TMDs global fits by the MAP Collaboration

Lorenzo Rossi

MAP Collaboration

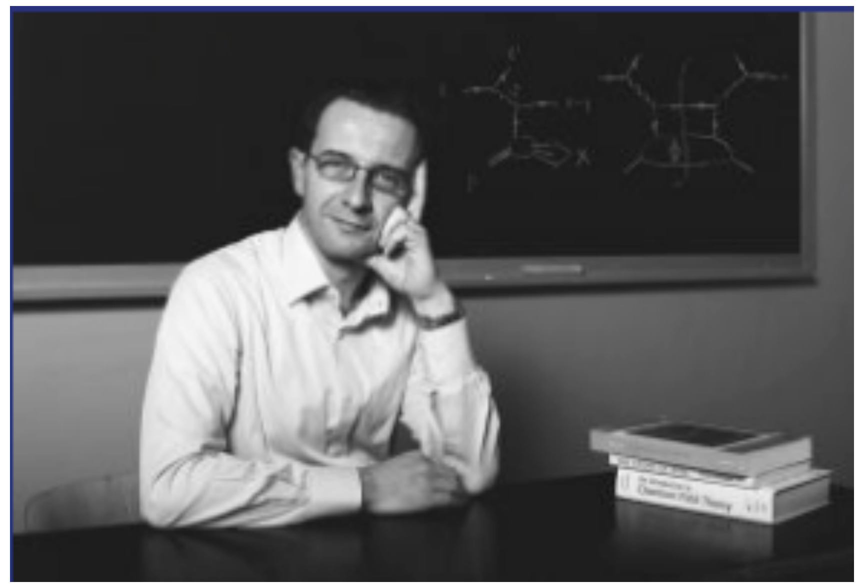
June 7th

Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DI PAVIA

Results obtained with contribution from:

Alessandro Bacchetta



Marco Radici

Matteo Cerutti

Andrea Signori

Valerio Bertone

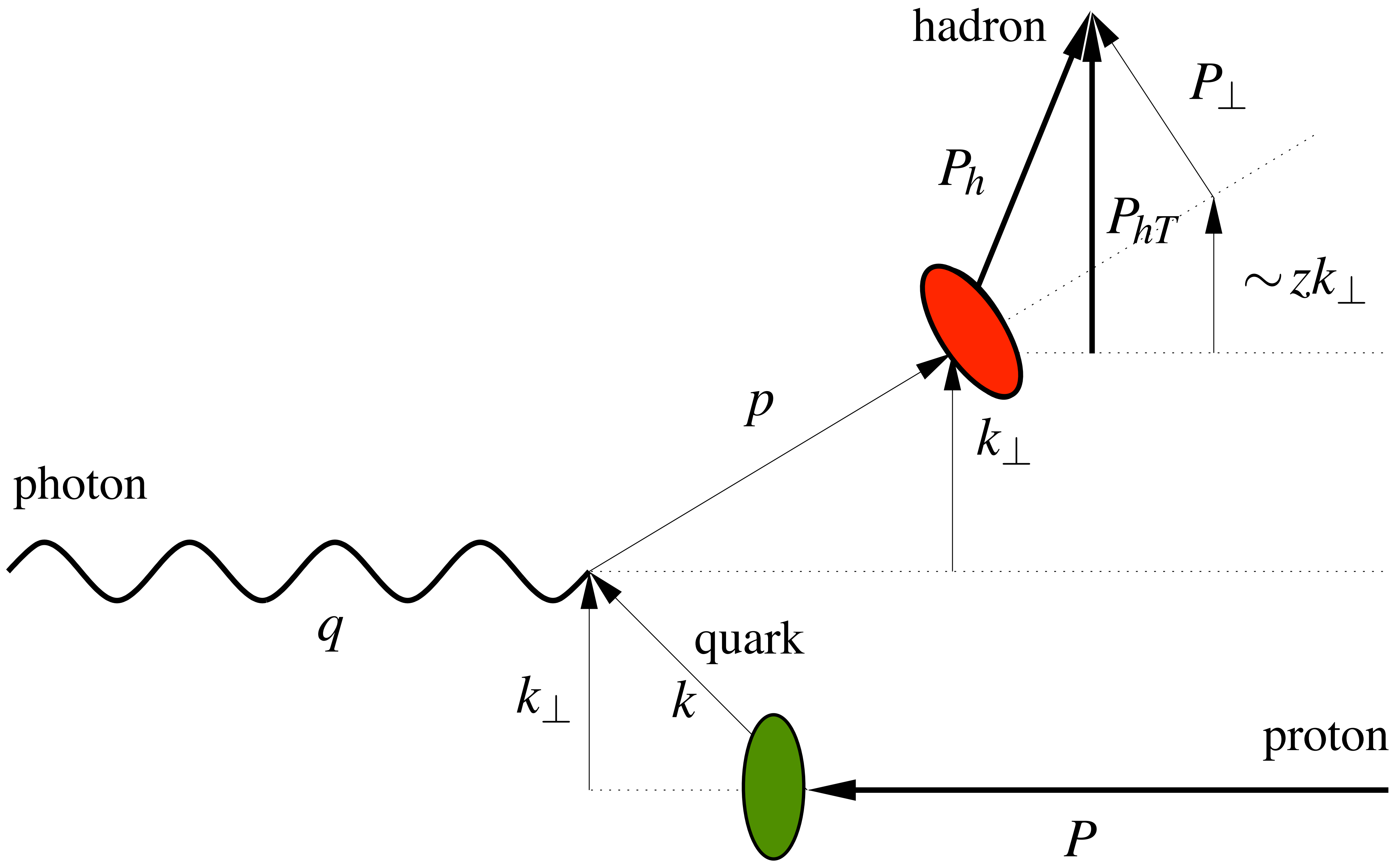
Chiara Bissolotti

Giuseppe Bozzi

Fulvio Piacenza

Simone Venturini

TMD Factorization - SIDIS process

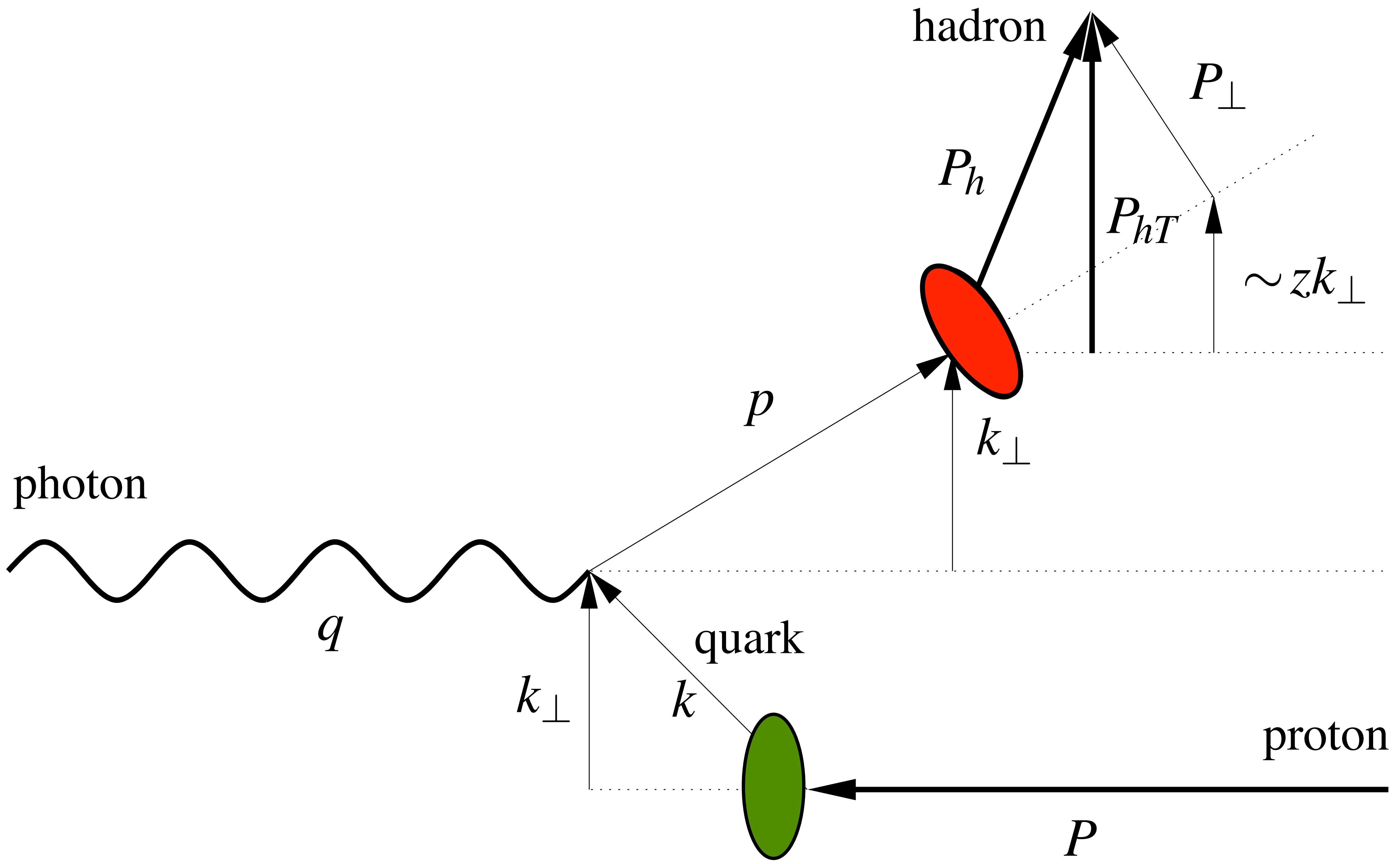


$$F_{UU,T}(x\,.\,z;\mu_F,\mathbf{P}_{hT}^2,Q^2) = x\sum_a H^a_{UU,T}(Q^2,\mu^2)\int d^2\mathbf{k}_\perp \mathbf{d}^2\mathbf{P}_\perp f_{\mathbf{1}}^{\mathbf{a}}(x,\mathbf{k}_\perp^2;\mu^2)D_{\mathbf{1}}^{\mathbf{a}\to\mathbf{h}}(z,\mathbf{P}_\perp^2;\mu^2)\delta^{(2)}(z\mathbf{k}_\perp - \mathbf{P}_{hT} + \mathbf{P}_\perp)$$

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

Bacchetta, Diehl, et al., JHEP 02 (2007)

TMD Factorization - SIDIS process



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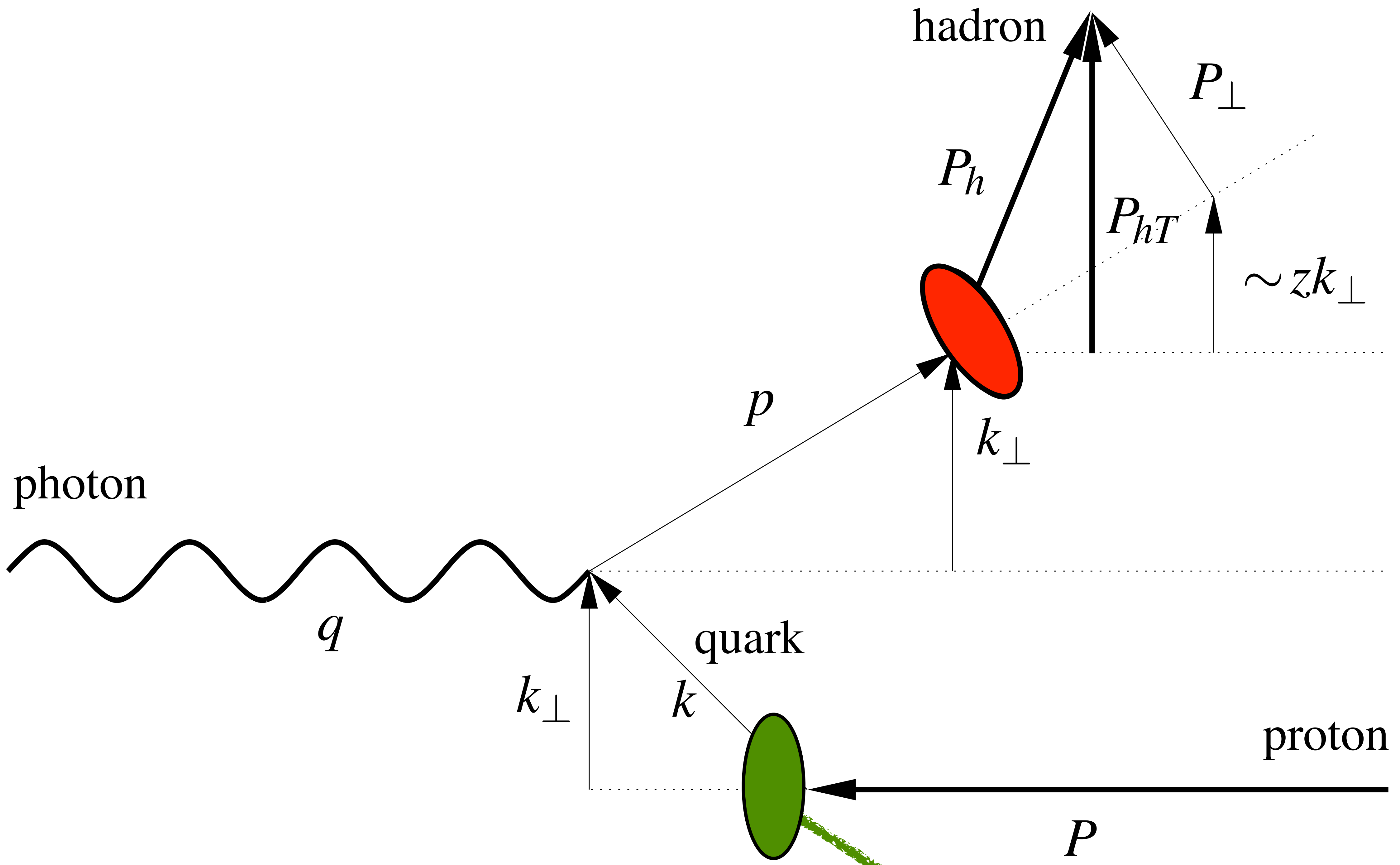
W Term

Bacchetta, Diehl, et al., JHEP 02 (2007)

TMD Factorization - SIDIS process



TMD PDF

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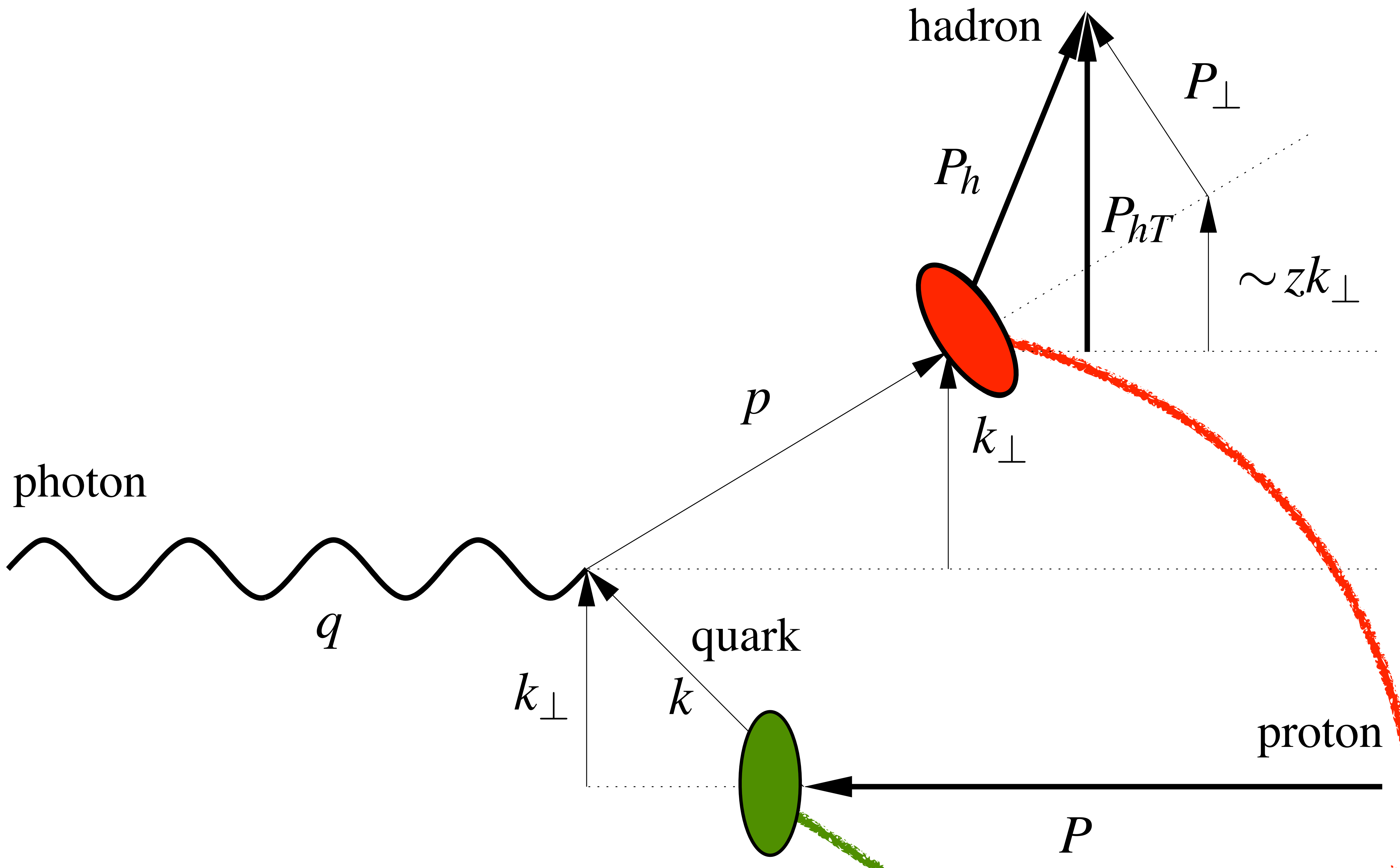
TMD Factorization - SIDIS process

TMD FF

TMD PDF



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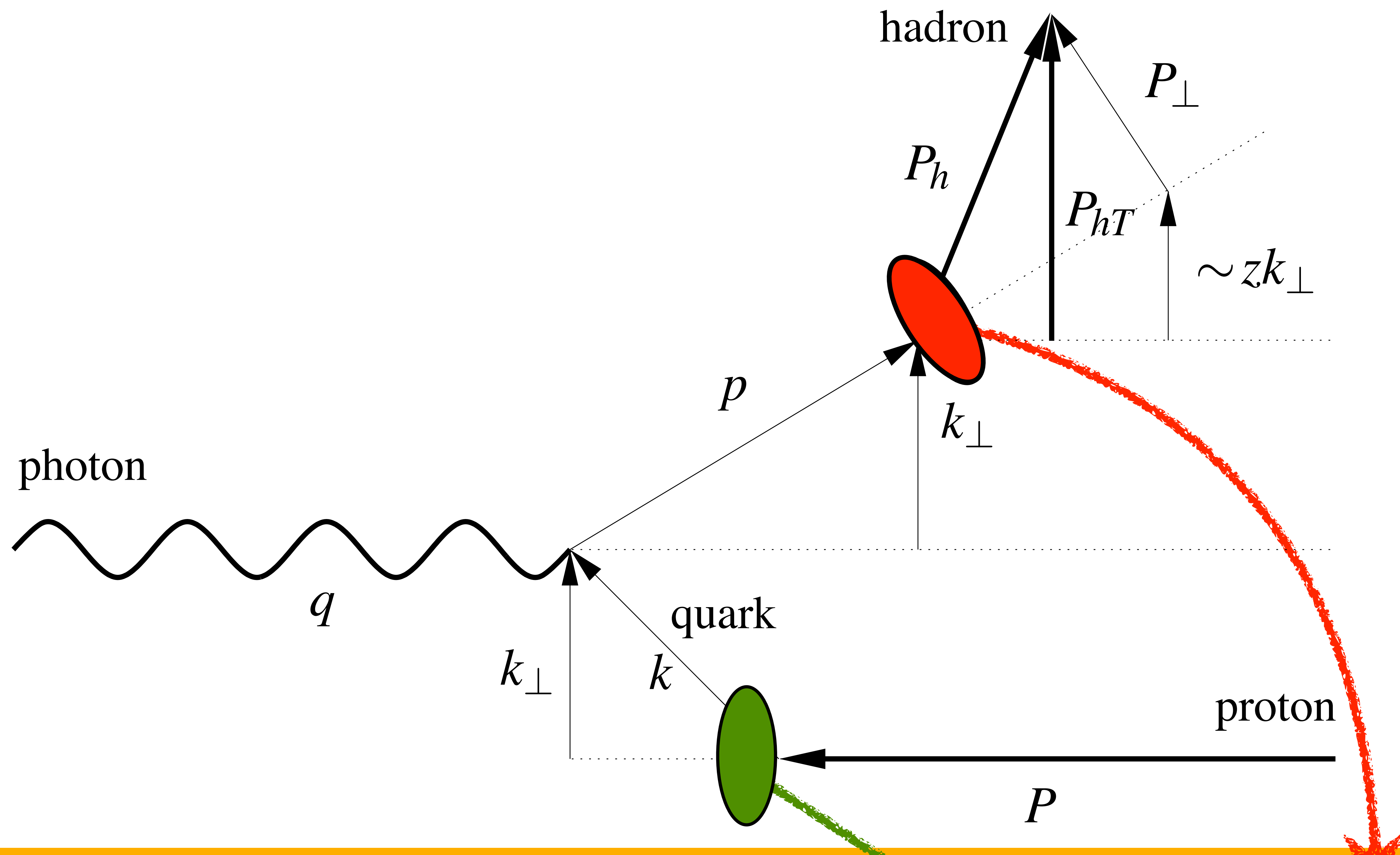
Bacchetta, Diehl, et al., JHEP 02 (2007)

TMD Factorization - SIDIS process

TMD FF

TMD PDF



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W Term

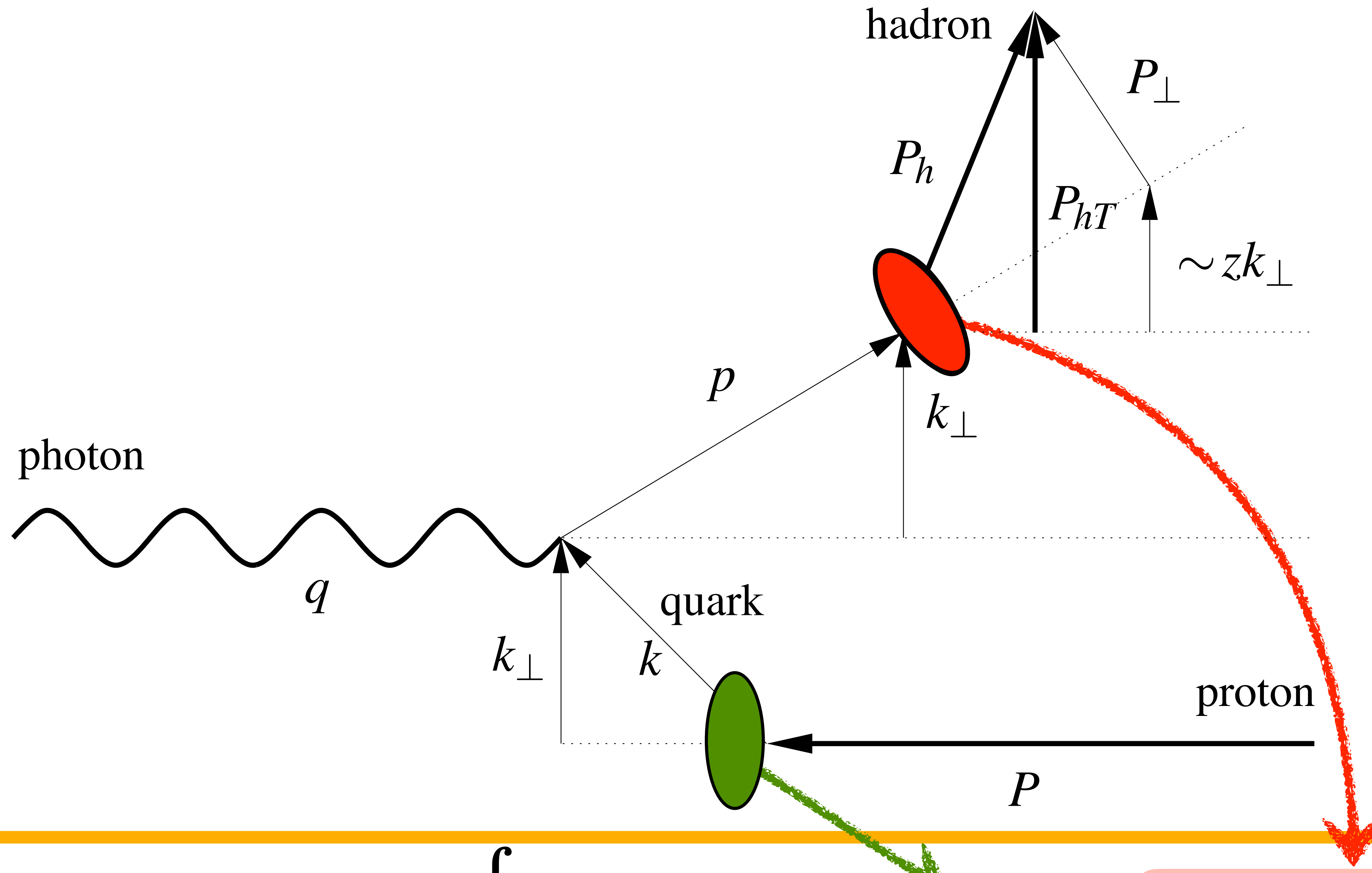
- The W term dominates in the region where $q_T \ll Q$

Bacchetta, Diehl, et al., JHEP 02 (2007)

TMD Factorization - SIDIS process

TMD FF

TMD PDF



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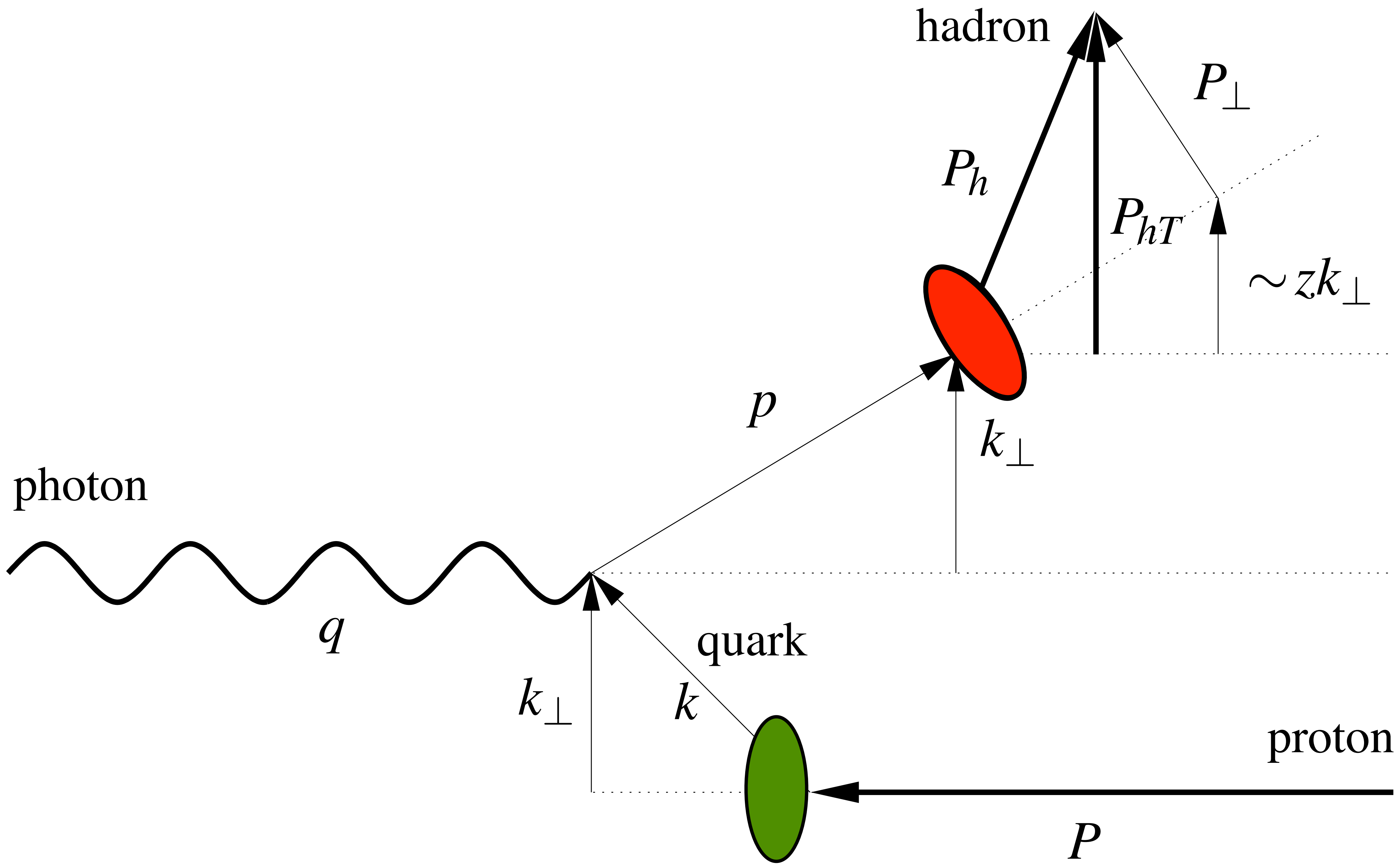
$$+Y_{UU,T}(Q^2,\mathbf{P}_{hT}^2) + \mathcal{O}(M^2/Q^2)$$

W Term

- The W term dominates in the region where $q_T \ll Q$
- The Y term has been excluded in the MAP analysis

Bacchetta, Diehl, et al., JHEP 02 (2007)

TMD Factorization - SIDIS process



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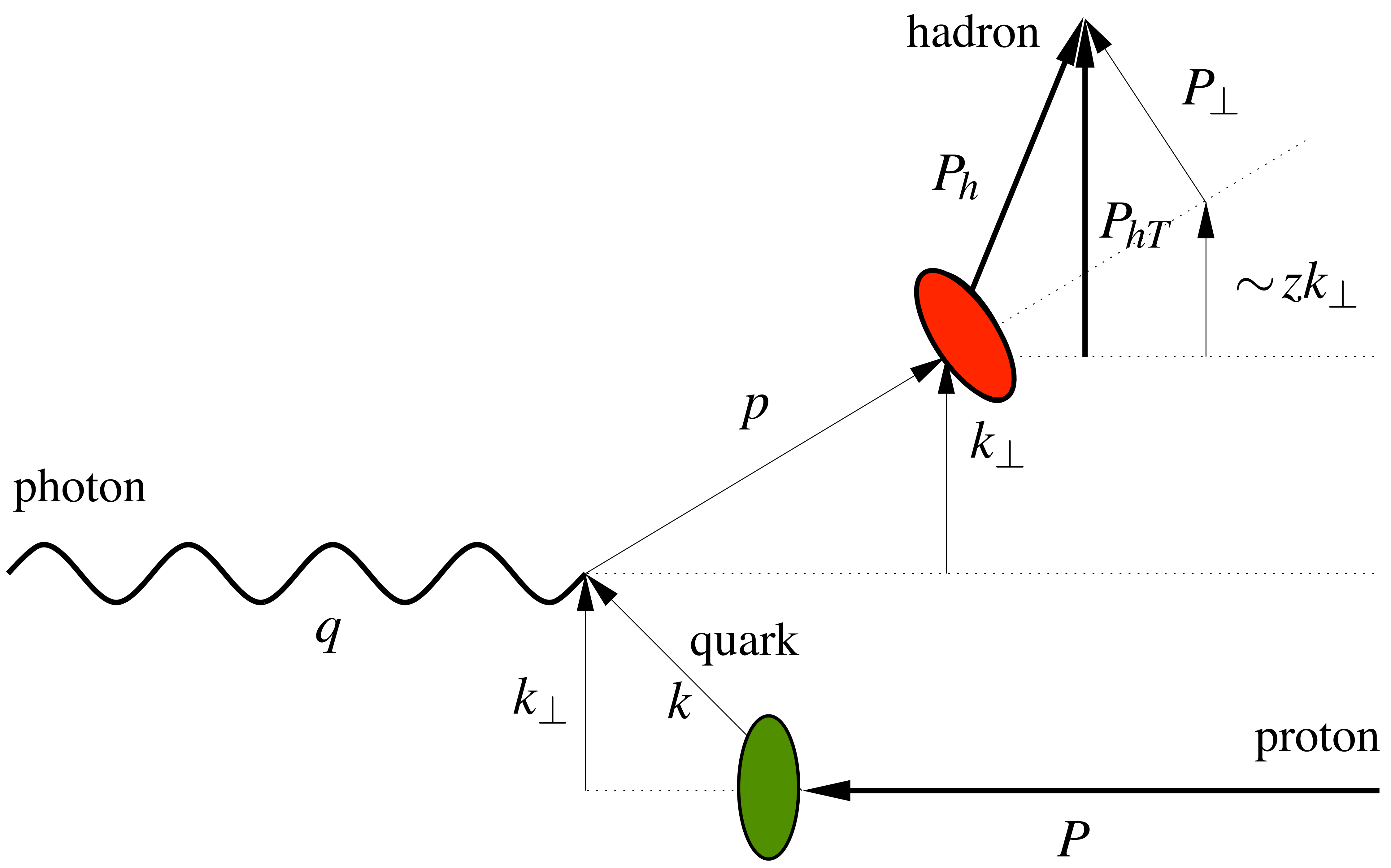

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Bacchetta, Diehl, et al., JHEP 02 (2007)

