OVERVIEW OF TMD PARTON DISTRIBUTIONS

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3DSPIN
MAPPING THE PROTON IN 3D
European Research Council
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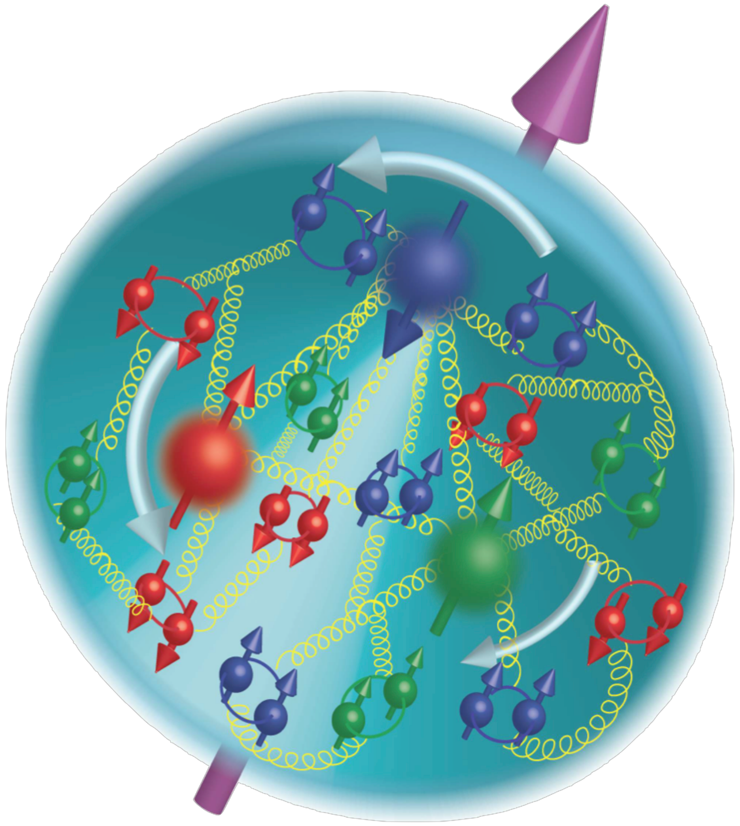
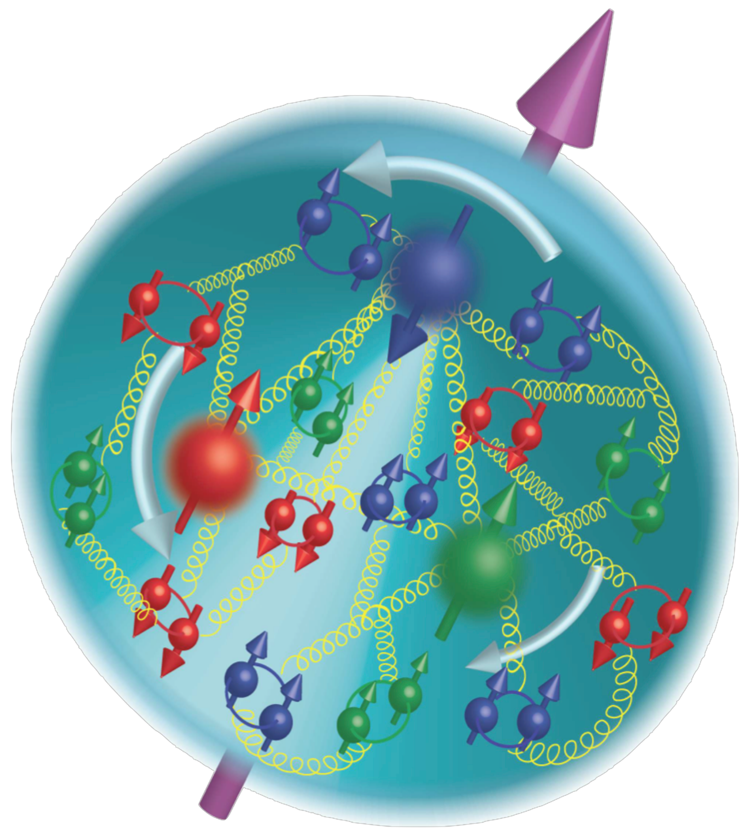
WHY IS IT INTERESTING TO MAP THE NUCLEON?



WHY IS IT INTERESTING TO MAP THE NUCLEON?

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



Check predictions

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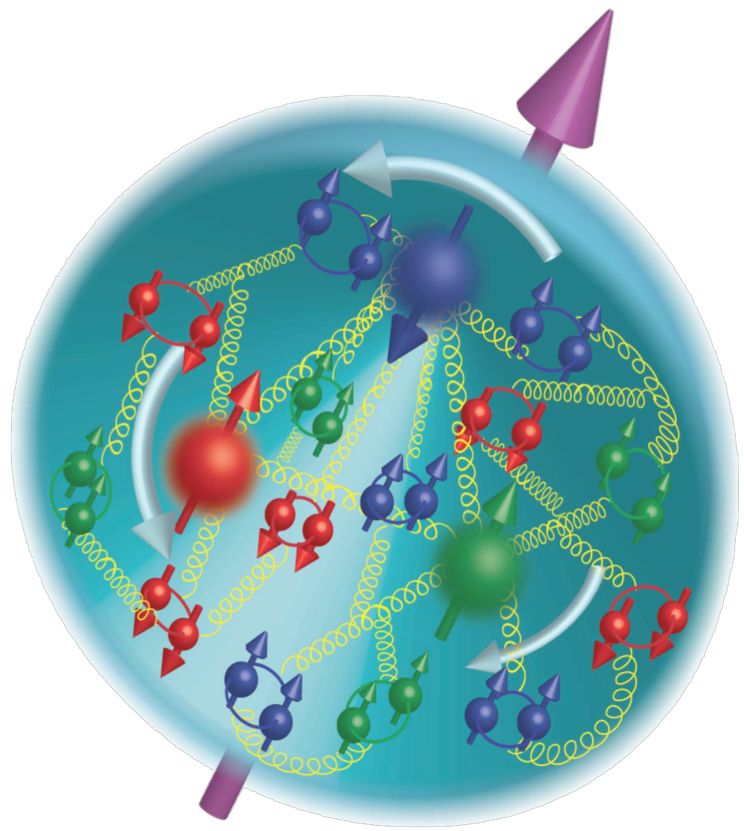
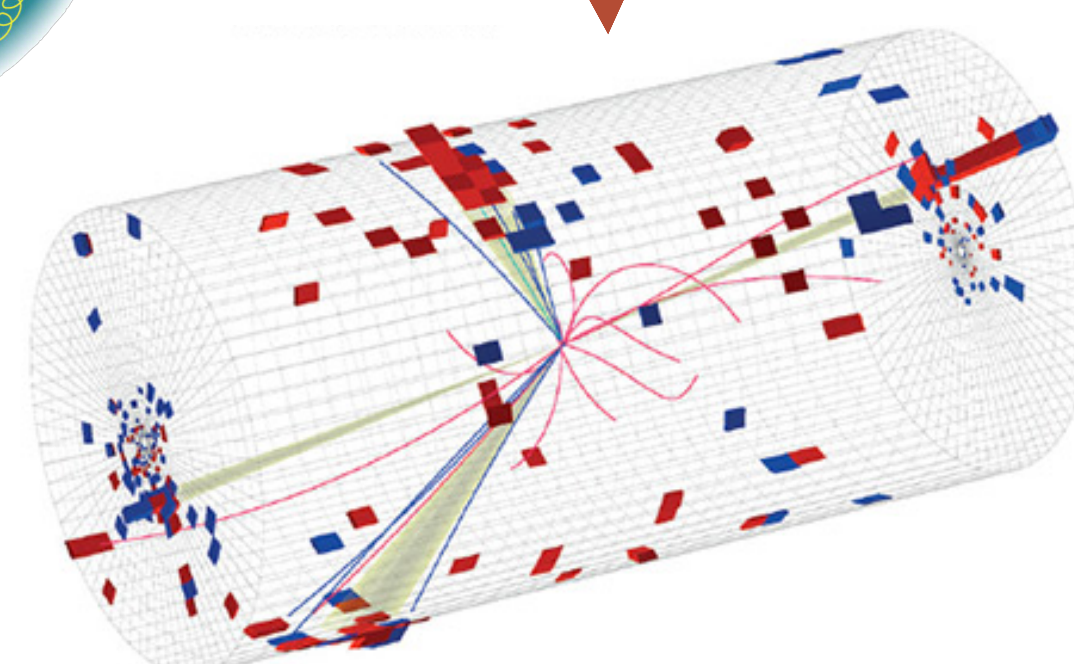
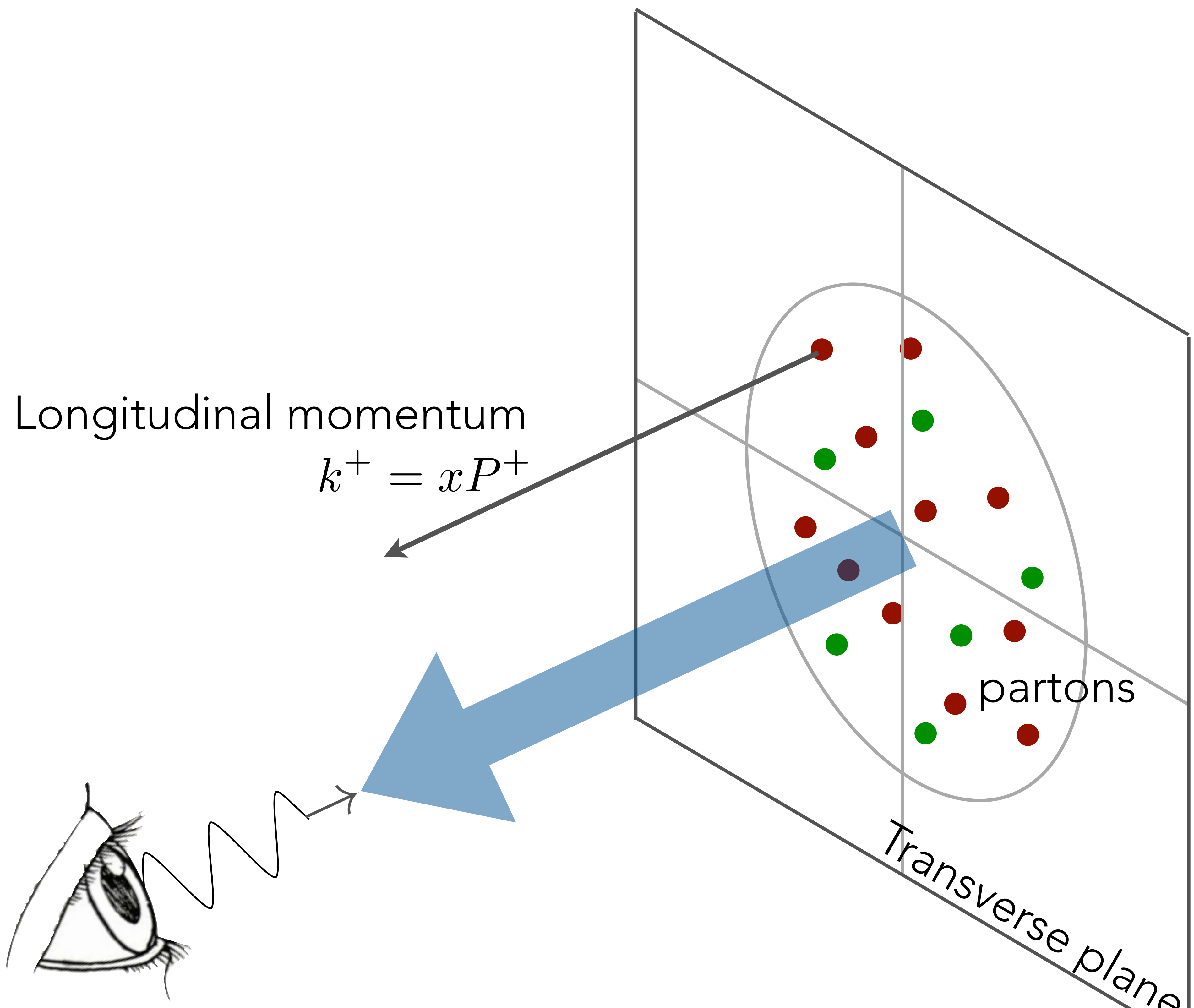
Make predictions



Check predictions

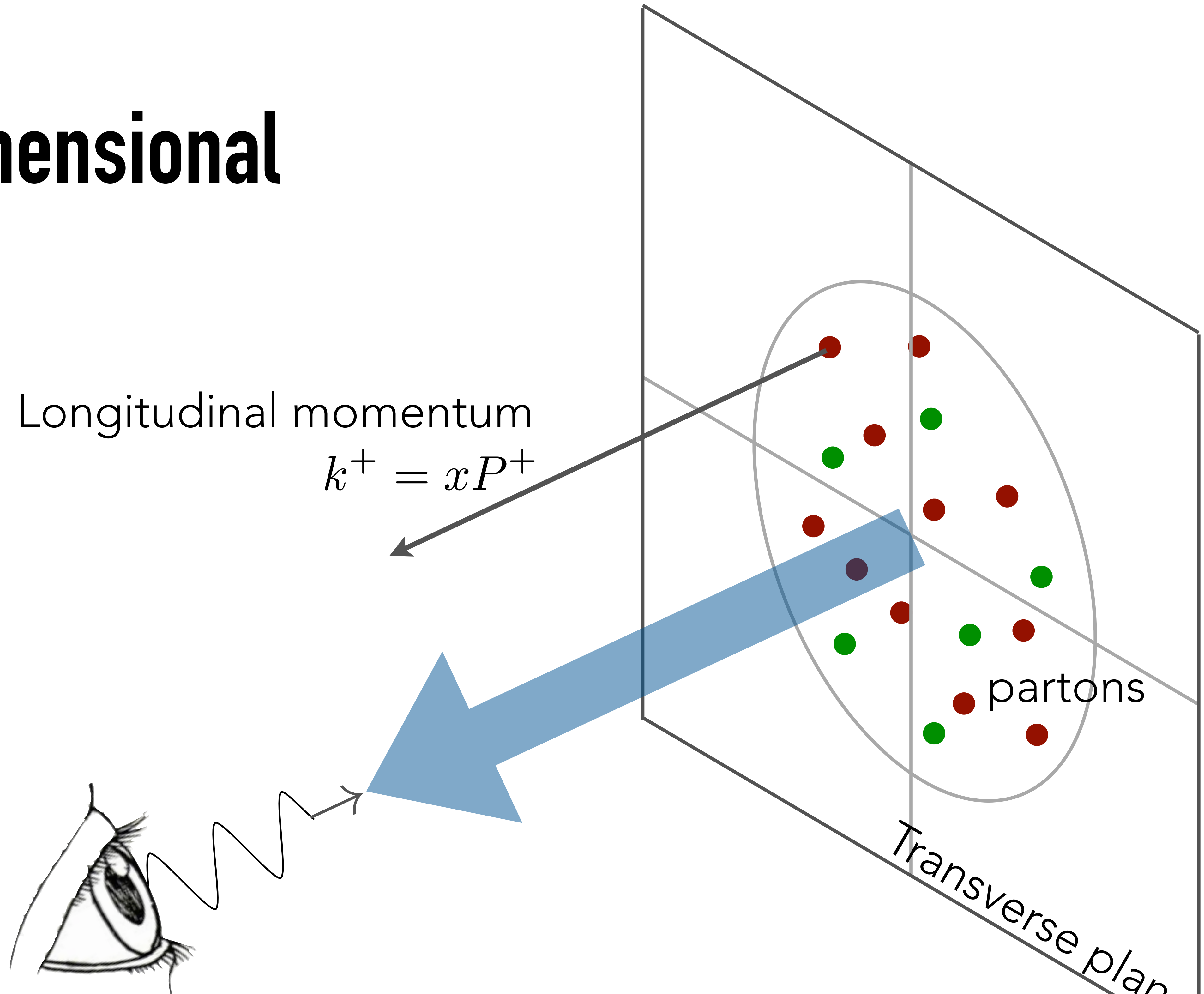



Longitudinal momentum
$k^+ = xP^+$
partons
Transverse plane

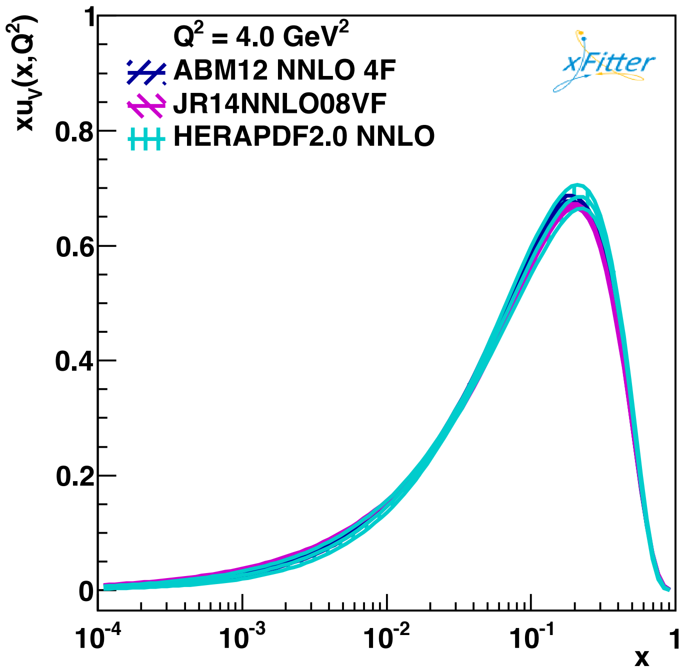
Parton Distribution Functions

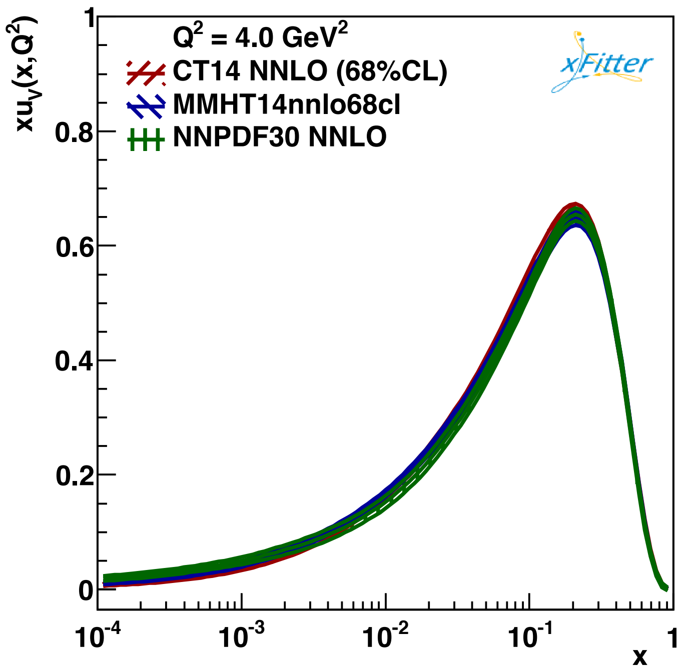
$f(x)$

1 dimensional



STANDARD PARTON DISTRIBUTION FUNCTIONS

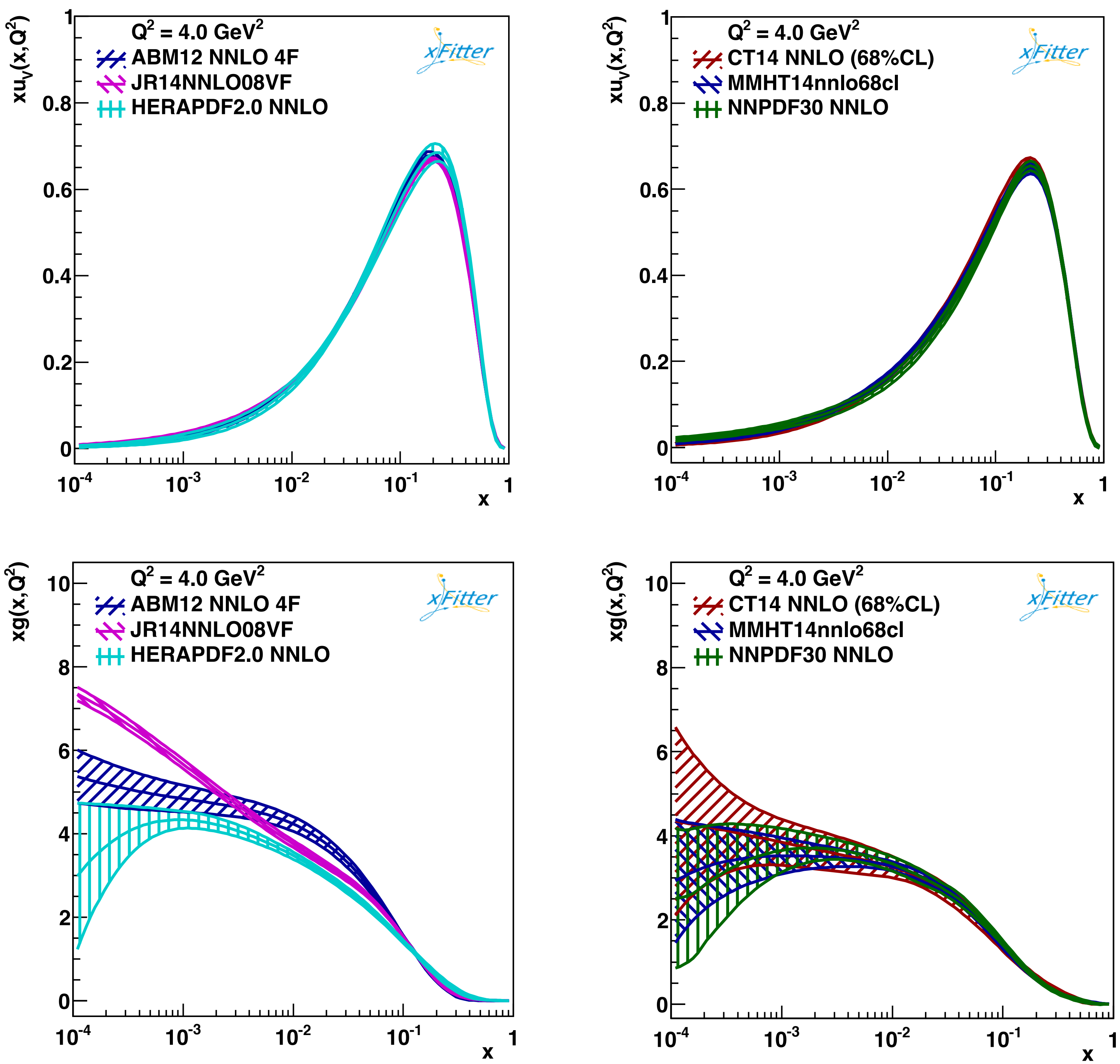




Standard collinear PDFs describe the distribution of partons in one dimension in momentum space. They are extracted through global fits

Accardi et al., arXiv:1603.08906

STANDARD PARTON DISTRIBUTION FUNCTIONS



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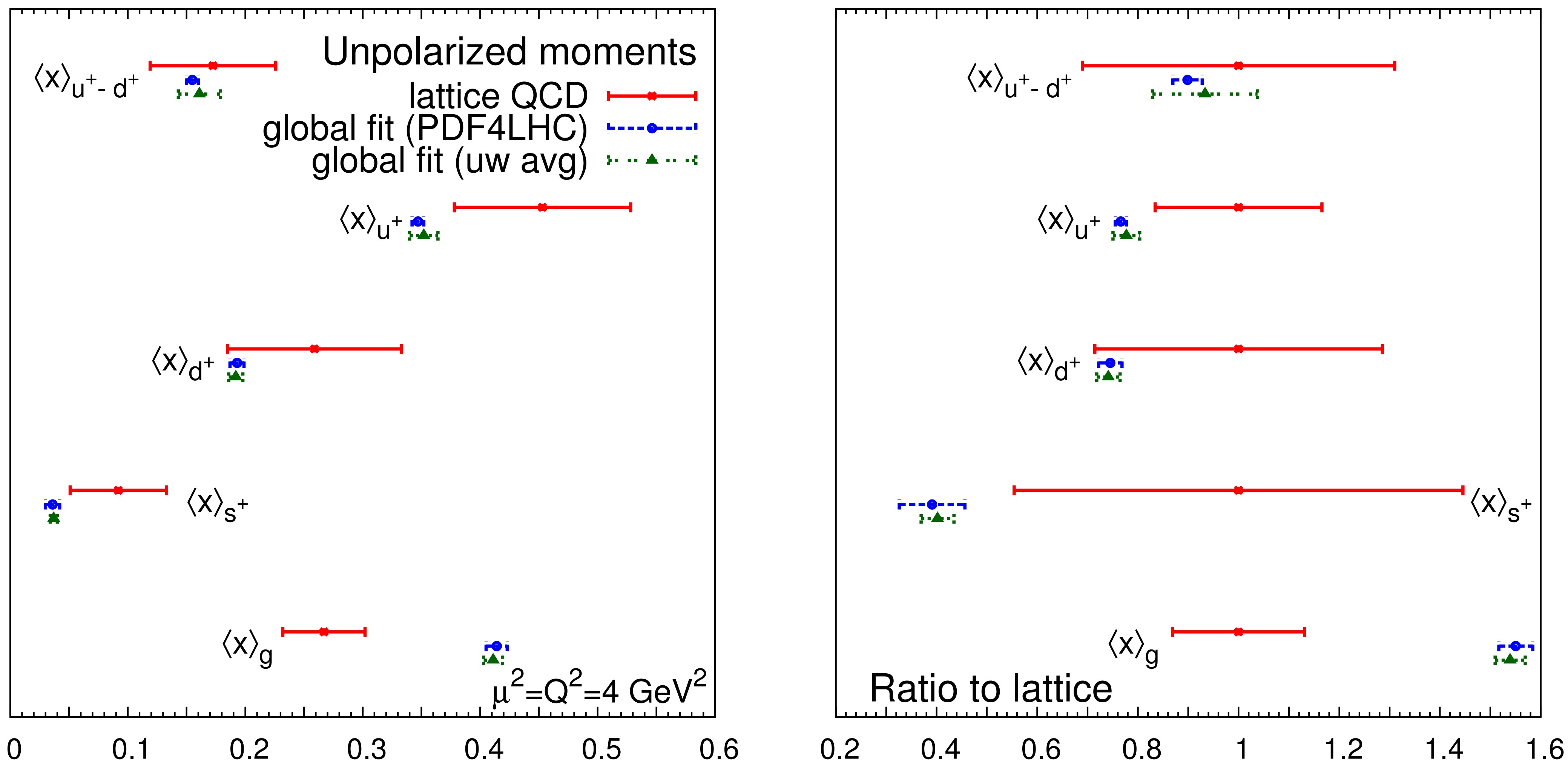
Accardi et al., arXiv:1603.08906

UNPOLARIZED PDF MOMENTS AND LATTICE QCD

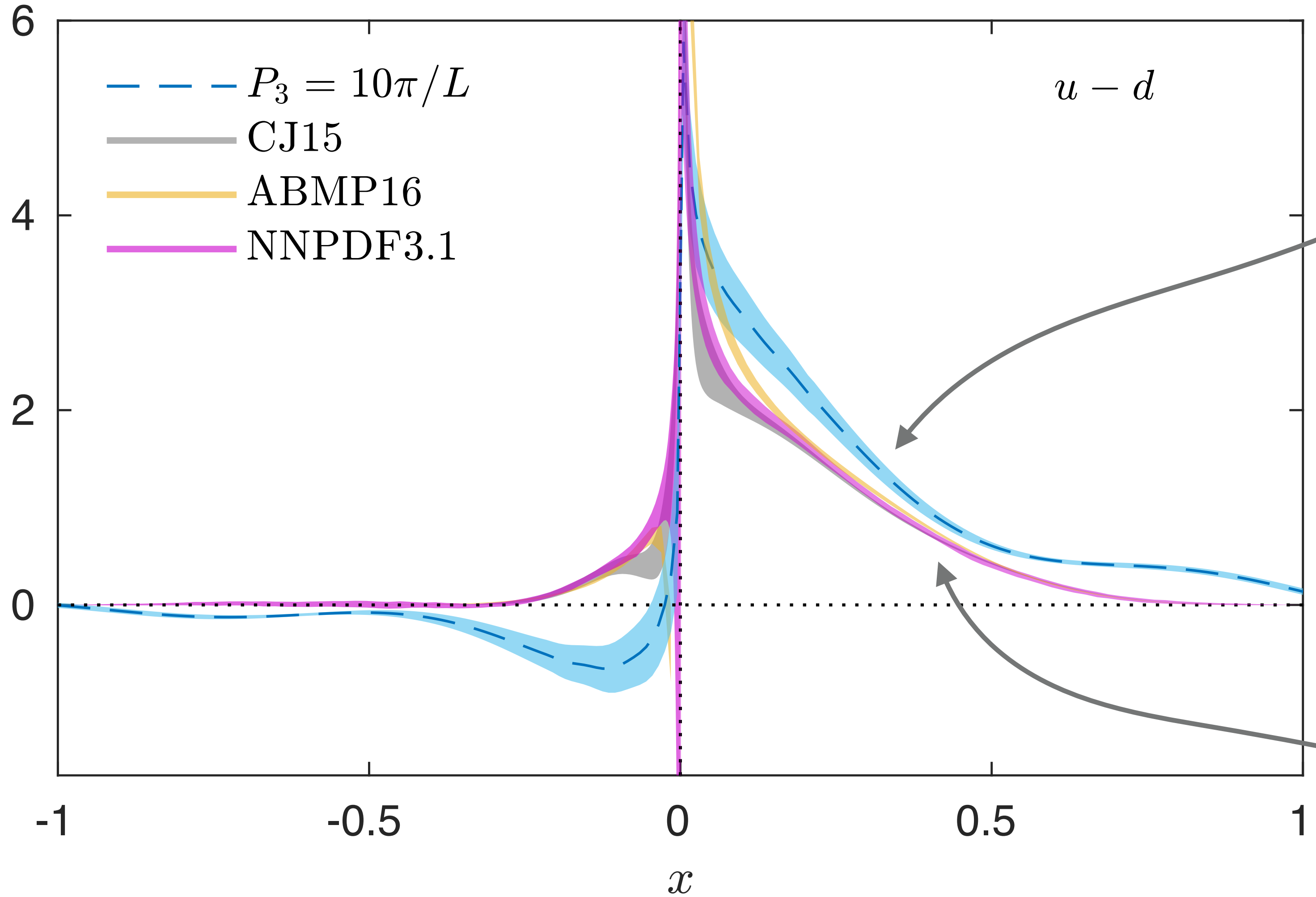


PDFLattice White Paper, arXiv:1711.07916

Fair agreement, but not perfect

FULL UNPOLARIZED PDF AND LATTICE QCD

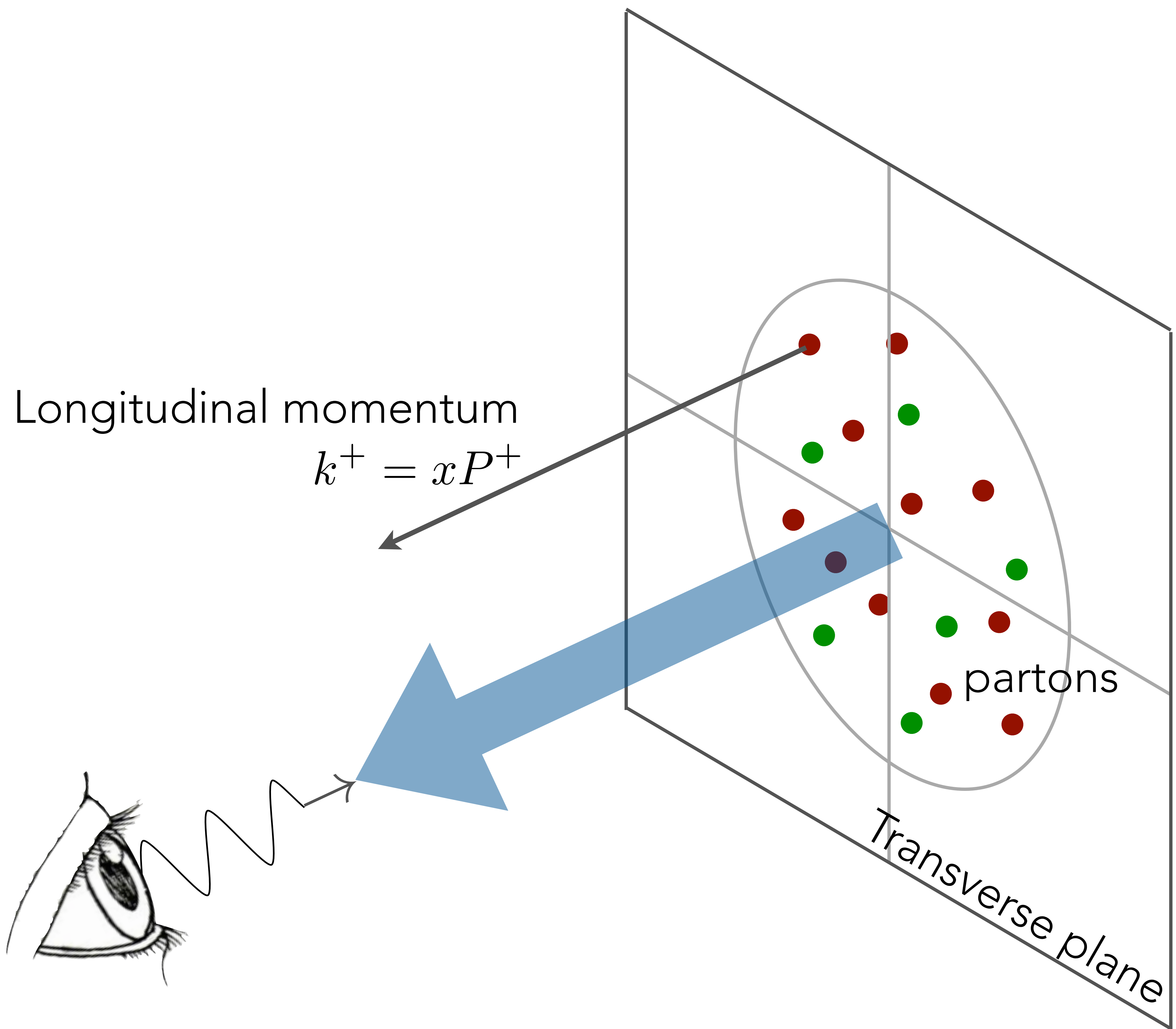
Alexandrou, Cichy, Constantinou, Hadjiyiannakou, Jansen, Scapellato, Steffens, arXiv:1902.00587
see previous talk by Martha

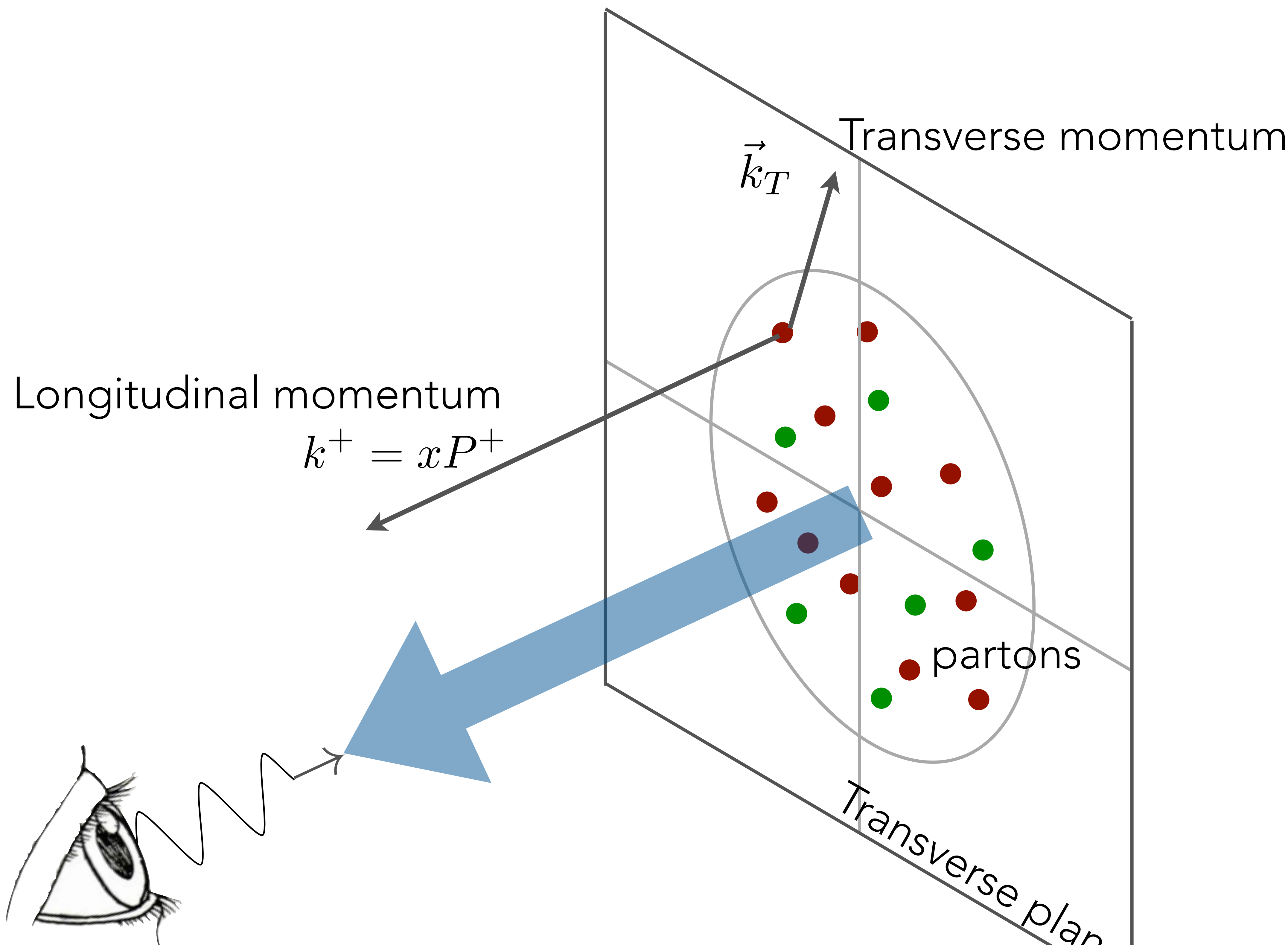


lattice calculation
(quasi-PDF approach)

global fits

antiquarks quarks


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


Transverse momentum
$\vec{k}_T$
Longitudinal momentum
$k^+ = xP^+$
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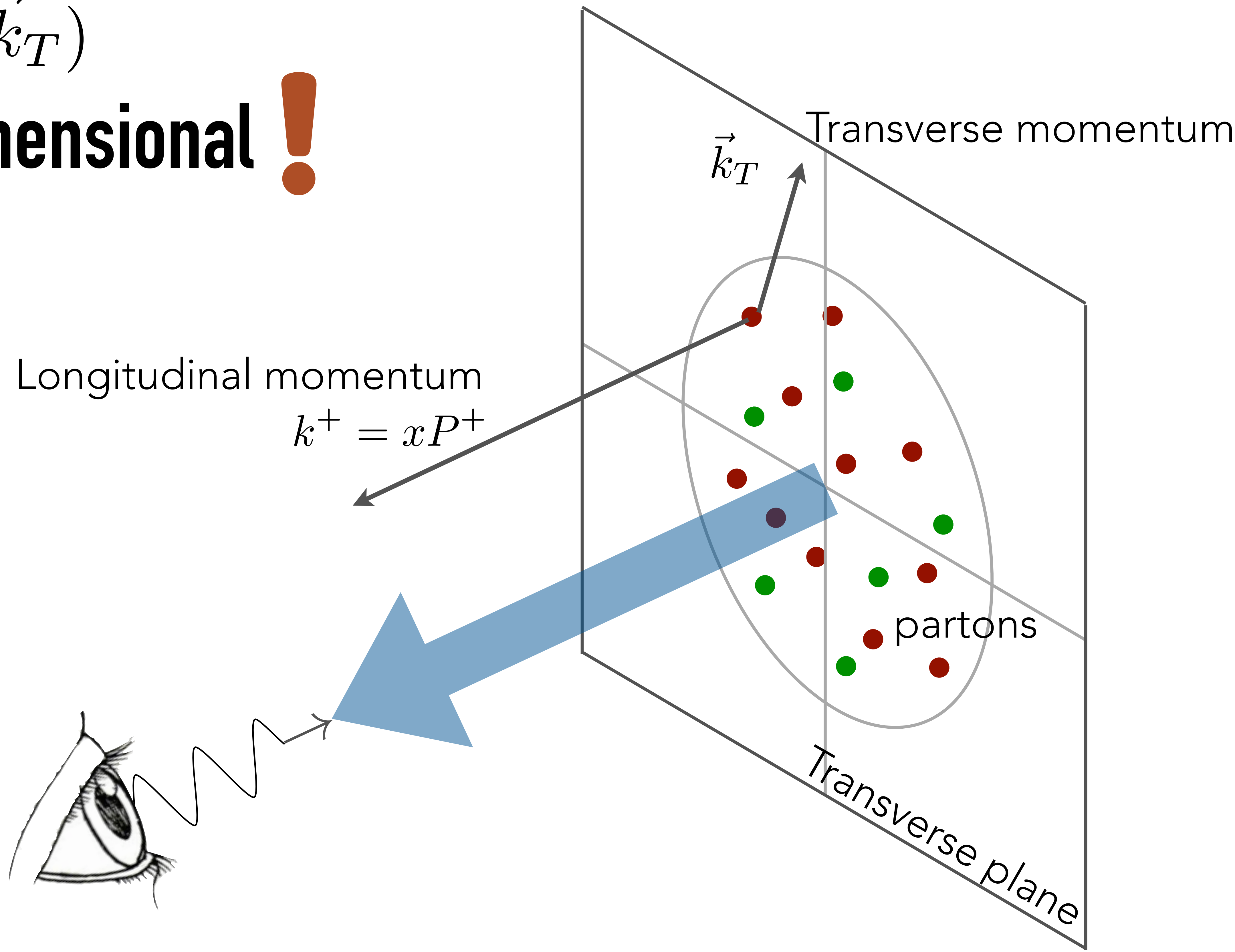
Transverse plane

Transverse-Momentum Distributions

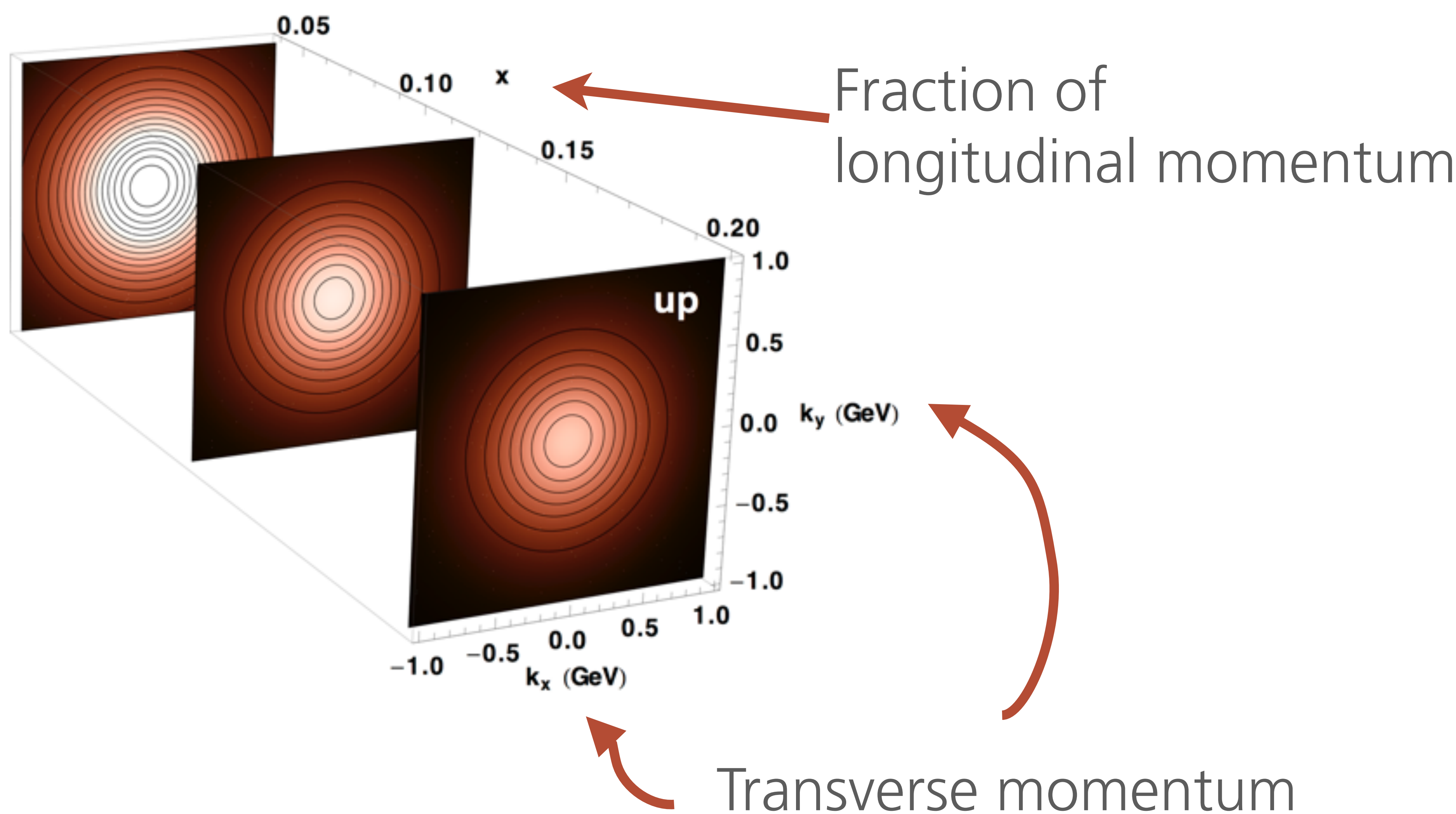
$f(x, \vec{k}_T)$

3 dimensional !



TRANSVERSE MOMENTUM DISTRIBUTIONS

TMDs describe the distribution of partons in three dimensions in momentum space. They also have to be extracted through global fits.



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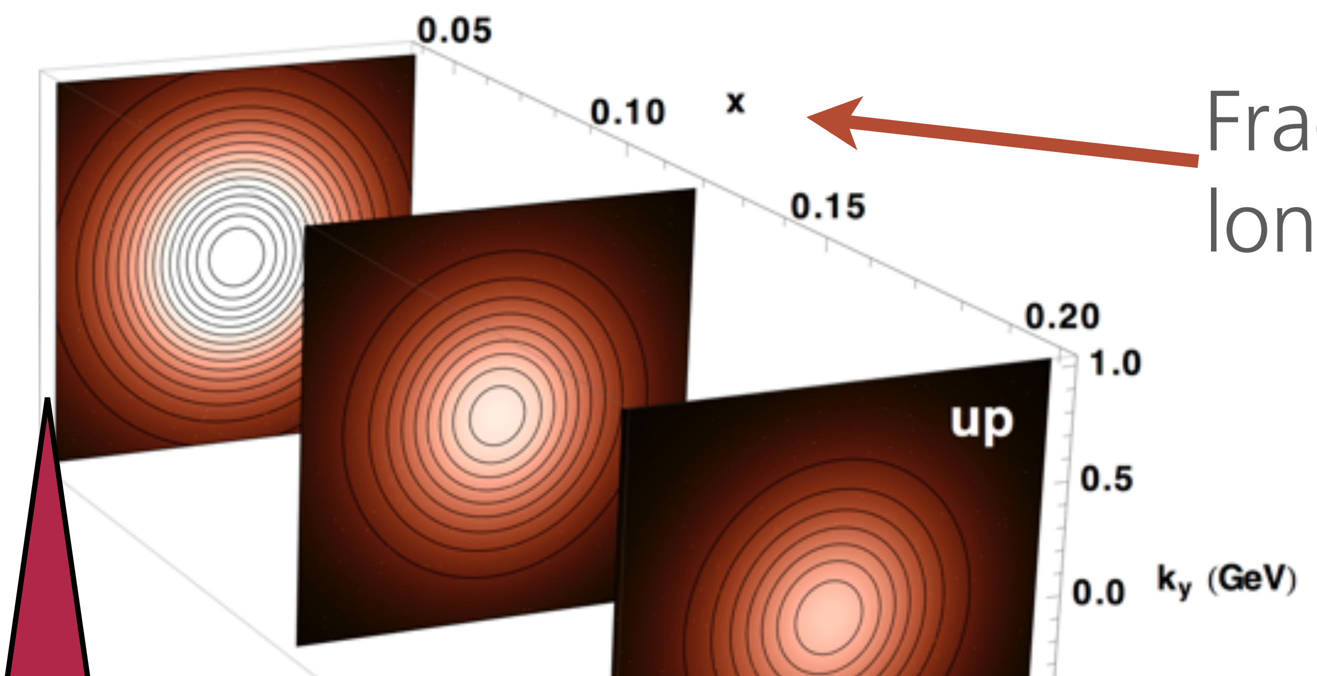


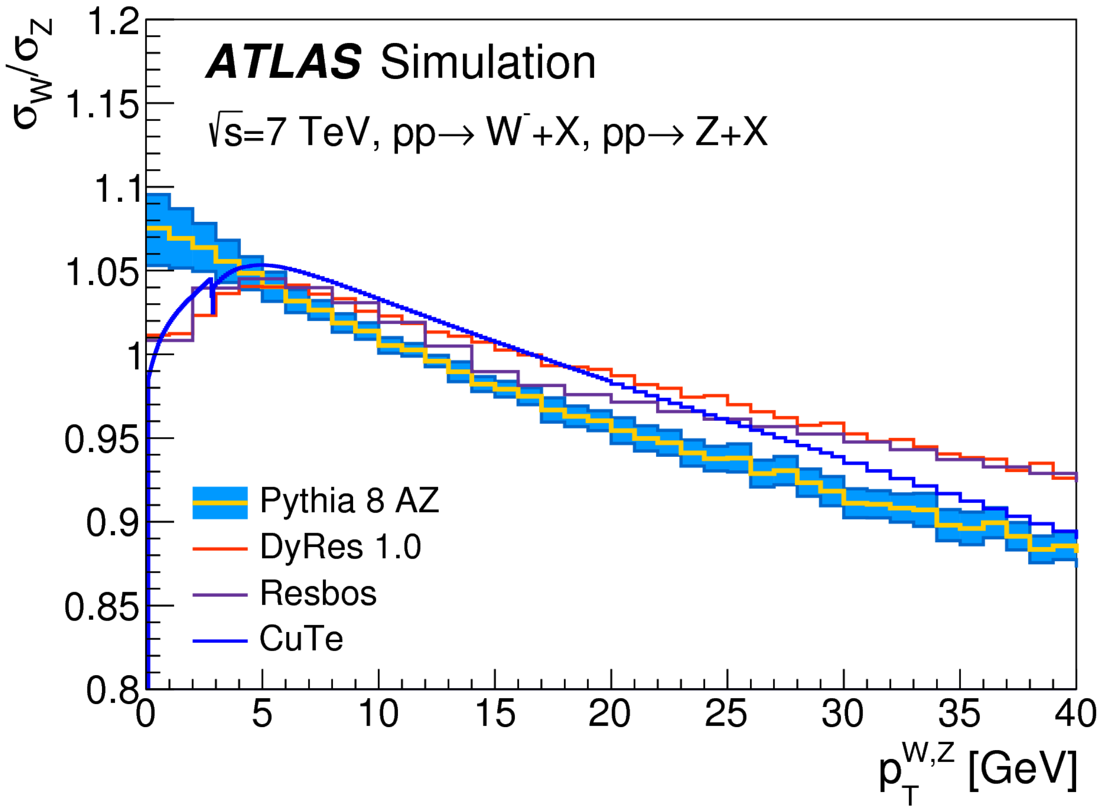
Fraction of longitudinal momentum

How “wide” is the distribution?
Is there a difference between flavors?
Does it get wider at low x?

momentum

PREDICTIONS THAT REQUIRE TMDS

from A. Apyan's talk at LHC EW Precision sub-group workshop
https://indico.cern.ch/event/801961/



also
ResBos2
Radish
SCETlib
…

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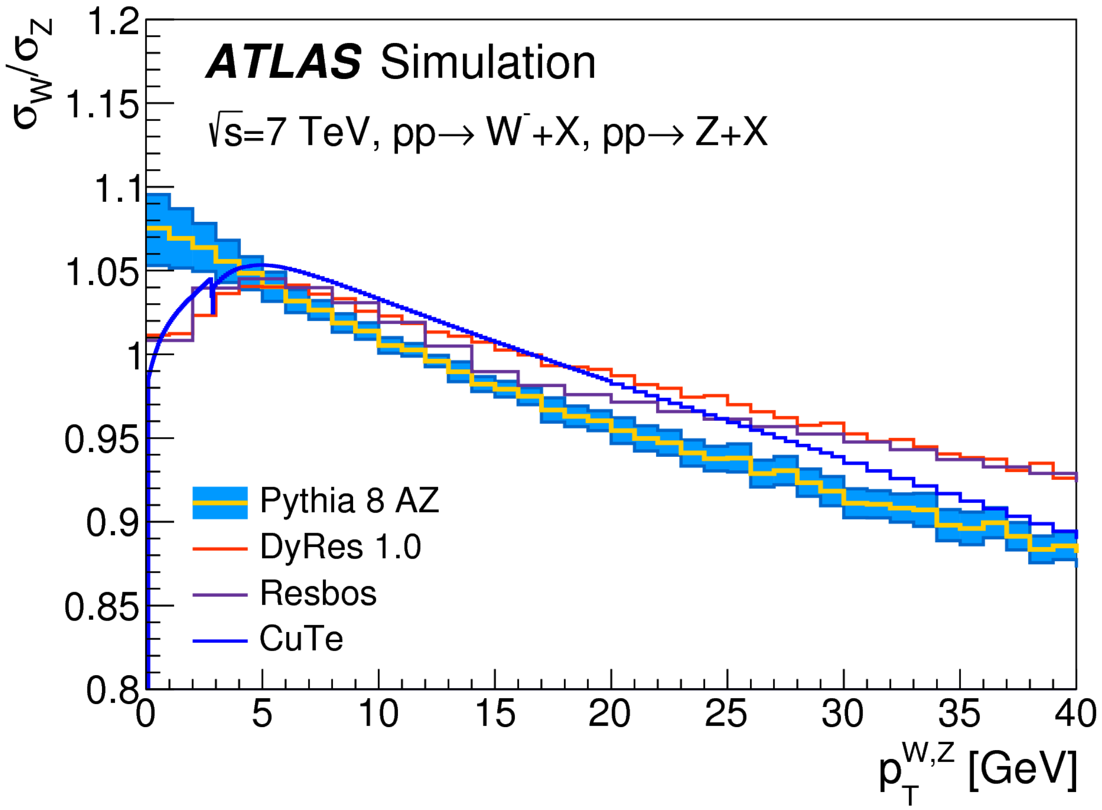

also
ResBos2
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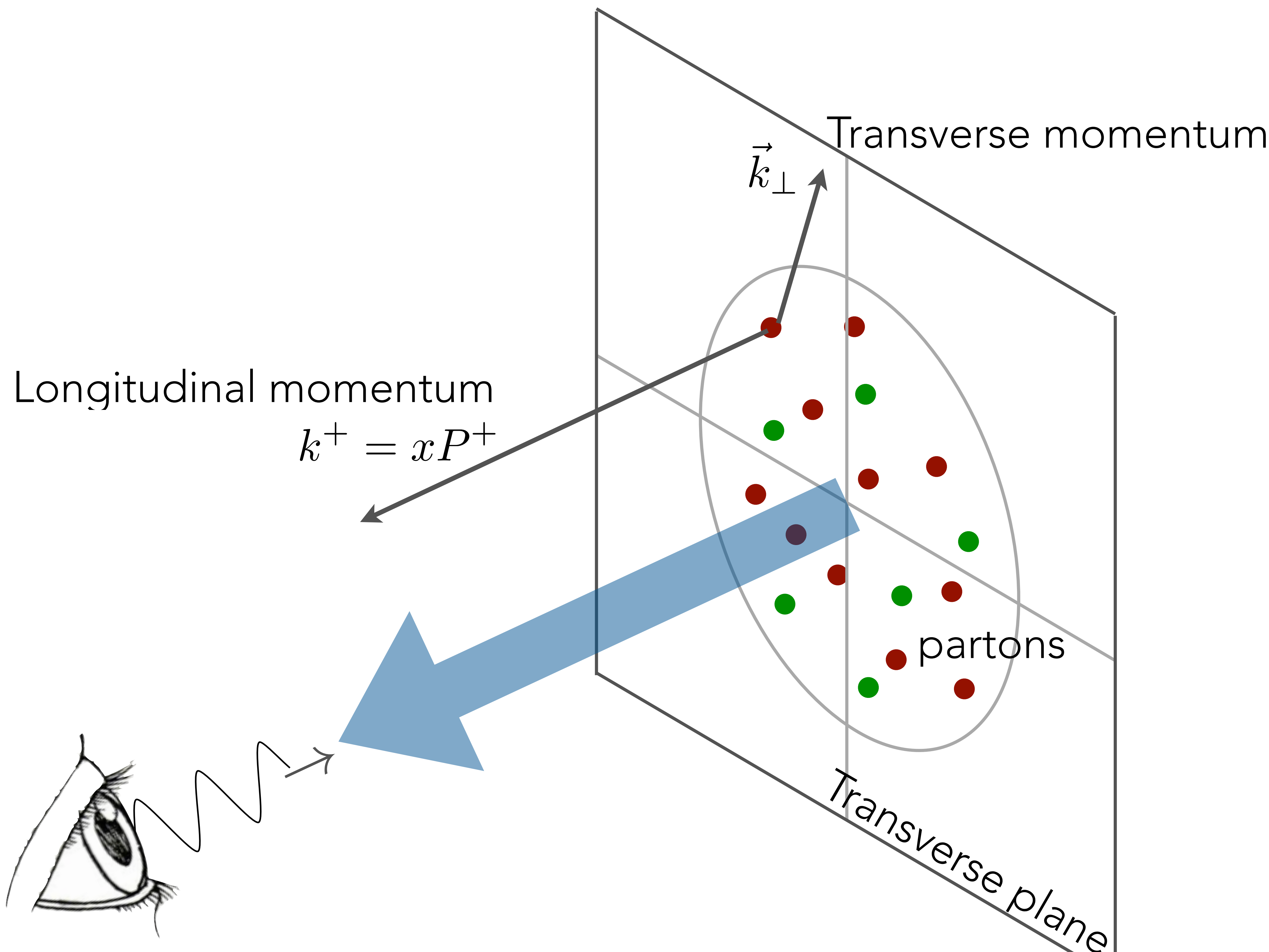
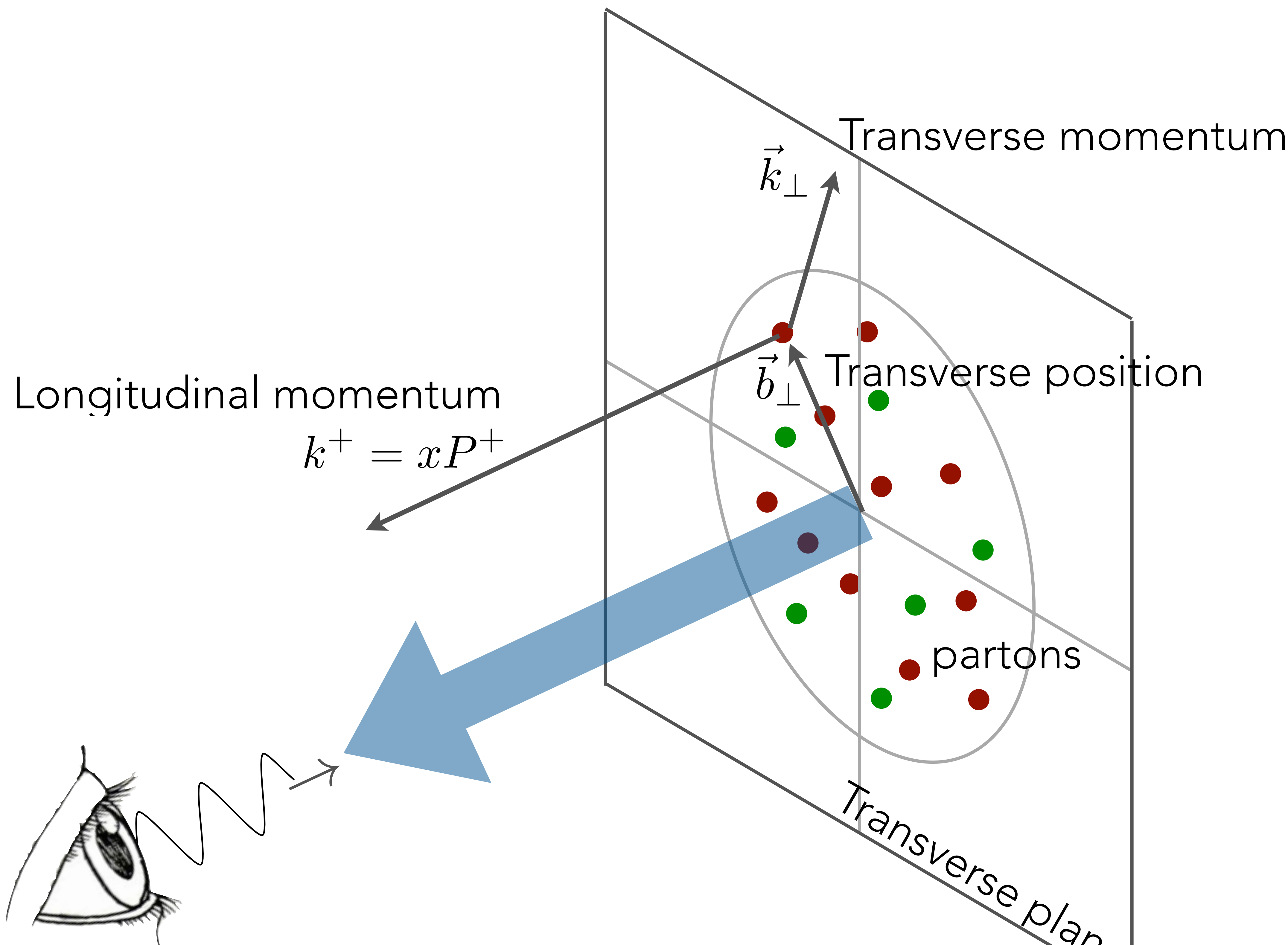
…

There is an entire industry of tools that make predictions for observables that involve TMDs. Most of them neglect important effects (especially at low p_T) coming from nonperturbative TMD components.

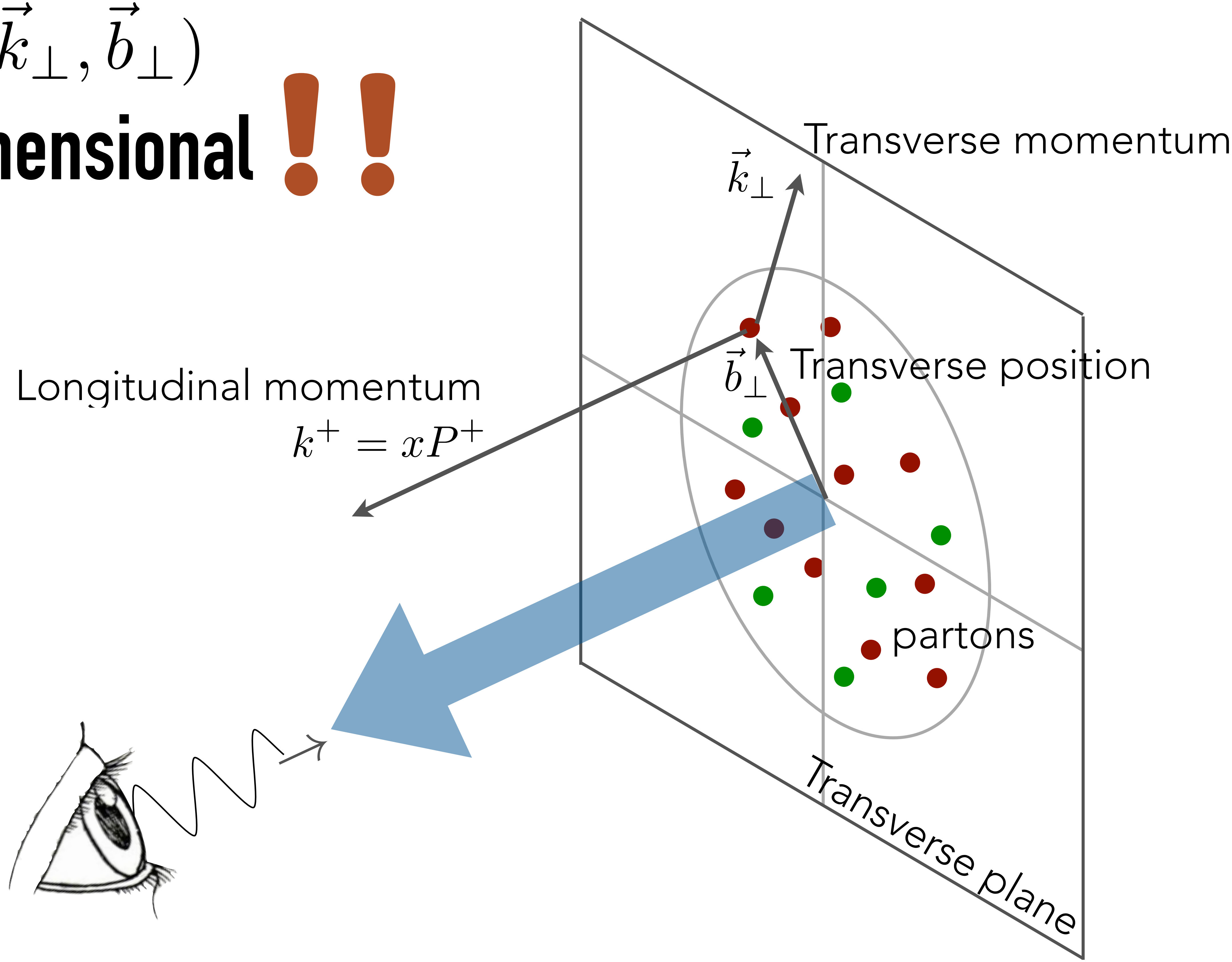

Transverse momentum
$\vec{k}_\perp$
Longitudinal momentum
$k^+ = xP^+$
partons
Transverse plane


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

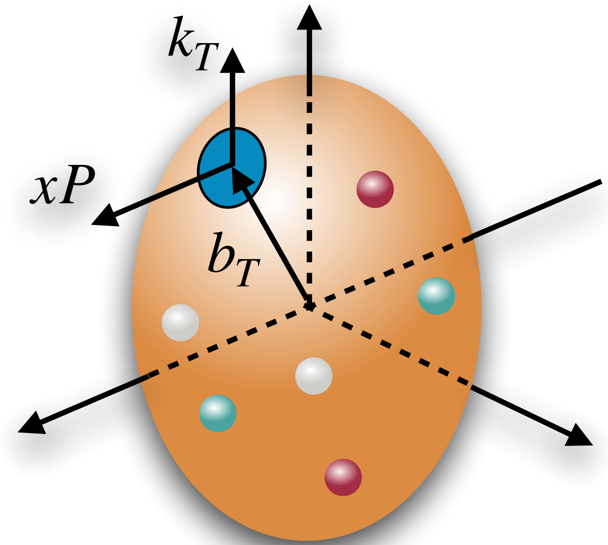
Wigner distributions

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

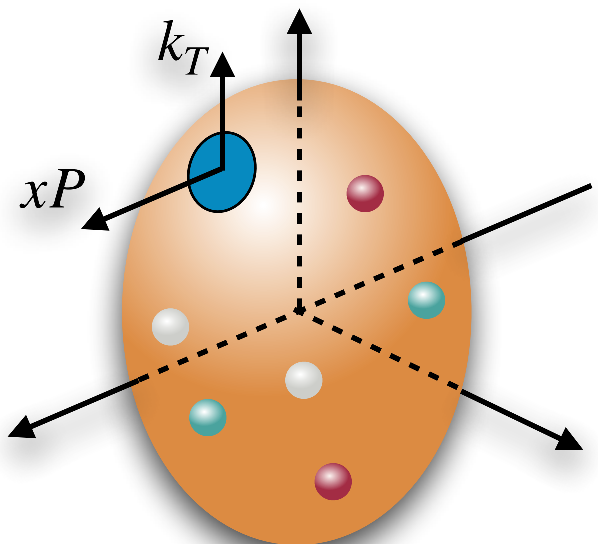
5 dimensional ‼



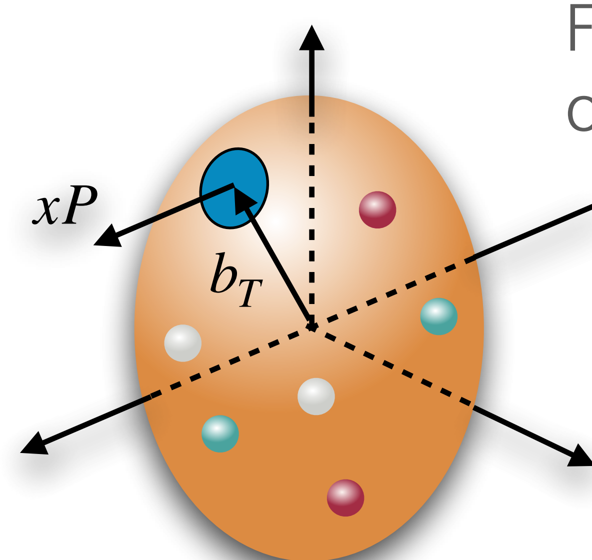
Wigner distributions (Fourier transform of GTMDs = Generalized Transverse Momentum Distributions)



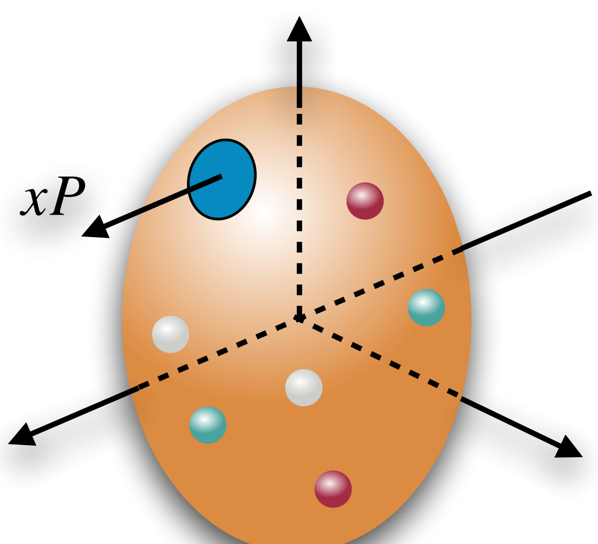
TMDs



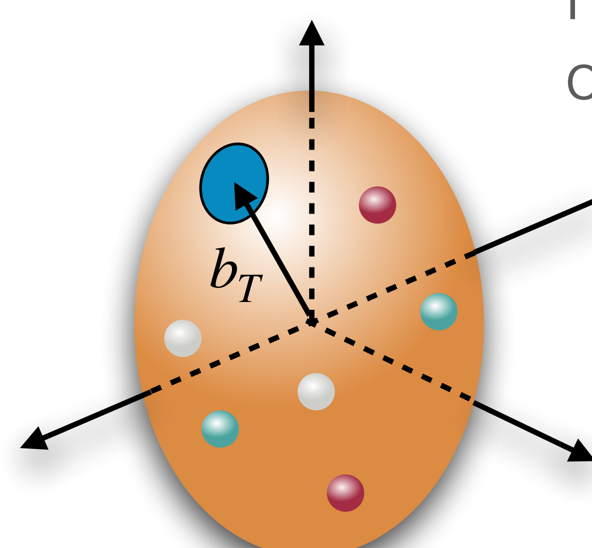
Fourier transform of GPDs



PDFs



Fourier transform of Form Factors



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

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 integration over transverse momentum
TMDs in red are time-reversal odd

Mulders-Tangerman, NPB 461 (96)
Boer-Mulders, PRD 57 (98)

TMD TABLE

helicity

quark pol.

