First attempts at a global fit of unpolarized Transverse Momentum Distributions

Alessandro Bacchetta

Funded by

3DSPIN
MAPPING THE PROTON IN 3D

European Research Council

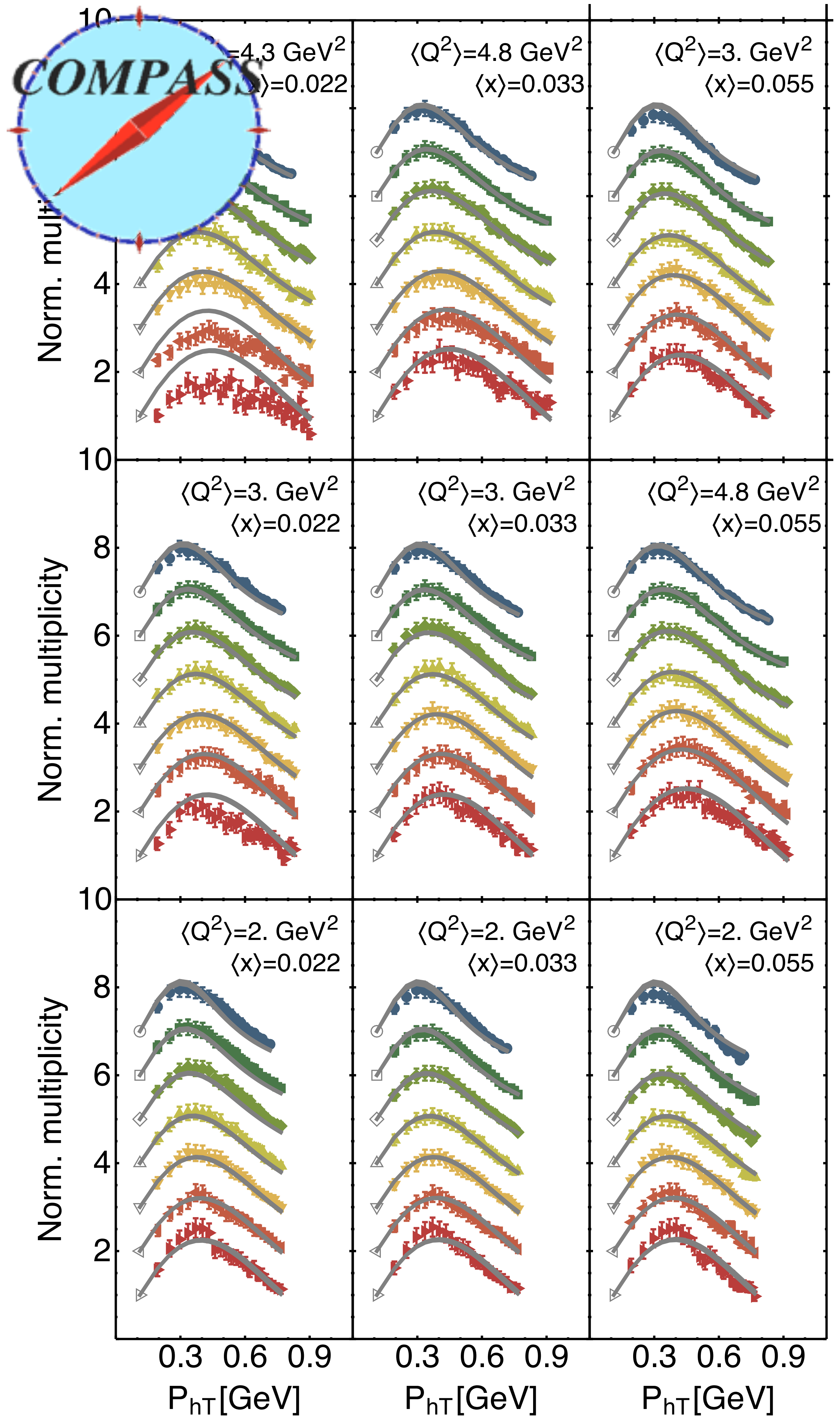
INFN
Istituto Nazionale di Fisica Nucleare

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

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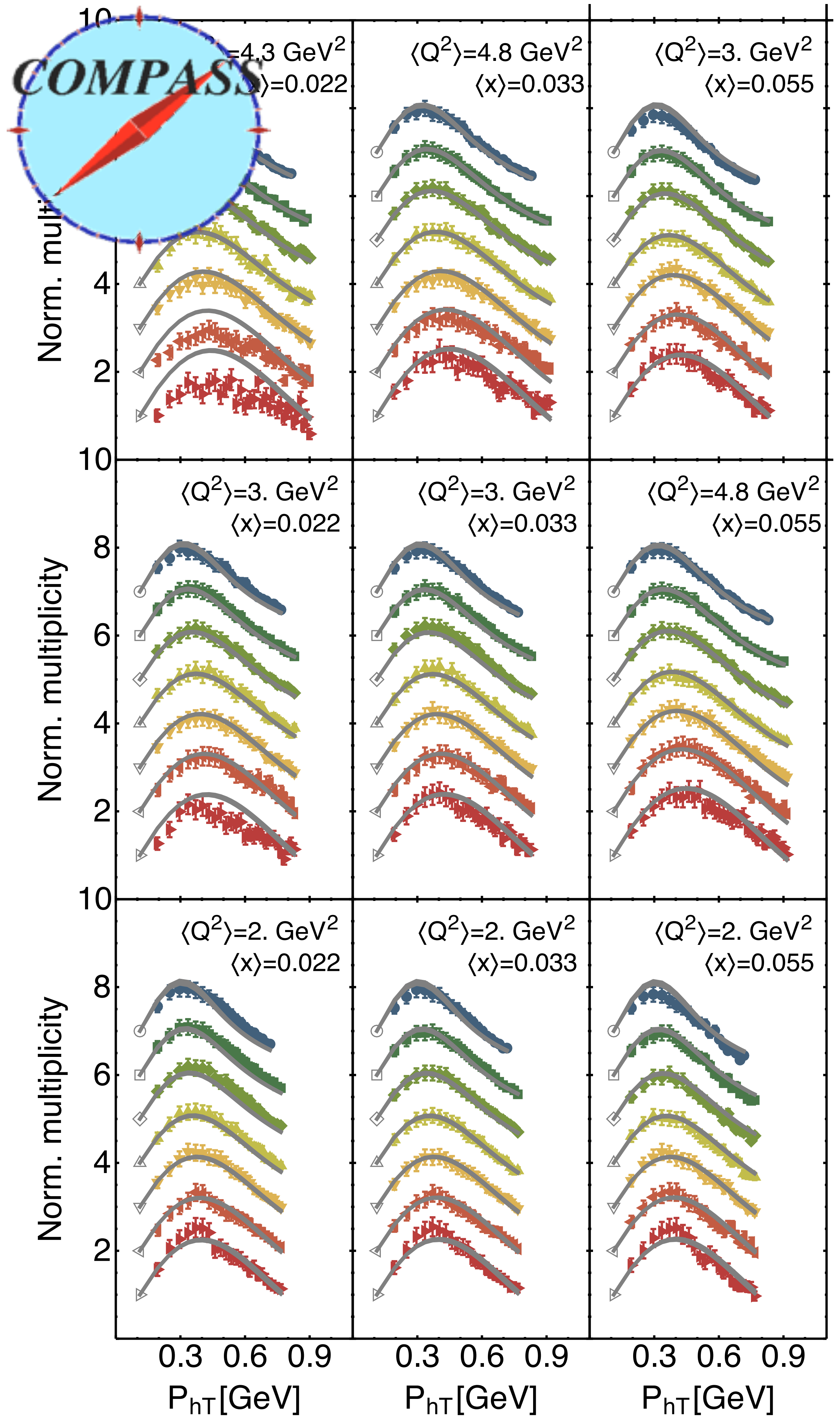
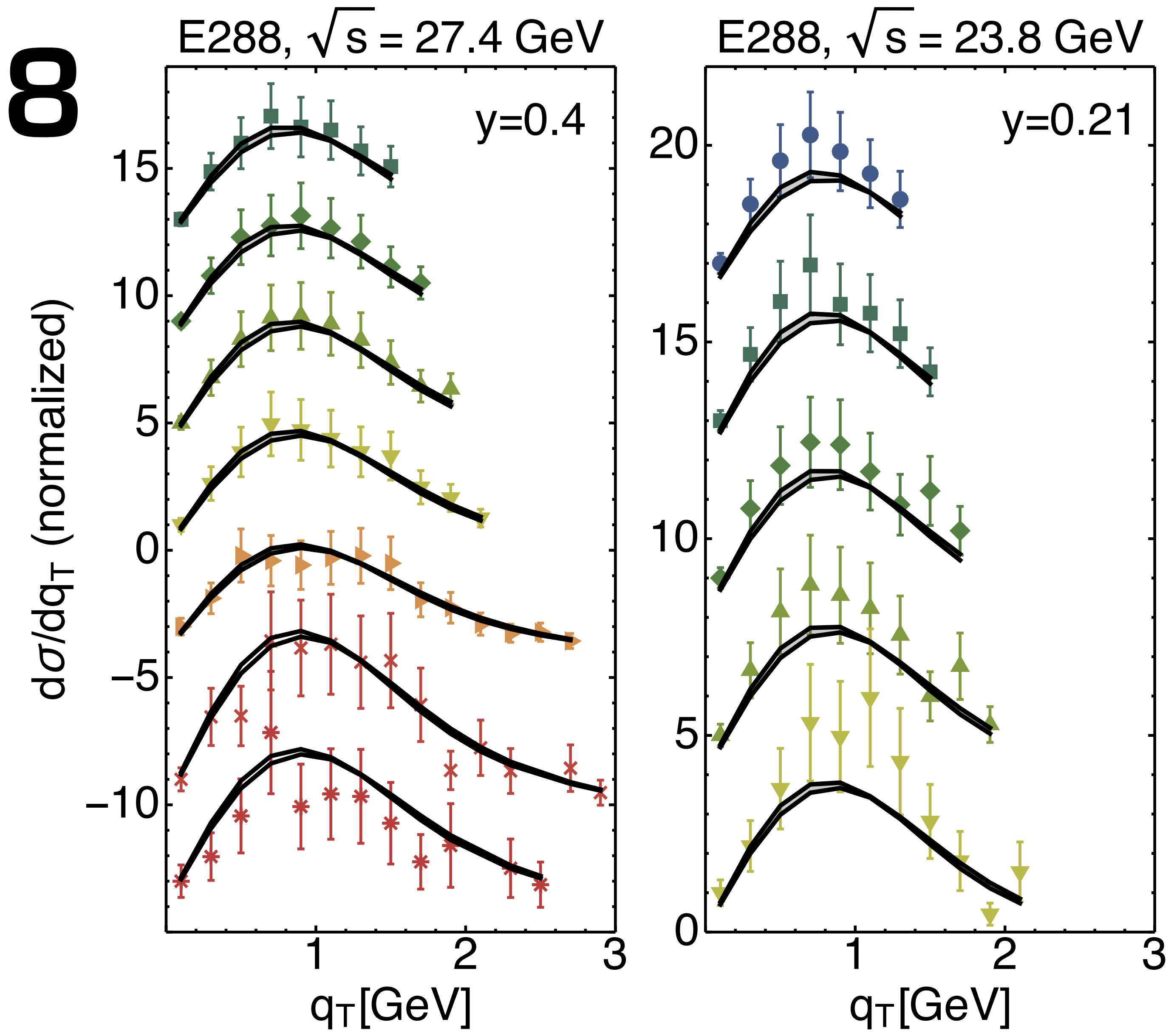


E288



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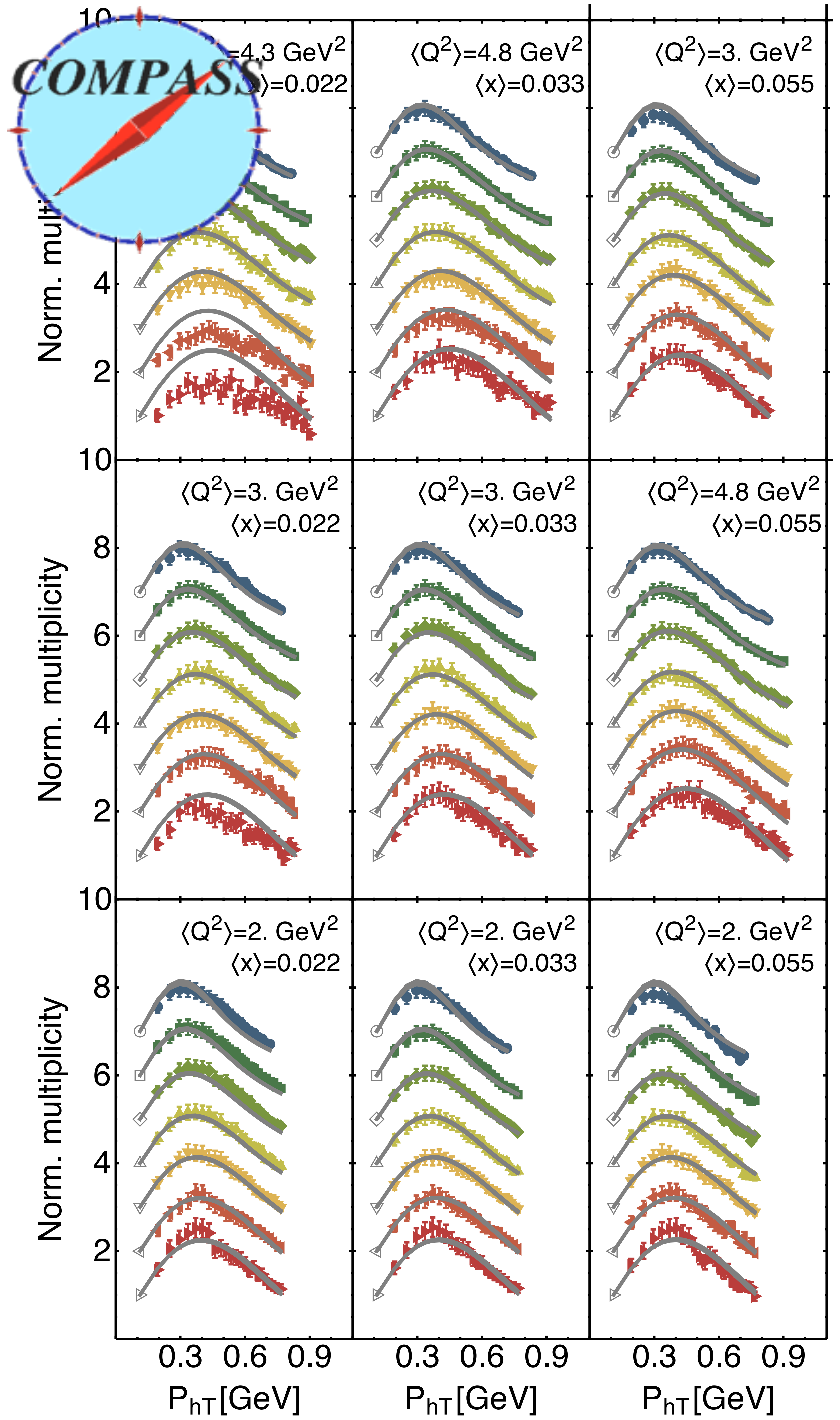

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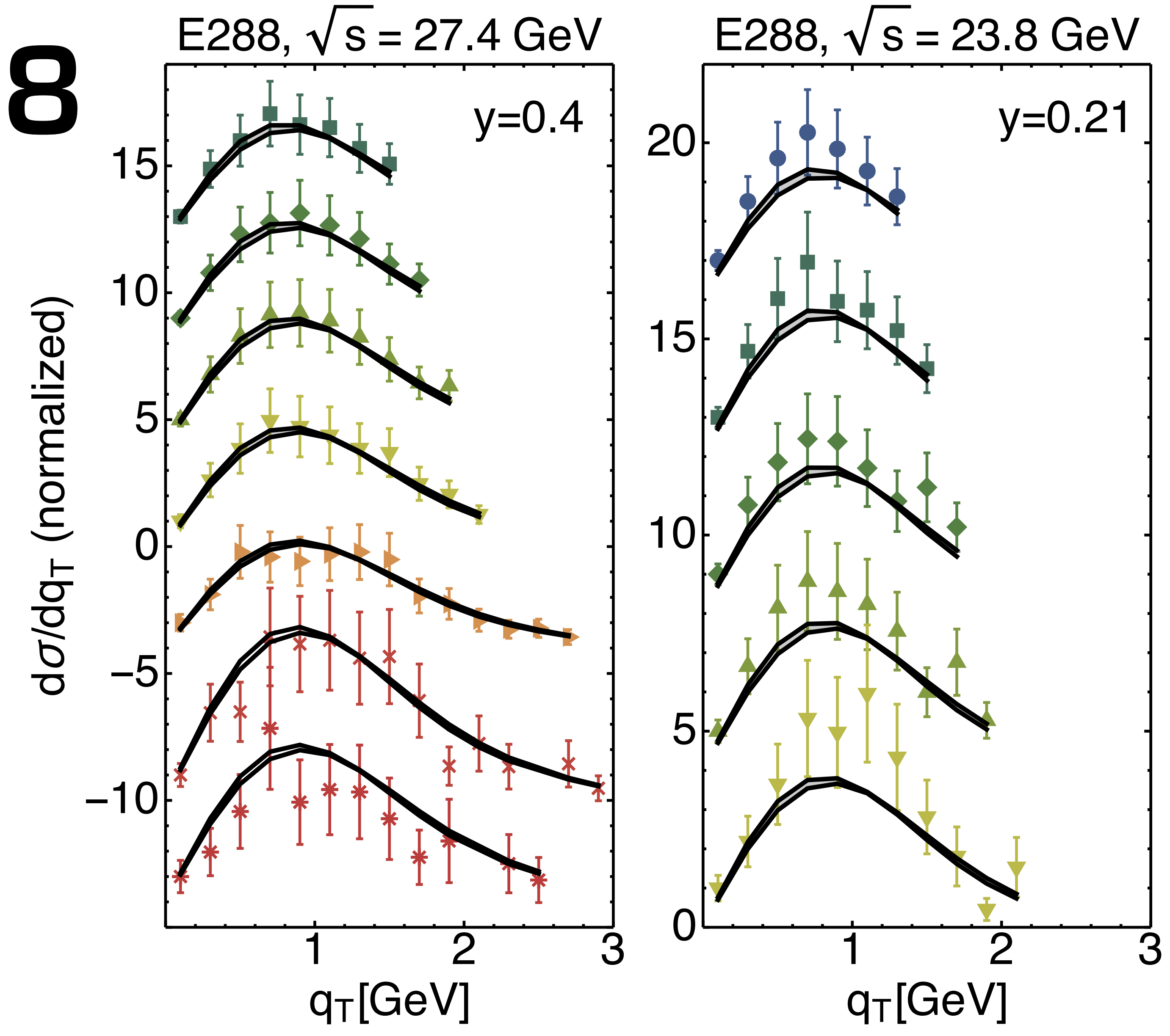

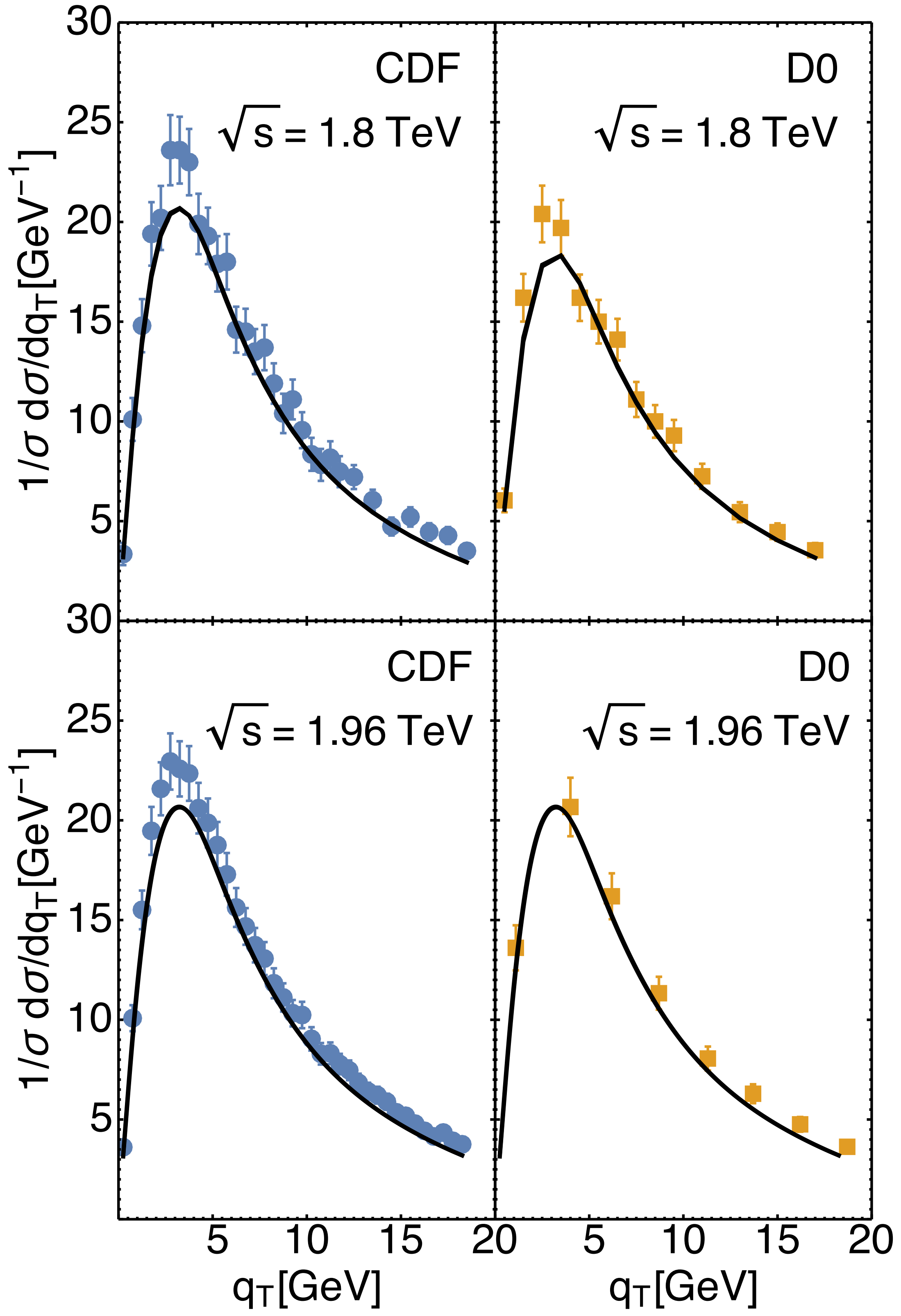

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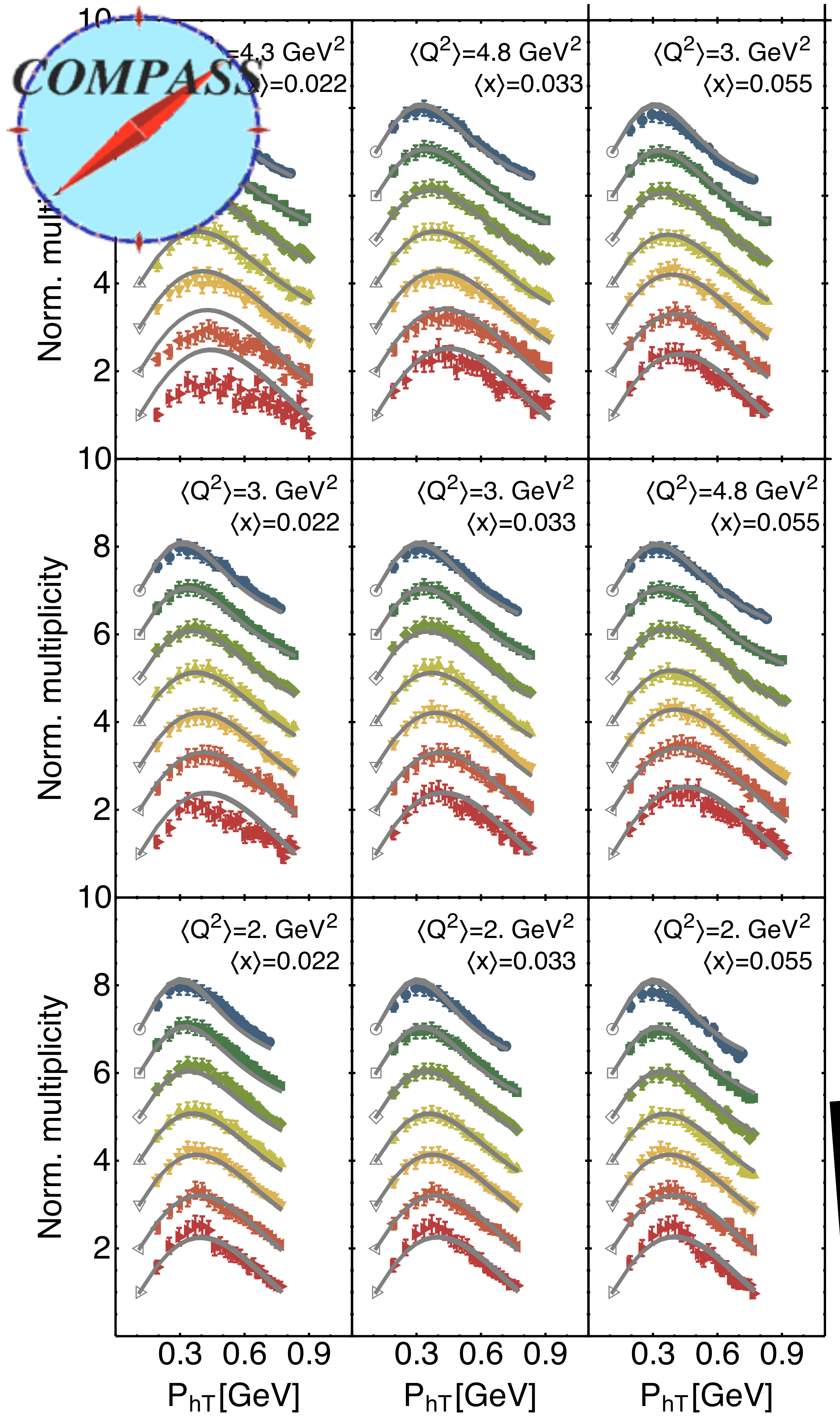

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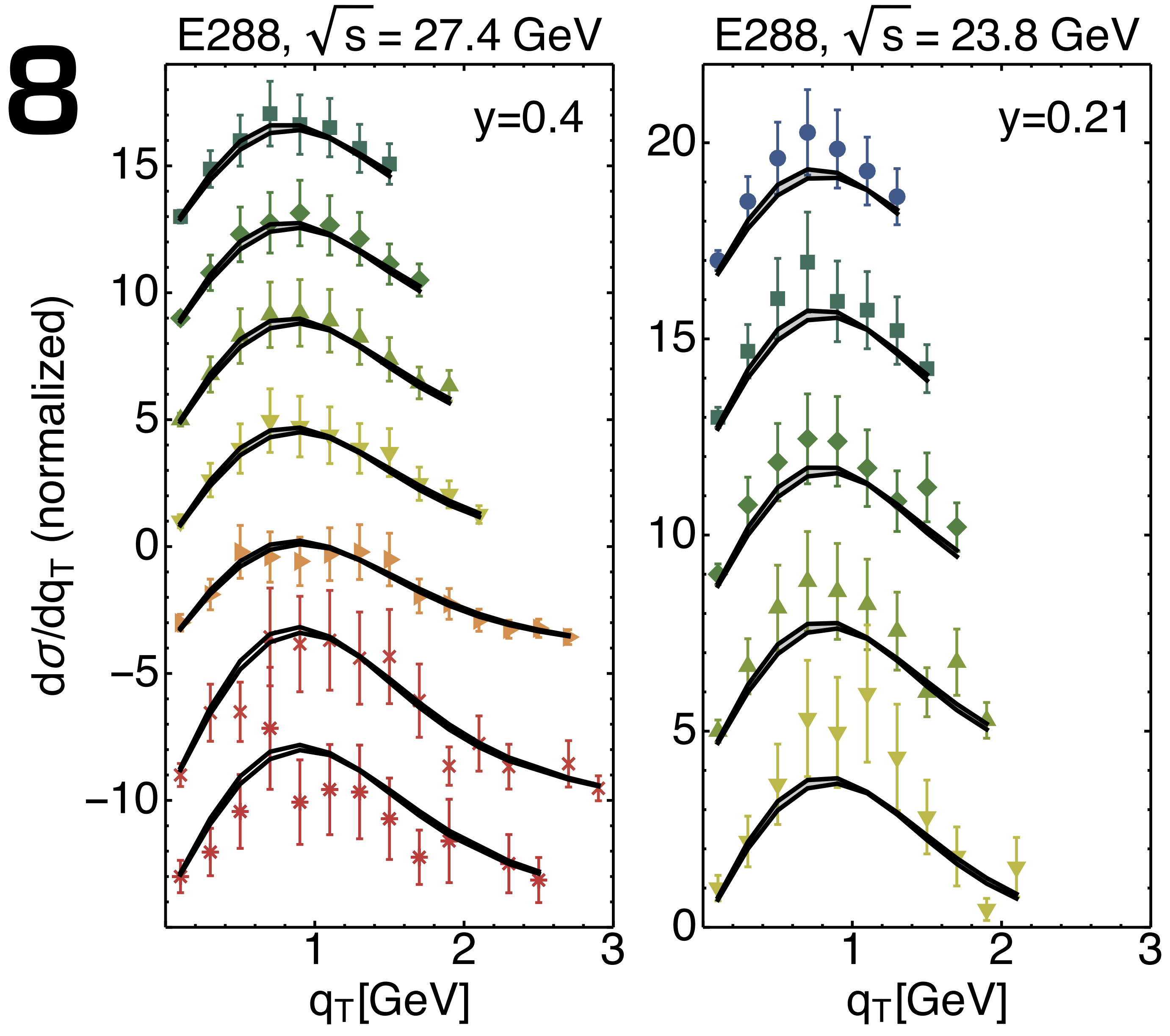
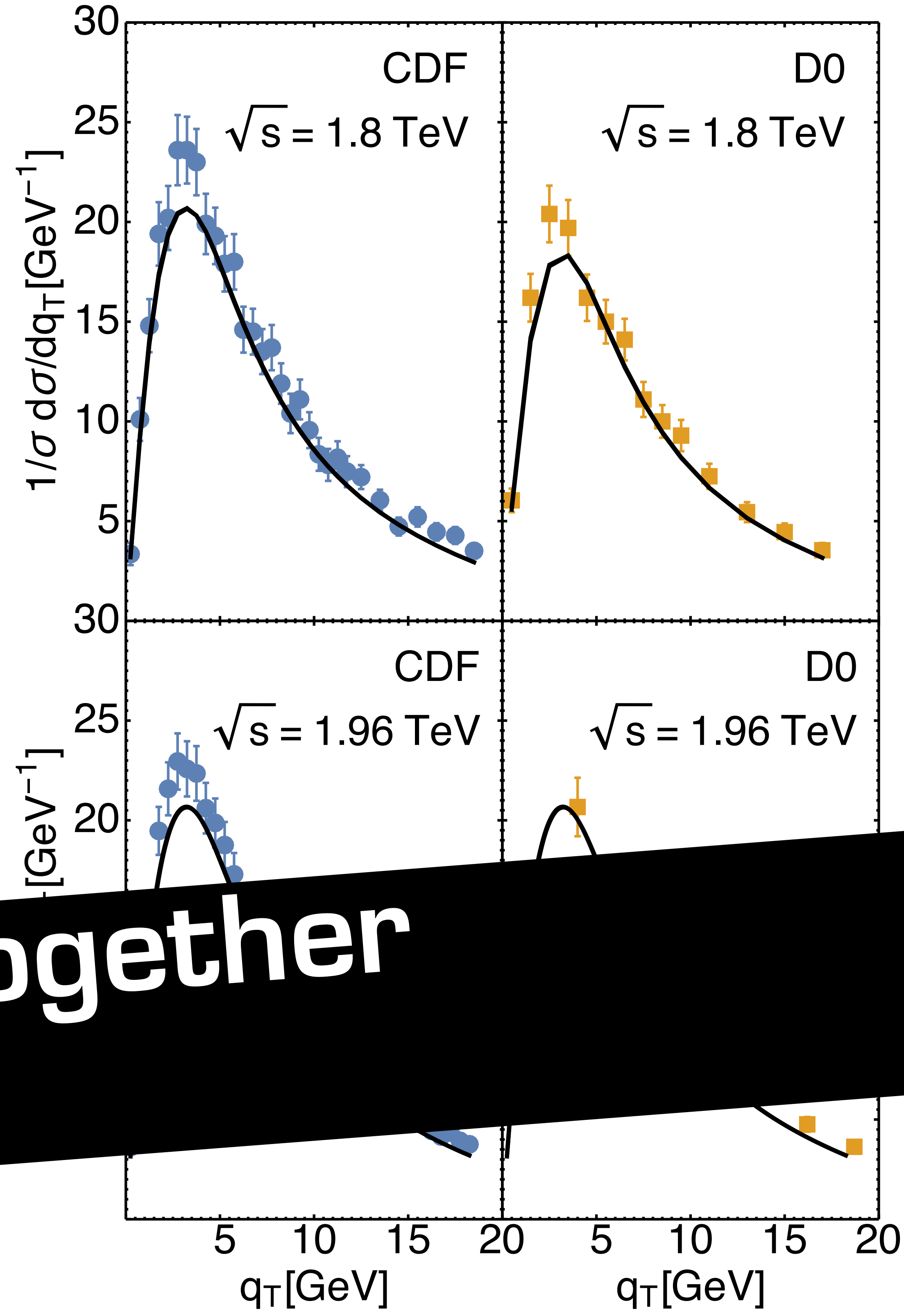




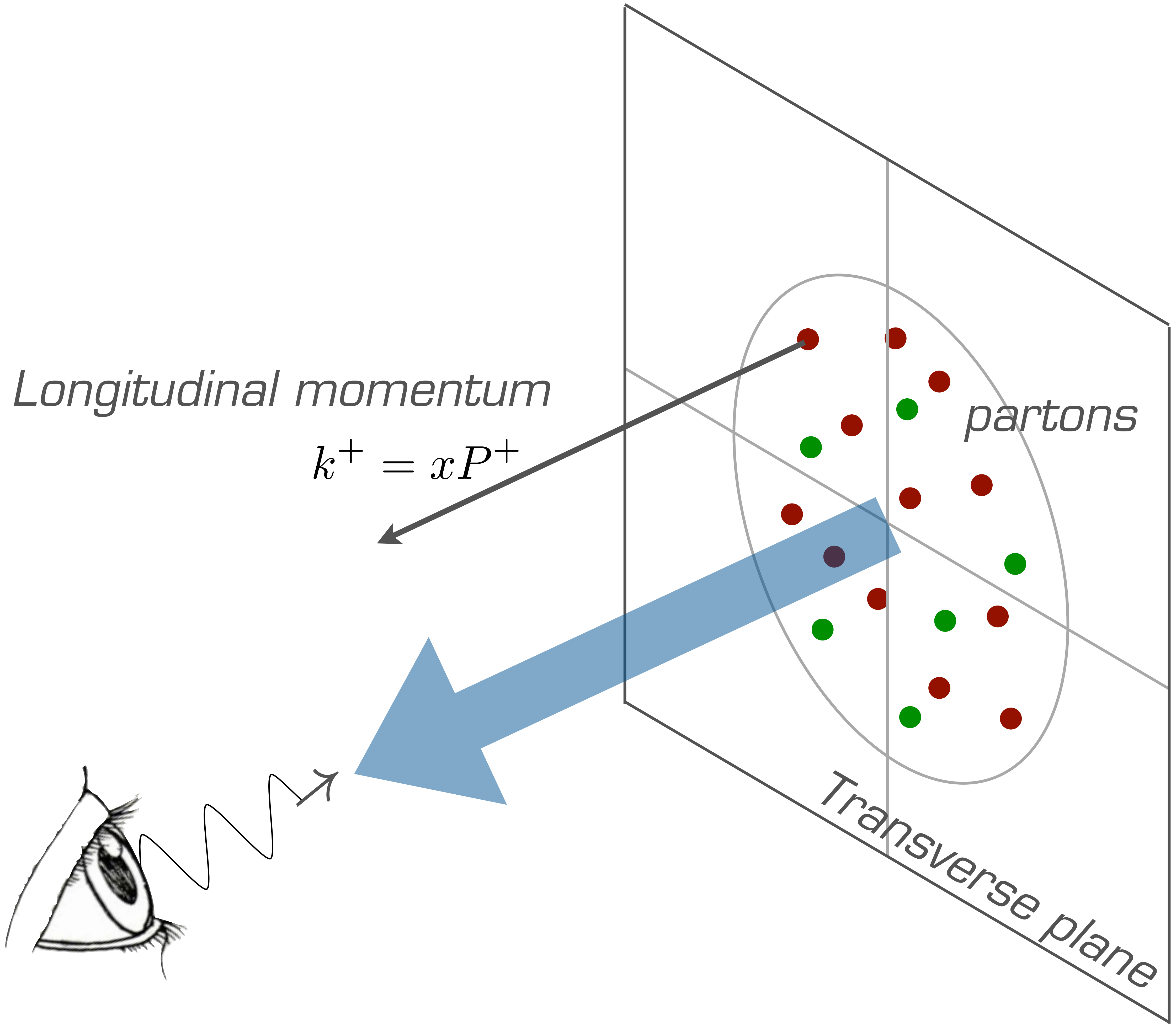
Pavia 2016: first TMD fit putting together SIDIS + Drell-Yan + Z production

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

Some introduction

Standard parton distribution functions

Standard collinear PDFs describe the distribution of partons in one dimension in momentum space



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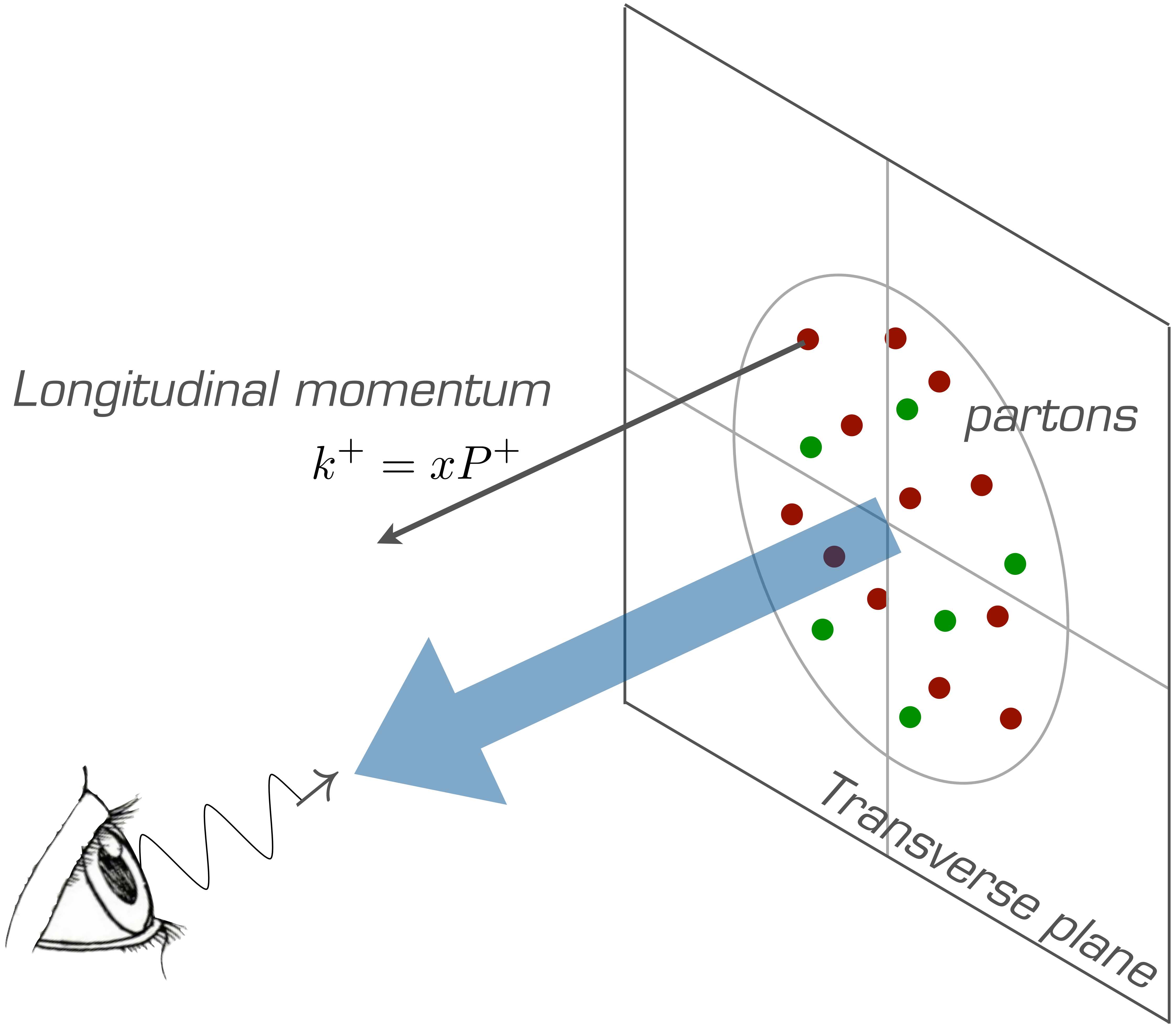
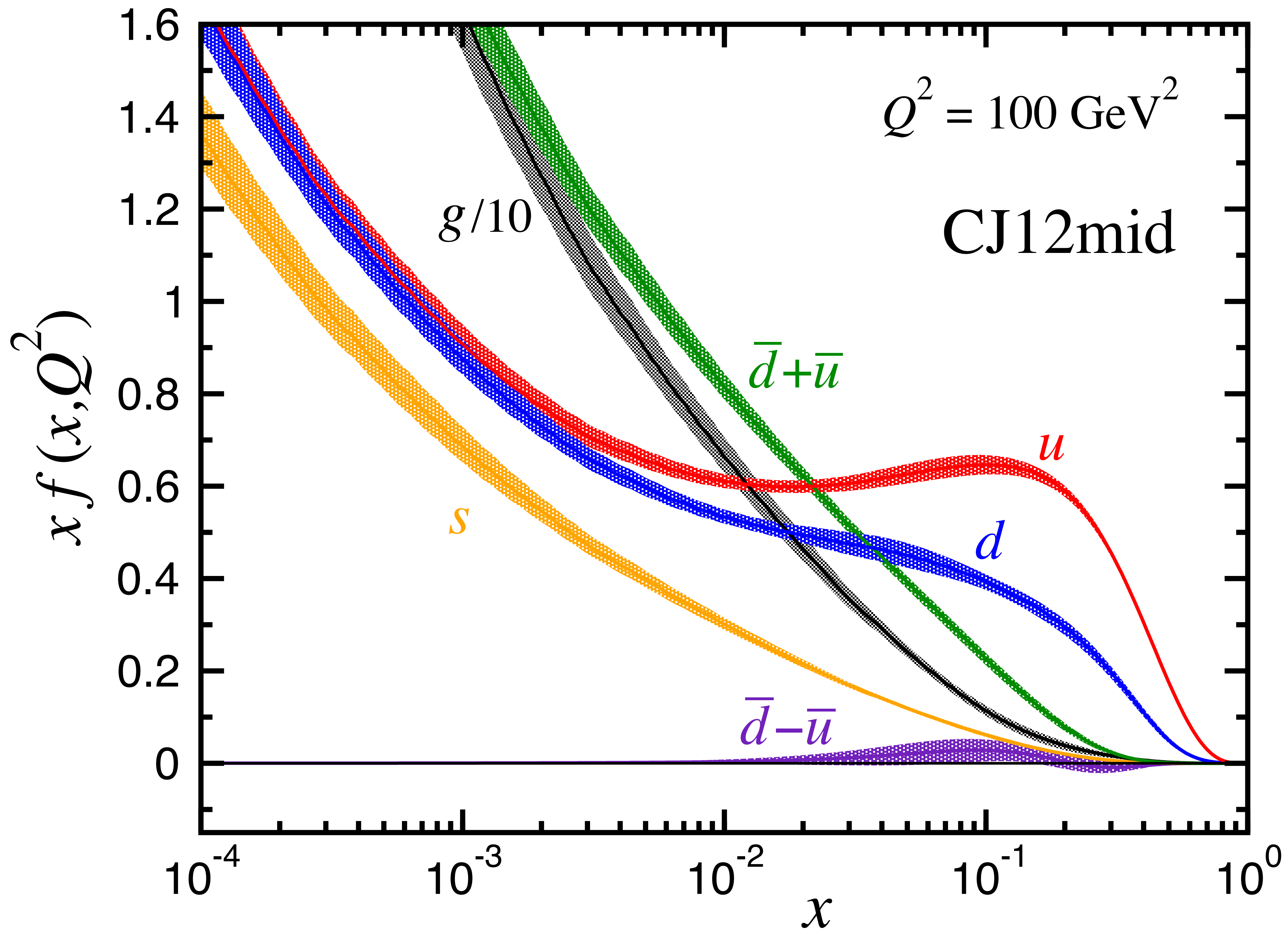
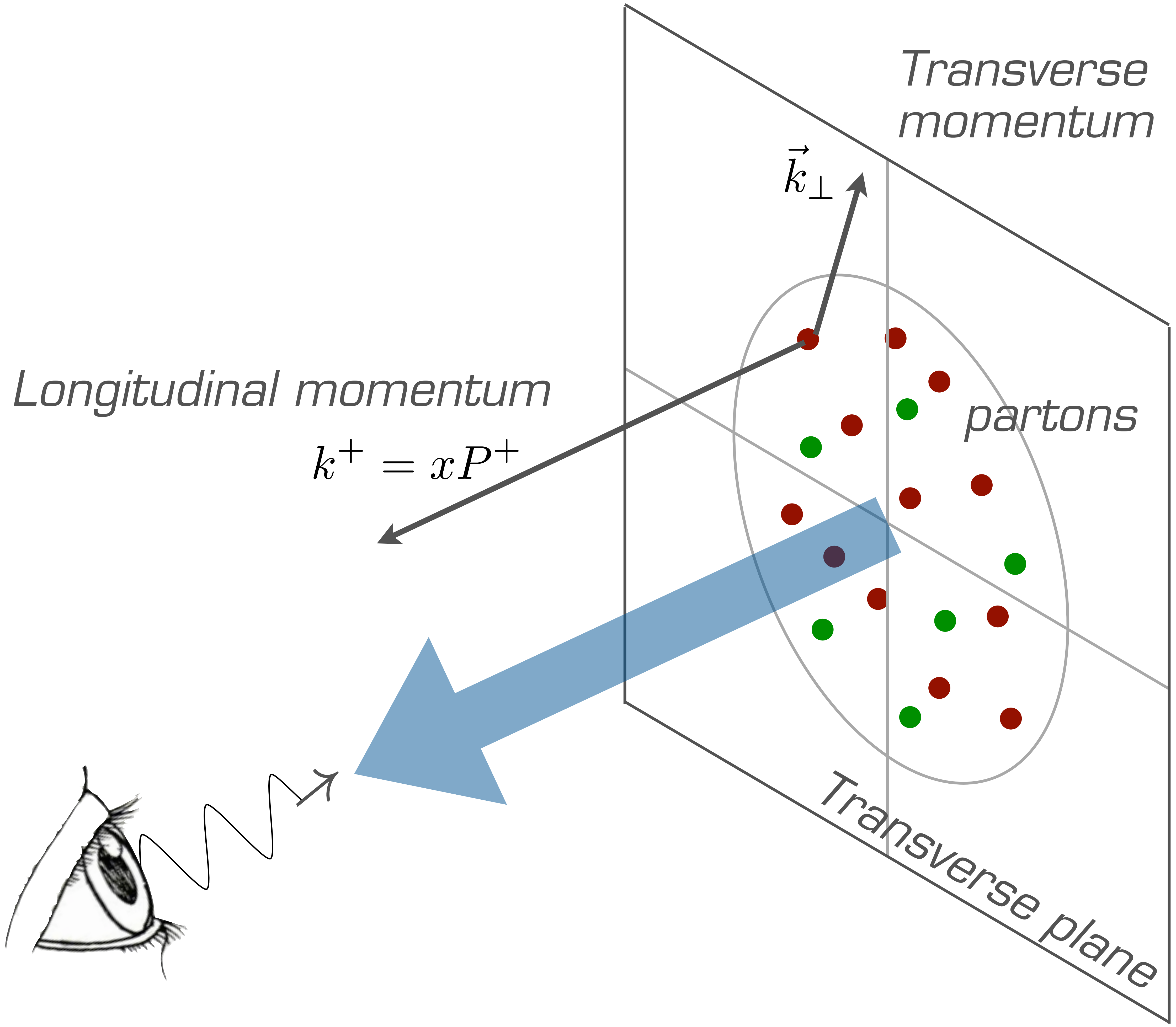




