First attempts at a global fit of unpolarized Transverse Momentum Distributions

Alessandro Bacchetta

Funded by

3DSPIN MAPPING THE PROTON IN 3D

European Research Council

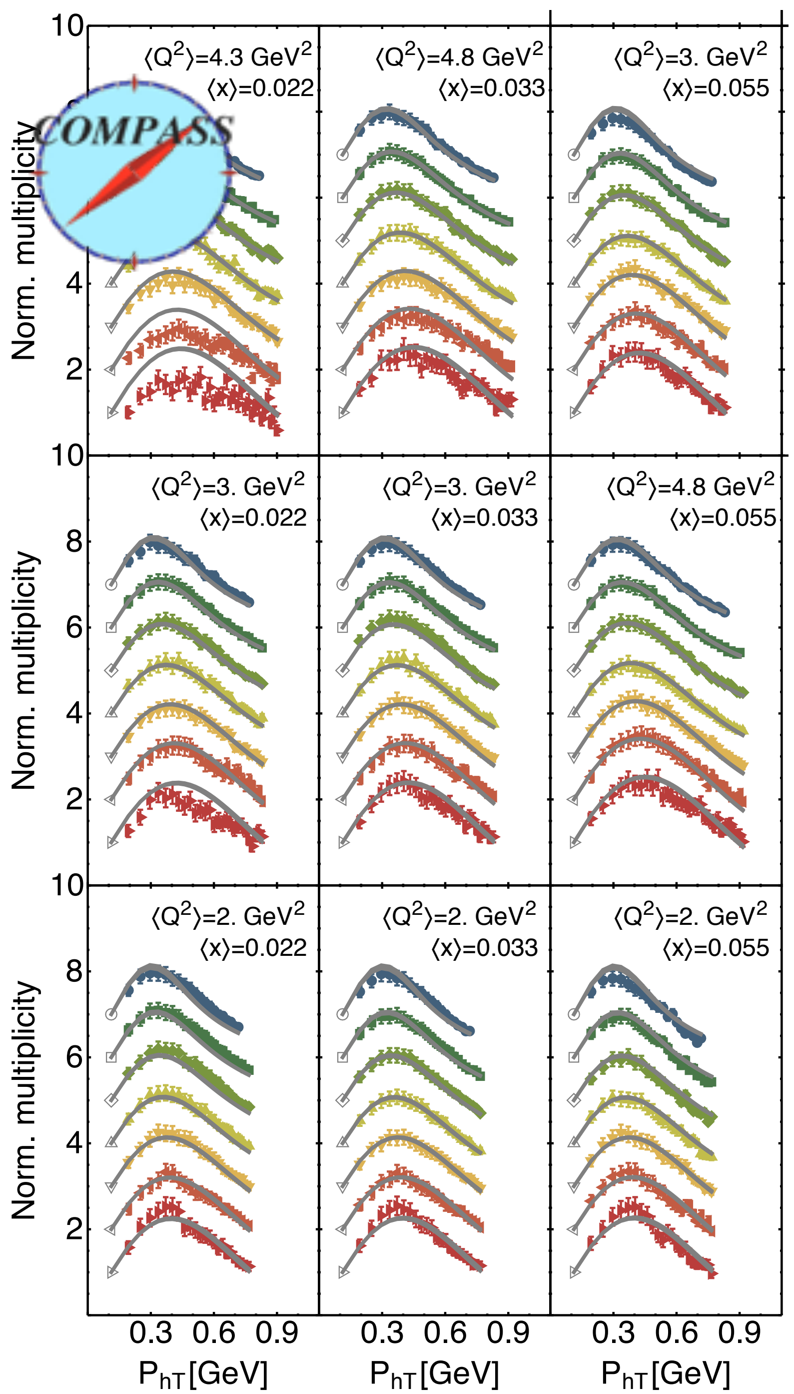
INFN Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DI PAVIA

In collaboration with

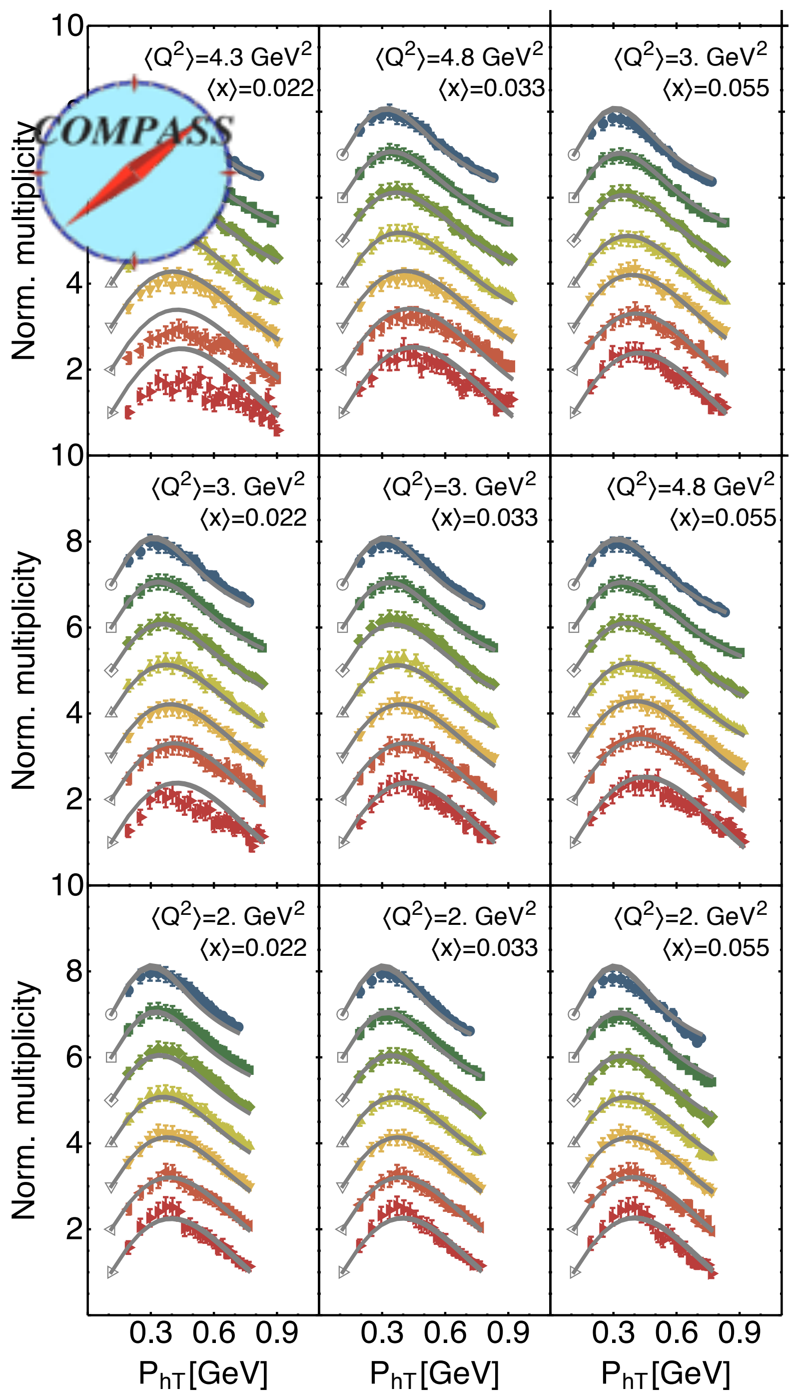
- Filippo Delcarro (PhD student, University of Pavia and INFN Pavia)
- Cristian Pisano (University of Pavia and INFN Pavia)
- Marco Radici (INFN Pavia)
- Andrea Signori (Vrije Universiteit Amsterdam and NIKHEF)

In a nutshell

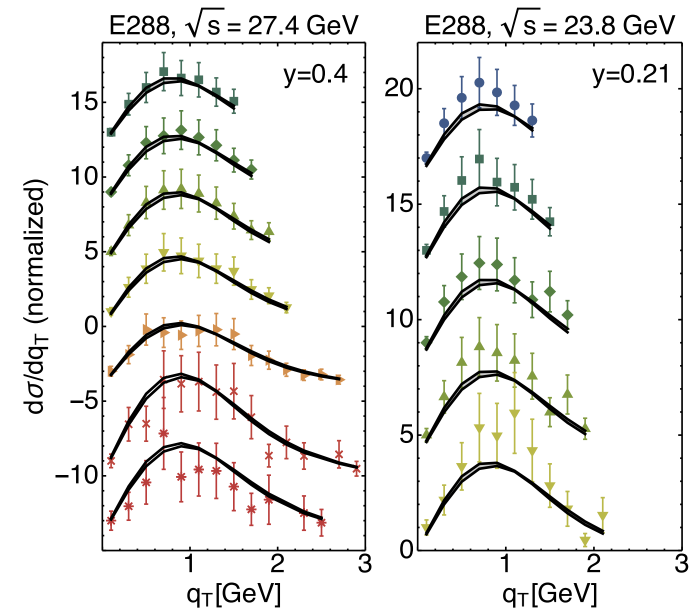


Bacchetta, Delcarro, Pisano, Radici, Signori, in preparation

In a nutshell

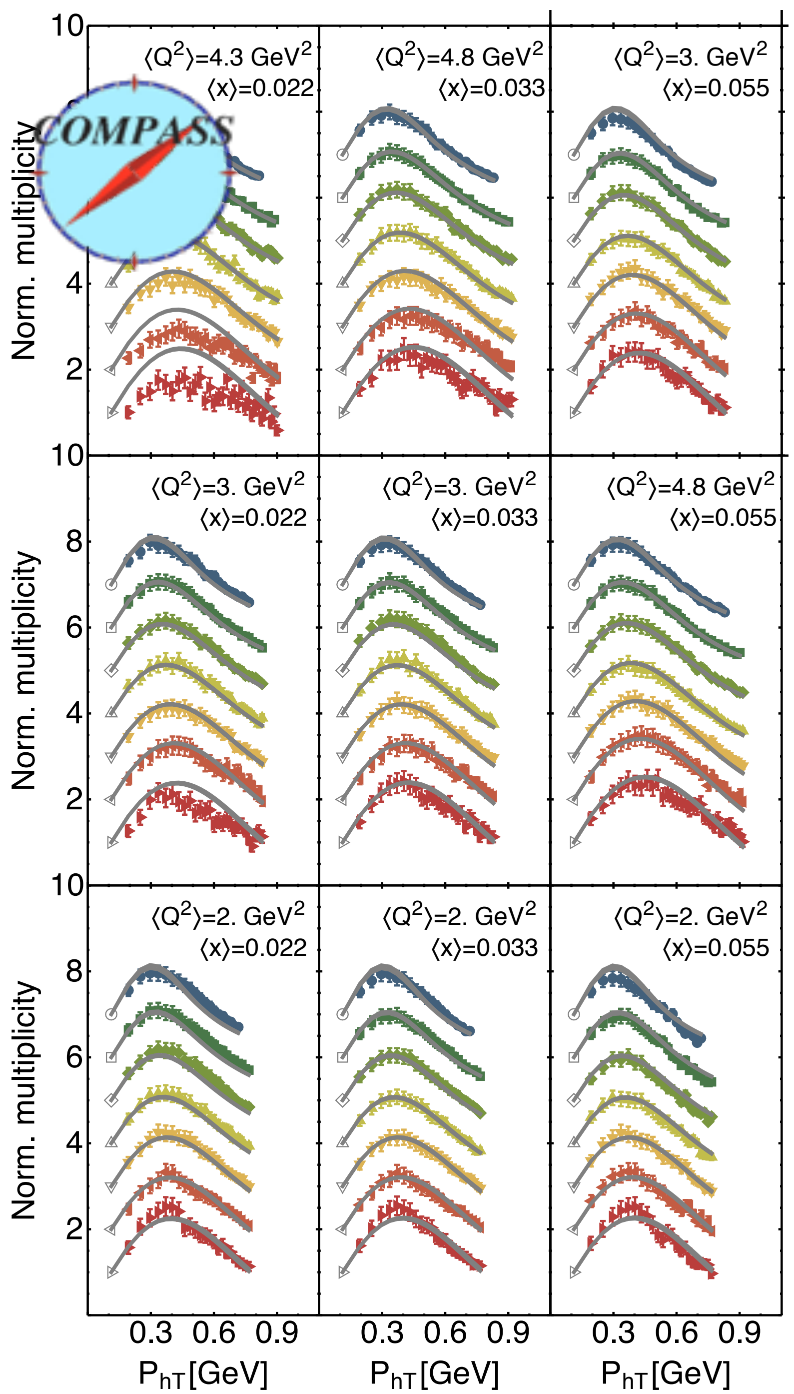


E28

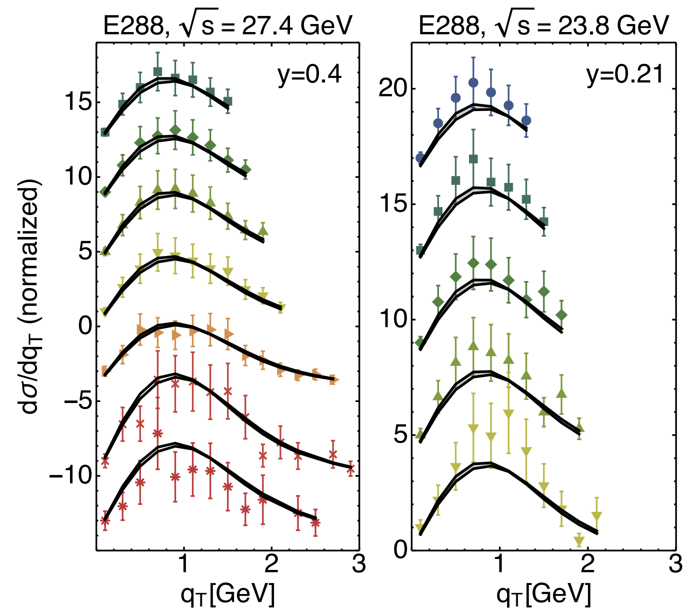


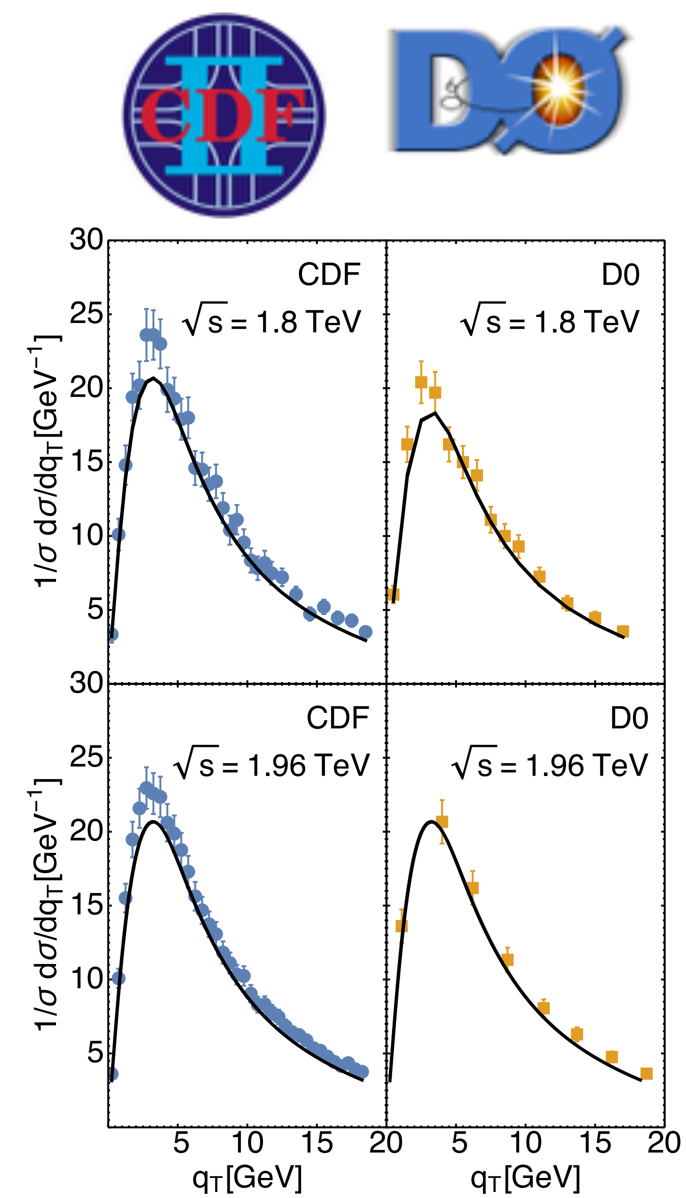
Bacchetta, Delcarro, Pisano, Radici, Signori, in preparation

In a nutshell



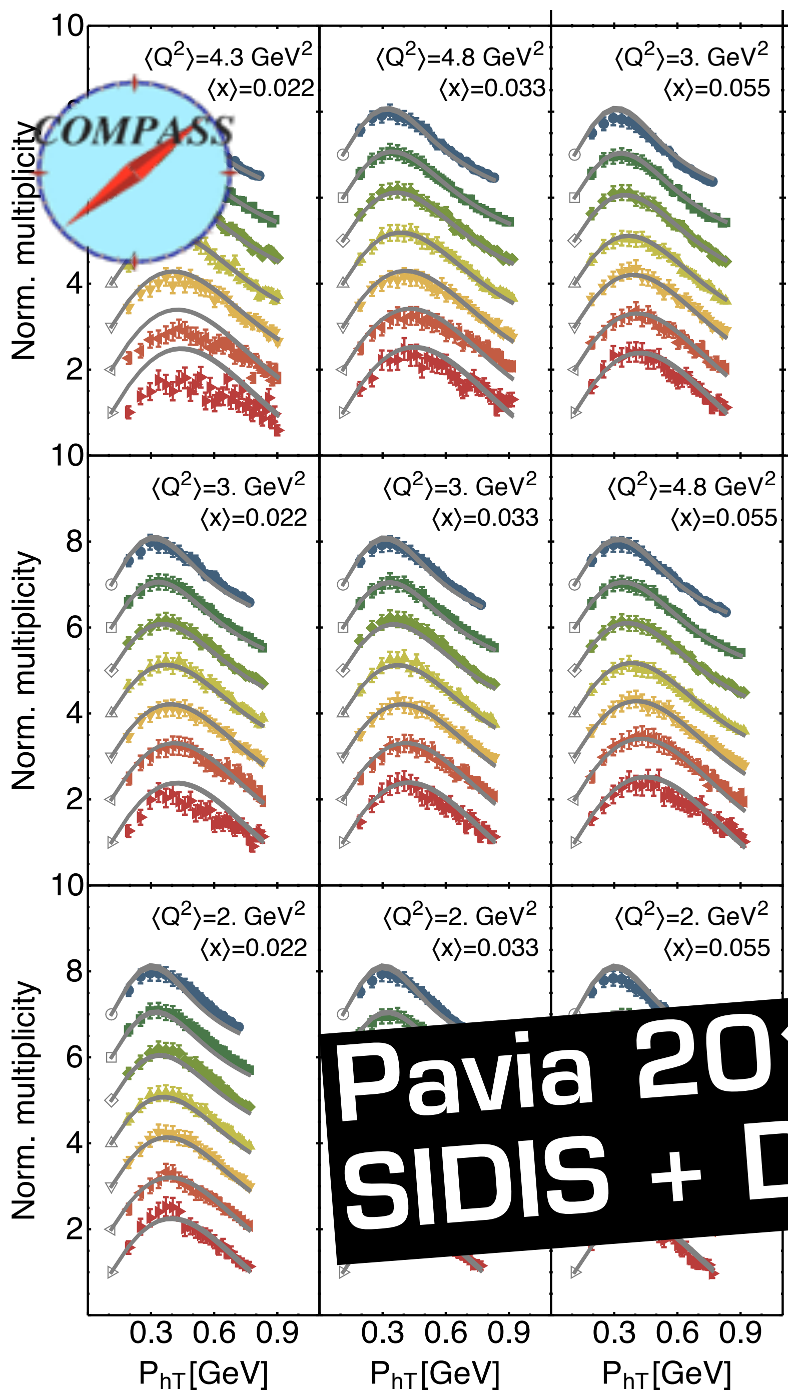
E28



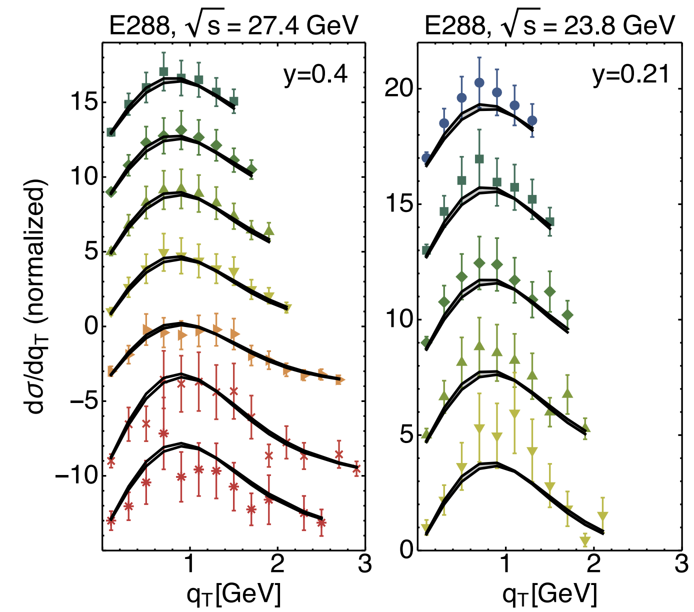


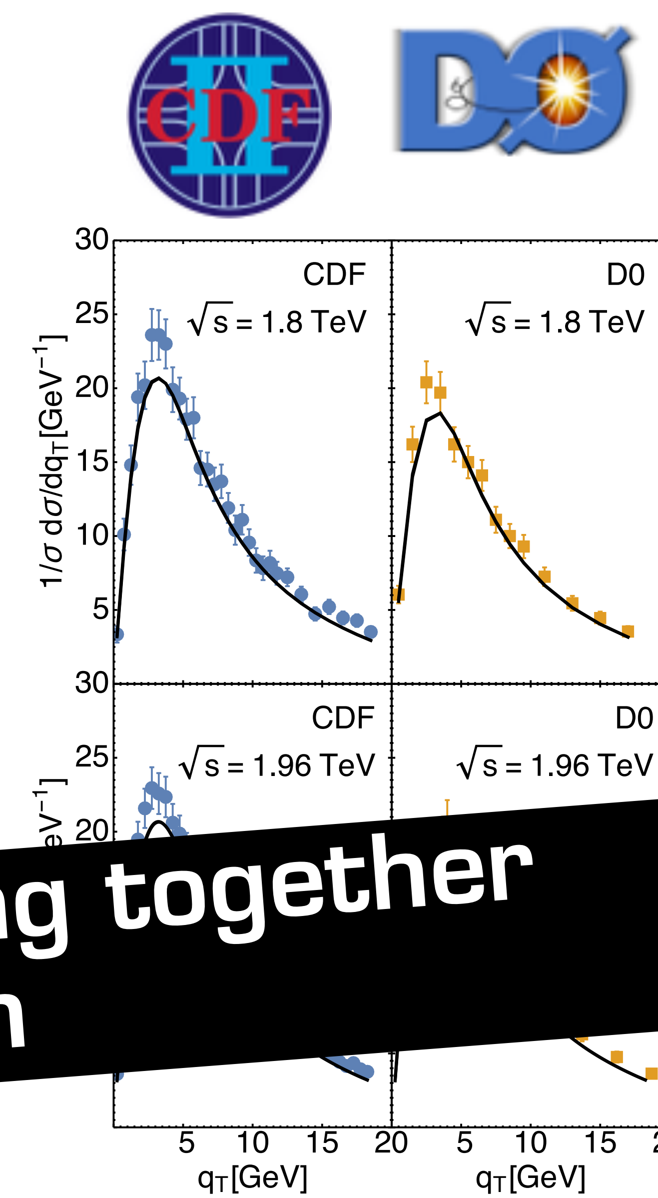
Bacchetta, Delcarro, Pisano, Radici, Signori, in preparation

In a nutshell



E28



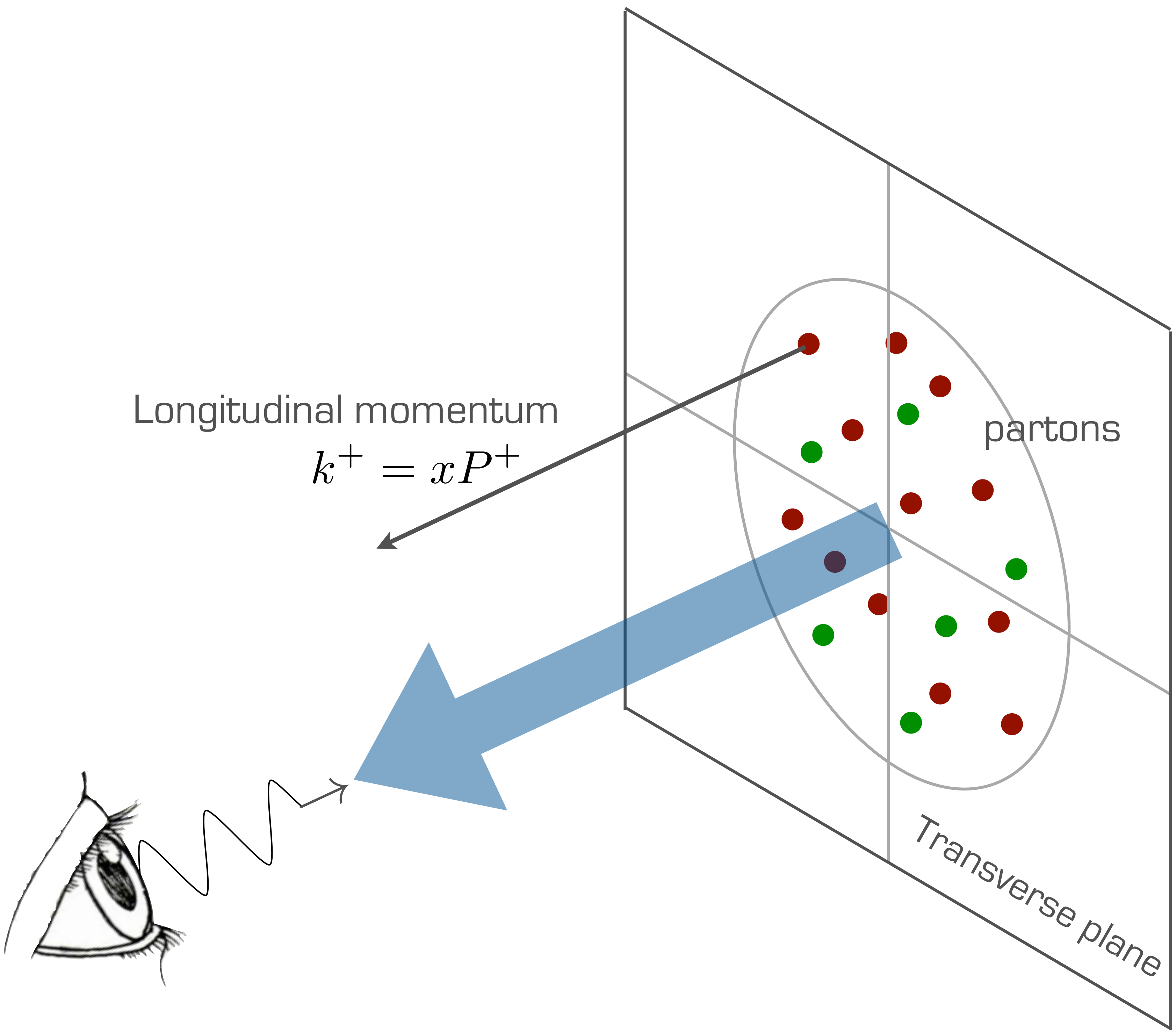


Pavia 2016: first TMD fit putting together SIDIS + Drell-Yan + Z production

Bacchetta, Delcarro, Pisano, Radici, Signori, in preparation

Some introduction

Mapping the structure of the proton

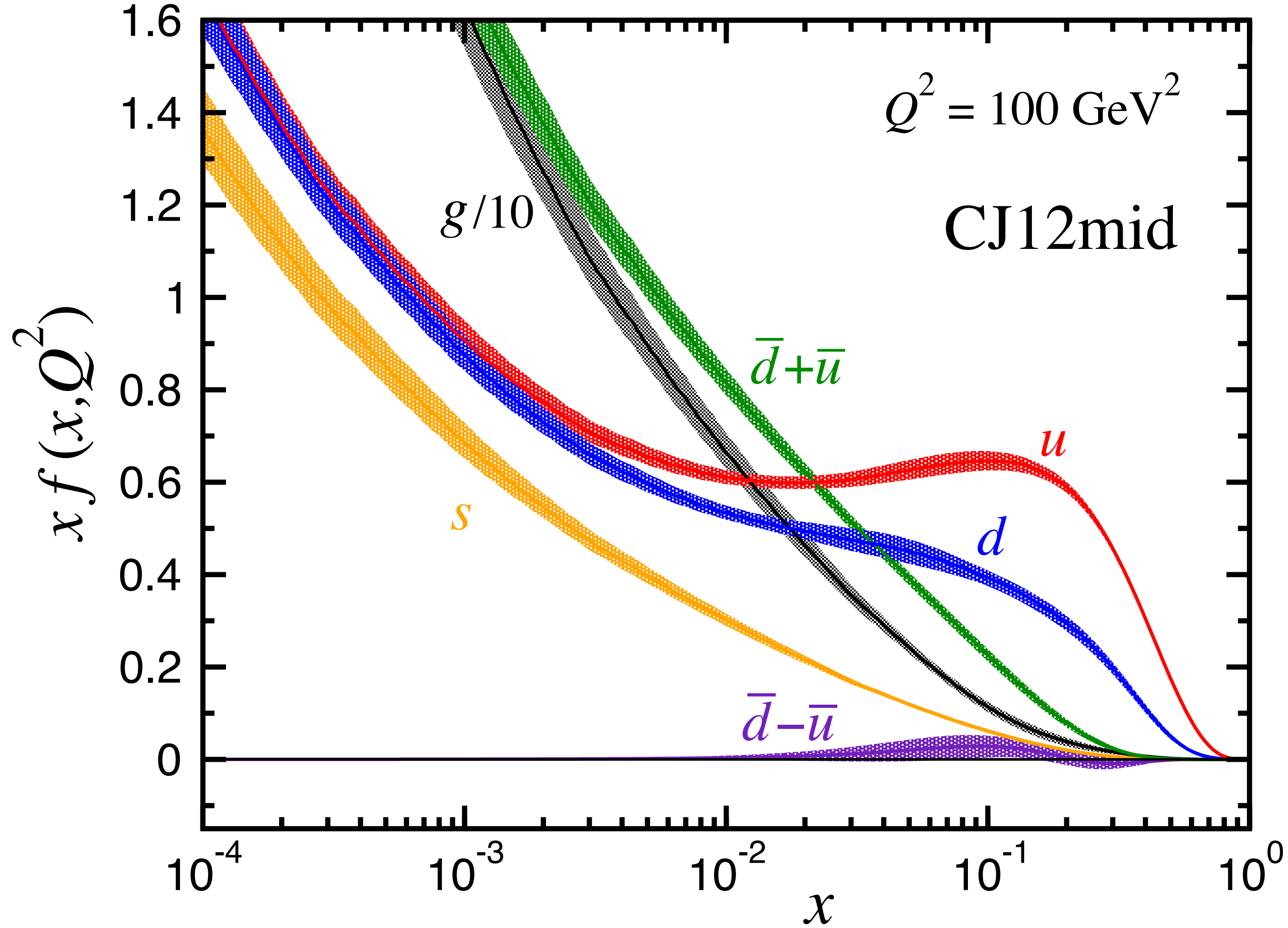


Standard parton distribution functions

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

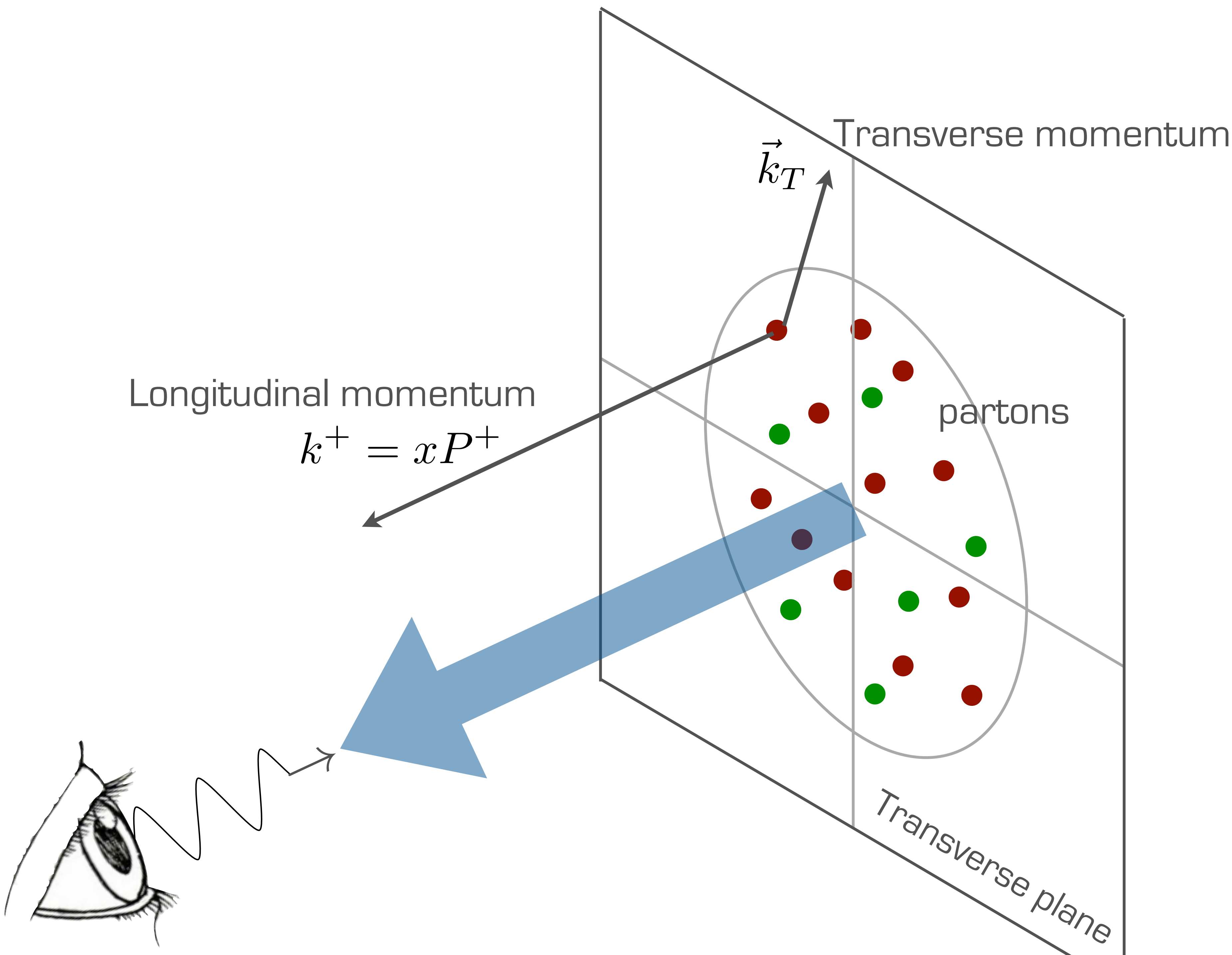
Standard parton distribution functions

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



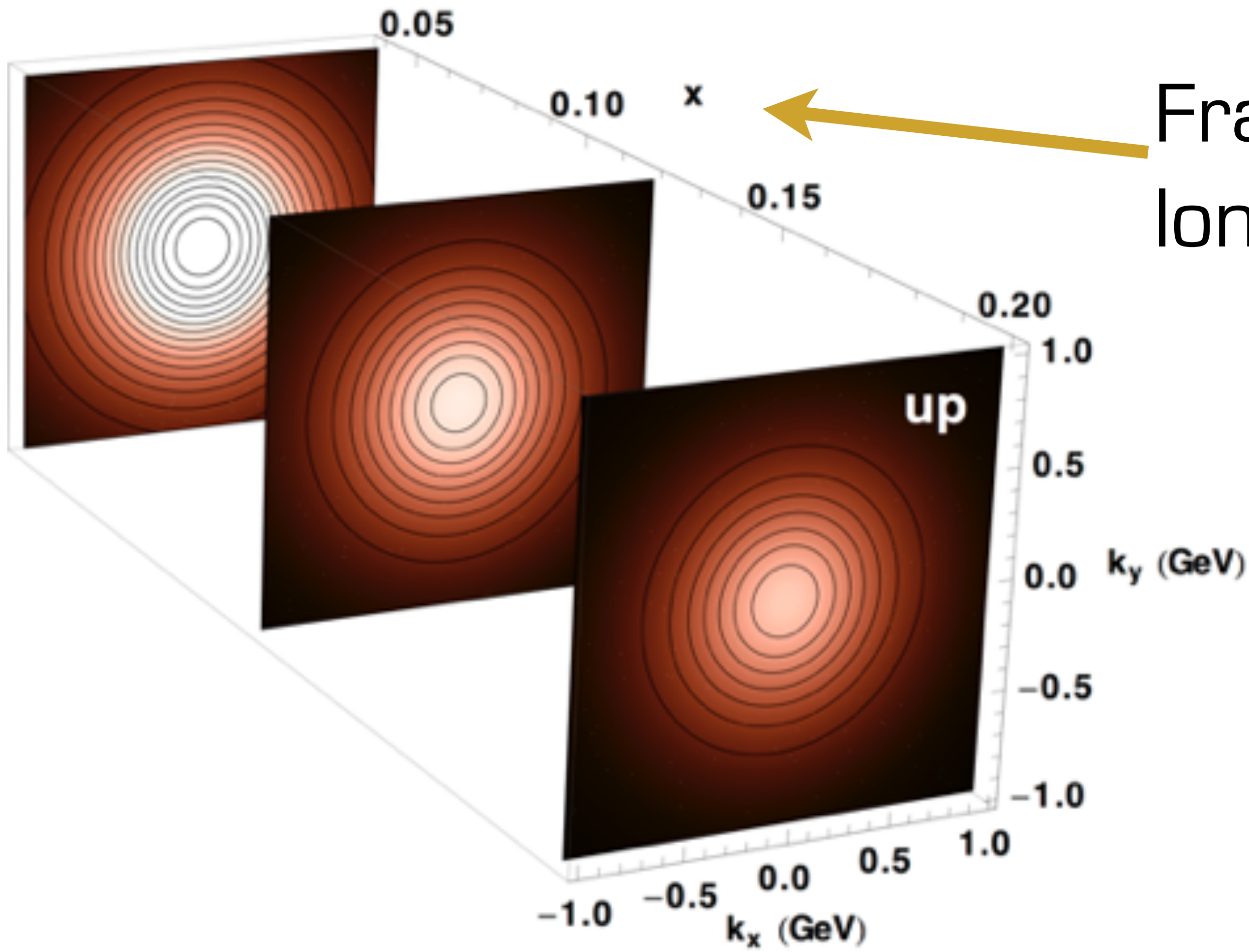
CTEQ-JLAB 12 set, Owens, Accardi, Melnitchouk, PRD87 (13)

Considering new dimensions



Transverse momentum distributions

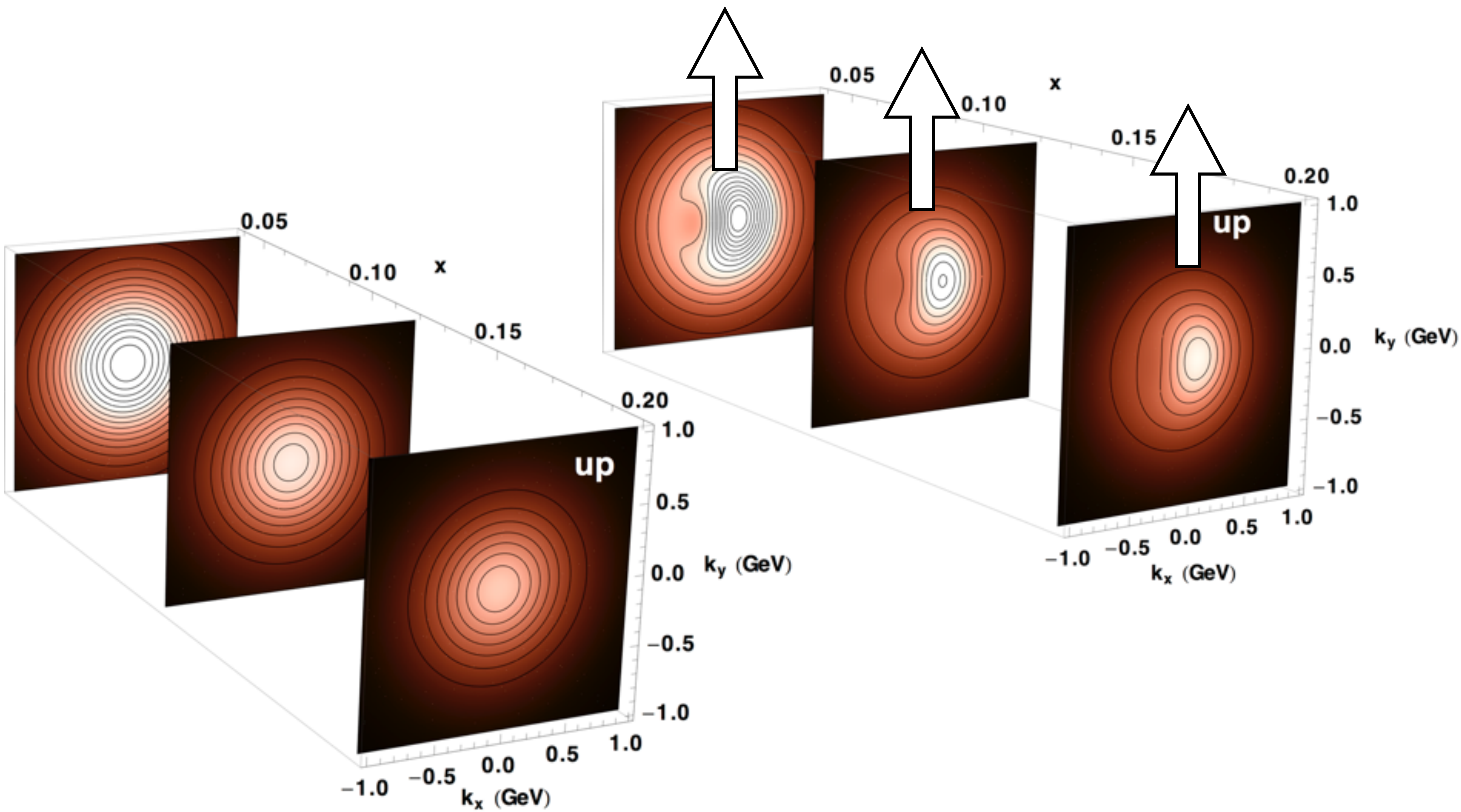
TMDs describe the distribution of partons in three dimensions in momentum space. They also have to be extracted through global fits.



