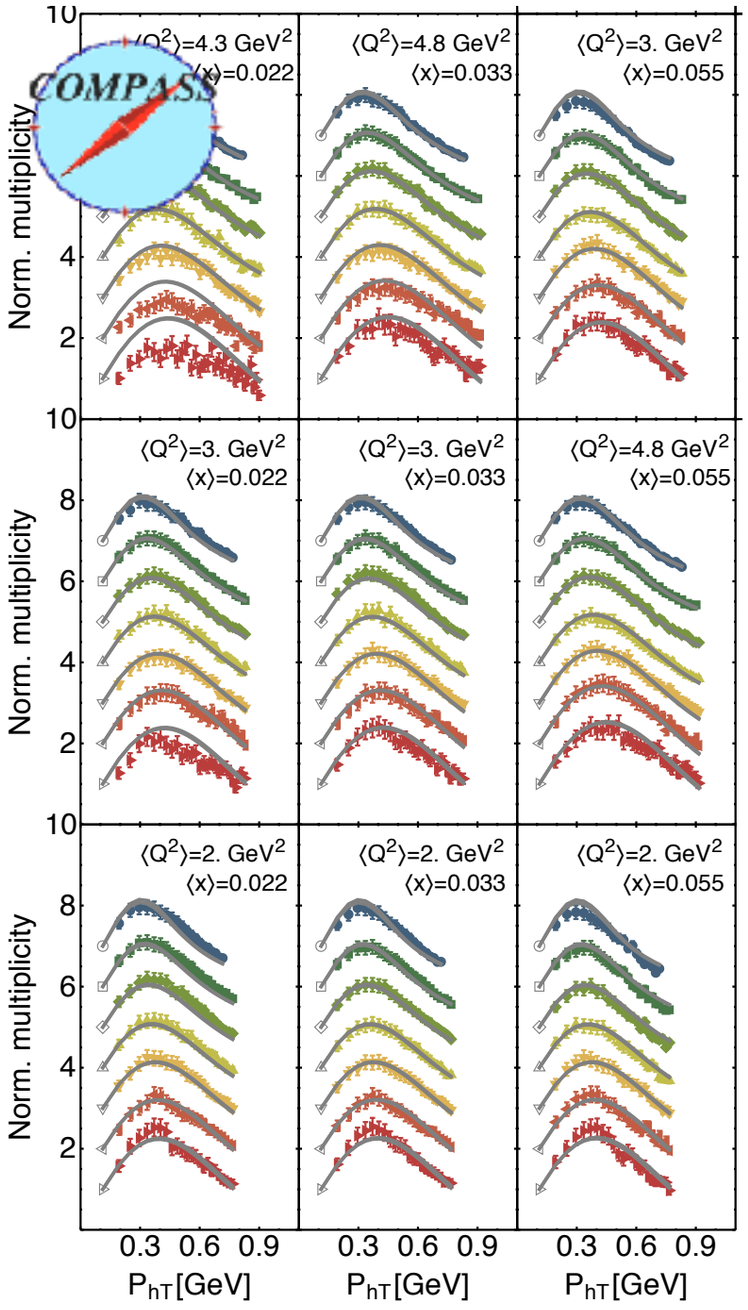
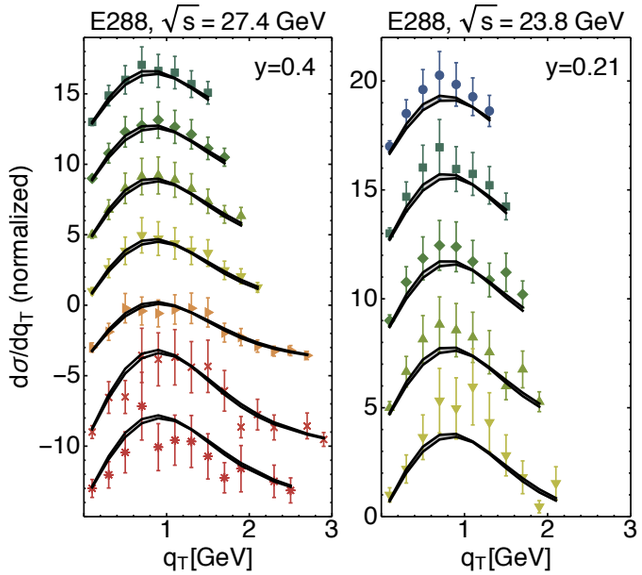


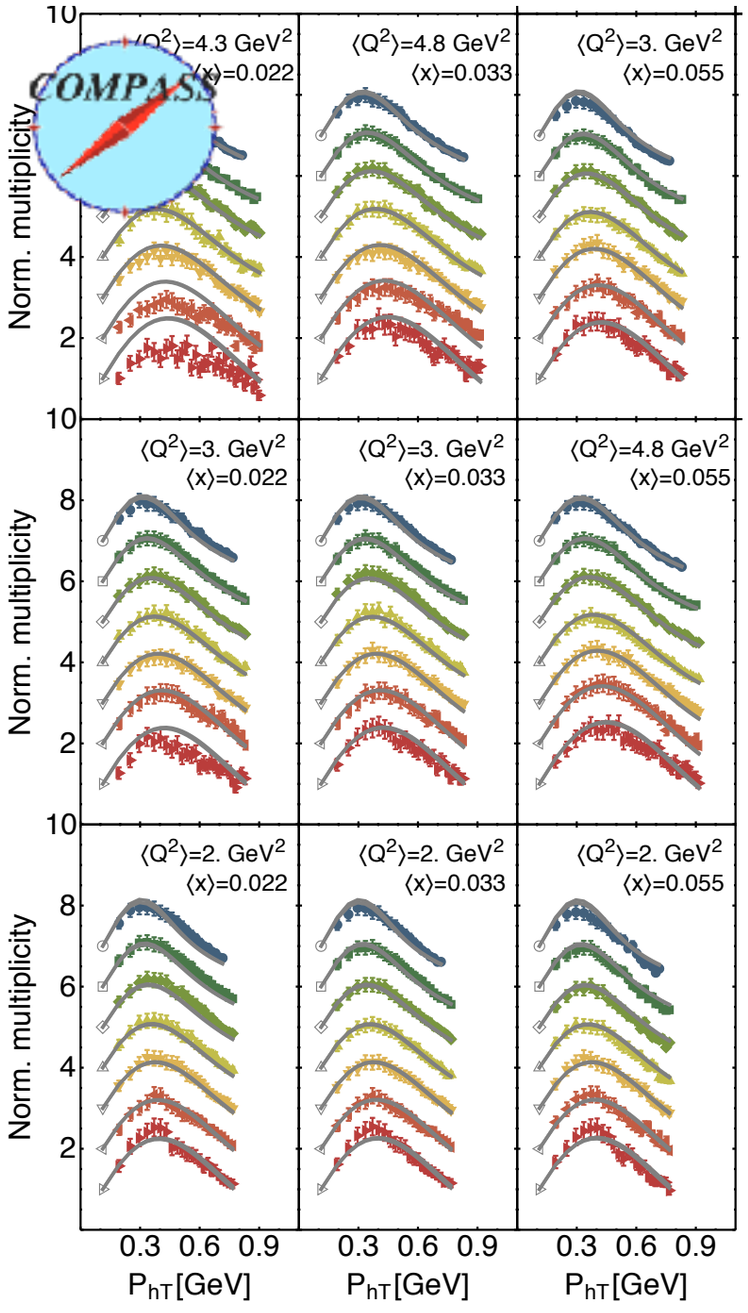
Drell-Yan

Fermilab



First global fit of TMDs

SIDIS



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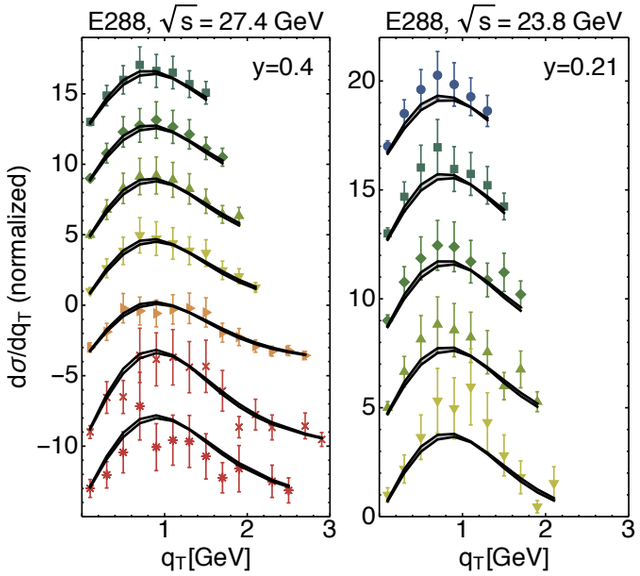
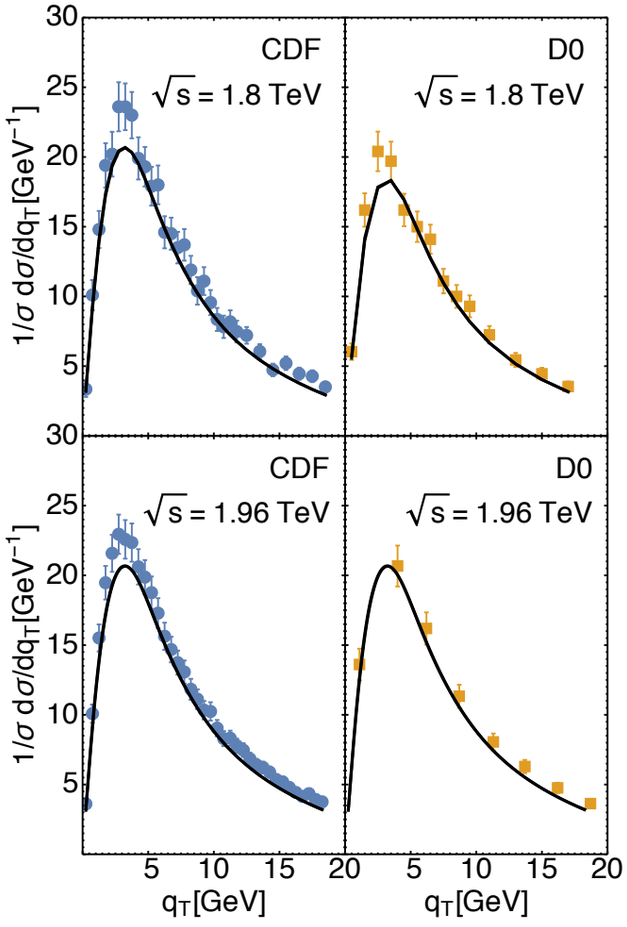


Z production



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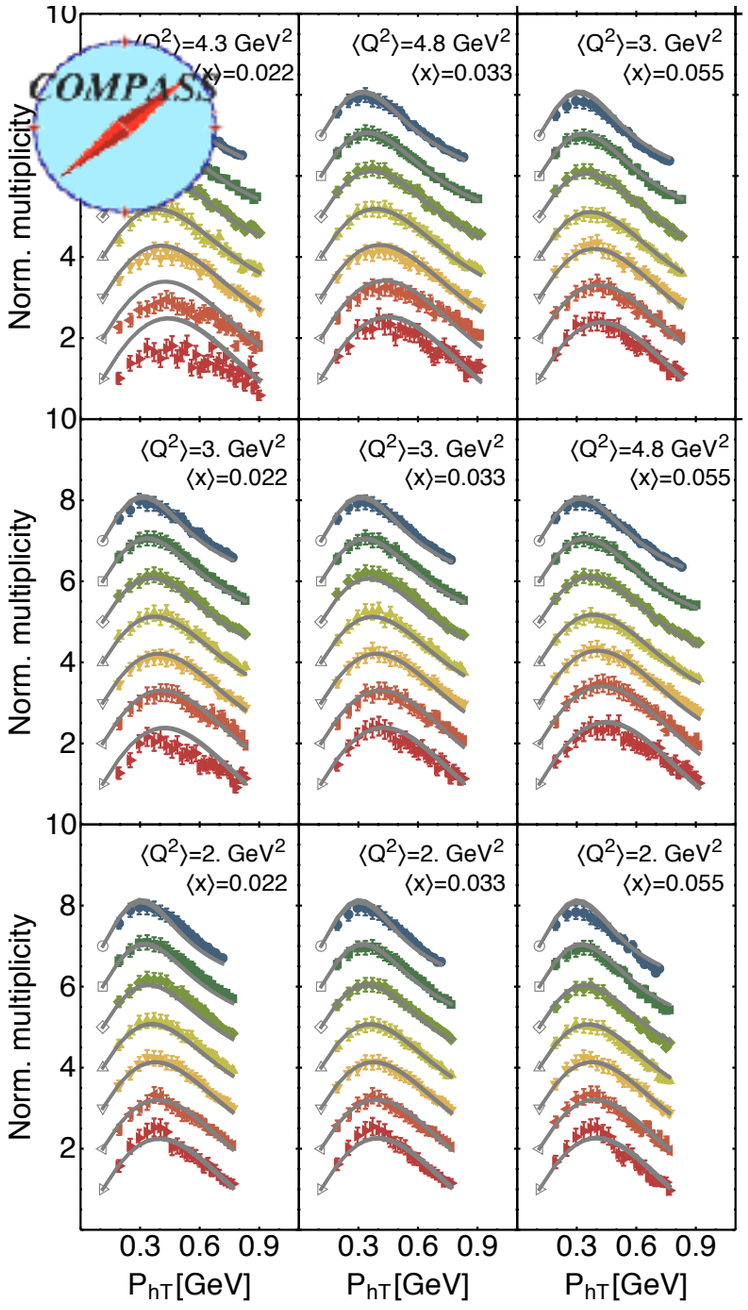

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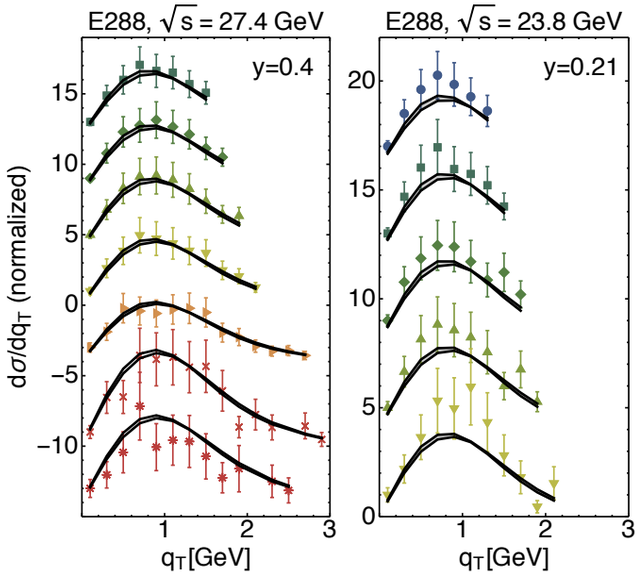
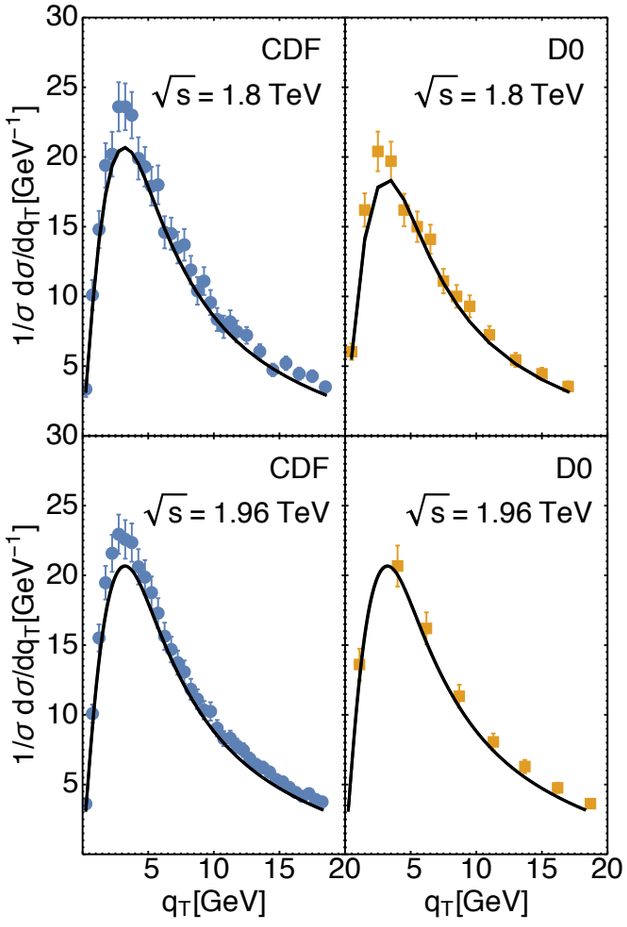


Next-to-Leading Log

Number of data points: 8059

Global χ^2/dof = 1.52

Z production



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

see talk by C. Pisano (Tuesday, WG 6)

First global fit of TMDs

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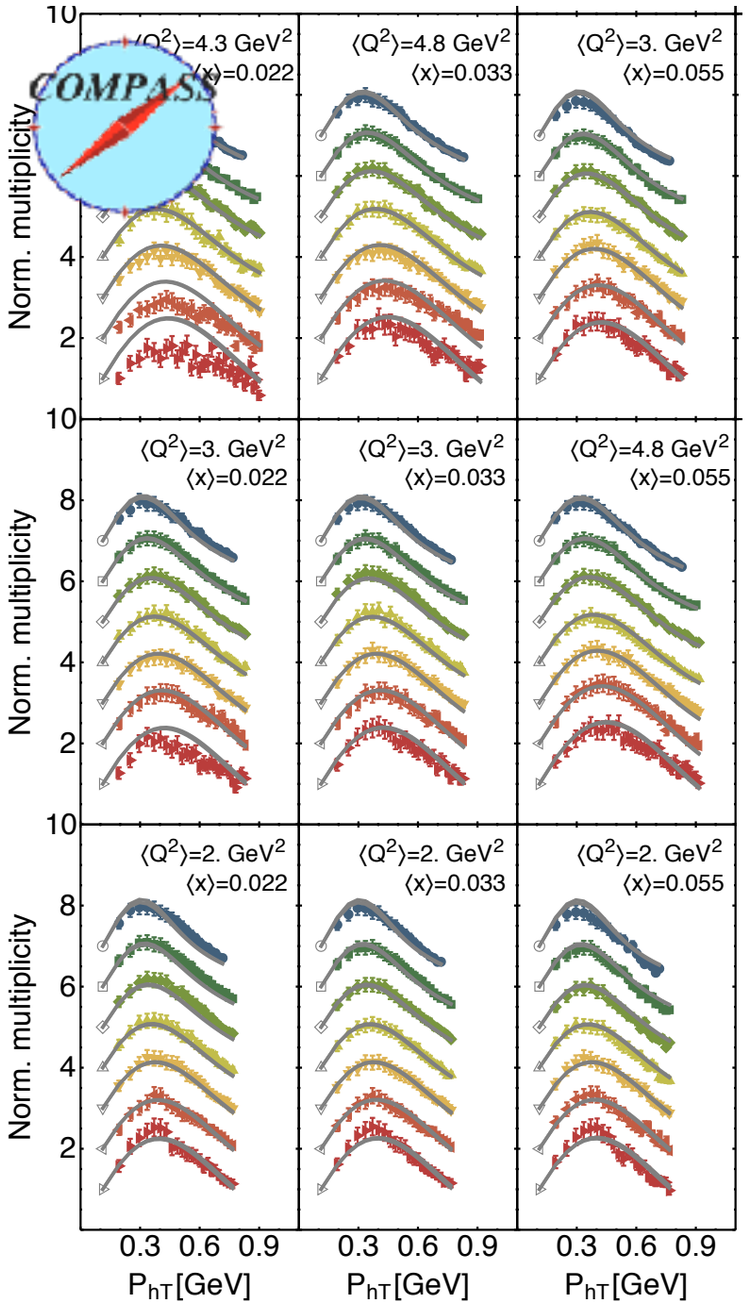

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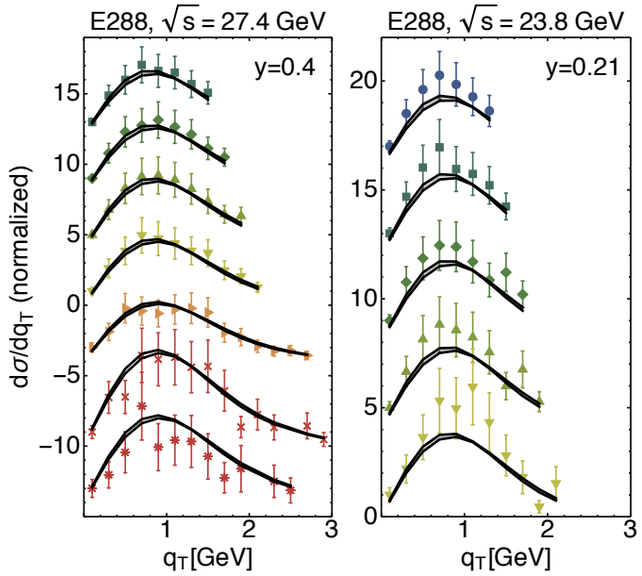