CTEQ-JLAB 12 set, Owens, Accardi, Melnitchouk, PRD87 (13)

Transverse Momentum Distributions

TMDs describe the distribution of partons in three dimensions in momentum space



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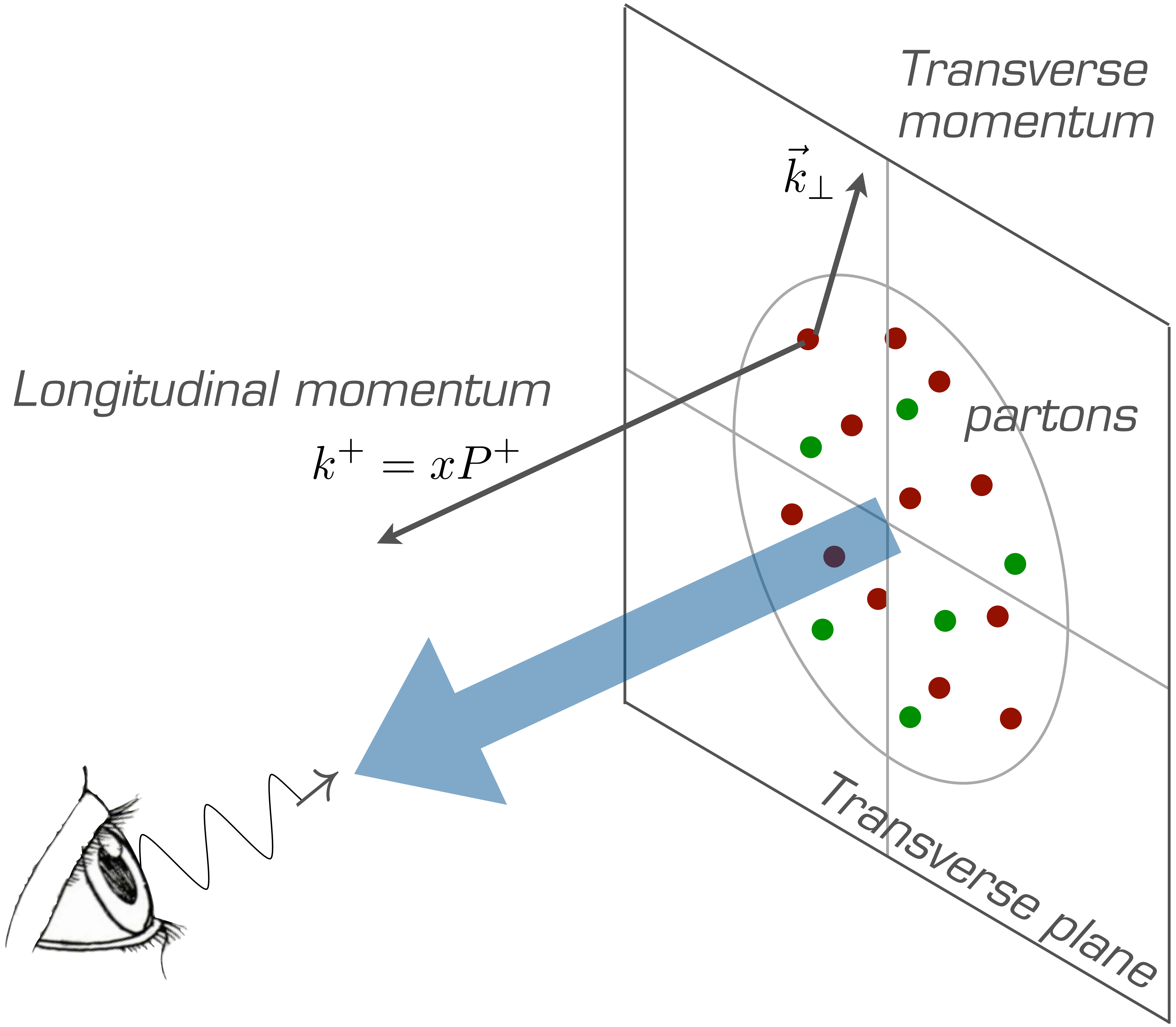
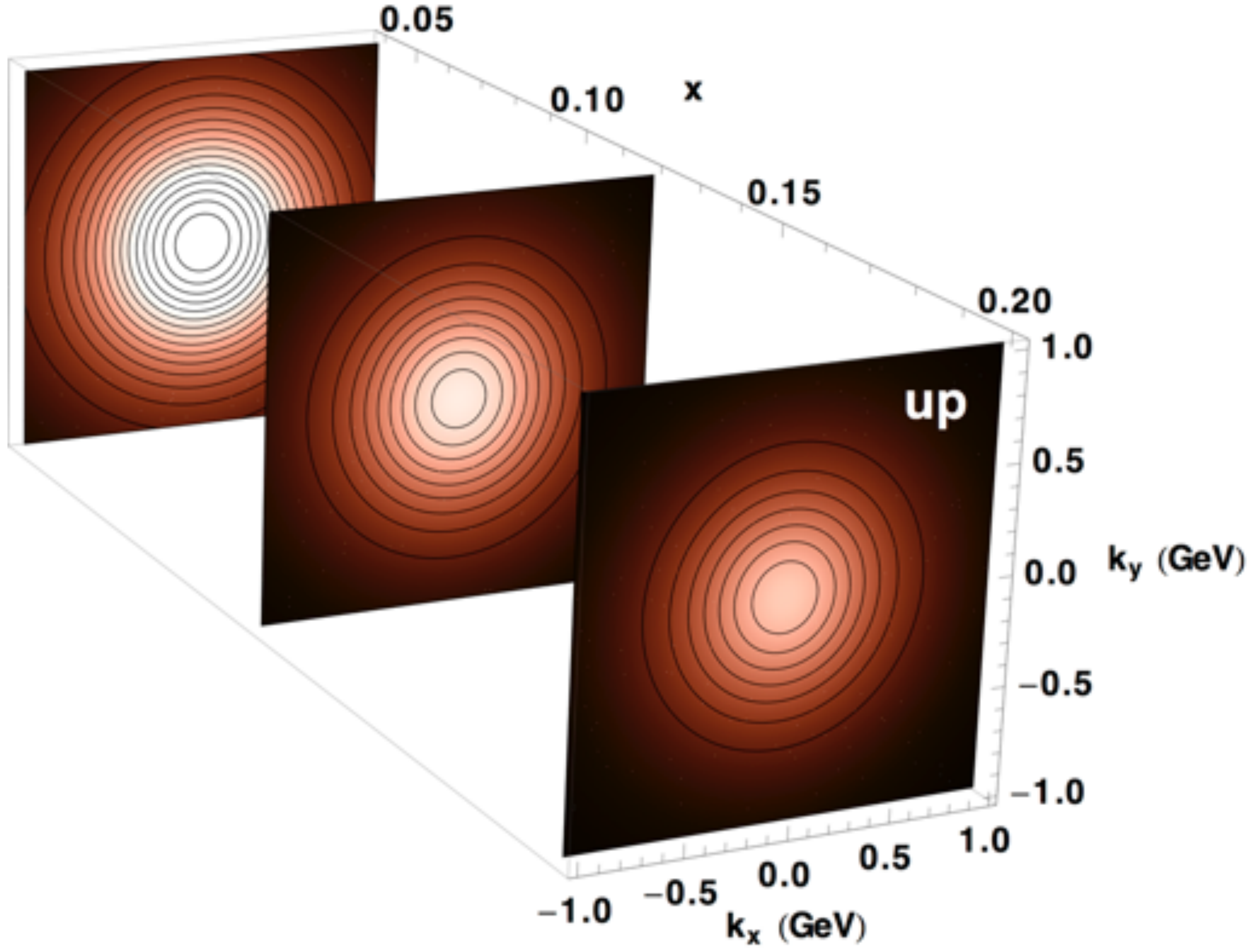
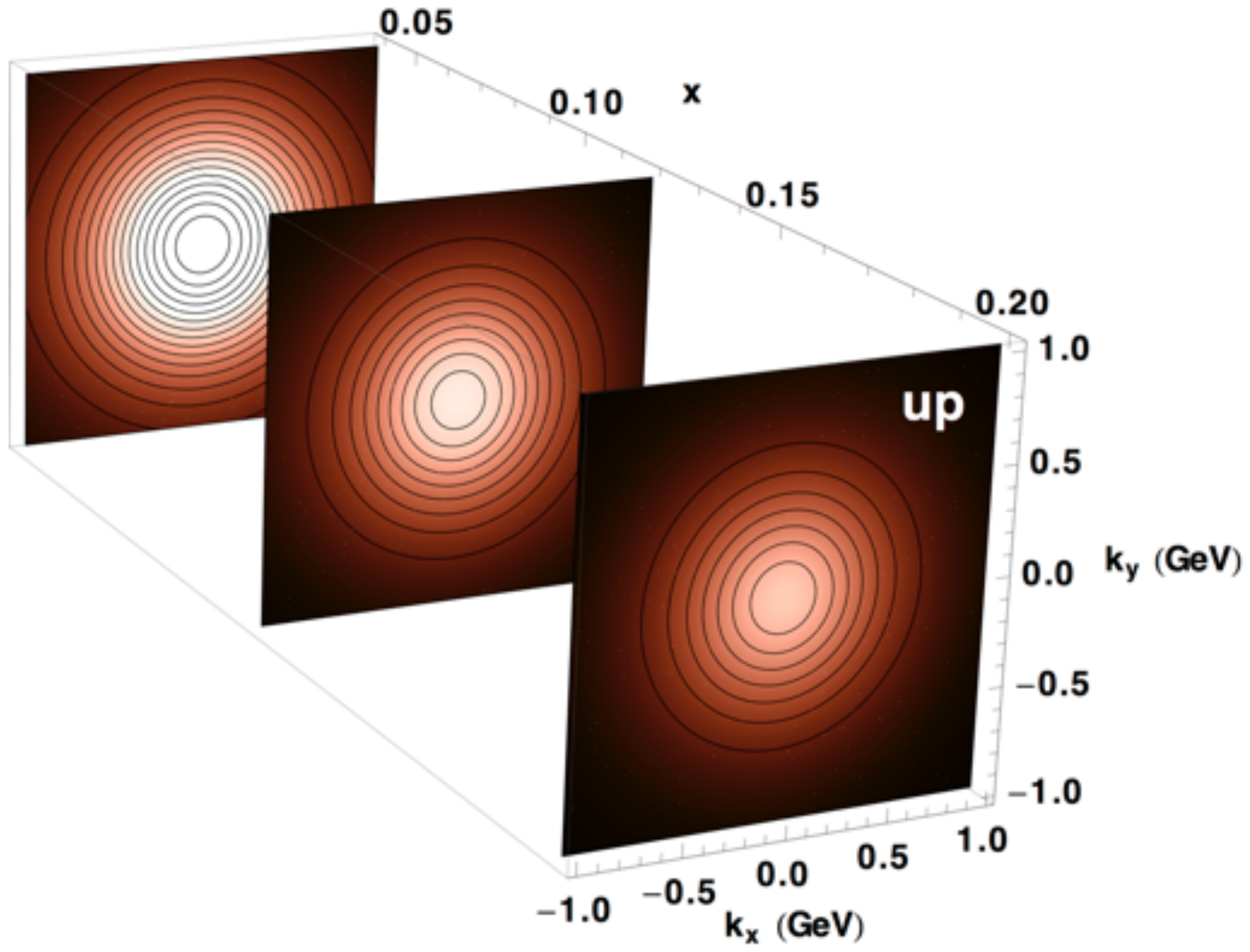


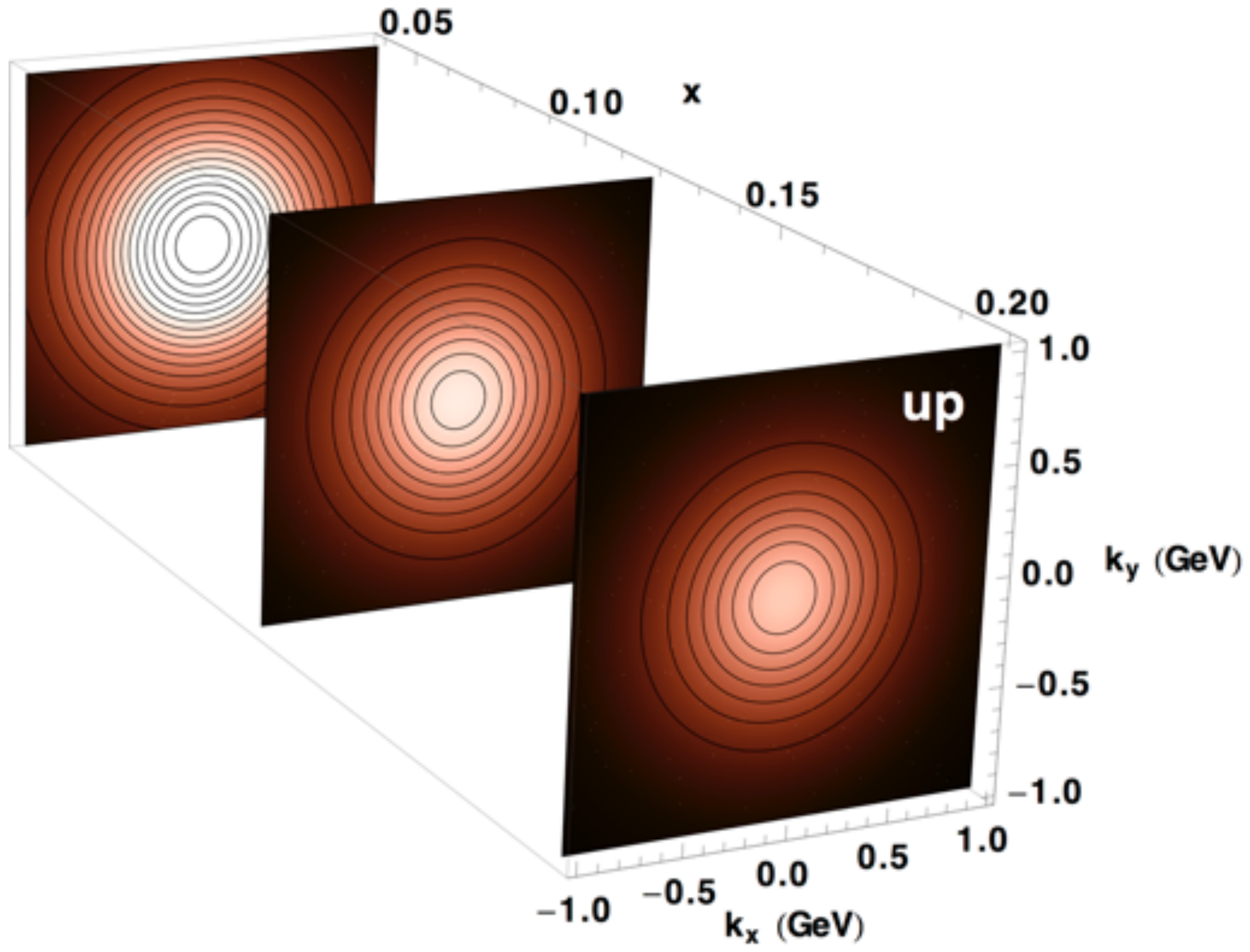


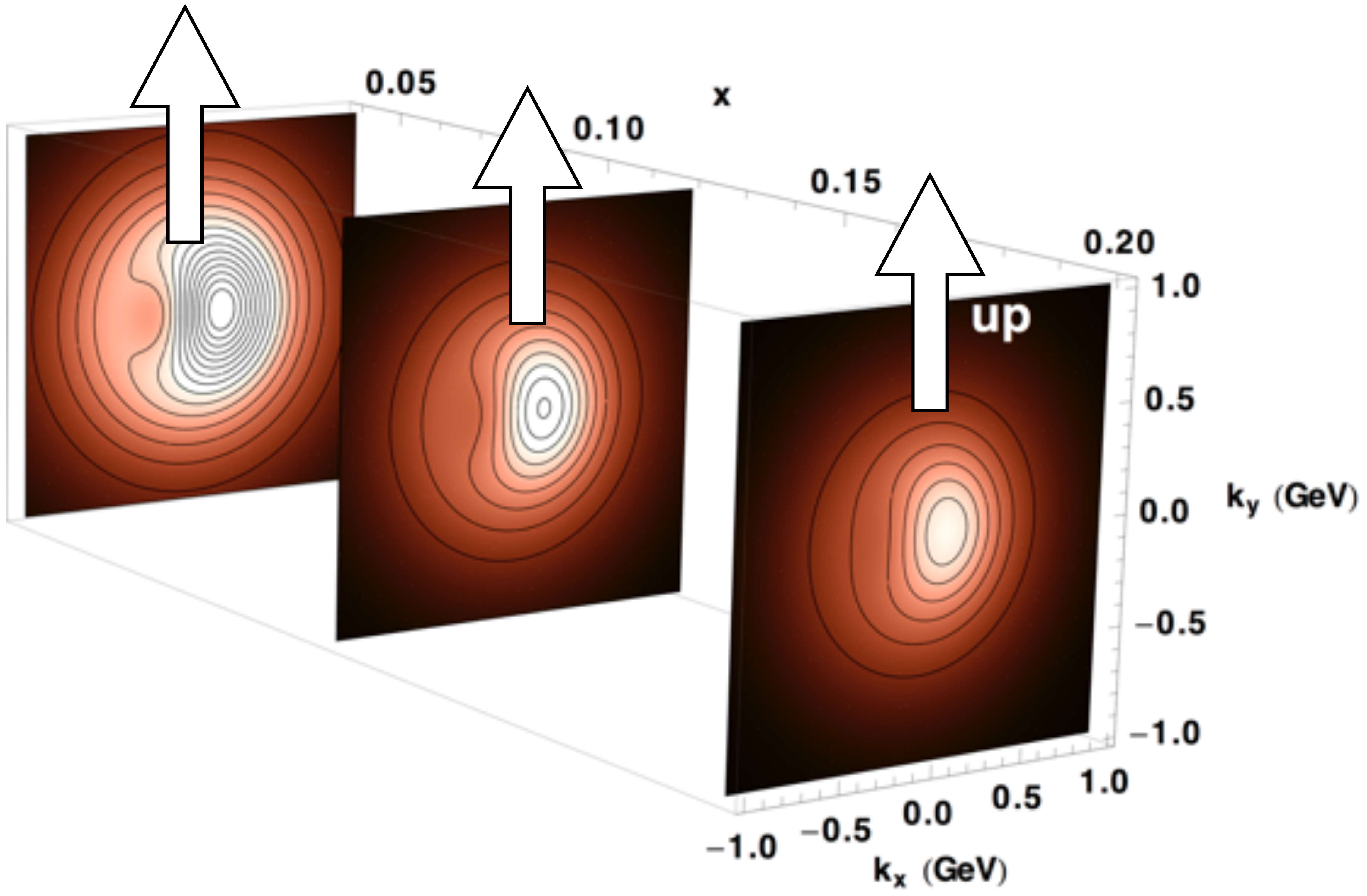
3D structure in momentum space



Unpolarized TMD: cylindrically symmetric

3D structure in momentum space





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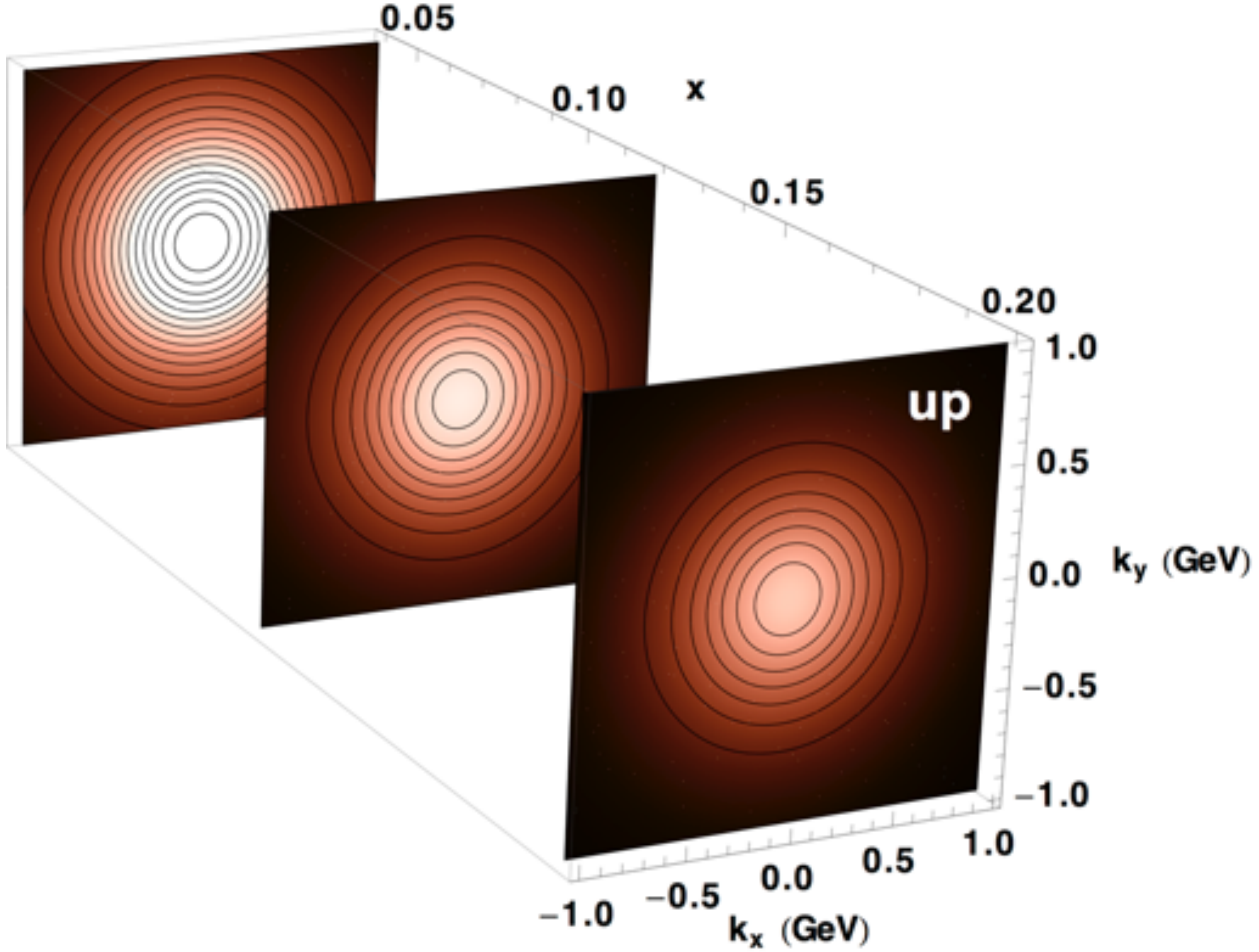
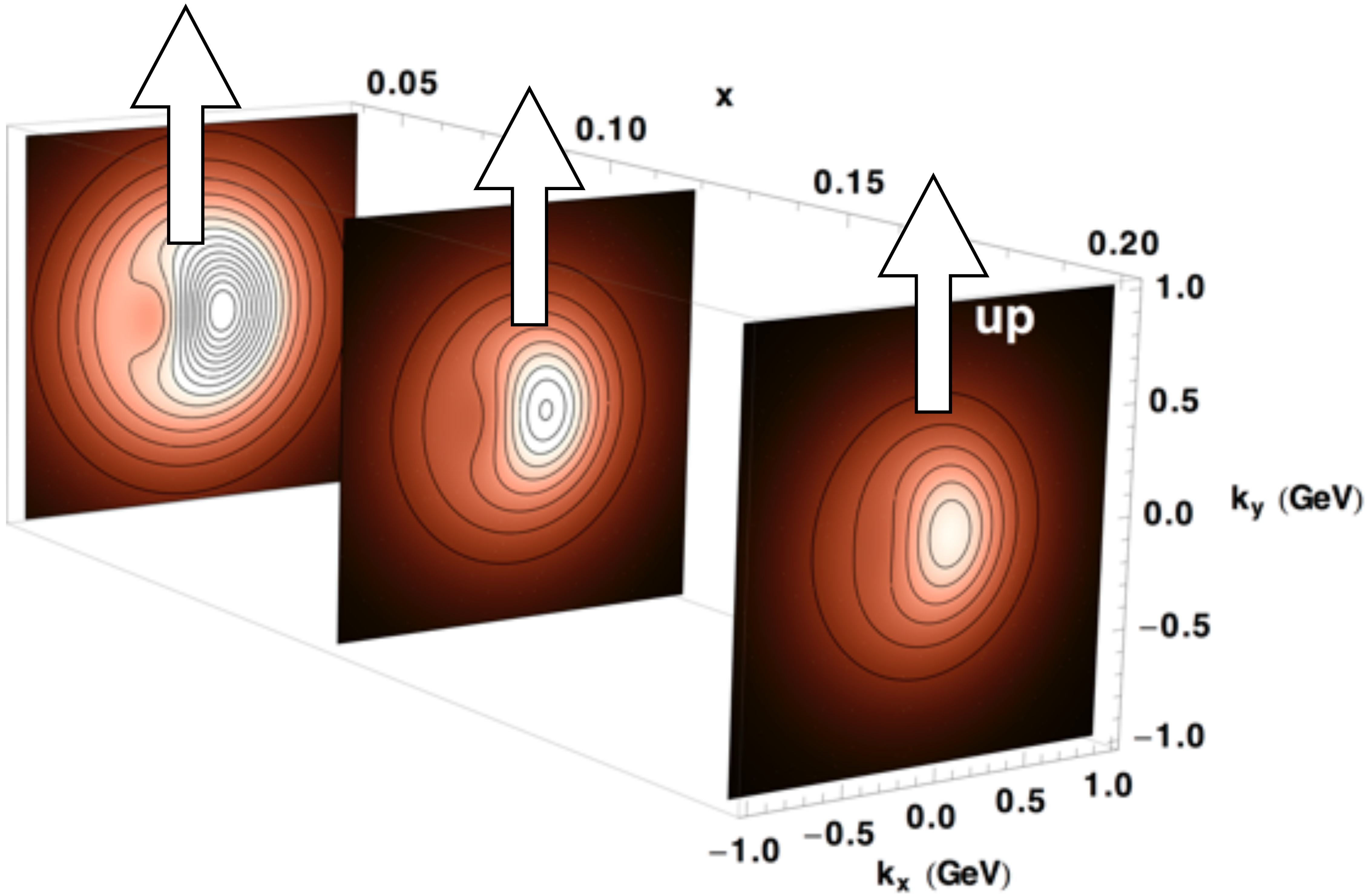
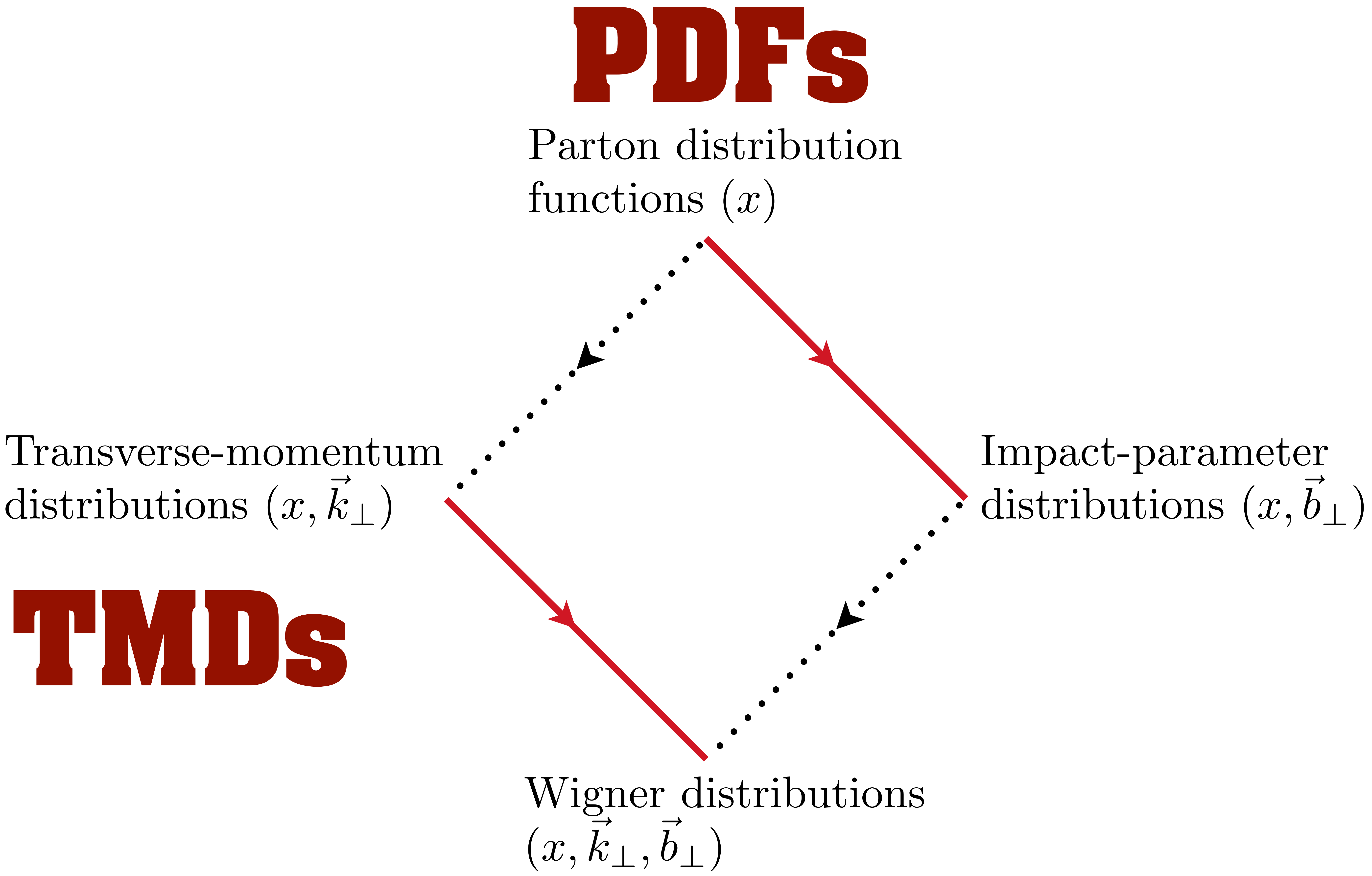




With transverse spin: distortions can occur, encoded in Sivers TMD
Requires presence of orbital angular momentum

Unpolarized TMD: cylindrically symmetric

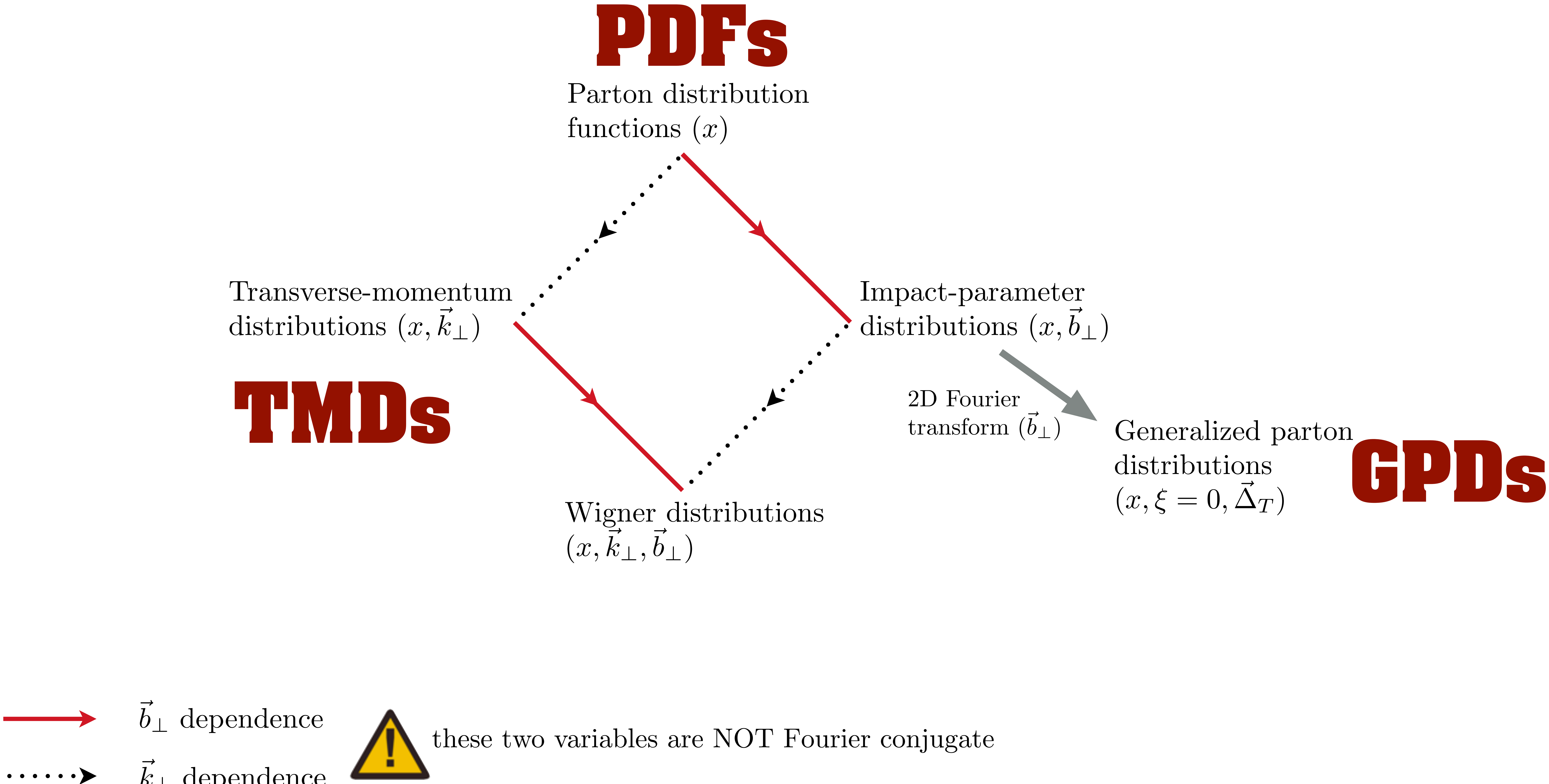


$\vec{b}_\perp$ dependence (solid red arrow)

$\vec{k}_\perp$ dependence (dotted black arrow)

⚠ these two variables are NOT Fourier conjugate

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



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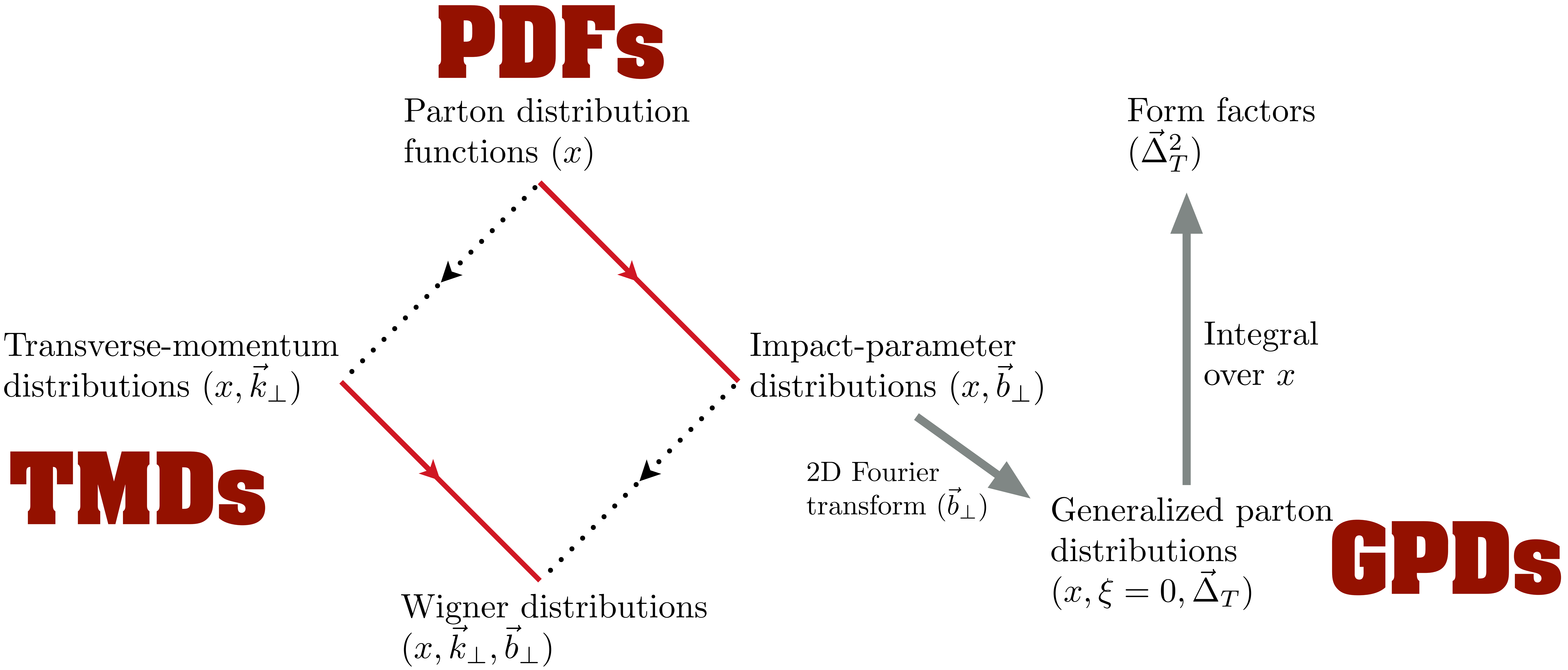

→ $\vec{b}_\perp$ dependence

⋯→ $\vec{k}_\perp$ dependence

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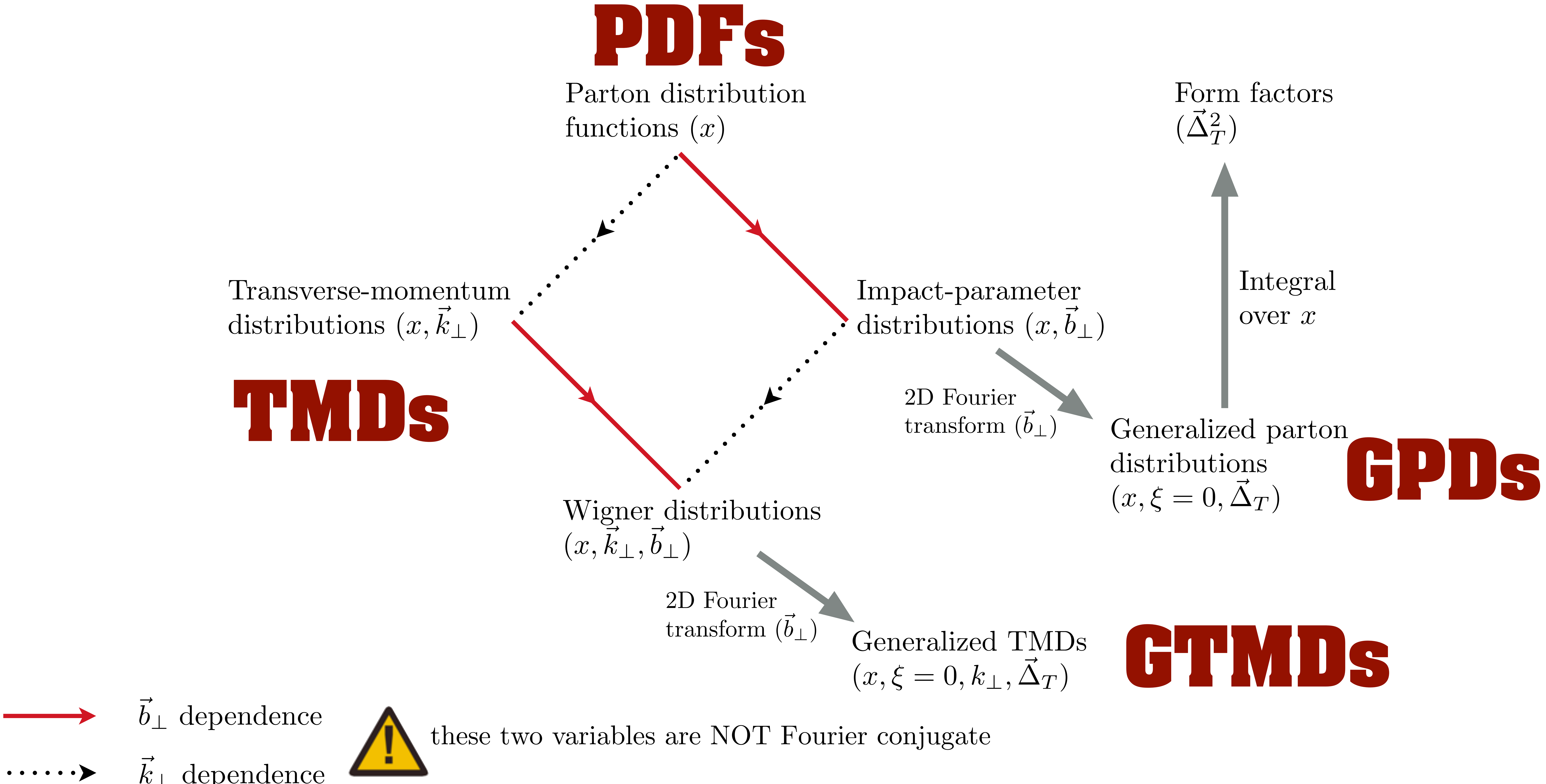