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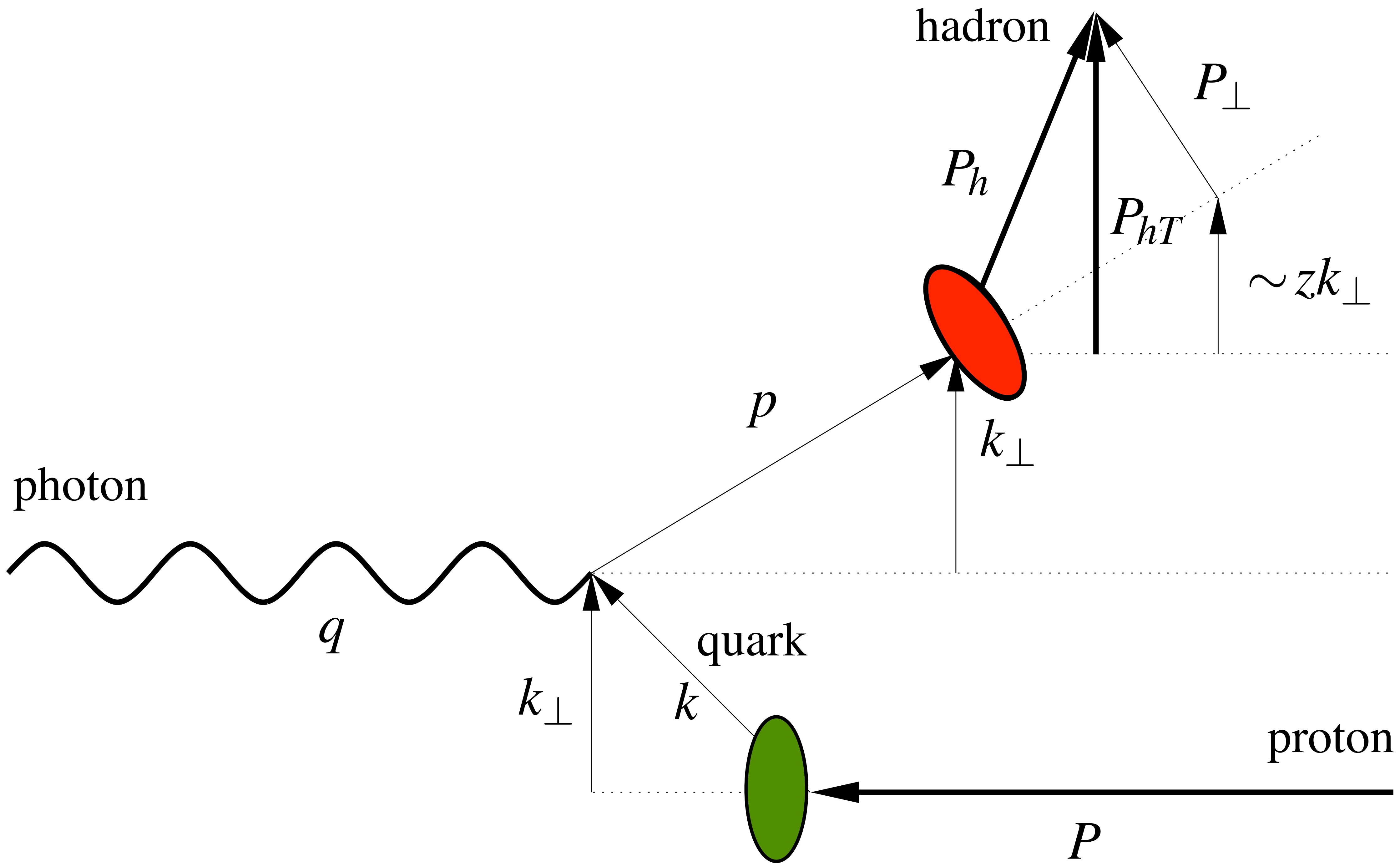

$$F_{UU,T}(x\,.\,z;\mu_F,\mathbf{P}_{hT}^2,Q^2) = x\sum_a H_{UU,T}^a(Q^2,\mu^2)\int d^2\mathbf{k}_\perp \mathbf{d^2P}_\perp f_\mathbf{1}^\mathbf{a}(x,\mathbf{k}_\perp^\mathbf{2};\mu^\mathbf{2})D_\mathbf{1}^\mathbf{a\to h}(z,\mathbf{P}_\perp^\mathbf{2};\mu^\mathbf{2})\delta^{(\mathbf{2})}(z\mathbf{k}_\perp - \mathbf{P}_{hT} + \mathbf{P}_\perp)$$

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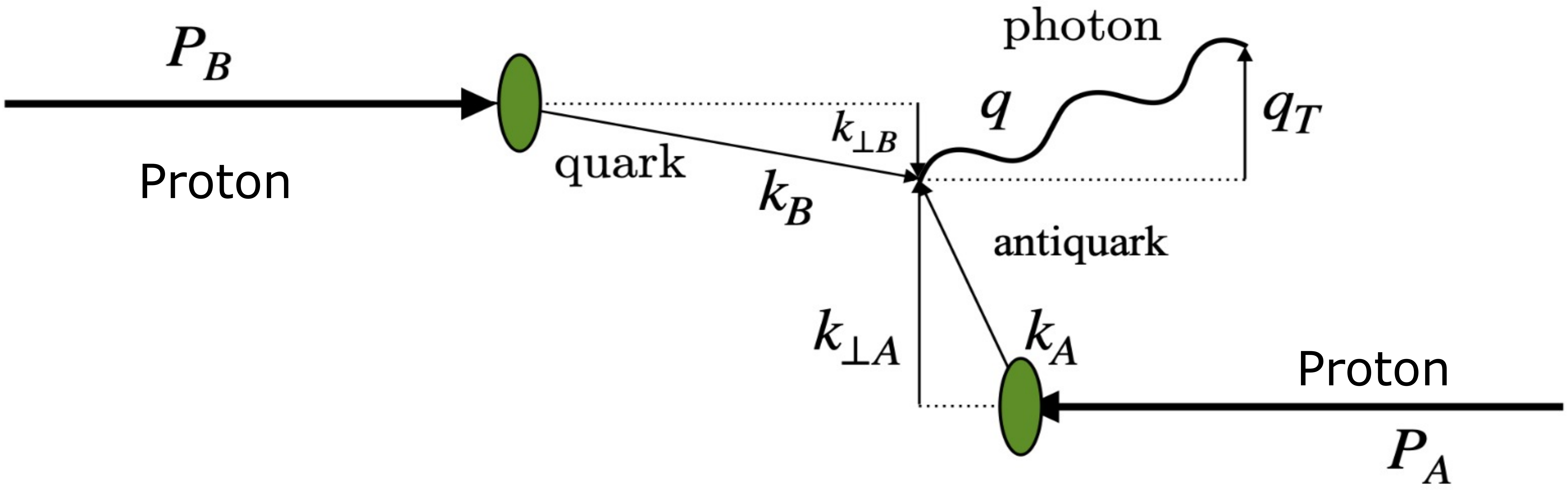
TMDs in imapct space to avoid convolutions

Bacchetta, Diehl, et al., JHEP 02 (2007)

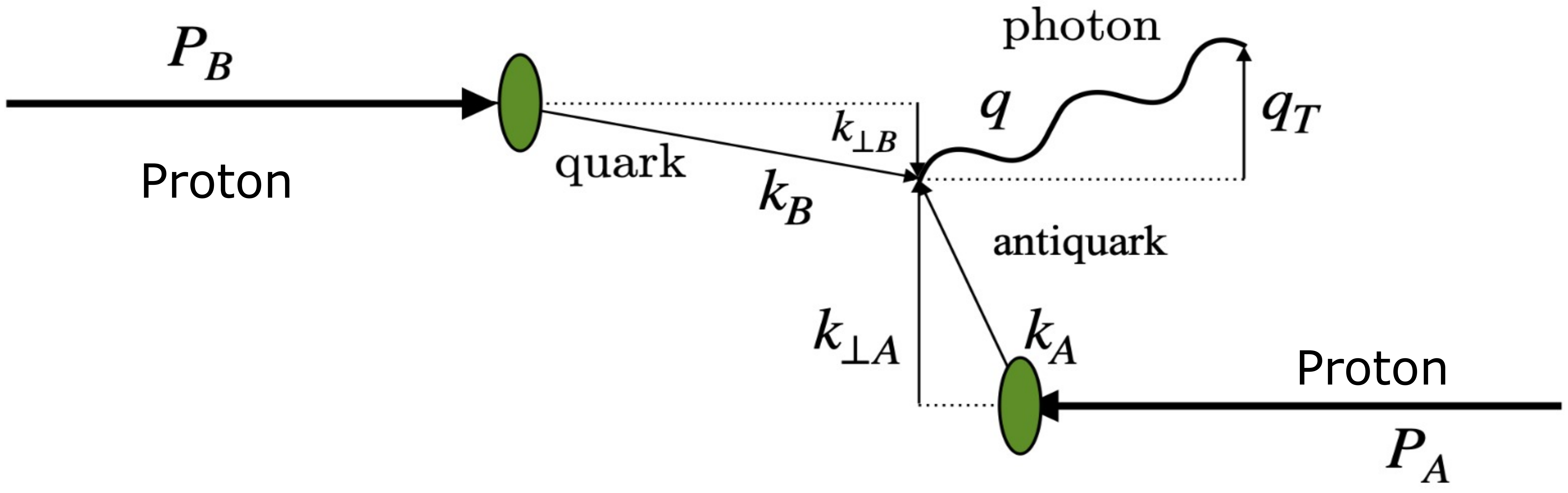
TMD Factorization - Drell Yan process



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

Arnold, Metz and Schlegel, Phys.Rev.D 79 (2009)

TMD Factorization - Drell Yan process



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

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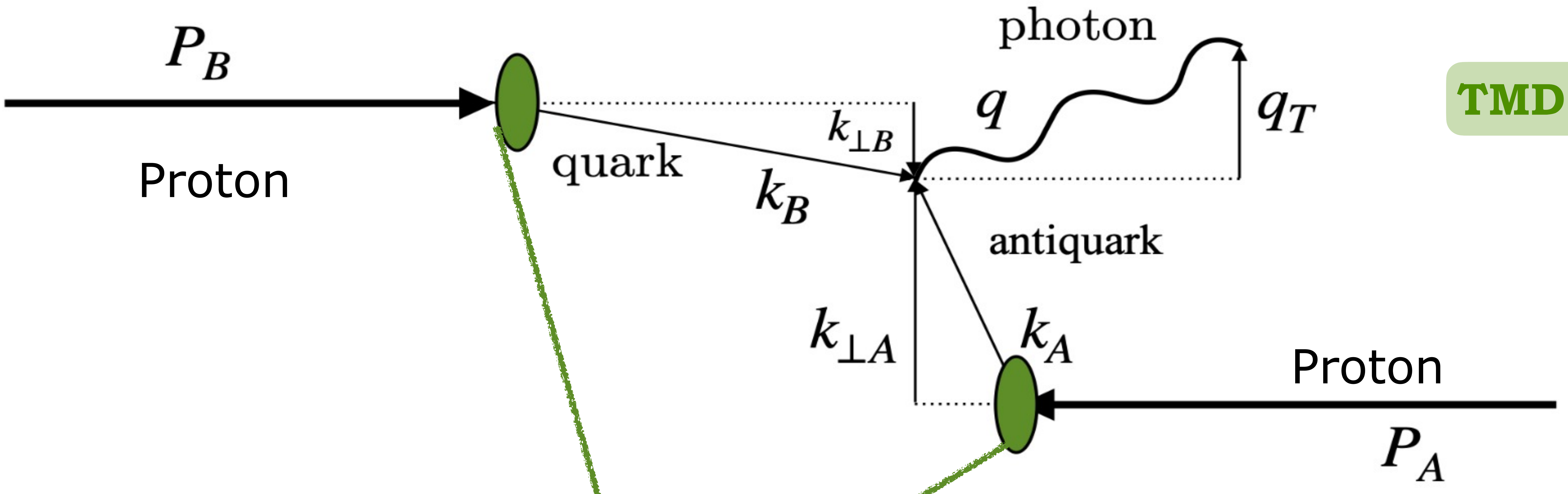

TMD PDFs

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TMD Factorization - structure of TMDs

$$\hat{f}_1^q(x_B, \mathbf{b}_T; \mu_F, \zeta_F) = [C \otimes f_1](x_B, b_\star; \mu_{b_\star}, \mu_{b_\star}^2) \exp\left\{ \int_{\mu_{b_\star}}^{\mu_F} \frac{d\mu'}{\mu'} \gamma(\mu', \zeta_F) \right\}$$

$$\times \left(\frac{\zeta}{\mu_{b_\star}^2}\right)^{K(b_\star, \mu_{b_\star})/2} \left[\frac{\zeta}{Q_0}\right]^{-g_K(\mathbf{b}_T)/2} f_1^{NP}(x, \mathbf{b}_T; \zeta, Q_0)$$

Collins, "Foundations of Perturbative QCD"

TMD Factorization - structure of TMDs

Matching coeff.
(perturbative calculable)

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(previous fit)

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Collins-Soper kernel

Collins, "Foundations of Perturbative QCD"

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Collins-Soper kernel

NP part of Collins-Soper Kernel

Collins, "Foundations of Perturbative QCD"

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Non perturbative part of TMDs

Collins, *"Foundations of Perturbative QCD"*

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Non perturbative part of TMDs

Fit extraction

Collins, *"Foundations of Perturbative QCD"*

Perturbative accuracy

-

Perturbative accuracy

Orders in powers of α_S

Accuracy	H and C	K and γ_F	γ_K	PDFs/FFs and α_S evol.
LL	0	-	1	-
NLL	0	1	2	LO
NLL’	1	1	2	NLO
NNLL	1	2	3	NLO
NNLL’	2	2	3	NNLO
N^3LL^-	2	3	4	NNLO + NLO
N^3LL	2	3	4	NNLO
N^3LL'	3	3	4	N^3LO

Perturbative accuracy

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N^3LL'	3	3	4	N^3LO

Perturbative accuracy

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NLL'	1	1	2	NLO
NNLL	1	2	3	NLO
NNLL'	2	2	3	NNLO
N^3LL^-	2	3	4	NNLO + NLO
N^3LL	2	3	4	NNLO
N^3LL'	3	3	4	N^3LO

Collinear fragmentation functions available beyond NLO only recently

A new global fit: MAPTMD22

	Accuracy	SIDIS	DY	Z production	N of points	χ^2/N_{data}
Pavia 2017 arXiv:1703.10157	NLL	✔	✔	✔	8059	1.55
SV 2019 arXiv:1912.06532	N^3LL	✔	✔	✔	1039	1.06
MAPTMD22	***N^3LL^-***	✔	✔	✔	***2031***	***1.06***

MAP Collaboration, JHEP 10 (2022)

A new extraction of proton quark unpolarized TMDs

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- Global analysis of Drell-Yan and Semi-Inclusive DIS data sets: ***2031*** data points

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MAP Collaboration, JHEP 10 (2022)

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MAP Collaboration, JHEP 10 (2022)

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- Perturbative accuracy: ***N^3LL^-***
- ***Normalization*** of SIDIS multiplicities beyond NLL
- Number of fitted parameters: ***21***
- Extremely good description: $\chi^2/\mathrm{N_{data}} = 1.06$

MAP Collaboration, JHEP 10 (2022)

MAPTMD22: datasets included

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Drell-Yan

Fixed-target low-energy DY

RHIC data

LHC and Tevatron data

MAPTMD22: datasets included

Drell-Yan → **484 points**

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SIDIS

HERMES data

COMPASS data

MAPTMD22: datasets included

Drell-Yan → **484 points**

Fixed-target low-energy DY

RHIC data

LHC and Tevatron data

SIDIS → **1547 points**

HERMES data

COMPASS data

MAPTMD22: datasets included

Drell-Yan → **484 points**

Fixed-target low-energy DY

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LHC and Tevatron data

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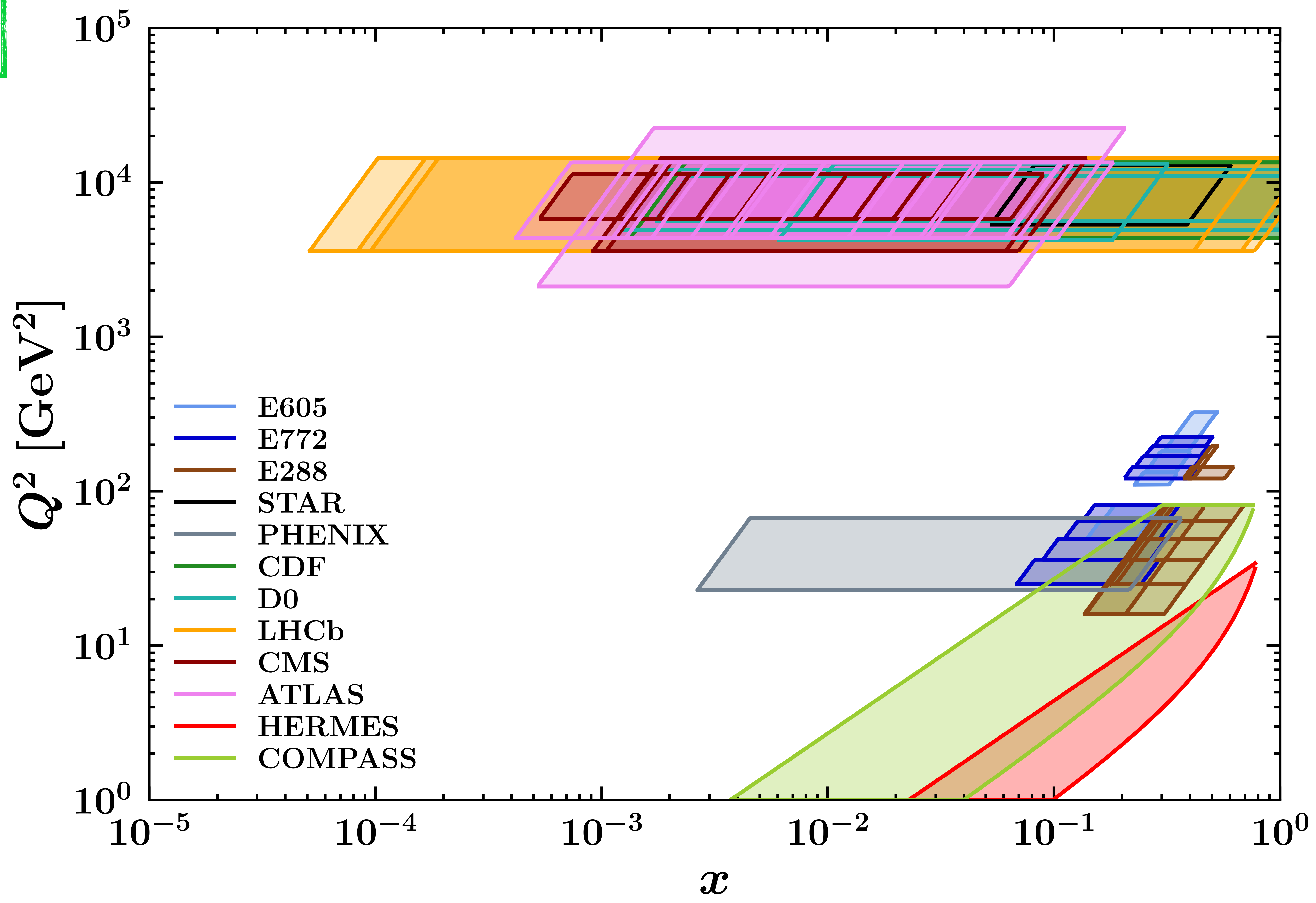
COMPASS data



Total: 2031 fitted points

MAPTMD22: Non perturbative part

$$f_{1\mathrm{NP}}(x, b_T^2) \propto \text{F.T. of } \left(e^{-\frac{k_\perp^2}{g_{1A}}} + \lambda_B k_\perp^2 e^{-\frac{k_\perp^2}{g_{1B}}} + \lambda_C e^{-\frac{k_\perp^2}{g_{1C}}} \right)$$

MAPTMD22: Non perturbative part

$$f_{1\mathrm{NP}}(x, b_T^2) \propto \text{F.T. of } \left(e^{-\frac{k_\perp^2}{g_{1A}}} + \lambda_B k_\perp^2 e^{-\frac{k_\perp^2}{g_{1B}}} + \lambda_C e^{-\frac{k_\perp^2}{g_{1C}}} \right)$$

$$g_1(x) = N_1 \frac{(1-x)^\alpha \; x^\sigma}{(1-\hat{x})^\alpha \; \hat{x}^\sigma}$$

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$$D_{1\mathrm{NP}}(x, b_T^2) \propto \text{F.T. of } \left(e^{-\frac{P_\perp^2}{g_{3A}}} + \lambda_{FB} k_\perp^2 e^{-\frac{P_\perp^2}{g_{3B}}} \right)$$

$$g_1(x) = N_1 \frac{(1-x)^\alpha \; x^\sigma}{(1-\hat{x})^\alpha \; \hat{x}^\sigma}$$

MAPTMD22: Non perturbative part

$$f_{1\mathrm{NP}}(x, b_T^2) \propto \text{F.T. of } \left(e^{-\frac{k_\perp^2}{g_{1A}}} + \lambda_B k_\perp^2 e^{-\frac{k_\perp^2}{g_{1B}}} + \lambda_C e^{-\frac{k_\perp^2}{g_{1C}}} \right)$$

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$$g_3(z) = N_3 \frac{(z^\beta + \delta)(1-z)^\gamma}{(\hat{z}^\beta + \delta)(1-\hat{z})^\gamma}$$

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$$g_K(b_T^2) = -g_2^2 \frac{b_T^2}{4}$$

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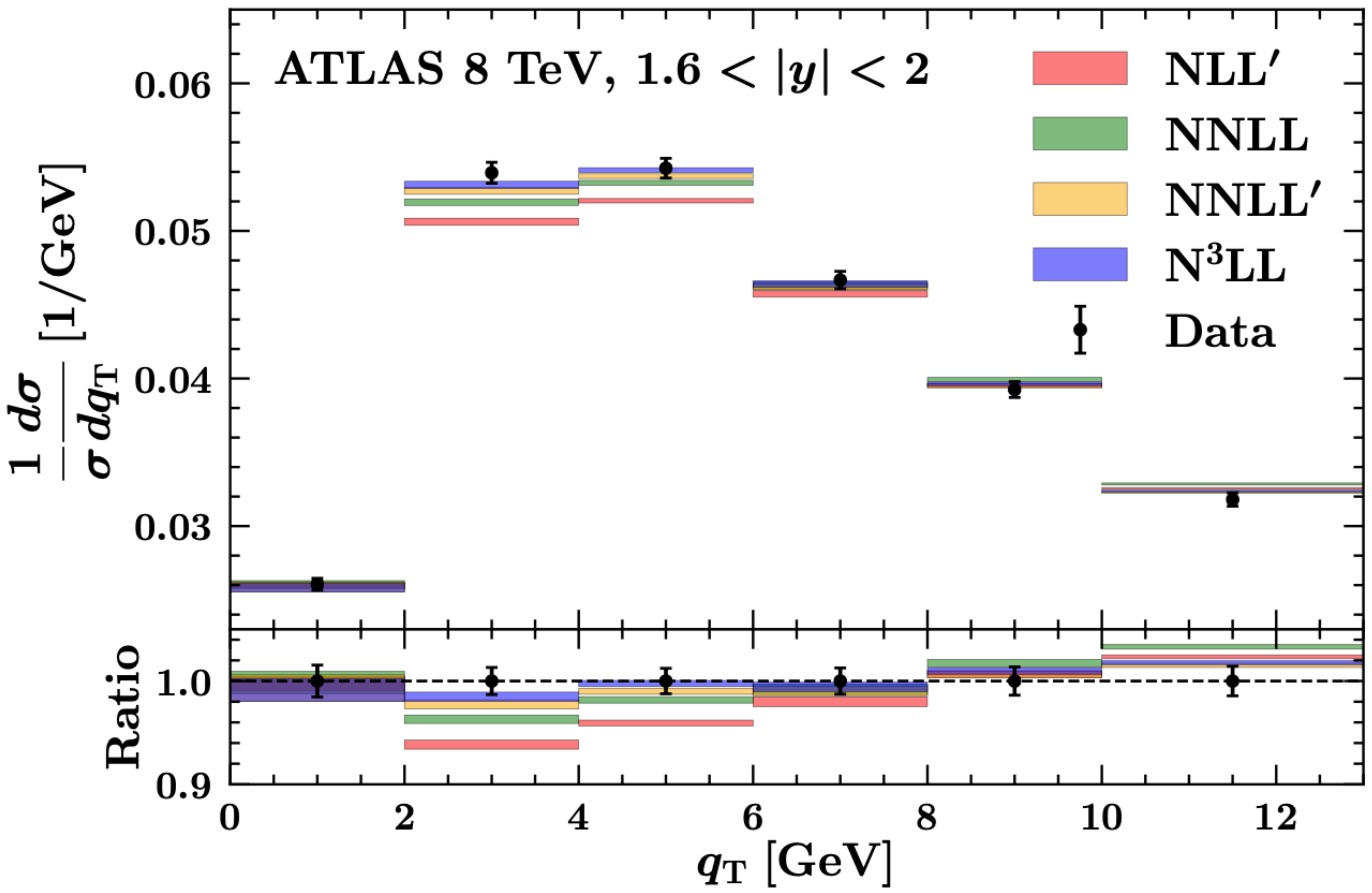
11 parameters for TMD PDF
+ 1 for NP evolution + 9 for TMD FF
= 21 free parameters