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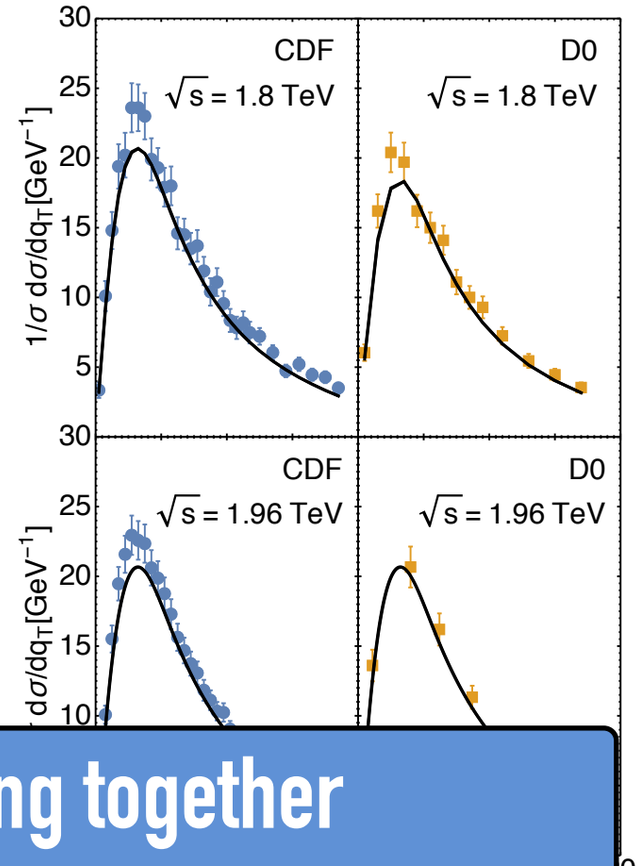

Next-to-Leading Log

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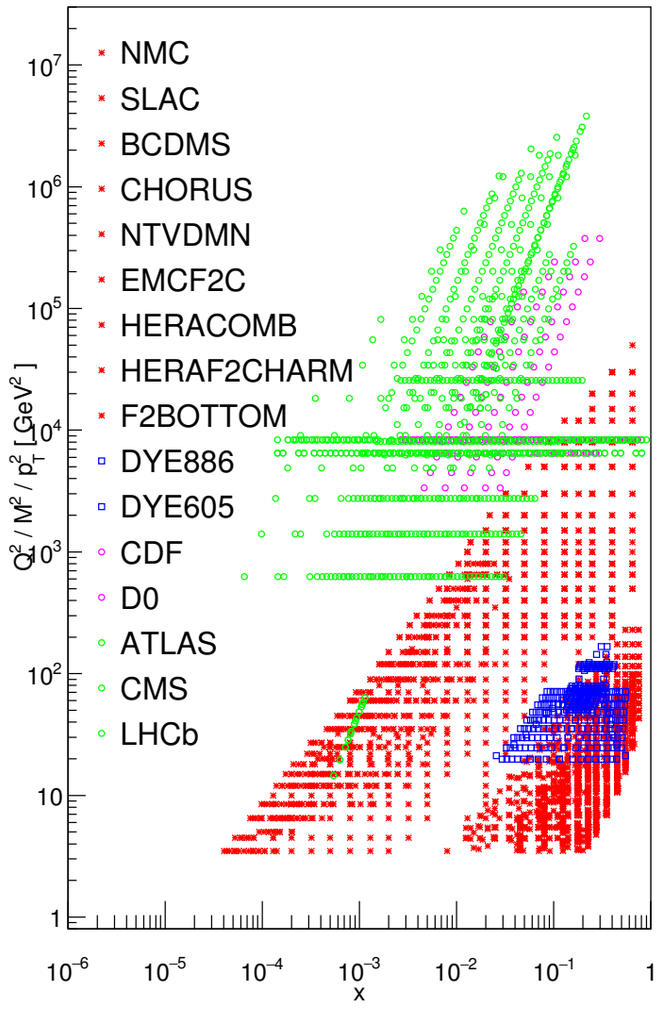
Pavia2016: first fit putting together semi-inclusive DIS, Drell-Yan and Z production

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

see talk by C. Pisano (Tuesday, WG 6)

It’s the dawn of TMD global fits era

Comparison with collinear PDFs



talk by E. Nocera at POETIC2016

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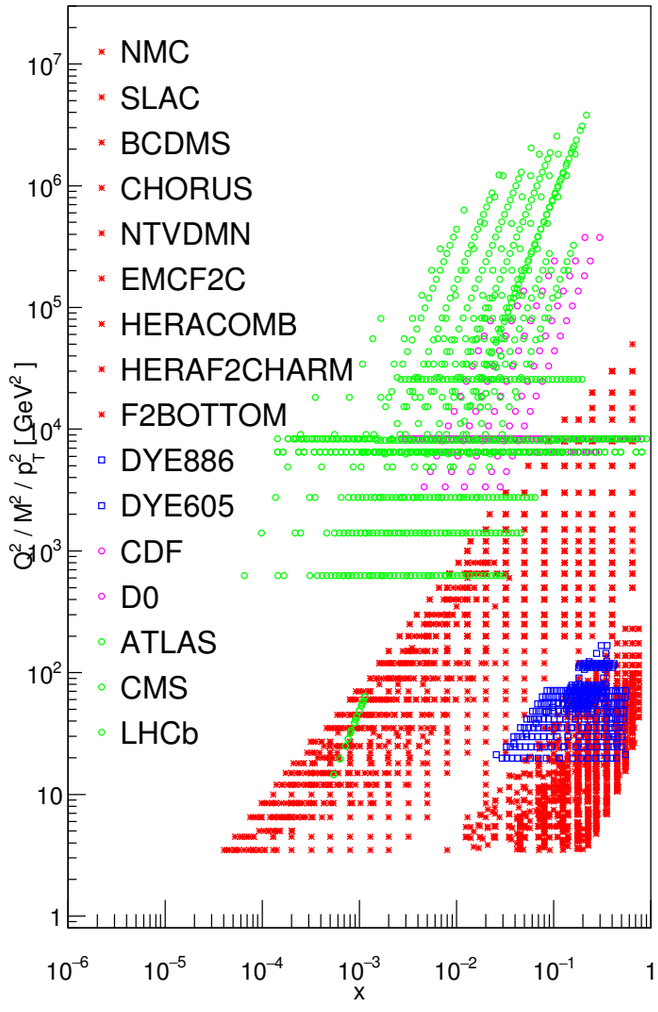

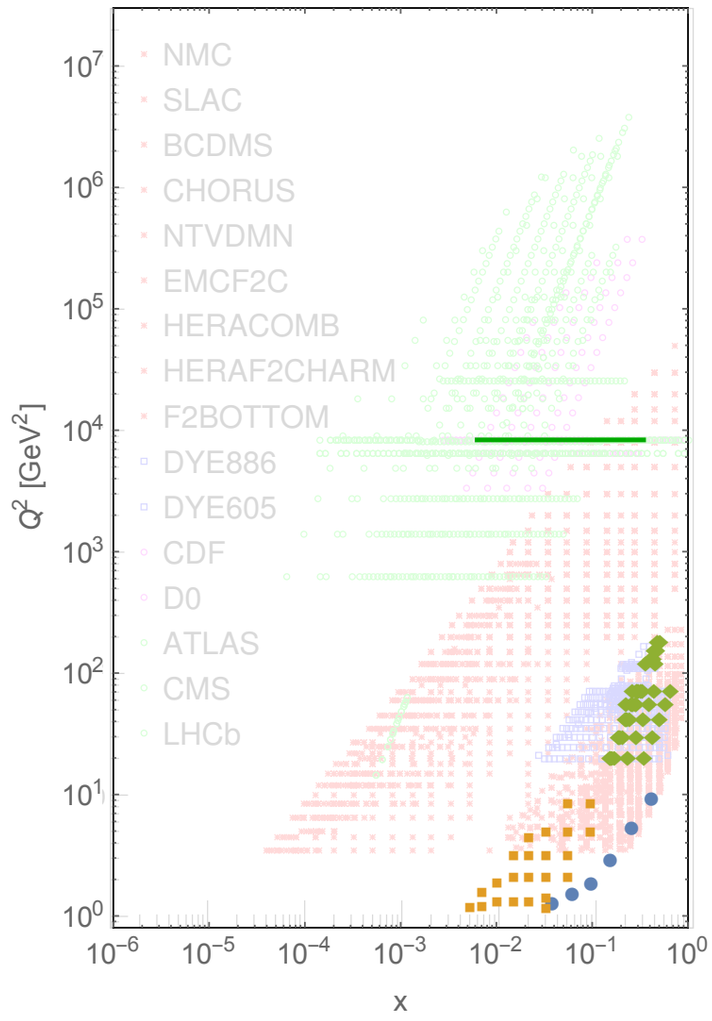

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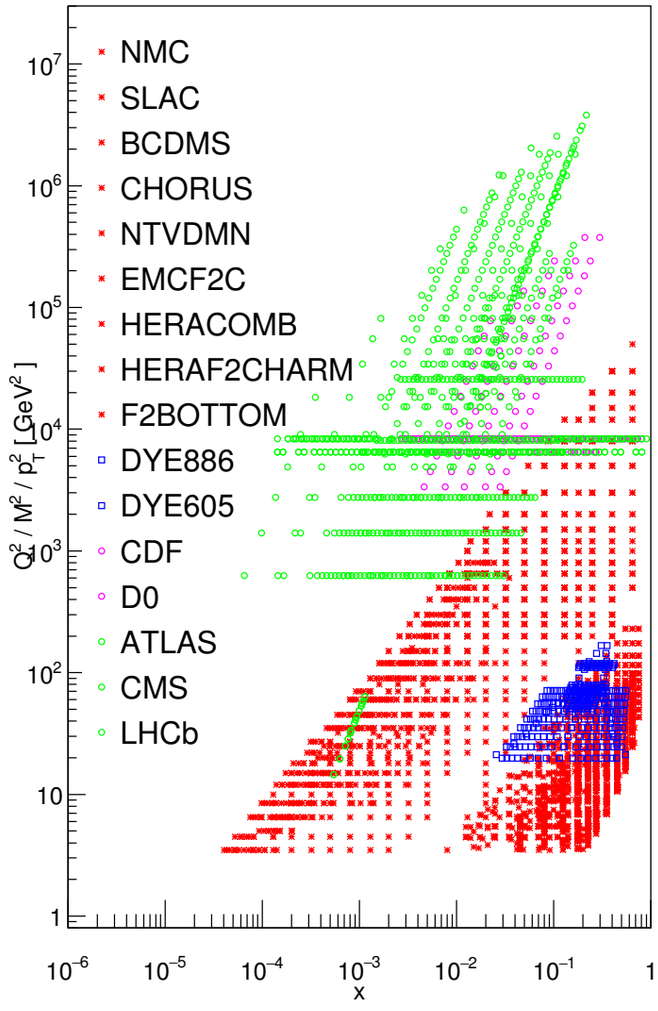

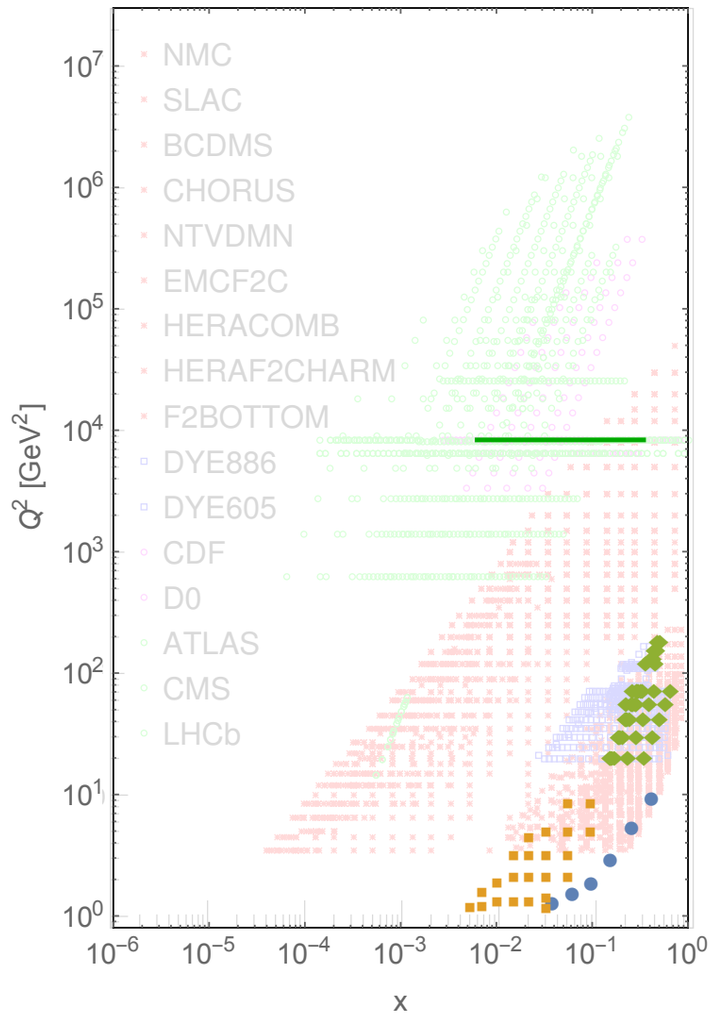

talk by E. Nocera at POETIC2016

On top of extending data set, many improvements are needed: higher perturbative orders, matching with high transverse momentum, flavor dependence, flexible functional forms…

“In children shoes”

A long path
lies ahead of us
We can follow the
footprints of older brothers (PDFs)

What are (some of) the open challenges?

The TMD table

quark pol.

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

Twist-2 TMDs

TMDs in black survive transverse-momentum integration.

TMDs in red are T-odd

The TMD table

unpolarised TMD

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unpolarised TMD

helicity

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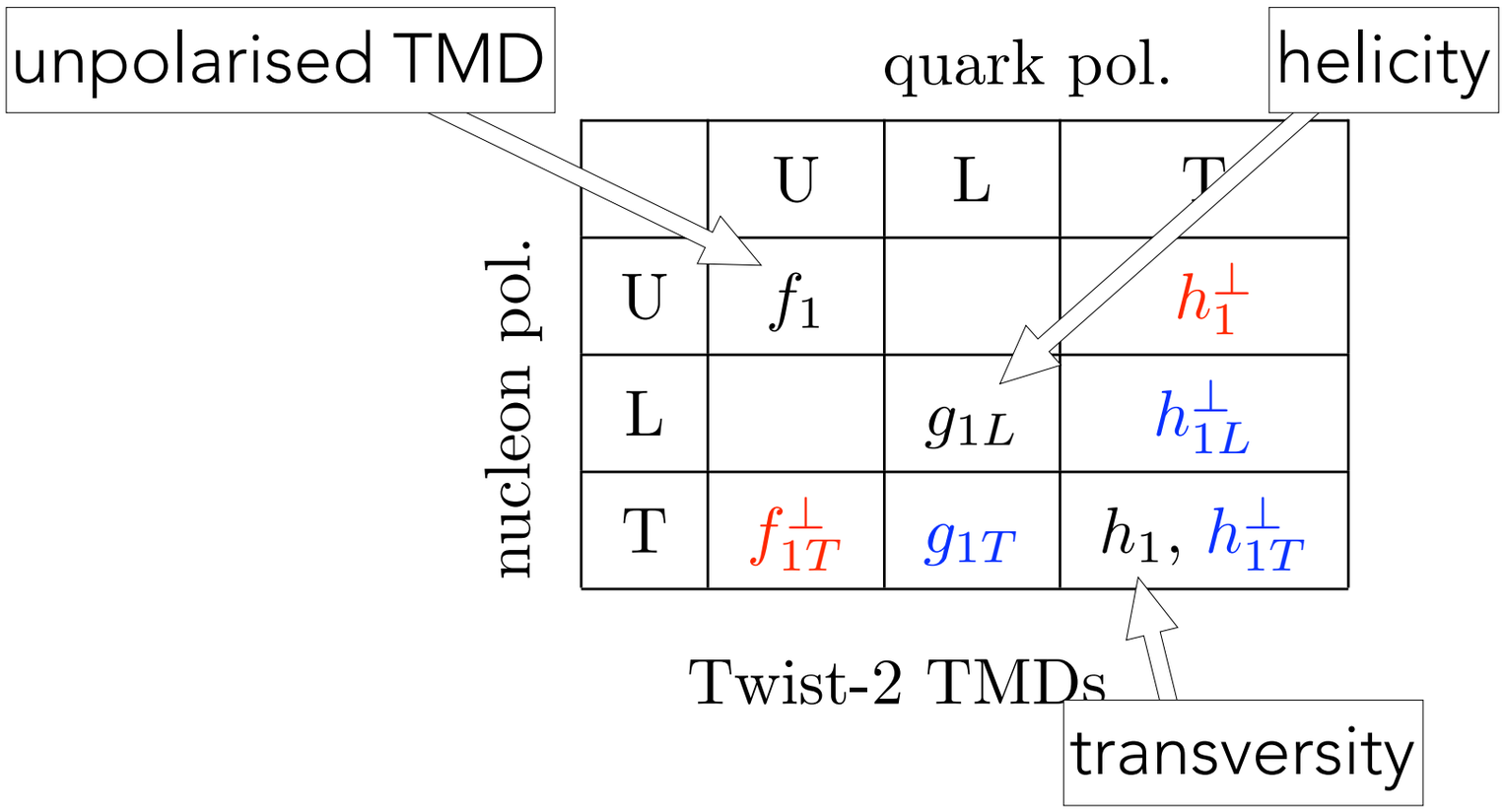

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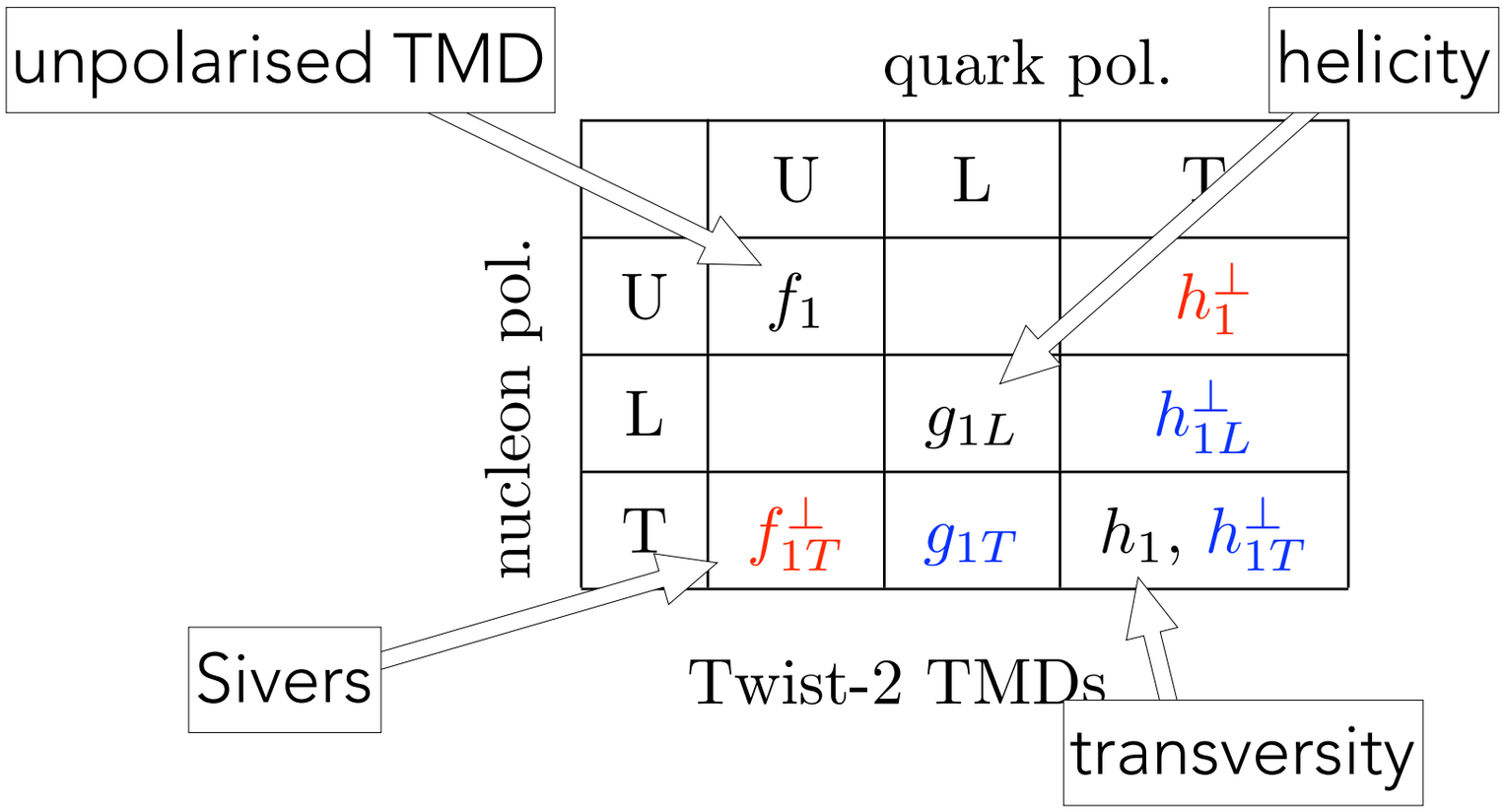