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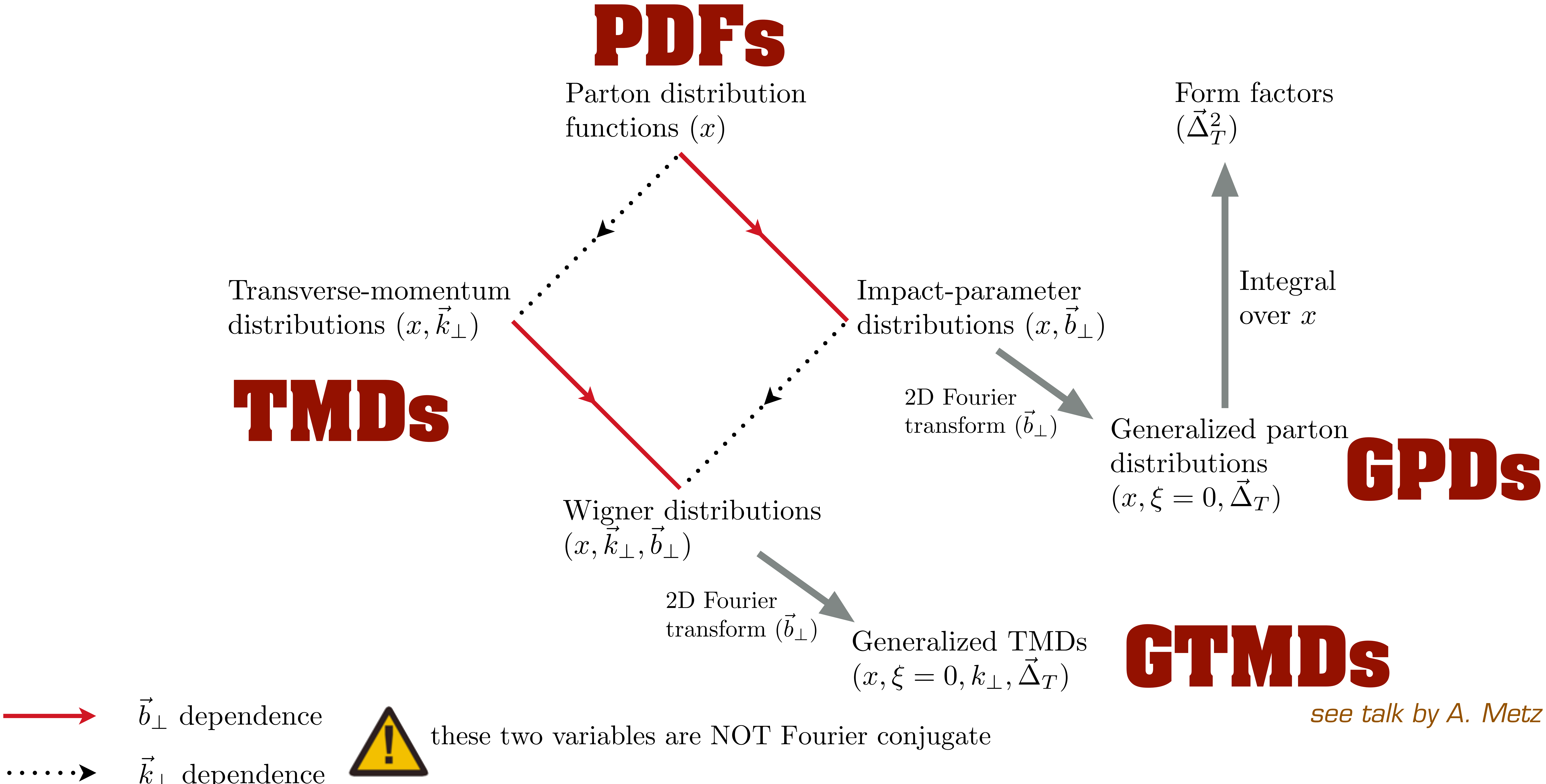

see talk by A. Metz

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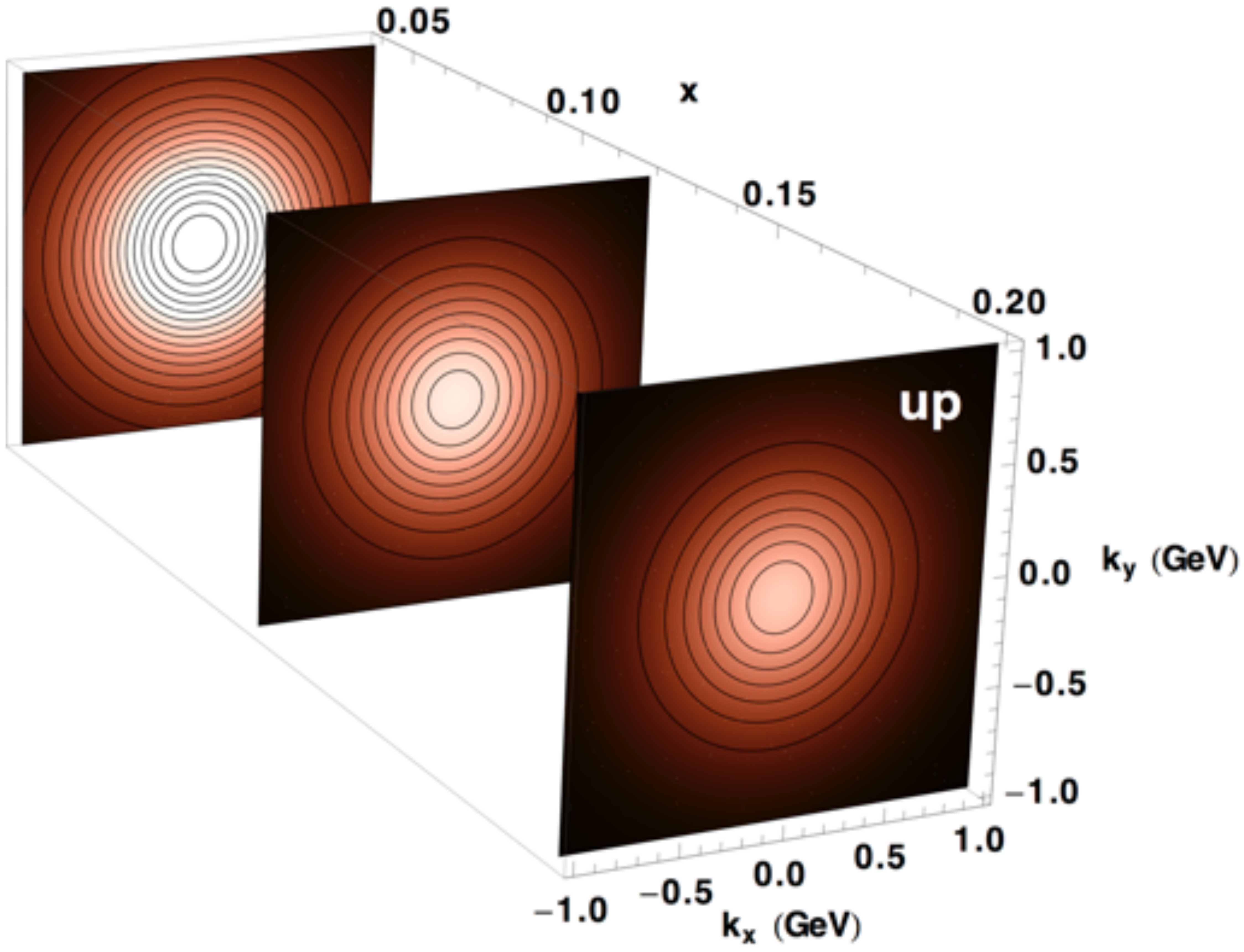
The unpolarized TMD



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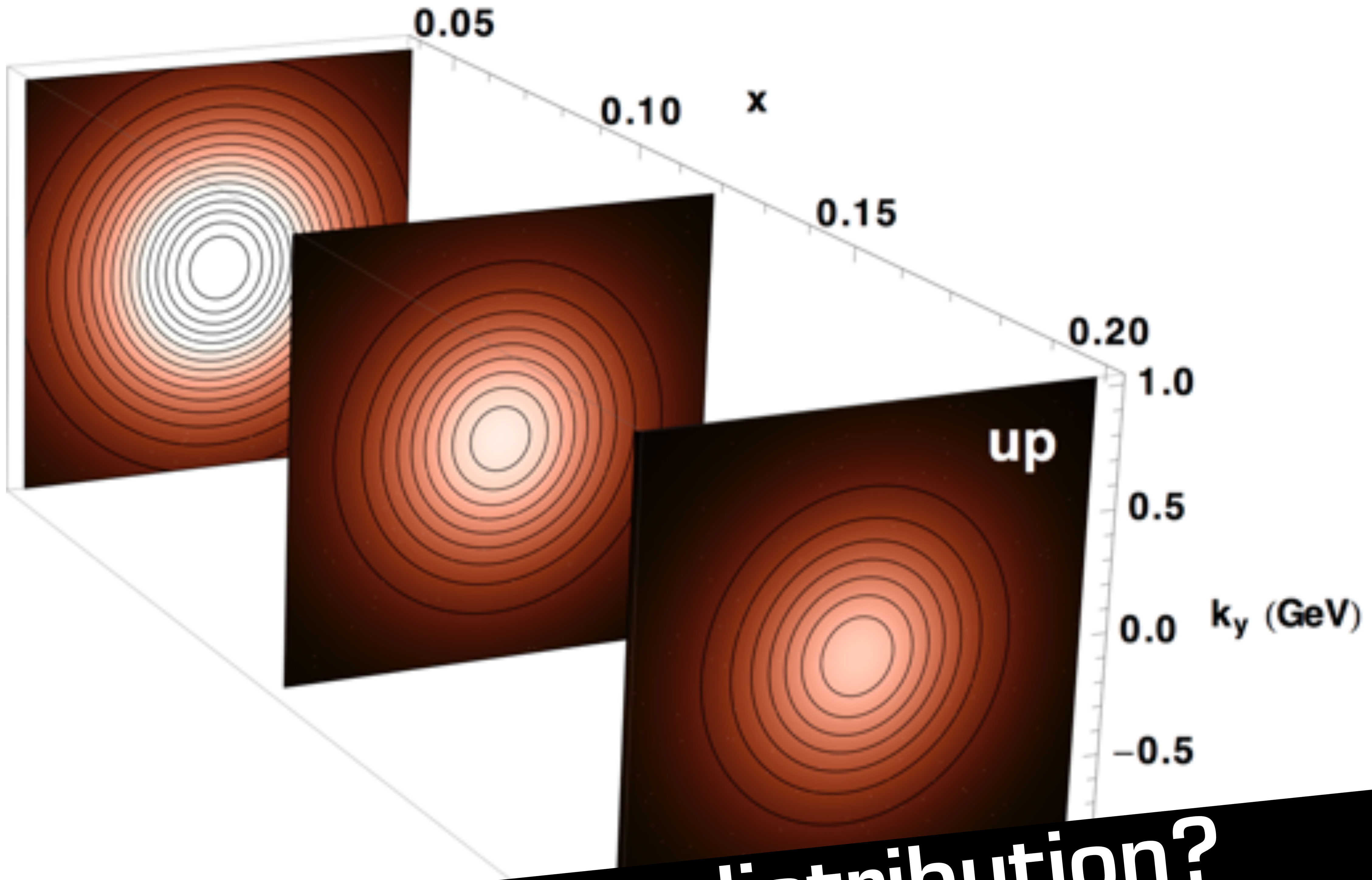
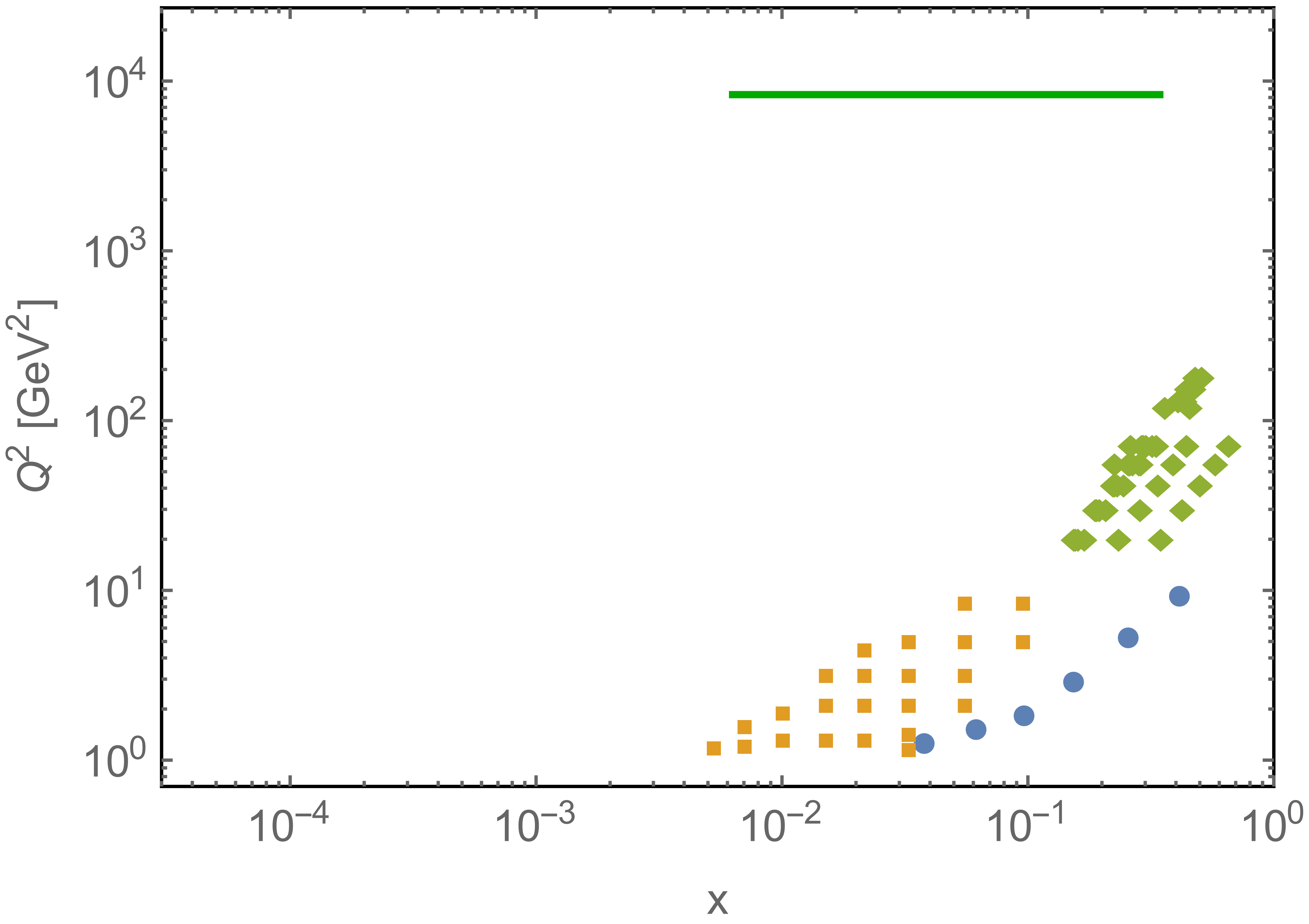


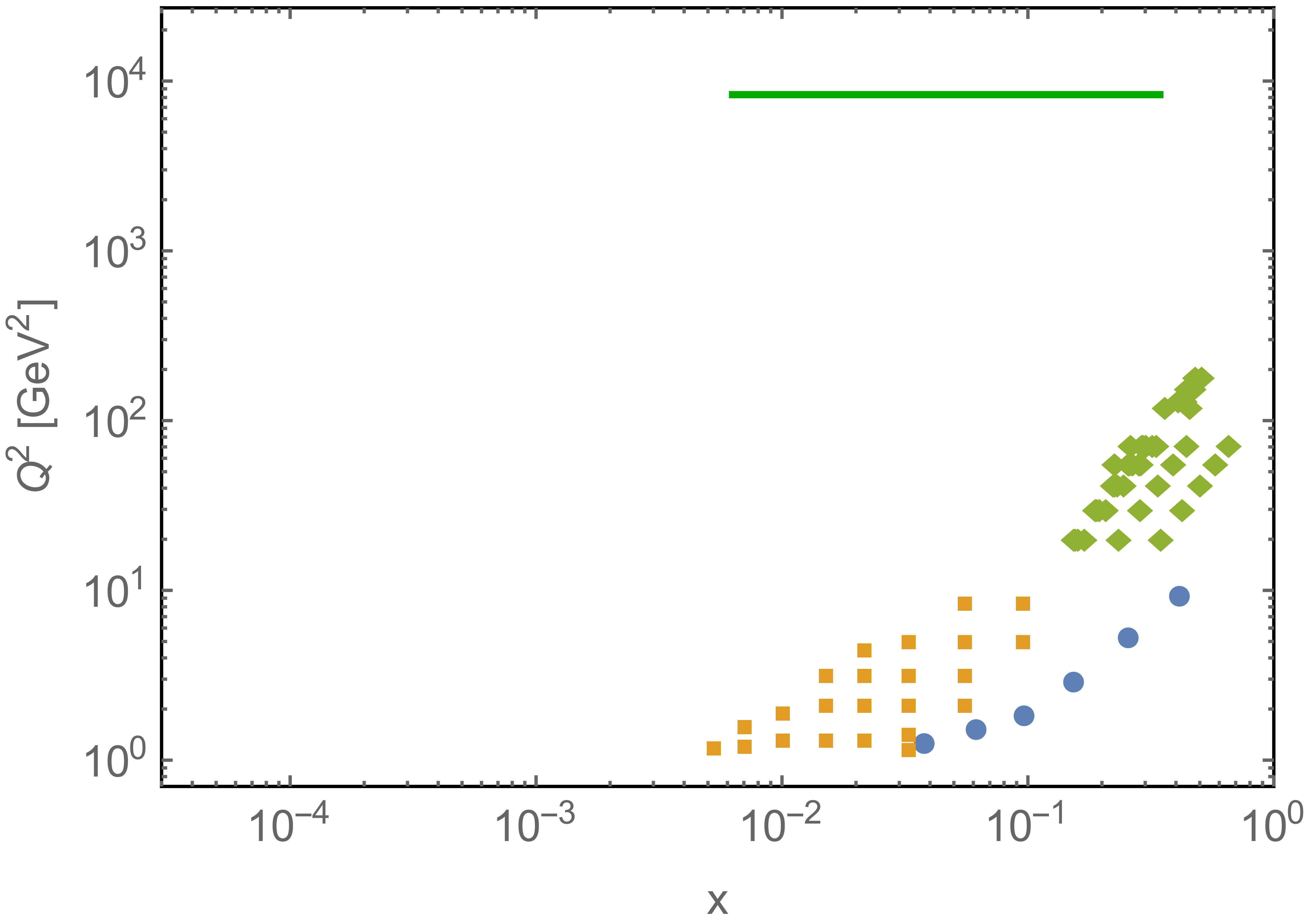
How "wide" is the distribution?
Is there a difference between flavors?
Does it get wider at low x?

Extracting TMDs

Experiments



Experiments

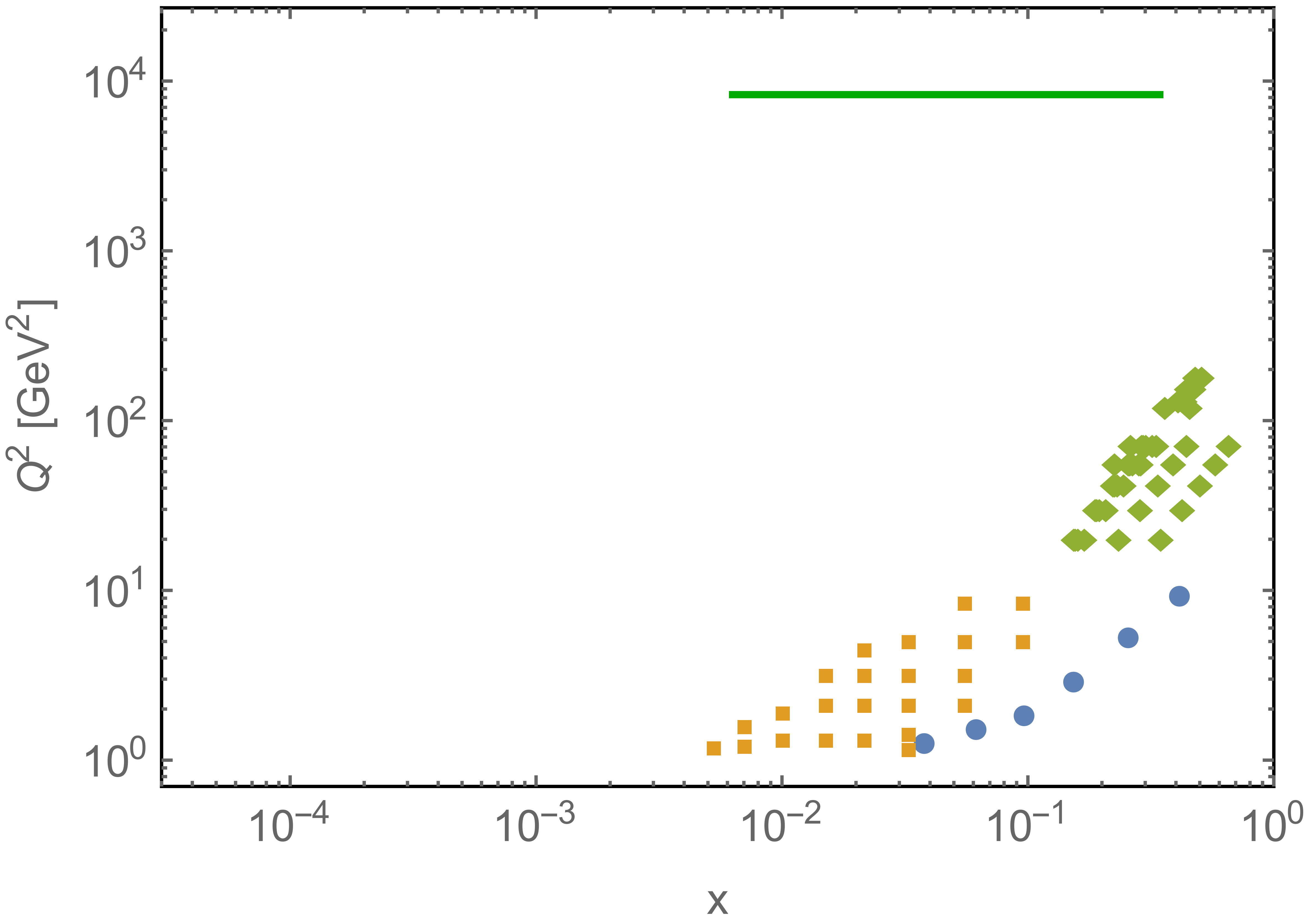


Drell-Yan@

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
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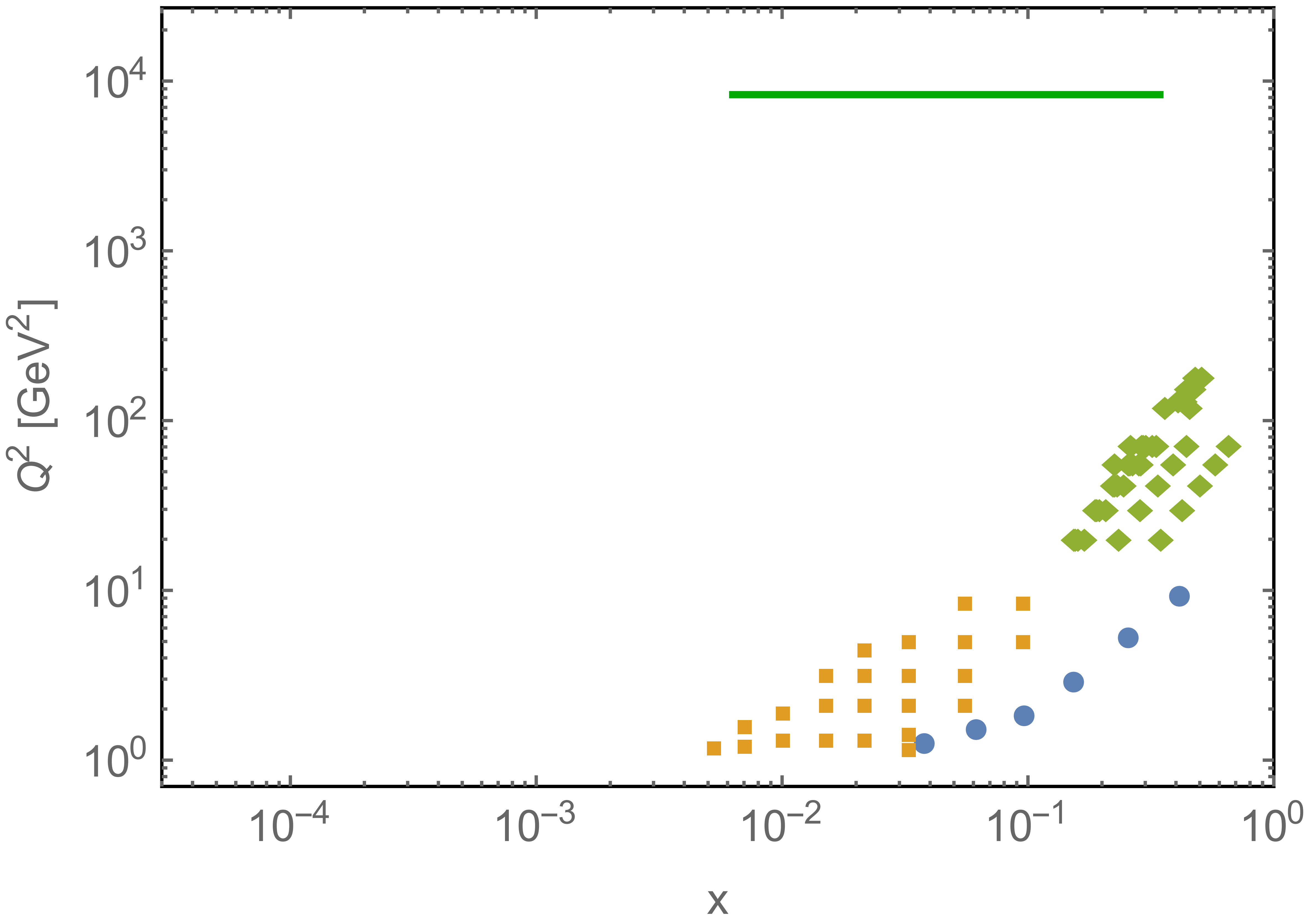

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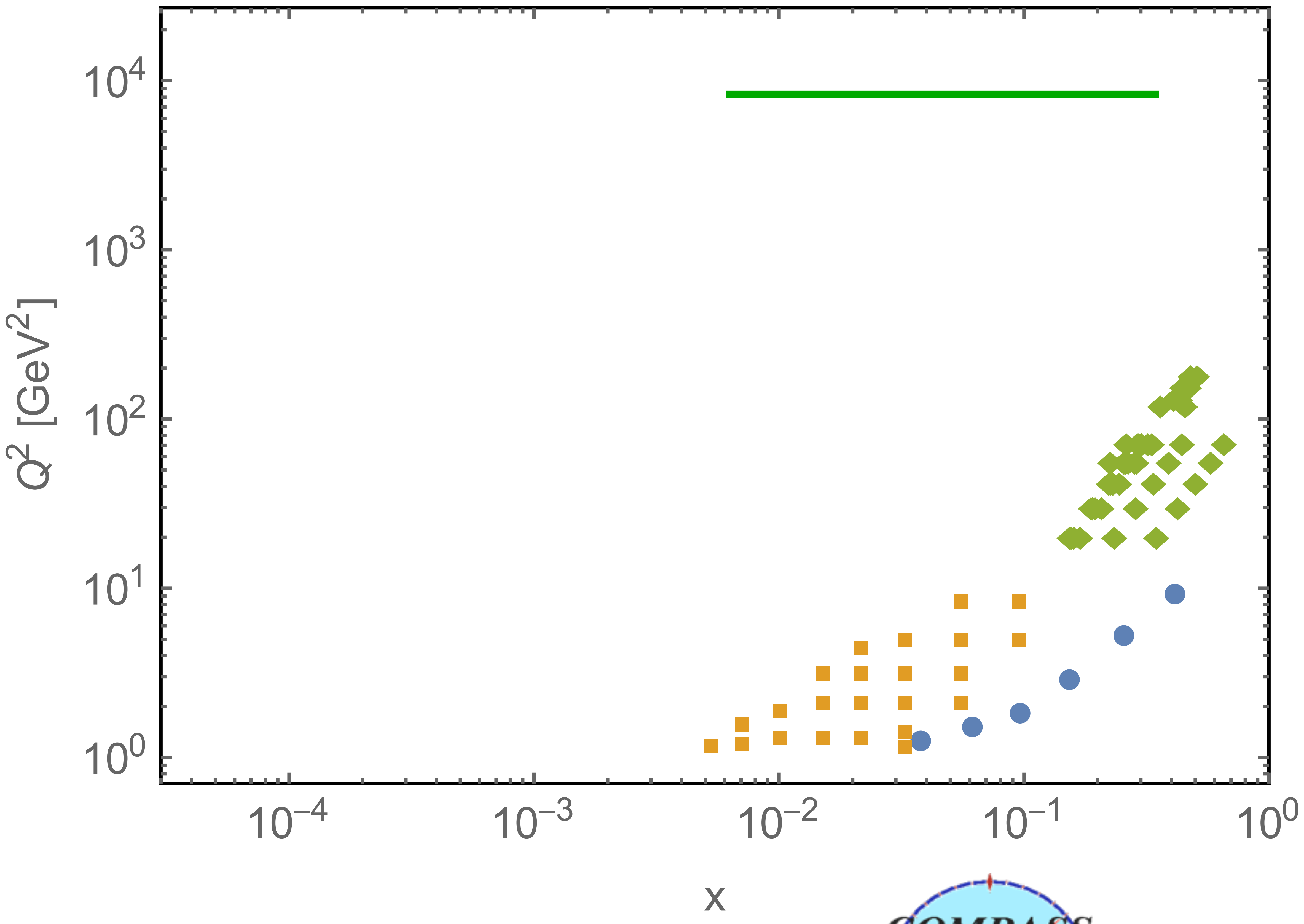

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SIDIS@ hermes

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 Pavia 2016 results 1/3

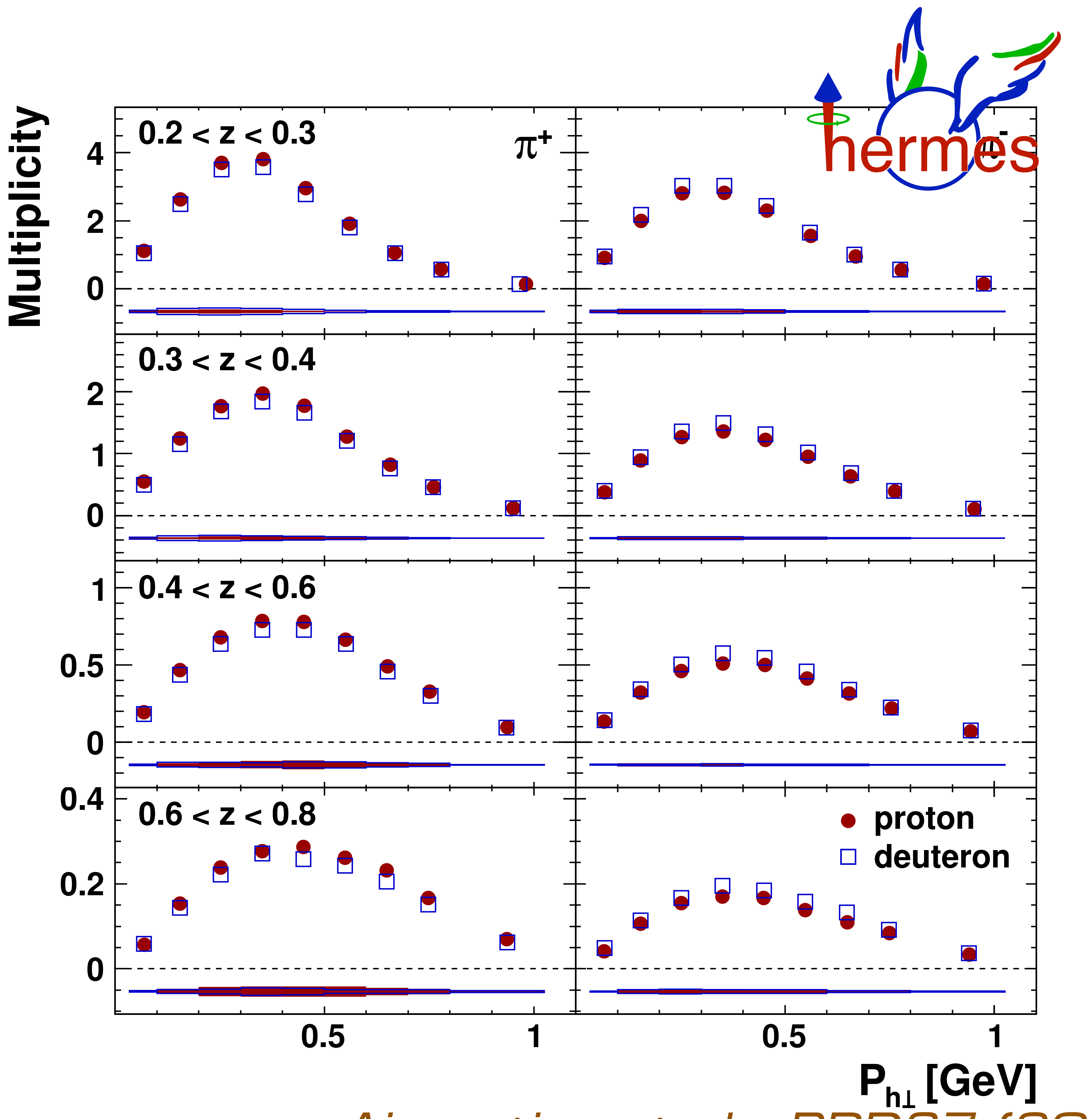
Total number of data points: 8059

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

Executive summary of results 2/3

HERMES, Q ≈ 1.5 GeV



Airapetian et al., PRD87 (2013)

Executive summary of results 2/3

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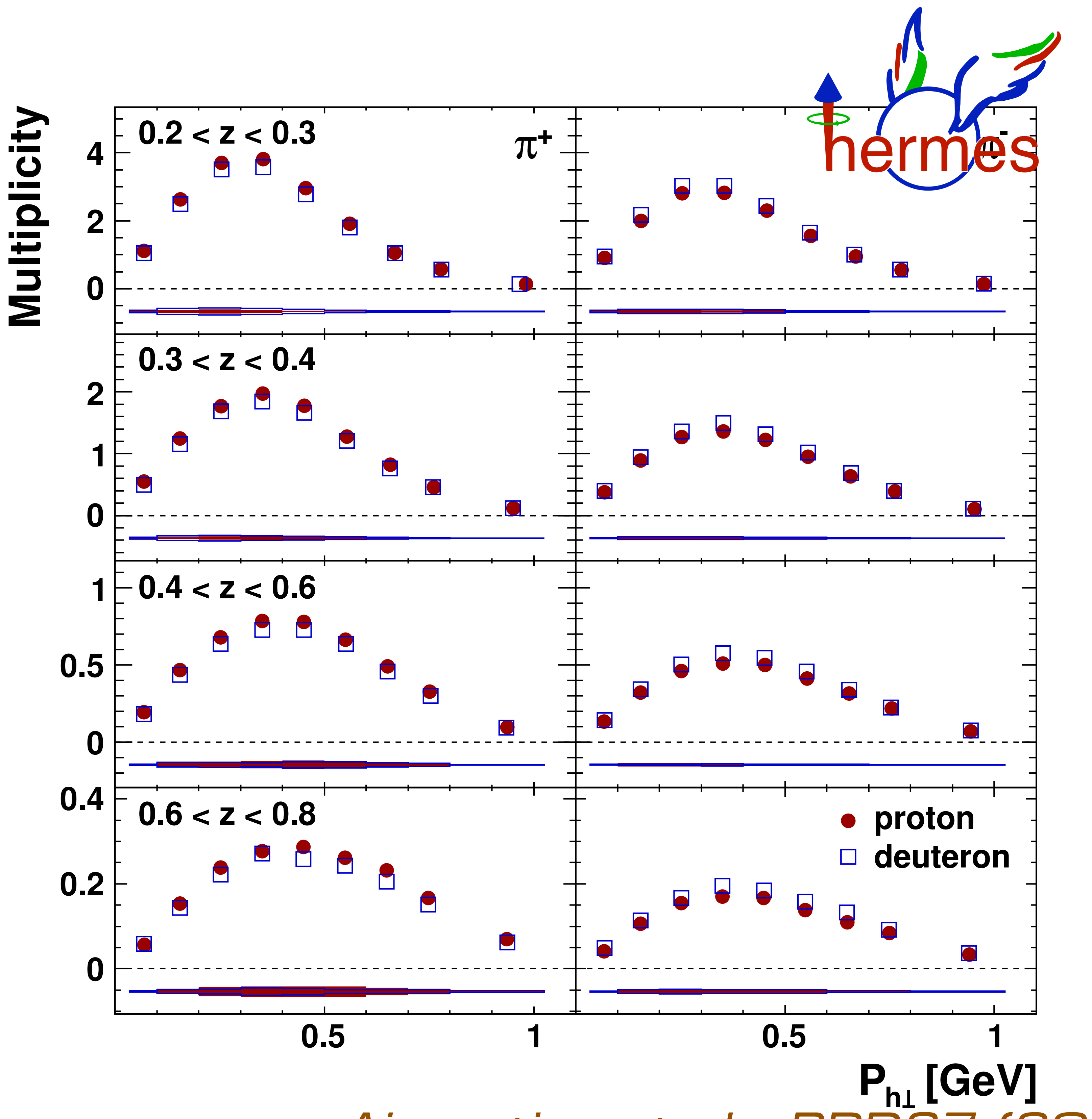

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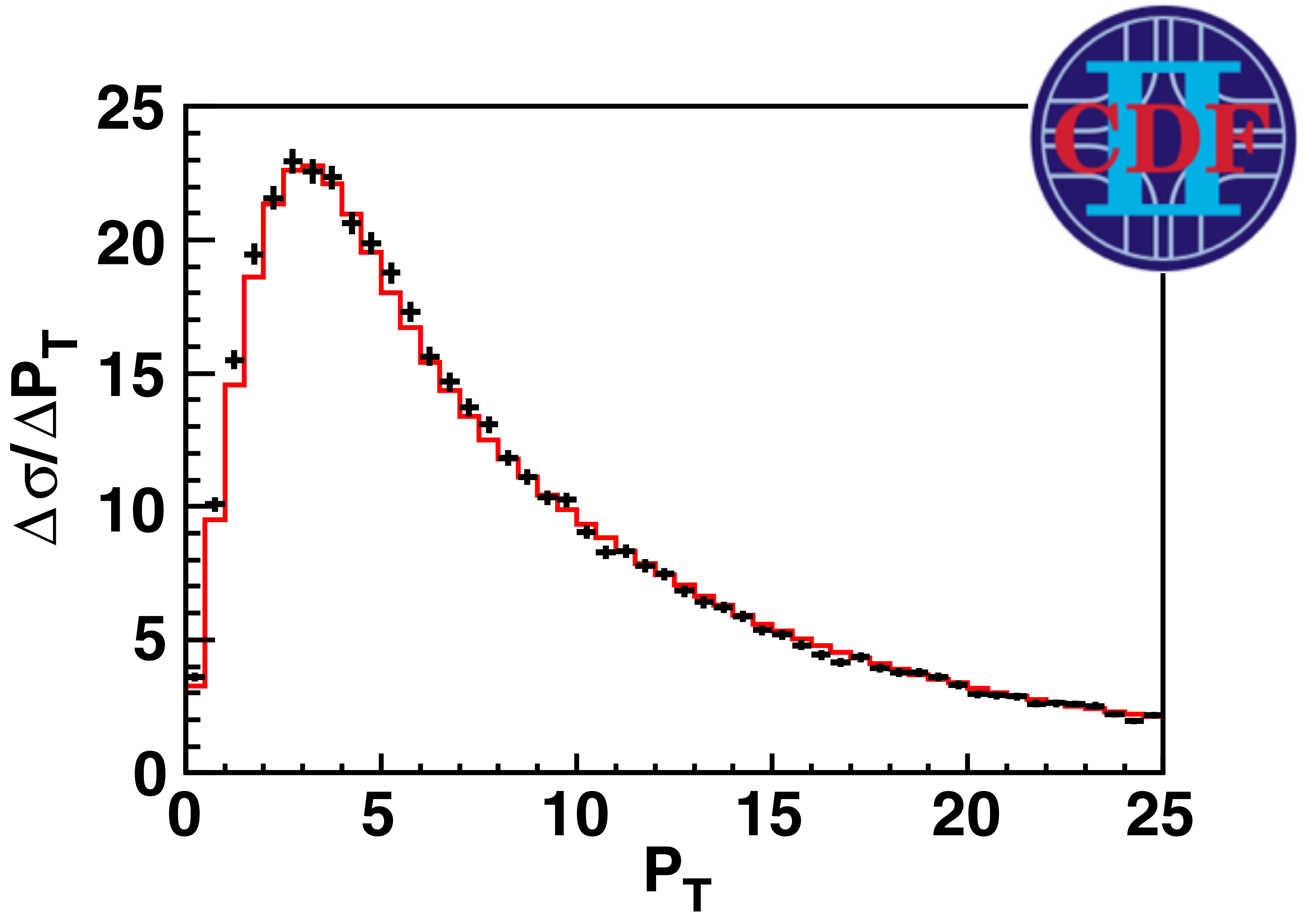
CDF, Q ≈ 91 GeV



Aaltonen et al., PRD86 (2012)

Executive summary of results 2/3

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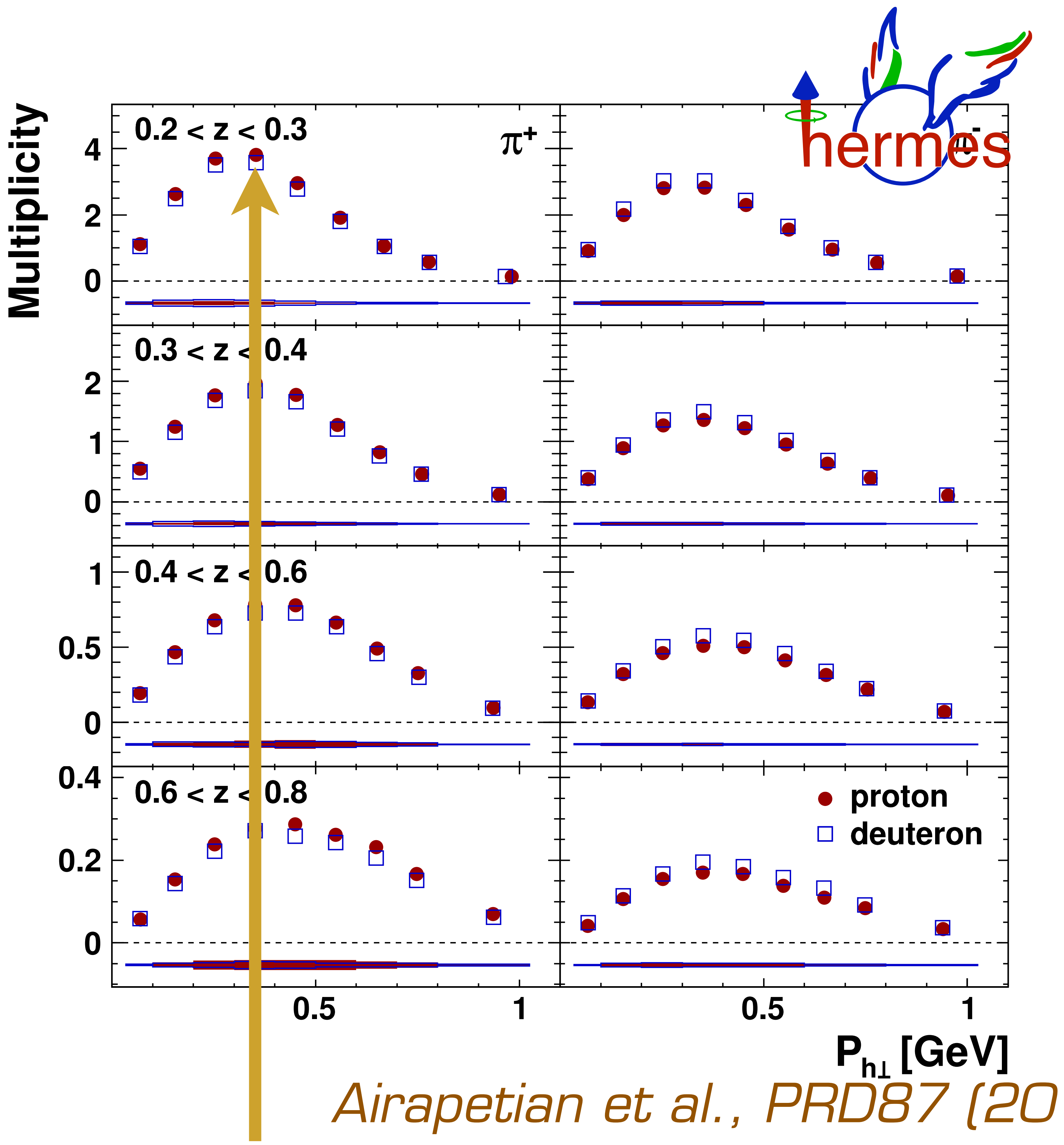

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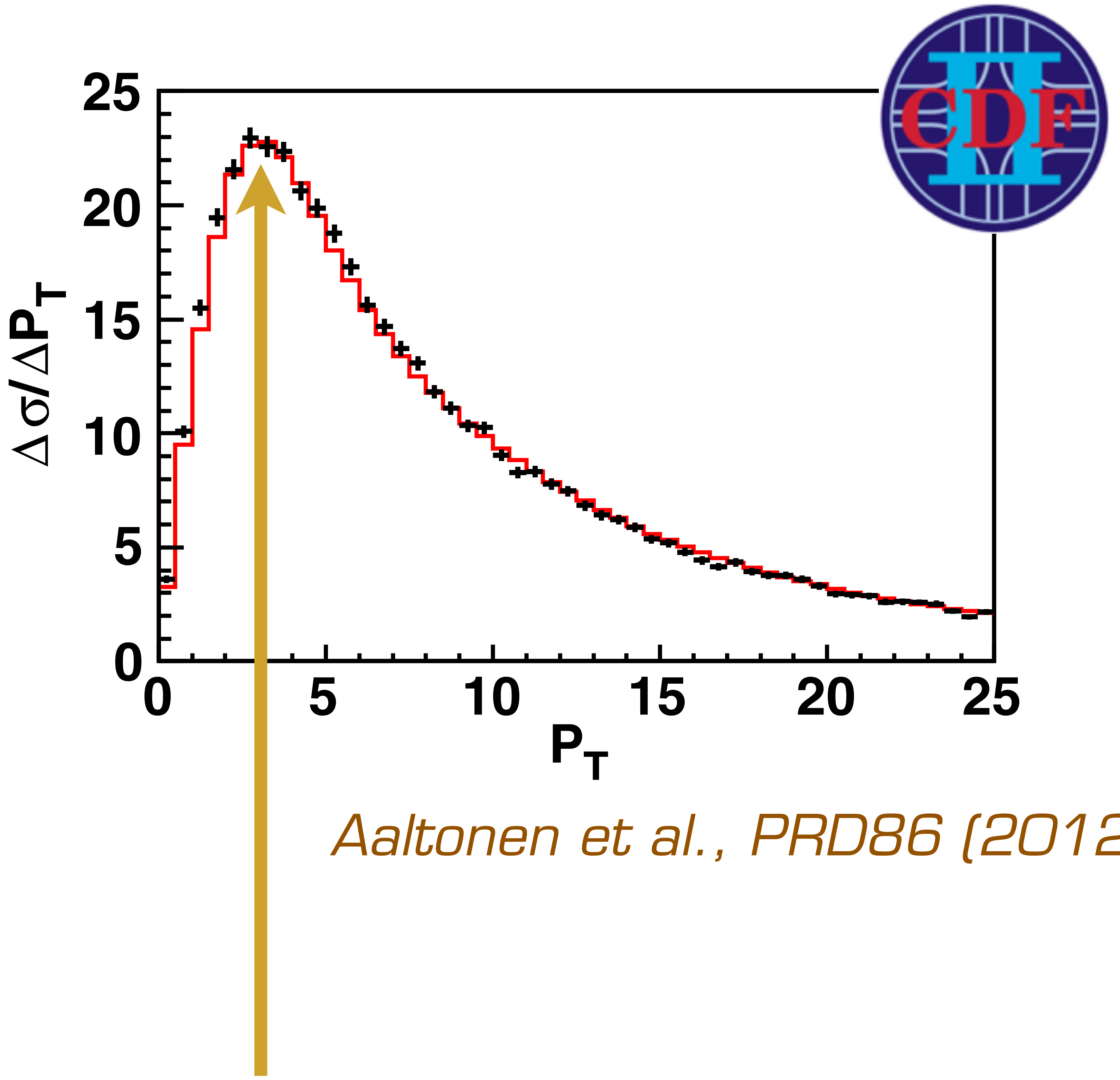
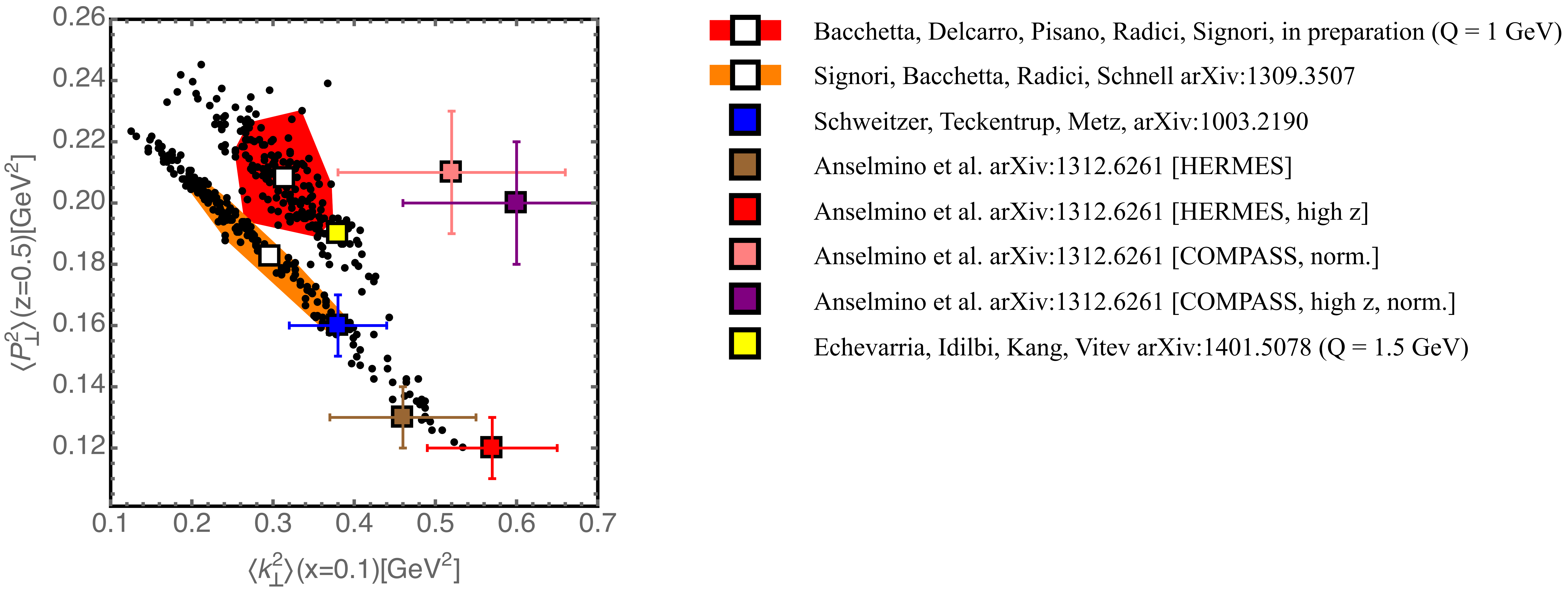