MAPTMD22: Normalization of SIDIS

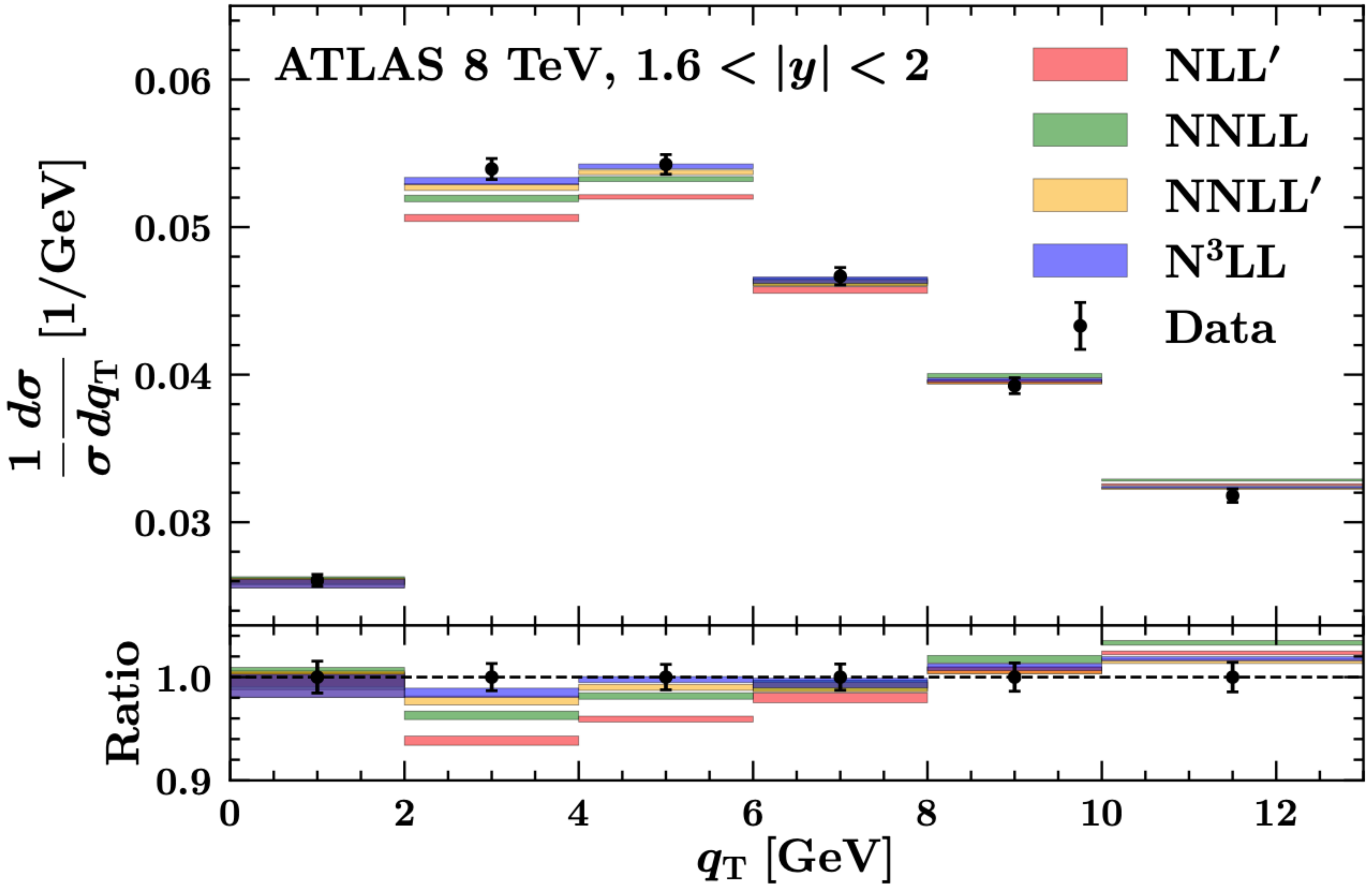
MAPTMD22: Normalization of SIDIS

High Energy Drell-Yan



MAPTMD22: Normalization of SIDIS

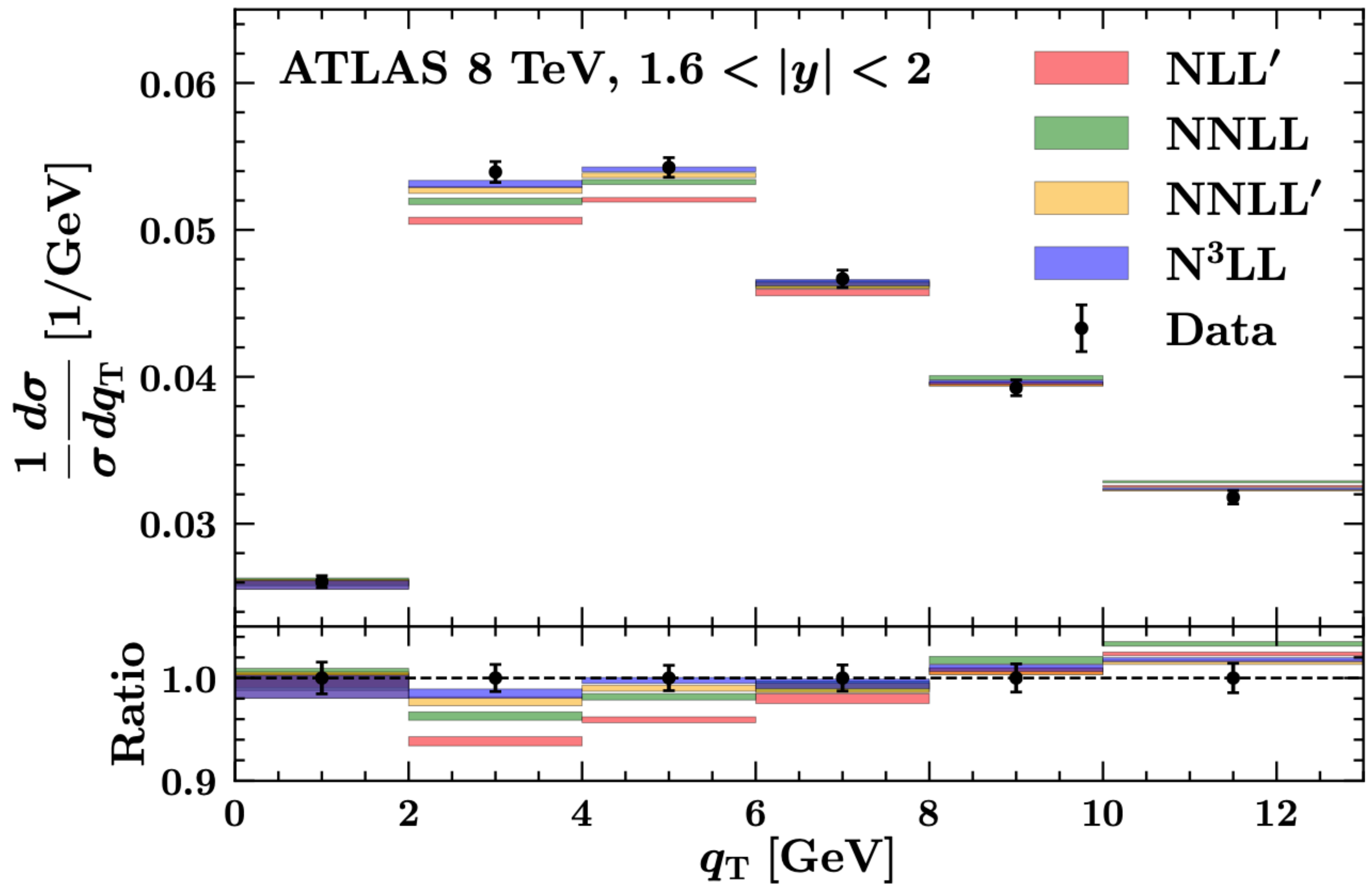
High Energy Drell-Yan



The description improves at high orders

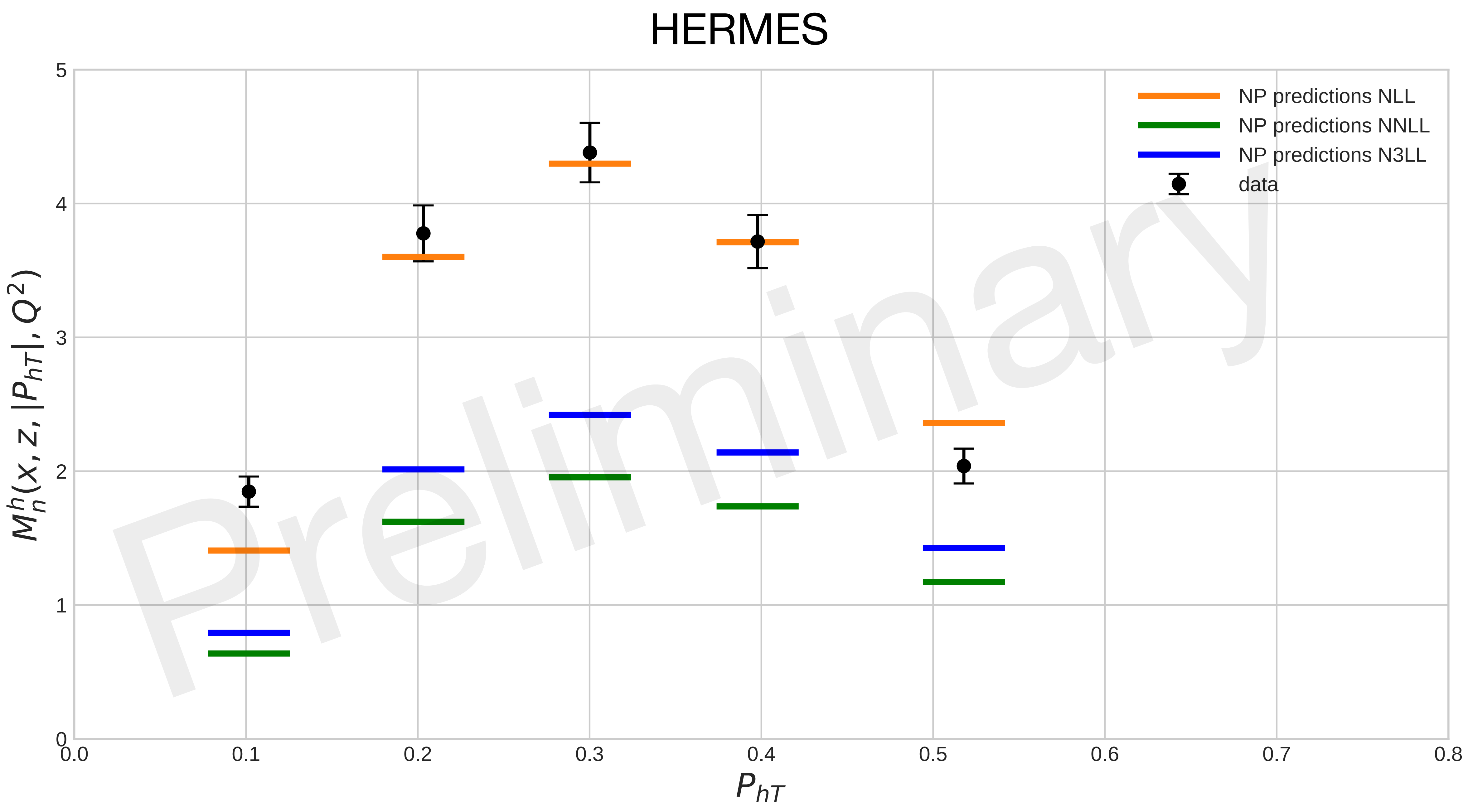
MAPTMD22: Normalization of SIDIS

<u>High Energy Drell-Yan</u>



The description improves at high orders

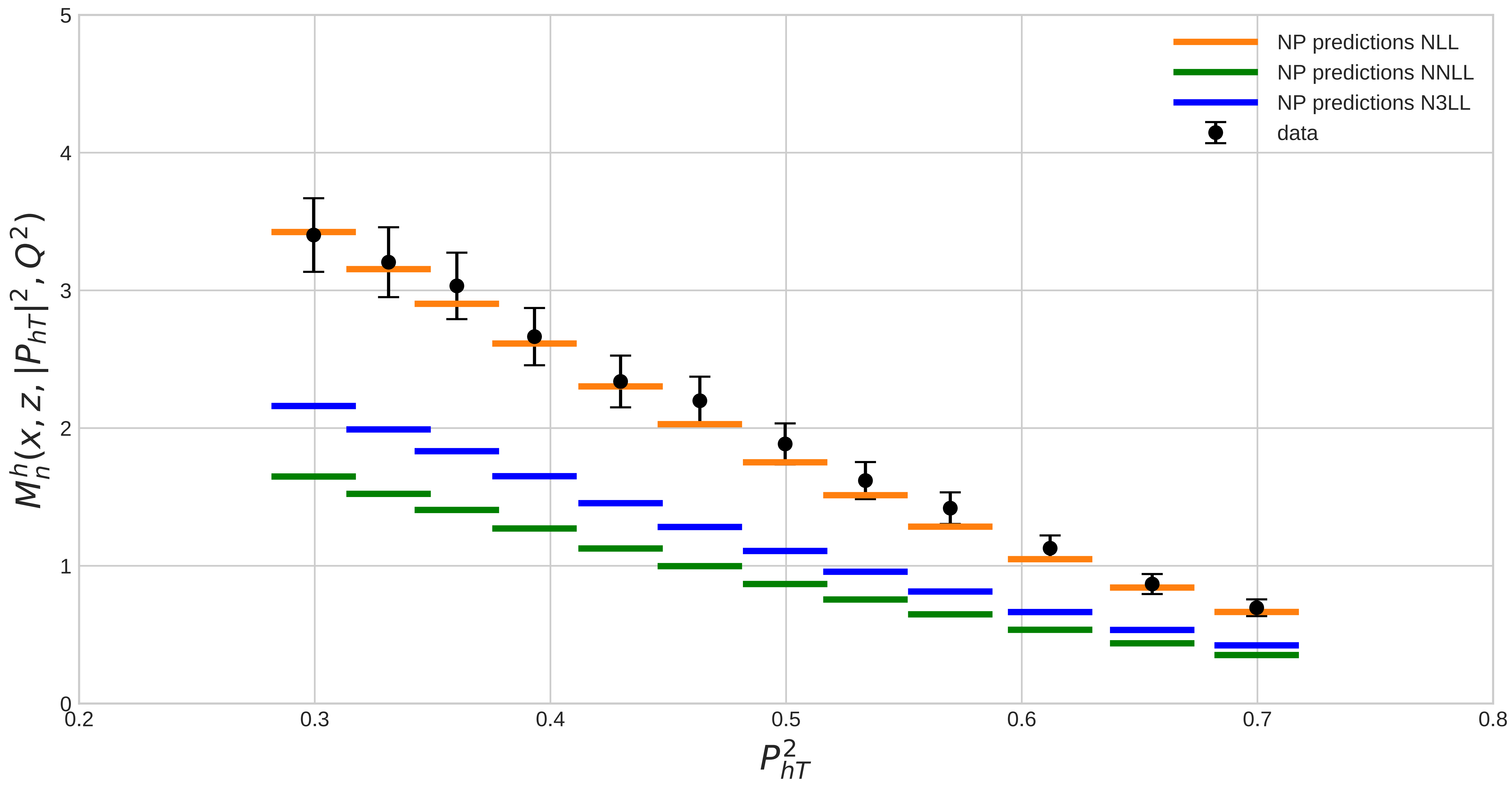
<u>SIDIS</u>



Strange behaviors at higher orders

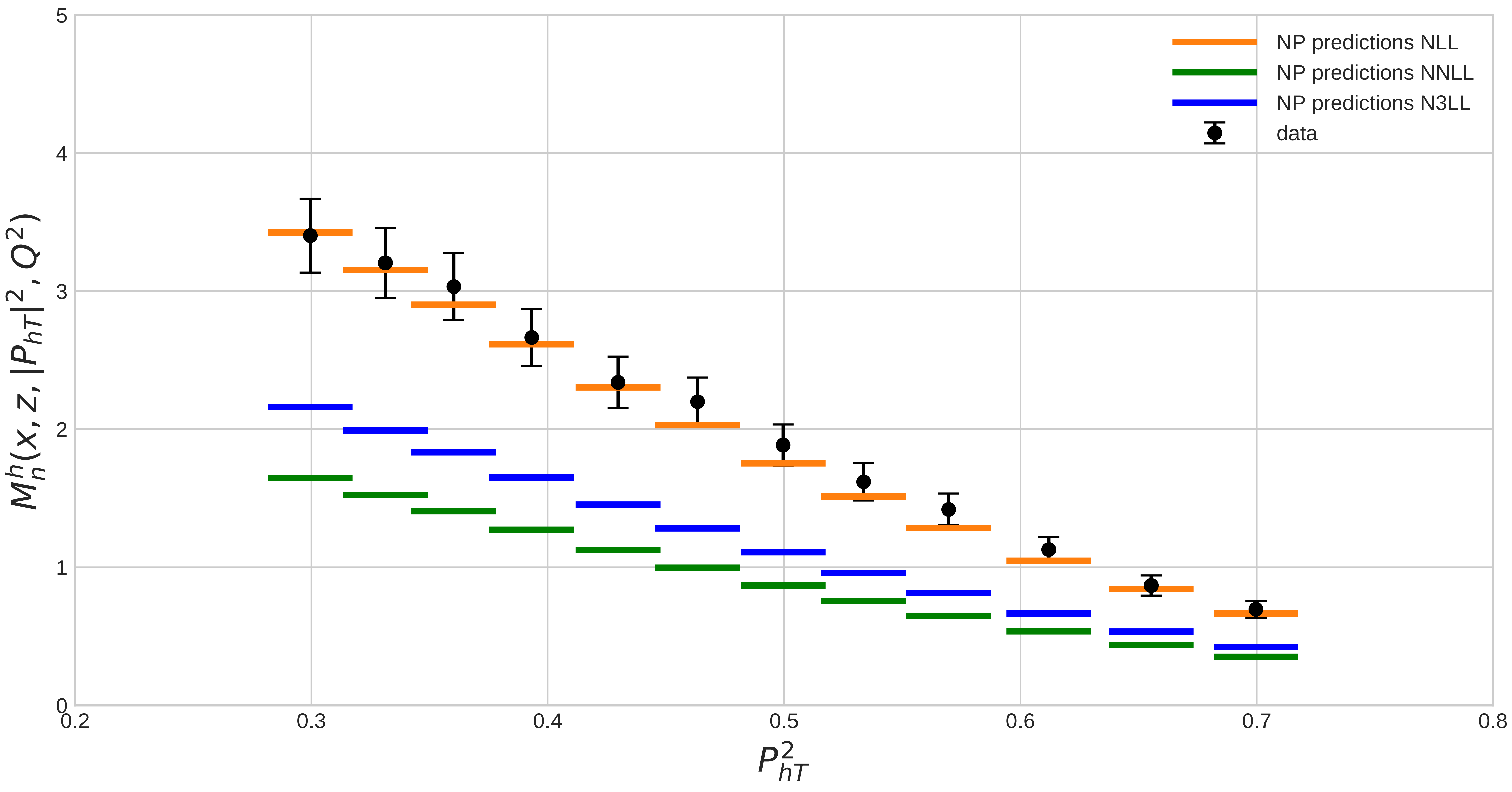
MAPTMD22: Normalization of SIDIS

COMPASS multiplicities (one of many bins)



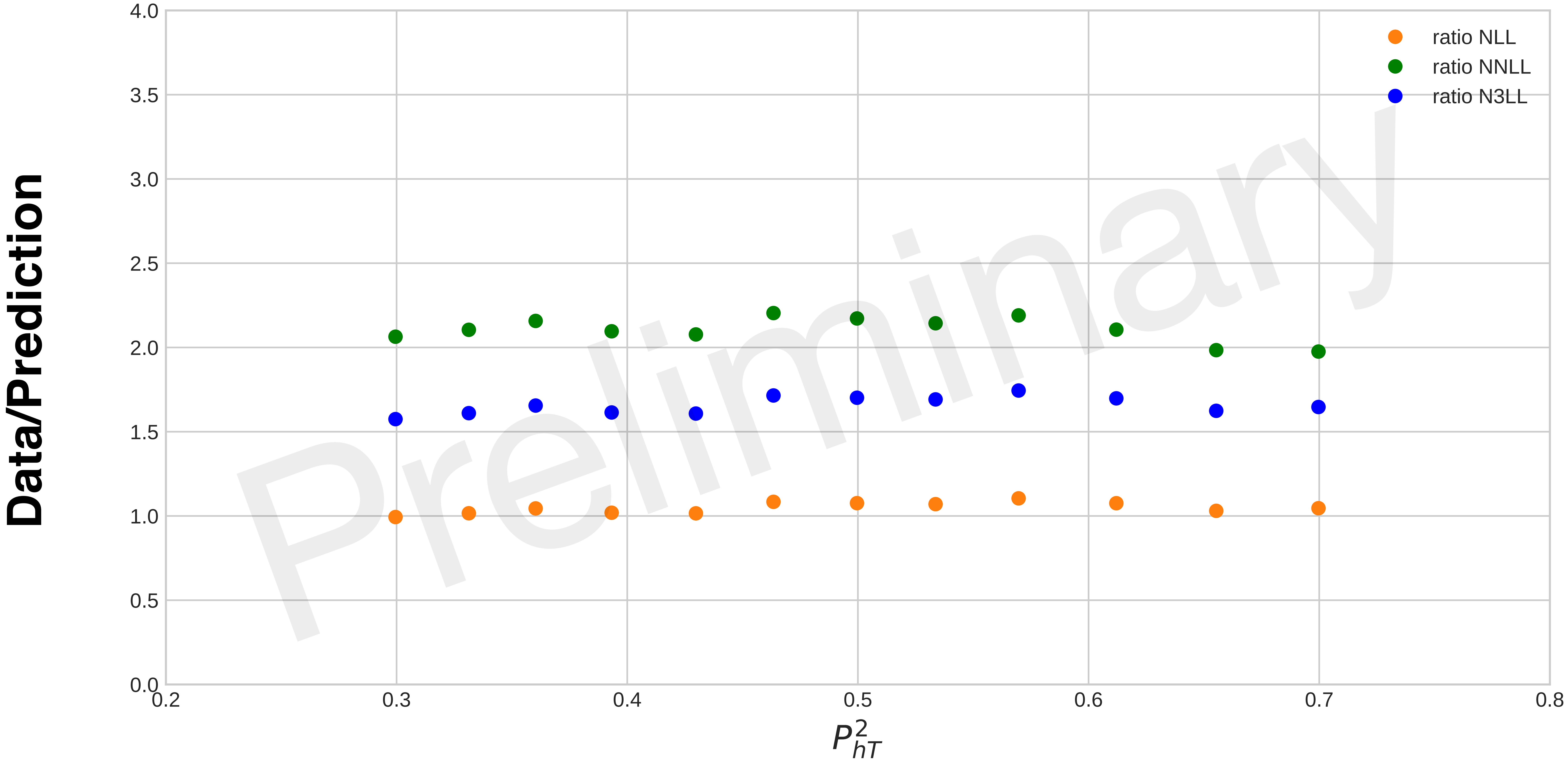
MAPTMD22: Normalization of SIDIS

COMPASS multiplicities (one of many bins)



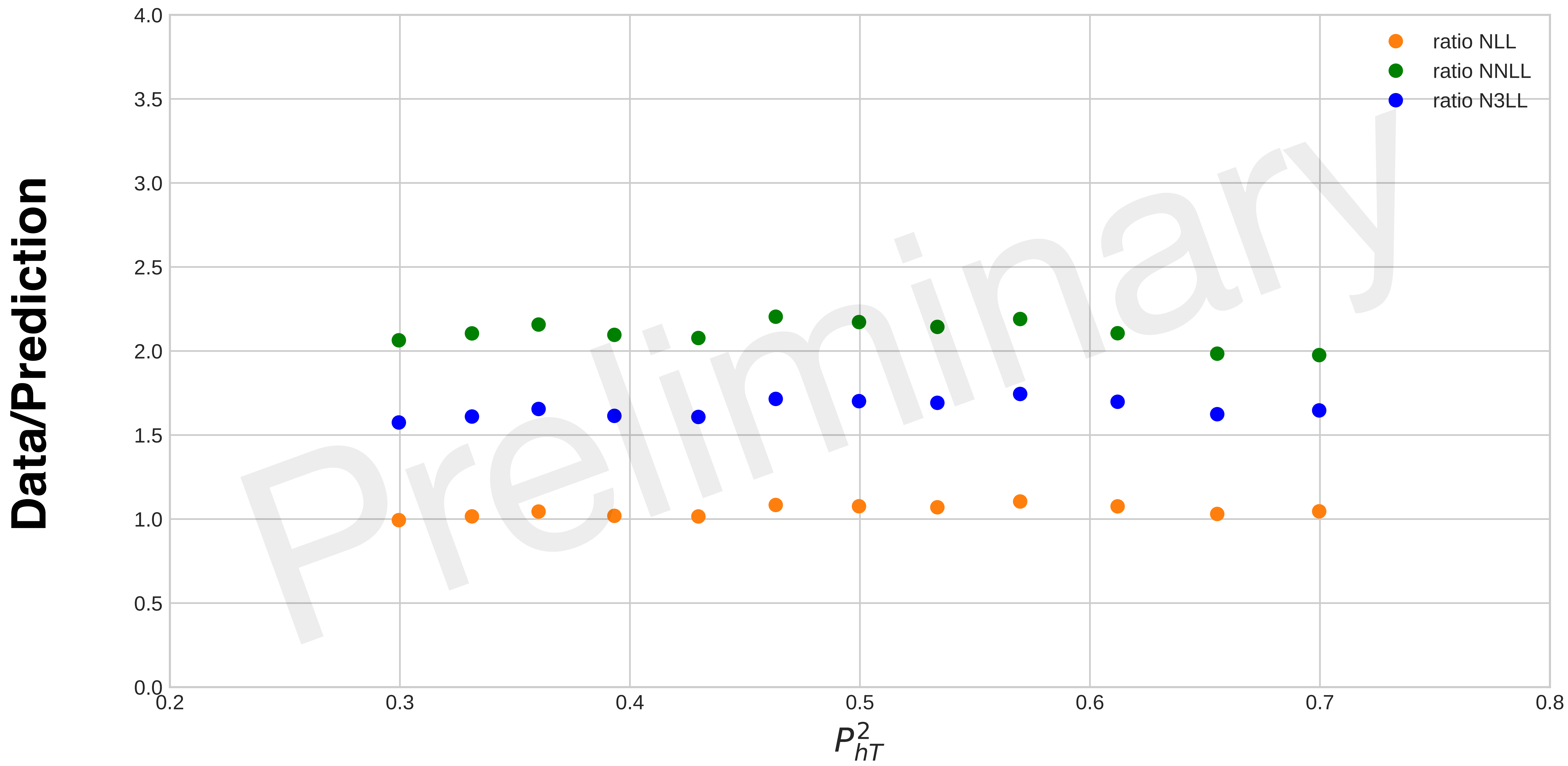
MAPTMD22: Normalization of SIDIS

COMPASS multiplicities (one of many bins)



MAPTMD22: Normalization of SIDIS

COMPASS multiplicities (one of many bins)



For different orders the discrepancy amounts to a nearly <u>constant</u> factor

MAPTMD22: Normalization of SIDIS

MAPTMD22: Normalization of SIDIS

SIDIS multiplicity

$$M(x, z, P_{hT}, Q) = \frac{d\sigma}{dx dQ dz dP_{hT}} \Bigg/ \frac{d\sigma}{dx dQ}$$

MAPTMD22: Normalization of SIDIS

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Collinear SIDIS cross section

$$\frac{d\sigma}{dxdQdz}$$

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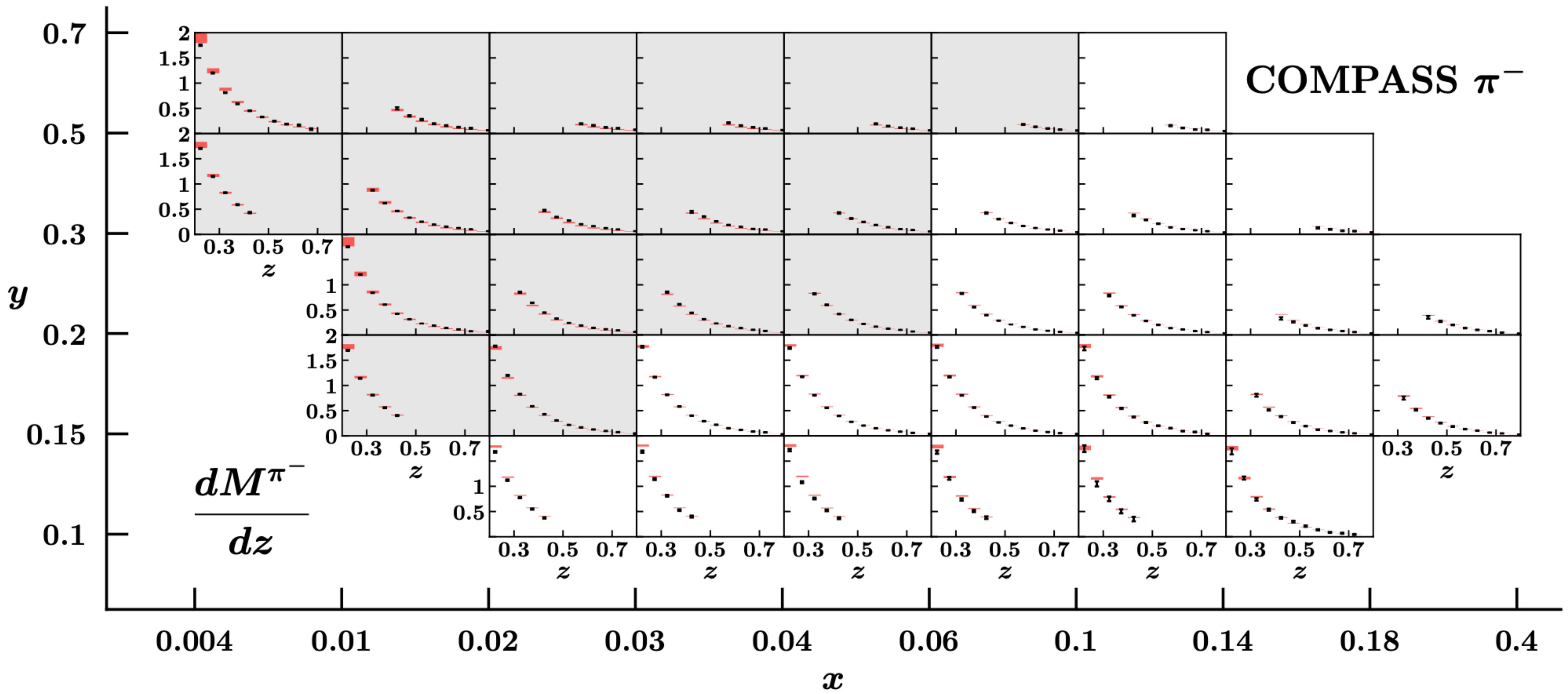
Collinear SIDIS cross section $$\frac{d\sigma}{dxdQdz}$$

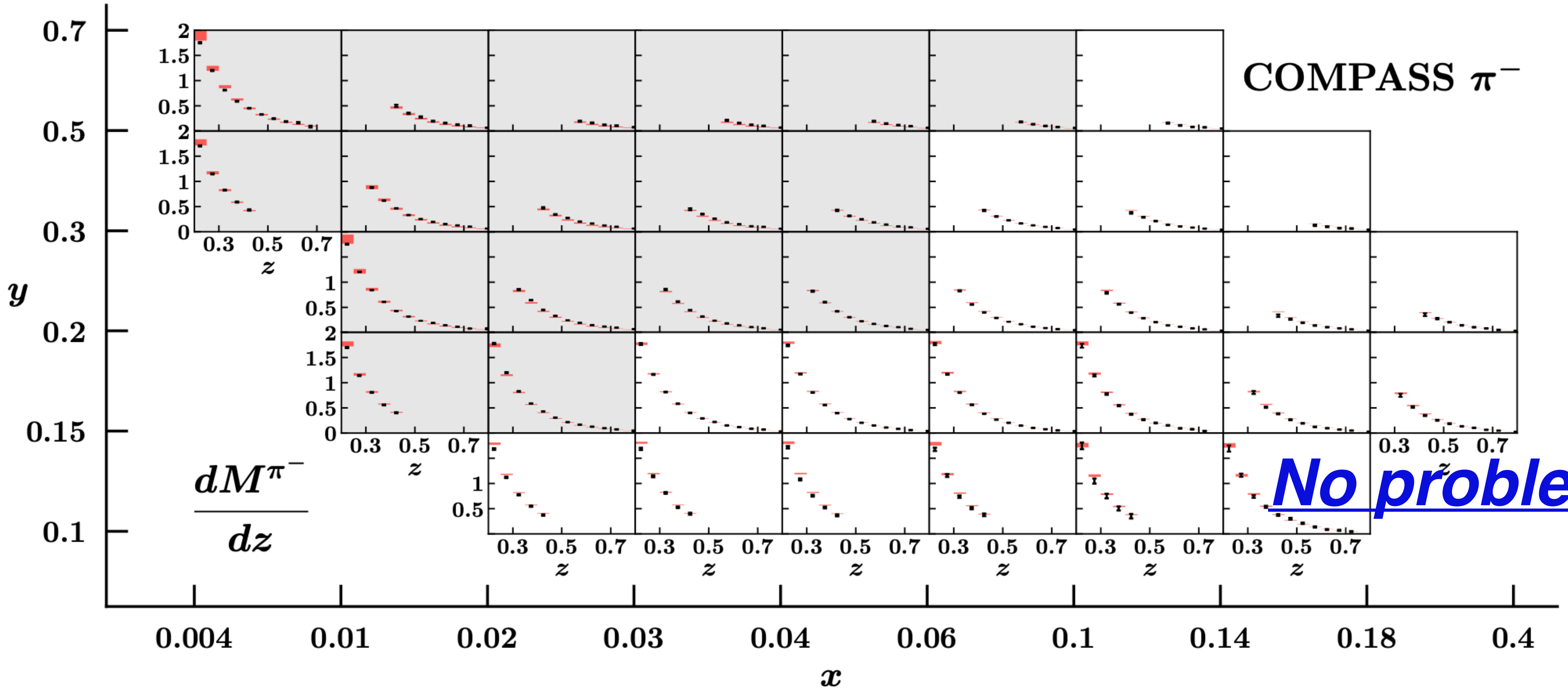


Khalek, Bertone, Nocera, arXiv: 2105.08725

MAPTMD22: Normalization of SIDIS

SIDIS multiplicity $M(x, z, P_{hT}, Q) = \frac{d\sigma}{dx dQ dz dP_{hT}} \Big/ \frac{d\sigma}{dx dQ}$

Collinear SIDIS cross section $\frac{d\sigma}{dx dQ dz}$



No problems of normalization

Khalek, Bertone, Nocera, arXiv: 2105.08725

MAPTMD22: Normalization of SIDIS

SIDIS multiplicity

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Collinear SIDIS cross section

$$\frac{d\sigma}{dx dQ dz}$$

$$\int dP_{hT} \frac{d\sigma}{dx dQ dz dP_{hT}} = \frac{d\sigma}{dx dQ dz}$$

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Collinear SIDIS cross section $$\frac{d\sigma}{dx dQ dz}$$

$$\int dP_{hT} \frac{d\sigma}{dx dQ dz dP_{hT}} = \frac{d\sigma}{dx dQ dz}$$

$$w(x, z, Q) = \frac{d\sigma}{dx dQ dz} \Big/ \int dP_{hT} \frac{d\sigma}{dx dQ dz dP_{hT}}$$

MAPTMD22: Normalization of SIDIS

SIDIS multiplicity

$$M(x,z,P_{hT},Q) = \frac{d\sigma}{dxdQdzdP_{hT}} \Bigg/ \frac{d\sigma}{dxdQ}$$

Collinear SIDIS cross section

$$\frac{d\sigma}{dxdQdz}$$

$$\int dP_{hT} \frac{d\sigma}{dxdQdzdP_{hT}} = \frac{d\sigma}{dxdQdz}$$

$$\boxed{w(x,z,Q) = \frac{d\sigma}{dxdQdz} \Bigg/ \int dP_{hT} \frac{d\sigma}{dxdQdzdP_{hT}}}$$

$$M(x,z,P_{hT},Q) = \boxed{w(x,z,Q)} \frac{d\sigma}{dxdQdzdP_{hT}} \Bigg/ \frac{d\sigma}{dxdQ}$$

MAPTMD22: Normalization of SIDIS

SIDIS multiplicity

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$$\frac{d\sigma}{dxdQdz}$$

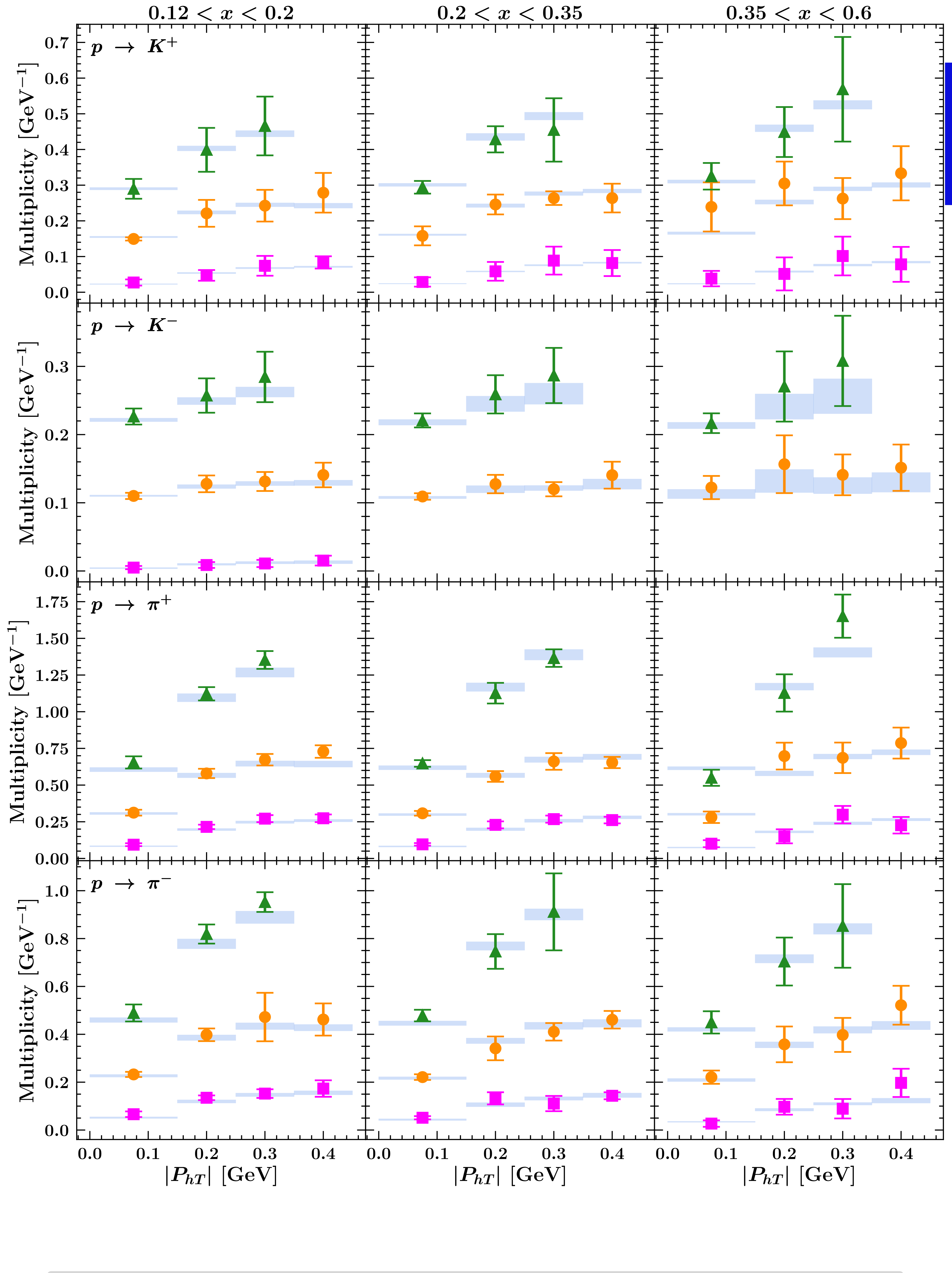
$$\int dP_{hT} \frac{d\sigma}{dxdQdzdP_{hT}} = \frac{d\sigma}{dxdQdz}$$

Fitting parameters <u>independent</u>

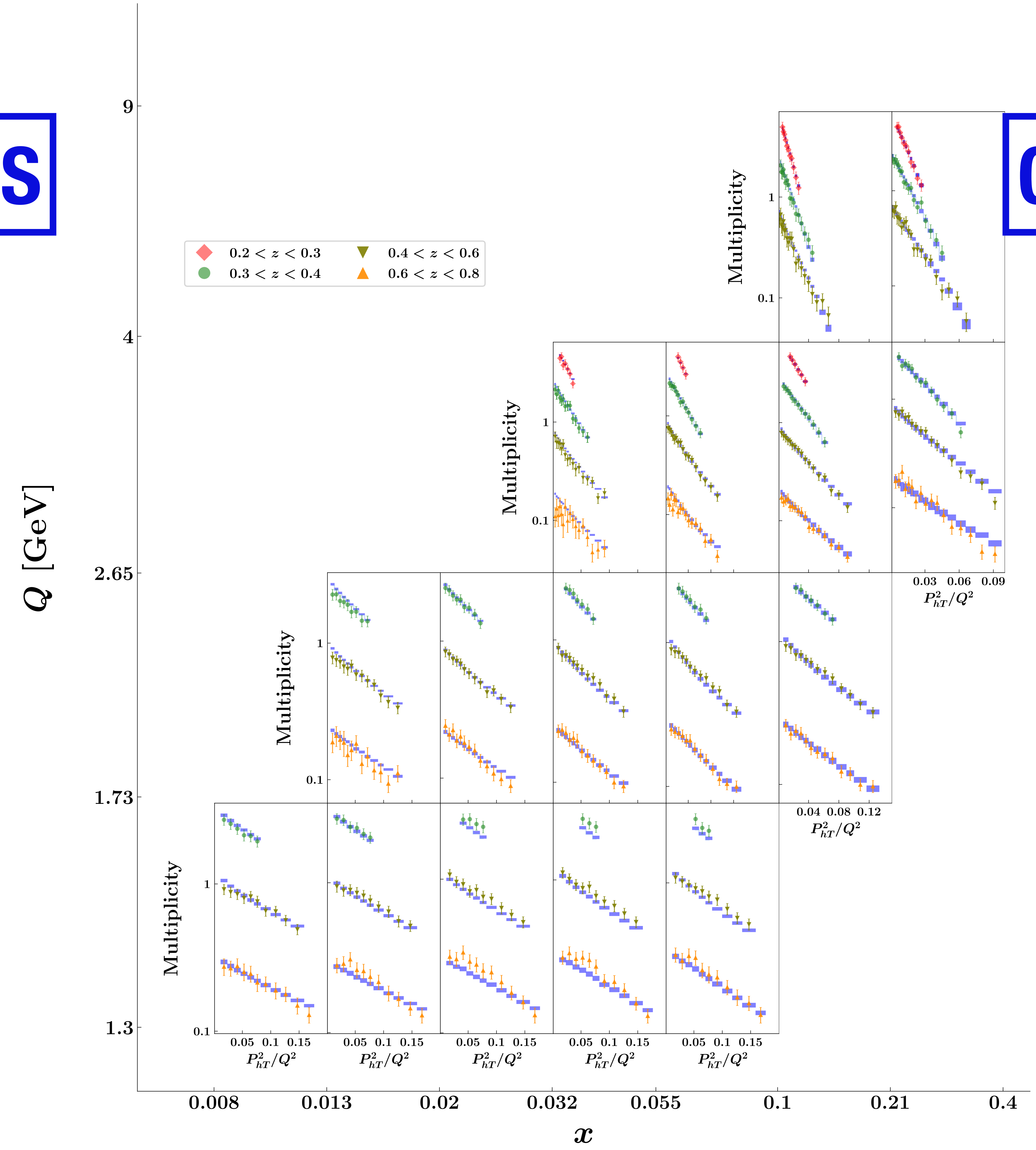
$$w(x, z, Q) = \frac{d\sigma}{dxdQdz} \Big/ \int dP_{hT} \frac{d\sigma}{dxdQdzdP_{hT}}$$

$$M(x, z, P_{hT}, Q) = w(x, z, Q) \frac{d\sigma}{dxdQdzdP_{hT}} \Big/ \frac{d\sigma}{dxdQ}$$