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Twist-2 TMDs

transversity

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Sivers

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transversity

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Twist-2 TMDs

helicity

Boer-Mulders

Sivers

transversity

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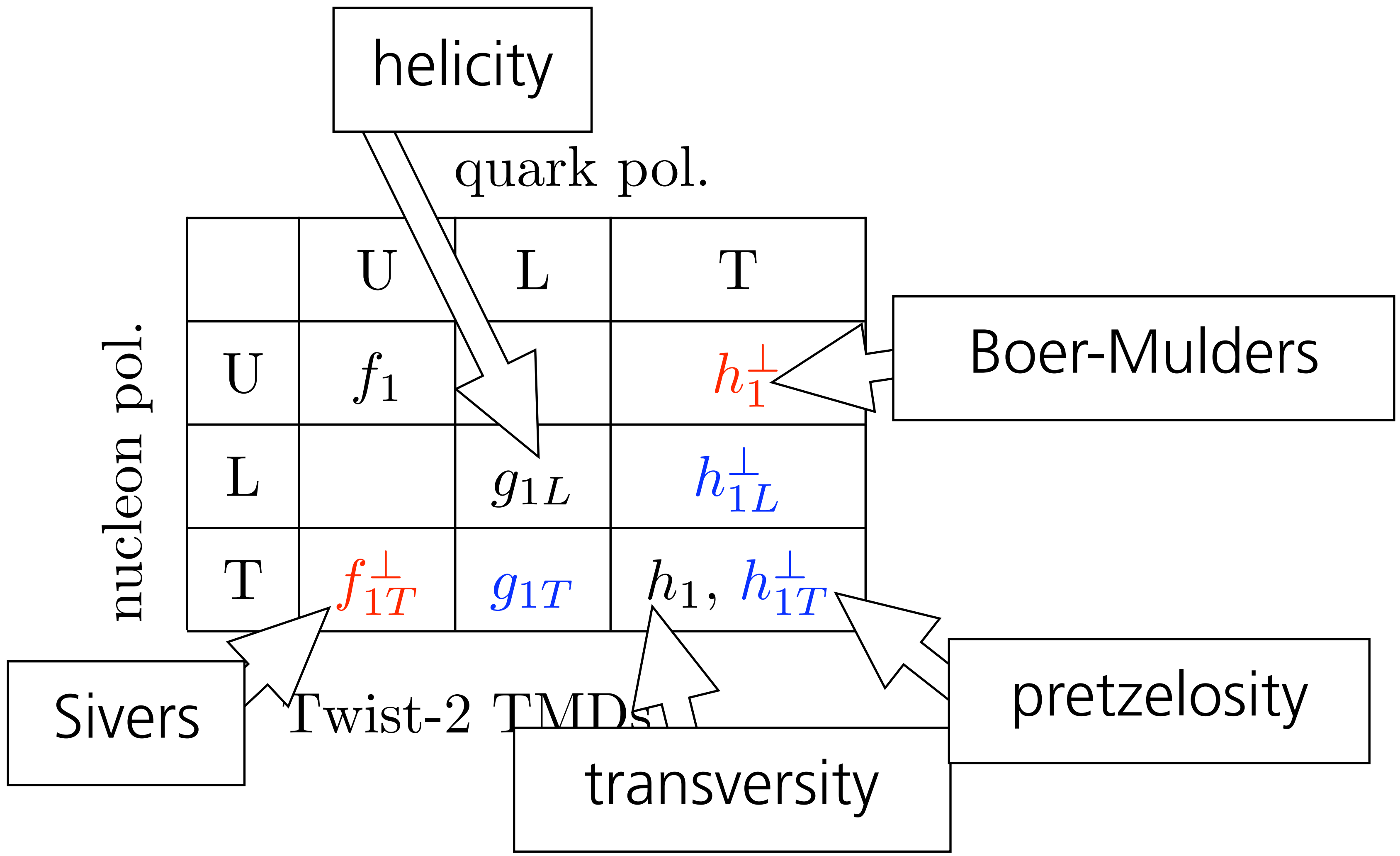

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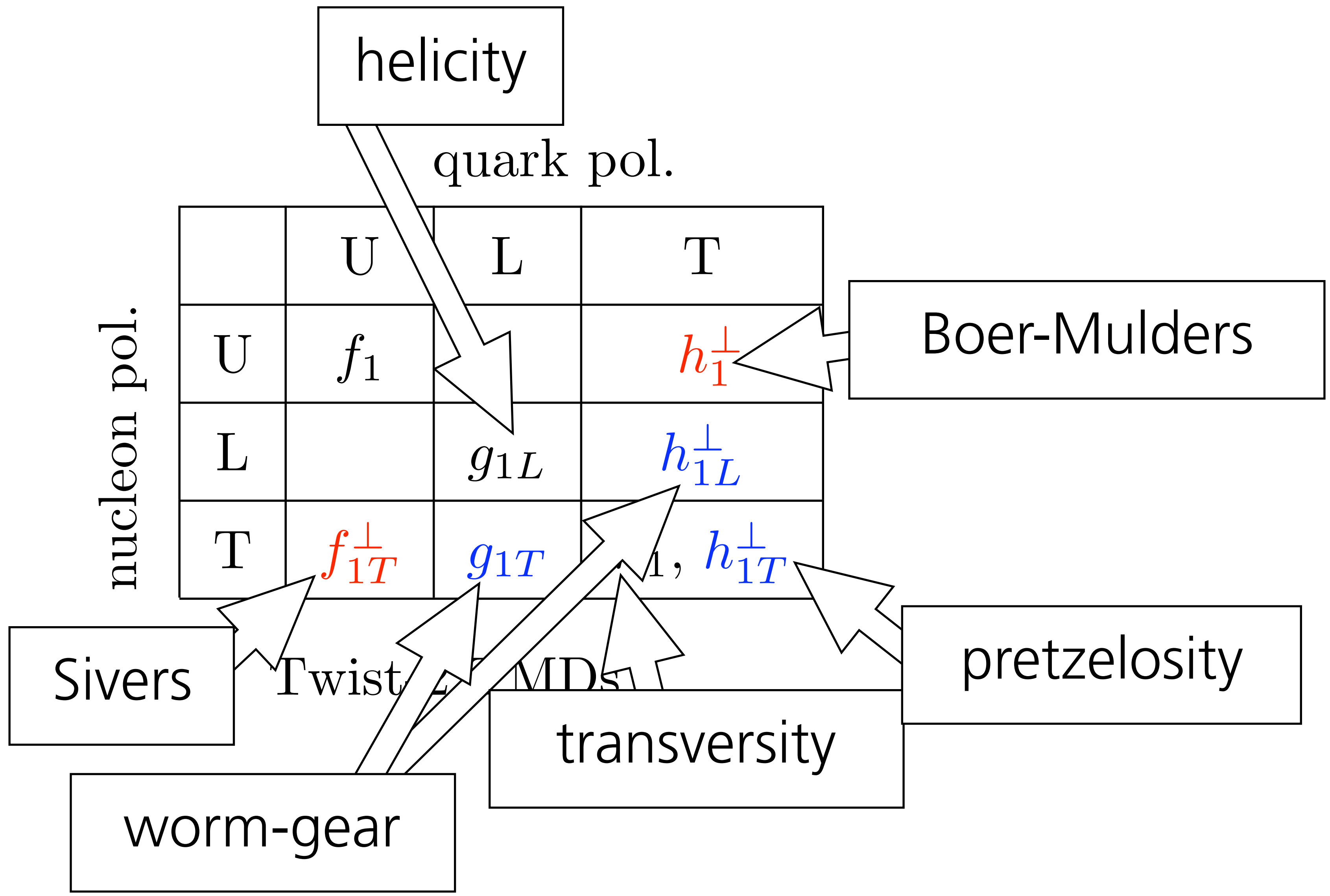

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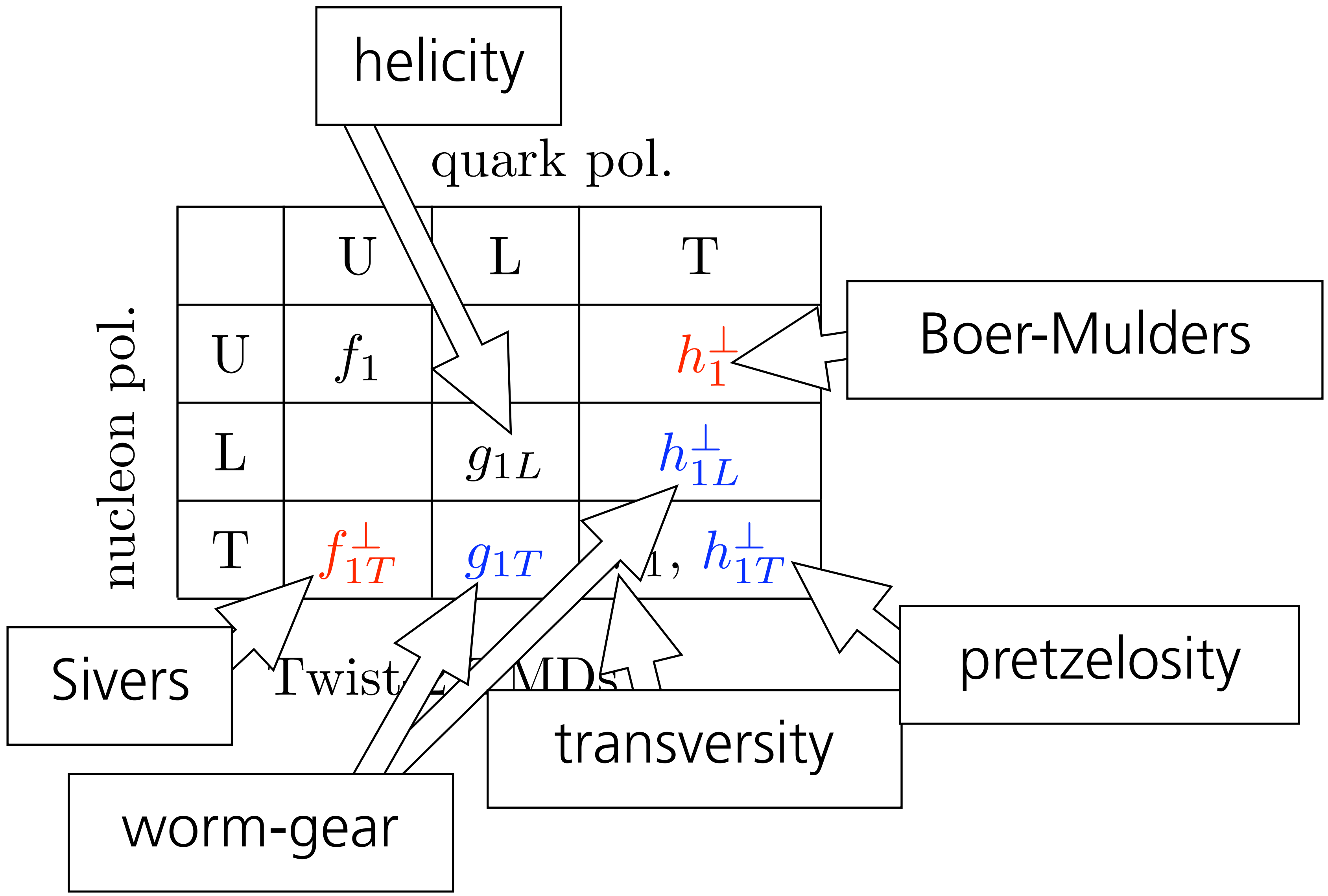

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Mulders-Tangerman, NPB 461 (96)
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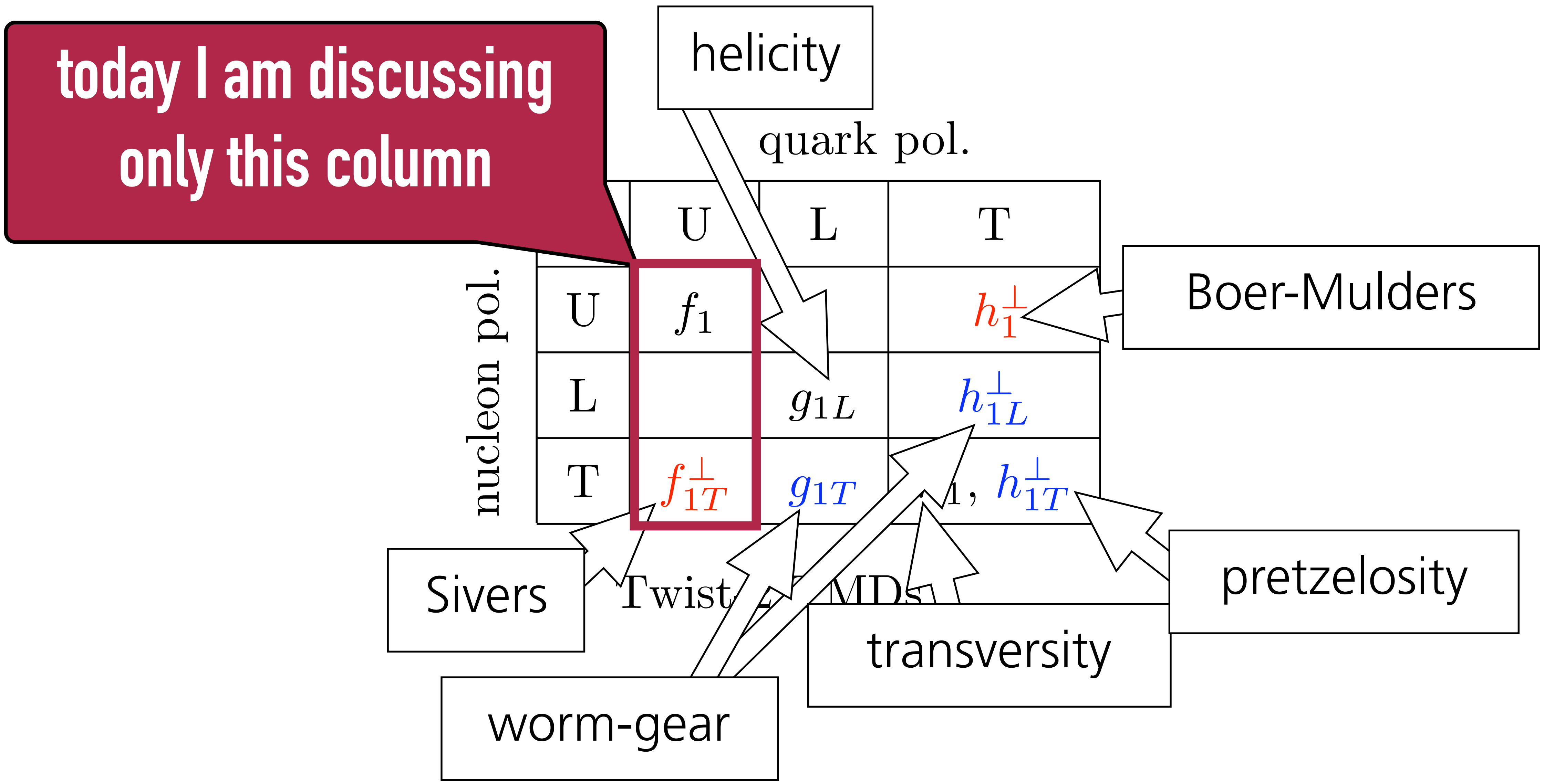
On top of these, there are twist-3 functions

TMD TABLE



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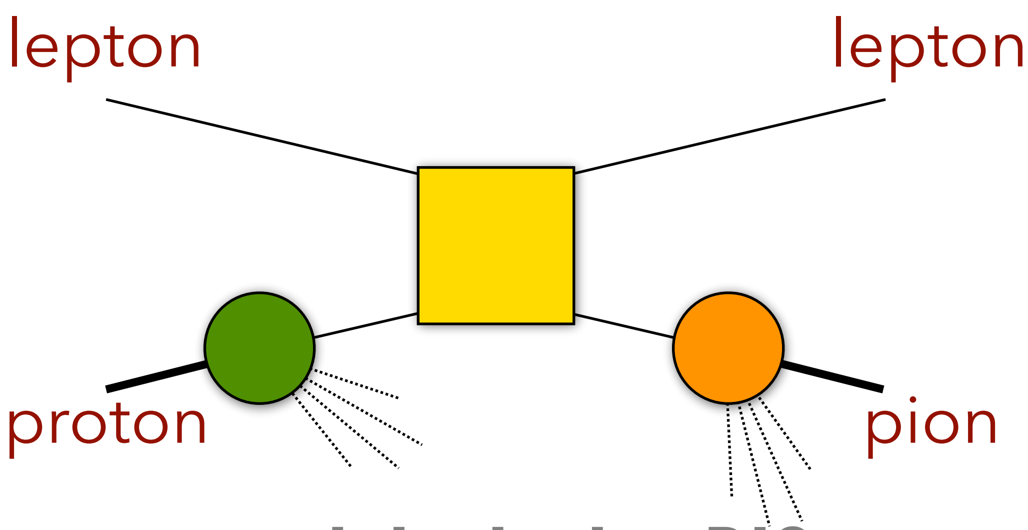
Mulders-Tangerman, NPB 461 (96)
Boer-Mulders, PRD 57 (98)

On top of these, there are twist-3 functions

UNPOLARISED QUARK TMD

FACTORIZATION AND UNIVERSALITY



semi-inclusive DIS

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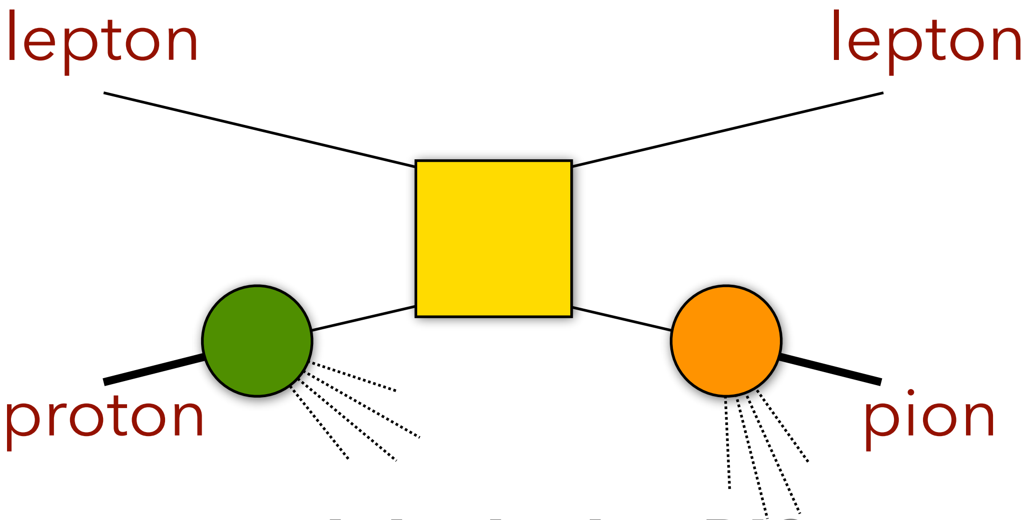

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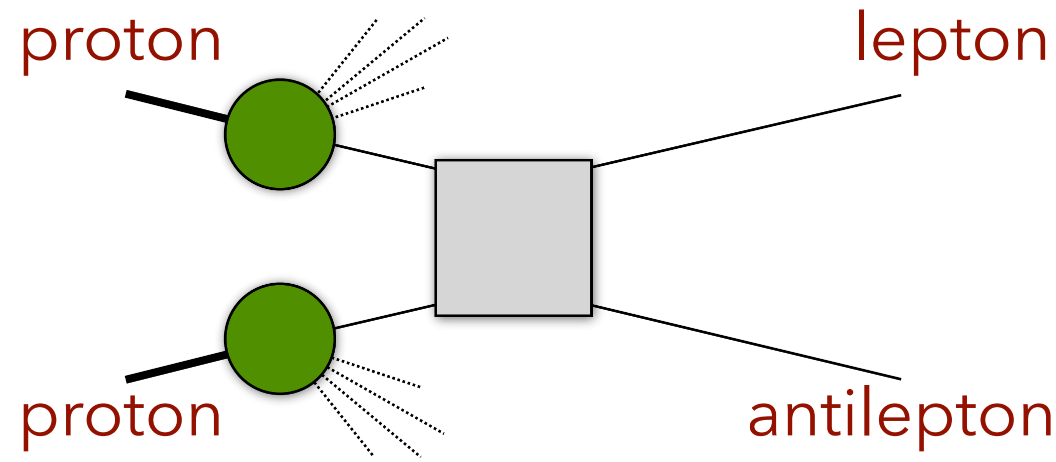

Drell-Yan

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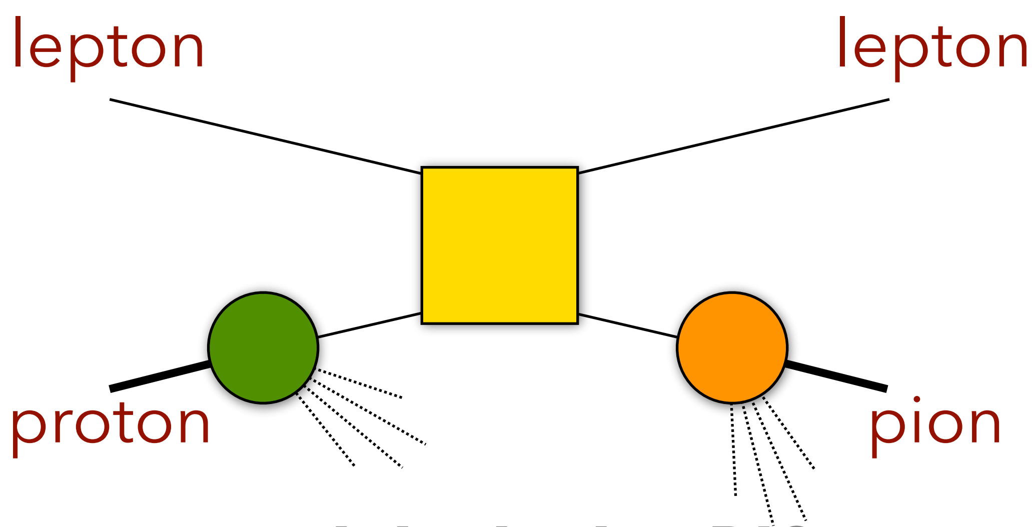

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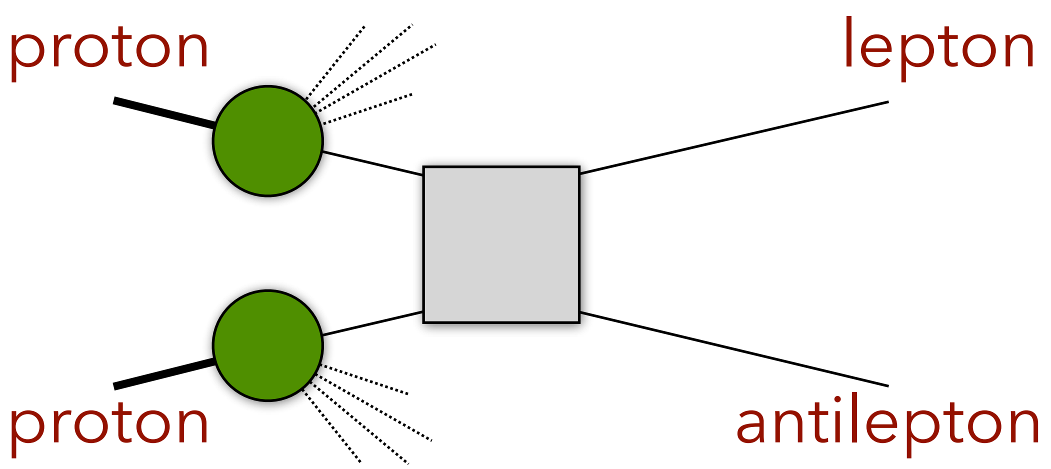
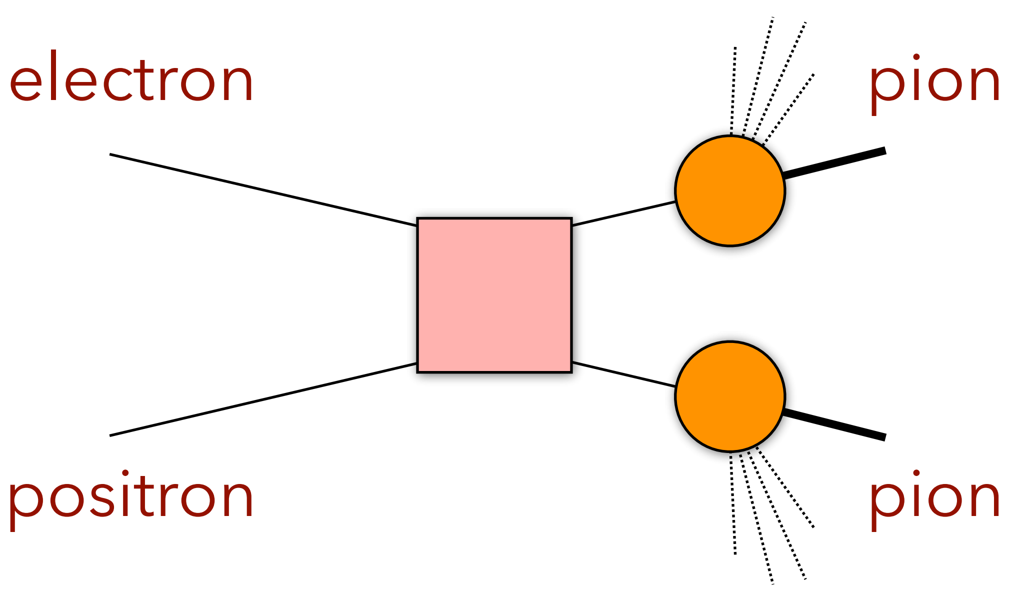
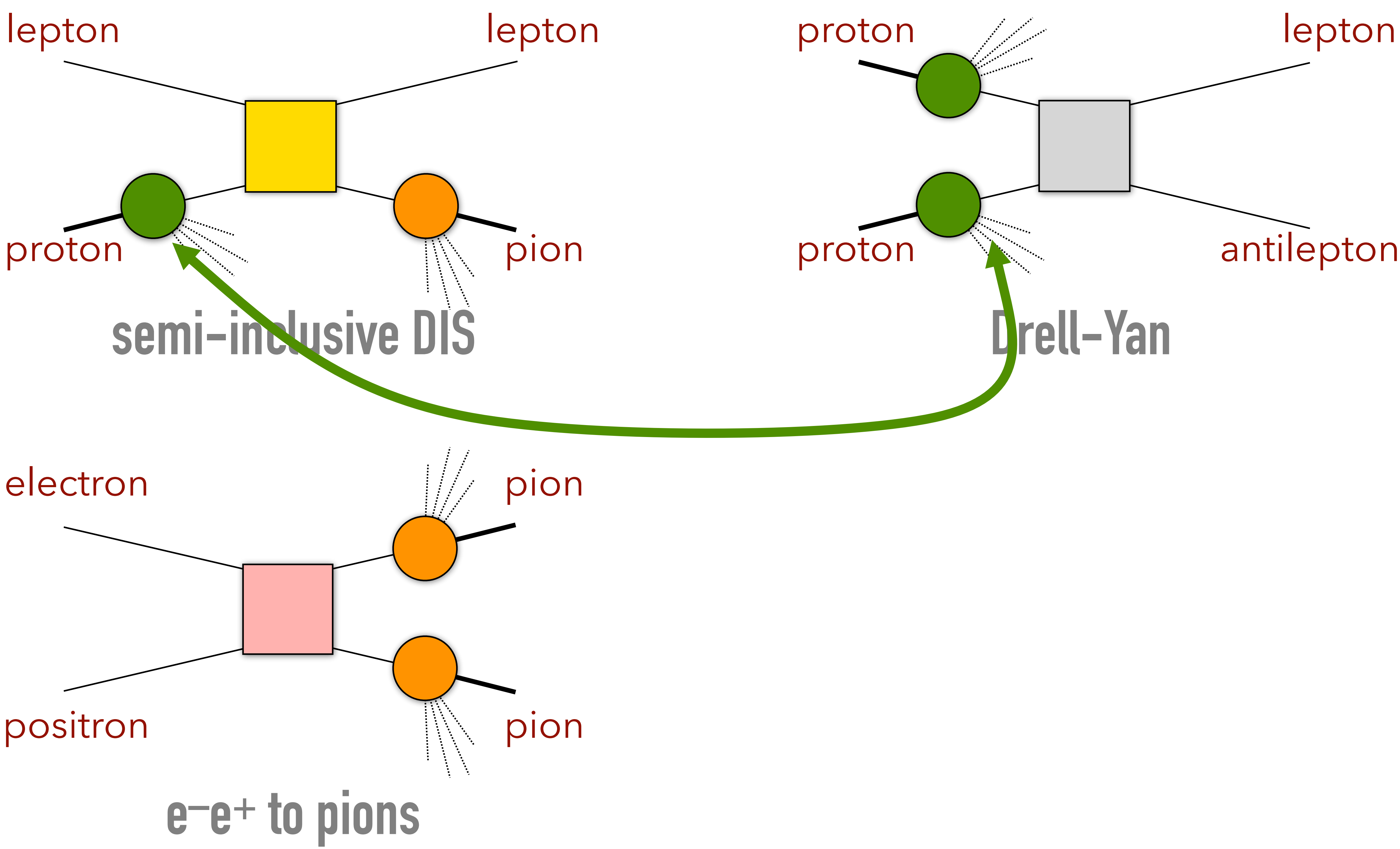


Drell-Yan



e^-e^+ to pions

FACTORIZATION AND UNIVERSALITY



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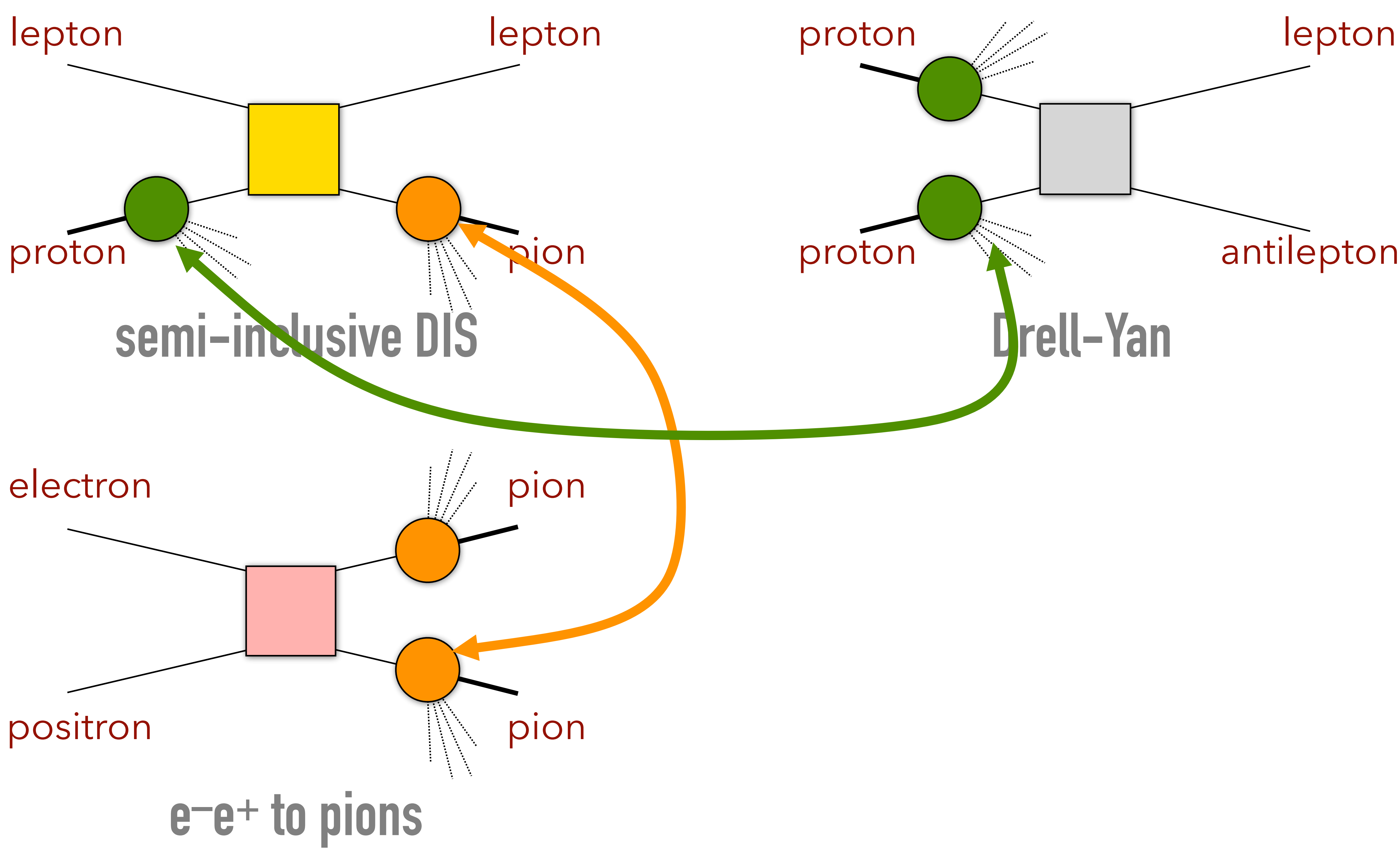

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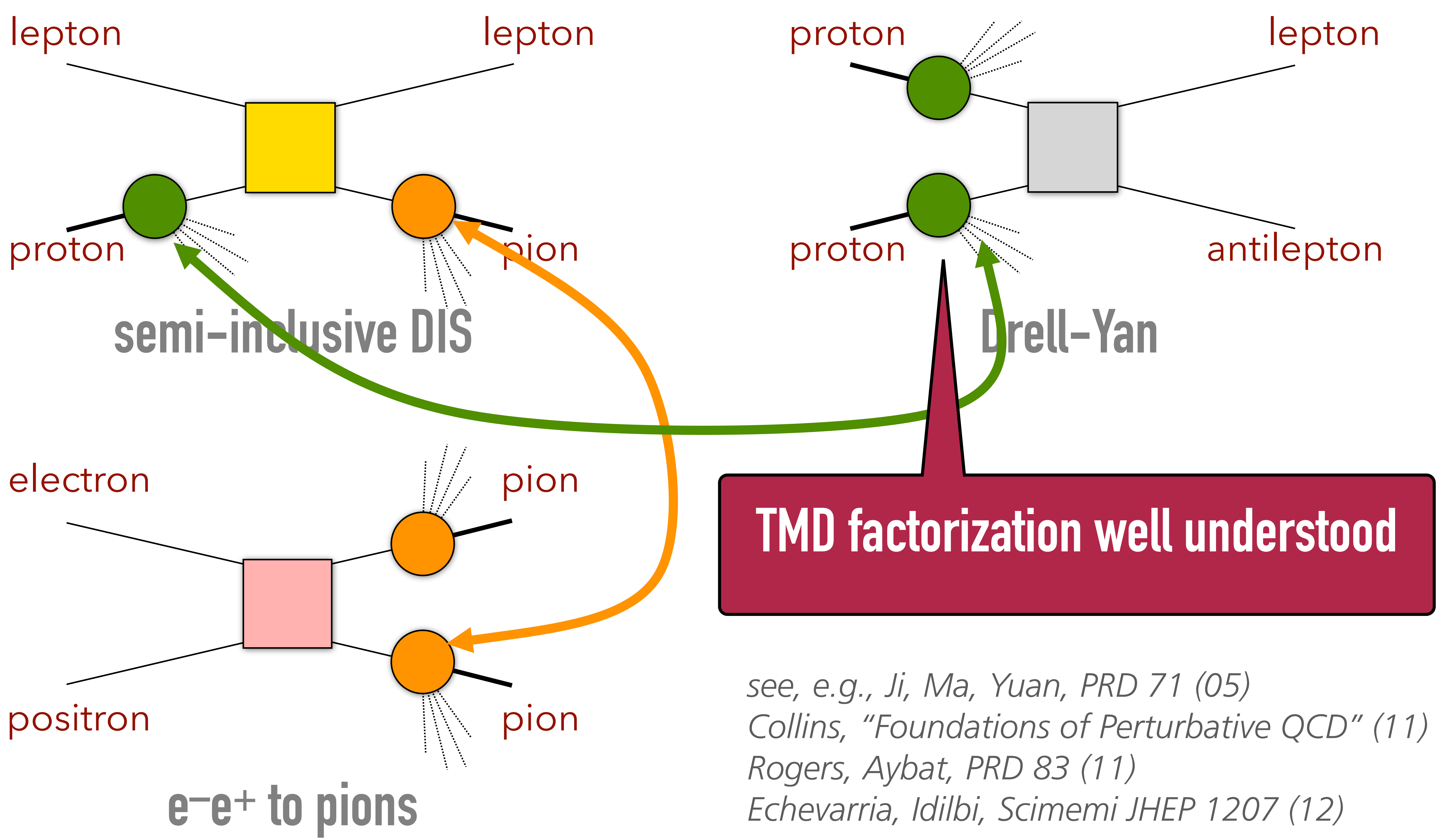
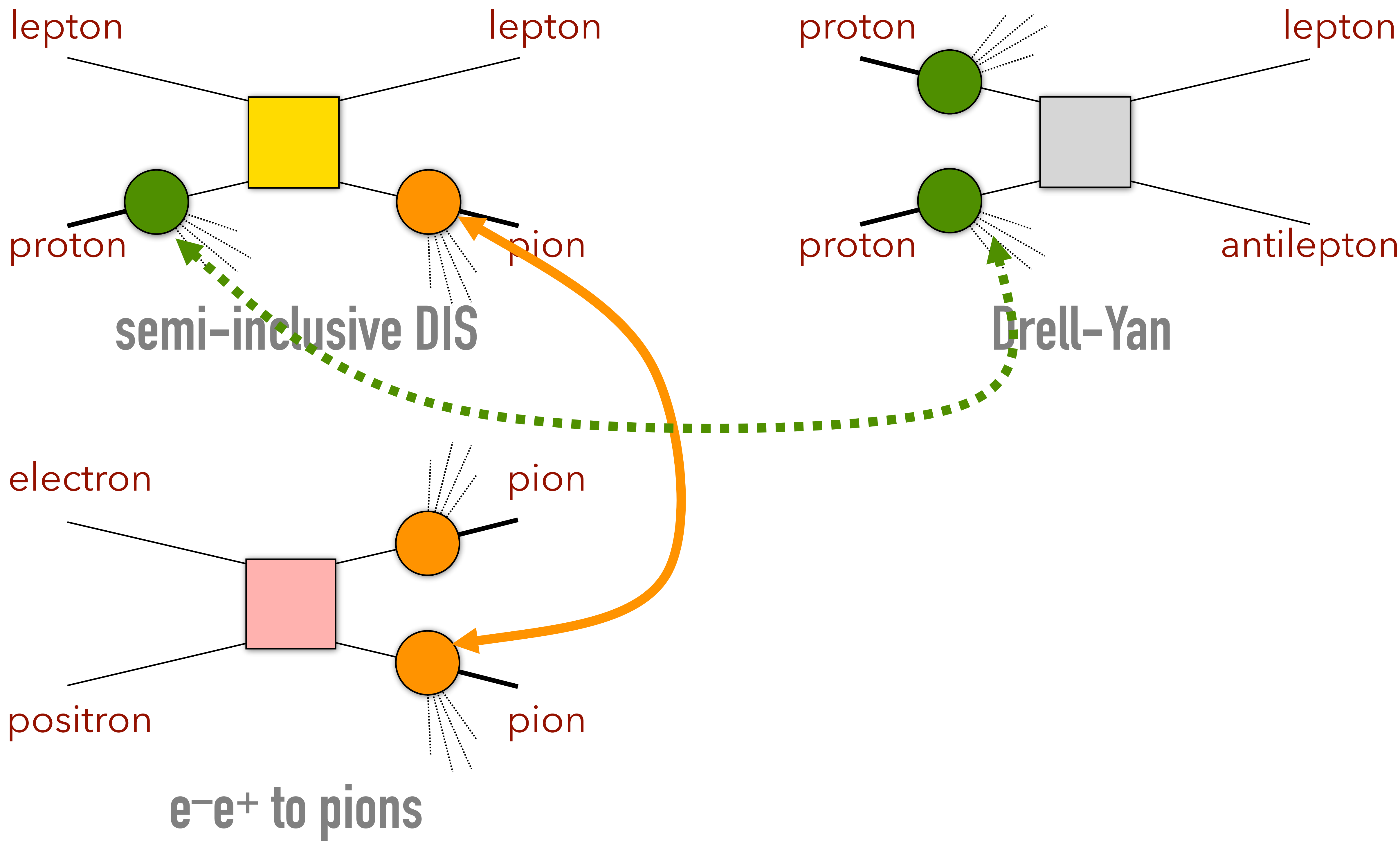


see, e.g., Ji, Ma, Yuan, PRD 71 (05)
Collins, "Foundations of Perturbative QCD" (11)
Rogers, Aybat, PRD 83 (11)
Echevarria, Idilbi, Scimemi JHEP 1207 (12)

FACTORIZATION AND UNIVERSALITY



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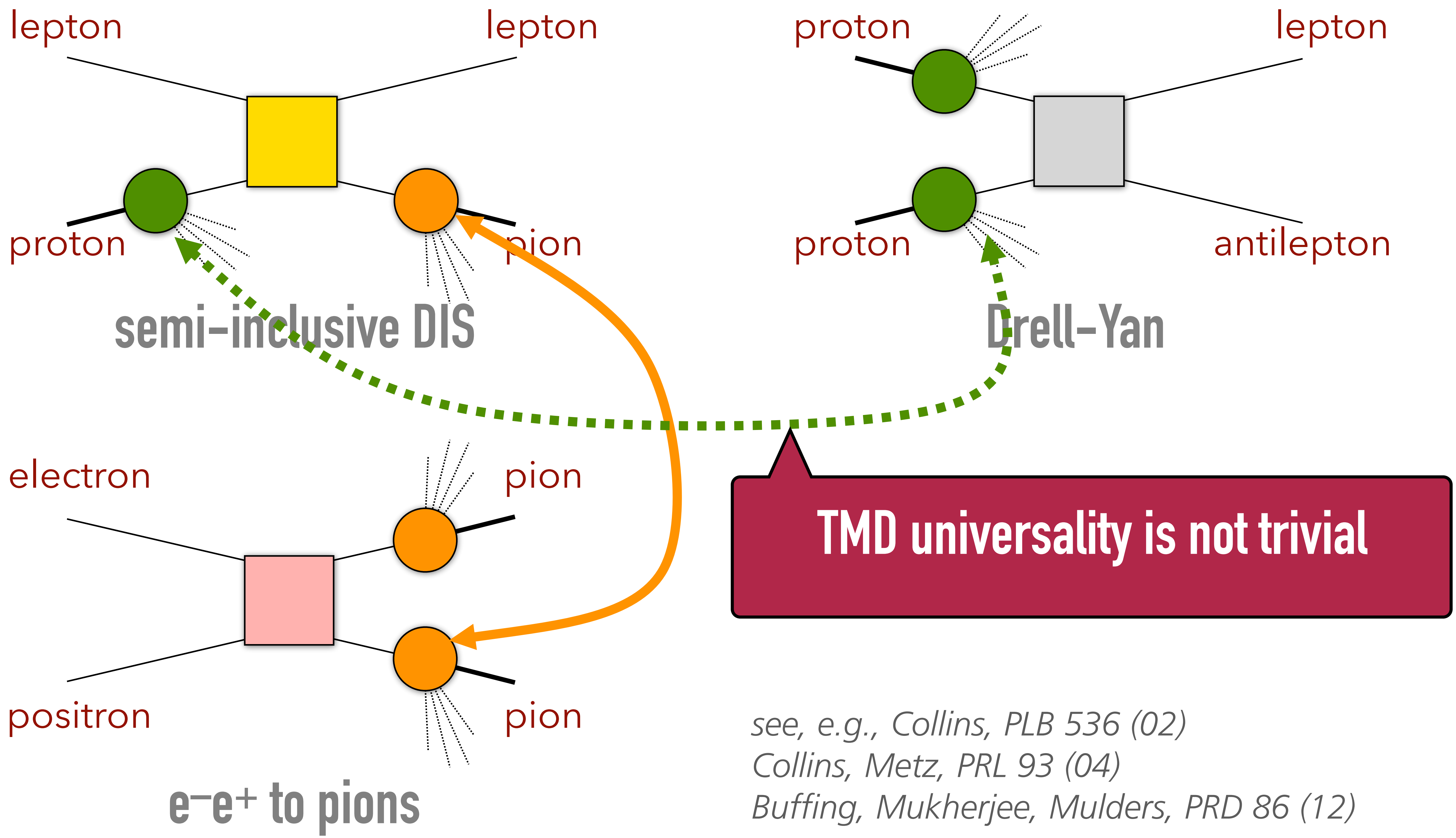

see, e.g., Collins, PLB 536 (02)
Collins, Metz, PRL 93 (04)
Buffing, Mukherjee, Mulders, PRD 86 (12)

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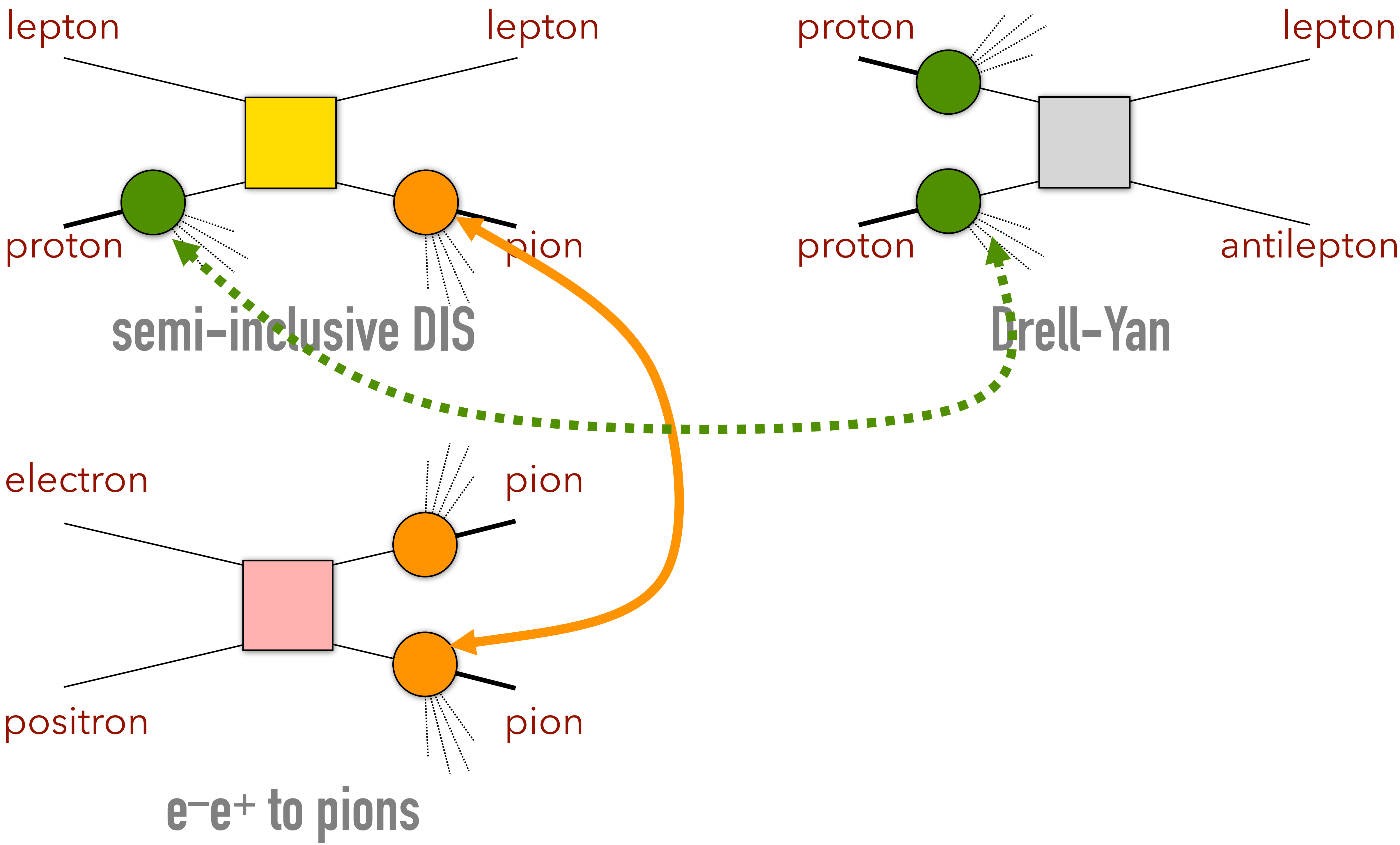

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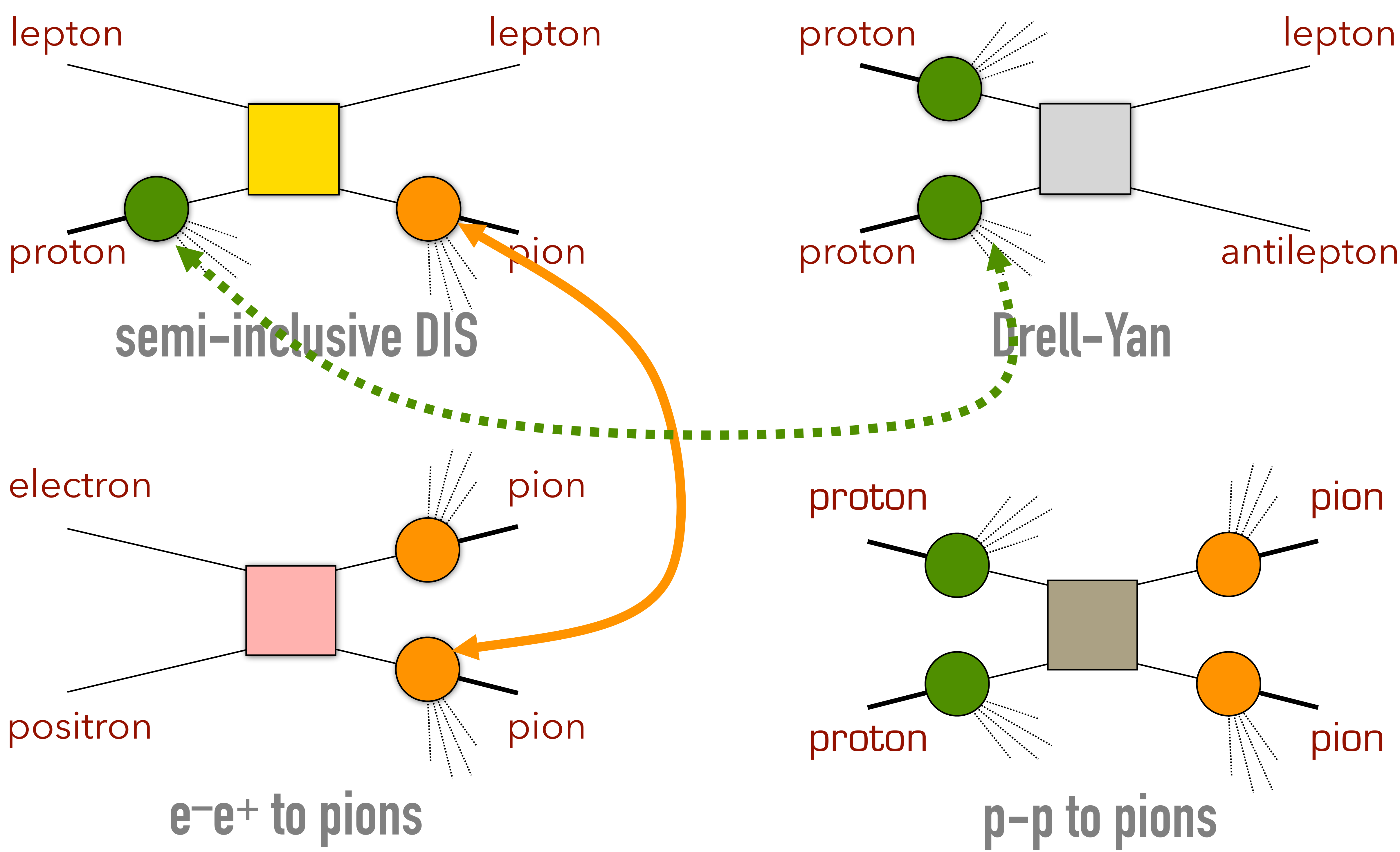

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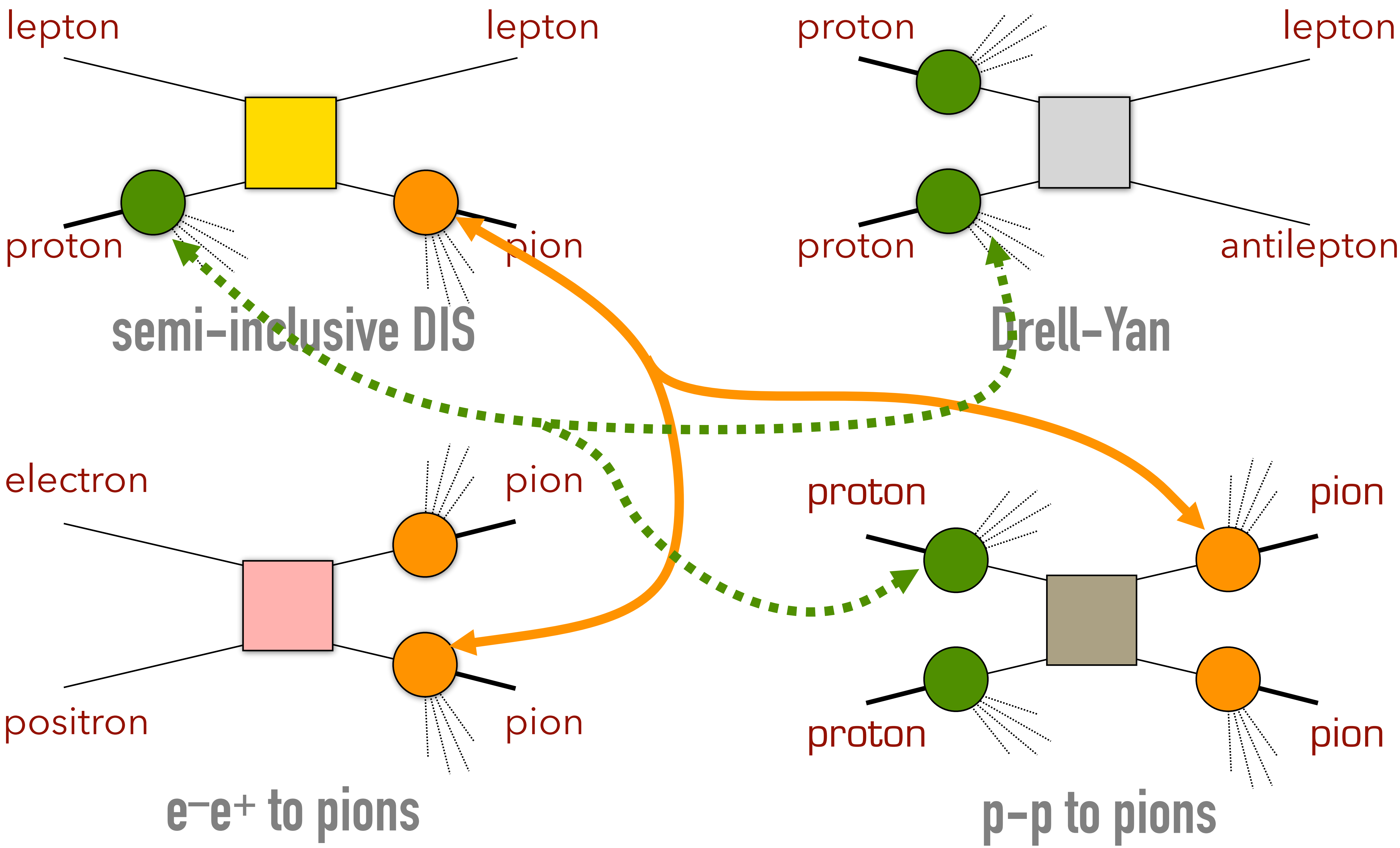

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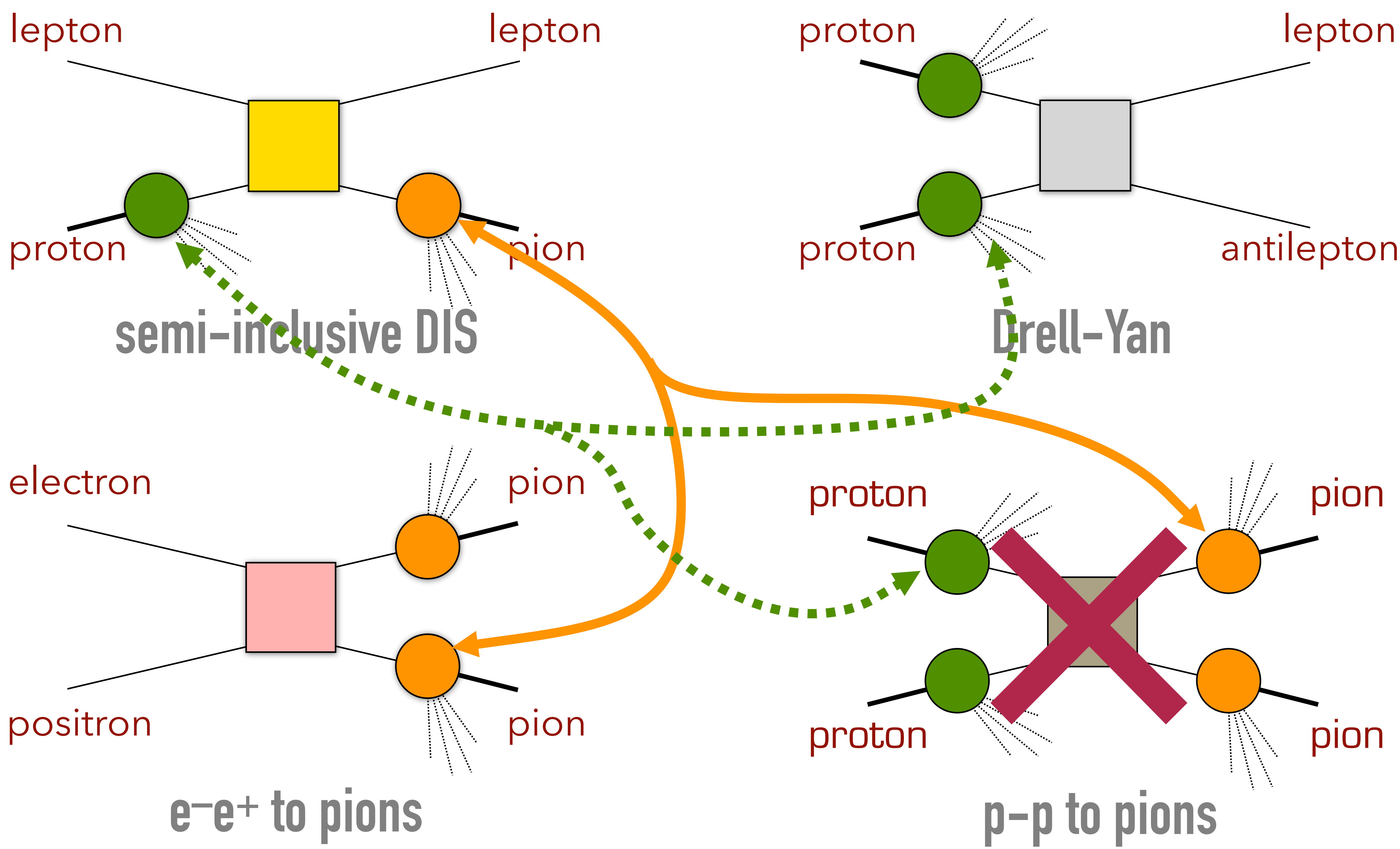
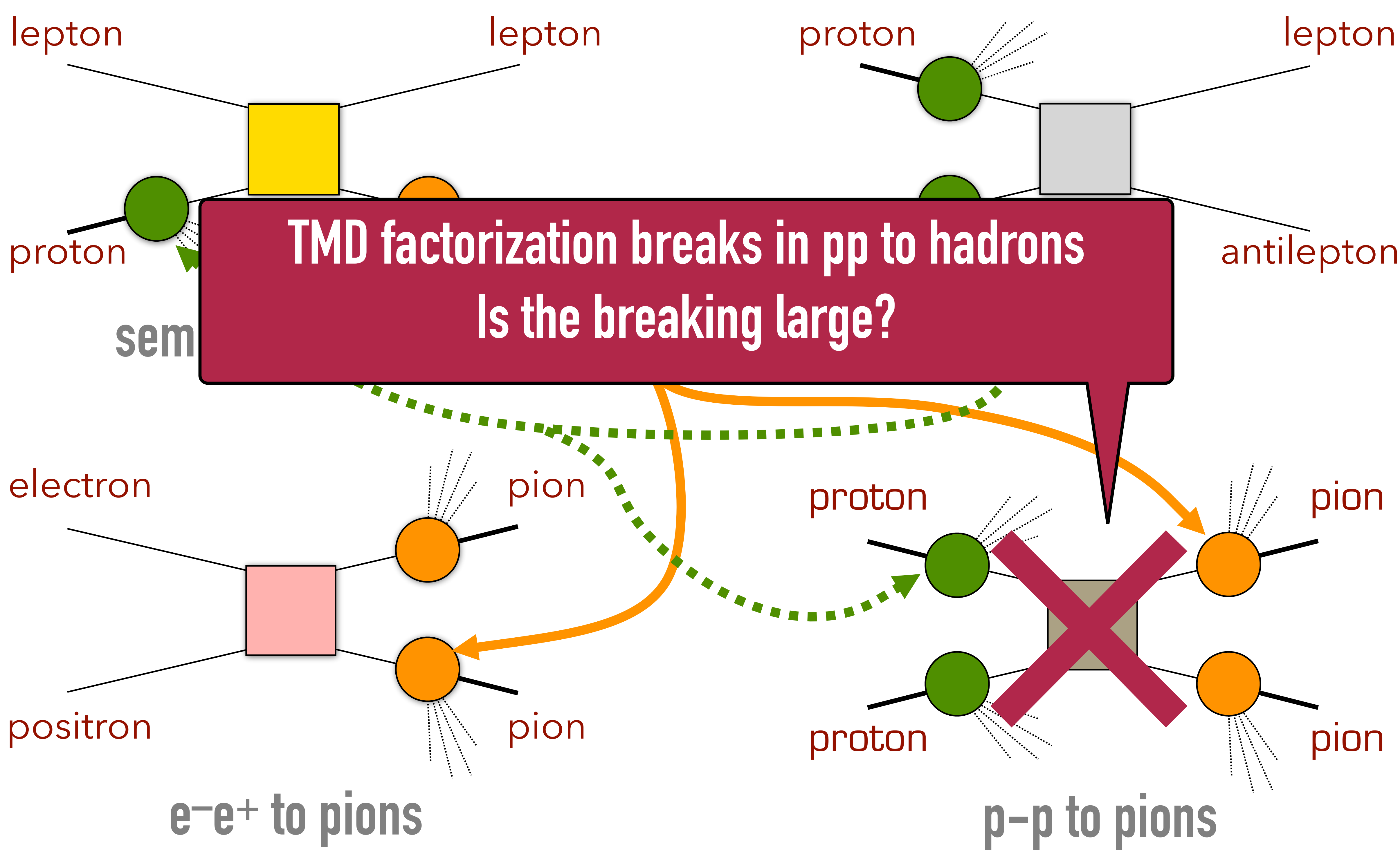


see, e.g., Rogers, Mulders, PRD81 (10)

Buffing, Kang, Lee, Liu, arXiv:1812.07549

FACTORIZATION AND UNIVERSALITY



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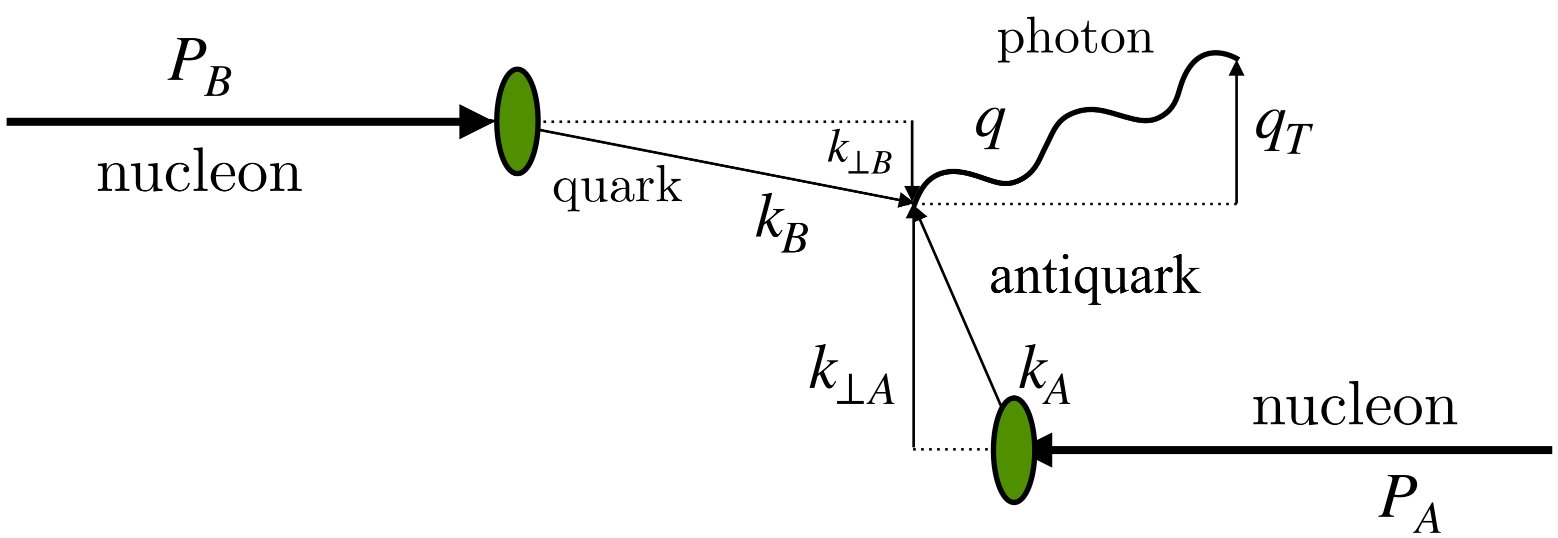
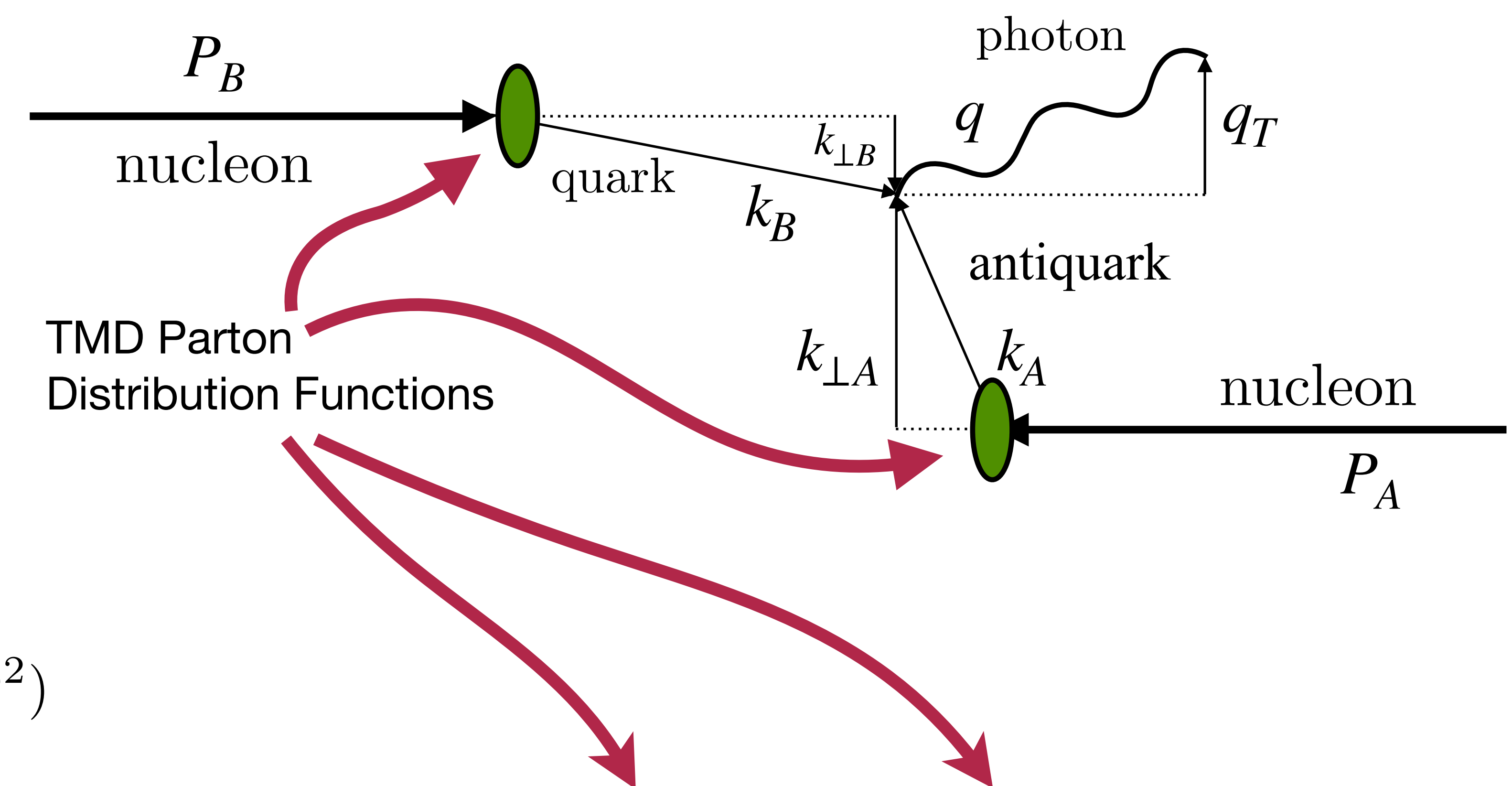
TMDS IN DRELL-YAN PROCESSES



$$
\begin{aligned}
&F_{UU}^{1}(x_A, x_B, \boldsymbol{q}_T^2, Q^2) \\
&\quad = \sum_a \mathcal{H}_{UU}^{1a}(Q^2, \mu^2) \int d^2\boldsymbol{k}_{\perp A}\, d^2\boldsymbol{k}_{\perp B}\, f_1^a\big(x_A, \boldsymbol{k}_{\perp A}^2; \mu^2\big)\, f_1^{\bar{a}}\big(x_B, \boldsymbol{k}_{\perp B}^2; \mu^2\big)\, \delta^{(2)}\big(\boldsymbol{k}_{\perp A} - \boldsymbol{q}_T + \boldsymbol{k}_{\perp B}\big) \\
&\qquad + Y_{UU}^{1}\big(Q^2, \boldsymbol{q}_T^2\big) + \mathcal{O}\big(M^2/Q^2\big)
\end{aligned}
$$