Fraction of longitudinal momentum

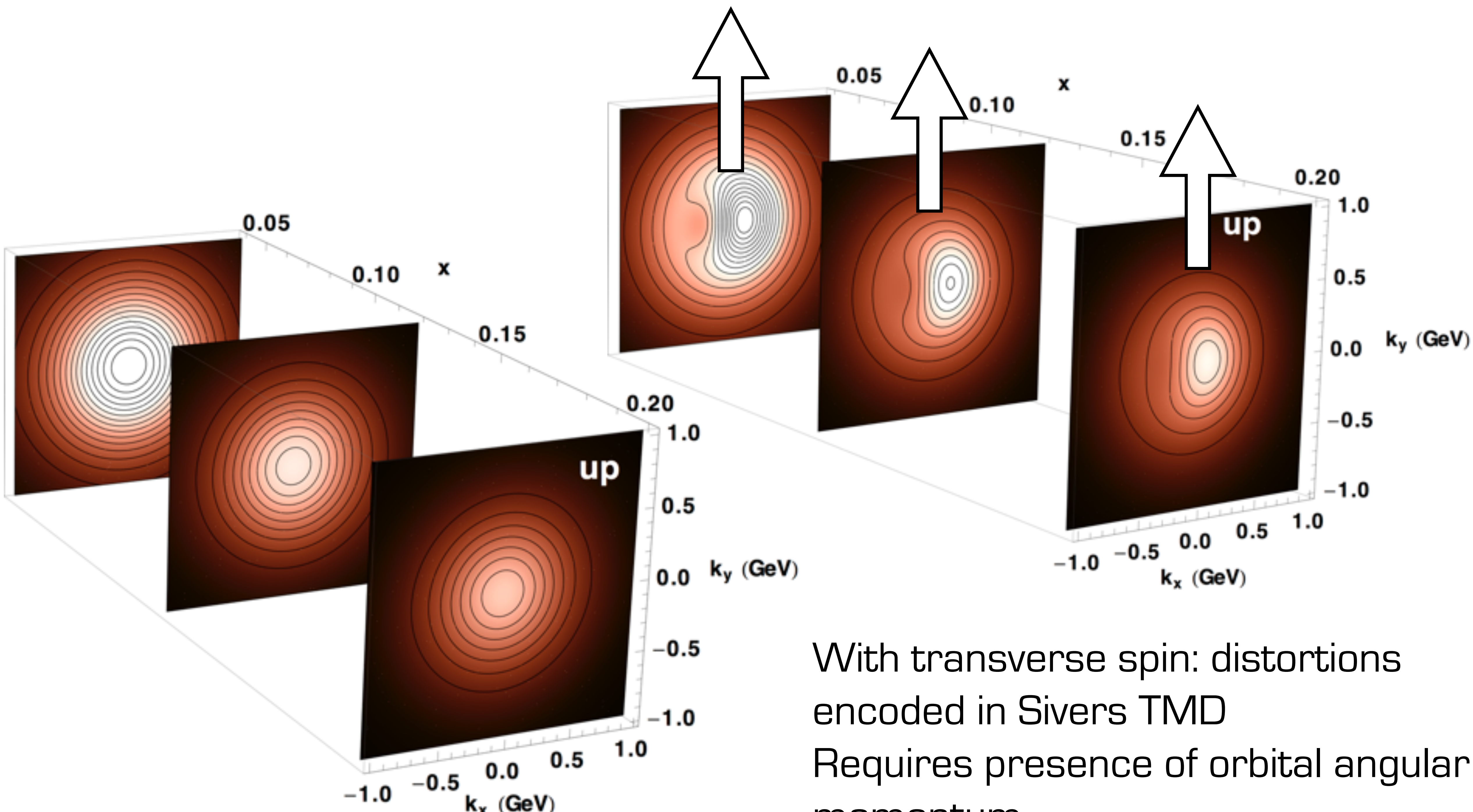
Transverse momentum

3D structure in momentum space



Unpolarized TMD: cylindrically symmetric

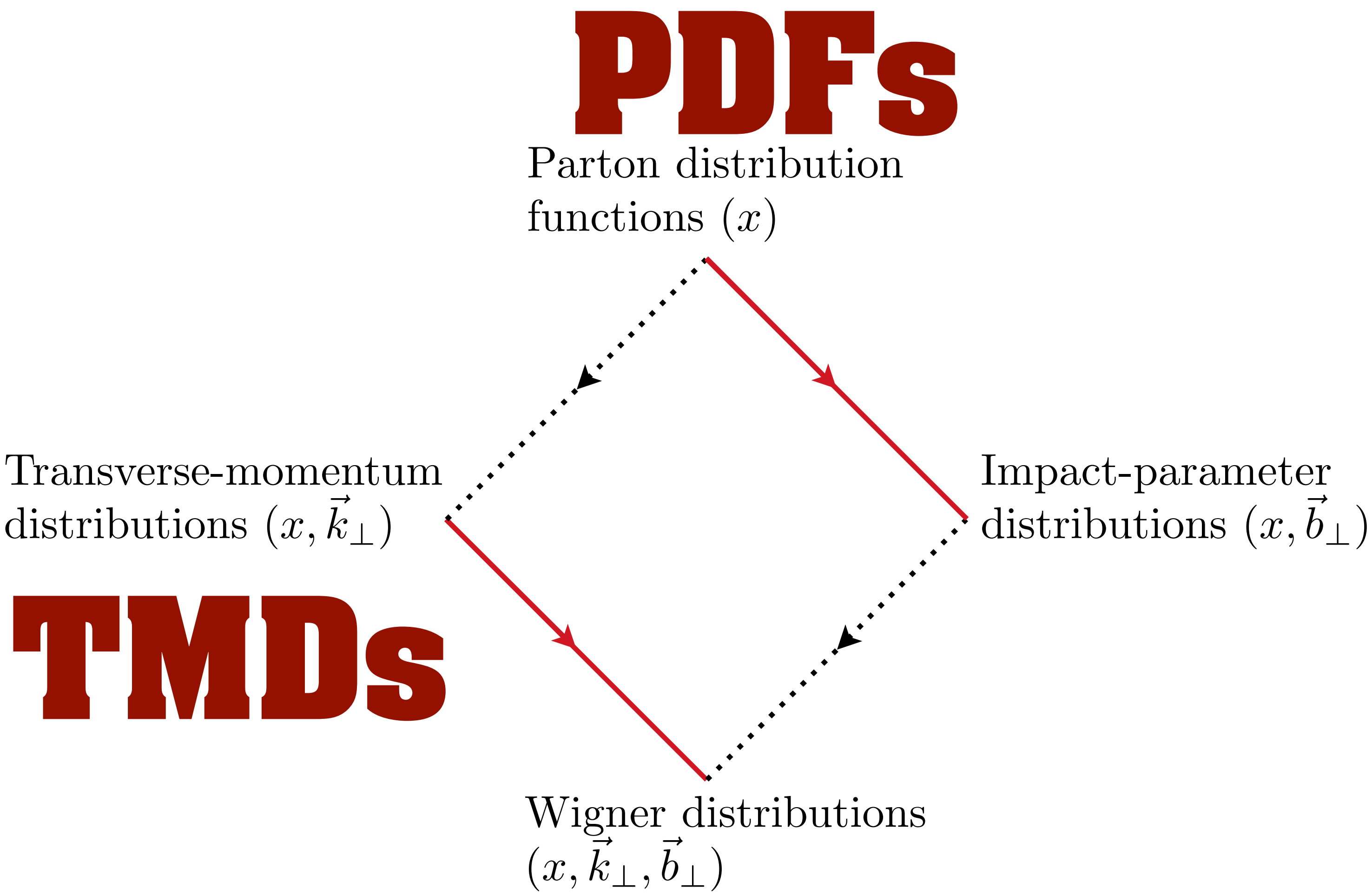
3D structure in momentum space



Unpolarized TMD: cylindrically symmetric

With transverse spin: distortions encoded in Sivers TMD

Requires presence of orbital angular momentum

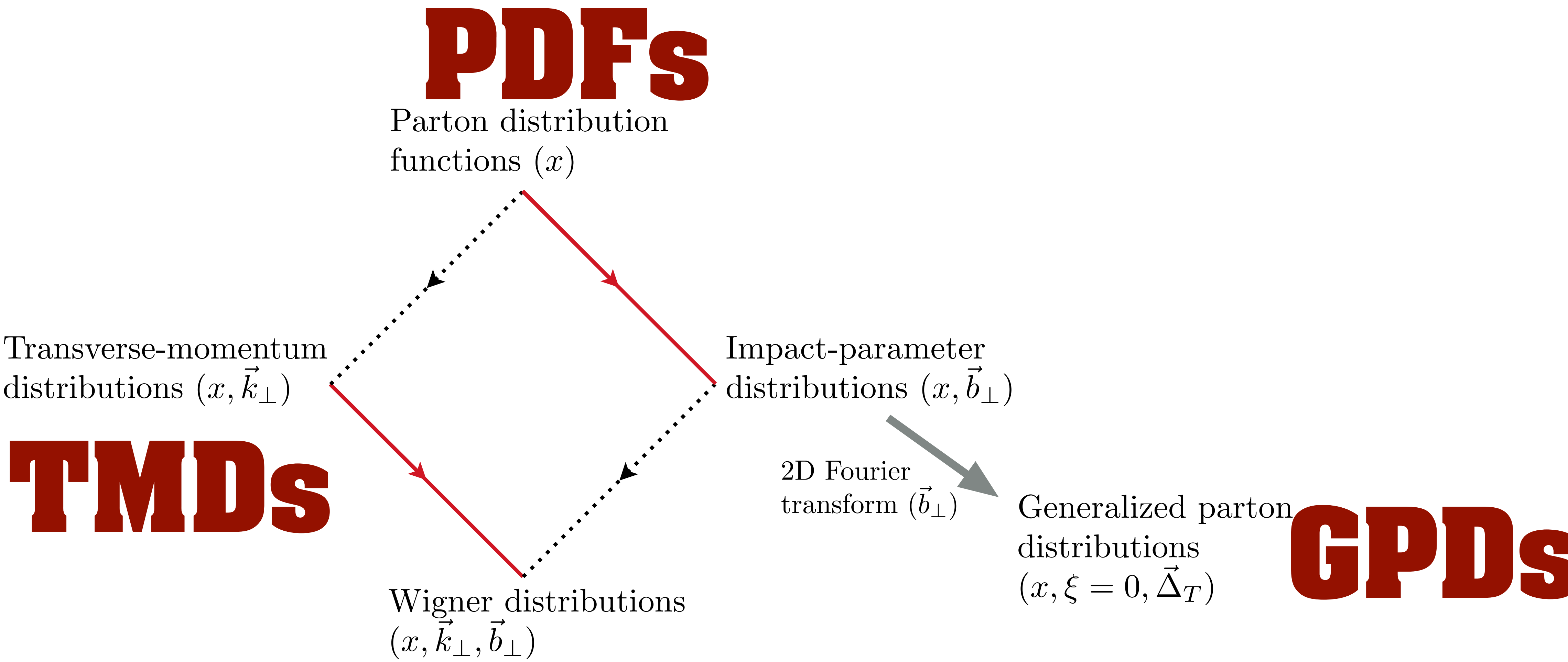


$\longrightarrow$ $\vec{b}_\perp$ dependence

$\dashrightarrow$ $\vec{k}_\perp$ dependence

⚠ these two variables are NOT Fourier conjugate

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

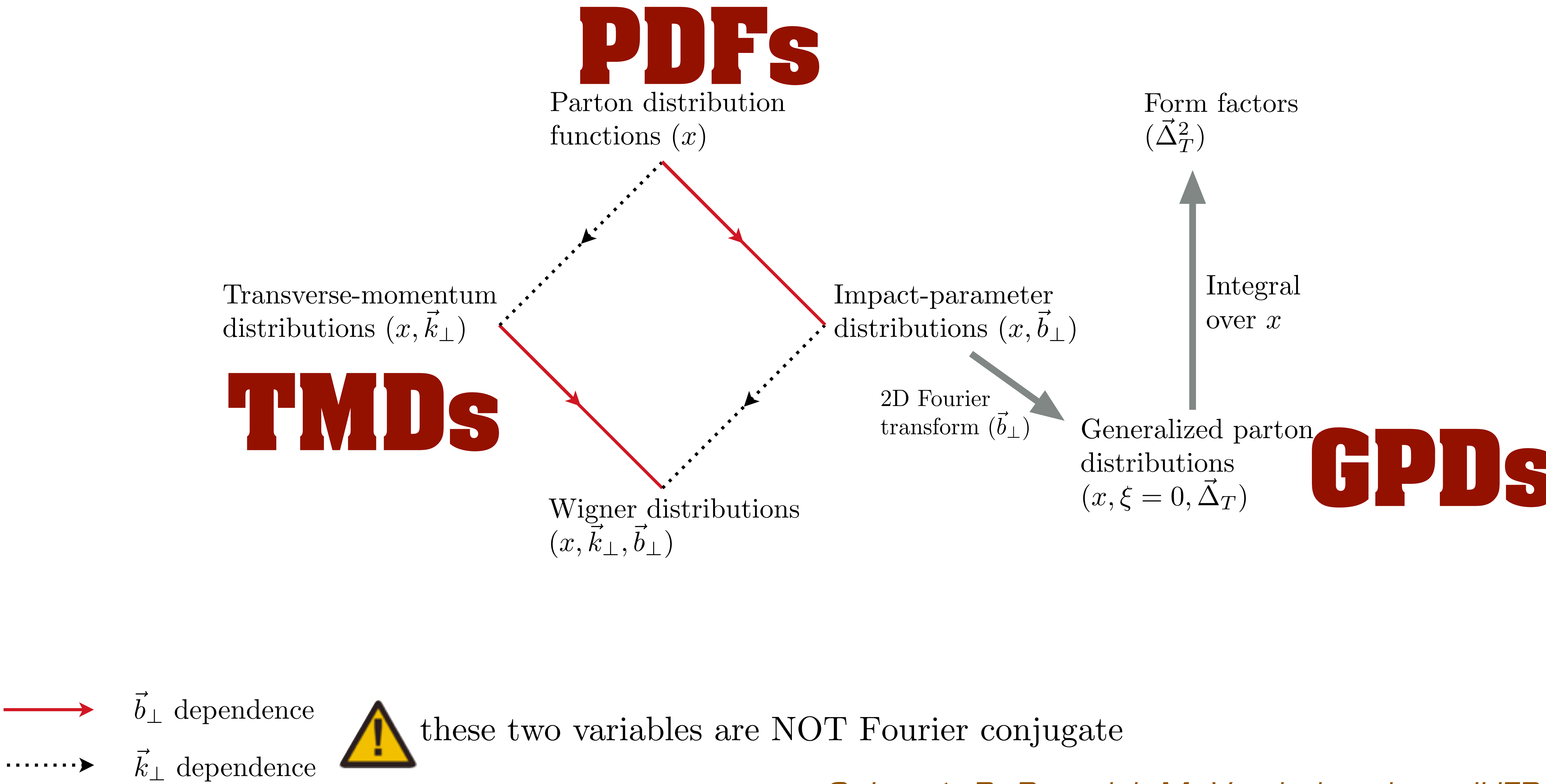


$\vec{b}_\perp$ dependence

$\vec{k}_\perp$ dependence

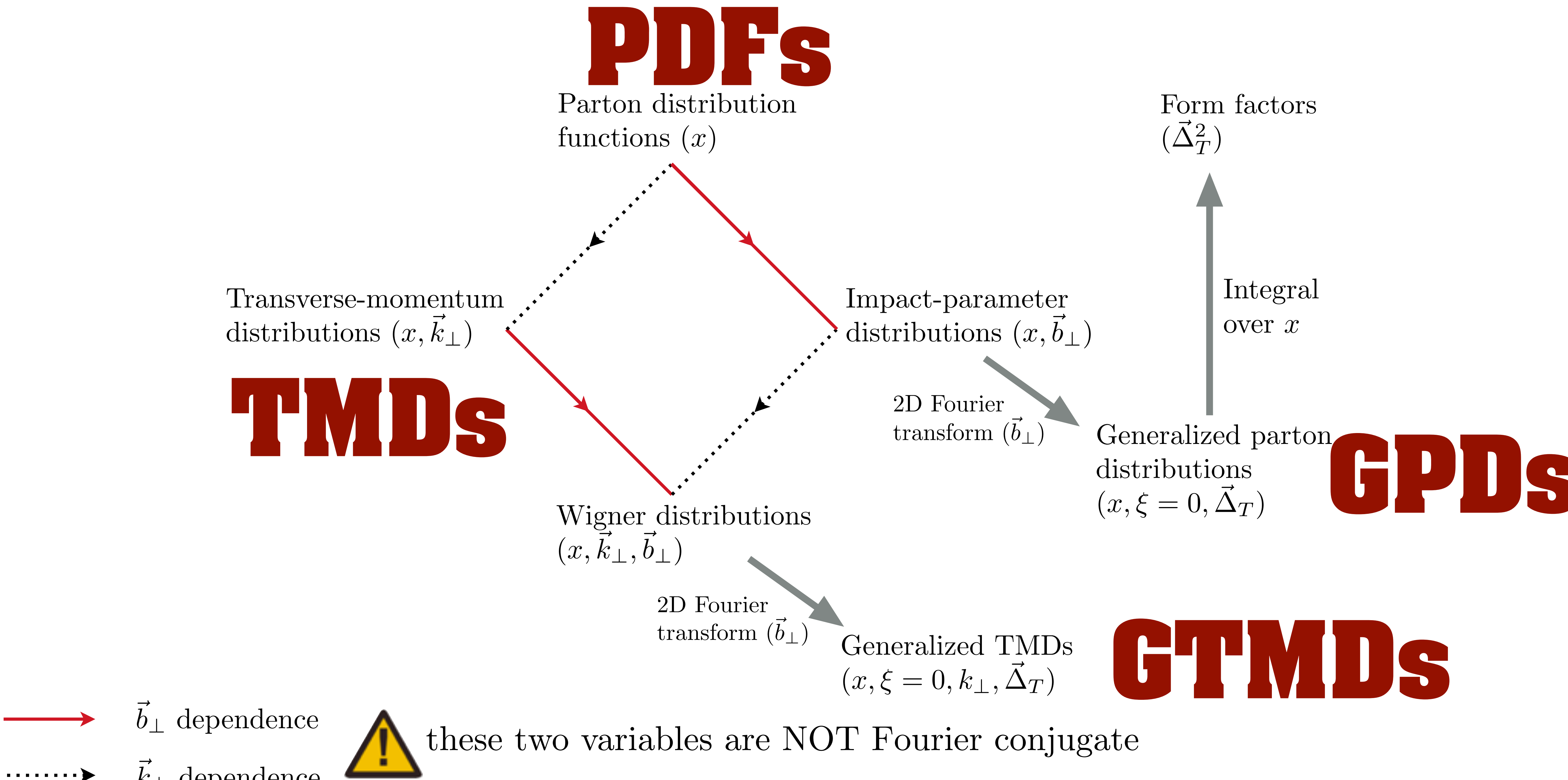
these two variables are NOT Fourier conjugate

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

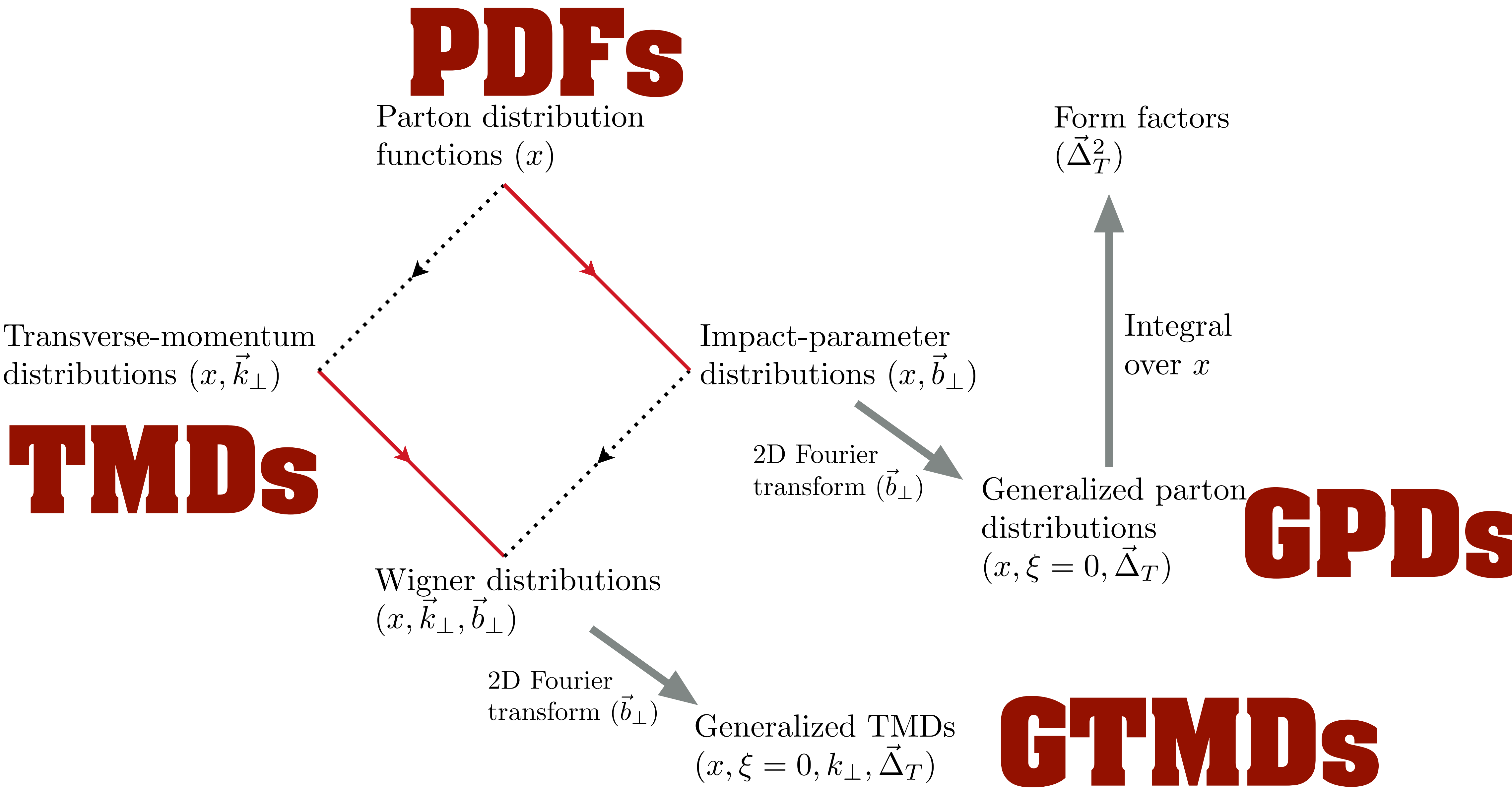


these two variables are NOT Fourier conjugate

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



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



see talk by A. Met

$\vec{b}_\perp$ dependence

$\vec{k}_\perp$ dependence

these two variables are NOT Fourier conjugate

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

Recent review

EPJ A (2016) 52

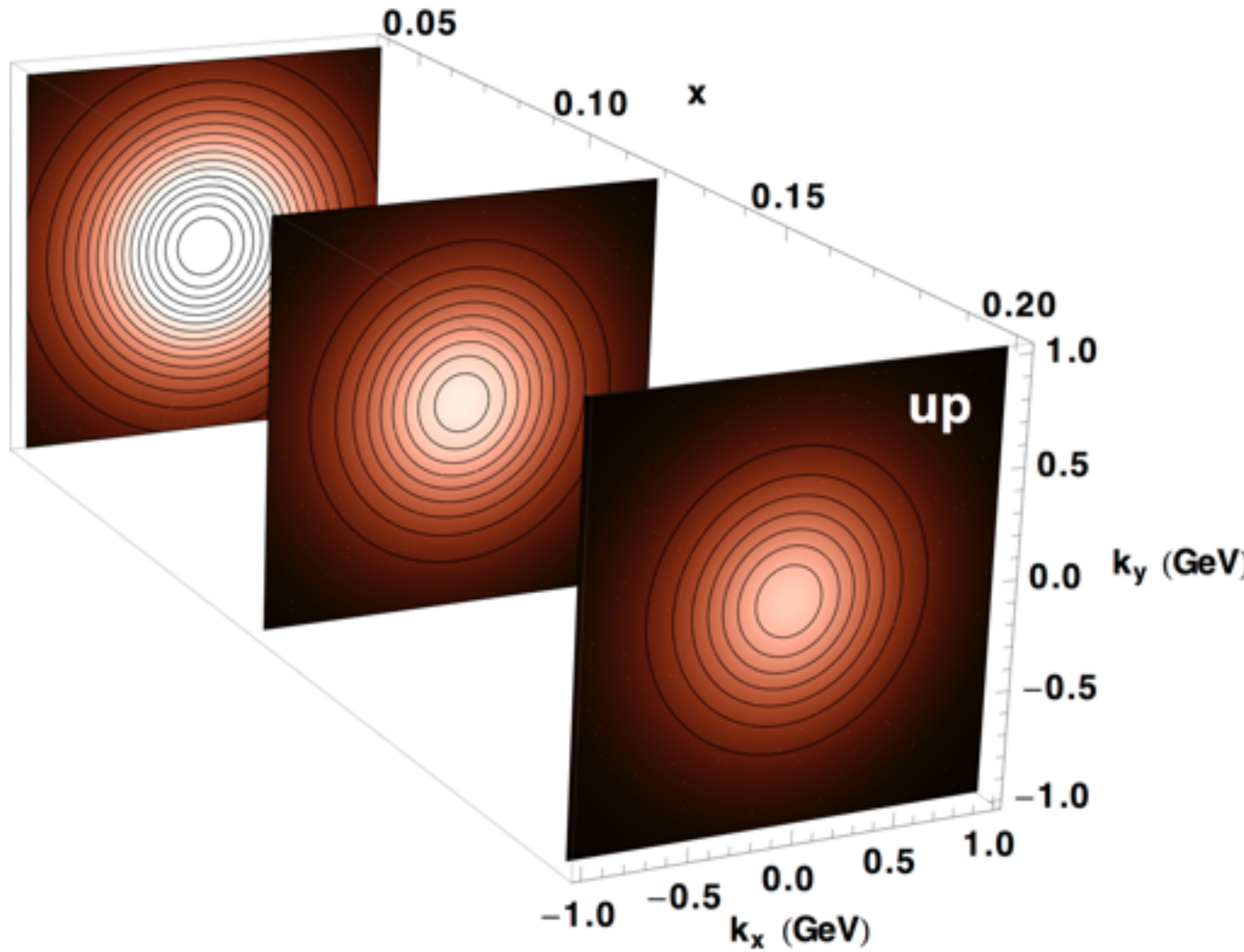
The European Physical Journal A
All Volumes & Issues

The 3-D Structure of the Nucleon

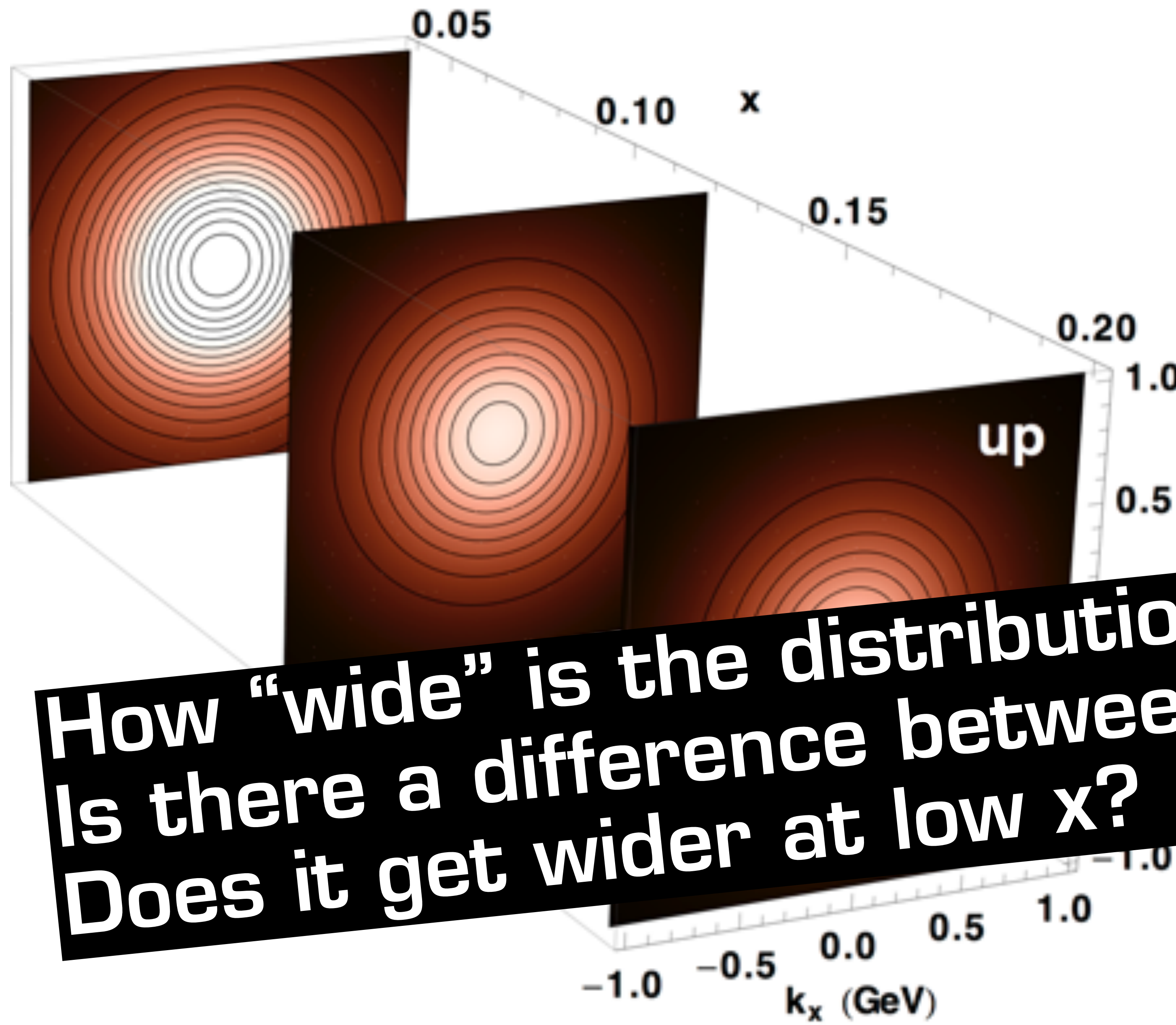
ISSN: 1434-6001 (Print) 1434-601X (Online)

In this topical collection (17 articles)

The unpolarized TMD



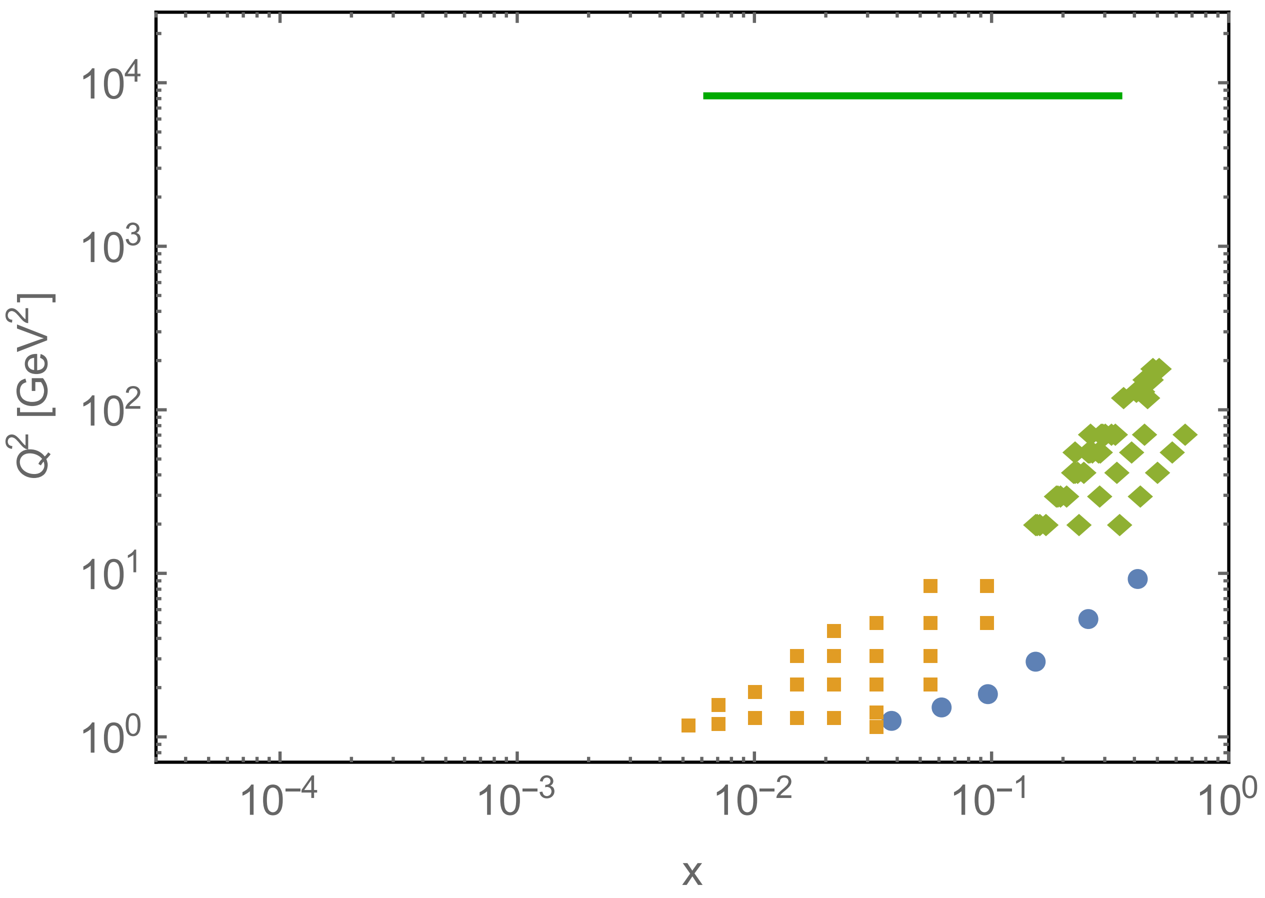
The unpolarized TMD



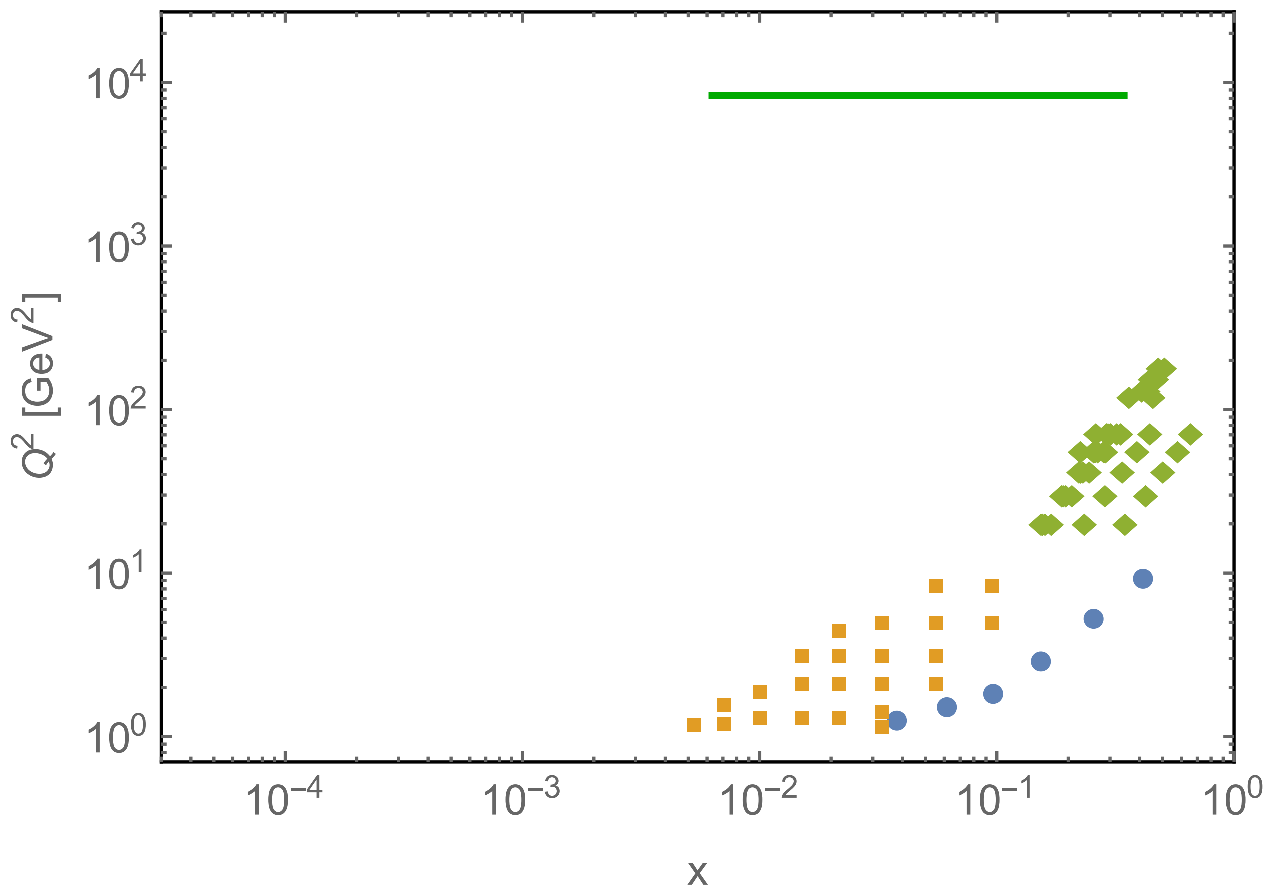
How “wide” is the distribution?
Is there a difference between flavors?
Does it get wider at low x?

Extracting TMDs

Experiments



Experiments

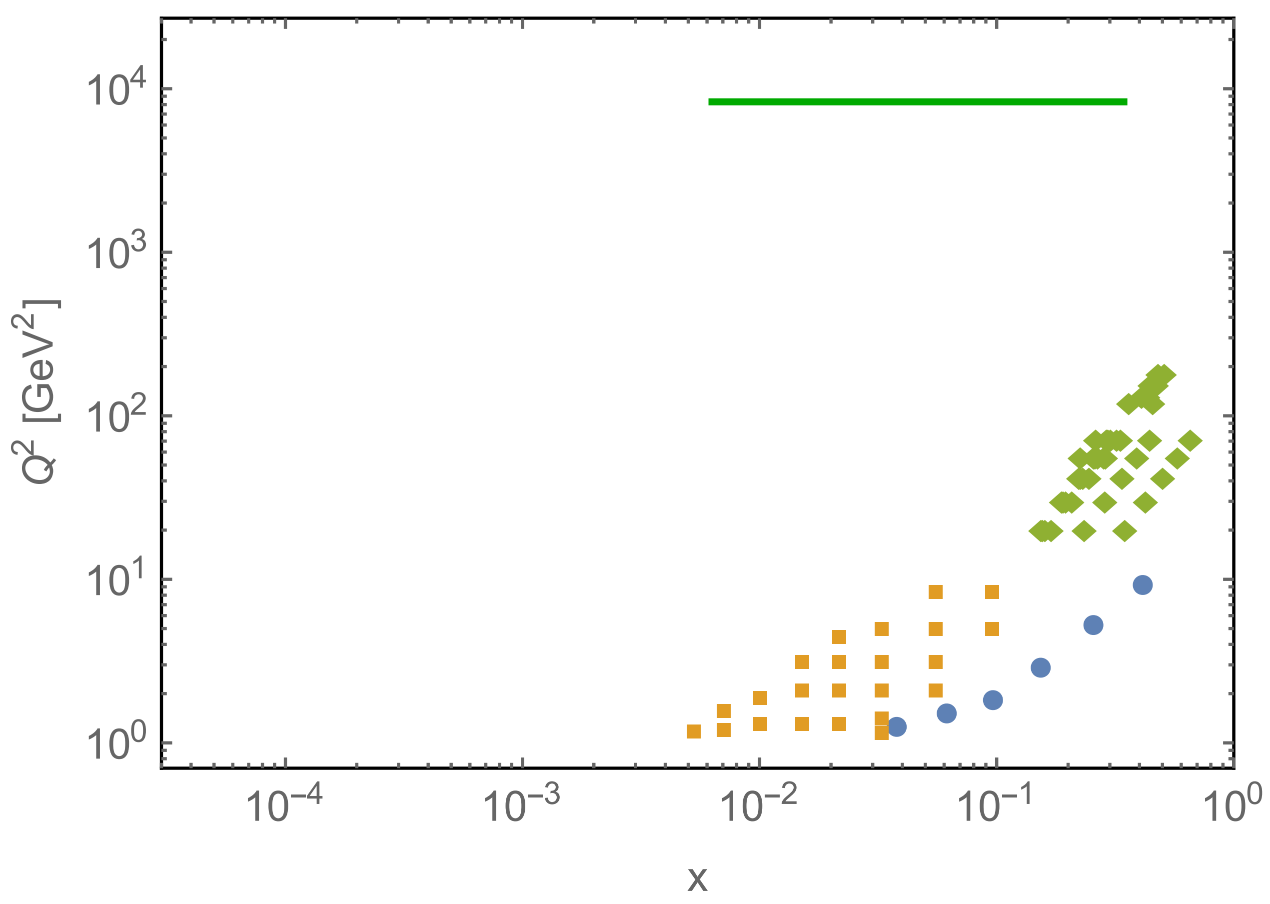


Drell-Yan@

Fermilab

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

Experiments



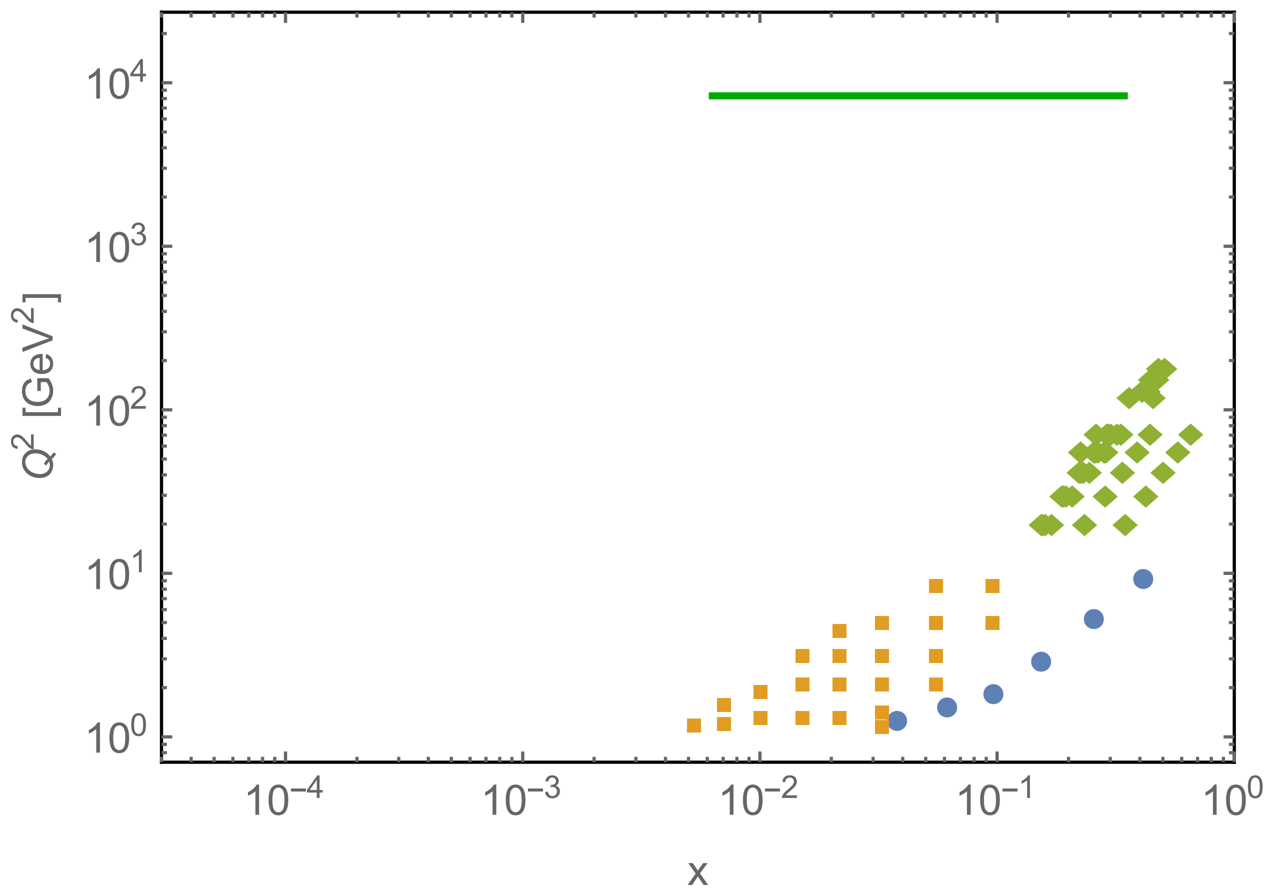
Z production@ Fermilab

Abbot et al. hep-ex/9909020
Affolder et al. hep-ex/0001021

Drell-Yan@ Fermilab

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

Experiments



Z production@ Fermilab

Abbot et al. hep-ex/9909020
Affolder et al. hep-ex/0001021

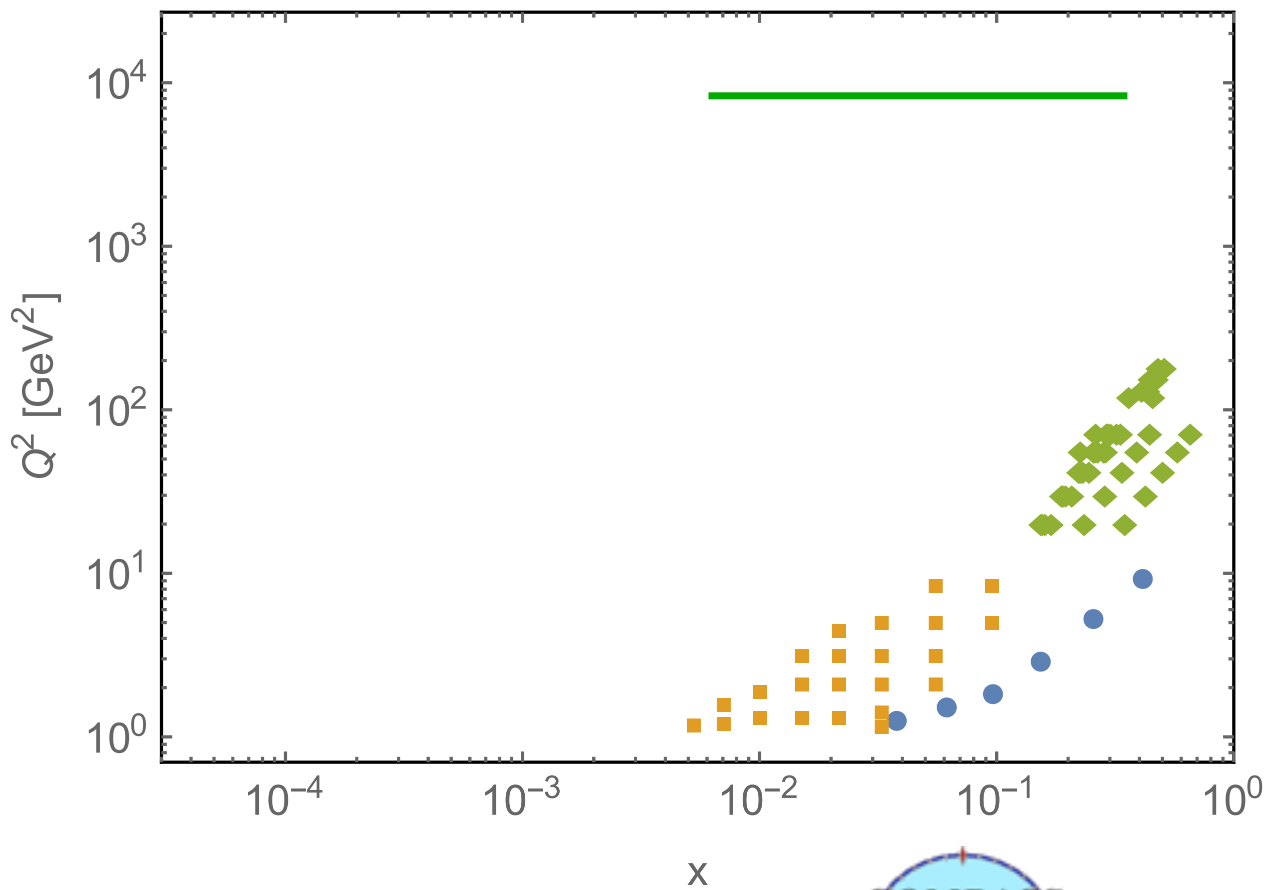
Drell-Yan@ Fermilab

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

SIDIS@ hermes

Airapetian et al., PRD87 (2013)

Experiments



Z production@ Fermilab

Abbot et al. hep-ex/9909020
Affolder et al. hep-ex/0001021

Drell-Yan@ Fermilab

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

SIDIS@ hermes

Airapetian et al., PRD87 (2013)