MAPTMD22 — Results of the fit $\chi^2/N_{data} = 1.06$

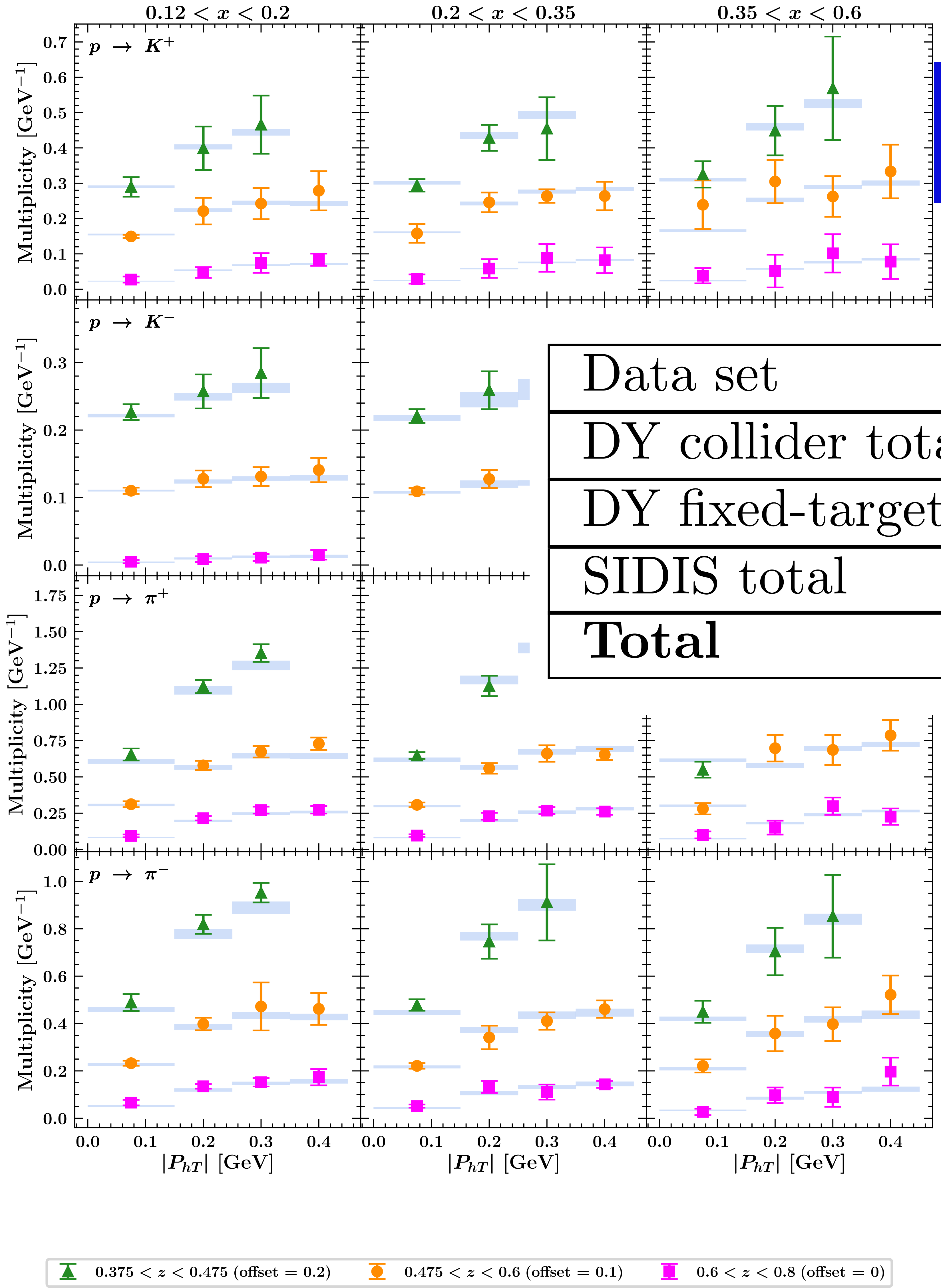


HERMES

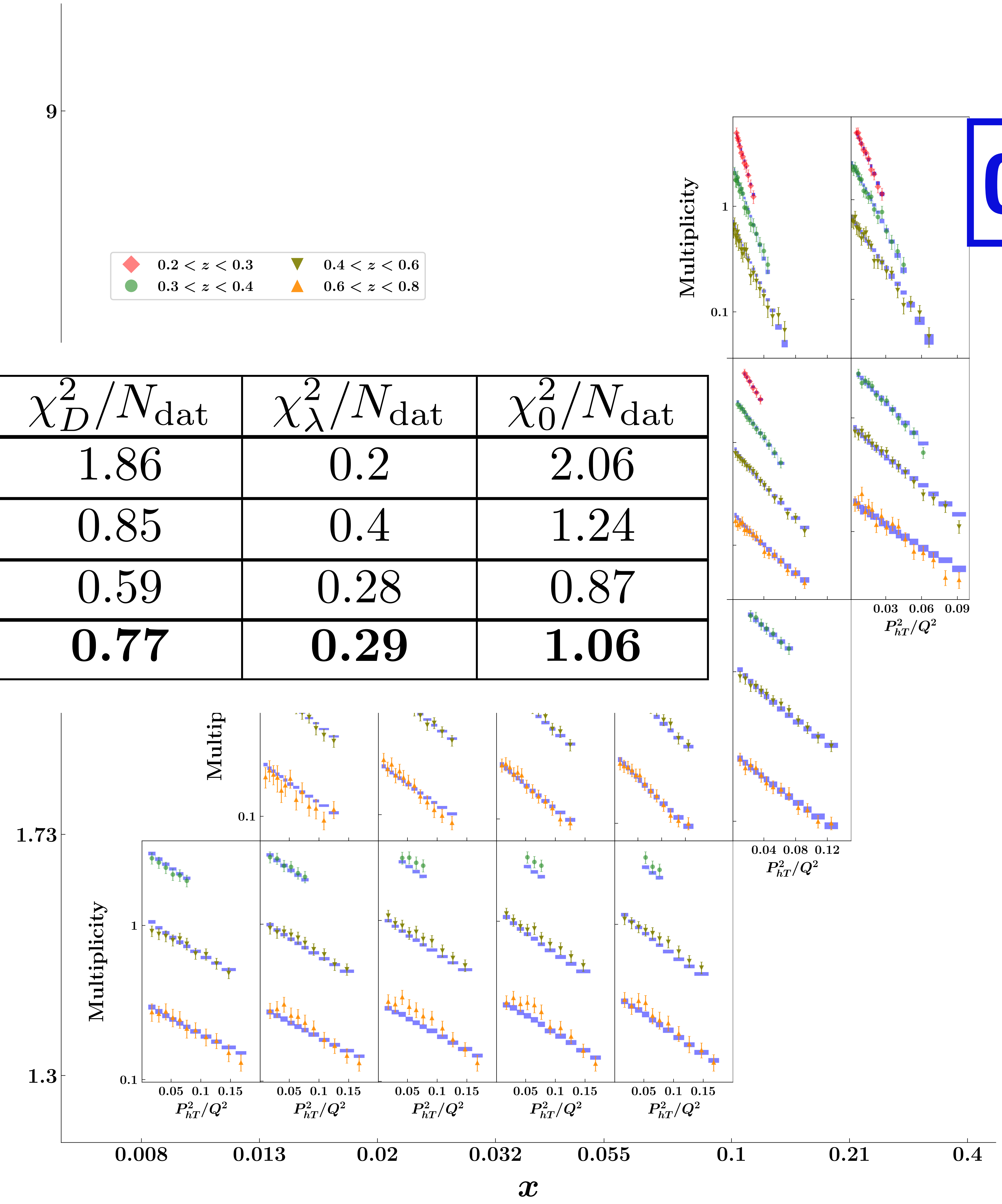


COMPASS

MAPTMD22 — Results of the fit $\chi^2/N_{data} = 1.06$



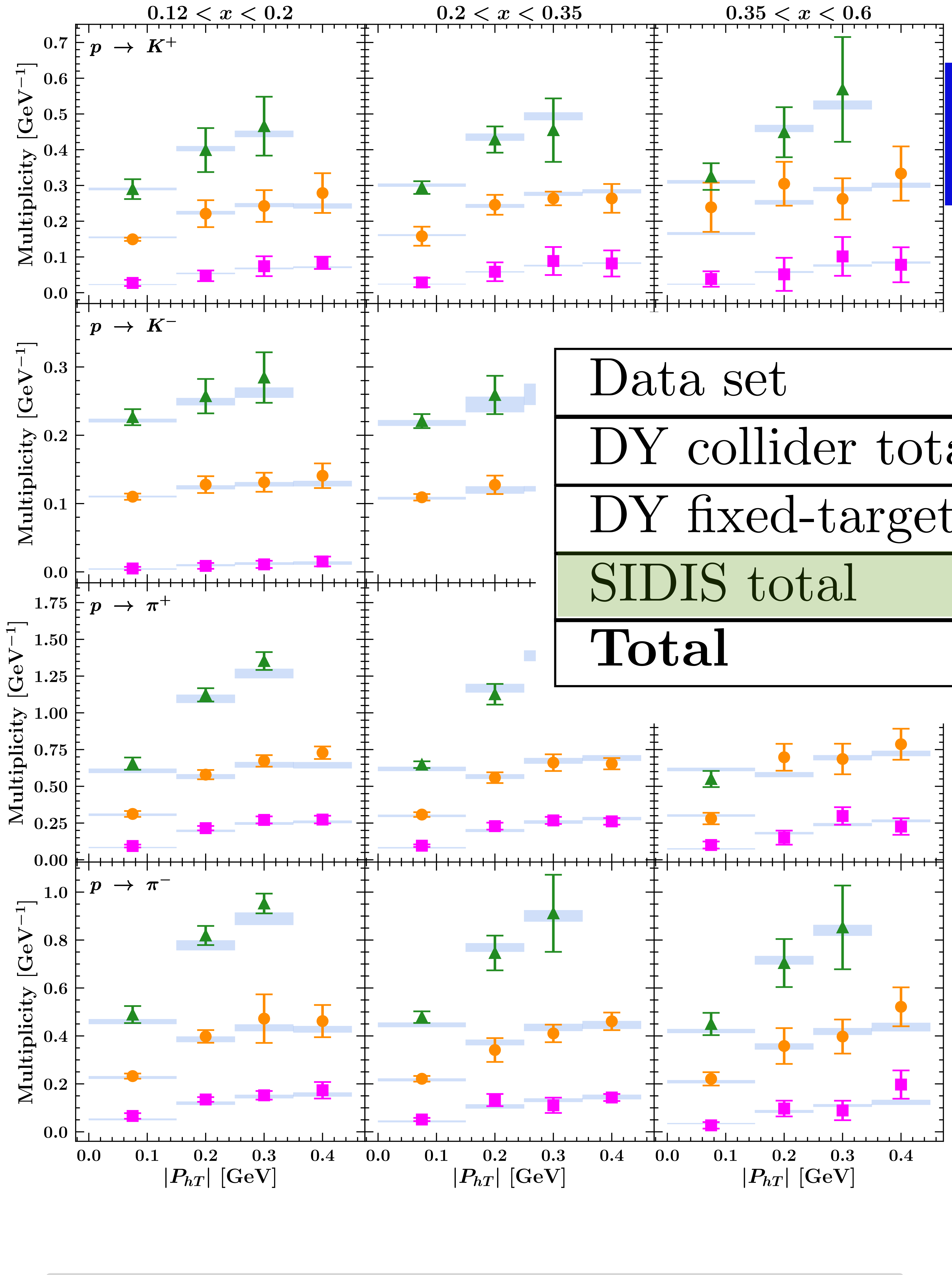
HERMES



COMPASS

Data set	$N_{\rm dat}$	$\chi_D^2/N_{\rm dat}$	$\chi_\lambda^2/N_{\rm dat}$	$\chi_0^2/N_{\rm dat}$
DY collider total	251	1.86	0.2	2.06
DY fixed-target total	233	0.85	0.4	1.24
SIDIS total	1547	0.59	0.28	0.87
Total	**2031**	**0.77**	**0.29**	**1.06**

MAPTMD22 — Results of the fit $\chi^2/N_{data} = 1.06$



Data set	$N_{\rm dat}$	$\chi^2_D/N_{\rm dat}$	$\chi^2_\lambda/N_{\rm dat}$	$\chi^2_0/N_{\rm dat}$
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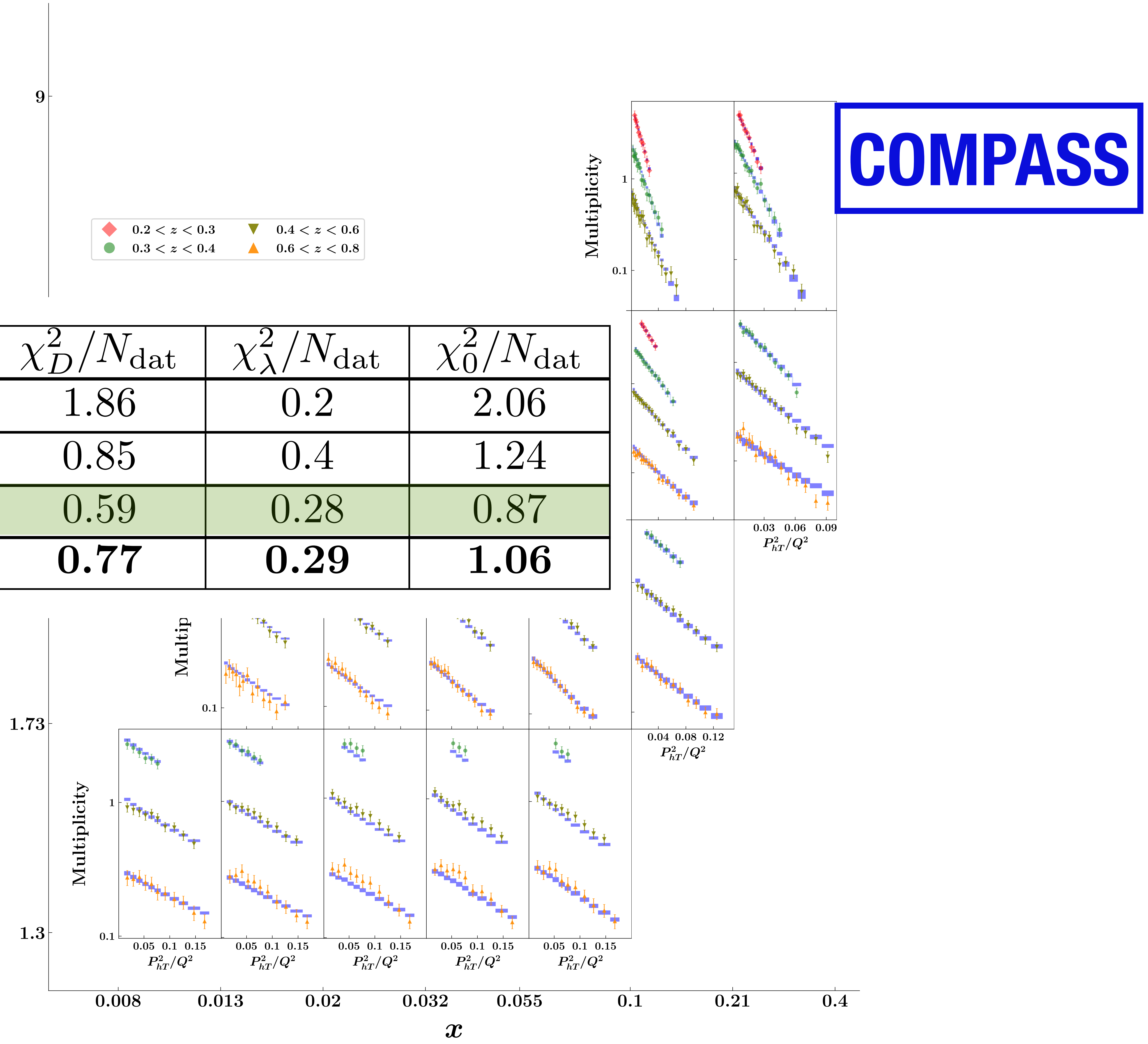
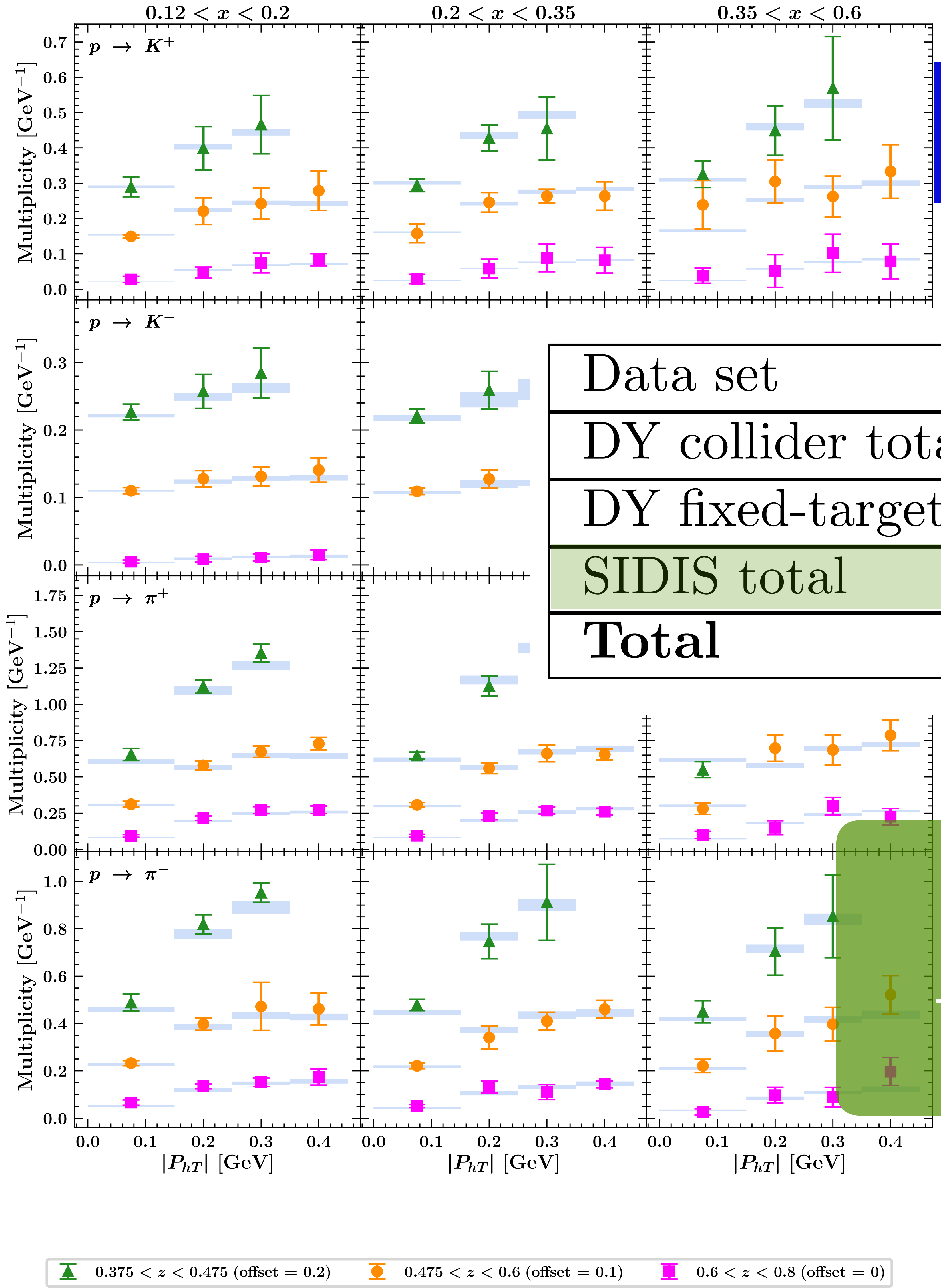
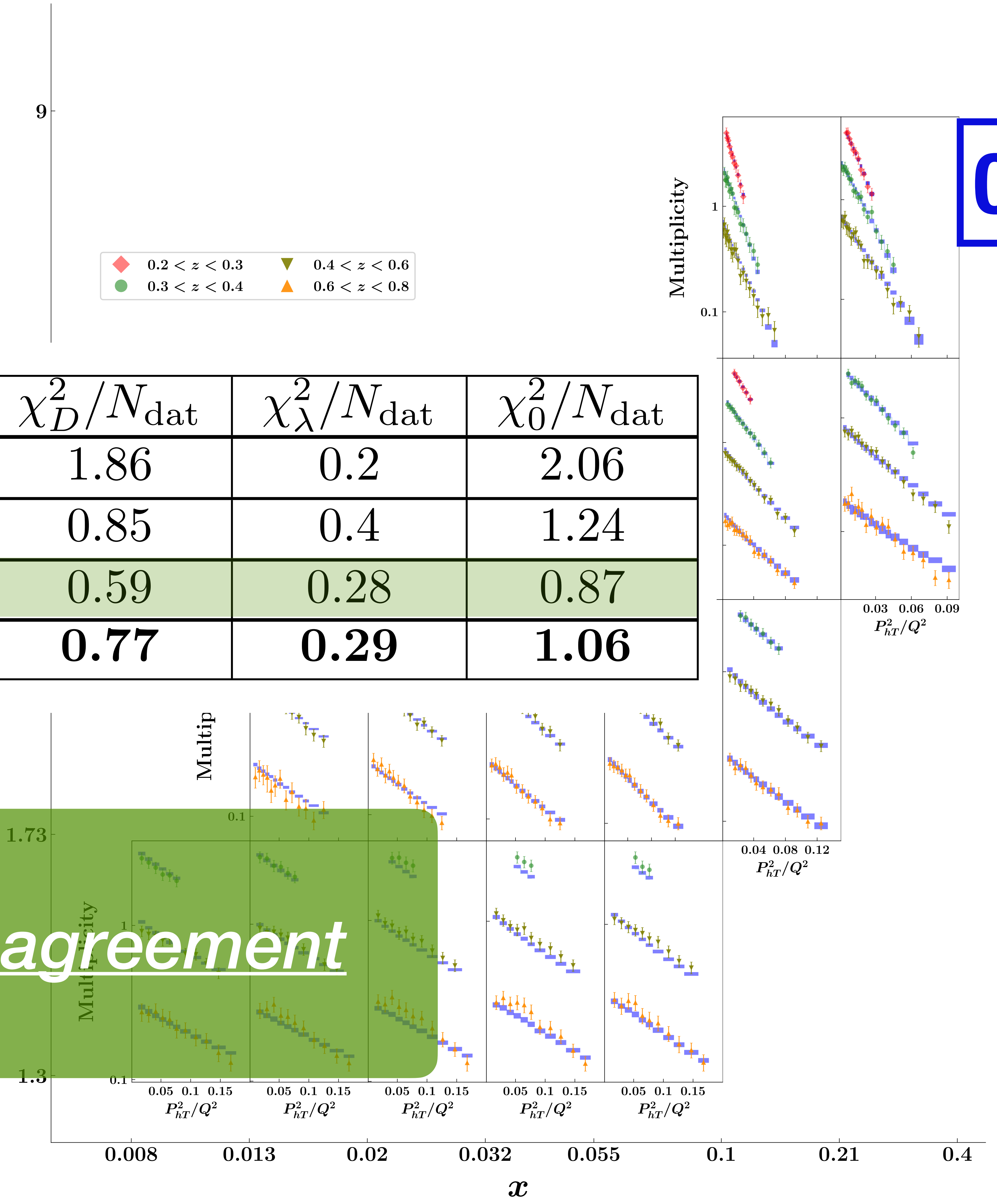


MAPTMD22 – Results of the fit $\chi^2/N_{data} = 1.06$

HERMES



COMPASS



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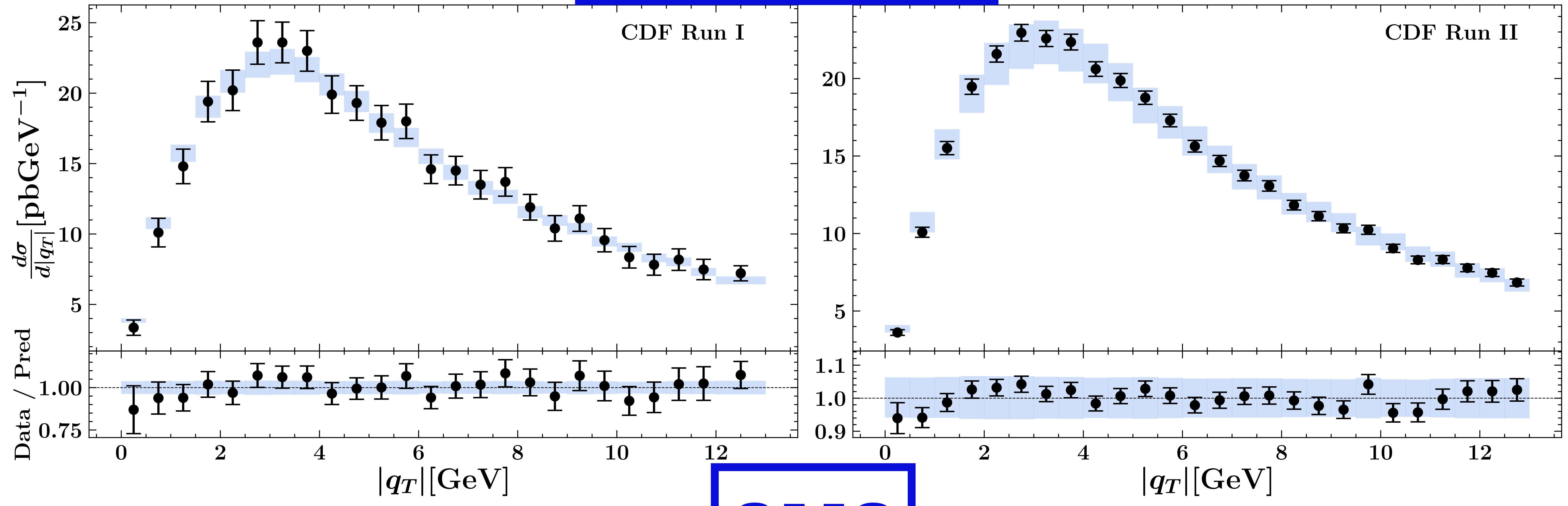
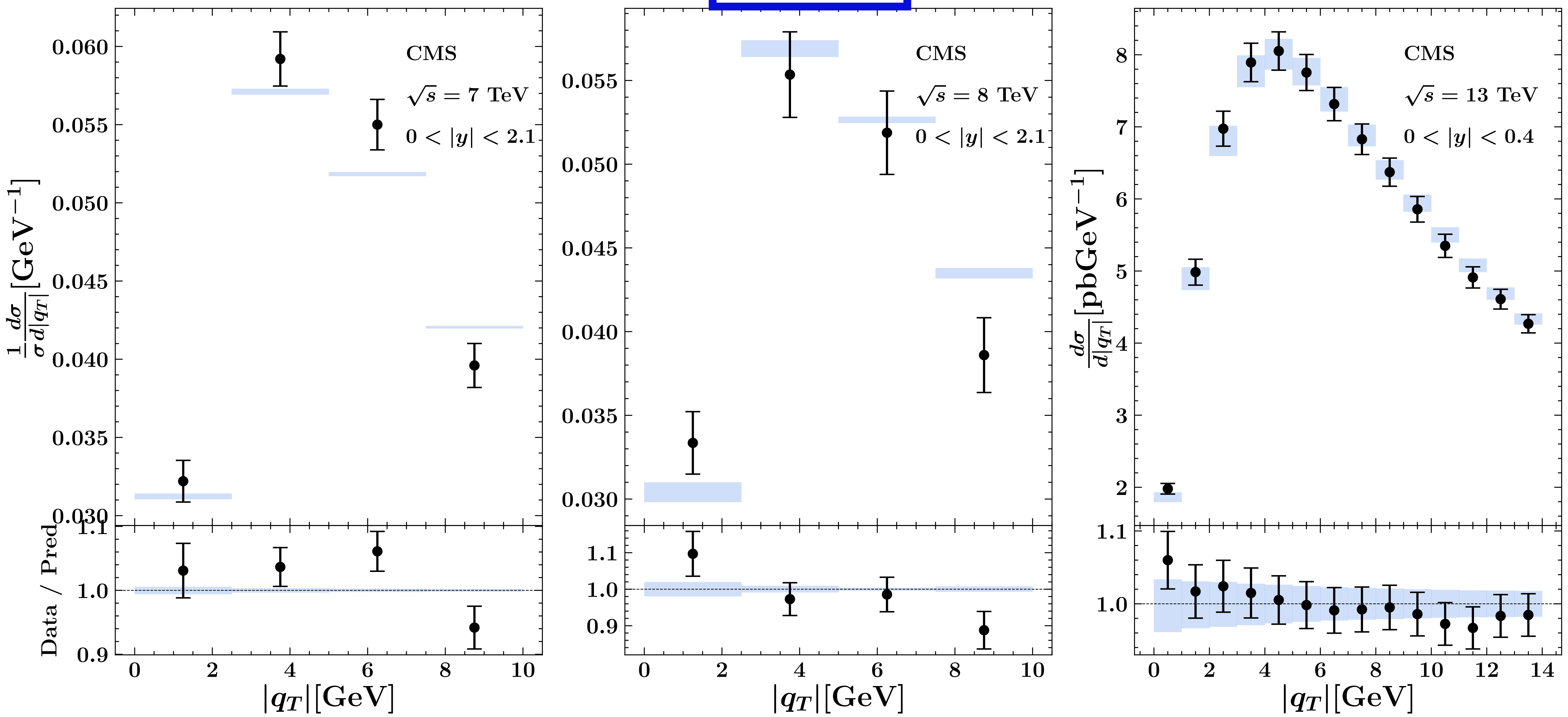
Very good agreement