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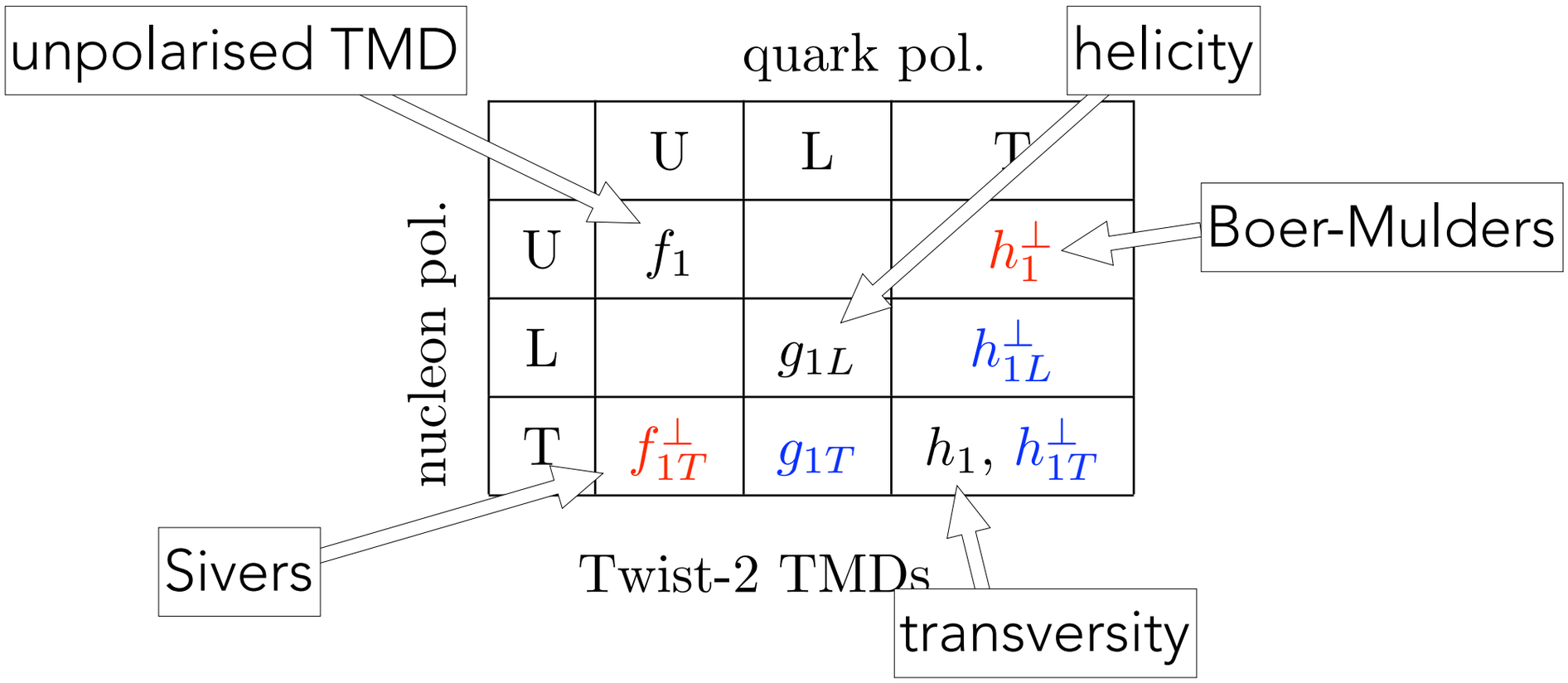

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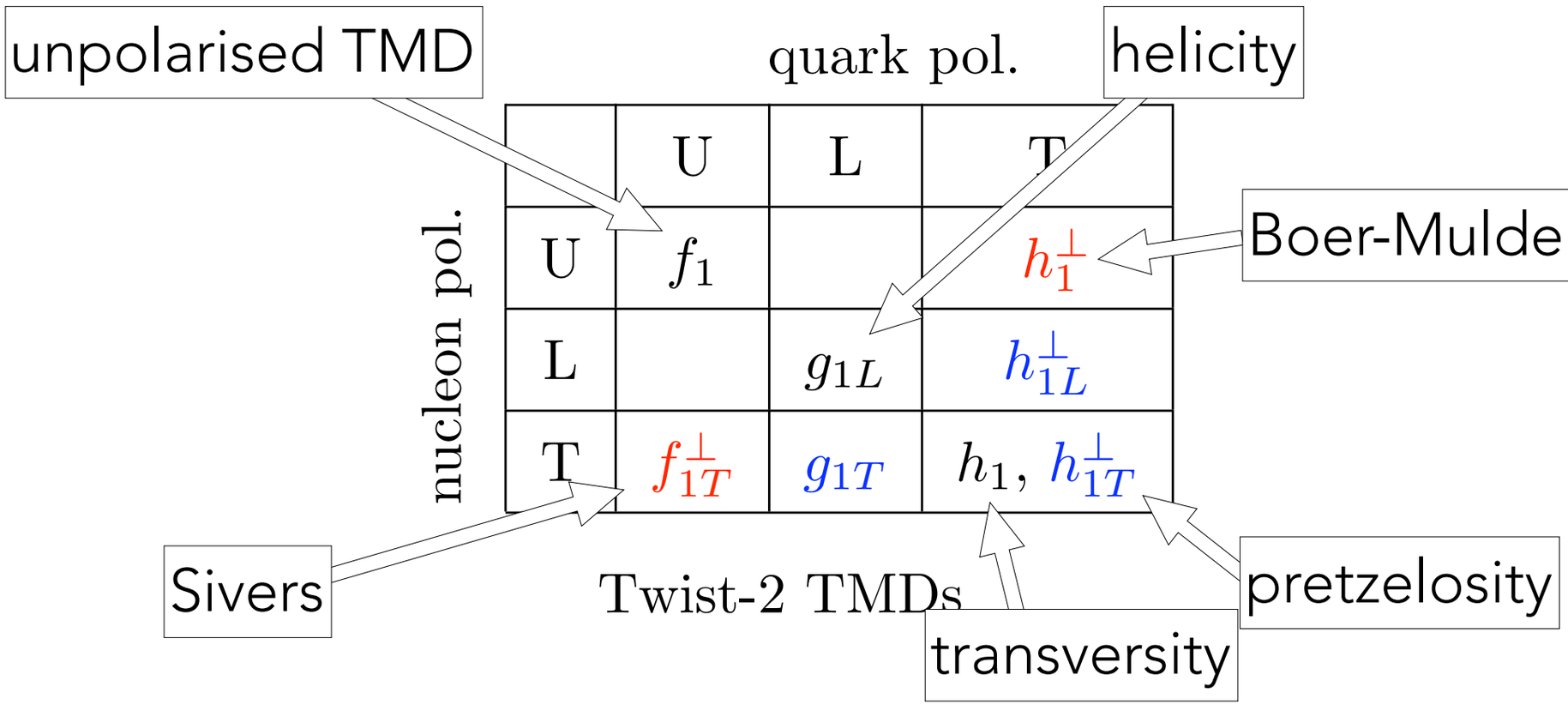

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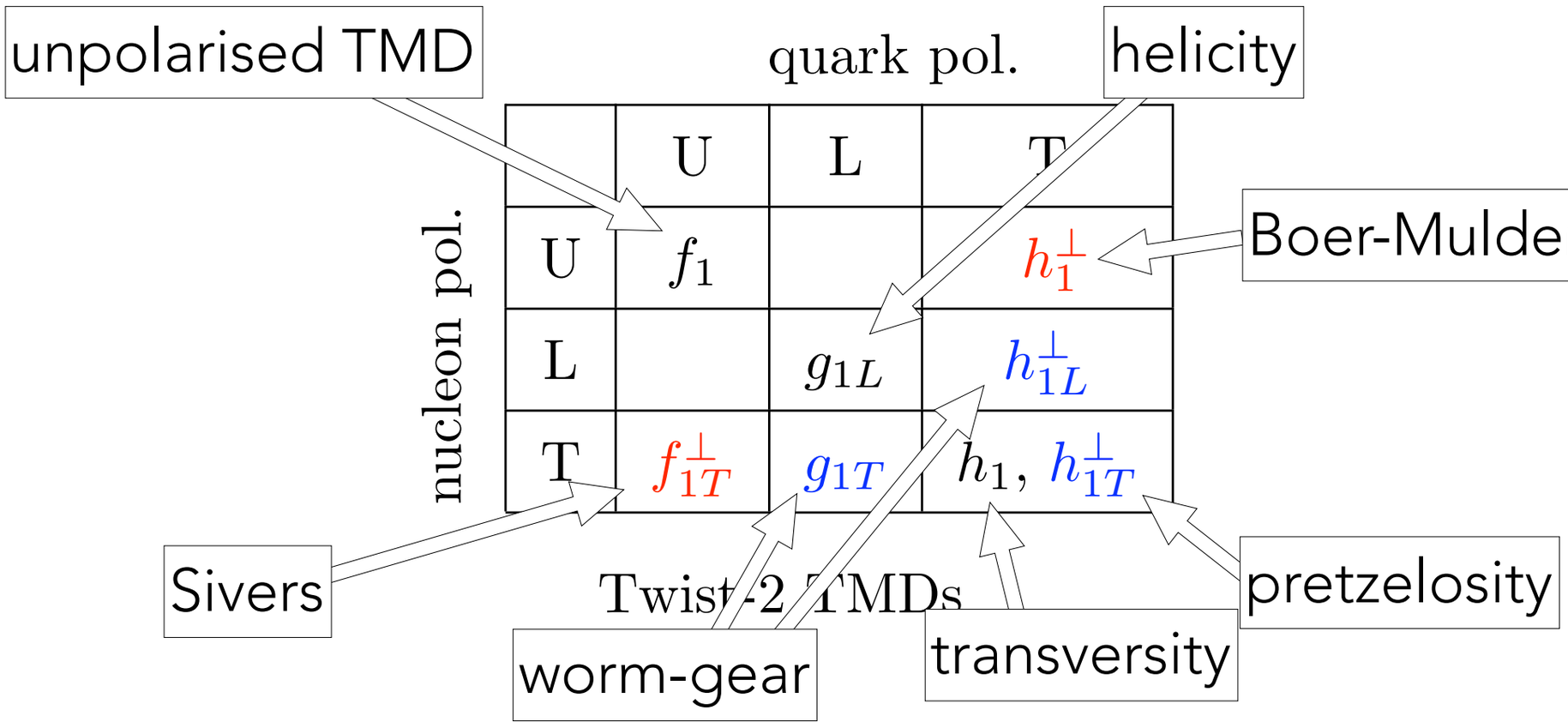

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Status of TMD phenomenology

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Data, theory, fits: we start being in a position to validate the formalism

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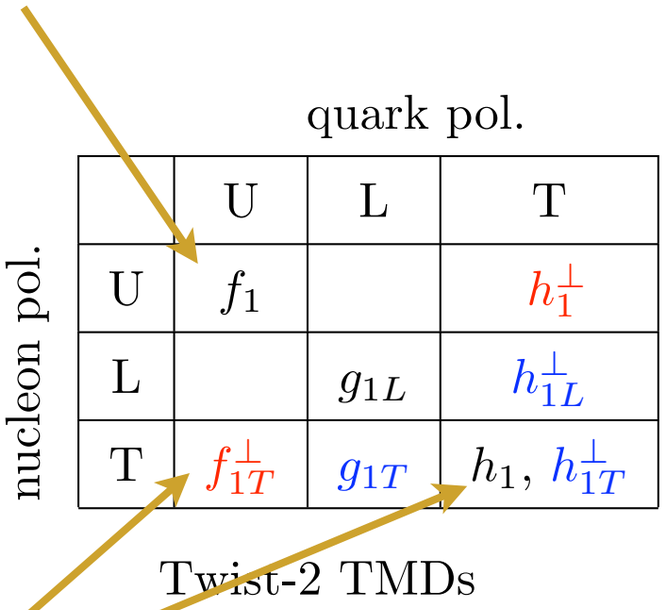

Limited data, theory, fits

see, e.g, Bacchetta, Radici, arXiv:1107.5755
Anselmino, Boglione, Melis, PRD86 (12)
Echevarria, Idilbi, Kang, Vitev, PRD 89 (14)
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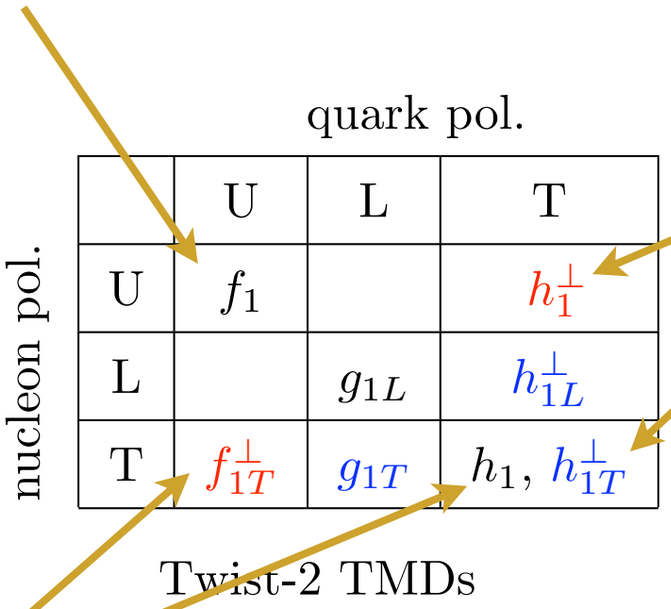

Only first attempts

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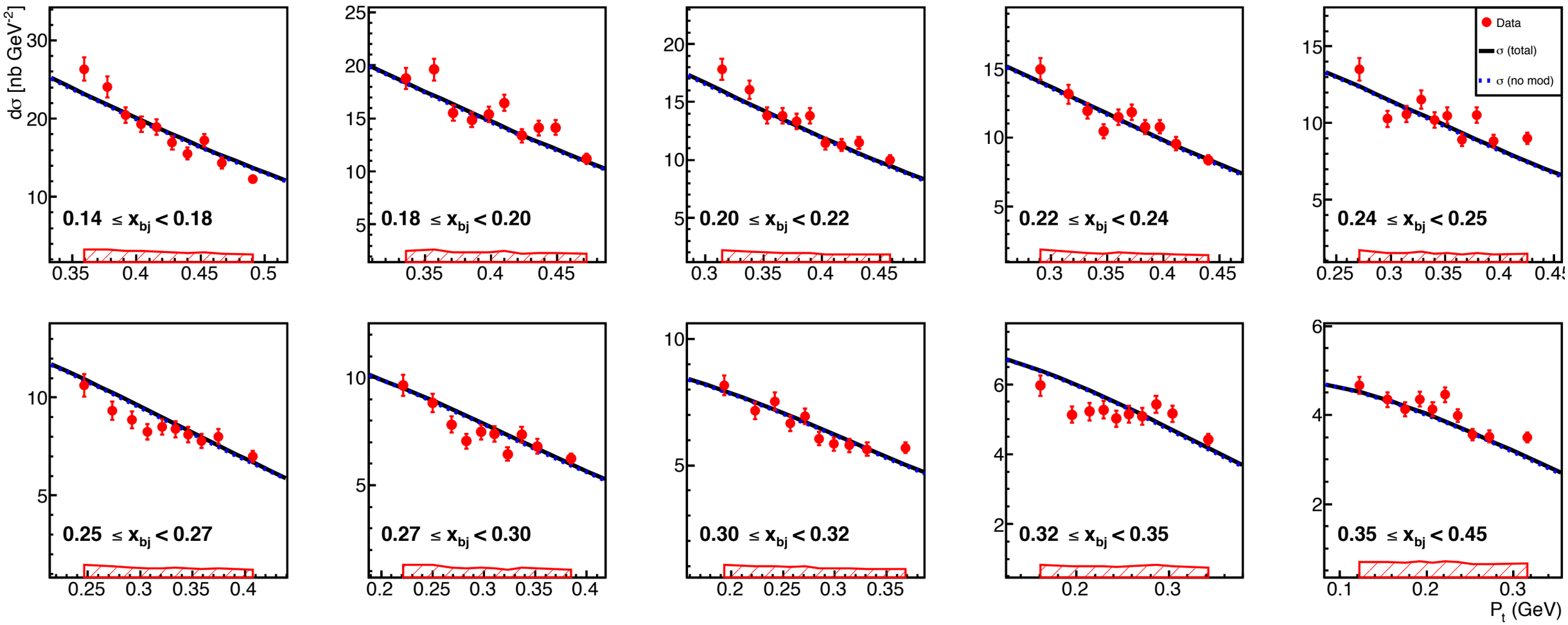
Lu, Ma, Schmidt, arXiv:0912.2031
Lefky, Prokudin arXiv:1411.0580
Barone, Boglione, Gonzalez, Melis, arXiv: 1502.04214

New data from JLab

Related to unpolarized TMDs



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Jefferson Lab

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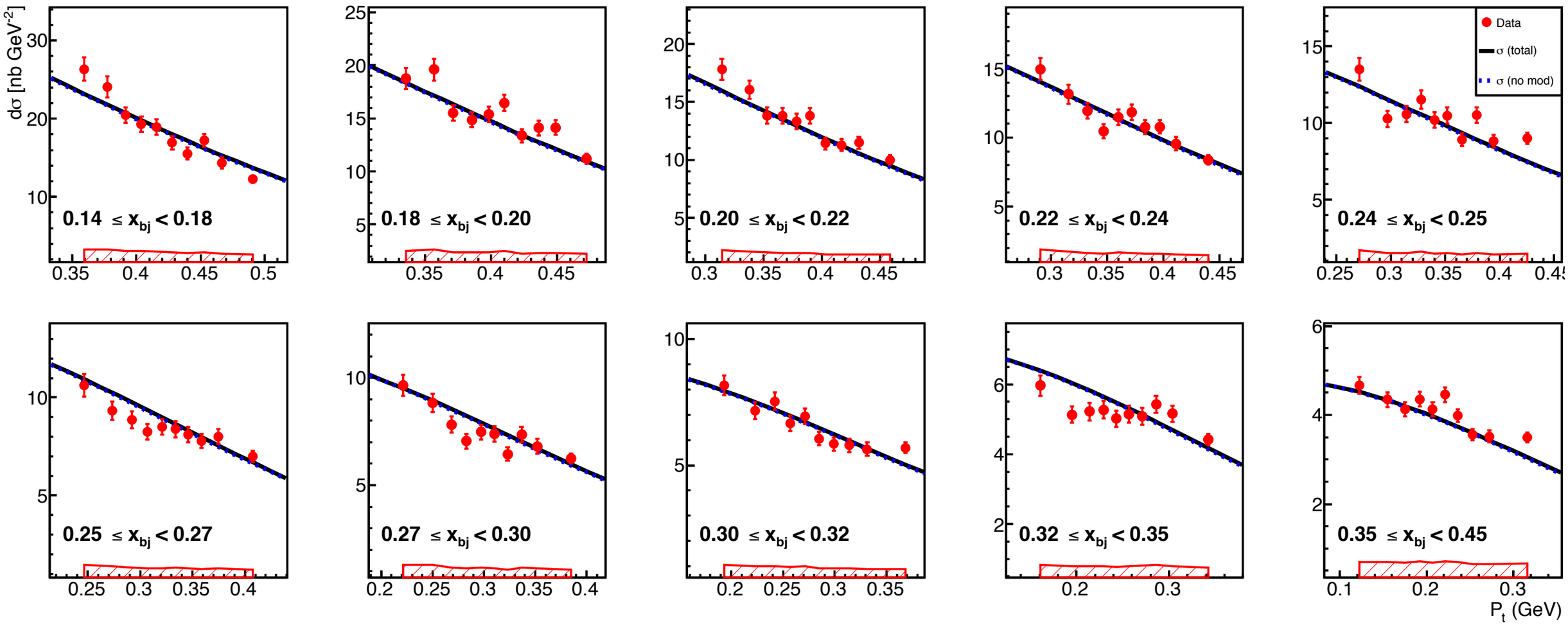

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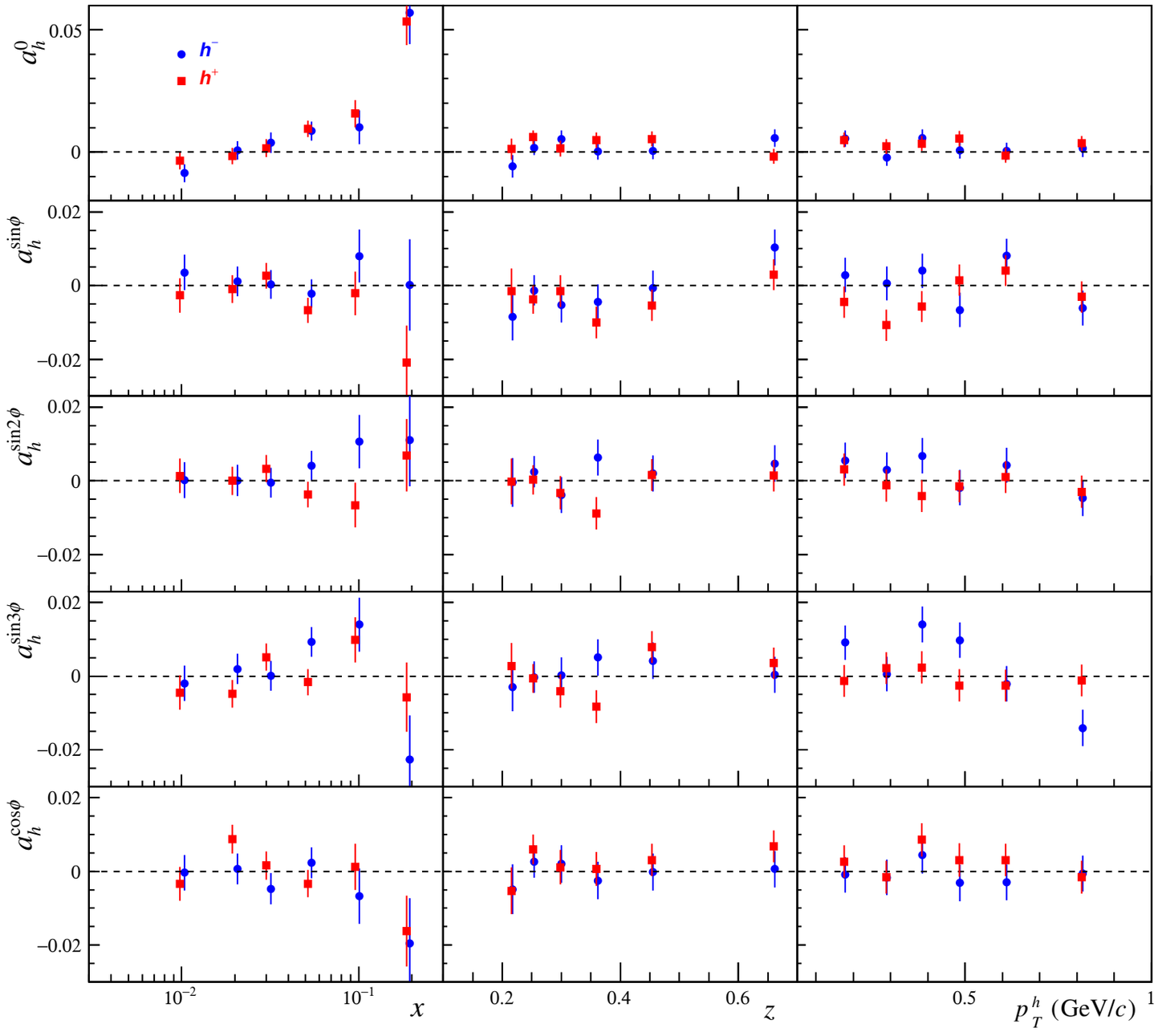
see talks by A. Puckett, K. Allada (Tuesday)