Aaltonen et al., PRD86 (2012)

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

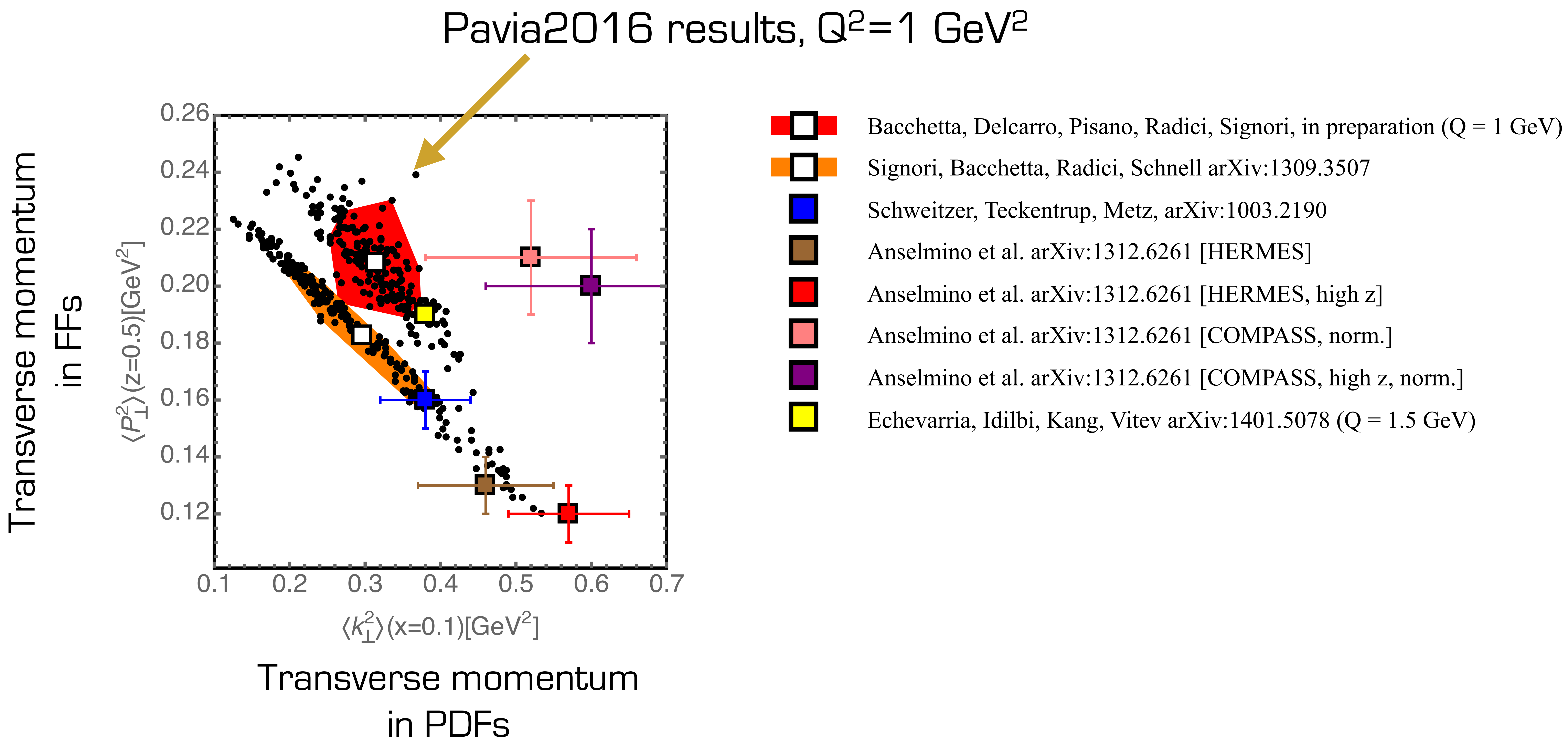
Executive summary of results 3/3

Transverse momentum in FFs



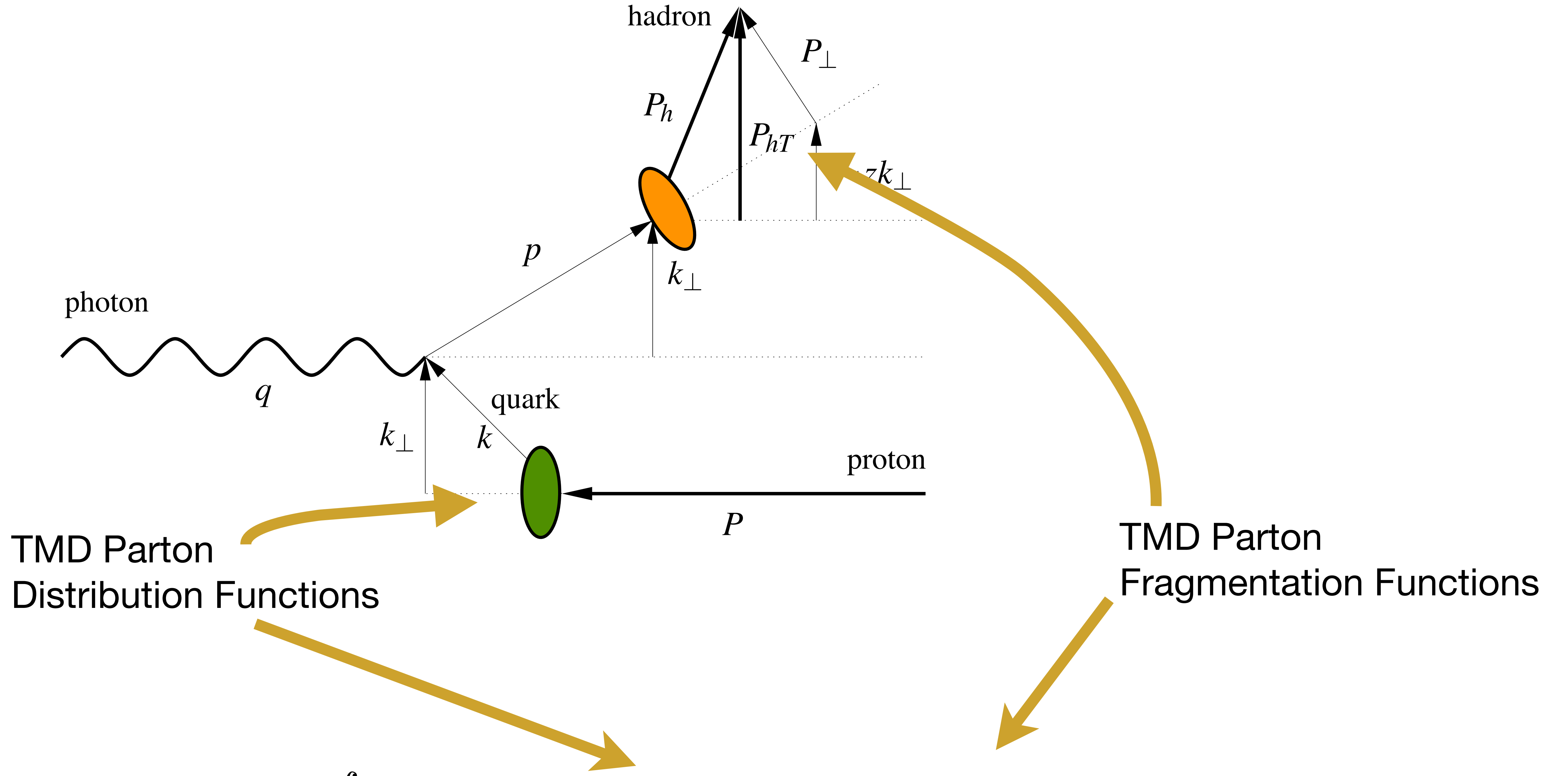
Transverse momentum in PDFs

Executive summary of results 3/3



Some details

Structure functions and TMDs



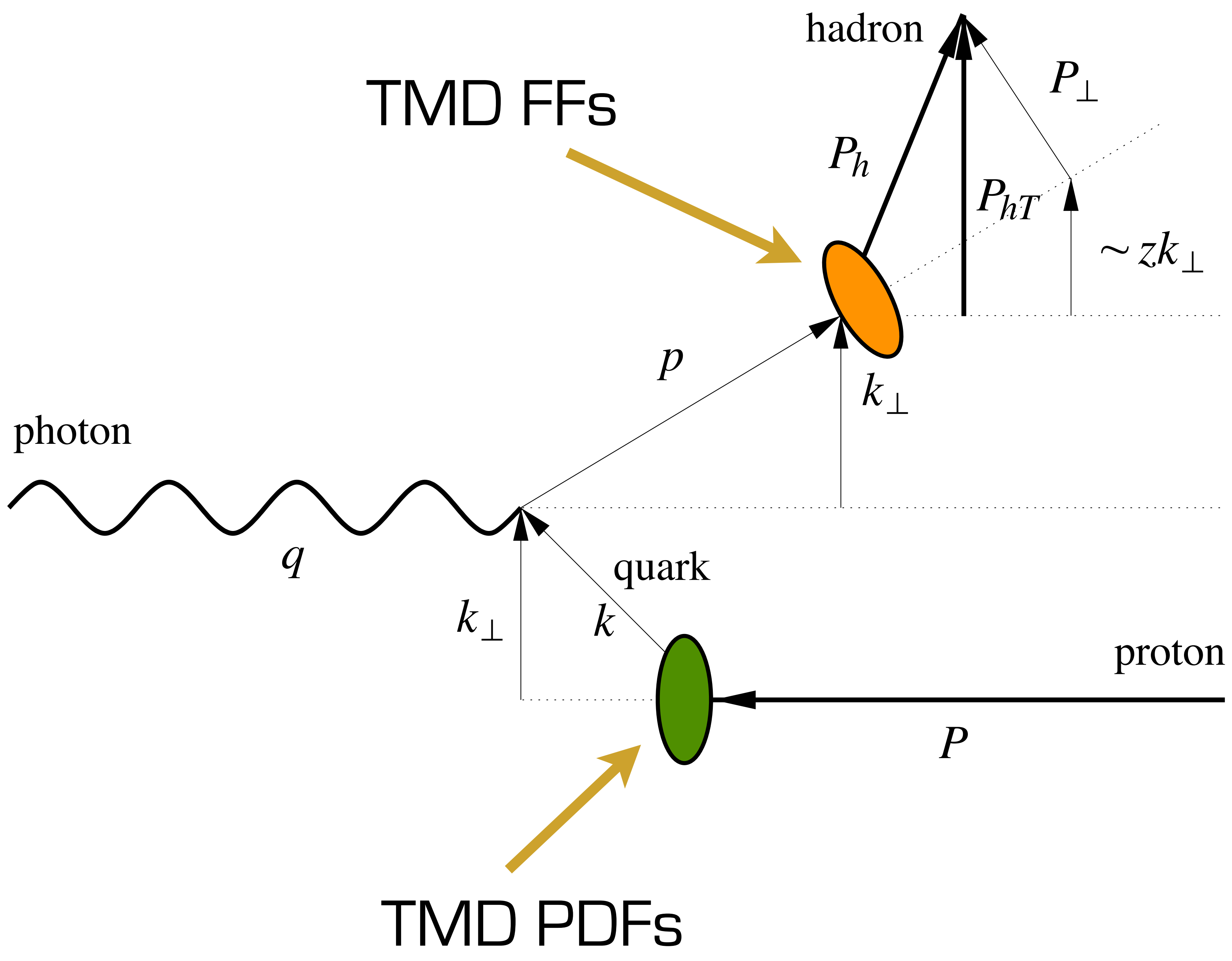
$$F_{UU,T}(x,z,\boldsymbol{P}_{hT}^2,Q^2) = \sum_a \mathcal{H}^a_{UU,T}(Q^2;\mu^2) \int d\boldsymbol{k}_\perp \, d\boldsymbol{P}_\perp \, f_1^a(x,\boldsymbol{k}_\perp^2;\mu^2)\, D_1^{a\to h}(z,\boldsymbol{P}_\perp^2;\mu^2)\, \delta(z\boldsymbol{k}_\perp - \boldsymbol{P}_{hT} + \boldsymbol{P}_\perp)$$

$$+ Y_{UU,T}(Q^2,\boldsymbol{P}_{hT}^2) + \mathcal{O}(M^2/Q^2)$$

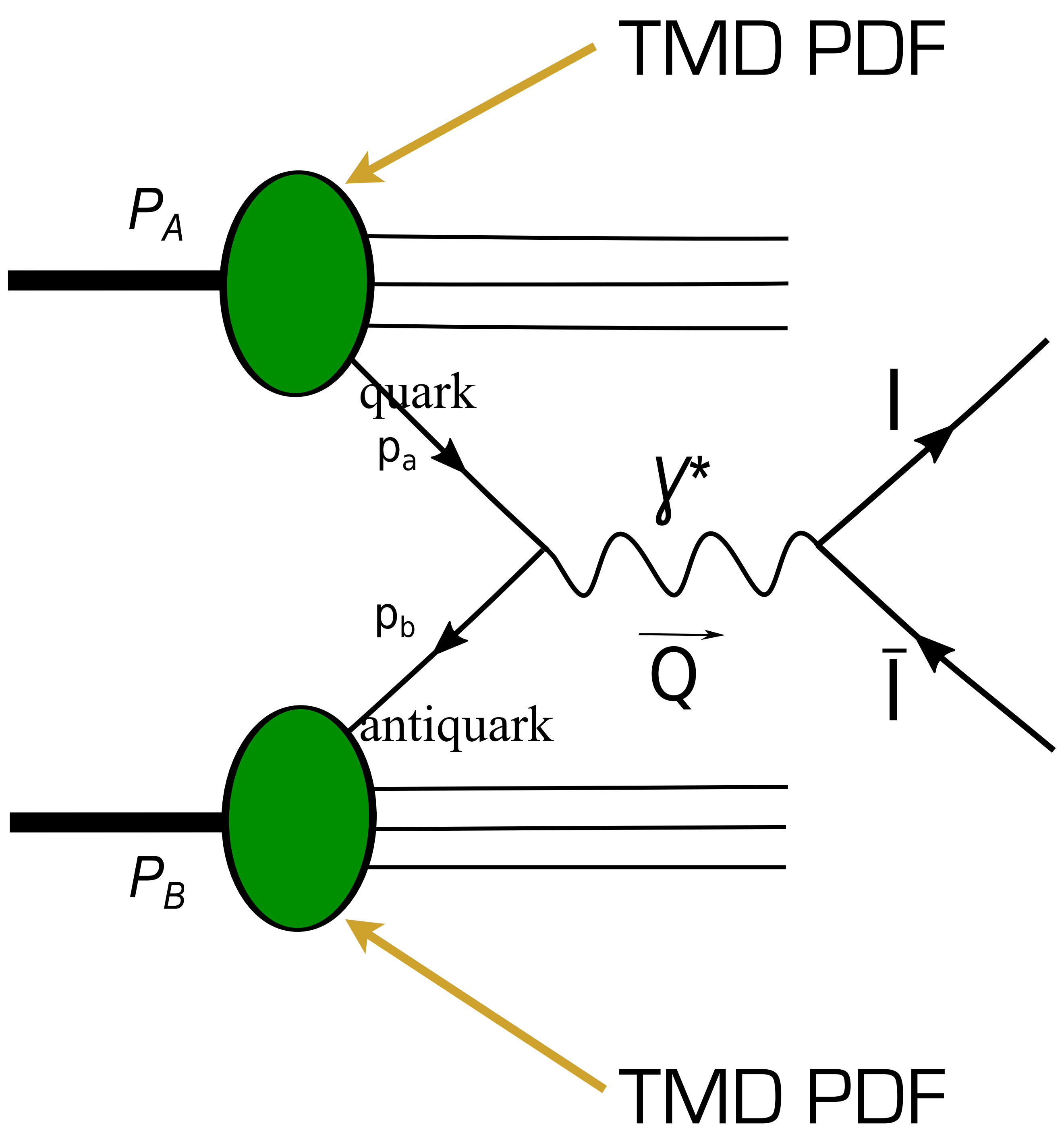
see talk by Bowen Wang

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

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

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

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

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

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collinear PDF

pQCD

nonperturbative part of evolution

nonperturbative part of TMD

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

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Perturbative ingredients

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

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

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

Perturbative ingredients

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

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

Pavia 2016 perturbative ingredients

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

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

μ and b$_*$ prescriptions

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

μ and b* prescriptions

Choice **Choice**

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μ and b* prescriptions

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

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

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

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DEMS 2014

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

Complex-b prescription — *Laenen, Sterman, Vogelsang, PRL 84 (00)*

Nonperturbative ingredients 1

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

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

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

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

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

Collins, Soper, Sterman, NPB250 (85)

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

Aidala, Field, Gamberg, Rogers, arXiv:1401.2654

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

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

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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

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Collins et al., arXiv:1605.00671

Justification: the modification is allowed because it affects a region where the TMD formalism is anyway unreliable (high transverse momentum), and allows us to recover the integrated cross-section (unitarity constraint) instead of leading to infinite results.

Pavia 2016 “choices”

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

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

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

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

Pavia 2016 "choices"

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

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

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

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

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

Effects of b$_*$ prescription

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

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

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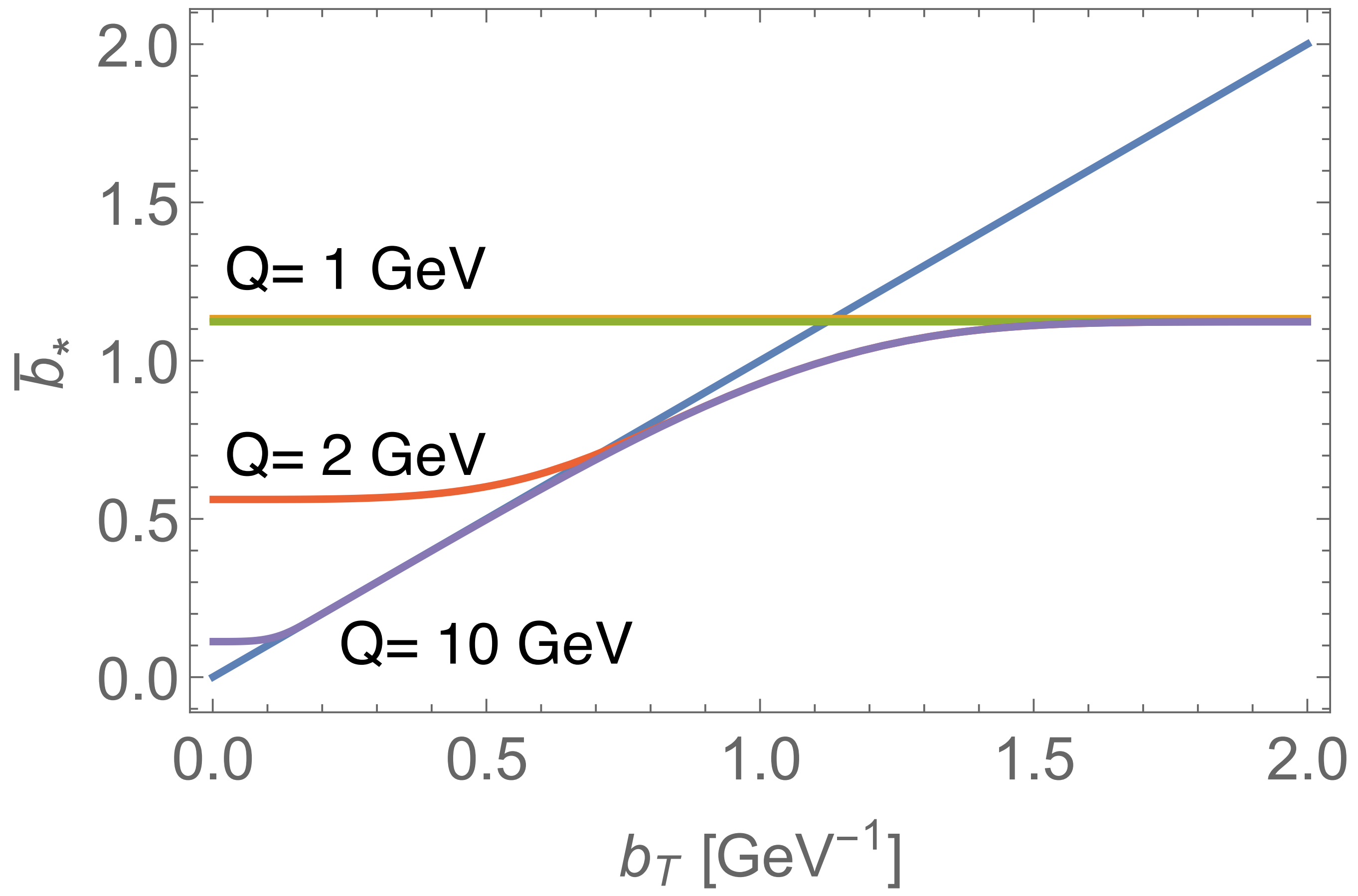
$$\mu_b = 2e^{-\gamma_E}/b_*$$



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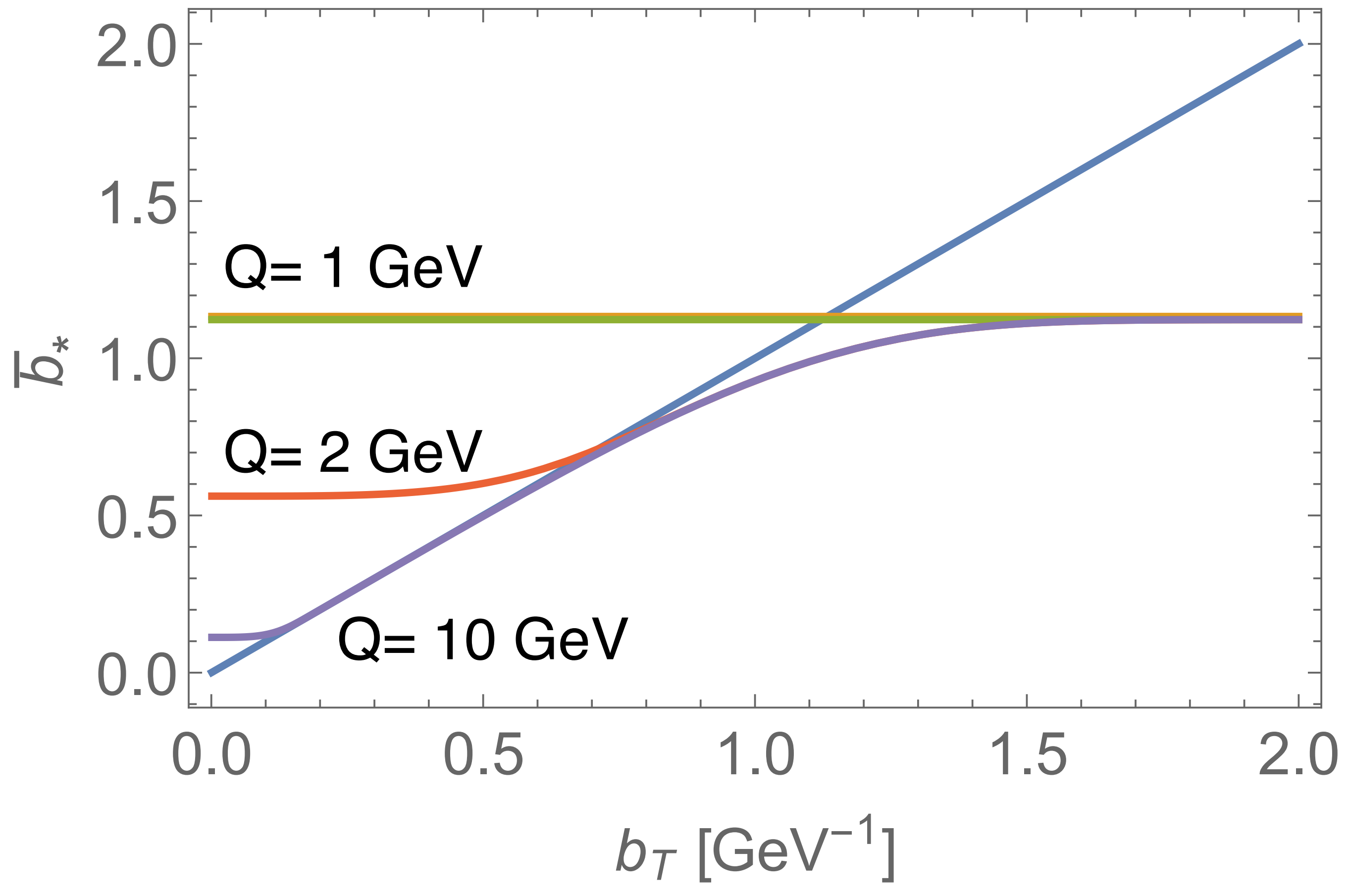

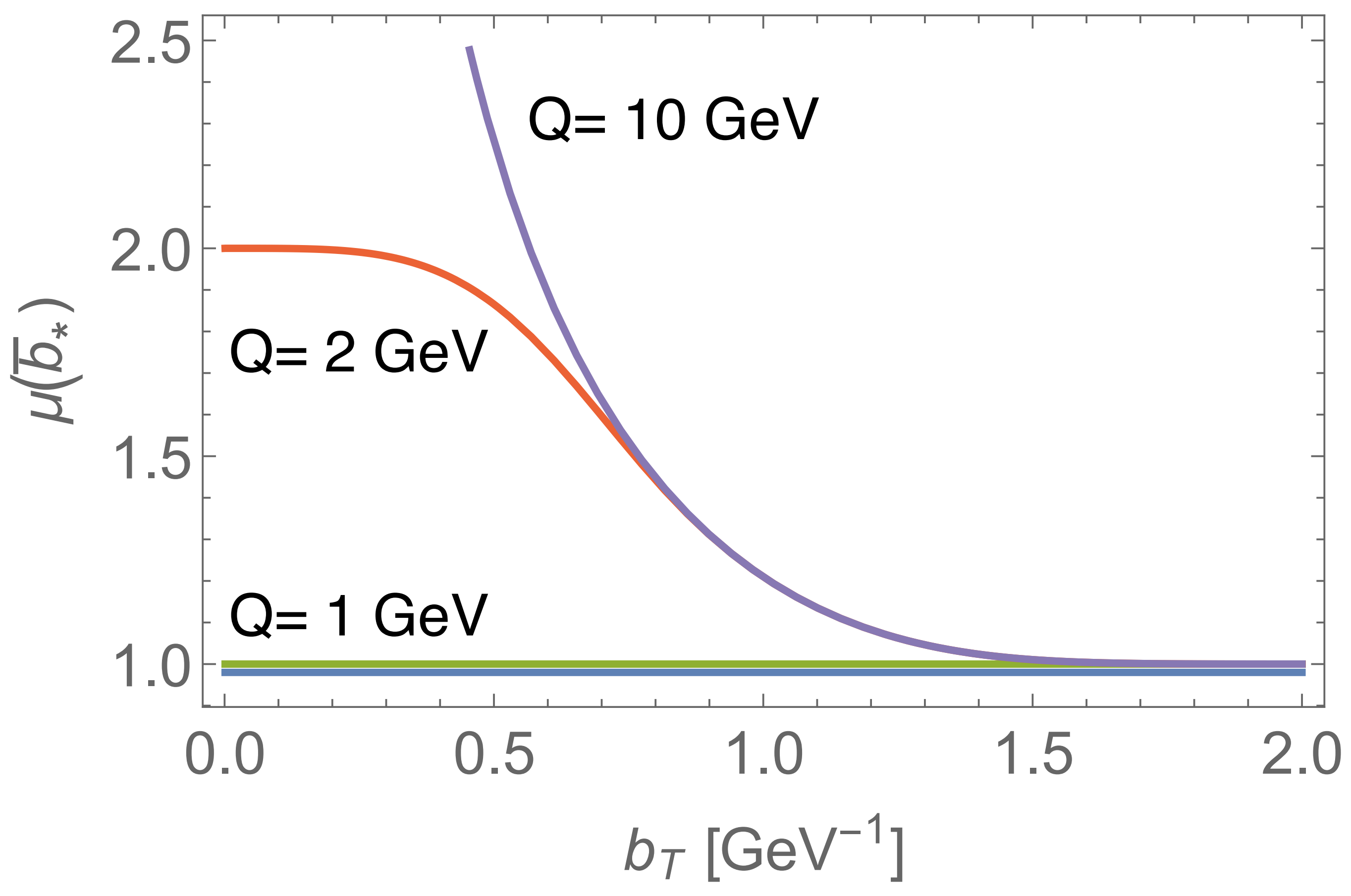

Effects of b$_*$ prescription

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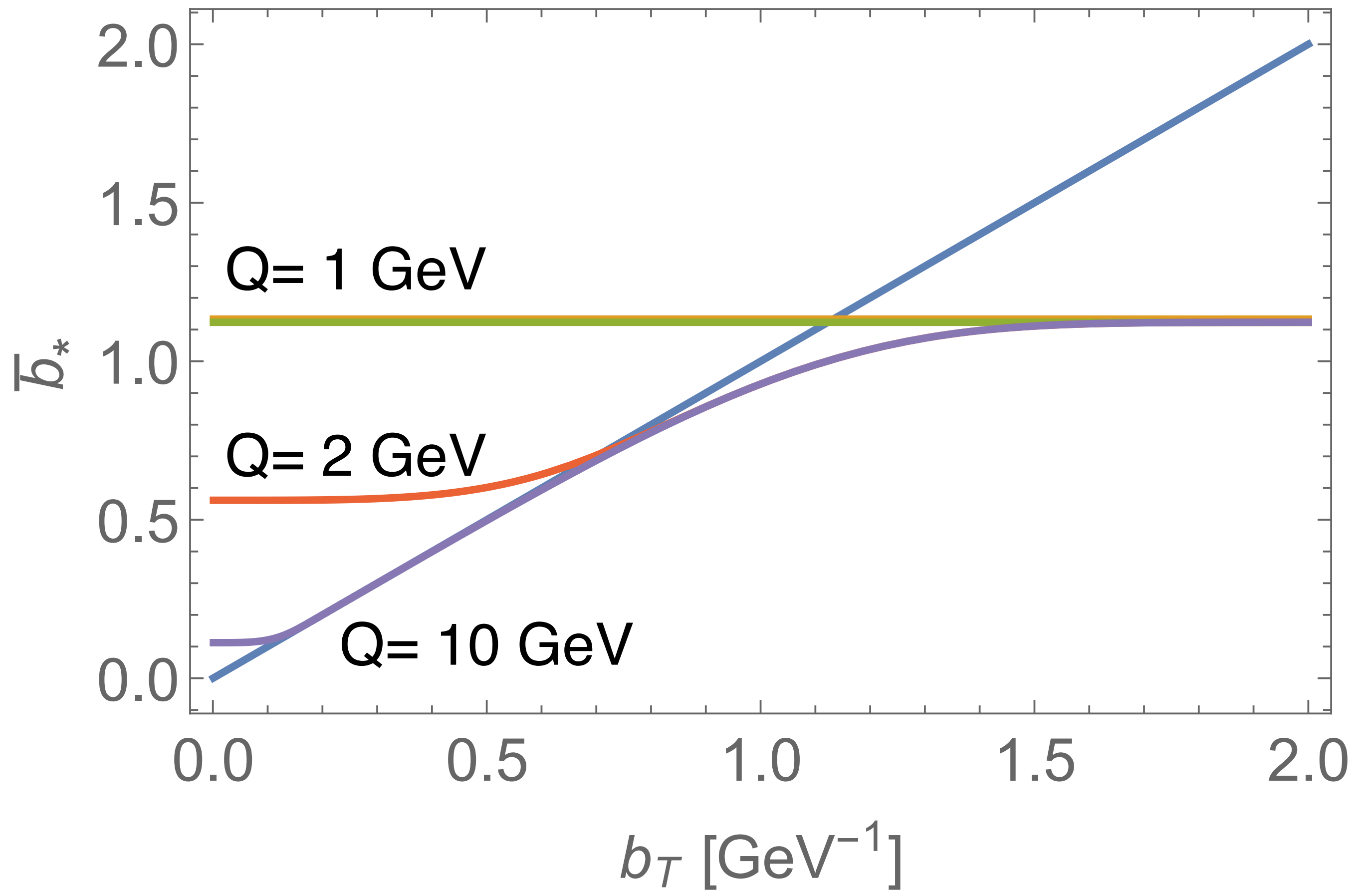
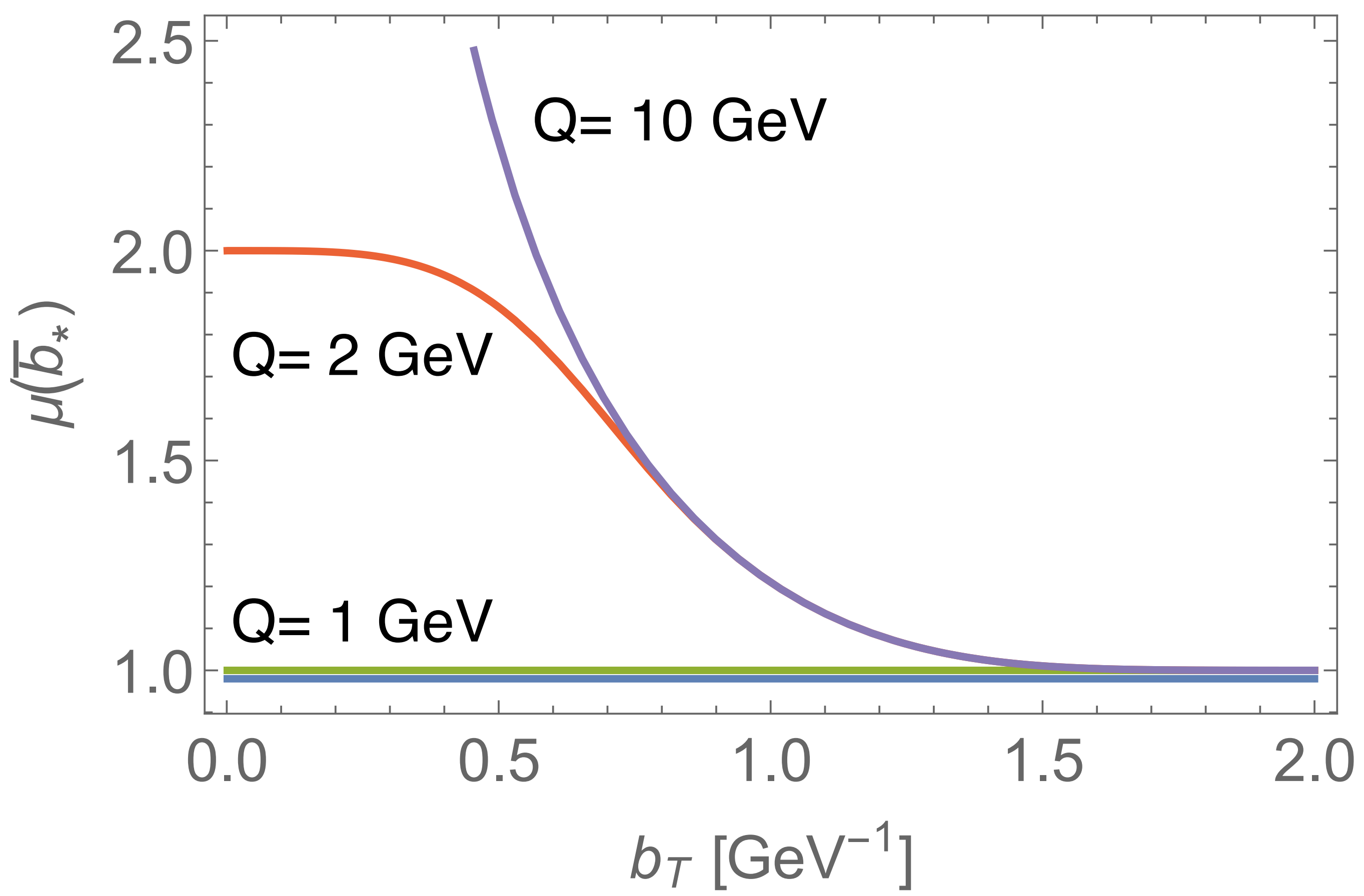
$$b_{\min} = \frac{2e^{-\gamma_E}}{Q}$$

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





μ_b never bigger than Q nor smaller than 1 GeV

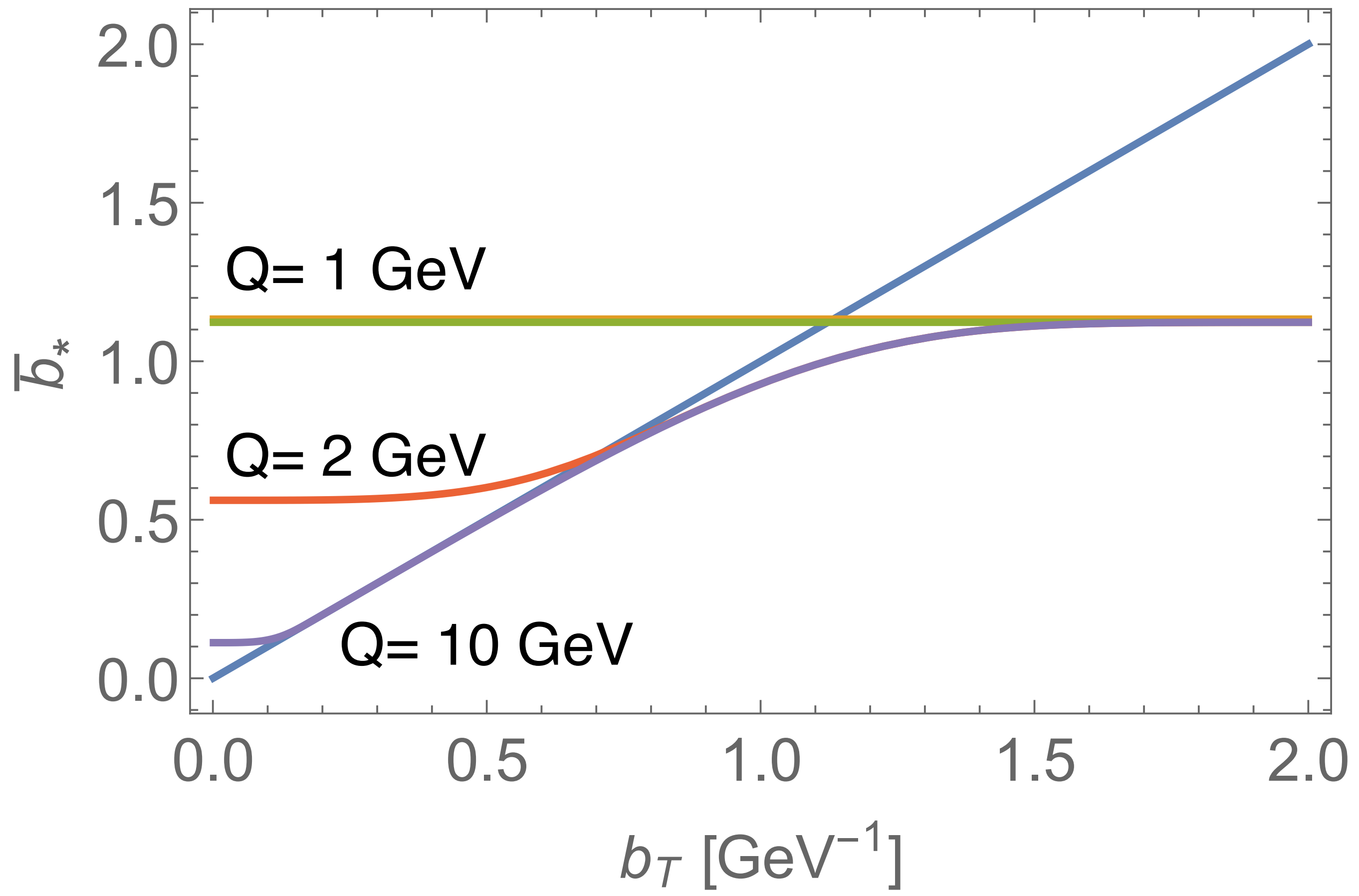
Effects of b_* prescription

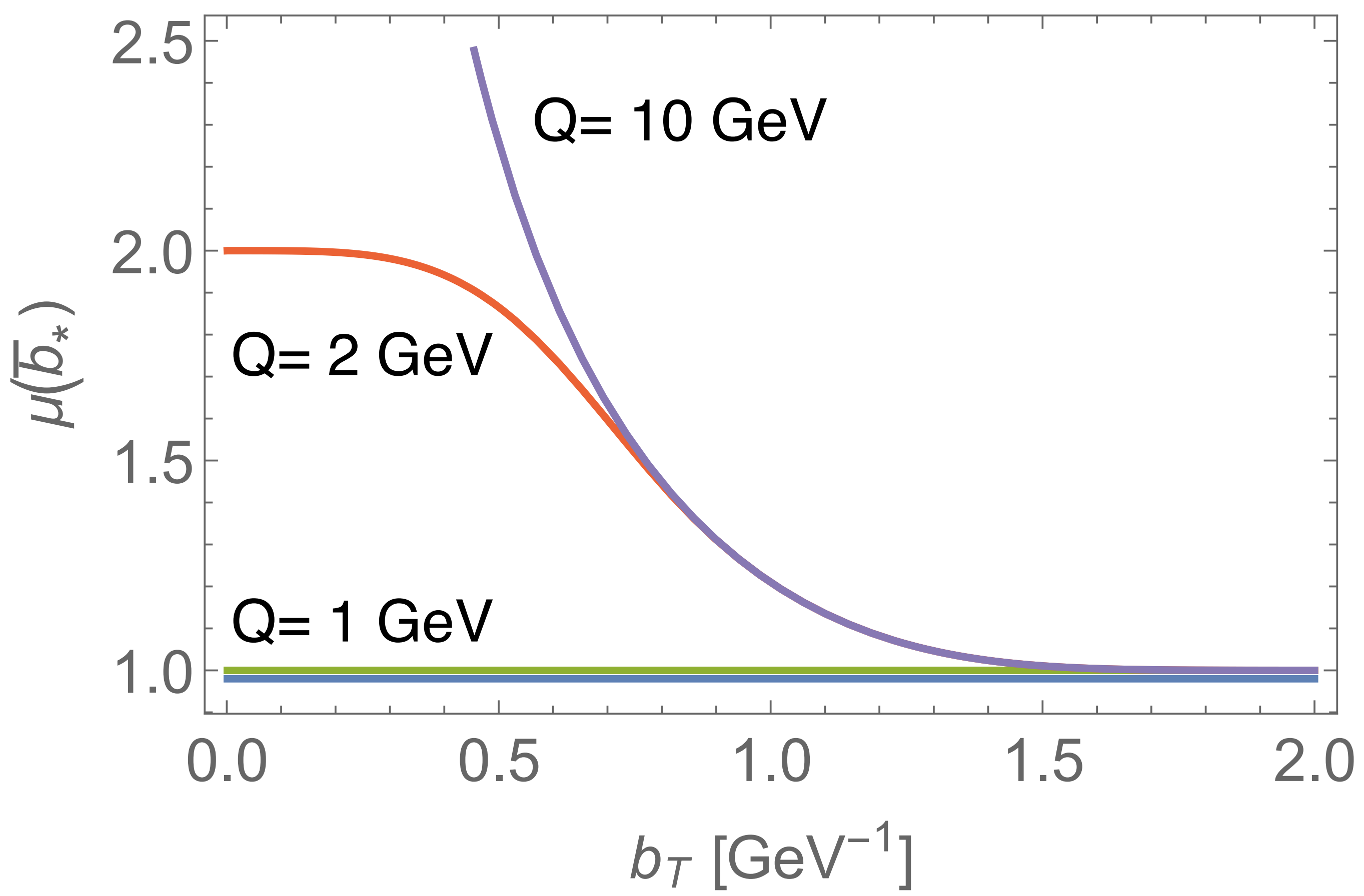
$$\bar{b}_* \equiv b_{\max}\left(\frac{1-e^{-b_T^4/b_{\max}^4}}{1-e^{-b_T^4/b_{\min}^4}}\right)^{1/4}$$