TMDS IN DRELL-YAN PROCESSES



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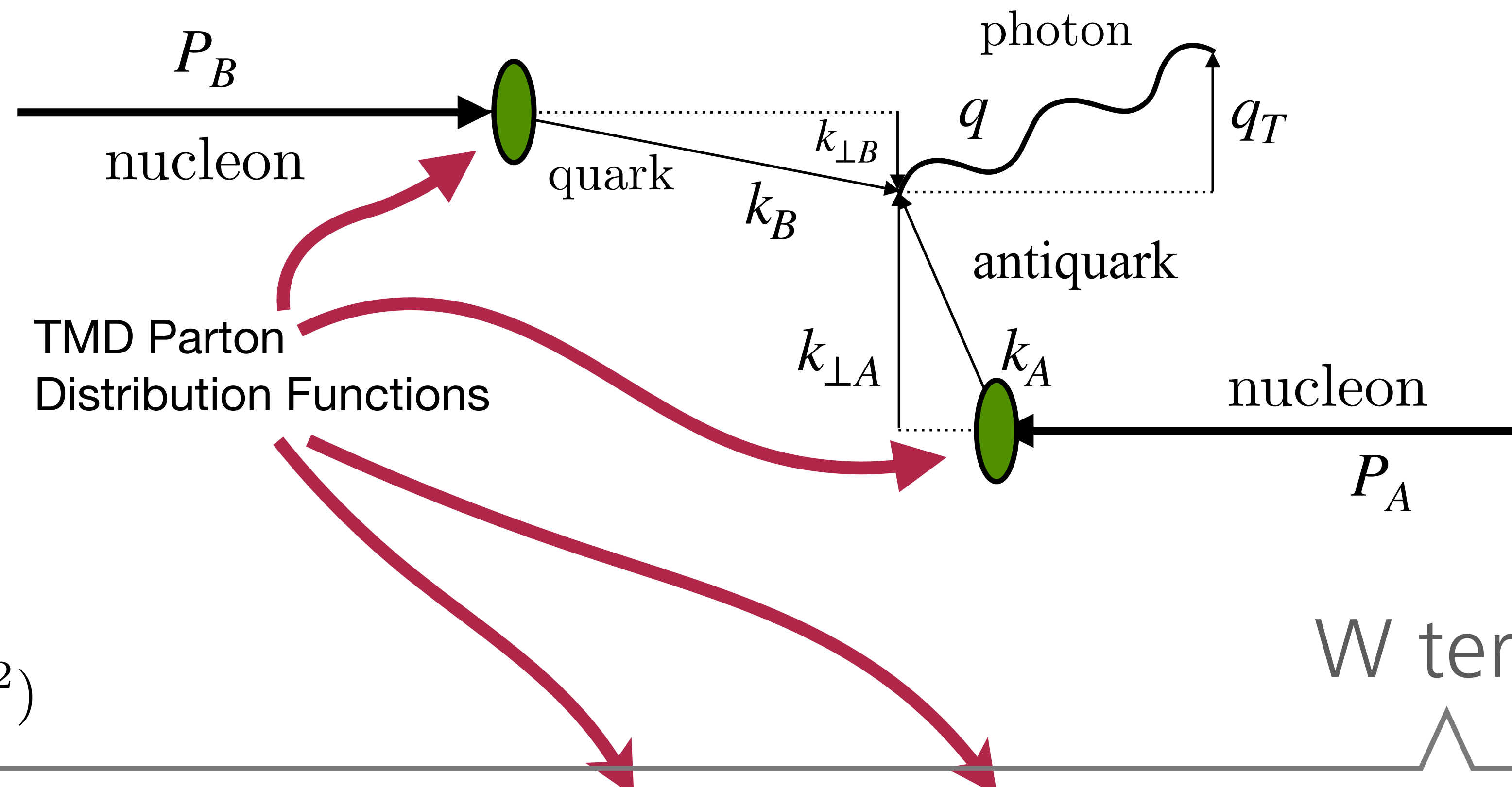
\end{aligned}
$$

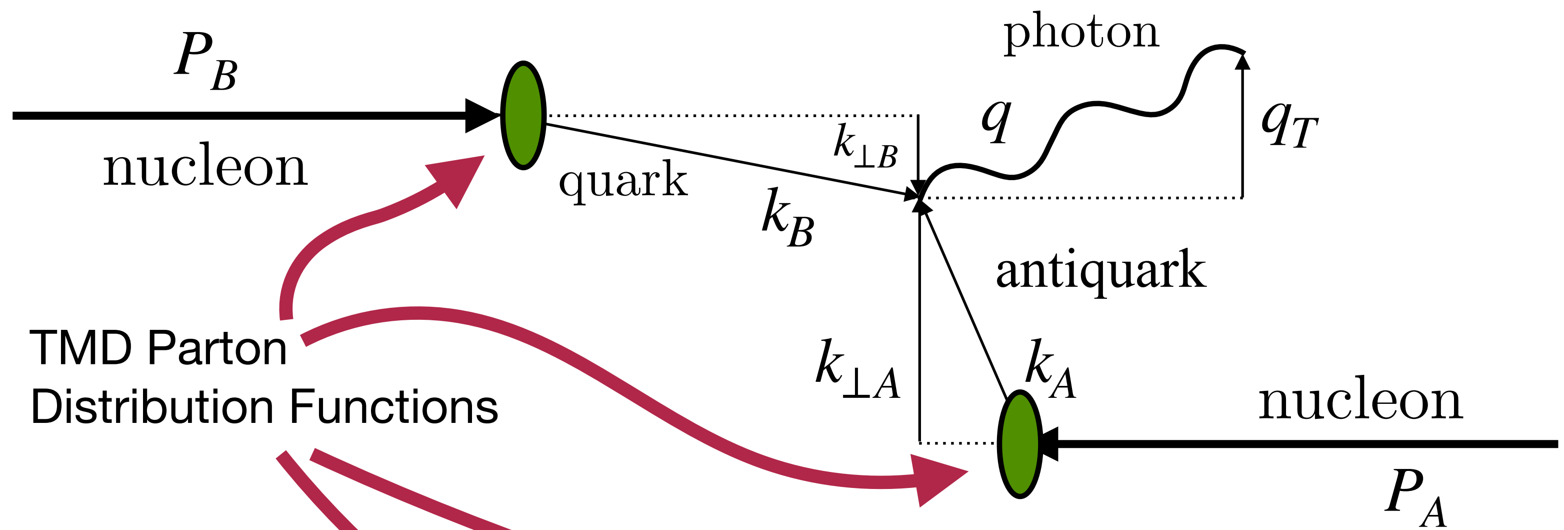
TMDS IN DRELL-YAN PROCESSES



W term

$$
\begin{aligned}
&F^1_{UU}(x_A, x_B, \boldsymbol{q}_T^2, Q^2) \\
&= \sum_a \mathcal{H}^{1a}_{UU}(Q^2, \mu^2) \int d^2\boldsymbol{k}_{\perp A}\, d^2\boldsymbol{k}_{\perp B}\, f_1^a(x_A, \boldsymbol{k}^2_{\perp A}; \mu^2)\, f_1^{\bar{a}}(x_B, \boldsymbol{k}^2_{\perp B}; \mu^2)\, \delta^{(2)}(\boldsymbol{k}_{\perp A} - \boldsymbol{q}_T + \boldsymbol{k}_{\perp B}) \\
&\quad + Y^1_{UU}(Q^2, \boldsymbol{q}_T^2) + \mathcal{O}(M^2/Q^2)
\end{aligned}
$$

TMDS IN DRELL-YAN PROCESSES



TMD Parton
Distribution Functions

W term

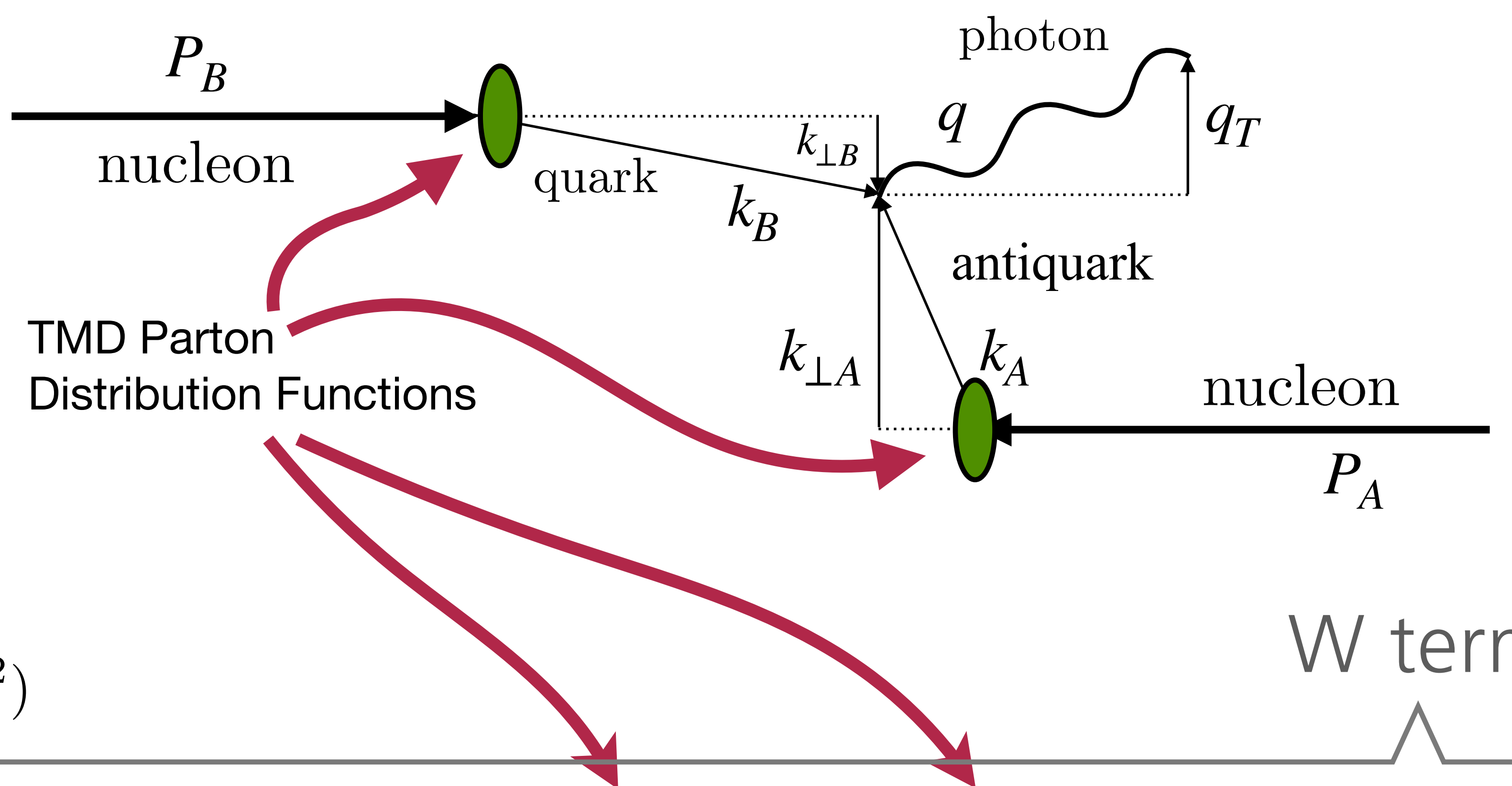
$$F_{UU}^{1}(x_A, x_B, \boldsymbol{q}_T^2, Q^2)$$

$$= \sum_a \mathcal{H}_{UU}^{1a}(Q^2, \mu^2) \int d^2\boldsymbol{k}_{\perp A}\, d^2\boldsymbol{k}_{\perp B}\, f_1^a(x_A, \boldsymbol{k}_{\perp A}^2; \mu^2)\, f_1^{\bar{a}}(x_B, \boldsymbol{k}_{\perp B}^2; \mu^2)\, \delta^{(2)}(\boldsymbol{k}_{\perp A} - \boldsymbol{q}_T + \boldsymbol{k}_{\perp B})$$

$$+ Y_{UU}^{1}(Q^2, \boldsymbol{q}_T^2) + \mathcal{O}(M^2/Q^2)$$

The W term, dominates at low transverse momentum ($q_T \ll Q$)

TMDS IN DRELL-YAN PROCESSES



$$F_{UU}^1(x_A, x_B, \boldsymbol{q}_T^2, Q^2)$$

W term

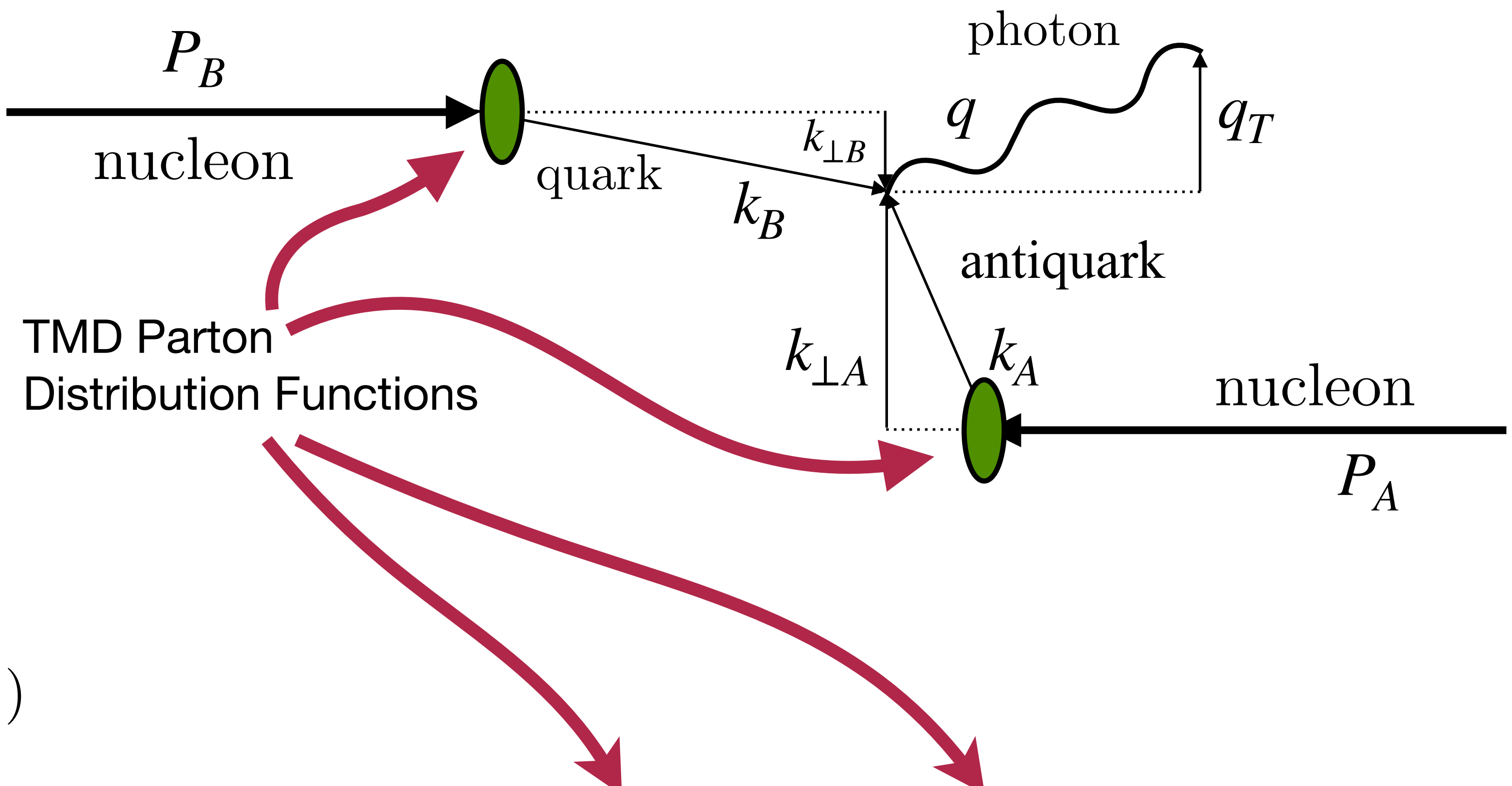
$$= \sum_a \mathcal{H}_{UU}^{1a}(Q^2,\mu^2) \int d^2\boldsymbol{k}_{\perp A}\, d^2\boldsymbol{k}_{\perp B}\, f_1^a(x_A, \boldsymbol{k}_{\perp A}^2;\mu^2)\, f_1^{\bar{a}}(x_B, \boldsymbol{k}_{\perp B}^2;\mu^2)\, \delta^{(2)}(\boldsymbol{k}_{\perp A} - \boldsymbol{q}_T + \boldsymbol{k}_{\perp B})$$

$$+ Y_{UU}^1(Q^2, \boldsymbol{q}_T^2) + \mathcal{O}(M^2/Q^2)$$

The W term, dominates at low transverse momentum ($q_T \ll Q$)

As q_T approaches Q, the Y term is needed to agree with perturbative calculations done in collinear factorization

TMDS IN DRELL-YAN PROCESSES



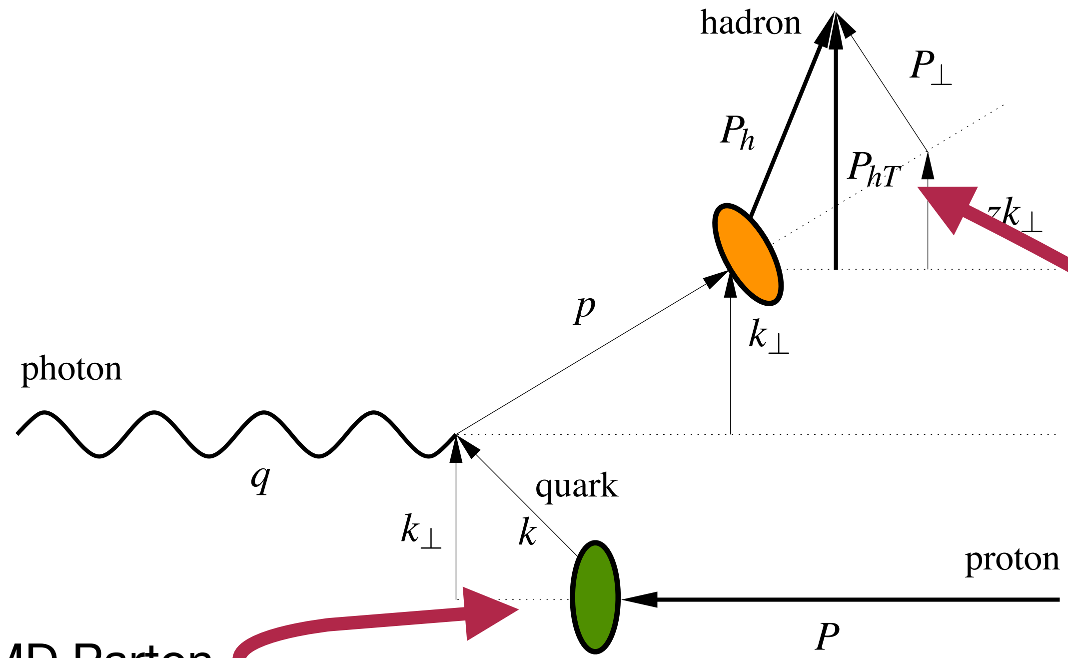
$$F_{UU}^1(x_A, x_B, \boldsymbol{q}_T^2, Q^2)$$

$$\approx \sum_a \mathcal{H}_{UU}^{1a}(Q^2, \mu^2) \int d^2\boldsymbol{k}_{\perp A}\, d^2\boldsymbol{k}_{\perp B}\, f_1^a(x_A, \boldsymbol{k}_{\perp A}^2; \mu^2)\, f_1^{\bar{a}}(x_B, \boldsymbol{k}_{\perp B}^2; \mu^2)\, \delta^{(2)}(\boldsymbol{k}_{\perp A} - \boldsymbol{q}_T + \boldsymbol{k}_{\perp B})$$

$$= \sum_a \mathcal{H}_{UU}^{1a}(Q^2; \mu^2) \int \frac{d\boldsymbol{b}_\perp^2}{4\pi} J_0(|\boldsymbol{b}_T||\boldsymbol{q}_T|) \tilde{f}_1^a(x_A, \boldsymbol{b}_\perp^2; \mu^2)\, \tilde{f}_1^{\bar{a}}(x_B, \boldsymbol{b}_\perp^2; \mu^2)$$

The analysis of the W term is usually done in Fourier-transformed space

TMDS IN SEMI-INCLUSIVE DIS



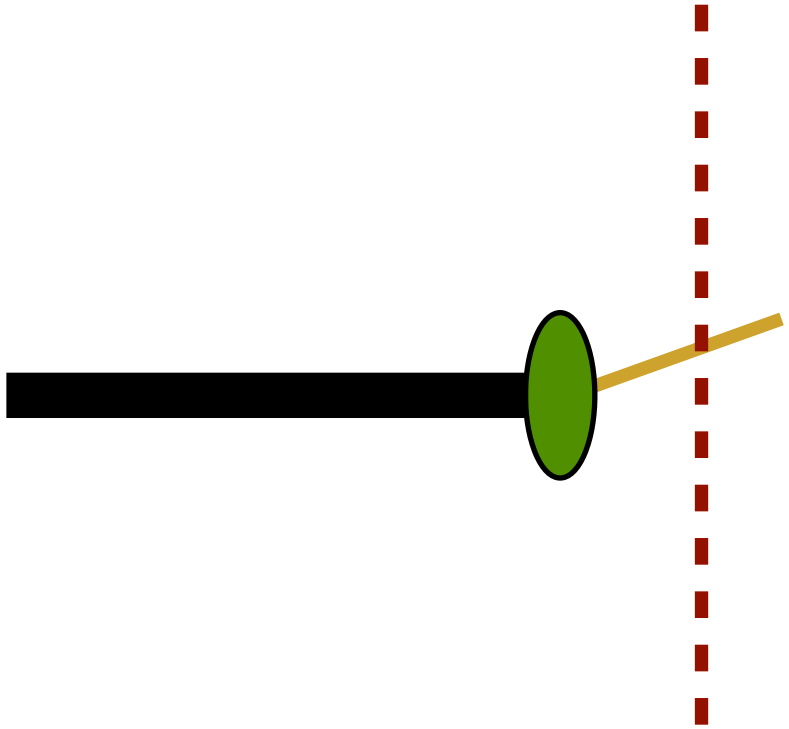
TMD Parton Distribution Functions

TMD Parton Fragmentation Functions

$$
\begin{aligned}
F_{UU,T}(x, z, \boldsymbol{P}_{hT}^2, Q^2) &= \sum_a \mathcal{H}_{UU,T}^a(Q^2;\mu^2) \int d\boldsymbol{k}_\perp \, d\boldsymbol{P}_\perp \, f_1^a(x, \boldsymbol{k}_\perp^2;\mu^2) \, D_1^{a\to h}(z, \boldsymbol{P}_\perp^2;\mu^2) \, \delta(z\boldsymbol{k}_\perp - \boldsymbol{P}_{hT} + \boldsymbol{P}_\perp) \\
&\quad + Y_{UU,T}(Q^2, \boldsymbol{P}_{hT}^2) + \mathcal{O}(M^2/Q^2) \\
&= x \sum_a \mathcal{H}_{UU,T}^a(Q^2;\mu^2) \int \frac{d\boldsymbol{b}_\perp^2}{4\pi} J_0(|\boldsymbol{b}_T||\boldsymbol{P}_{h\perp}|) \tilde{f}_1^a(x, z^2\boldsymbol{b}_\perp^2;\mu^2) \, \tilde{D}_1^{a\to h}(z, \boldsymbol{b}_\perp^2;\mu^2) \\
&\quad + Y_{UU,T}(Q^2, \boldsymbol{P}_{hT}^2) + \mathcal{O}(M^2/Q^2)
\end{aligned}
$$

DIFFERENT CONTRIBUTIONS TO TRANSVERSE MOMENTUM

"intrinsic" transverse momentum

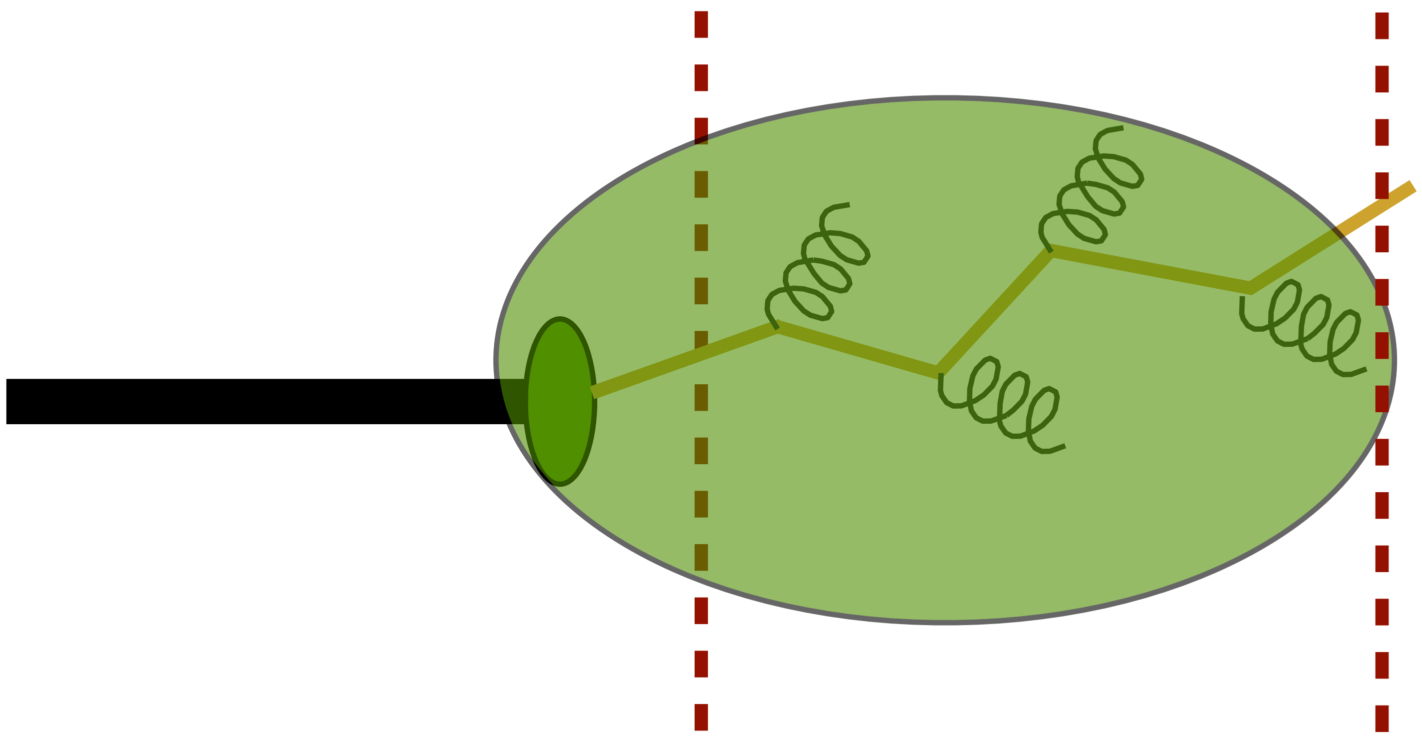


$$|k_\perp| \sim \Lambda_{\mathrm{QCD}}$$

DIFFERENT CONTRIBUTIONS TO TRANSVERSE MOMENTUM

"intrinsic" transverse momentum

soft and collinear gluon radiation



$|k_\perp| \sim \Lambda_{\mathrm{QCD}}$

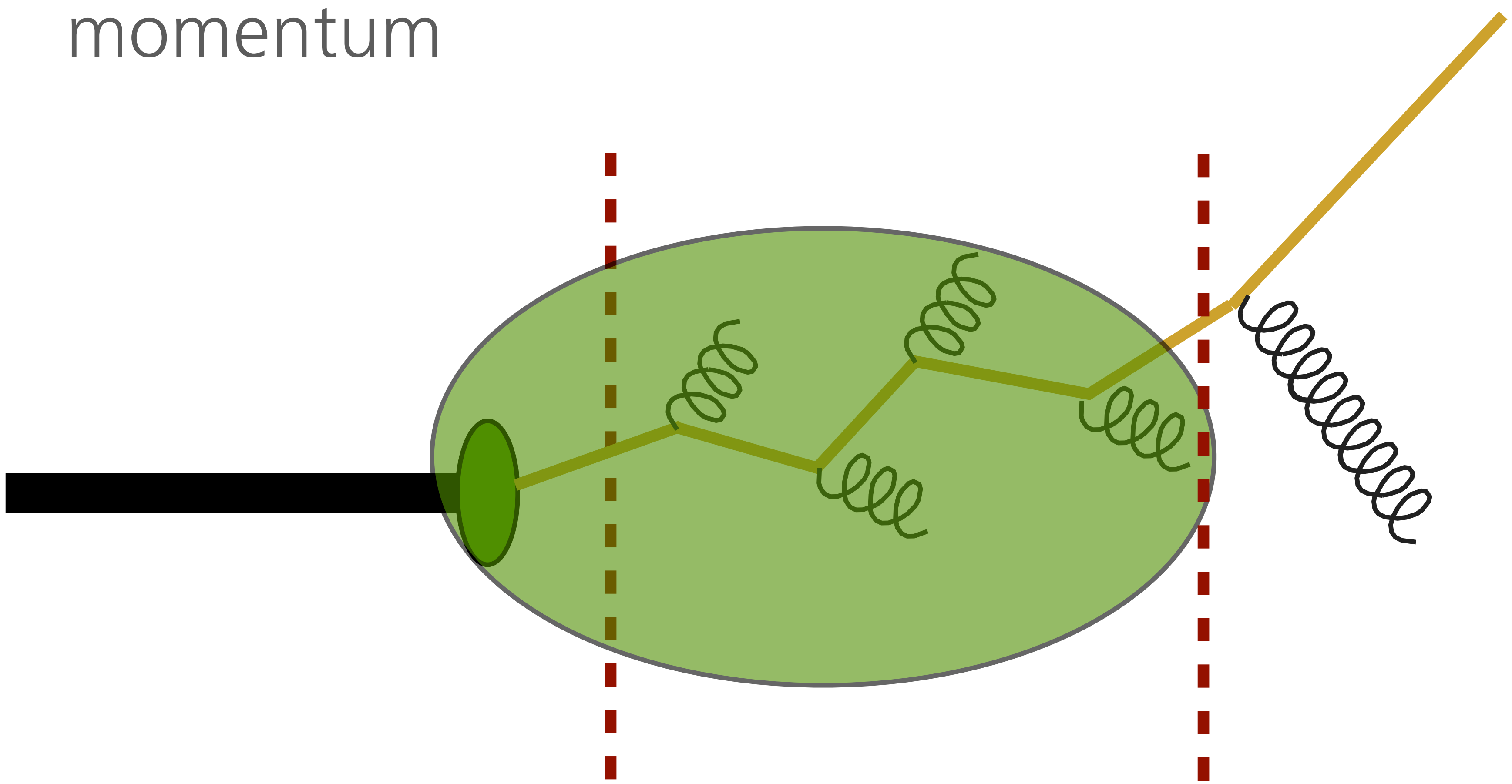
$|k_\perp| \ll Q$

DIFFERENT CONTRIBUTIONS TO TRANSVERSE MOMENTUM

"intrinsic" transverse momentum

soft and collinear gluon radiation

hard gluon radiation



$|k_\perp| \sim \Lambda_{\mathrm{QCD}}$

$|k_\perp| \ll Q$

$|k_\perp| \sim Q$

TMD FACTORIZATION

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

see, e.g., Rogers, Aybat, PRD 83 (11),
Collins, "Foundations of Perturbative QCD" (11)

other possible schemes, e.g.,
Laenen, Sterman, Vogelsang, PRL 84 (00)
Bozzi, Catani, De Florian, Grazzini, NPB737 (06)
Echevarria, Idilbi, Schaefer, Scimemi, EPJ C73 (13)

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$$\widetilde{f}_1^a(x, b_T; \mu^2) = \sum_i (\tilde{C}_{a/i} \otimes f_1^i)(x, b_*; \mu_b) e^{\tilde{S}(b_*; \mu_b, \mu)} e^{g_K(b_T) \ln \frac{\mu}{\mu_0}} \hat{f}_{\rm NP}^a(x, b_T)$$

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$$\mu_b = \frac{2e^{-\gamma_E}}{b_*}$$

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perturbative Sudakov form factor

$$\widetilde{f}_1^a(x, b_T; \mu^2) = \sum_i (\tilde{C}_{a/i} \otimes f_1^i)(x, b_*; \mu_b) e^{\tilde{S}(b_*;\mu_b,\mu)} e^{g_K(b_T) \ln \frac{\mu}{\mu_0}} \hat{f}^a_{\text{NP}}(x, b_T)$$

$$\mu_b = \frac{2e^{-\gamma_E}}{b_*}$$

collinear PDF

matching coefficients (perturbative)

nonperturbative part of evolution

nonperturbative part of TMD

see, e.g., Rogers, Aybat, PRD 83 (11),
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LOGARITHMIC ACCURACY

Sudakov form factor

LL $\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right)$

LOGARITHMIC ACCURACY

Sudakov form factor

LL $$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right)$$

NLL $$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right), \quad \alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$$

LOGARITHMIC ACCURACY

	Sudakov form factor	matching coeff.
LL	$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right)$	$\tilde{C}^0$
NLL	$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right), \quad \alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$	$\tilde{C}^0$

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NLL′	$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right), \quad \alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$	$\left(\tilde{C}^0 + \alpha_S \tilde{C}^1\right)$

LOGARITHMIC ACCURACY

	Sudakov form factor	matching coeff.
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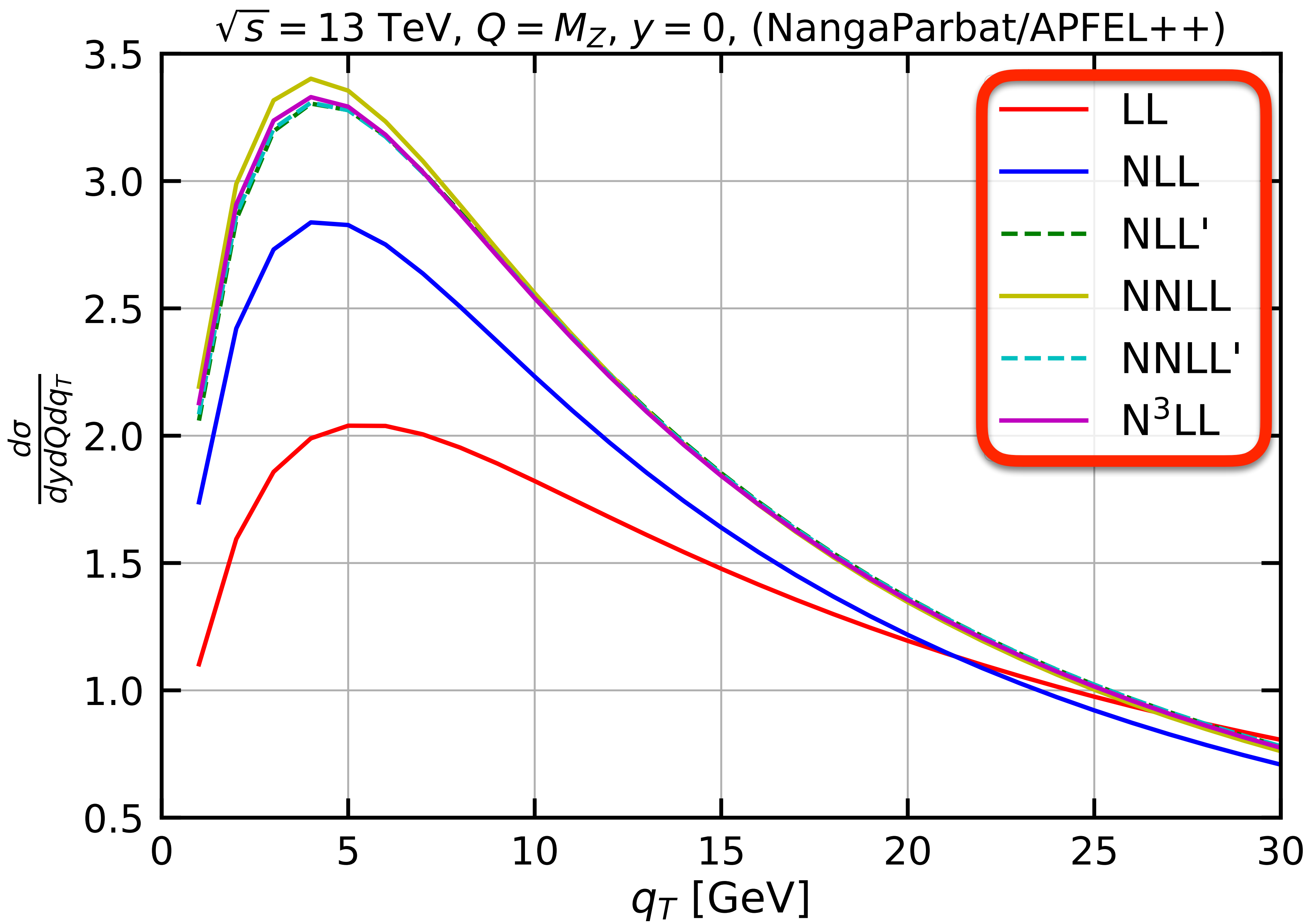
NLL′	$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right), \quad \alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$	$\left(\tilde{C}^0 + \alpha_S \tilde{C}^1\right)$

the difference between the two is NNLL $\qquad \alpha_S^n \ln^{2n-2}\left(\frac{Q^2}{\mu_b^2}\right)$

COMPARISON OF DIFFERENT ORDERS

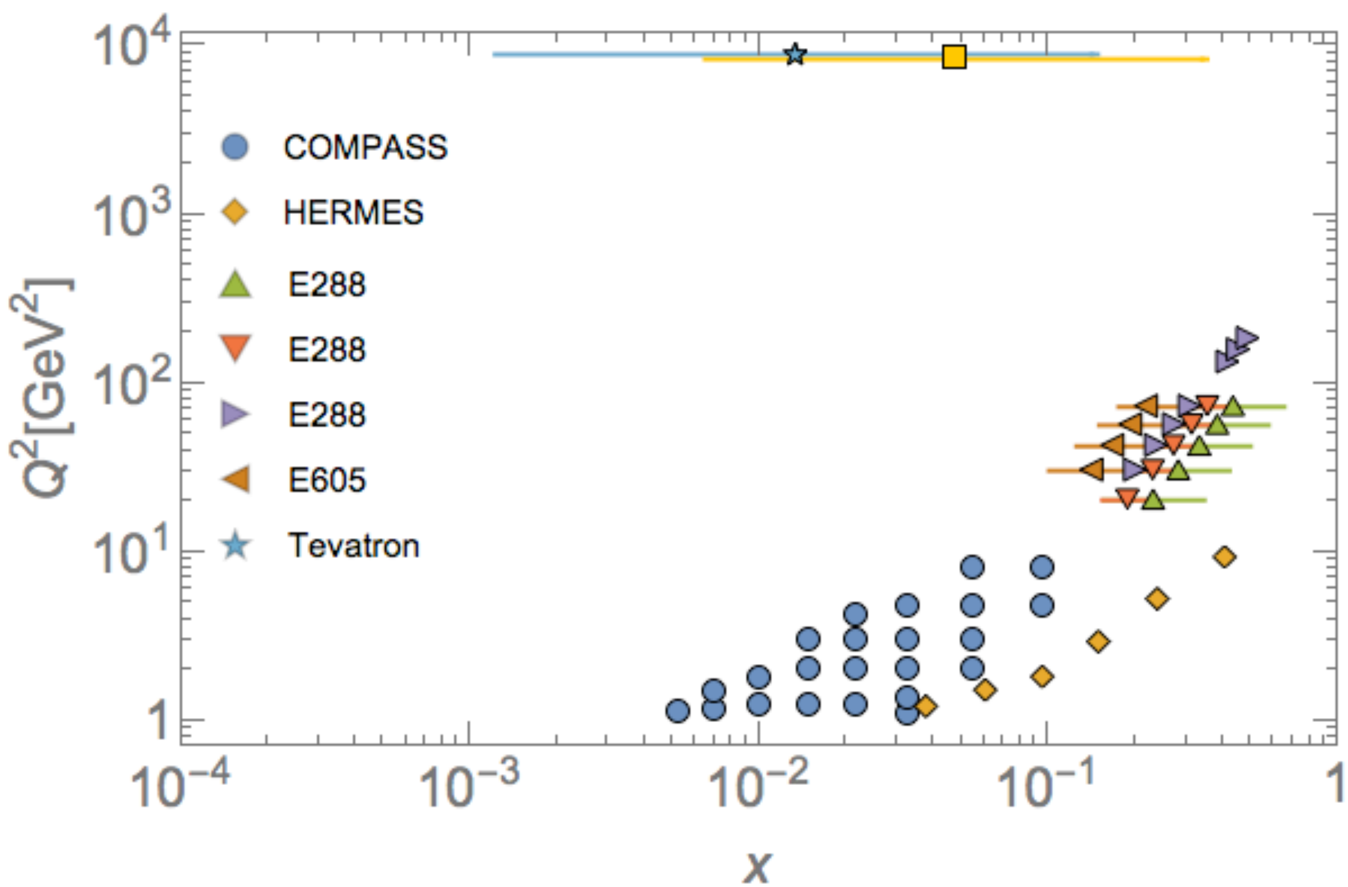
V. Bertone's talk at IWHSS 2019



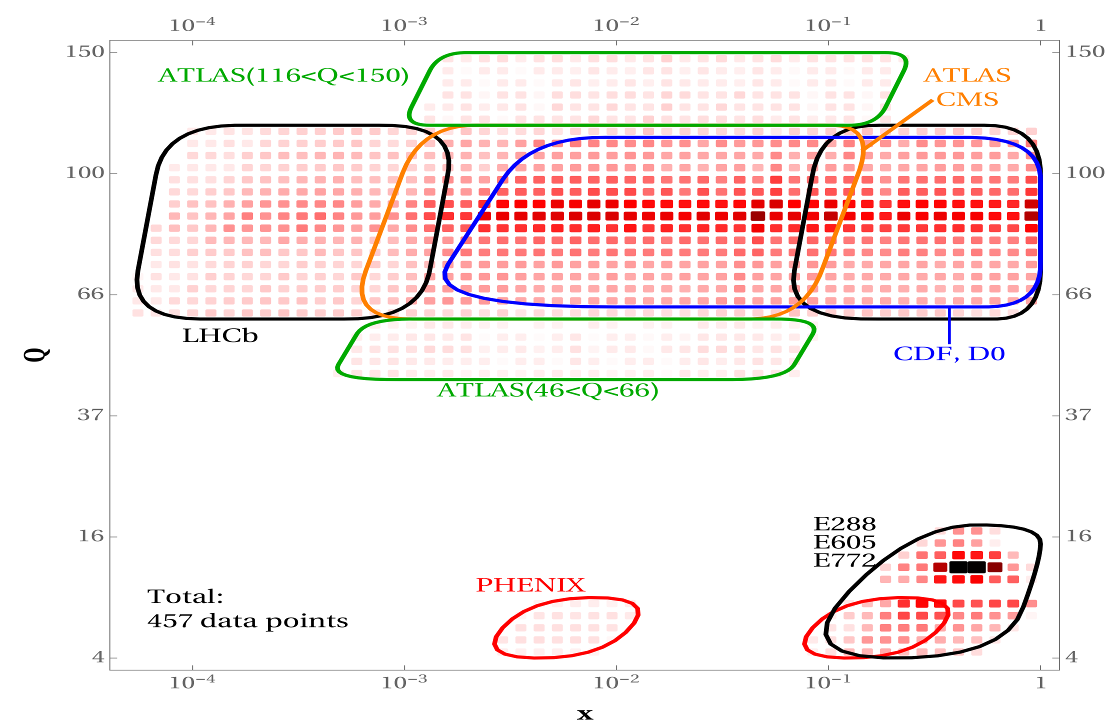
TMD FITS OF UNPOLARIZED DATA

	Framework	HERMES	COMPASS	DY	Z production	N of points
Pavia 2013 arXiv:1309.3507	parton model	✔	✘	✘	✘	1538
Torino 2014 arXiv:1312.6261	parton model	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NNLL	✘	✘	✔	✔	223
EIKV 2014 arXiv:1401.5078	NLL	1 (x,Q^2) bin	1 (x,Q^2) bin	✔	✔	500 (?)
SIYY 2014 arXiv:1406.3073	NLL′	✘	✔	✔	✔	200 (?)
Pavia 2017 arXiv:1703.10157	NLL	✔	✔	✔	✔	8059
SV 2017 arXiv:1706.01473	NNLL′	✘	✘	✔	✔	309
BSV 2019 arXiv:1902.08474	NNLL′	✘	✘	✔	✔	457

x–Q² COVERAGE



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



Bertone, Scimemi, Vladimirov, arXiv:1902.08474

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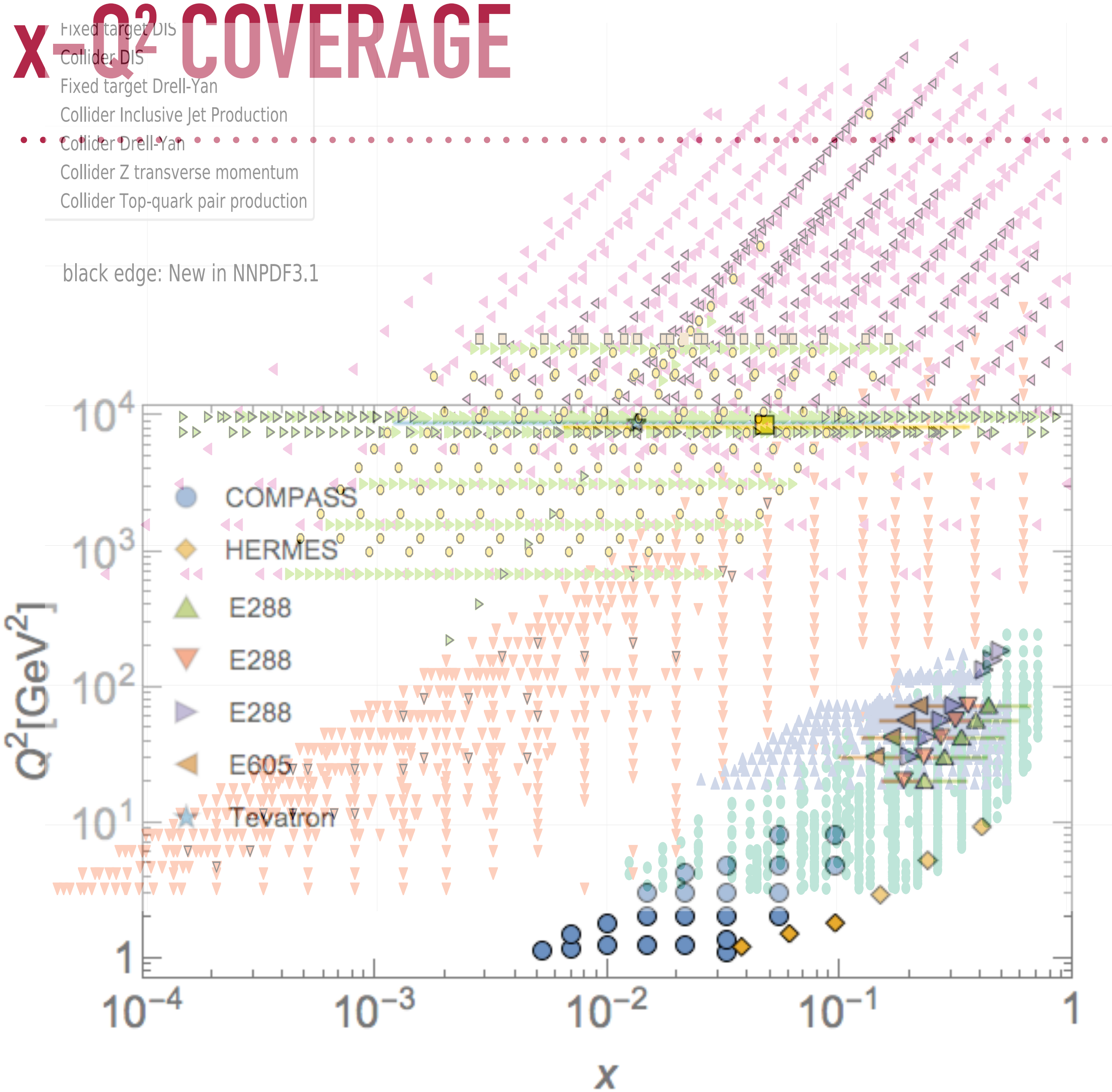

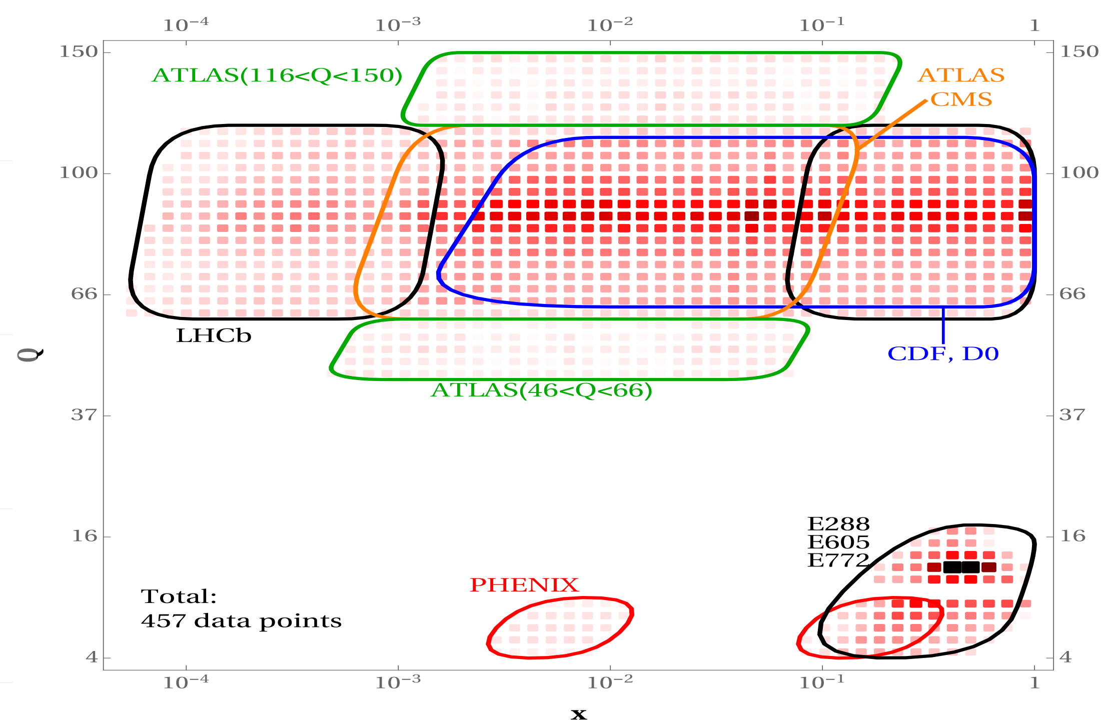

Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

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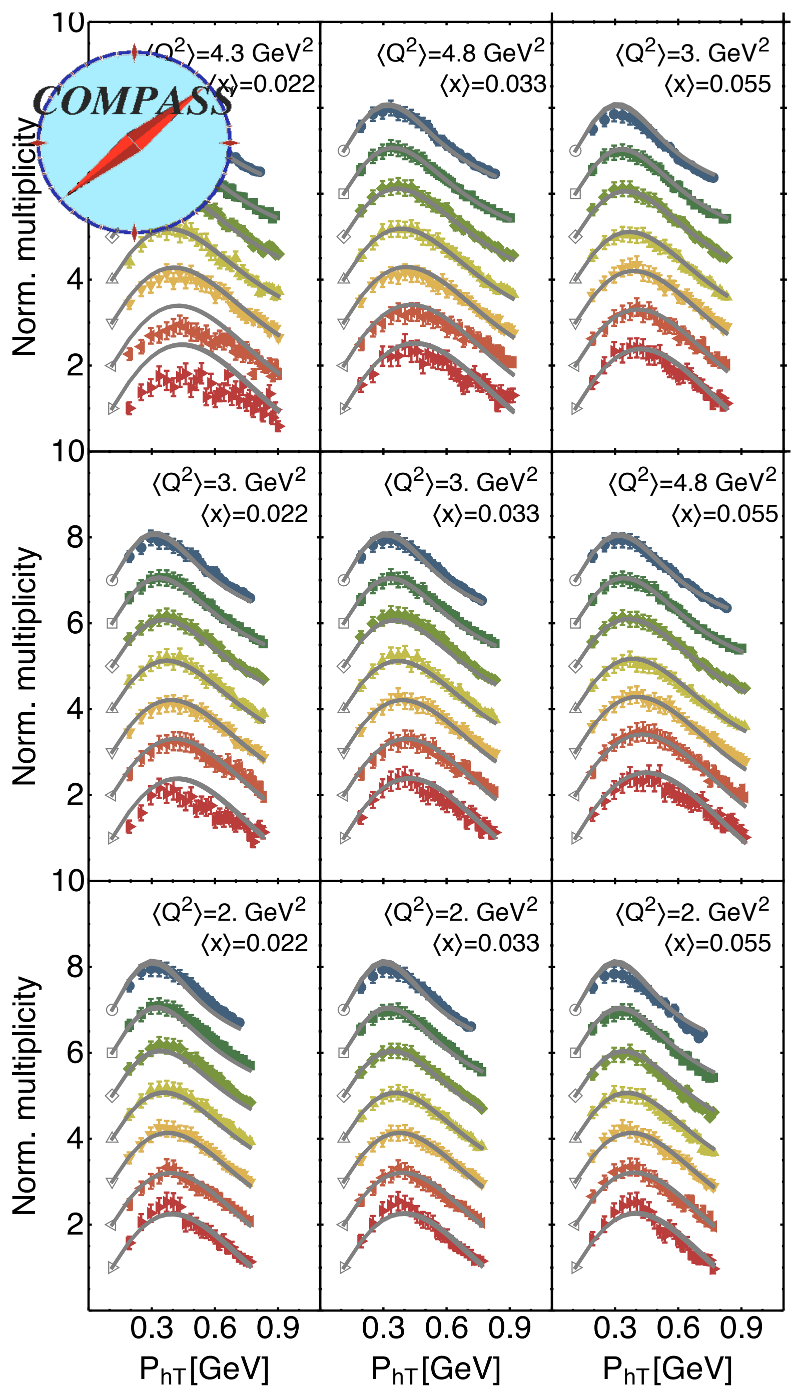
FIRST TMD GLOBAL FIT

SIDIS



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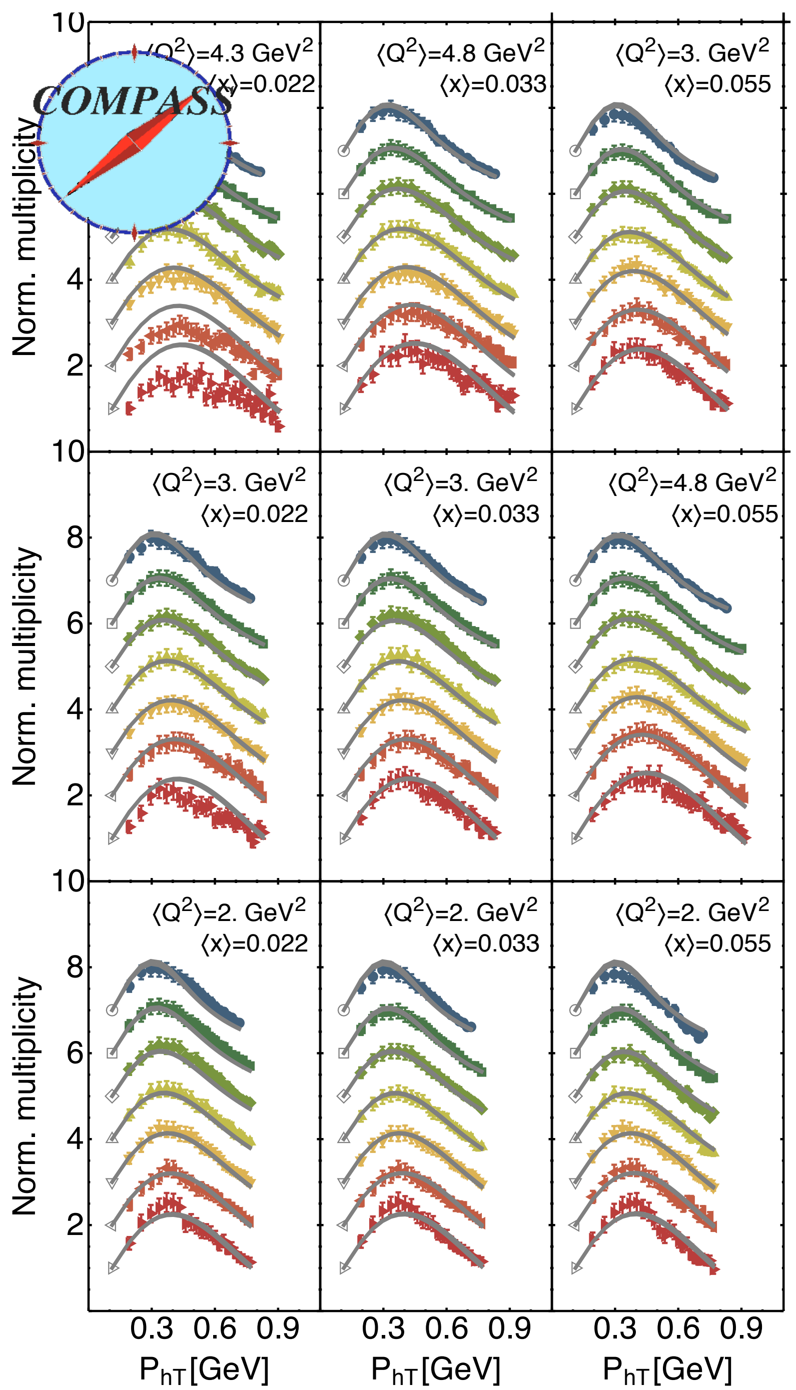
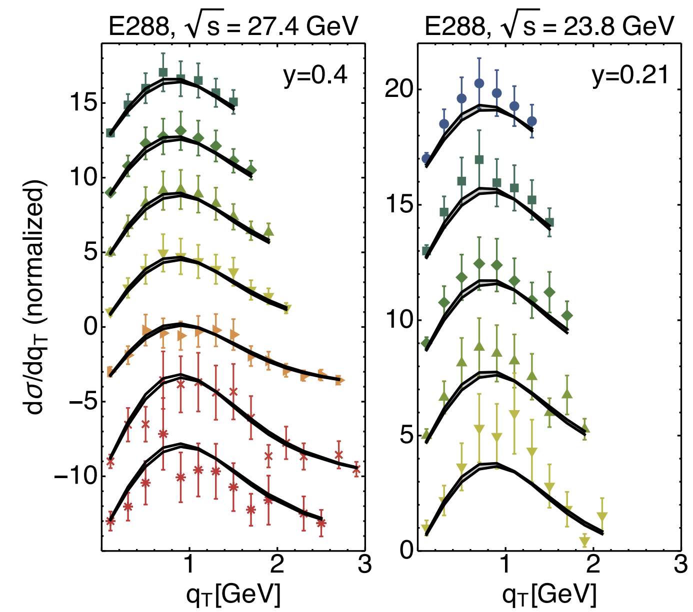


Drell-Yan

Fermilab



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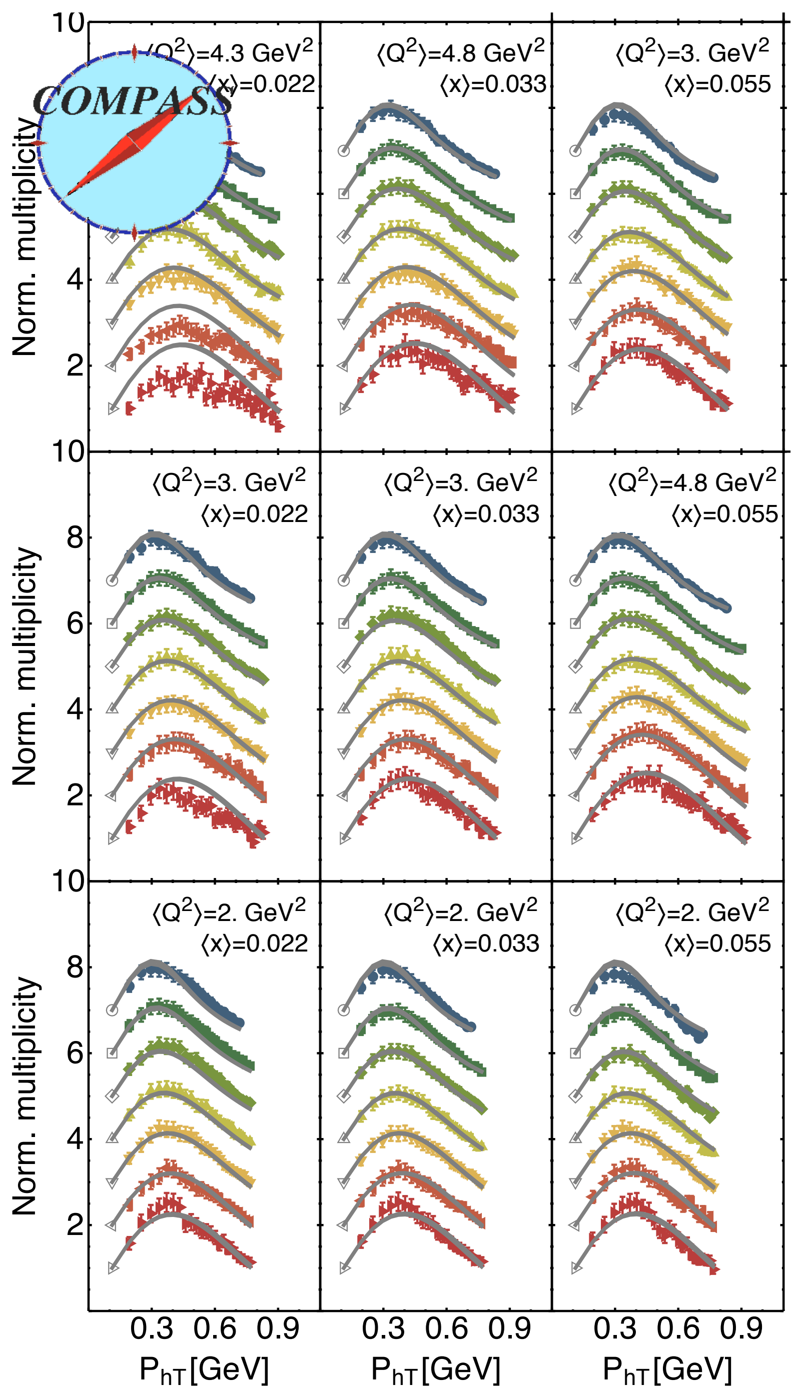

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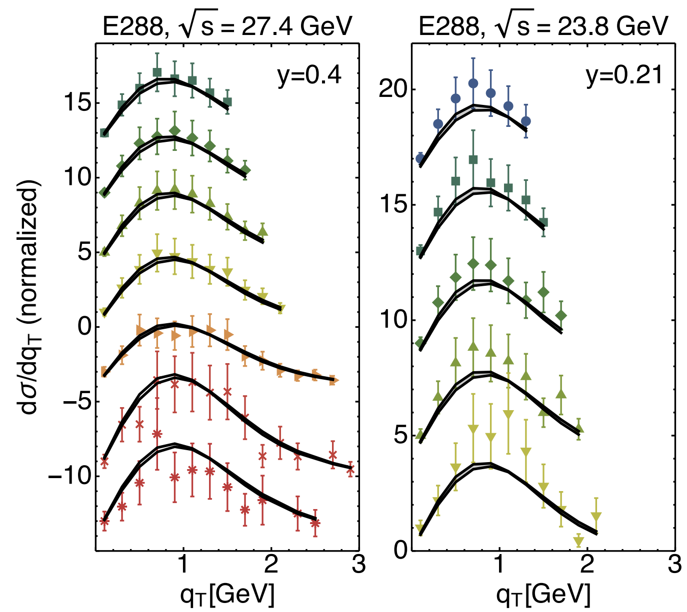
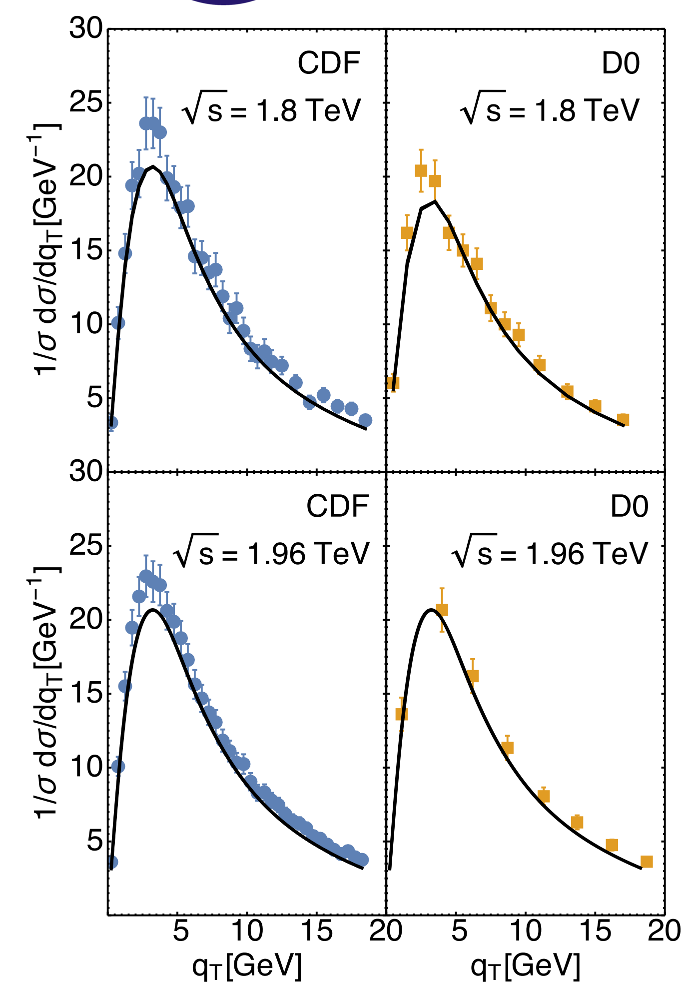
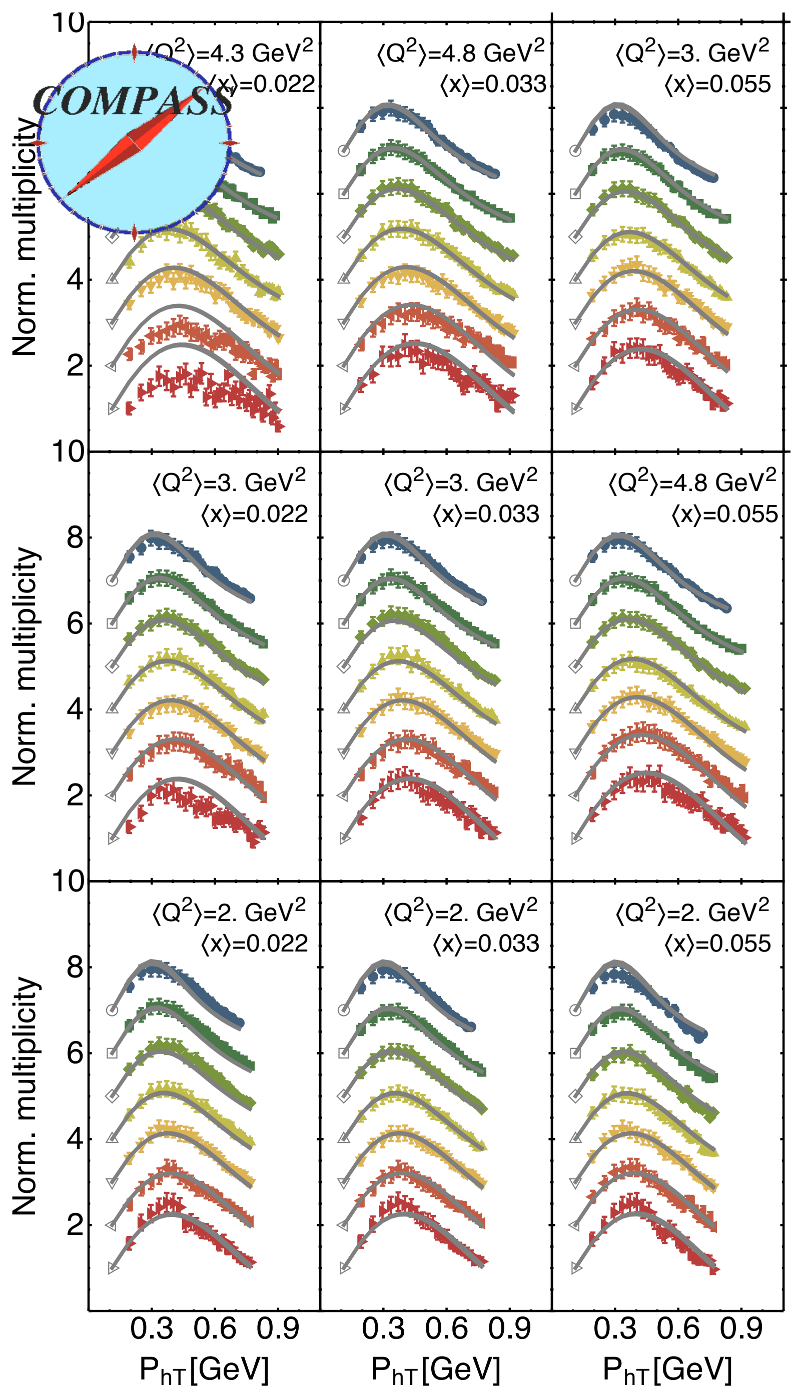