MAPTMD22 — Results of the fit $\chi^2/N_{data} = 1.06$

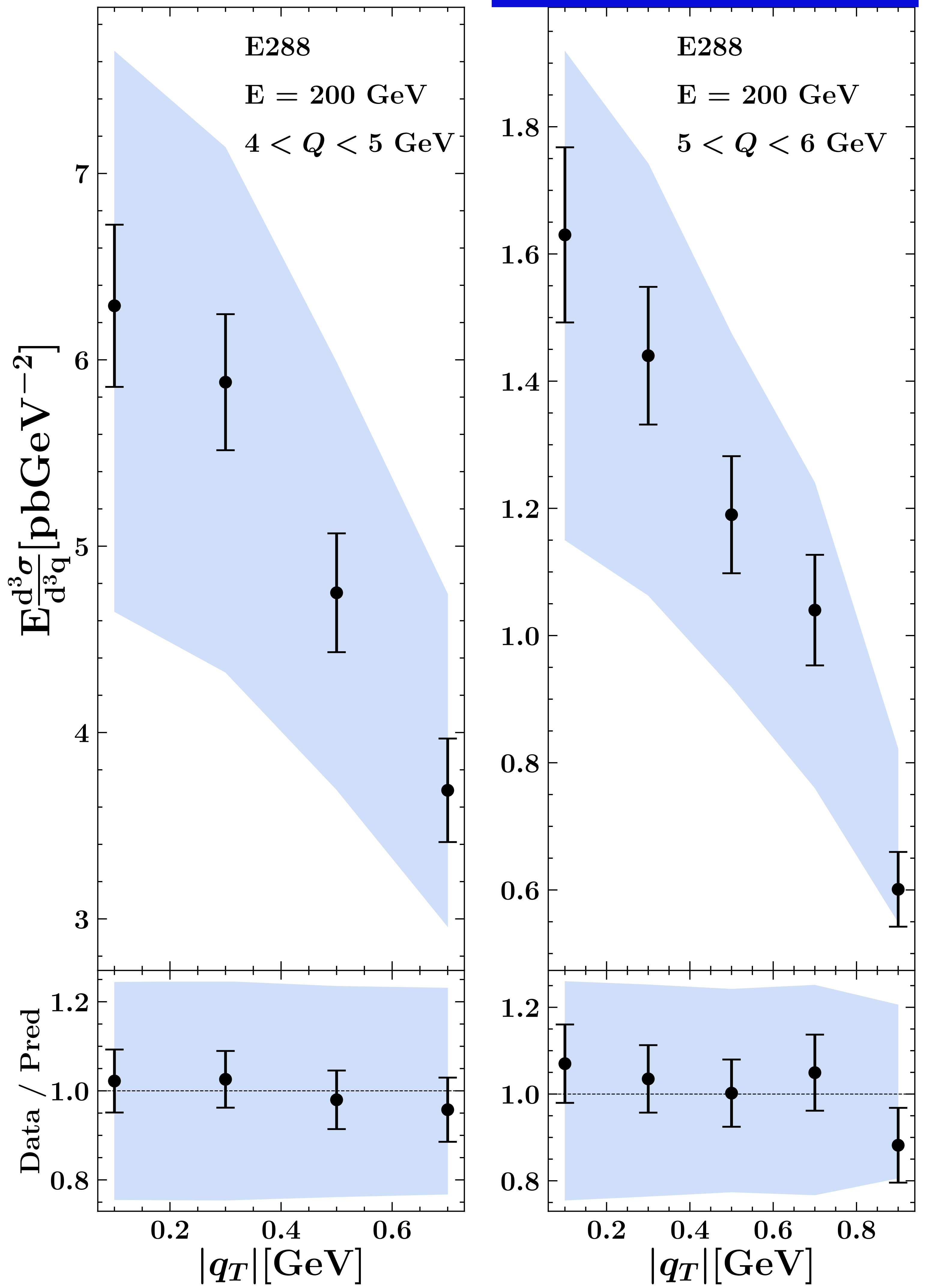
TEVATRON



CMS

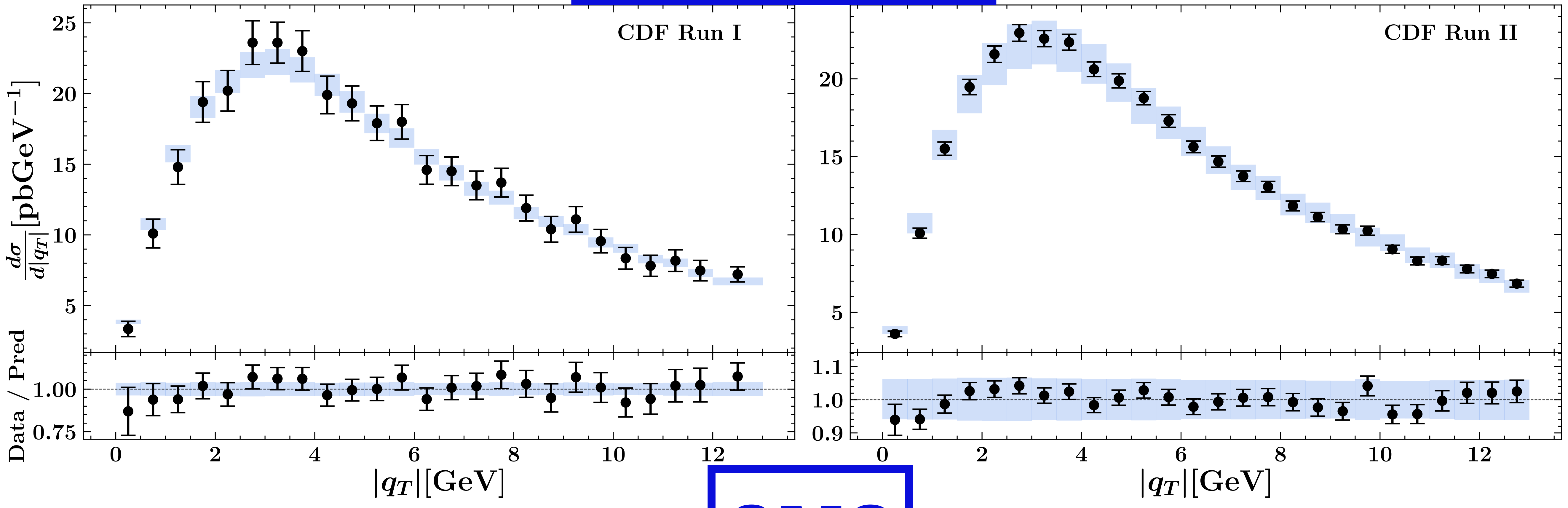


FERMILAB

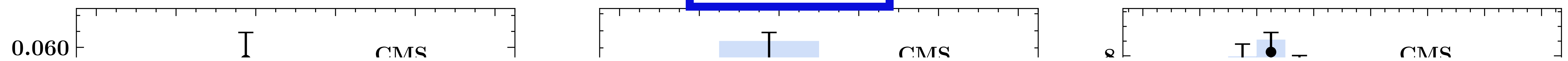


MAPTMD22 — Results of the fit $\chi^2/N_{data} = 1.06$

TEVATRON



CMS



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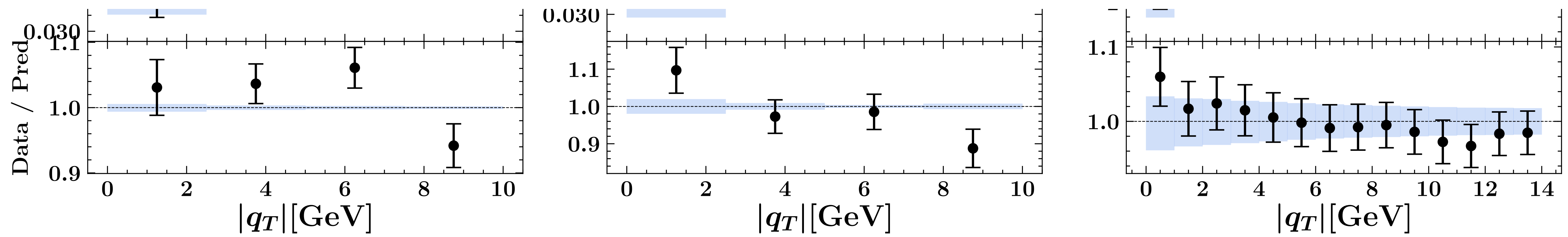

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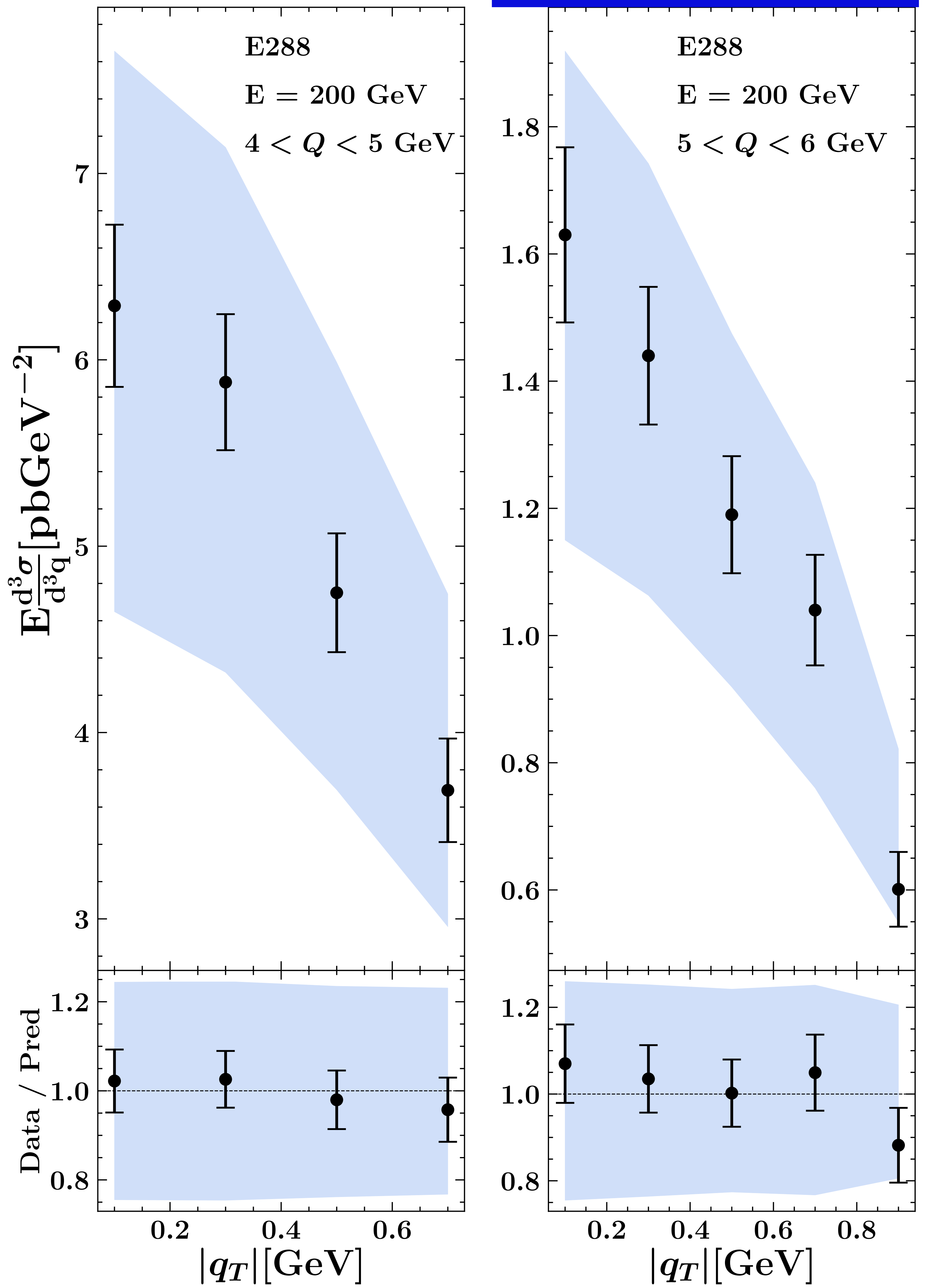
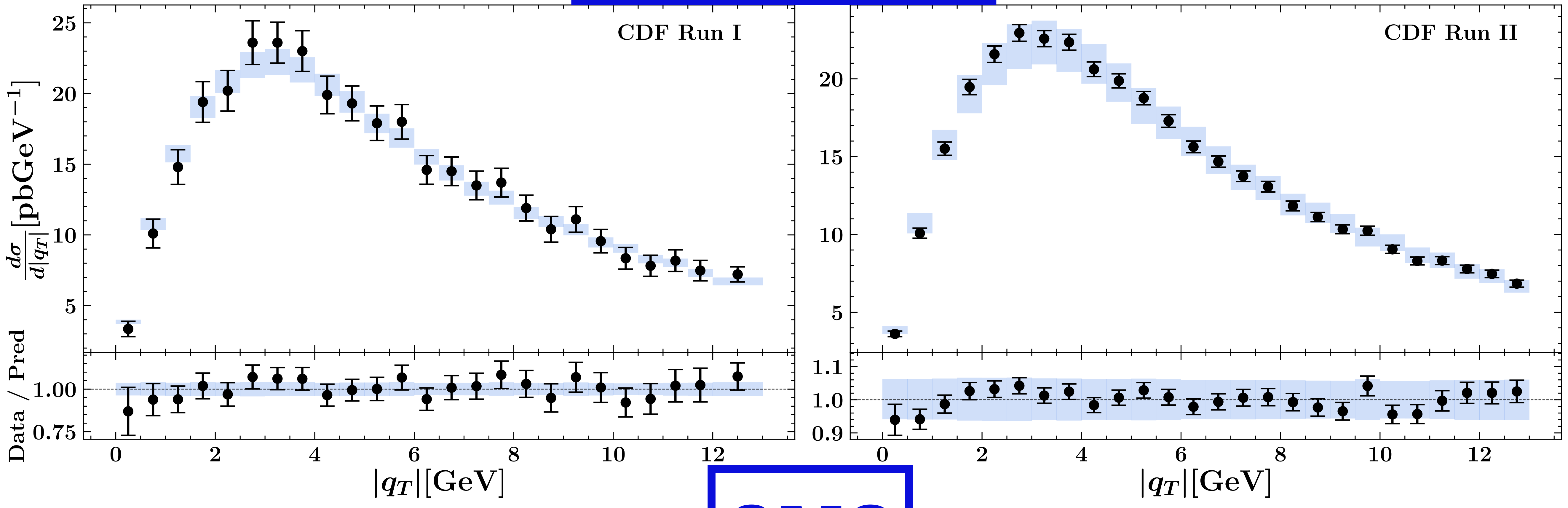
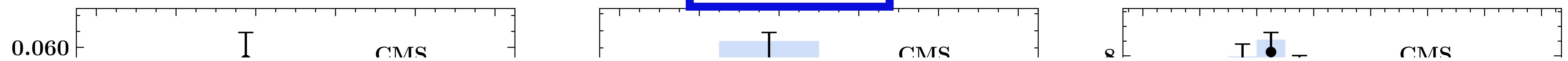


MAPTMD22 — Results of the fit $\chi^2/N_{data} = 1.06$

TEVATRON



CMS



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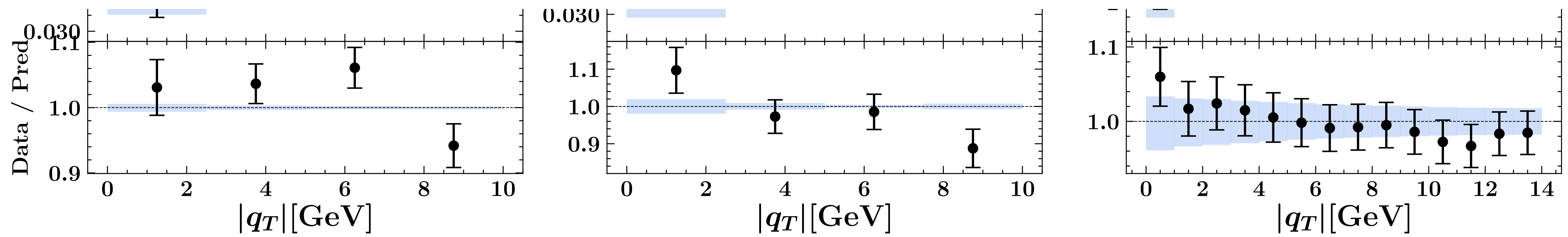

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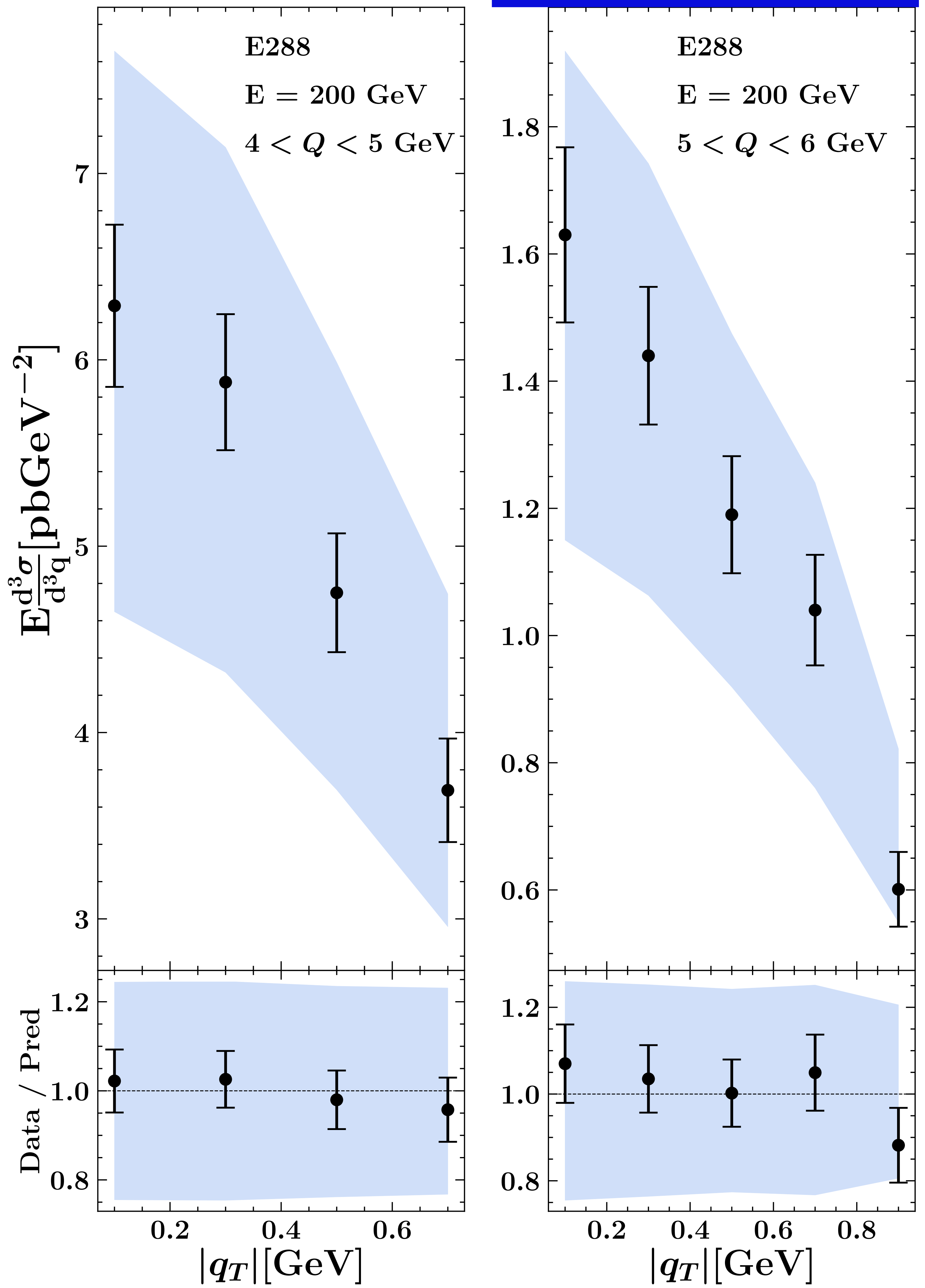

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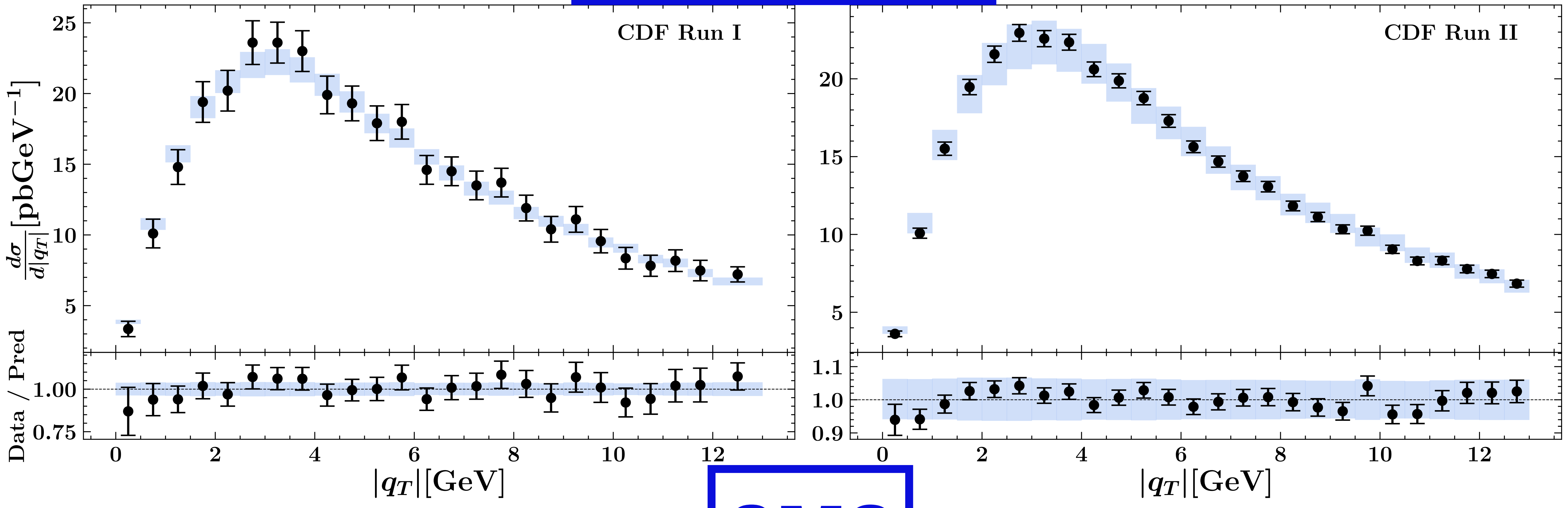
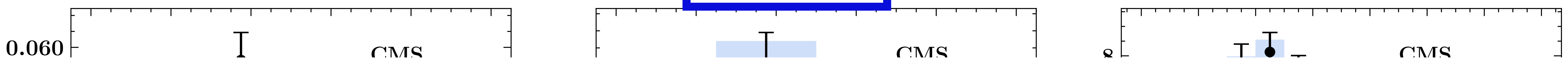
TEVATRON



CMS



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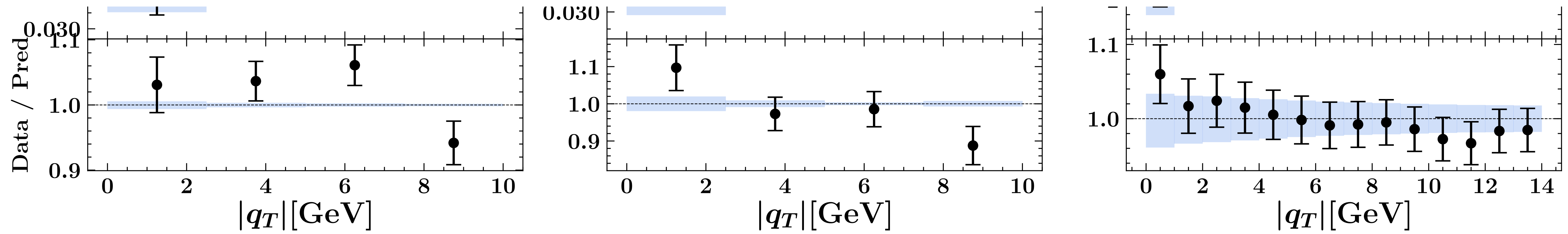

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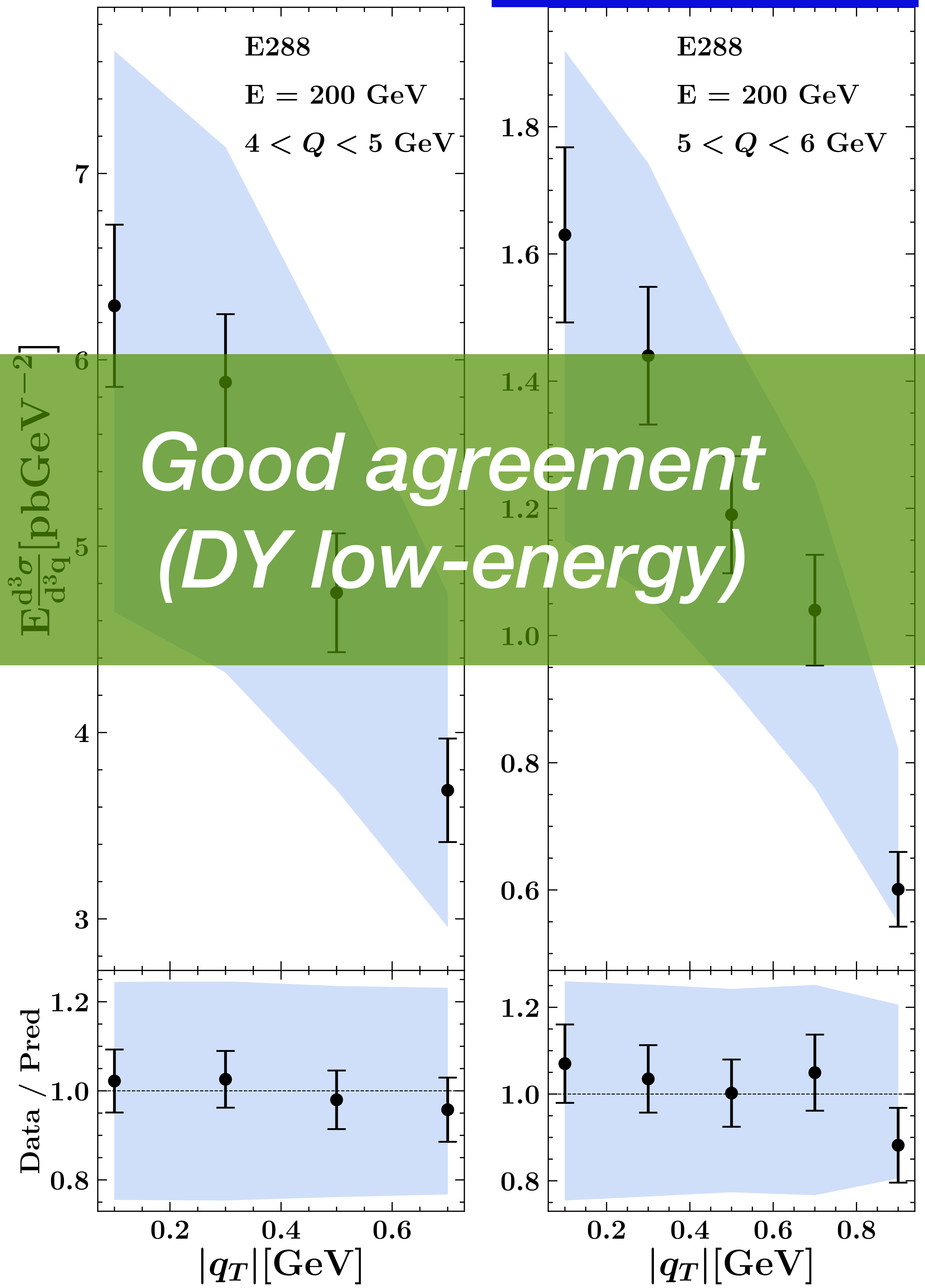

Good agreement (DY low-energy)

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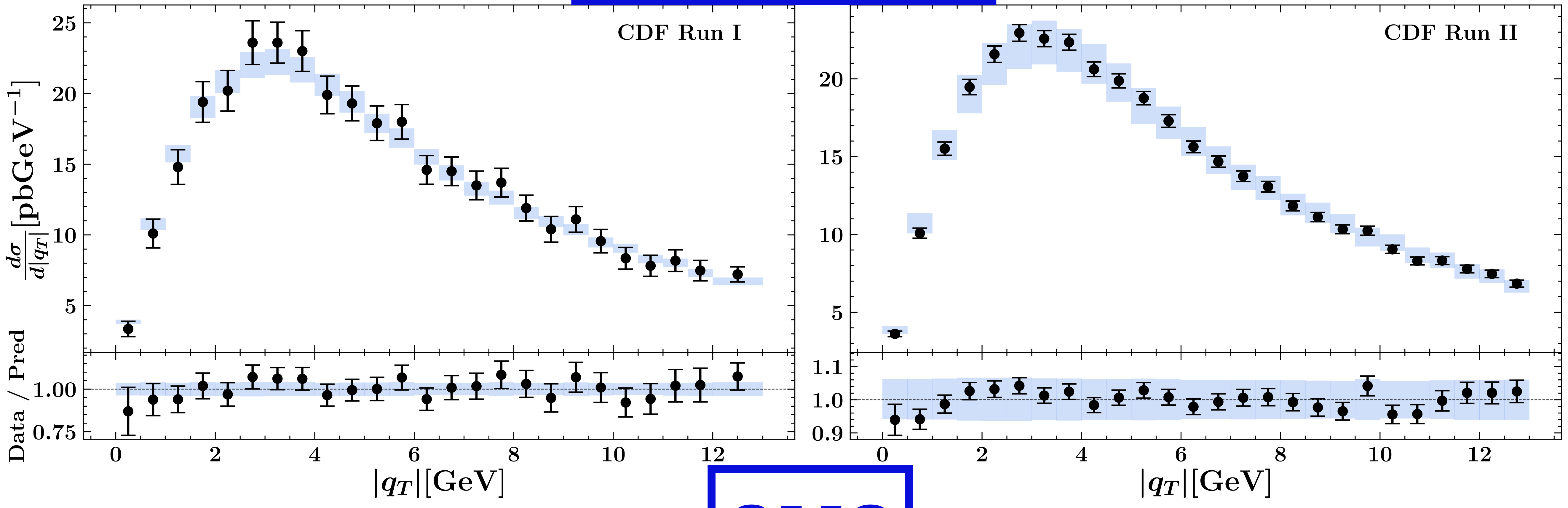
TEVATRON



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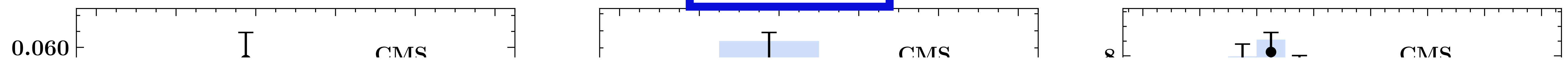

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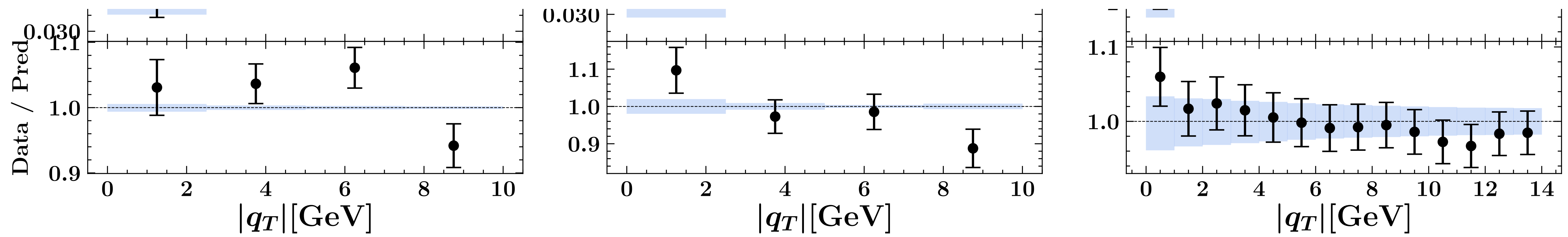

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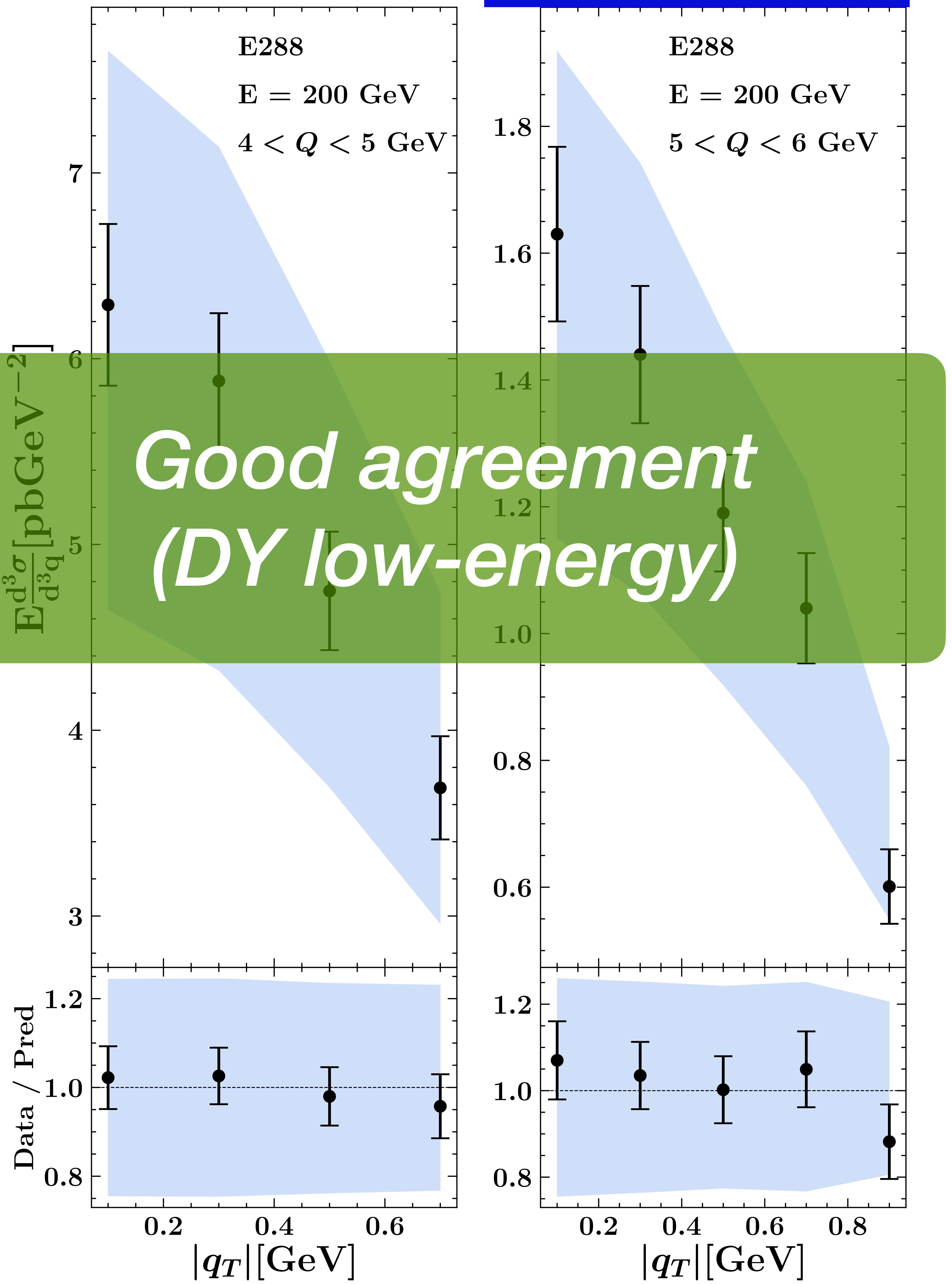