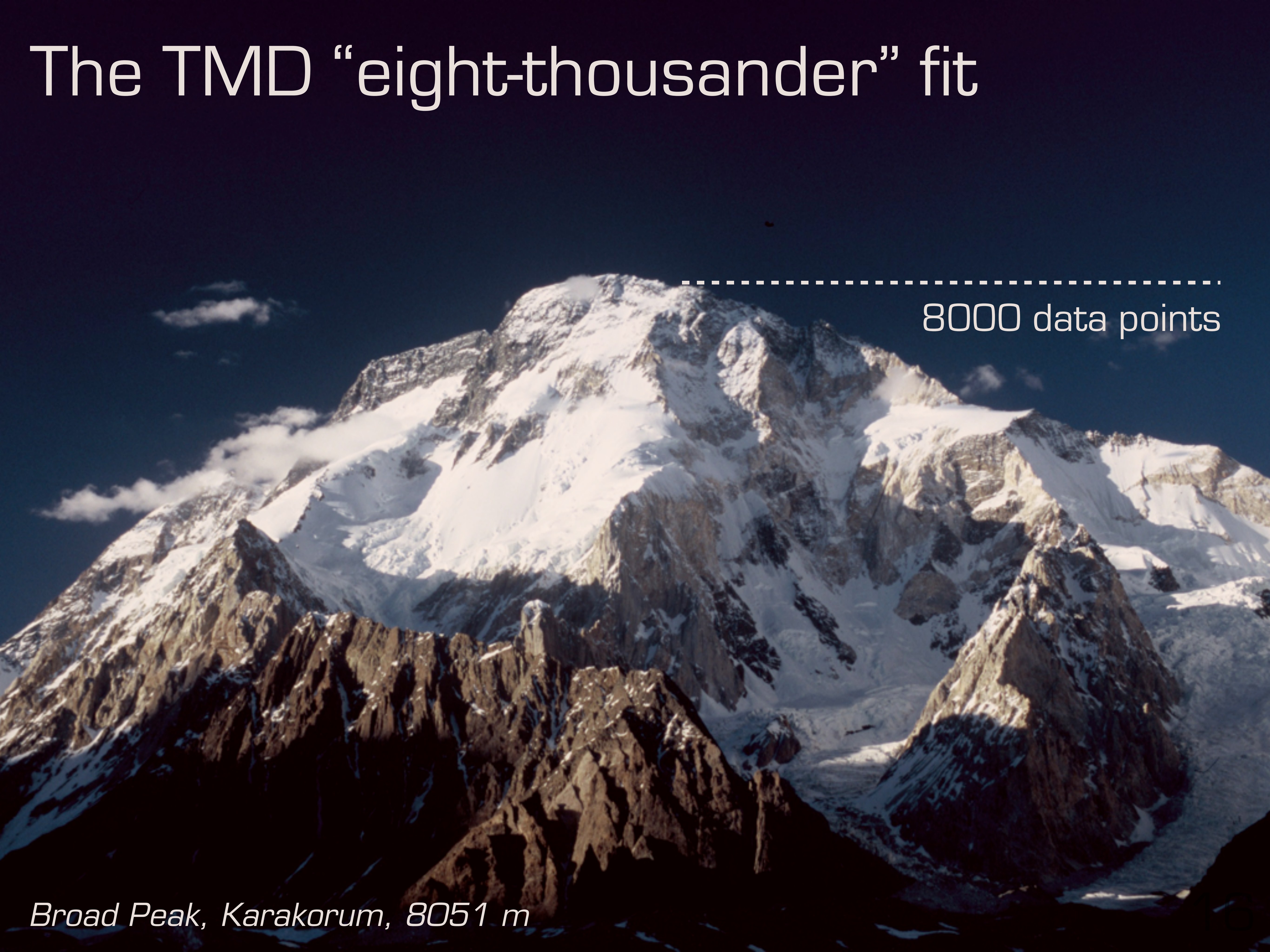
SIDIS@ COMPASS

Adolph et al., EPJ C73 (13)

Presently *or soon* available fits

	Framework	HERMES	COMPASS	DY	Z production	N of points
KN 2006 *hep-ph/0506225*	NLL	✘	✘	✔	✔	98
Pavia 2013 (+Amsterdam,Bilbao) *arXiv:1309.3507*	No evo	✔	✘	✘	✘	1538
Torino 2014 (+JLab) *arXiv:1312.6261*	No evo	✔ (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 (?)
Pavia 2016	NLL	✔	✔	✔	✔	8059

The TMD "eight-thousander" fit



Broad Peak, Karakorum, 8051 m

The TMD "eight-thousander" fit

Broad Peak, Karakorum, 8051 m

Executive summary of results 1/3

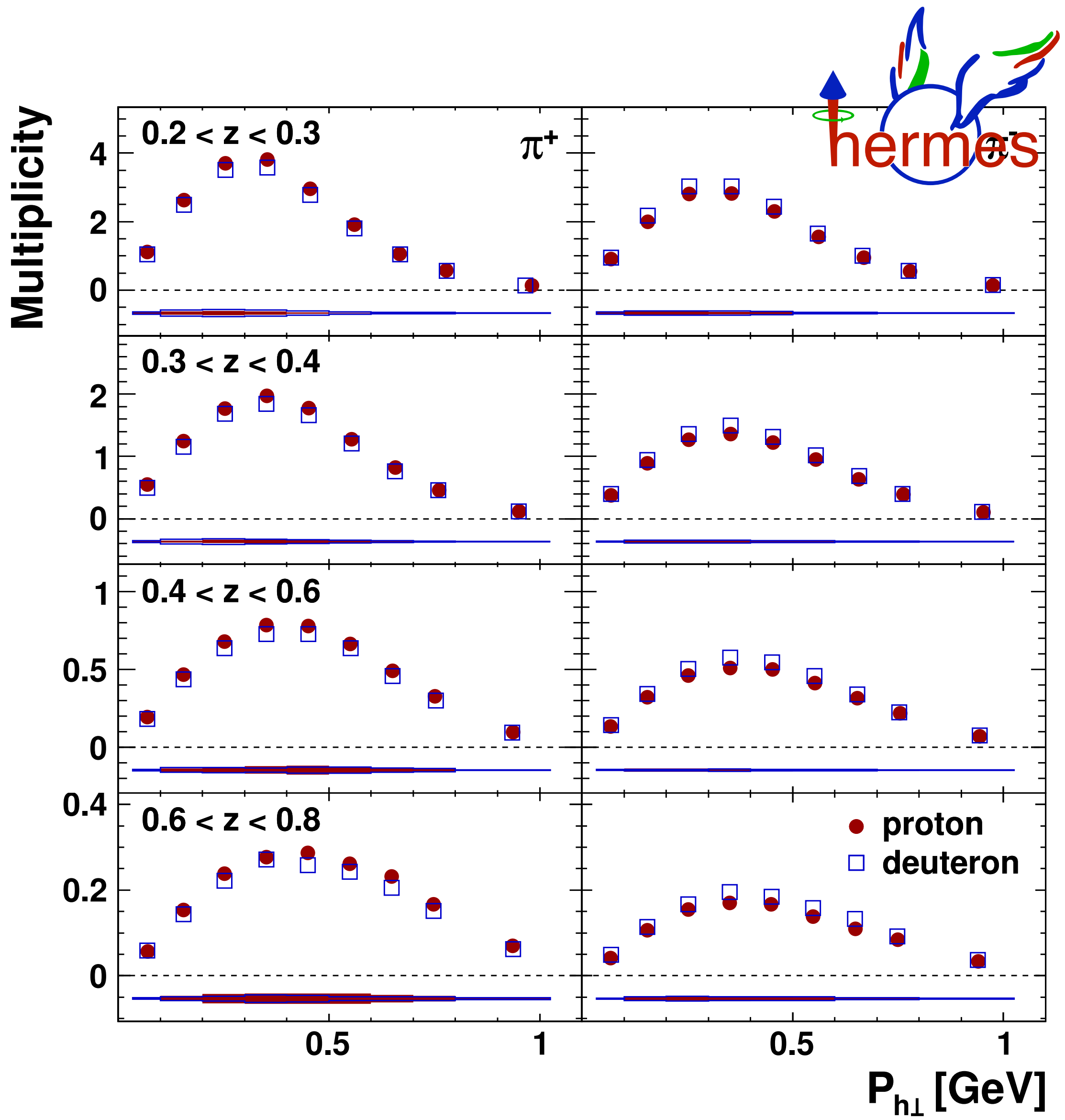
Total number of data points: 8059

Total number of free parameters: 11
(4 for TMD PDFs, 6 for TMD FFs, 1 for TMD evolution)

Total χ^2/dof = 1.52±0.03

TMD evolution

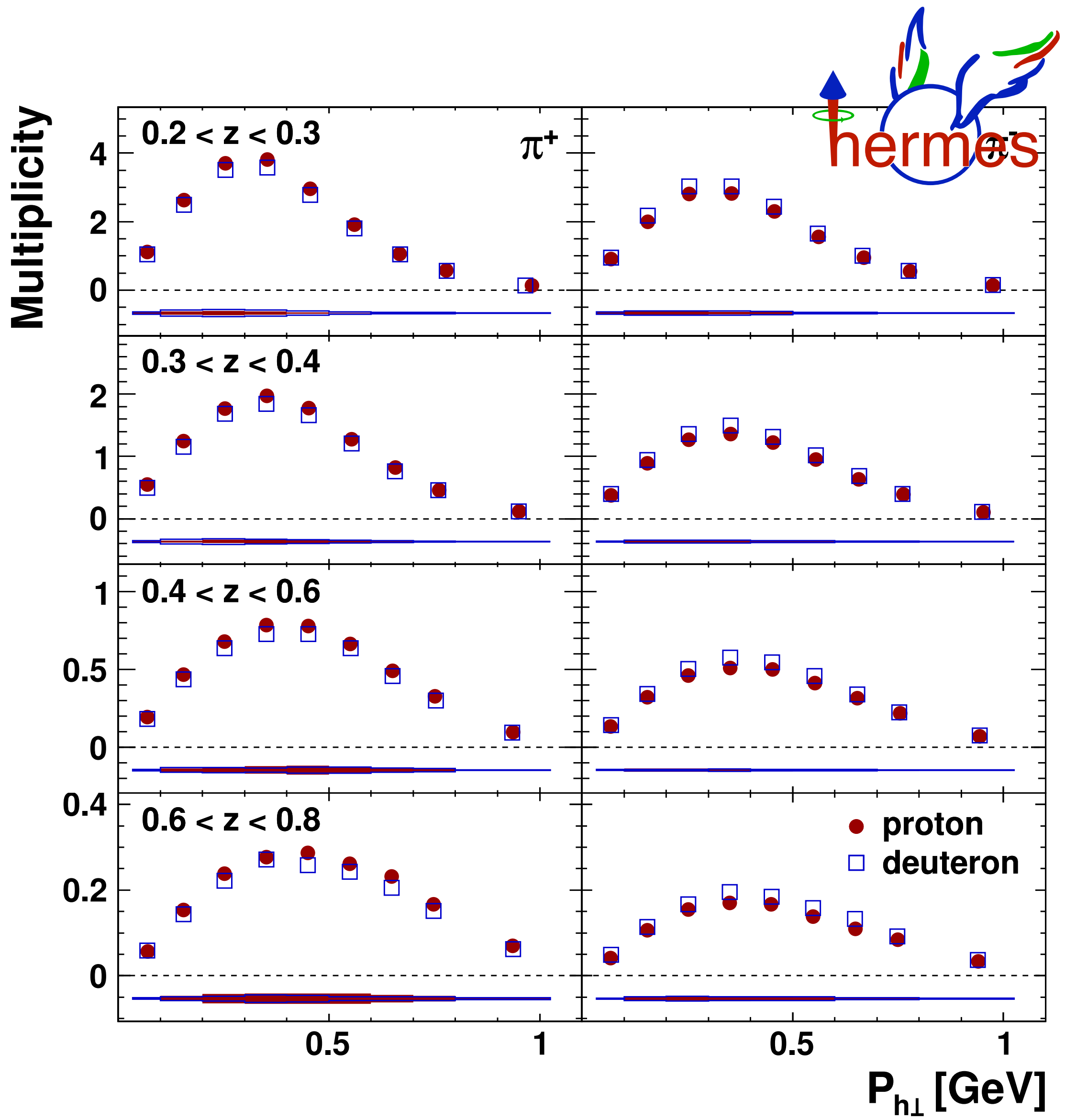
HERMES, Q ≈ 1.5 GeV



Airapetian et al., PRD87 (2013)

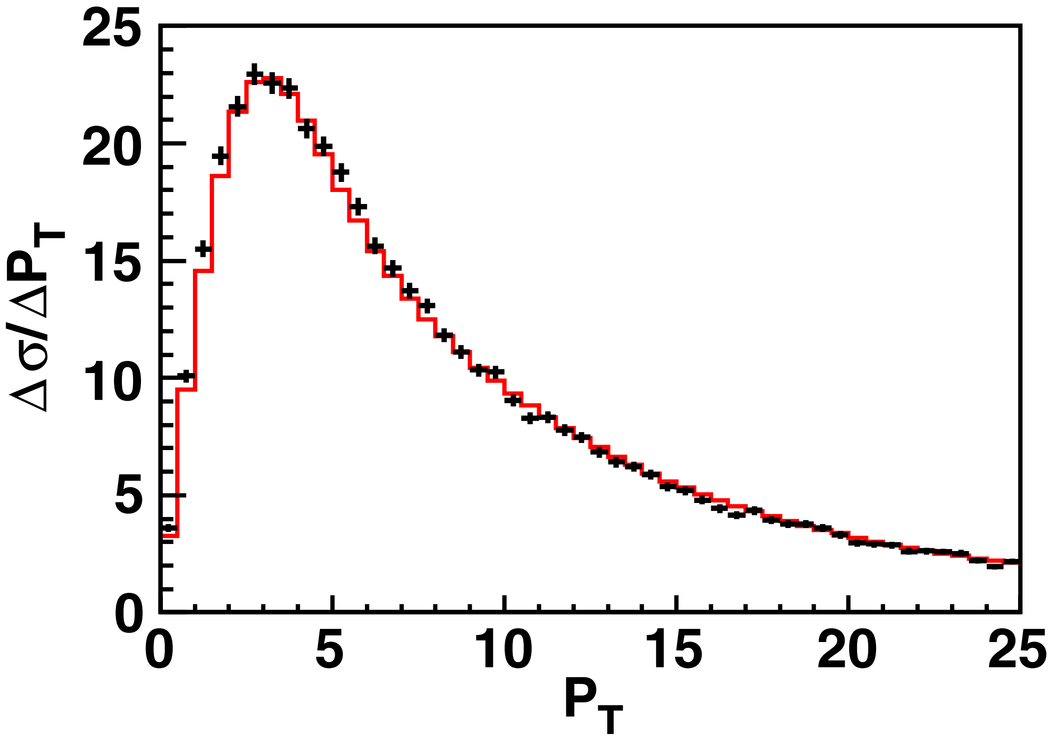
TMD evolution

HERMES, Q ≈ 1.5 GeV



Airapetian et al., PRD87 (2013)

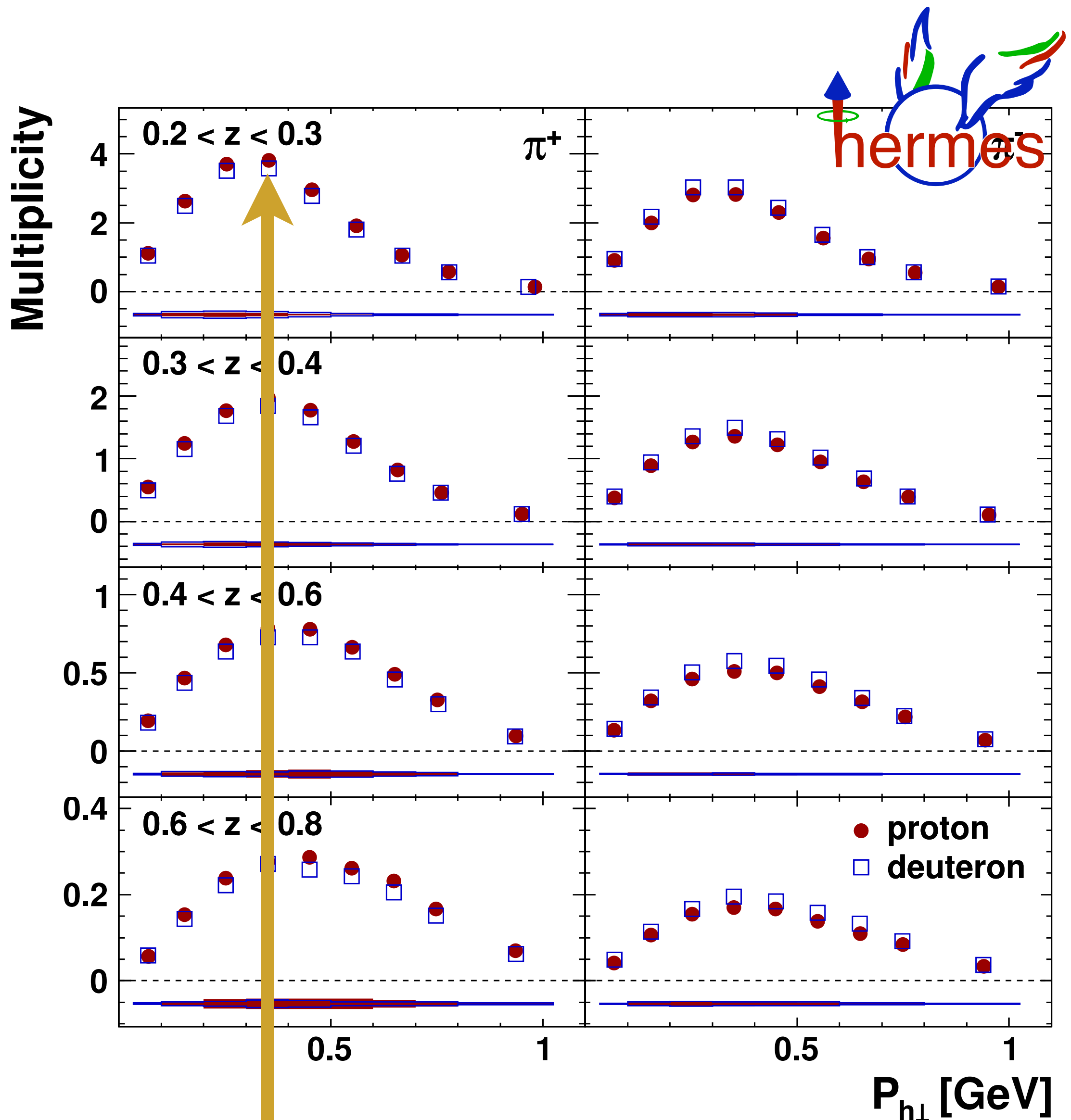
CDF, Q ≈ 91 GeV



Aaltonen et al., PRD86 (2012)

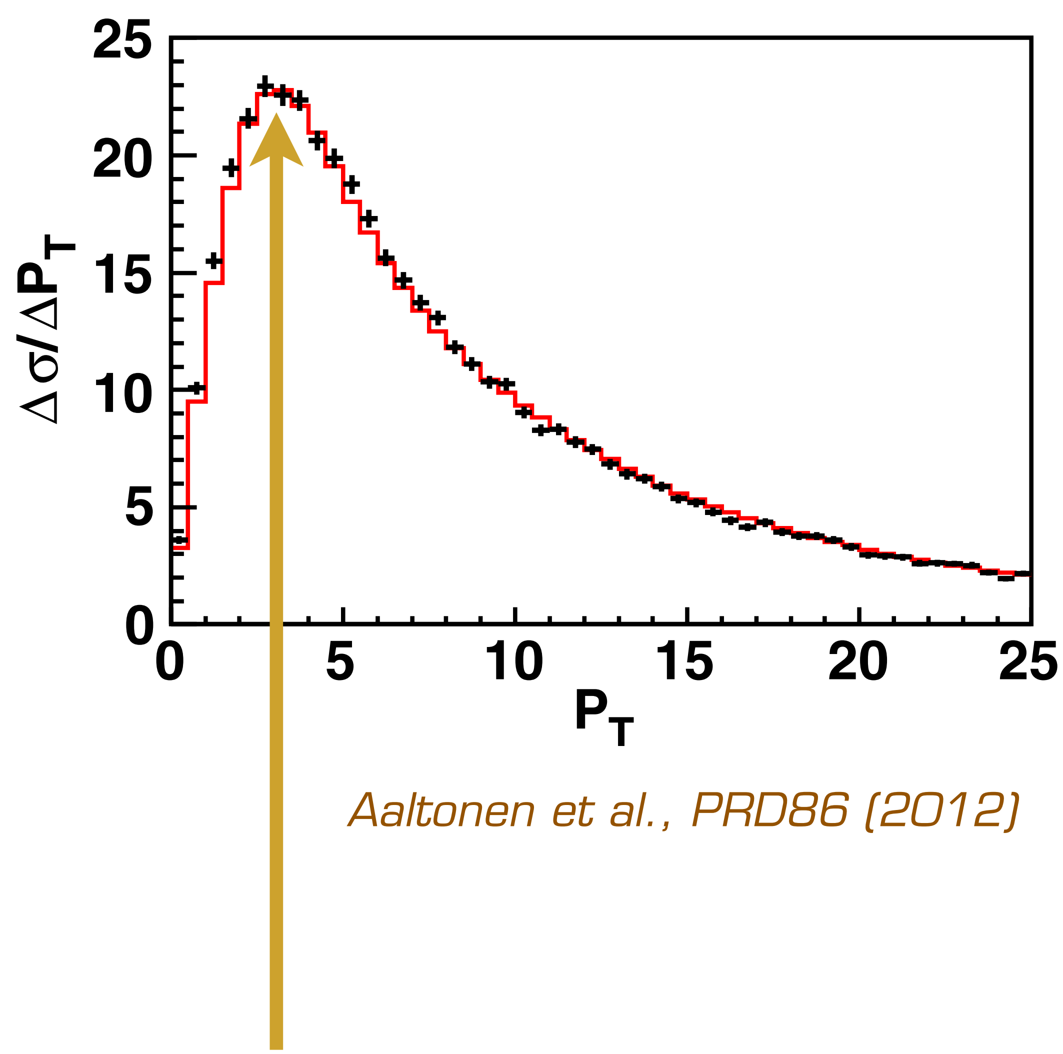
TMD evolution

HERMES, Q ≈ 1.5 GeV



Airapetian et al., PRD87 (2013)

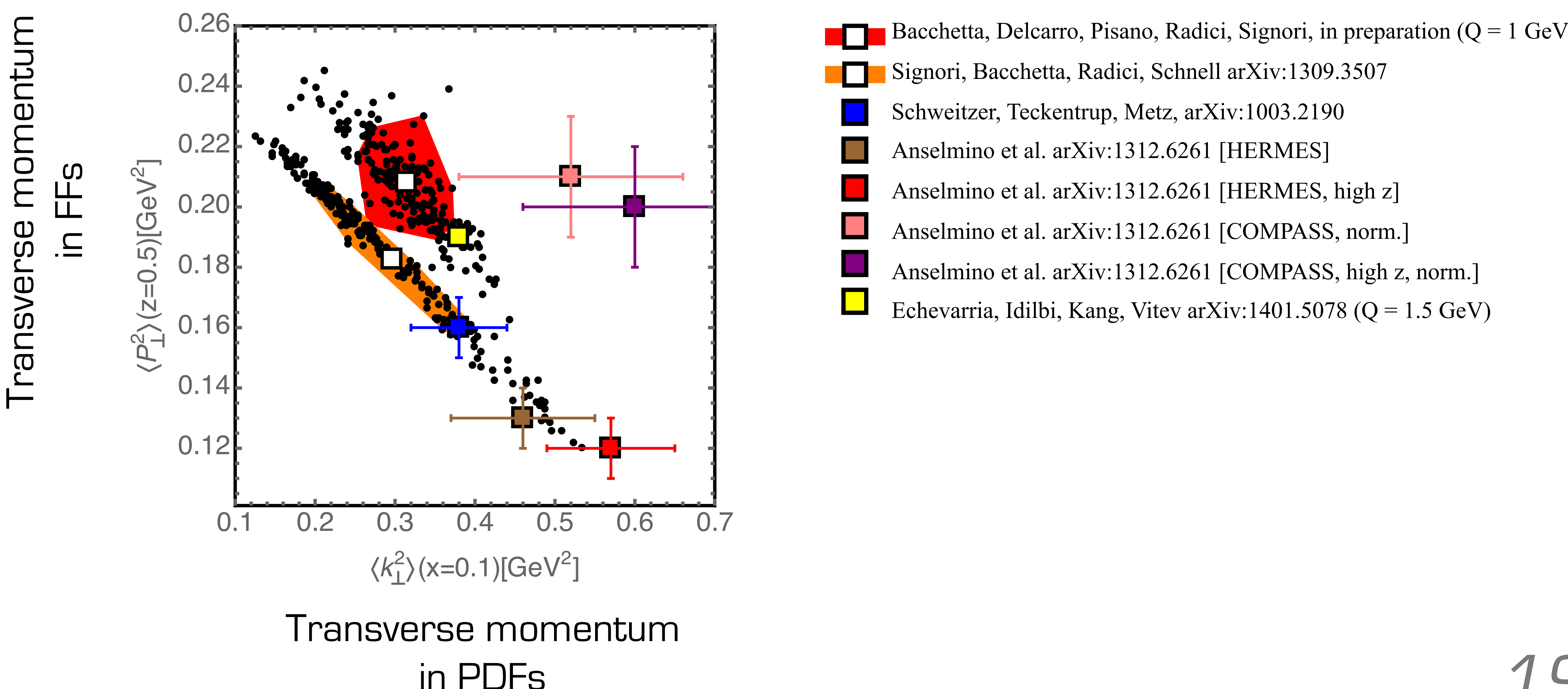
CDF, Q ≈ 91 GeV



Aaltonen et al., PRD86 (2012)

Width of TMDs changes of one order of magnitude: we can we explain this with TMD evolution

Executive summary of results 3/3

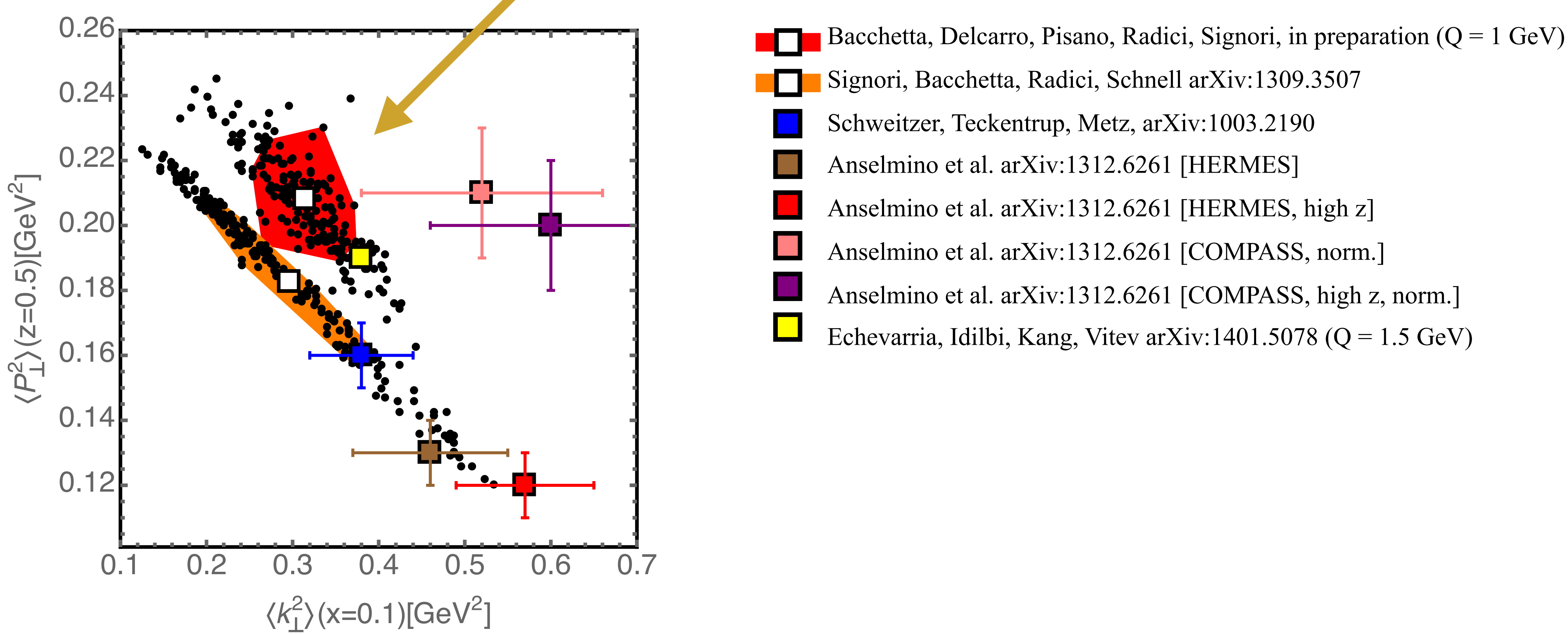


19

Executive summary of results 3/3

Pavia2016 results, Q^2=1 GeV^2

Transverse momentum in FFs

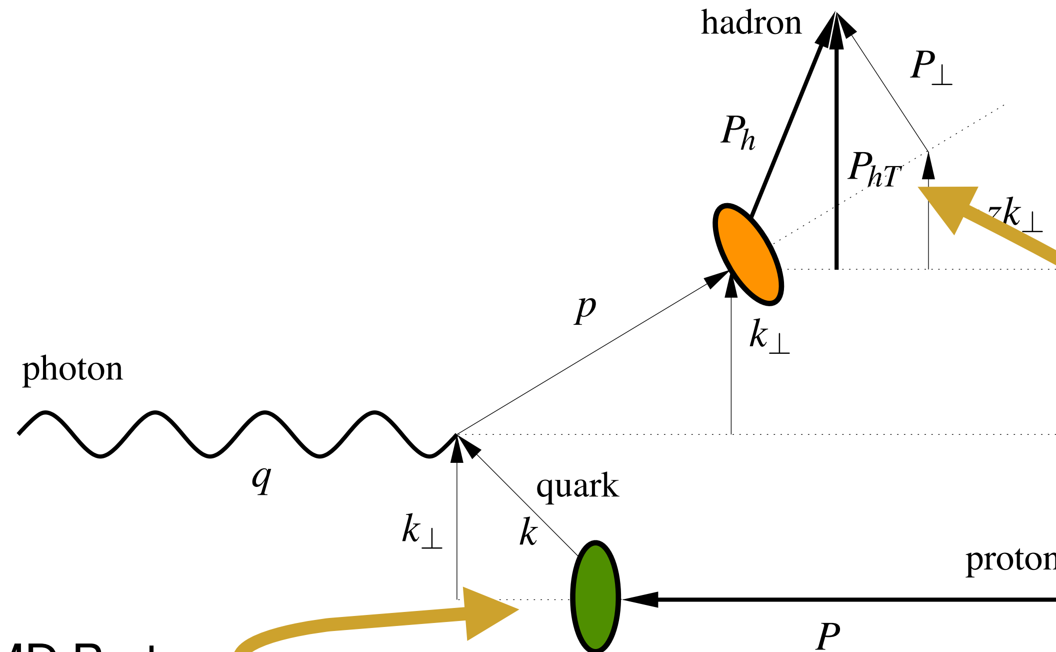


Transverse momentum in PDFs

19

Some details

Structure functions and TMDs



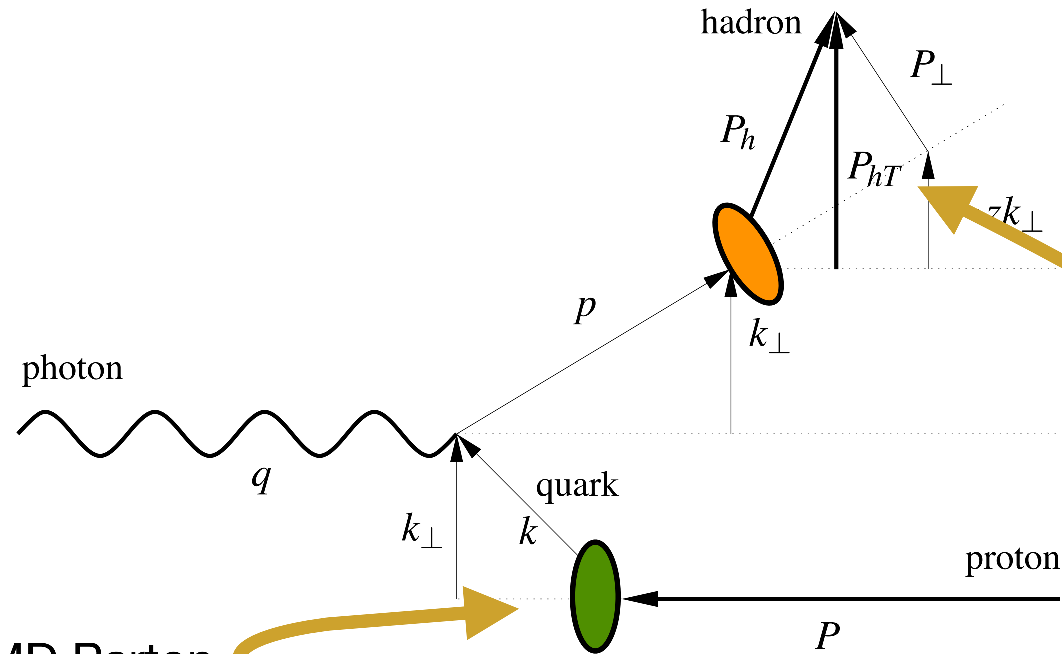
TMD Parton
Distribution Functions

TMD Parton
Fragmentation Functions

$$F_{UU,T}(x,z,\boldsymbol{P}_{hT}^2,Q^2)=\sum_a \mathcal{H}_{UU,T}^a(Q^2;\mu^2)\int d\boldsymbol{k}_\perp\, d\boldsymbol{P}_\perp\, f_1^a(x,\boldsymbol{k}_\perp^2;\mu^2)\, D_1^{a\to h}(z,\boldsymbol{P}_\perp^2;\mu^2)\,\delta(z\boldsymbol{k}_\perp-\boldsymbol{P}_{hT}+\boldsymbol{P}_\perp)$$
$$+\,Y_{UU,T}(Q^2,\boldsymbol{P}_{hT}^2)+\mathcal{O}(M^2/Q^2)$$

see talk by Bowen Wang for further discussion

Structure functions and TMDs



TMD Parton Distribution Functions

TMD Parton Fragmentation Functions

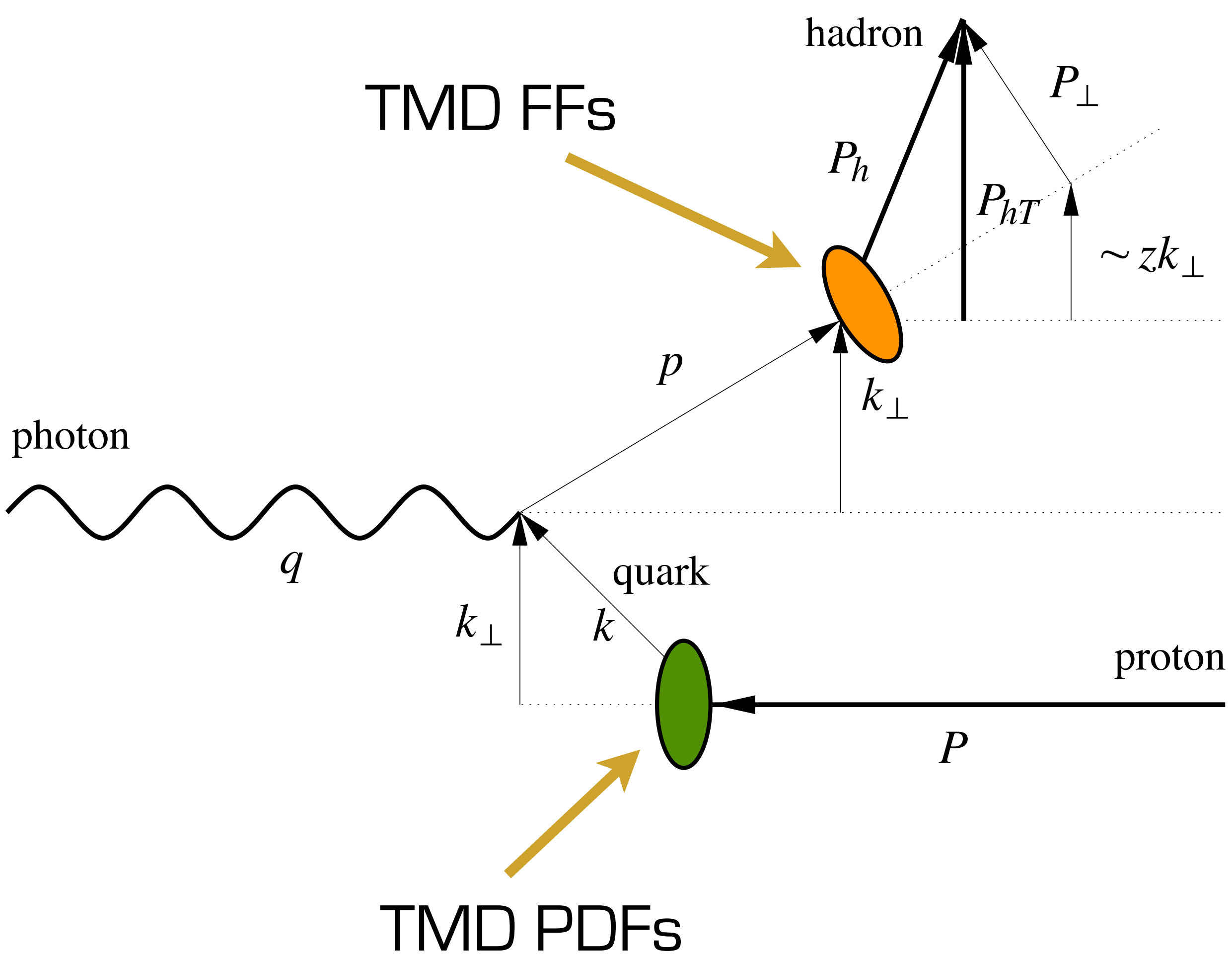
$$F_{UU,T}(x,z,\boldsymbol{P}_{hT}^2,Q^2) = \sum_a \mathcal{H}^a_{UU,T}(Q^2;\mu^2) \int d\boldsymbol{k}_\perp \, d\boldsymbol{P}_\perp \, f_1^a(x,\boldsymbol{k}_\perp^2;\mu^2) \, D_1^{a\to h}(z,\boldsymbol{P}_\perp^2;\mu^2) \, \delta(z\boldsymbol{k}_\perp - \boldsymbol{P}_{hT} + \boldsymbol{P}_\perp)$$
$$+ \cancel{Y_{UU,T}(Q^2,} \boldsymbol{P}_{hT}^2) + \mathcal{O}(M^2/Q^2)$$

not implemented in Pavia 2016

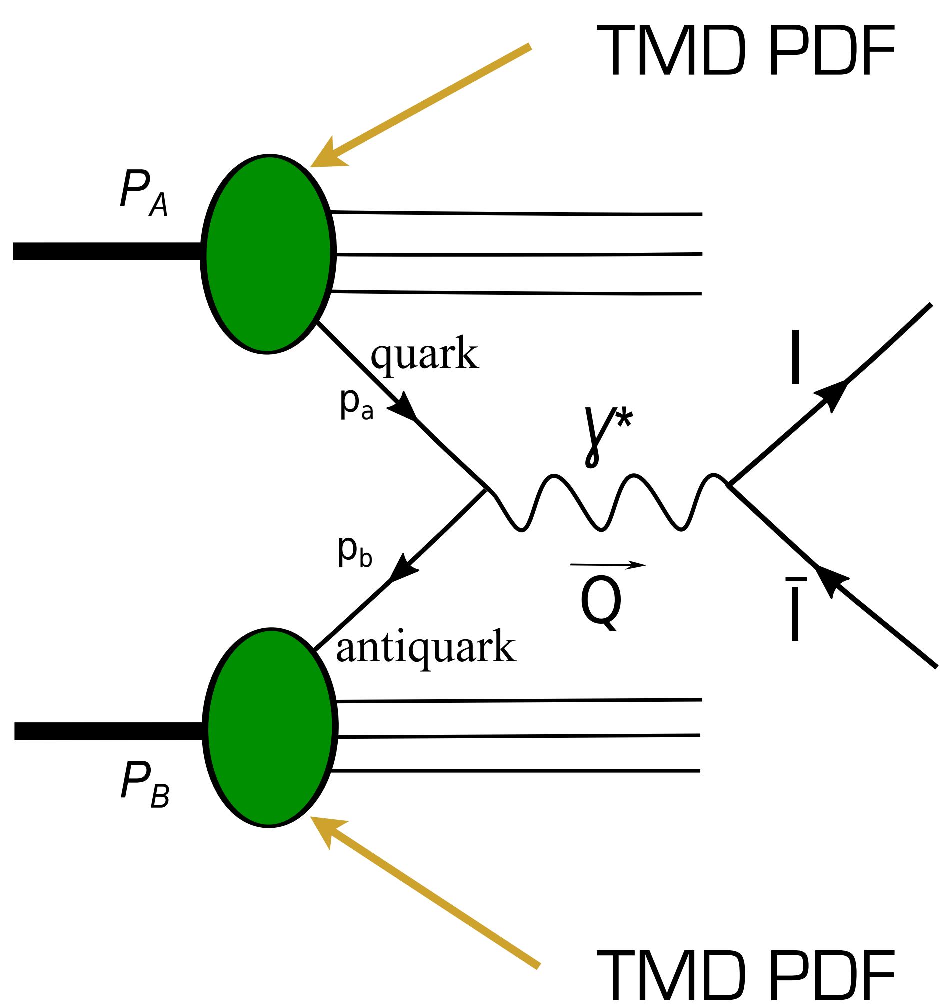
see talk by Bowen Wang for further discussion

Semi-inclusive DIS vs. Drell-Yan/Z production

$$l(\ell) + N(\mathcal{P}) \to l(\ell') + h(\mathcal{P}_h) + X$$



$$A + B \to \gamma^* \to l^+l^-$$
$$A + B \to Z \to l^+l^-$$



TMD evolution: Fourier transform

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

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)

TMD evolution: Fourier transform

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

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

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)

TMD evolution: Fourier transform

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

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

collinear PDF

pQCD

nonperturbative part of evolution

nonperturbative part of TMD

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)

Perturbative ingredients

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

Perturbative ingredients

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

$A_1\big(\mathcal{O}(\alpha_S^1)\big)$ $\quad$ $A_2\big(\mathcal{O}(\alpha_S^2)\big)$ $\quad$ $A_3\big(\mathcal{O}(\alpha_S^3)\big)$ $\quad \ldots$

$B_1\big(\mathcal{O}(\alpha_S^1)\big)$ $\quad$ $B_2\big(\mathcal{O}(\alpha_S^2)\big)$ $\quad \ldots$

Perturbative ingredients

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

$A_1\big(\mathcal{O}(\alpha_S^1)\big)$	$A_2\big(\mathcal{O}(\alpha_S^2)\big)$	$A_3\big(\mathcal{O}(\alpha_S^3)\big)$	$\ldots$
	$B_1\big(\mathcal{O}(\alpha_S^1)\big)$	$B_2\big(\mathcal{O}(\alpha_S^2)\big)$	$\ldots$
$C_0\big(\mathcal{O}(\alpha_S^0)\big)$	$C_1\big(\mathcal{O}(\alpha_S^1)\big)$	$C_2\big(\mathcal{O}(\alpha_S^2)\big)$	$\ldots$

Perturbative ingredients

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

$A_1(\mathcal{O}(\alpha_S^1))$	$A_2(\mathcal{O}(\alpha_S^2))$	$A_3(\mathcal{O}(\alpha_S^3))$	$\dots$
	$B_1(\mathcal{O}(\alpha_S^1))$	$B_2(\mathcal{O}(\alpha_S^2))$	$\dots$
$C_0(\mathcal{O}(\alpha_S^0))$	$C_1(\mathcal{O}(\alpha_S^1))$	$C_2(\mathcal{O}(\alpha_S^2))$	$\dots$

$H_0(\mathcal{O}(\alpha_S^0))$	$H_1(\mathcal{O}(\alpha_S^1))$	$H_2(\mathcal{O}(\alpha_S^2))$	$\dots$
	$Y_1(\mathcal{O}(\alpha_S^1))$	$Y_2(\mathcal{O}(\alpha_S^2))$	$\dots$

Pavia 2016 perturbative ingredients

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

$A_1(\mathcal{O}(\alpha_S^1))$ ✔	$A_2(\mathcal{O}(\alpha_S^2))$ ✔	$A_3(\mathcal{O}(\alpha_S^3))$	$\ldots$
	$B_1(\mathcal{O}(\alpha_S^1))$ ✔	$B_2(\mathcal{O}(\alpha_S^2))$	$\ldots$
$C_0(\mathcal{O}(\alpha_S^0))$ ✔	$C_1(\mathcal{O}(\alpha_S^1))$	$C_2(\mathcal{O}(\alpha_S^2))$	$\ldots$
$H_0(\mathcal{O}(\alpha_S^0))$ ✔	$H_1(\mathcal{O}(\alpha_S^1))$	$H_2(\mathcal{O}(\alpha_S^2))$	$\ldots$
	$Y_1(\mathcal{O}(\alpha_S^1))$	$Y_2(\mathcal{O}(\alpha_S^2))$	$\ldots$

μ and b$_*$ prescriptions

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

μ and b_* prescriptions

Choice Choice

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

μ and b* prescriptions

Choice **Choice**

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

$$\mu_b = 2e^{-\gamma_E}/b_* \qquad b_* \equiv \frac{b_T}{\sqrt{1 + b_T^2/b_{\rm max}^2}}$$

Collins, Soper, Sterman, NPB250 (85)

$$\mu_b = 2e^{-\gamma_E}/b_* \qquad b_* \equiv b_{\rm max}\left(1 - e^{-\frac{b_T^4}{b_{\rm max}^4}}\right)^{1/4}$$