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

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

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





μ_b never bigger than Q nor smaller than 1 GeV

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

Functional form of TMDs at 1 GeV

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

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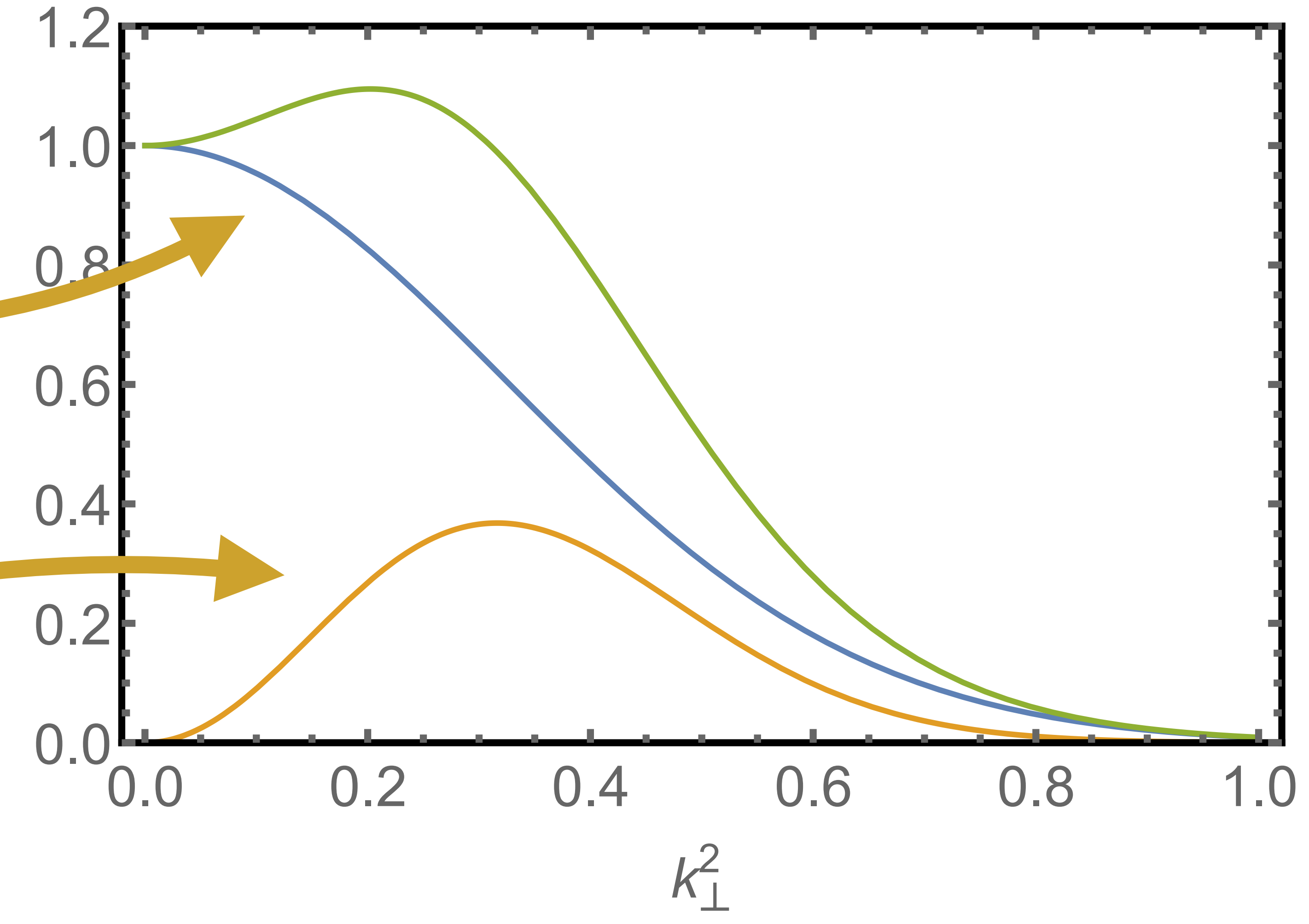

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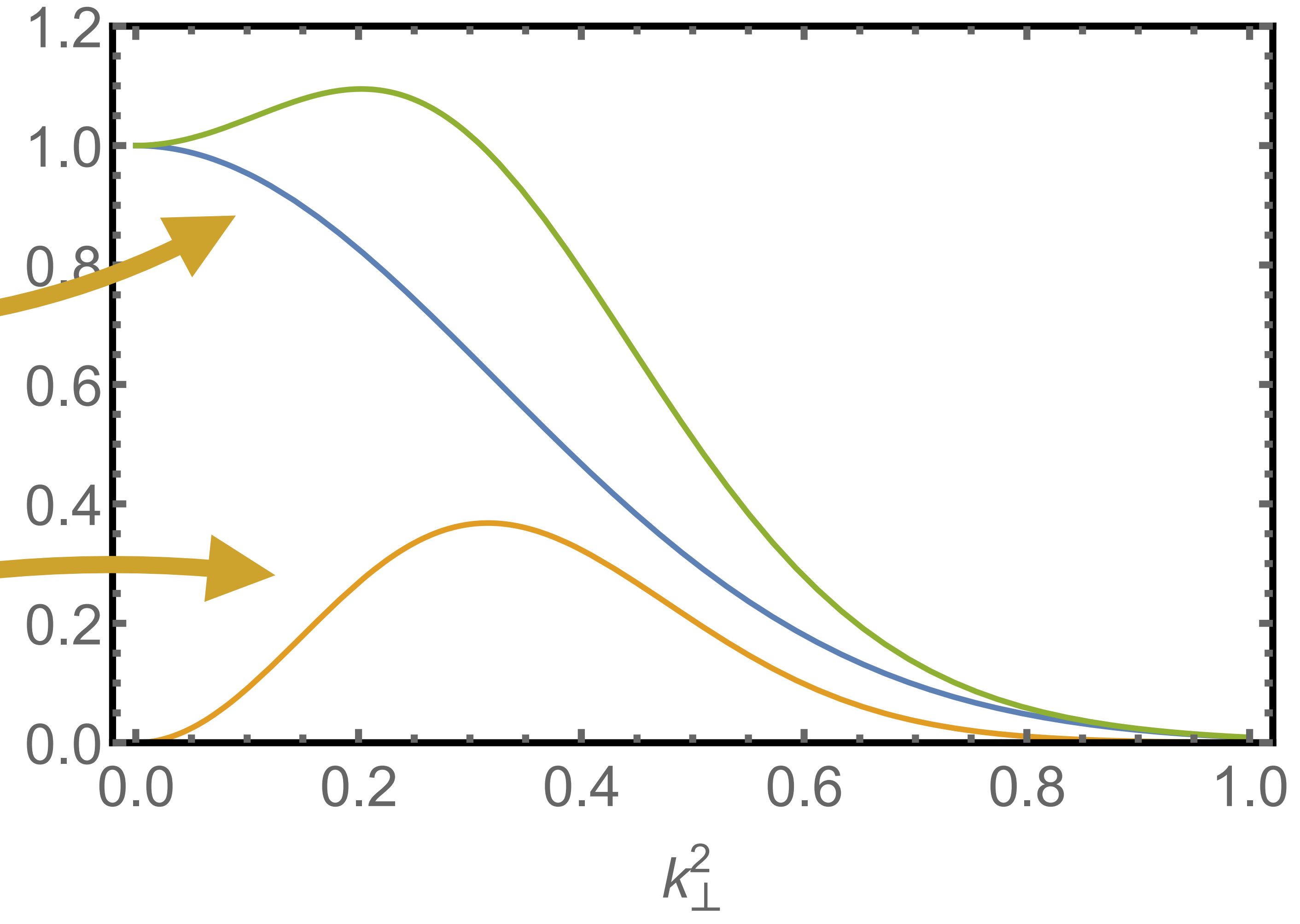

x-dependent width $\langle \boldsymbol{k}_{\perp,a}^2 \rangle(x) = \langle \hat{\boldsymbol{k}}_{\perp,a}^2 \rangle \frac{(1-x)^\alpha x^\sigma}{(1-\hat{x})^\alpha \hat{x}^\sigma}$,

where $\langle \hat{\boldsymbol{k}}_{\perp,a}^2 \rangle \equiv \langle \boldsymbol{k}_{\perp,a}^2 \rangle(\hat{x})$, and $\hat{x} = 0.1$.

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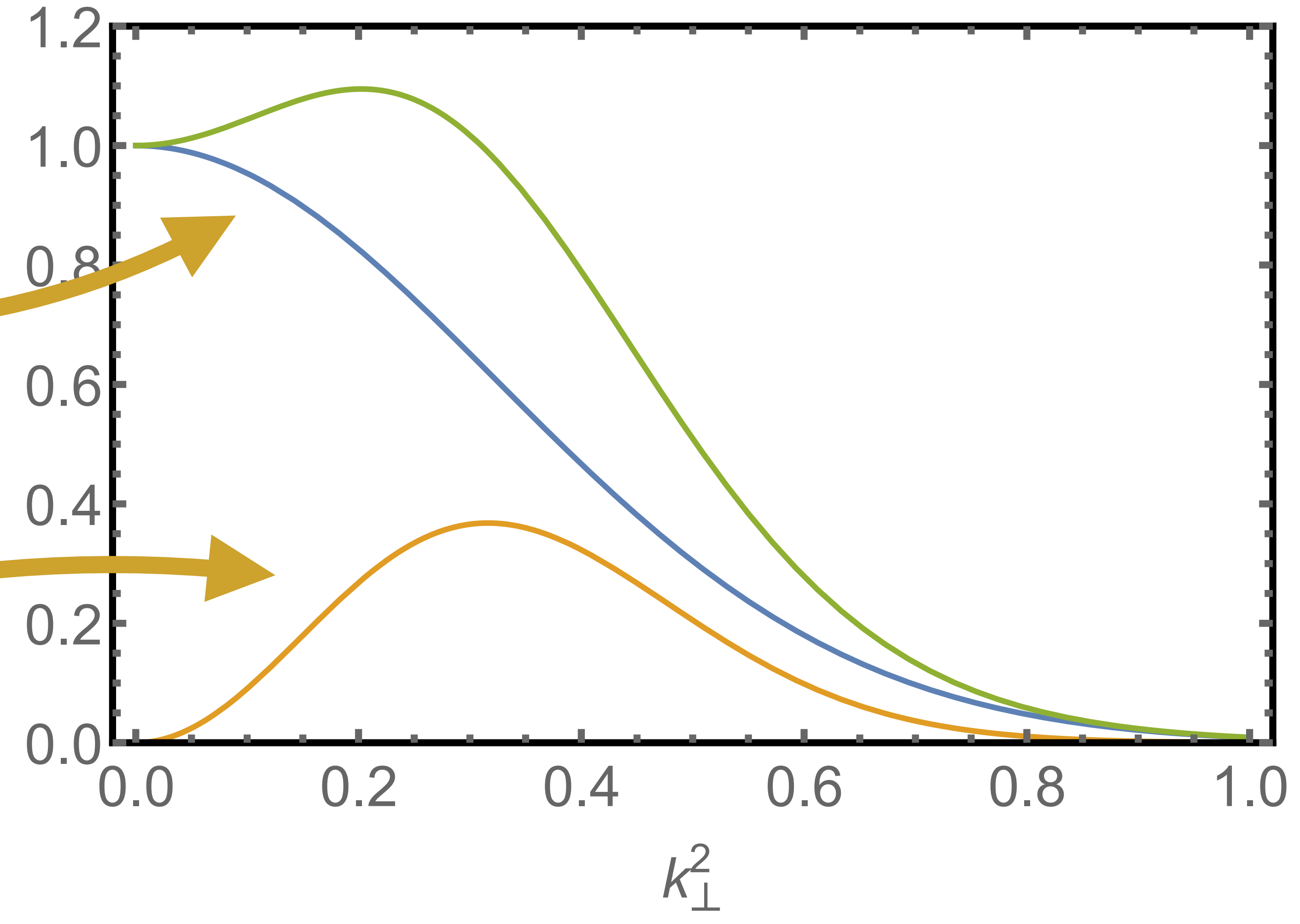

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Fragmentation function is similar
Including TMD PDFs and FFs, in total: 11 free parameters
(4 for TMD PDFs, 6 for TMD FFs, 1 for TMD evolution)

Data selection

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

$$0.2 < z < 0.7$$

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

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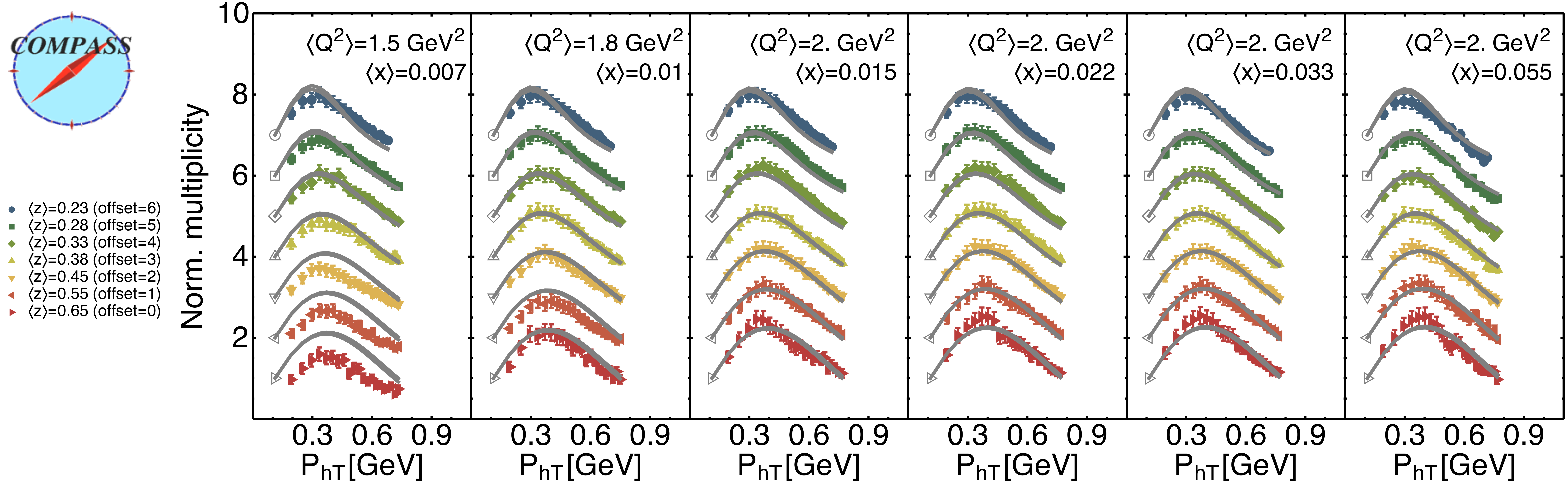
$$P_{hT}, q_T < \text{Min}[0.2\ Q, 0.7\ Qz] + 0.5 \text{ GeV}$$

Total number of data points: 8059
Total $\chi^2/\text{dof} = 1.52$

Preliminary

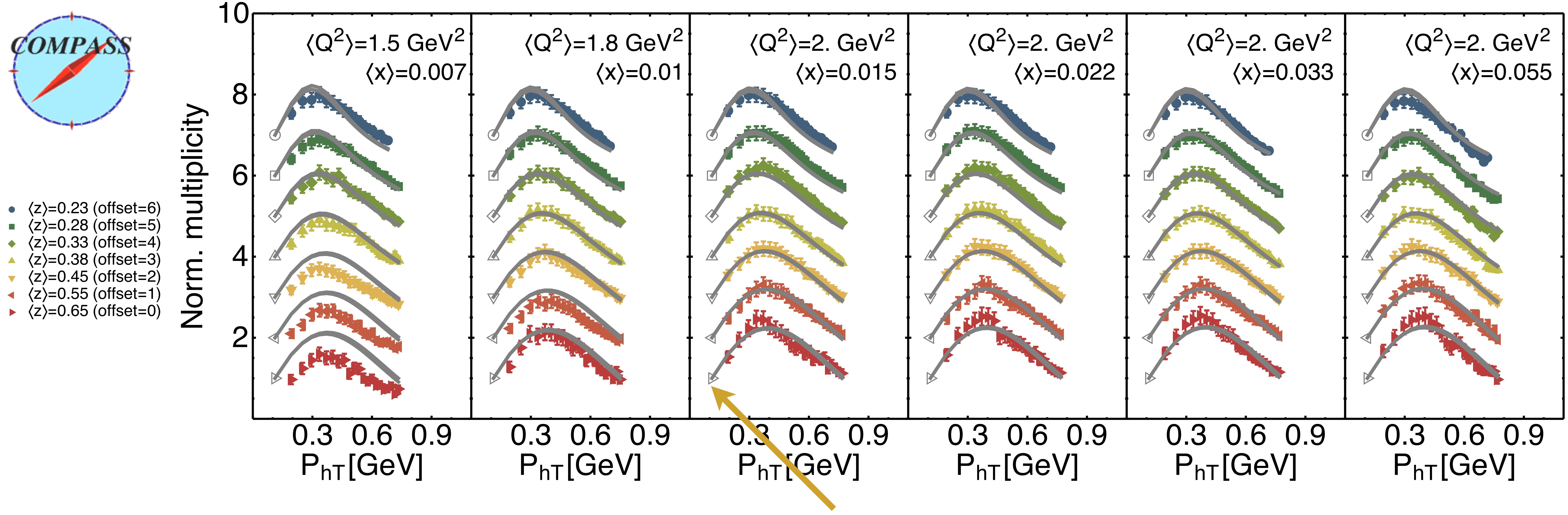
Data vs. theory plots

COMPASS selected bins



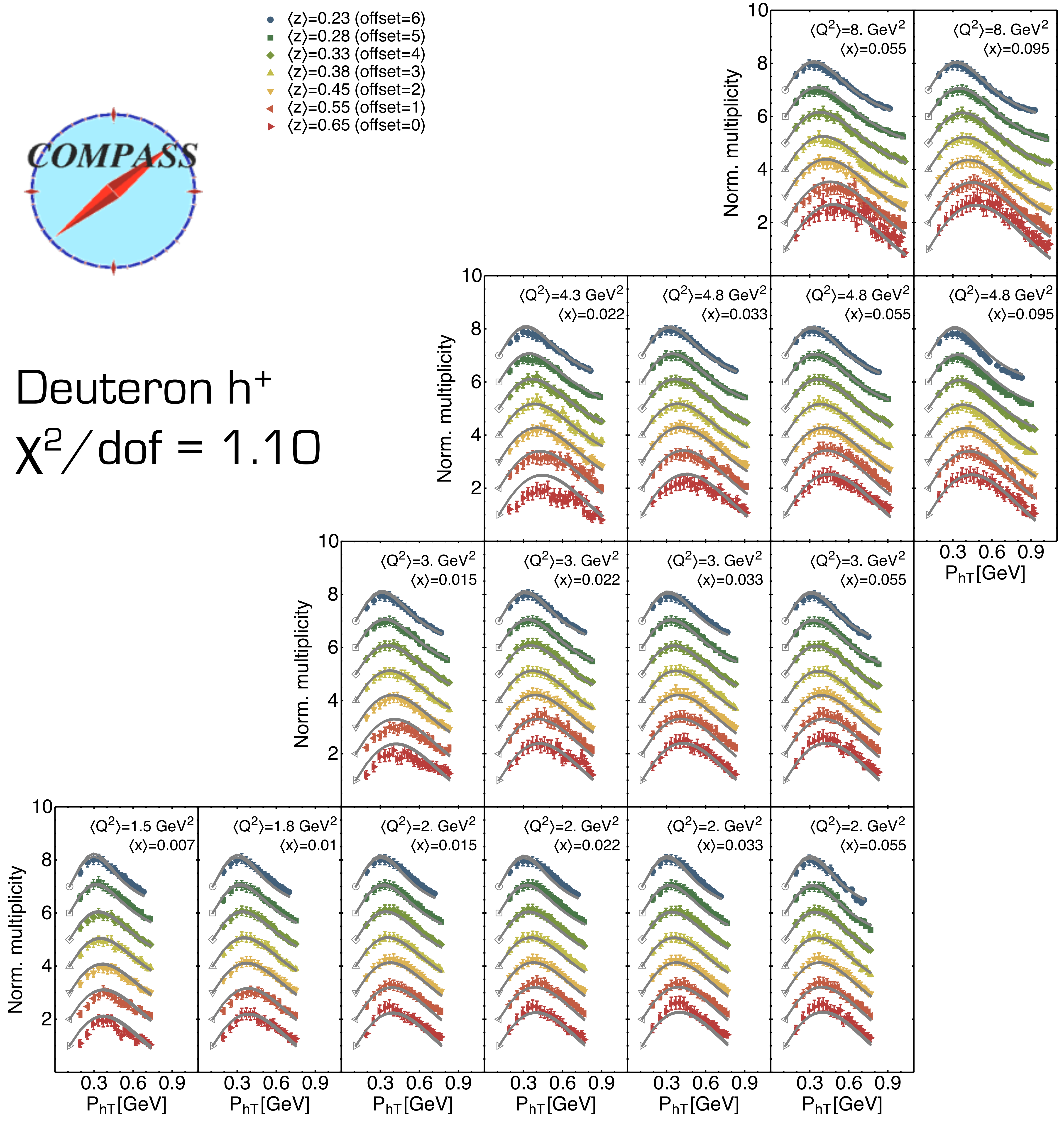
Deuteron h− $\chi^2/\text{dof} = 1.58$

COMPASS selected bins



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

First points are not fitted, but used as normalization

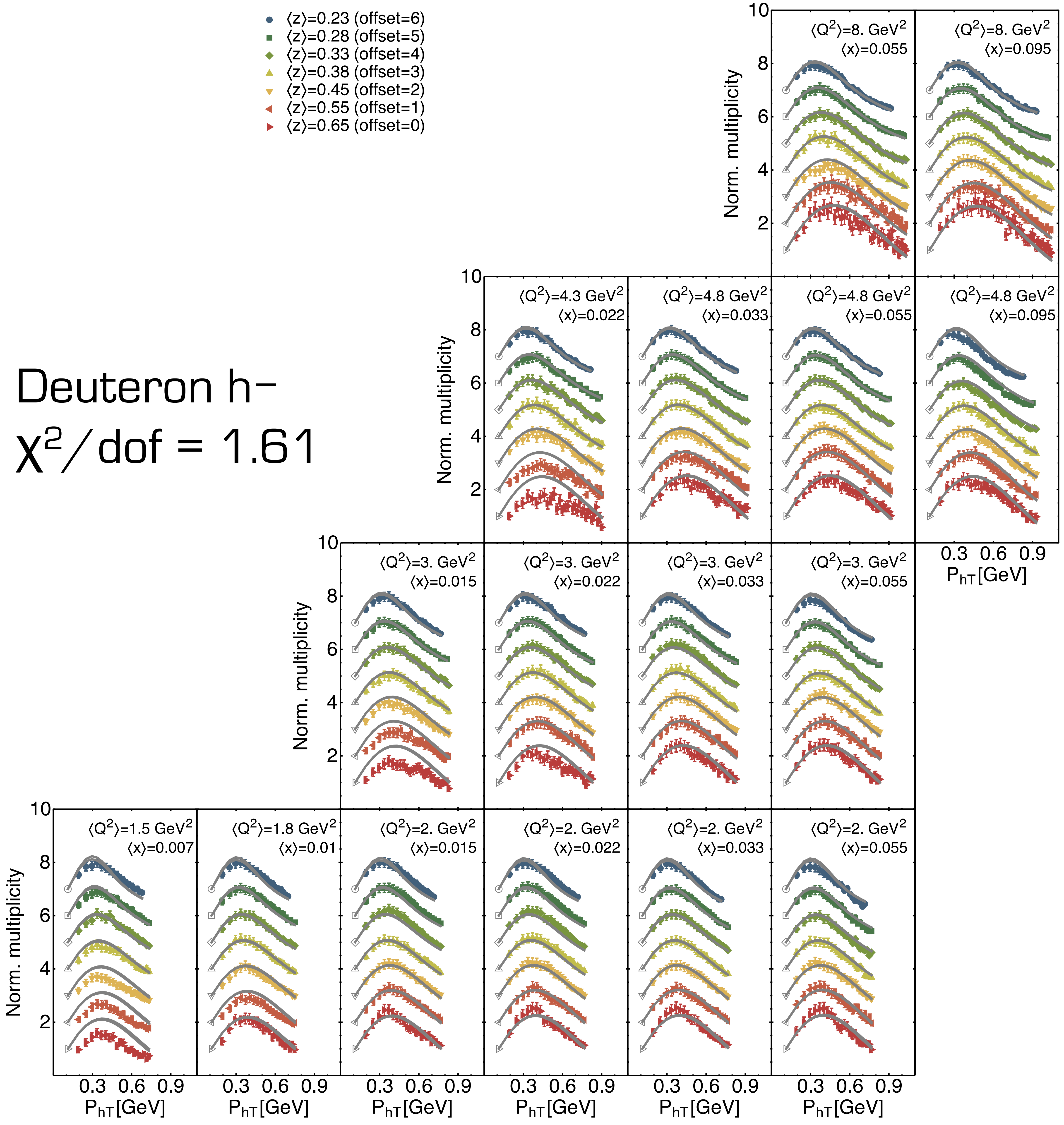


Deuteron h^+

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

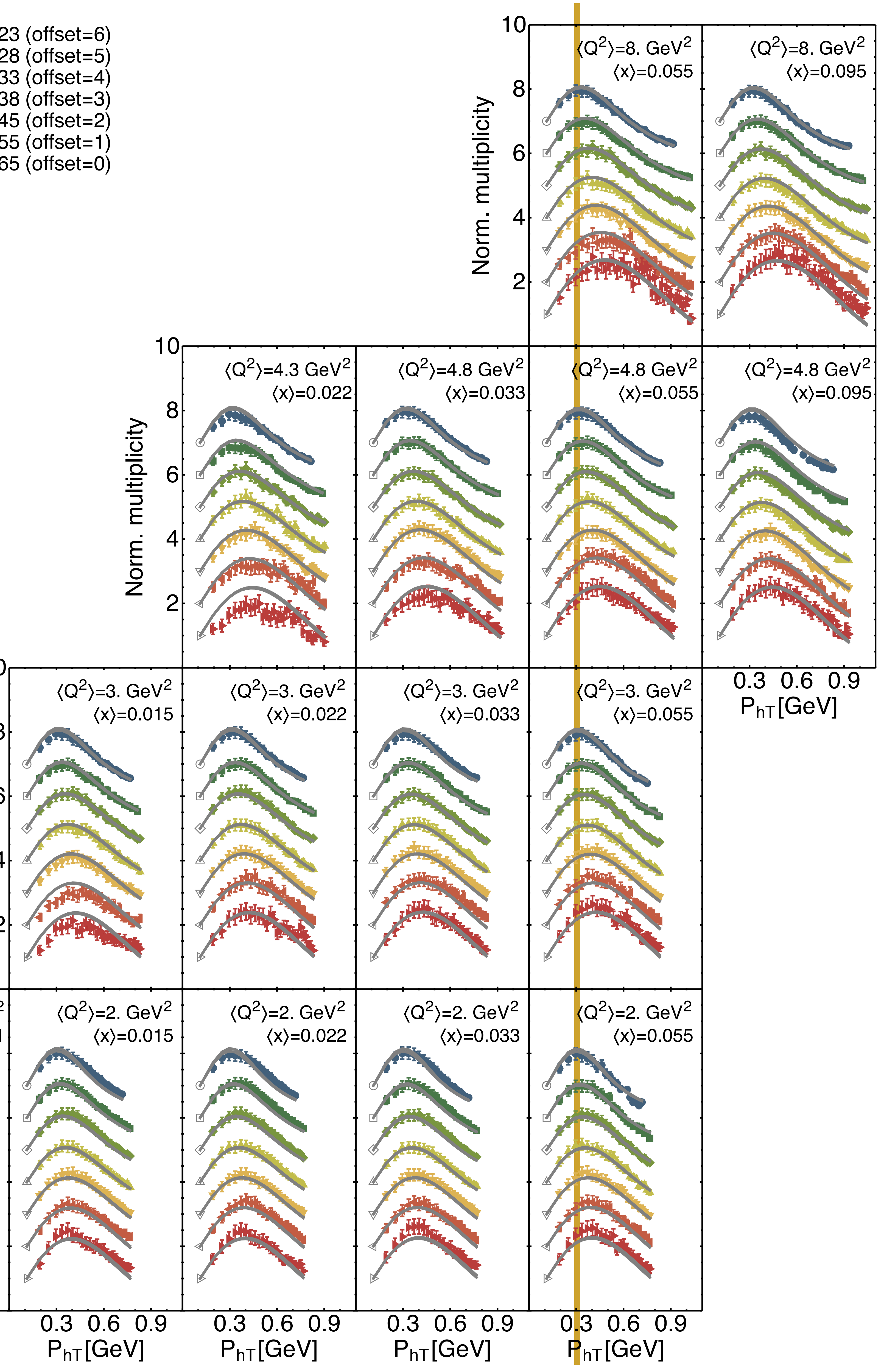
Deuteron h^-

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



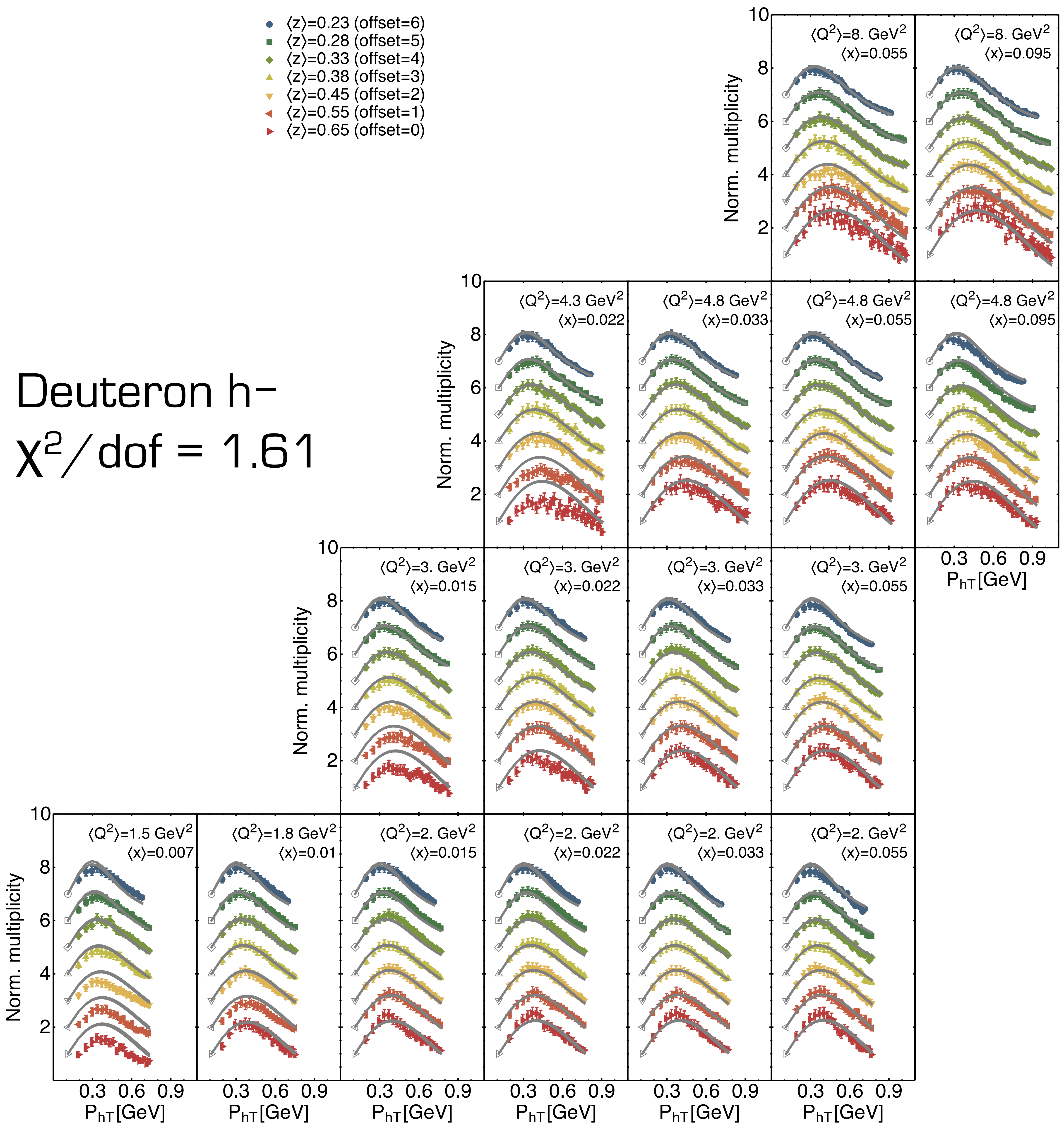
Deuteron h⁺

$\chi^2/dof = 1.10$

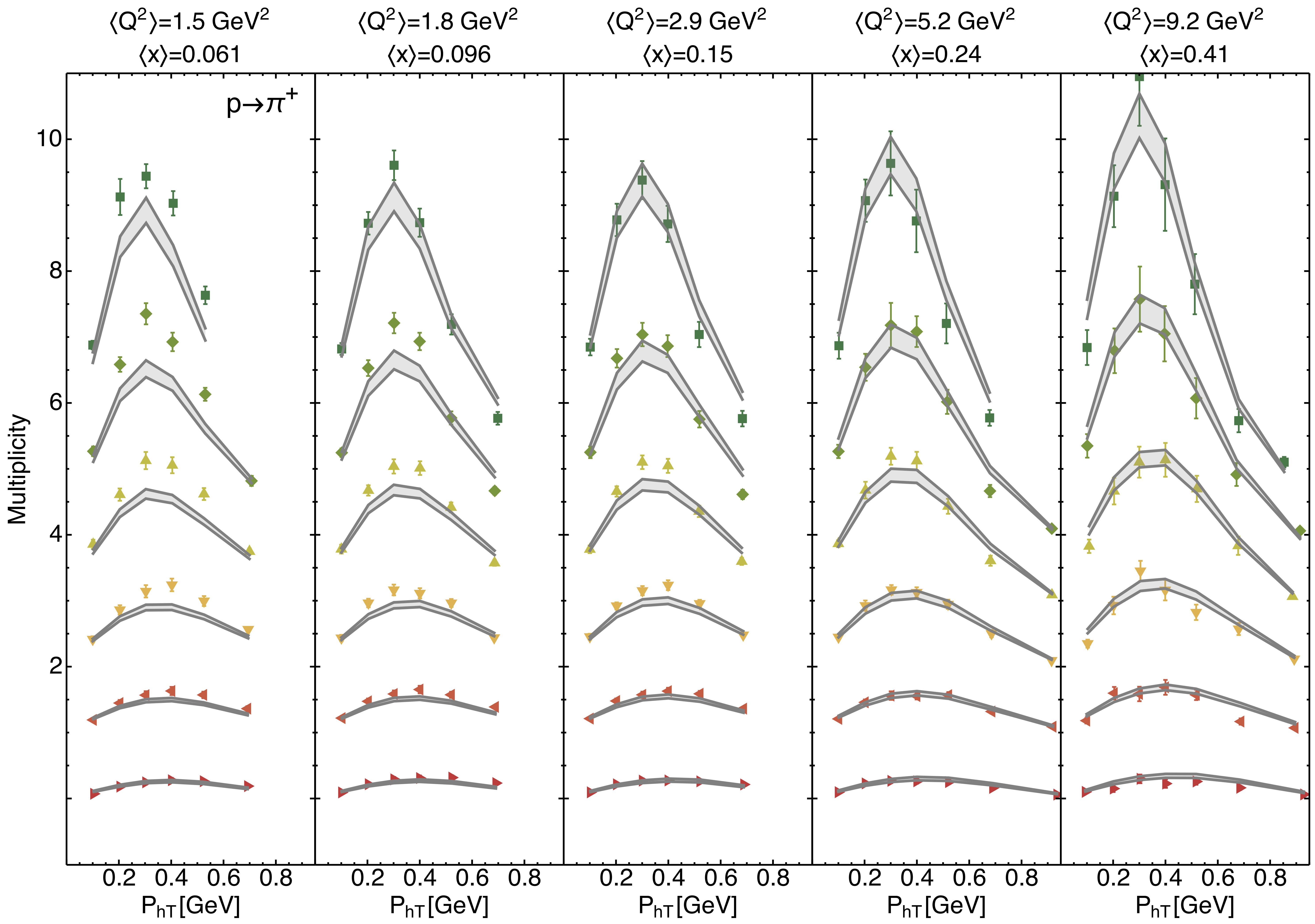


Deuteron h−

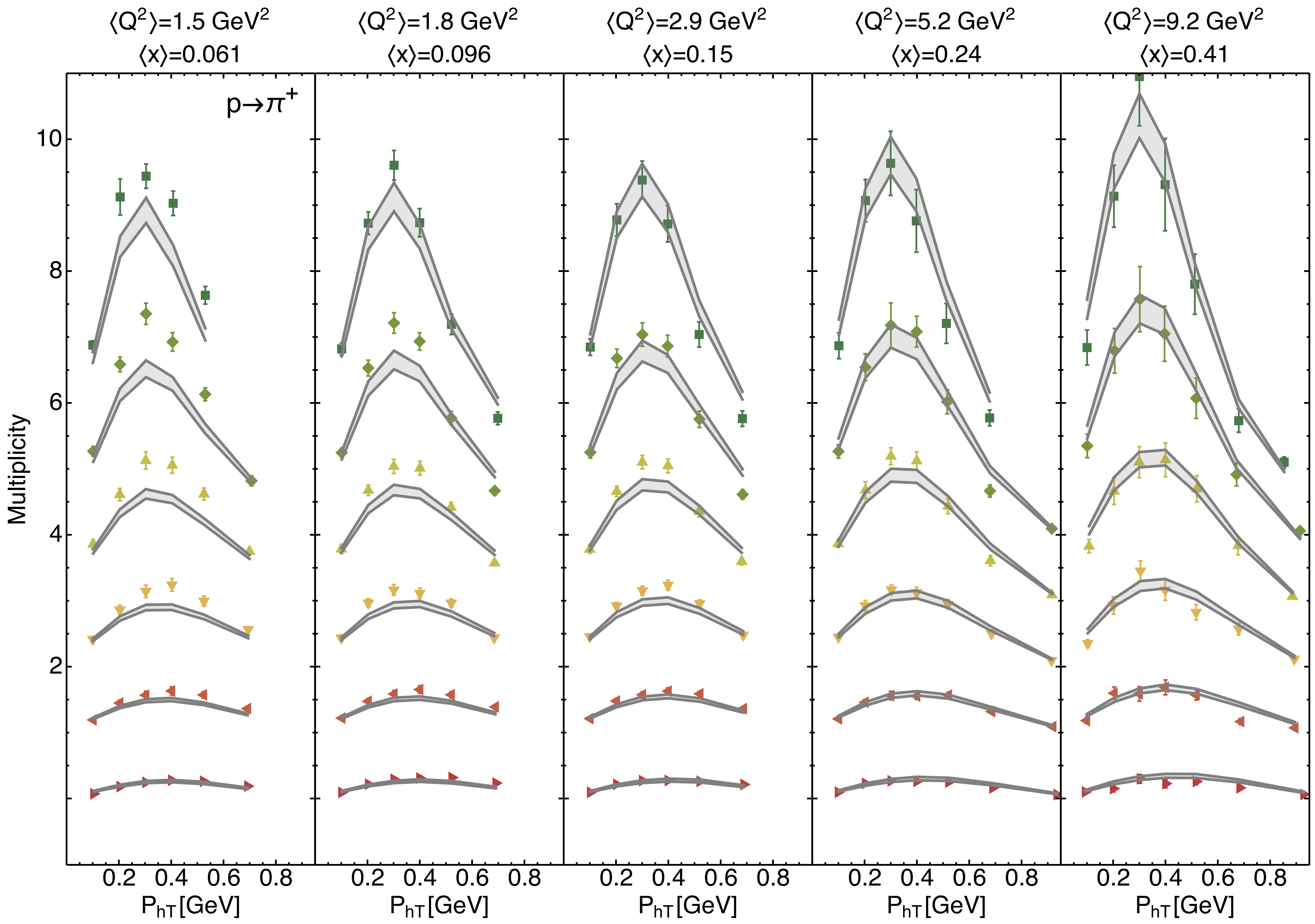
$\chi^2/dof = 1.61$



HERMES, selected bins



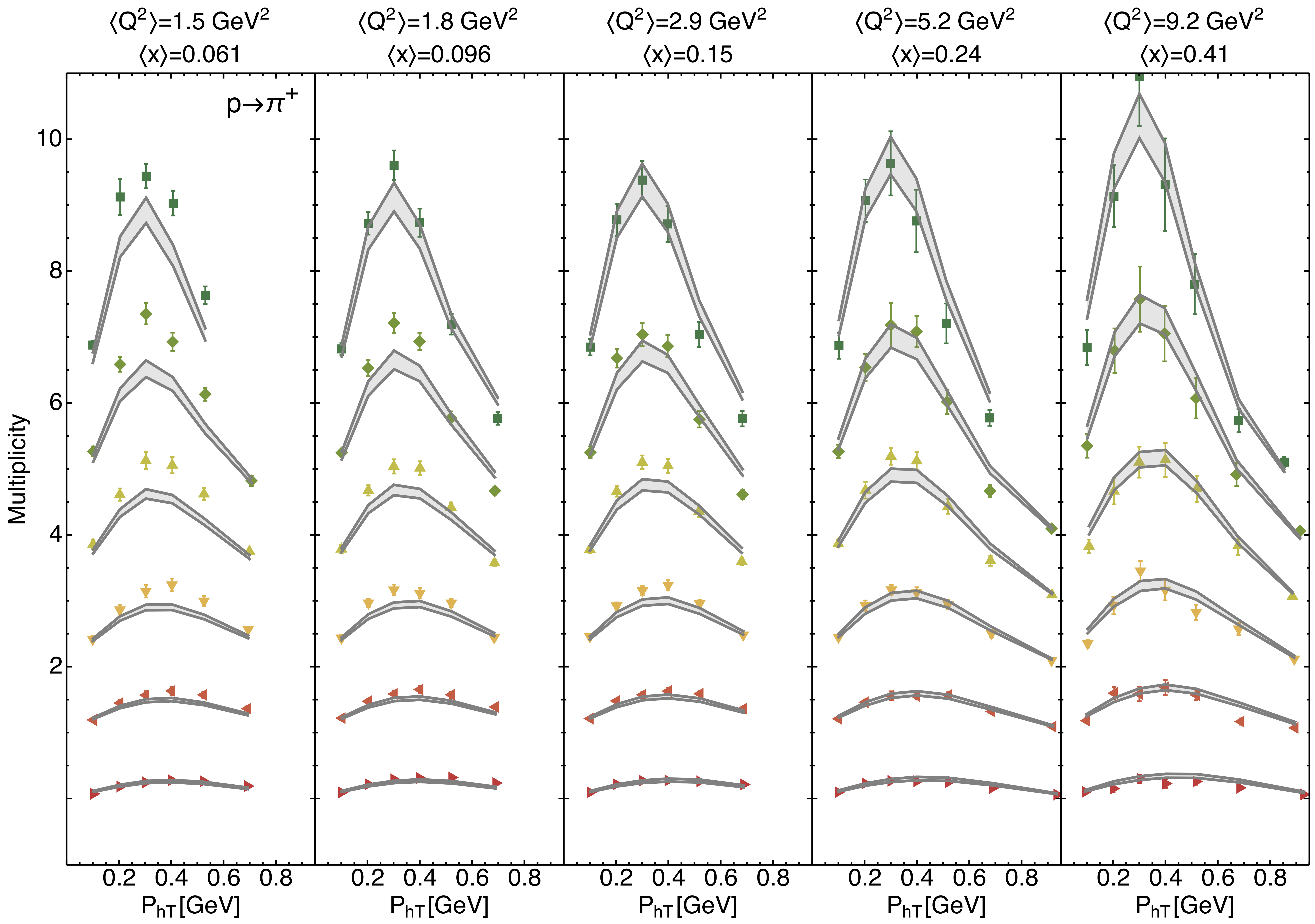
HERMES, selected bins



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

The worst of all channels...