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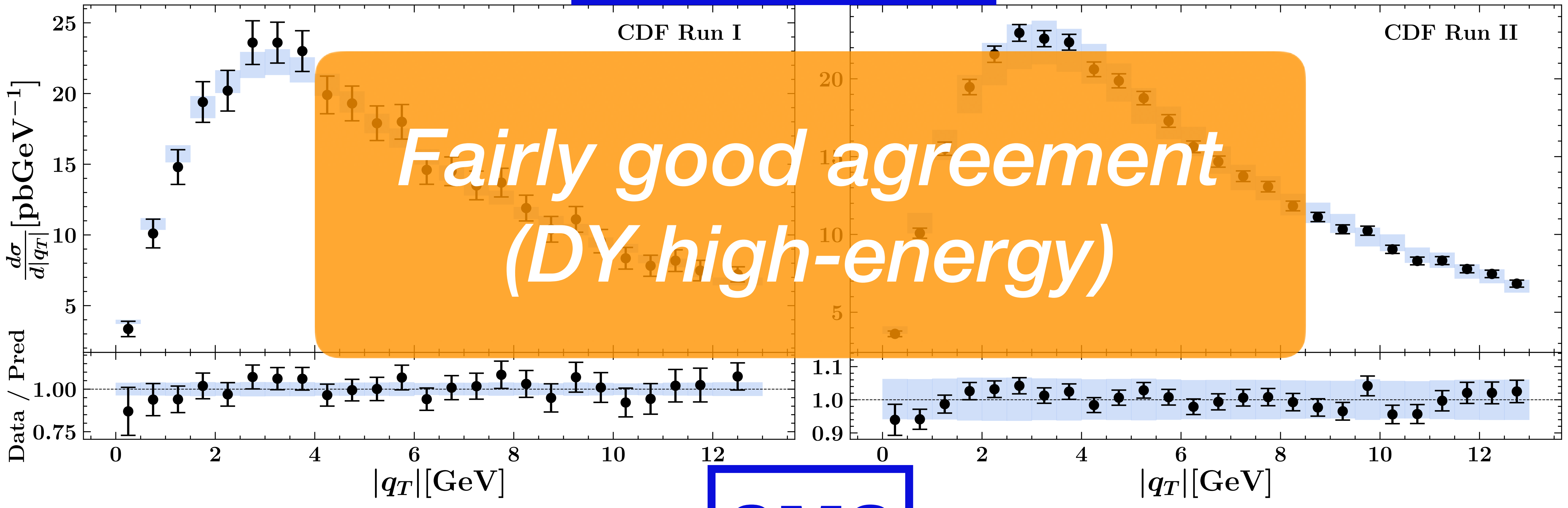

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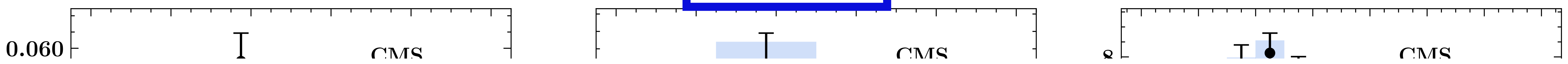

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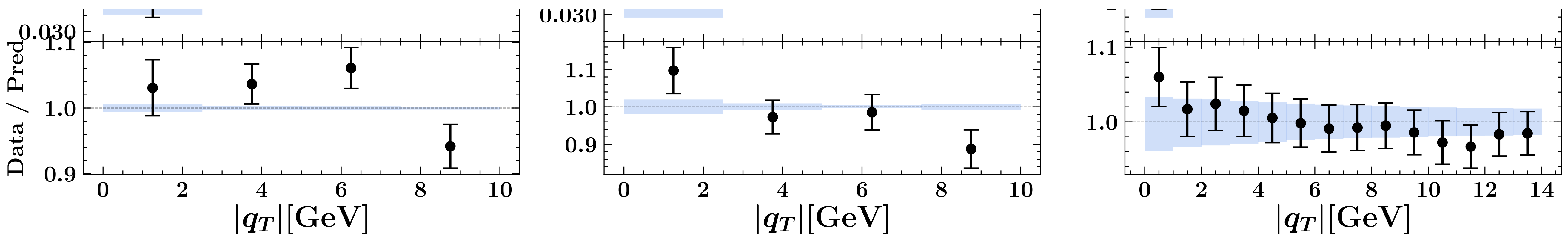
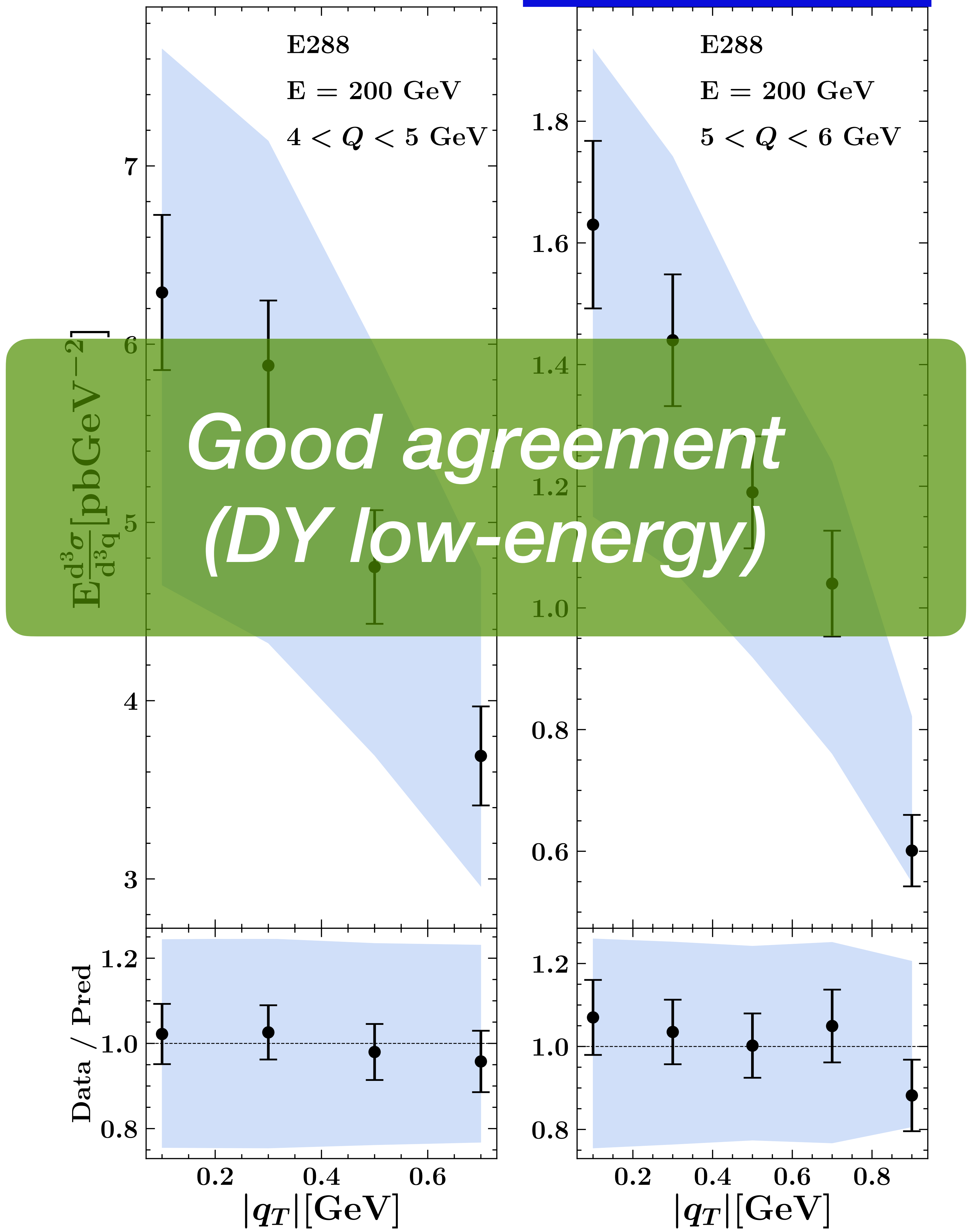
Total	**2031**	**0.77**	**0.29**	**1.06**

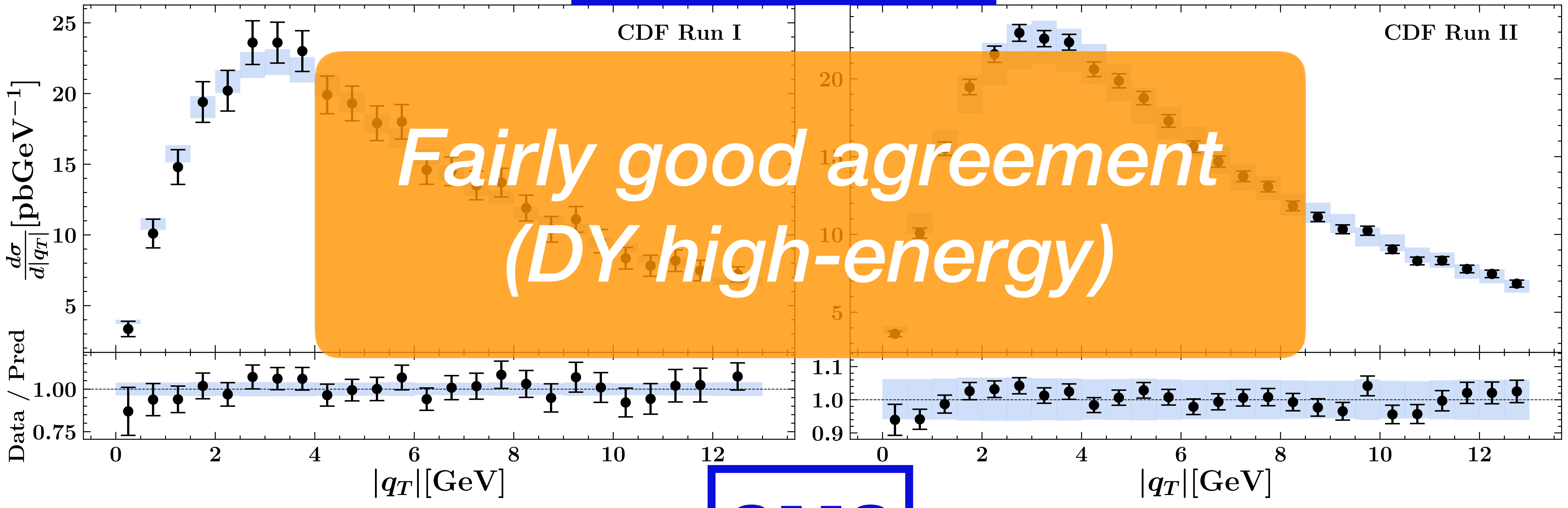


FERMILAB

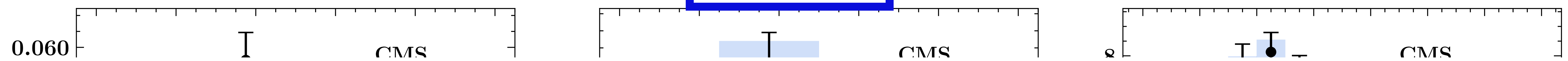


MAPTMD22 — Results of the fit $\chi^2/N_{data} = 1.06$

TEVATRON



CMS



Data set	N_{dat}	χ^2_D/N_{dat}	$\chi^2_\lambda/N_{\text{dat}}$	χ^2_0/N_{dat}
DY collider total	251	1.86	0.2	2.06
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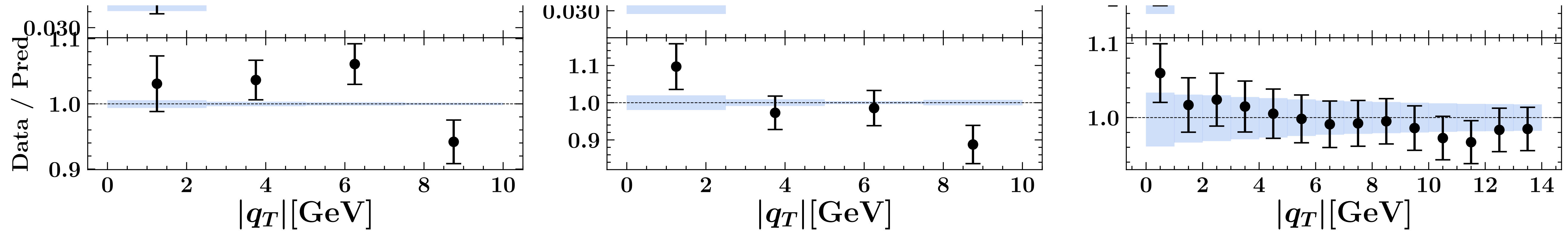

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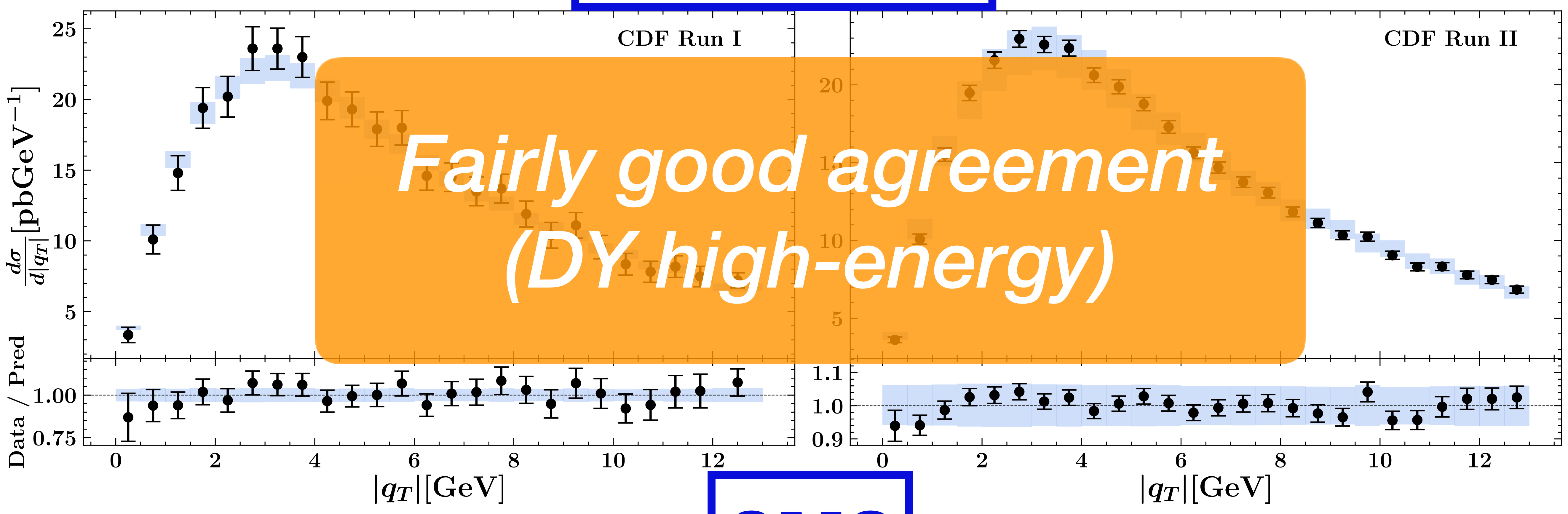

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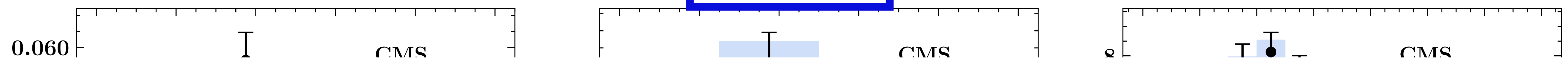

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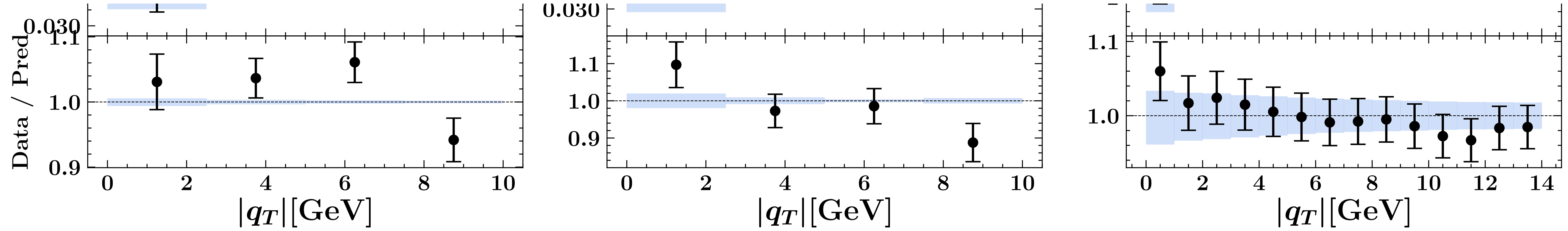
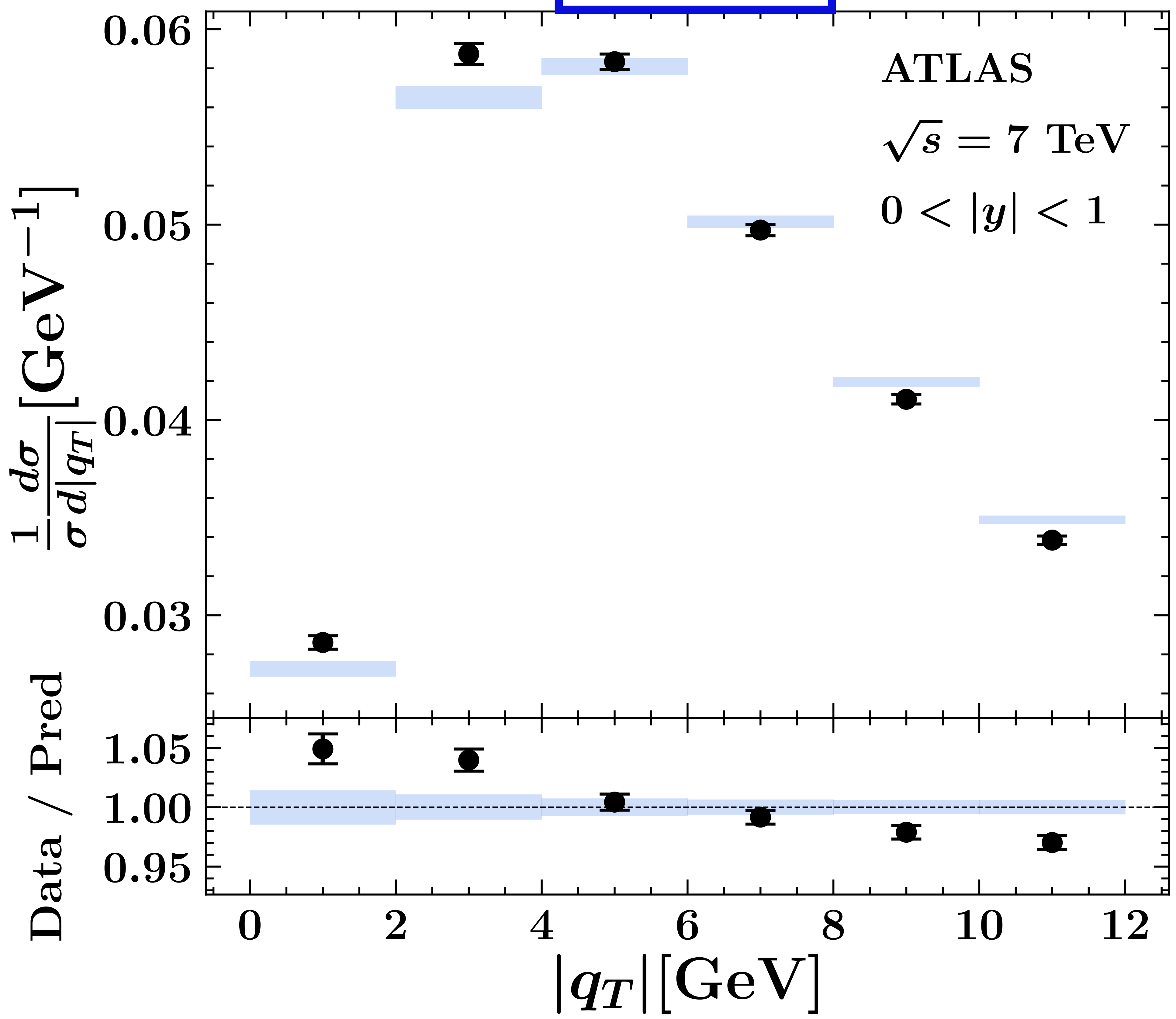


ATLAS



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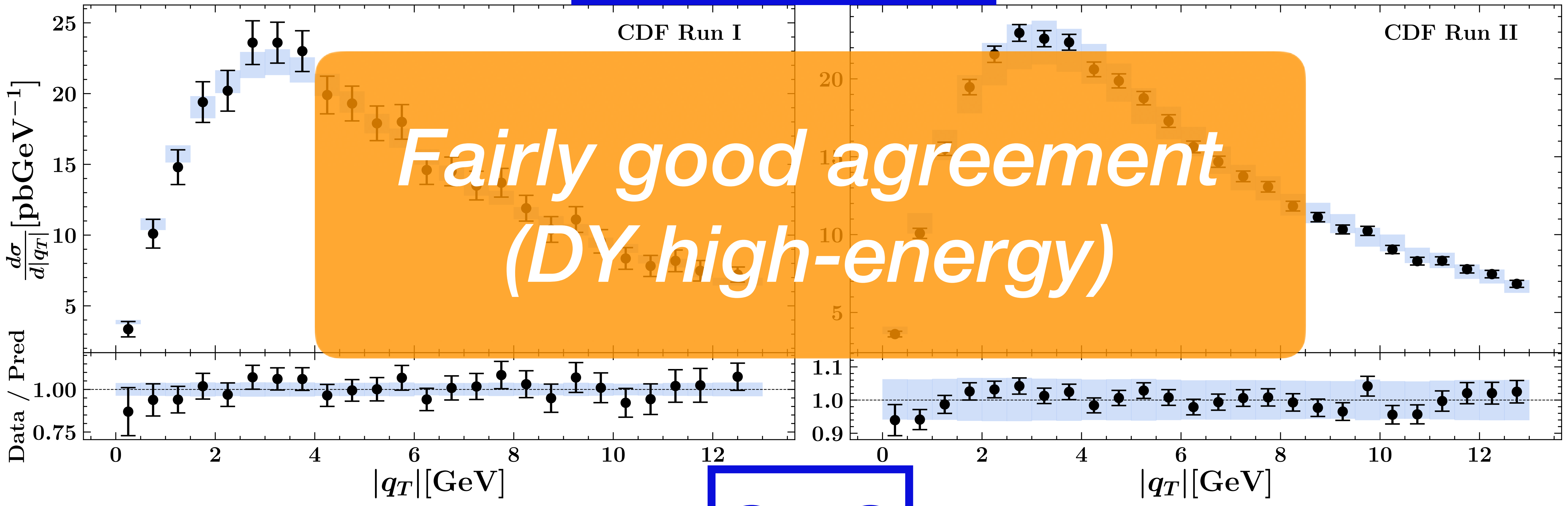

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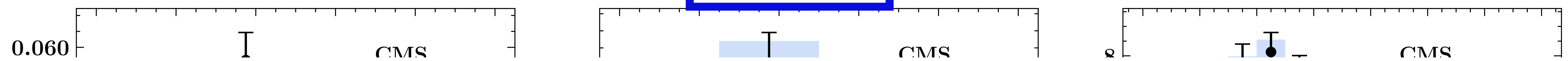

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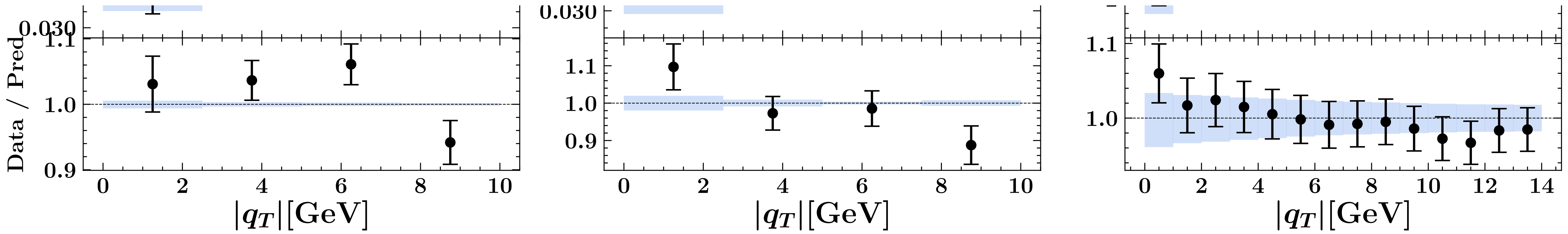

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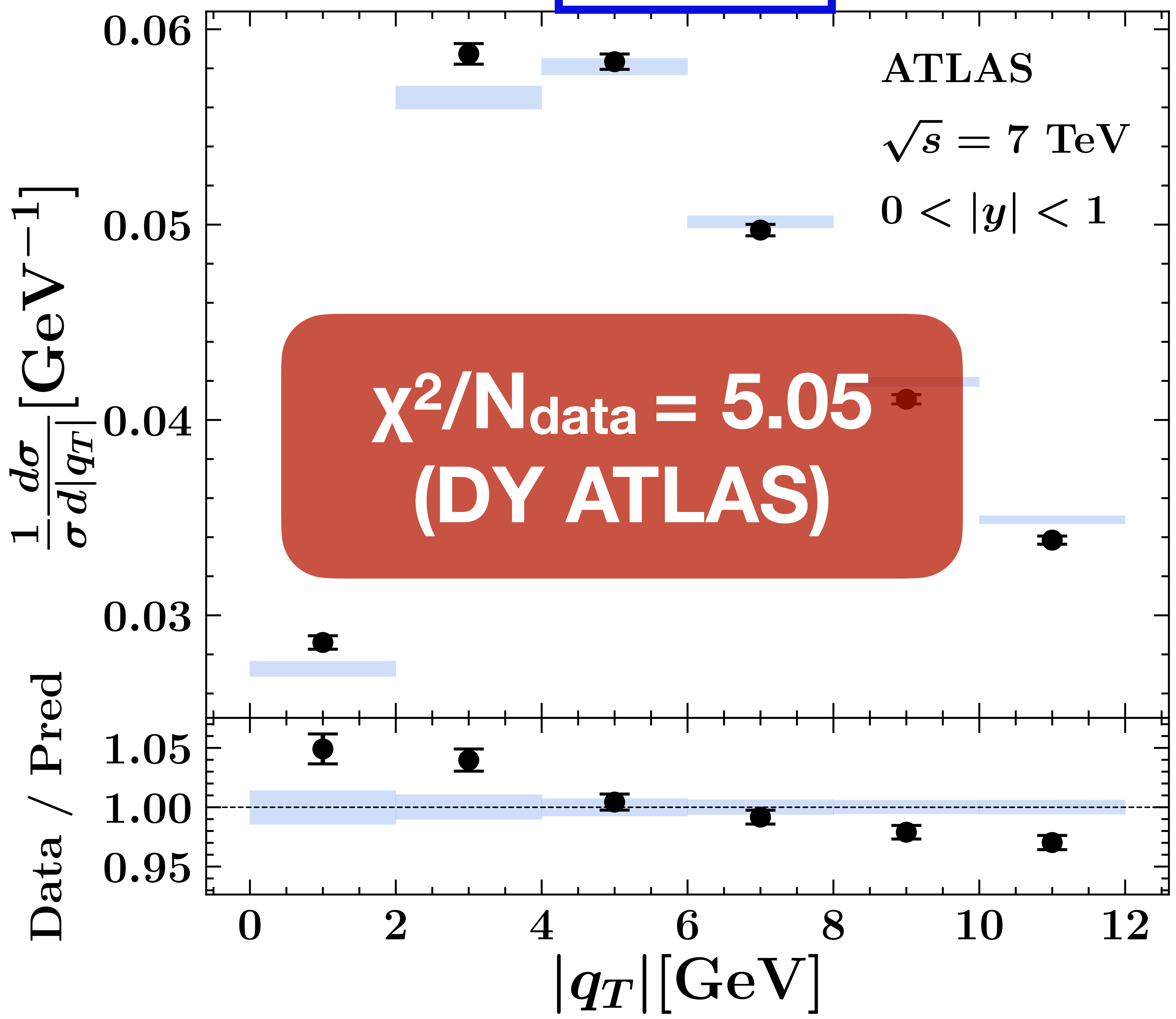
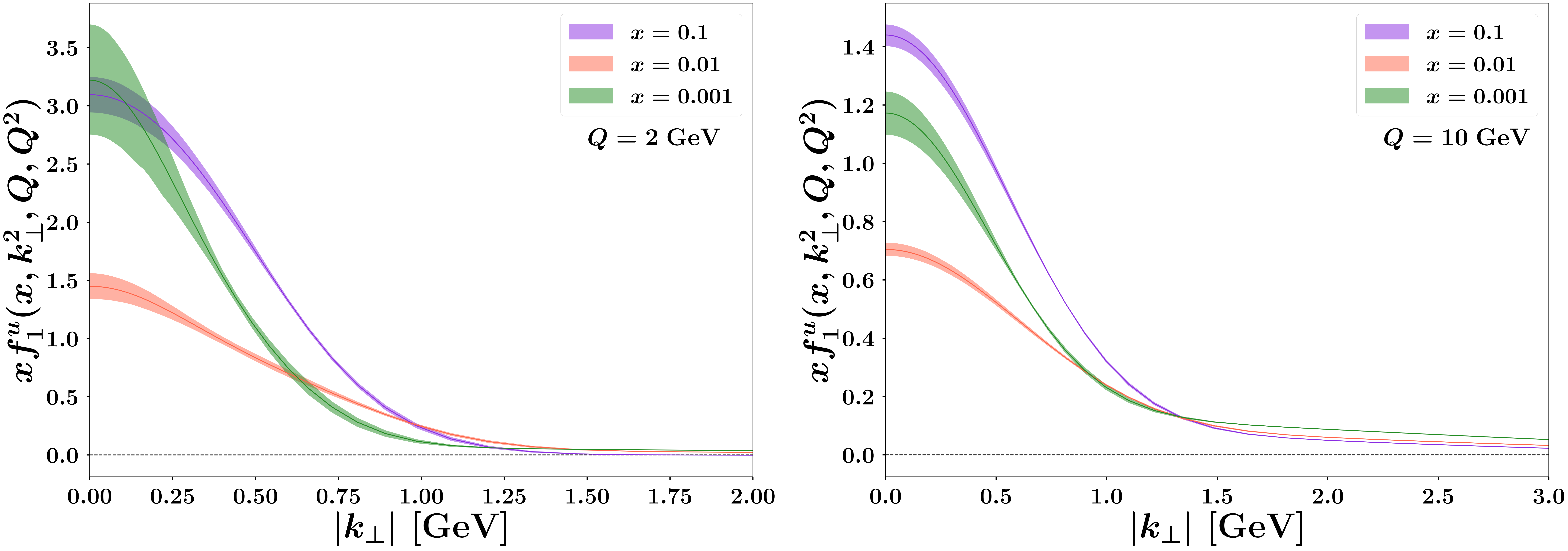