Bacchetta, Echevarria, Mulders, Radici, Signori
arXiv:1508.00402

$$\mu_b = Q_0 + q_T \qquad b_* = b_T$$

DEMS 2014

μ and b* prescriptions

Choice Choice

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

$\mu_b = 2e^{-\gamma_E}/b_*$ $\qquad b_* \equiv \dfrac{b_T}{\sqrt{1+b_T^2/b_{\max}^2}}$ $\qquad$ *Collins, Soper, Sterman, NPB250 (85)*

$\mu_b = 2e^{-\gamma_E}/b_*$ $\qquad b_* \equiv b_{\max}\left(1-e^{-\frac{b_T^4}{b_{\max}^4}}\right)^{1/4}$ $\qquad$ *Bacchetta, Echevarria, Mulders, Radici, Signori arXiv:1508.00402*

$\mu_b = Q_0 + q_T$ $\qquad b_* = b_T$ $\qquad$ *DEMS 2014*

Complex-b prescription $\qquad$ *Laenen, Sterman, Vogelsang, PRL 84 (00)*

Nonperturbative ingredients 1

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

Nonperturbative ingredients 1

Choice

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

Nonperturbative ingredients 1

Choice

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

$$e^{-\frac{b_T^2}{\langle b_T^2 \rangle}}$$

almost everybody

$$e^{-\frac{b_T^2}{\left\langle b_T^2(x) \right\rangle_a}}$$

Pavia 2013, KN 2006

$$e^{-\lambda_1 b_T} \left(1 + \lambda_2 b_T^2\right)$$

DEMS 2014

Nonperturbative ingredients 2

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

Nonperturbative ingredients 2

Choice

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

Nonperturbative ingredients 2

Choice

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

$$-g_2 \frac{b_T^2}{2}$$

Collins, Soper, Sterman, NPB250 (85)

$$-2\, g_2 \ln\left(1 + \frac{b_T^2}{4}\right)$$

Aidala, Field, Gamberg, Rogers
arXiv:1401.2654

$$-g_0(b_{\max})\left(1 - \exp\left[-\frac{C_F \alpha_s(\mu_{b_*}) b_T^2}{\pi g_0(b_{\max}) b_{\max}^2}\right]\right)$$

Collins, Rogers
arXiv:1412.3820

Low-b_T modifications

$$\log\left(Q^2 b_T^2\right) \to \log\left(Q^2 b_T^2 + 1\right)$$

see, e.g., Bozzi, Catani, De Florian, Grazzini
hep-ph/0302104

Low-b_T modifications

$$\log\left(Q^2 b_T^2\right) \to \log\left(Q^2 b_T^2 + 1\right)$$

see, e.g., Bozzi, Catani, De Florian, Grazzini
hep-ph/0302104

$$b_*(b_c(b_\mathrm{T})) = \sqrt{\frac{b_\mathrm{T}^2 + b_0^2/(C_5^2 Q^2)}{1 + b_\mathrm{T}^2/b_\mathrm{max}^2 + b_0^2/(C_5^2 Q^2 b_\mathrm{max}^2)}}$$

$$b_\mathrm{min} \equiv b_*(b_c(0)) = \frac{b_0}{C_5 Q}\sqrt{\frac{1}{1 + b_0^2/(C_5^2 Q^2 b_\mathrm{max}^2)}}$$

Collins et al.
arXiv:1605.00671

Low-b_T modifications

$$\log\left(Q^2 b_T^2\right) \to \log\left(Q^2 b_T^2 + 1\right)$$

see, e.g., Bozzi, Catani, De Florian, Grazzini
hep-ph/0302104

$$b_*(b_c(b_\mathrm{T})) = \sqrt{\frac{b_\mathrm{T}^2 + b_0^2/(C_5^2 Q^2)}{1 + b_\mathrm{T}^2/b_\mathrm{max}^2 + b_0^2/(C_5^2 Q^2 b_\mathrm{max}^2)}}$$

$$b_\mathrm{min} \equiv b_*(b_c(0)) = \frac{b_0}{C_5 Q}\sqrt{\frac{1}{1 + b_0^2/(C_5^2 Q^2 b_\mathrm{max}^2)}}$$

Collins et al.
arXiv:1605.00671

- The justification is to recover the integrated result ("unitarity constraint")
- Modification at low b_T is allowed because resummed calculation is anyway unreliable there

Pavia 2016 “choices”

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

Pavia 2016 “choices”

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

$$g_K = -g_2 \frac{b_T^2}{2} \qquad\qquad \mu_0 = 1\,\mathrm{GeV}$$

Pavia 2016 “choices”

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

$$g_K = -g_2 \frac{b_T^2}{2} \qquad \mu_0 = 1\,\mathrm{GeV}$$

$$\mu_b = 2e^{-\gamma_E}/b_* \qquad \bar{b}_* \equiv b_{\max} \left(\frac{1 - e^{-b_T^4/b_{\max}^4}}{1 - e^{-b_T^4/b_{\min}^4}} \right)^{1/4} \qquad b_{\max} = 2e^{-\gamma_E}$$

$$b_{\min} = \frac{2e^{-\gamma_E}}{Q}$$

Pavia 2016 “choices”

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

$$g_K = -g_2 \frac{b_T^2}{2} \qquad \mu_0 = 1\,\mathrm{GeV}$$

$$\mu_b = 2e^{-\gamma_E}/b_* \qquad \bar{b}_* \equiv b_{\rm max} \left(\frac{1 - e^{-b_T^4/b_{\rm max}^4}}{1 - e^{-b_T^4/b_{\rm min}^4}} \right)^{1/4} \qquad b_{\rm max} = 2e^{-\gamma_E}$$

$$b_{\rm min} = \frac{2e^{-\gamma_E}}{Q}$$

Collinear PDF and FF sets: GJR08 NLO, DSS14 NLO for pions, DSS 07 for kaons

Pavia 2016 “choices”

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

$$g_K = -g_2 \frac{b_T^2}{2}$$

These are all choices that should be at some point checked/challenged

$$\mu_b = 2e^{-\gamma_E}/b_* \qquad \bar{b}_* \equiv b_{\rm max}\left(\frac{1 - e^{-b_T^4/b_{\rm max}^4}}{1 - e^{-b_T^4/b_{\rm min}^4}}\right)^{1/4} \qquad b_{\rm max} = 2e^{-\gamma_E}$$

$$b_{\rm min} = \frac{2e^{-\gamma_E}}{Q}$$

Collinear PDF and FF sets: GJR08 NLO, DSS14 NLO for pions, DSS 07 for kaons

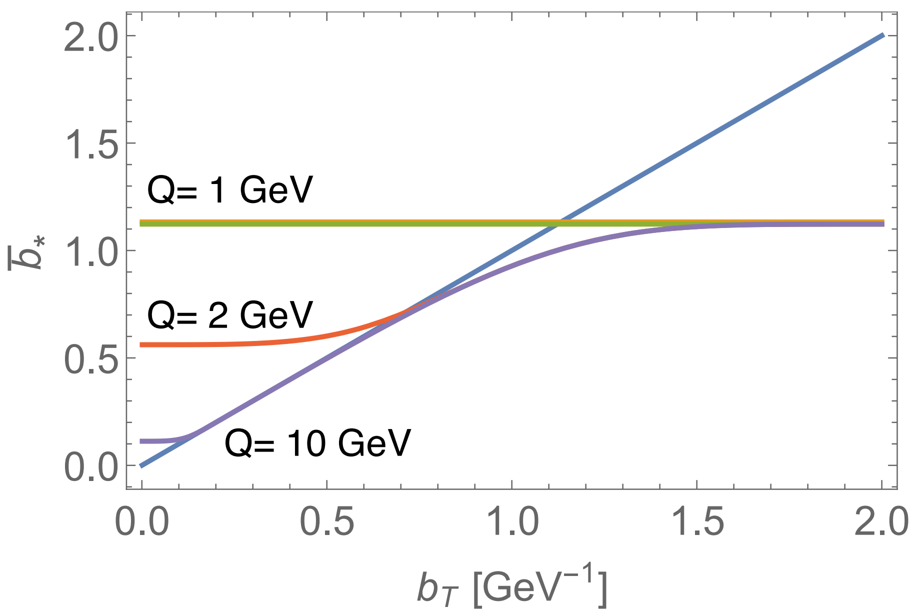
Effects of $\bar{b}_*$ prescription

$$\bar{b}_* \equiv b_{\max}\left(\frac{1-e^{-b_T^4/b_{\max}^4}}{1-e^{-b_T^4/b_{\min}^4}}\right)^{1/4}$$

$$b_{\max} = 2e^{-\gamma_E}$$

$$b_{\min} = \frac{2e^{-\gamma_E}}{Q}$$

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

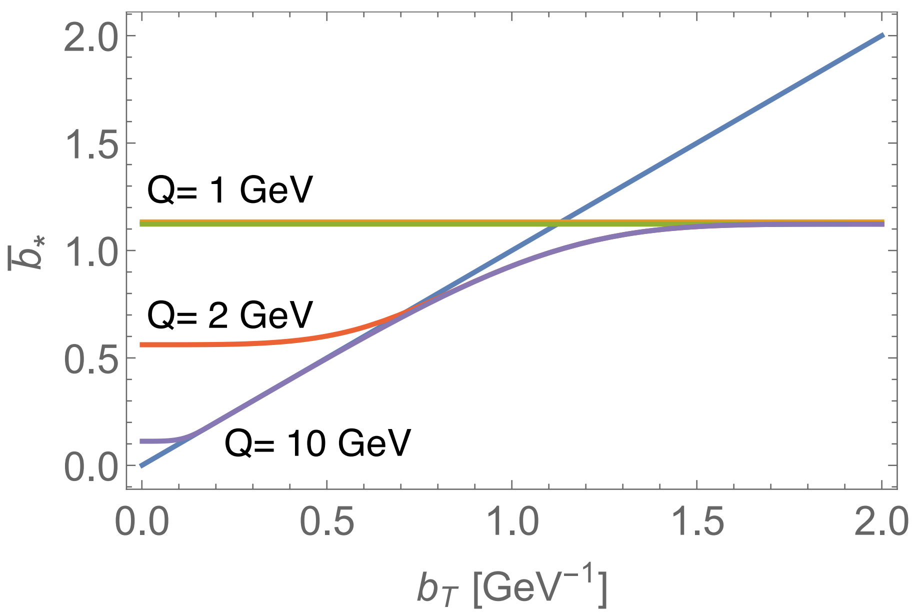


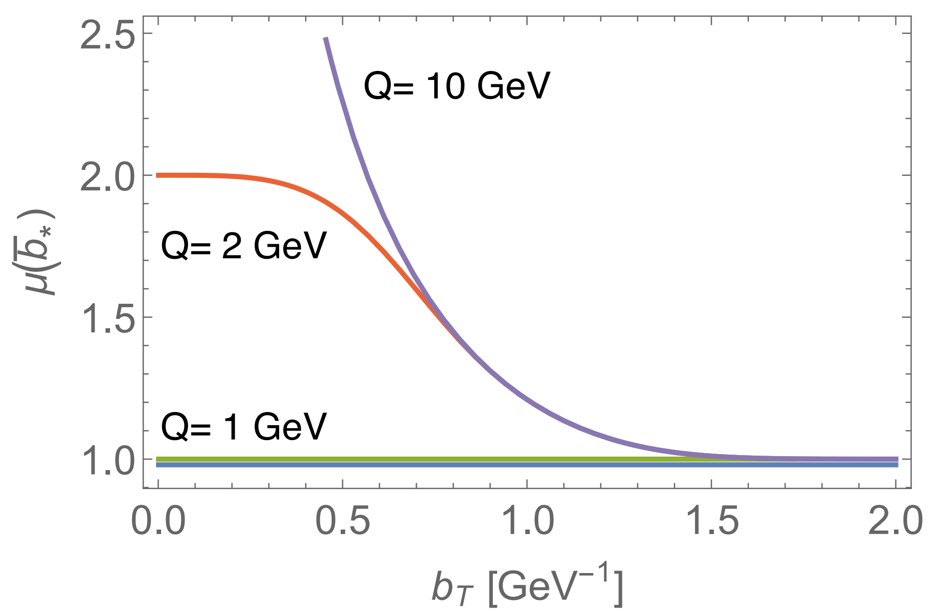
Effects of $\bar{b}_*$ prescription

$$\bar{b}_* \equiv b_{\max}\left(\frac{1-e^{-b_T^4/b_{\max}^4}}{1-e^{-b_T^4/b_{\min}^4}}\right)^{1/4} \qquad b_{\max} = 2e^{-\gamma_E}$$

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

$$b_{\min} = \frac{2e^{-\gamma_E}}{Q}$$



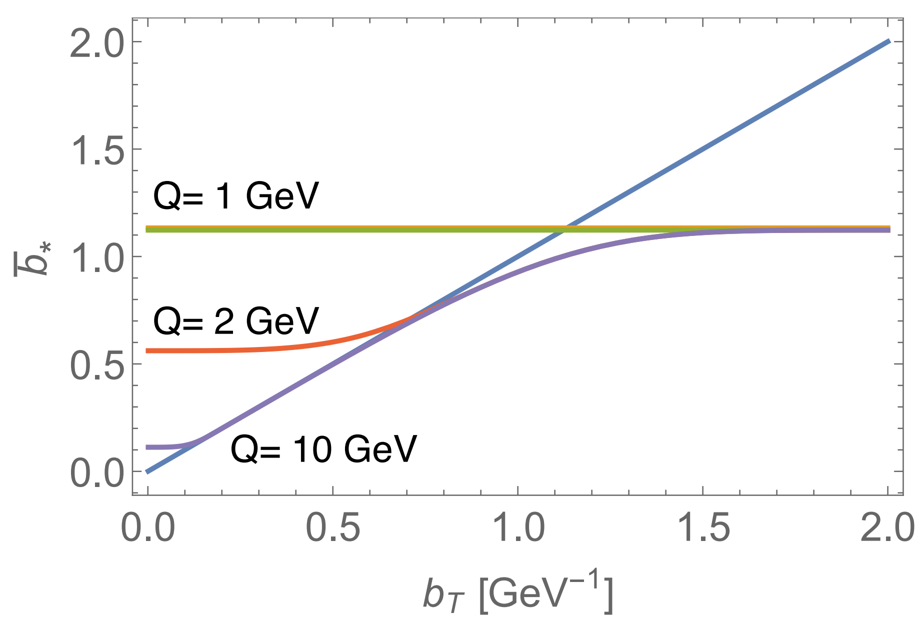


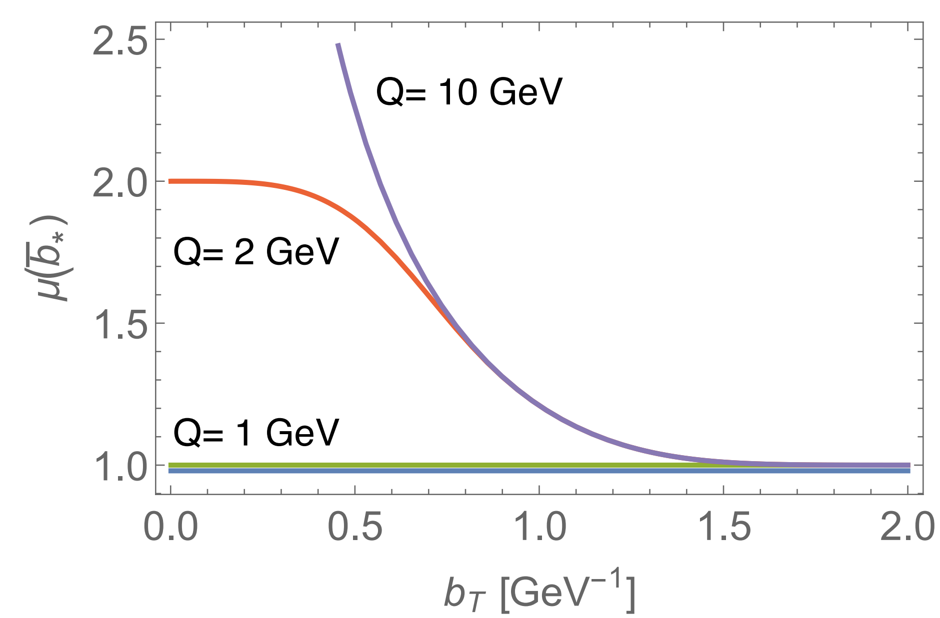
Effects of $\bar{b}_*$ prescription

$$\bar{b}_* \equiv b_{\max}\left(\frac{1-e^{-b_T^4/b_{\max}^4}}{1-e^{-b_T^4/b_{\min}^4}}\right)^{1/4} \qquad b_{\max} = 2e^{-\gamma_E}$$

$$b_{\min} = \frac{2e^{-\gamma_E}}{Q}$$

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





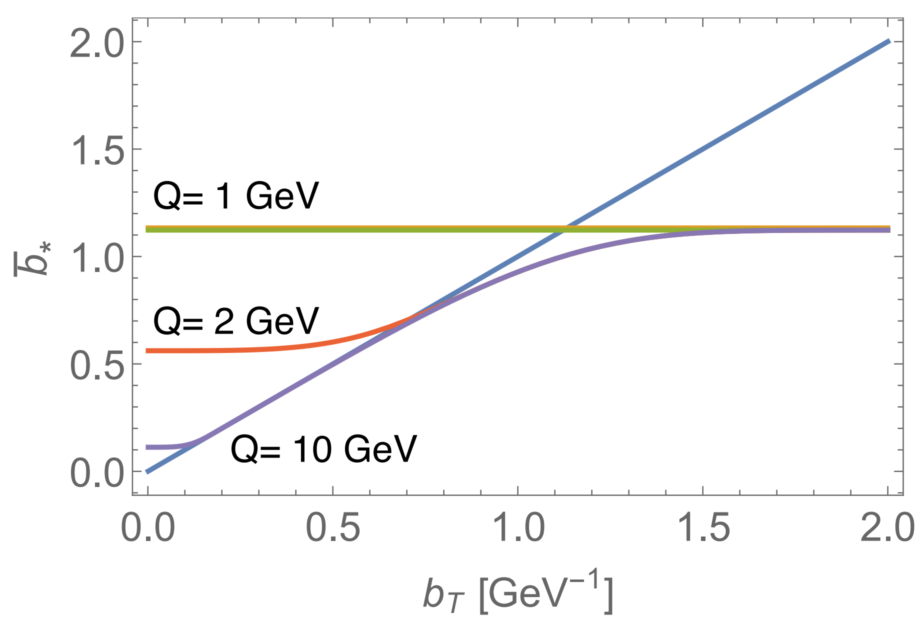
μ_b never bigger than Q nor

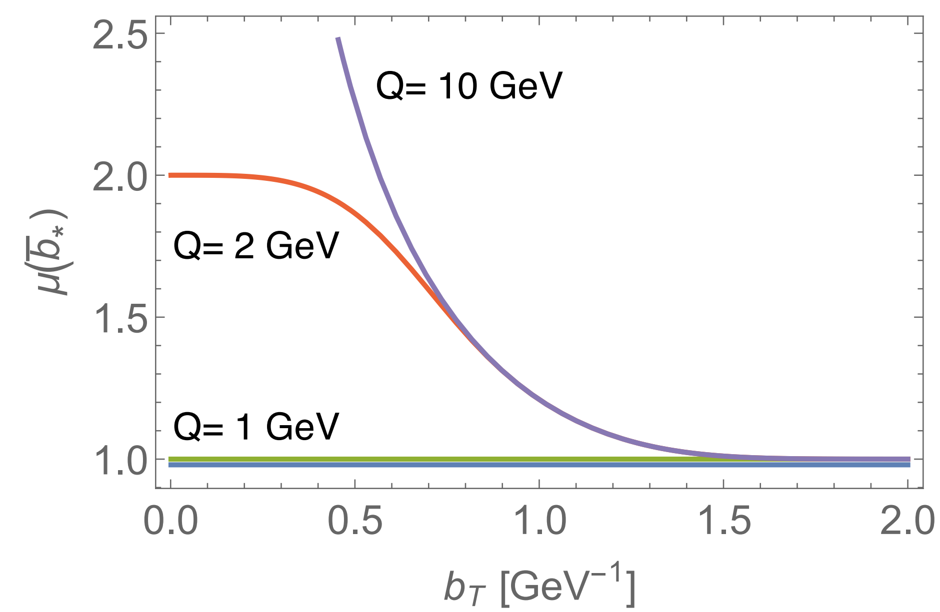
Effects of $\bar{b}_*$ prescription

$$\bar{b}_* \equiv b_{\max}\left(\frac{1-e^{-b_T^4/b_{\max}^4}}{1-e^{-b_T^4/b_{\min}^4}}\right)^{1/4} \qquad b_{\max} = 2e^{-\gamma_E}$$

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

$$b_{\min} = \frac{2e^{-\gamma_E}}{Q}$$





μ_b never bigger than Q nor

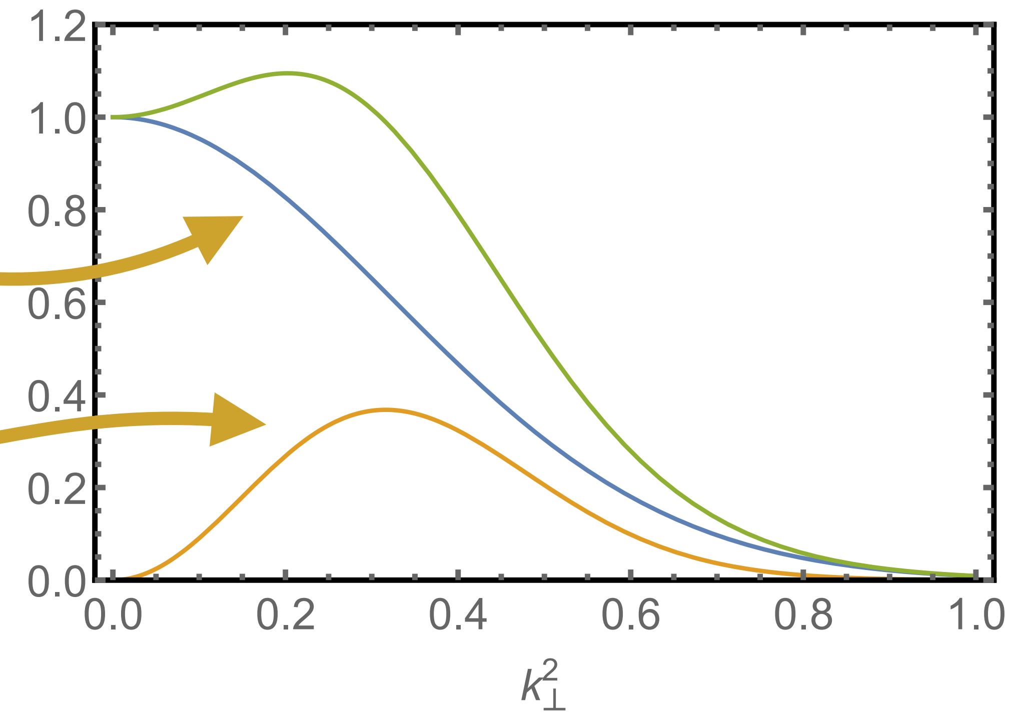
No significant effect at high Q, but large effect at low Q (inhibits gluon radiation)

Functional form of TMDs at 1 GeV

$$\hat{f}^{a}_{\rm NP} = \text{F.T. of} \left(e^{-\frac{k_\perp^2}{\langle k_{\perp,a}^2 \rangle}} + \lambda k_\perp^2 \, e^{-\frac{k_\perp^2}{\langle k_{\perp,a}^2 \rangle'}} \right)$$

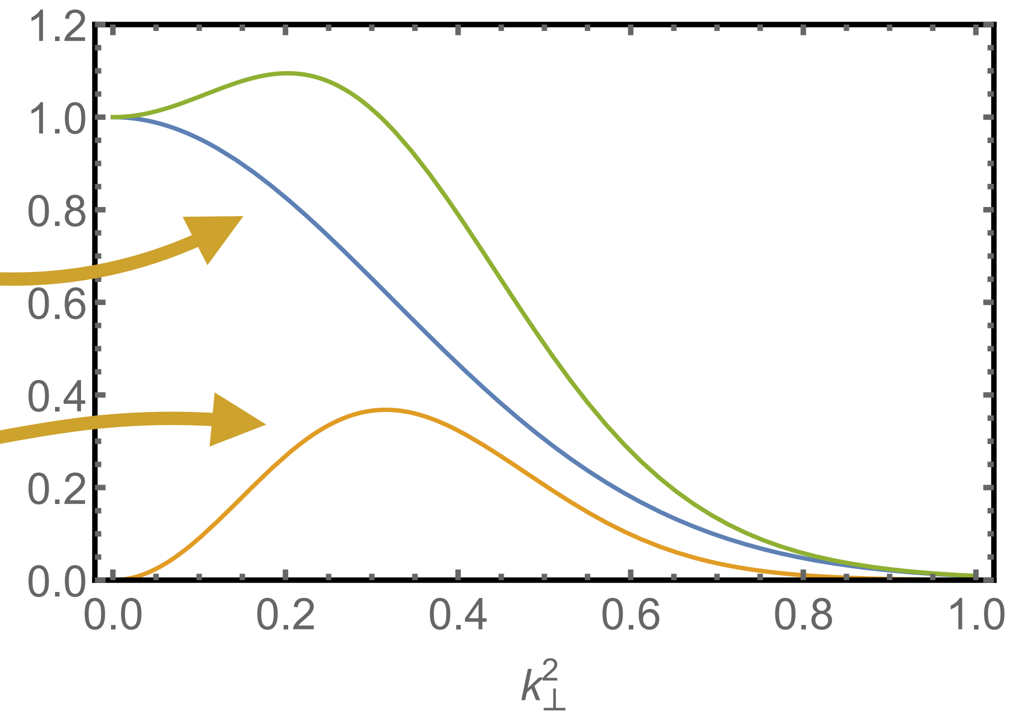
Functional form of TMDs at 1 GeV

$$\hat{f}^{a}_{\mathrm{NP}} = \text{F.T. of}\left(e^{-\frac{k_\perp^2}{\langle k_{\perp,a}^2\rangle}} + \lambda k_\perp^2 e^{-\frac{k_\perp^2}{\langle k_{\perp,a}^2\rangle'}} \right)$$



Functional form of TMDs at 1 GeV

$$\hat{f}^a_{\mathrm{NP}} = \text{F.T. of } \left(e^{-\frac{k_\perp^2}{\langle k^2_{\perp,a}\rangle}} + \lambda k_\perp^2 e^{-\frac{k_\perp^2}{\langle k^2_{\perp,a}\rangle'}} \right)$$

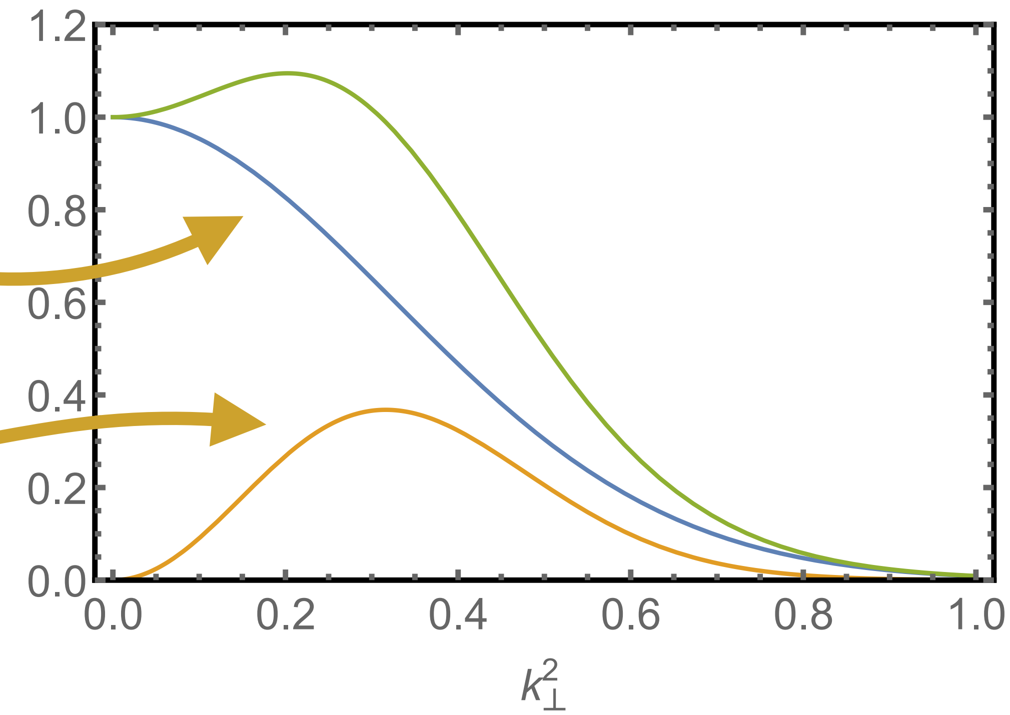


x-dependent width

$$\langle \boldsymbol{k}^2_{\perp,a}\rangle(x) = \langle \hat{\boldsymbol{k}}^2_{\perp,a}\rangle \, \frac{(1-x)^\alpha x^\sigma}{(1-\hat{x})^\alpha \hat{x}^\sigma} \,, \qquad \text{where } \langle \hat{\boldsymbol{k}}^2_{\perp,a}\rangle \equiv \langle \boldsymbol{k}^2_{\perp,a}\rangle(\hat{x}), \text{ and } \hat{x} = 0.1.$$

Functional form of TMDs at 1 GeV

$$\hat{f}^a_{\rm NP} = \text{F.T. of} \left(e^{-\frac{k_\perp^2}{\langle k_{\perp,a}^2 \rangle}} + \lambda k_\perp^2 e^{-\frac{k_\perp^2}{\langle k_{\perp,a}^2 \rangle'}} \right)$$



x-dependent width $\langle \boldsymbol{k}_{\perp,a}^2 \rangle(x) = \langle \hat{\boldsymbol{k}}_{\perp,a}^2 \rangle \dfrac{(1-x)^\alpha x^\sigma}{(1-\hat{x})^\alpha \hat{x}^\sigma}$, where $\langle \hat{\boldsymbol{k}}_{\perp,a}^2 \rangle \equiv \langle \boldsymbol{k}_{\perp,a}^2 \rangle(\hat{x})$, and $\hat{x} = 0.1$.

Fragmentation function is similar
Including TMD PDFs and FFs, in total: 11 free parameters
(4 for TMD PDFs, 6 for TMD FFs, 1 for TMD evolution)

