MAPTMD22 : femtography of unpolarized protons and pions at N^{3}LL accuracy

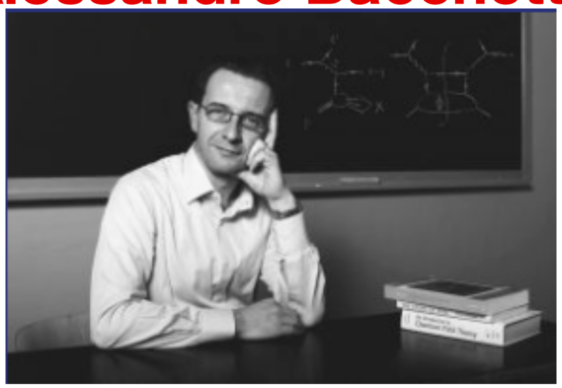
Marco Radici

INFN
Istituto Nazionale di Fisica Nucleare
Sezione Pavia

for the **MAP** Collaboration
(**M**ulti-dimensional **A**nalysis of **P**artonic distributions)
https://github.com/MapCollaboration/

Results with contributions from…

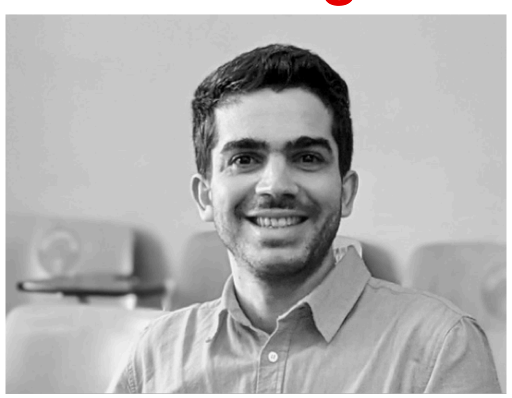
Alessandro Bacchetta



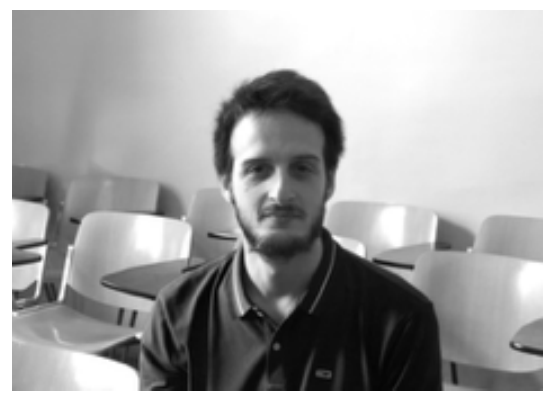
Marco Radici

Matteo Cerutti

Andrea Signori



Valerio Bertone



Chiara Bissolotti

Giuseppe Bozzi

Fulvio Piacenza

Simone Venturini

…and published in…

JHEP

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Unpolarized transverse momentum distributions from a global fit of Drell-Yan and semi-inclusive deep-inelastic scattering data

The MAP Collaboration[1]

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arXiv:2210.01733

PHYSICAL REVIEW D **107,** 014014 (2023)

Extraction of pion transverse momentum distributions from Drell-Yan data

Matteo Cerutti,[1,2,*] Lorenzo Rossi,[1,2,†] Simone Venturini,[1,2,‡] Alessandro Bacchetta,[1,2,§] Valerio Bertone,[3,∥] Chiara Bissolotti,[4,¶] and Marco Radici[2,**]

(MAP Collaboration)[††]