Visualization of TMD PDFs



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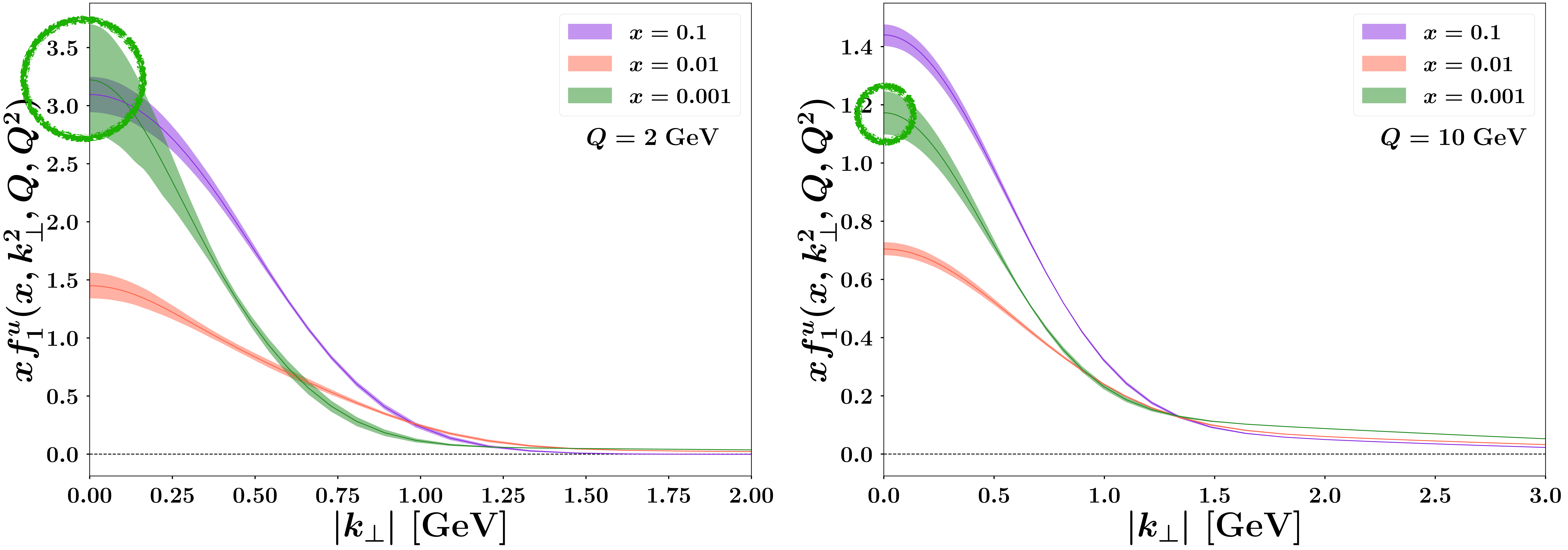
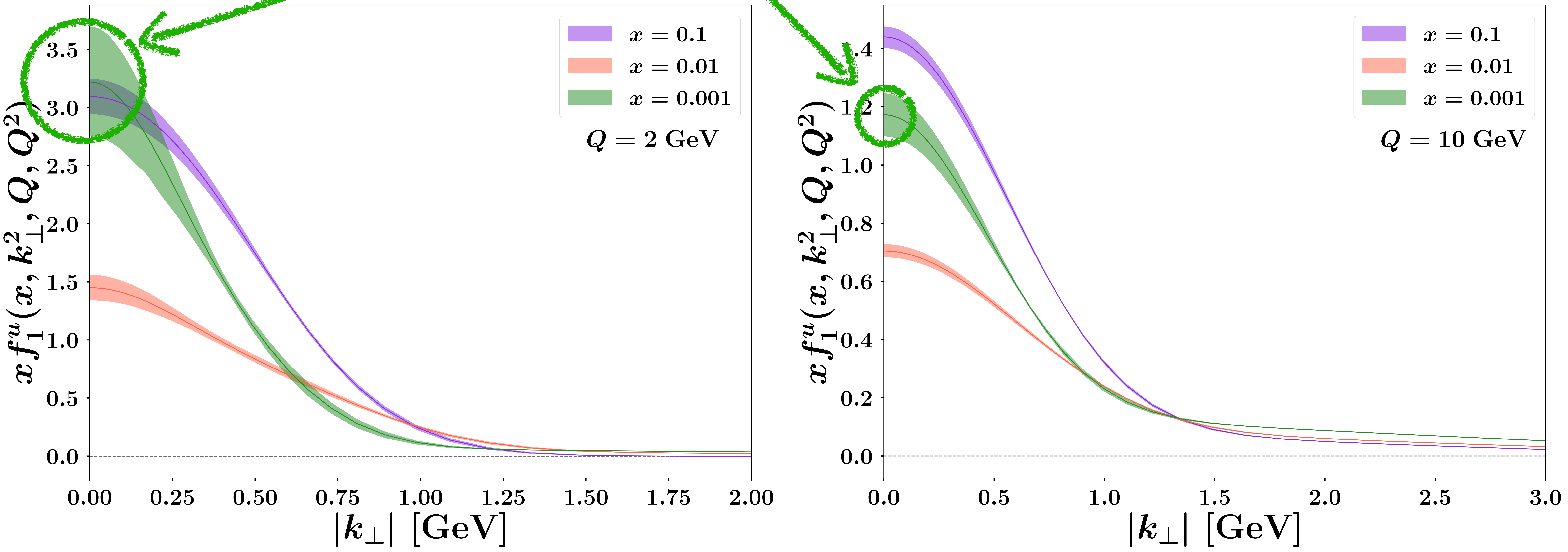
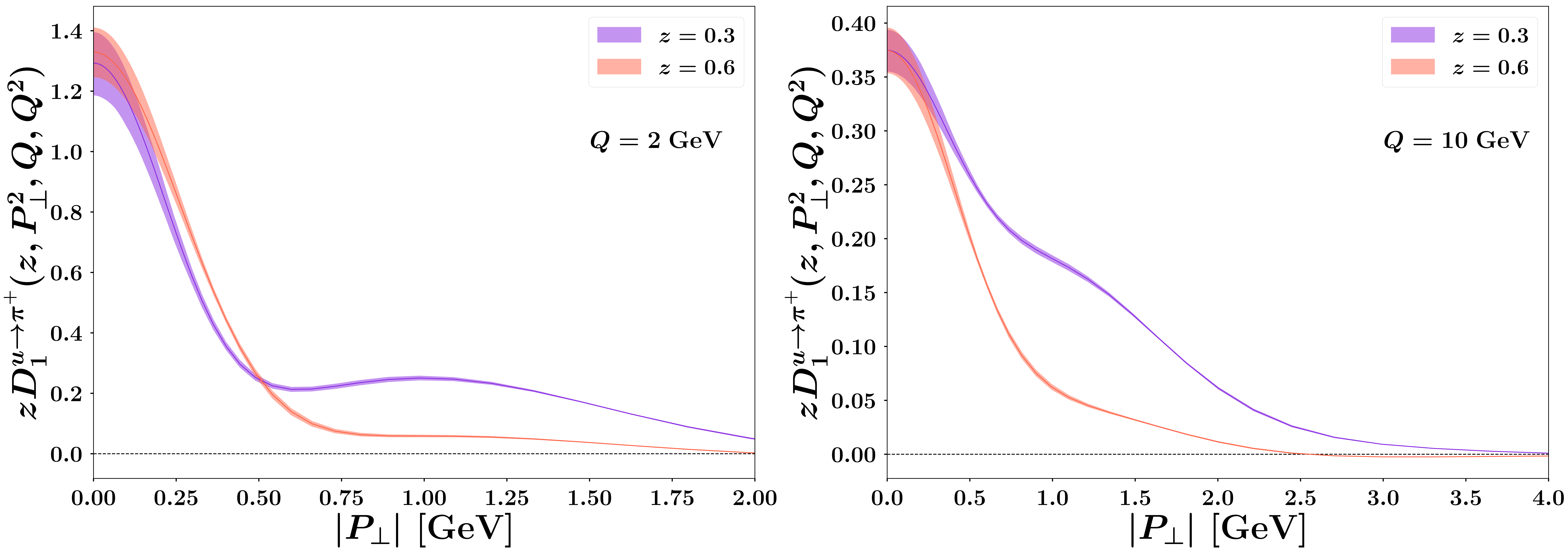


Visualization of TMD PDFs

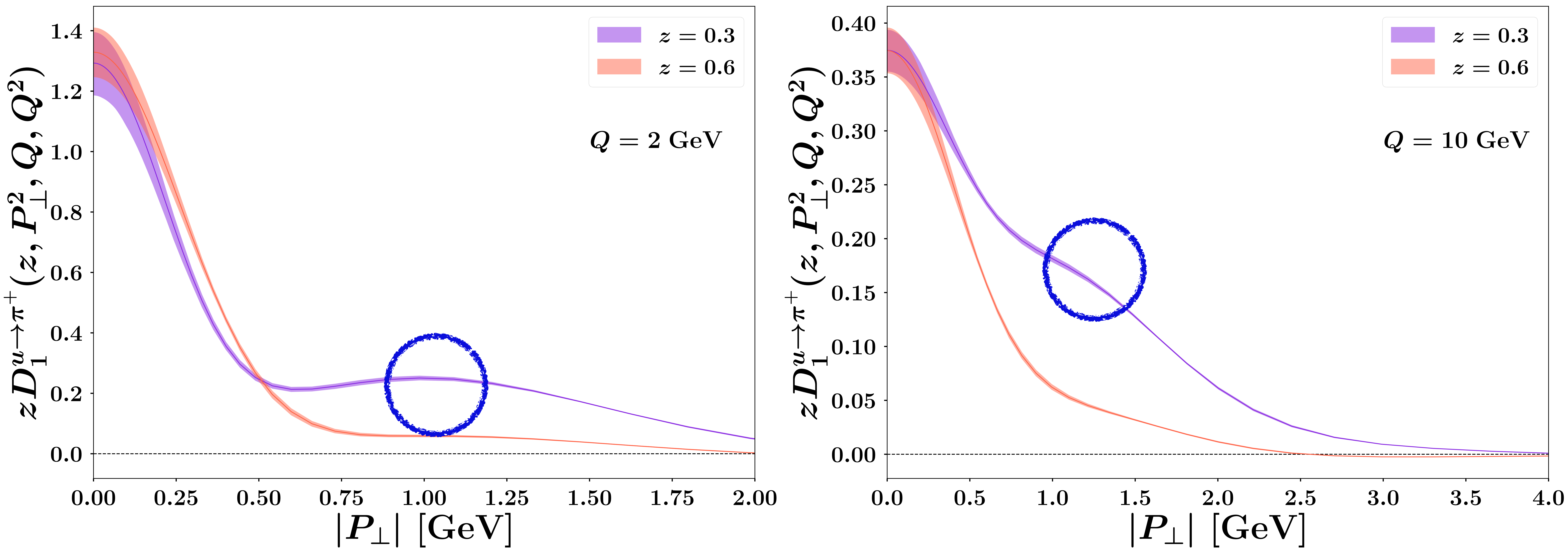
Need more data at low-x



Visualization of TMD FFs



Visualization of TMD FFs



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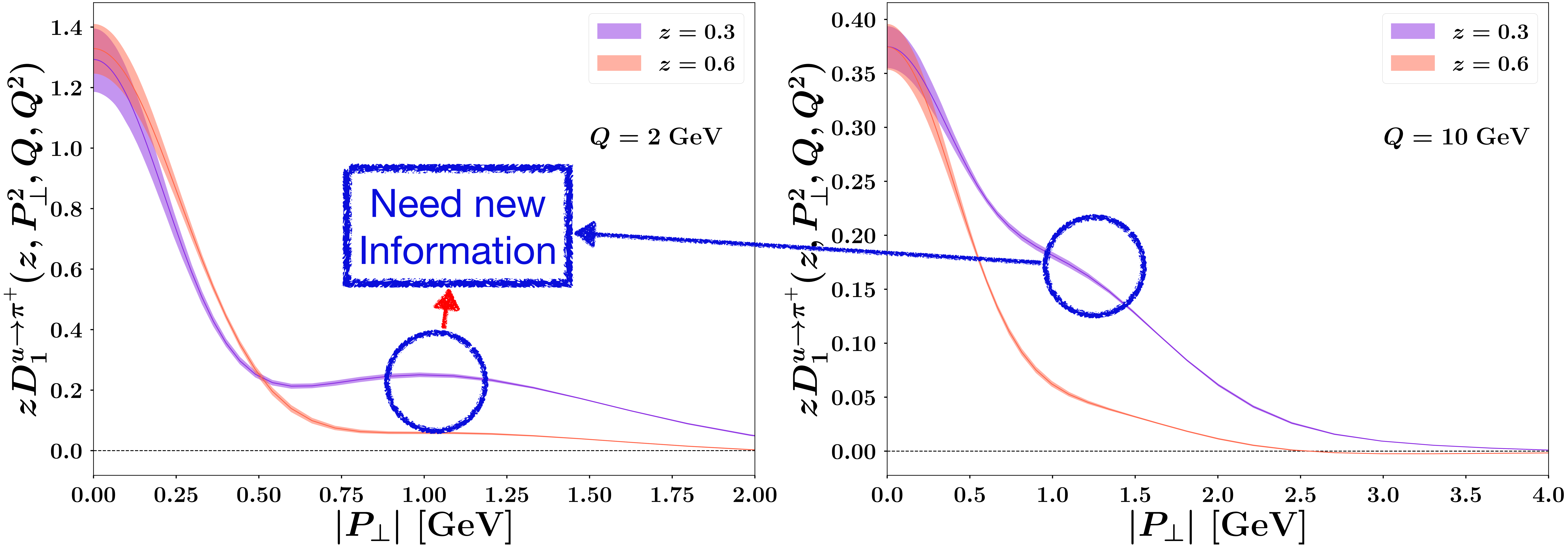
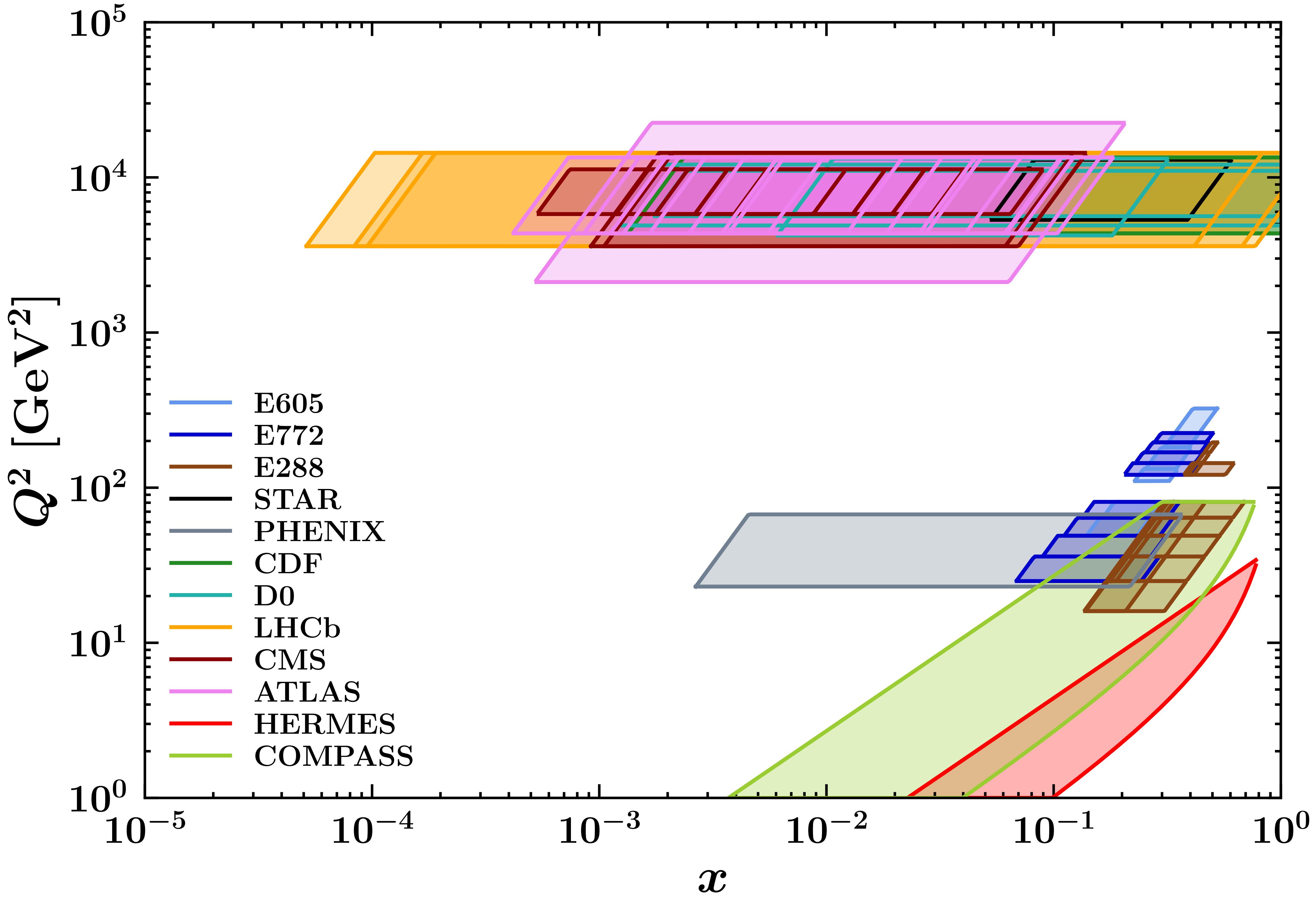


Impact studies



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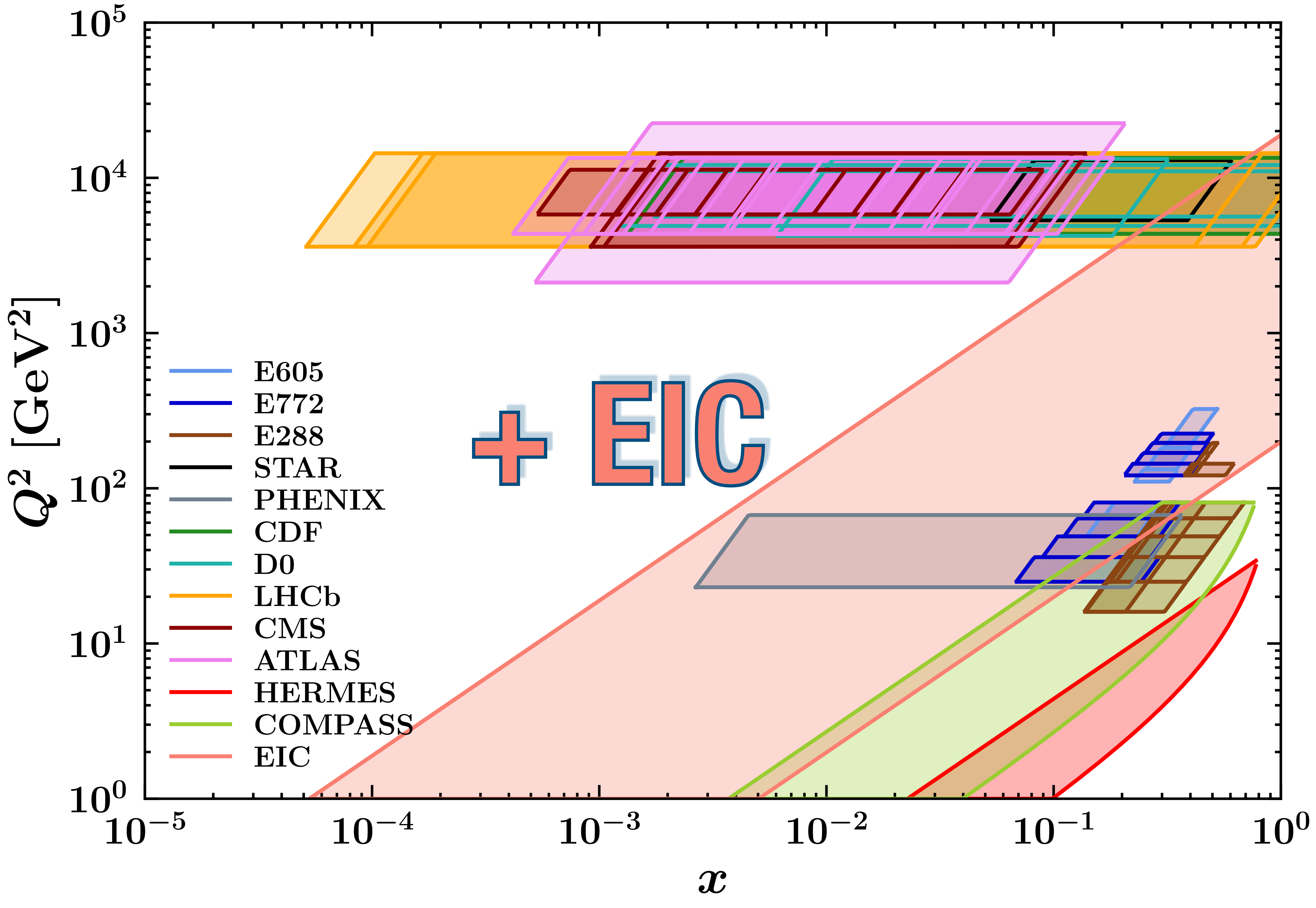
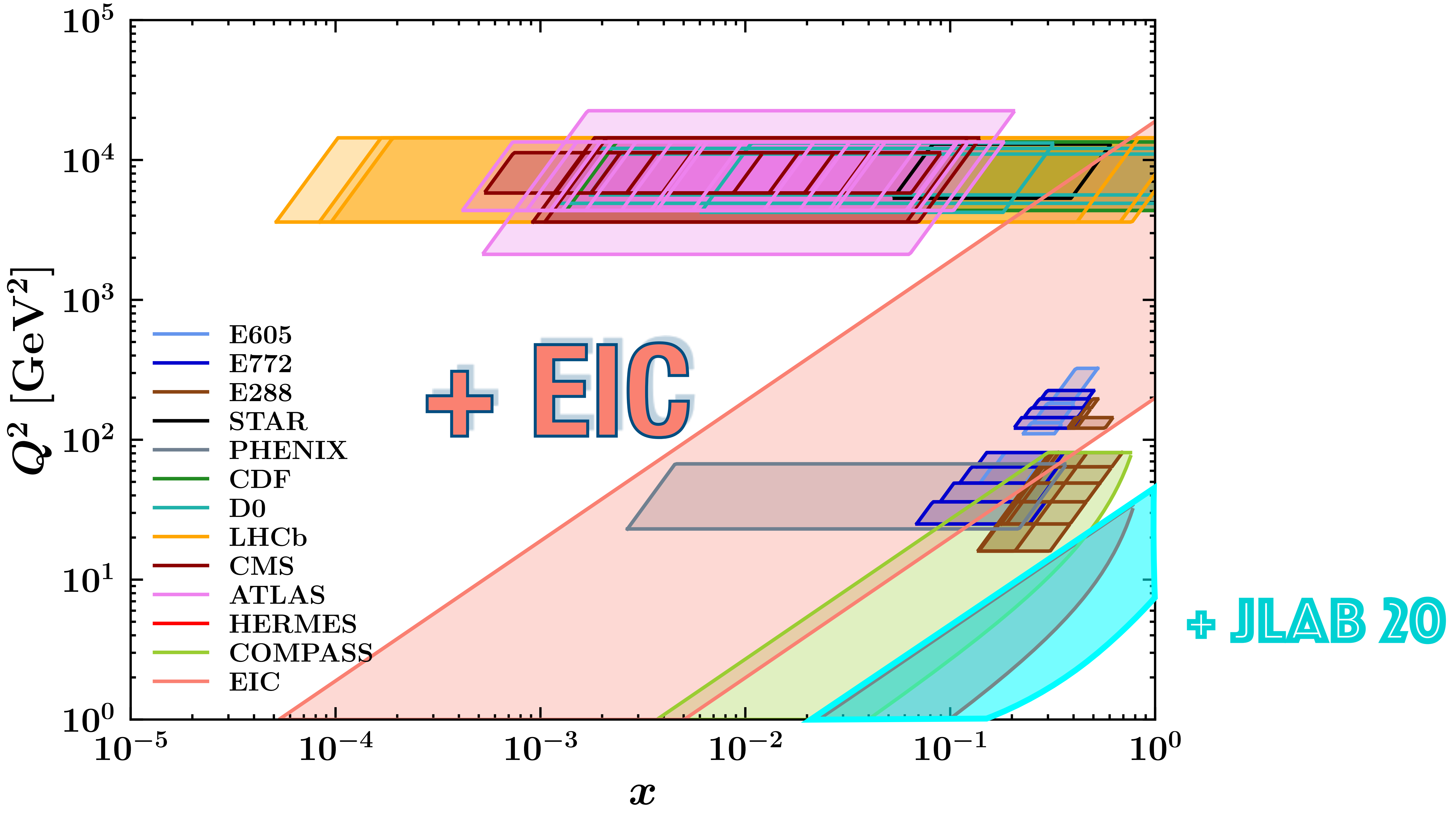


ELECTRON ION COLLIDER

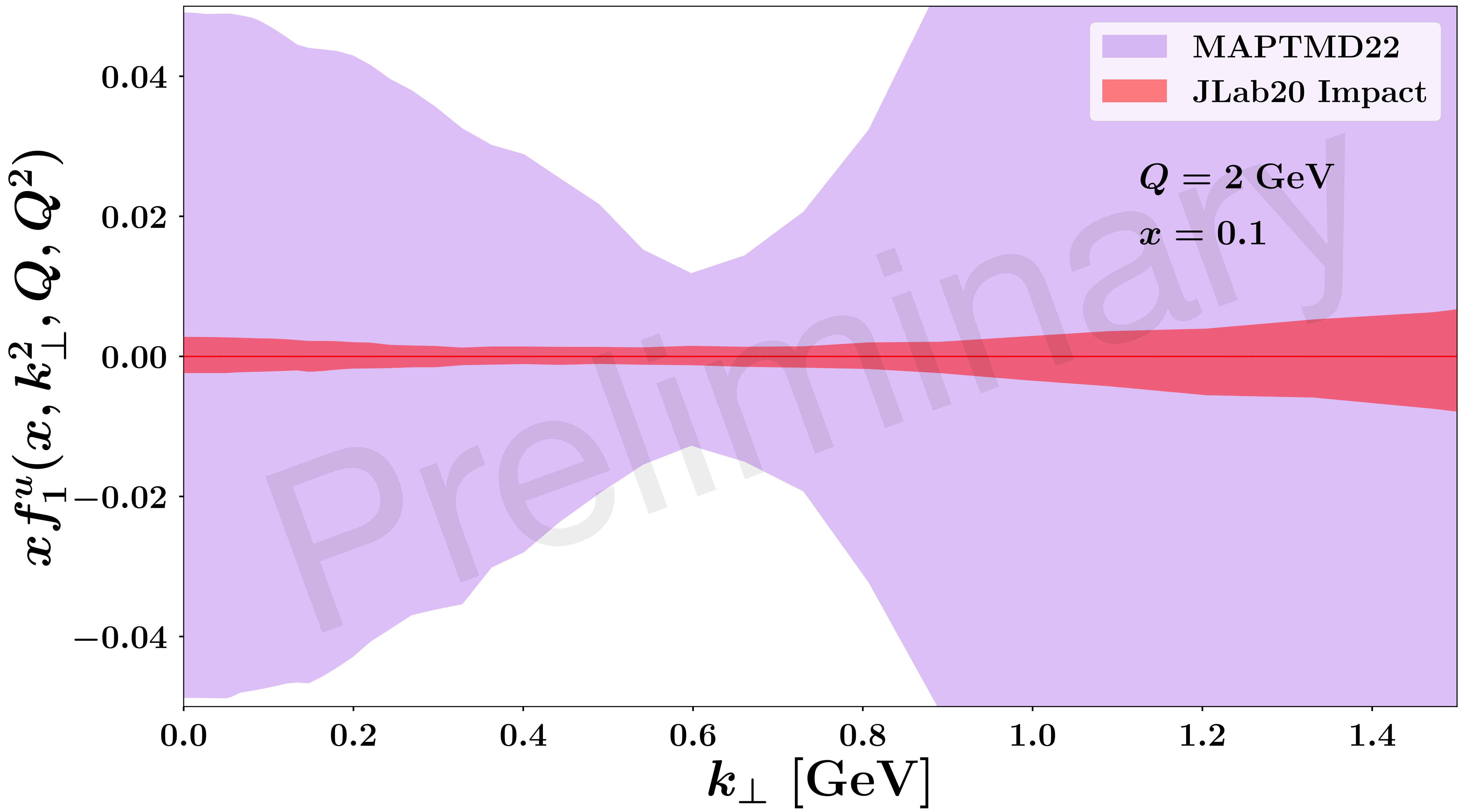
Impact studies

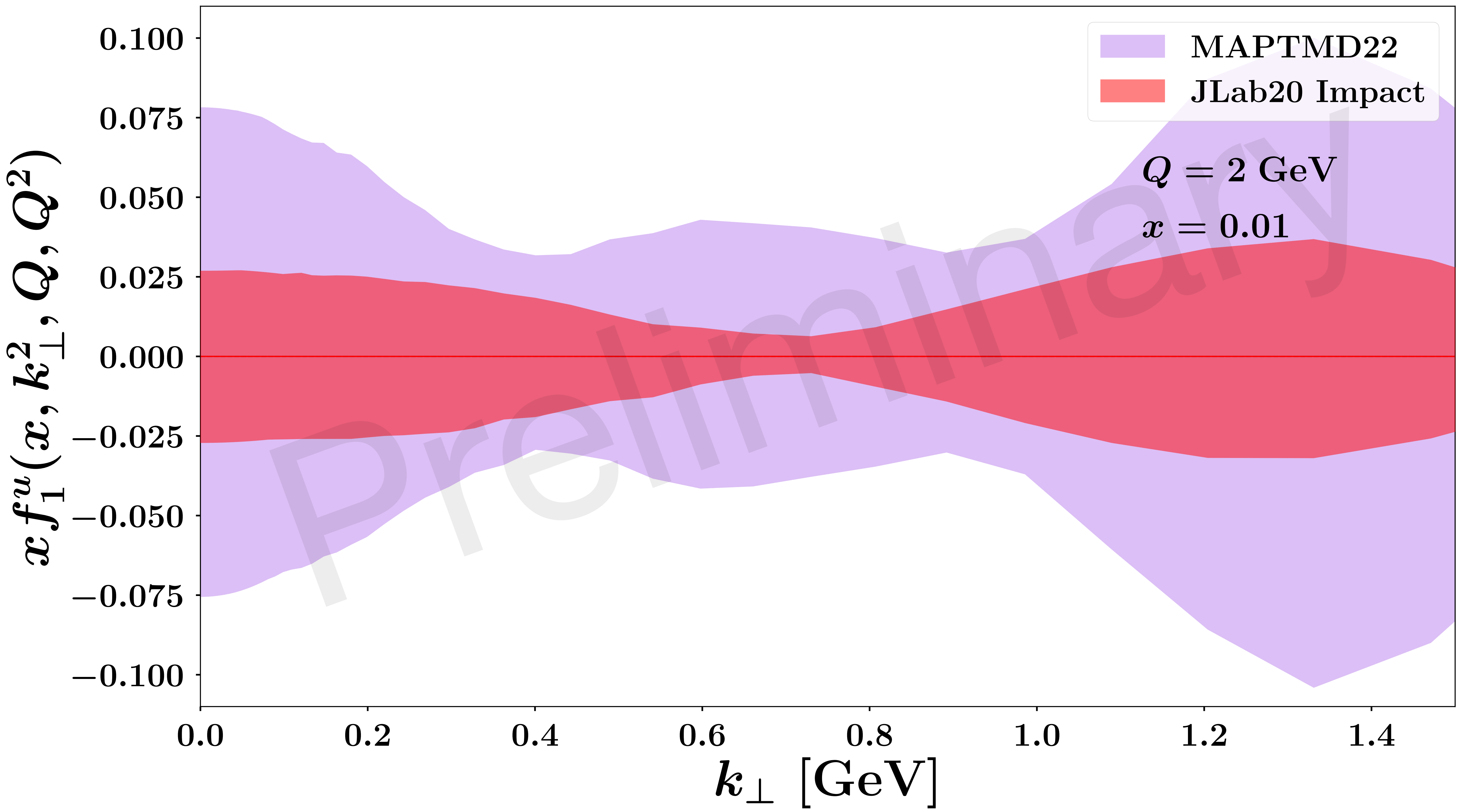


ELECTRON ION COLLIDER

JEFFERSON LAB 20+

Impact studies - JLab 20+





Better constrain at high x and low Q

A new global fit: MAPTMD22

	Accuracy	SIDIS	DY	Z production	N of points	χ^2/N_{data}
Pavia 2017 arXiv:1703.10157	NLL –	✔	✔	✔	8059	1.55
SV 2019 arXiv:1912.06532	N^3LL	✔	✔	✔	1039	1.06
MAPTMD22	***N^3LL^-***	✔	✔	✔	***2031***	***1.06***

MAP Collaboration, JHEP 10 (2022)

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MAPTMD22	***N^{3}LL$_-$***	✔	✔	✔	***2031***	***1.06***

And the other hadrons?