Data selection

$$Q^2 > 1.4\ \mathrm{GeV}^2$$

$$0.2 < z < 0.7$$

$$P_{hT}, q_T < \mathrm{Min}[0.2\ Q, 0.7\ Qz] + 0.5\ \mathrm{GeV}$$

Data selection

$$Q^2 > 1.4\ \mathrm{GeV}^2$$

$$0.2 < z < 0.7$$

$$P_{hT}, q_T < \mathrm{Min}[0.2\ Q, 0.7\ Qz] + 0.5\ \mathrm{GeV}$$

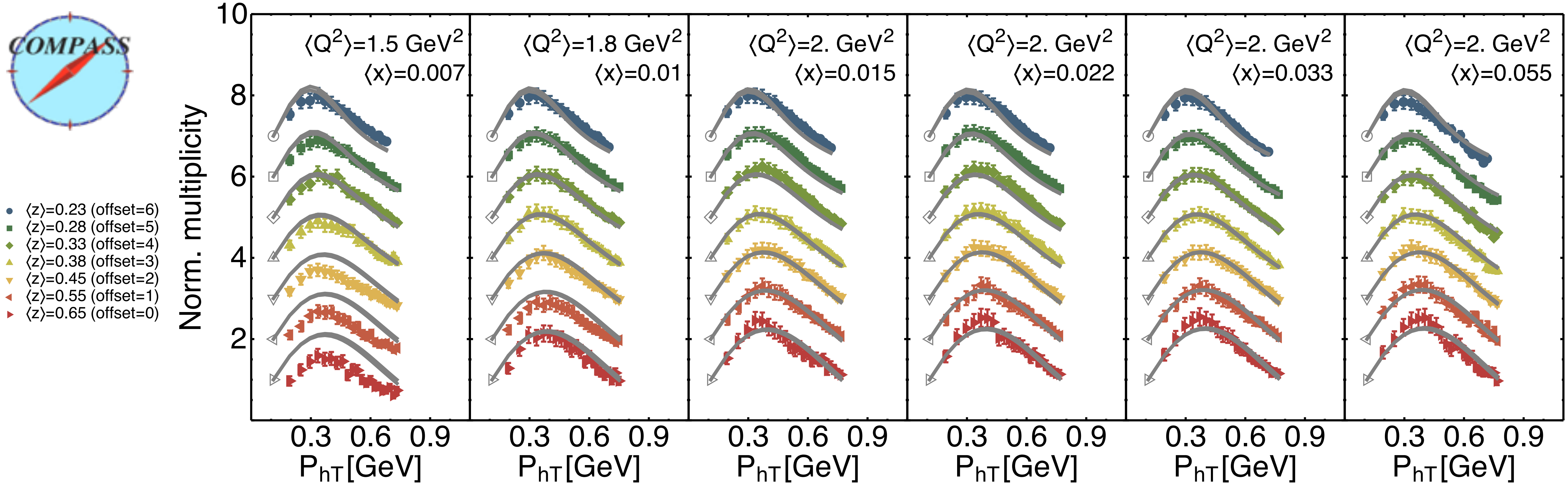
Total number of data points: 8059

Total χ^2/dof = 1.52

Preliminary

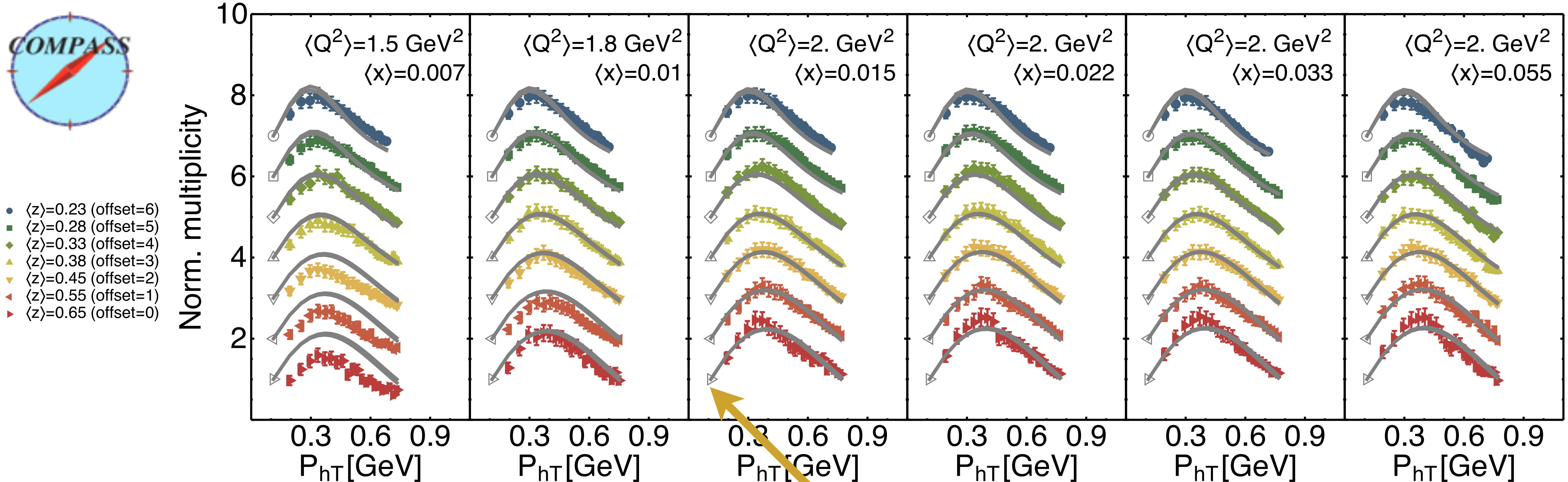
Data vs. theory plots

COMPASS selected bins



Deuteron h− $\chi^2/\mathrm{dof} = 1.58$

COMPASS selected bins

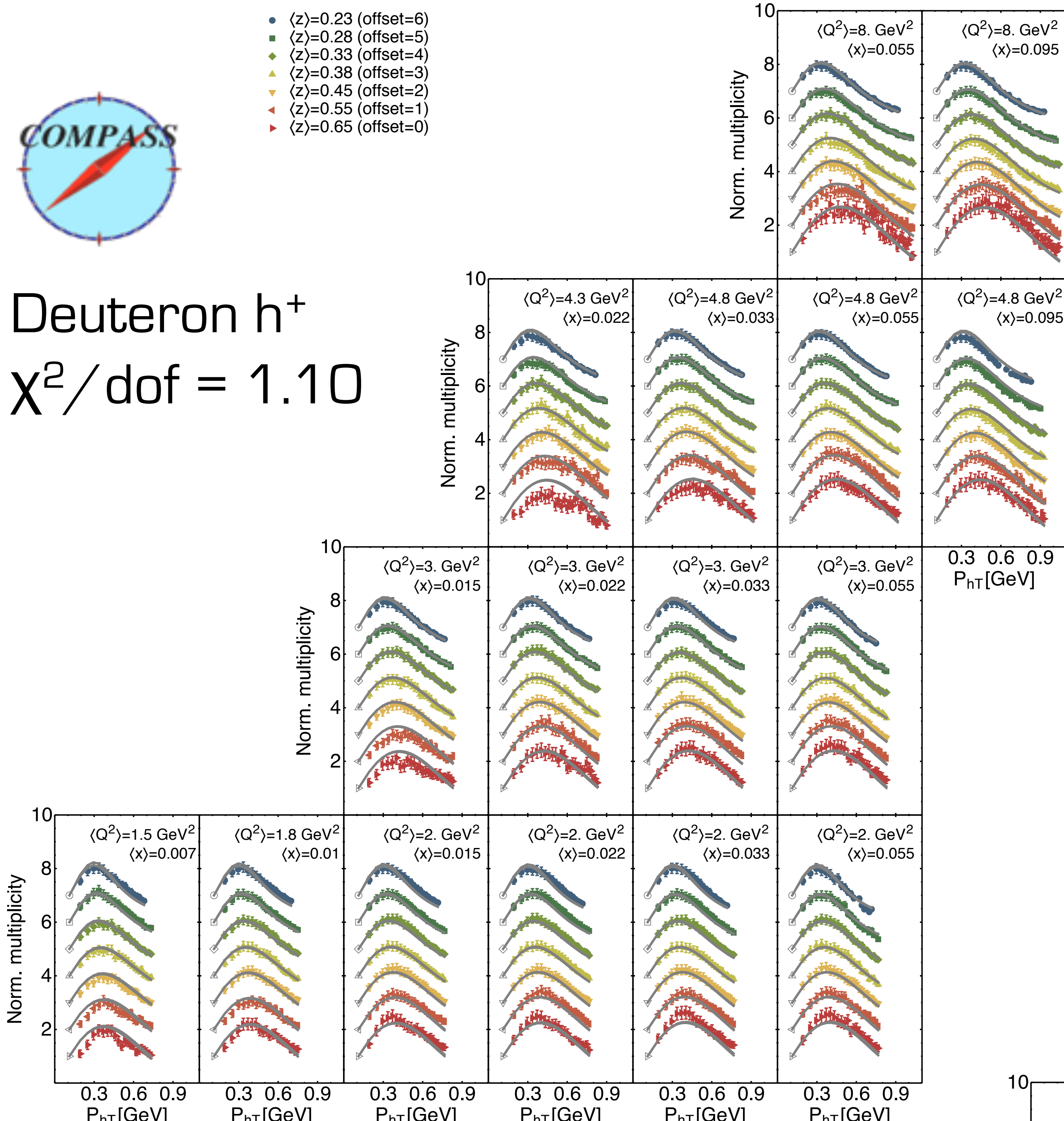


First points are not fitted, but used as normalization

Deuteron h− $\chi^2/\text{dof} = 1.58$

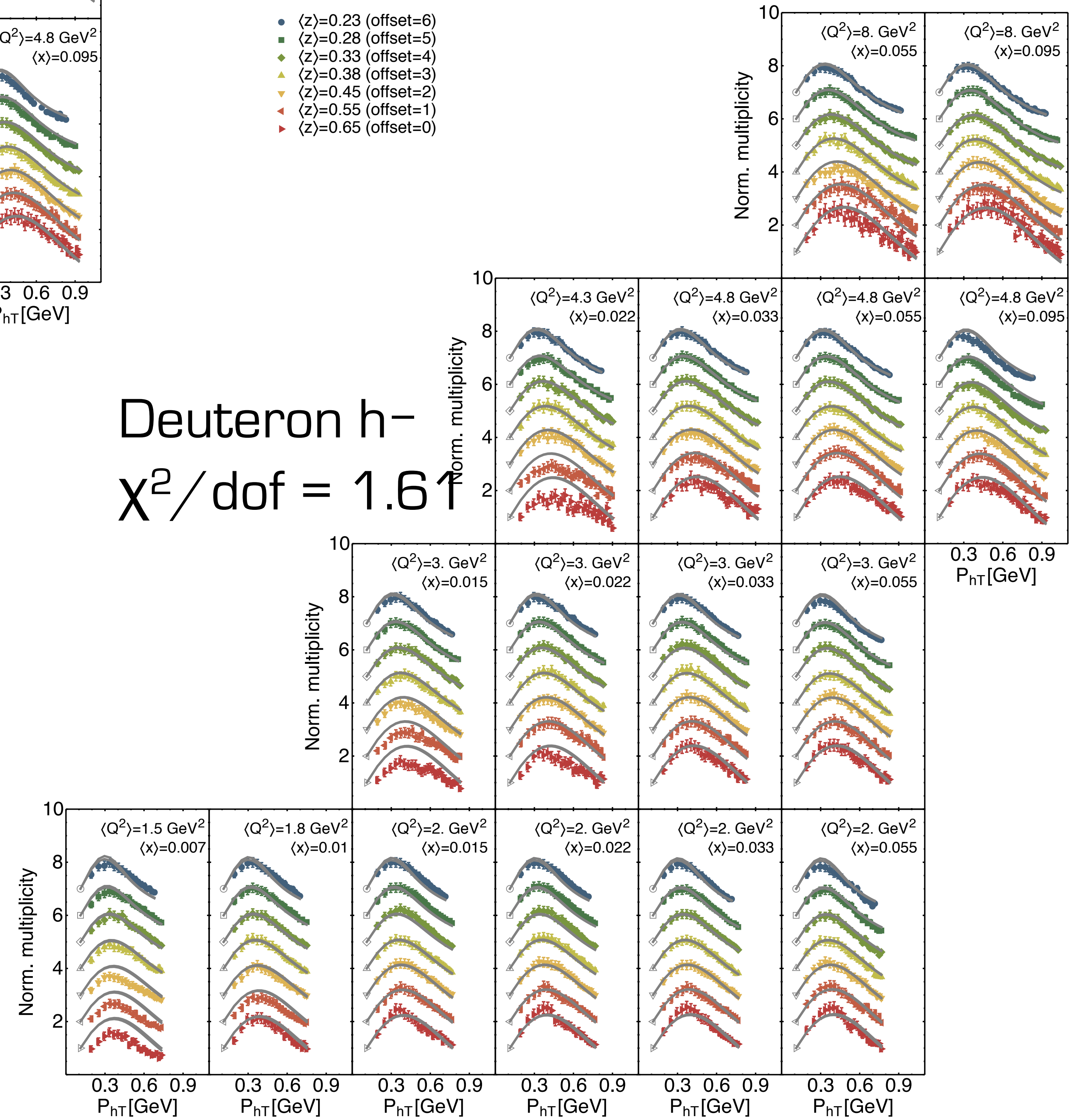
Deuteron h^+

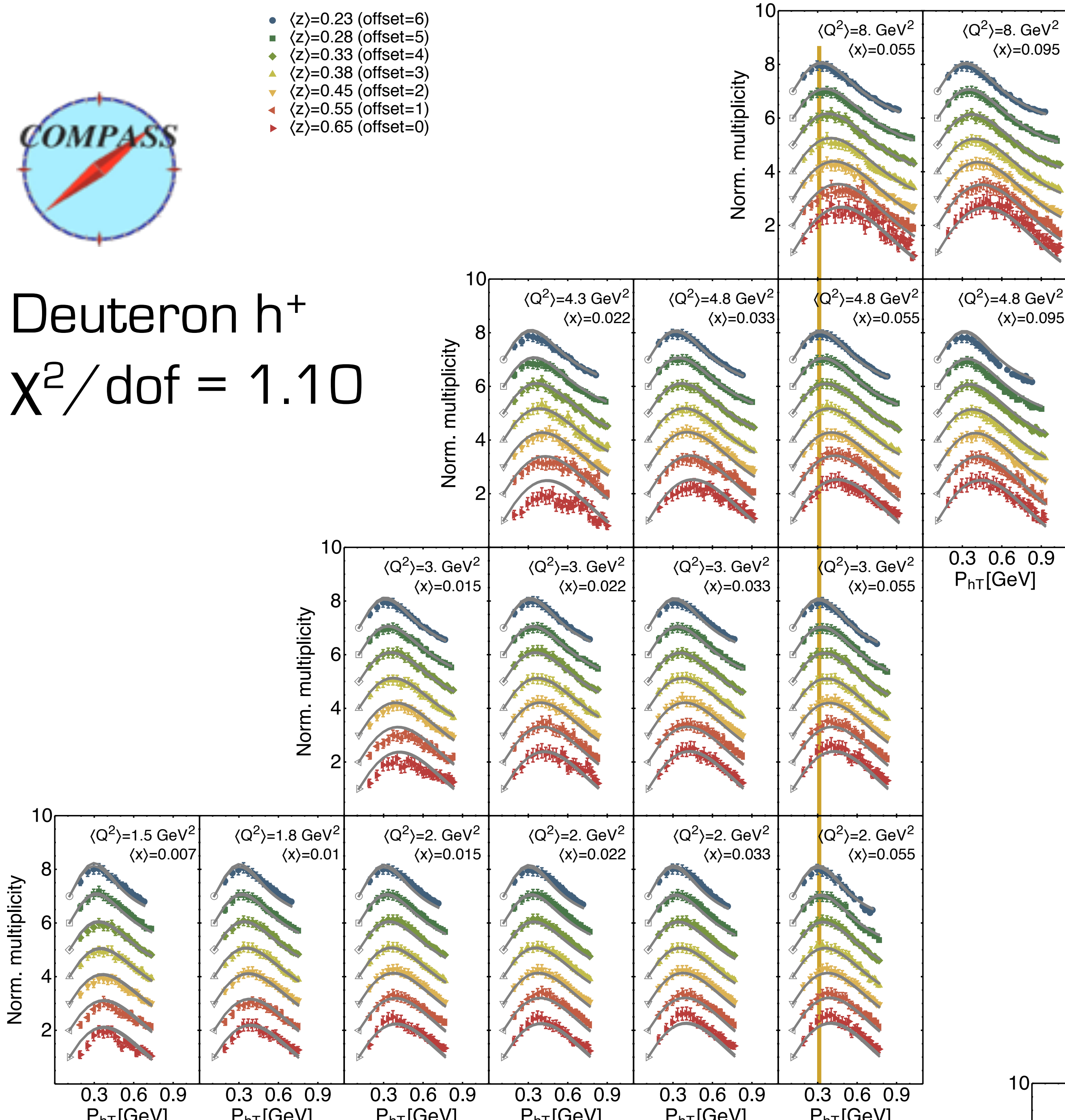
$\chi^2/\text{dof} = 1.10$



Deuteron h^-

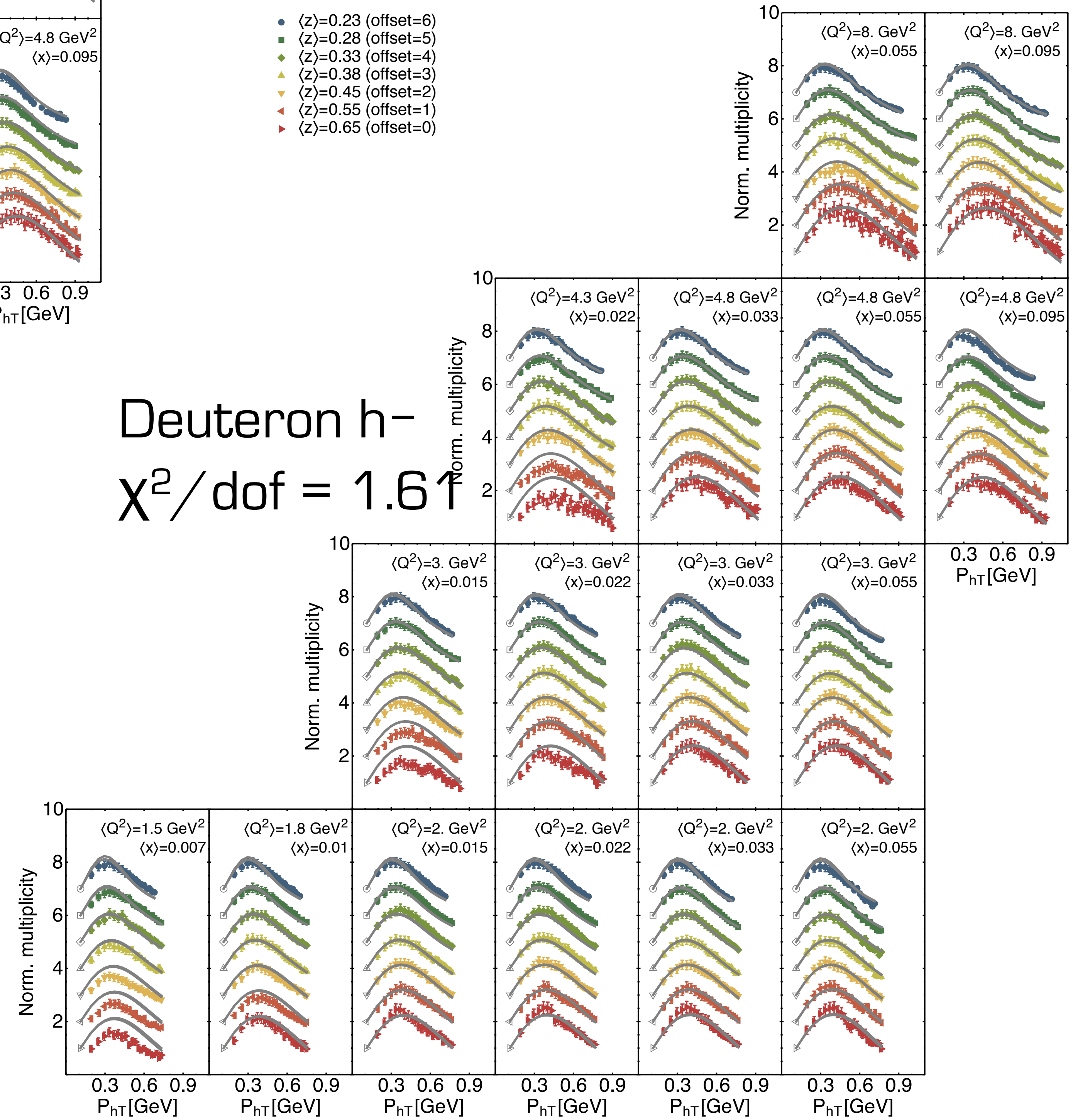
$\chi^2/\text{dof} = 1.61$





Deuteron h^+

$\chi^2/\text{dof} = 1.10$

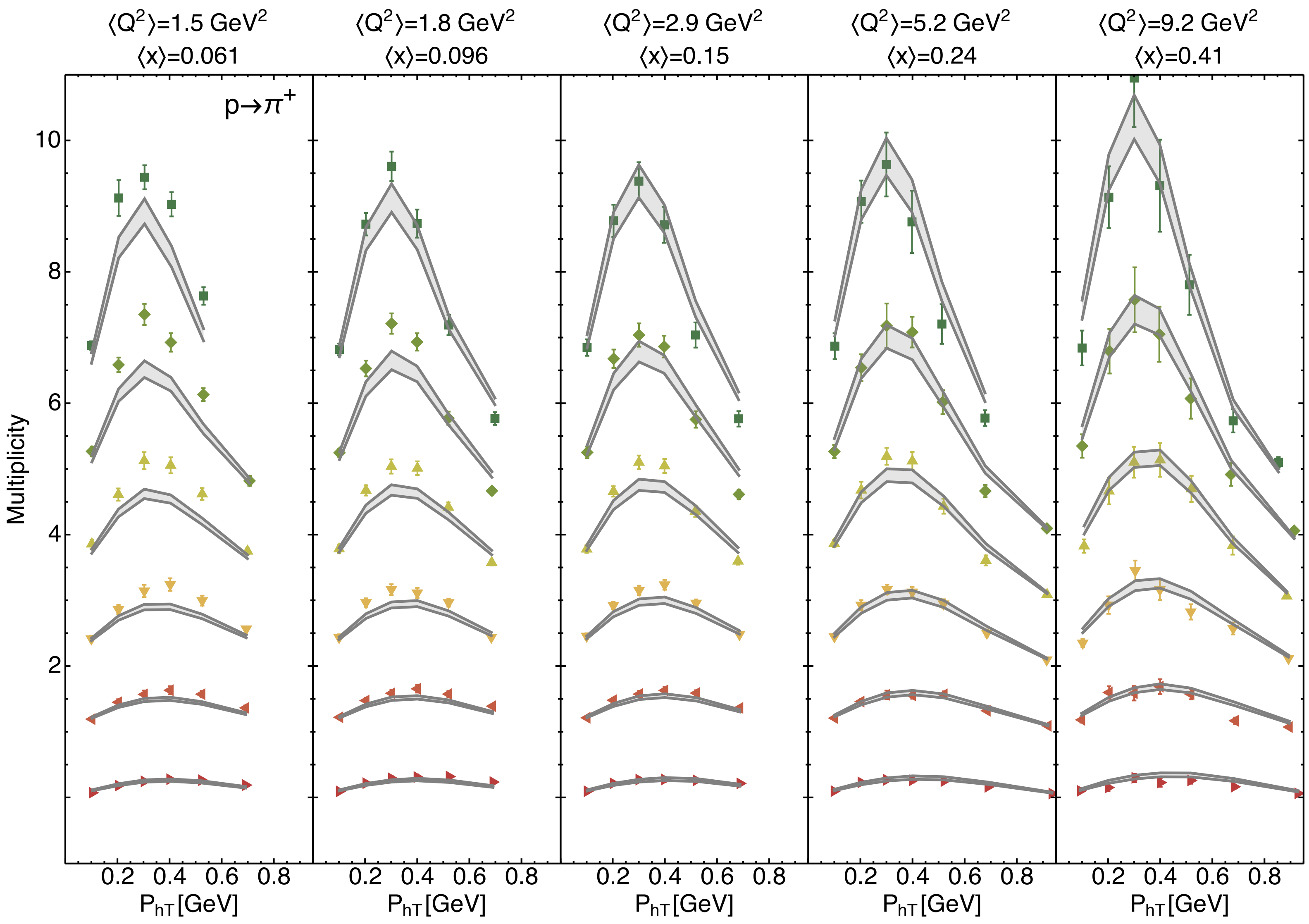


Deuteron h^-

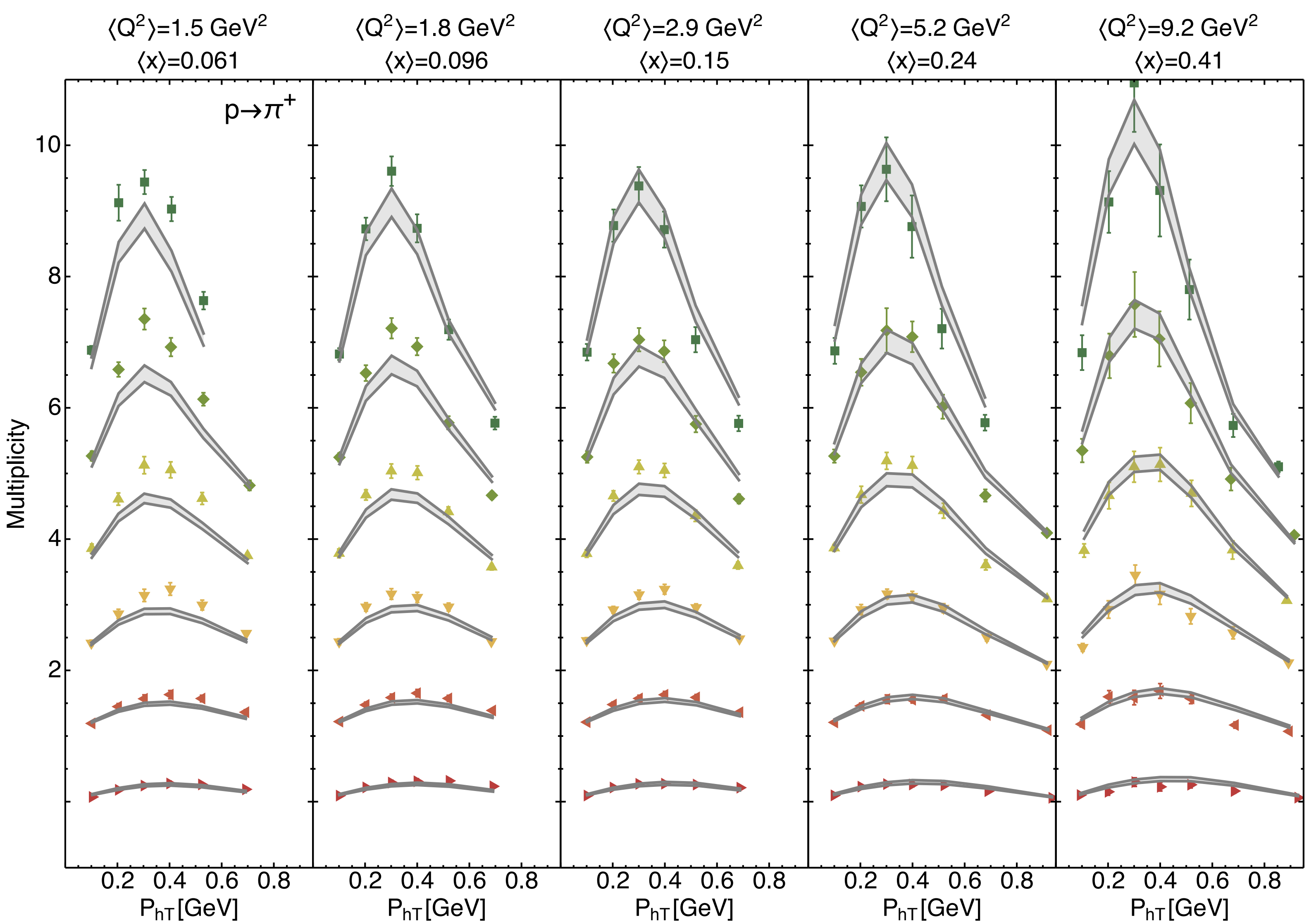
$\chi^2/\text{dof} = 1.61$

Aidala, Field, Gamberg, Rogers
arXiv:1401.2654

HERMES, selected bins



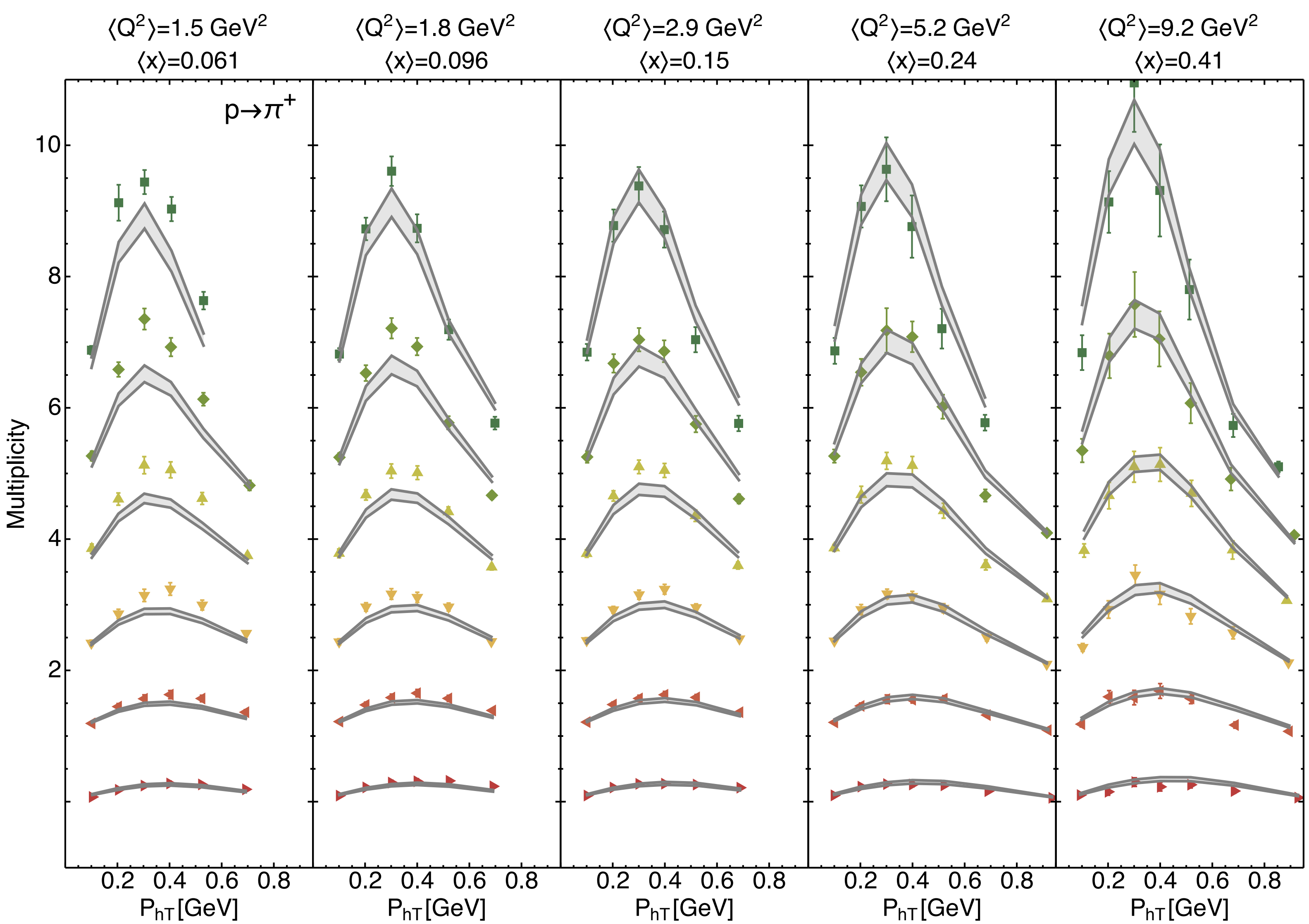
HERMES, selected bins



$\chi^2/\text{dof} = 4.80$

The worst of all channels...

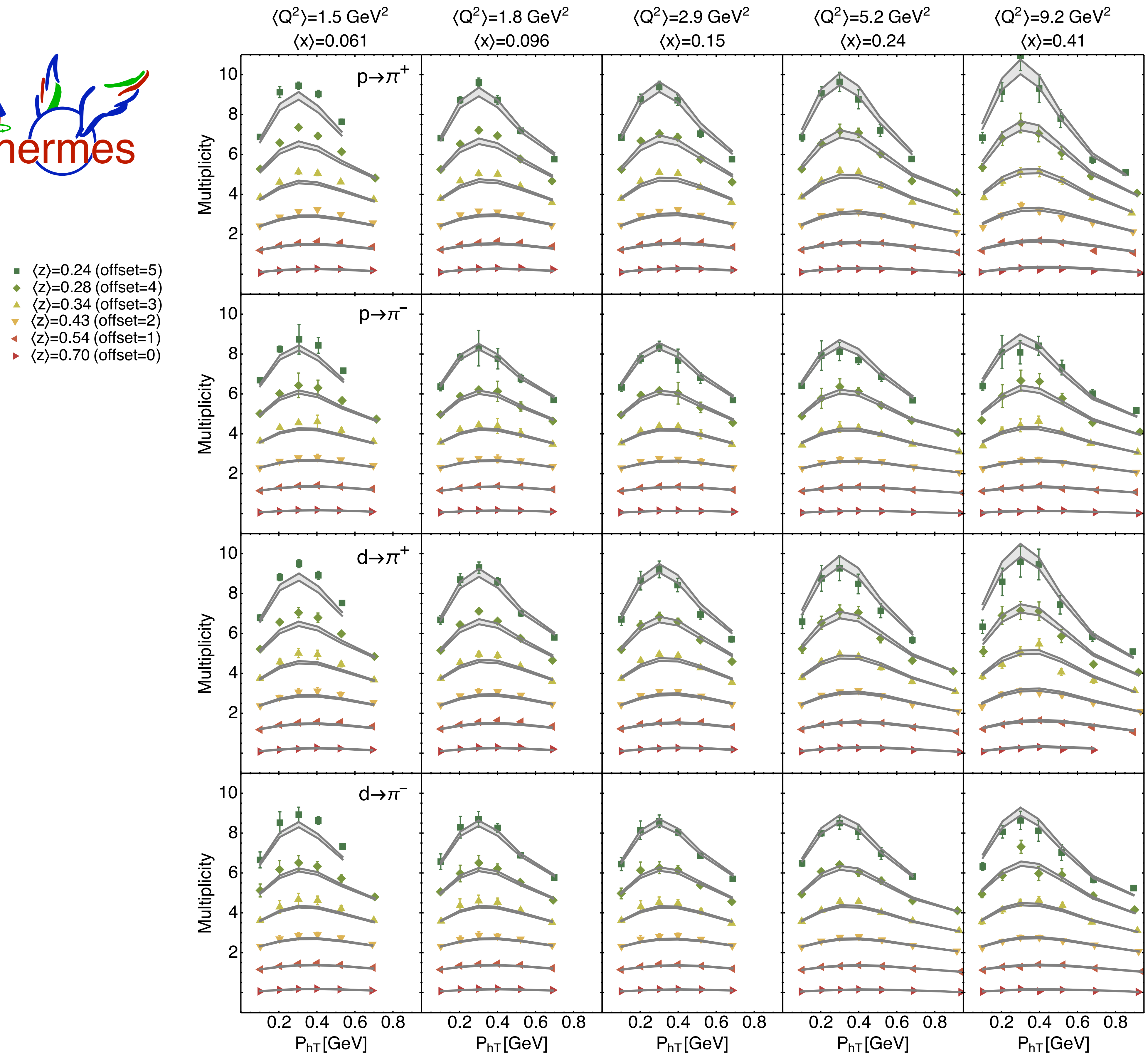
HERMES, selected bins



$\chi^2/\text{dof} = 4.80$

The worst of all channels...

However normalizing the theory curves to the first bin, without changing the parameters of the fit, χ^2/dof becomes good



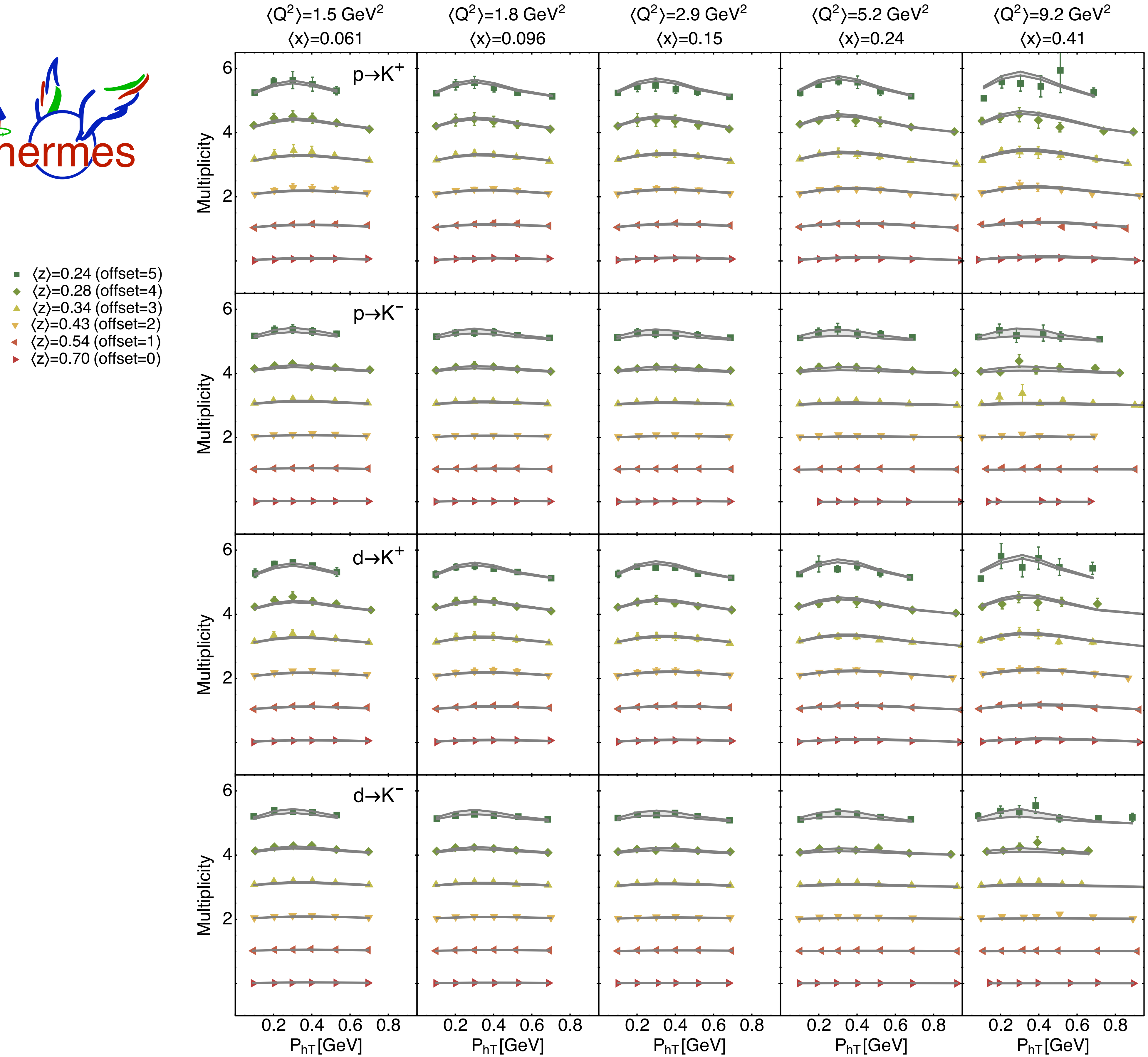
χ^2/dof

4.8

2.5

3.5

2.0



χ^2/dof

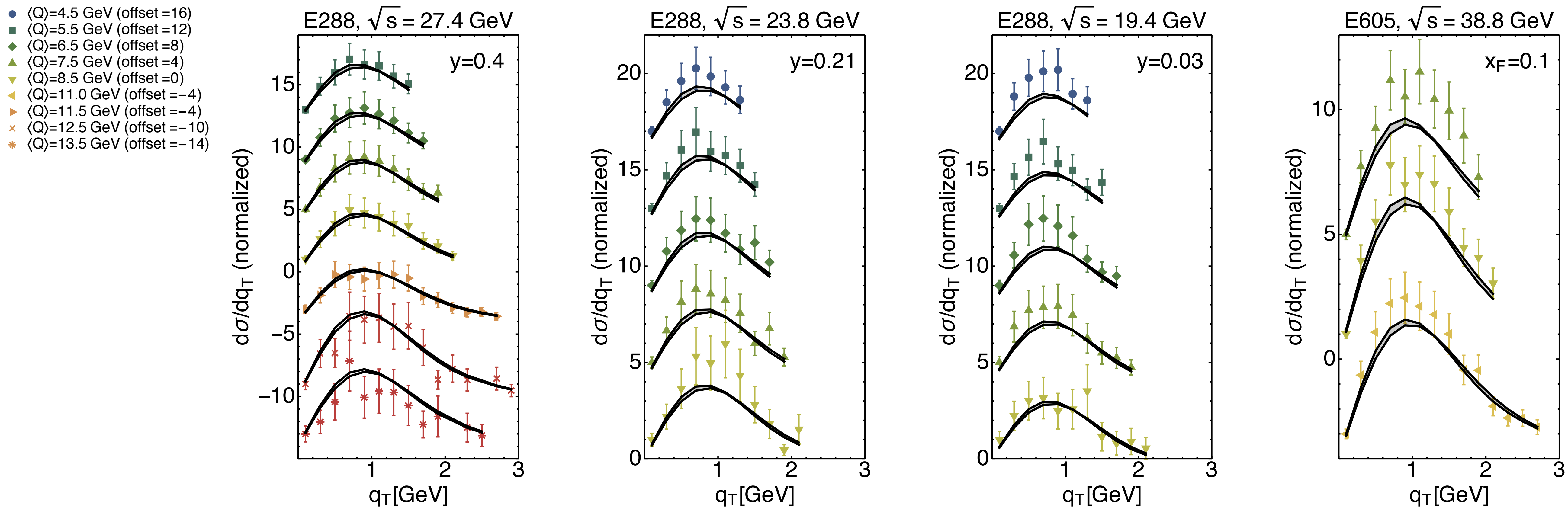
0.9

0.8

1.3

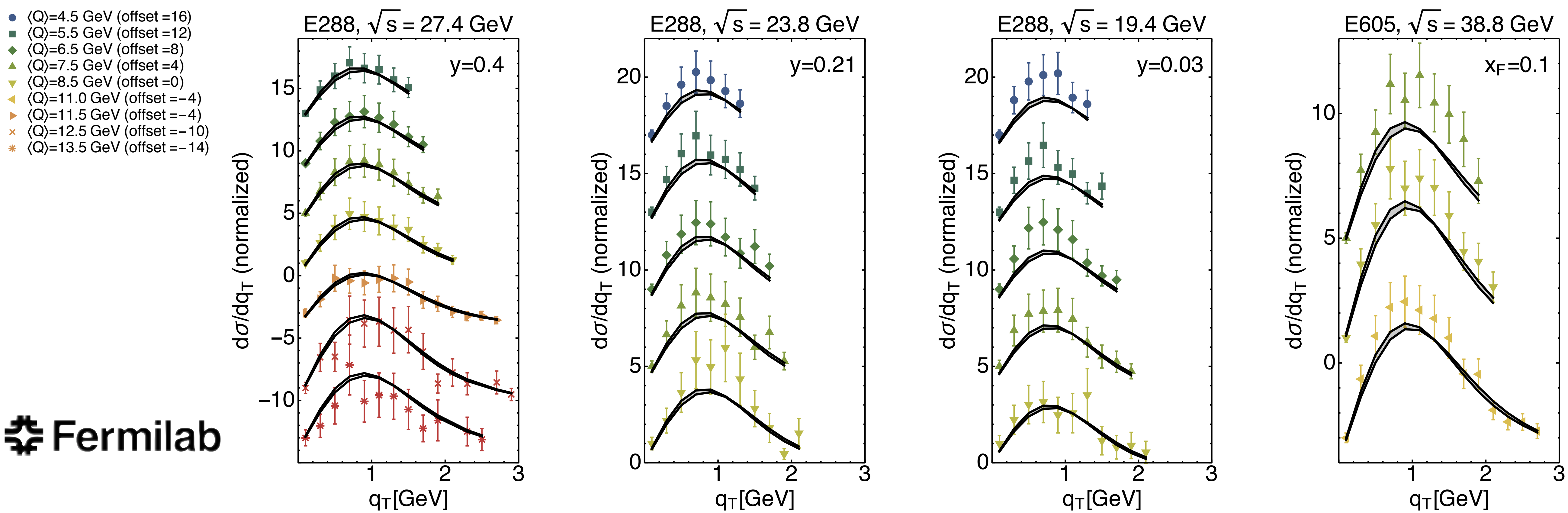
2.5

Drell-Yan data



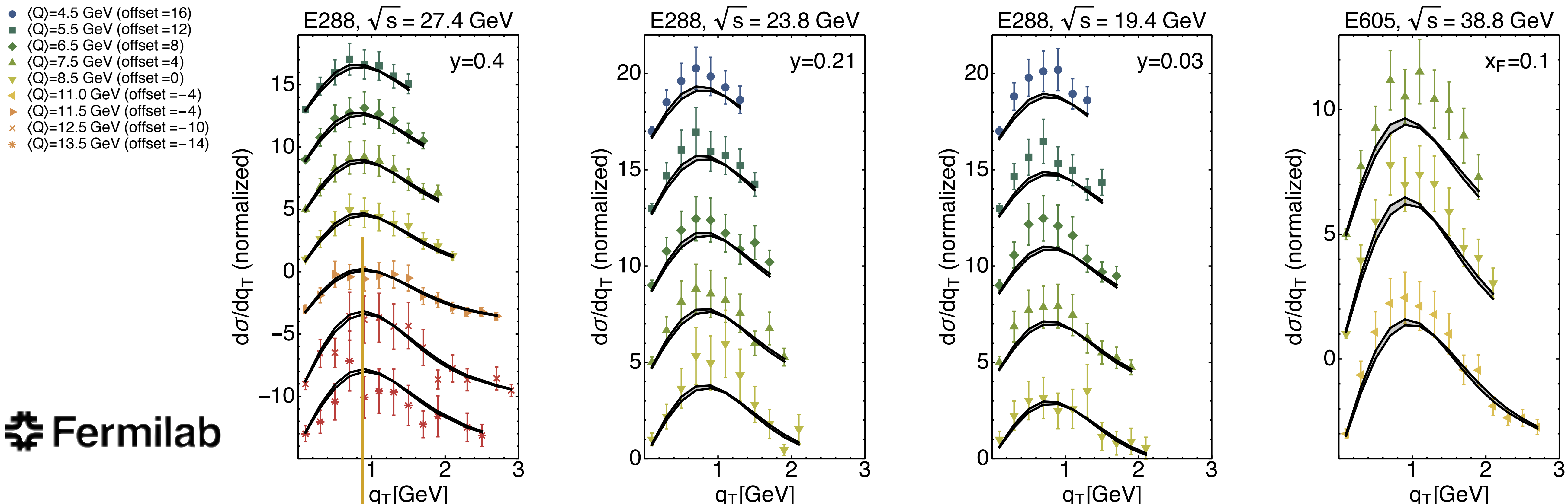
χ^2/dof	0.32	0.84	0.99	1.13

Drell-Yan data



χ^2/dof	0.32	0.84	0.99	1.13

Drell-Yan data

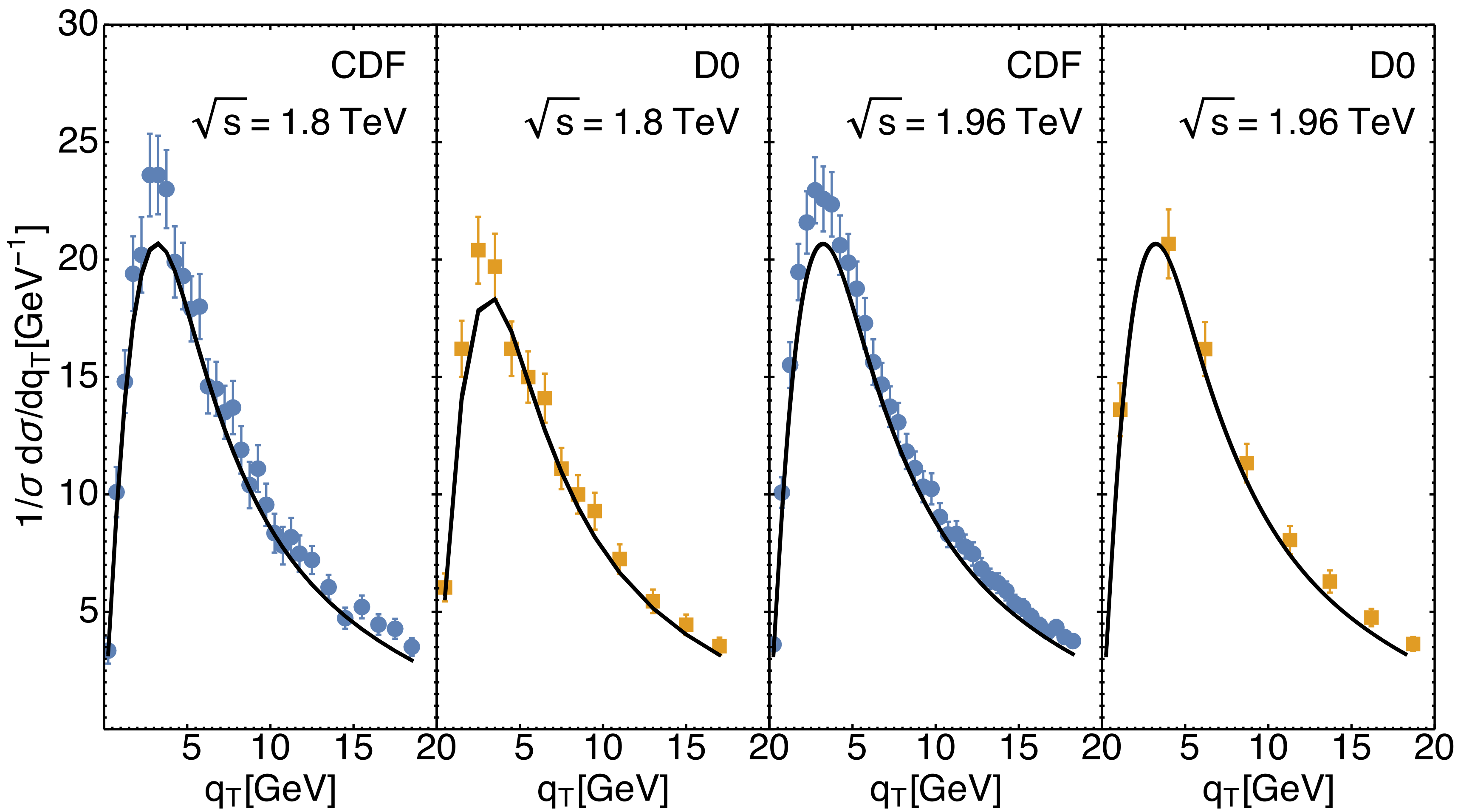


Fermilab

χ^2/dof	0.32	0.84	0.99	1.13

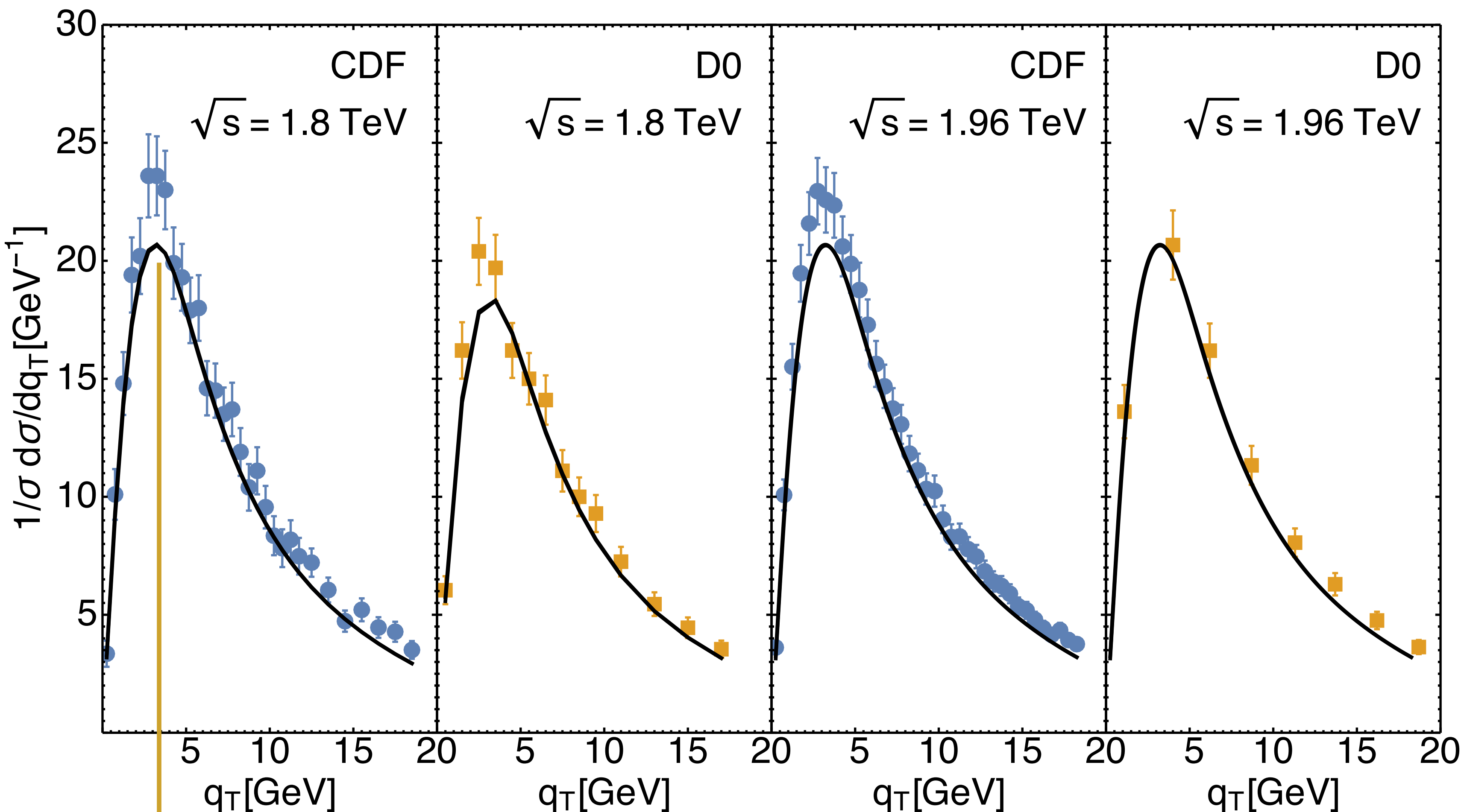
the peak was at 0.4 GeV and now is at 1 GeV