Z production



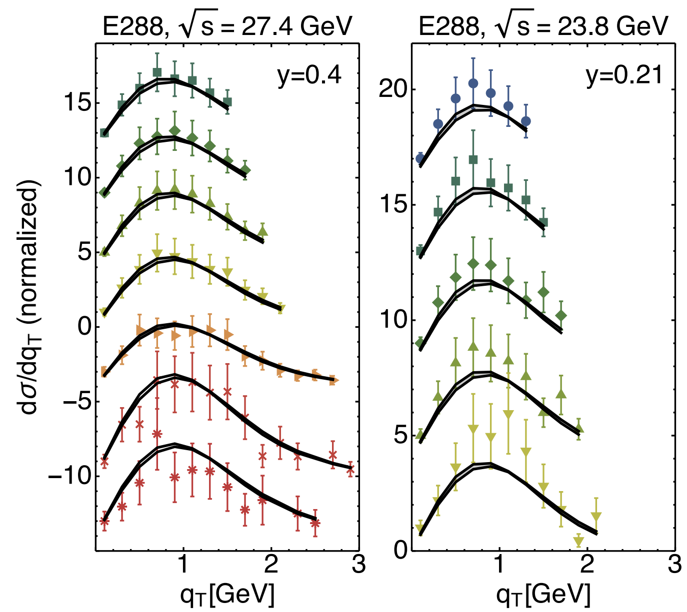
FIRST TMD GLOBAL FIT

SIDIS



Drell-Yan

Fermilab



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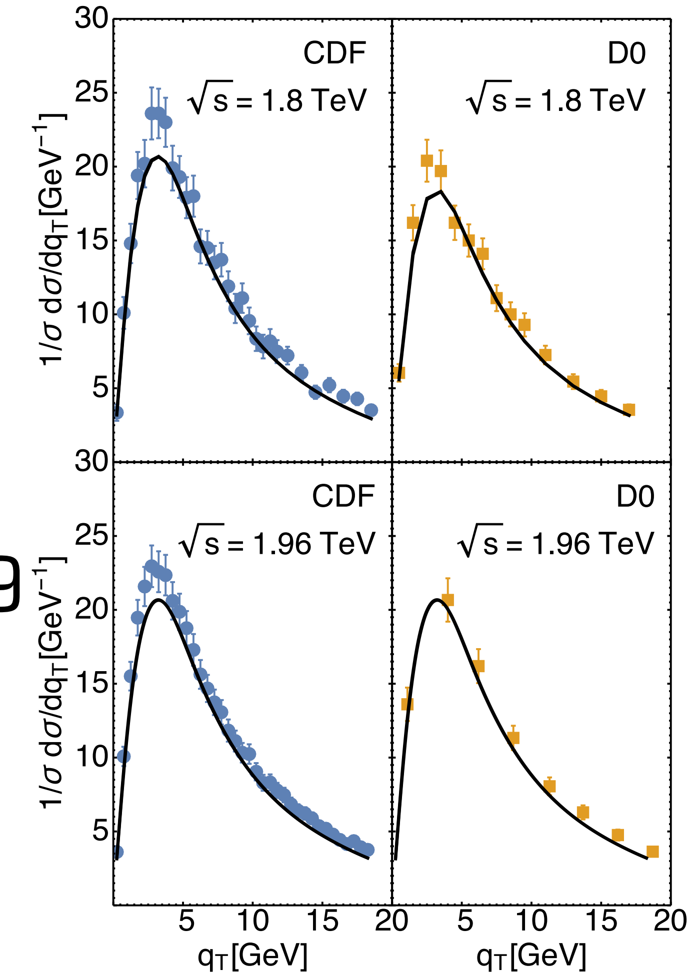


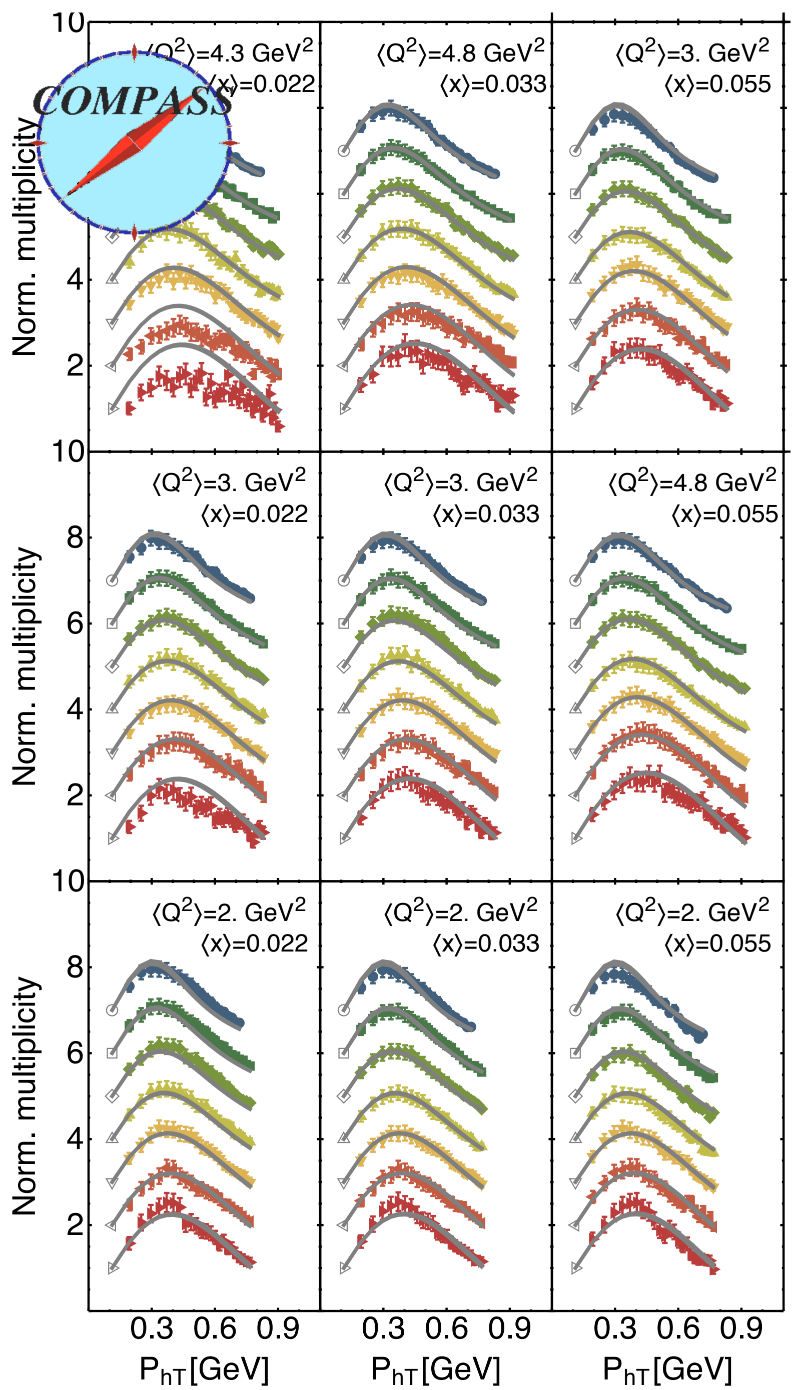
Number of data points: 8059

Global $\chi^2/\mathrm{dof} = 1.55$

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

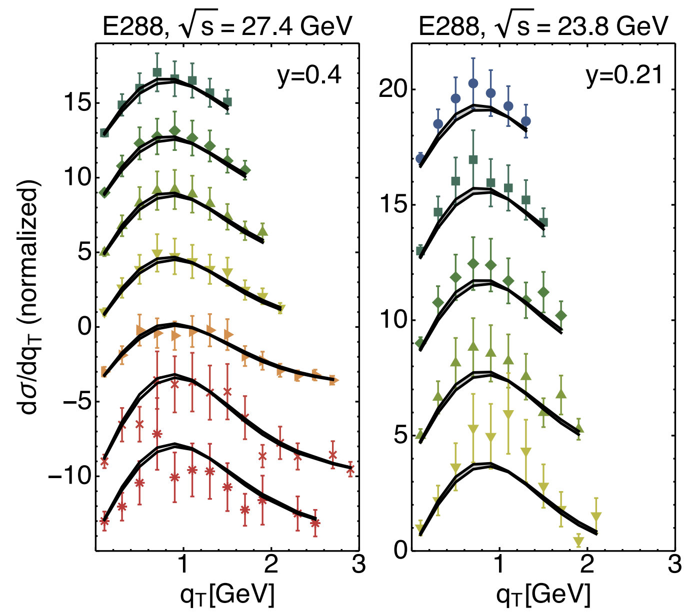
FIRST TMD GLOBAL FIT

SIDIS



Drell-Yan

Fermilab



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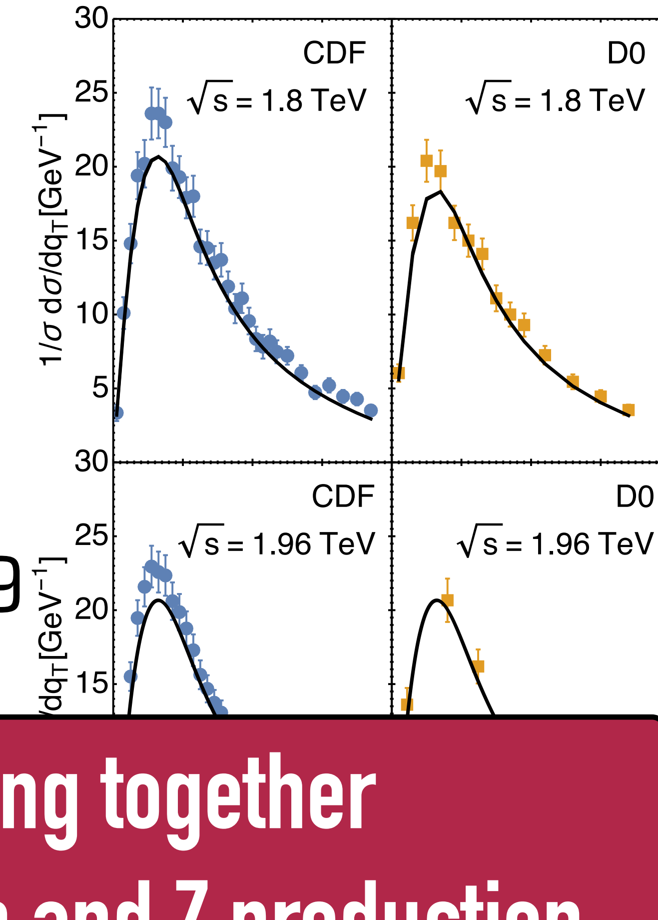

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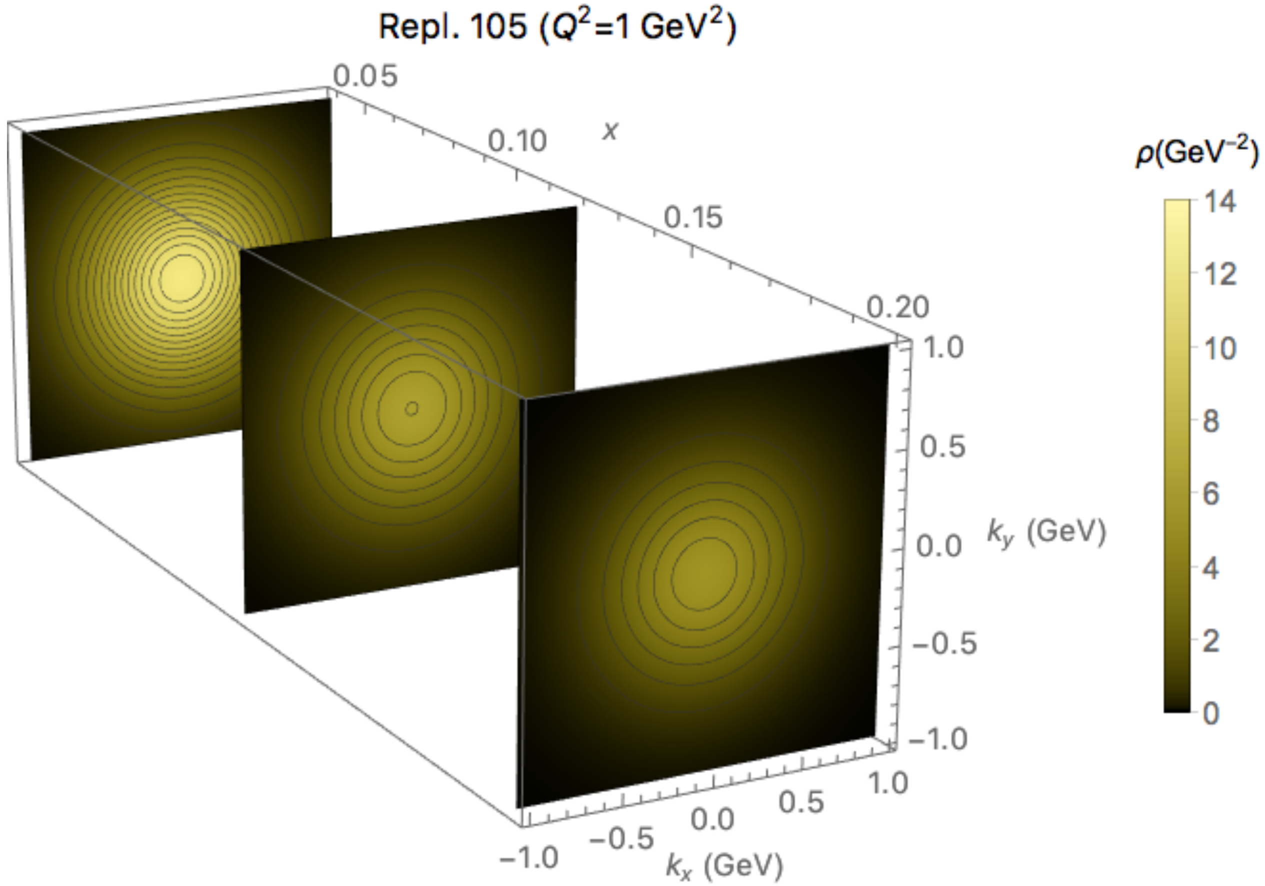
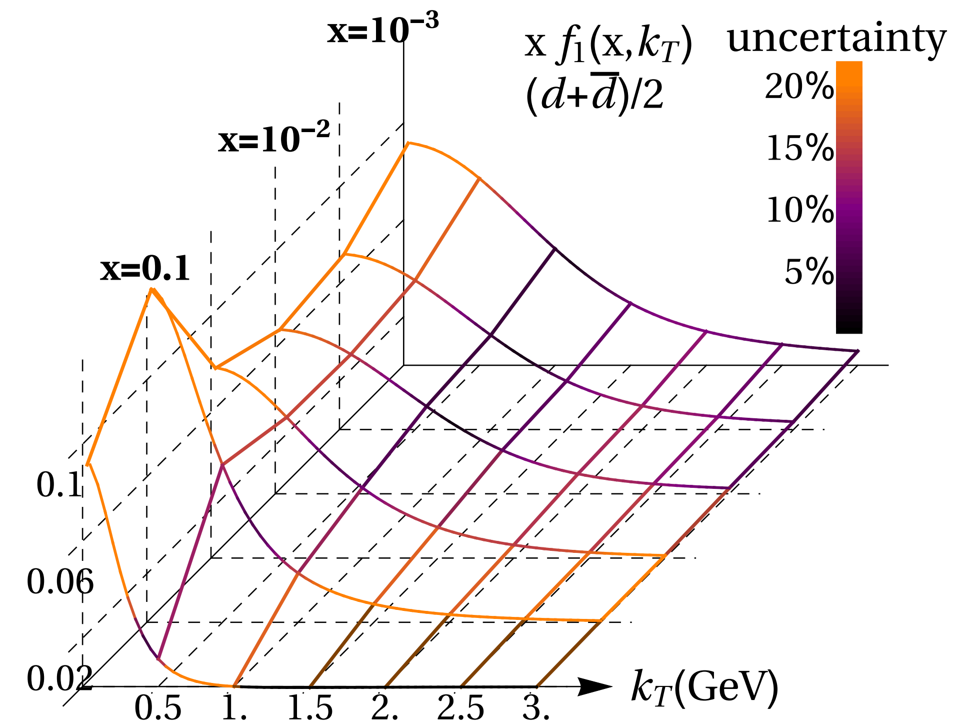
Pavia2017: first fit putting together semi-inclusive DIS, Drell-Yan and Z production

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

3D DISTRIBUTIONS EXTRACTED FROM DATA





Bertone, Scimemi, Vladimirov,
arXiv:1902.08474

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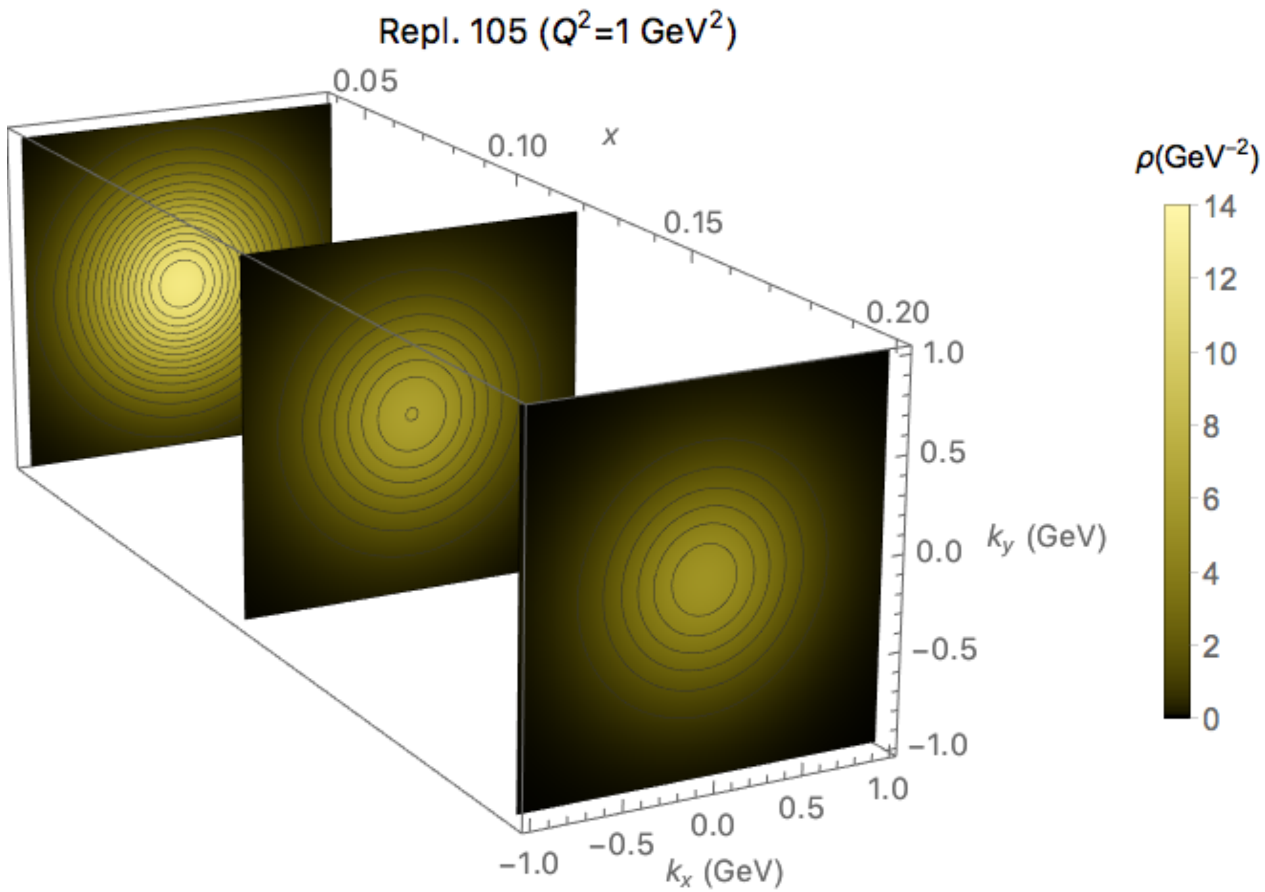
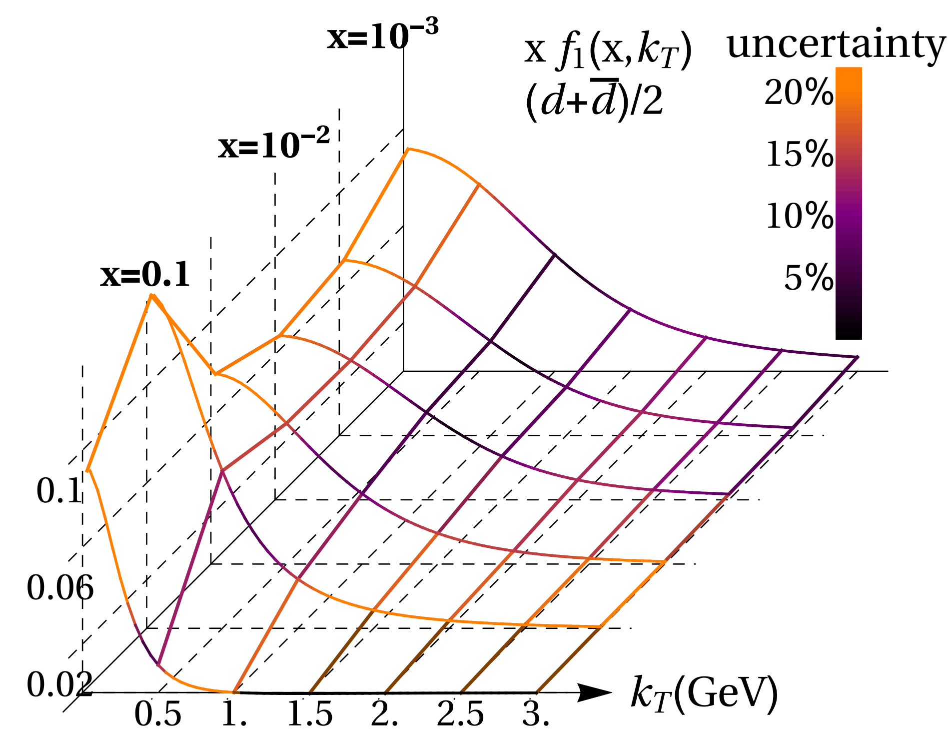




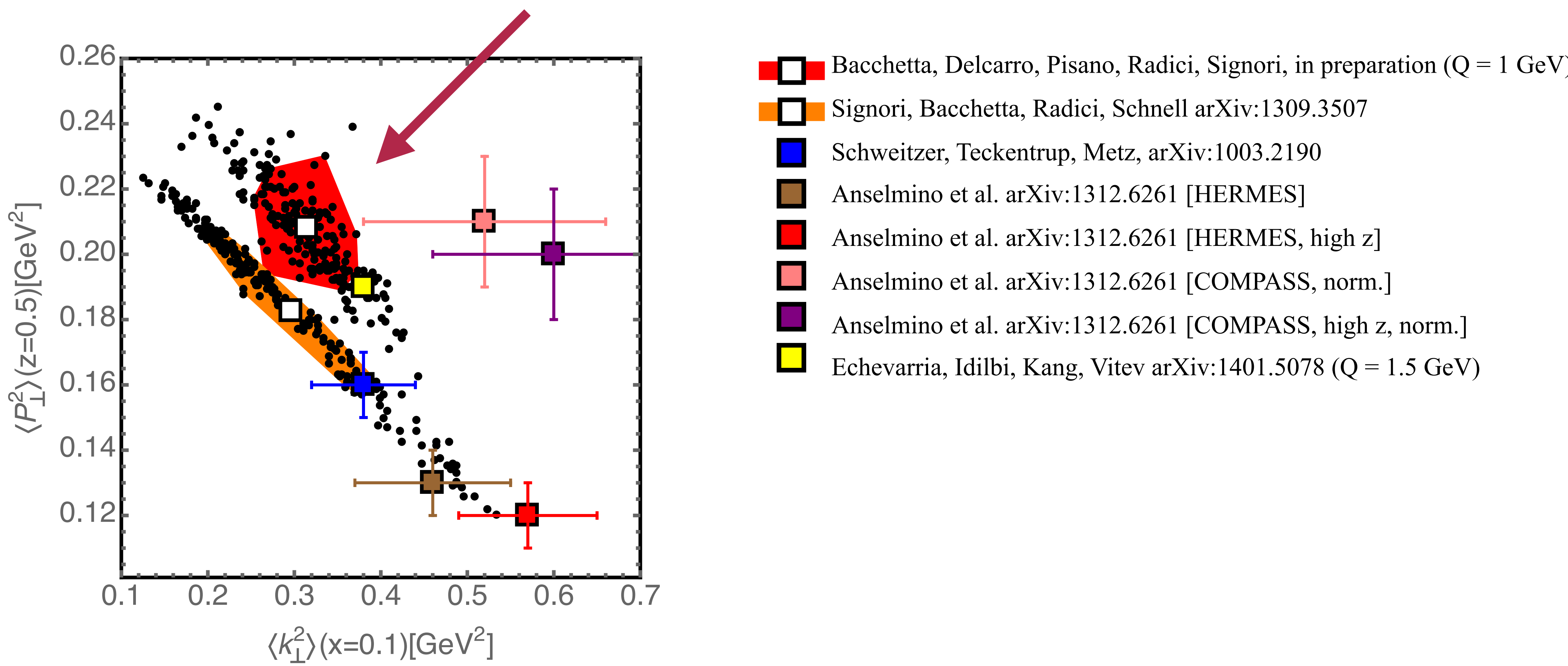
Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

Bertone, Scimemi, Vladimirov, arXiv:1902.08474

MEAN TRANSVERSE MOMENTUM SQUARED

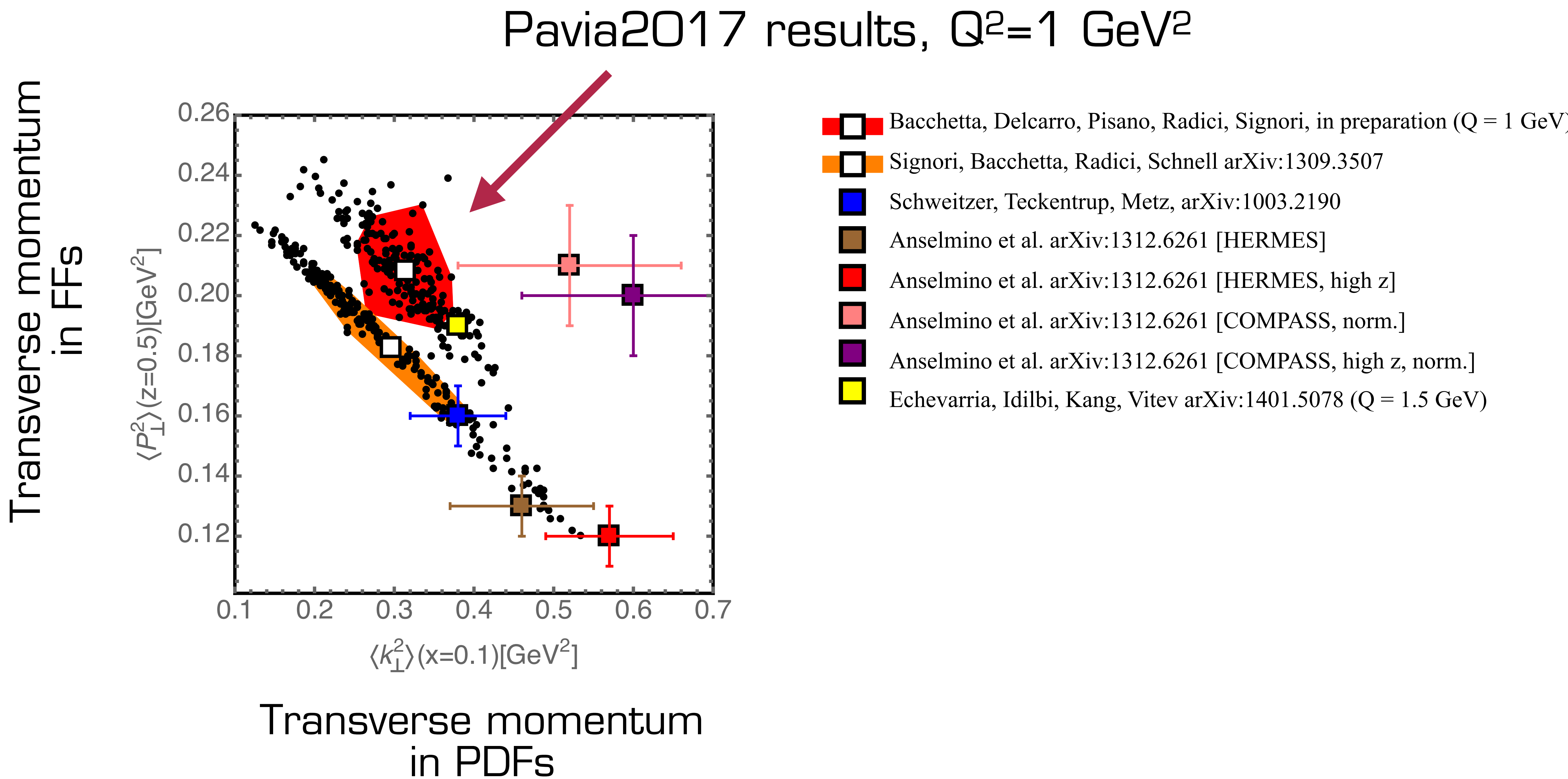
Pavia2017 results, Q^2=1 GeV^2

Transverse momentum in FFs



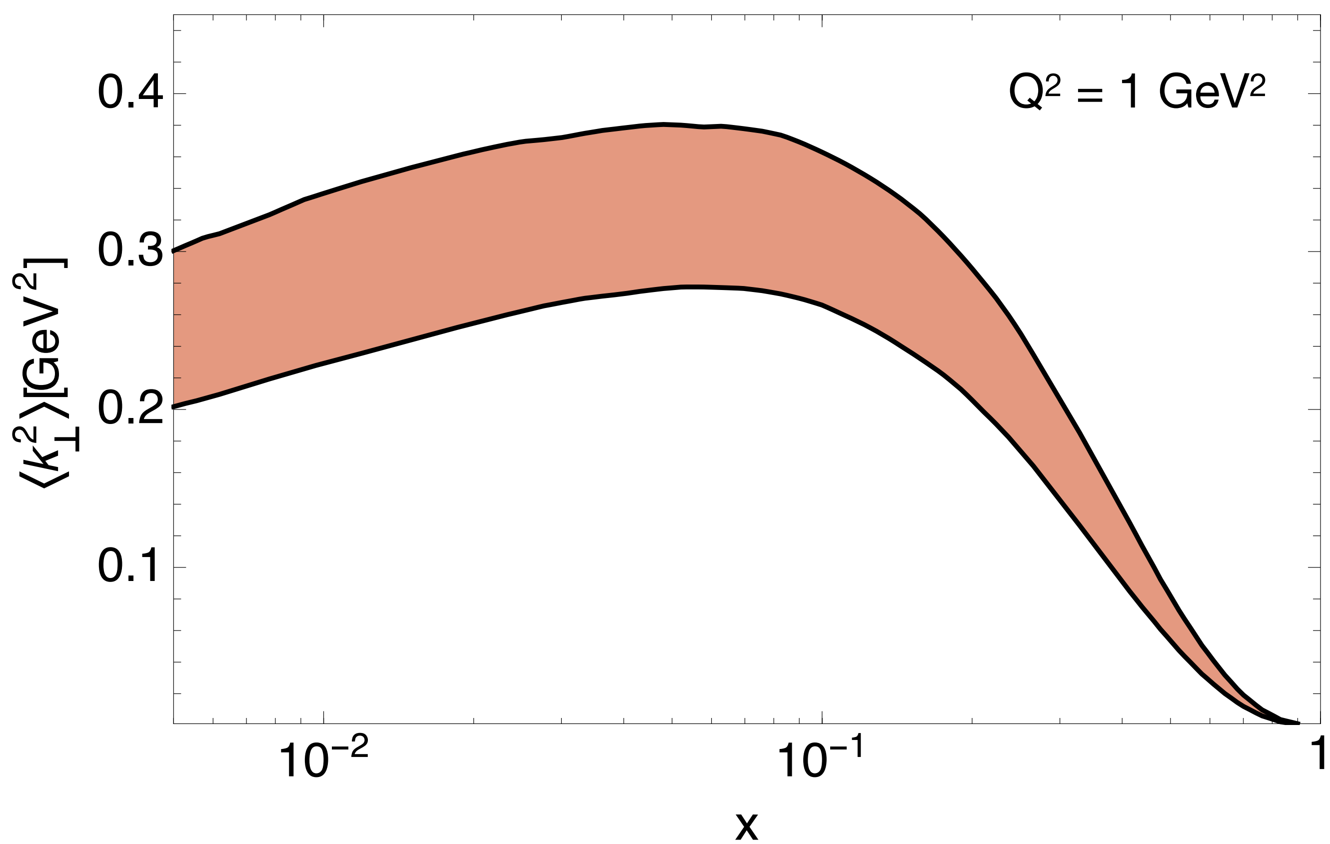
Transverse momentum in PDFs

MEAN TRANSVERSE MOMENTUM SQUARED



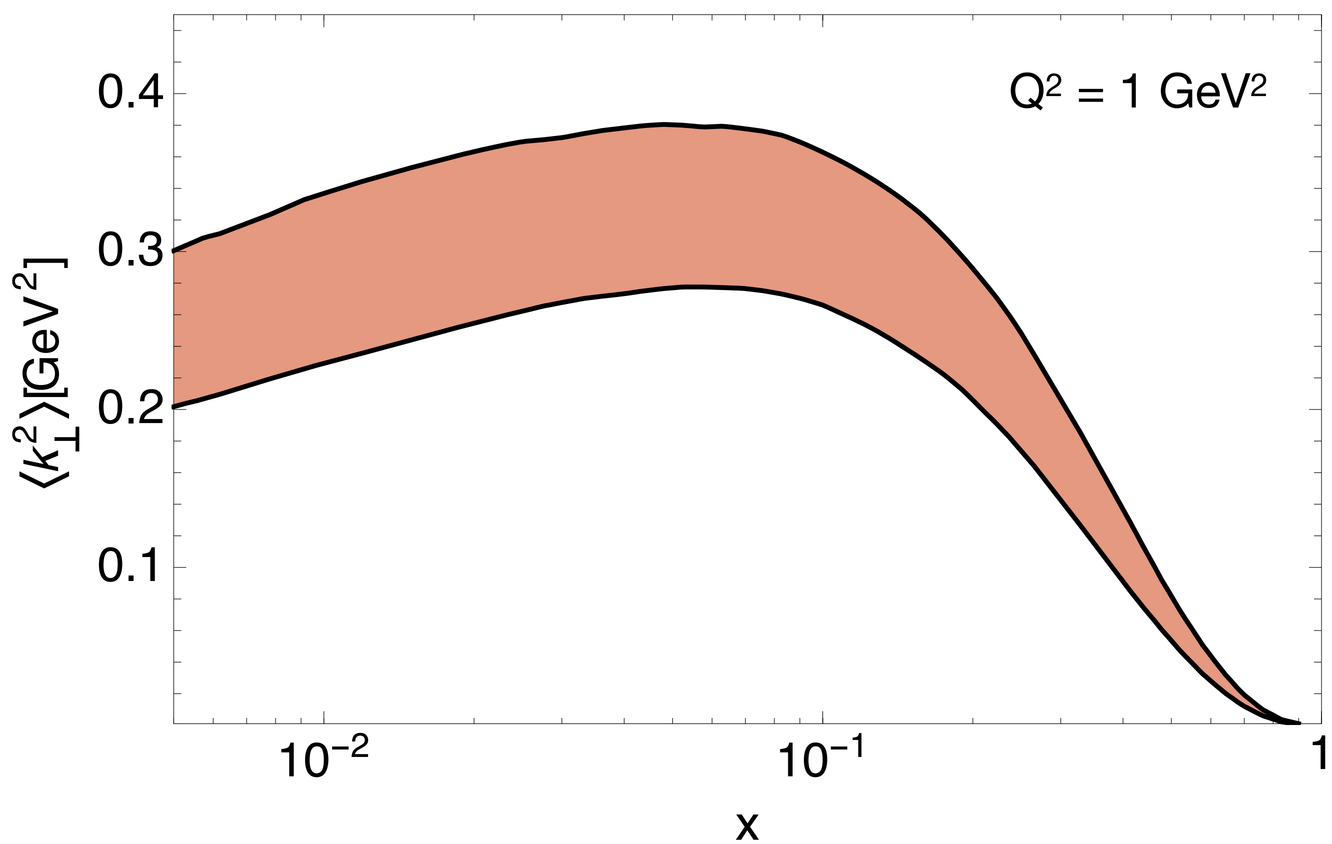
CAVEAT: intrinsic transverse momentum depends on TMD evolution “scheme” and its parameters

AVERAGE TRANSVERSE MOMENTUM SQUARED



AVERAGE TRANSVERSE MOMENTUM SQUARED

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



AVERAGE TRANSVERSE MOMENTUM SQUARED

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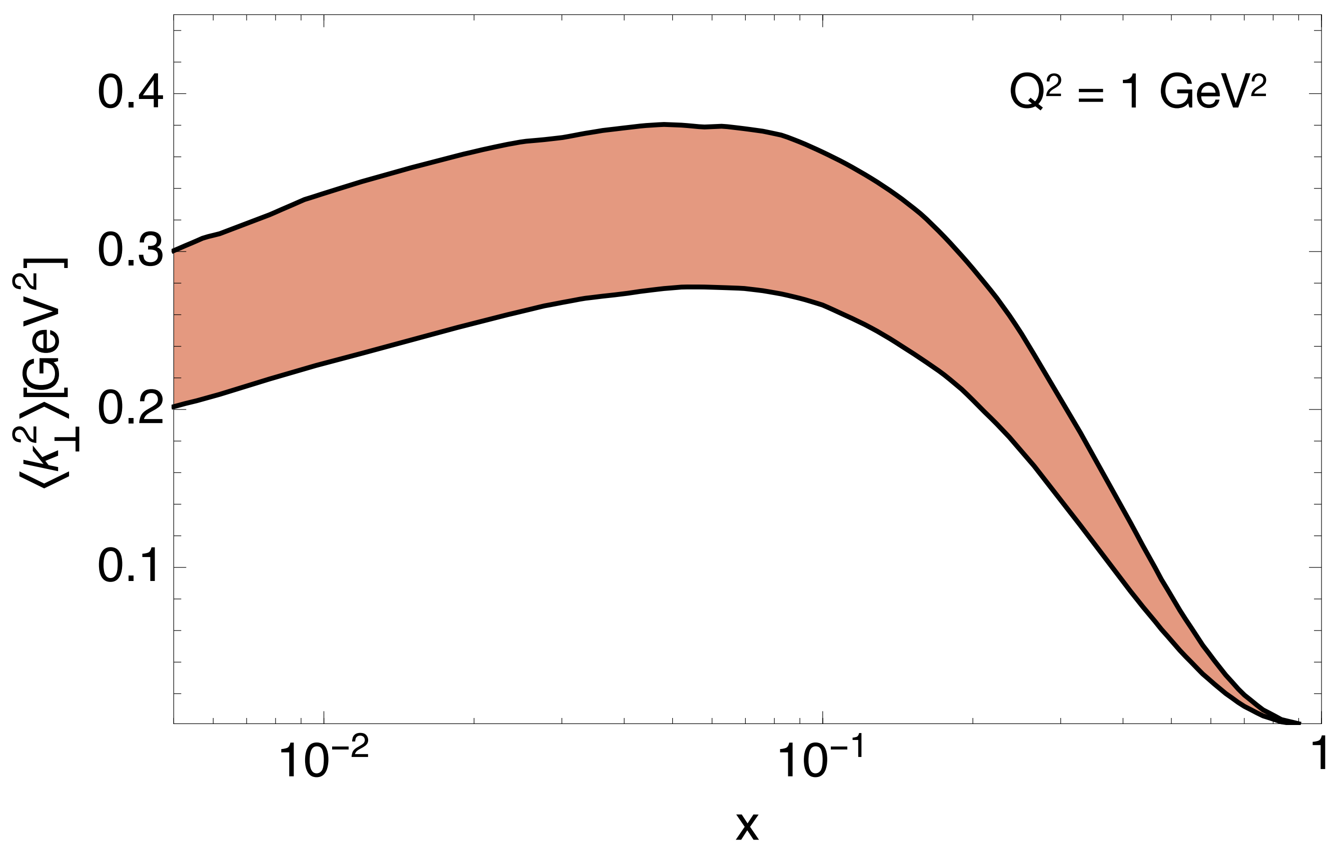
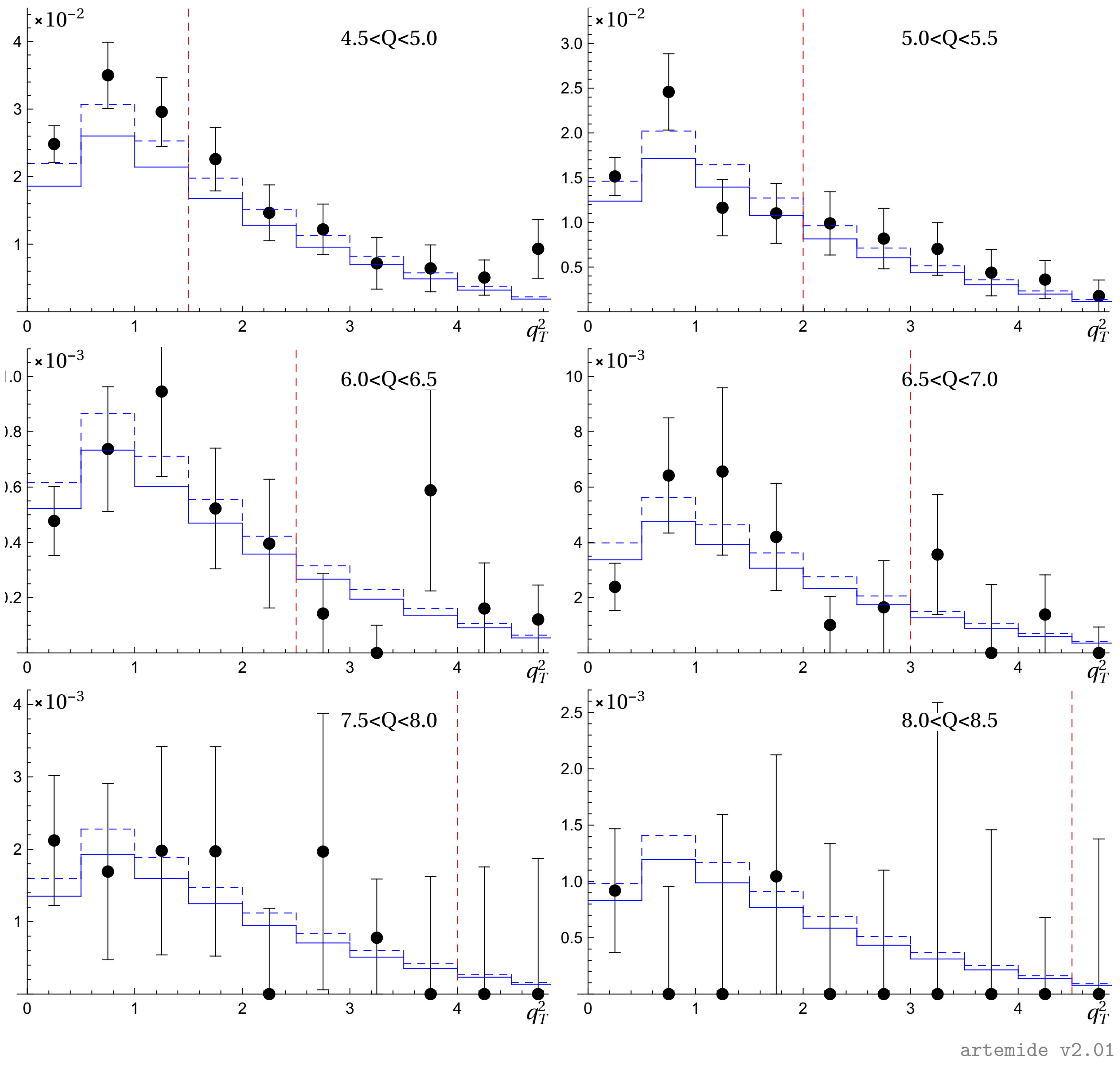


The fact that it goes to zero at x=1 is built in, but the sharp decrease seems to be data-driven.
However, it could still be an artefact of the fit.

PION TMDS



$d\sigma/dQdq_T$ [nb/GeV^2]

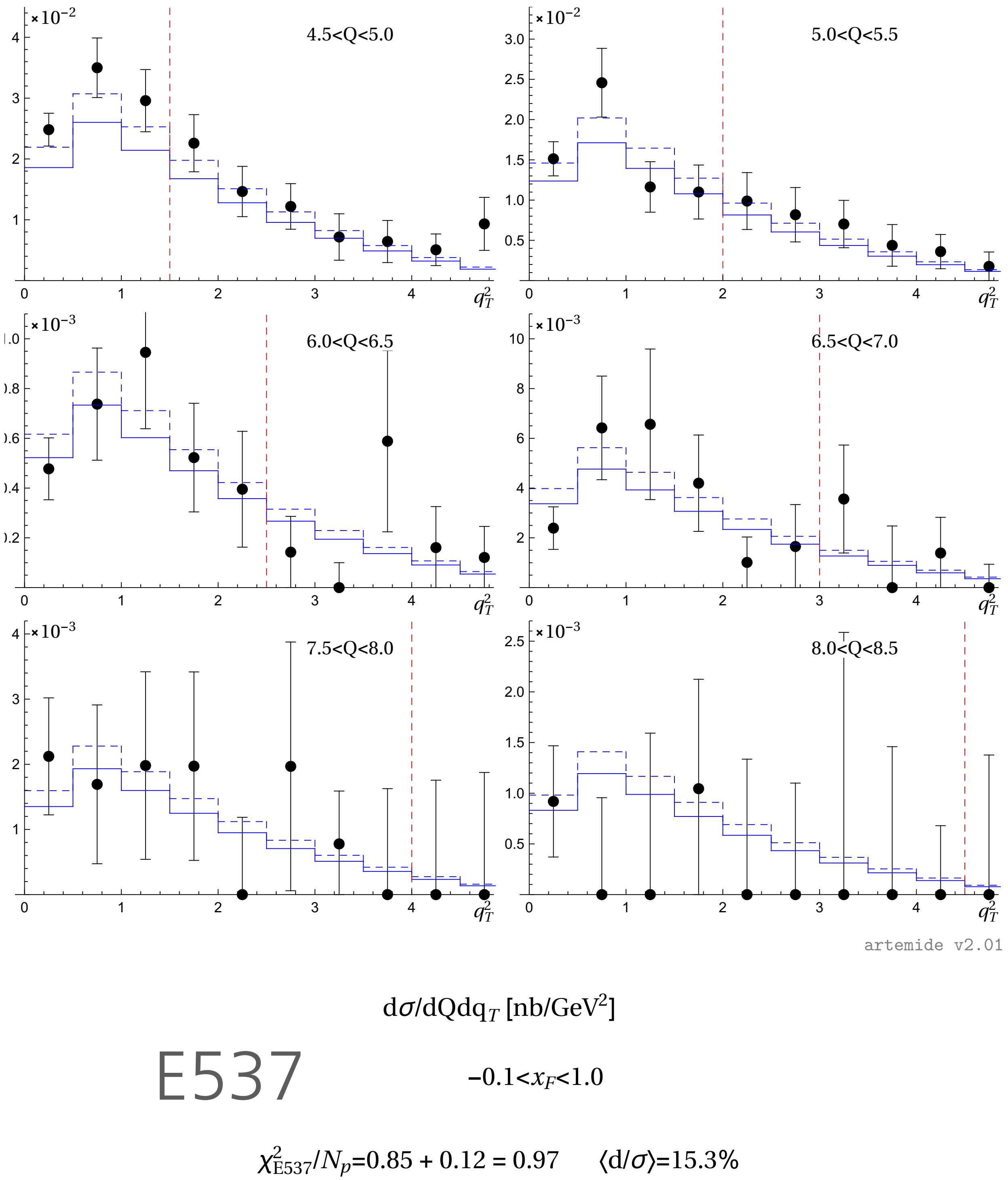
E537

$-0.1<x_F<1.0$

χ^2_{E537}/N_p=0.85 + 0.12 = 0.97 $\langle d/\sigma \rangle$=15.3%

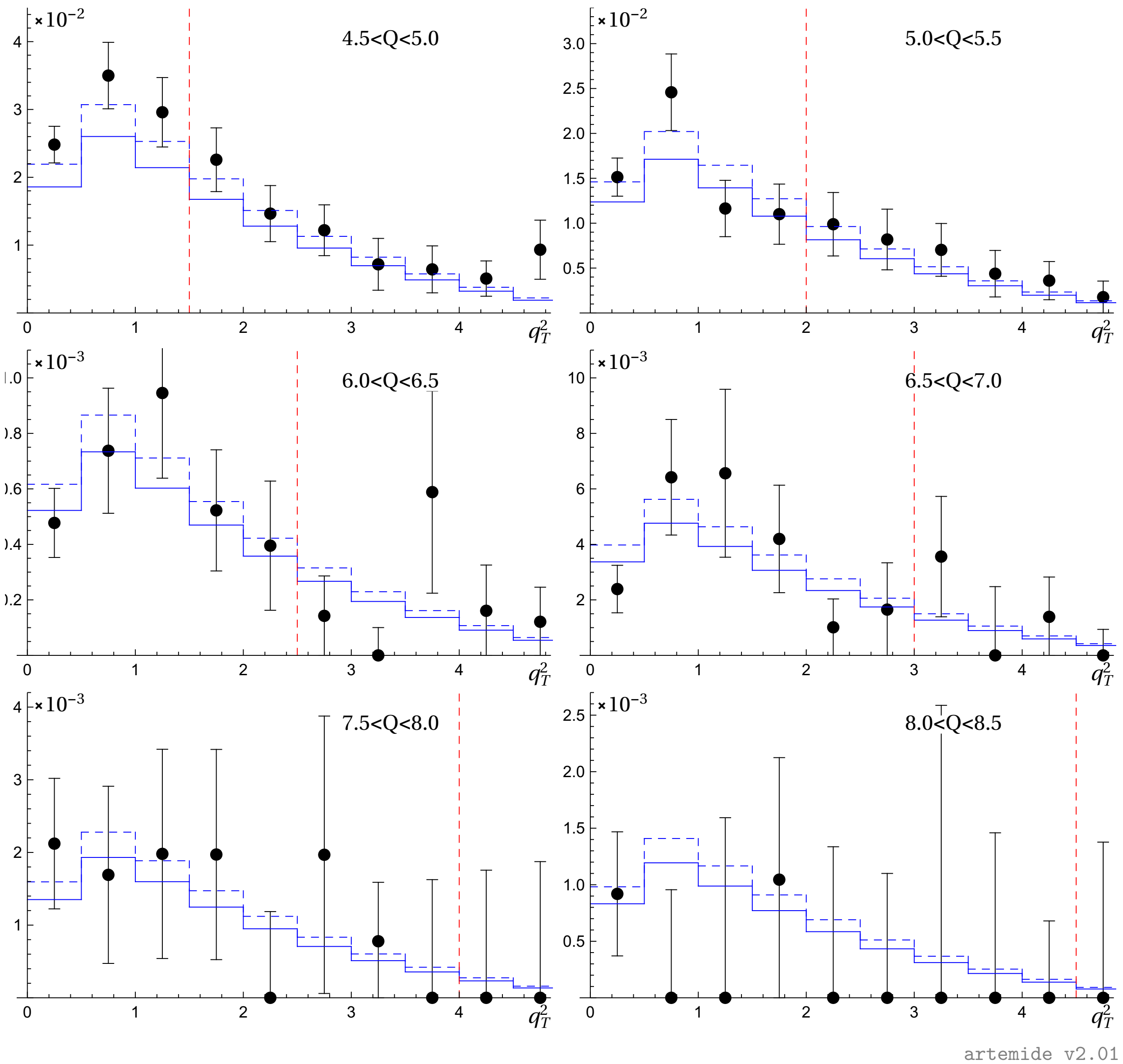
PION TMDS

Vladimirov, arXiv:1907.10356



E537

PION TMDS



$d\sigma/dQdq_T$ [nb/GeV^2]

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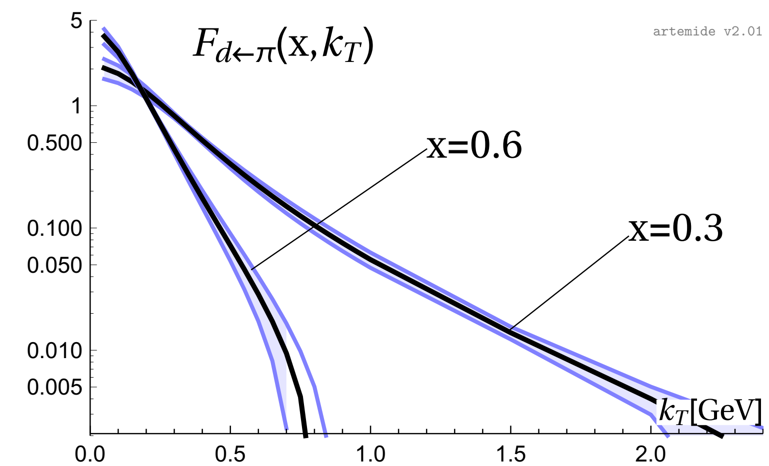
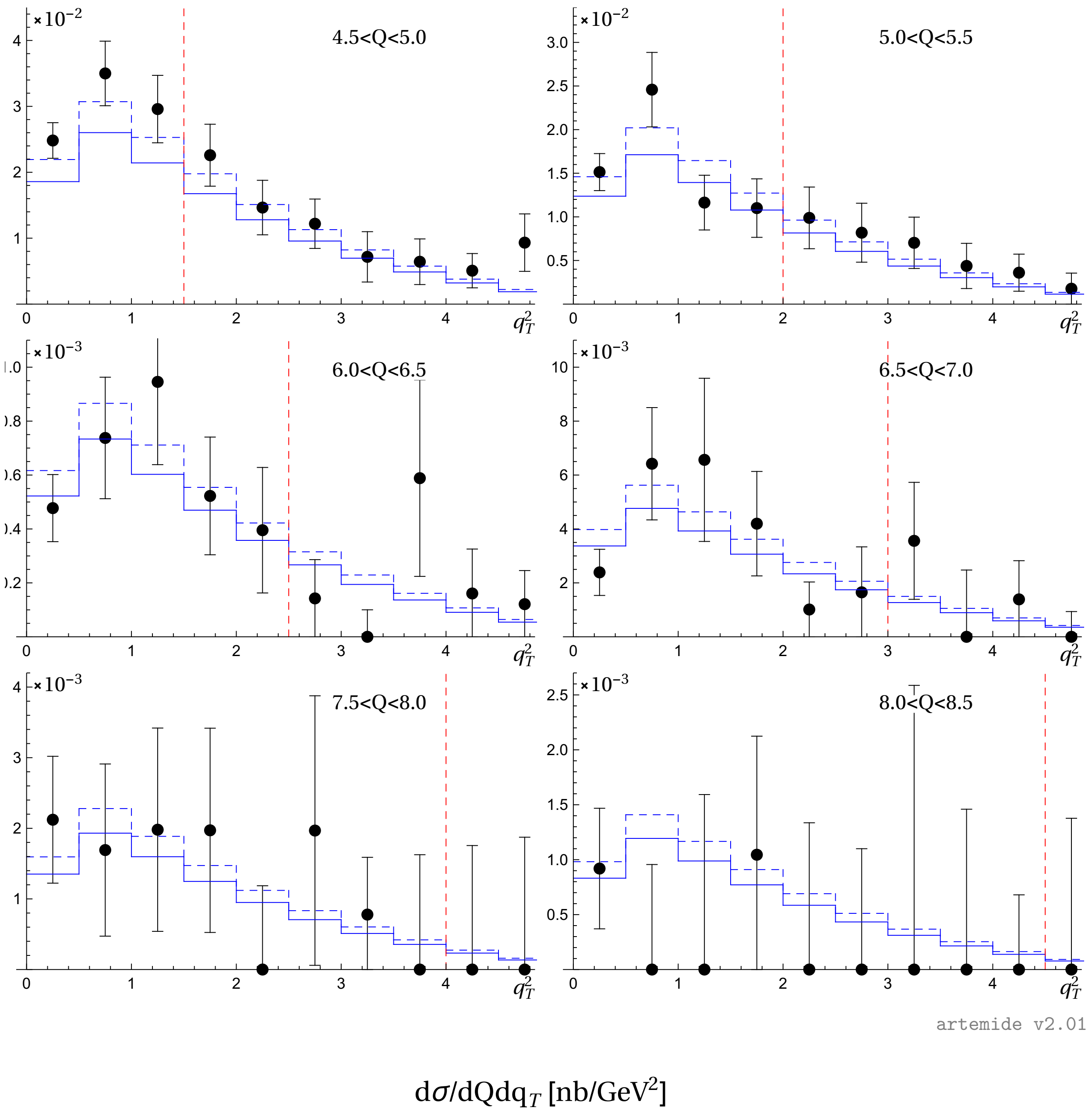
Vladimirov, arXiv:1907.10356



narrower at high x

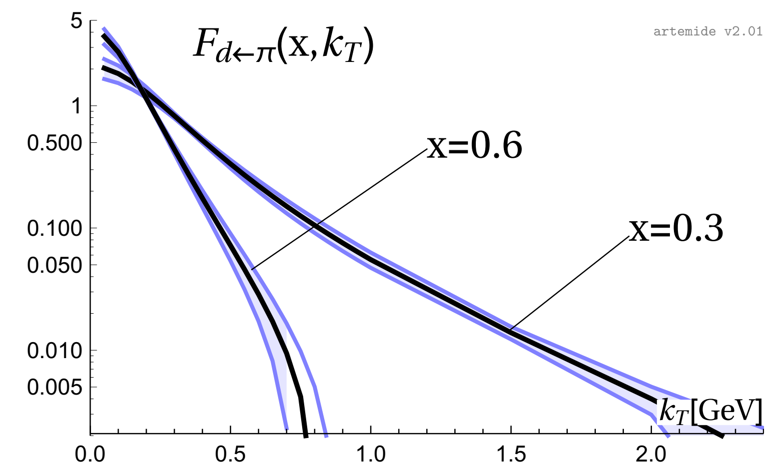
PION TMDS



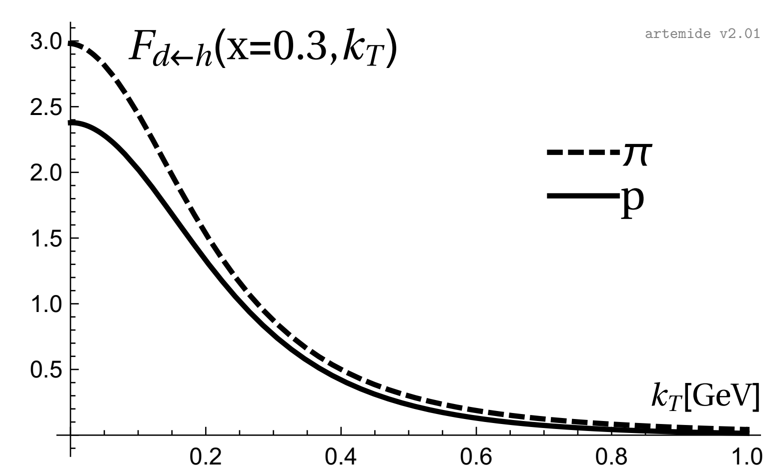
E537

χ^2_{E537}/N_p=0.85 + 0.12 = 0.97 ⟨d/σ⟩=15.3%

Vladimirov, arXiv:1907.10356



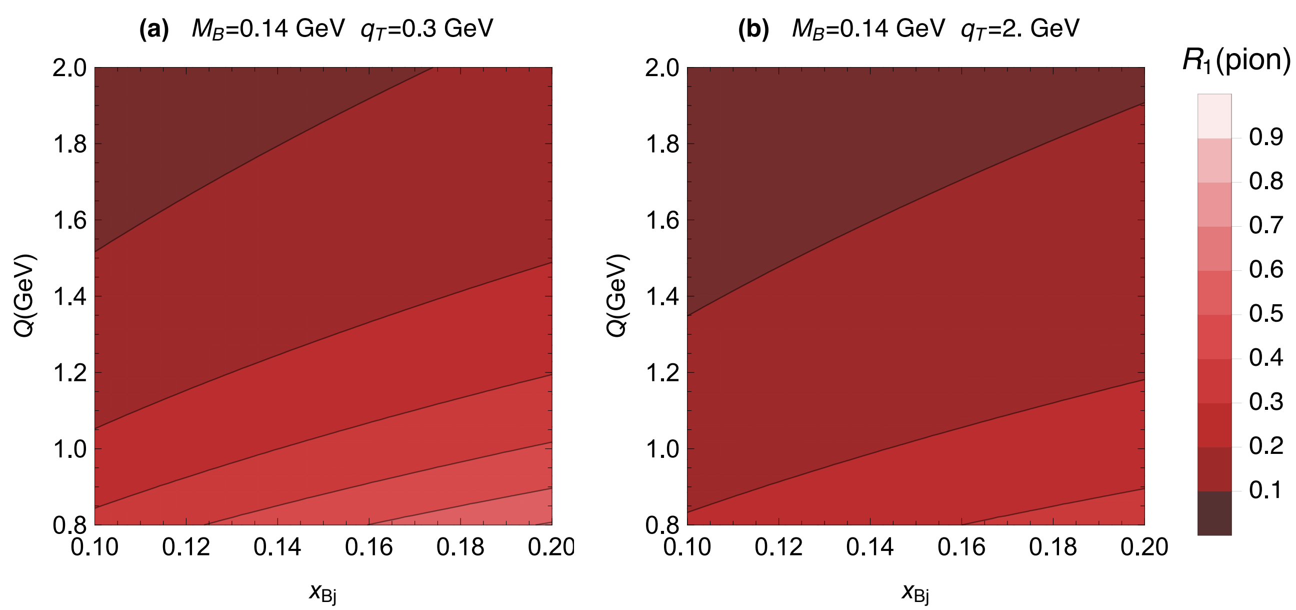
narrower at high x



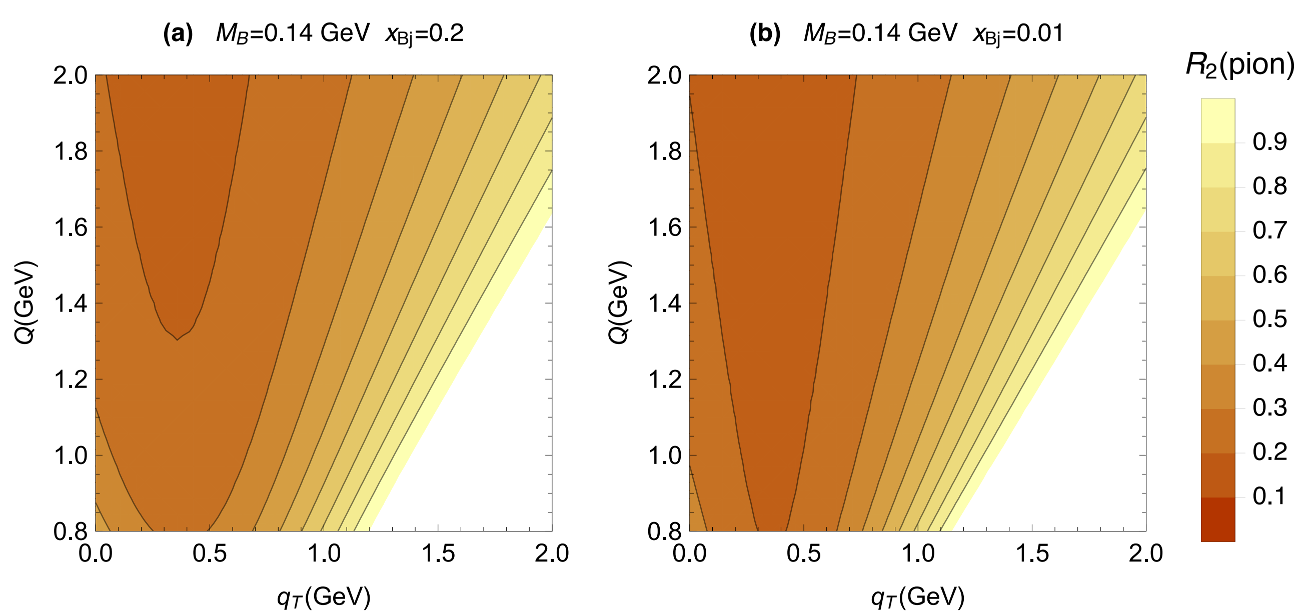
narrower than proton

STUDY OF "SAFE REGIONS" FOR TMD PHYSICS

Boglione, Dotson, Gamberg, Gordon, Gonzalez, Prokudin, Rogers, Sato, arXiv:1904.12882

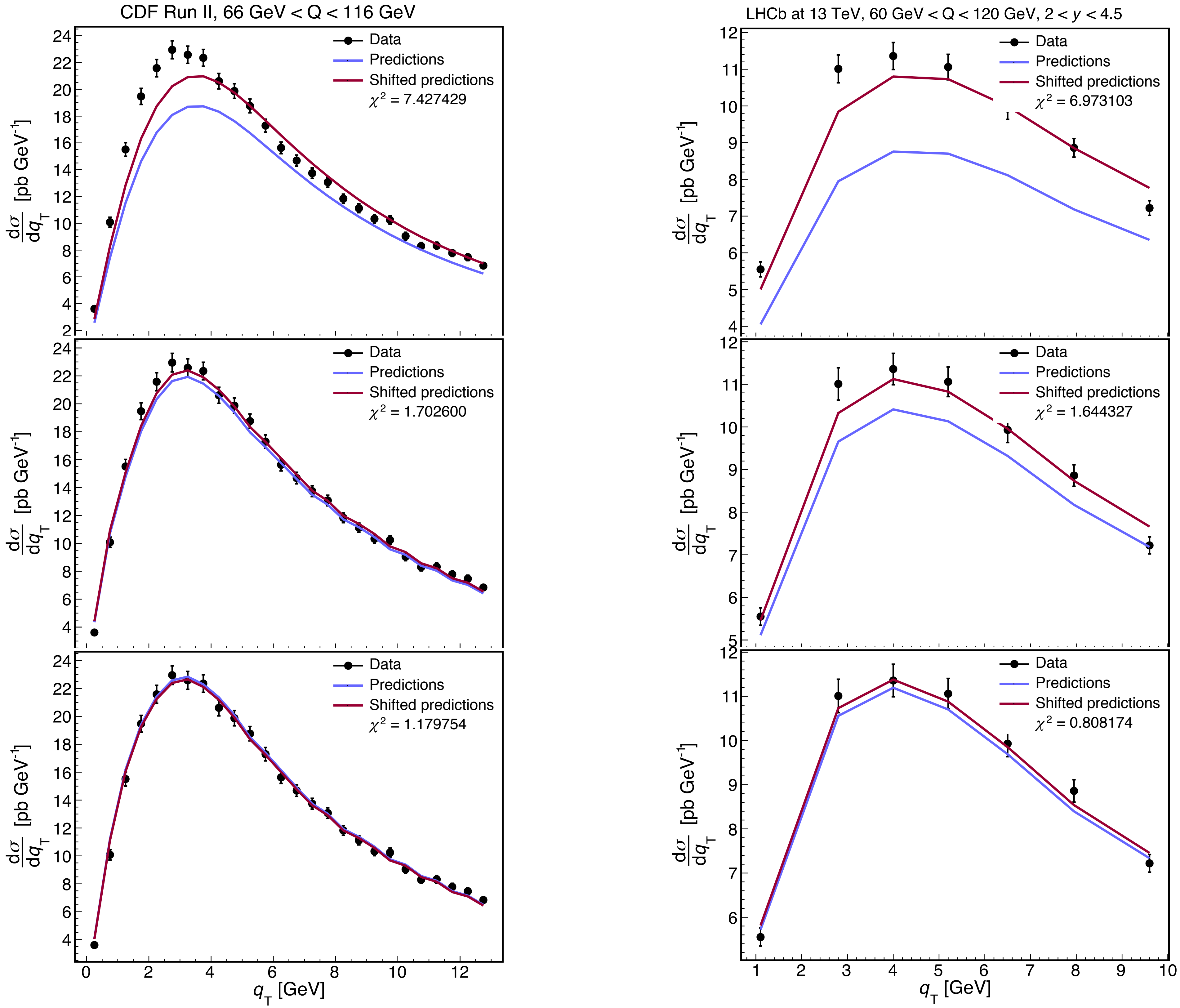


low value of R_1 required to avoid target fragmentation region



low value of R_2 required to stay in TMD region

IMPROVEMENT OF ACCURACY



NLL

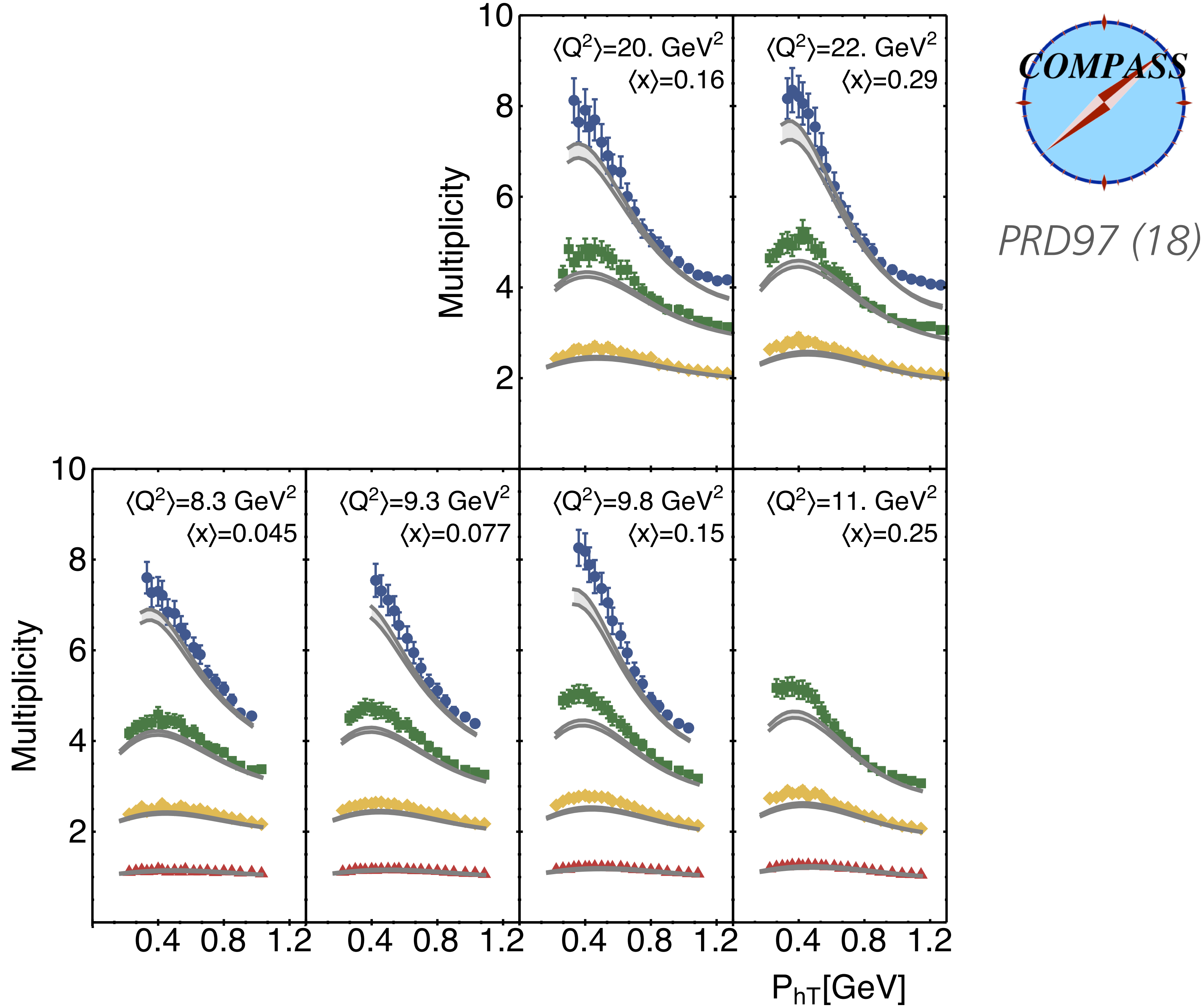
NNLL

NNNLL

PROBLEMS

PROBLEMS WITH NORMALISATION

F. Delcarro's talk at IWHSS 2018

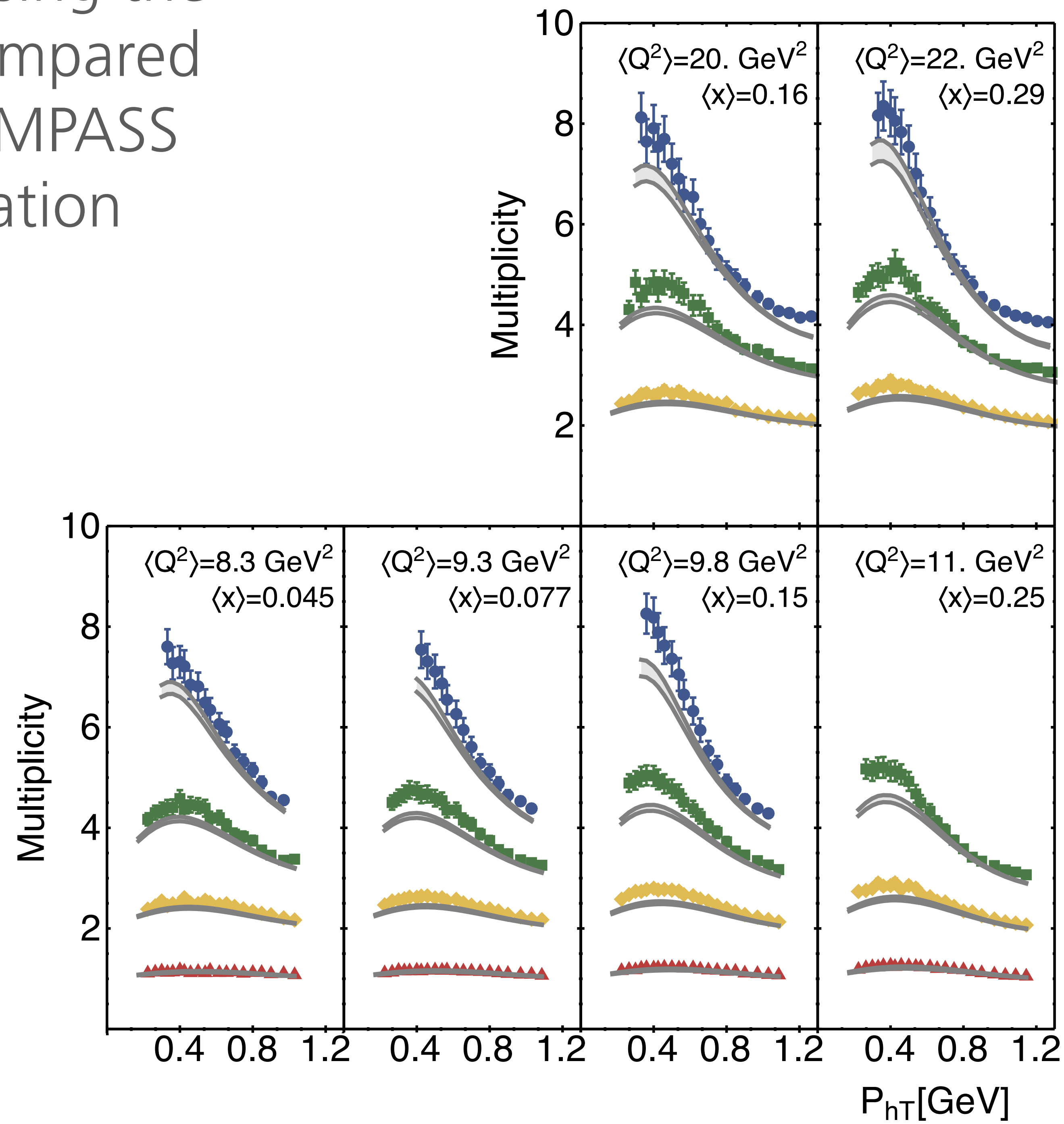


PRD97 (18)