New data from COMPASS

Related to polarized TMDs

COMPASS, arXiv:1609.06062



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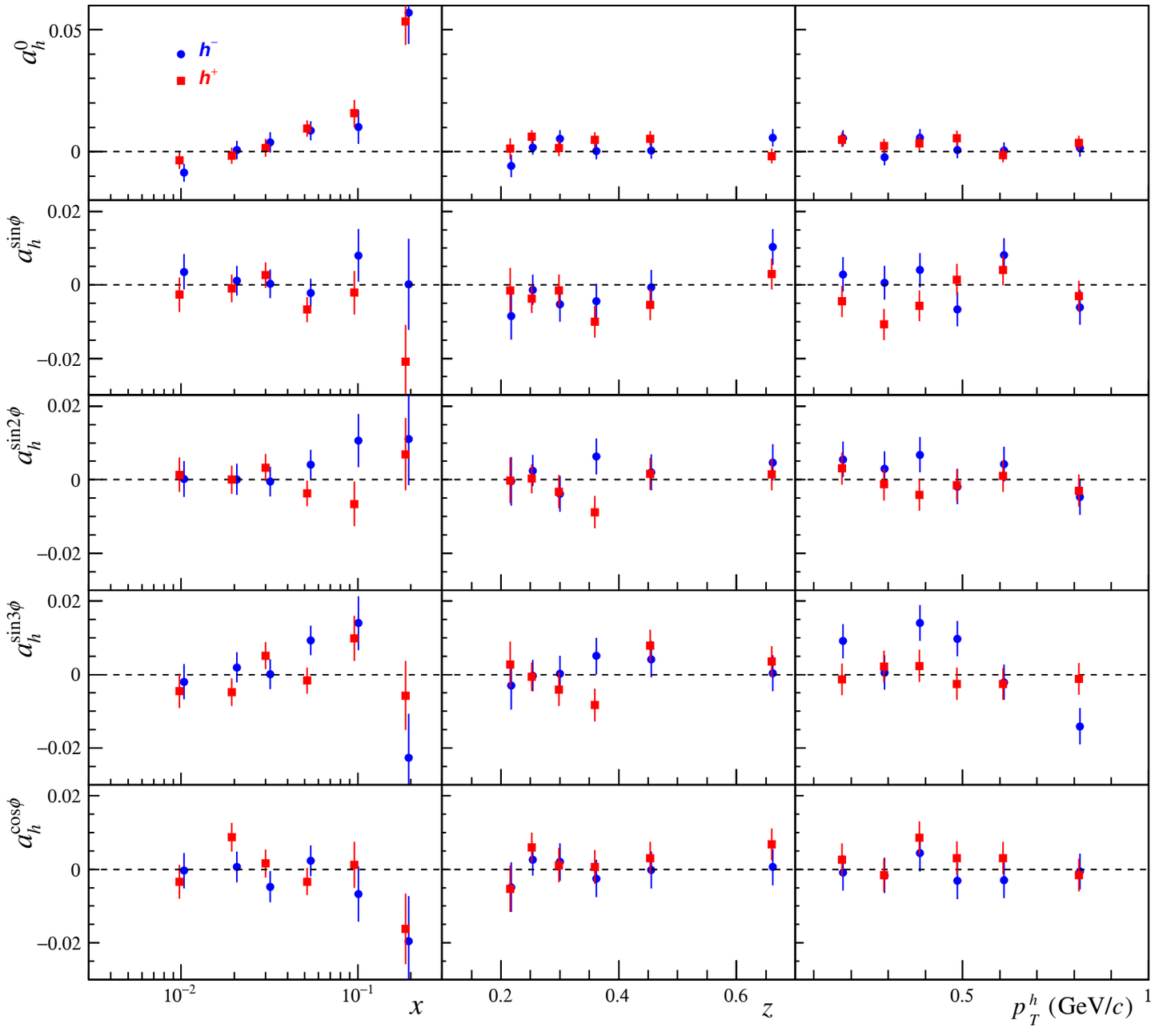

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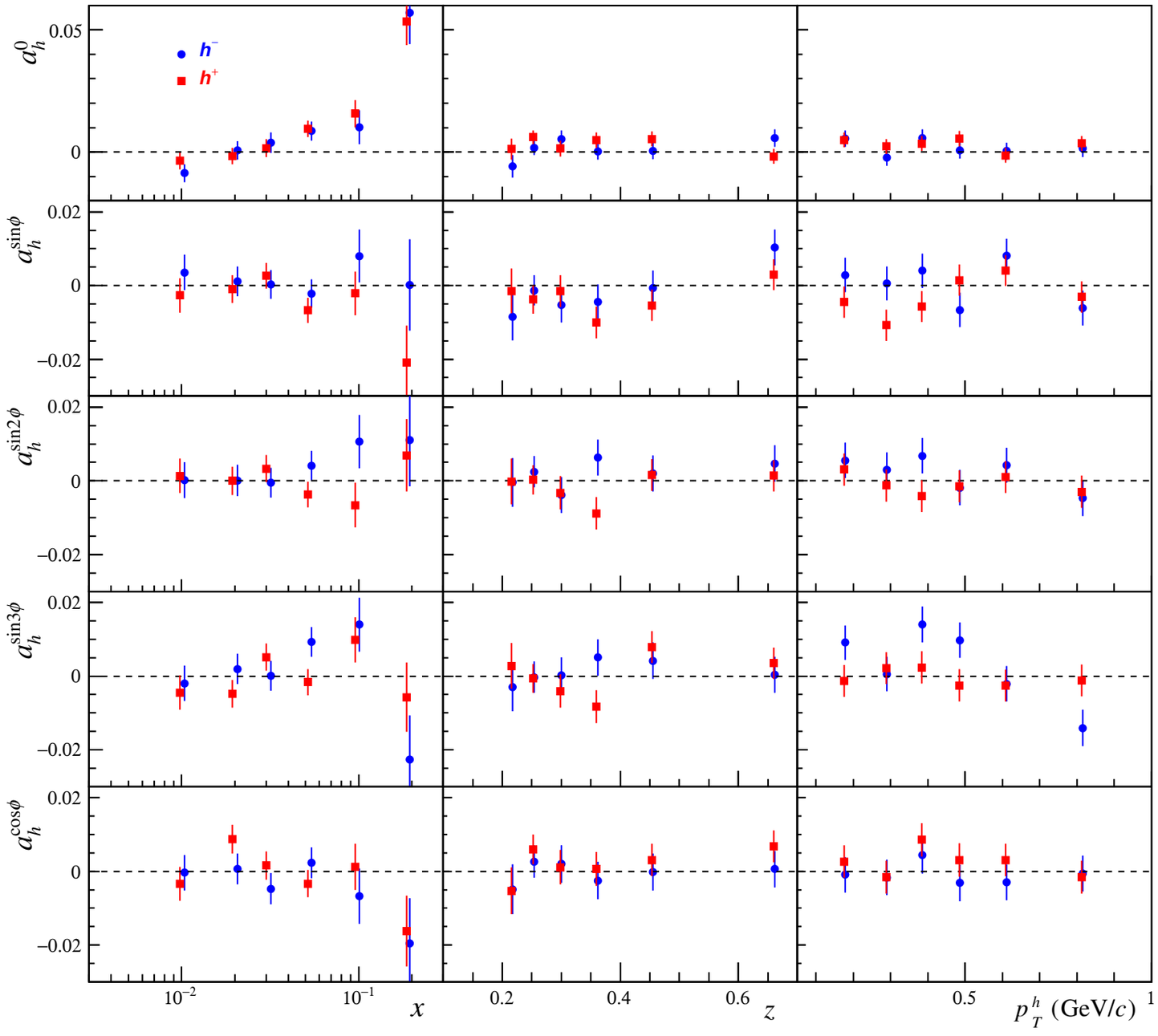

see talk by B. Parsamyan (Wednesday, WG6)

Nontrivial universality of Sivers TMD

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Sivers function SIDIS $= -$ Sivers function Drell–Yan

Collins, PLB 536 (02)

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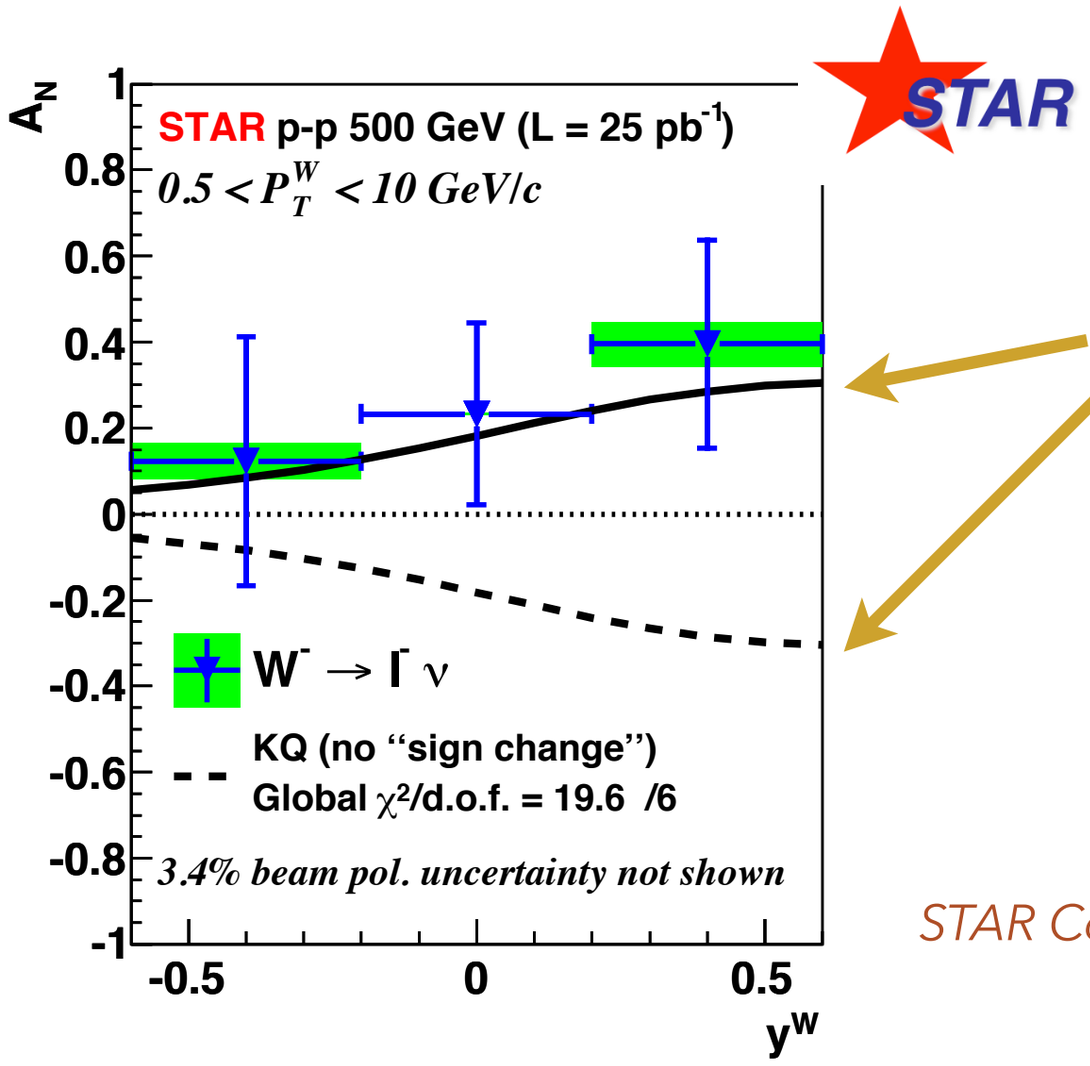

first evidence
of sign change?

STAR Collab. arXiv:1511.06003

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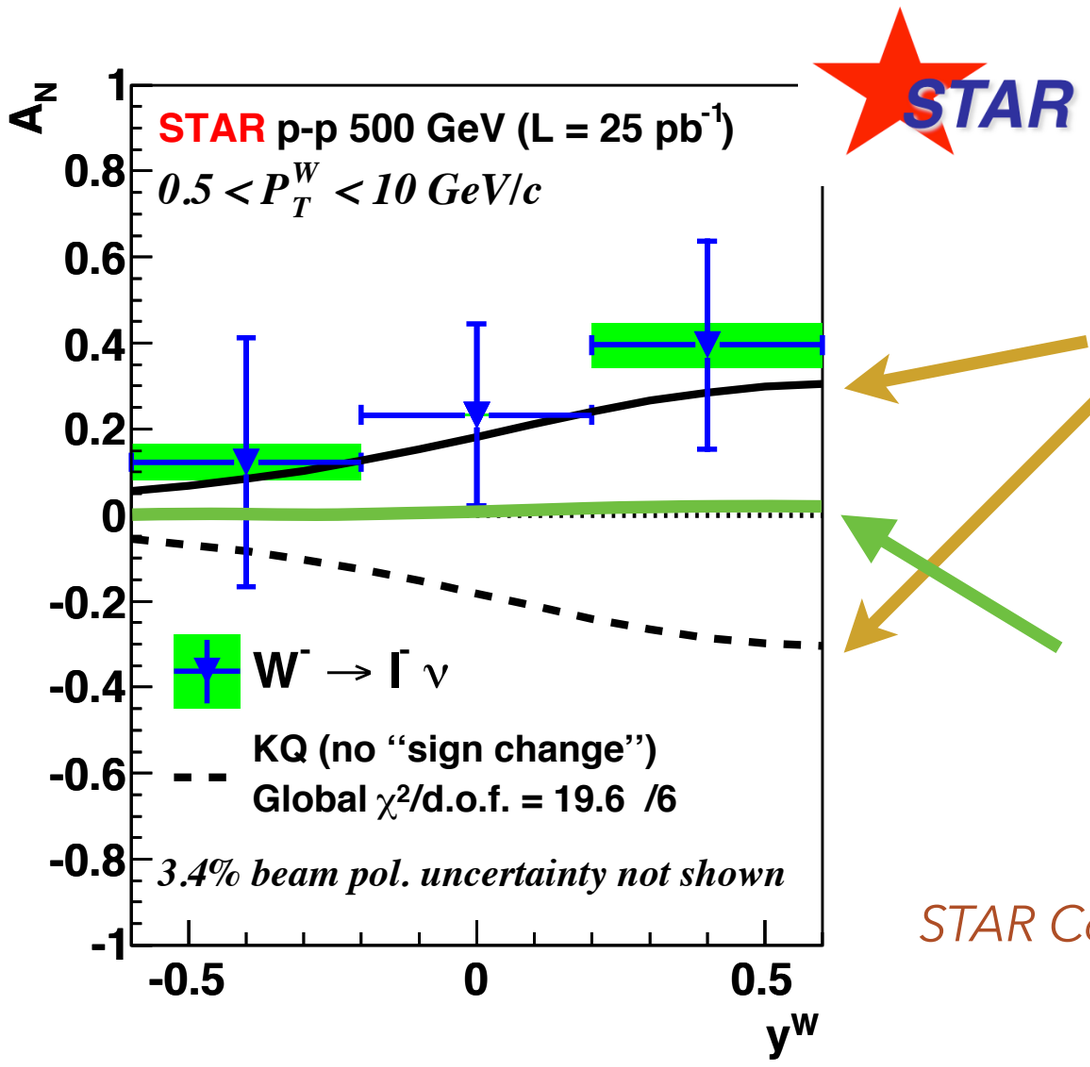

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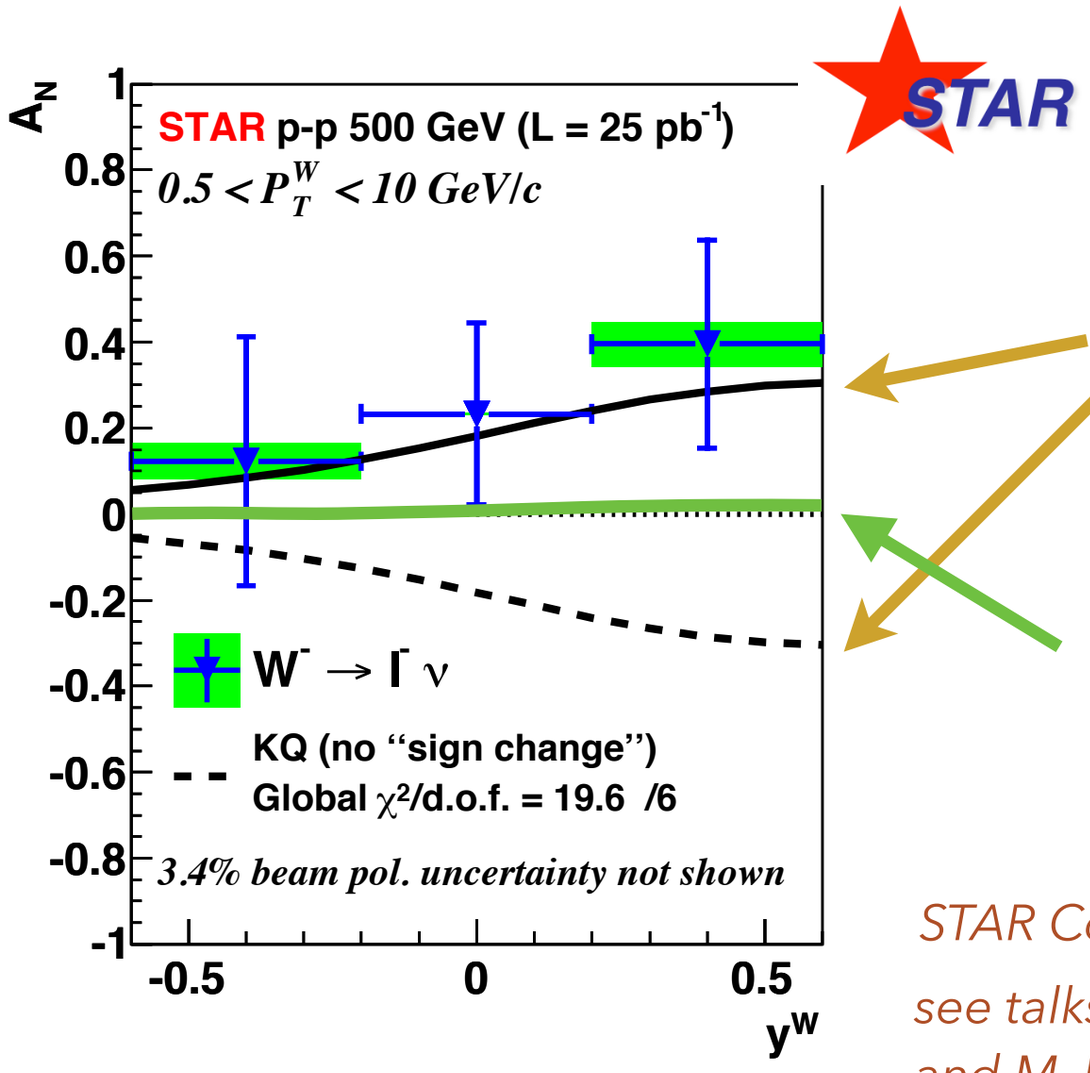

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see talksby J. Drachenberg, and M. Boer for PHENIX (Wednesday, WG6)

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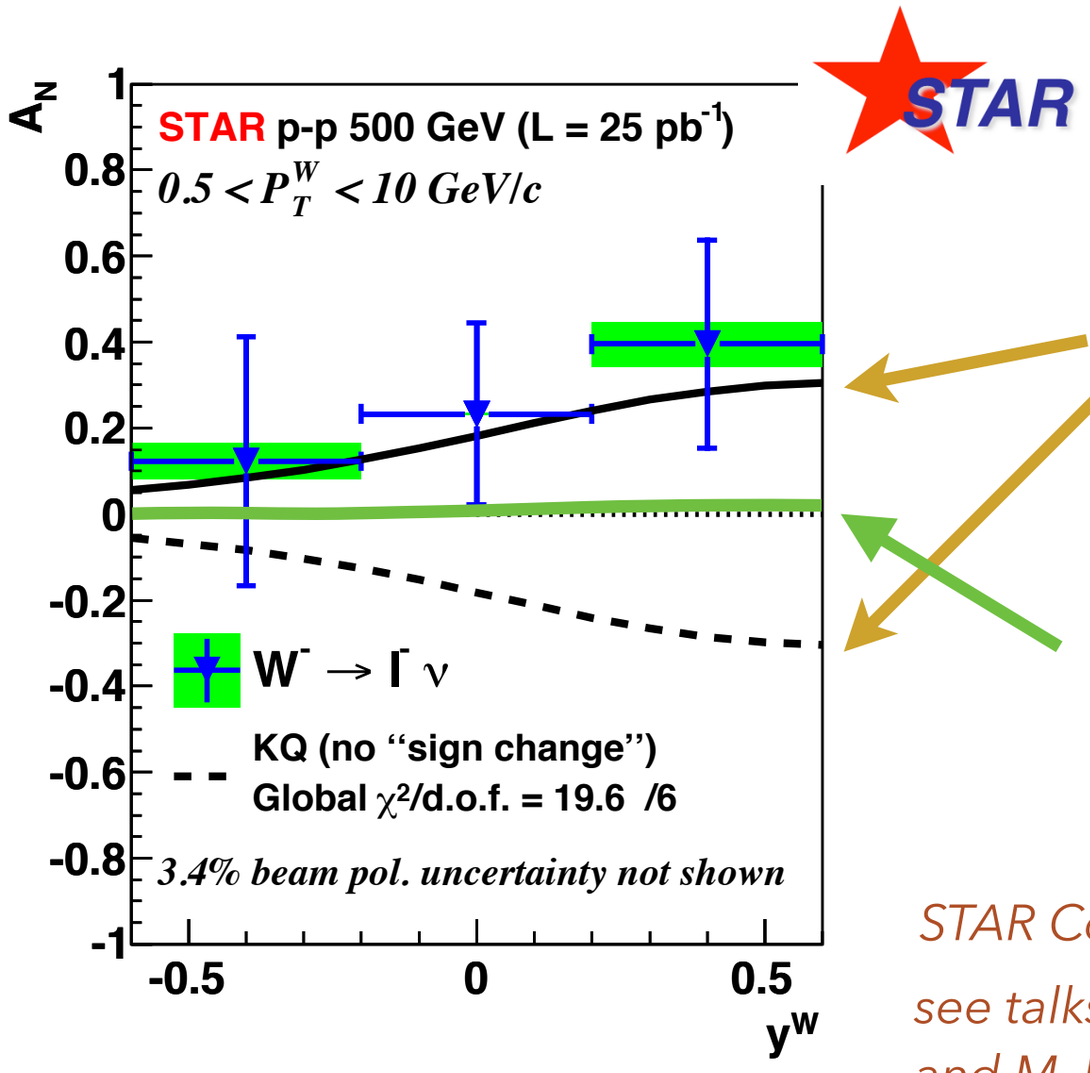