Z-boson data



χ^2/dof 1.4 1.1 2.0

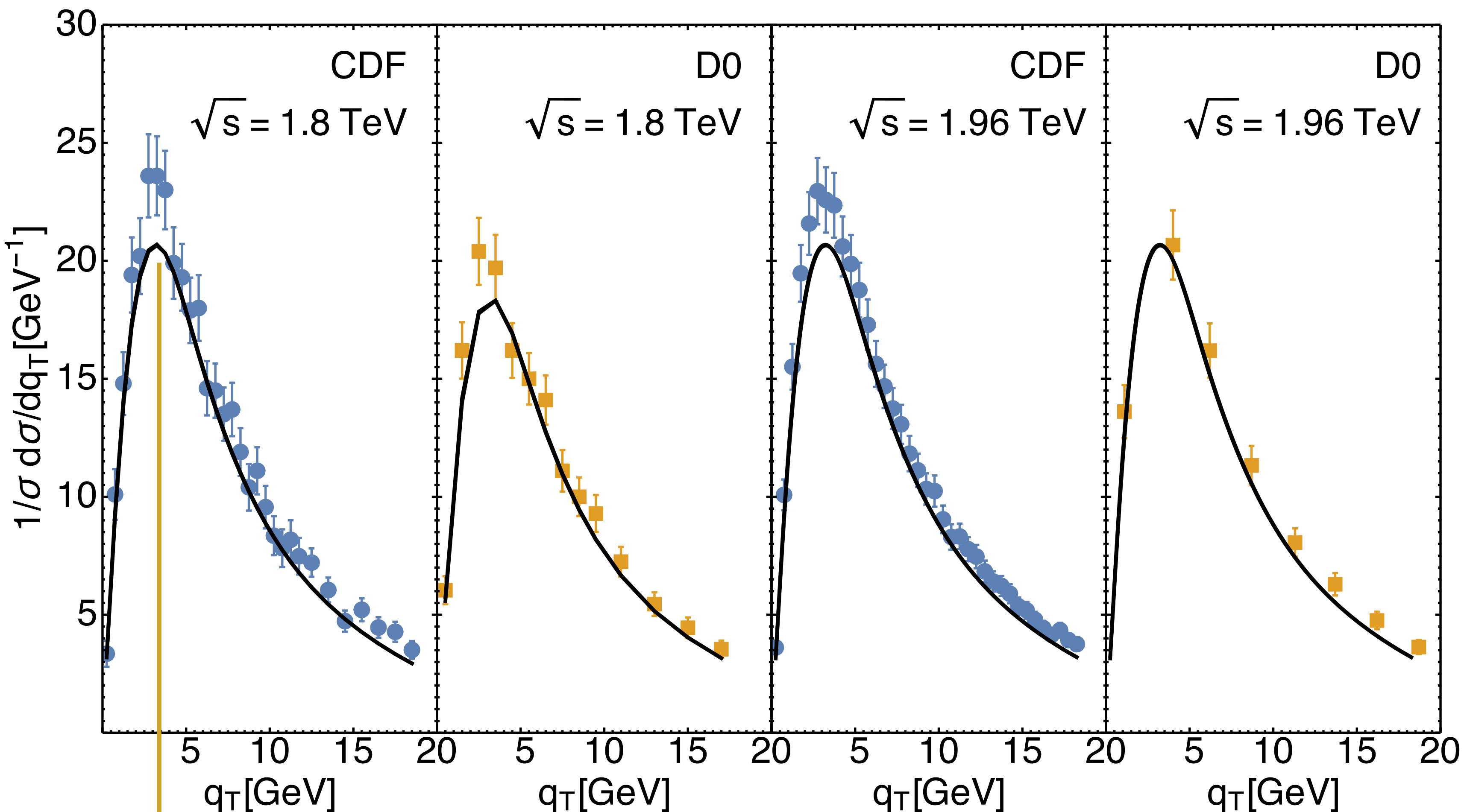
Z-boson data



χ^2/dof 1.4 1.1 2.0

the peak now is at 4 GeV

Z-boson data



χ^2/dof 1.4 1.1 2.0

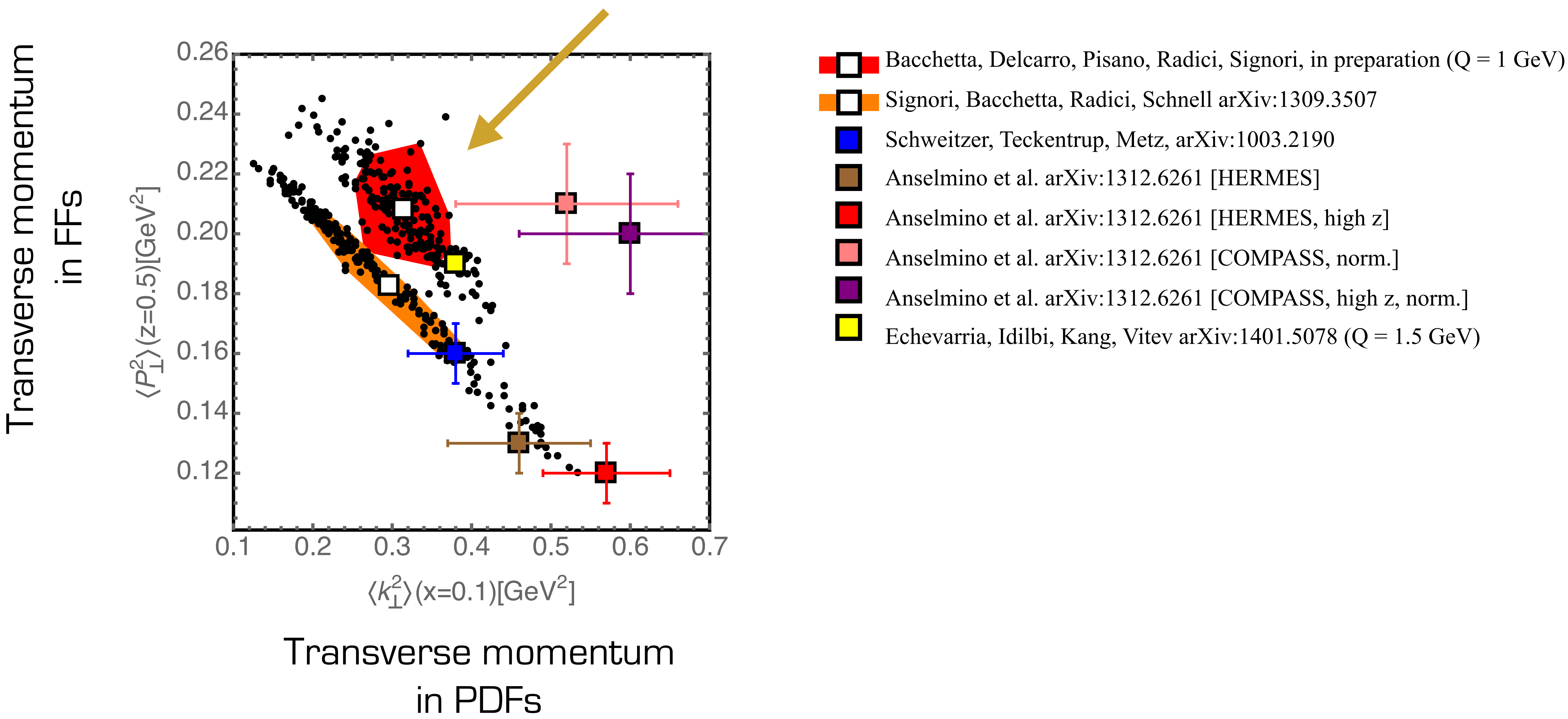
the peak now is at 4 GeV

Most of the χ^2 due to normalization,

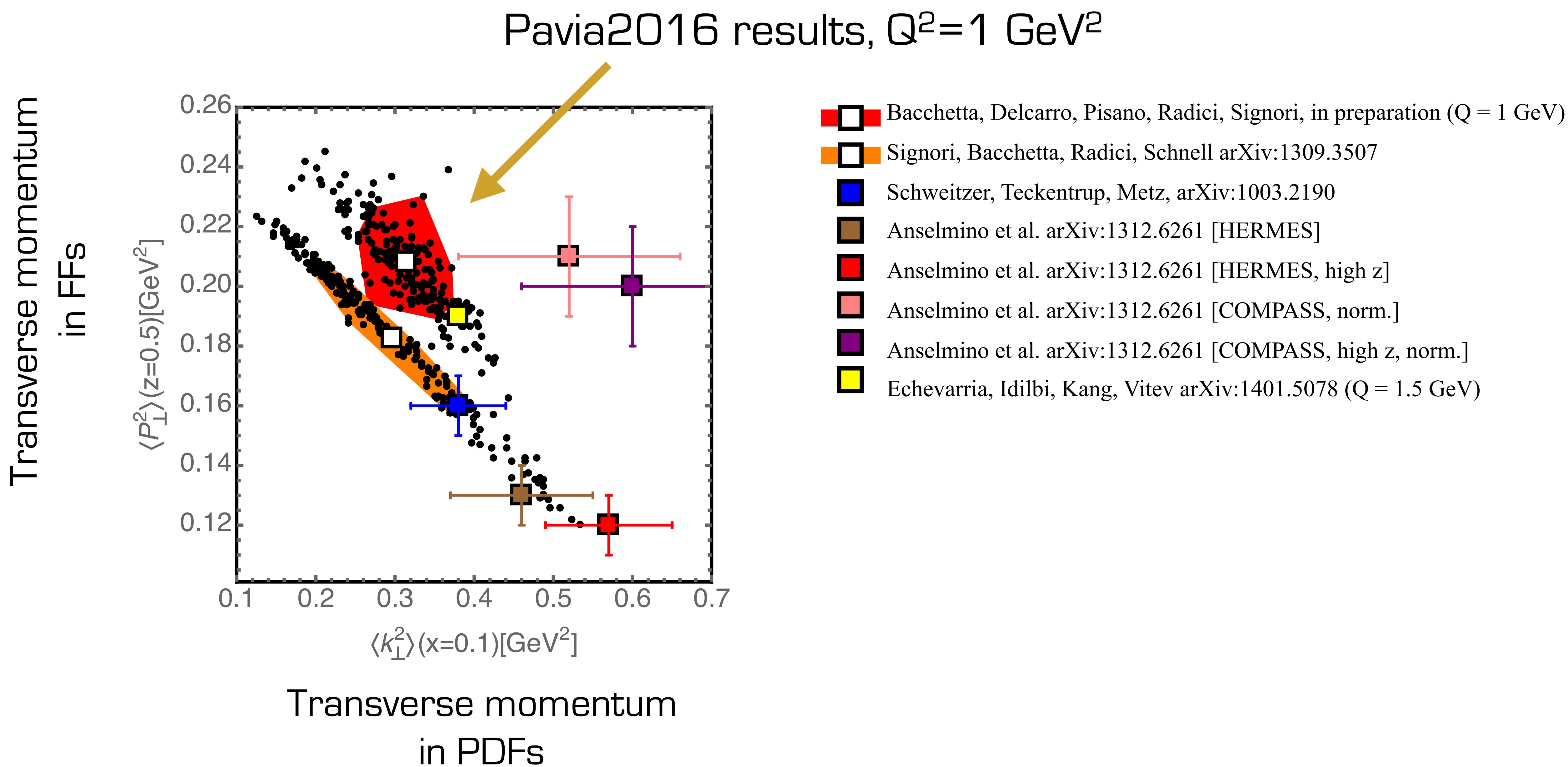
Some outcomes

Executive summary of results 3/3

Pavia2016 results, $Q^2=1$ GeV^2



Executive summary of results 3/3

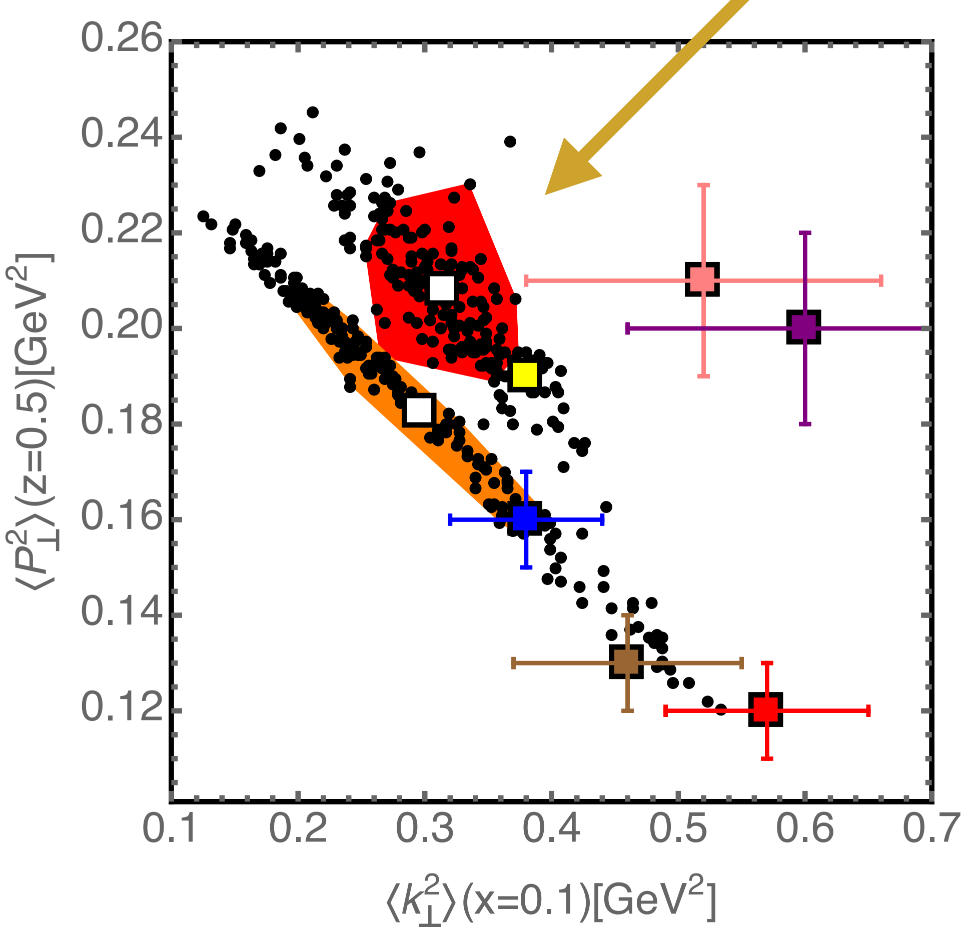


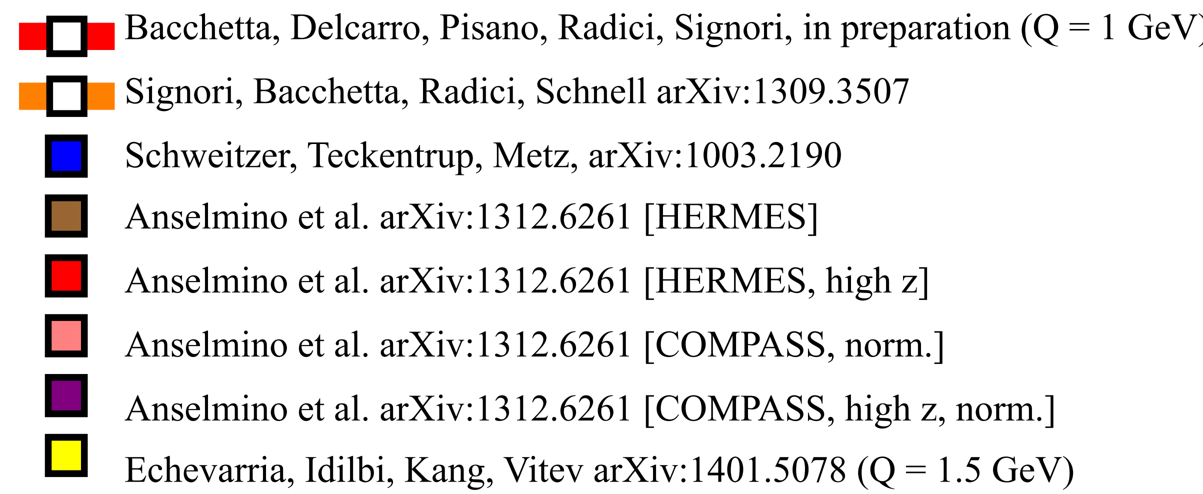
CAVEAT: intrinsic transverse momentum depends on TMD evolution "scheme" and its parameters

Executive summary of results 3/3

Pavia2016 results, Q^2=1 GeV^2

Transverse momentum in FFs





Transverse momentum in PDFs

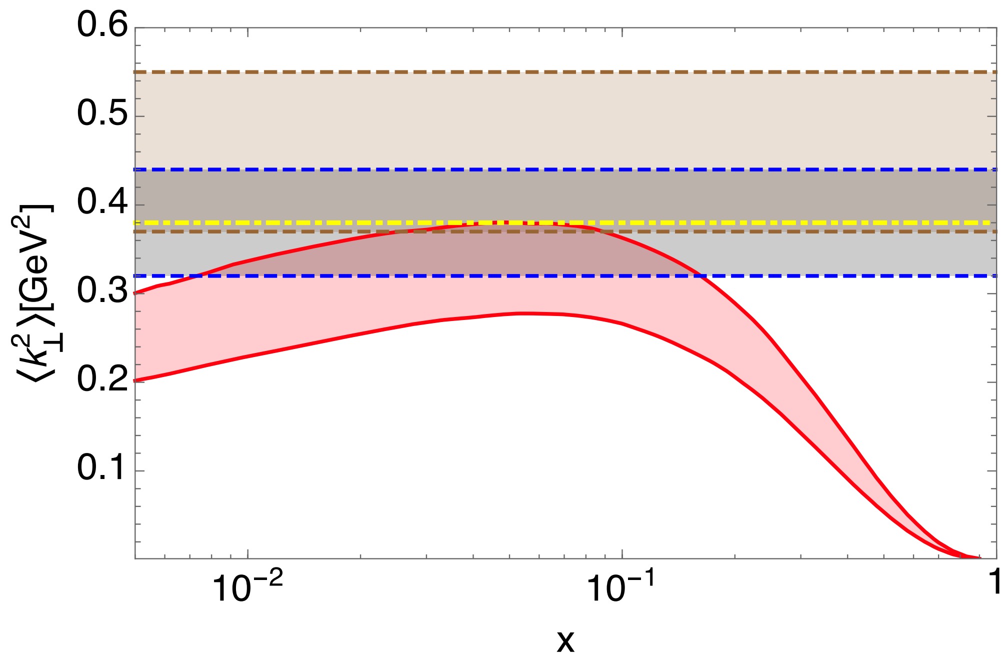
Anti correlation between transverse momentum in TMD PDFs and in TMD FFs, in spite of Drell-Yan data

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

Mean transverse momentum squared

same color coding as previous slide

at Q =1 G

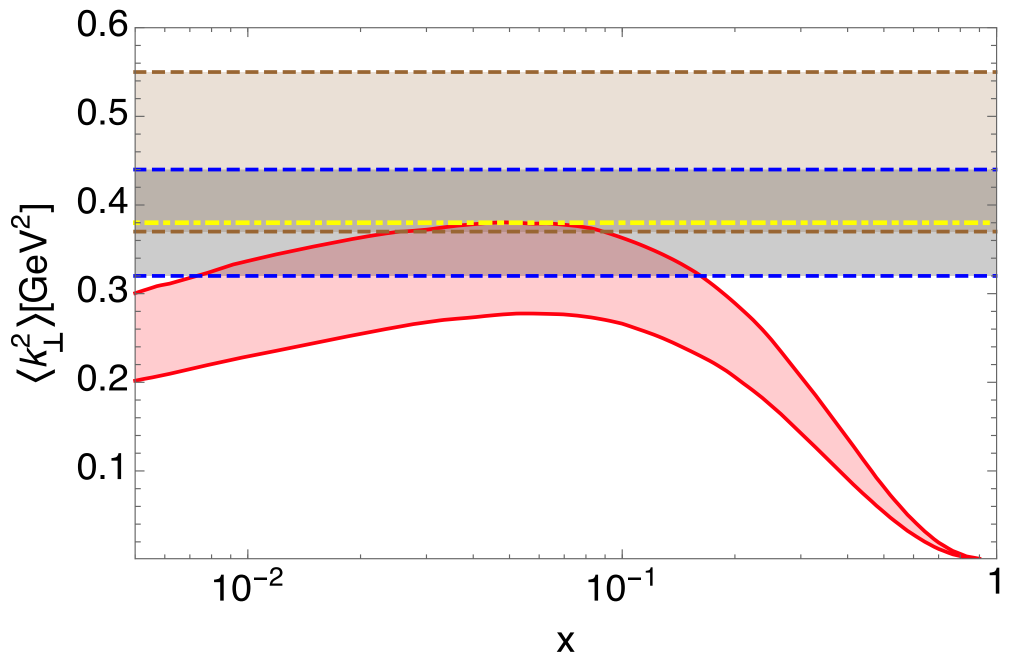


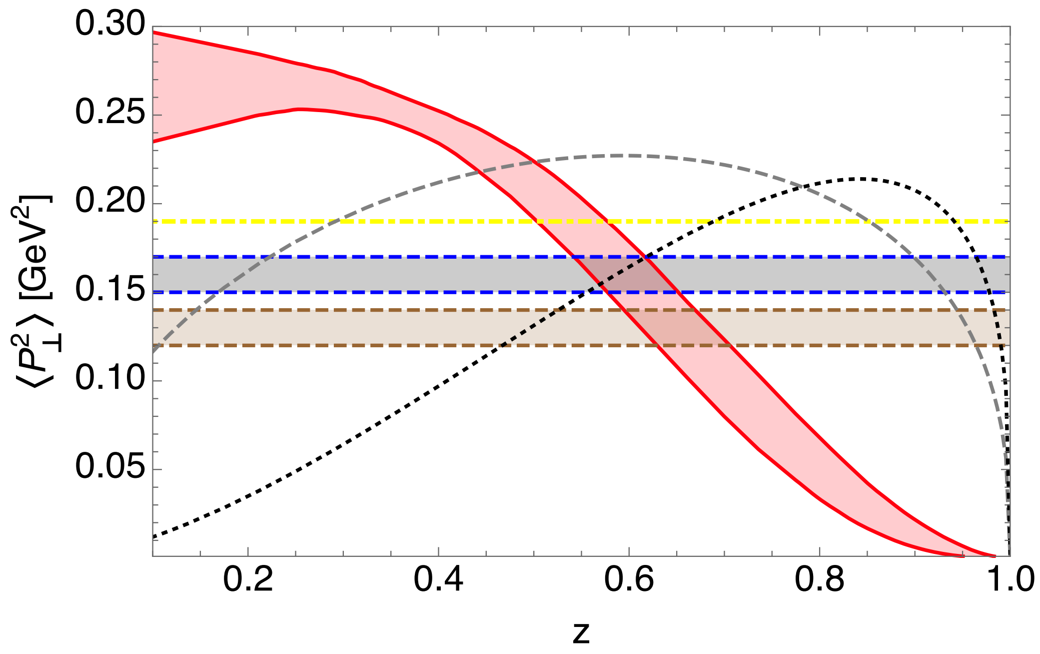
In TMD distribution functions

Mean transverse momentum squared

same color coding as previous slide

at Q =1 G





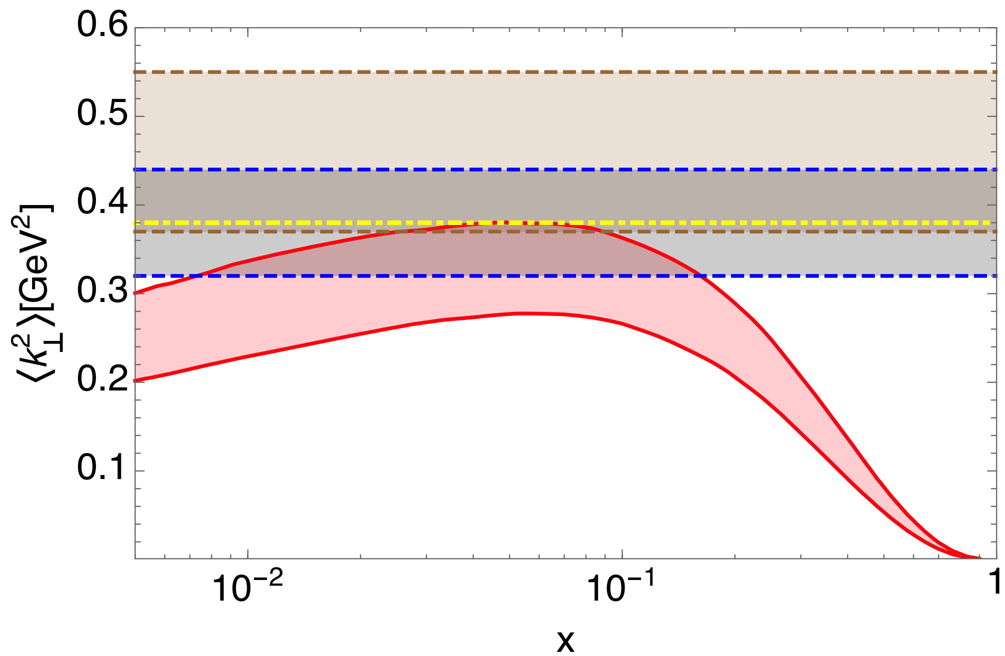
In TMD distribution functions

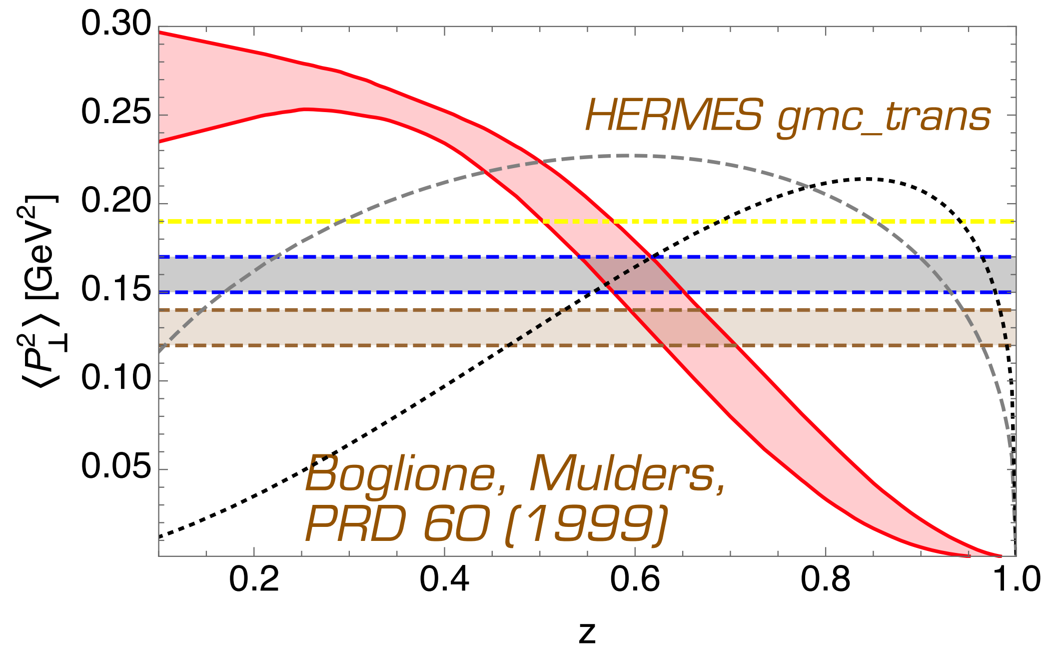
In TMD fragmenta

Mean transverse momentum squared

same color coding as previous slide

at Q =1 G





In TMD distribution functions

In TMD fragmentat

Nonperturbative evolution parameters

TMD evolution is not uniquely determined by pQCD calculations.
Nonperturbative input is needed to determine evolution precisely.
Different schemes may behave differently.

	g_2 (GeV^2)	b_{max}(GeV^{-1})
BLNY 2003	0.68 ± 0.02	0.5
KN 2006	0.184 ± 0.018	1.5
EIKV 2014	0.18	1.5
Pavia 2016	0.12 ± 0.01	1.123

Nonperturbative evolution parameters

TMD evolution is not uniquely determined by pQCD calculations.
Nonperturbative input is needed to determine evolution precisely.
Different schemes may behave differently.

	g_2 (GeV^2)	b_{max}(GeV^{-1})
BLNY 2003	0.68 ± 0.02	0.5
KN 2006	0.184 ± 0.018	1.5
EIKV 2014	0.18	1.5
Pavia 2016	0.12 ± 0.01	1.123

Faster evolution: transverse momentum increases faster due to gluon radiation

Nonperturbative evolution parameters

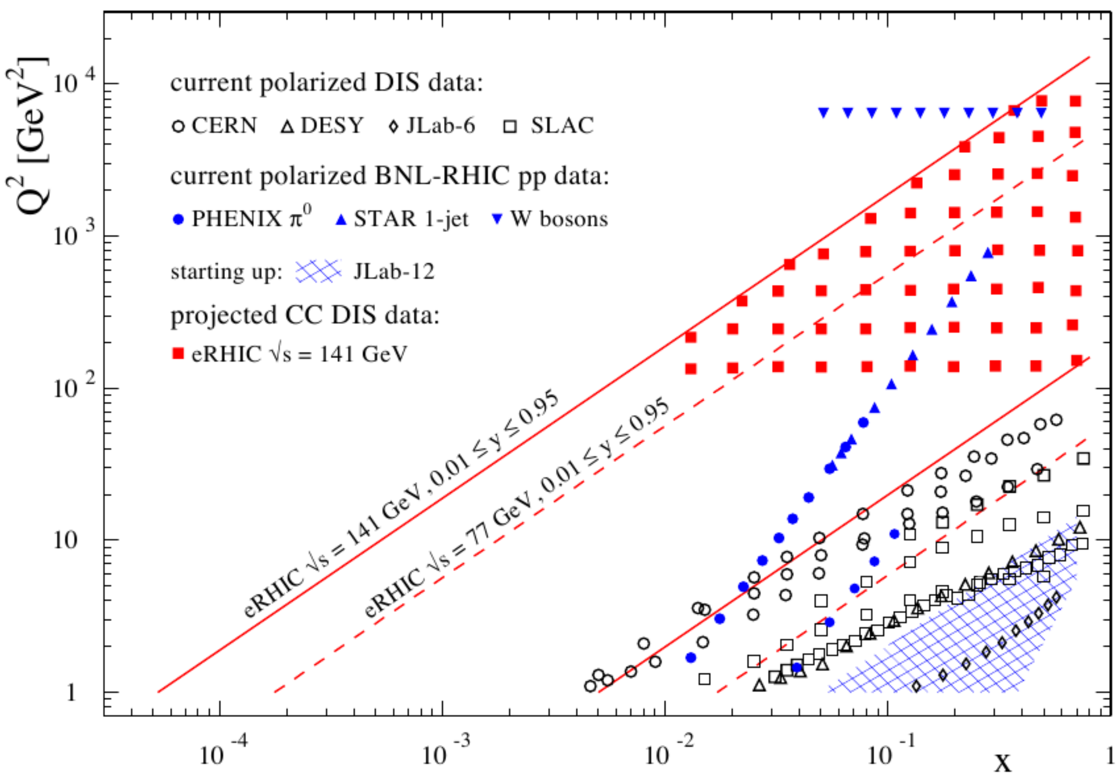
TMD evolution is not uniquely determined by pQCD calculations.
Nonperturbative input is needed to determine evolution precisely.
Different schemes may behave differently.

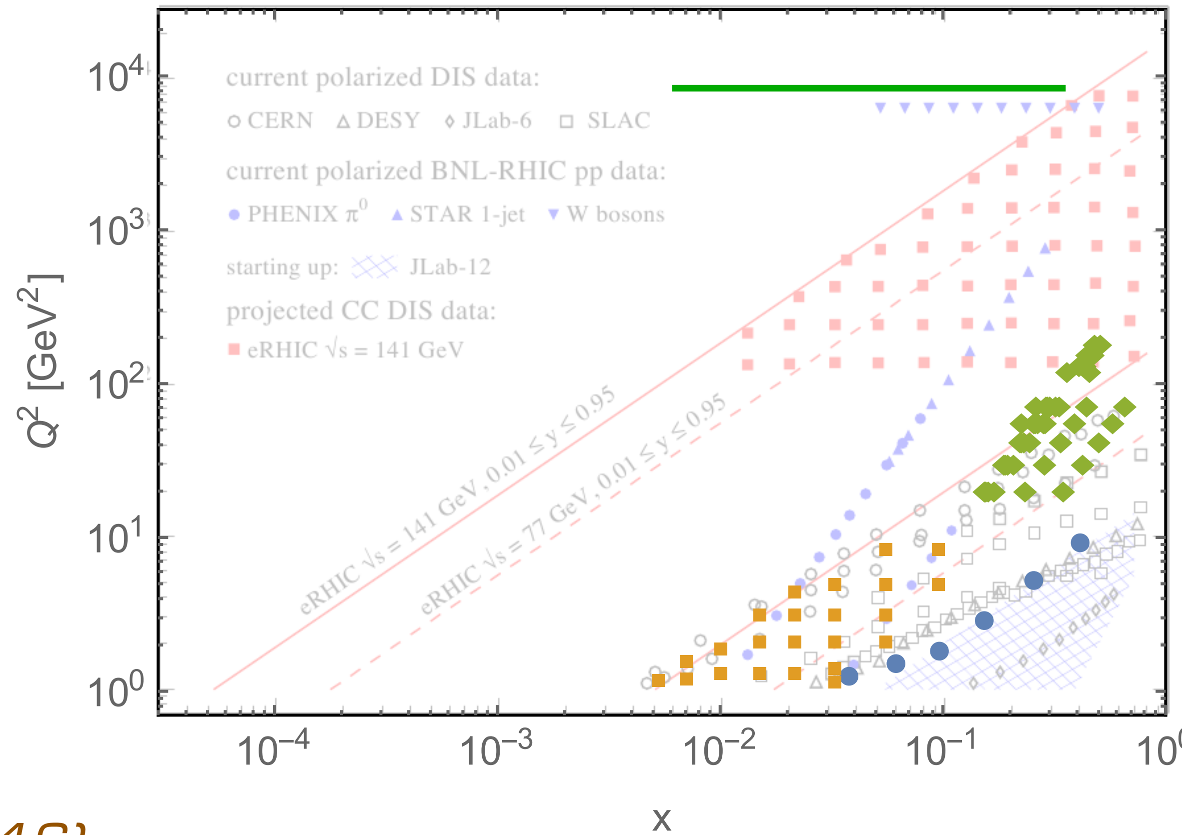
	g_2 (GeV^2)	b_{max}(GeV^{-1})
BLNY 2003	0.68 ± 0.02	0.5
KN 2006	0.184 ± 0.018	1.5
EIKV 2014	0.18	1.5
Pavia 2016	0.12 ± 0.01	1.123

Faster evolution: transverse momentum increases faster due to gluon radiation

Slower evolution: the effect of gluon radiation is weaker

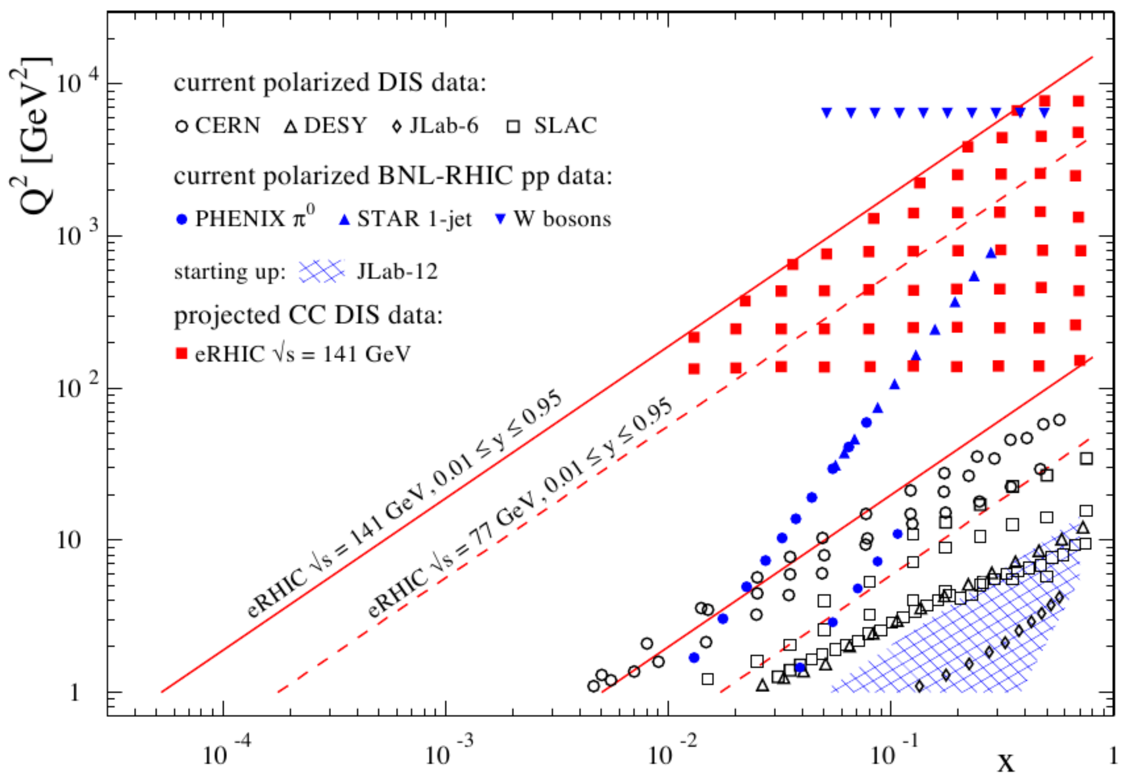
Comparison with future perspectives

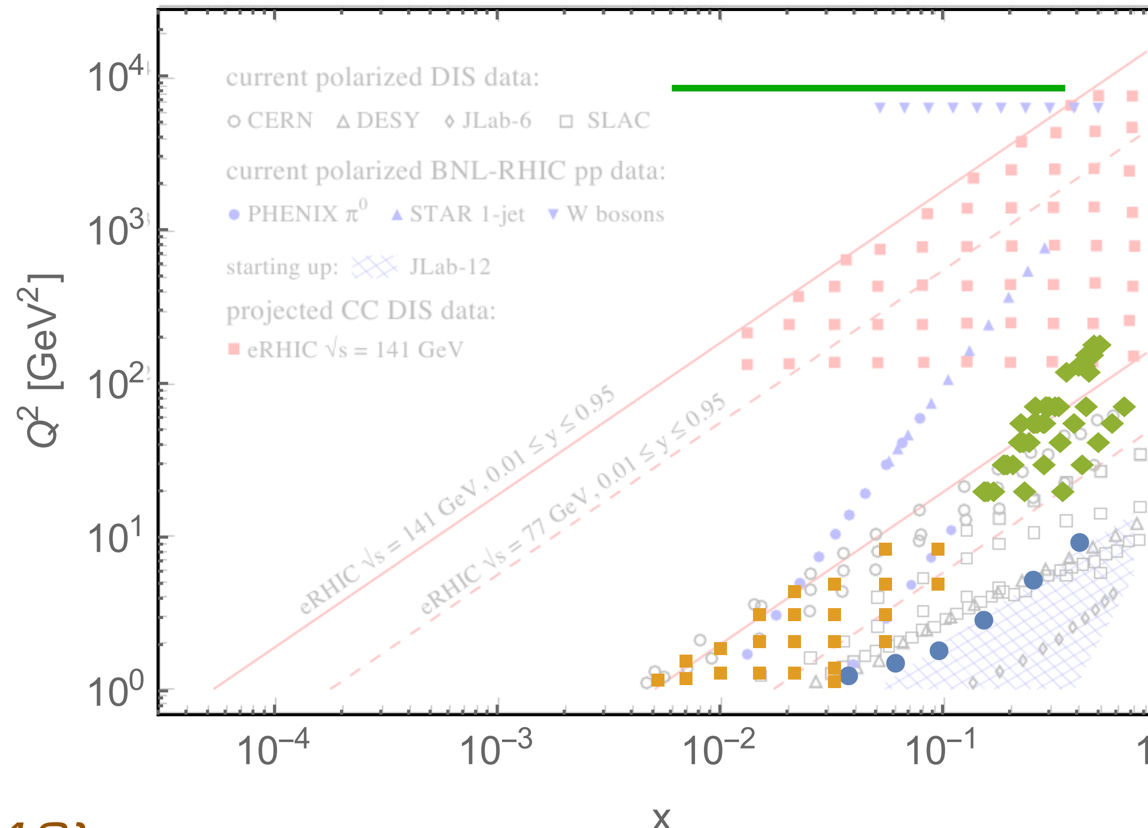




from EIC white paper EPJA 52 (2016)

Comparison with future perspectives

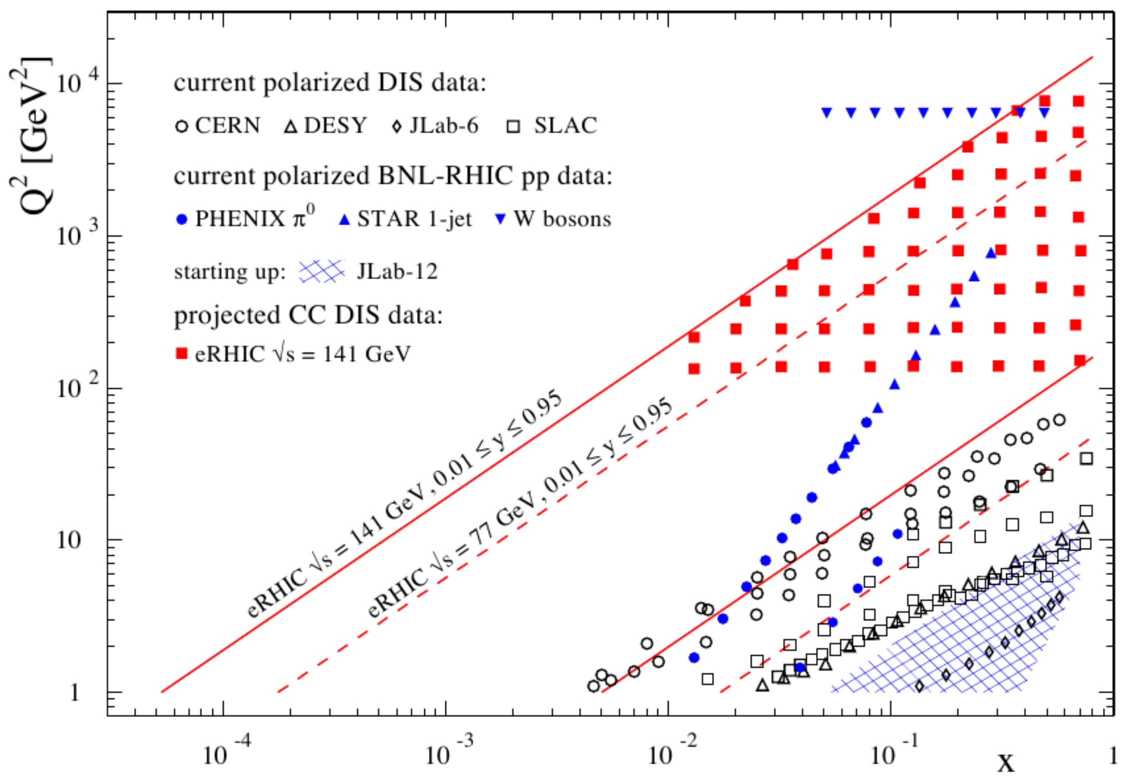


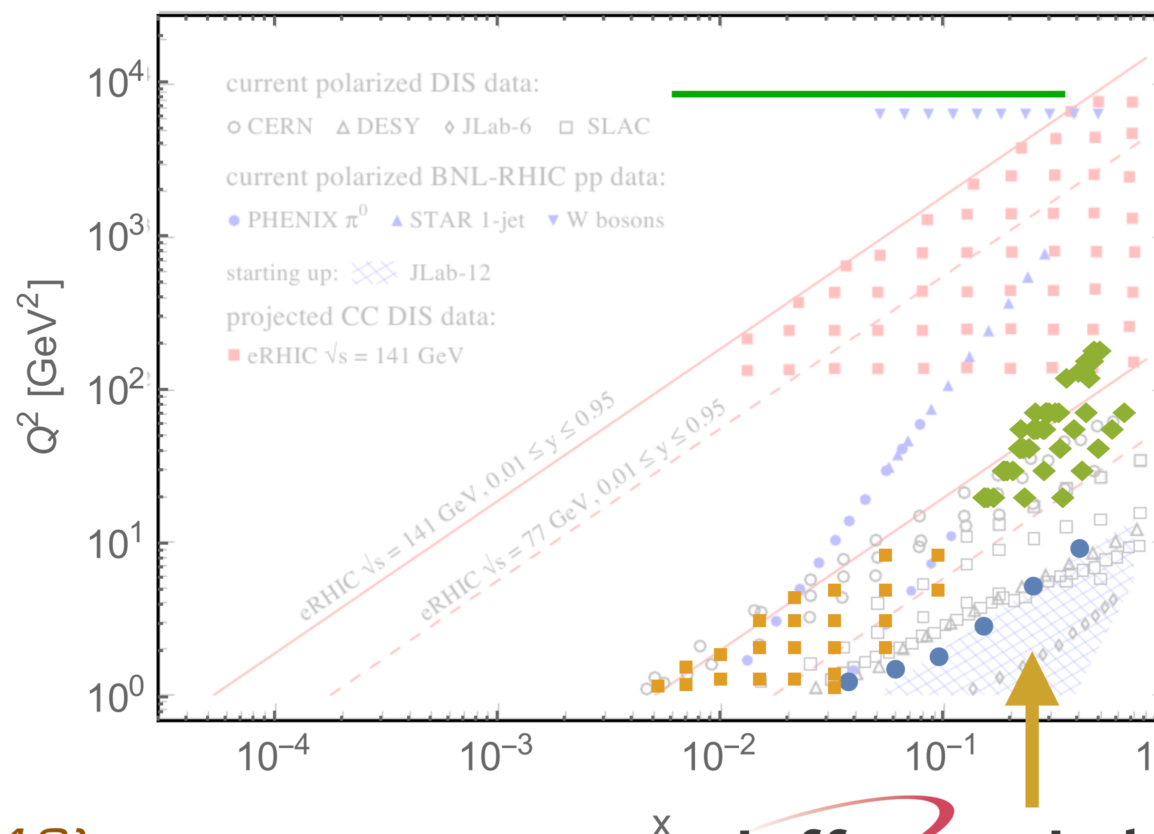


from EIC white paper EPJA 52 (2016)

To test the formalism, we would need more data covering the same x range and spanning over a large range in Q^2. Data from JLab and Drell-Yan would be very important.

Comparison with future perspectives



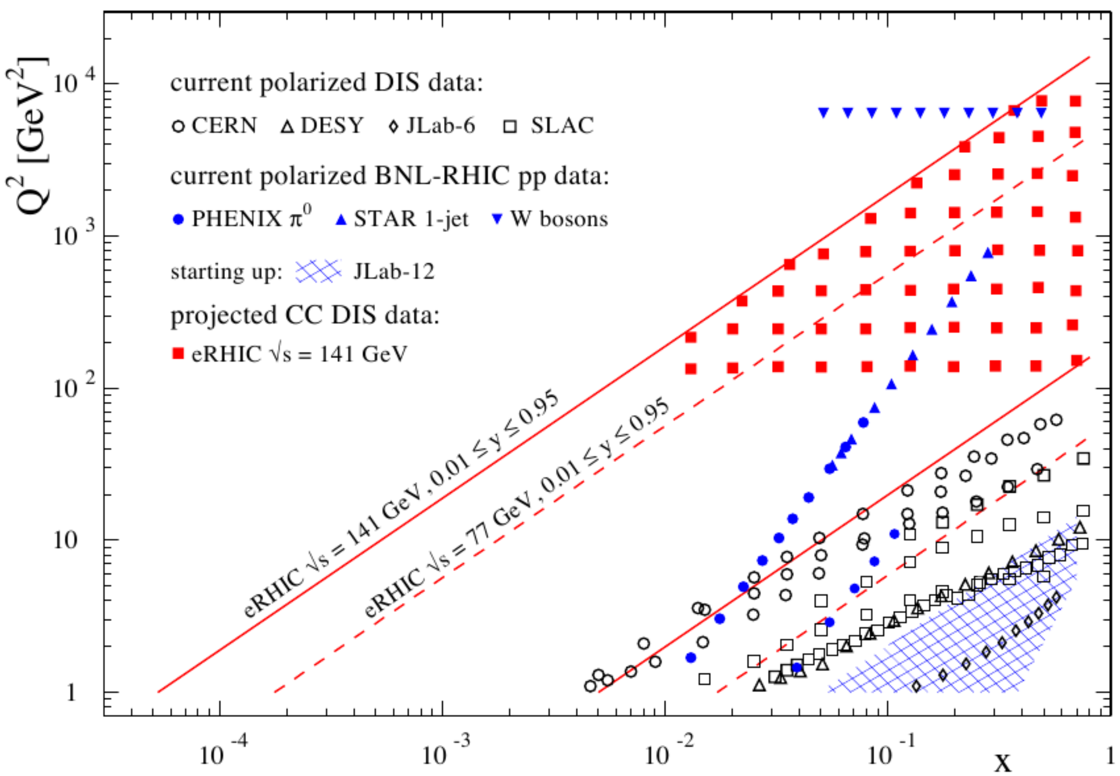


from EIC white paper EPJA 52 (2016)

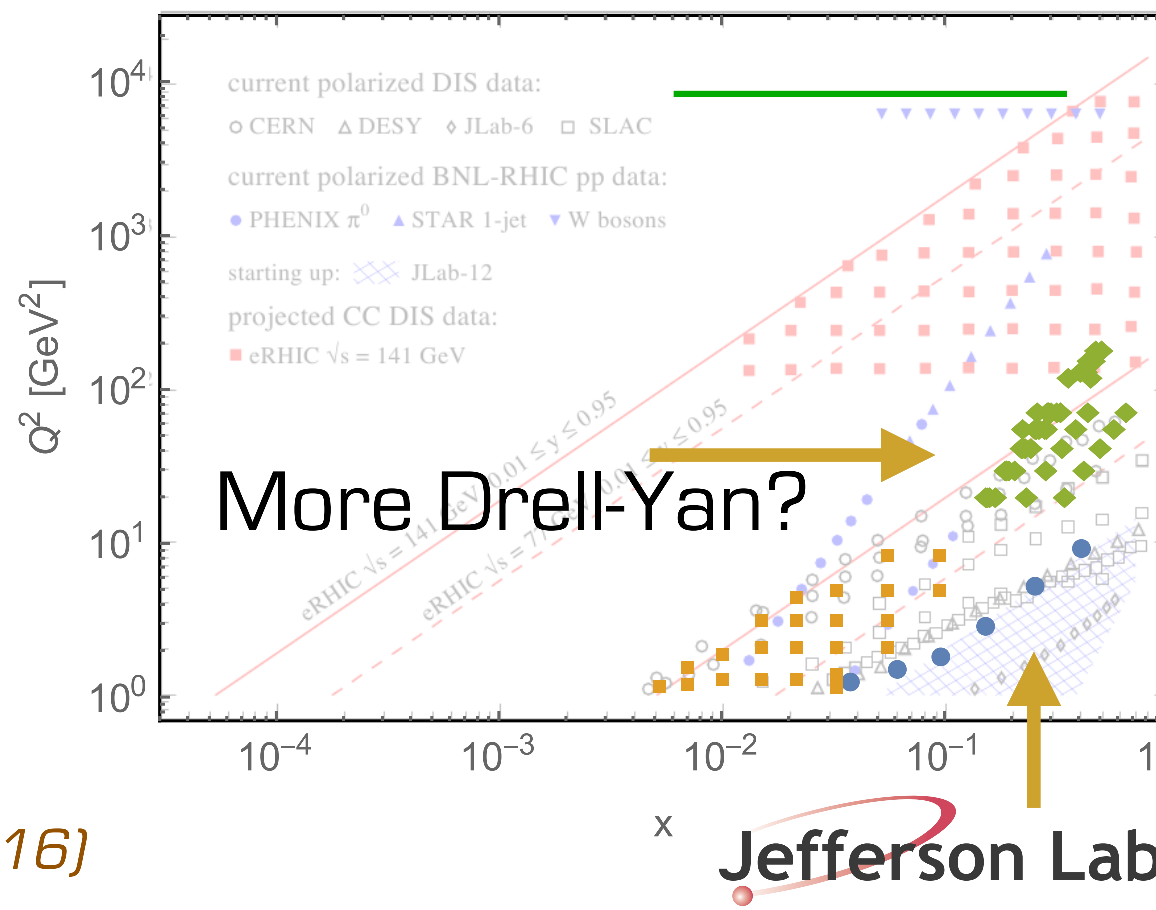
Jefferson Lab

To test the formalism, we would need more data covering the same x range and spanning over a large range in Q^2. Data from JLab and Drell-Yan would be very important.