PROBLEMS WITH NORMALISATION

F. Delcarro's talk at IWHSS 2018

We made predictions using the PV17 extraction and compared them with the new COMPASS data, without normalization factors



PRD97 (18)

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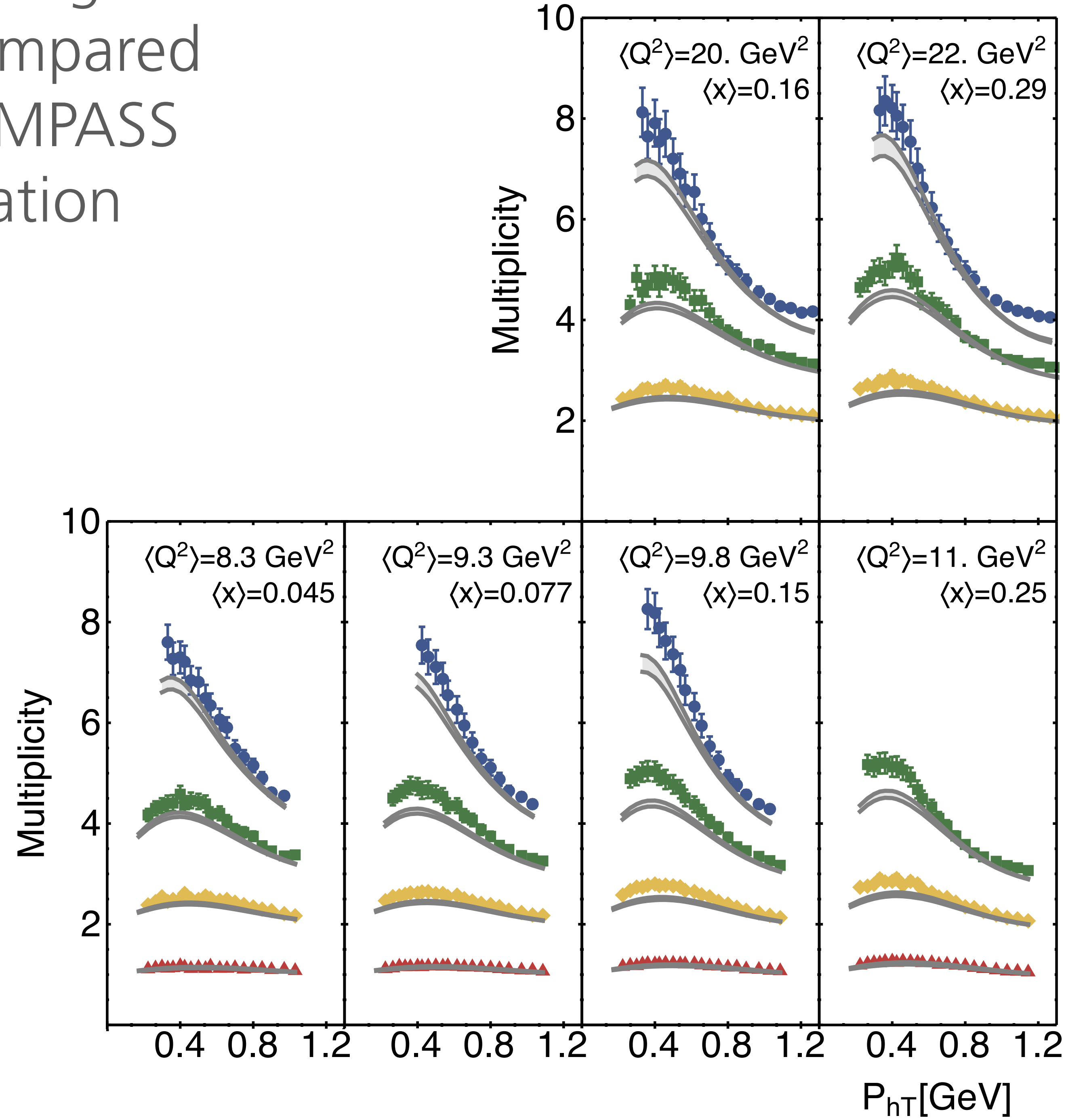
The agreement is bad



PRD97 (18)

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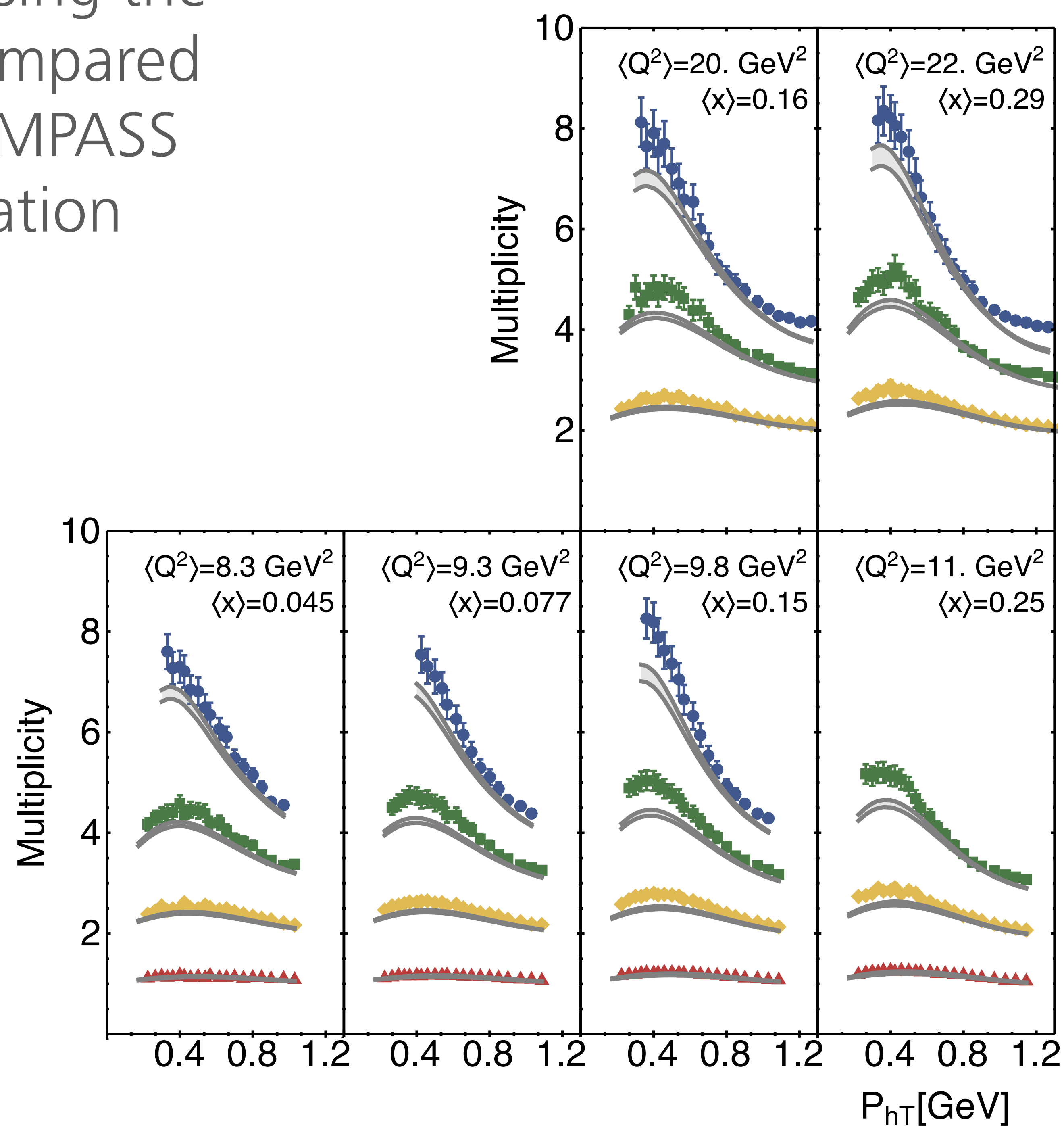
Going to NLL' or NNLL the situation worsens!



PRD97 (18)

PROBLEMS WITH NORMALISATION

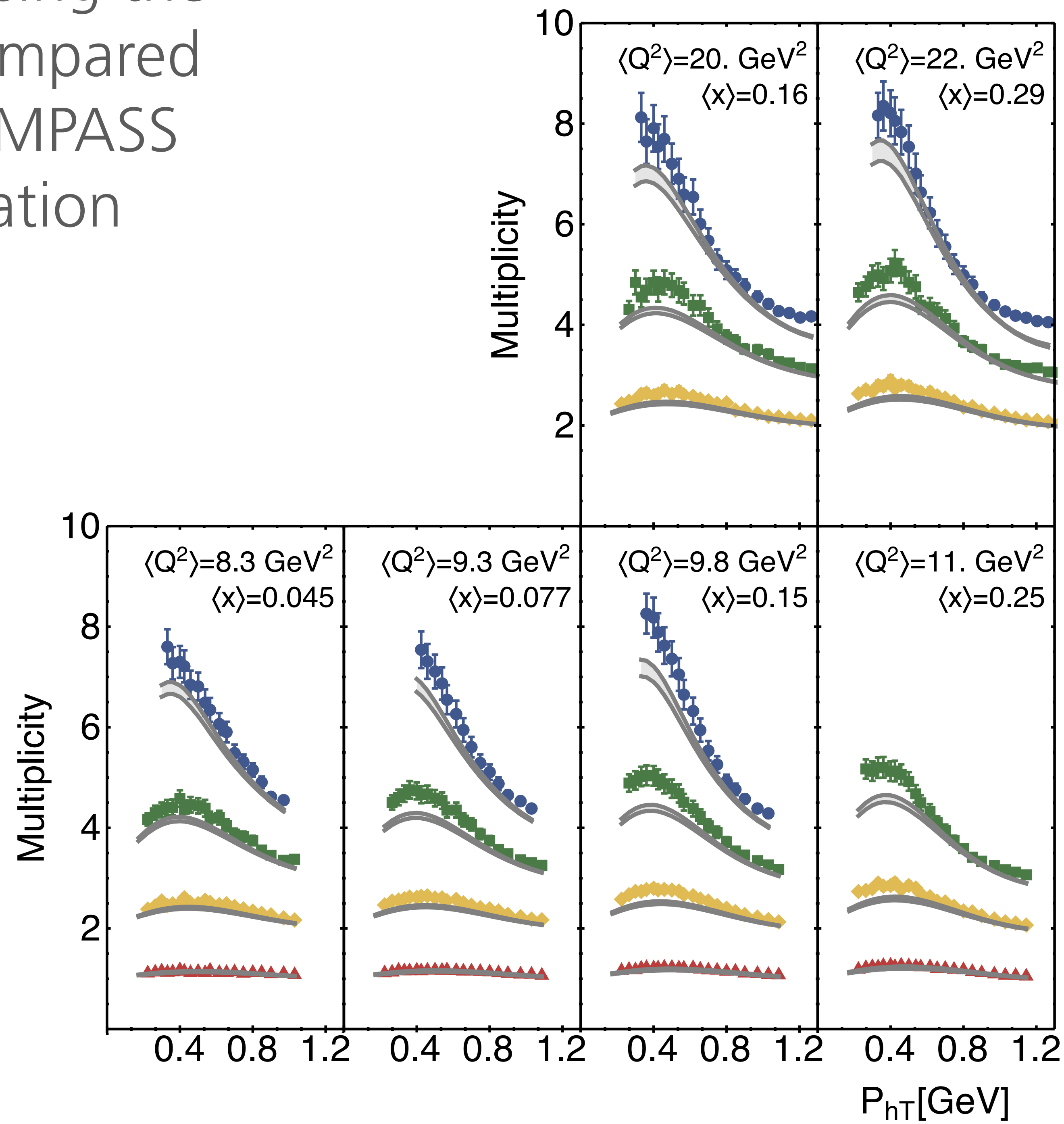
F. Delcarro's talk at IWHSS 2018

We made predictions using the PV17 extraction and compared them with the new COMPASS data, without normalization factors

The agreement is bad

Going to NLL' or NNLL the situation worsens!

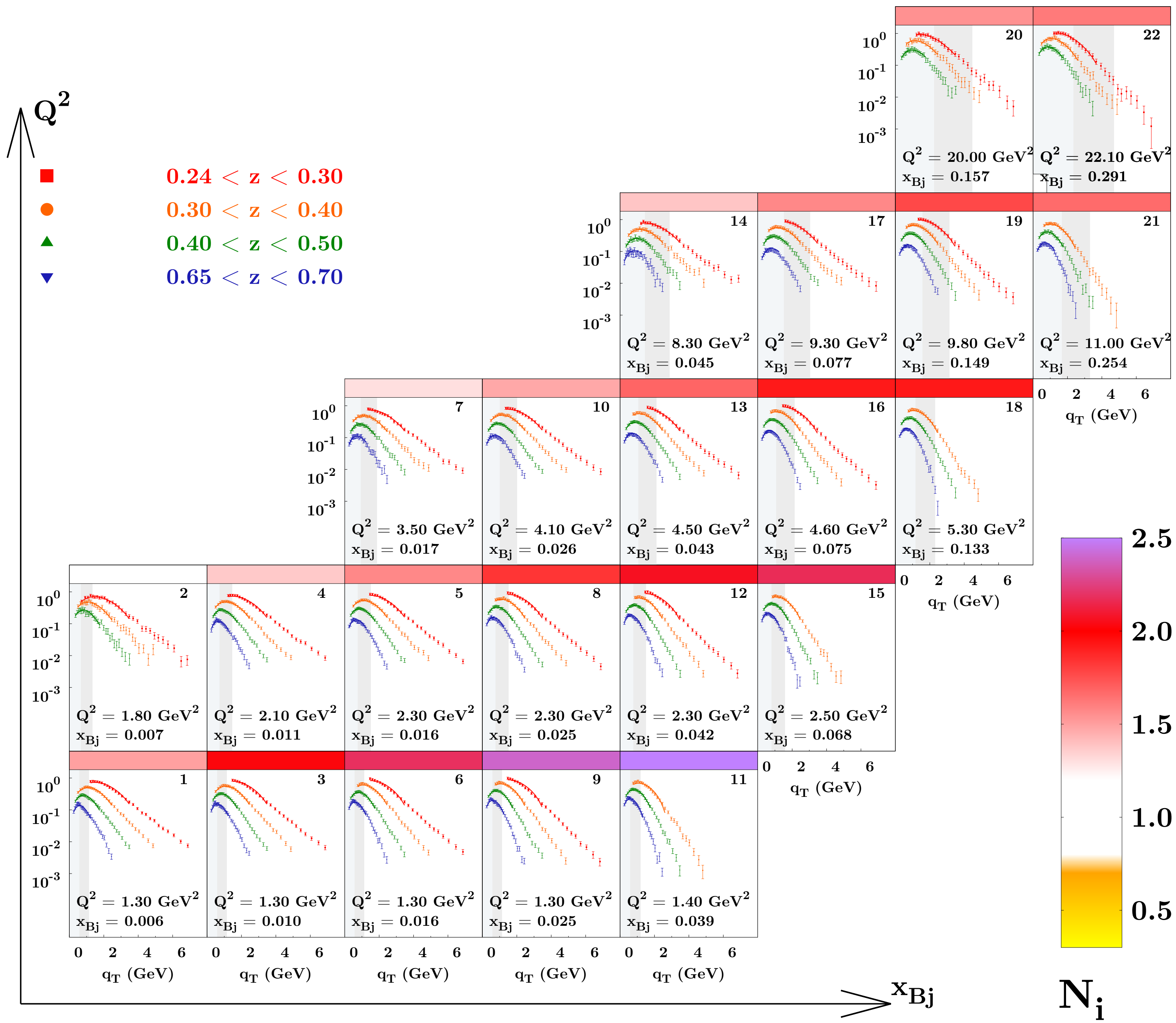
We are still struggling to find a way out…



PRD97 (18)

PROBLEMS WITH NORMALIZATION

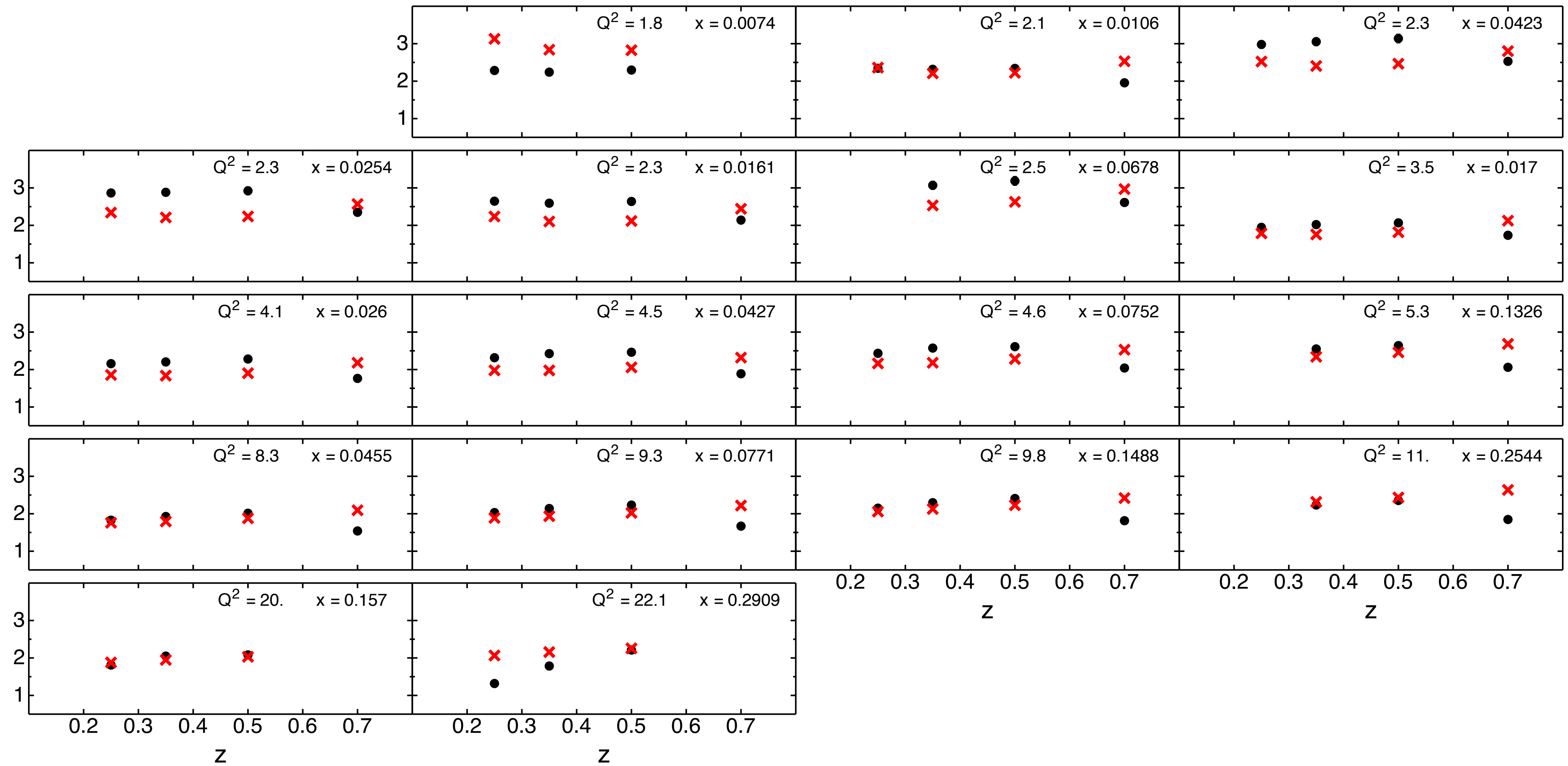
talk by O. Gonzalez at DIS2019



Torino's group also confirmed that large normalisation factors have to be introduced to describe COMPASS data

PROBLEMS WITH NORMALIZATION

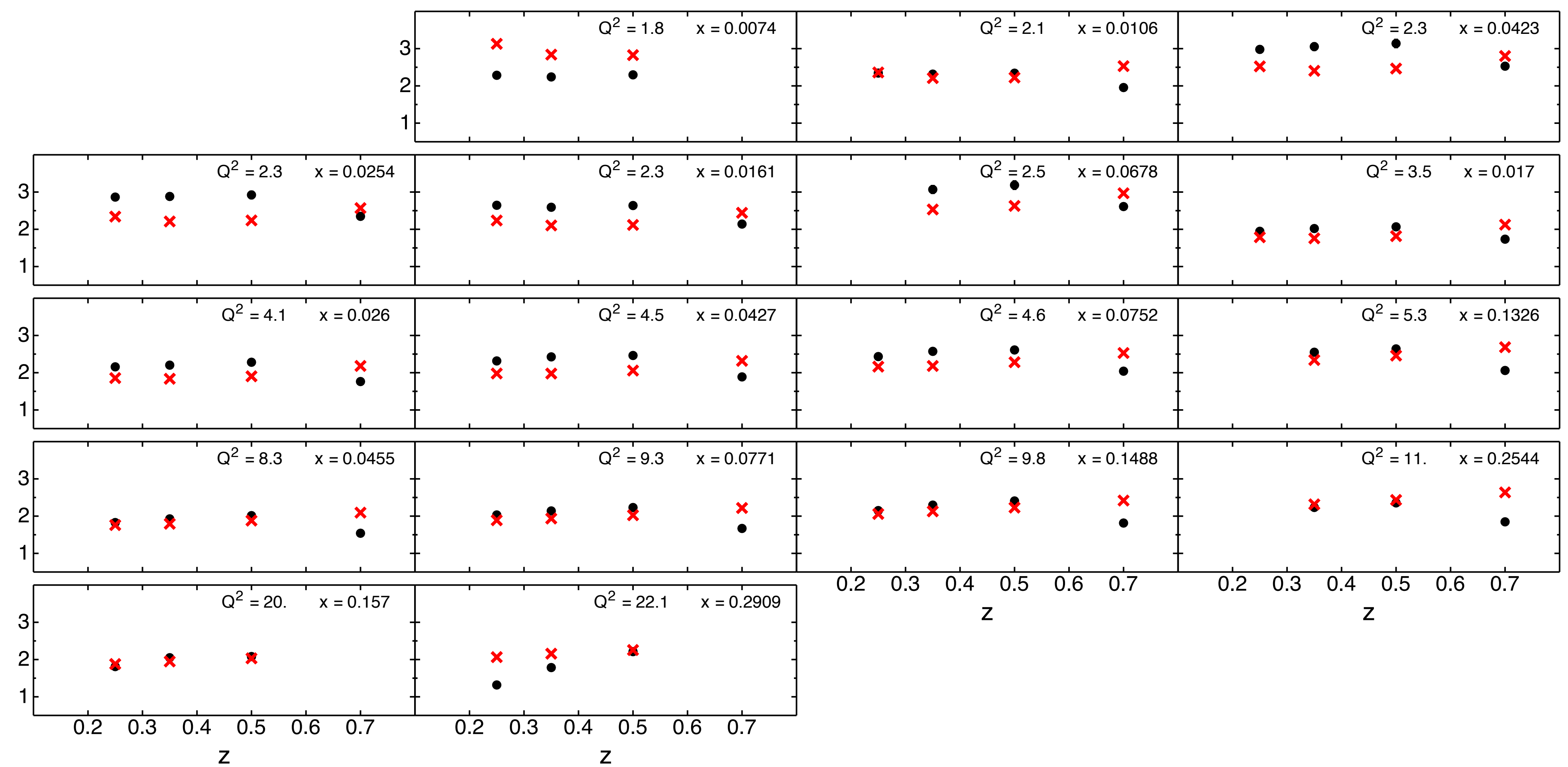
to appear in F. Piacenza's PhD thesis



Red dots: ratio between collinear formula and integral of TMD part at order α_S

PROBLEMS WITH NORMALIZATION

to appear in F. Piacenza's PhD thesis



Red dots: ratio between collinear formula and integral of TMD part at order α_S

PROBLEMS WITH NORMALIZATION

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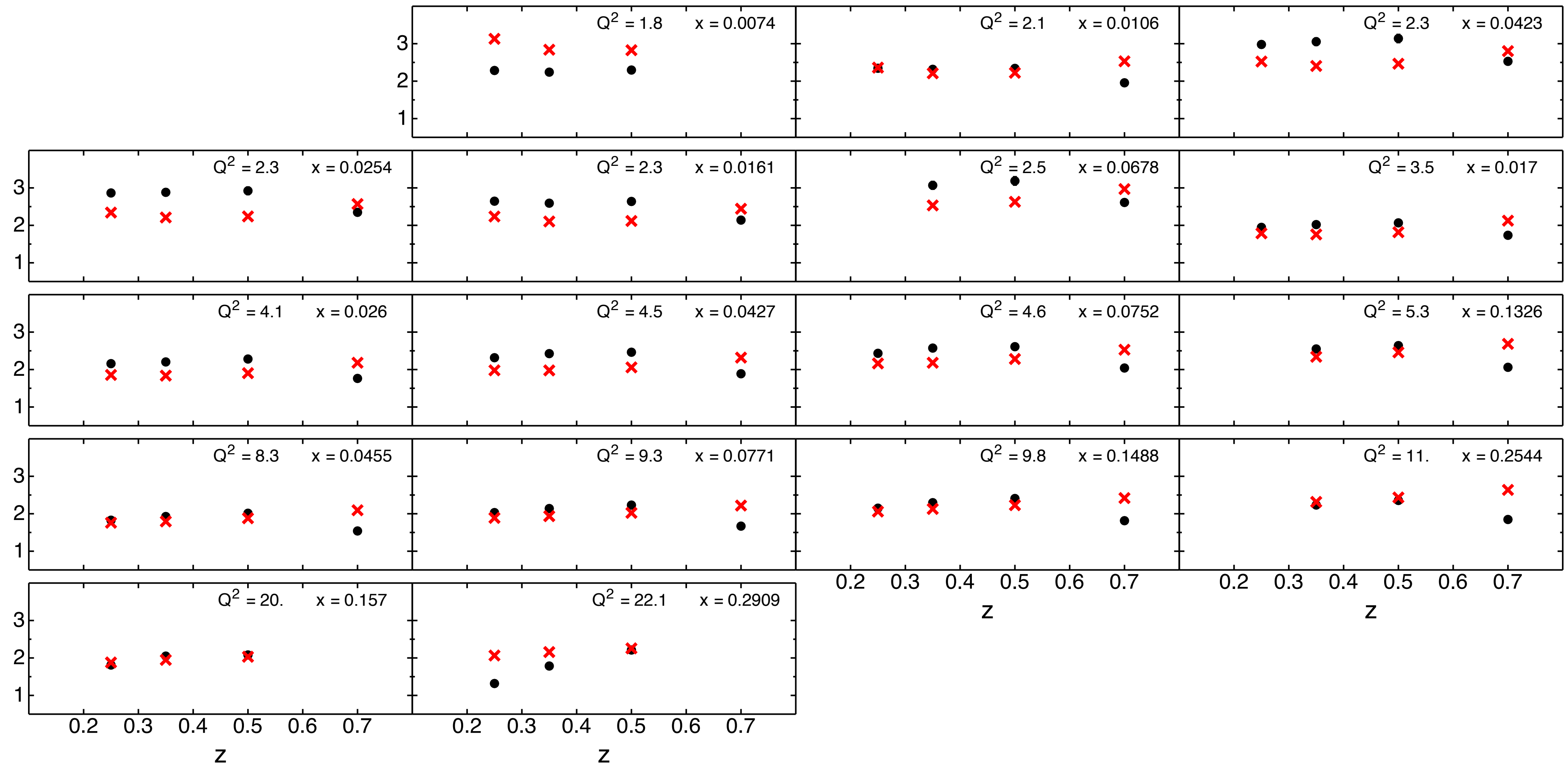
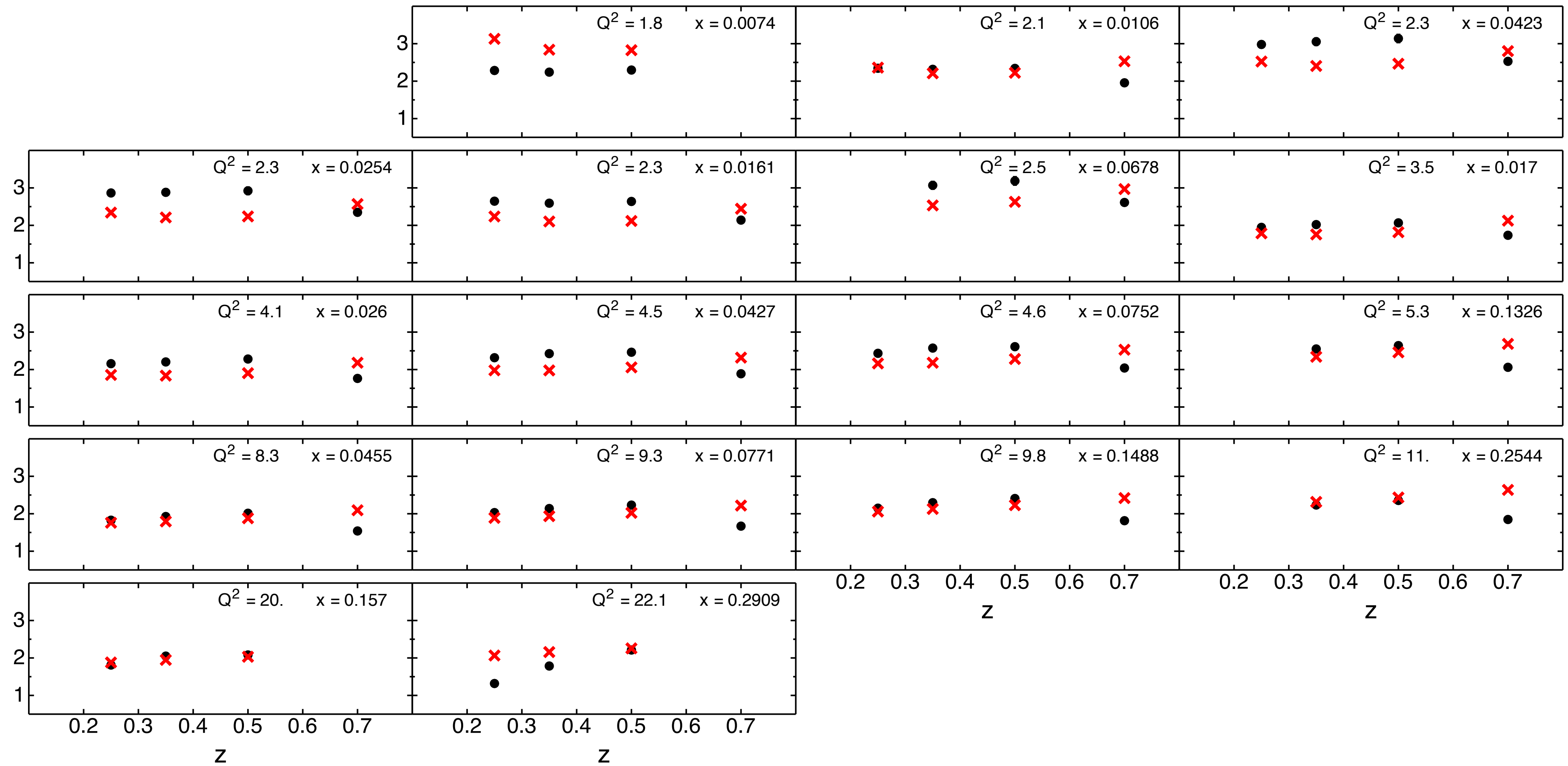


Red dots: ratio between collinear formula and integral of TMD part at order α_S

Black dots: large normalisation factors required to fit COMPASS multiplicities at NLL'

PROBLEMS WITH NORMALIZATION

to appear in F. Piacenza's PhD thesis



Red dots: ratio between collinear formula and integral of TMD part at order α_S

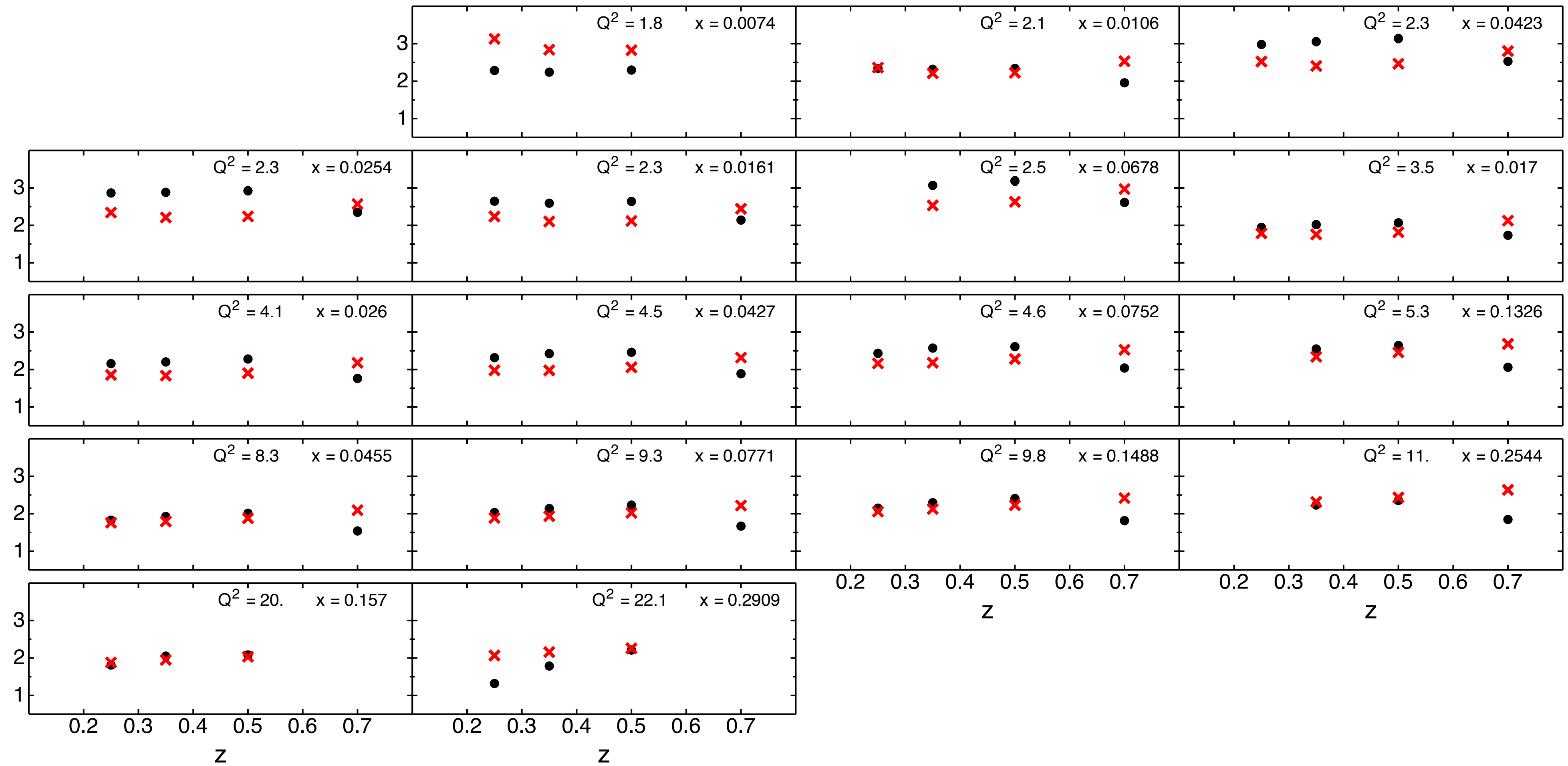
BAD

Black dots: large normalisation factors required to fit COMPASS multiplicities at NLL'

BAD

PROBLEMS WITH NORMALIZATION

to appear in F. Piacenza's PhD thesis



Red dots: ratio between collinear formula and integral of TMD part at order α_S

BAD

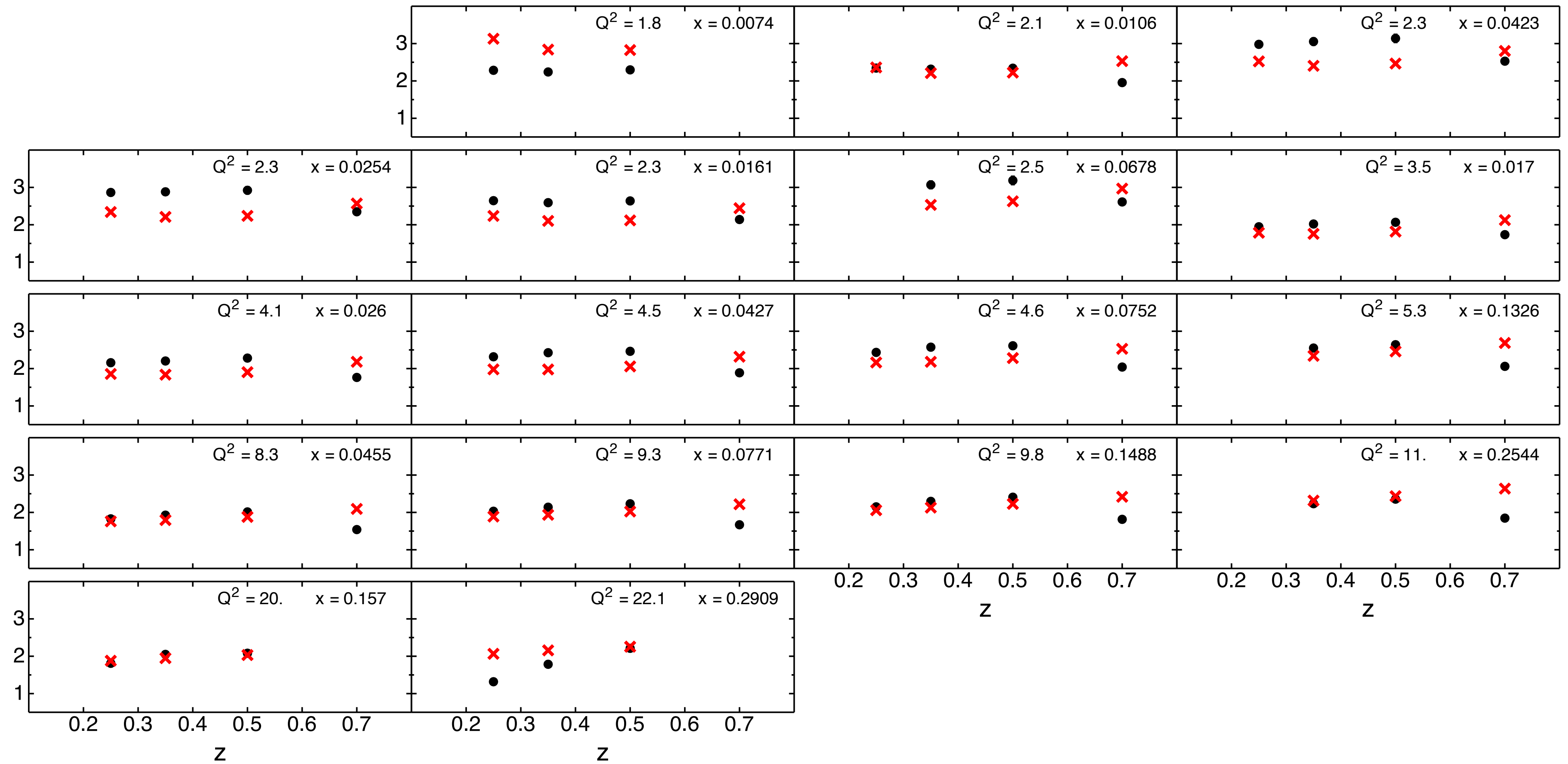
Black and red dots are similar

Black dots: large normalisation factors required to fit COMPASS multiplicities at NLL'

BAD

PROBLEMS WITH NORMALIZATION

to appear in F. Piacenza's PhD thesis



Red dots: ratio between collinear formula and integral of TMD part at order α_S

BAD

Black and red dots are similar

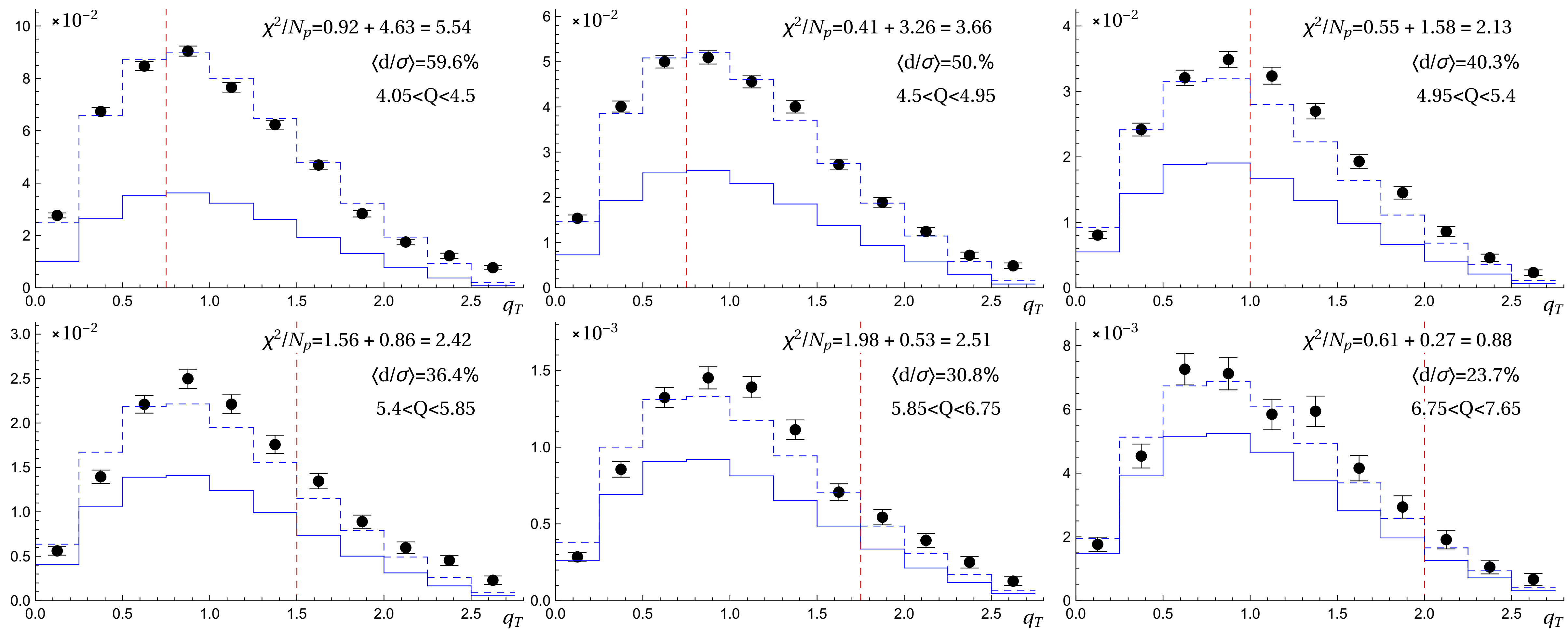
Black dots: large normalisation factors required to fit COMPASS multiplicities at NLL'

BAD

GOOD?

PROBLEMS WITH PIONS

Vladimirov, arXiv:1907.10356

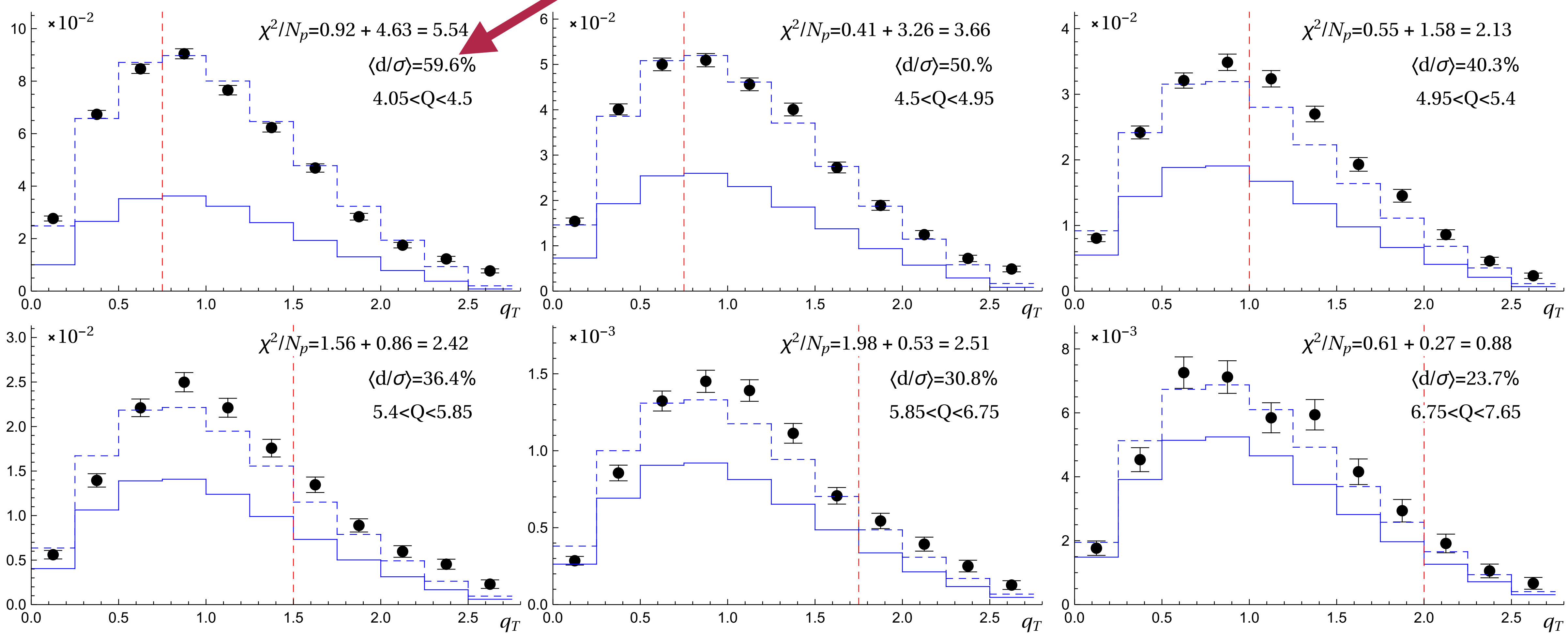


E615

PROBLEMS WITH PIONS

Vladimirov, arXiv:1907.10356

large normalization factors



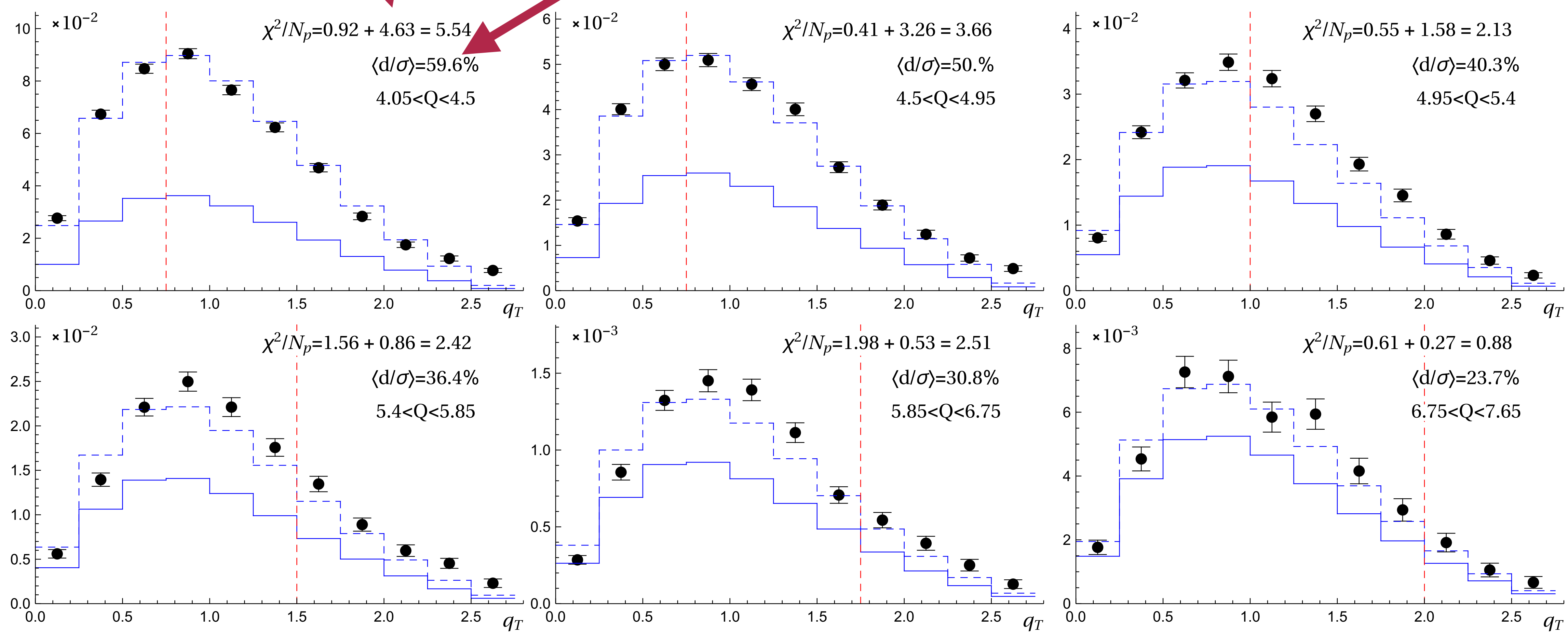
E615

PROBLEMS WITH PIONS

Vladimirov, arXiv:1907.10356

large χ² contribution from normalization

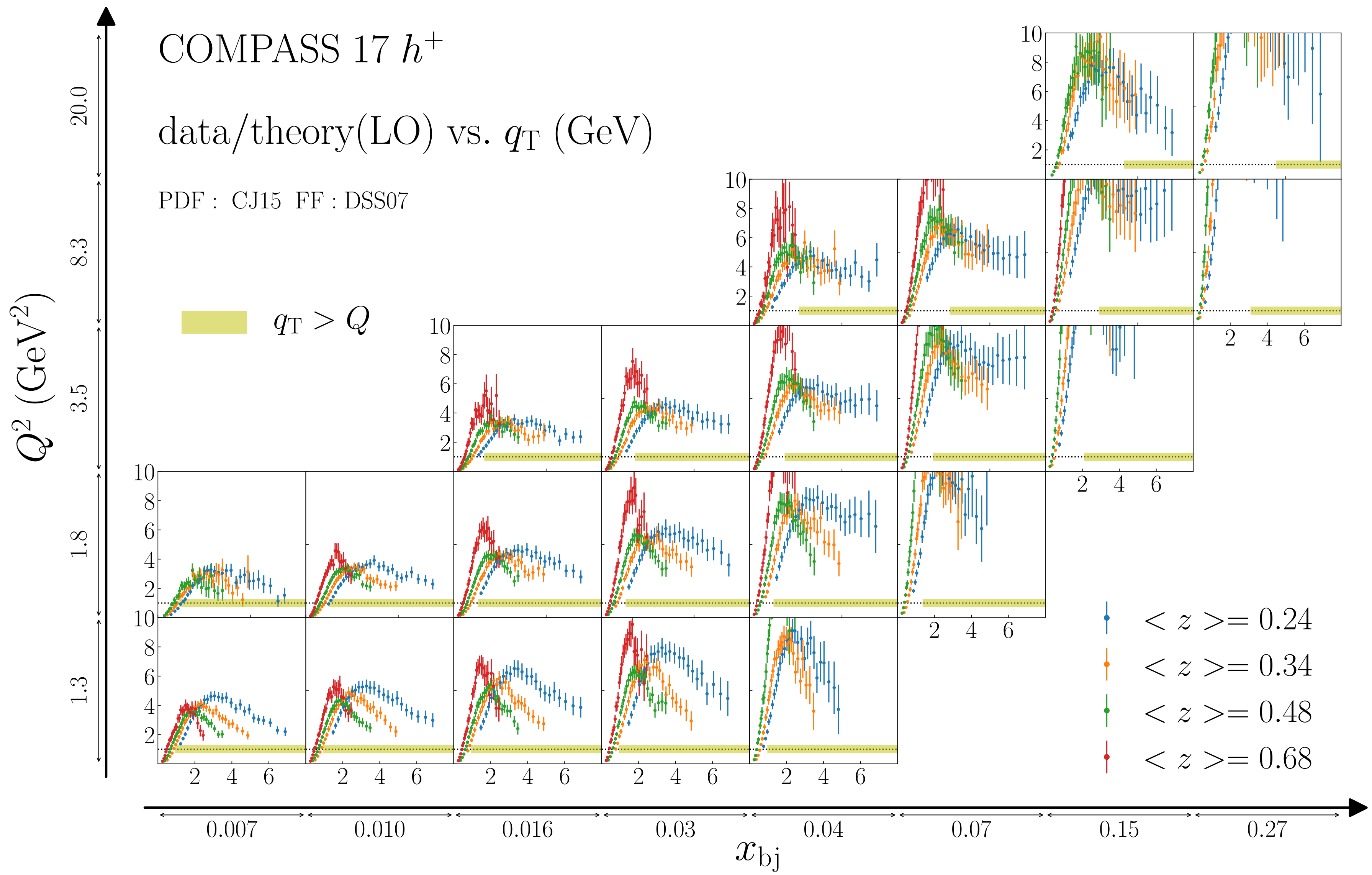
large normalization factors



E615

PROBLEMS WITH HIGH TRANSVERSE MOMENTUM

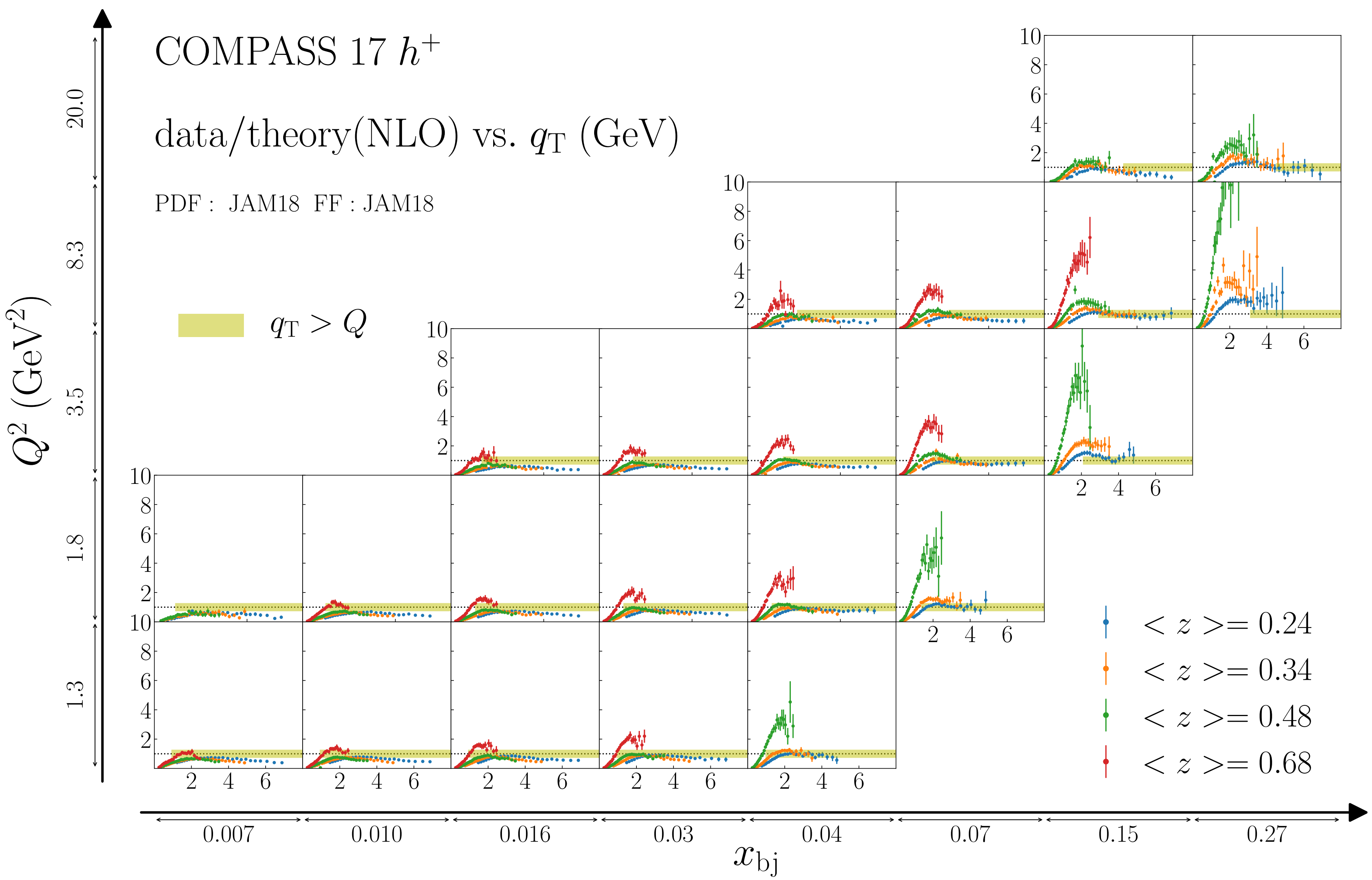
Gonzalez-Hernandez, Rogers, Sato, Wang arXiv:1808.04396



At high q_T, the collinear formalism should be valid, but large discrepancies are observed

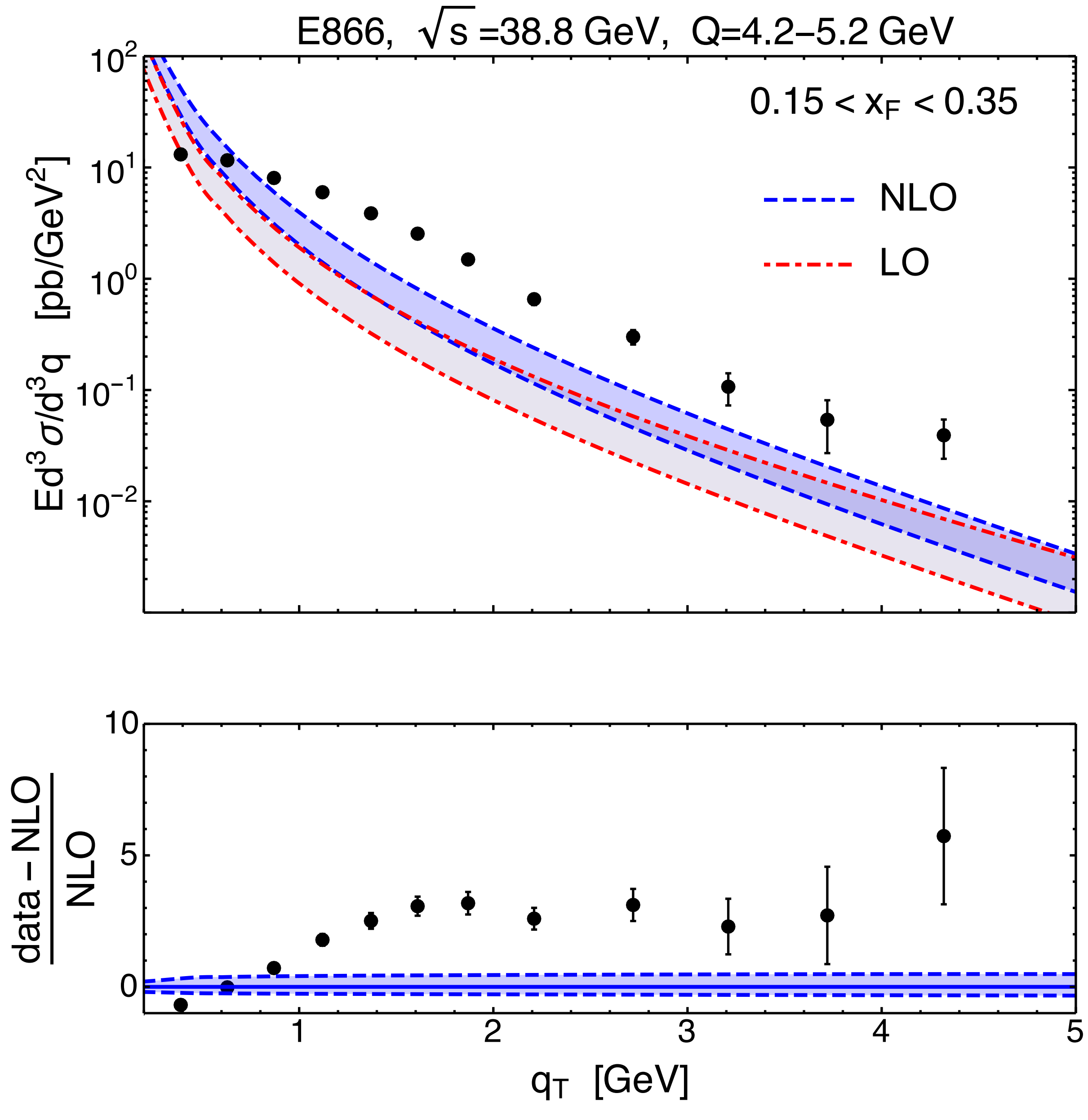
PROBLEMS WITH HIGH TRANSVERSE MOMENTUM

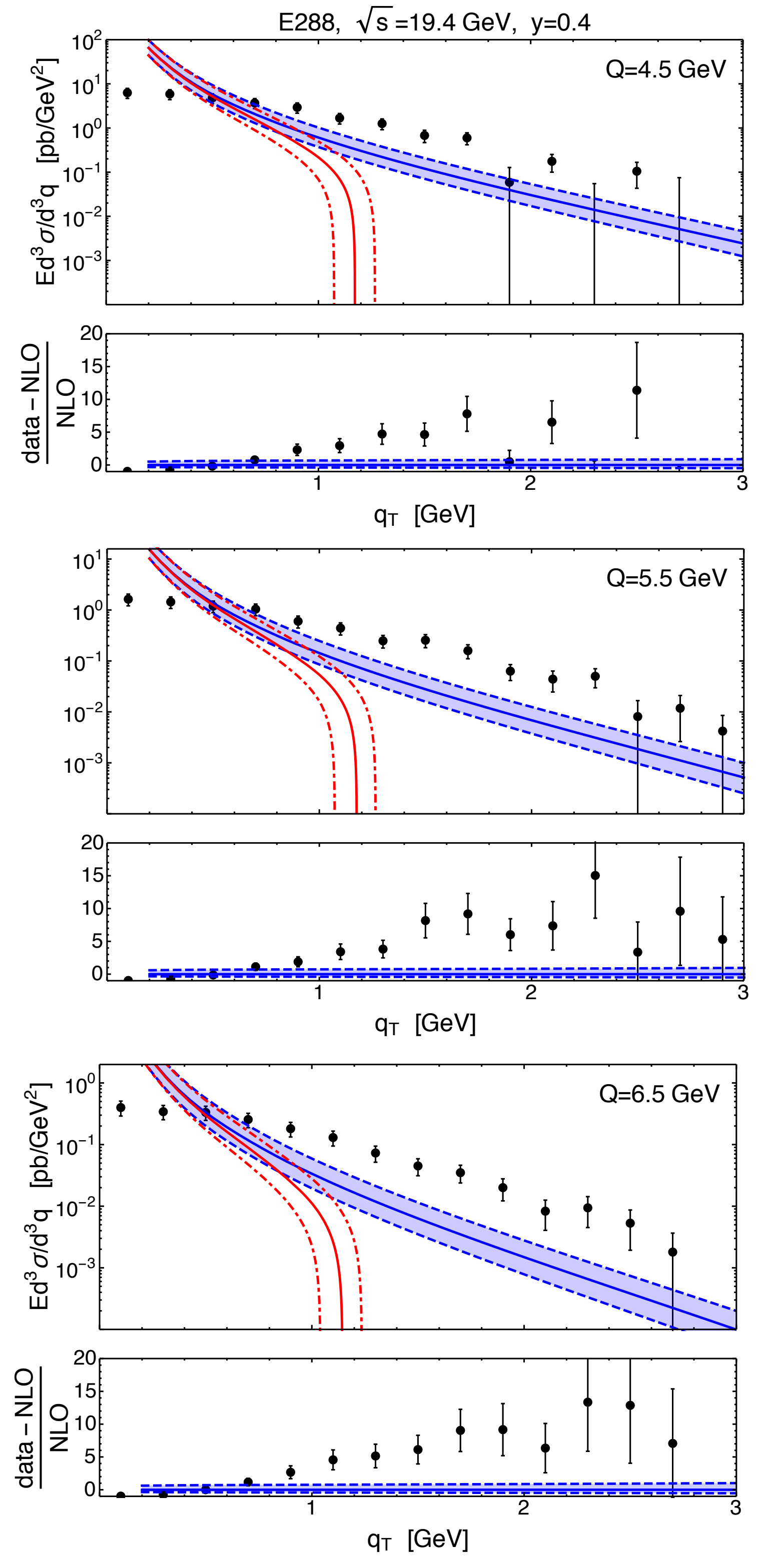
Gonzalez-Hernandez, Rogers, Sato, Wang arXiv:1808.04396



The discrepancies could be largely resolved by including NLO and modifying the gluon collinear fragmentation function

However, large discrepancies are found also in low-energy DY scattering data





Bacchetta, Bozzi, Lambertsen, Piacenza, Steinglechner, Vogelsang arXiv:1901.06916

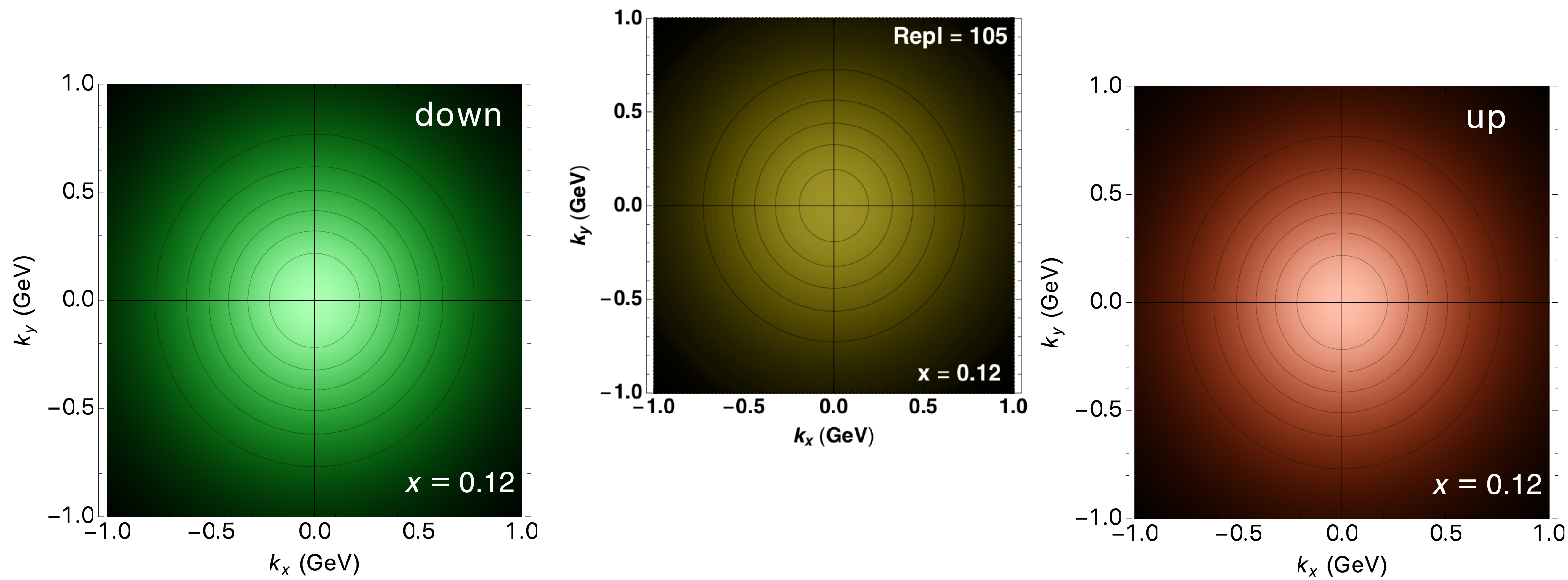
BOTTOM LINE

BOTTOM LINE

Normalizations discrepancies are all over the place, at least a low/moderate Q!