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[3] *IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France*
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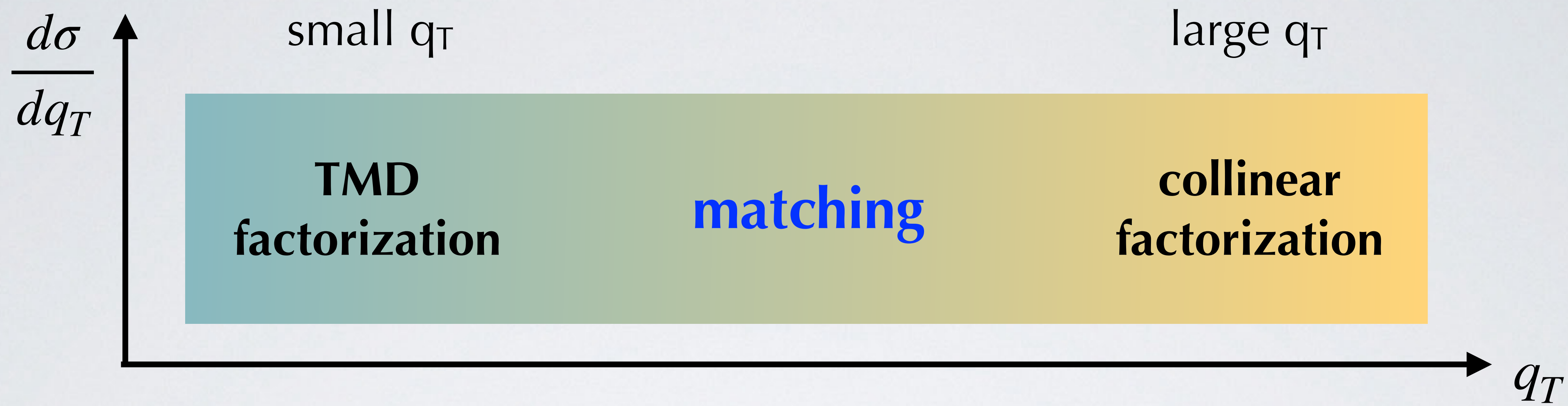
(Received 11 October 2022; accepted 21 December 2022; published 11 January 2023)

We map the distribution of unpolarized quarks inside a unpolarized pion as a function of the quark's transverse momentum, encoded in unpolarized transverse momentum distributions (TMDs). We extract the pion TMDs from available data of unpolarized pion-nucleus Drell–Yan processes, where the cross section is differential in the lepton-pair transverse momentum. In the cross section, pion TMDs are convoluted with nucleon TMDs that we consistently take from our previous studies. We obtain a fairly good agreement with data. We present also predictions for pion-nucleus scattering that is being measured by the COMPASS Collaboration.

DOI: 10.1103/PhysRevD.107.014014

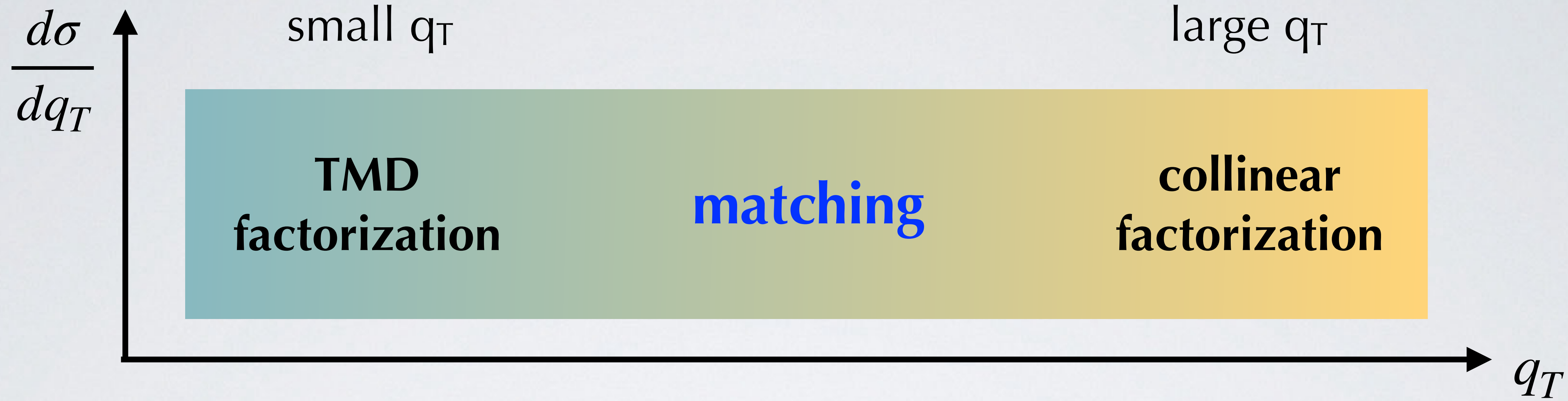
TMD factorization



	$\Lambda_{QCD} \lesssim q_T \ll Q$	$\Lambda_{QCD} \ll q_T \ll Q$	$\Lambda_{QCD} \ll Q \lesssim q_T$	
$+\,\mathcal{O}(q_T^2/Q^2)$	W-term	Y-term $Y(q_T^2, Q^2)$ such that	Fixed-Order (F.O.)	$+\,\mathcal{O}(M^2/q_T^2)$

$$0 \longleftarrow Y \sim (\mathrm{F.O.} - W) \longrightarrow \mathrm{F.O.}$$

TMD factorization



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our analysis is in this regime where W-term dominates.
Y-term is not included