MAP Collaboration, JHEP 10 (2022)

Available fits of Pion TMDs

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	Accuracy	DY	N of points	χ^2/N_{data}
Wang et al, 2017 arXiv:1707.05207	NLL	✔	96	1.61
VPion 2019 arXiv:1907.10356	N^2LL'	✔	80	1.44
MAPTMDPion22	$\mathbf{N^3LL^-}$	✔	***138***	***1.54***
Jam 2023 arXiv:2302.01192	N^2LL	✔	93	1.37

MAP Collaboration, PRD 107 (2023)

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Best theoretical accuracy

MAP Collaboration, PRD 107 (2023)

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MAP Collaboration, PRD 107 (2023)

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Fairly good description

MAP Collaboration, PRD 107 (2023)

MAPTMDPion22: Included datasets

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Pion-induced Drell-Yan process

MAPTMDPion22: Included datasets

Pion-induced Drell-Yan process

$$\pi^- + W \to \mu_+ + \mu_- + X$$

MAPTMDPion22: Included datasets

Pion-induced Drell-Yan process

$$\pi^- + W \rightarrow \mu_+ + \mu_- + X$$

Experiment	$\sqrt{s}$ [GeV]	Q [GeV]	N_{bins}	x_F	
E615 (Q-diff)	21.8	$4.05 < Q < 13.05$	10 (8)	$0 < x_F < 1$	W. J. Stirling et al. 1993
E537 (Q-diff)	15.3	$4.0 < Q < 9.0$	10	$-0.1 < x_F < 1$	E. Anassontzis et al. 1988

MAPTMDPion22: Included datasets

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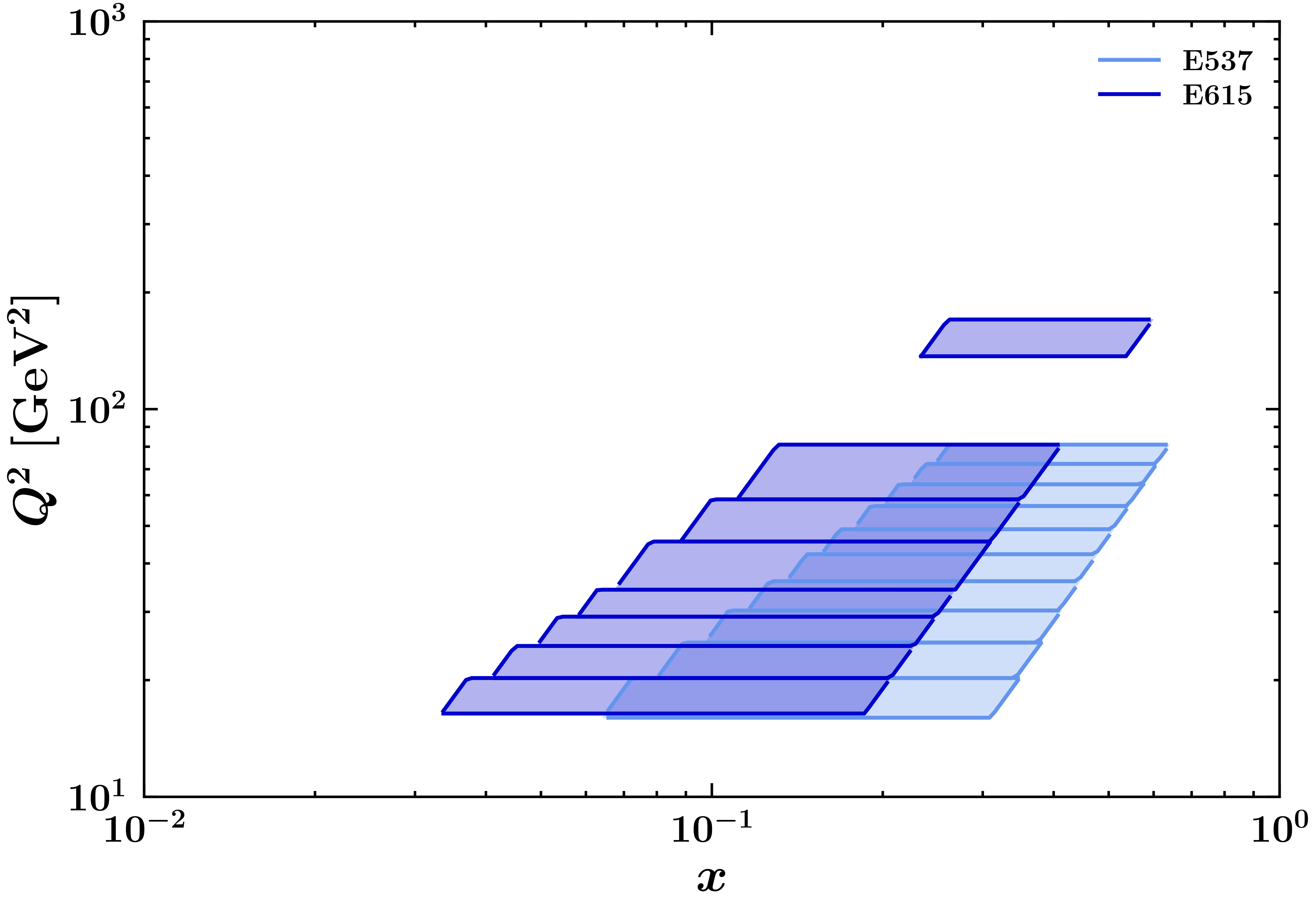

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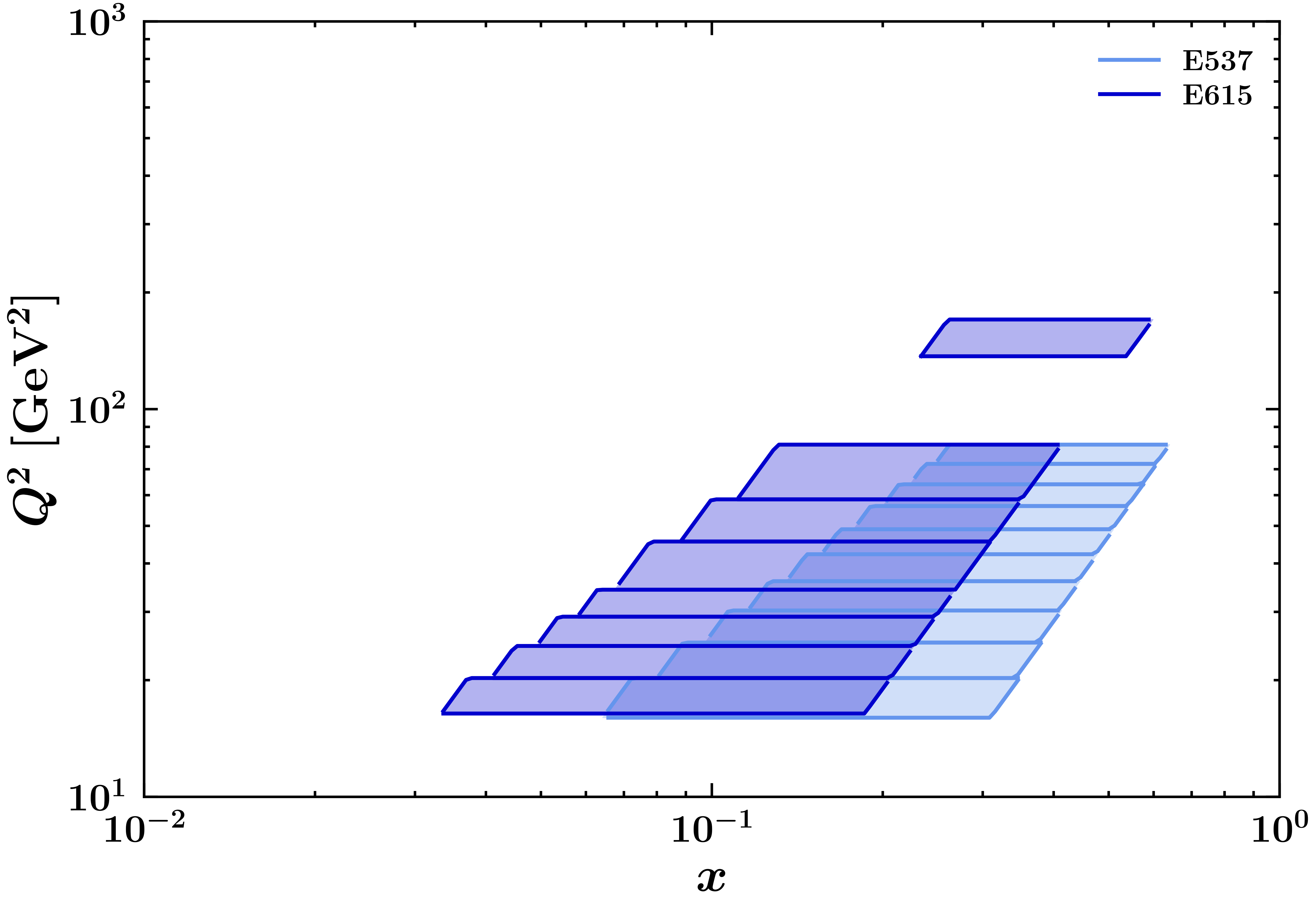

Small region covered by the available datasets

MAPTMDPion22: Included datasets

Experiment	Number of points	Statistical errors	Systematic errors	Theoretical errors
E615 (Q-diff)	74/155	5%	16%	5-8%
E537 (Q-diff)	64/150	15-20%	8%	5-8%
Total	138/305	Large Uncertainties	Large Normalization Errors	Extra uncertainties

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Presence of many and different kind of errors

MAPTMDPion22: Models

MAPTMDPion22: Models

Proton

MAPTMDPion22: Models

Proton

↓

MAPTMD22

MAPTMDPion22: Models

Proton

↓

MAPTMD22

Pion

MAPTMDPion22: Models

Proton → ***MAPTMD22***

Pion → ***xFitter20***

MAPTMDPion22: Models

Proton → **MAPTMD22**

Pion → ***xFitter20***

$$f_{1\pi}^{NP}(x,\zeta,\mathbf{b}_T) = e^{-g_{1\pi}(x)\frac{\mathbf{b}_T^2}{4}}$$

MAPTMDPion22: Models

Proton → **MAPTMD22**

Pion → *xFitter20*

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$$g_{1\pi}(x) = N_{1\pi}\frac{x^{\sigma_\pi}(1-x)^{\alpha_\pi^2}}{\hat{x}^{\sigma_\pi}(1-\hat{x})^{\alpha_\pi^2}}$$

MAPTMDPion22: Models

Proton

MAPTMD22

Pion → ***xFitter20***

$$f_{1\pi}^{NP}(x,\zeta,\mathbf{b}_T) = e^{-g_{1\pi}(x)\frac{\mathbf{b}_T^2}{4}}$$

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3 fitting parameters

MAPTMDPion22: Fit Results

MAP Collaboration, PRD 107 (2023)

MAPTMDPion22: Fit Results

MAP Collaboration, PRD 107 (2023)

MAPTMDPion22: Fit Results

Good agreement in the shape

MAP Collaboration, PRD 107 (2023)

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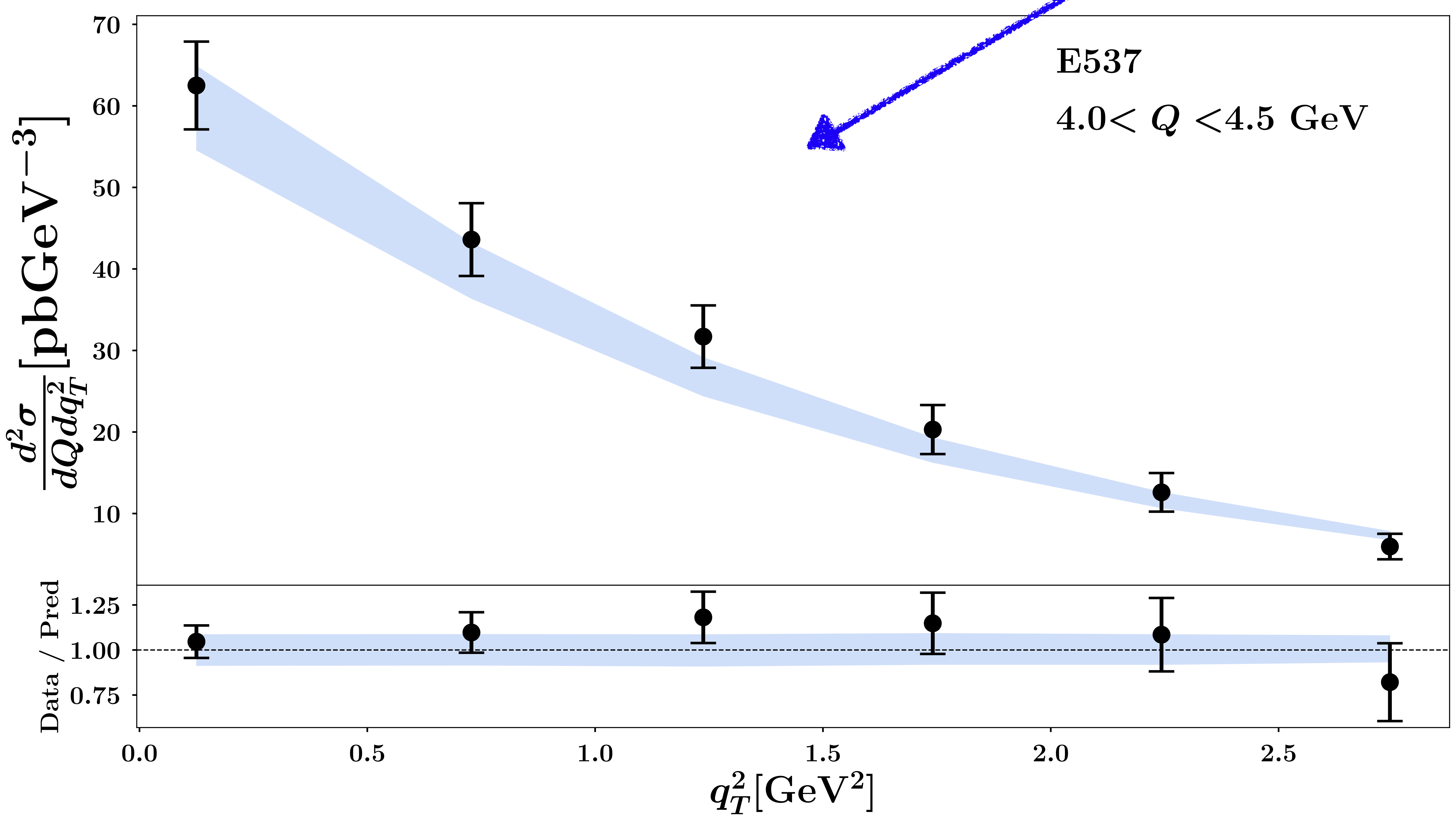
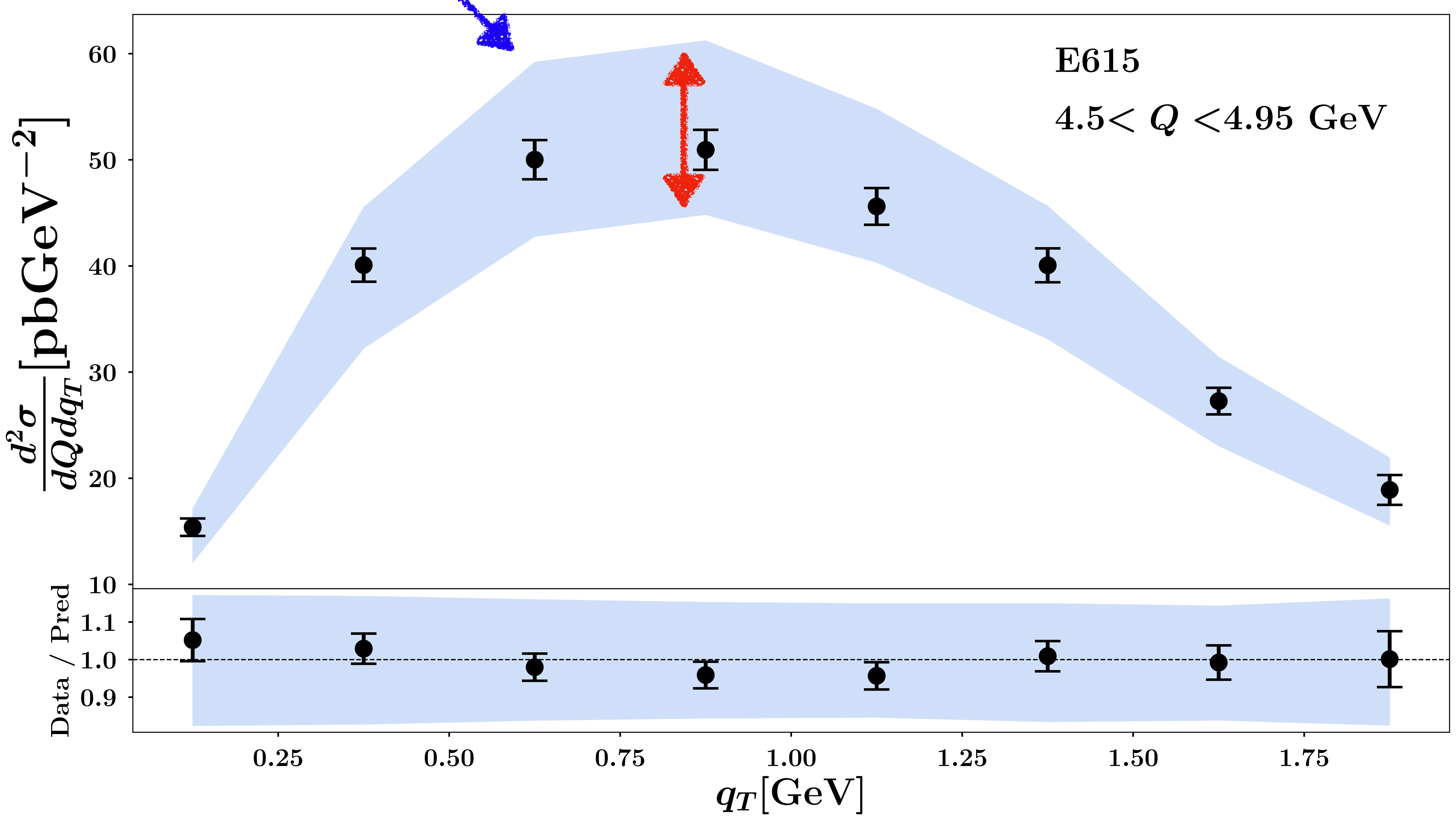




MAP Collaboration, PRD 107 (2023)

MAPTMDPion22: Fit Results

Good agreement in the shape

Quite big normalization errors

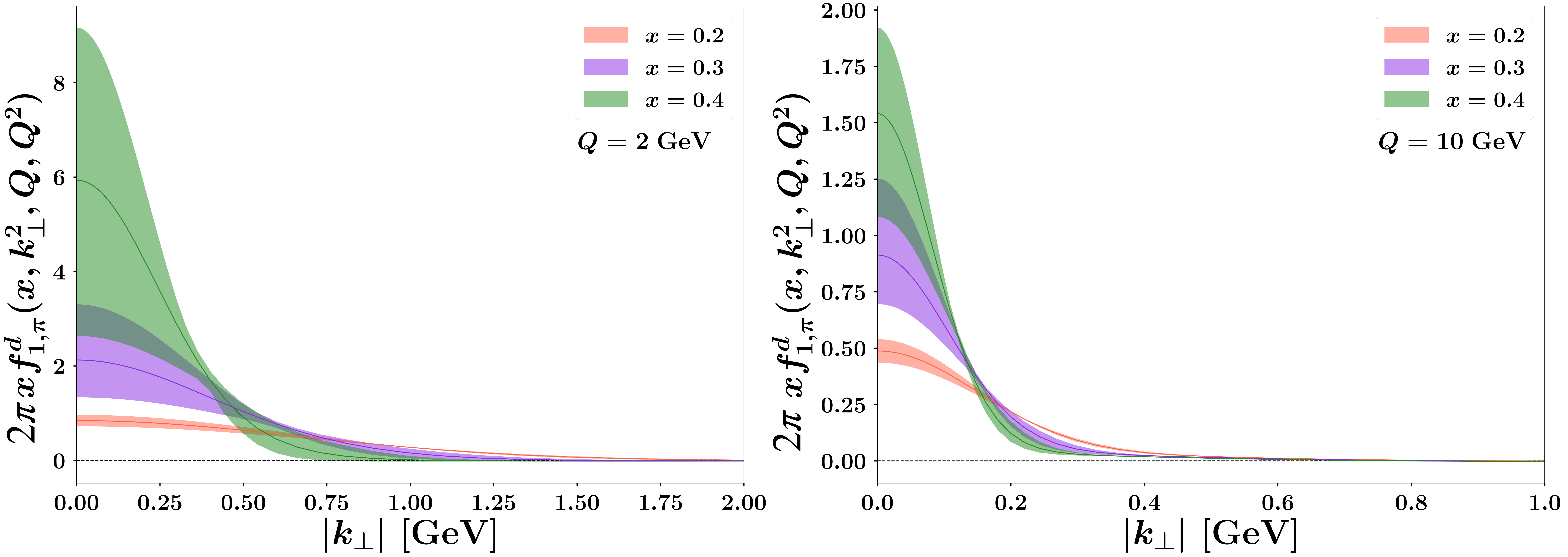
MAP Collaboration, PRD 107 (2023)

MAPTMDPion22: Fit Results

MAP Collaboration, PRD 107 (2023)

Visualization of Pion TMD PDFs

$N_{1\pi}[\text{GeV}^2] = 0.47 \pm 0.12$ $\sigma_\pi = 4.50 \pm 2.25$ $\alpha_\pi = 4.40 \pm 1.34$



MAP Collaboration, PRD 107 (2023)

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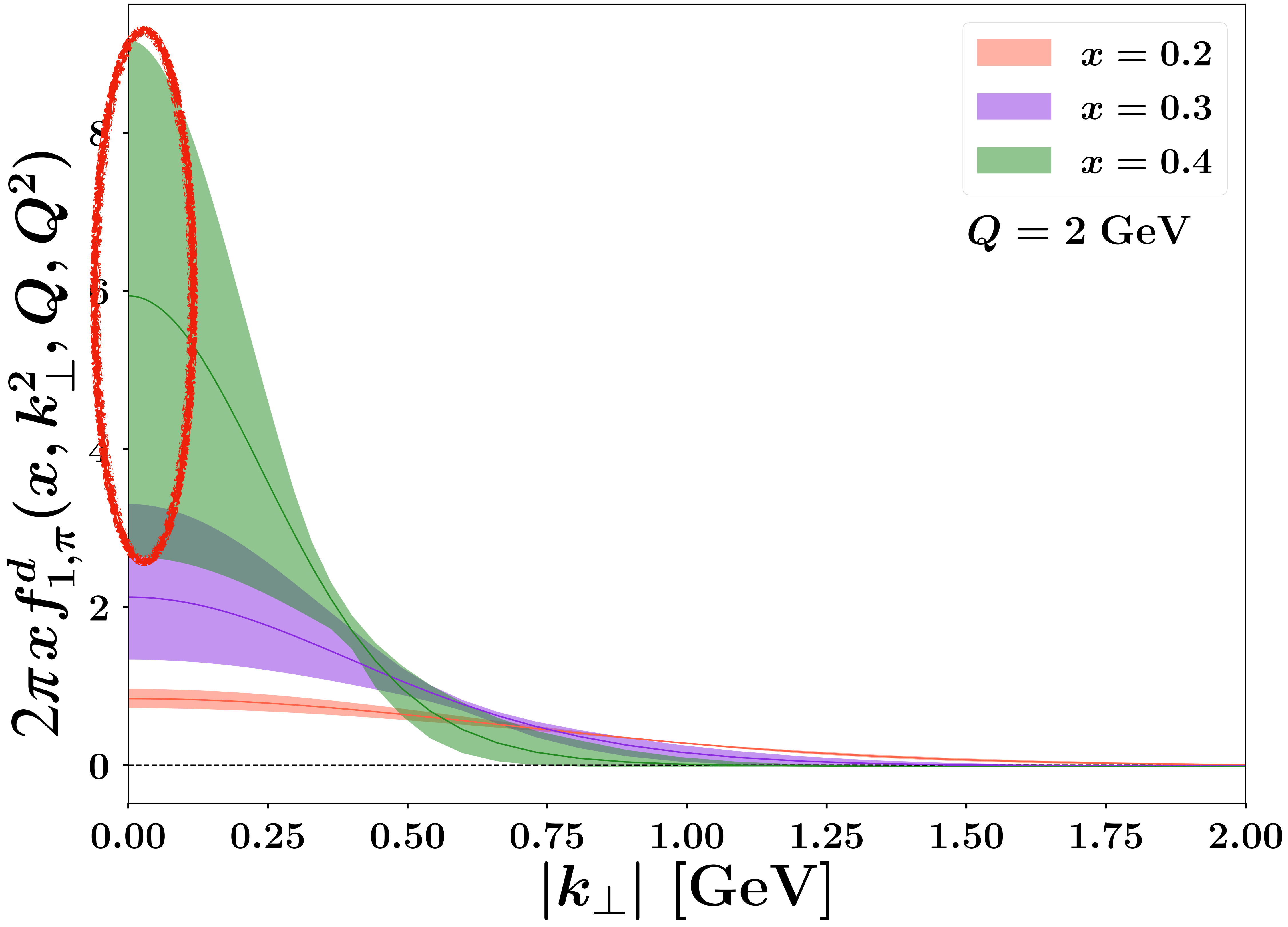

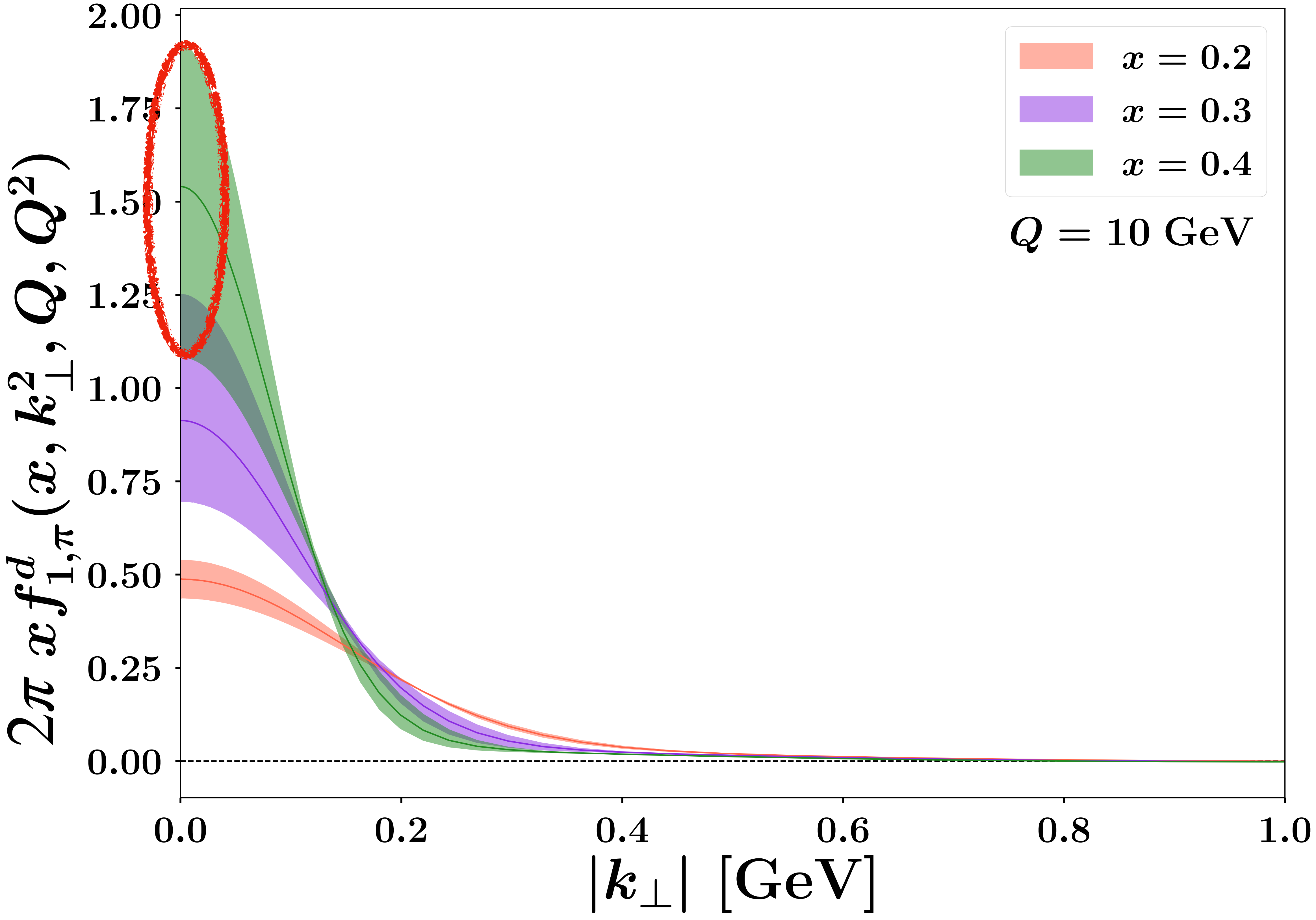

MAP Collaboration, PRD 107 (2023)

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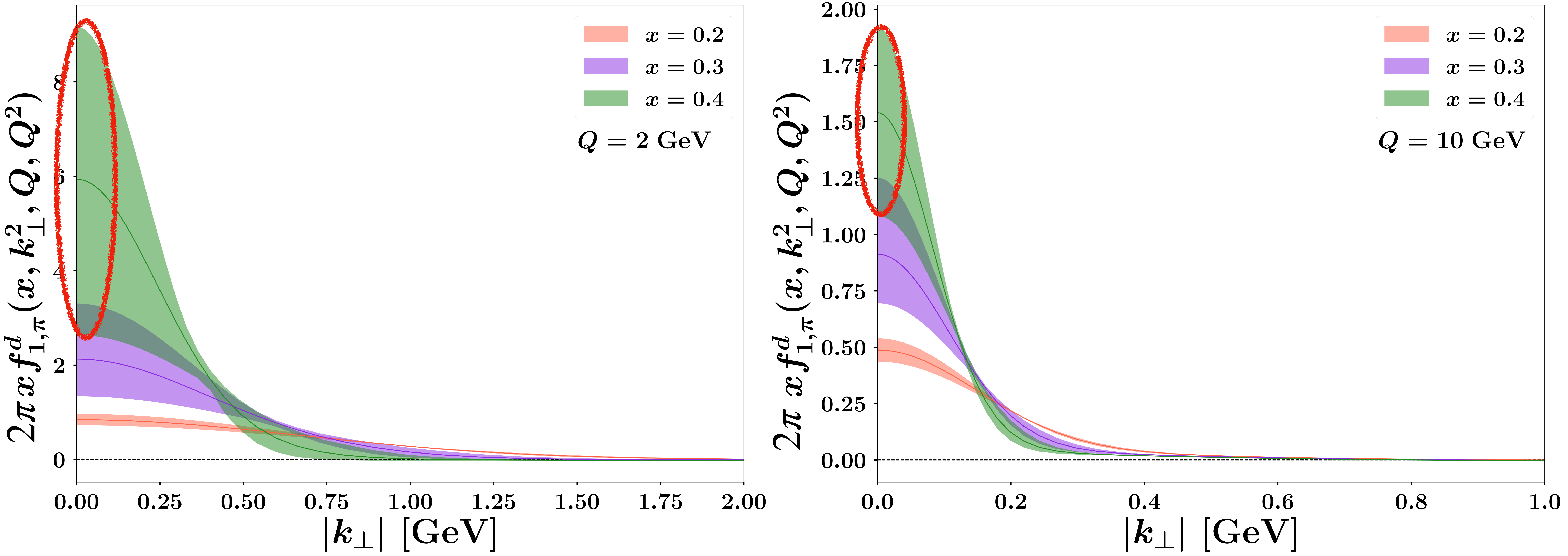

MAP Collaboration, PRD 107 (2023)

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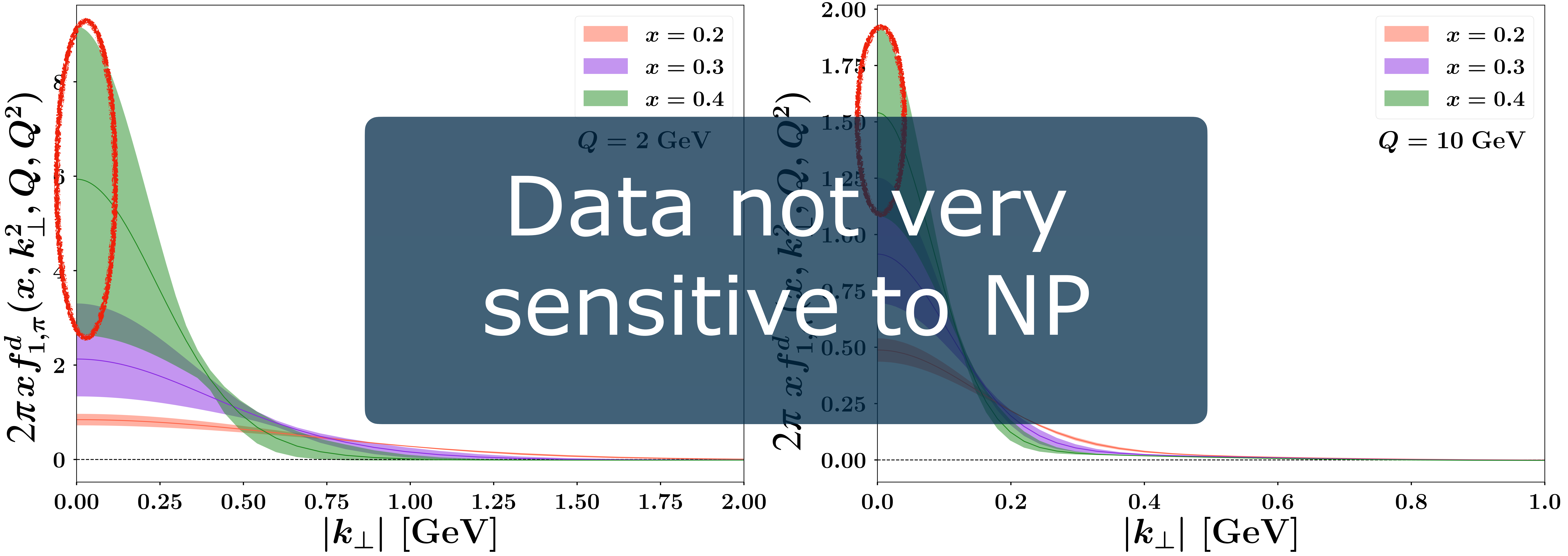

Data not very sensitive to NP

MAP Collaboration, PRD 107 (2023)

Visualization of Pion TMD PDFs

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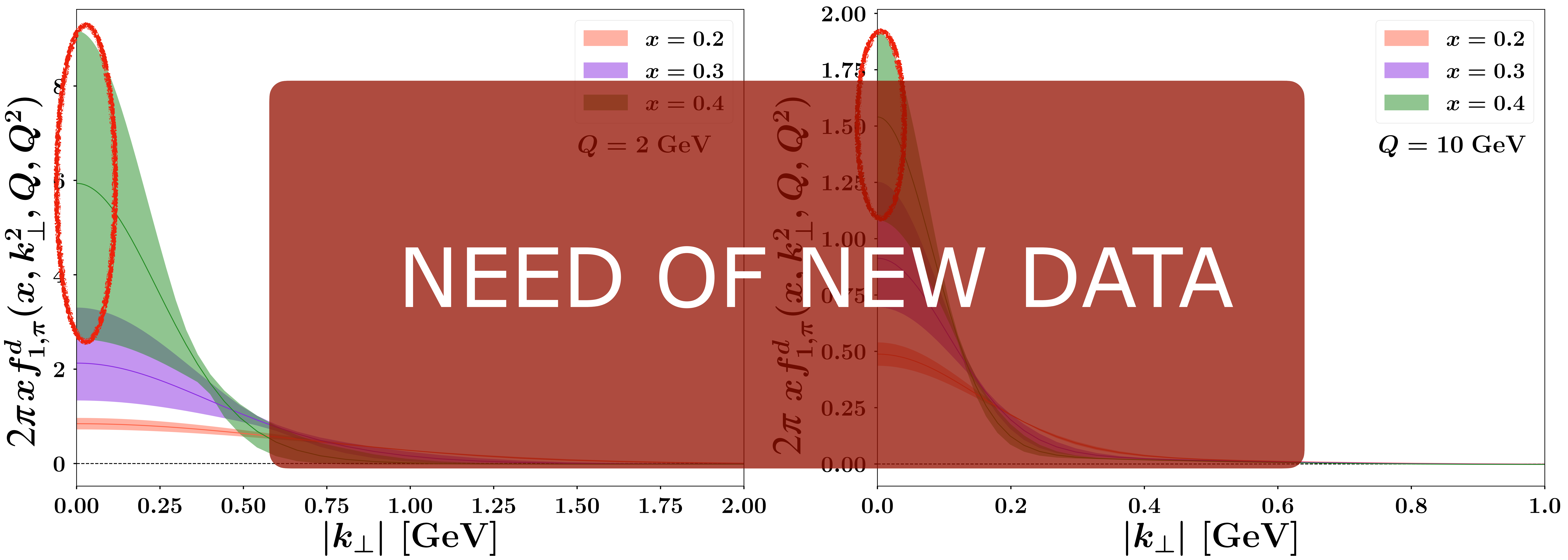

MAP Collaboration, PRD 107 (2023)

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- Refinement of Pion TMDs (COMPASS data, Power corrections, PRV model)