HERMES, selected bins

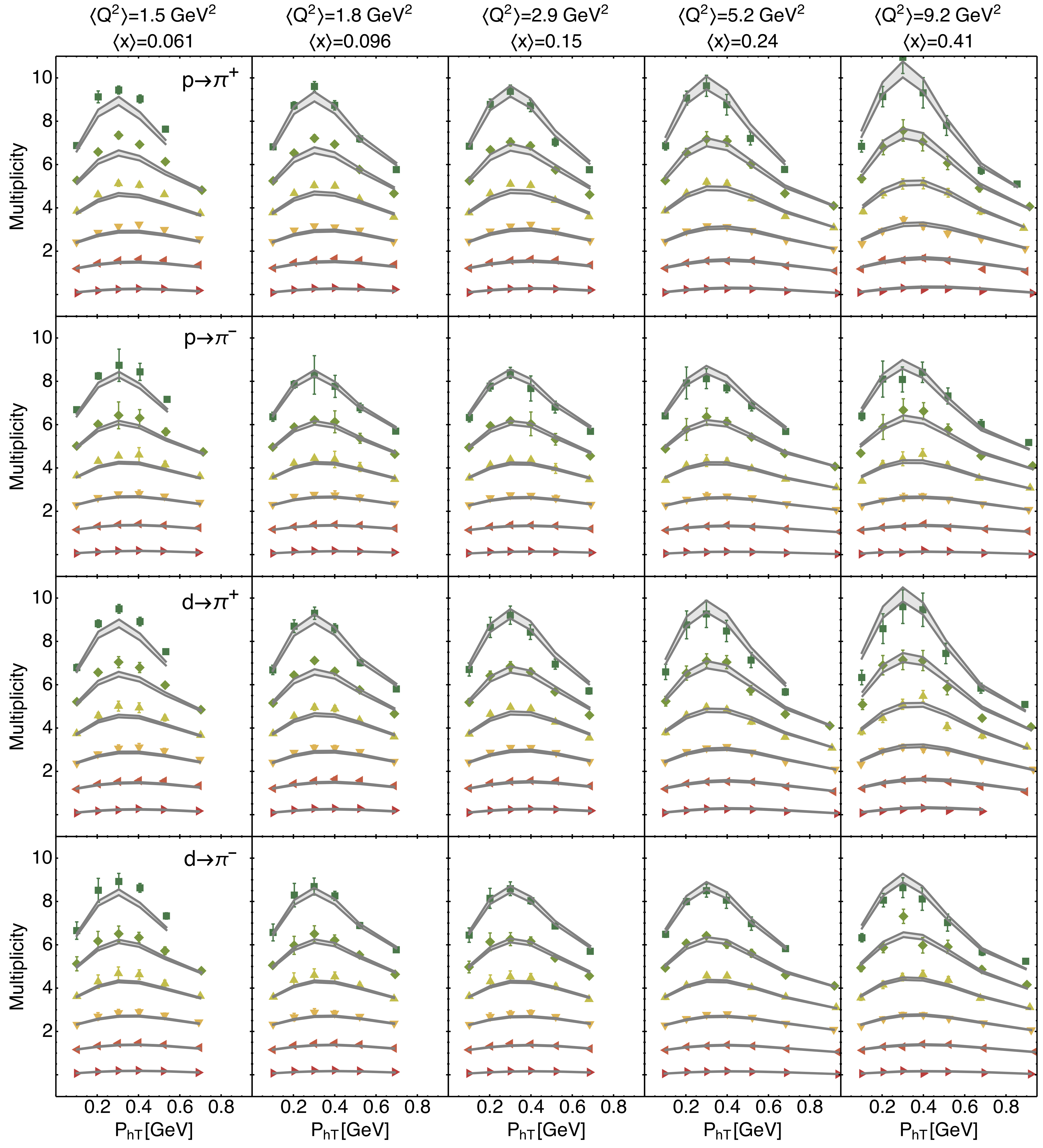


$\chi^2/\mathrm{dof} = 4.80$

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

⟨z⟩=0.24 (offset=5)
⟨z⟩=0.28 (offset=4)
⟨z⟩=0.34 (offset=3)
⟨z⟩=0.43 (offset=2)
⟨z⟩=0.54 (offset=1)
⟨z⟩=0.70 (offset=0)



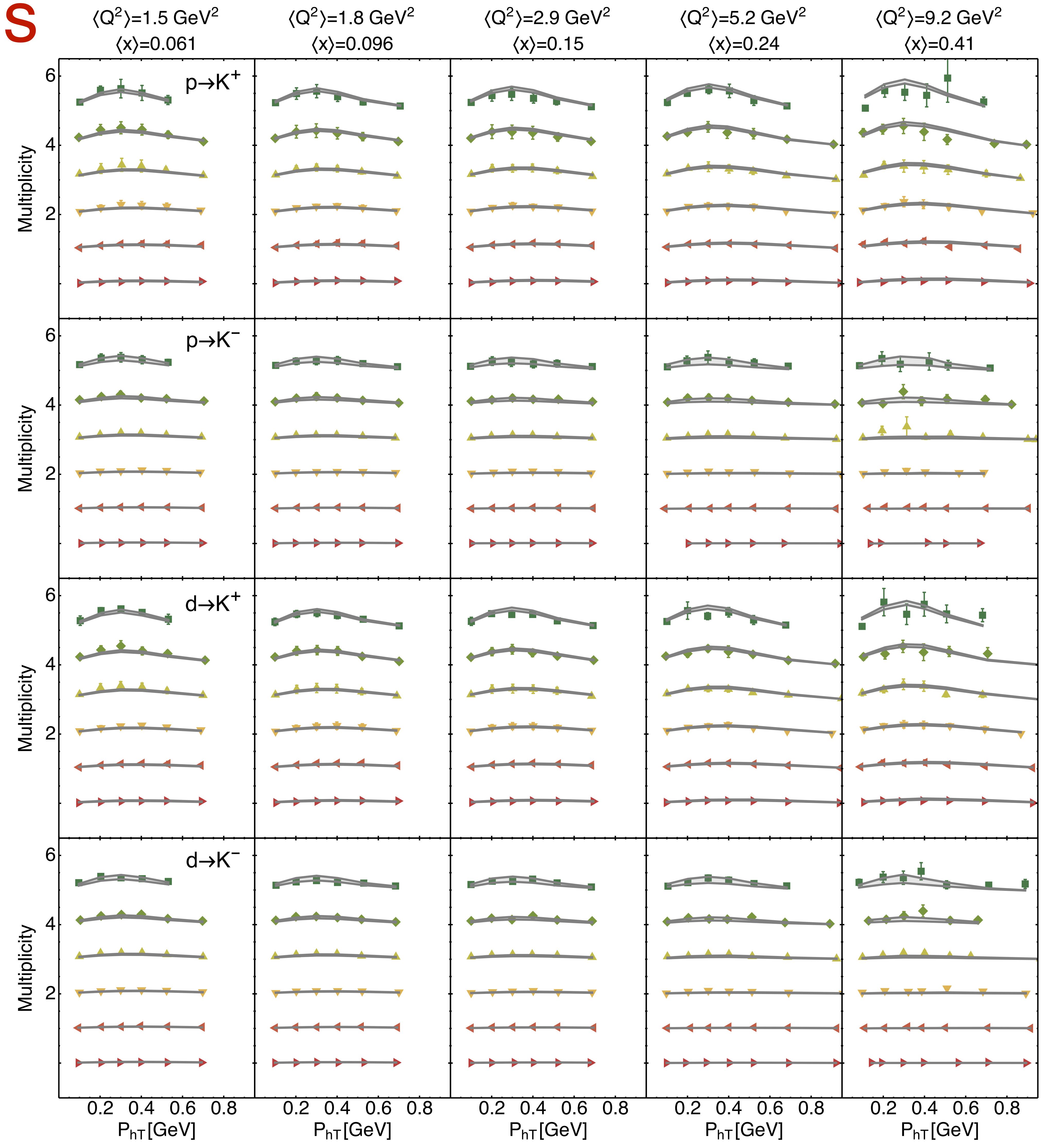
χ^2/dof

4.8

2.5

3.5

2.0



χ^2/dof

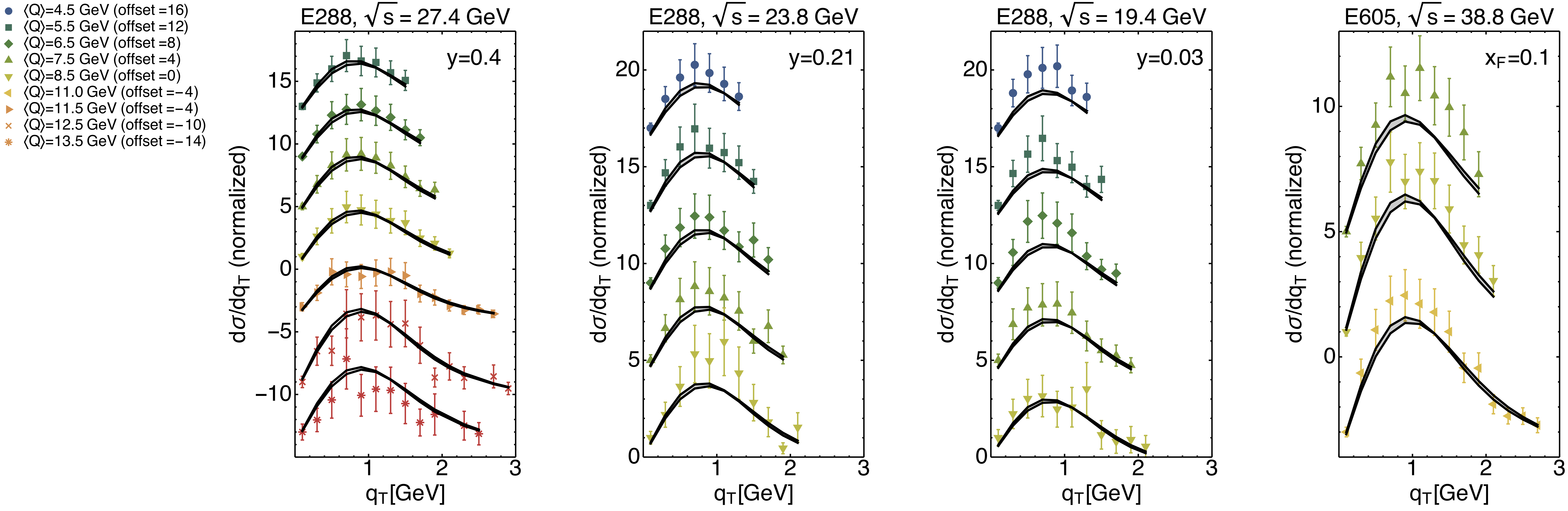
0.9

0.8

1.3

2.5

Drell-Yan data



χ^2/dof 0.32 0.84 0.99 1.13

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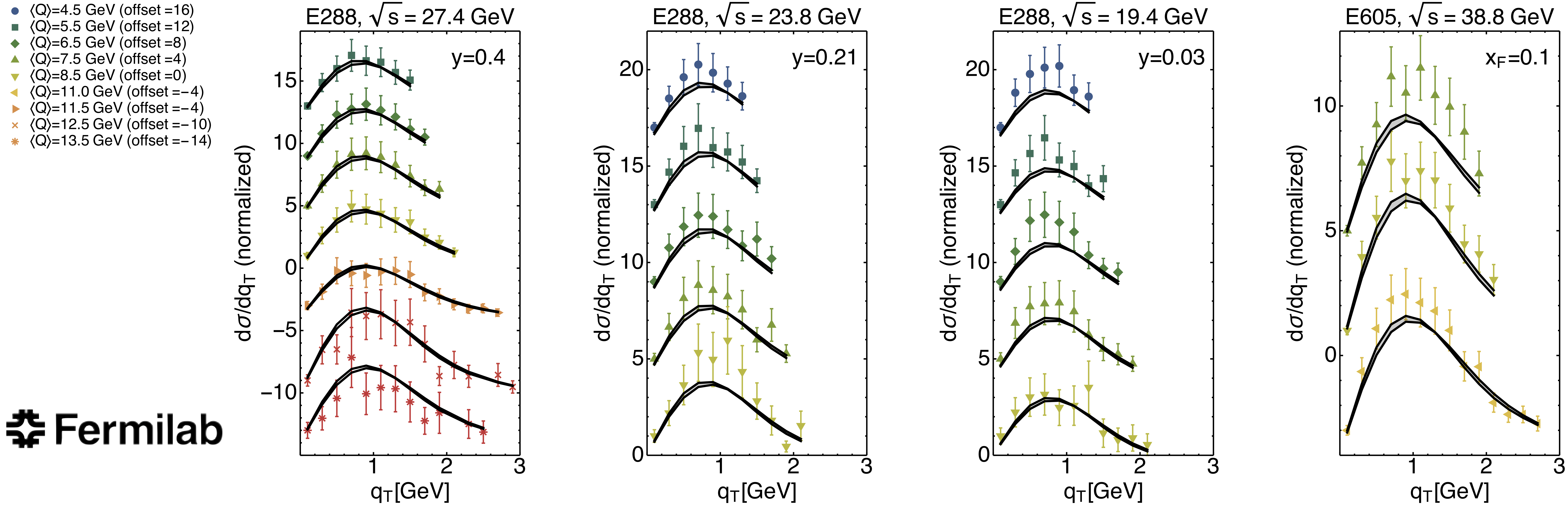
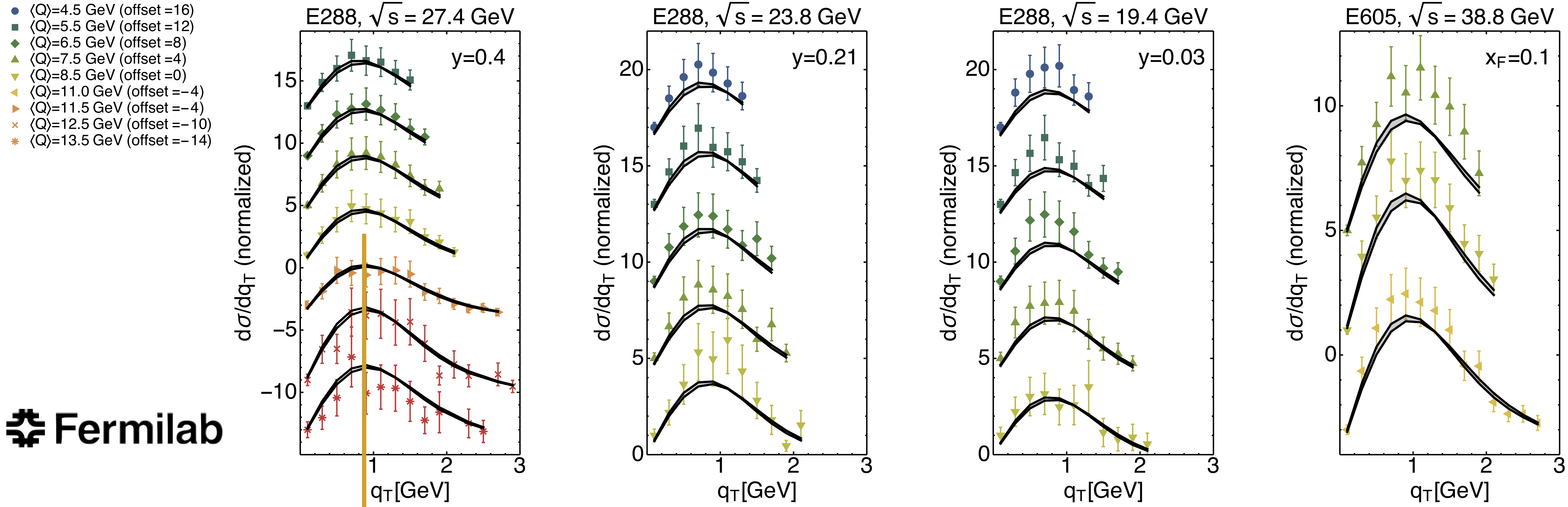


χ^2/dof	0.32	0.84	0.99	1.13

Fermilab

Drell-Yan data

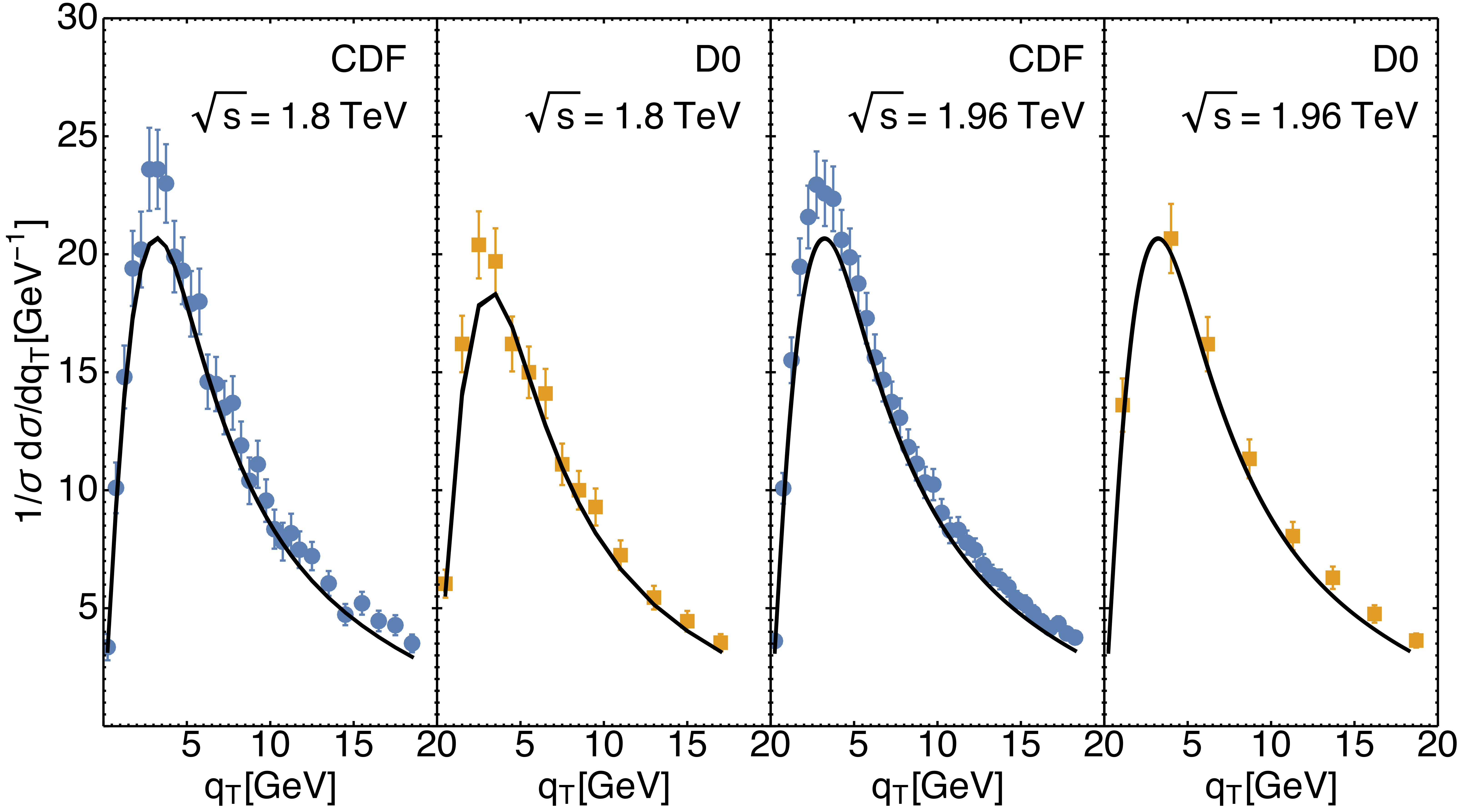


Fermilab

χ^2/dof 0.32 0.84 0.99 1.13

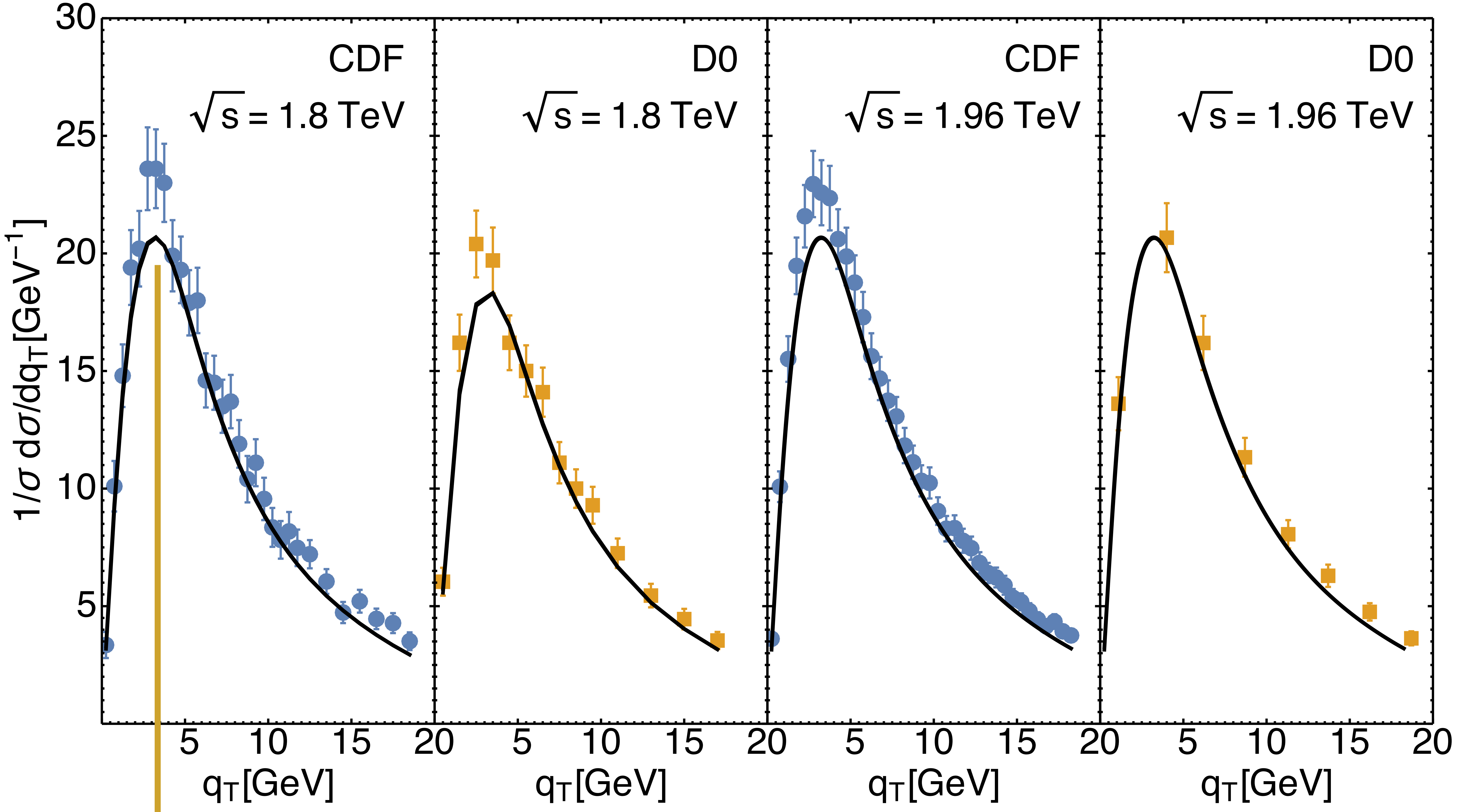
the peak was at 0.4 GeV and now is at 1 GeV

Z-boson data



χ^2/dof	1.4	1.1	2.0	1.7

Z-boson data



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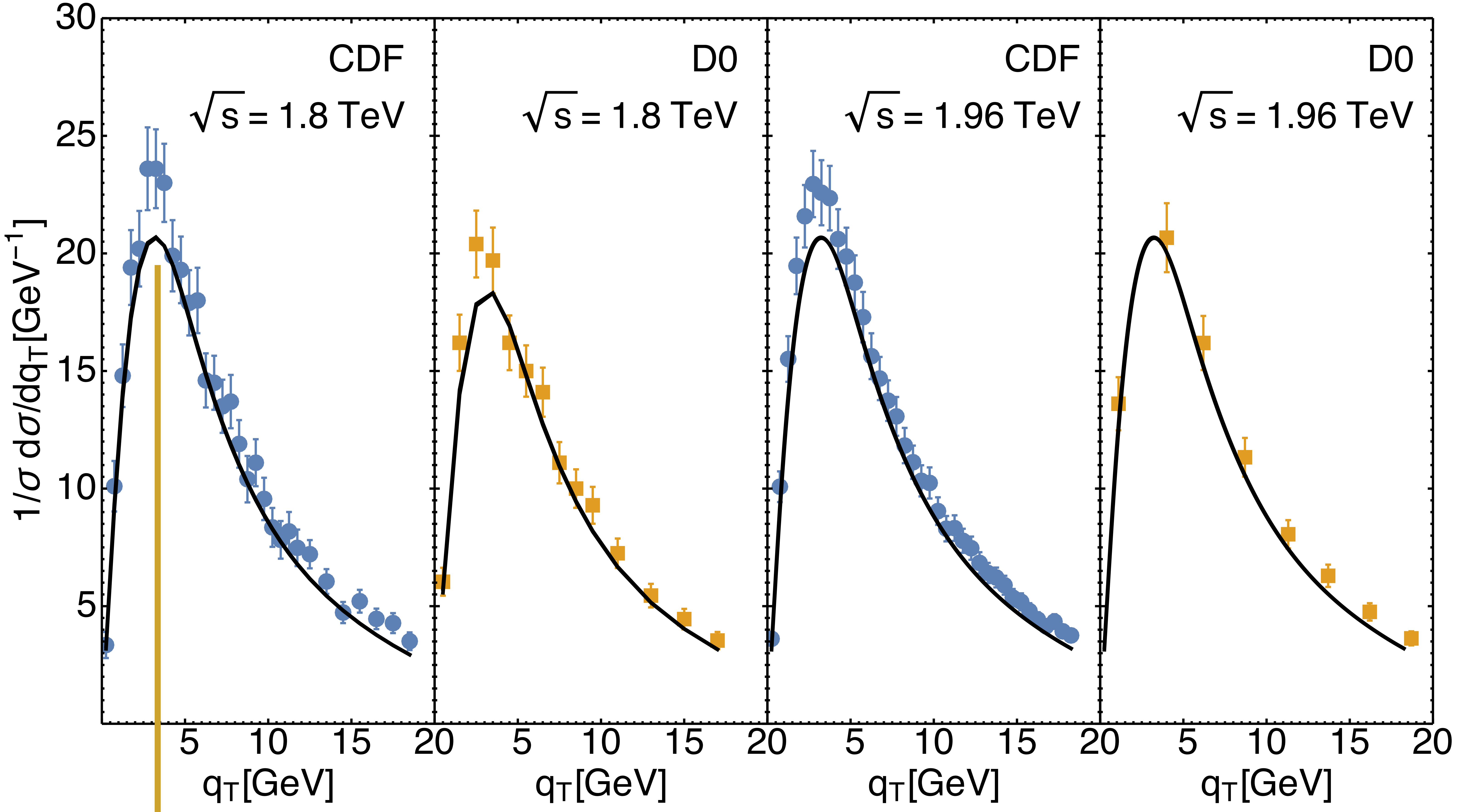
the peak now is at 4 GeV

Z-boson data



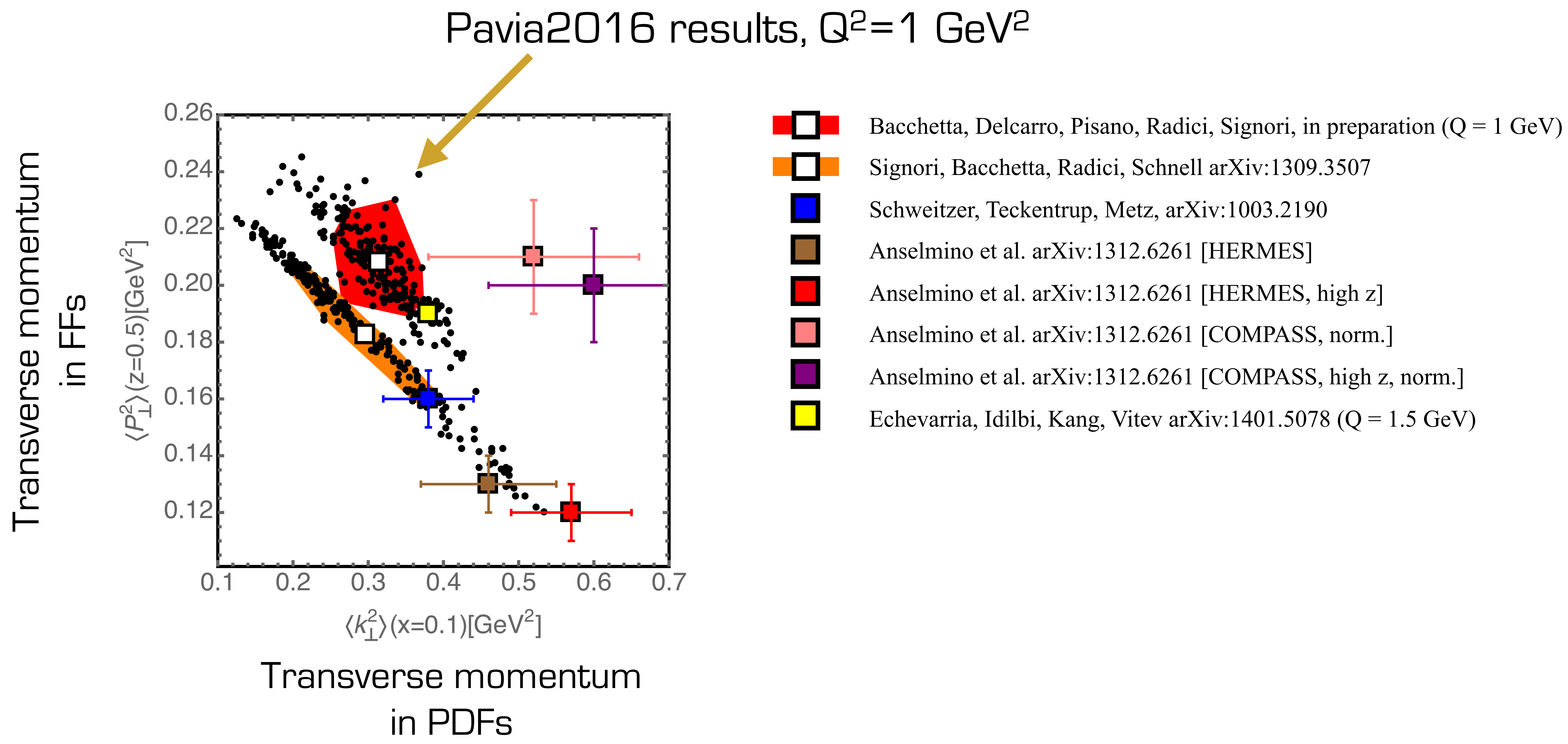
$\chi^2/$dof 1.4 1.1 2.0 1.7

the peak now is at 4 GeV

Most of the χ^2 due to normalization, not to shape

Some outcomes

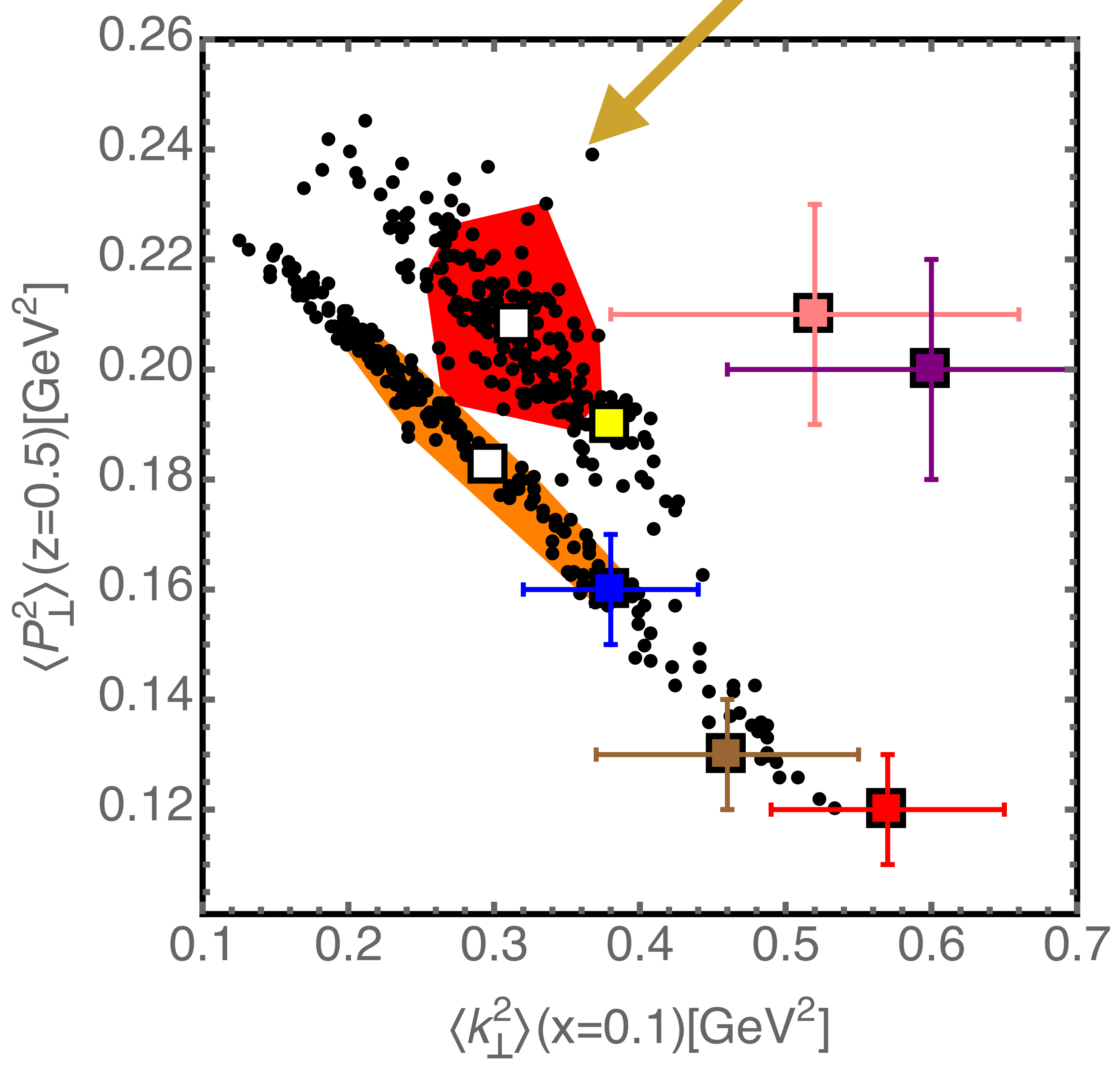
Mean transverse momentum squared



Mean transverse momentum squared

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

Transverse momentum in FFs



Transverse momentum in PDFs

Bacchetta, Delcarro, Pisano, Radici, Signori, in preparation (Q = 1 GeV)
Signori, Bacchetta, Radici, Schnell arXiv:1309.3507
Schweitzer, Teckentrup, Metz, arXiv:1003.2190
Anselmino et al. arXiv:1312.6261 [HERMES]
Anselmino et al. arXiv:1312.6261 [HERMES, high z]
Anselmino et al. arXiv:1312.6261 [COMPASS, norm.]
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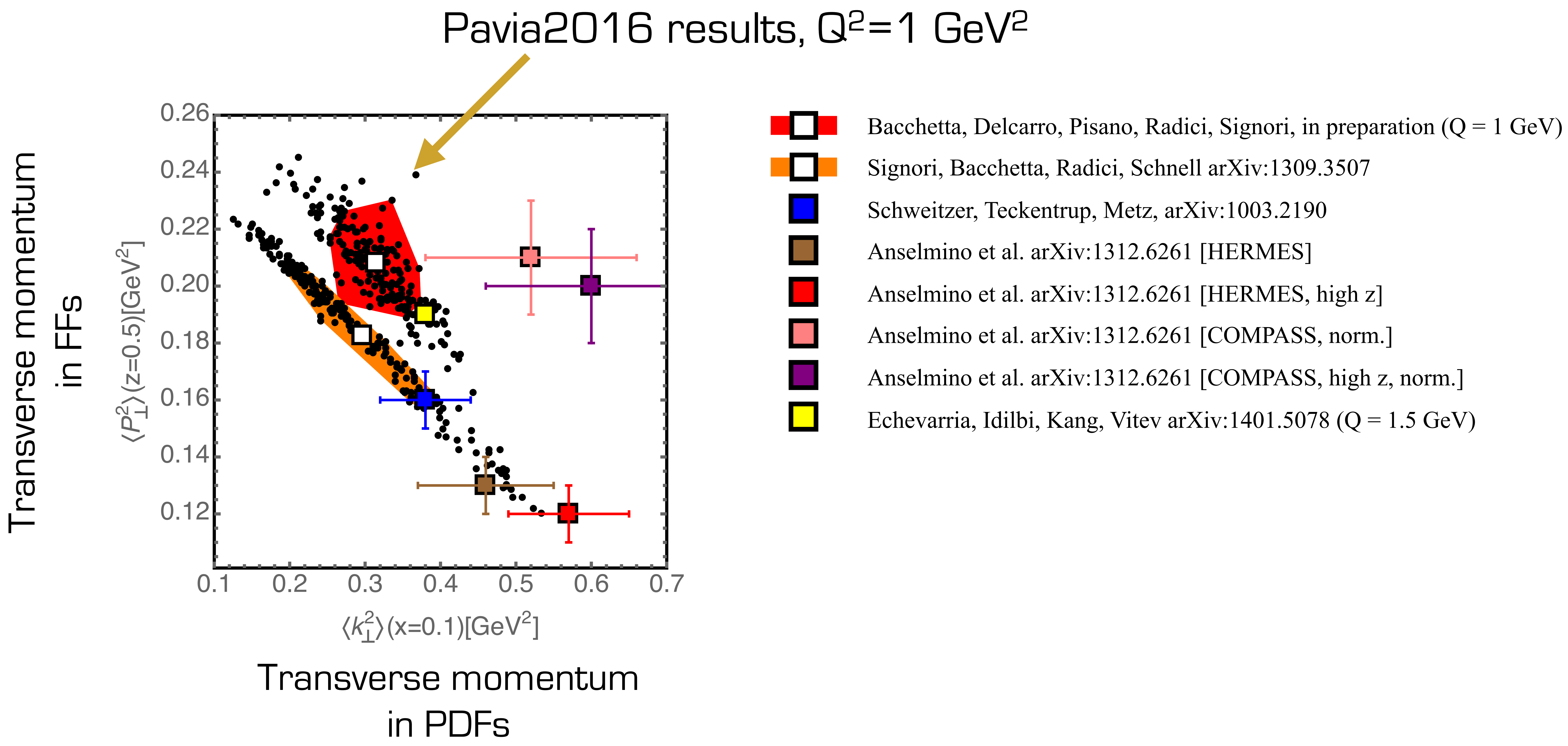
Echevarria, Idilbi, Kang, Vitev arXiv:1401.5078 (Q = 1.5 GeV)

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

Mean transverse momentum squared

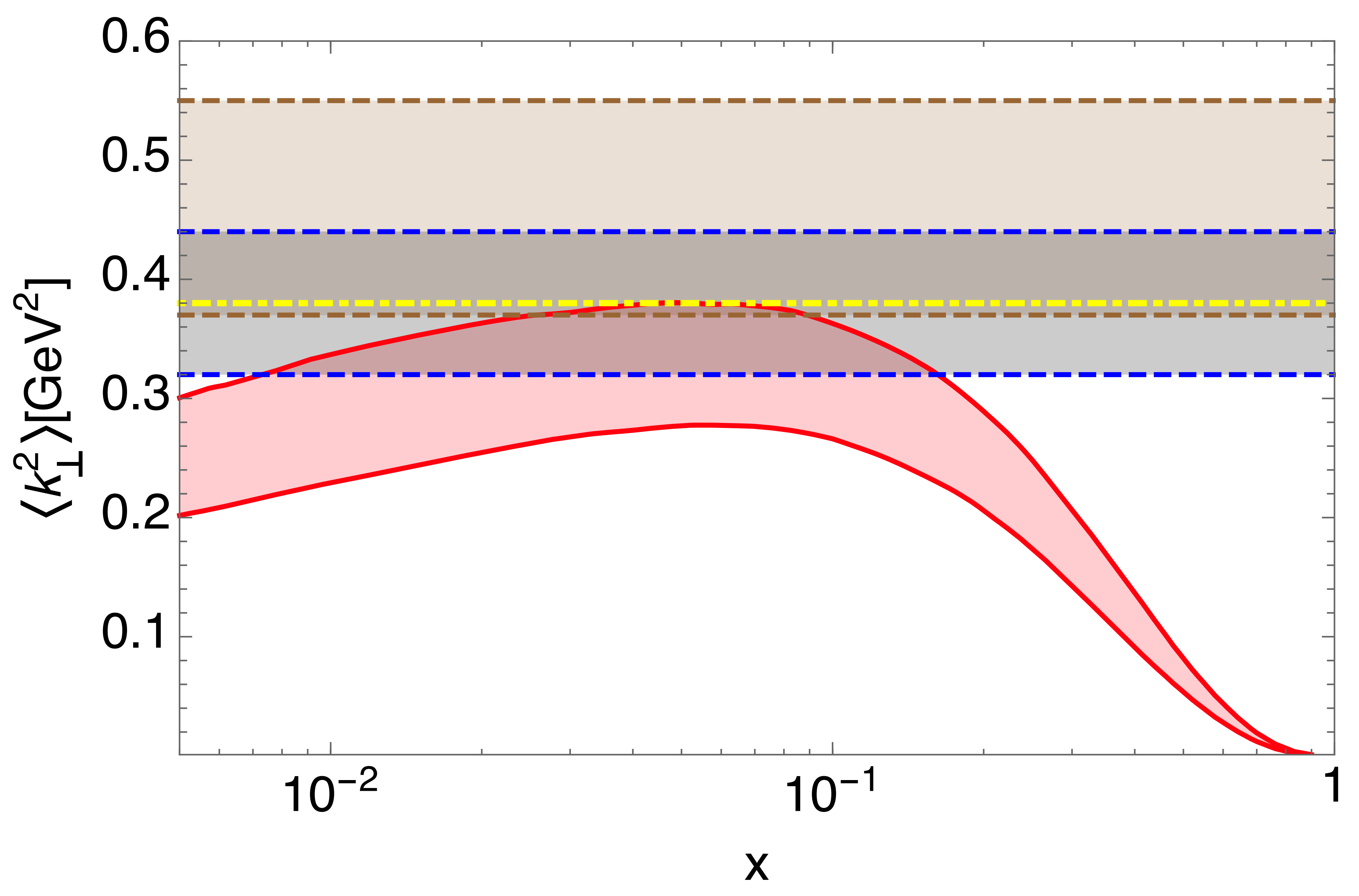


CAVEAT: intrinsic transverse momentum depends on TMD evolution “scheme” and its parameters

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

Mean transverse momentum squared

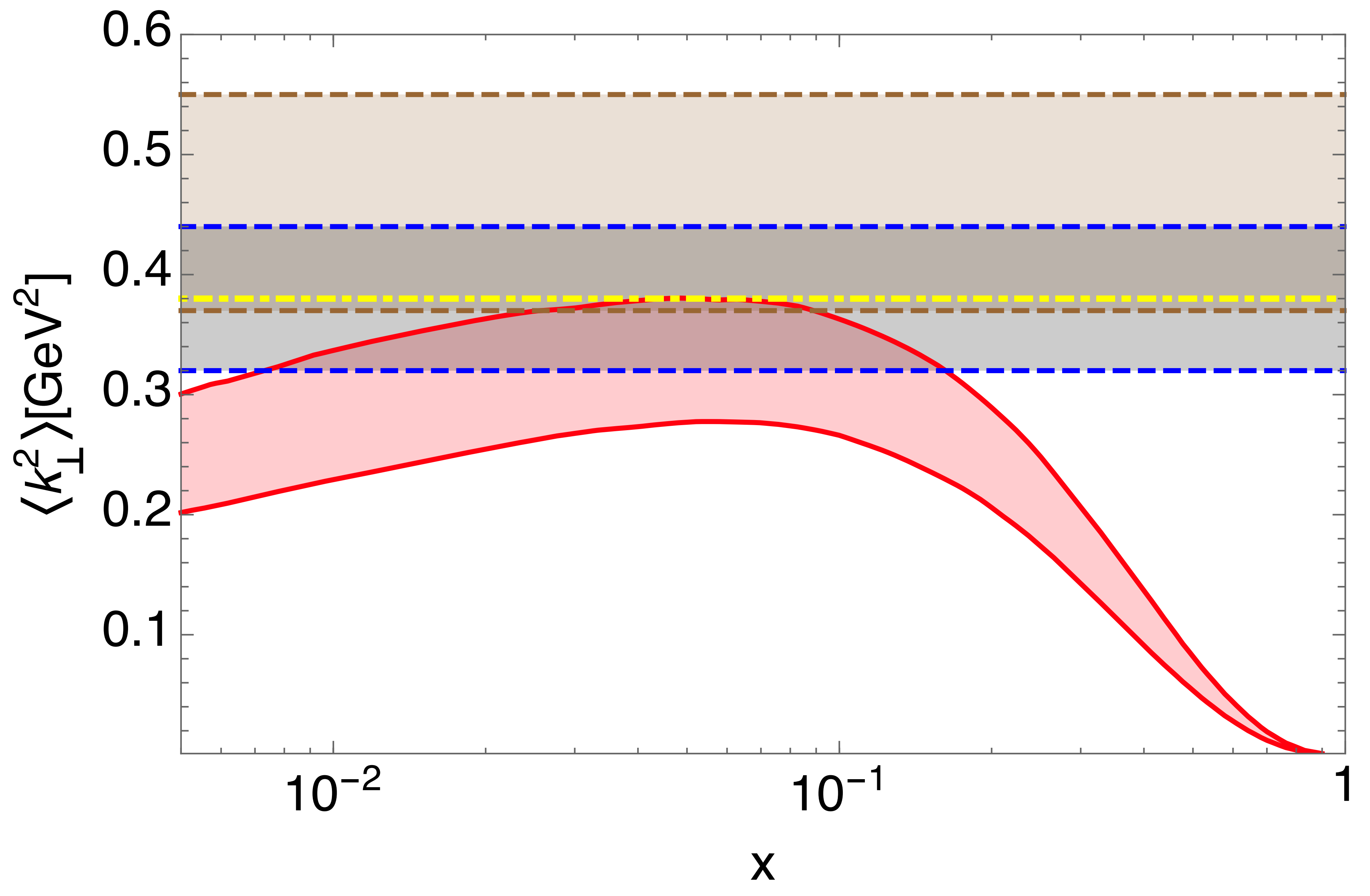
same color coding as previous slide



In TMD distribution functions

Mean transverse momentum squared

same color coding as previous slide



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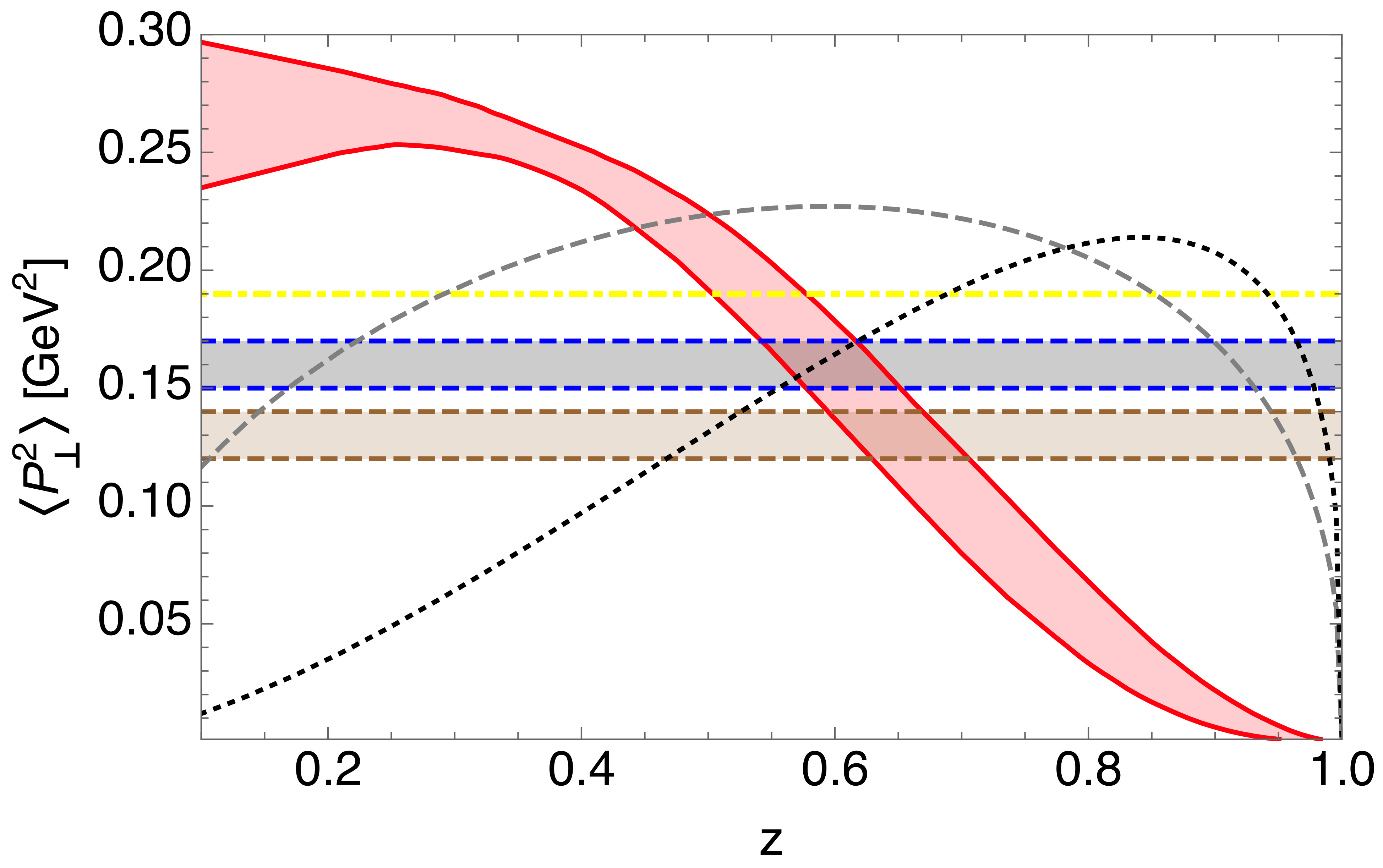
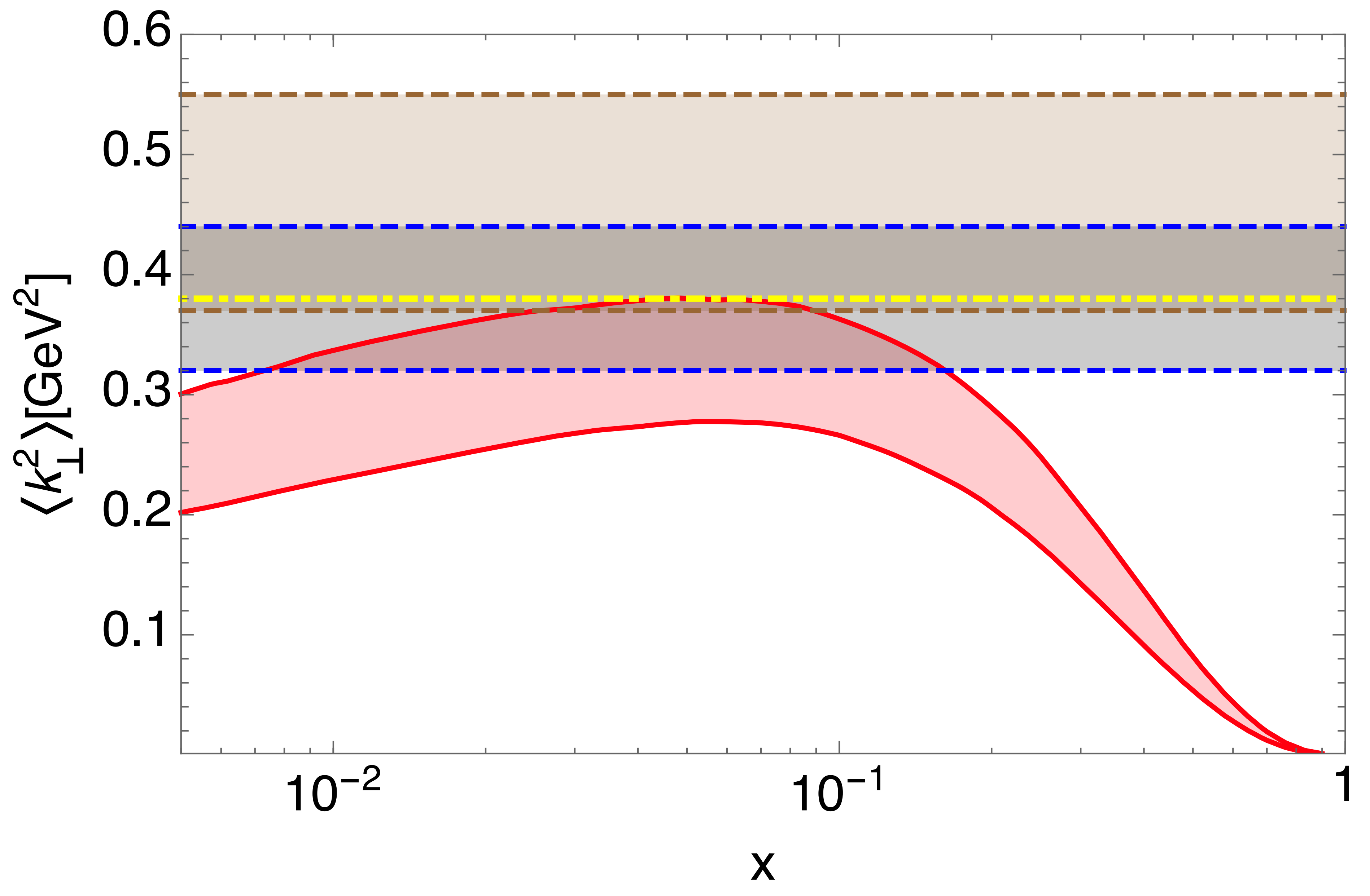