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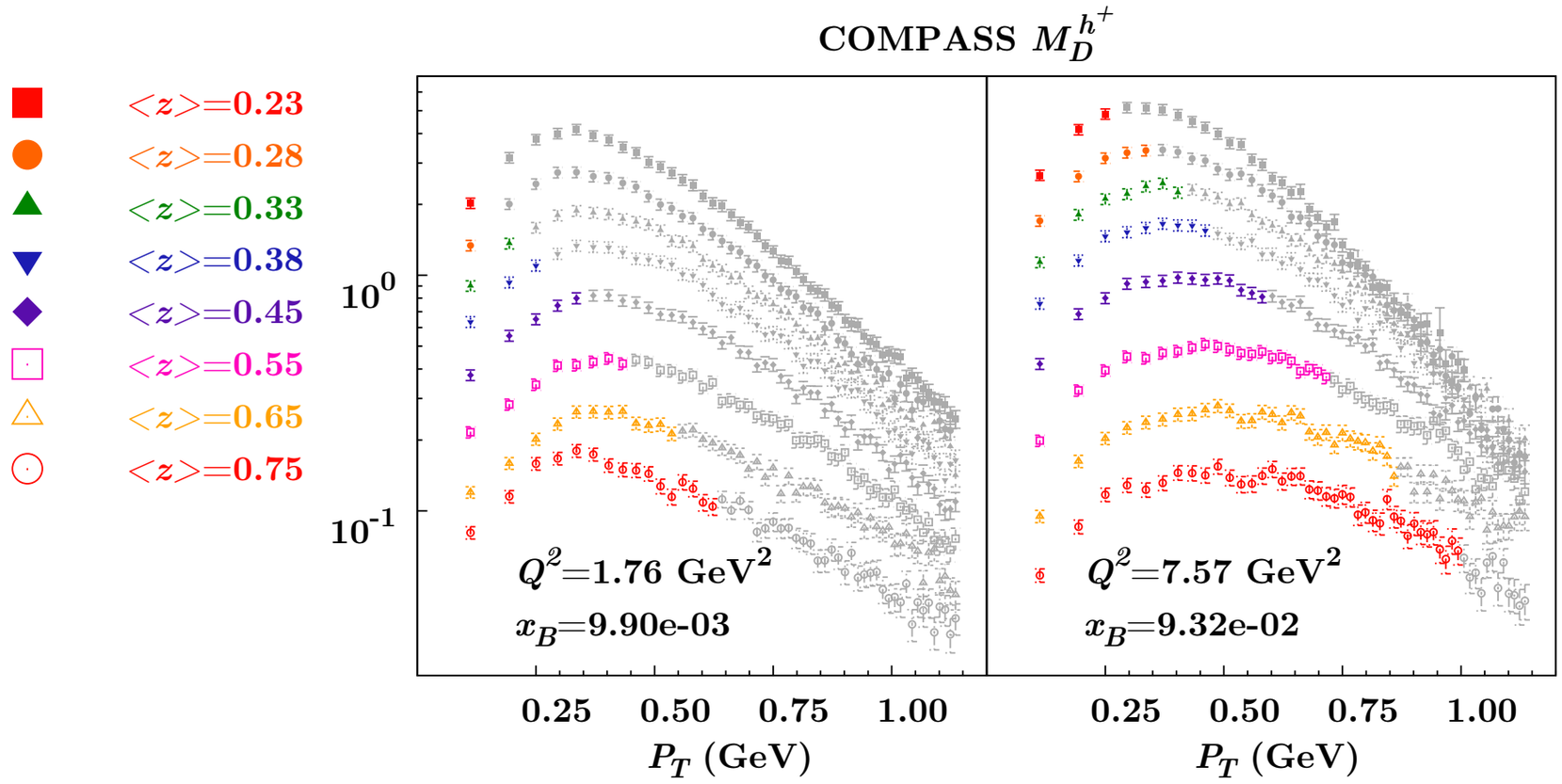
Can COMPASS give a similar evidence?

see talk by B. Parsamyan (Wednesday, WG6)

Limits of applicability of TMD factorization?

Boglione et al., arXiv: 1611.10329
Collins et al., arXiv: 1605.00671



see talk by L. Gamberg (Tuesday, WG 6)

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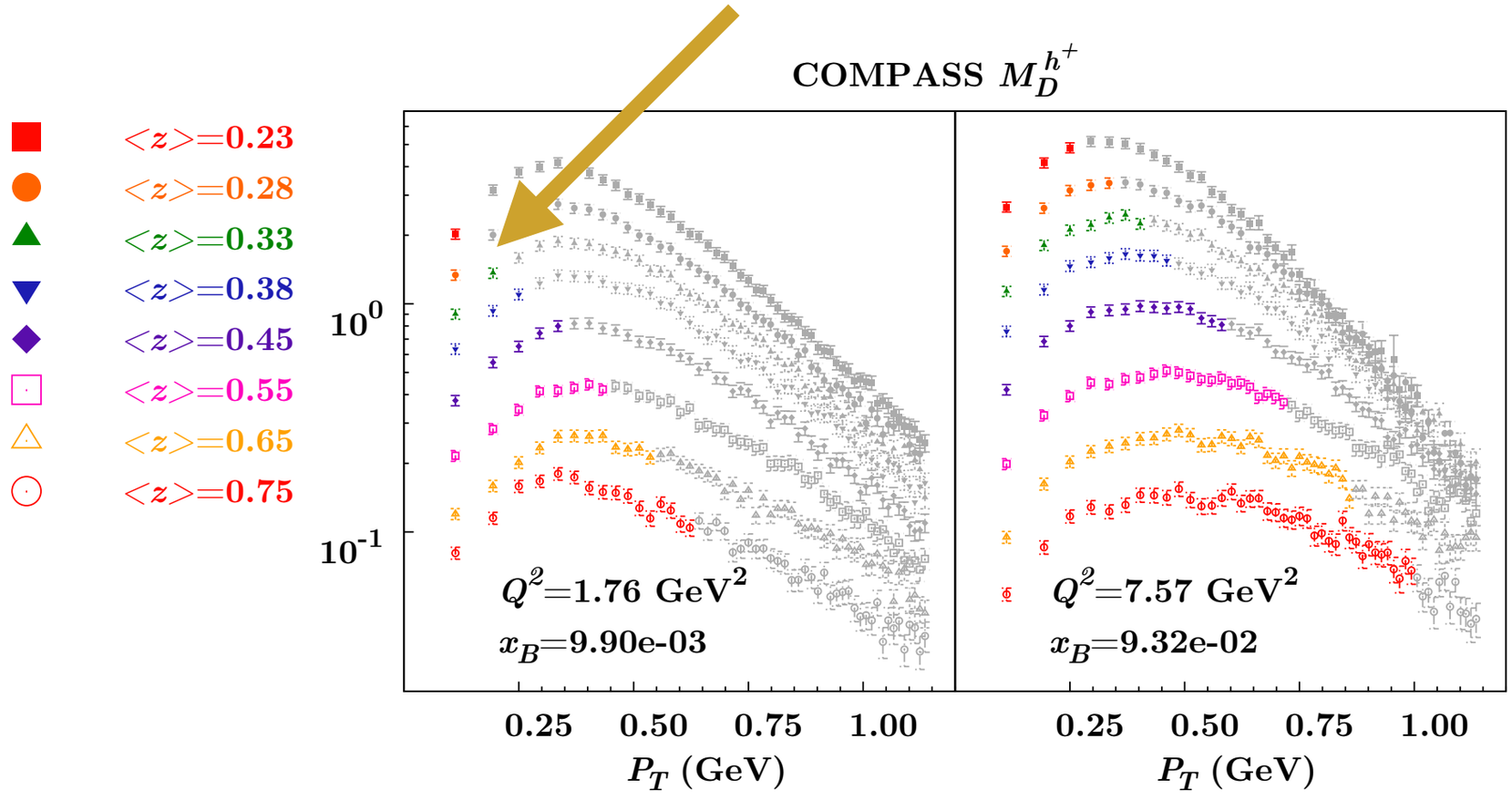
To avoid current fragmentation, when z is low and Q is low, P_{hT} must be very low…



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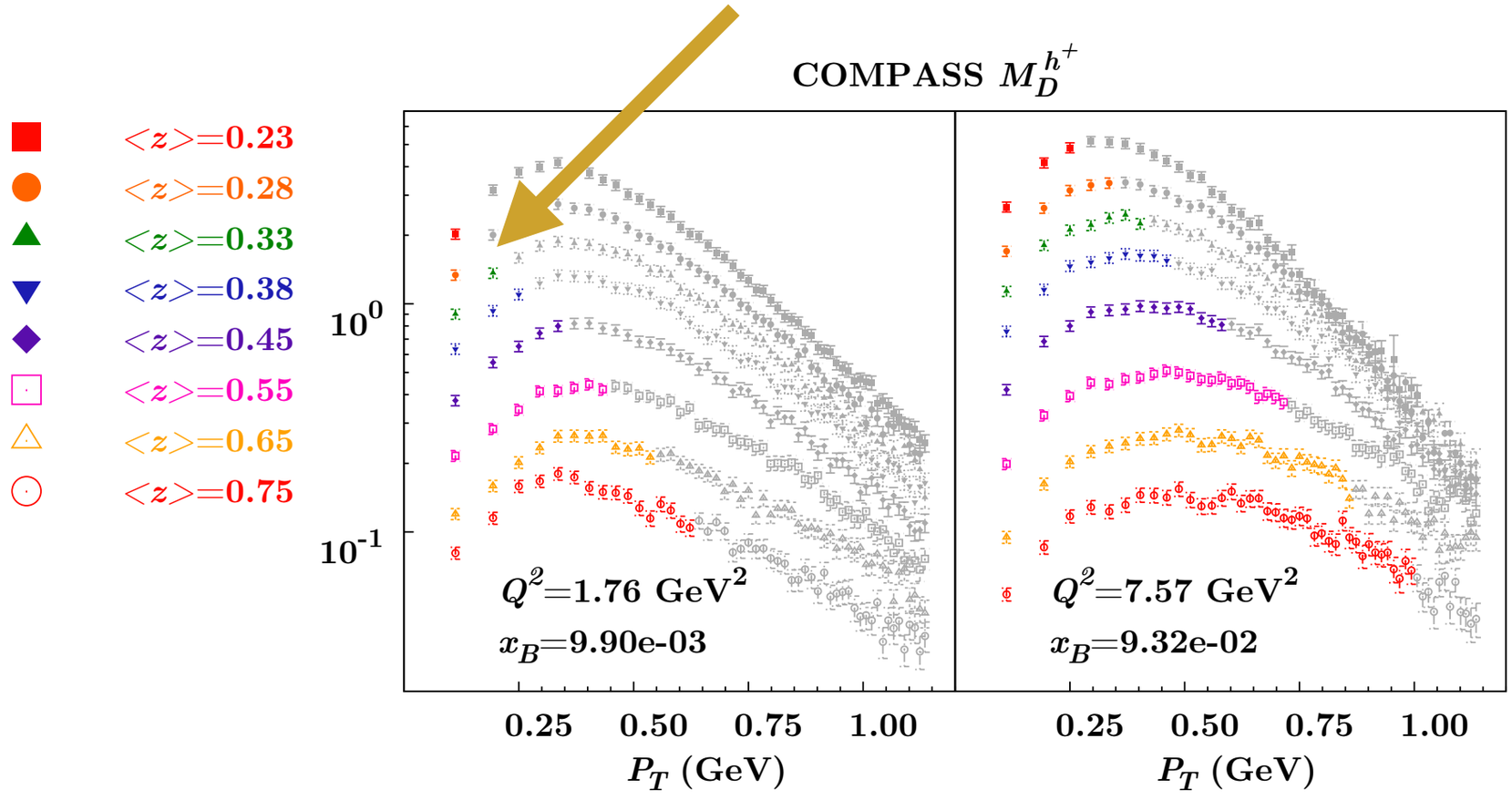
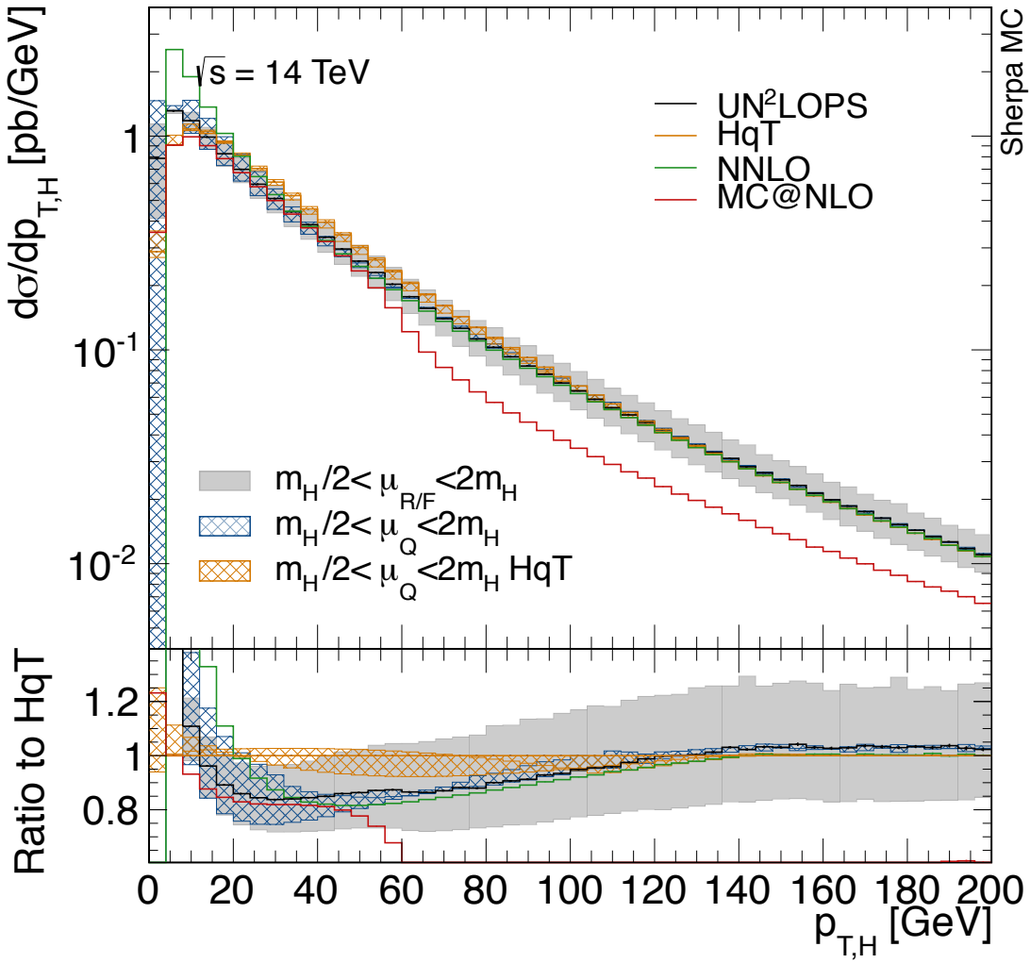


Imposing a strict cutoff to avoid target fragmentation severely reduces the data set (from 8000 to 500 data points)

see talk by L. Gamberg (Tuesday, WG 6)

TMD Monte Carlo tools

from S. Prestel's talk of this morning



PQCD evol^n dominant uncertainty in resummation/TMD region
Goal of Deductor/Dire/Vincia projects: More accurate & precise showers.

see talk by N. Sato (Thursday, WG6+WG7)

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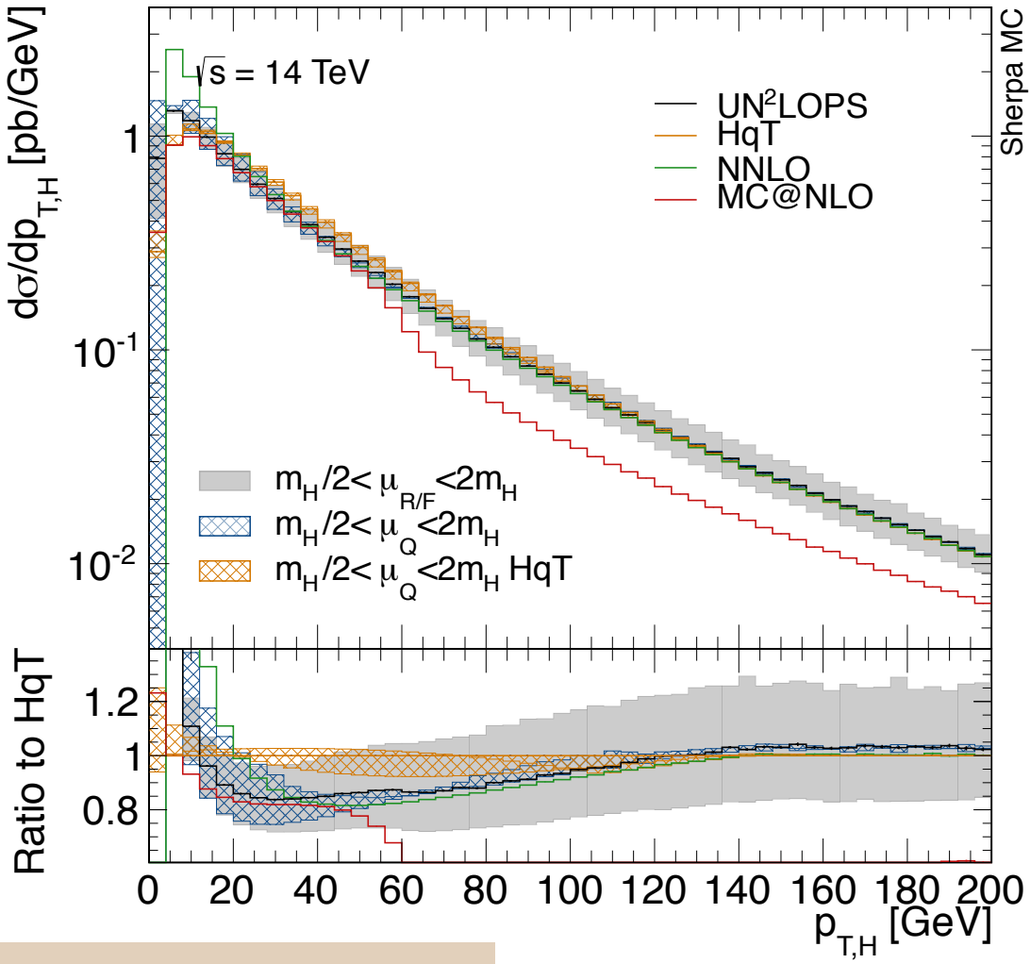

TMD formalism

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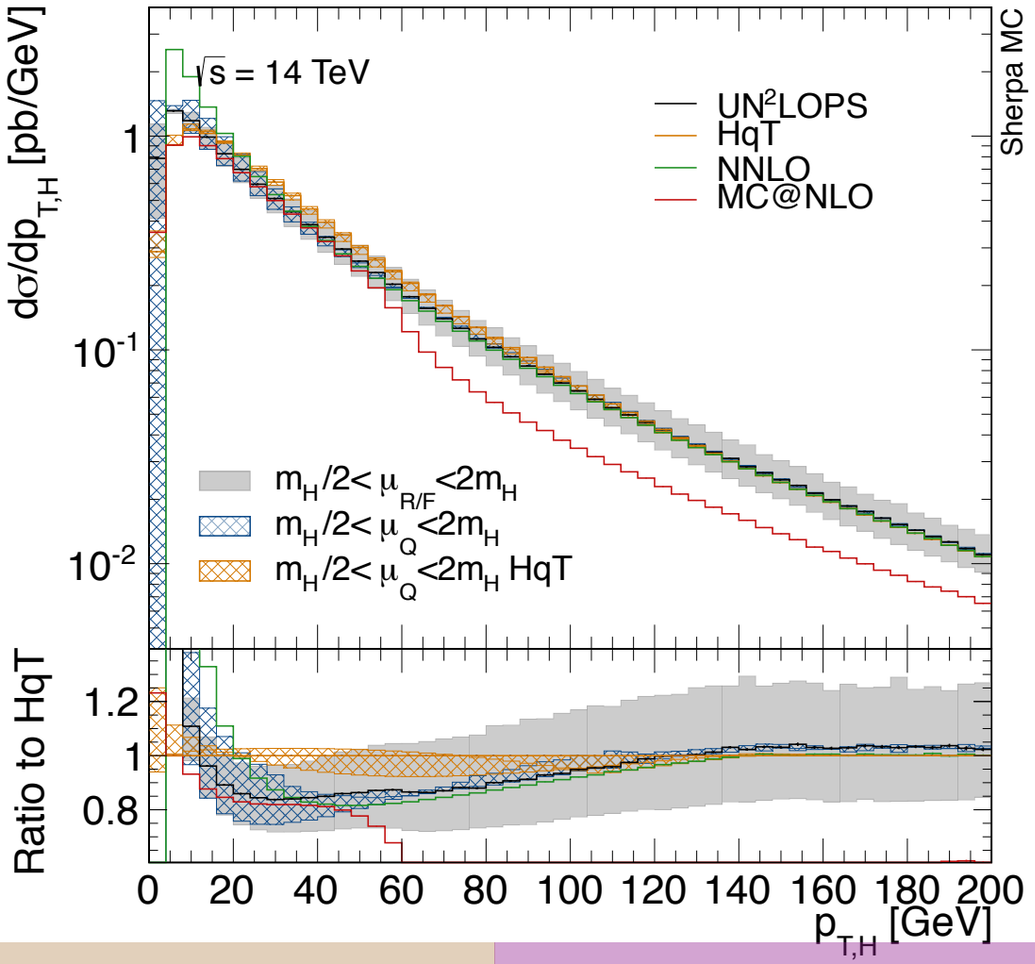