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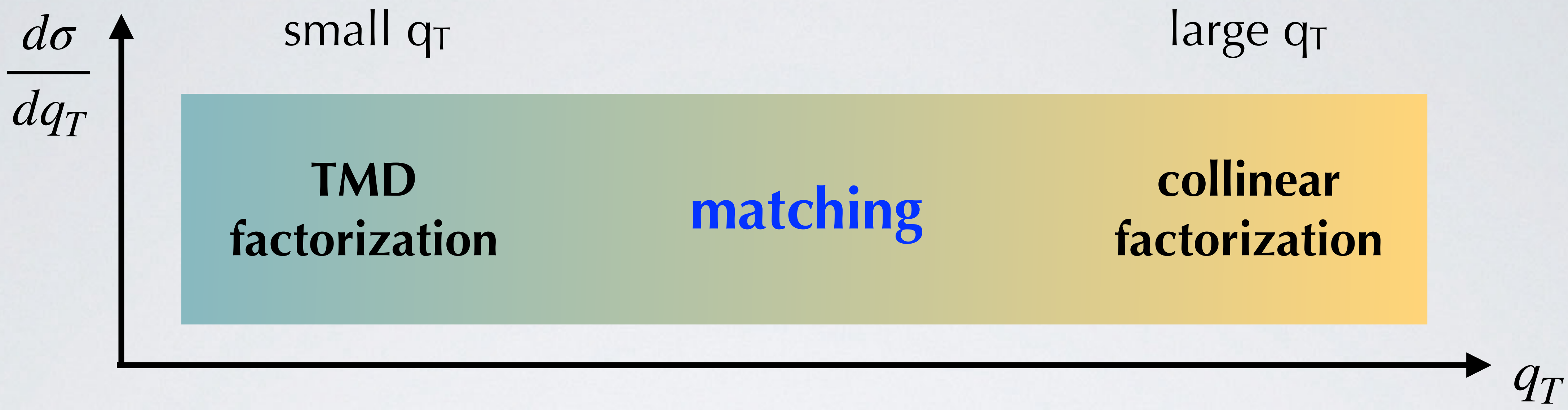

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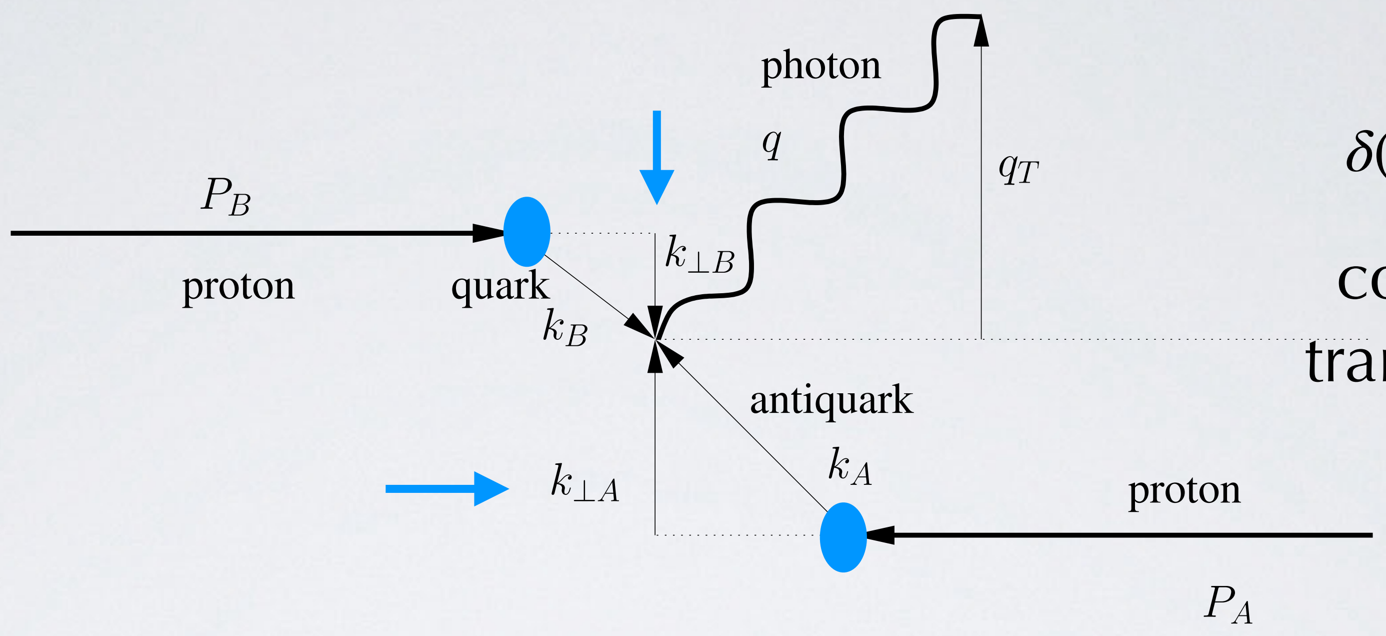
at low Q (SIDIS), these cancelations do not occur: where is the limit for TMD factorization (W) to be valid?