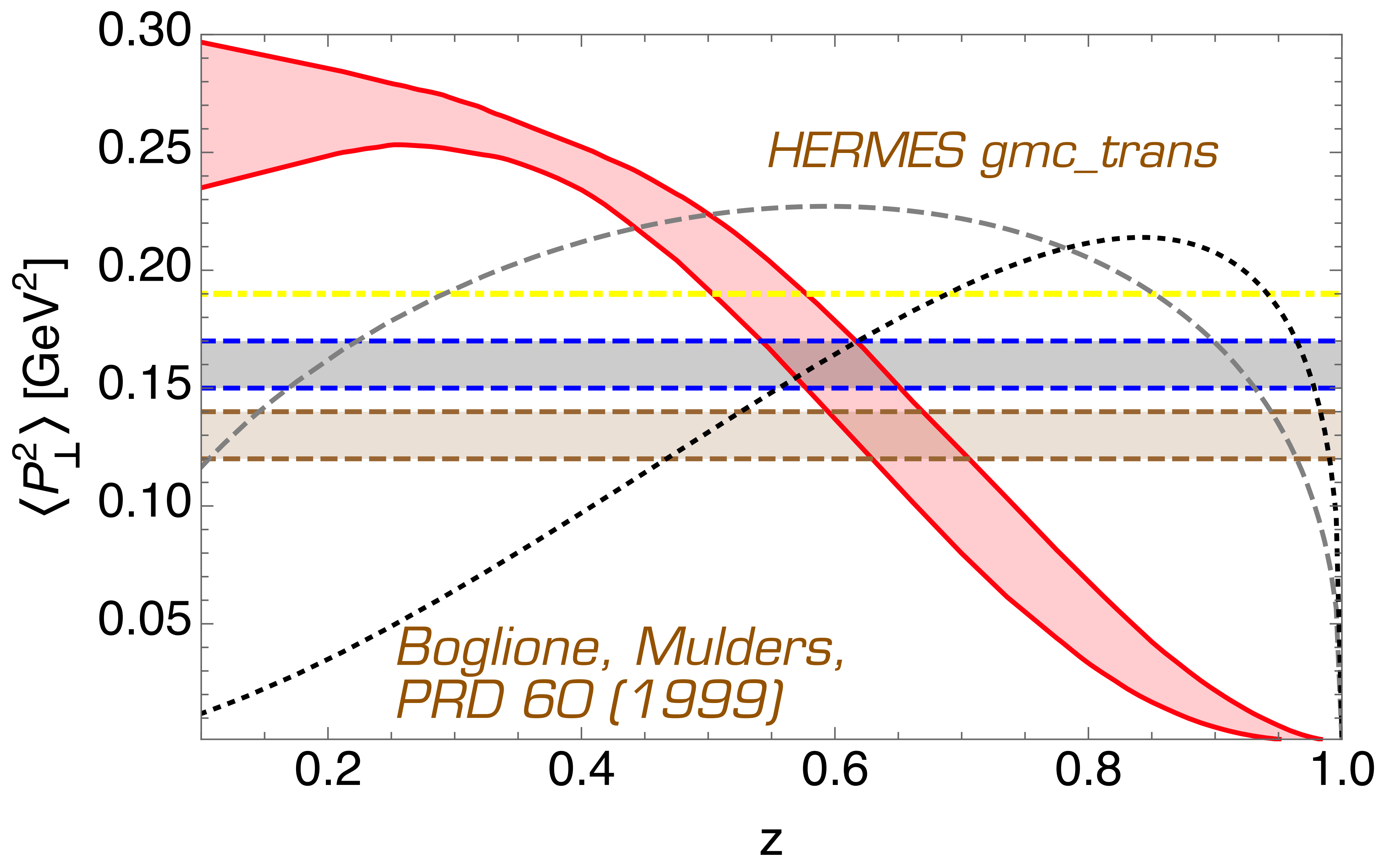
In TMD fragmentation functions

Mean transverse momentum squared

same color coding as previous slide



In TMD distribution functions



In TMD fragmentation functions

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
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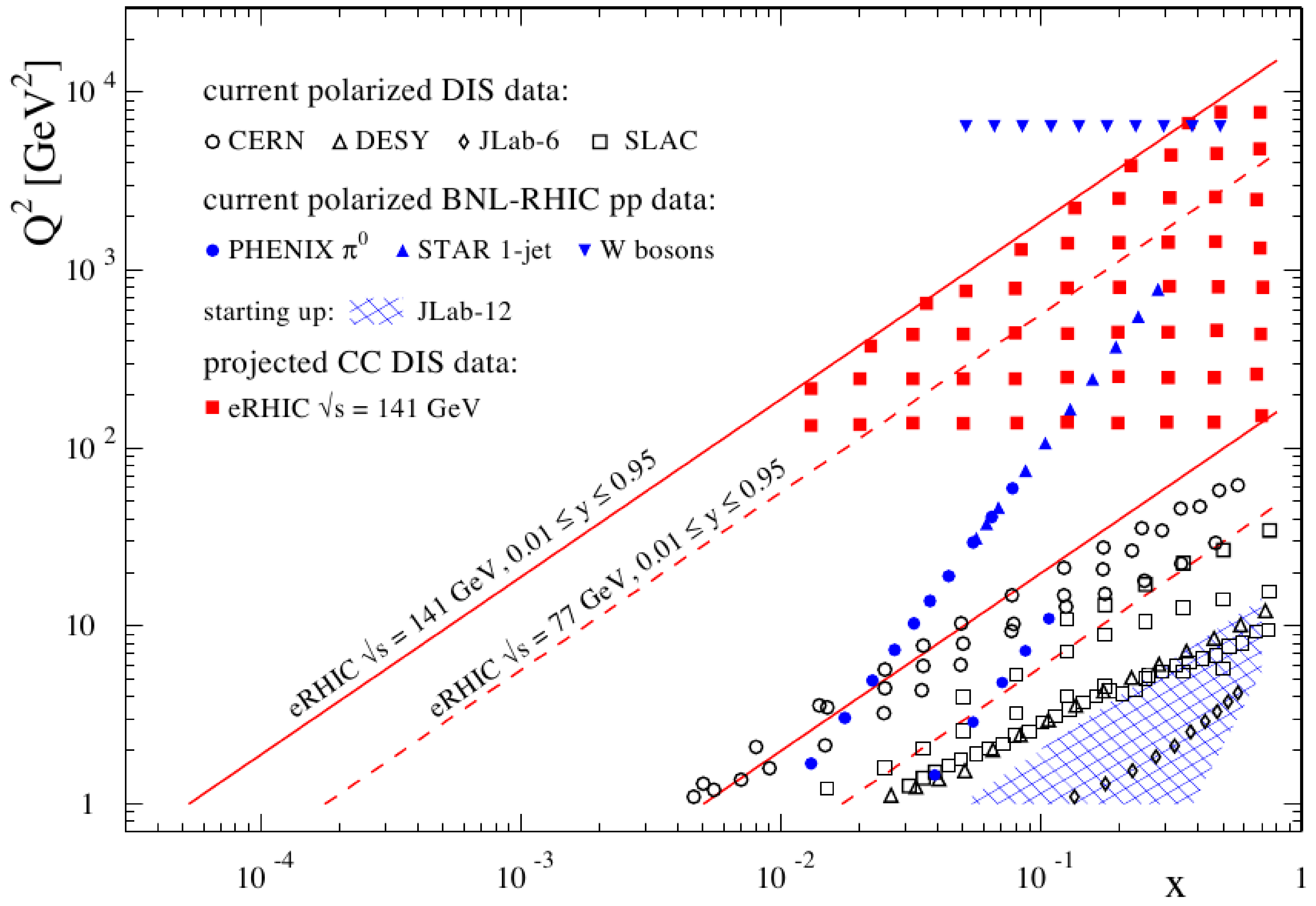
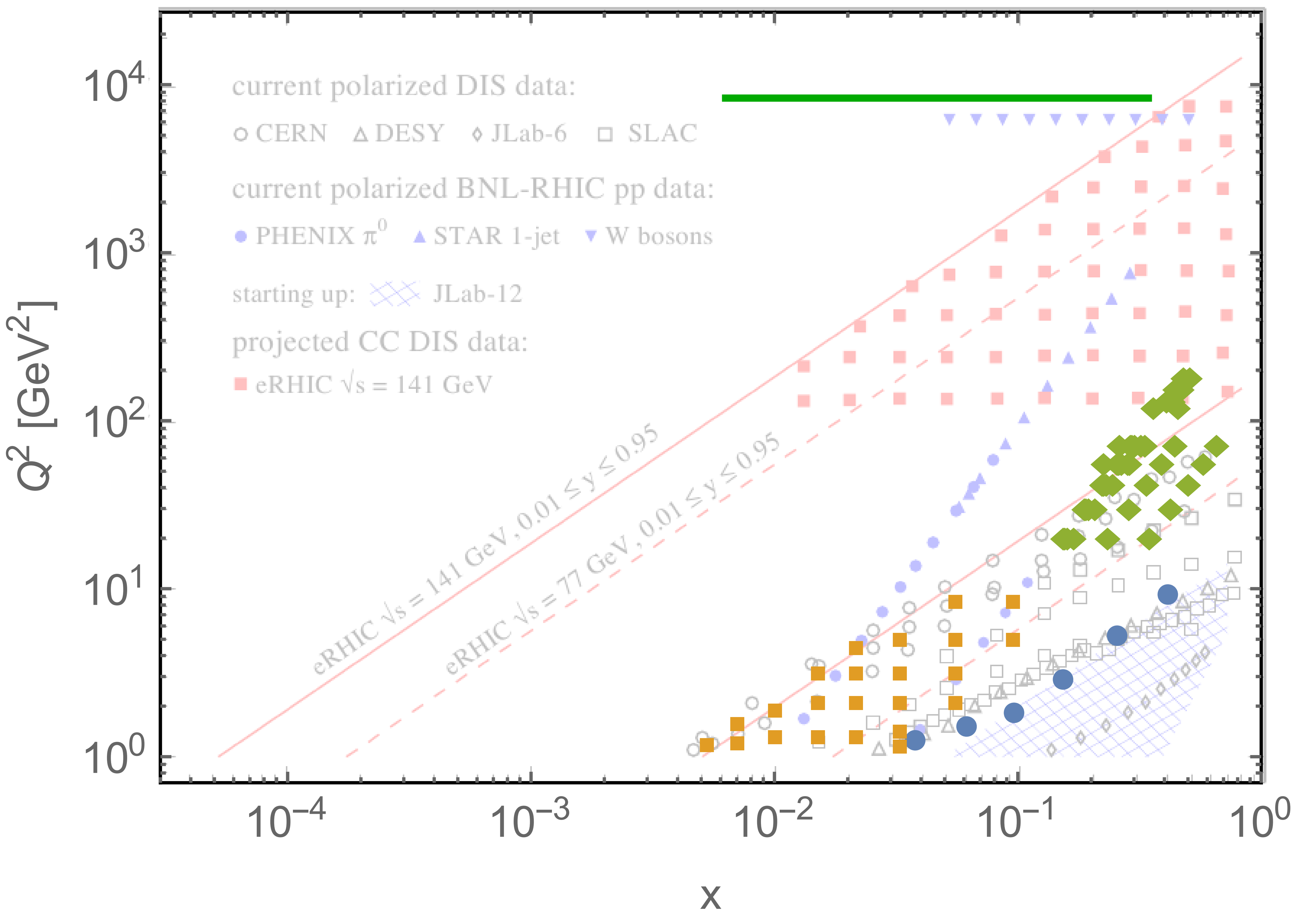
Faster evolution: transverse momentum increases faster due to gluon radiation

Slower evolution: the effect of gluon radiation is weaker

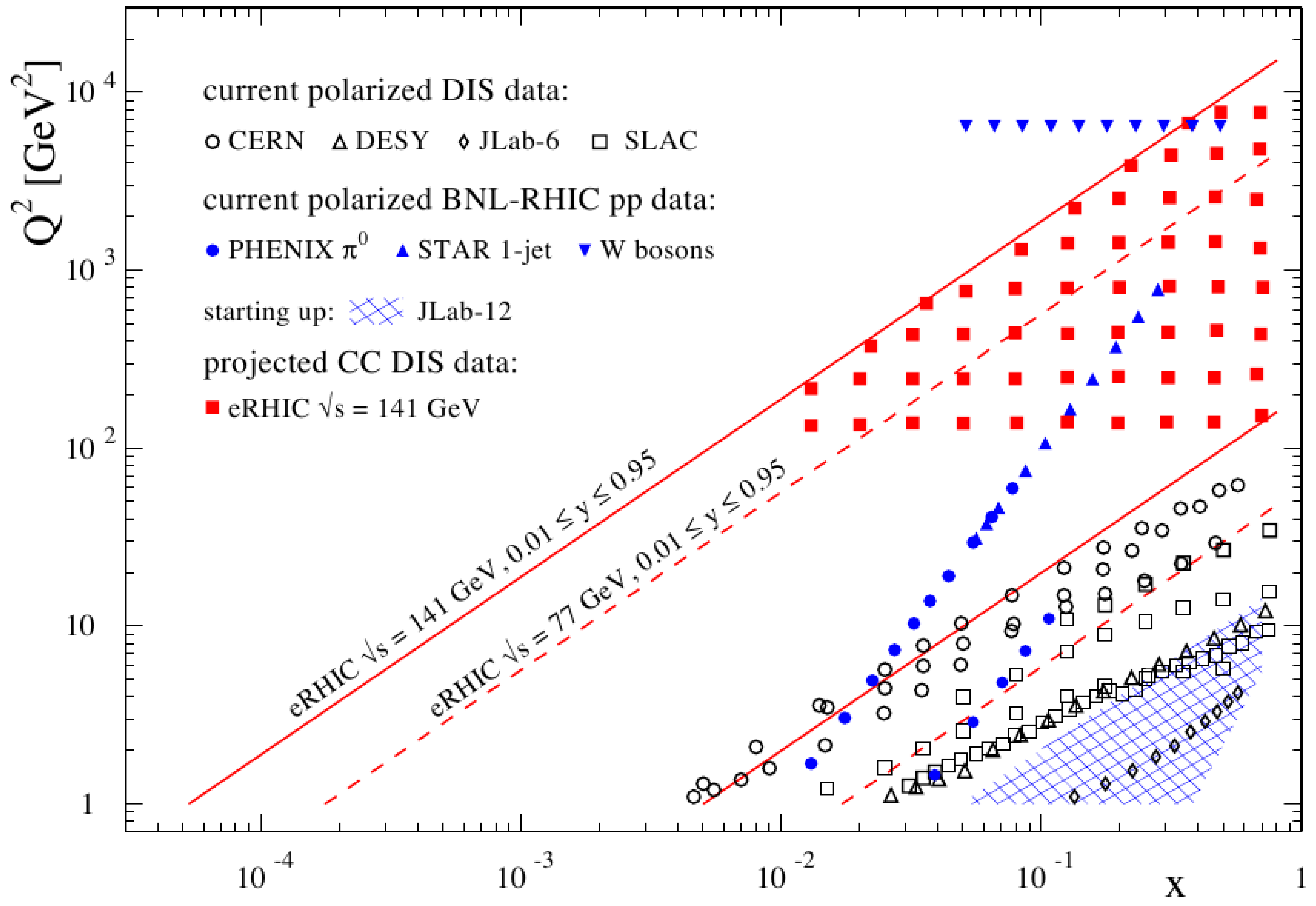
Comparison with future perspectives



from EIC white paper EPJA 52 (2016)



Comparison with future perspectives



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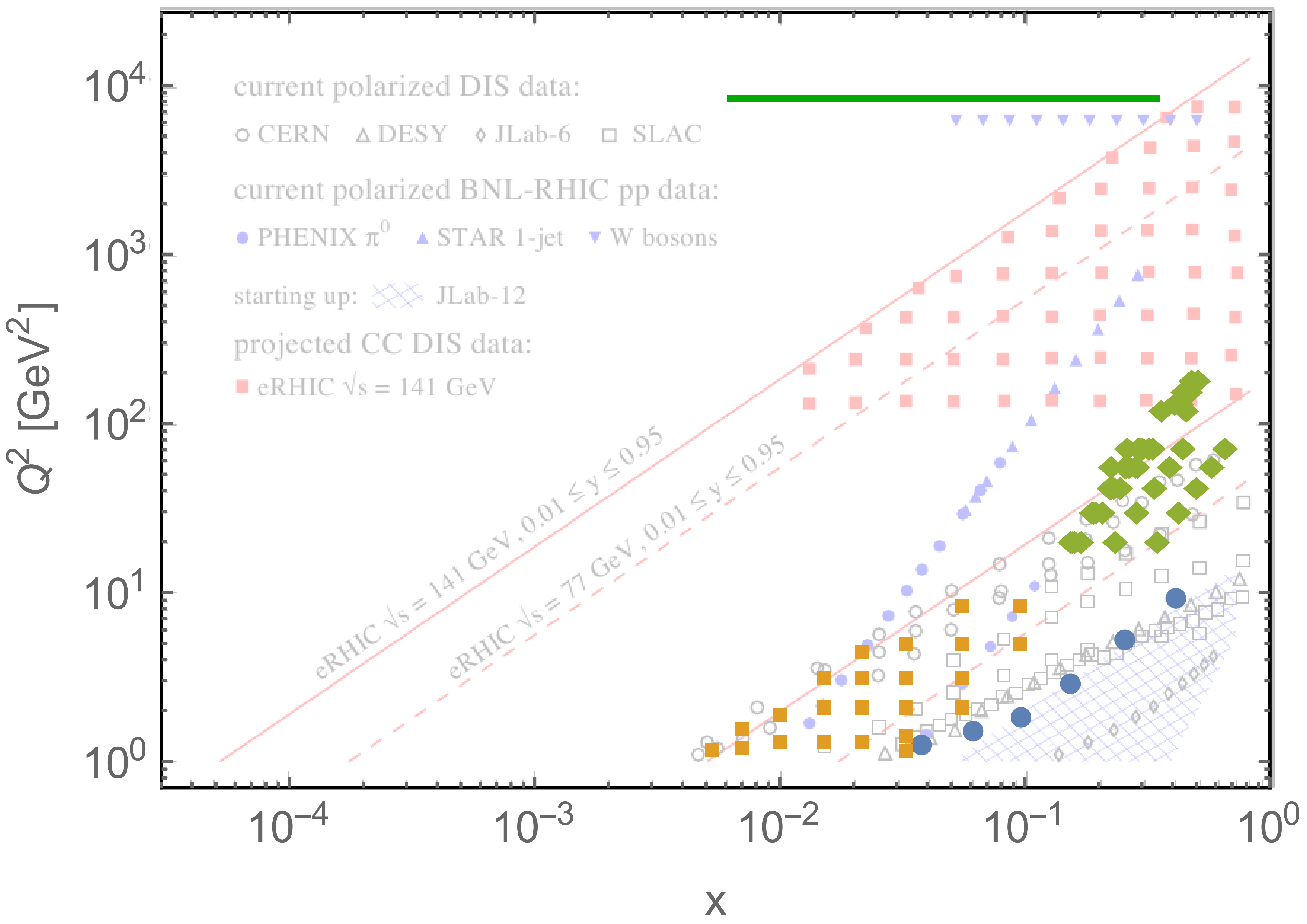

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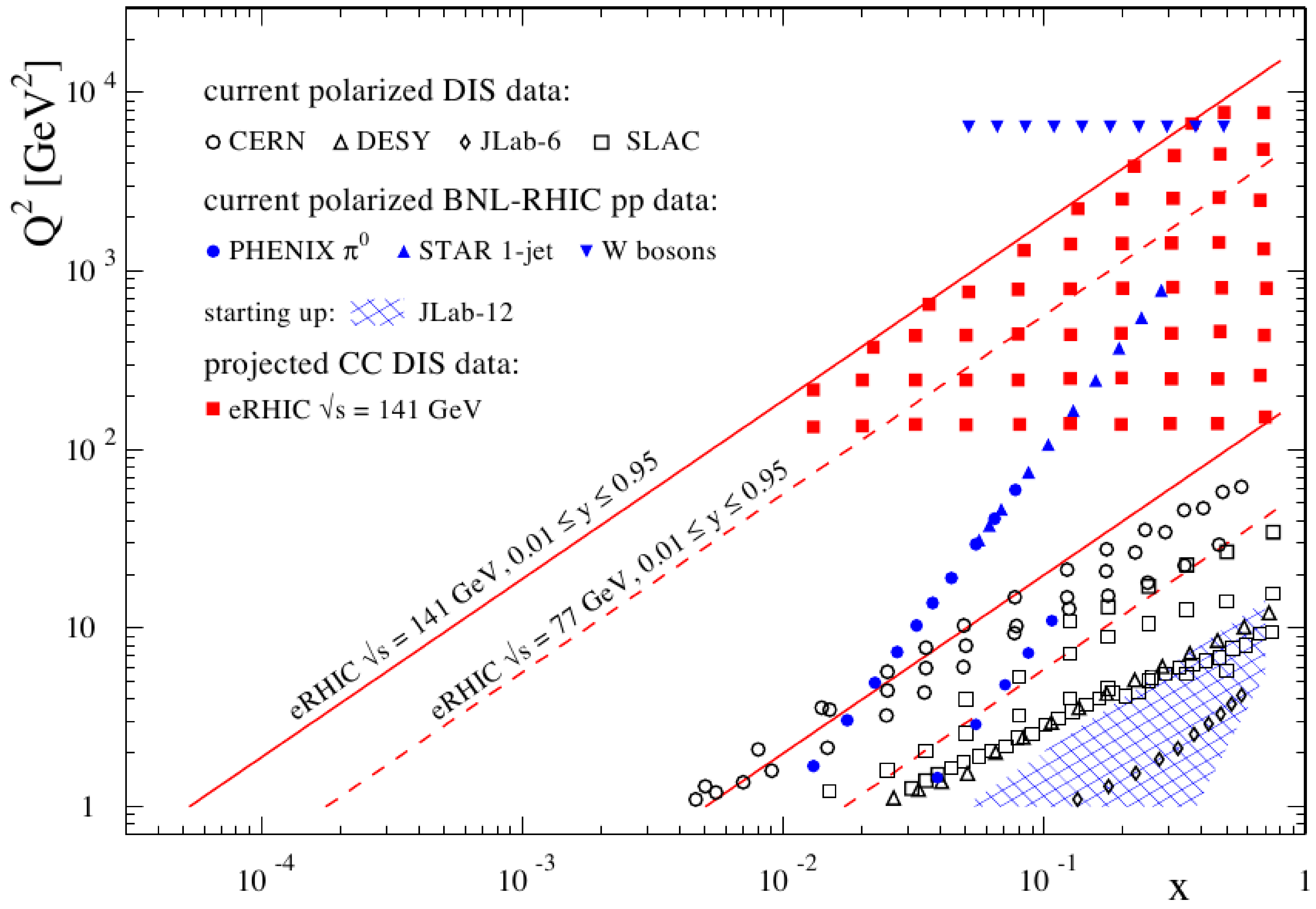
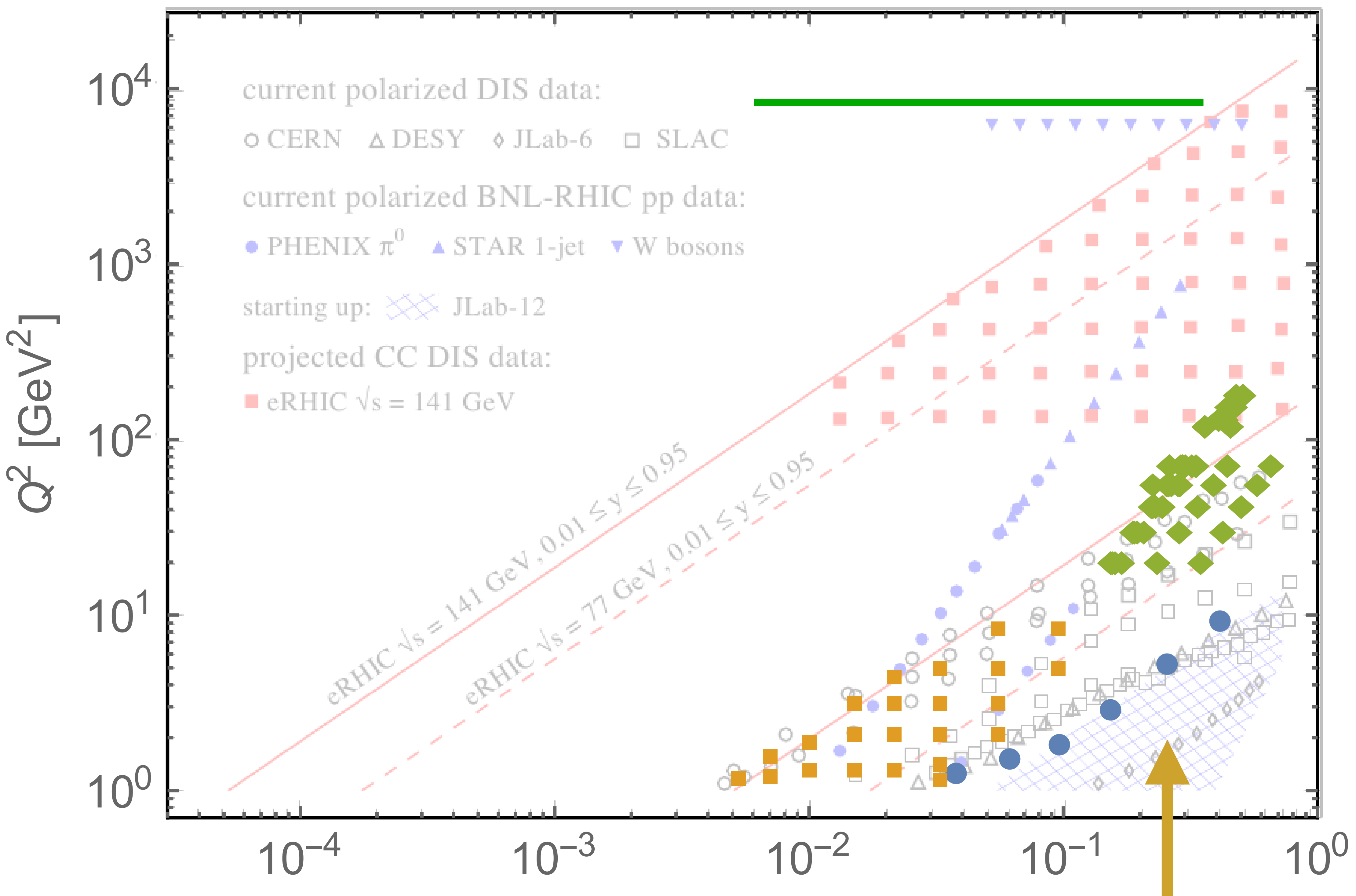


from EIC white paper EPJA 52 (2016)



Jefferson Lab

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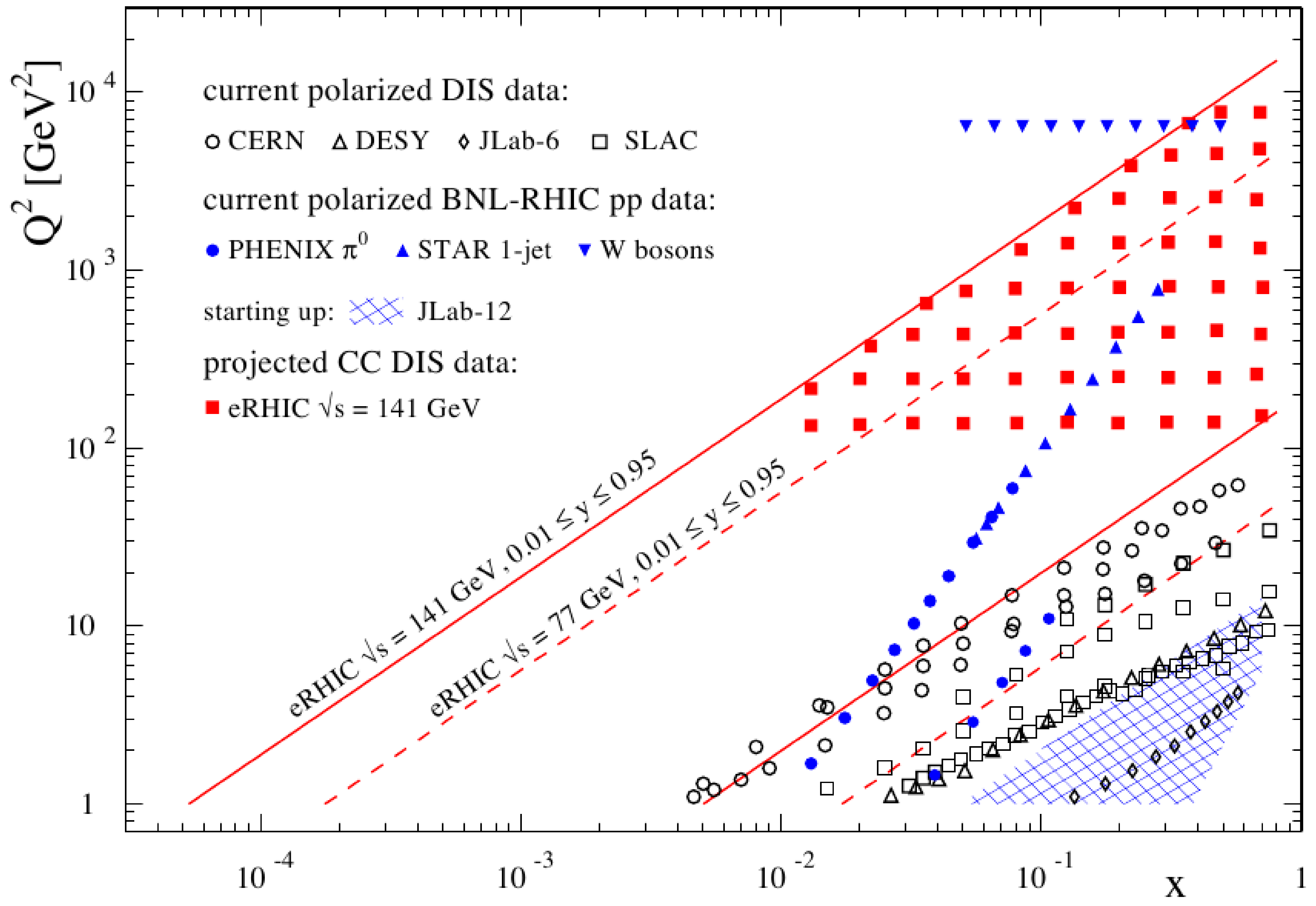

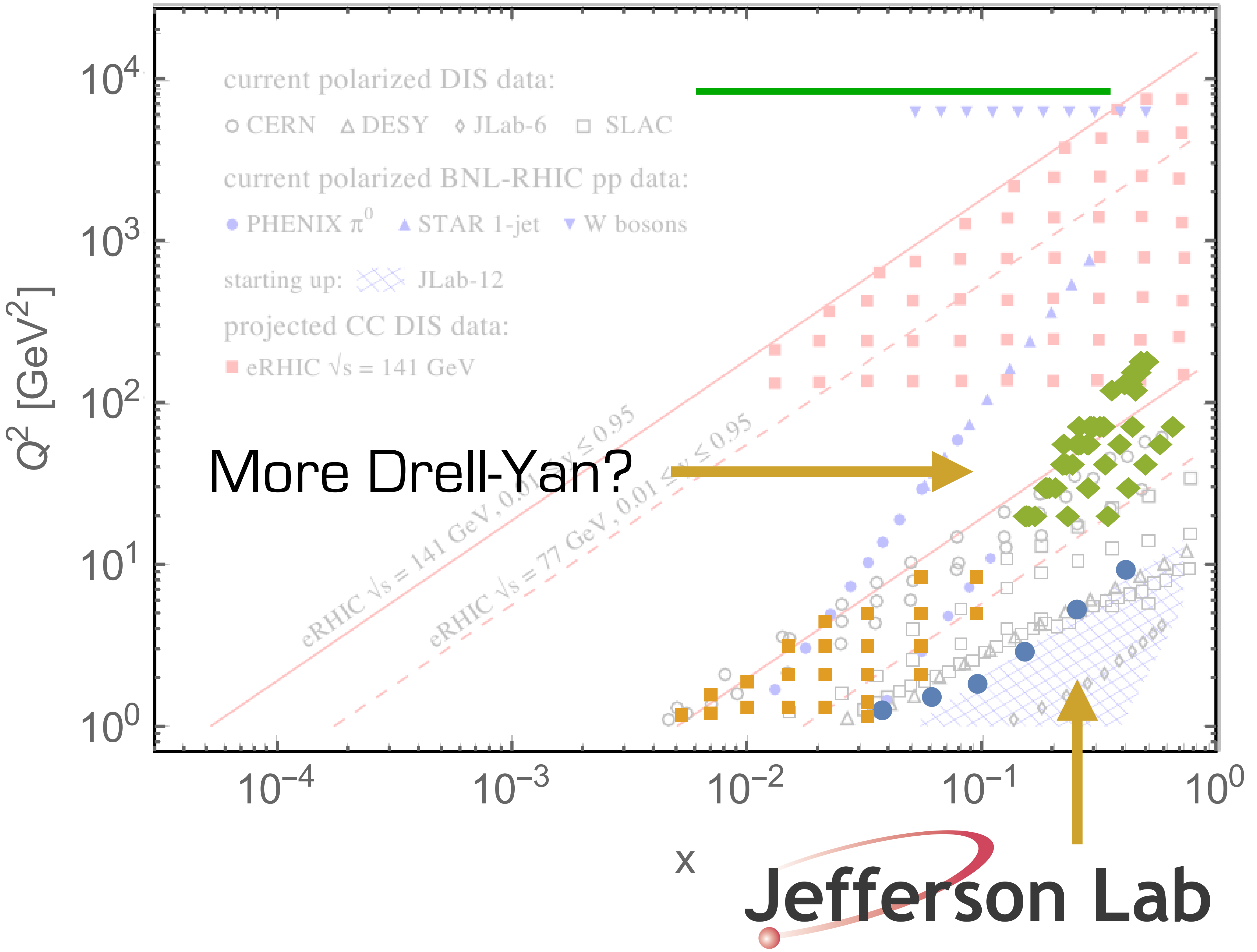

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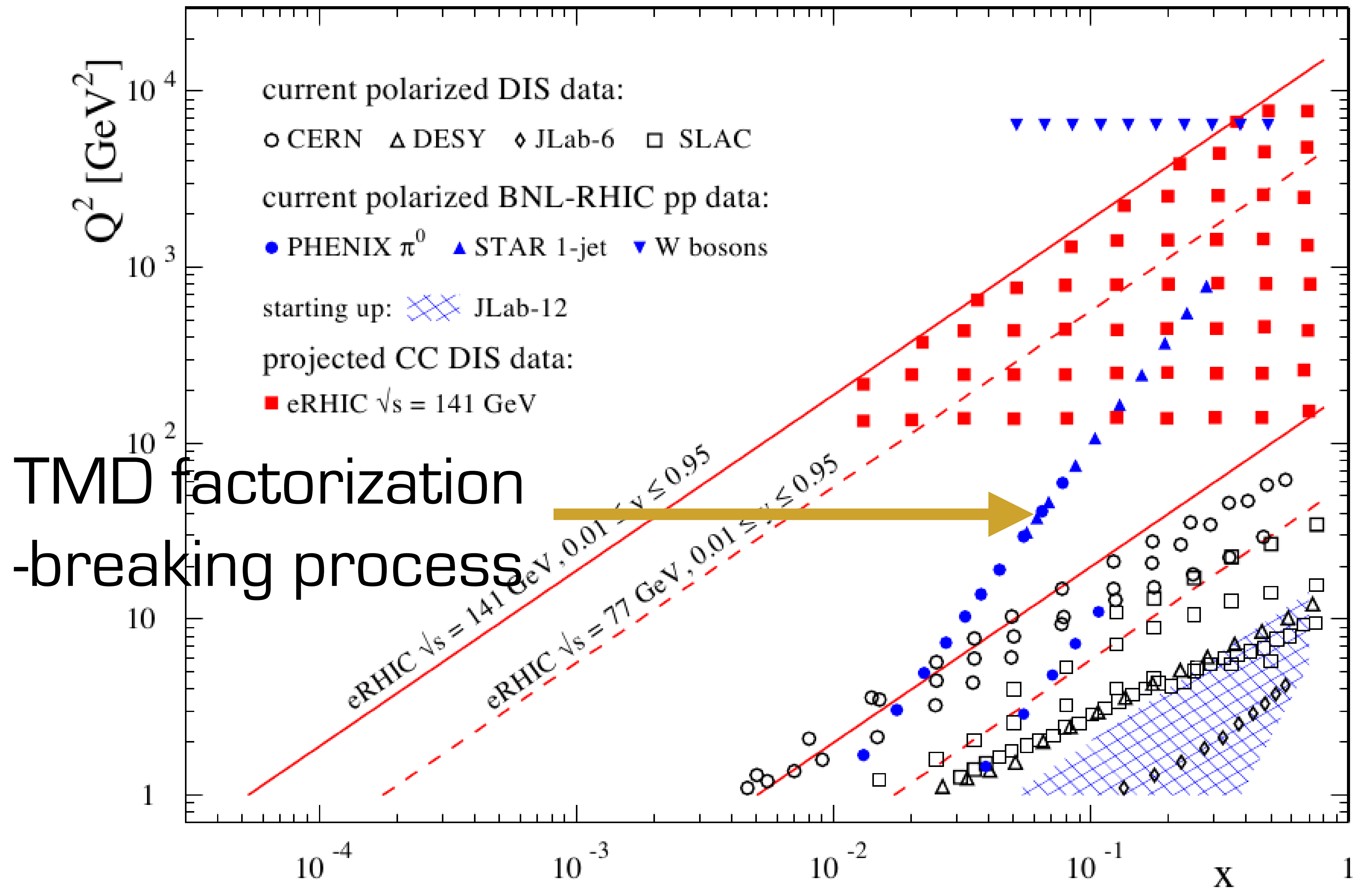

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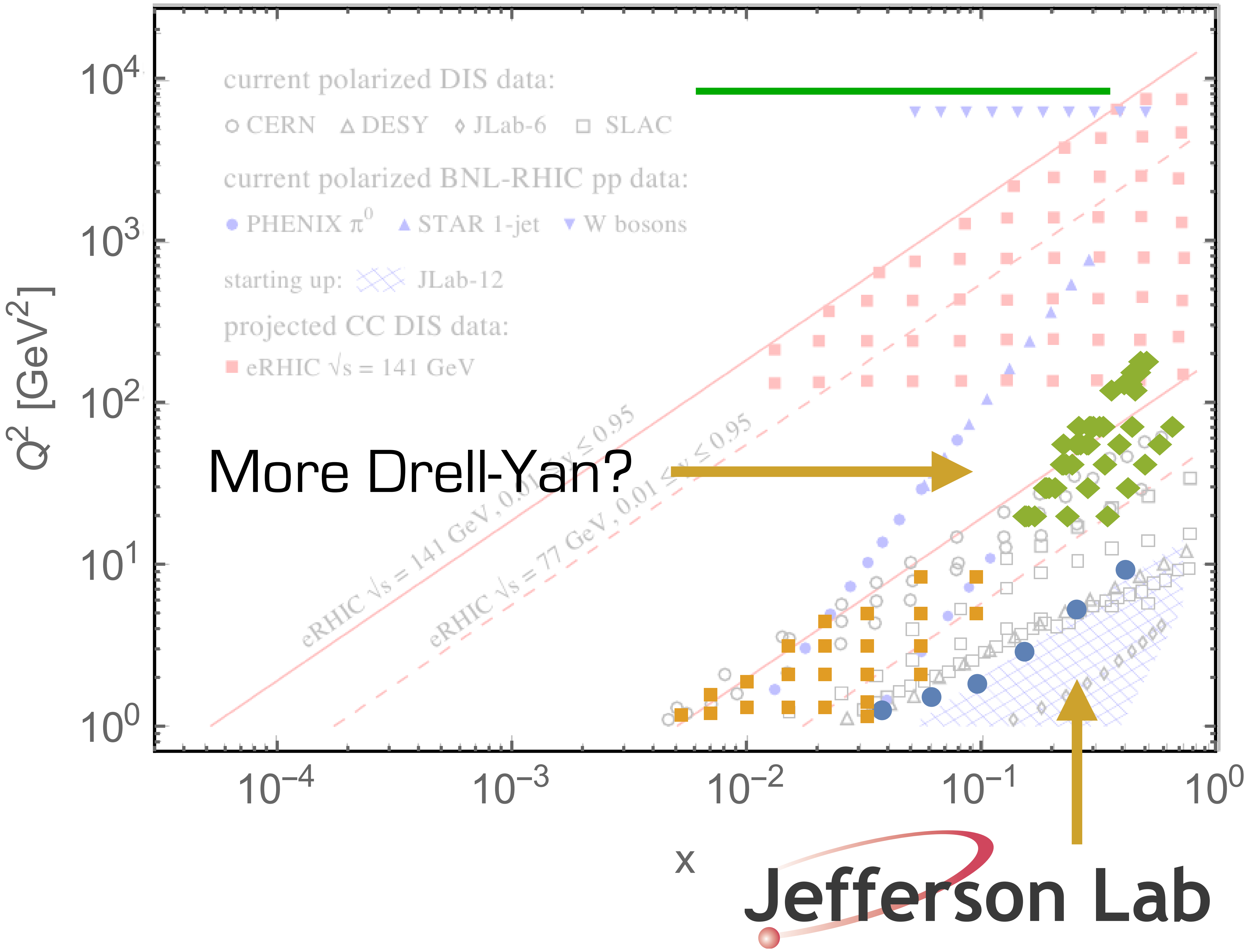

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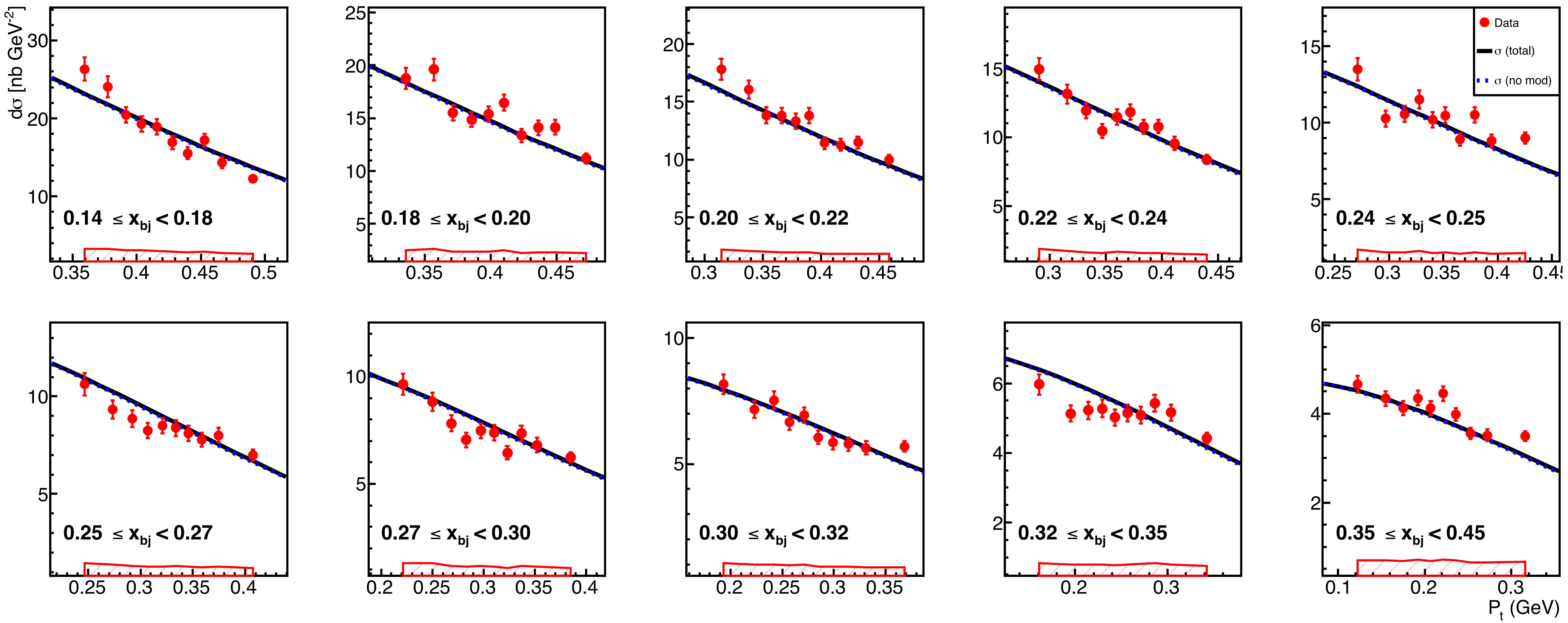
Recent ^{3}He data from JLab Hall A

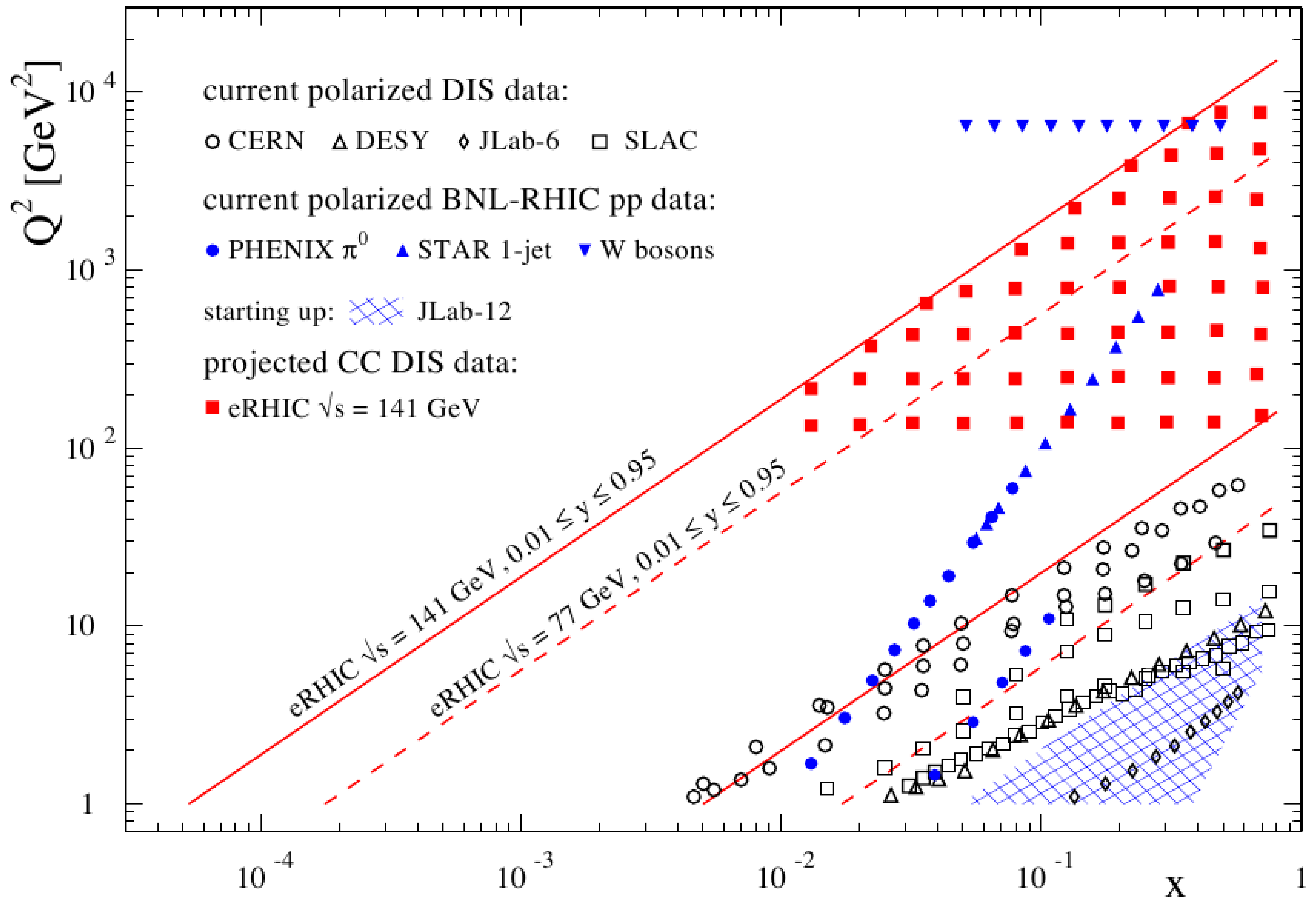


Jefferson Lab

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!