TMD formalism | collinear formalism

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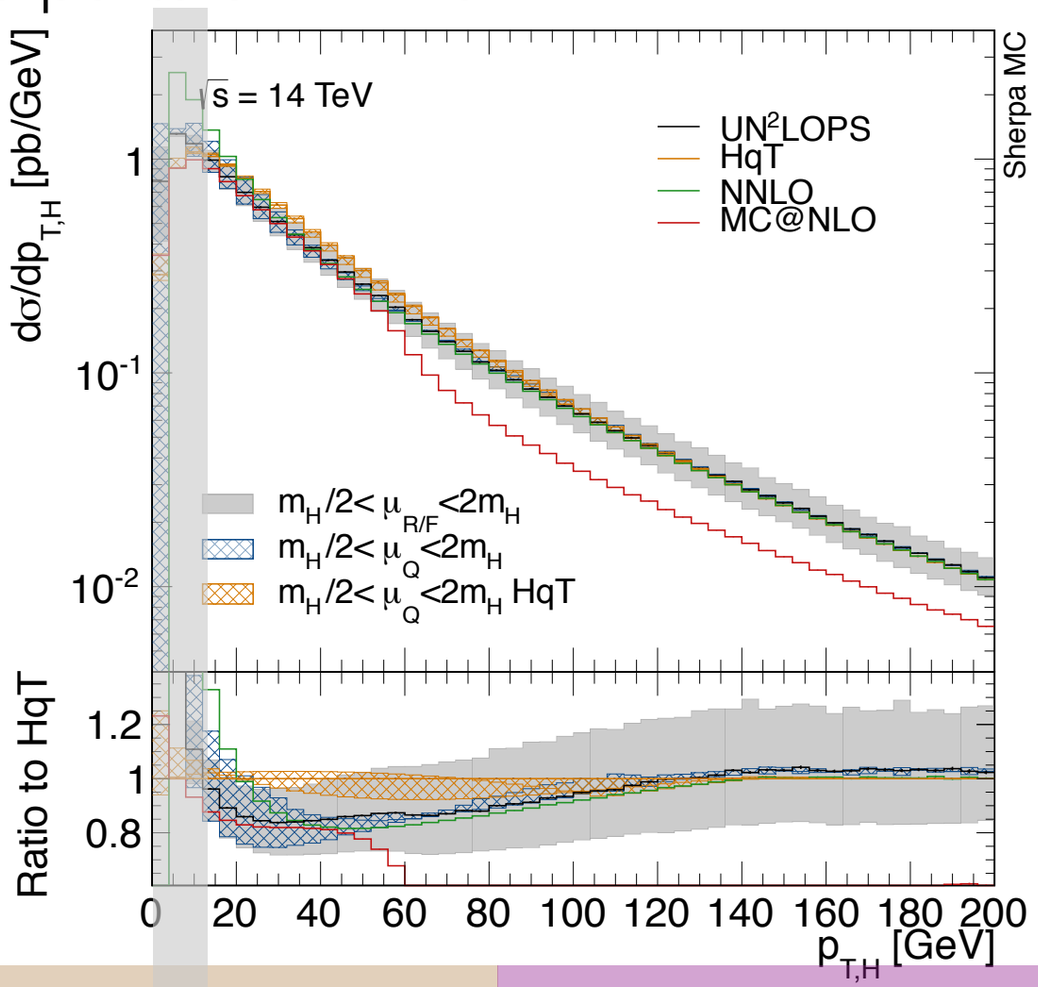
Nonperturbative parts of TMDs



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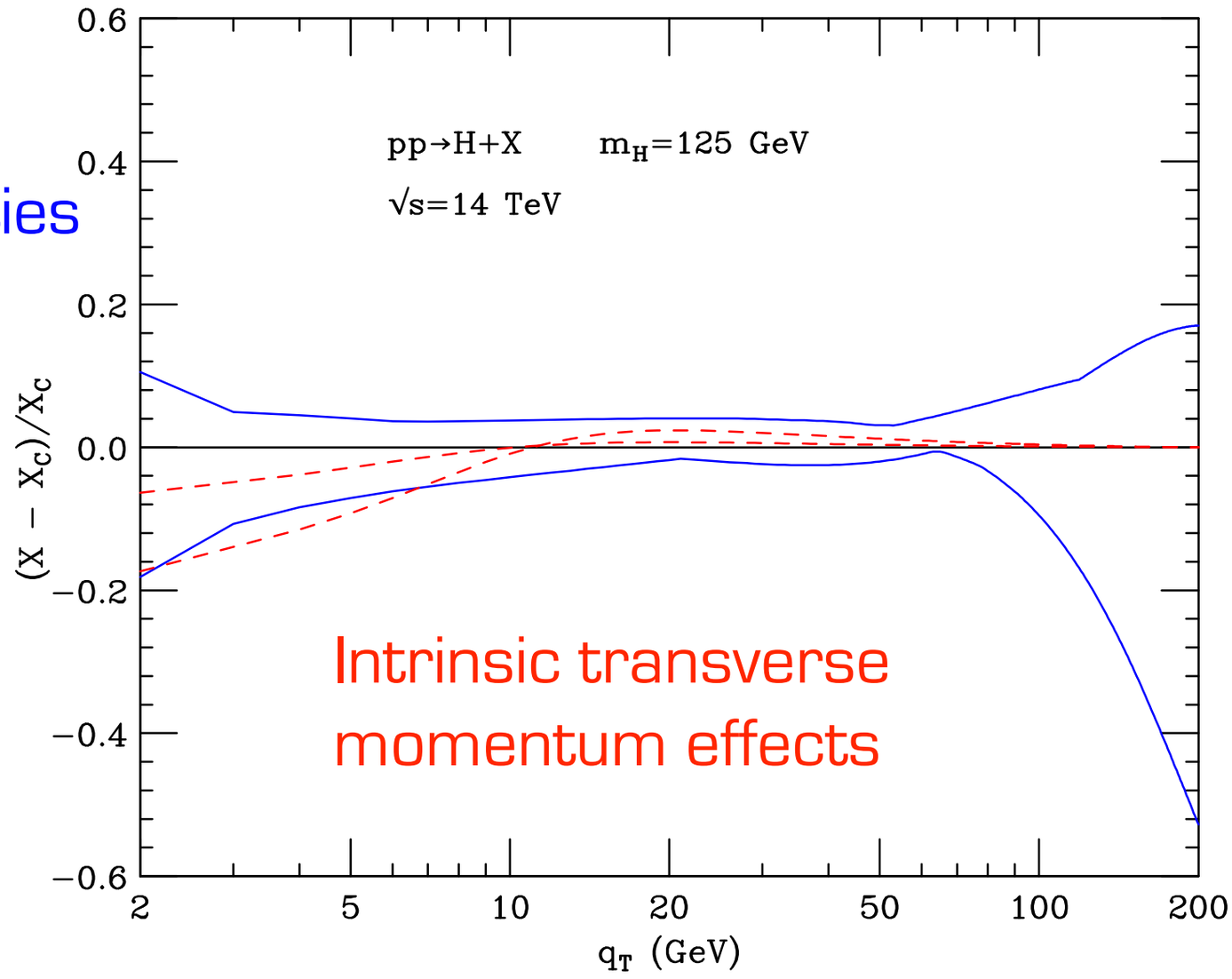
Higgs transverse momentum

PDF uncertainties



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

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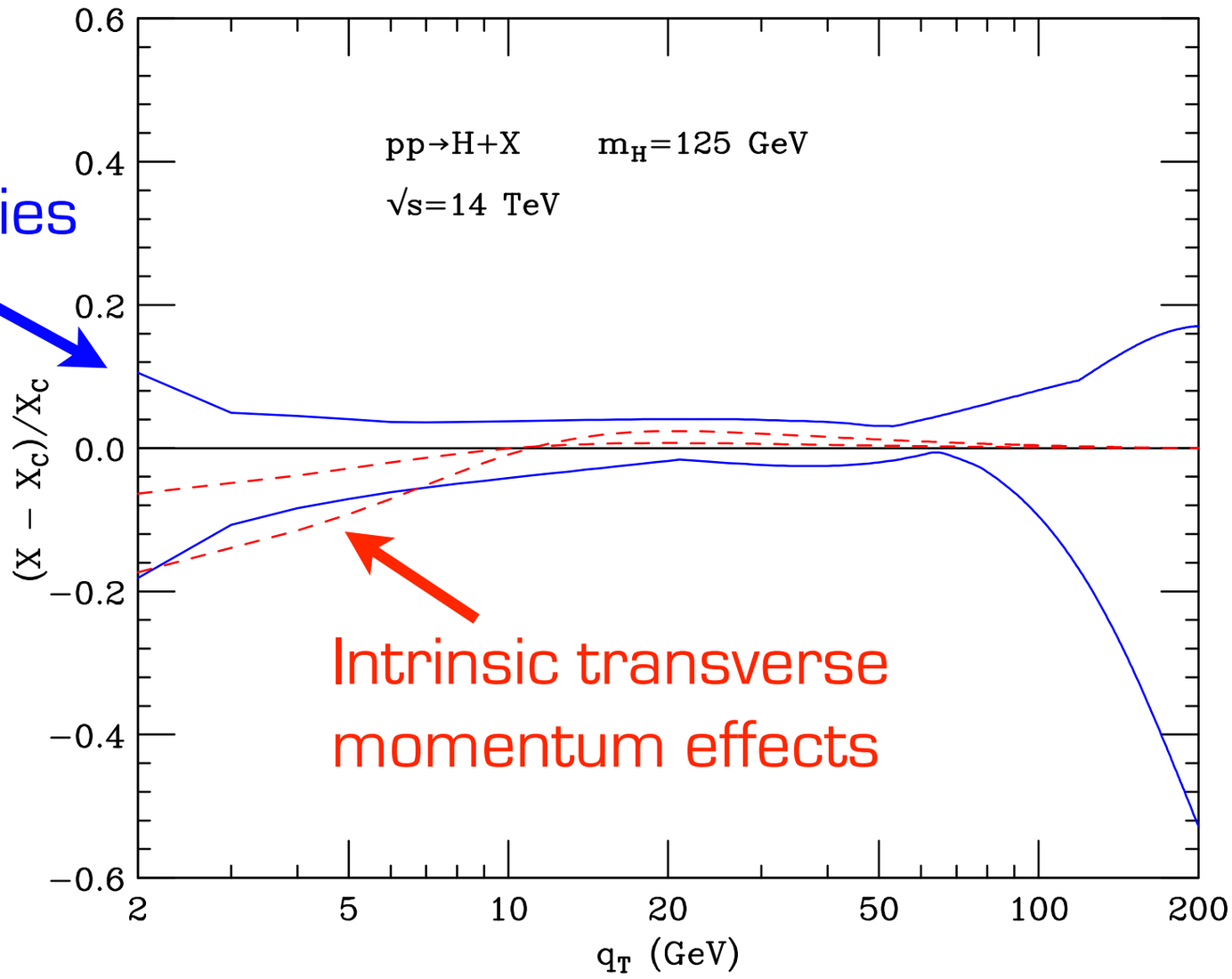

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Impact on high-energy physics

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

see talks by I. Bertram, F. Balli (Thursday, WG4)

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
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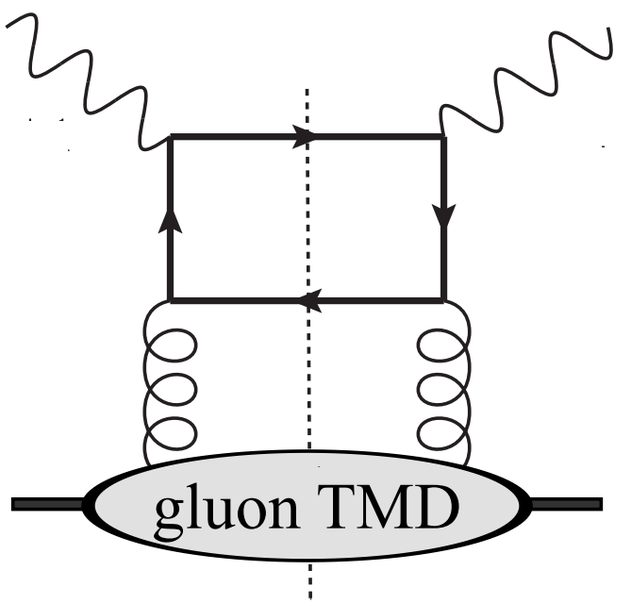
Pythia tune containing also intrinsic transverse momentum of partons

ATLAS Collab. arXiv:1701.07240

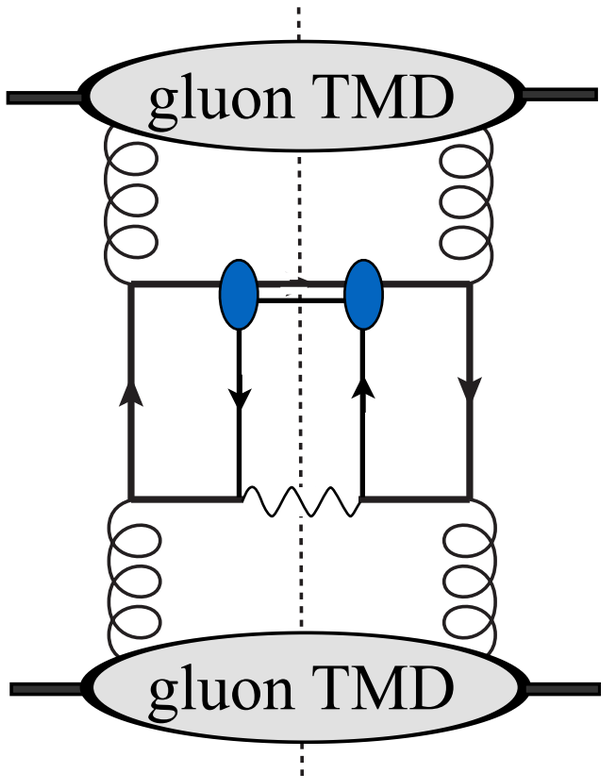
see talks by I. Bertram, F. Balli (Thursday, WG4)

Gluon TMDs

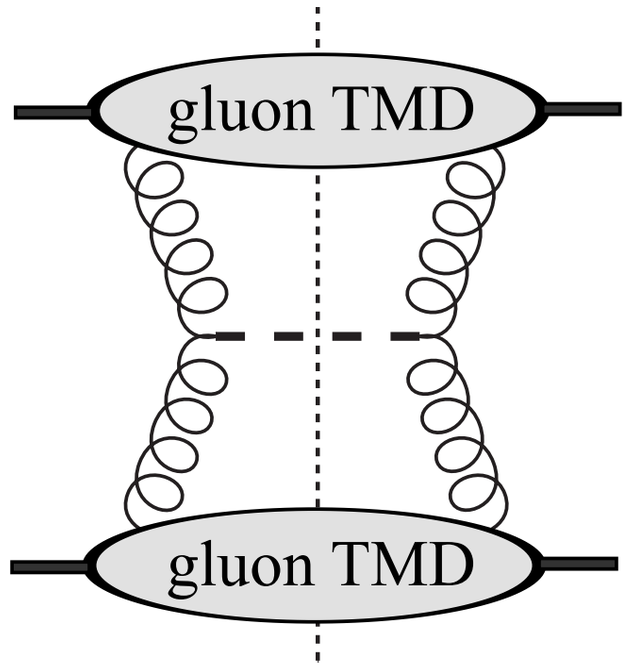
$e\,p \to e$ jet jet X



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



$p\,p \to \eta_c\,X$



see, e.g., Boer, den Dunnen, Pisano, Schlegel, Vogelsang, PRL108 (12)
den Dunnen, Lansberg, Pisano, Schlegel, PRL 112 (14)

see talks by J.-P. Lansberg (Tuesday, WG7, Wednesday, WG5)
T. Van Daal (Thursday, WG6+WG7)

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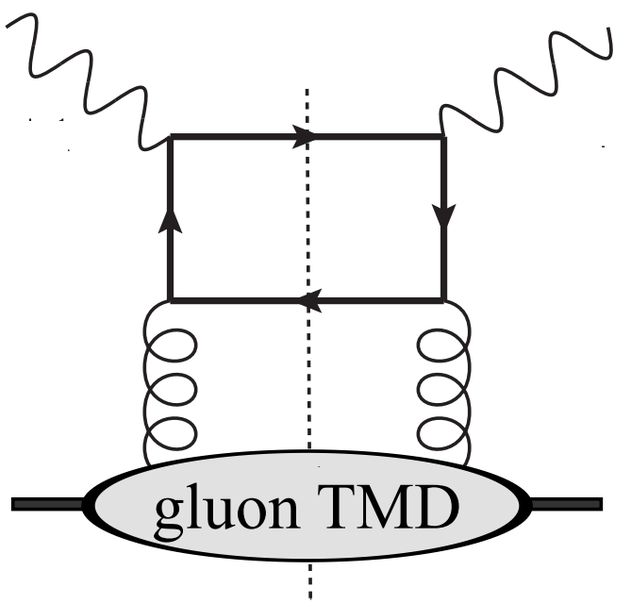

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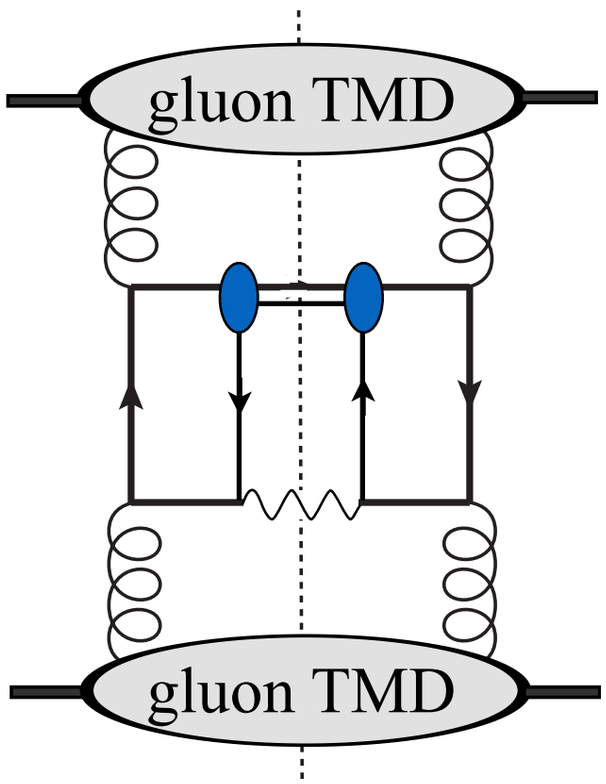

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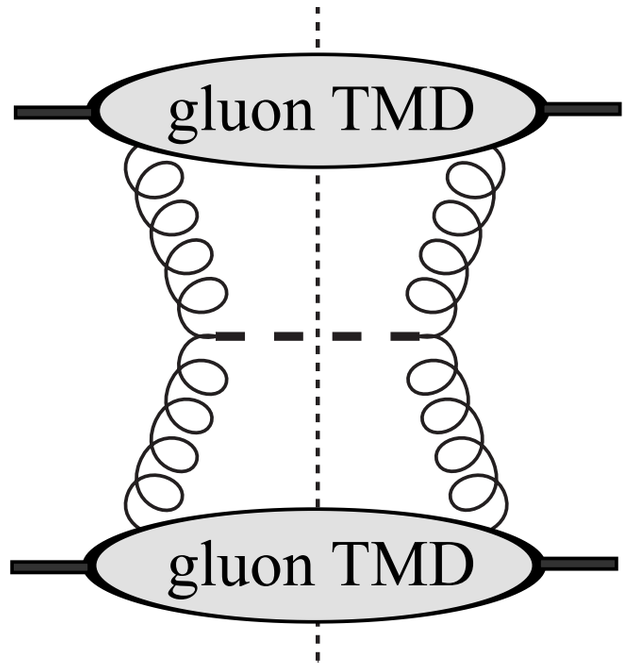

Only explorations so far

.., Boer, den Dunnen, Pisano, Schlegel, Vogelsang, PRL108 (12)
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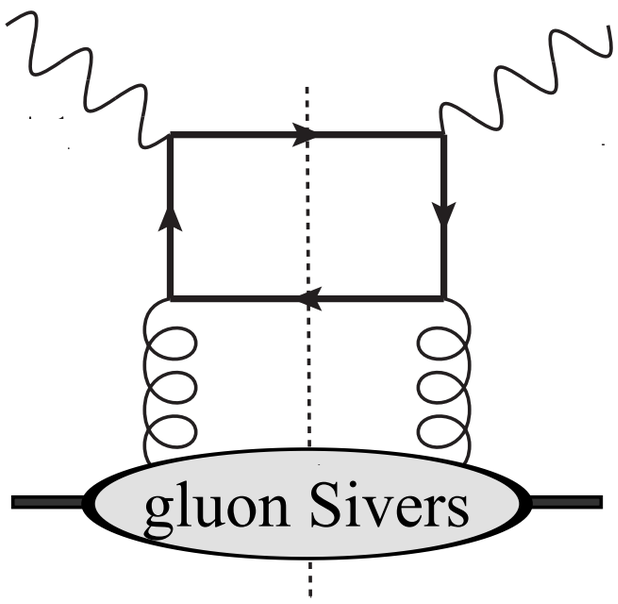
$$e\,p \to e\,h\,h\,X$$