TMD factorization: Drell-Yan

$$M^2 \ll Q^2$$
$$q_T^2 \ll Q^2$$

W-term dominant



$\delta(\mathbf{k}_{\perp A} + \mathbf{k}_{\perp B} - \mathbf{q}_T)$

convolution upon transverse momenta

$$\frac{d\sigma}{dq_T dy dQ} \sim W(x_A, x_B, q_T, Q) \sim \mathscr{H}^{\mathrm{DY}}(Q^2) \left[f_1^{\bar{q}}(x_A, \mathbf{k}_{\perp A}^2; Q^2) \otimes f_1^q(x_B, \mathbf{k}_{\perp B}^2; Q^2) \right]$$

hard factor **TMD PDF anti-q** **TMD PDF q**

TMDs depend on two scales μ, ζ ; can be chosen as $\zeta=\mu^2=Q^2$

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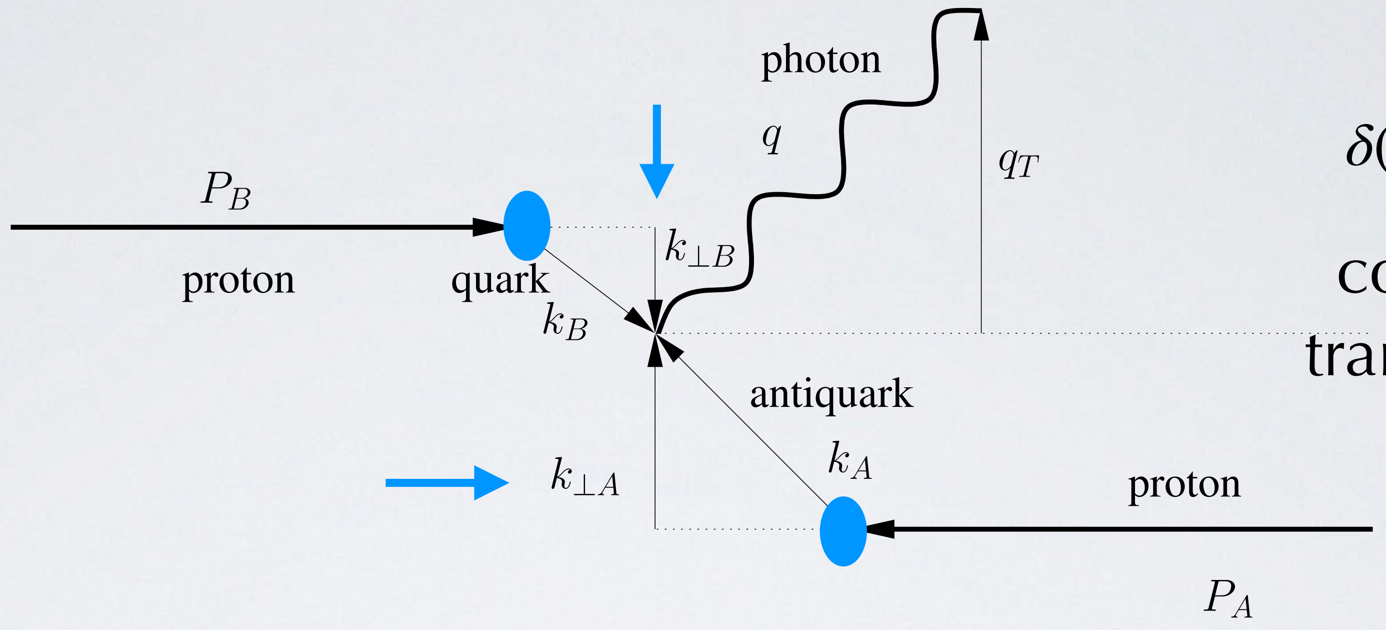