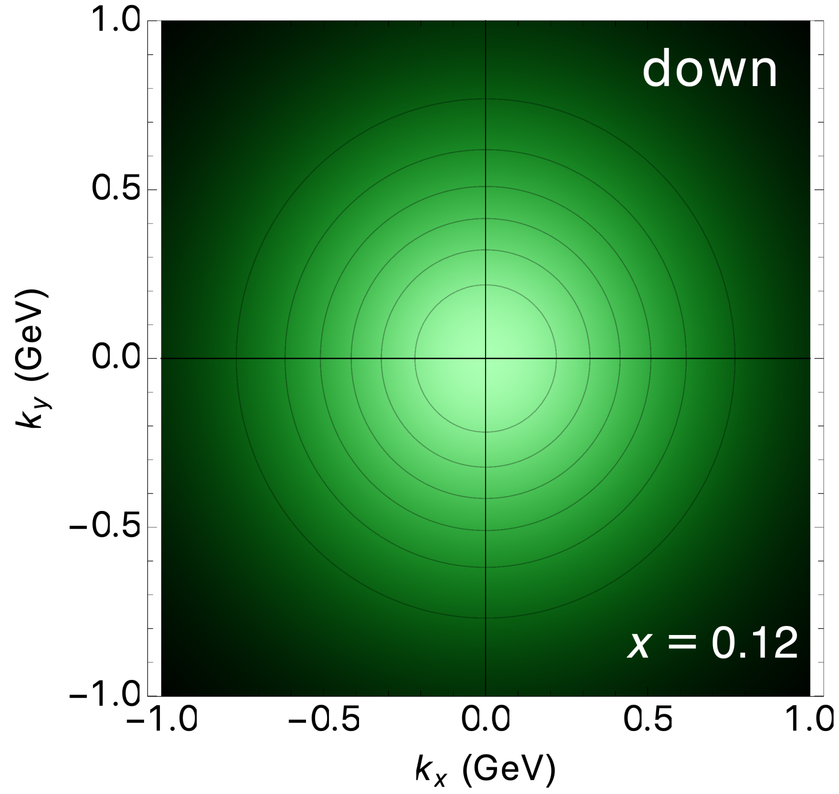
SIVERS QUARK TMD

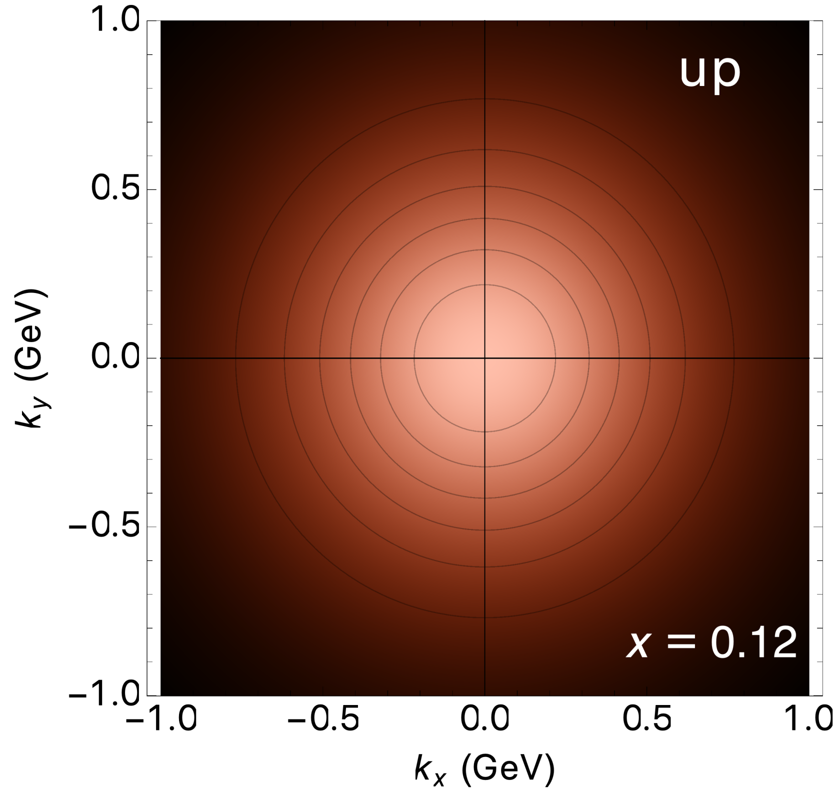
THE PROTON IN 3D (IN MOMENTUM SPACE)



At the moment, the unpolarized analysis is done with no flavour dependence

THE PROTON IN 3D (IN MOMENTUM SPACE)

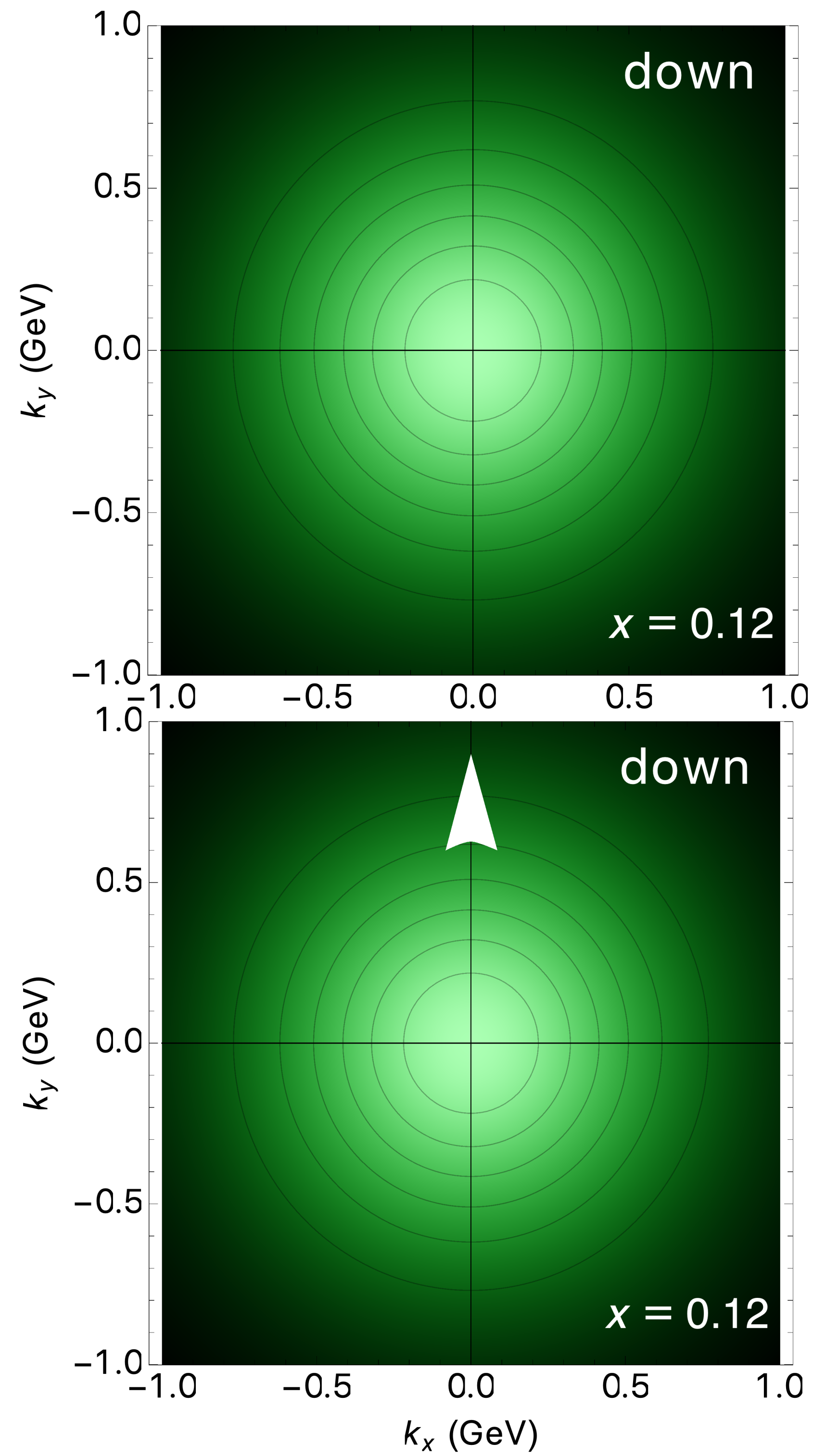




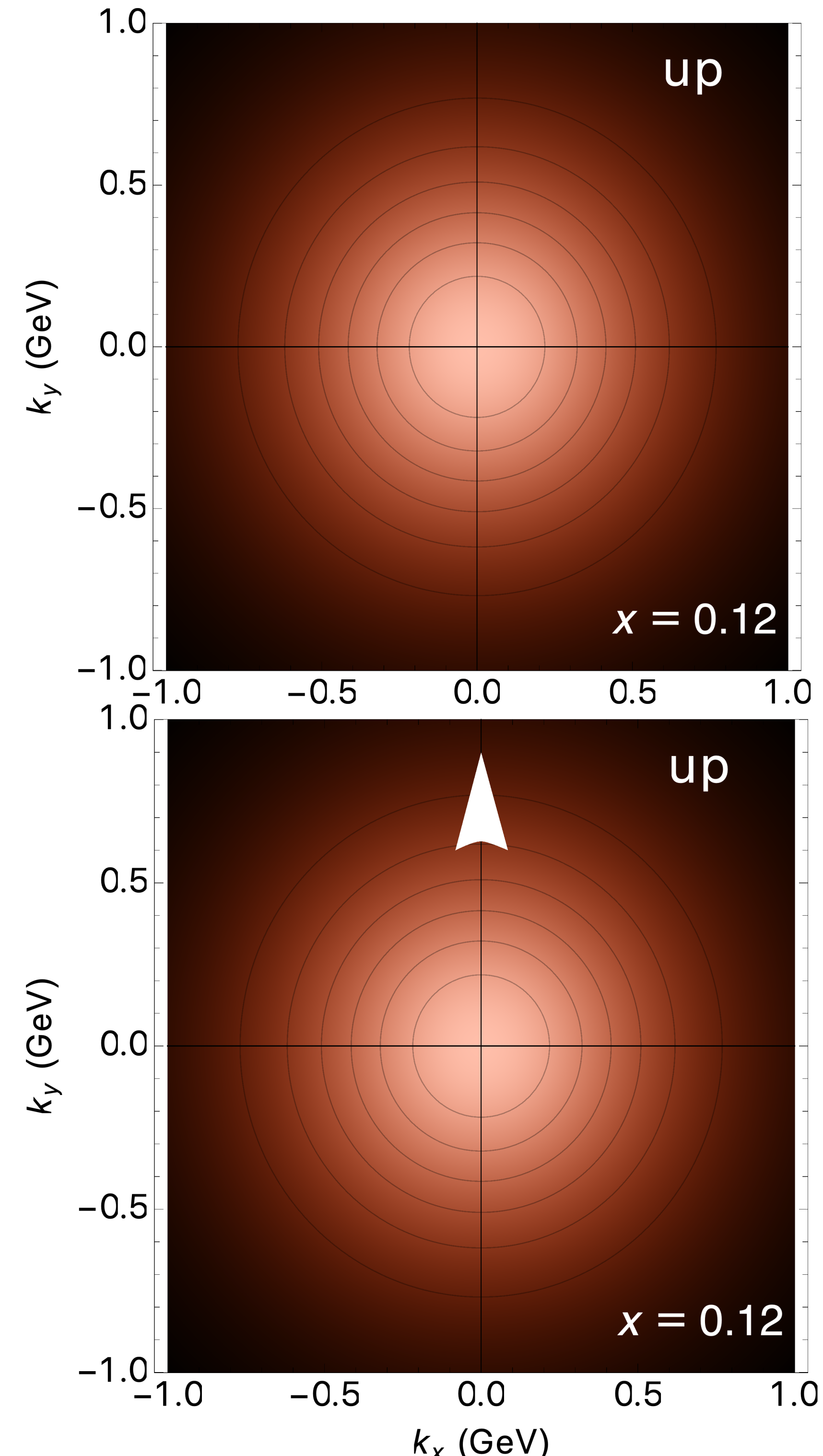
This is an image of the quark structure averaged over spin.

What happens if we include spin?

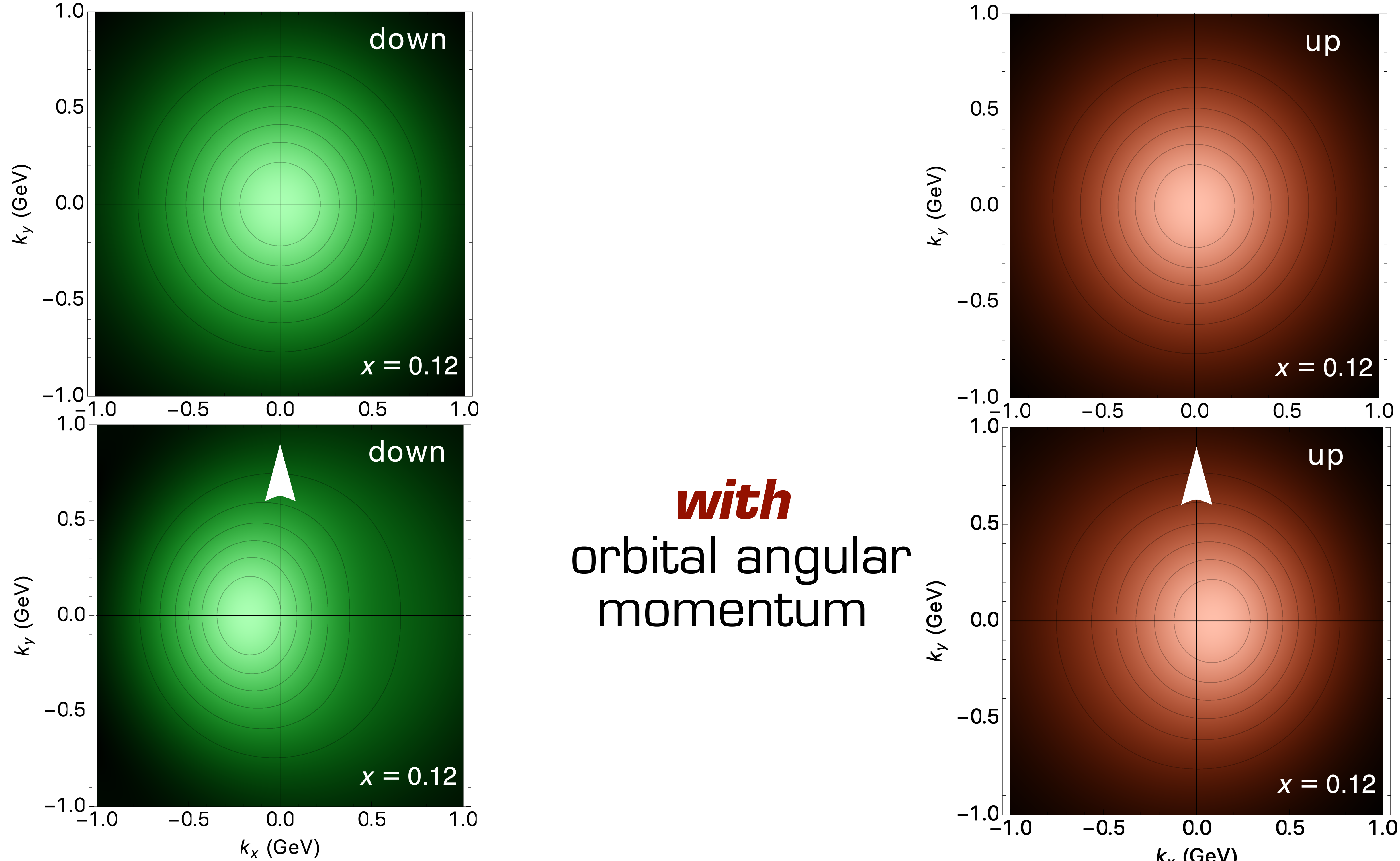
THE PROTON IN 3D (IN MOMENTUM SPACE)



without
orbital angular momentum

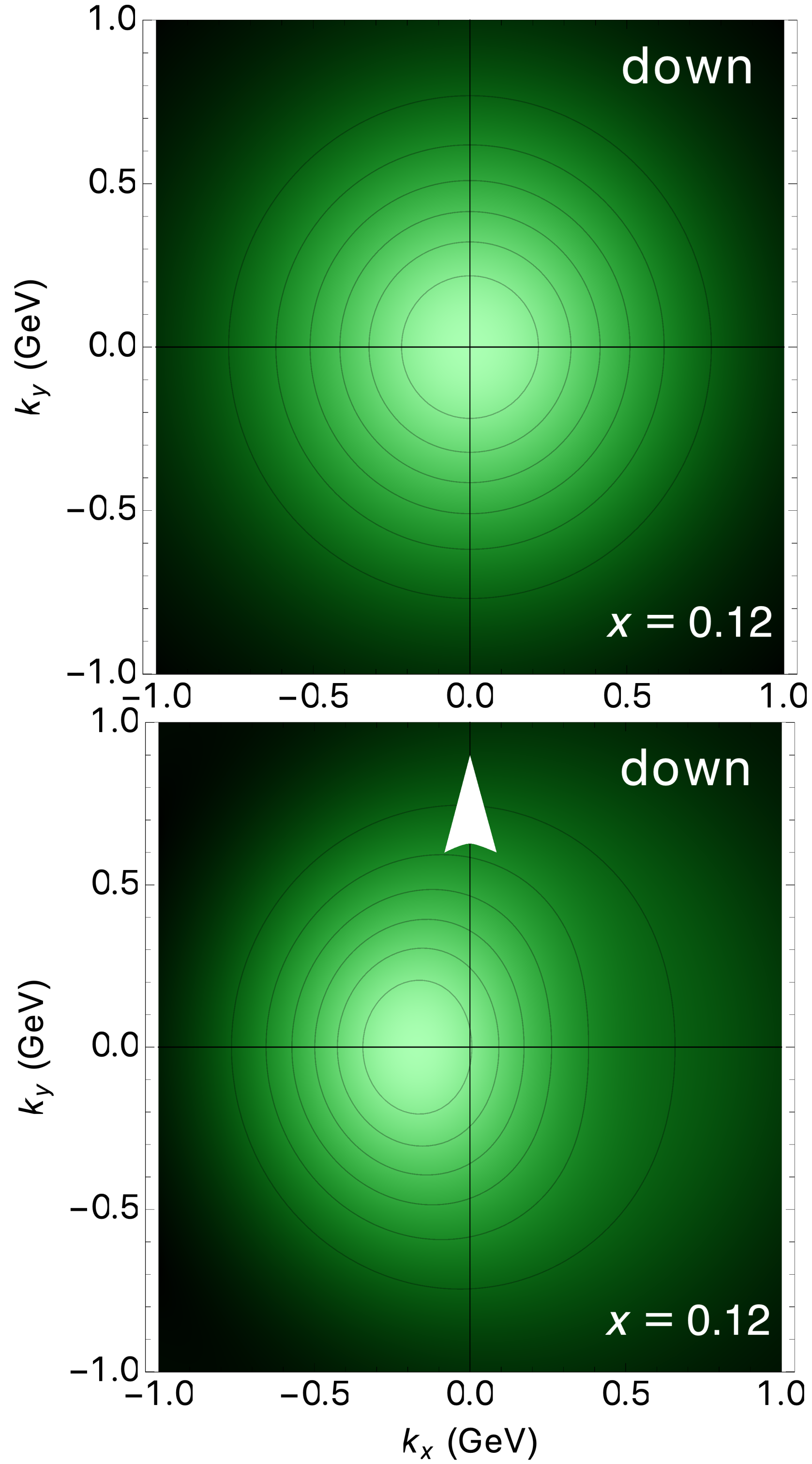


THE PROTON IN 3D (IN MOMENTUM SPACE)

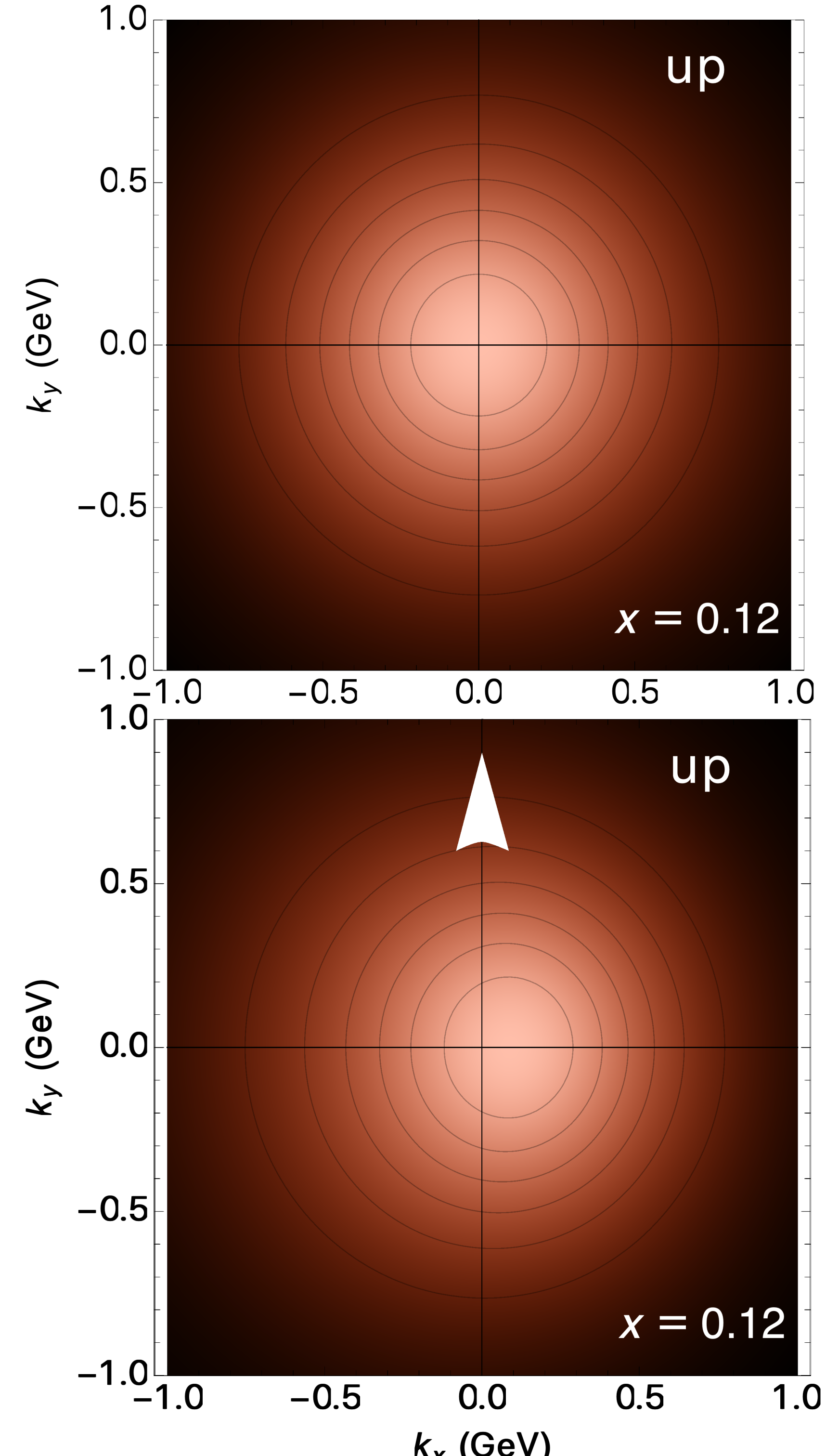


with
orbital angular momentum

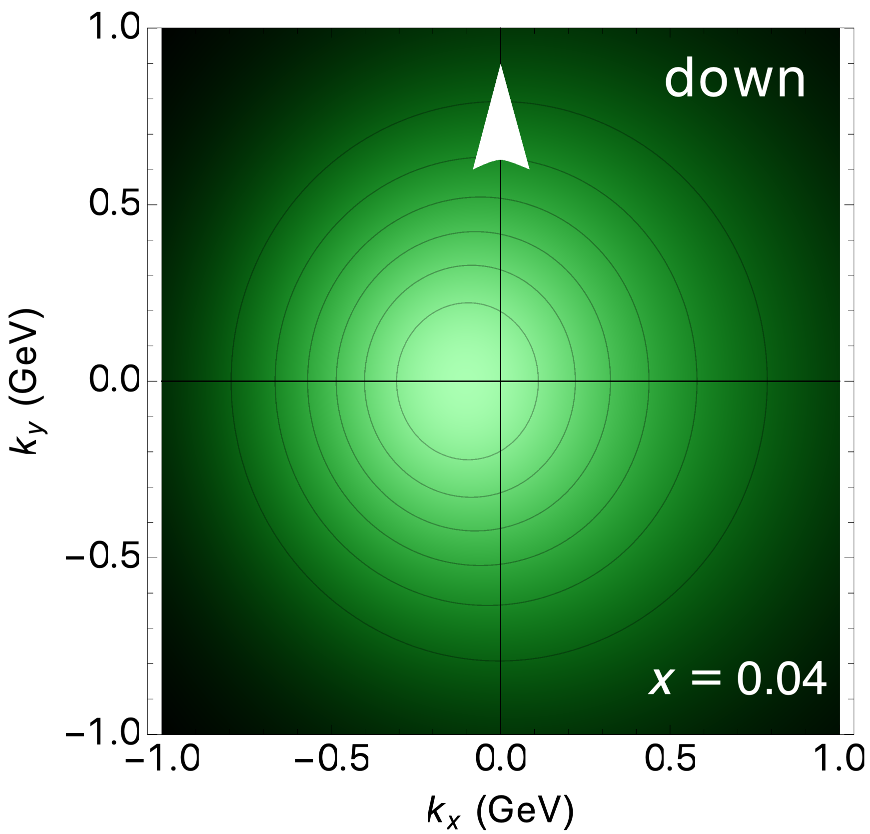
THE PROTON IN 3D (IN MOMENTUM SPACE)

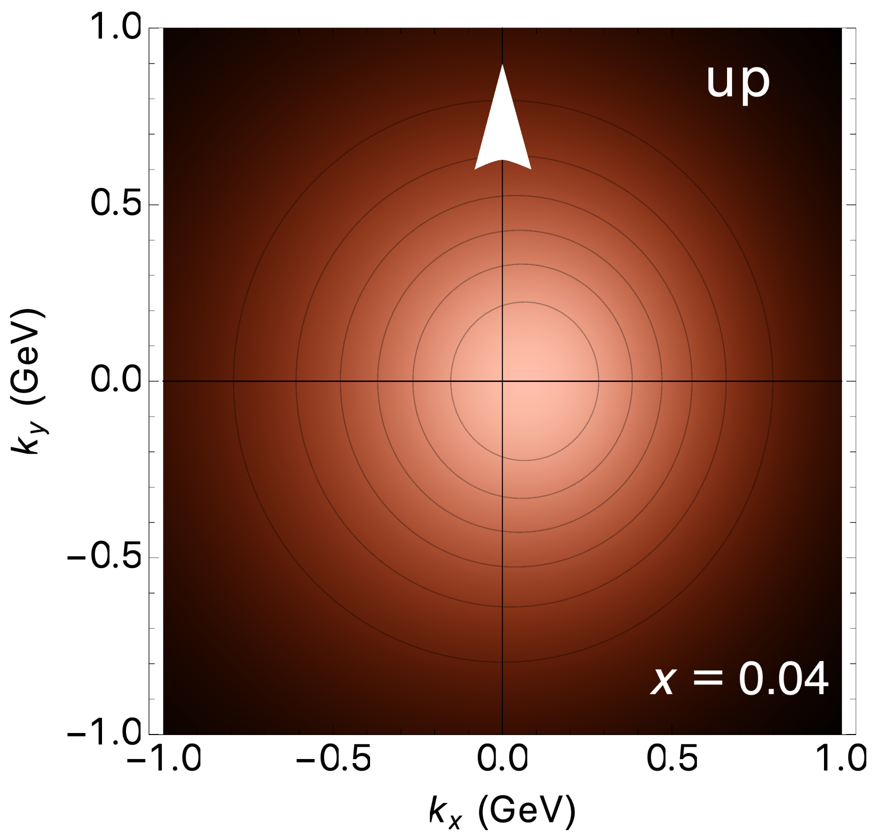


with
orbital angular momentum
"Sivers effect"



"REAL" 3D IMAGES IN MOMENTUM SPACE

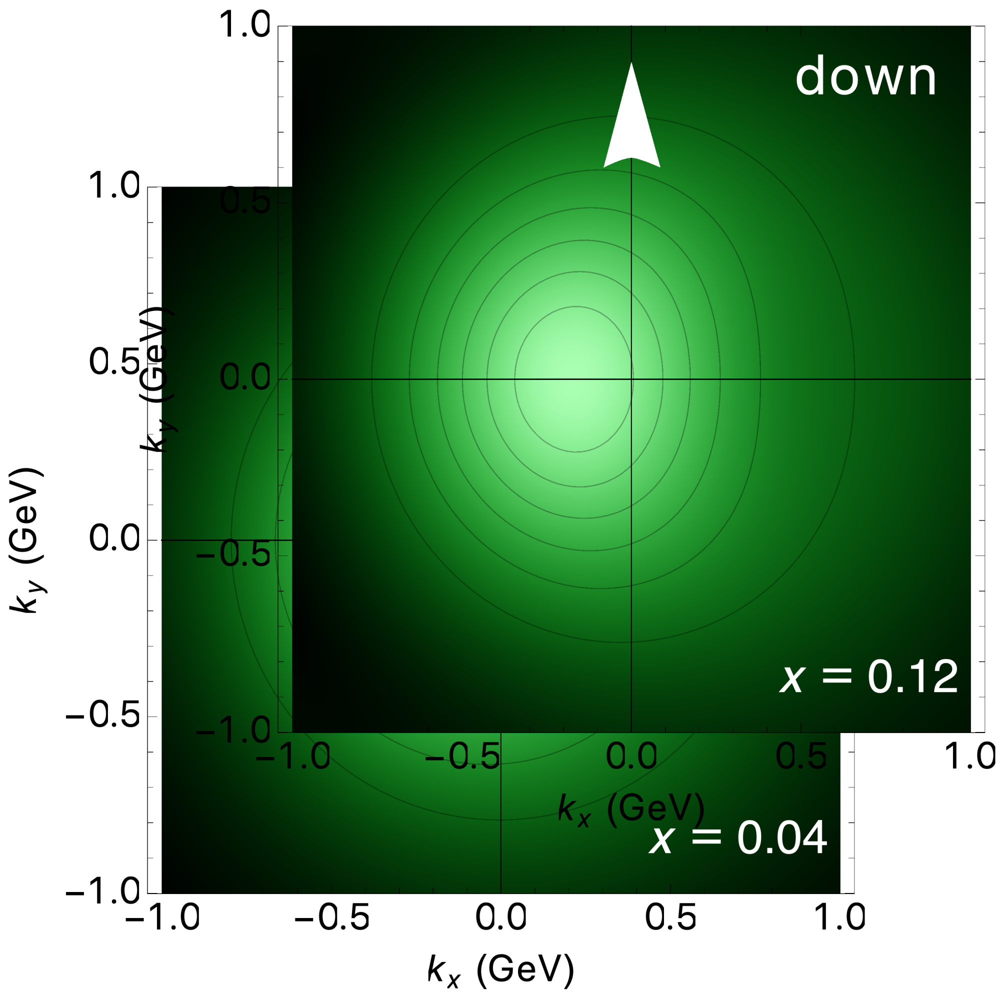


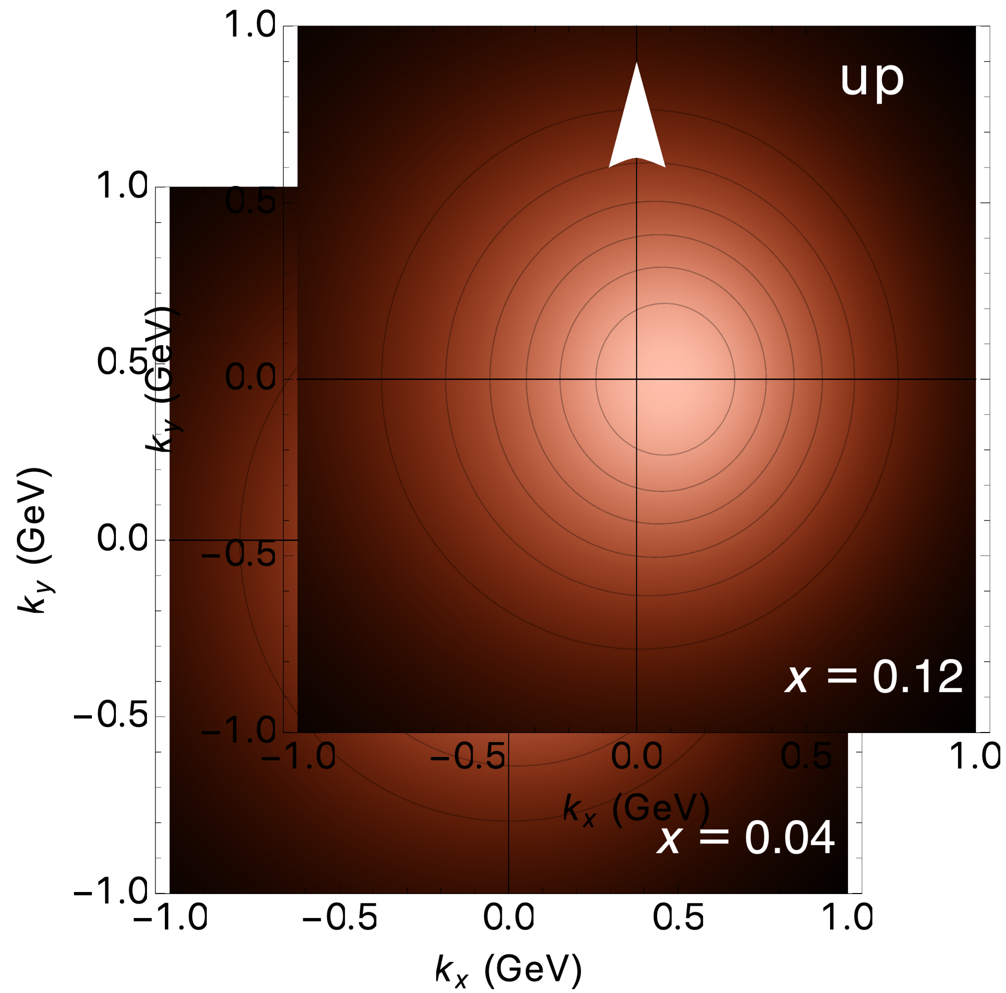


These are images entirely based on data (polarized and unpolarized)

Bacchetta, Delcarro, Pisano, Radici, in preparation

"REAL" 3D IMAGES IN MOMENTUM SPACE





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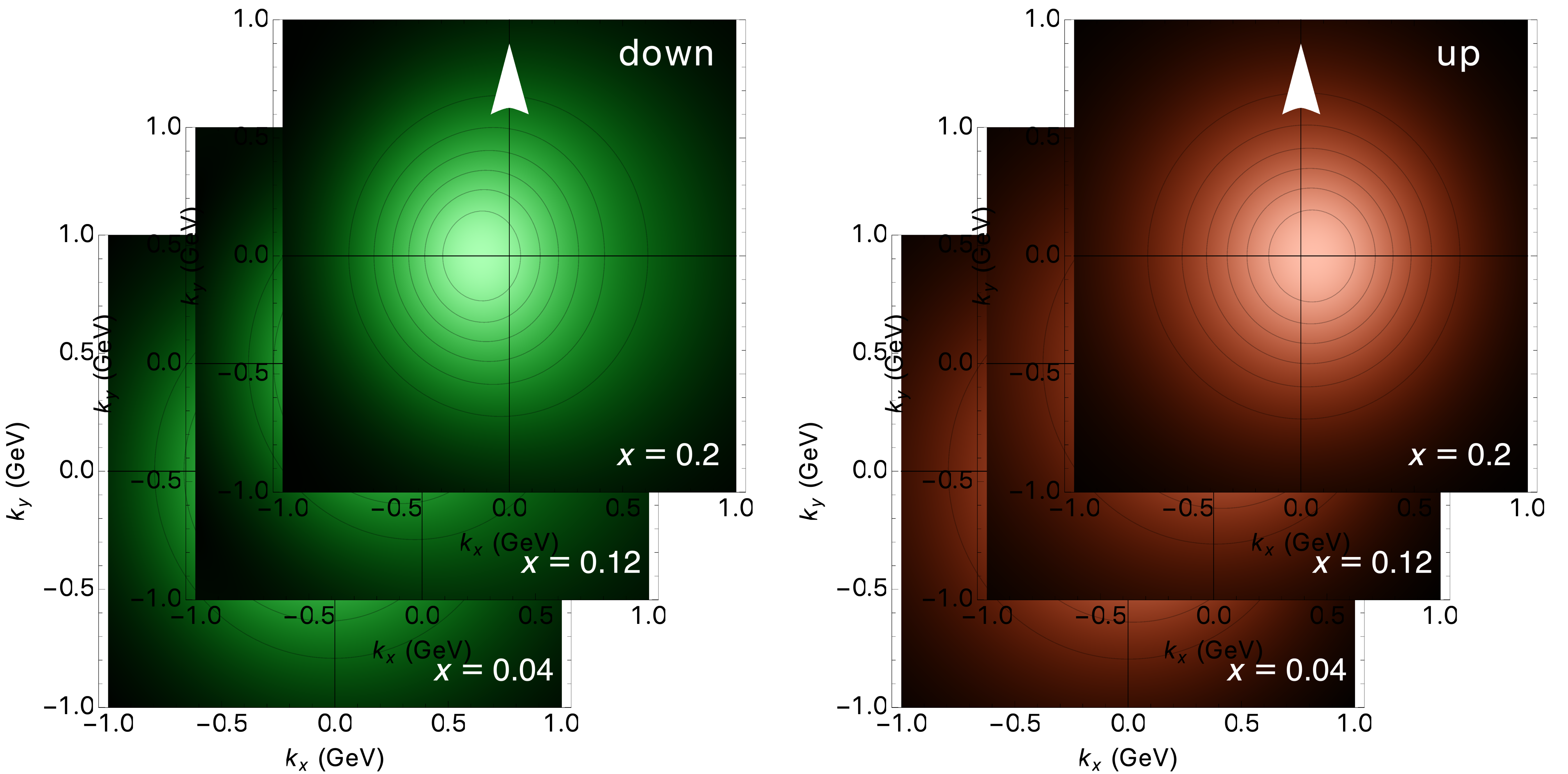

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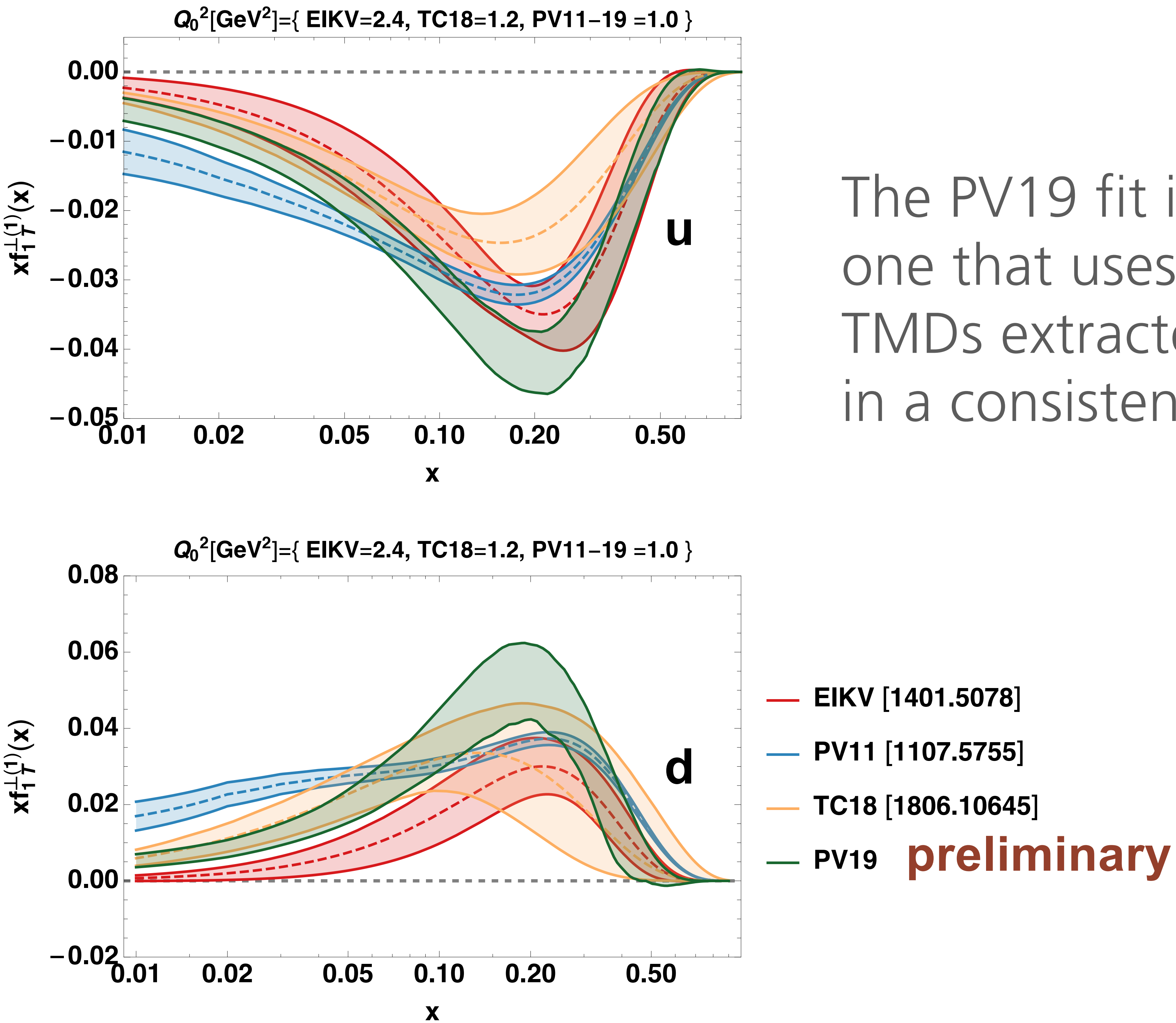
Bacchetta, Delcarro, Pisano, Radici, in preparation

SIVERS FUNCTION EXTRACTIONS

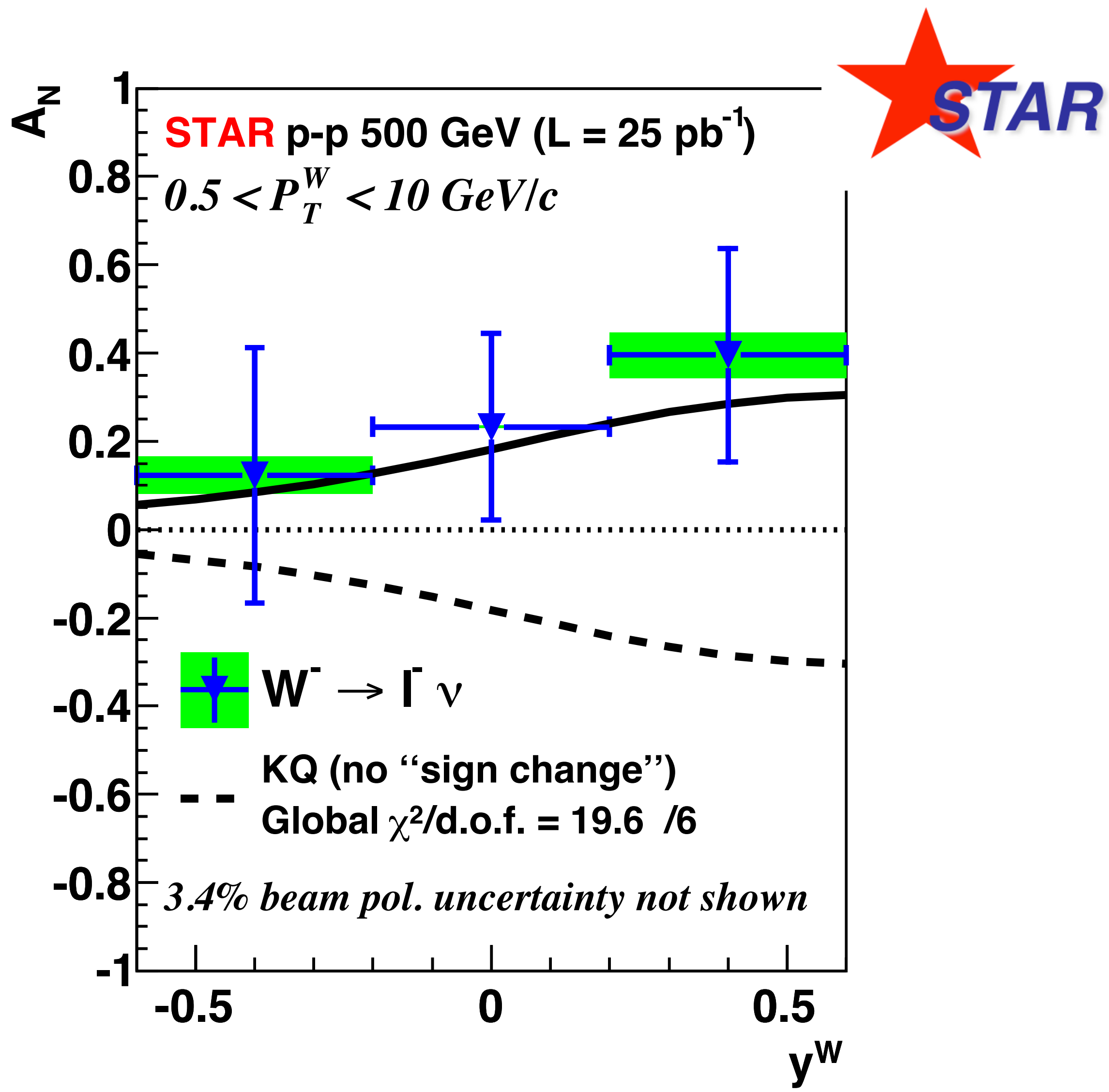


The PV19 fit is the only one that uses unpolarized TMDs extracted from data in a consistent way

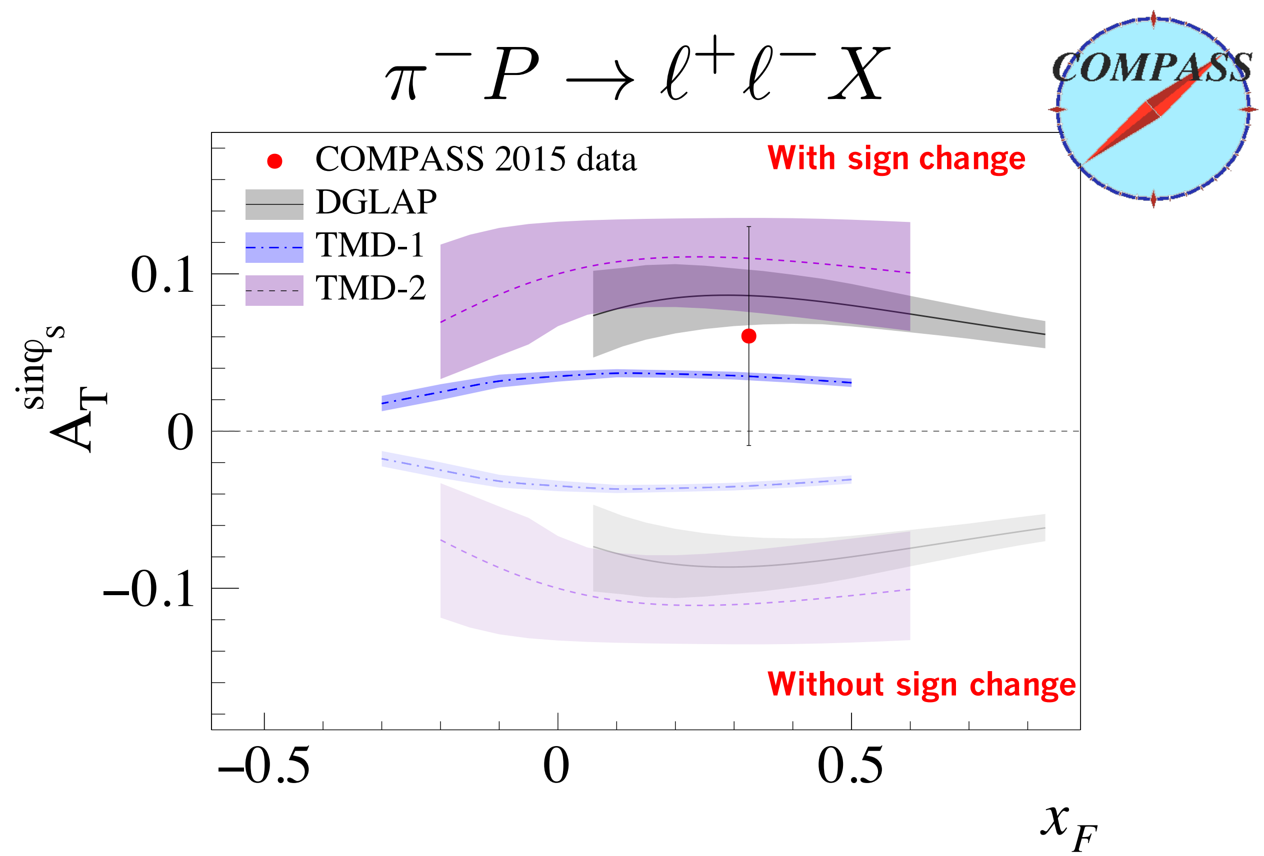
SIVERS FUNCTION SIGN CHANGE

Sivers function SIDIS = – Sivers function Drell-Yan

Collins, PLB 536 (02)



STAR Collab. arXiv:1511.06003



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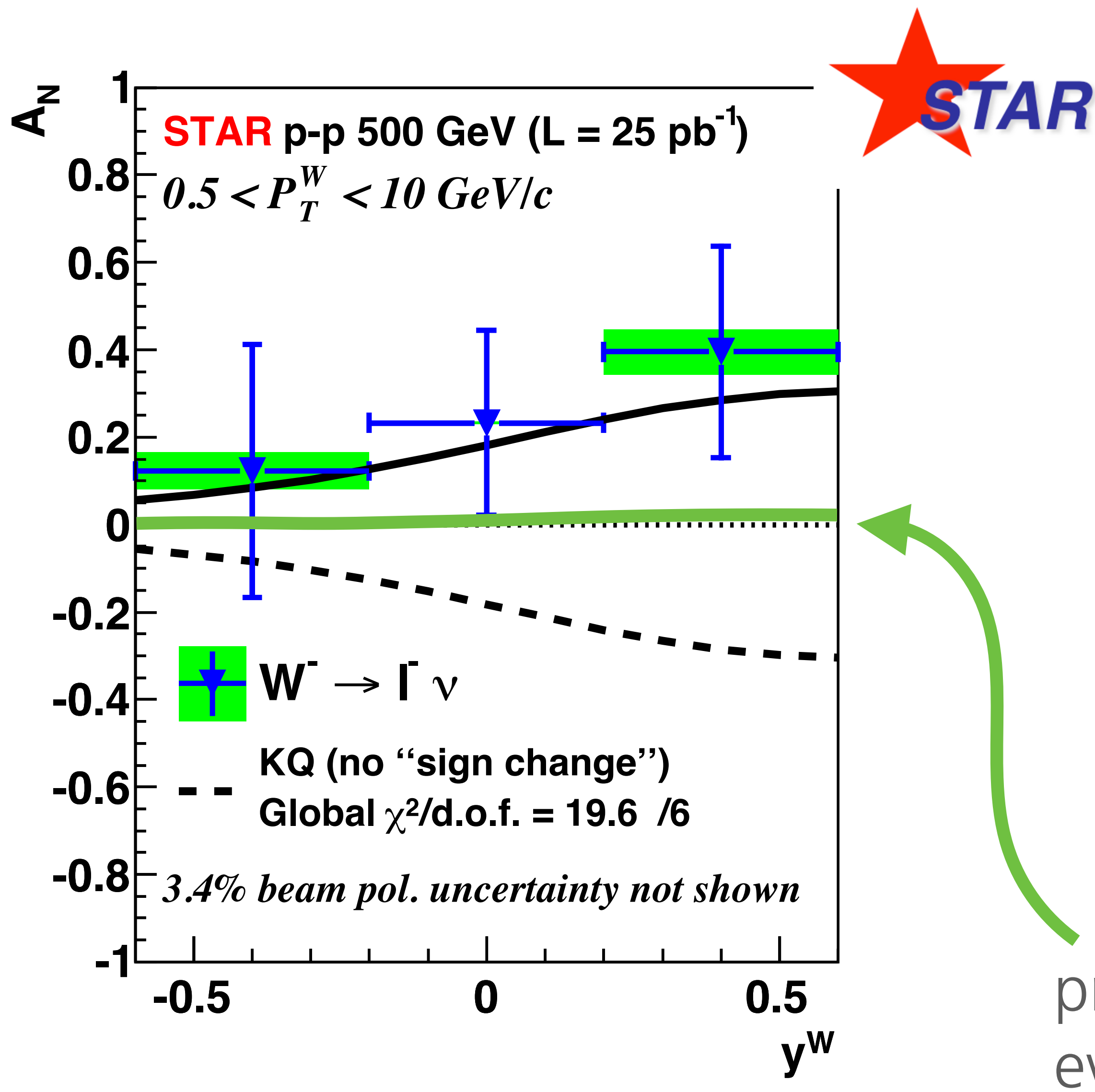
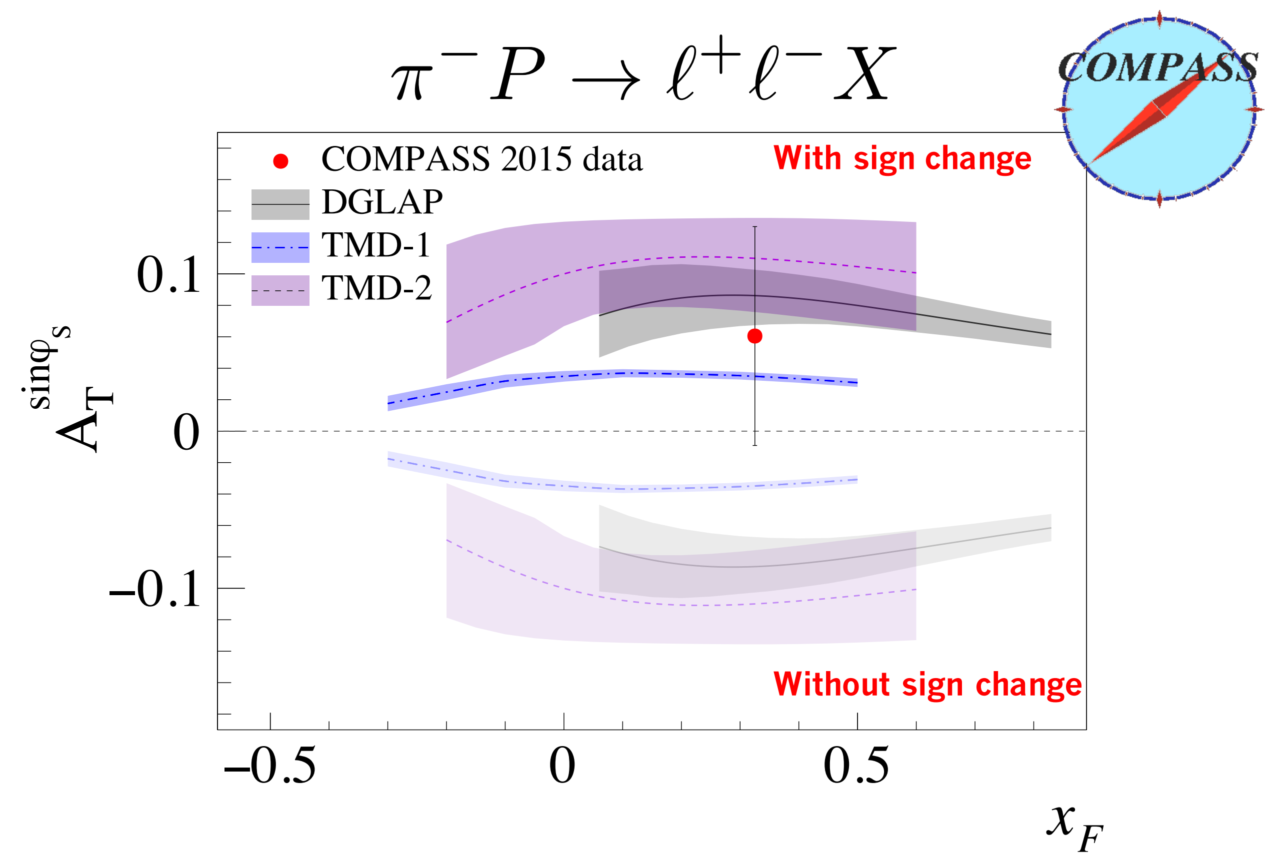
Collins, PLB 536 (02)

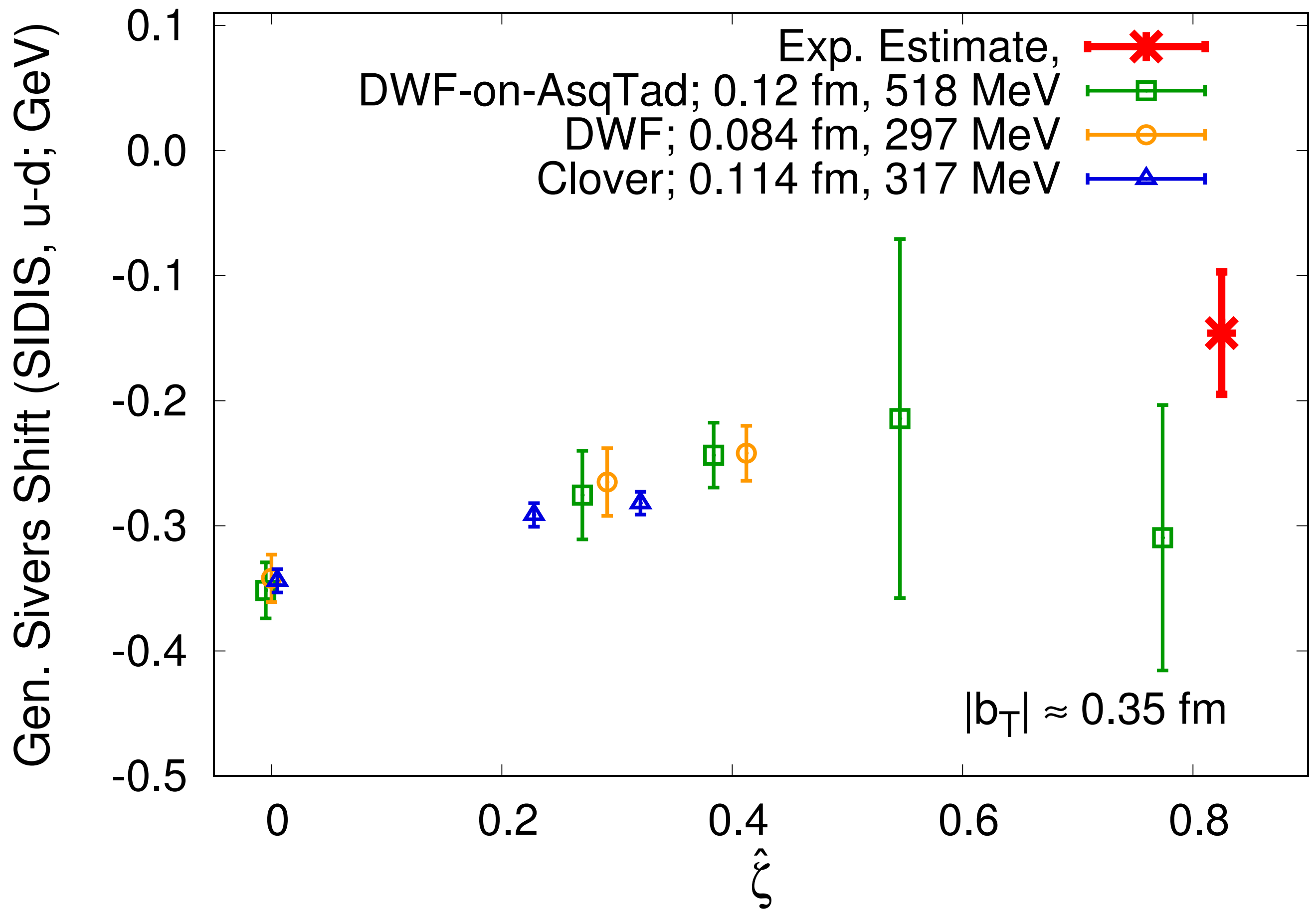


STAR Collab. arXiv:1511.06003



prediction with TMD evolution equations

SIVERS SHIFT IN LATTICE QCD

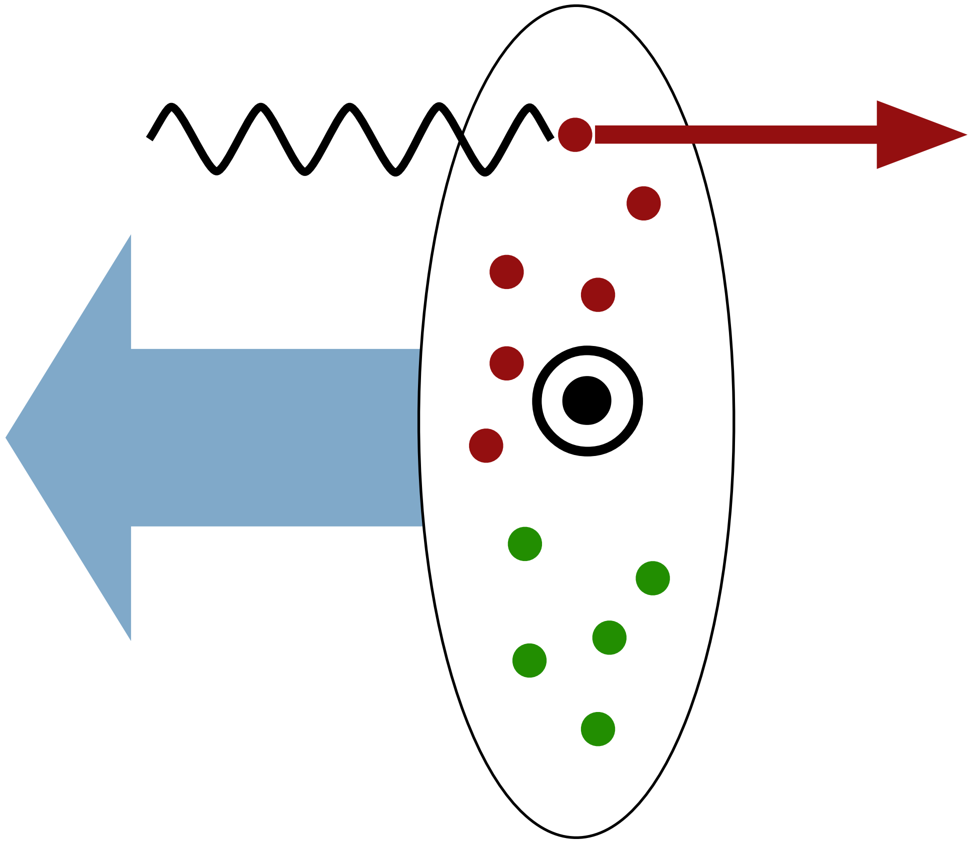


Yoon et al., arXiv:1706.03406

Pioneering lattice studies are in agreement with phenomenology

SIVERS FUNCTION AND ANGULAR MOMENTUM

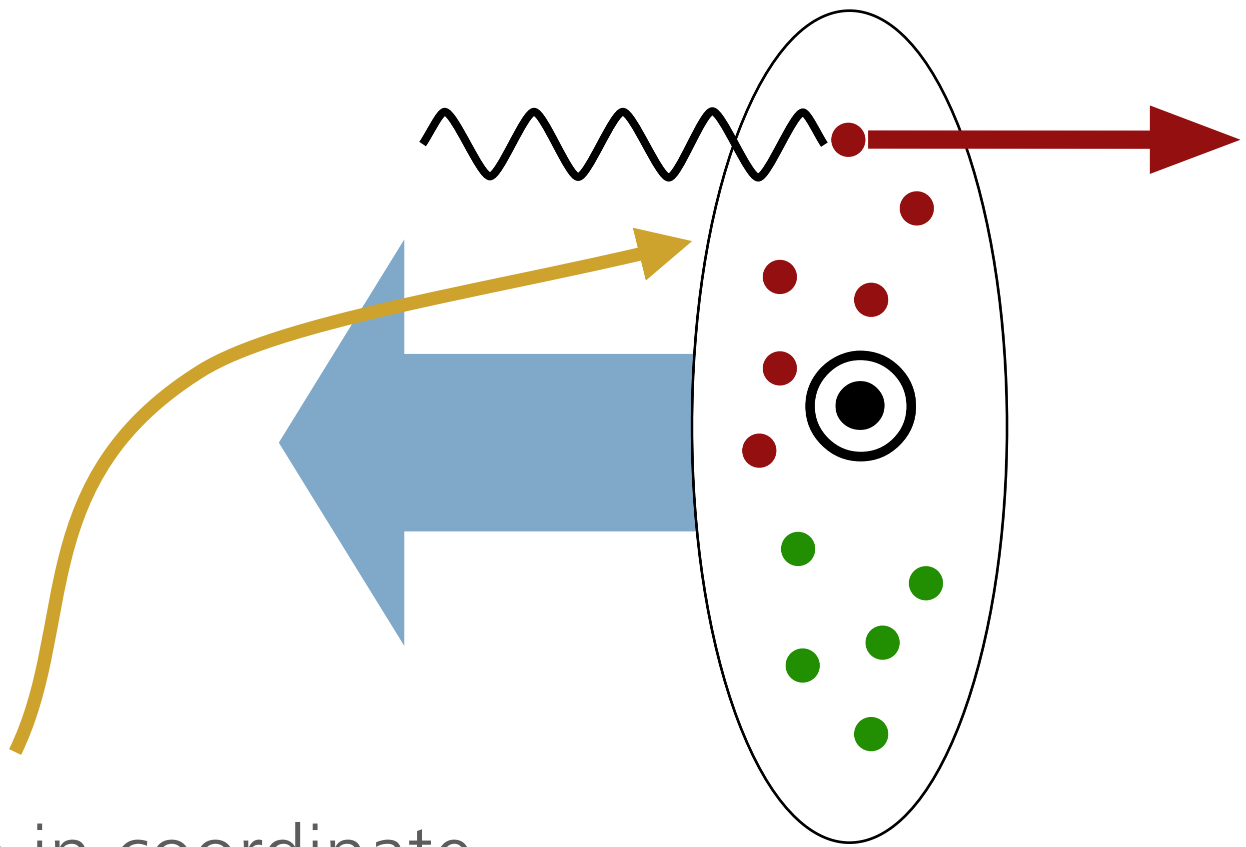
based on Burkardt, PRD66 (02)



Bacchetta, Radici, PRL107 (11)

SIVERS FUNCTION AND ANGULAR MOMENTUM

based on Burkardt, PRD66 (02)



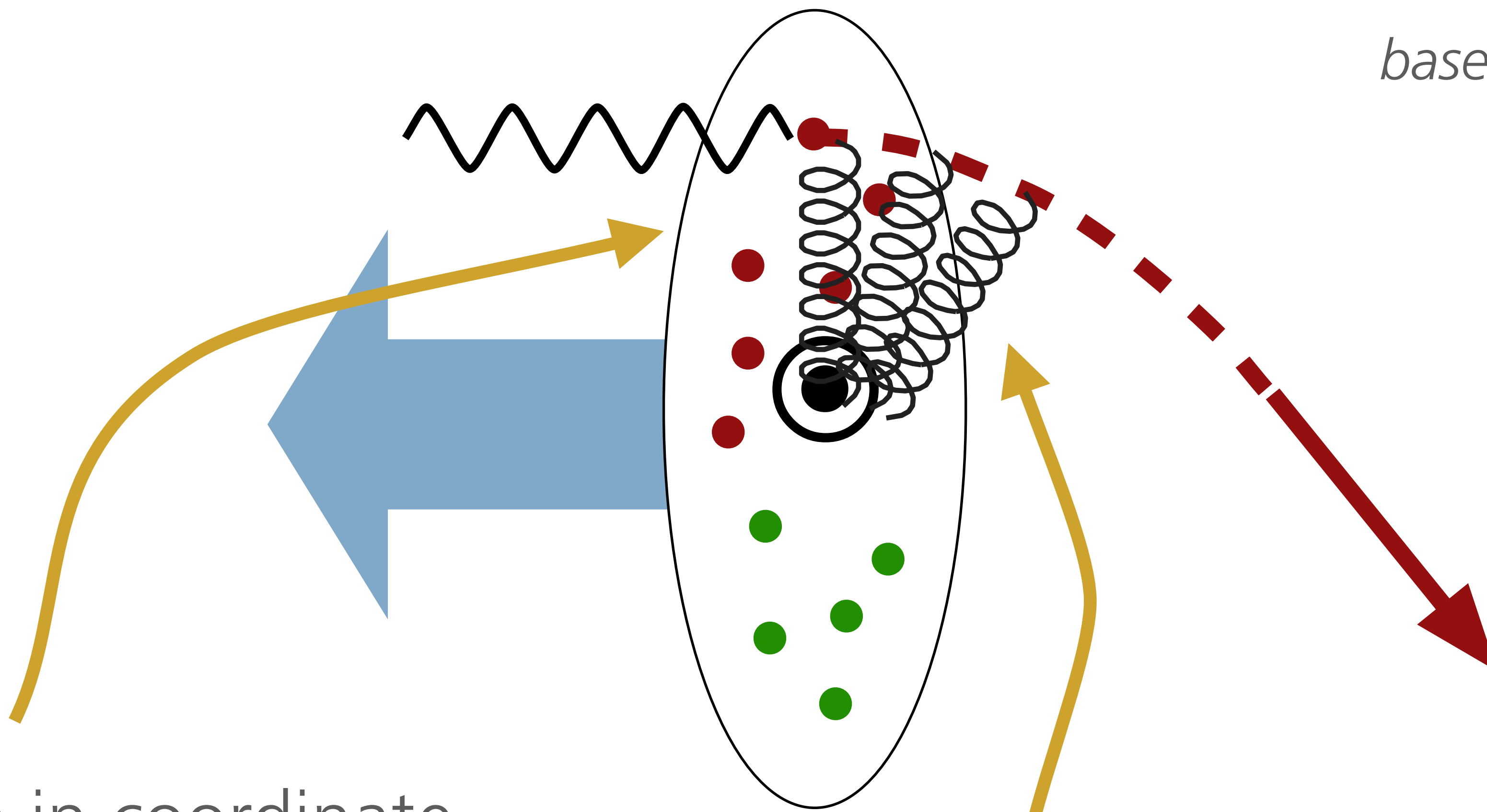
Distortion in coordinate space related to orbital angular momentum

$$E^a(x,0,0;Q_L^2)\ L(x) = f_{1T}^{\perp(0)a}(x;Q_L^2)$$

Bacchetta, Radici, PRL107 (11)