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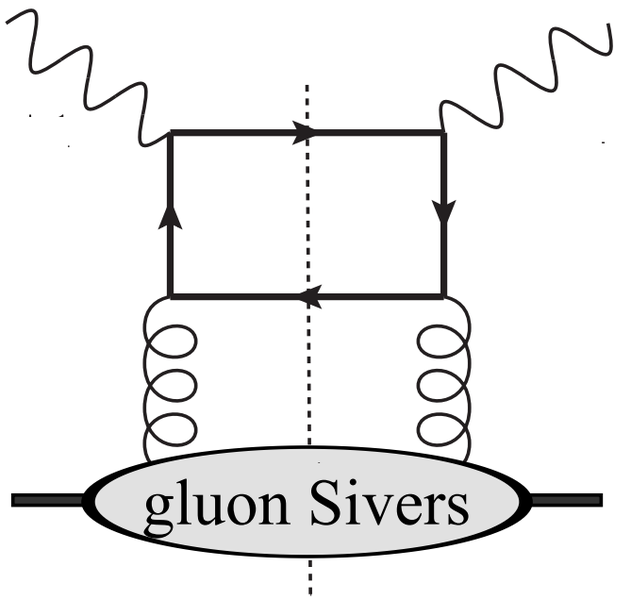
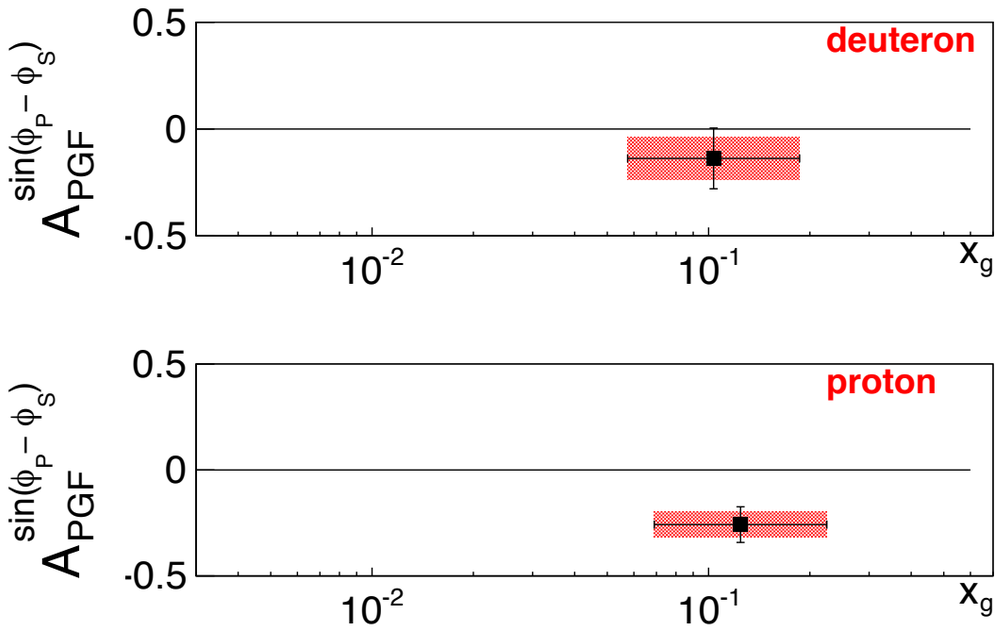


COMPASS, 1701.02453



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

Gluon TMDs

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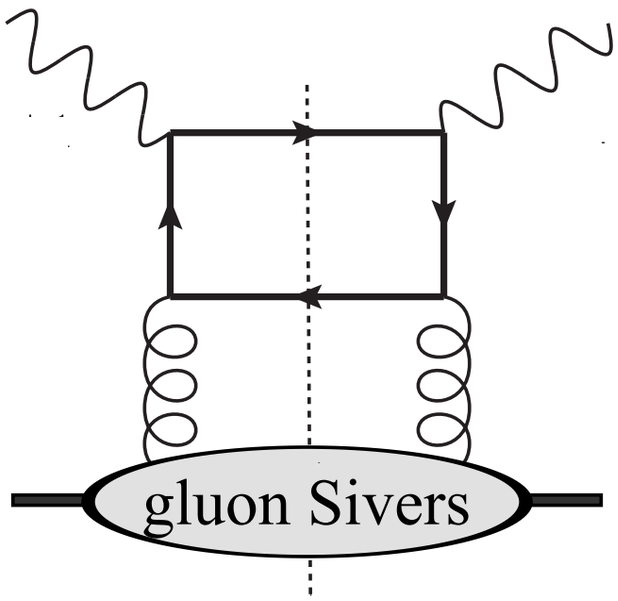

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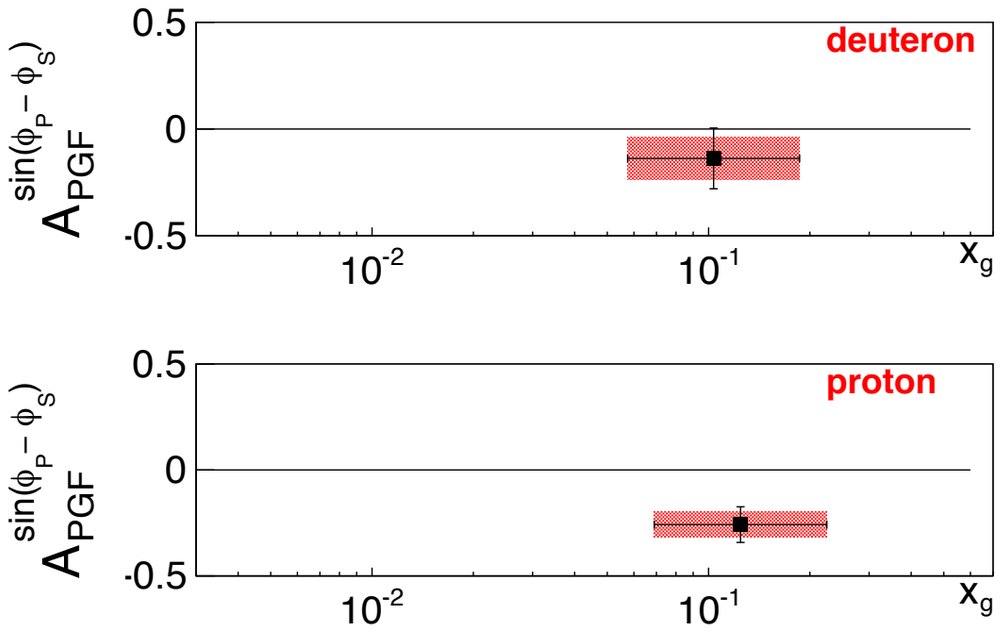

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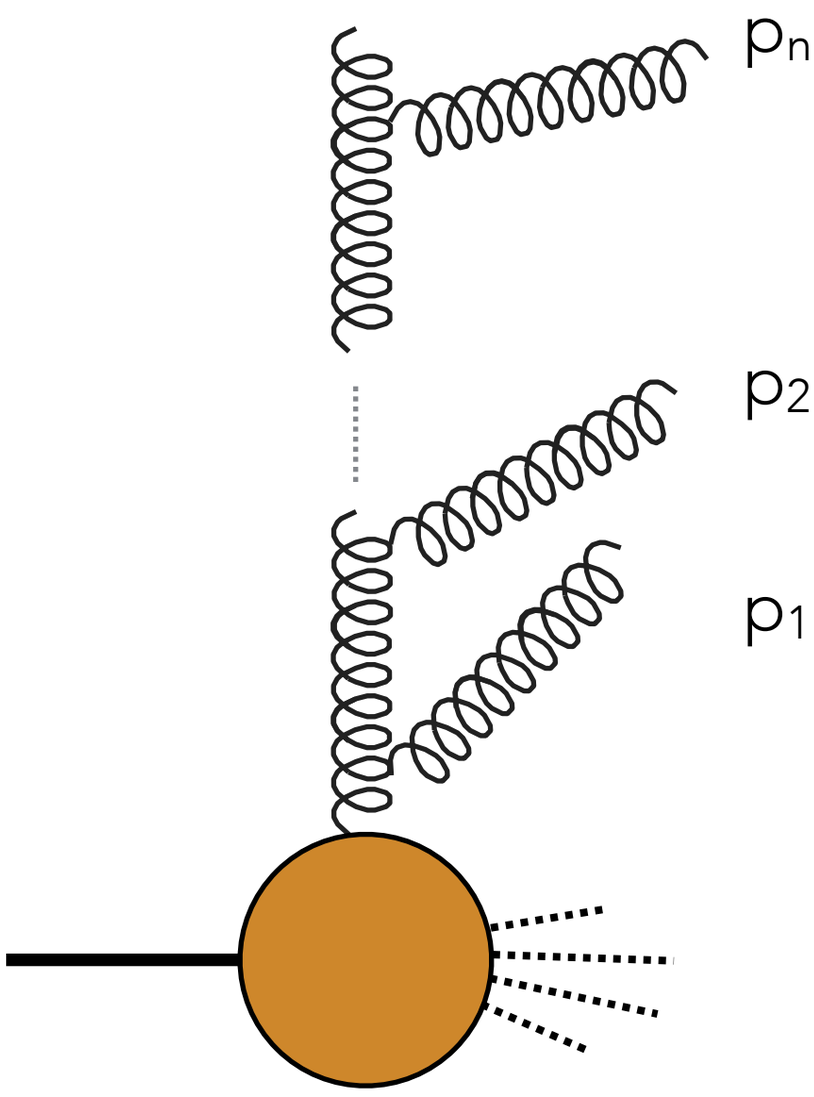
see talk A. Szabelsky (Wednesday, WG6)

Gluon TMDs at low x



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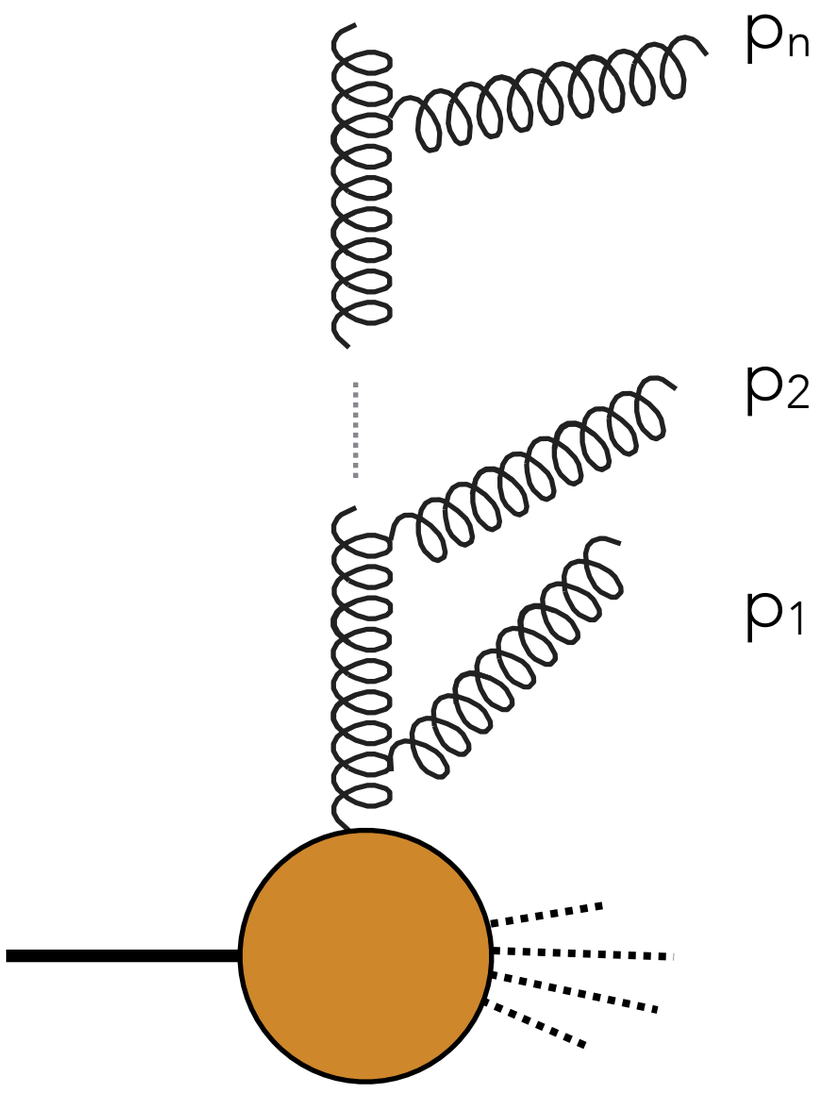
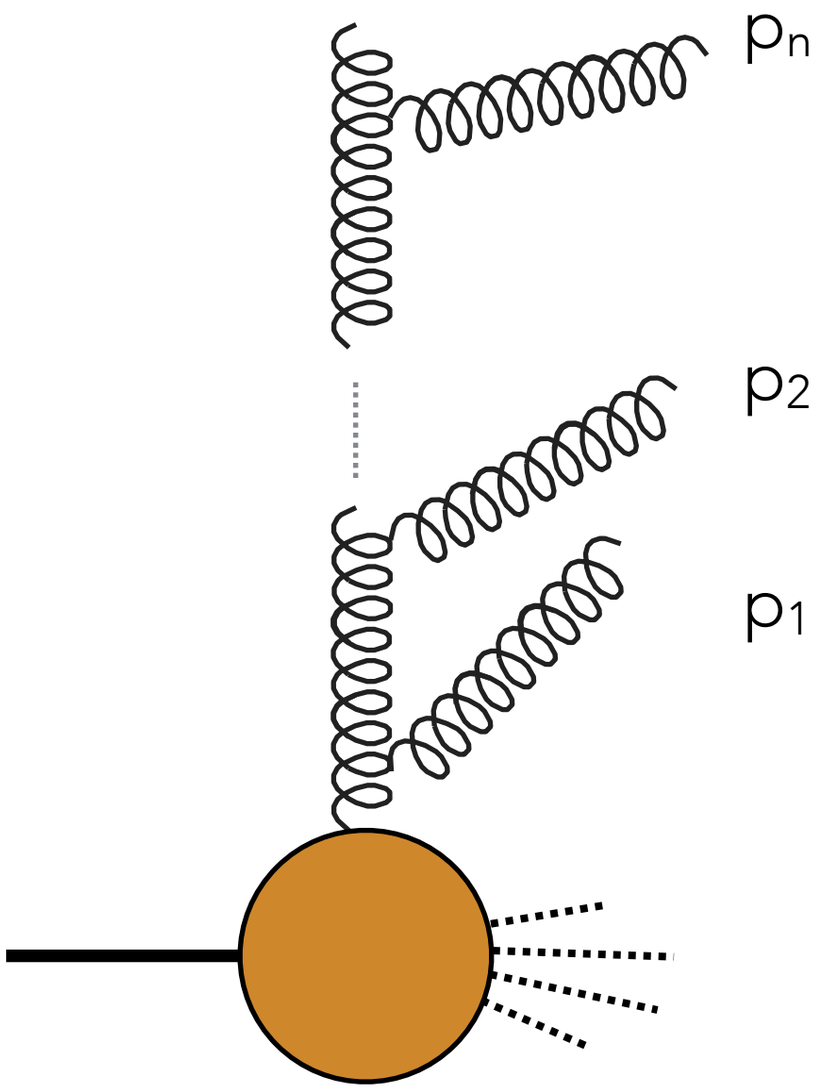


Based on CCFM formalism, which should be valid at low x for gluons only (different logarithms are resummed)

Often referred to as “unintegrated PDFs” and “k_T factorization”

Gluon TMDs at low x



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Implies differences also in the integrated observables

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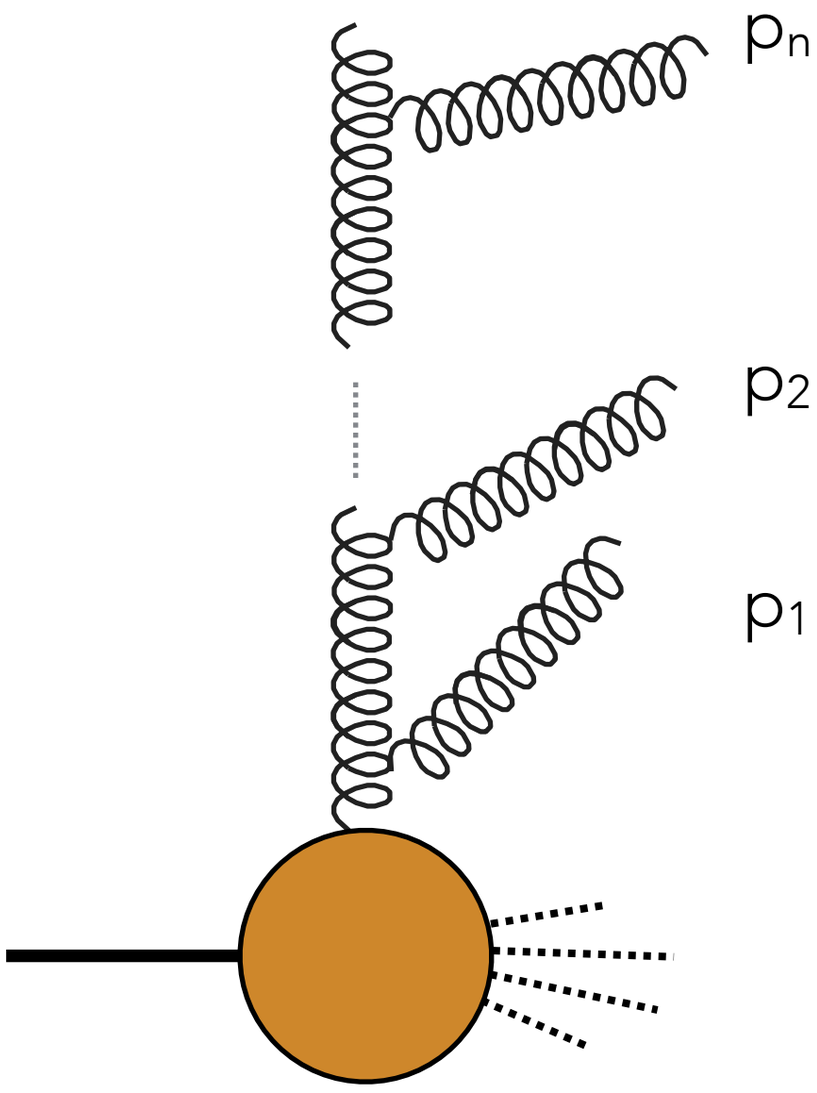