Comparison with future perspectives

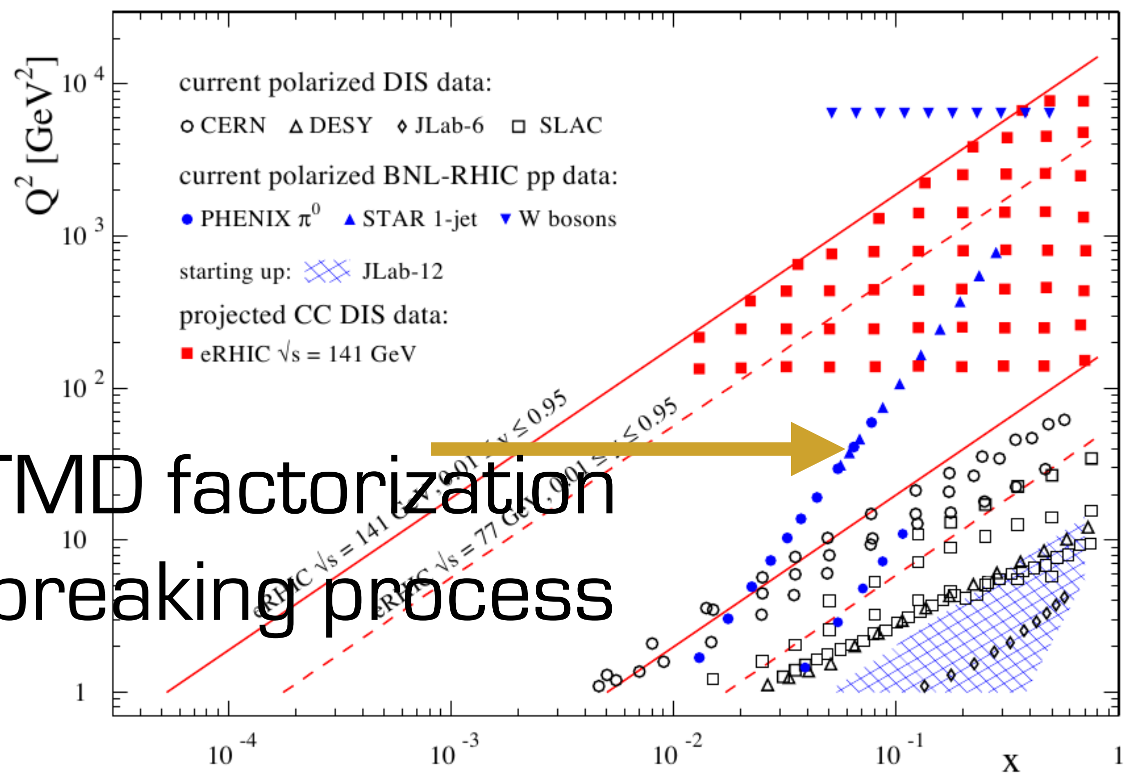


from EIC white paper EPJA 52 (2016)

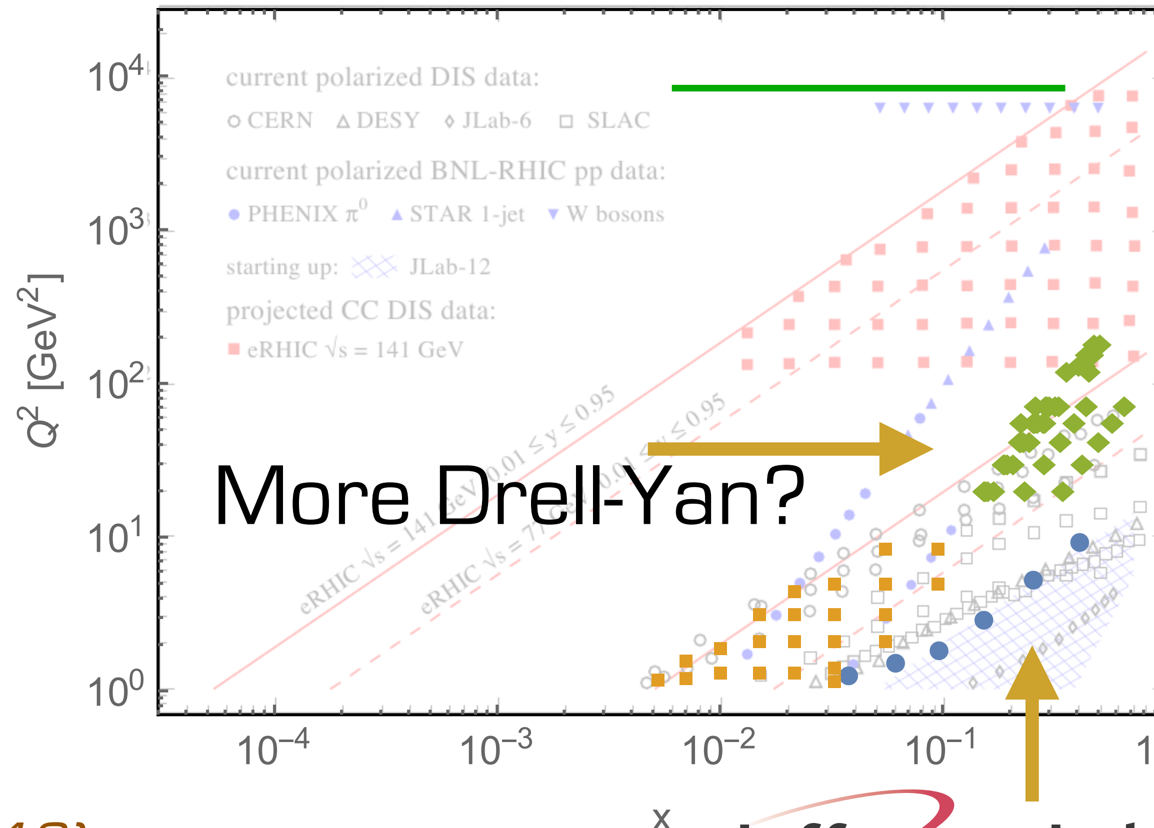


To test the formalism, we would need more data covering the same x range and spanning over a large range in Q^2. Data from JLab and Drell-Yan would be very important.

Comparison with future perspectives



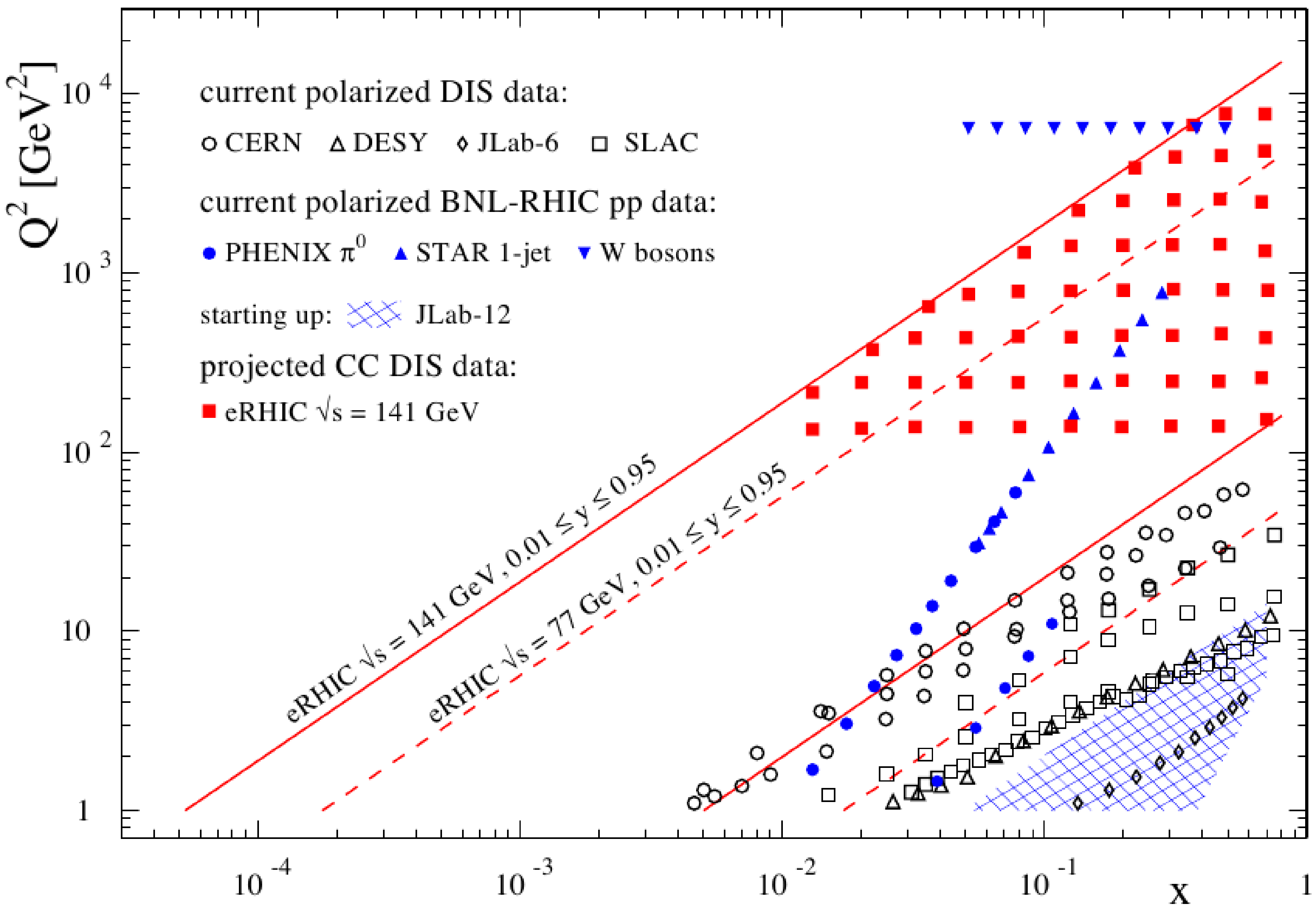
from EIC white paper EPJA 52 (2016)



Jefferson Lab

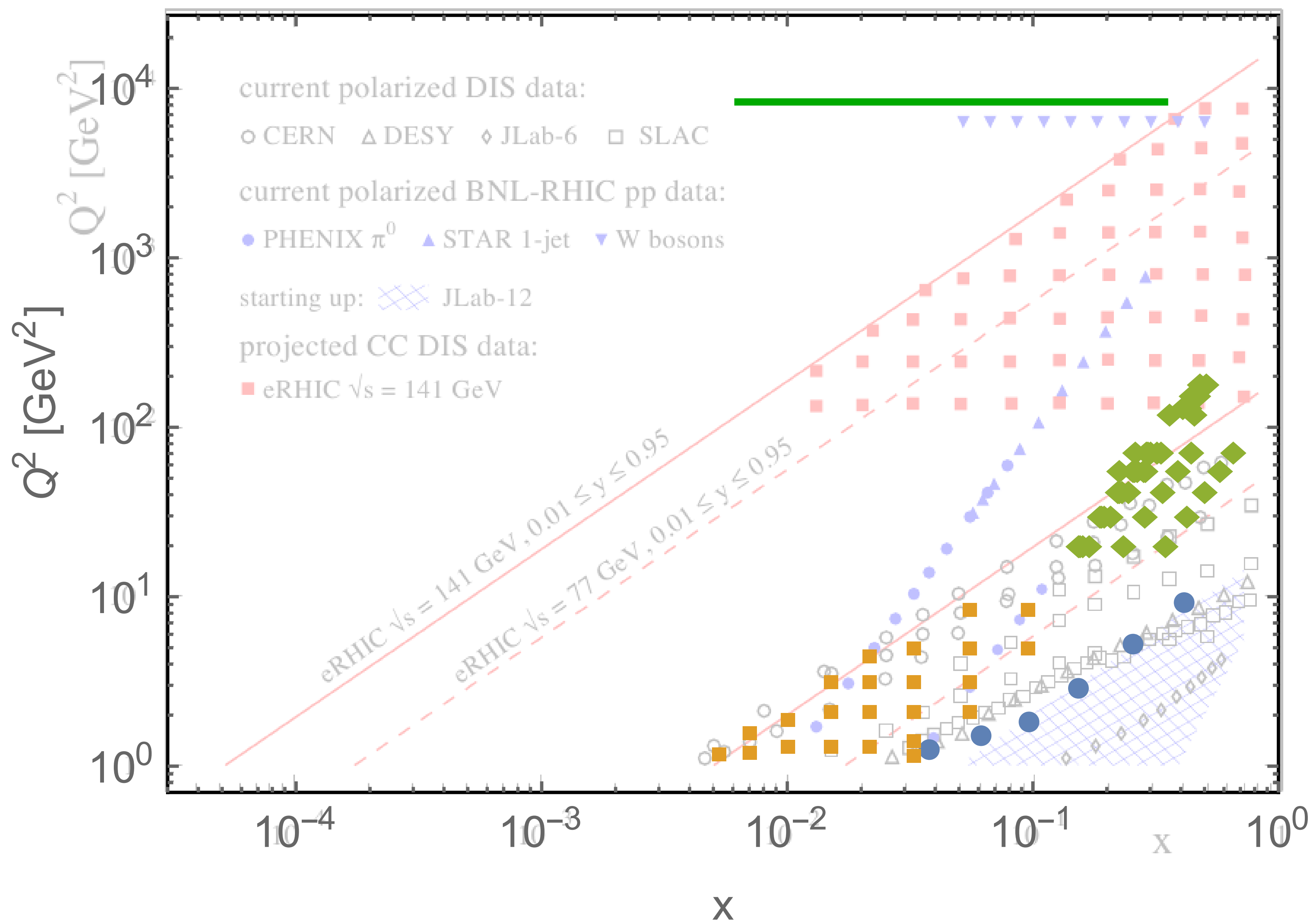
To test the formalism, we would need more data covering the same x range and spanning over a large range in Q^2. Data from JLab and Drell-Yan would be very important.

Future perspectives

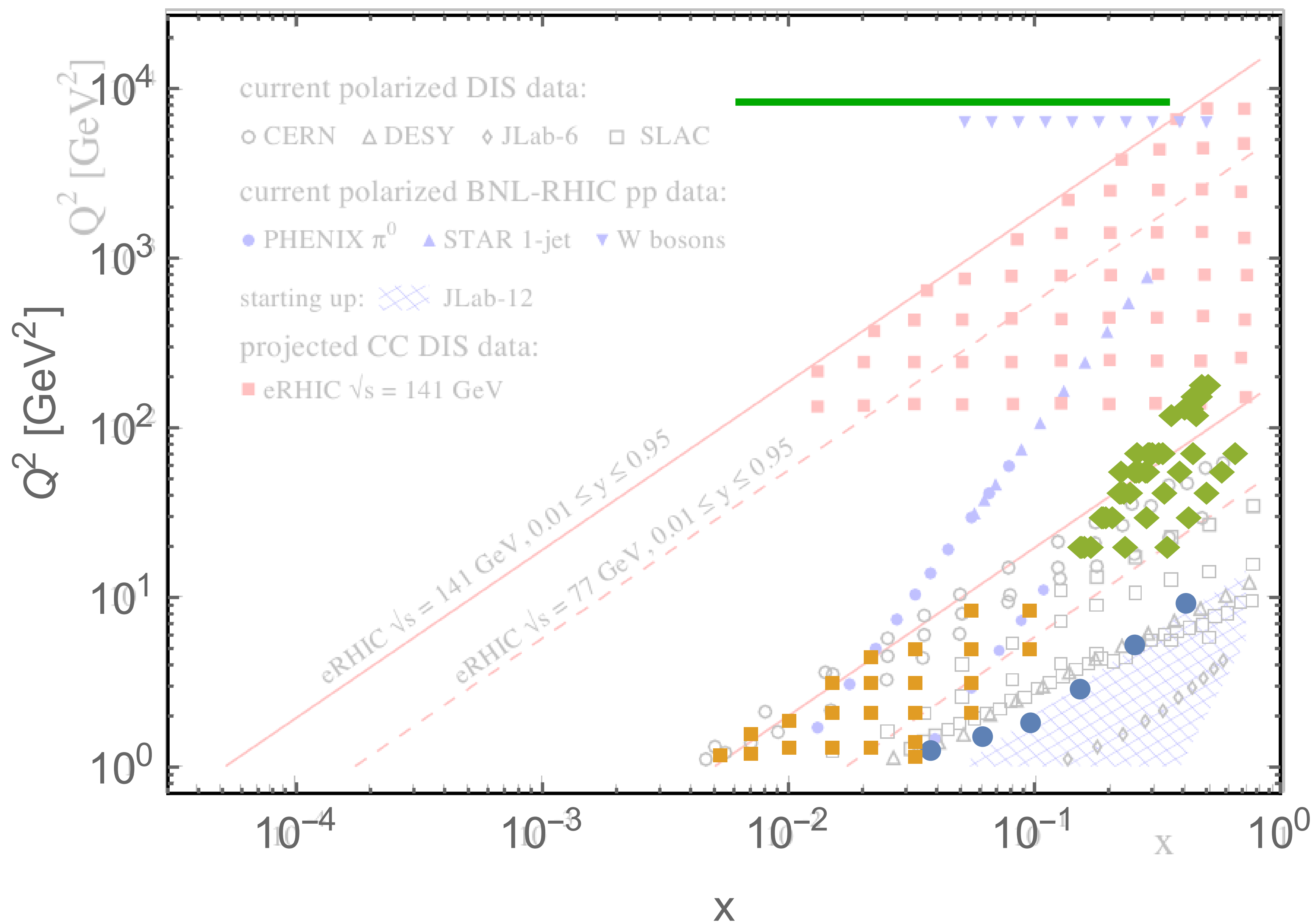


from EIC white paper EPJA 52 (2016)

Future perspectives

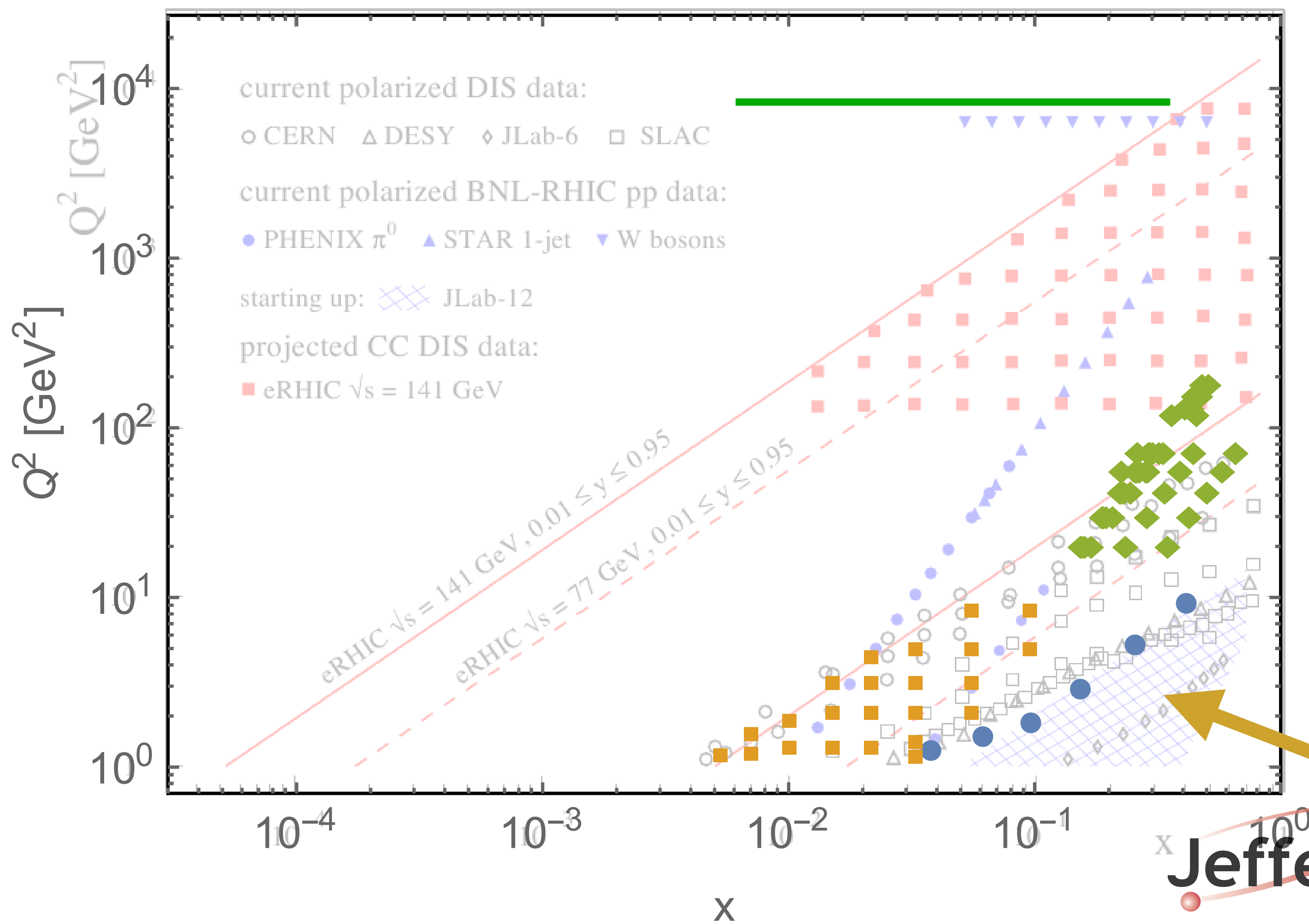


Future perspectives



To test the formalism, we would need more data covering the same x range and spanning over a large range in Q^2.
Data from JLab and Drell-Yan would be very important.

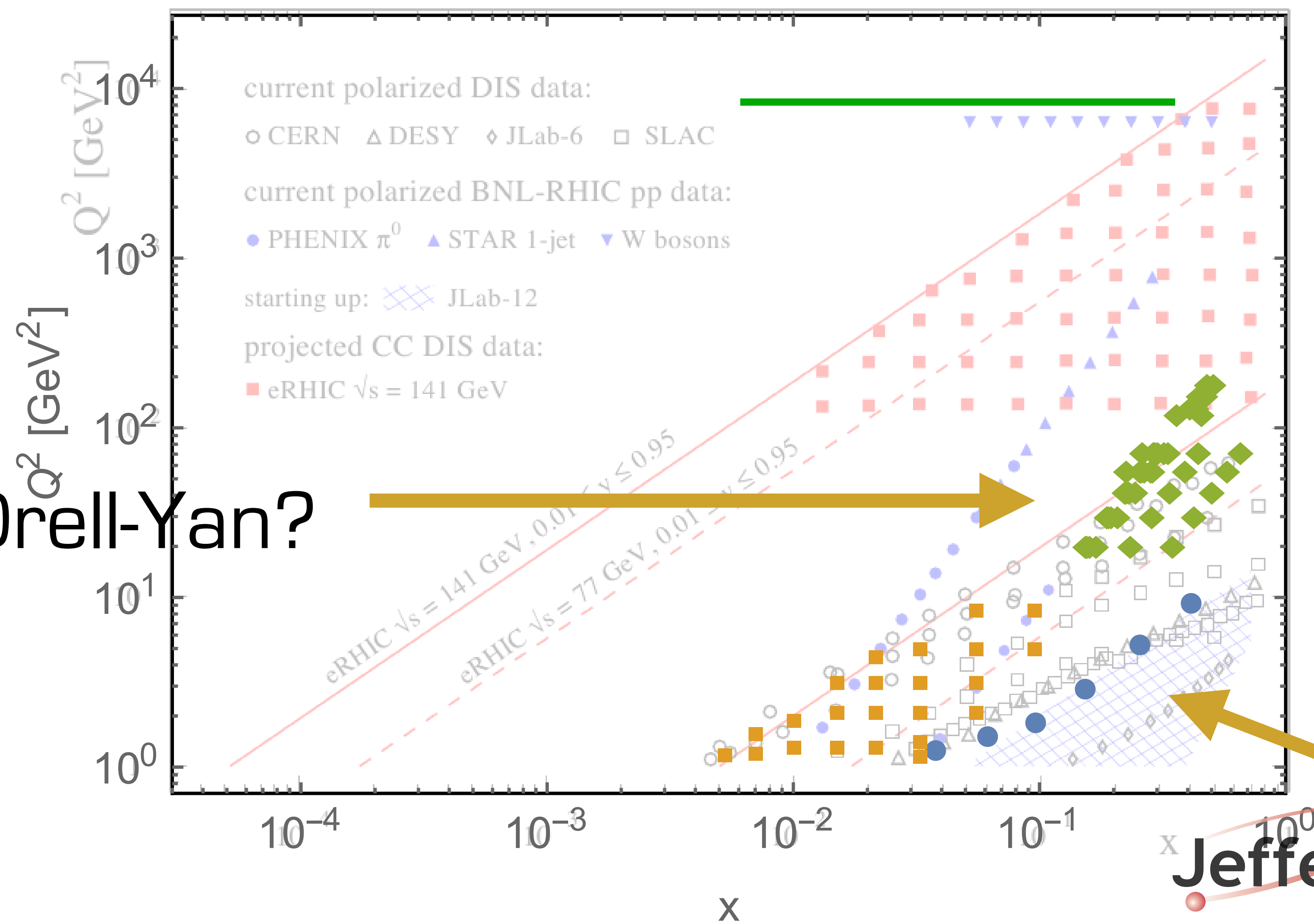
Future perspectives



Jefferson Lab

To test the formalism, we would need more data covering the same x range and spanning over a large range in Q^2.
Data from JLab and Drell-Yan would be very important.

Future perspectives



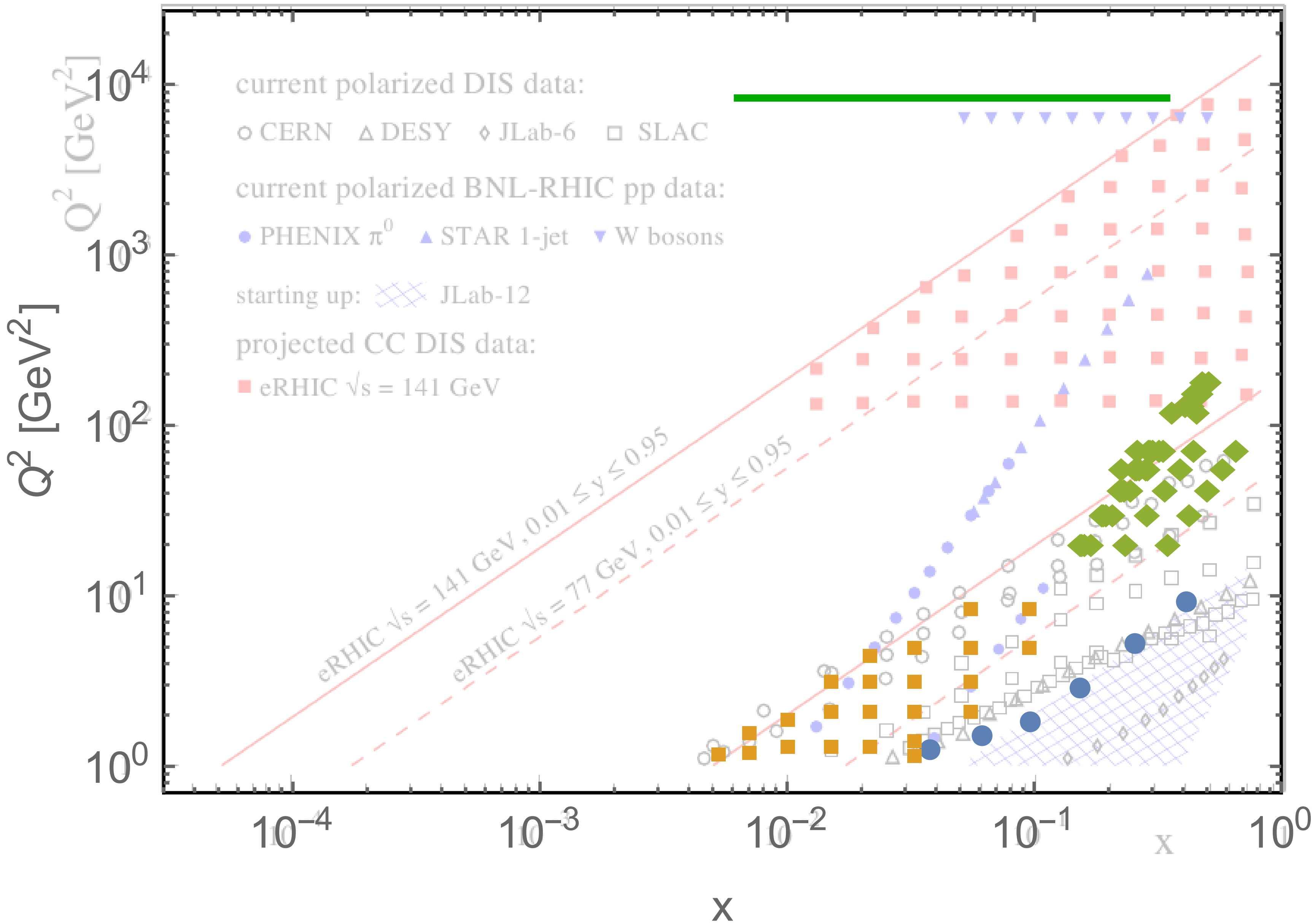
More Drell-Yan?

Jefferson Lab

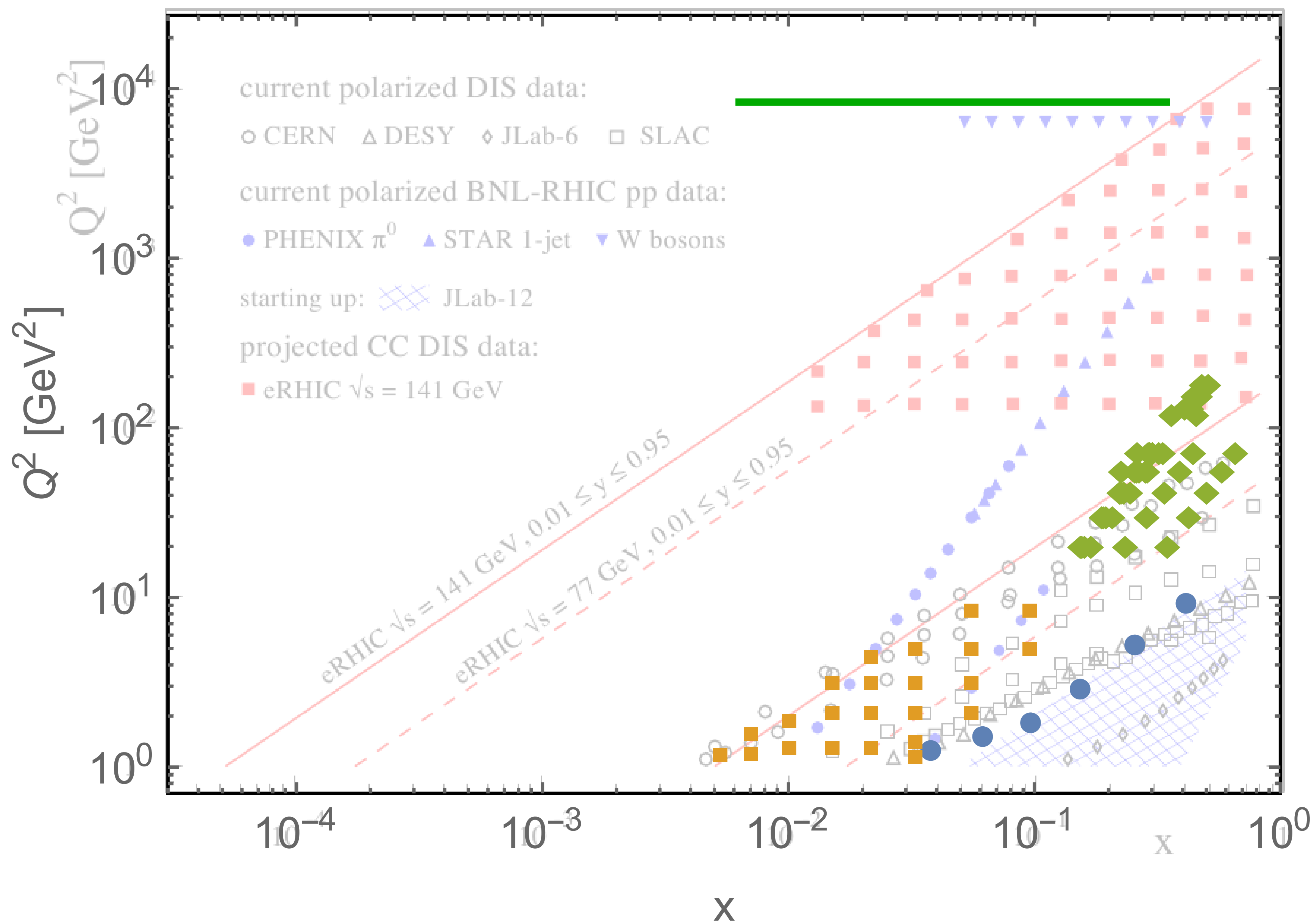
To test the formalism, we would need more data covering the same x range and spanning over a large range in Q^2.

Data from JLab and Drell-Yan would be very important.

Future perspectives

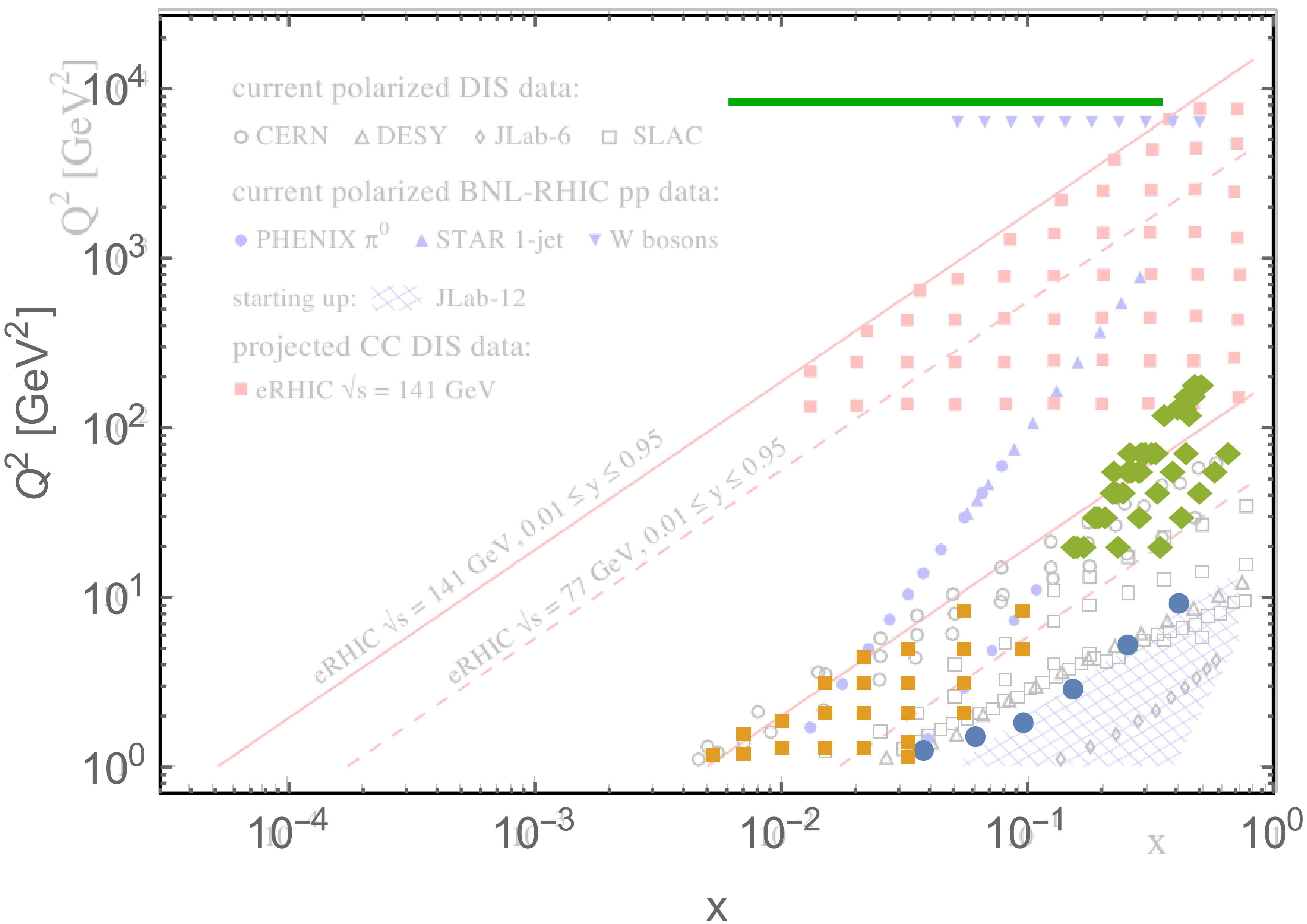


Future perspectives



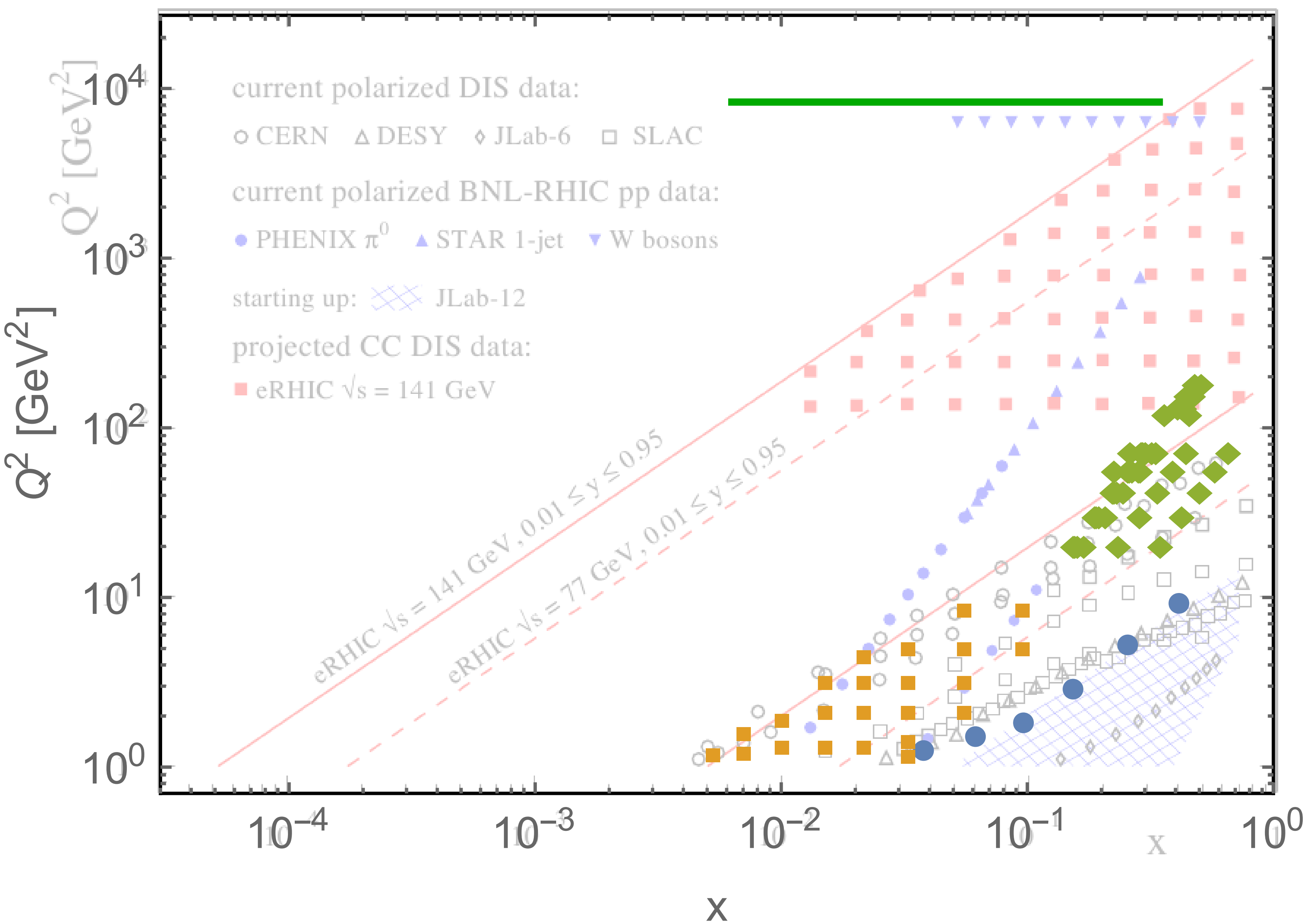
To test the formalism, we would need more data covering the same x range and spanning over a large range in Q^2.
Data from JLab and Drell-Yan would be very important.

Future perspectives



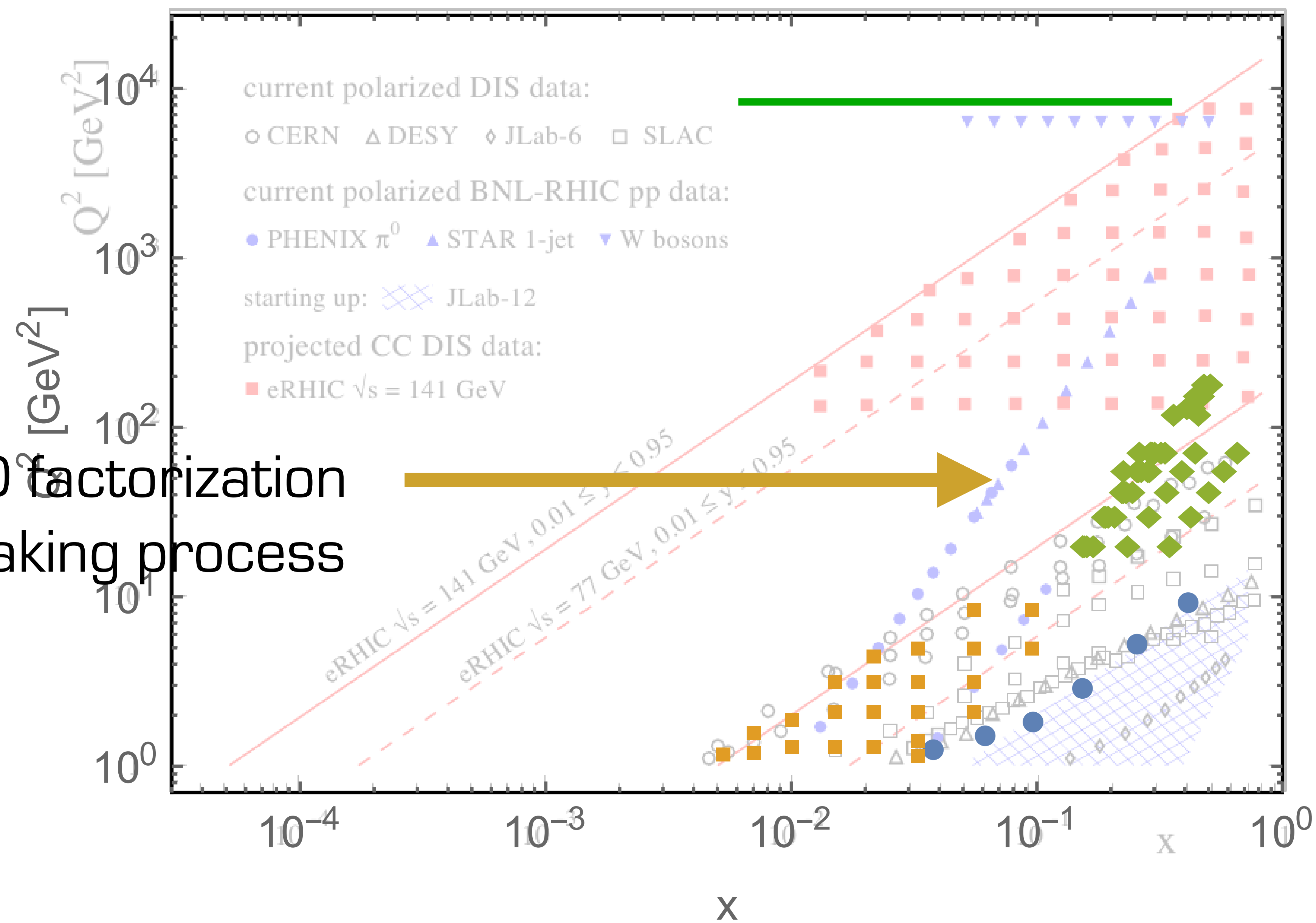
To test the formalism, we would need more data covering the same x range and spanning over a large range in Q^2.
Data from JLab and Drell-Yan would be very important.