Comparison with future perspectives



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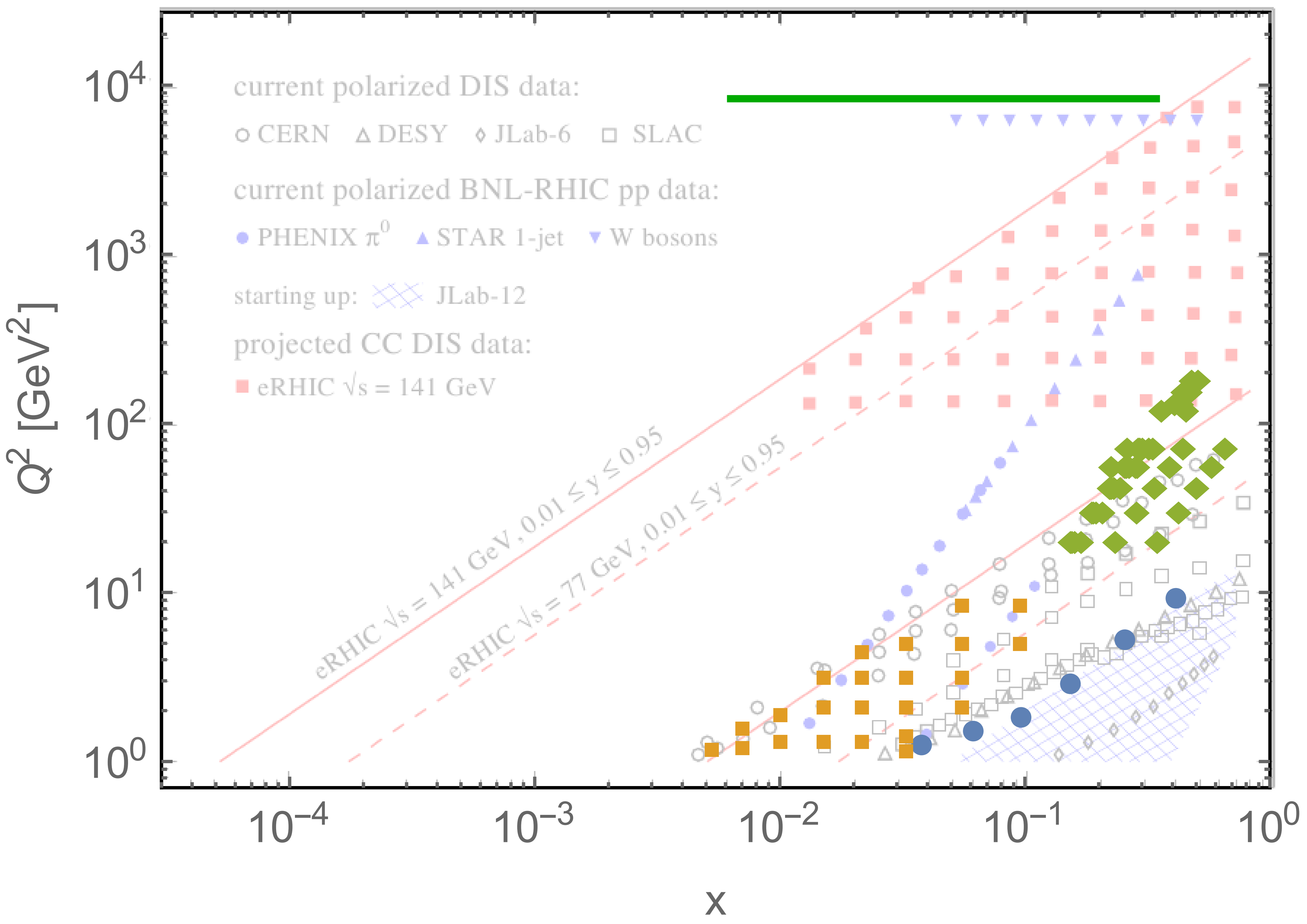

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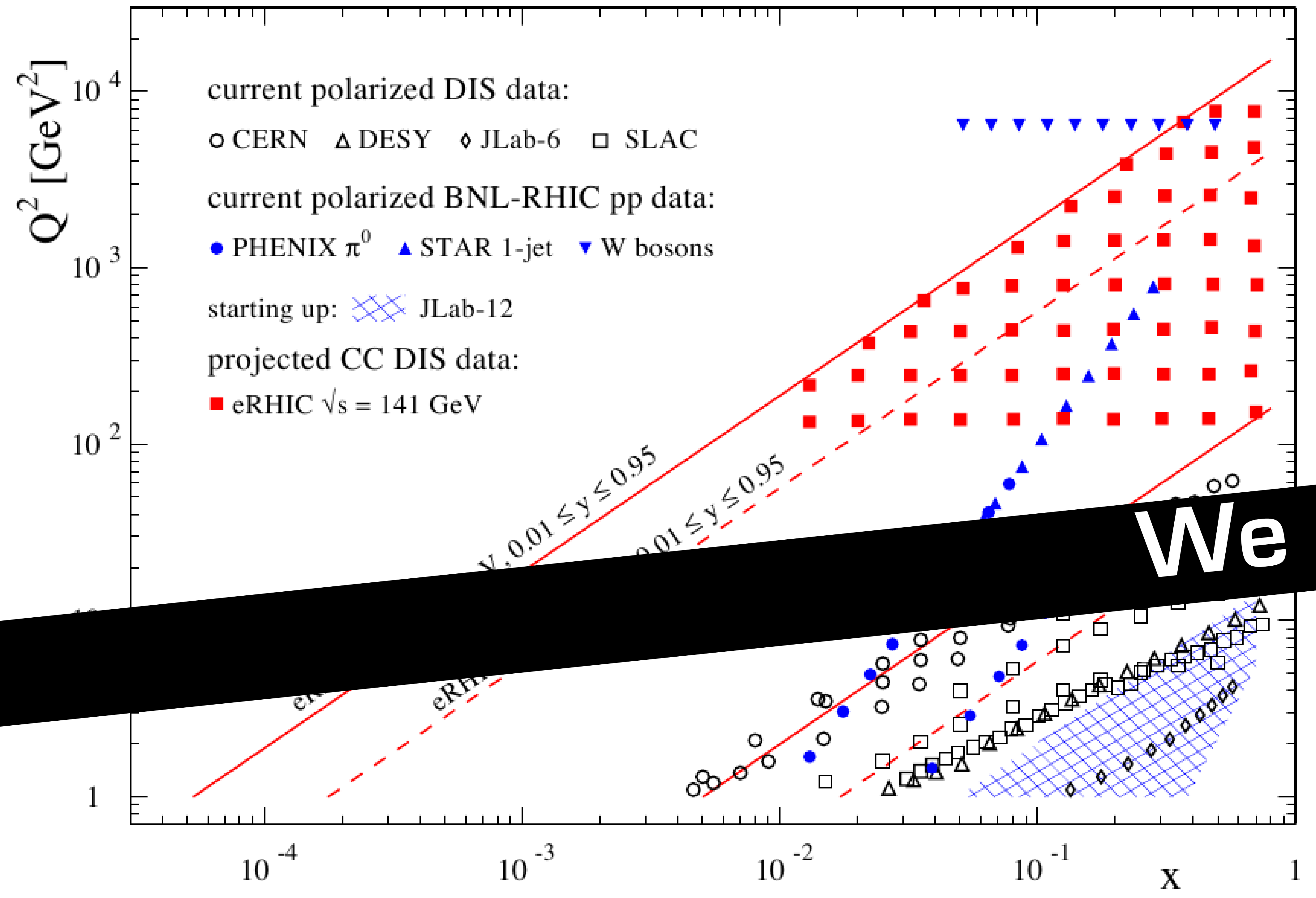

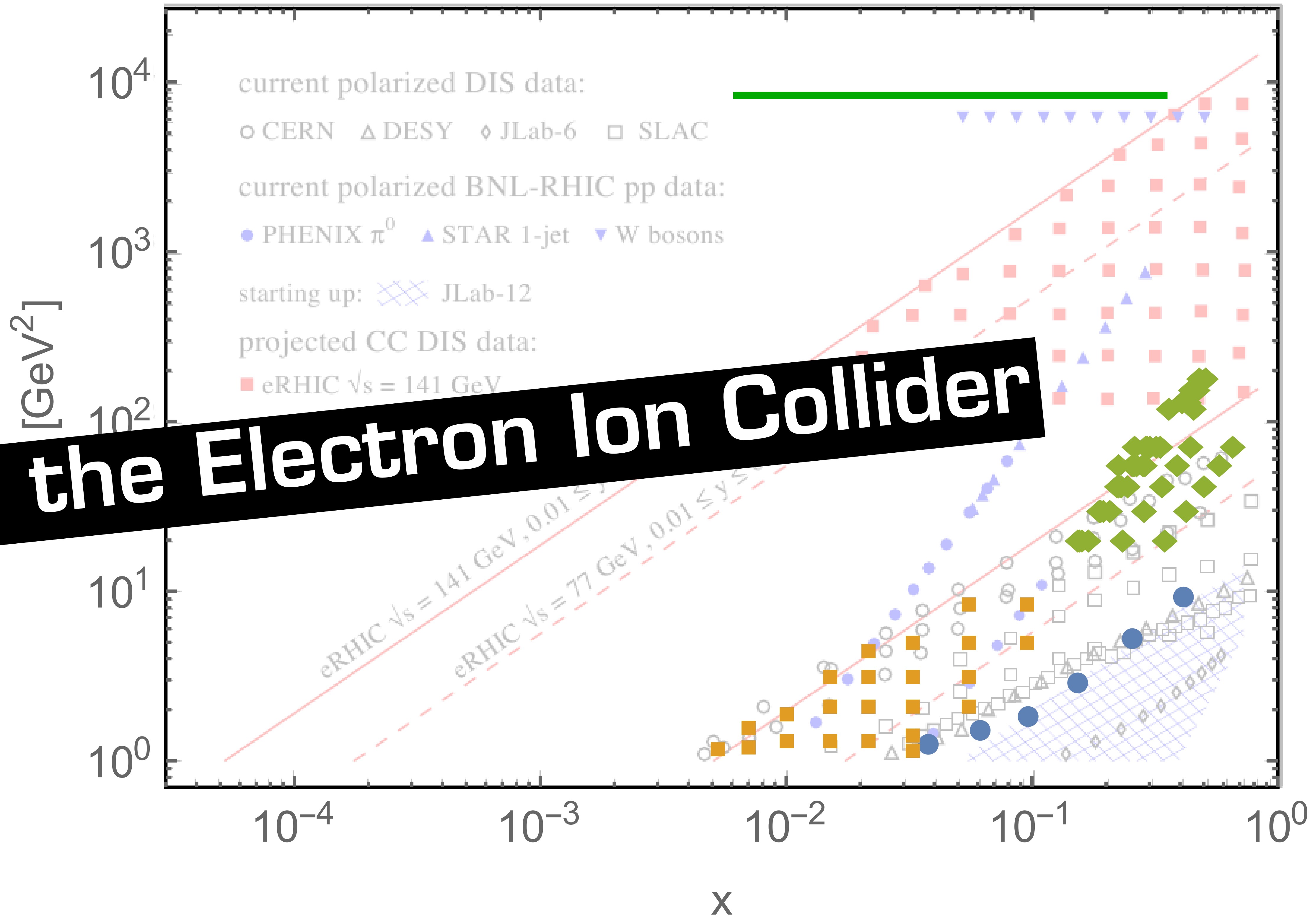

We need the Electron Ion Collider

from EIC white paper EPJA 52 (2016)

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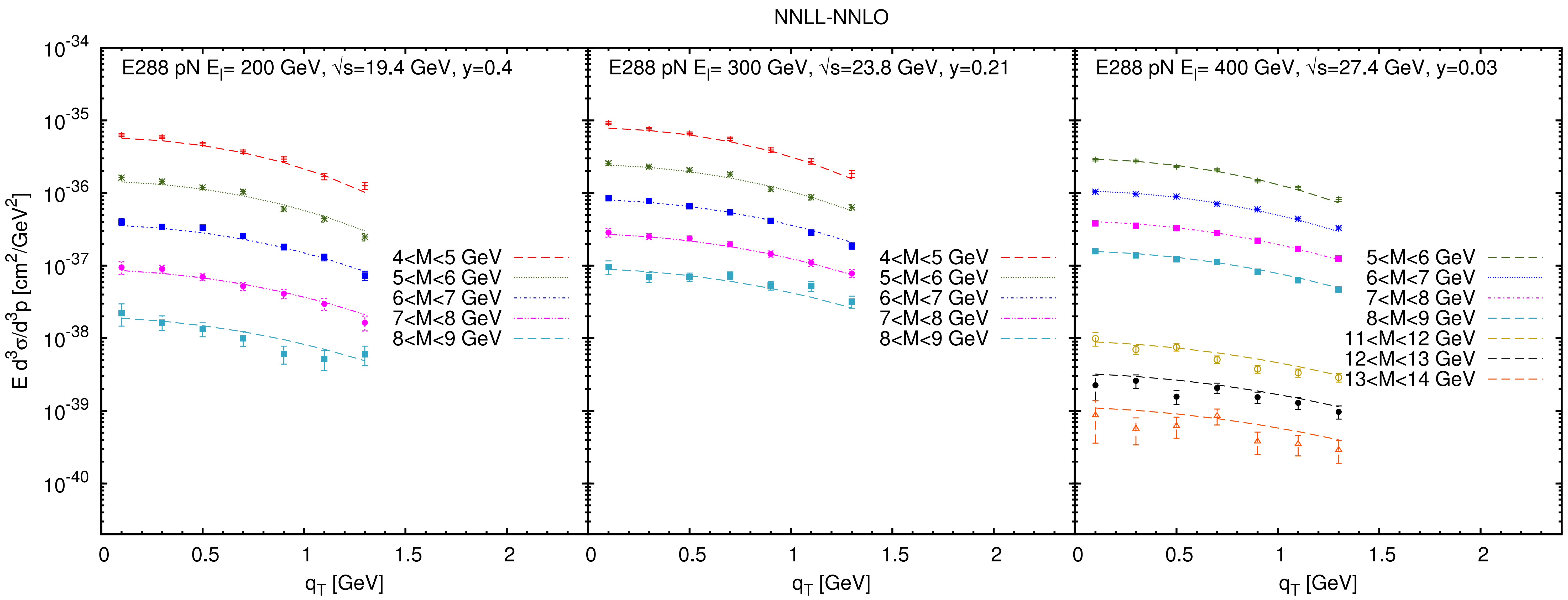
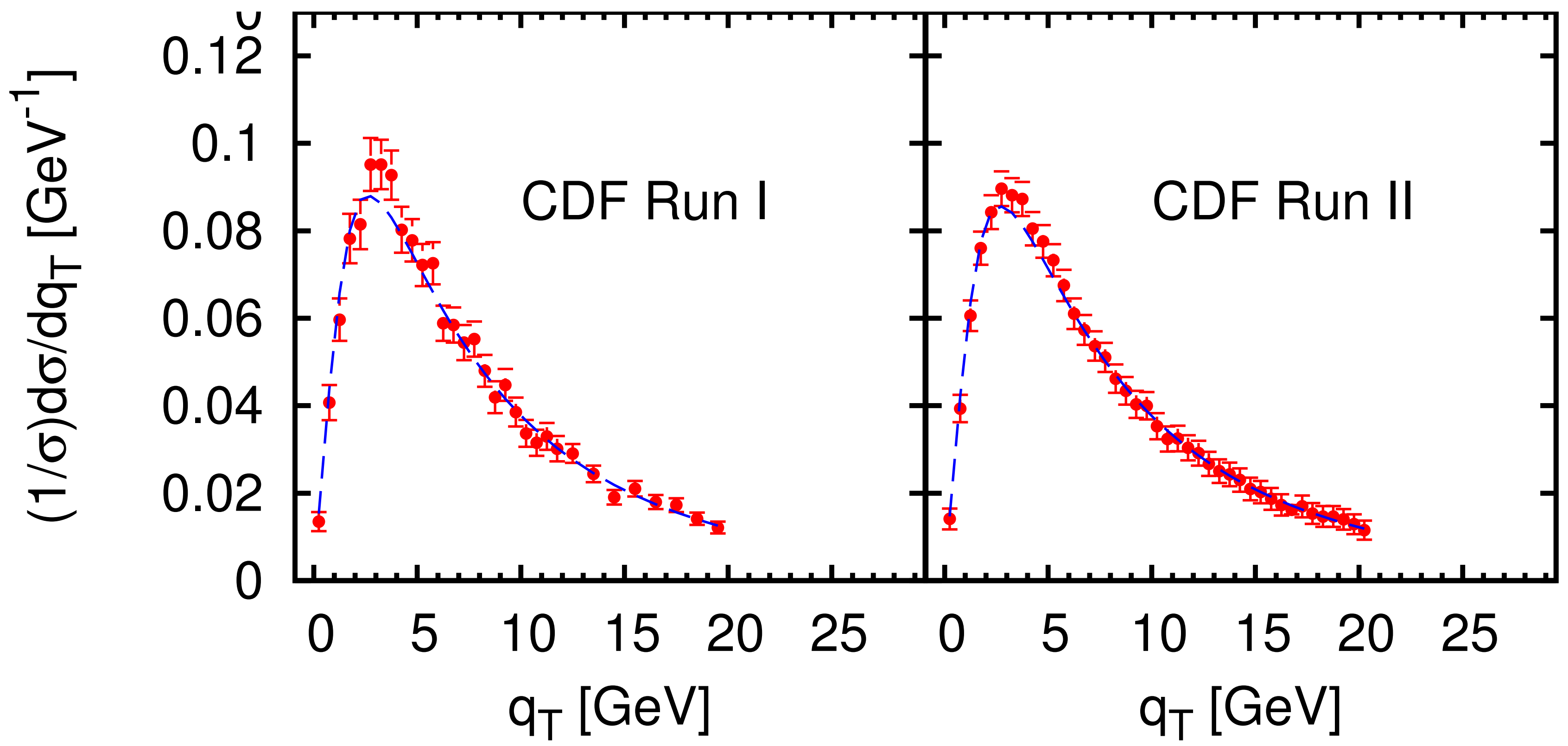
- Most of the discrepancies come from the normalisation

- Y terms still to be implemented

Drell-Yan + Z production data (DEMS 2014)

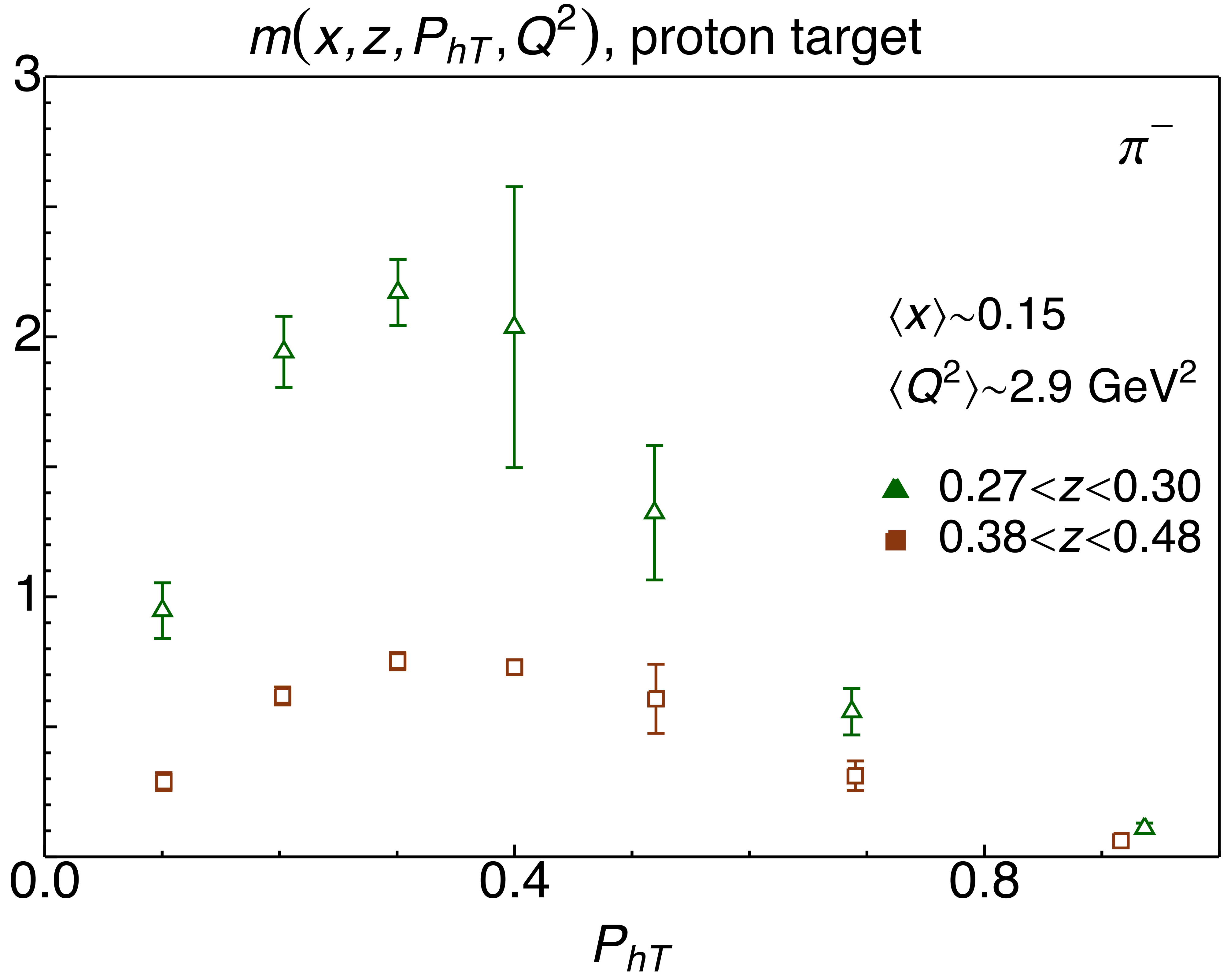
D'Alesio, Echevarria, Melis, Scimemi, JHEP 1411 (14)





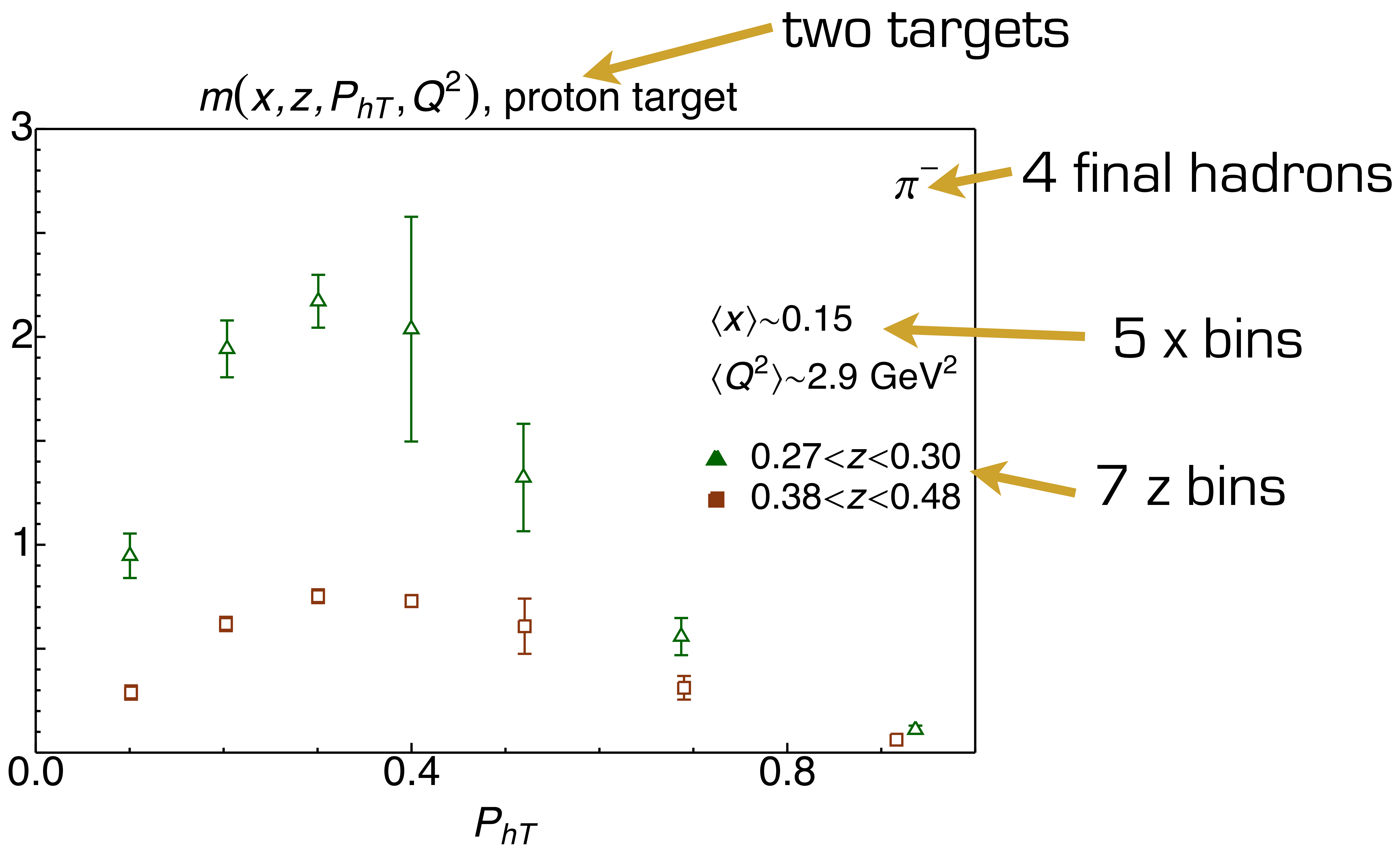
The fit implements TMD evolution at Next-to-Next-to-Leading log (state of the art)
Several choices are peculiar to this fit and not "standard"
The agreement with data is excellent ($\chi^2/\text{dof} = 1.10$)

The replica method



Example of original data

The replica method



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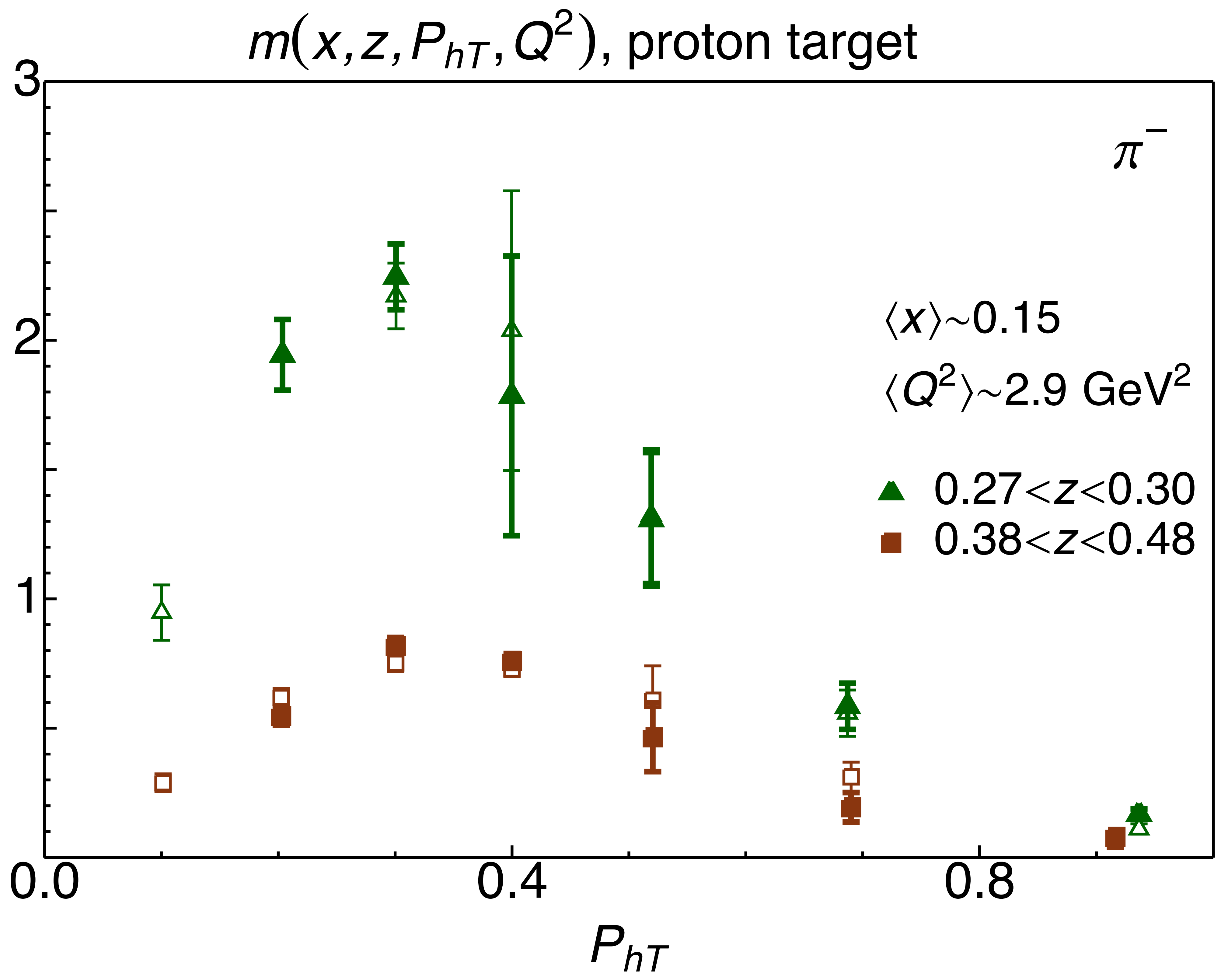
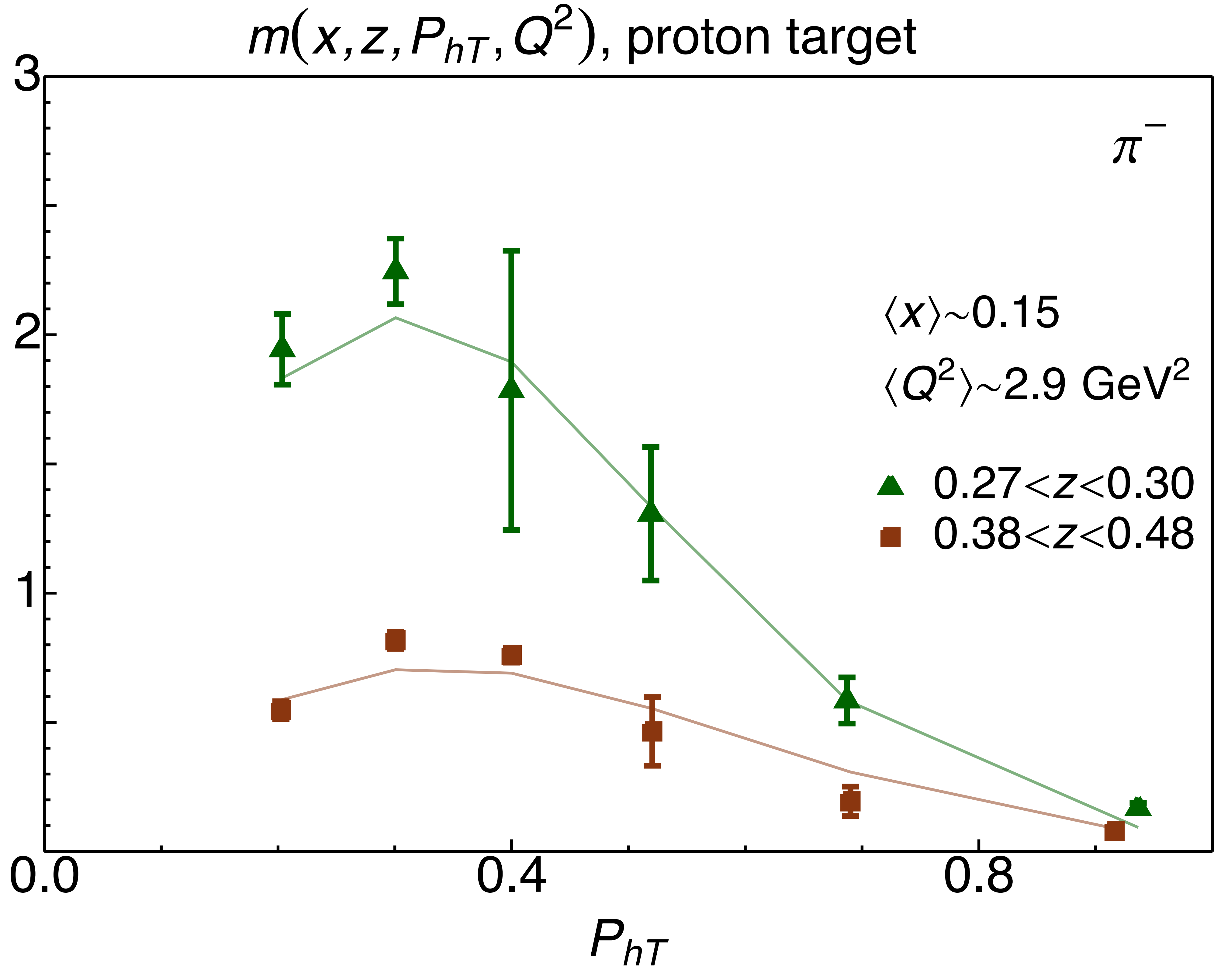


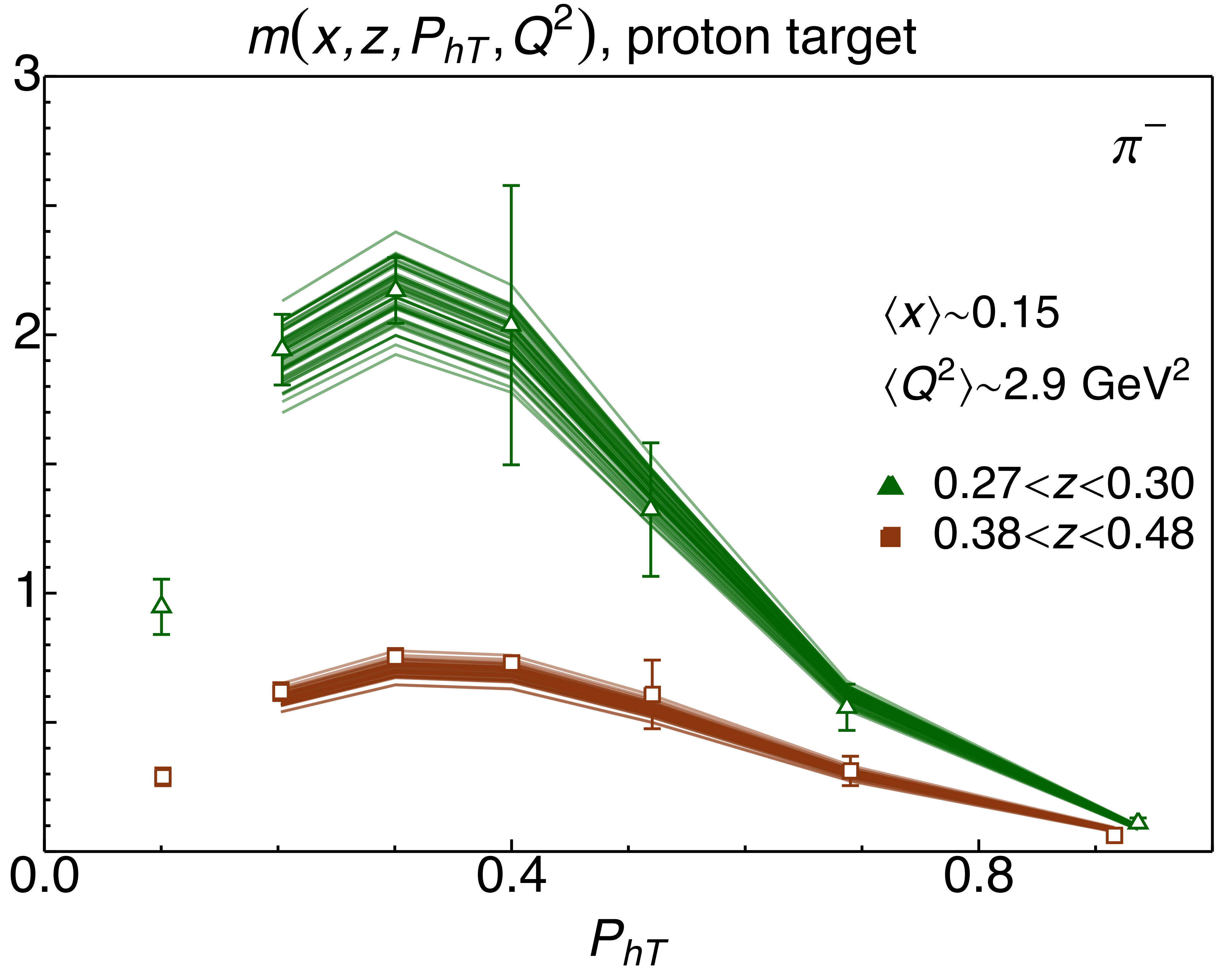
Data are replicated (with Gaussian distribution)

The replica method



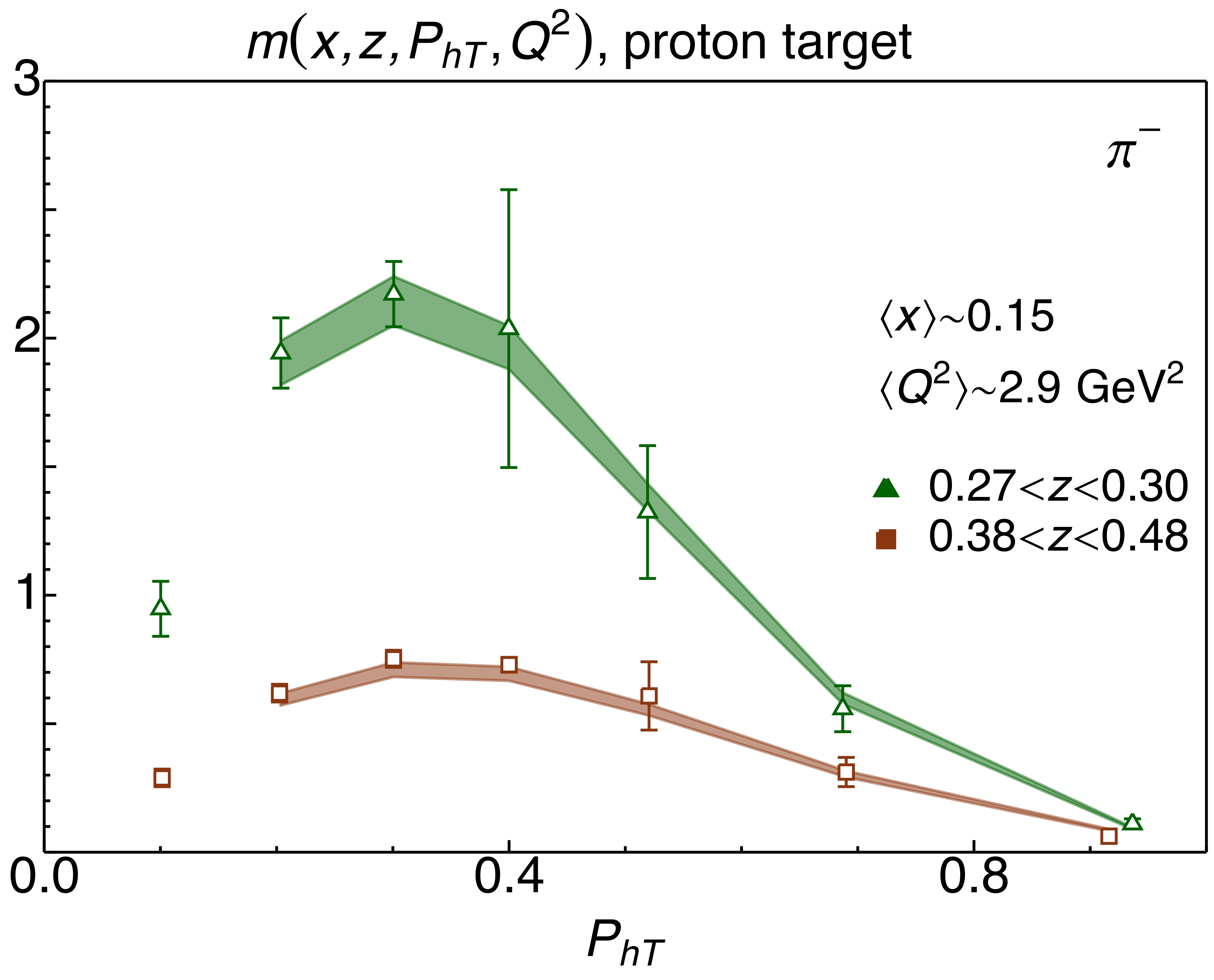
The fit is performed on the replicated data

The replica method



The procedure is repeated 200 times

The replica method



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