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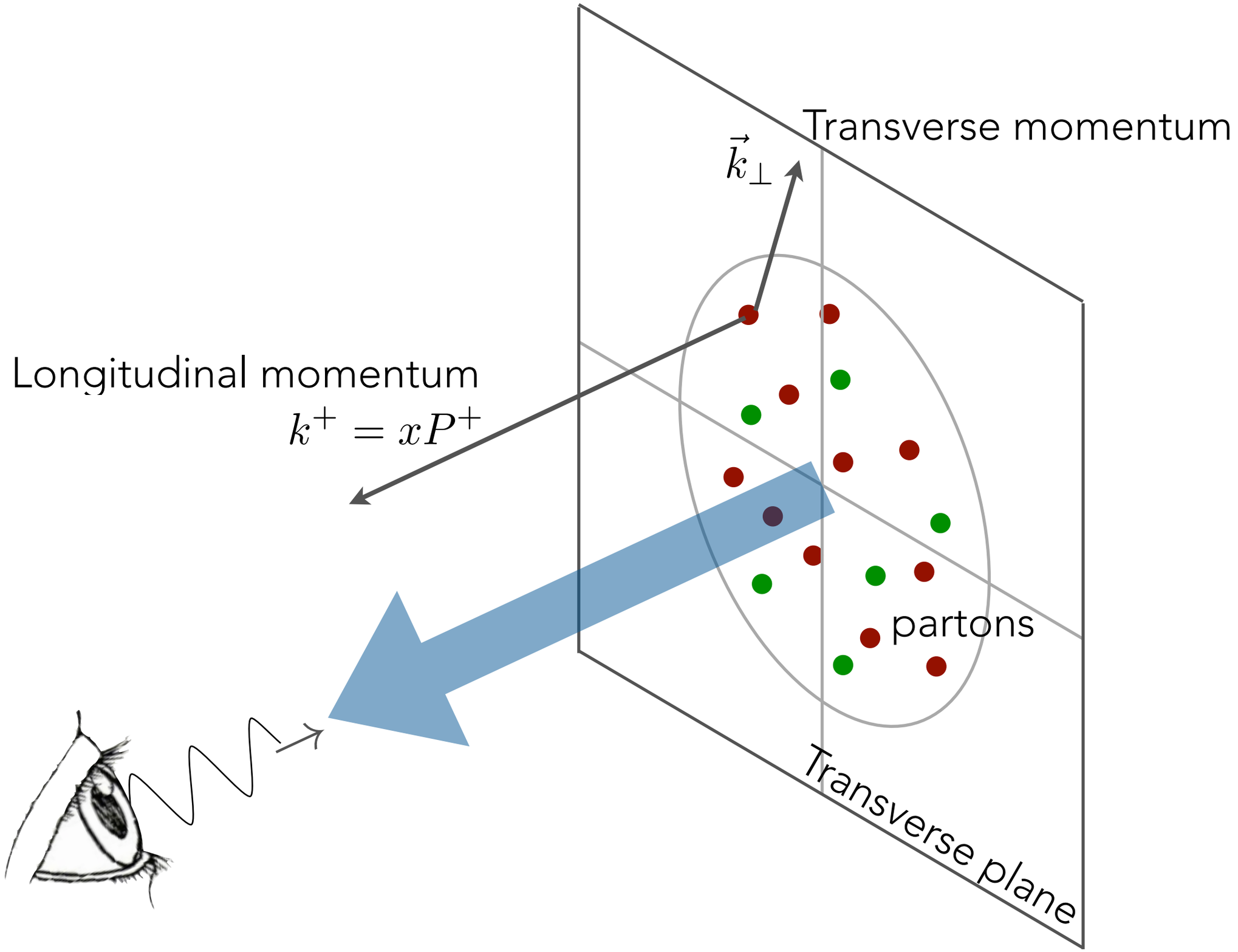
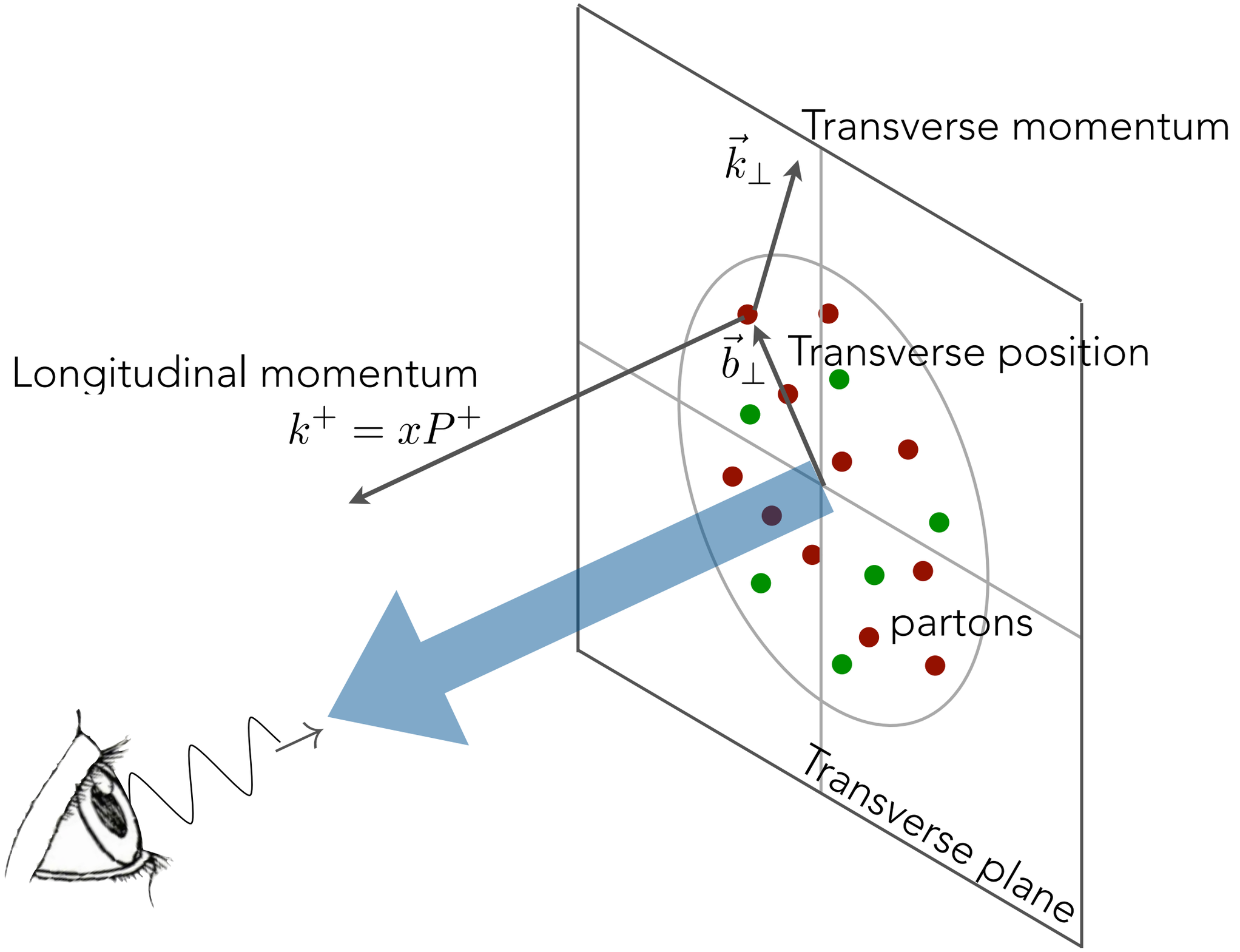
see talks by K. Kutak (Tuesday, WG4),
M. Serino (Wednesday, WG2),
J. Zhou (Wednesday, WG6)
I. Balitsky, E. Petreska, R. Zlebcik, A. Kusina (Thursday, WG2)

Even higher dimensions?


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


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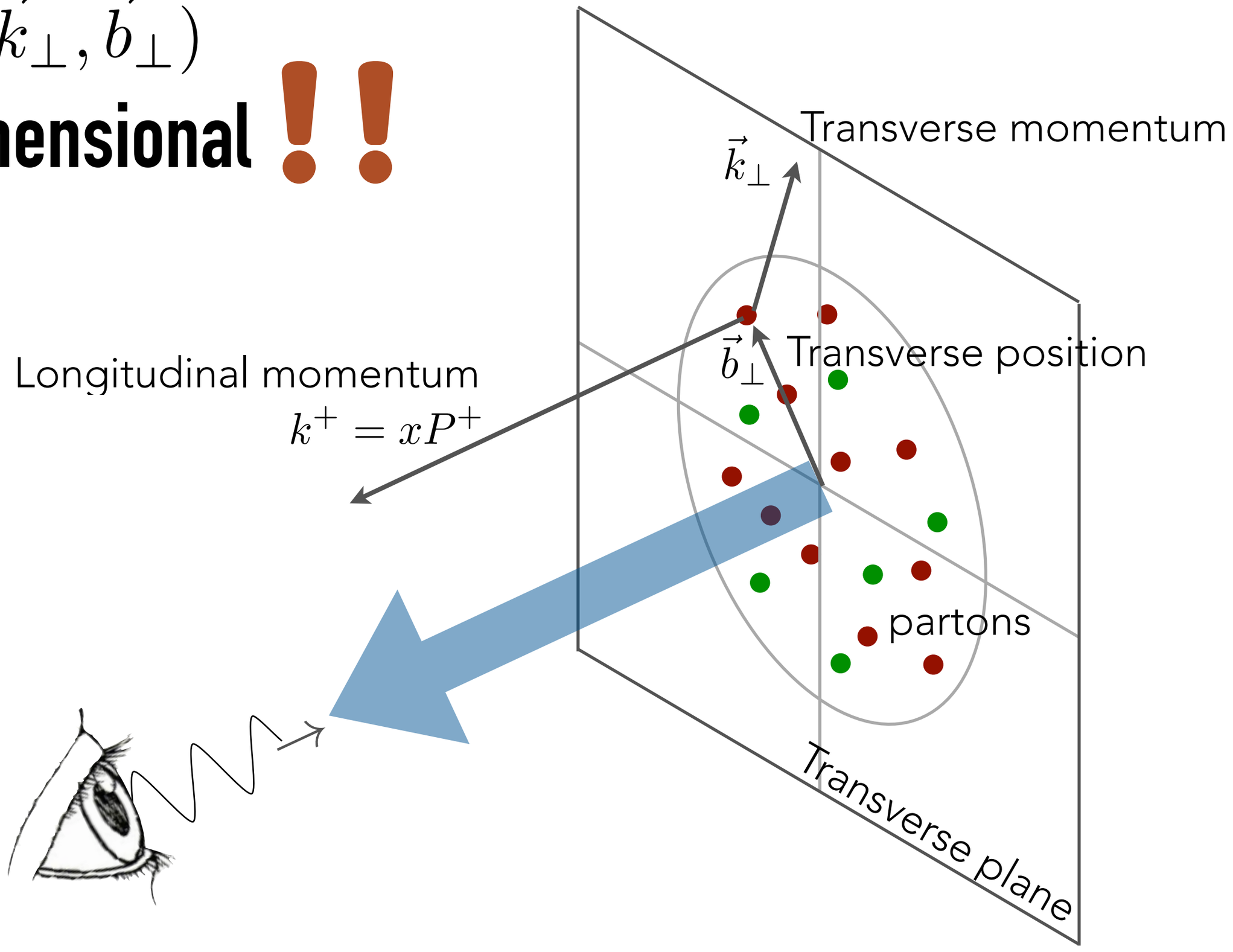
Wigner distributions

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

5 dimensional !!



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

PDFs

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PDFs

Parton distribution functions (x)

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PDFs

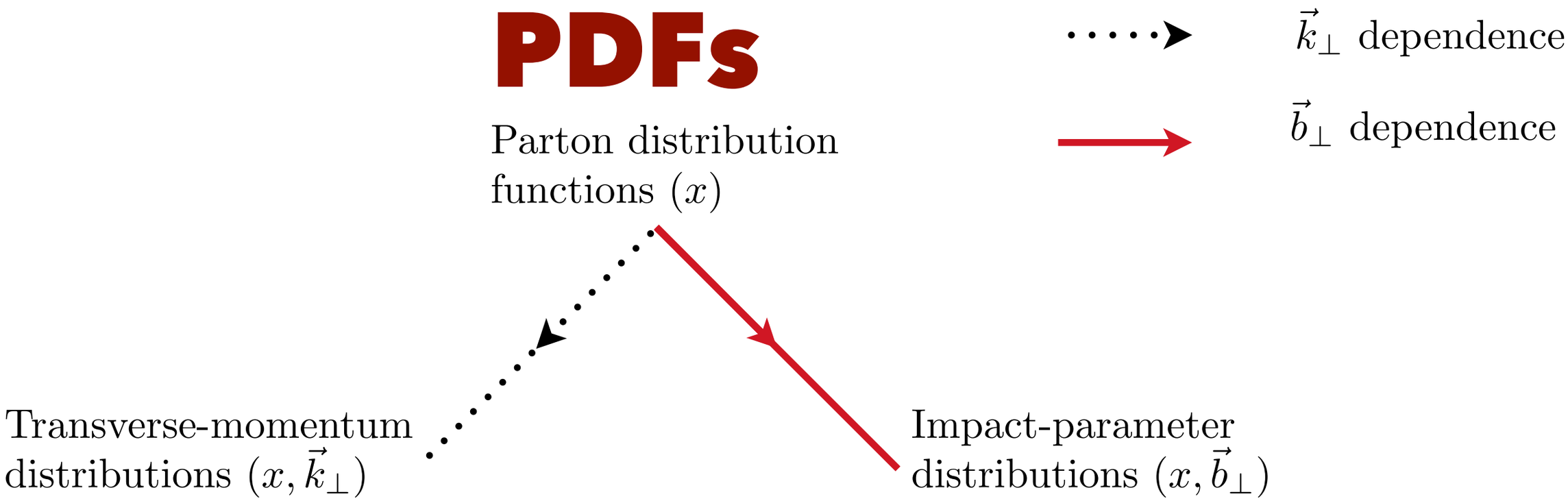
Parton distribution functions (x)

$\vec{k}_\perp$ dependence

Transverse-momentum distributions $(x, \vec{k}_\perp)$

TMDs

PDFs


$\vec{k}_\perp$ dependence
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Impact-parameter distributions $(x, \vec{b}_\perp)$

TMDs

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Generalized parton distributions $(x, \xi = 0, \vec{\Delta}_T)$

GPDs

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

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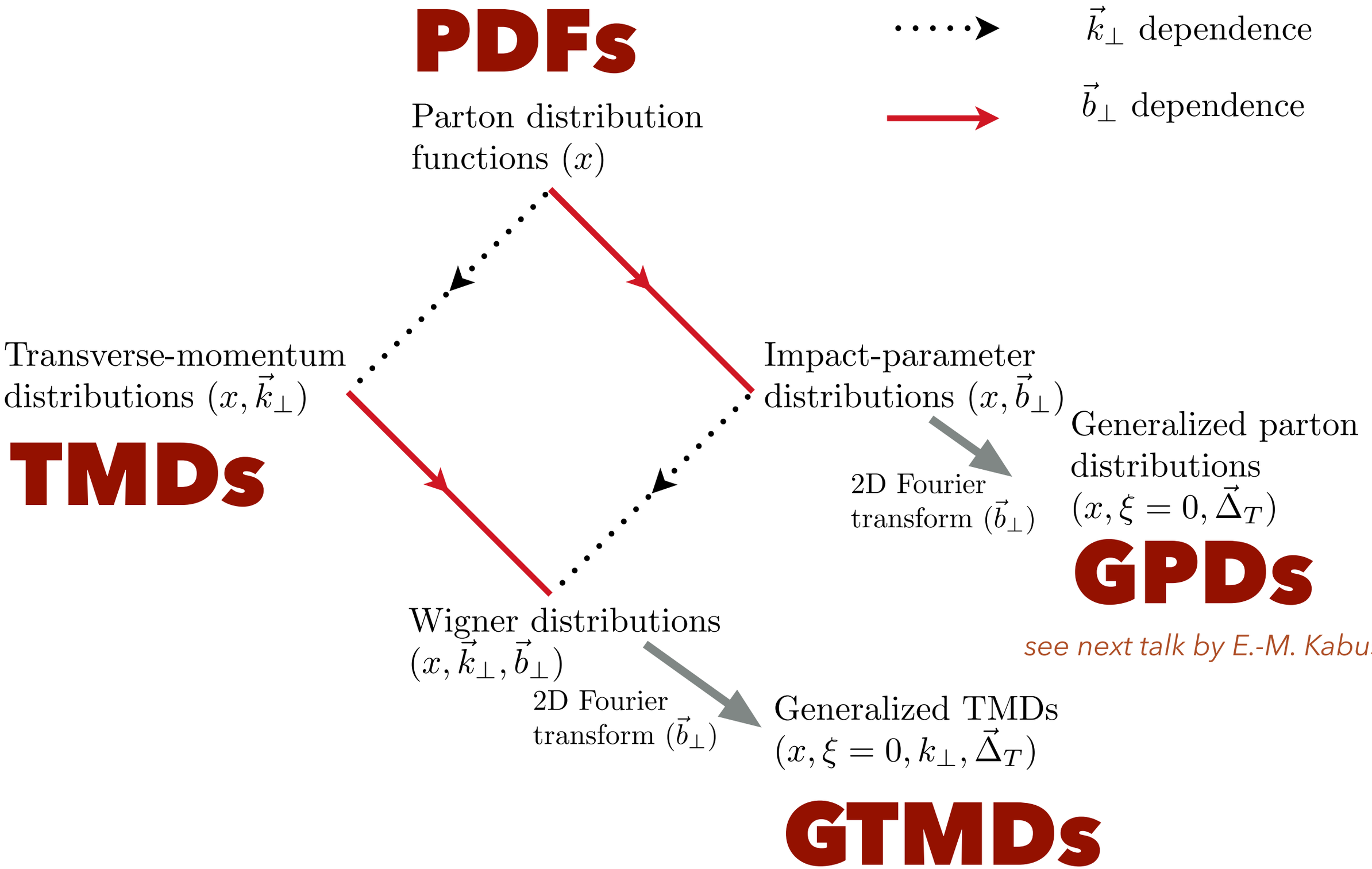

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see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (

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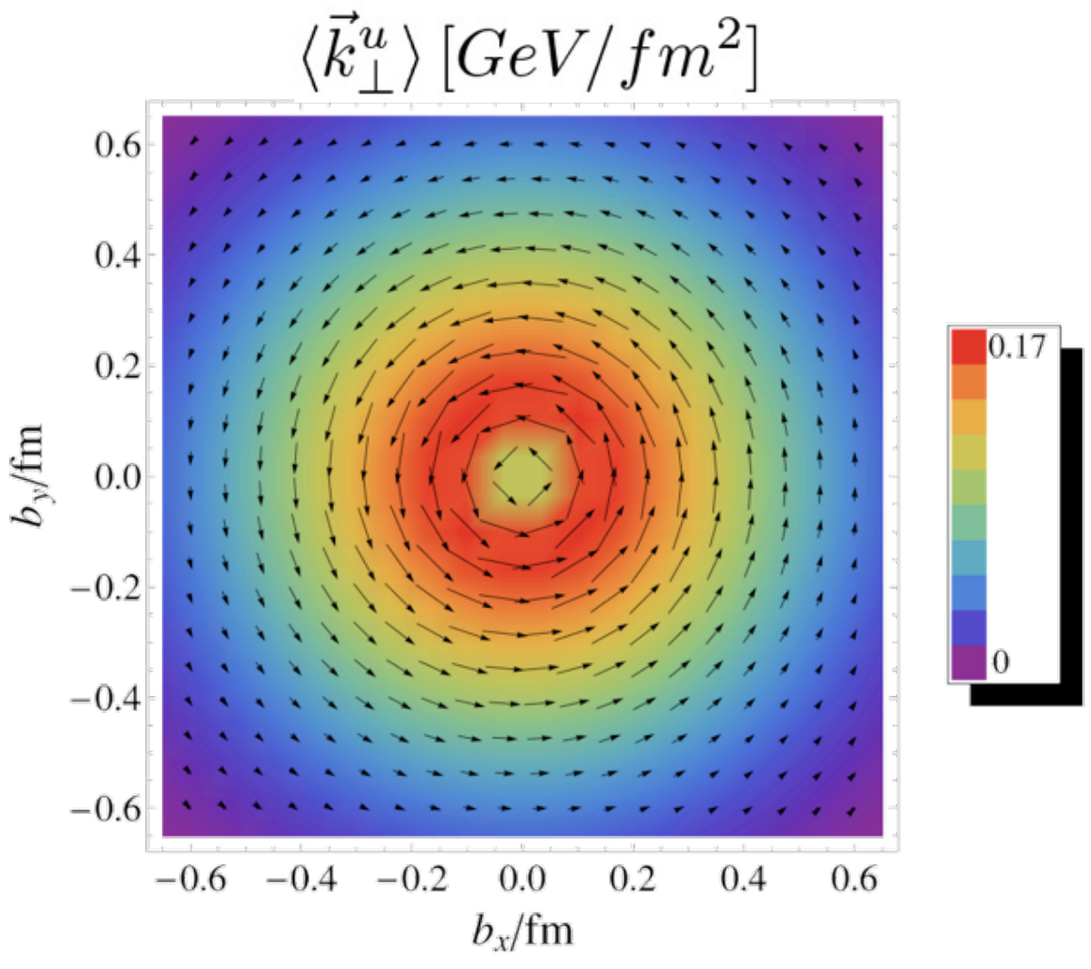
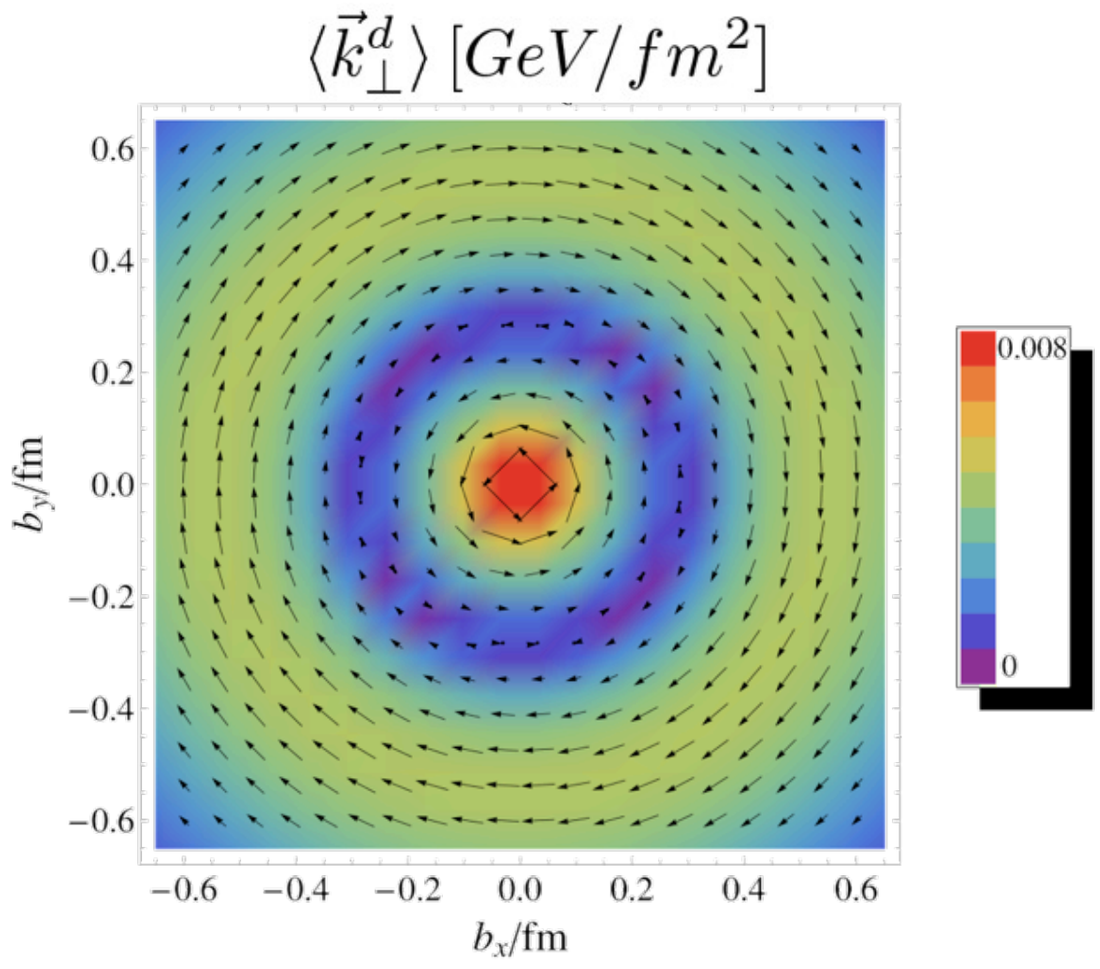
see talks by Y. Hatta (Tuesday, WG2), T. Maji (Wednesday, WG1), S. Bhattacharya (Wednesday, WG6), A. Mukherjee (Thursday, WG6)

Generalized TMDs and Wigner distributions

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)

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- The global fit era has started, much road to be covered to try to reach PDF fits