SIVERS FUNCTION AND ANGULAR MOMENTUM

based on Burkardt, PRD66 (02)



Distortion in coordinate space related to orbital angular momentum

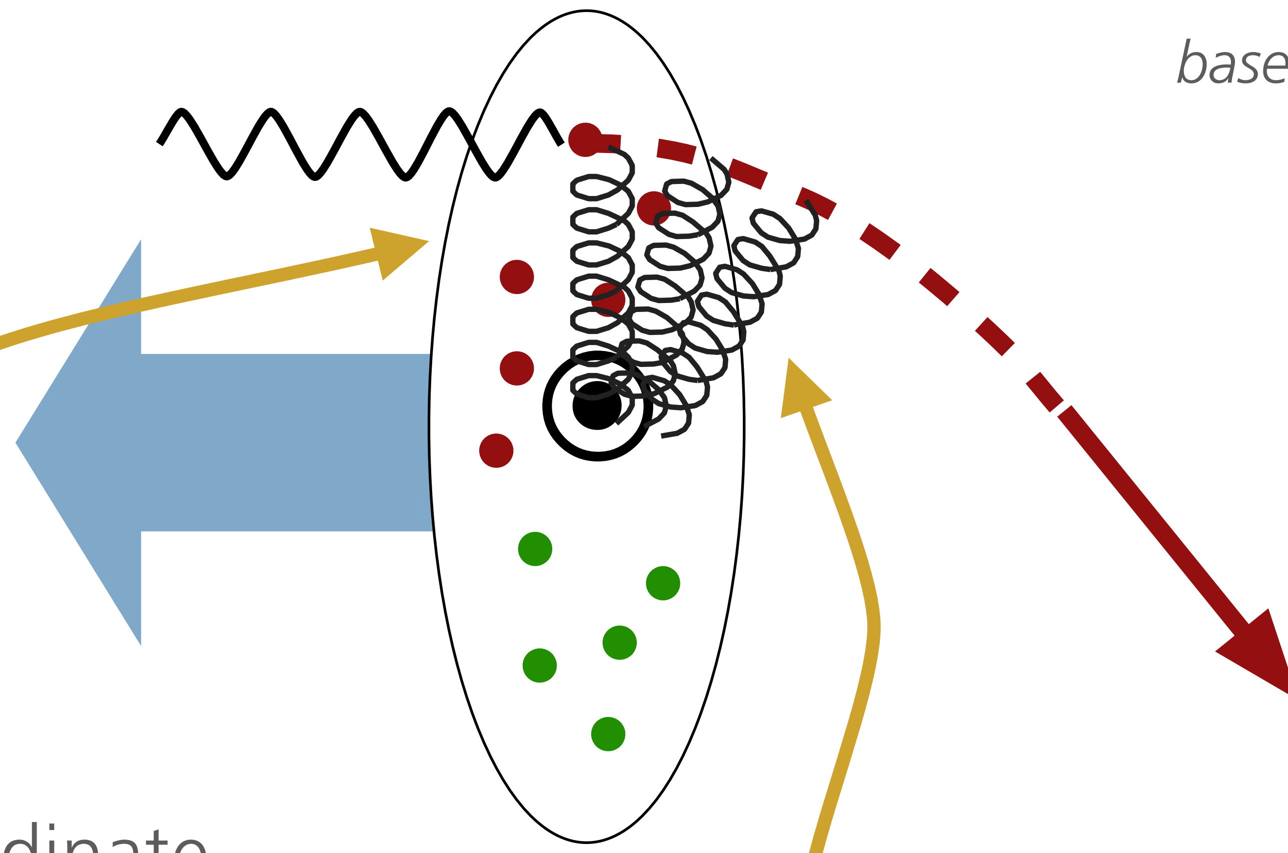
Lensing function (final-state interaction)

$$E^a(x,0,0;Q_L^2)\ L(x) = f_{1T}^{\perp(0)a}(x;Q_L^2)$$

Bacchetta, Radici, PRL107 (11)

SIVERS FUNCTION AND ANGULAR MOMENTUM

based on Burkardt, PRD66 (02)



Distortion in coordinate space related to orbital angular momentum

Lensing function (final-state interaction)

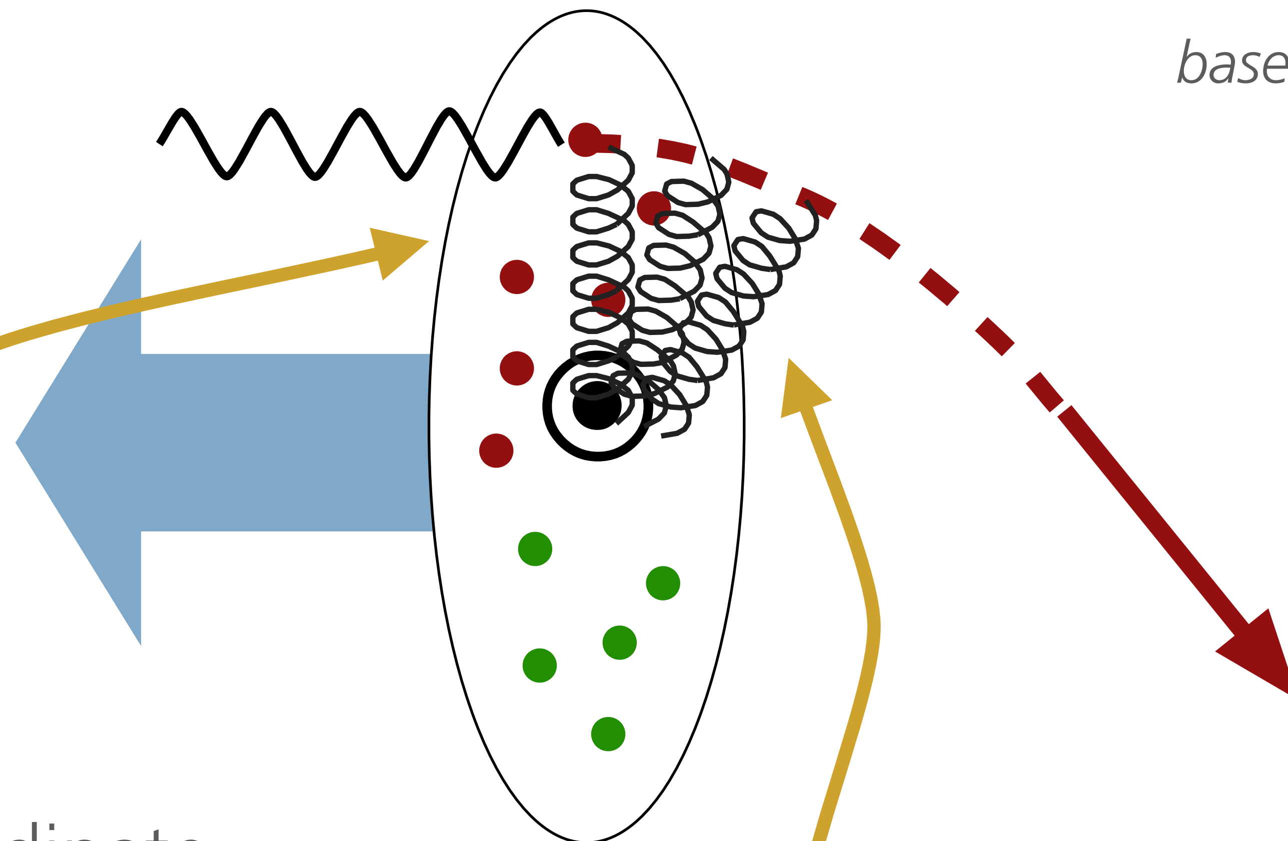
Sivers function (distortion in transverse-momentum space)

$$E^a(x,0,0;Q_L^2)\ L(x) = f_{1T}^{\perp(0)a}(x;Q_L^2)$$

Bacchetta, Radici, PRL107 (11)

SIVERS FUNCTION AND ANGULAR MOMENTUM

based on Burkardt, PRD66 (02)



Sivers function (distortion in transverse-momentum space)

Distortion in coordinate space related to orbital angular momentum

Lensing function (final-state interaction)

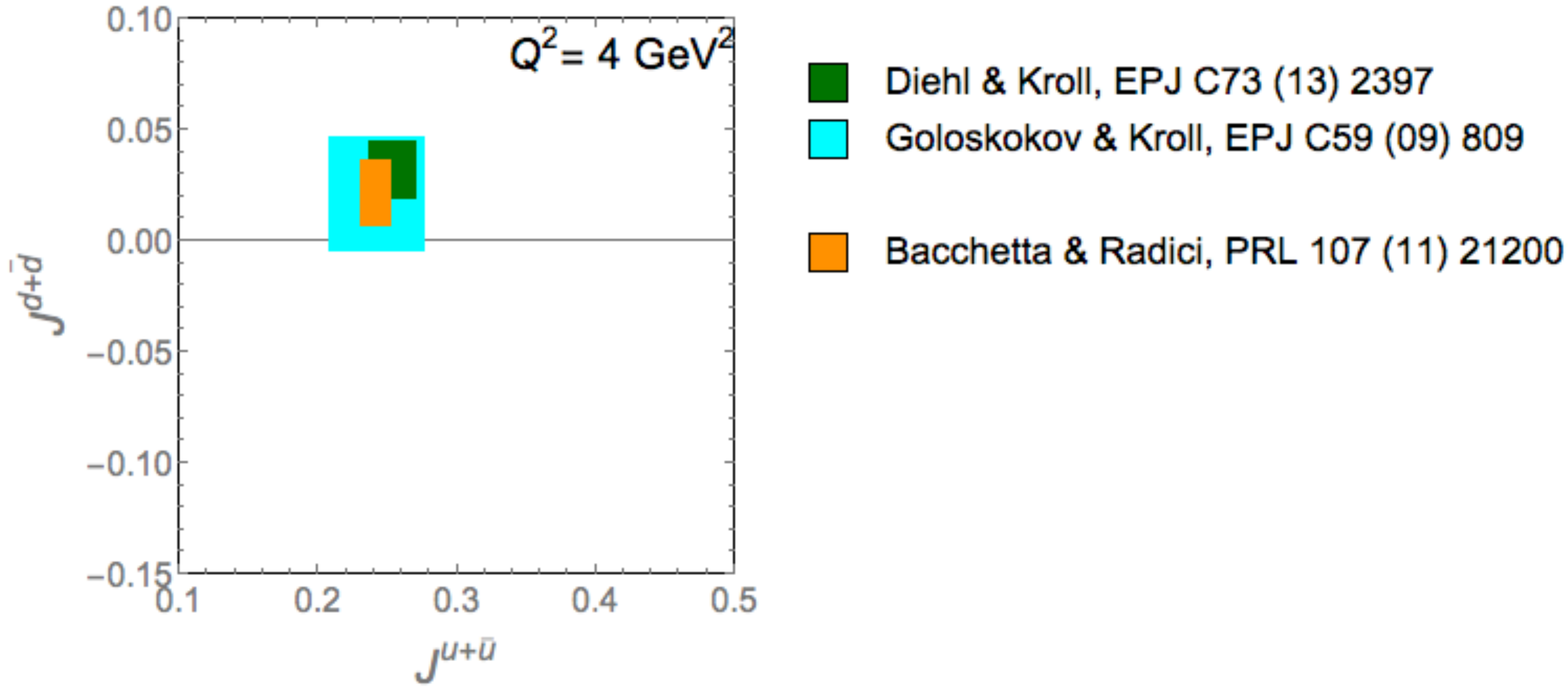
$^{a}(x; Q_L^2)$

acchetta, Radici, PRL107 (11)

This appealing picture works only with two-body systems (quark+spectator)

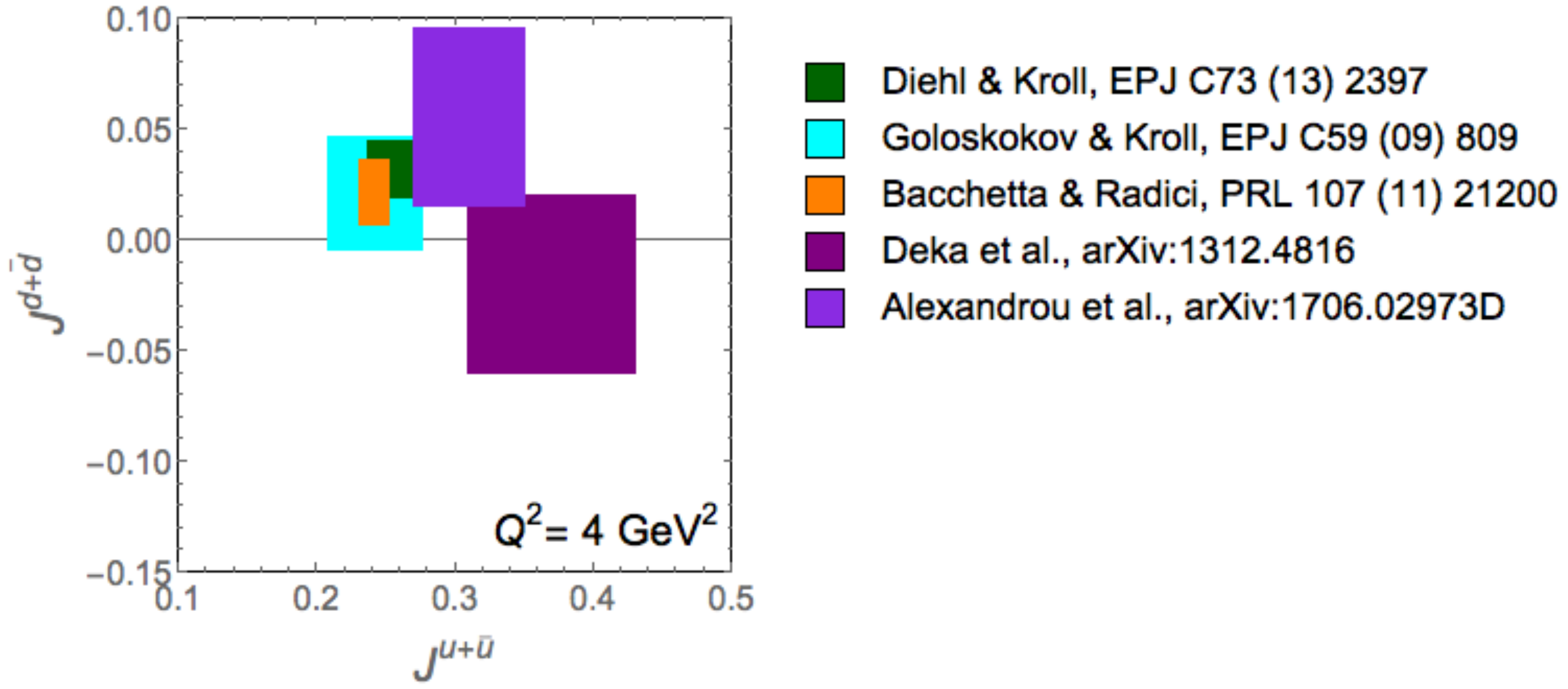
Pasquini, Rodini, Bacchetta, arXiv:1907.06960

CONNECTION WITH TOTAL ANGULAR MOMENTUM



Estimate of angular momentum based on lensing assumptions + Sivers fit

CONNECTION WITH TOTAL ANGULAR MOMENTUM



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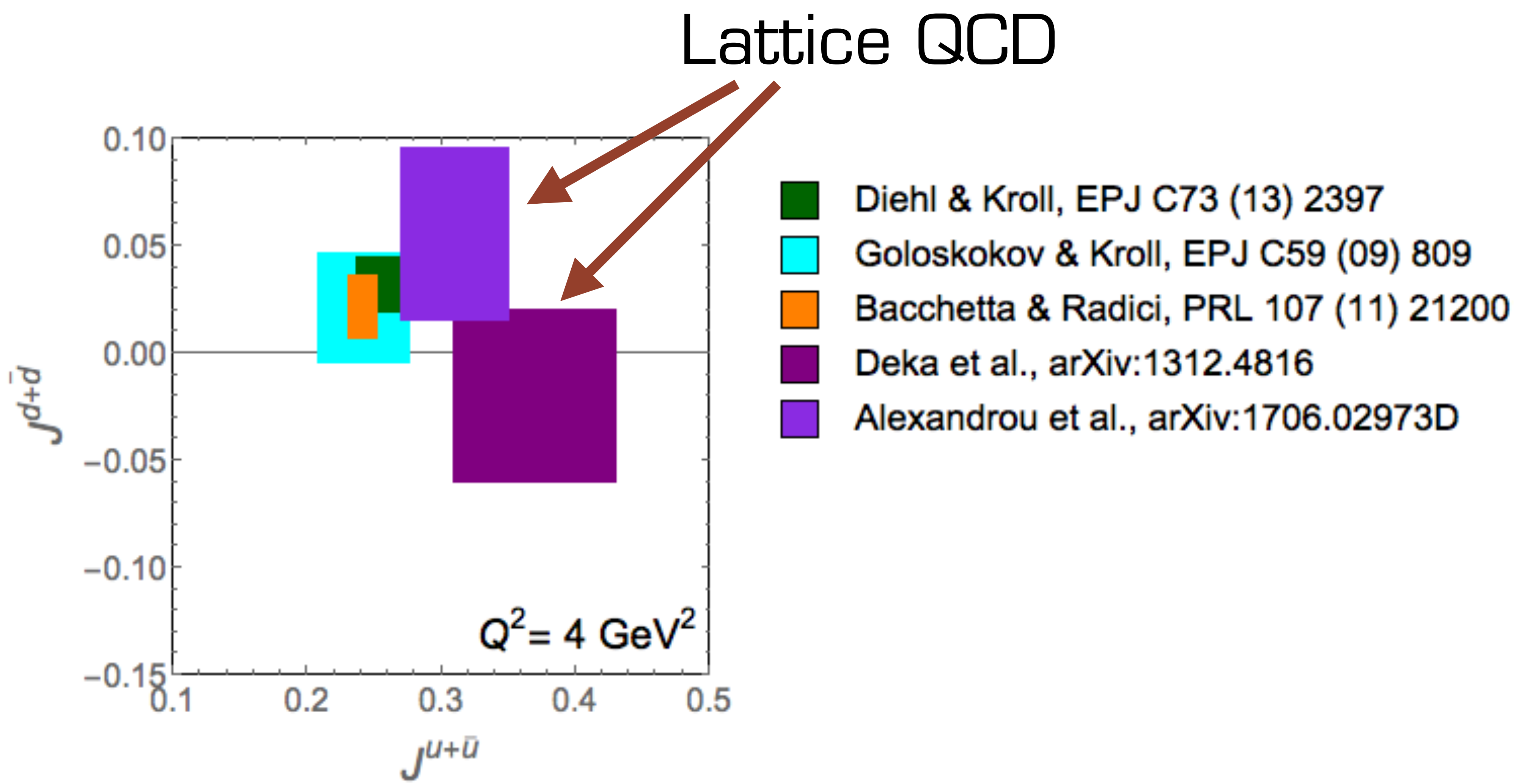
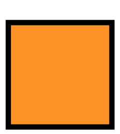
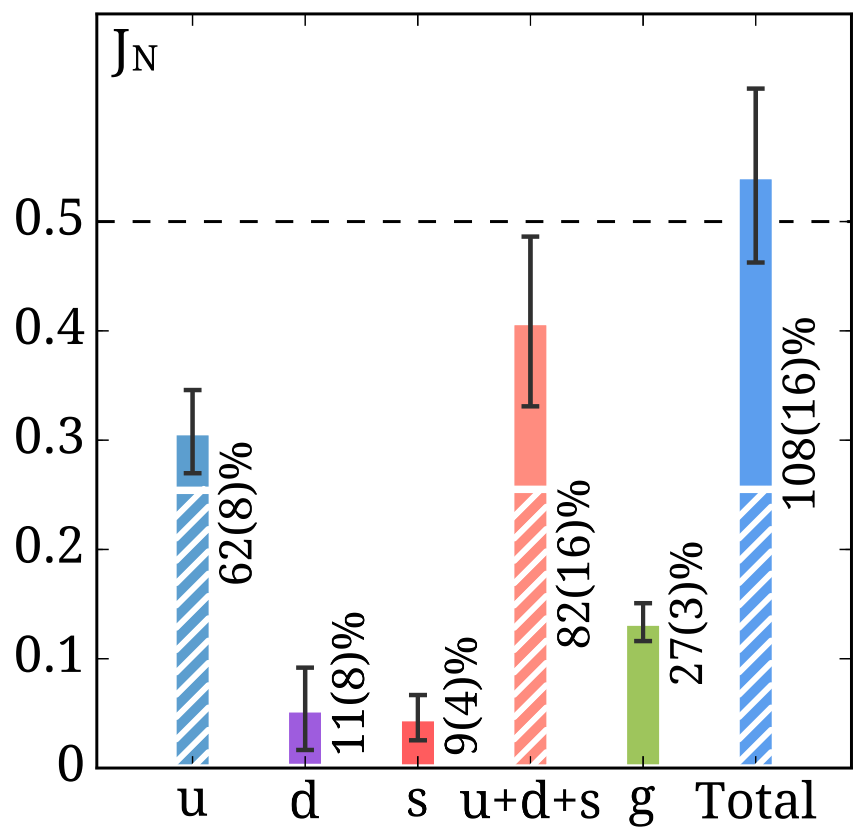




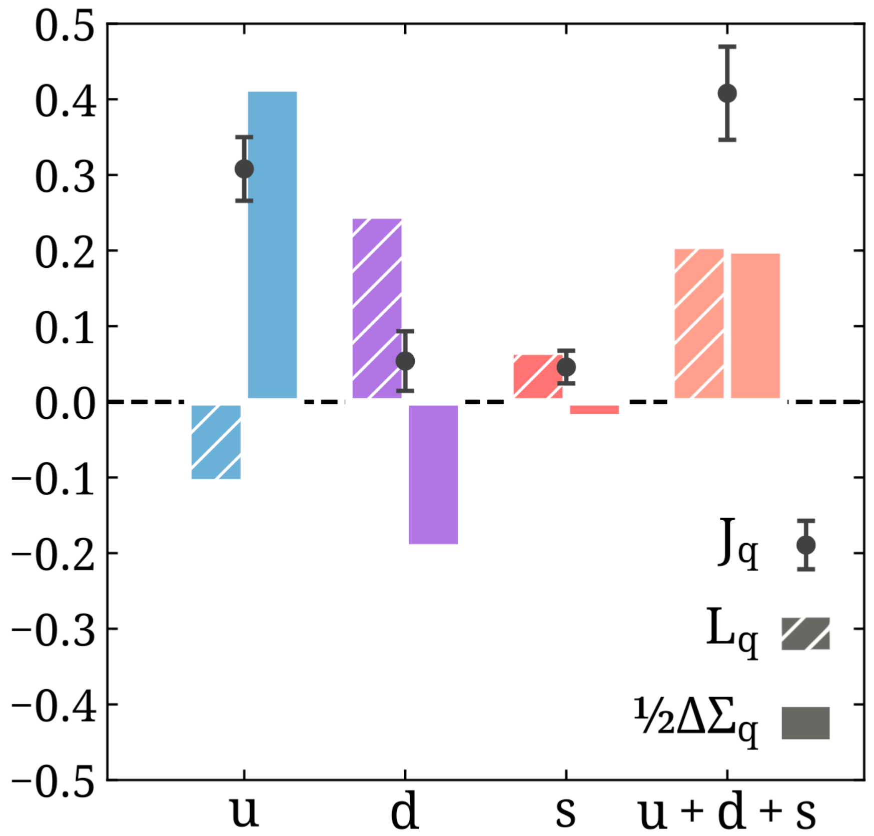
Estimate of angular momentum based on lensing assumptions + Sivers fit

PROTON SPIN BUDGET ACCORDING TO LATTICE QCD

C. Alexandrou et al, arXiv:1706.02973



Total angular momentum
(quarks+antiquarks)

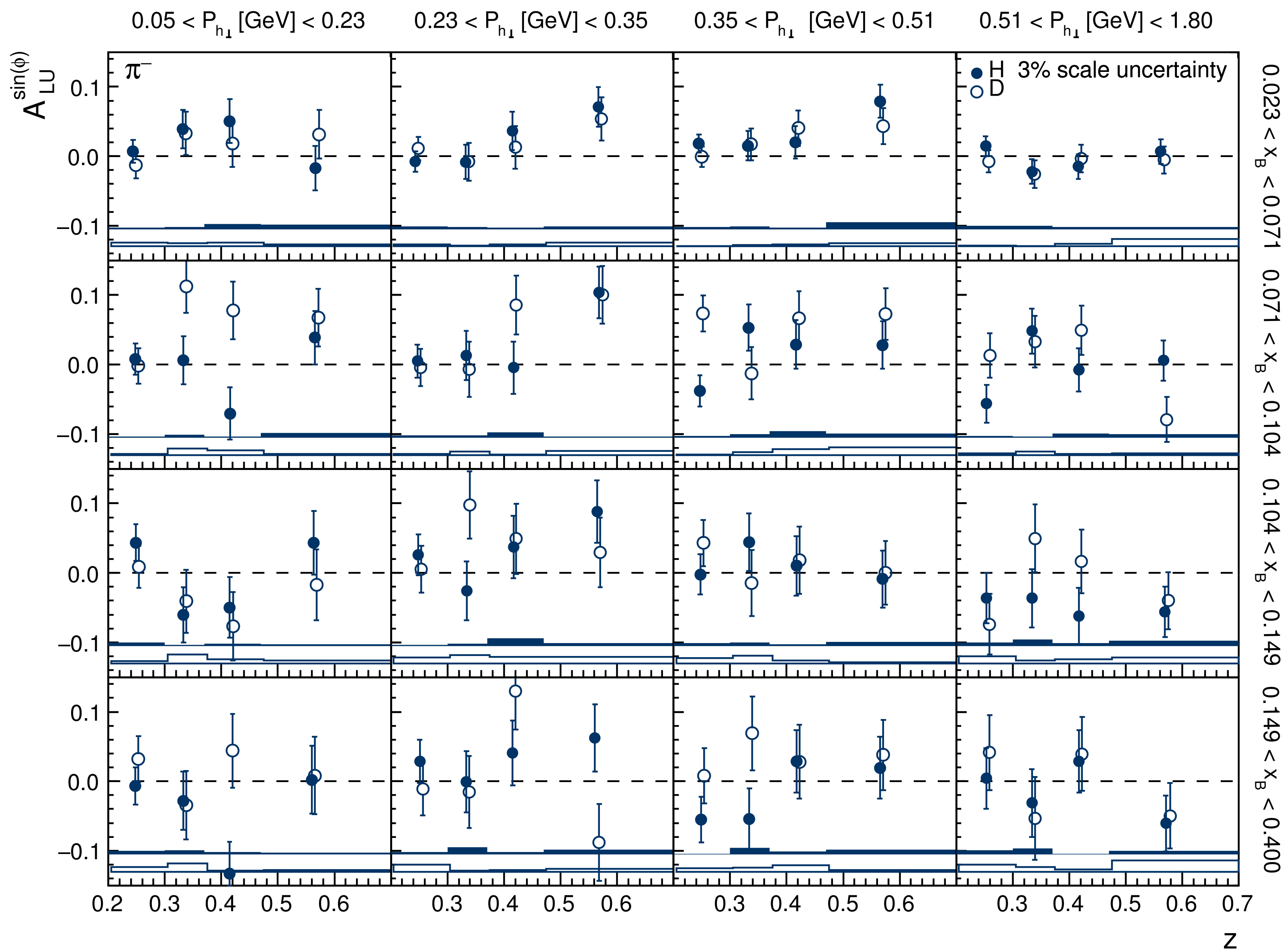


Separate OAM and spin
(quarks+antiquarks)

THE FUTURE

“NEW” DATA FROM HERMES!

Multidimesional binning



HERMES Collab., arXiv:1903.08544

"NEW" DATA FROM HERMES!

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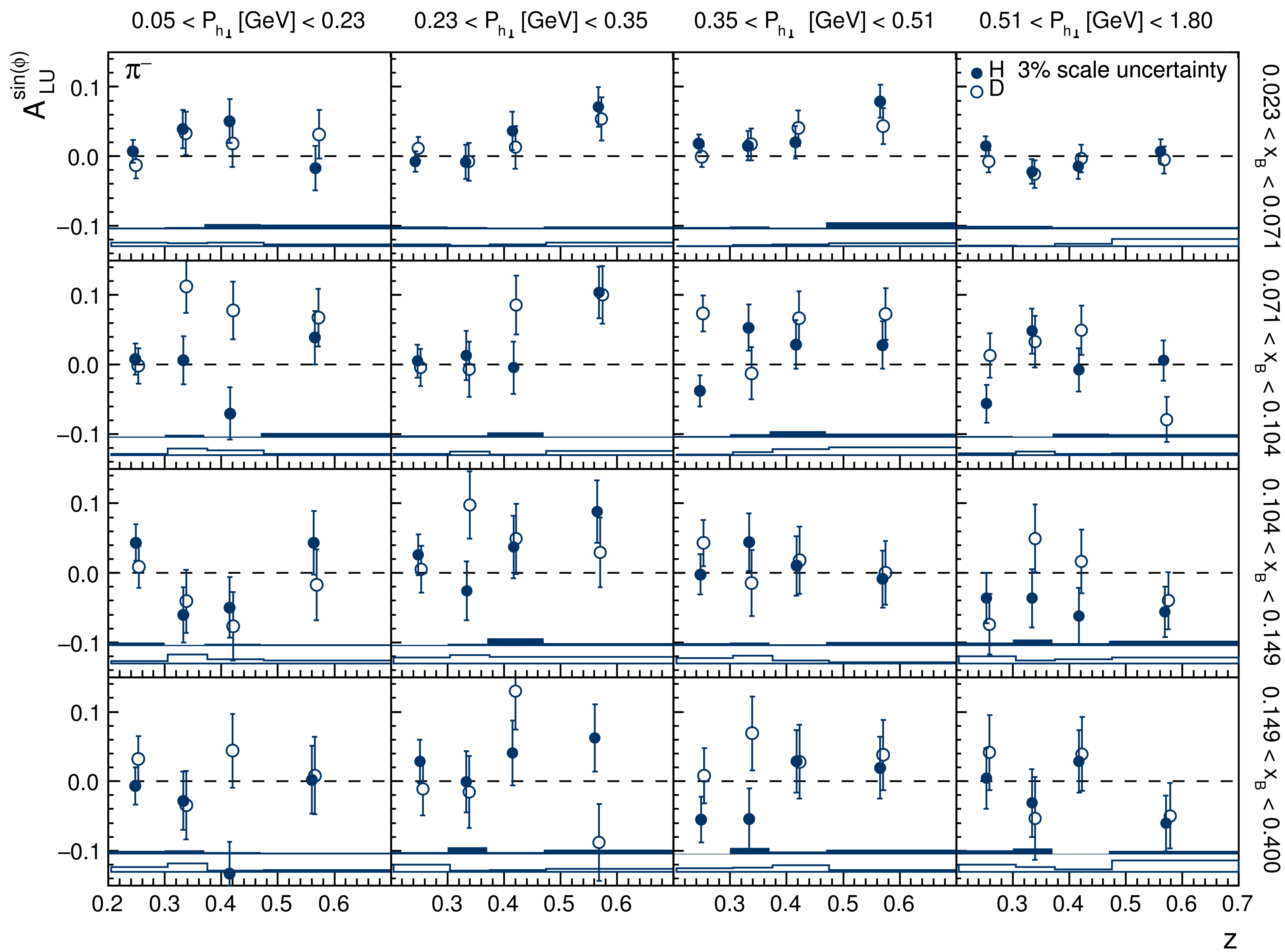

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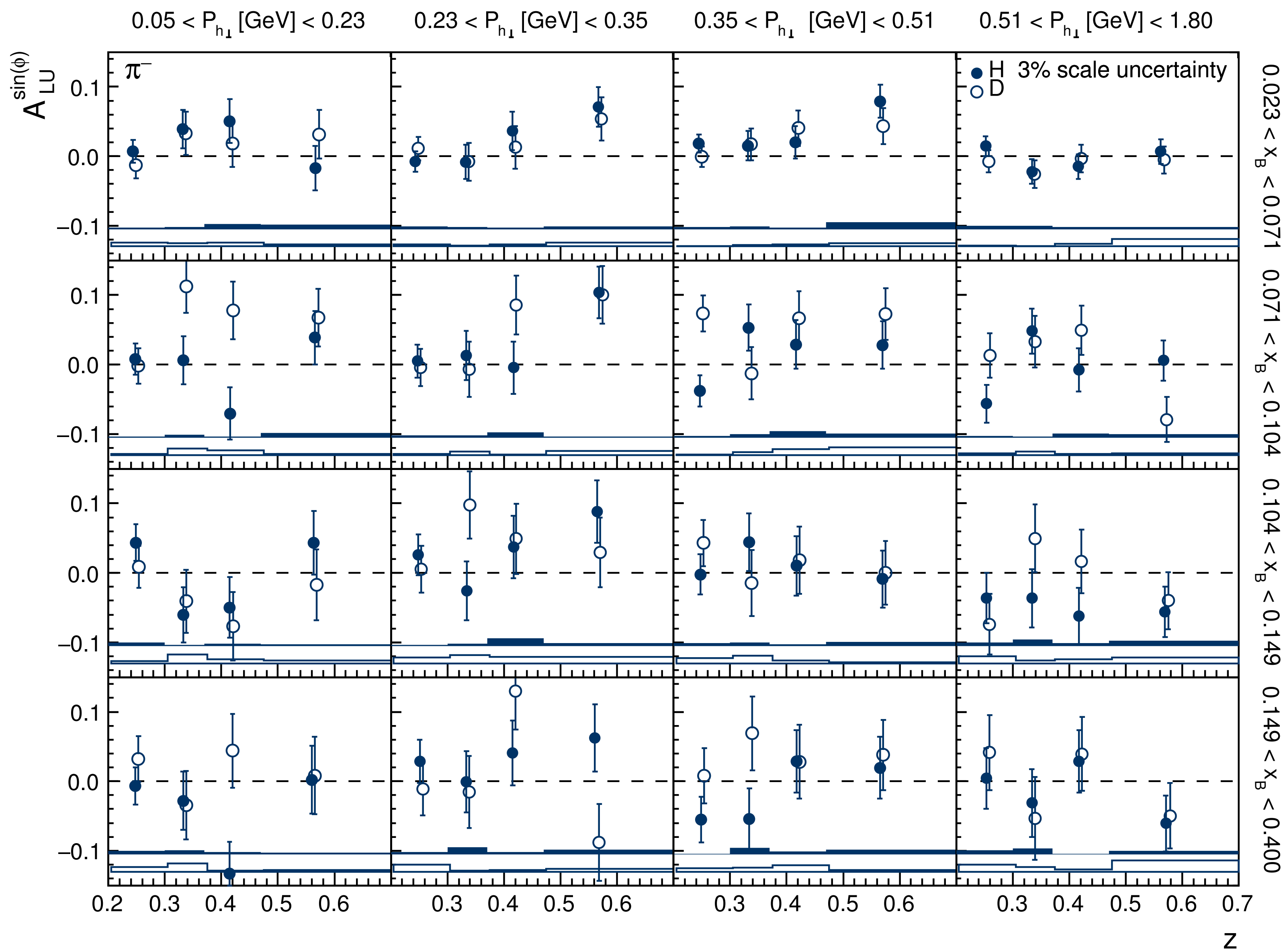
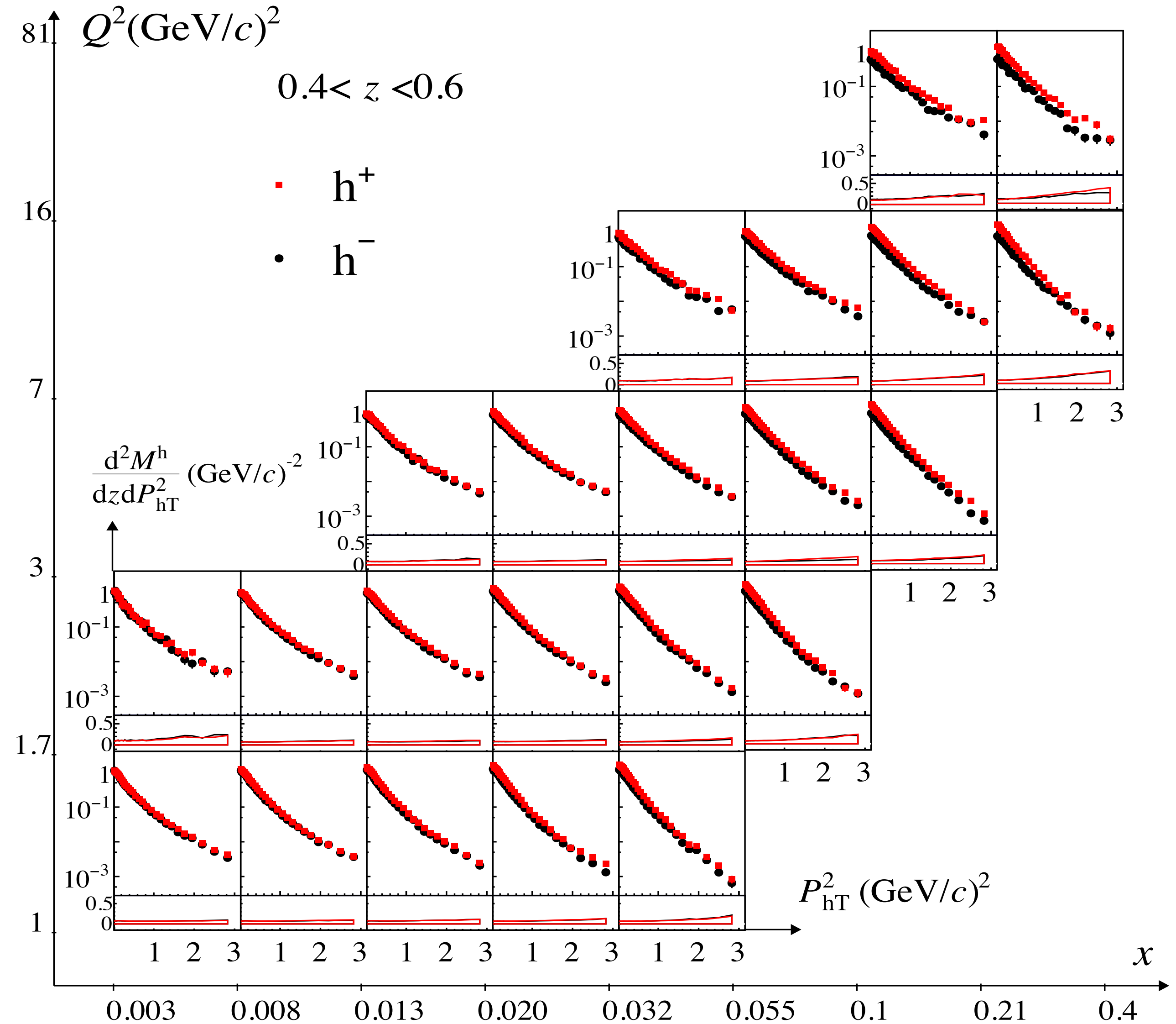


HERMES Collab., arXiv:1903.08544

Even if the experiments was closed 10 years ago, they are still producing results

NEW DATA FROM COMPASS

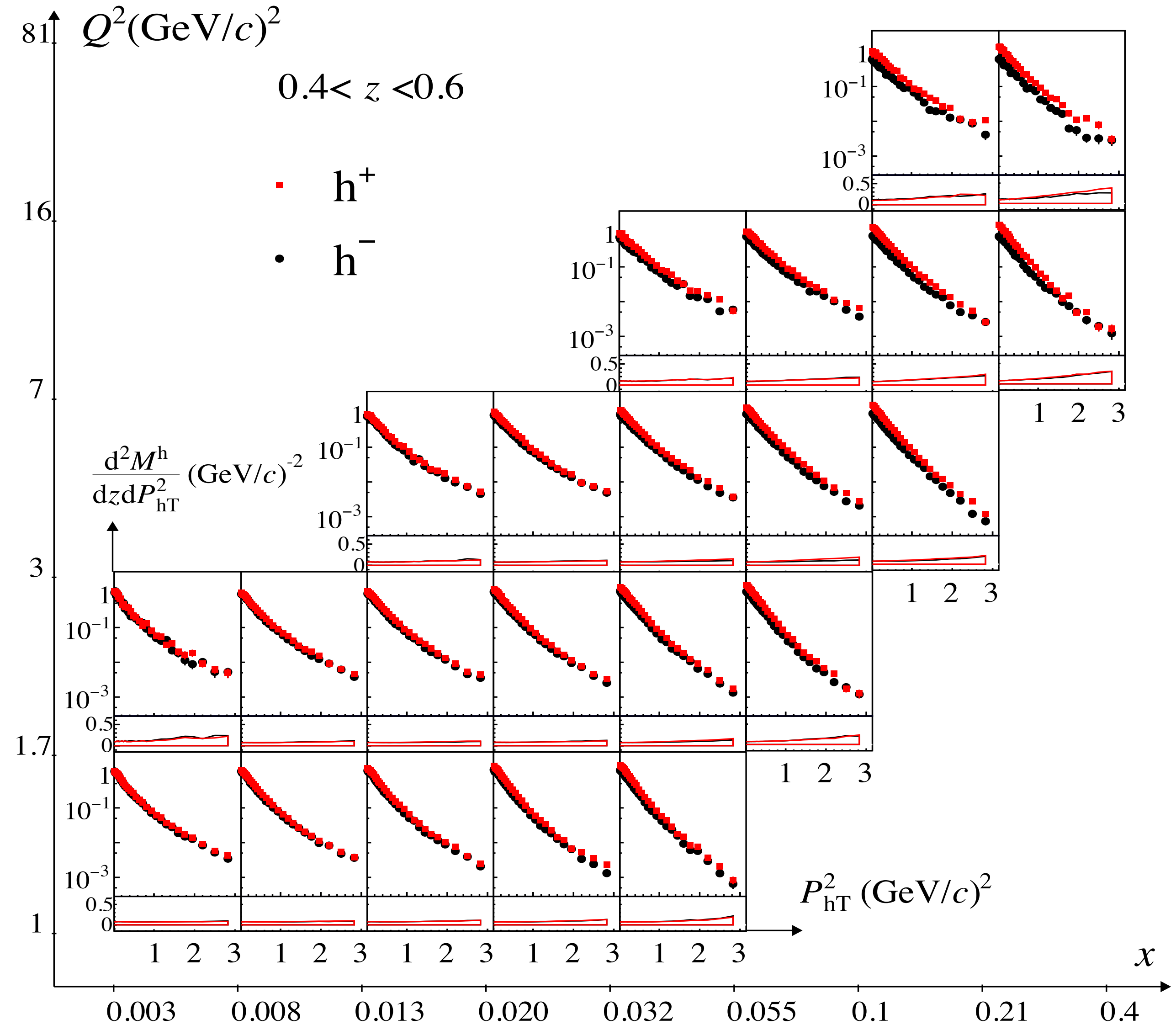
Multidimesional binning



COMPASS Collab., arXiv:1709.07374

NEW DATA FROM COMPASS

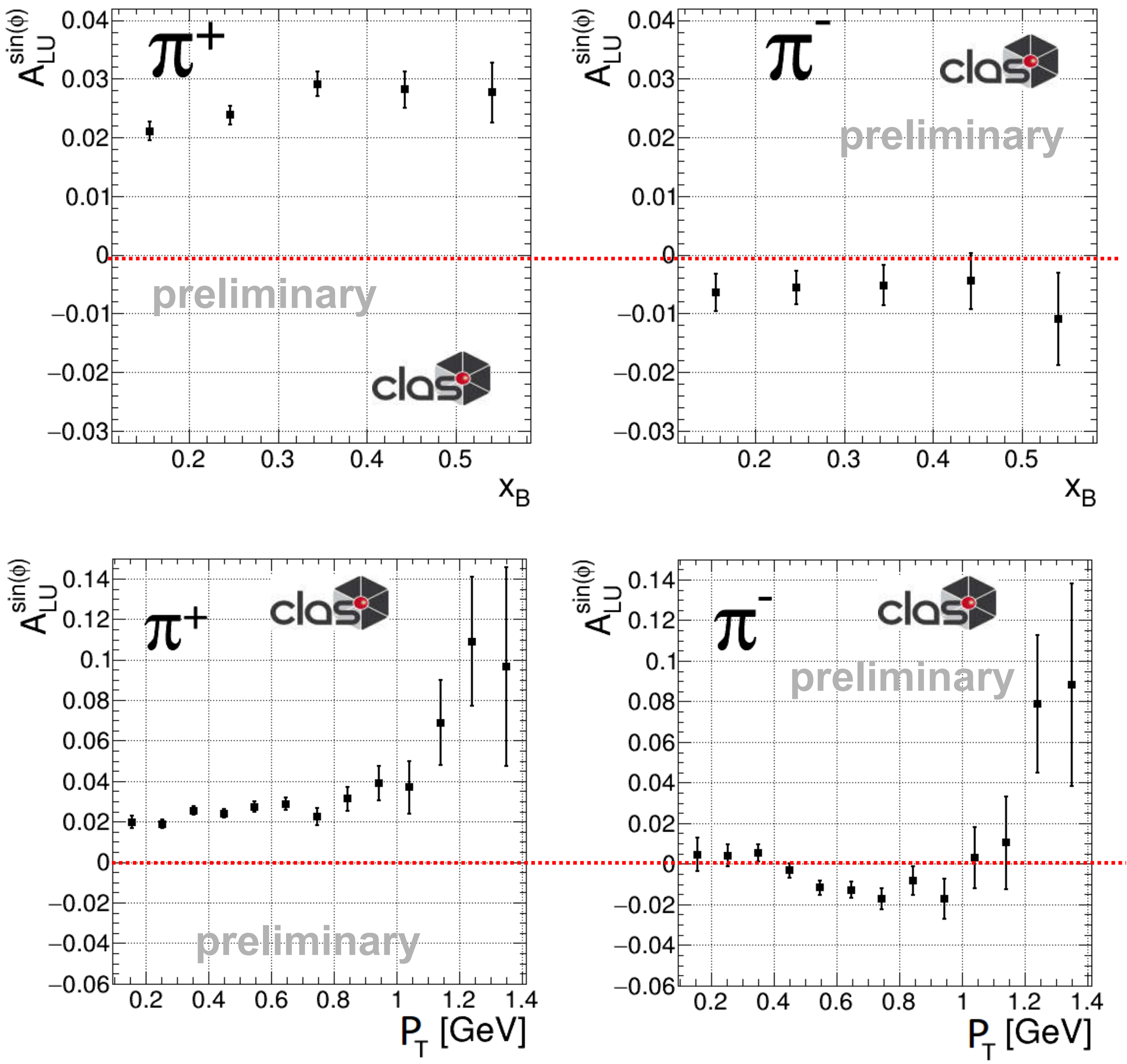
Multidimesional binning



COMPASS Collab., arXiv:1709.07374

COMPASS is in “full swing” mode.
Will provide data about pion structure as well.

FIRST JLAB PRELIMINARY DATA



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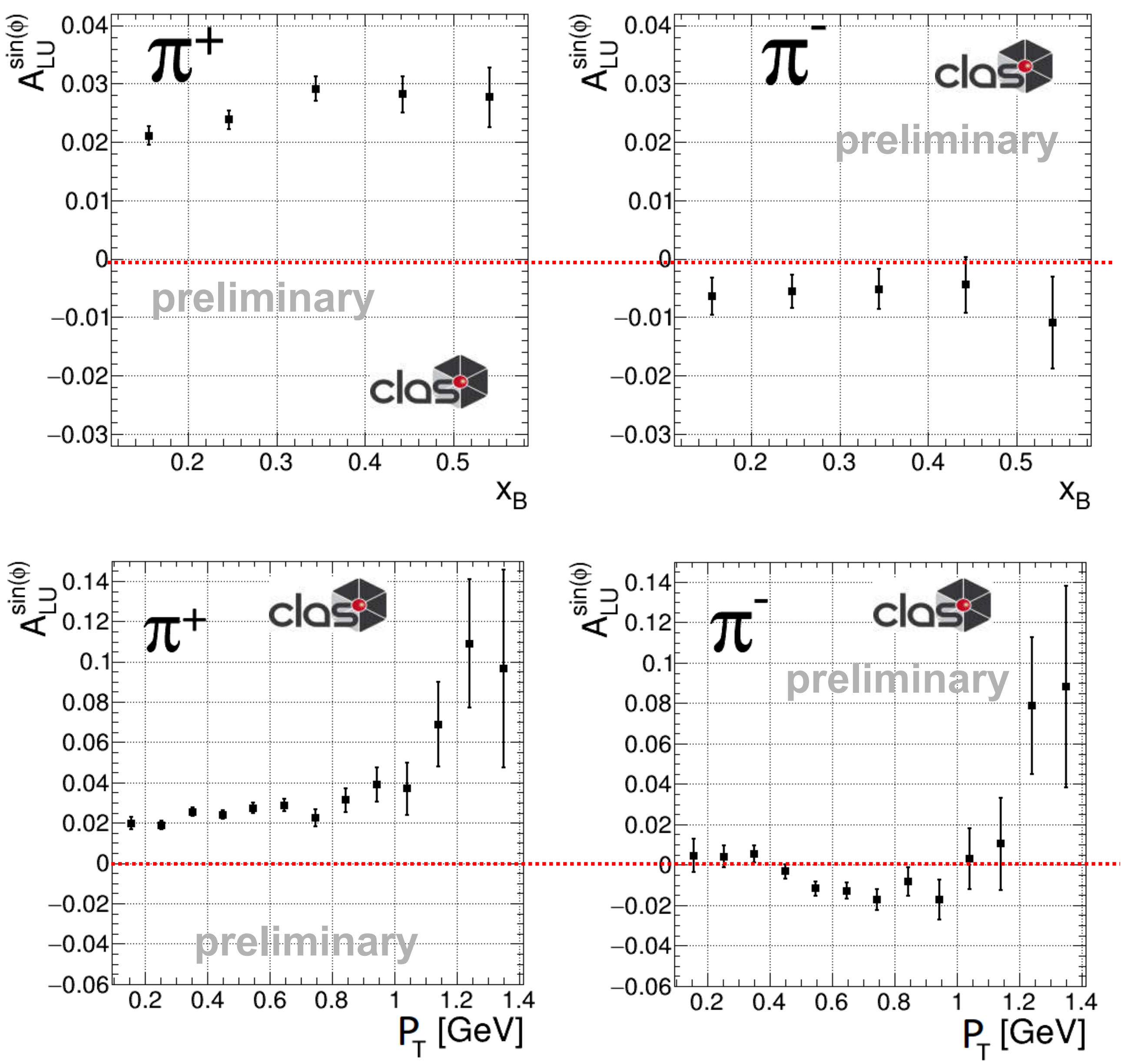
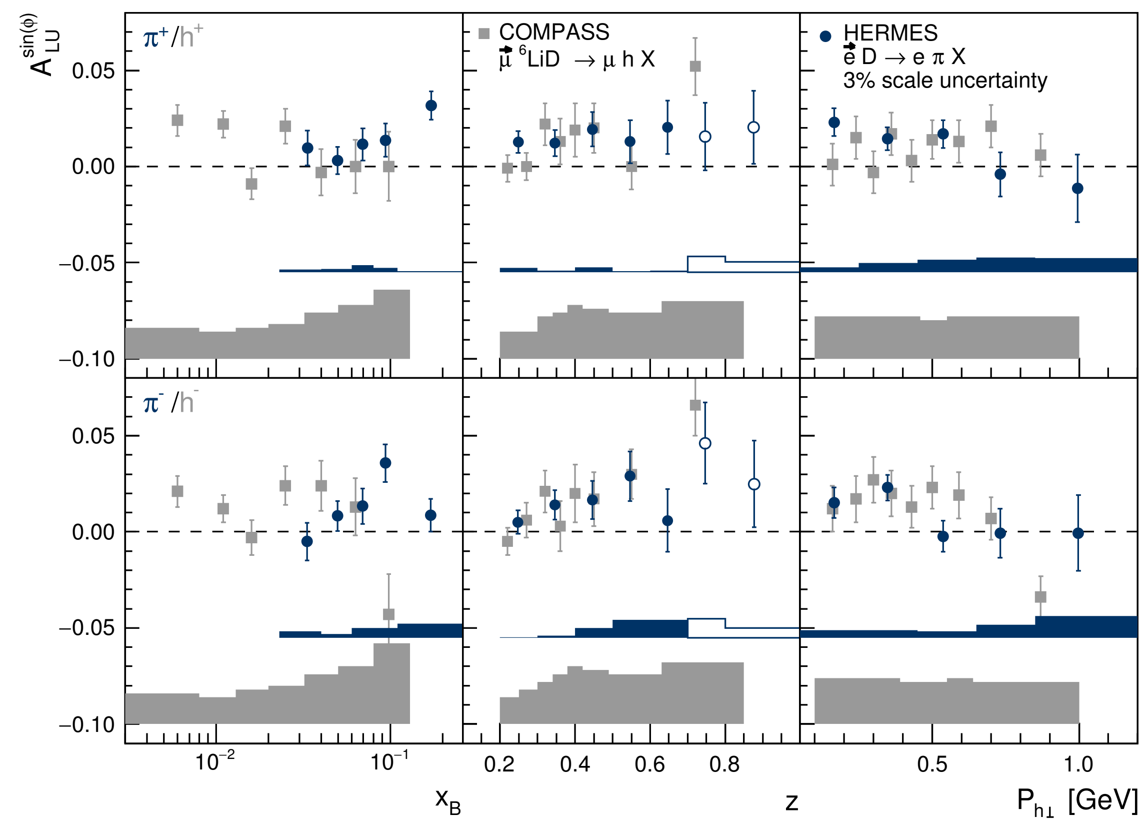


hermes

COMPASS



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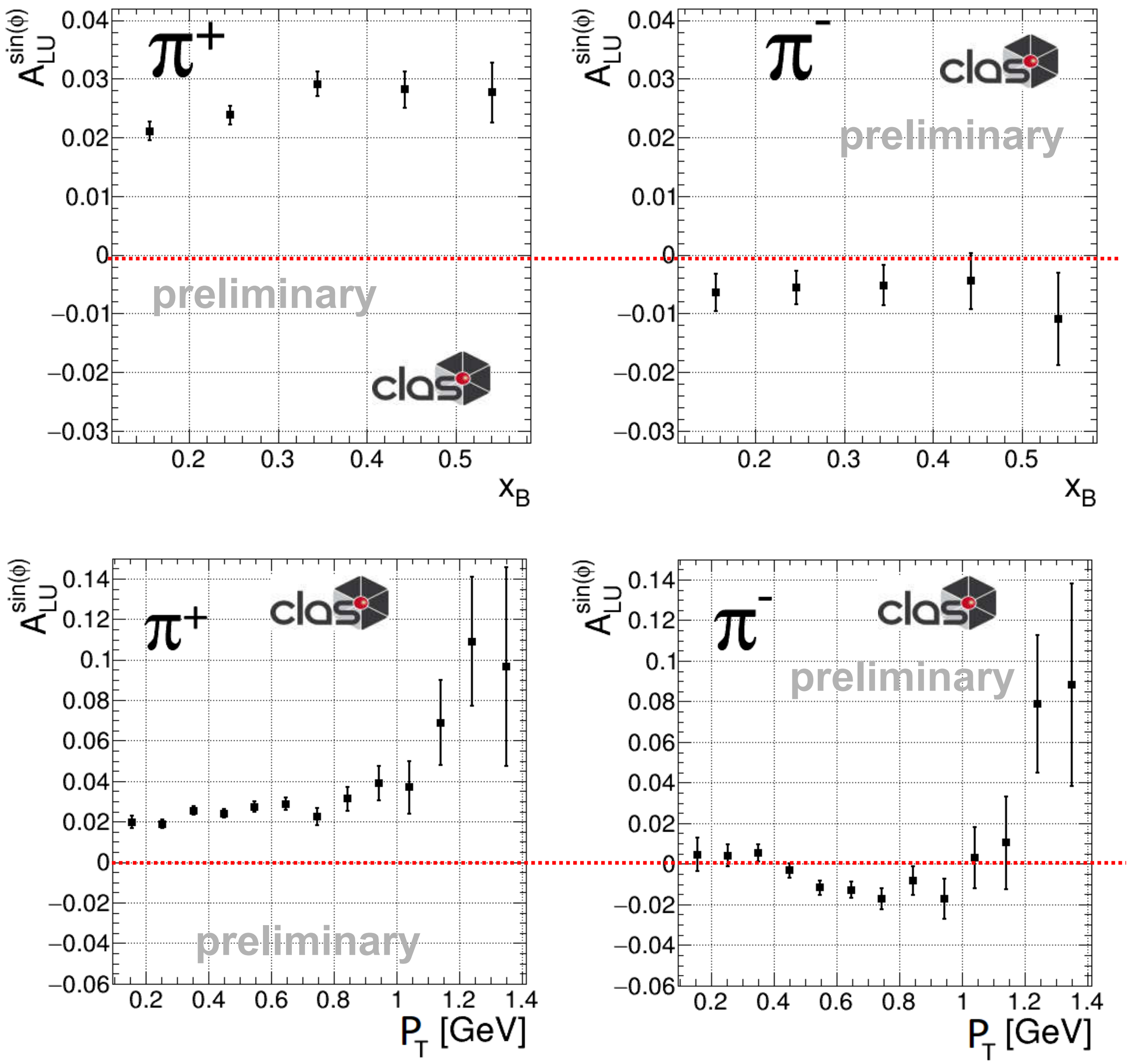

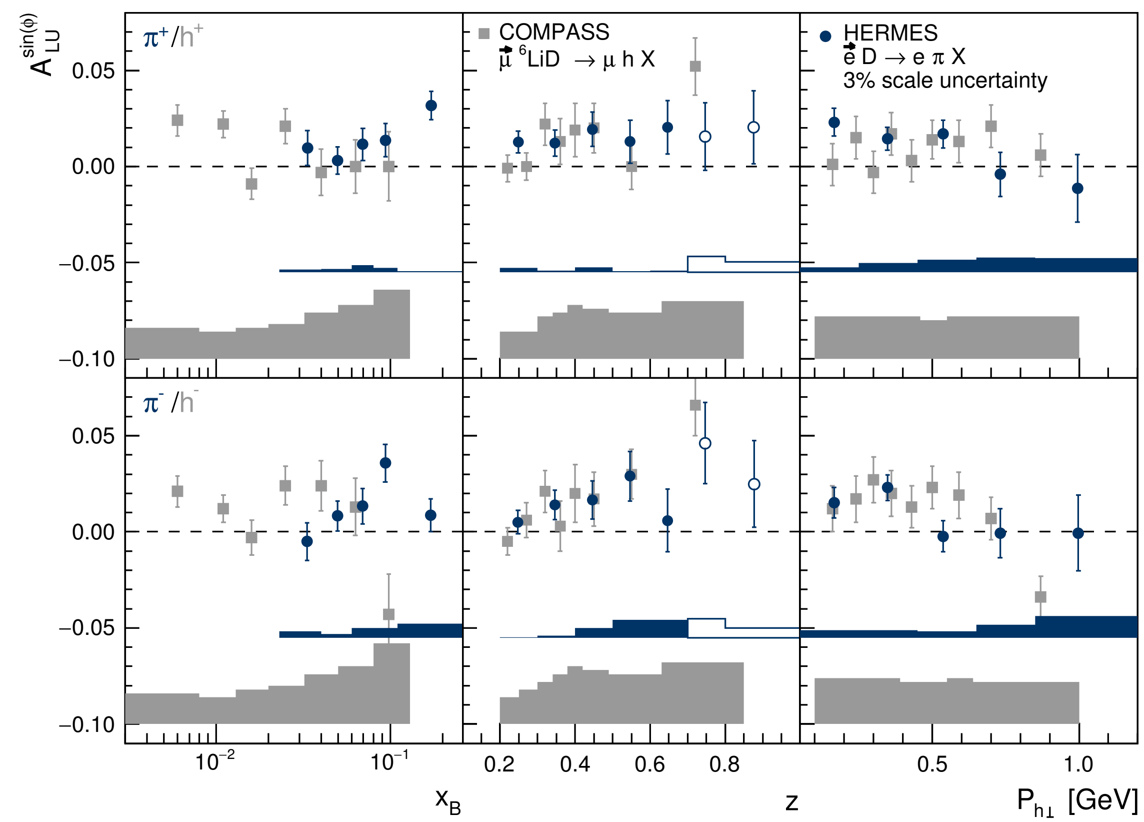

Only 2% of approved data taking

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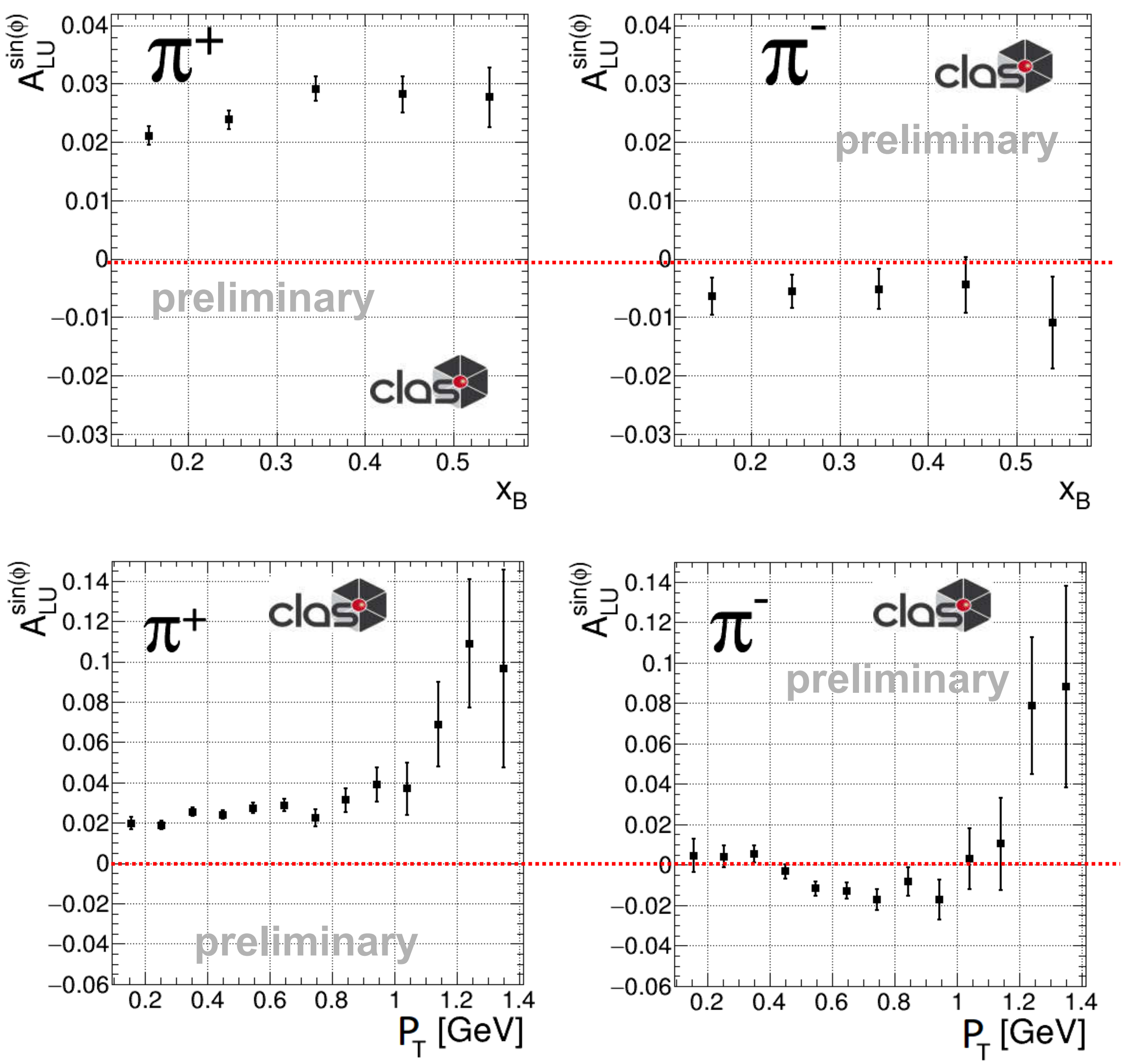
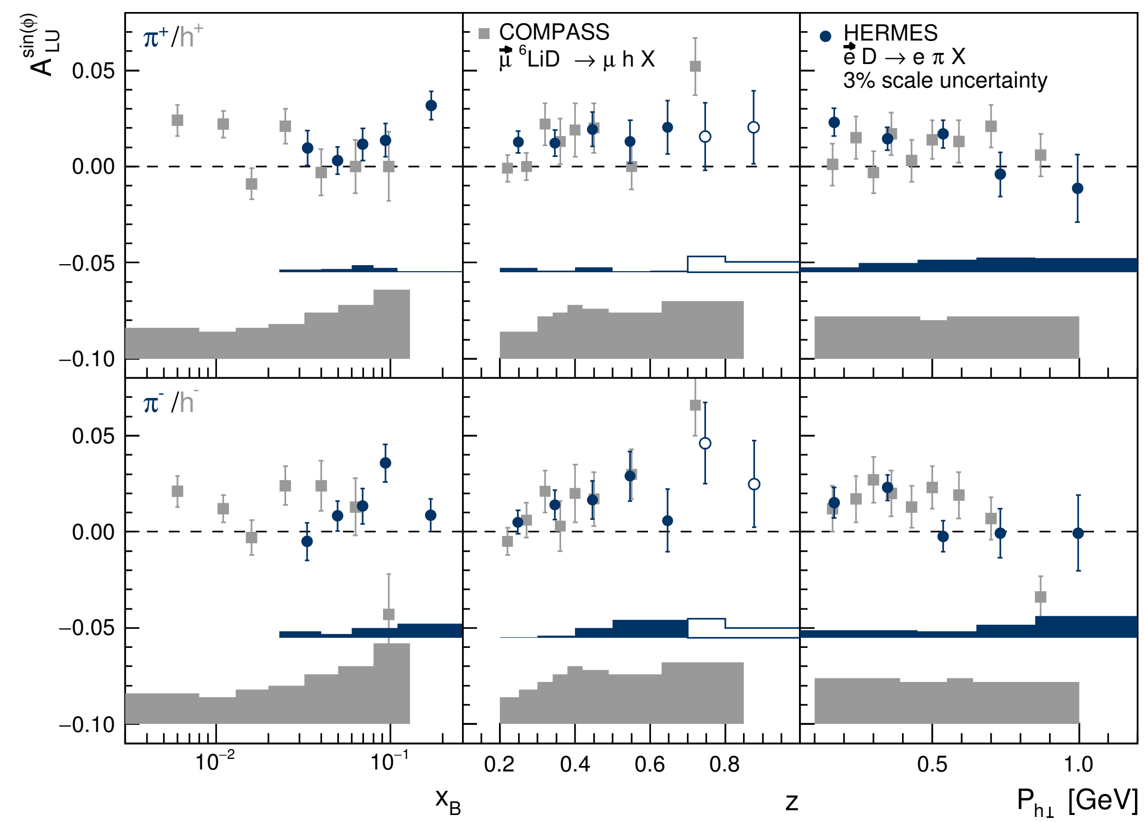


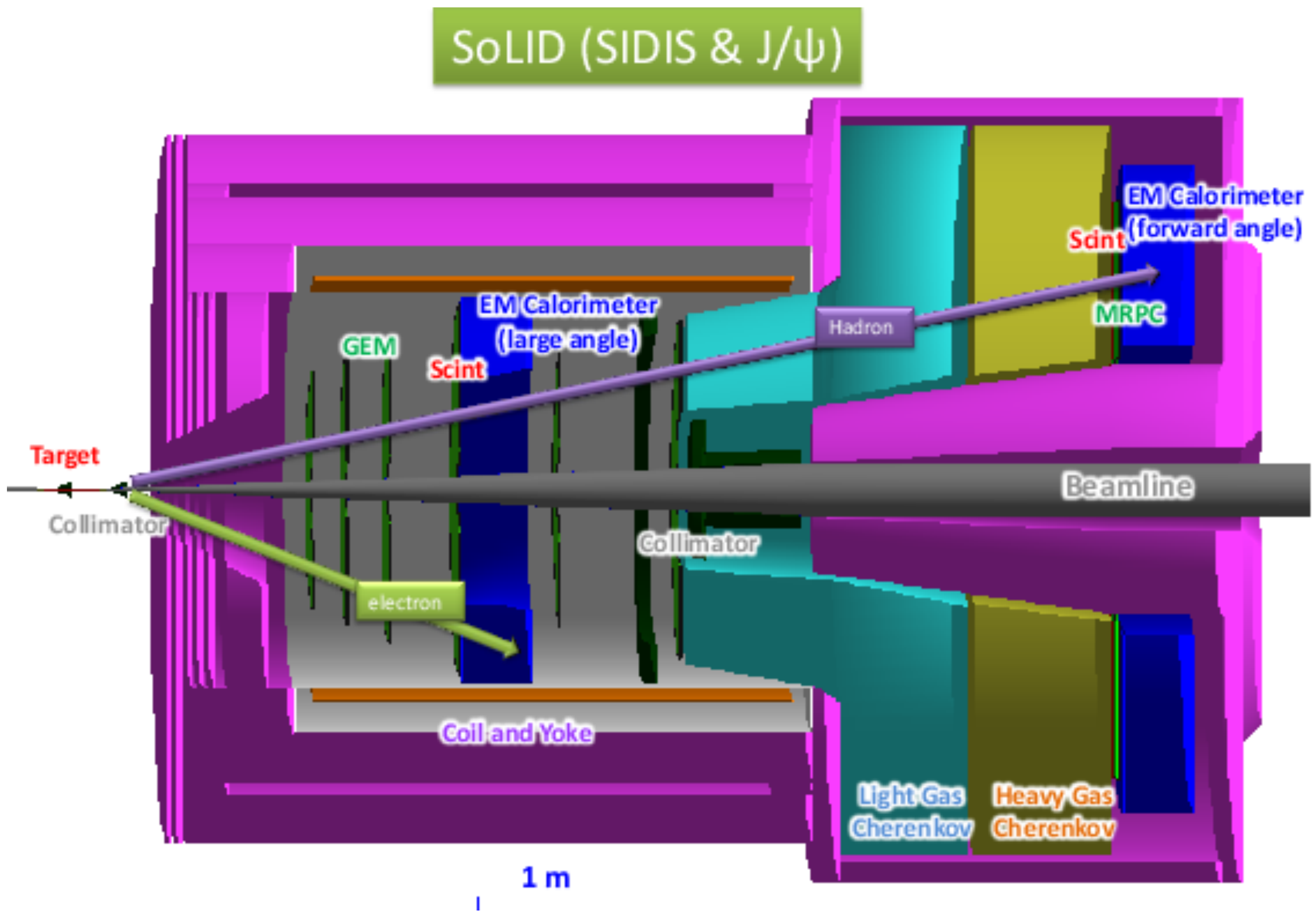


AWESOME!