Future perspectives



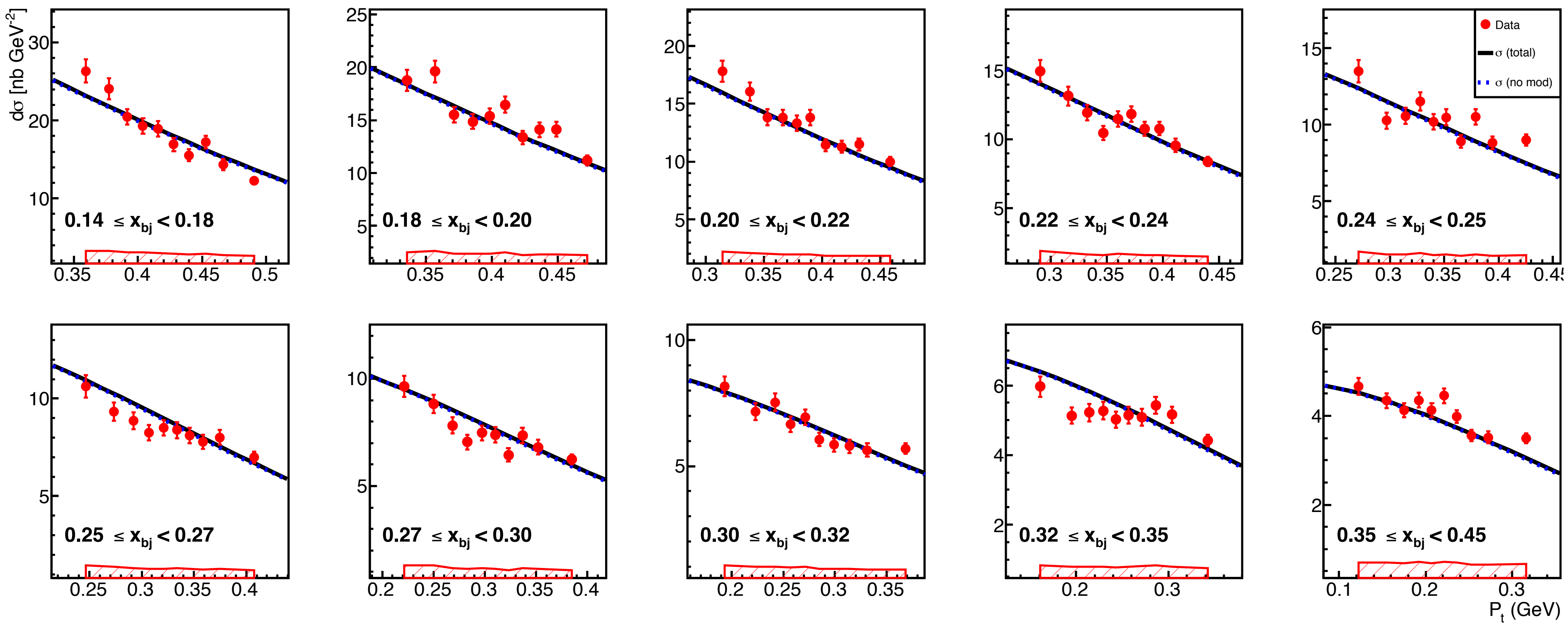
To test the formalism, we would need more data covering the same x range and spanning over a large range in Q^2.
Data from JLab and Drell-Yan would be very important.

Future perspectives



To test the formalism, we would need more data covering the same x range and spanning over a large range in Q^2.
Data from JLab and Drell-Yan would be very important.

Recent ^{3}He data from JLab Hall A

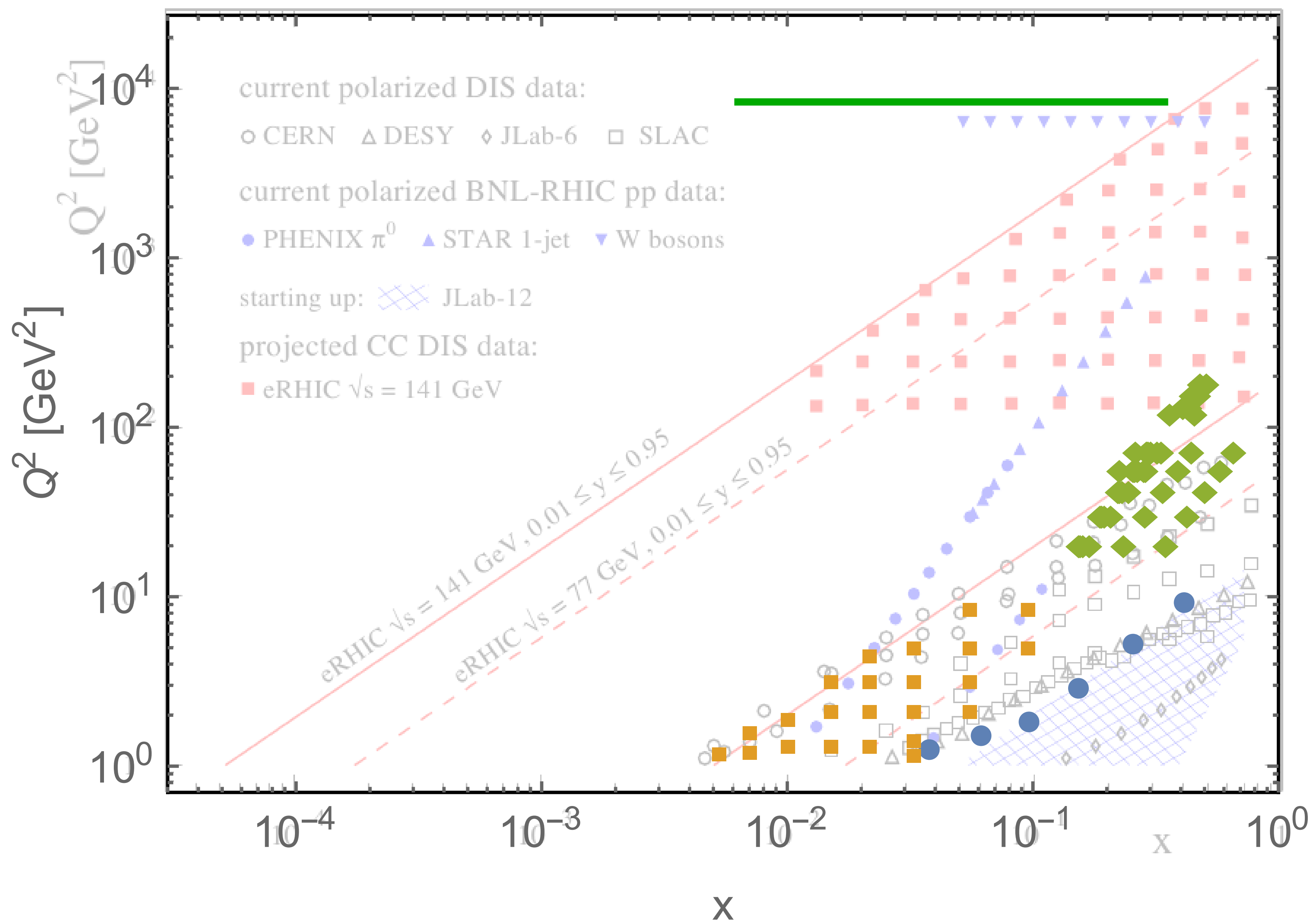


Jefferson Lab

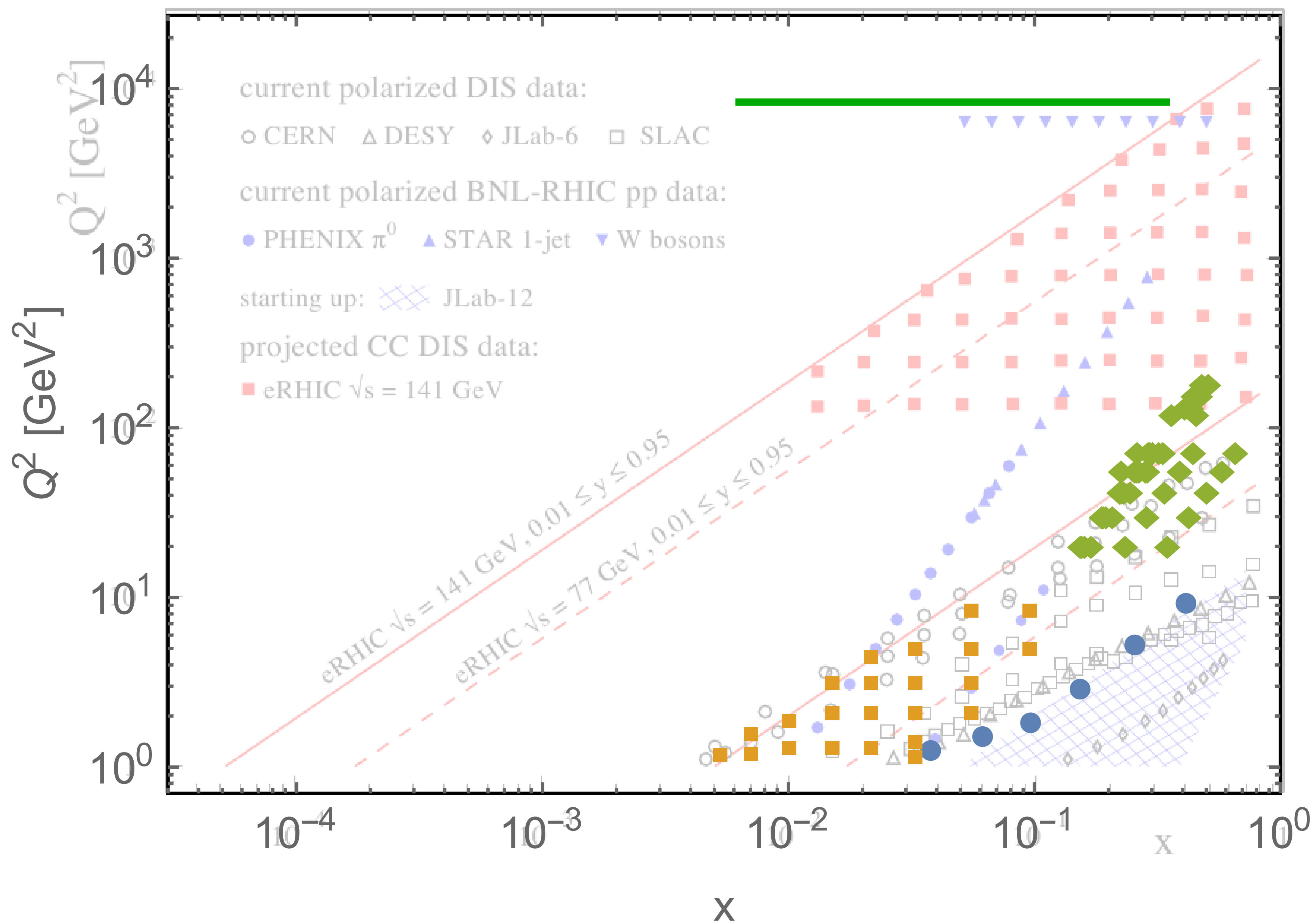
Yan et al., [arXiv:1610.02350]

Not included in the present fits on the ground that it is at 6 GeV: needs to be checked!

Future perspectives

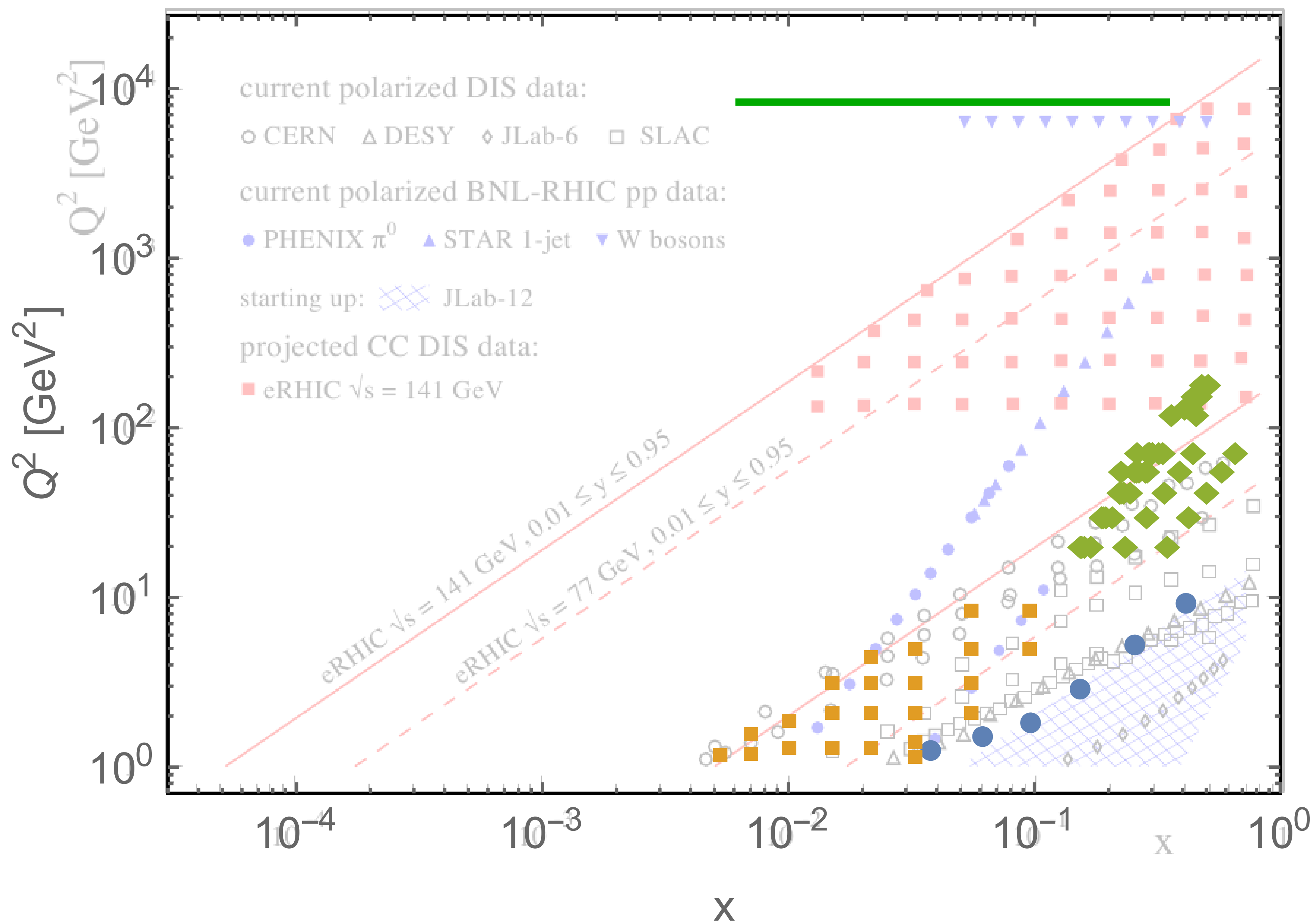


Future perspectives



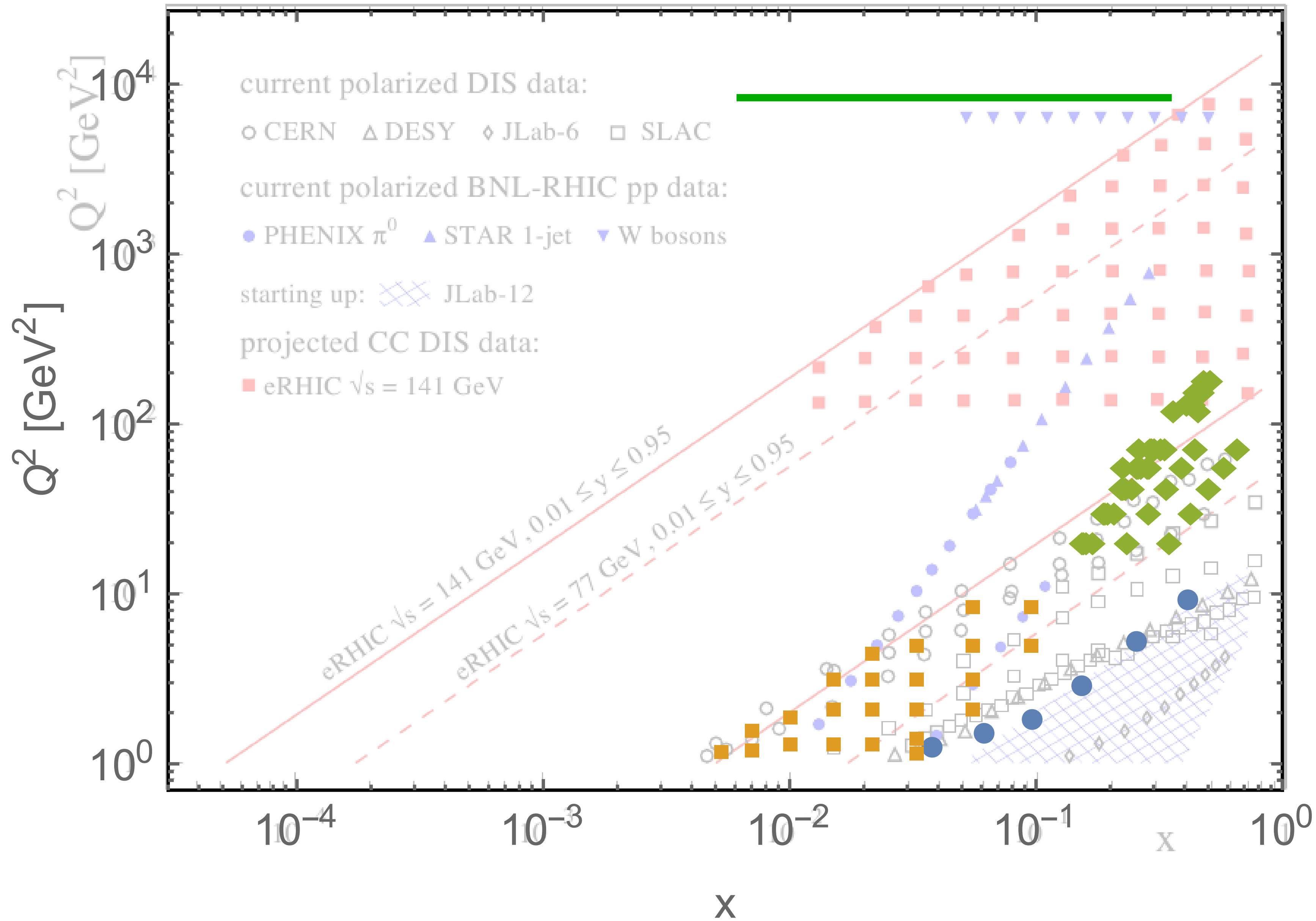
To test the formalism, we would need more data covering the same x range and spanning over a large range in Q^2.
Data from JLab and Drell-Yan would be very important.

Future perspectives



To test the formalism, we would need more data covering the same x range and spanning over a large range in Q^2.
Data from JLab and Drell-Yan would be very important.

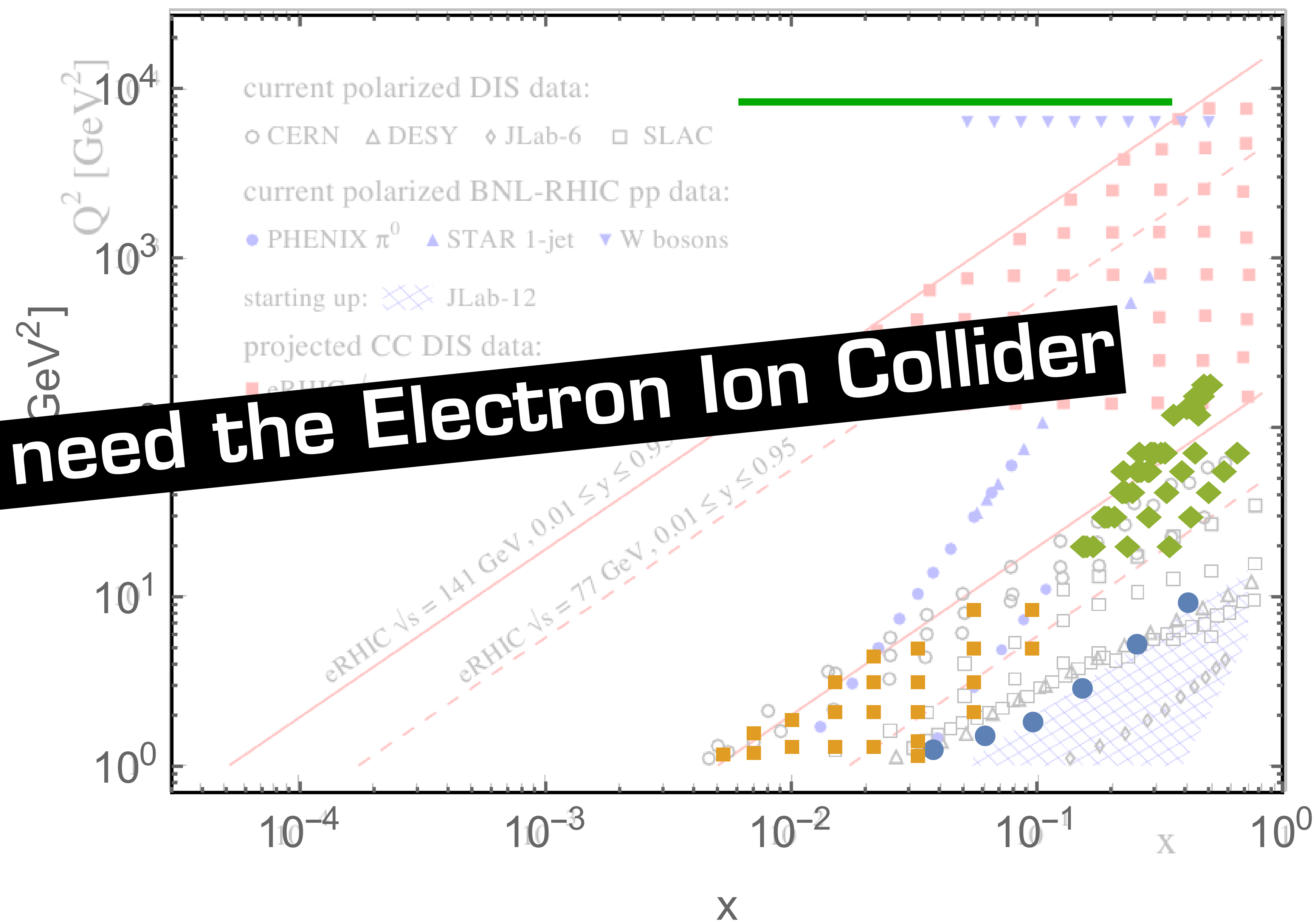
Future perspectives



To test the formalism, we would need more data covering the same x range and spanning over a large range in Q^2.

Data from JLab and Drell-Yan would be very important.

Future perspectives



We need the Electron Ion Collider

To test the formalism, we would need more data covering the same x range and spanning over a large range in Q^2.
Data from JLab and Drell-Yan would be very important.

Conclusions

Conclusions

- We demonstrated for the first time that it is possible to fit simultaneously SIDIS, DY, and Z boson data

Conclusions

- We demonstrated for the first time that it is possible to fit simultaneously SIDIS, DY, and Z boson data

- We extracted unpolarized TMDs using several thousand data points

Conclusions

- We demonstrated for the first time that it is possible to fit simultaneously SIDIS, DY, and Z boson data
- We extracted unpolarized TMDs using several thousand data points
- The TMD framework seems to hold pretty well

Conclusions

- We demonstrated for the first time that it is possible to fit simultaneously SIDIS, DY, and Z boson data

- We extracted unpolarized TMDs using several thousand data points

- The TMD framework seems to hold pretty well

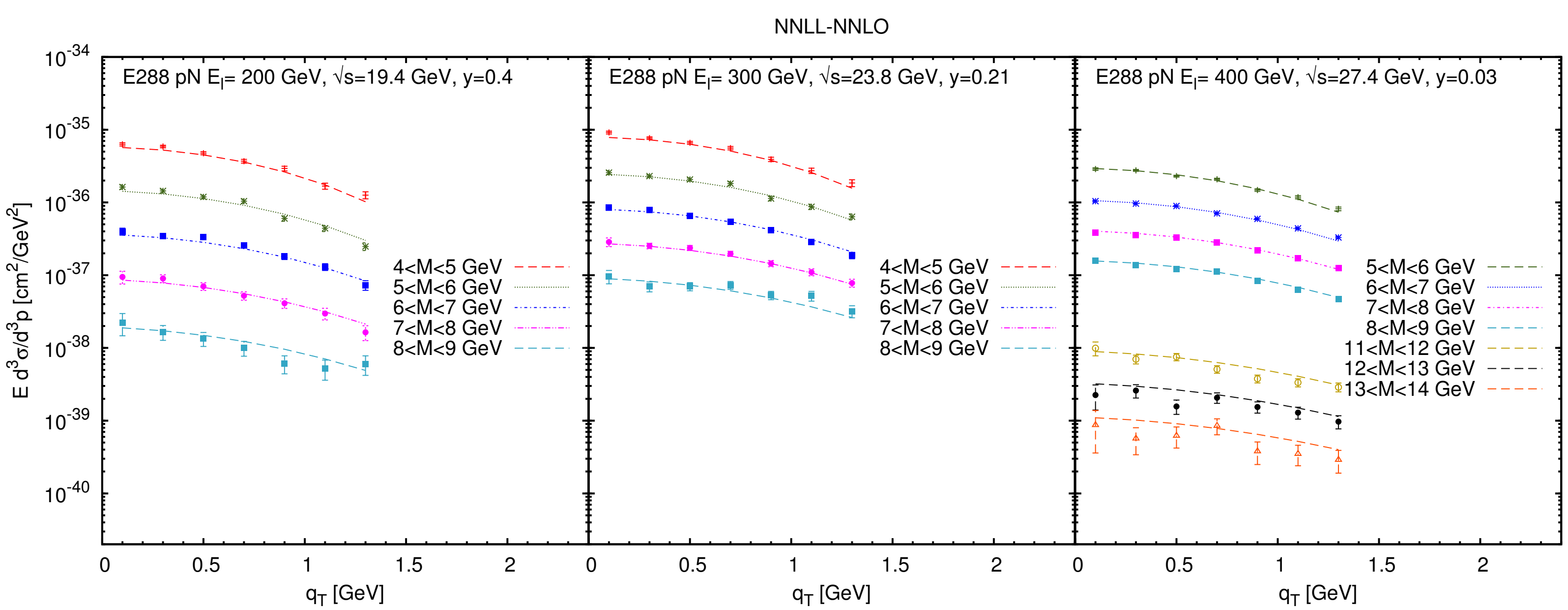
- Most of the discrepancies come from the normalisation

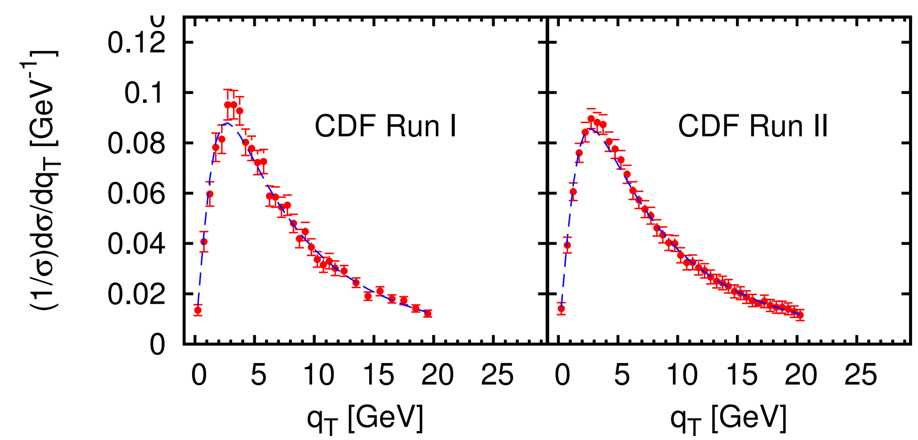
Conclusions

- We demonstrated for the first time that it is possible to fit simultaneously SIDIS, DY, and Z boson data
- We extracted unpolarized TMDs using several thousand data points
- The TMD framework seems to hold pretty well
- Most of the discrepancies come from the normalisation
- Y terms still to be implemented

Drell-Yan + Z production data (DEMS

D'Alesio, Echevarria, Melis, Scimemi, JHEP 1411 (14)



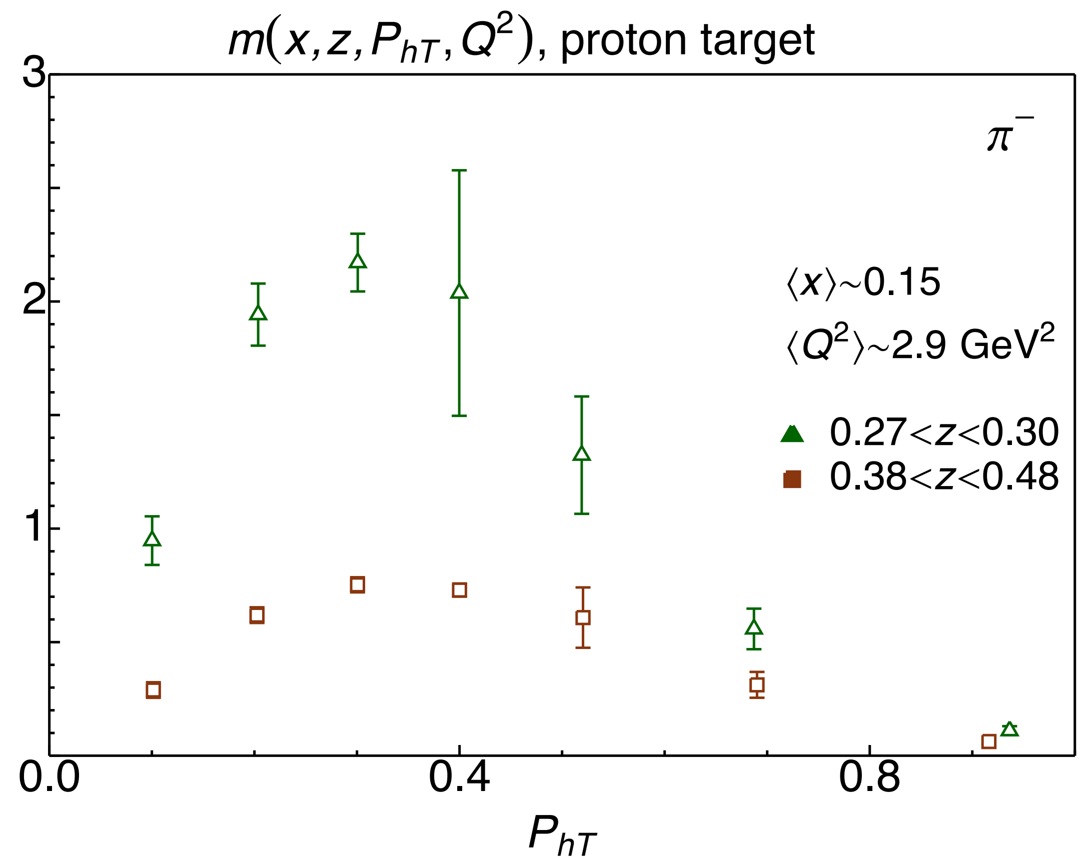


The fit implements TMD evolution at Next-to-Next-to-Leading log (state of the art)

Several choices are peculiar to this fit and not "standard"

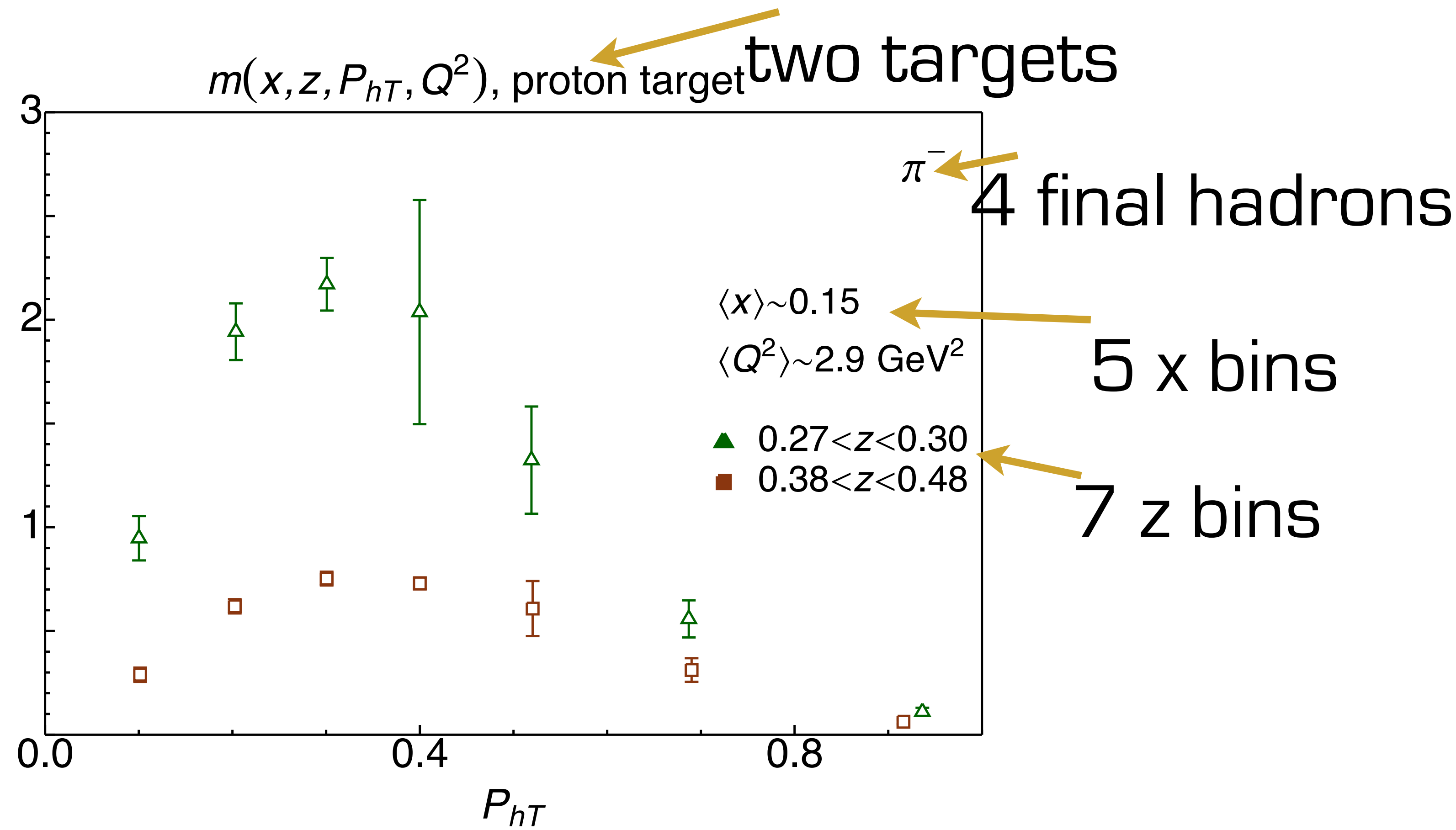
The agreement with data is excellent ($\chi^2/\mathrm{dof} = 1.10$)

The replica method



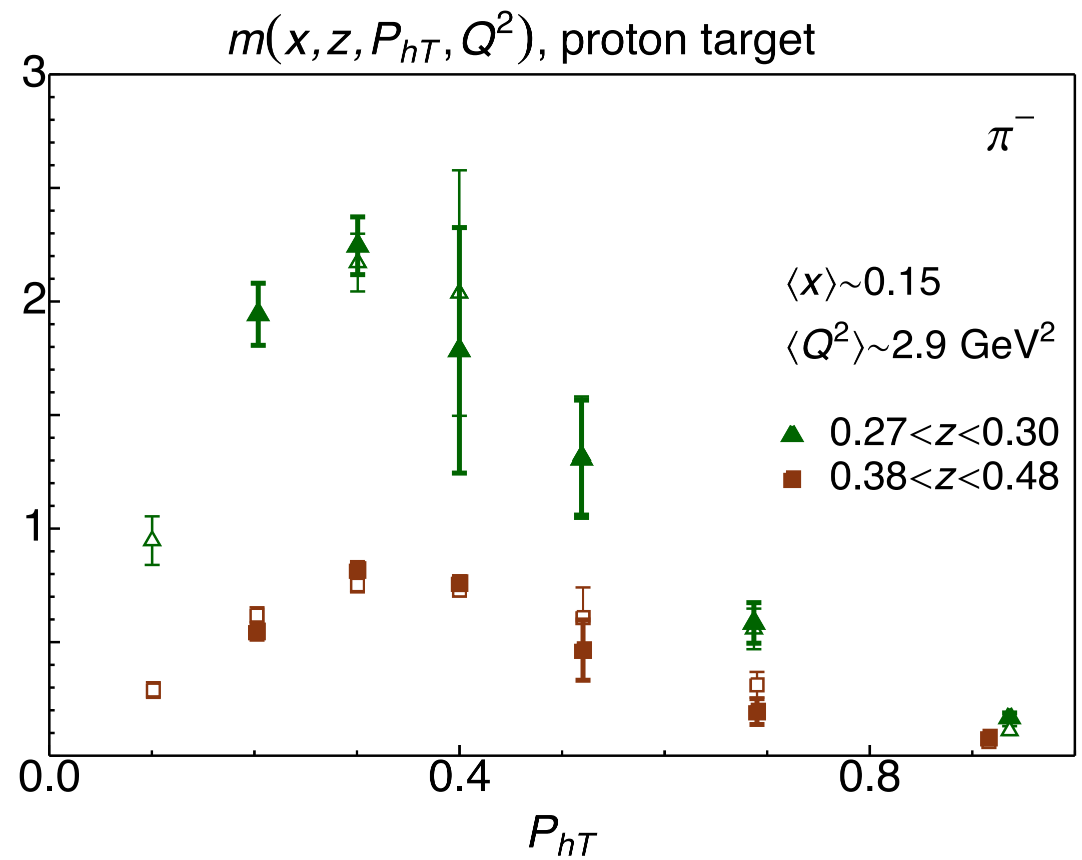
Example of original data

The replica method



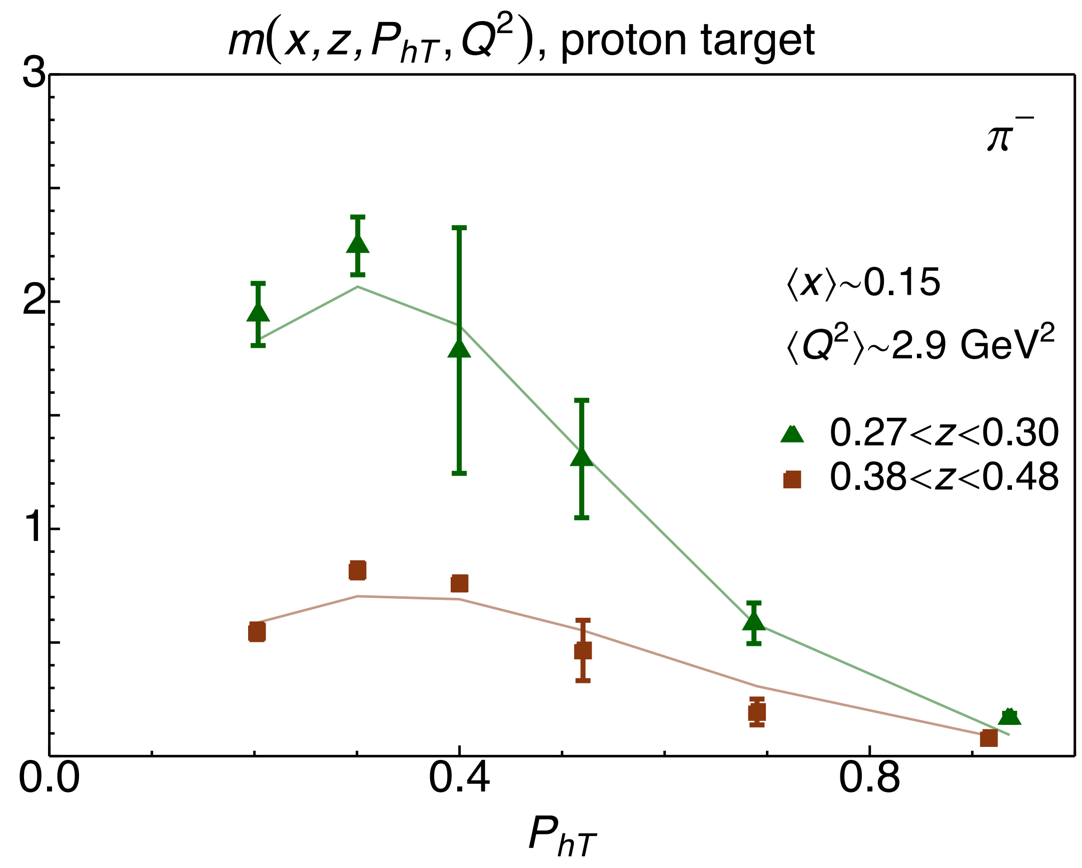
Example of original data

The replica method



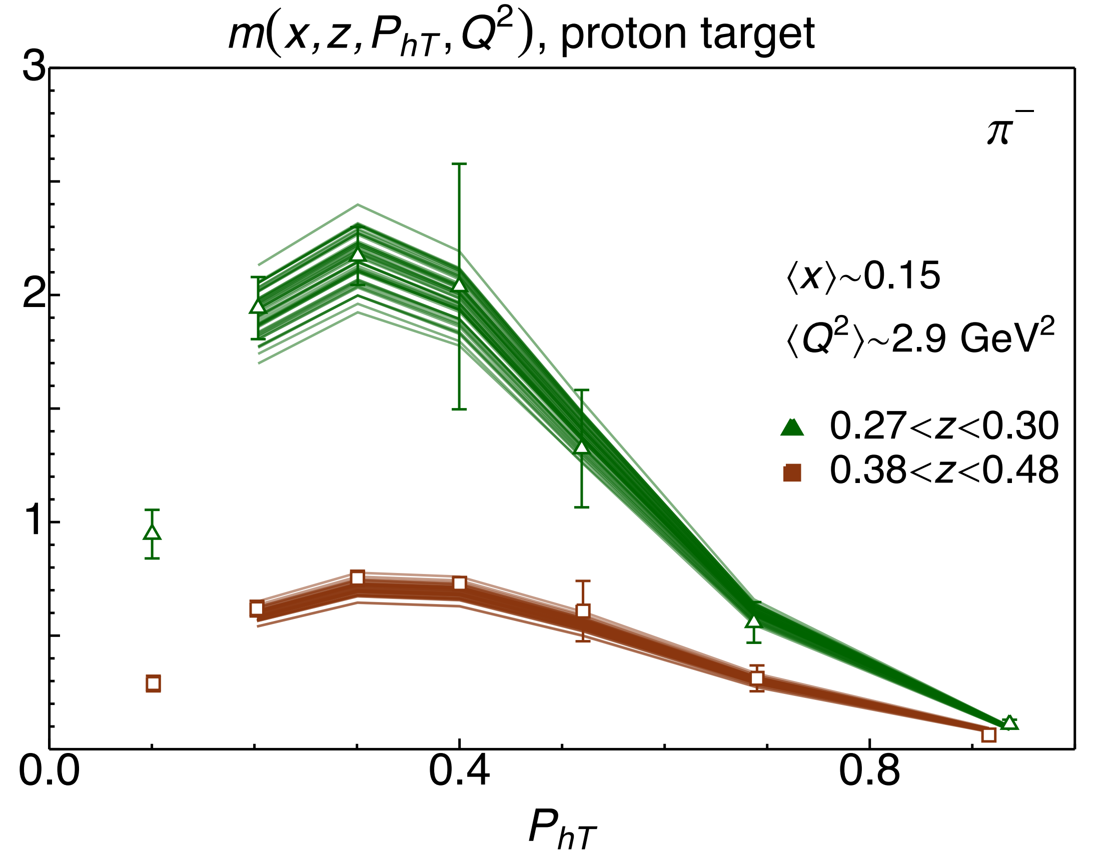
Data are replicated (with Gaussian distribution)

The replica method



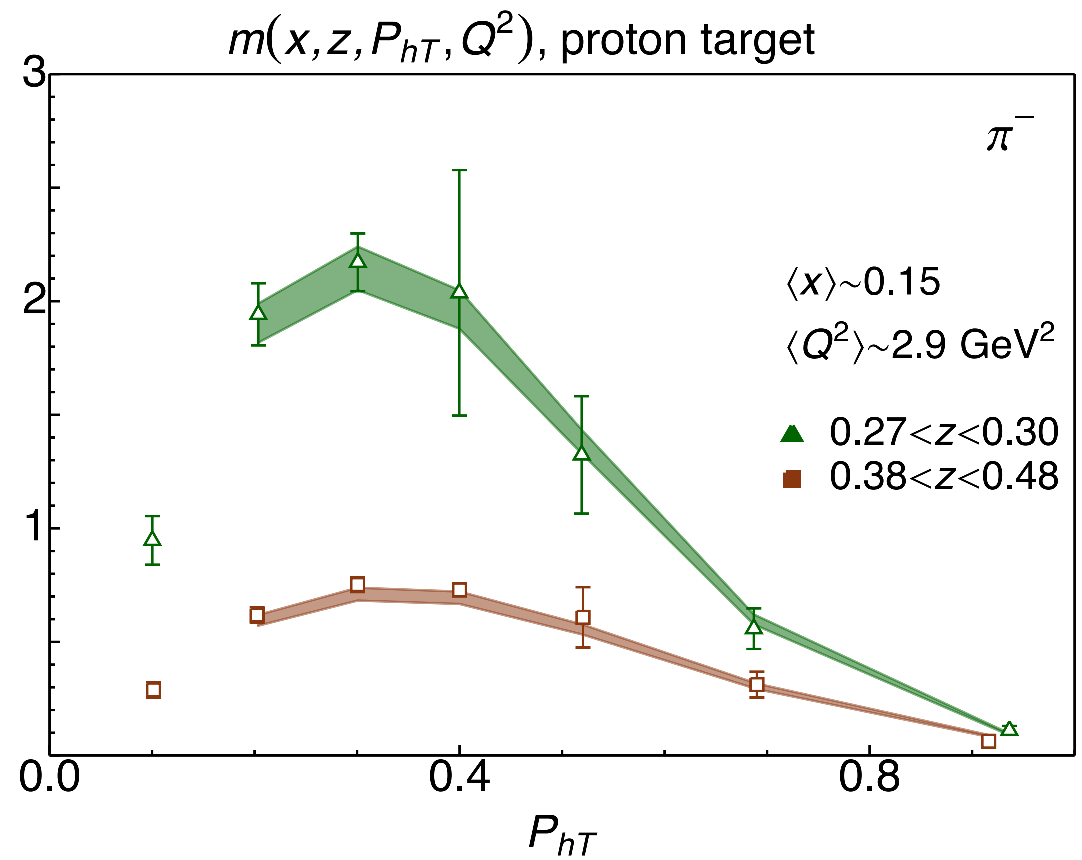
The fit is performed on the replicated data

The replica method



The procedure is repeated 200 times

The replica method



For each point, a central 68% confidence interval is identified