Only 2% of approved data taking

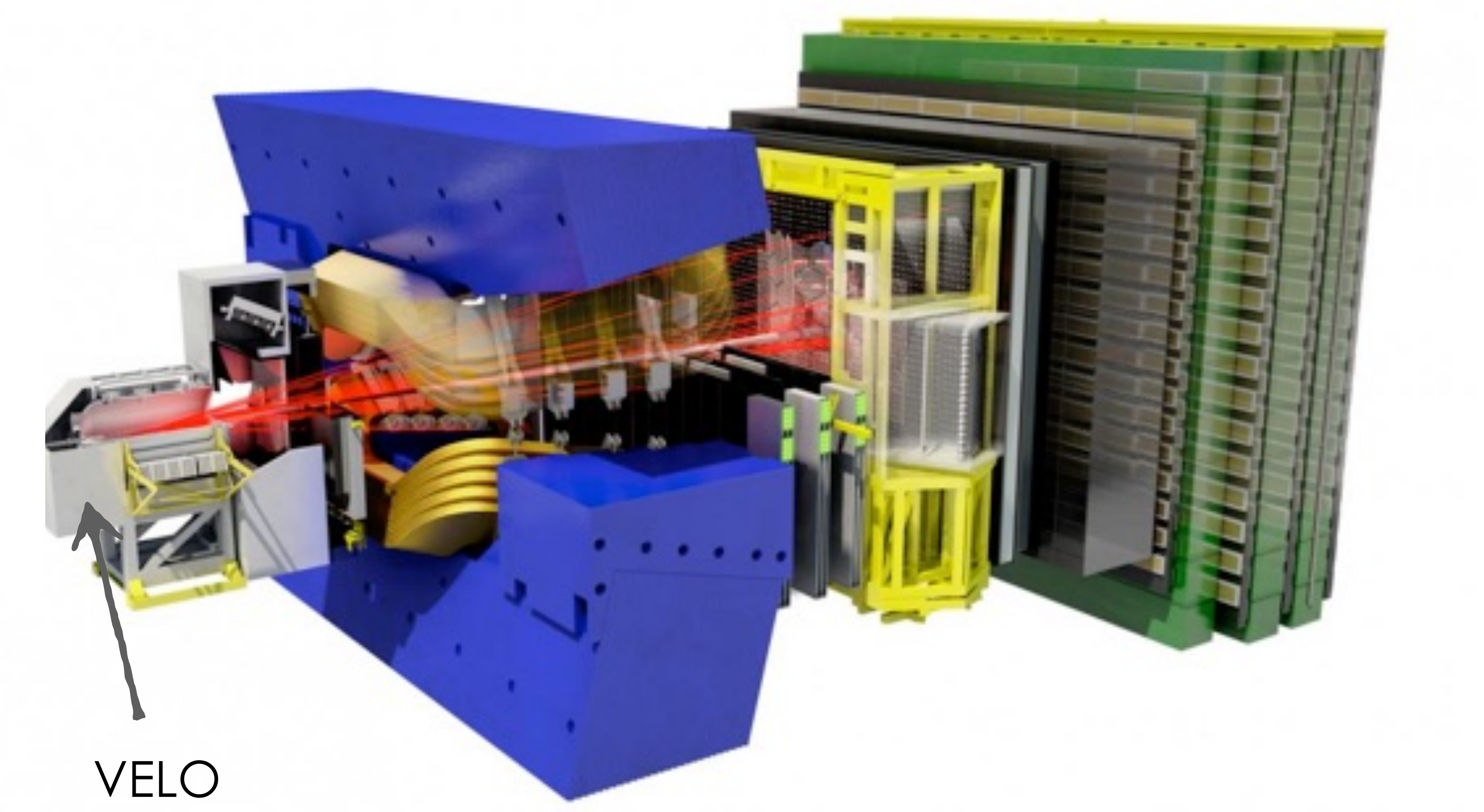
SOLID @ JLAB

see J-P Chen's talk



LHCb FIXED TARGET, INCLUDING POLARISATION

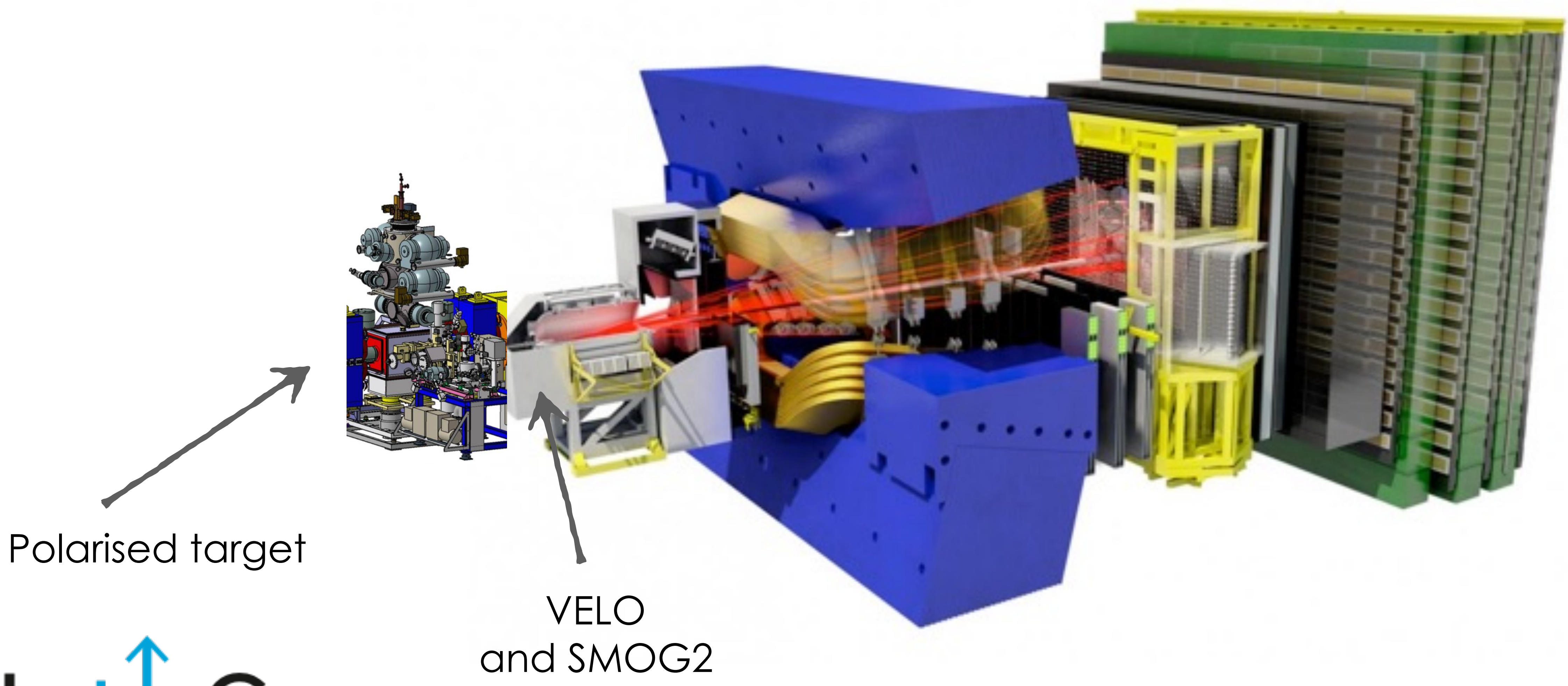
https://indico.cern.ch/event/755856/



VELO
and SMOG2

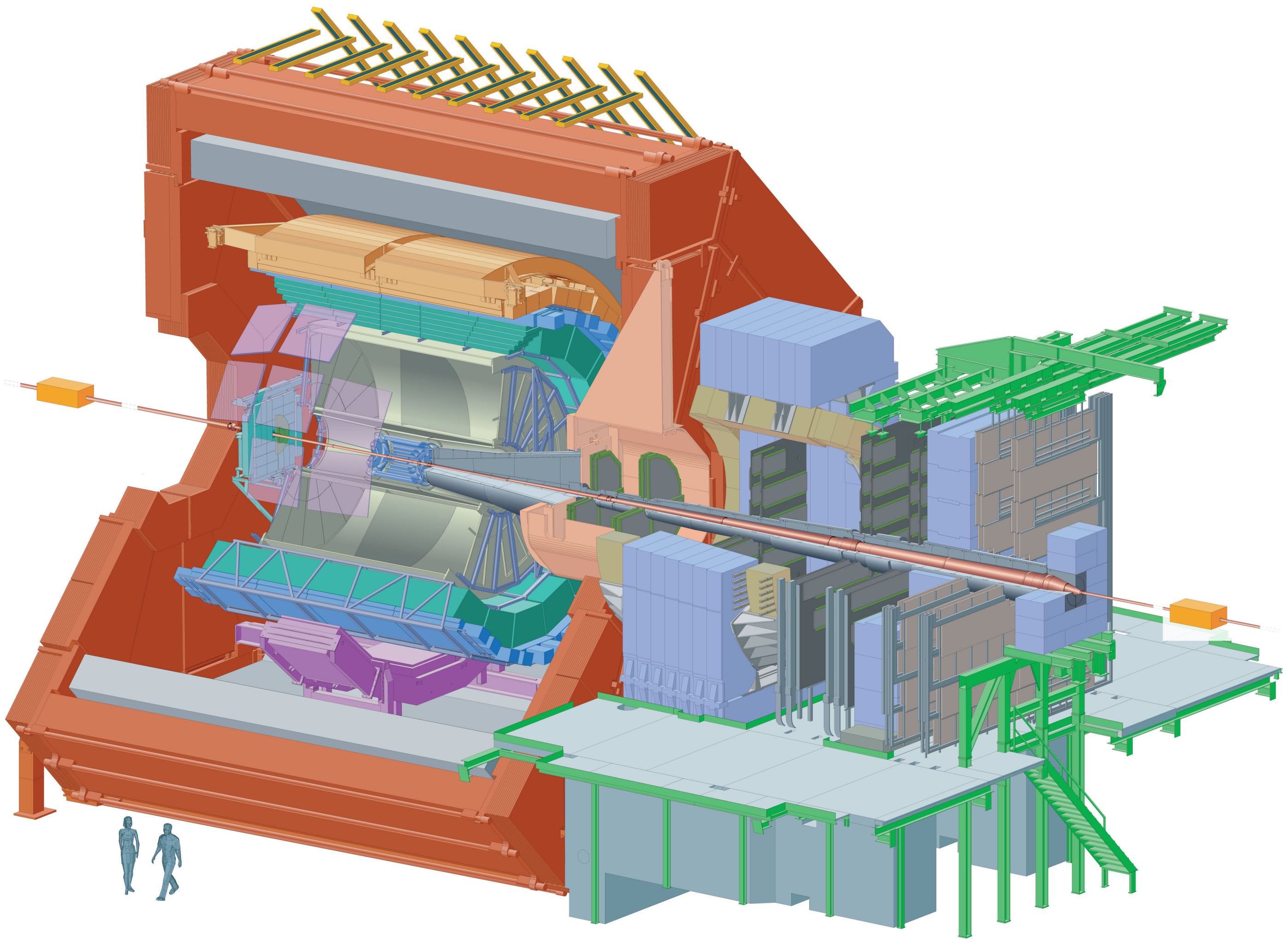
LHCb FIXED TARGET, INCLUDING POLARISATION

https://indico.cern.ch/event/755856/



ALICE FIXED TARGET

https://indico.cern.ch/event/755856/



ALICE FIXED TARGET

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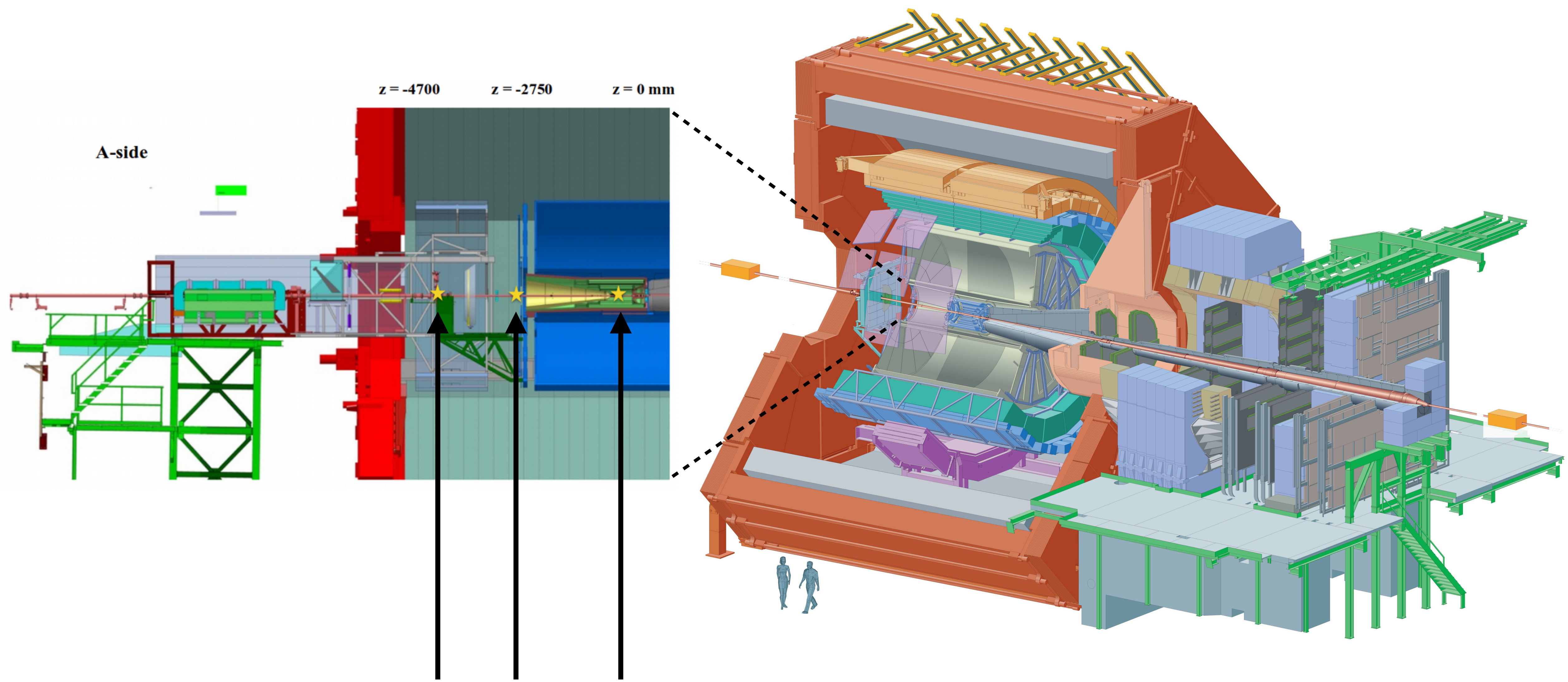
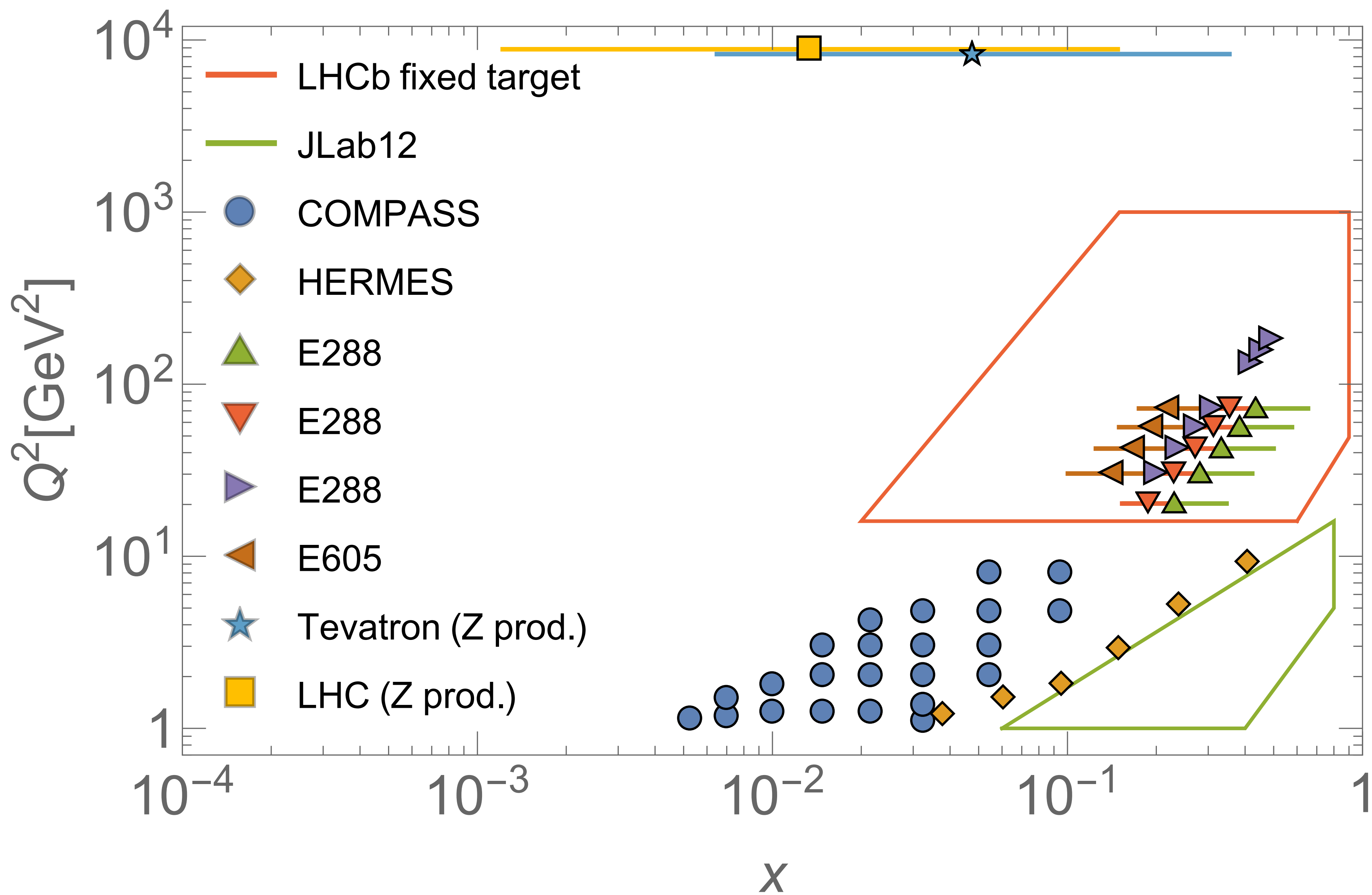


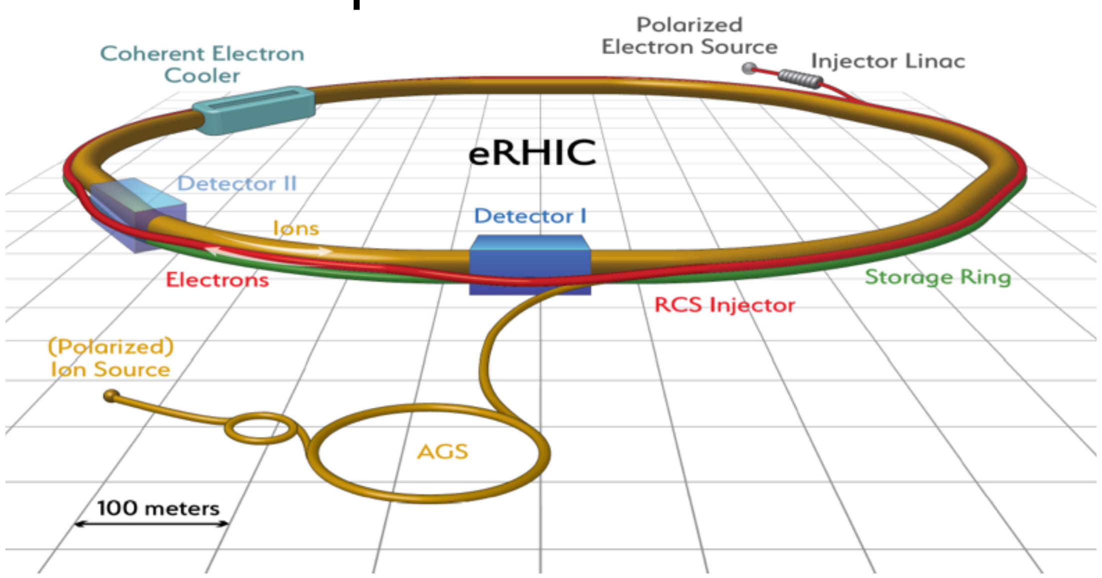
Possible fixed-target positioning

EXPECTED EXTENSION OF DATA RANGE

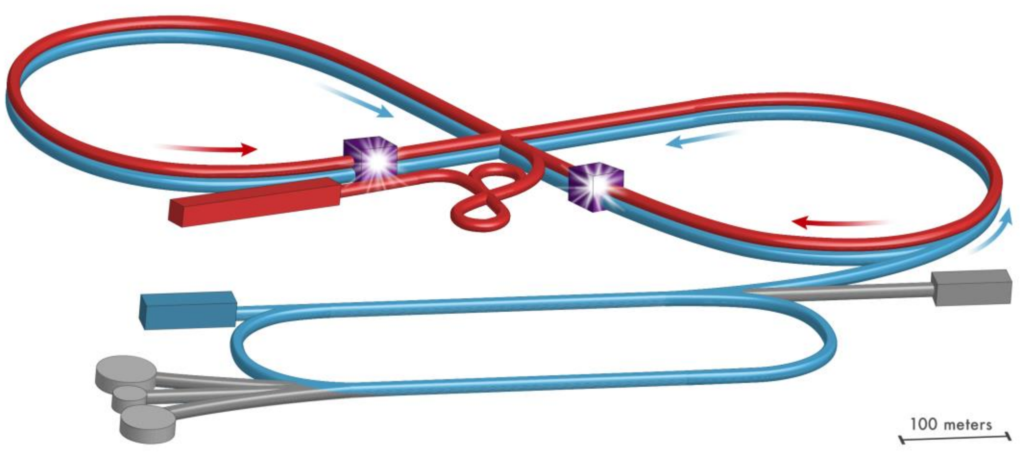


THE ELECTRON-ION COLLIDER PROJECT

BNL concept



JLab concept



- High luminosity: (10^{34} cm^{-2} s^{-1})
- Variable CM energy: 20-100 GeV
- Highly polarized beams
- Protons and other nuclei

THANKS TO HADRONIC PHYSICS GROUP IN PAVIA

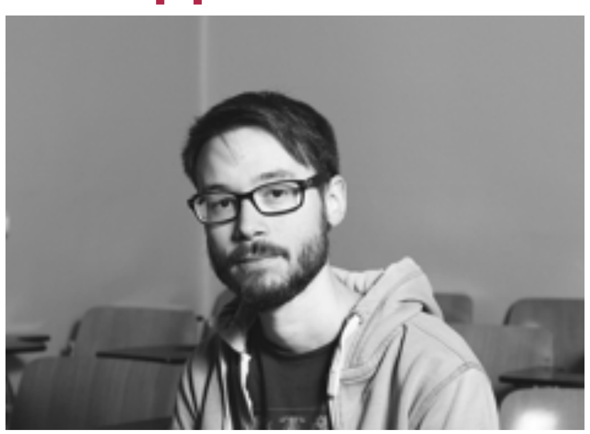
Valerio Bertone

Chiara Bissolotti

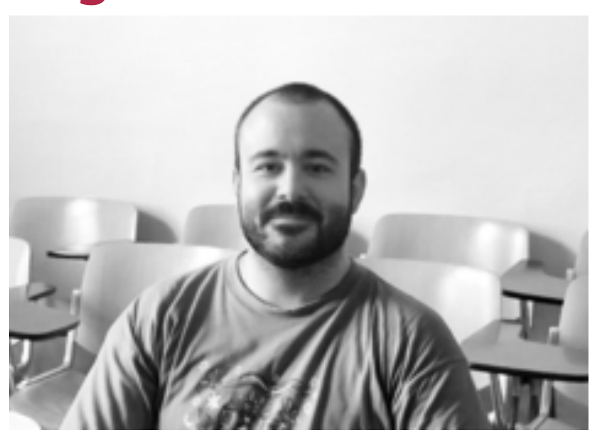
Giuseppe Bozzi

Francesco Celiberto

Filippo Delcarro



Miguel G. Echevarria



Barbara Pasquini

Fulvio Piacenza

Cristian Pisano

Marco Radici

Simone Rodini

CONCLUSIONS

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- Full-fledged TMD extractions up to NNLL accuracy are coming out and being constantly improved

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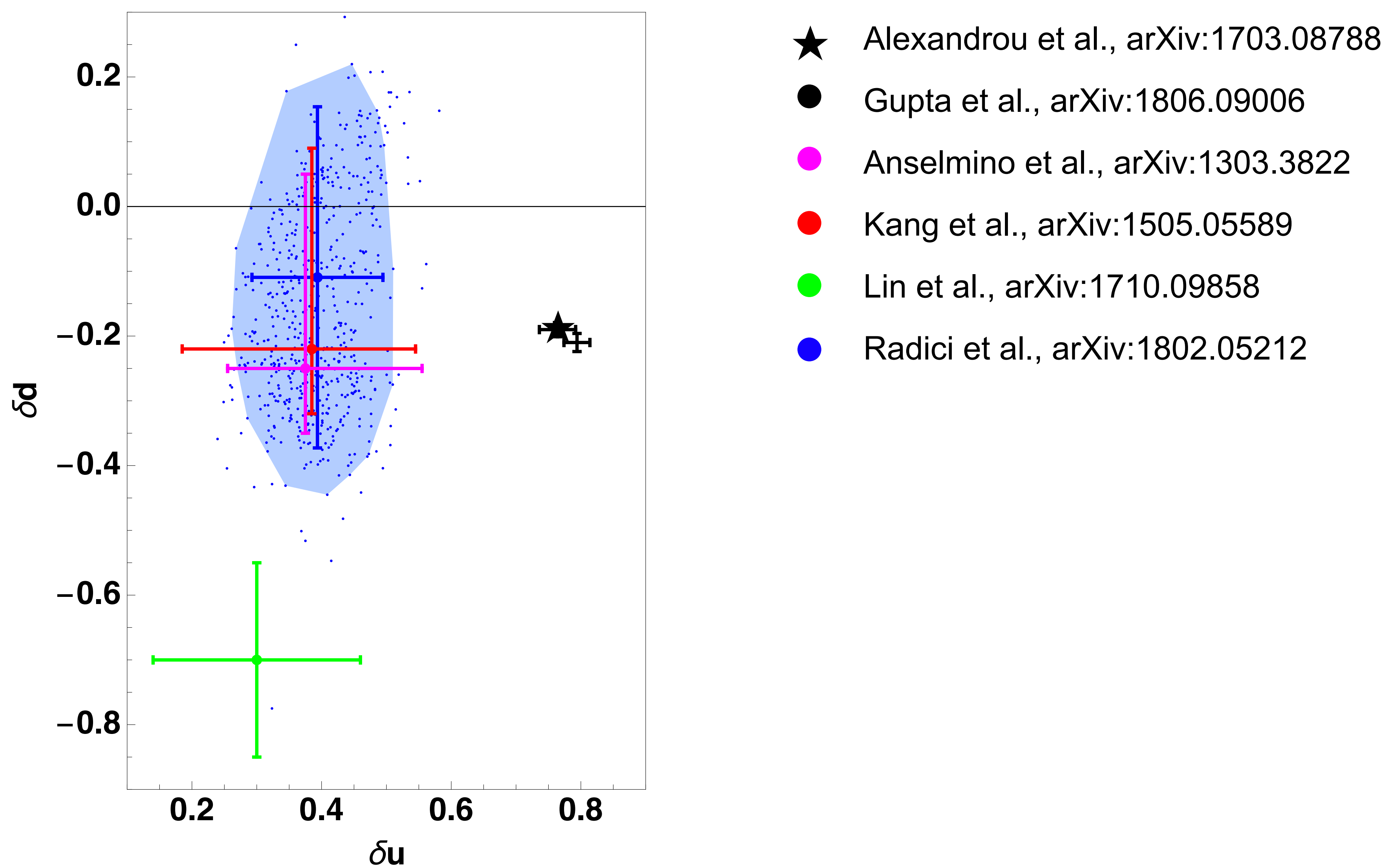
CONCLUSIONS

- Full-fledged TMD extractions up to NNLL accuracy are coming out and being constantly improved
- We are facing problems with normalizations of SIDIS data, in particular when going at higher accuracy
- Consistent extractions of the Sivers function are also now possible
- We expect a steady flow of data coming up in the next years

BACKUP SLIDES

TRANSVERSELY POLARIZED PDF MOMENTS AND LATTICE QCD

Tensor charge $$\delta q \equiv g_T^q = \int_0^1 dx \ \left[h_1^q(x,Q^2) - h_1^{\bar{q}}(x,Q^2)\right]$$



TRANSVERSELY POLARIZED PDF MOMENTS AND LATTICE QCD

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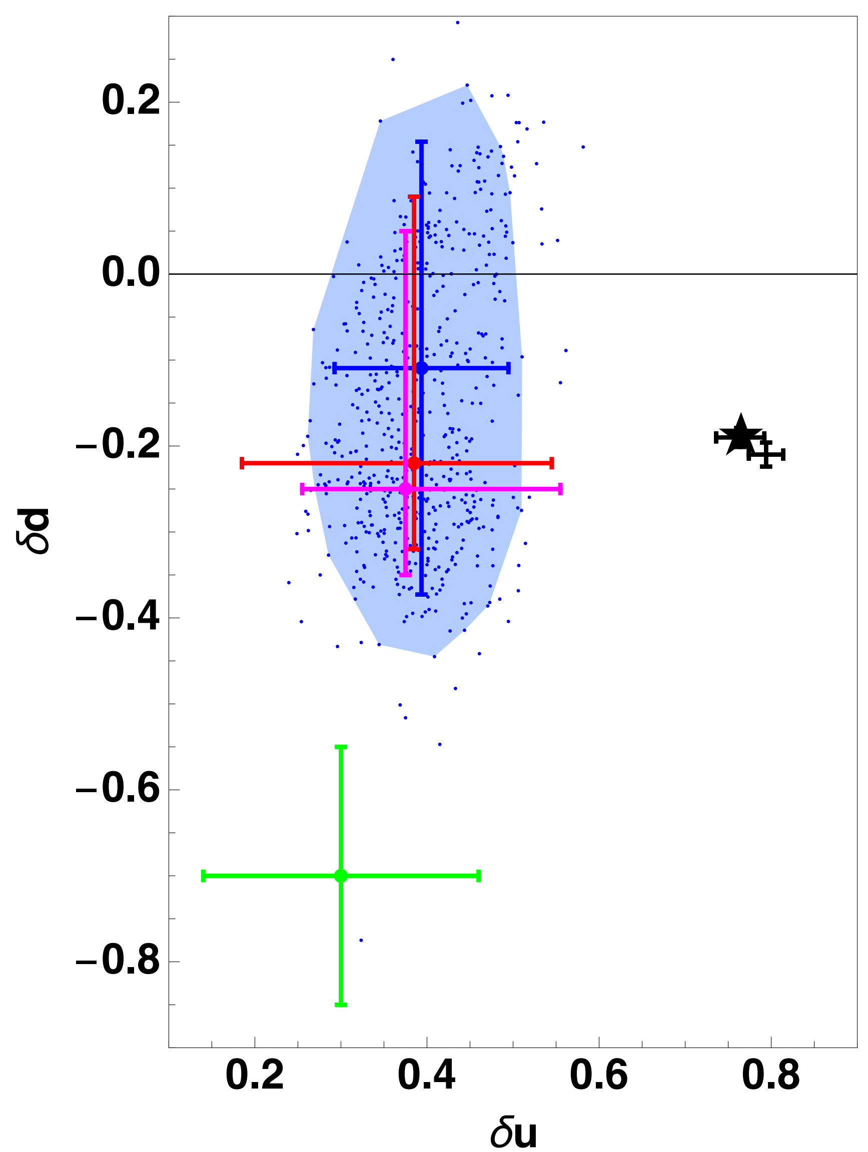
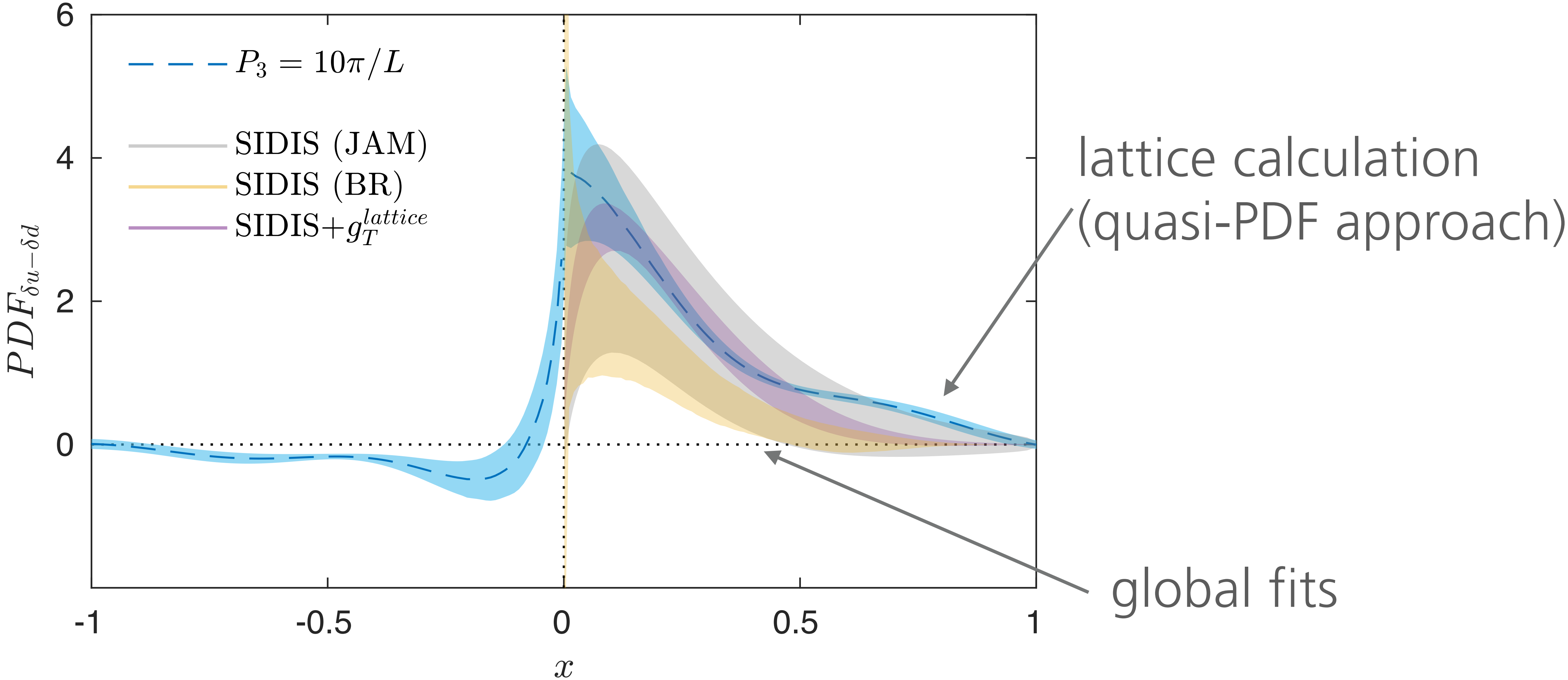


★ Alexandrou et al., arXiv:1703.08788
● Gupta et al., arXiv:1806.09006
● Anselmino et al., arXiv:1303.3822
● Kang et al., arXiv:1505.05589
● Lin et al., arXiv:1710.09858
● Radici et al., arXiv:1802.05212

At the moment, there is a clear tension between extractions and lattice calculations

FULL TRANSVERSITY PDF AND LATTICE QCD

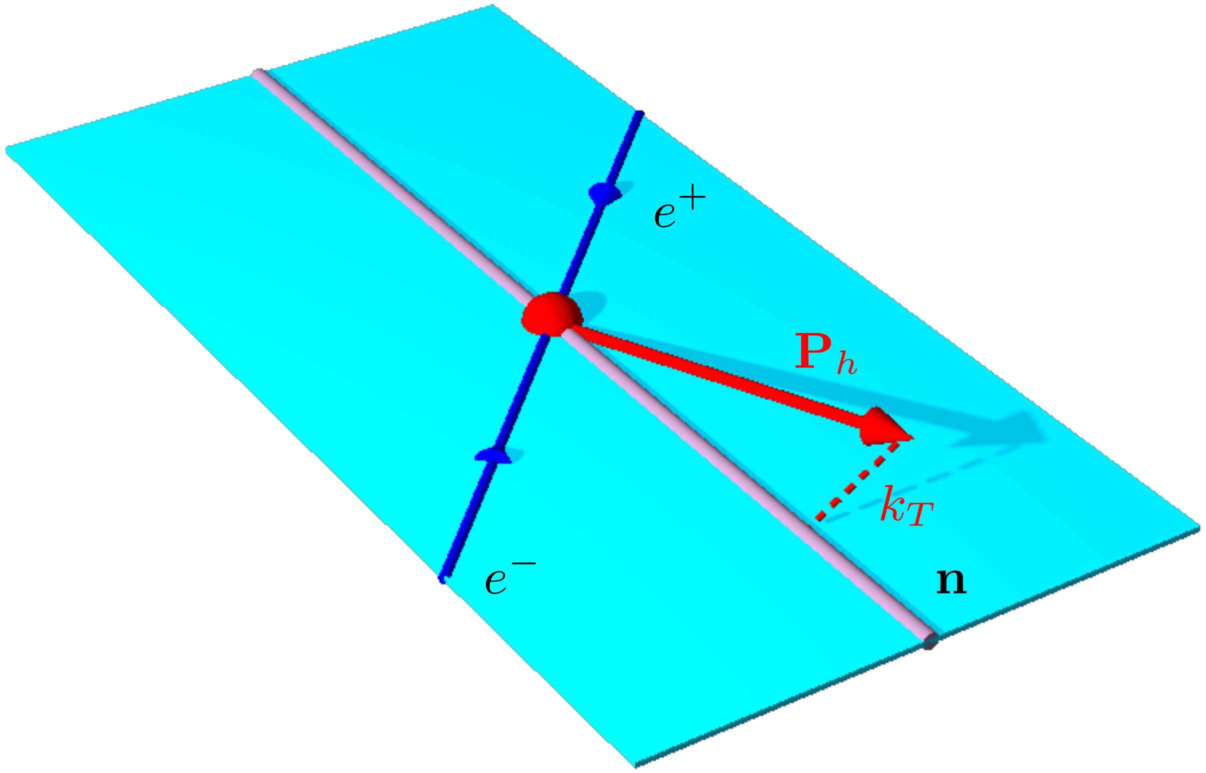


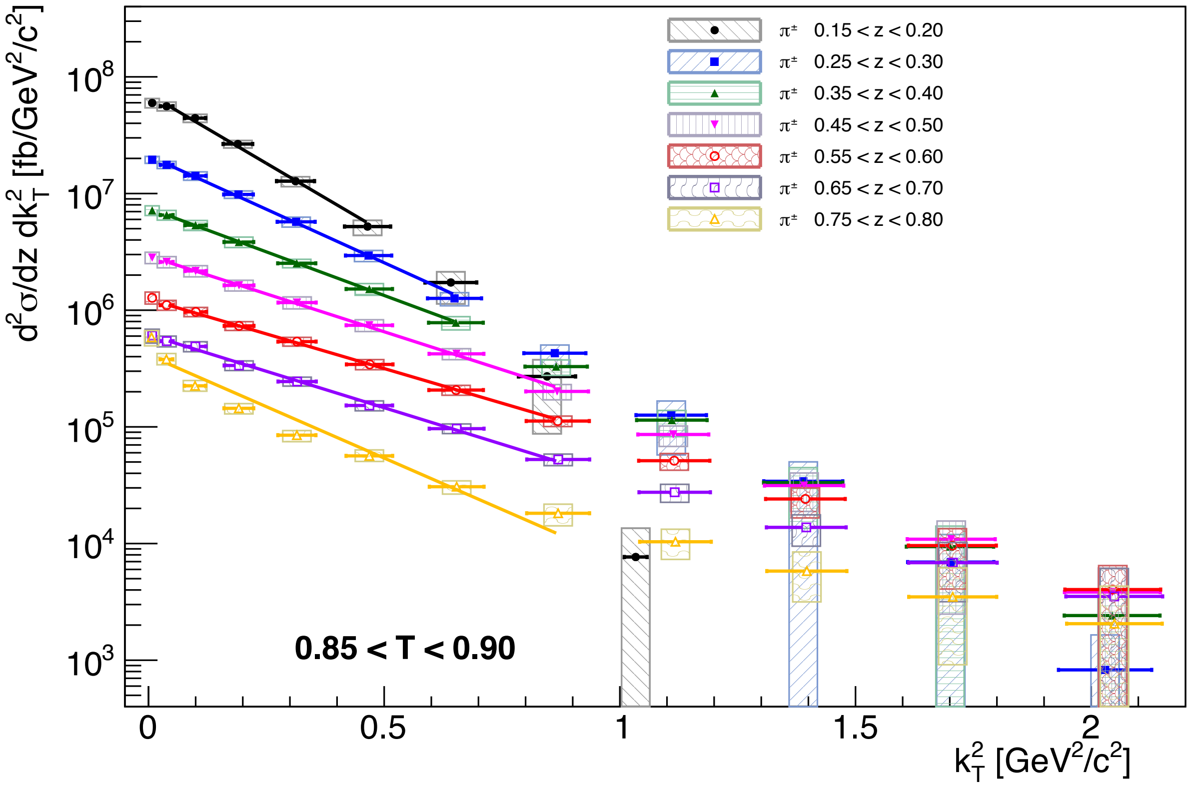
plot courtesy of F. Steffens

Alexandrou, at al. arXiv:1902.00587
Radici, Bacchetta, arXiv:1802.05212
Lin et al., arXiv:1710.09858

TRANSVERSE MOMENTUM IN FRAGMENTATION FUNCTIONS

Seidl et al., arXiv:1807.02101



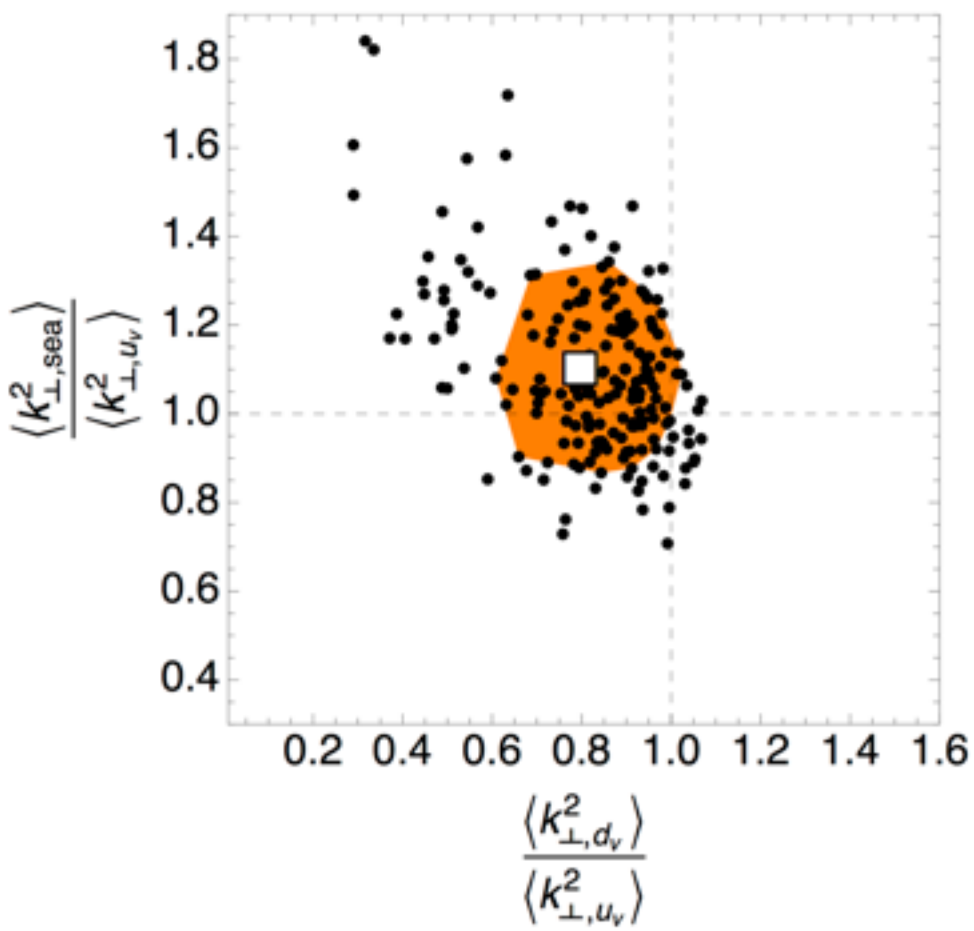


First direct measurement of TMD effects in fragmentation functions
Makes use of thrust axis: the formalism should take it into account

FLAVOR DEPENDENCE OF TMDS

Signori, Bacchetta, Radici, Schnell JHEP 1311 (13)

Ratio of width of sea / width of up valence



Ratio width of down valence/ width of up valence

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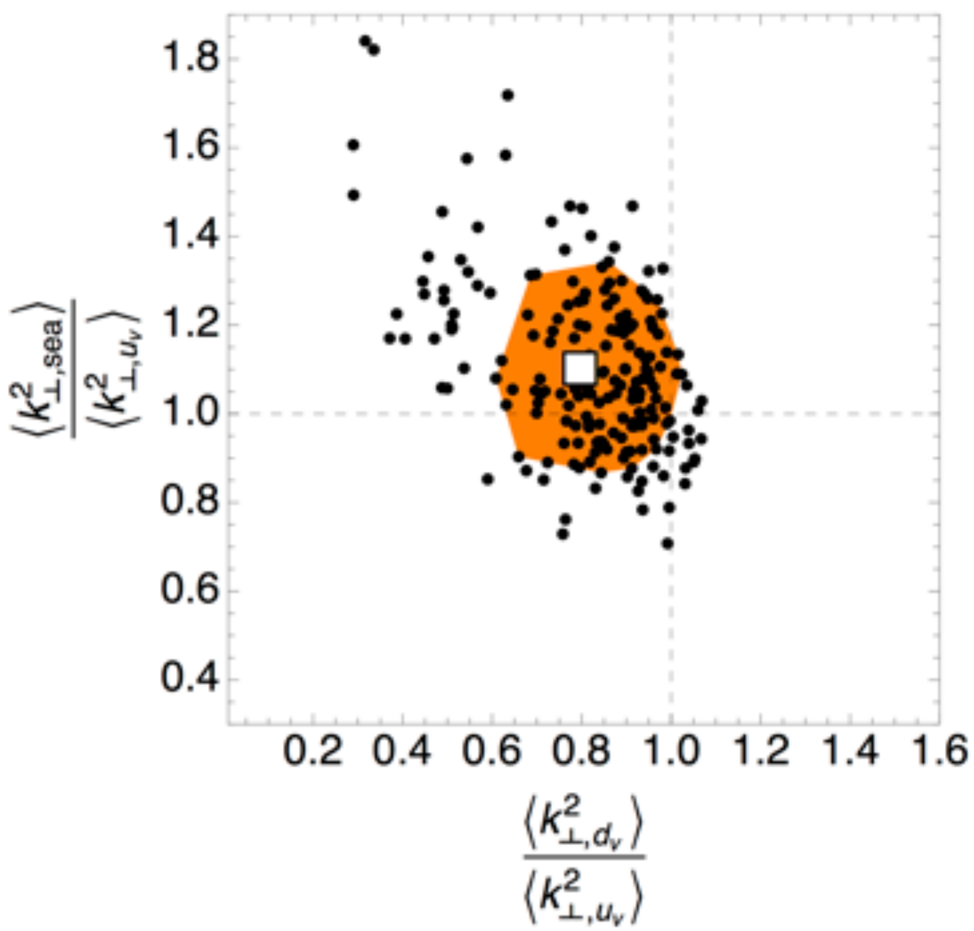

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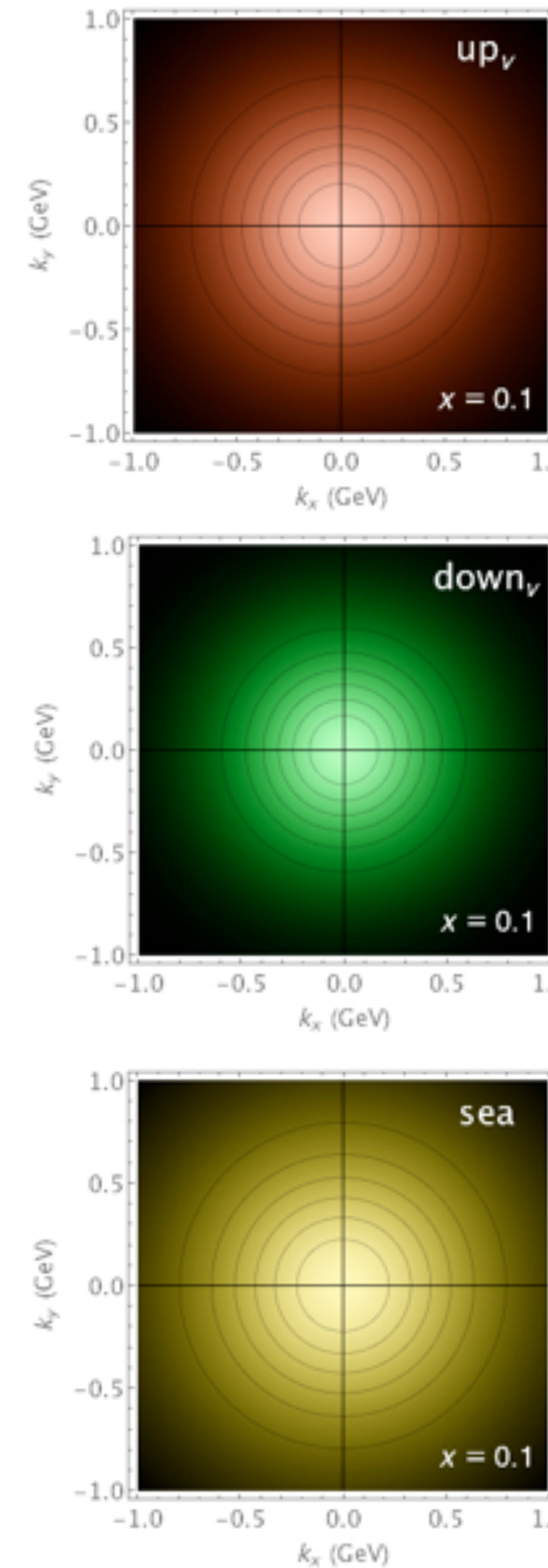

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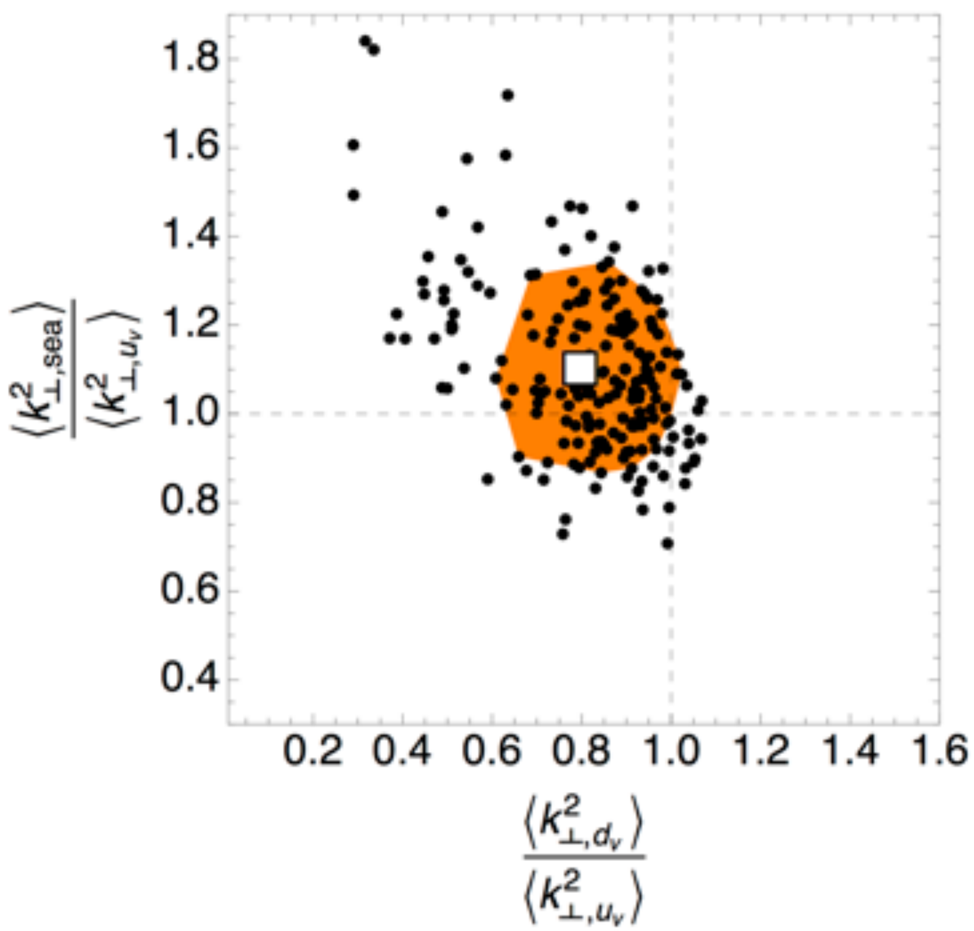

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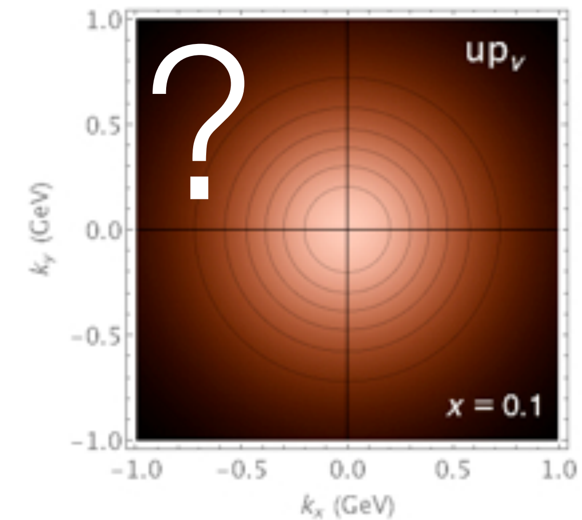

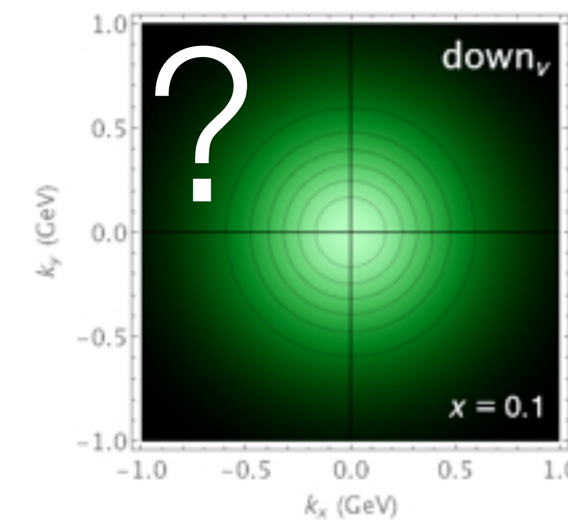

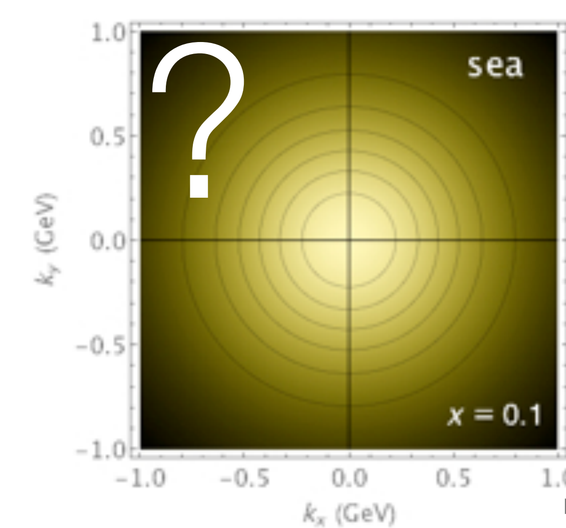

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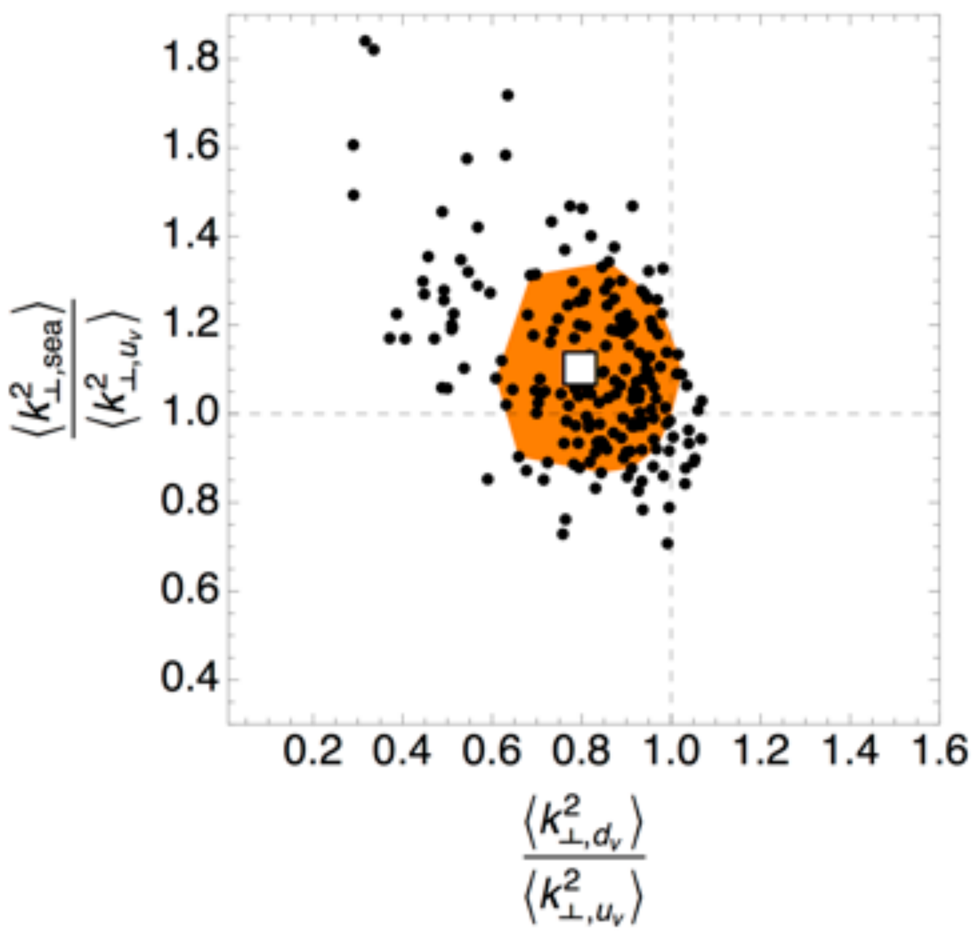

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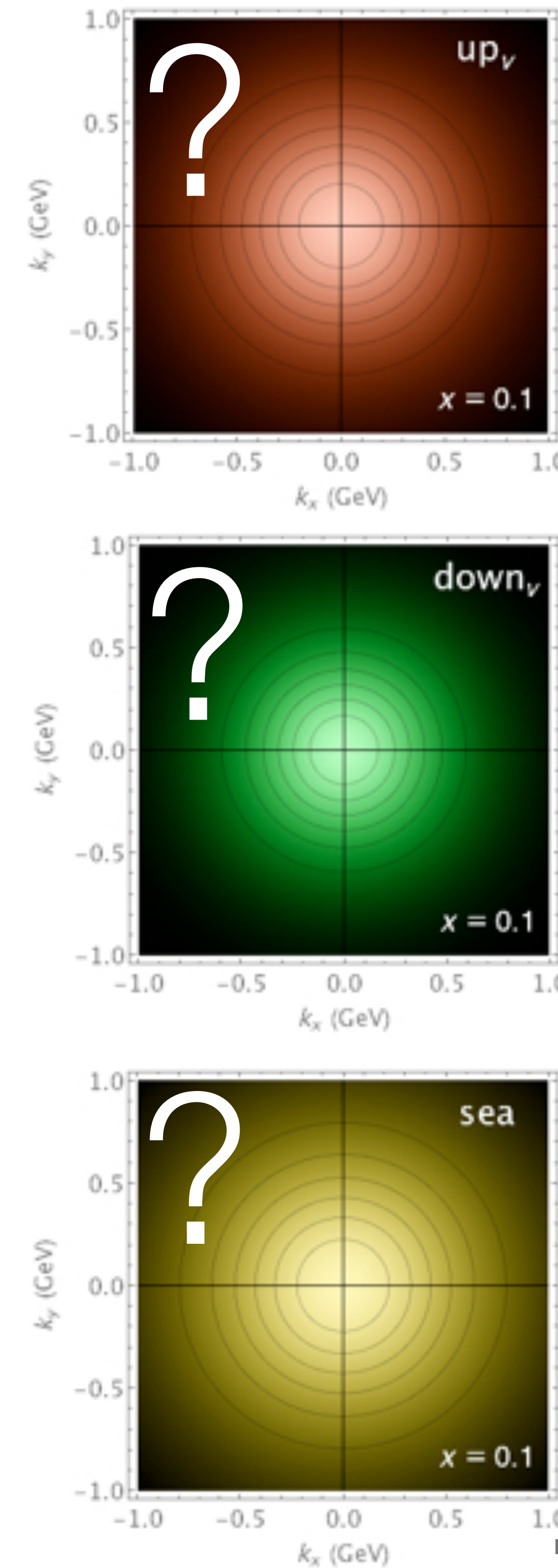
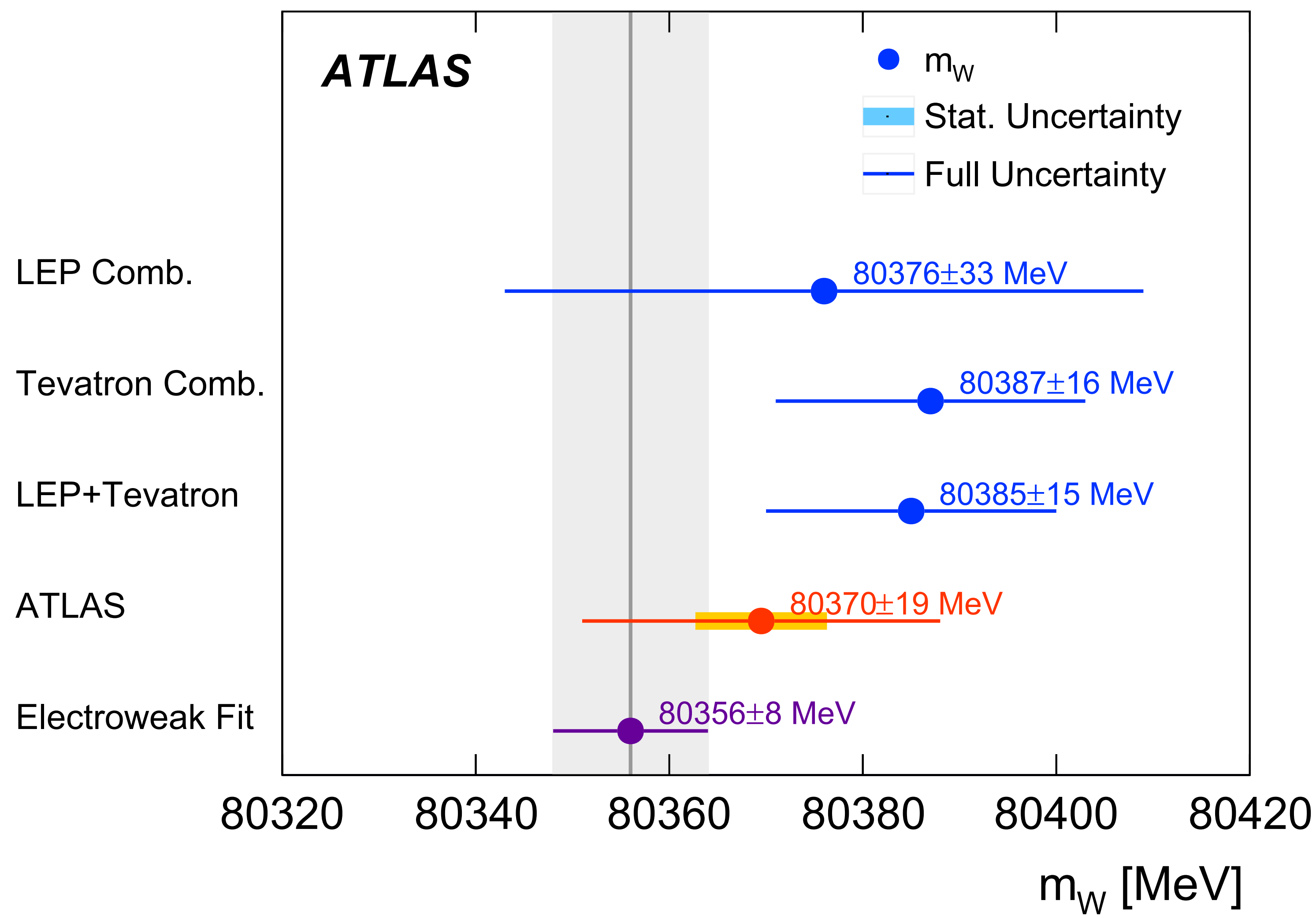


There is room for flavour dependence, but we don't control it well

IMPACT ON W MASS DETERMINATION

ATLAS Collab. arXiv:1701.07240



$$m_W = 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV}$$
$$= 80370 \pm 19\ \text{MeV},$$

$$m_{W^+} - m_{W^-} = -29 \pm 28\ \text{MeV}.$$

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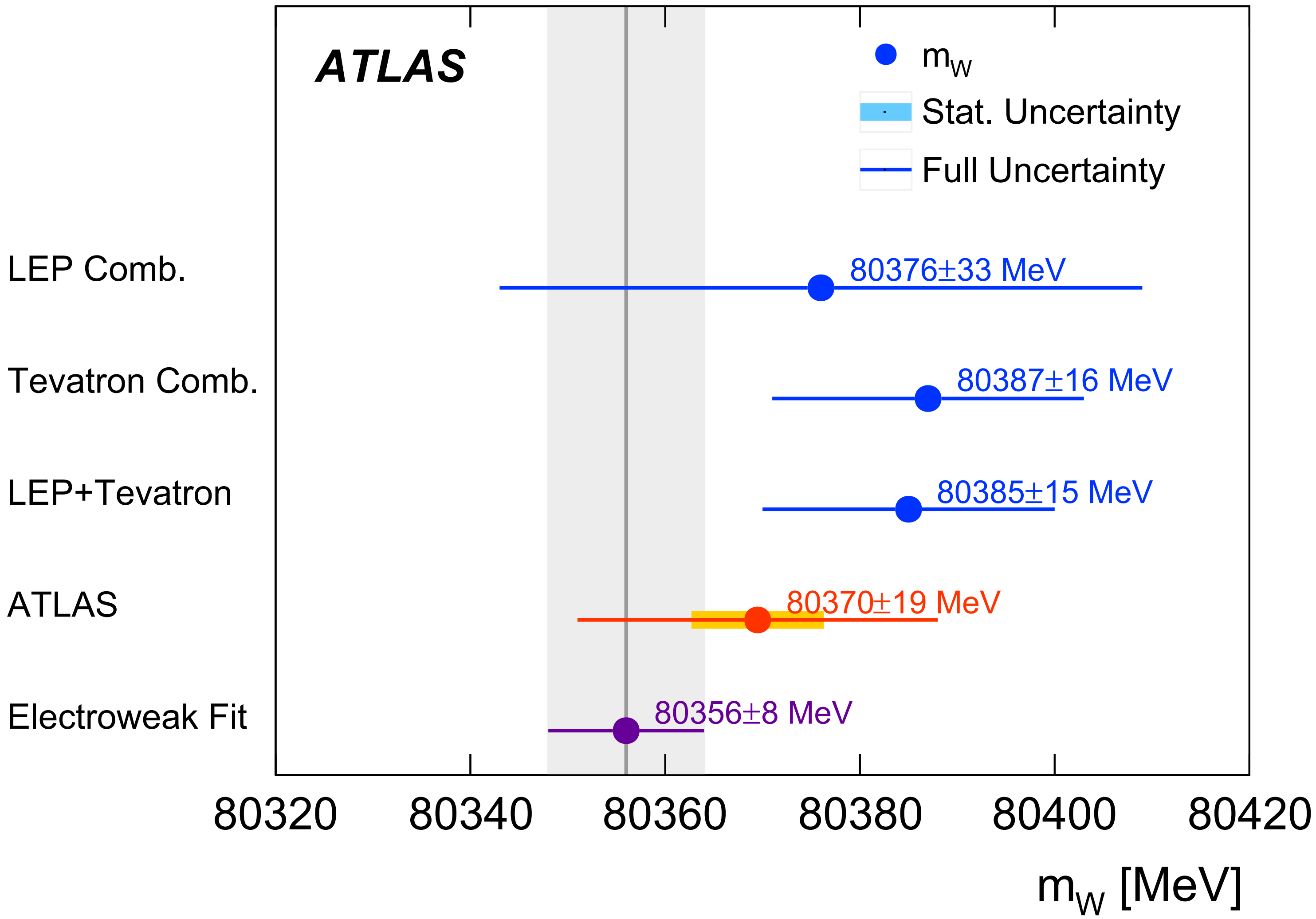

All analyses assume that TMDs are not flavour dependent.
What happens if they are?

$$m_W = 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})\ \text{MeV}$$
$$= 80370 \pm 19\ \text{MeV},$$

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Try some judicious choices of flavour dependent widths and check

IMPACT ON W MASS DETERMINATION

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Try some judicious choices of flavour dependent widths and check

Set	u_v	d_v	u_s	d_s	s
1	0.34	0.26	0.46	0.59	0.32
2	0.34	0.46	0.56	0.32	0.51
3	0.55	0.34	0.33	0.55	0.30
4	0.53	0.49	0.37	0.22	0.52
5	0.42	0.38	0.29	0.57	0.27

IMPACT ON W MASS DETERMINATION

Bacchetta, Bozzi, Radici, Ritzmann, Signori, arXiv:1807.02101

Try some judicious choices of flavour dependent widths and check

Set	u_v	d_v	u_s	d_s	s	
1	0.34	0.26	0.46	0.59	0.32	narrow, medium, large
2	0.34	0.46	0.56	0.32	0.51	narrow, large, narrow
3	0.55	0.34	0.33	0.55	0.30	large, narrow, large
4	0.53	0.49	0.37	0.22	0.52	large, medium, narrow
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5	0.42	0.38	0.29	0.57	0.27	medium, narrow, large

	ΔM_{W^+}		ΔM_{W^-}	
Set	m_T	$p_{T\ell}$	m_T	$p_{T\ell}$
1	0	-1	-2	3
2	0	-6	-2	0
3	-1	9	-2	-4
4	0	0	-2	-4
5	0	4	-1	-3

IMPACT ON W MASS DETERMINATION

Bacchetta, Bozzi, Radici, Ritzmann, Signori, arXiv:1807.02101

Try some judicious choices of flavour dependent widths and check

Set	u_v	d_v	u_s	d_s	s
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narrow, medium, large
narrow, large, narrow
large, narrow, large
large, medium, narrow
medium, narrow, large

	ΔM_{W^+}		ΔM_{W^-}	
Set	m_T	$p_{T\ell}$	m_T	$p_{T\ell}$
1	0	-1	-2	3
2	0	-6	-2	0
3	-1	9	-2	-4
4	0	0	-2	-4
5	0	4	-1	-3

Not taking into account the flavour dependence of TMDs can lead to errors in the determination of the W mass