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hard factor **TMD PDF anti-q** **TMD PDF q**

Fourier Transform: from convolution to simple product

$$= \mathscr{H}^{\mathrm{DY}}(Q^2) \frac{1}{2\pi} \int_0^\infty db_T \, b_T \, J_0(b_T, q_T) \; \tilde{f}_1^{\bar{q}}(x_A, b_T^2; Q^2) \; \tilde{f}_1^q(x_B, b_T^2; Q^2)$$

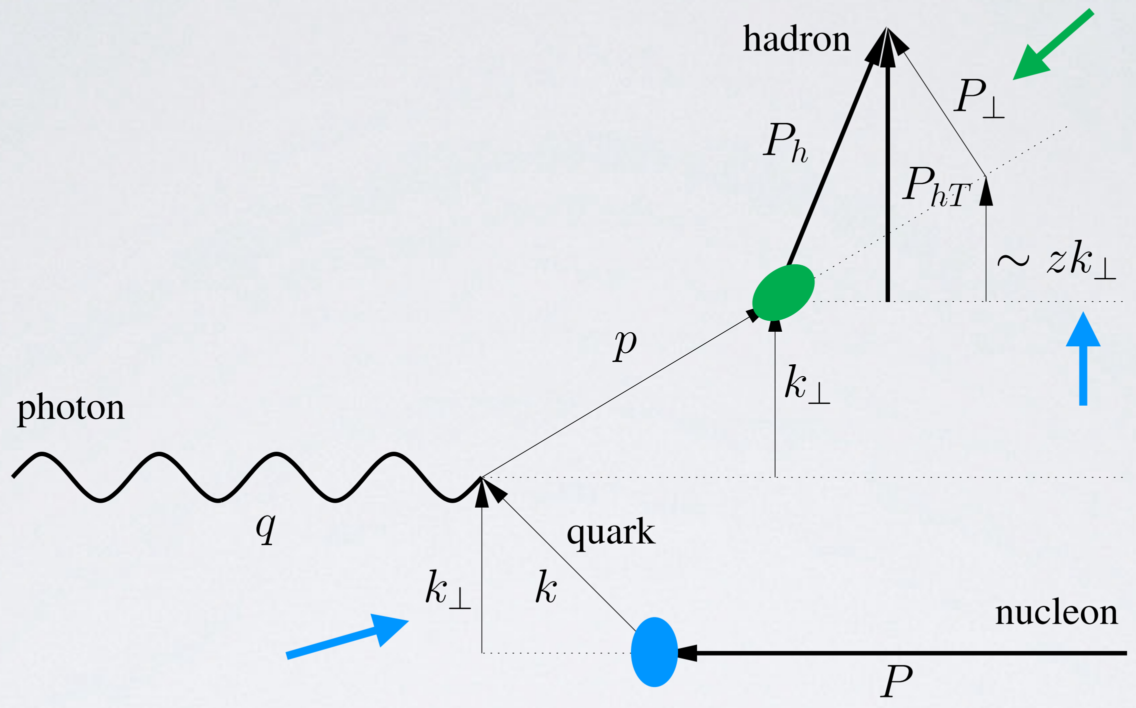
TMDs depend on two scales μ, ζ ; can be chosen as ζ=μ²=Q²

TMD factorization: SIDIS

$$M^2 \ll Q^2$$

$$q_T^2 = \frac{P_{hT}^2}{z^2} \ll Q^2$$

W-term dominant



$$-z\mathbf{q}_T \approx \mathbf{P}_{hT} = z\mathbf{k}_\perp + \mathbf{P}_\perp$$

$$\delta(\mathbf{k}_\perp + \mathbf{P}_\perp/z + \mathbf{q}_T)$$

convolution upon transverse momenta

$$\frac{d\sigma}{dx\,dz\,dq_T\,dQ} \sim W(x,z,q_T,Q) \sim \mathscr{H}^{\mathrm{SIDIS}}(Q^2) \left[f_1^q(x,\mathbf{k}_\perp^2;Q^2) \otimes D_1^{q\to h}(z,\mathbf{P}_\perp^2;Q^2) \right]$$

hard factor | **TMD PDF** | **TMD FF**

Fourier Transform: from convolution to simple product

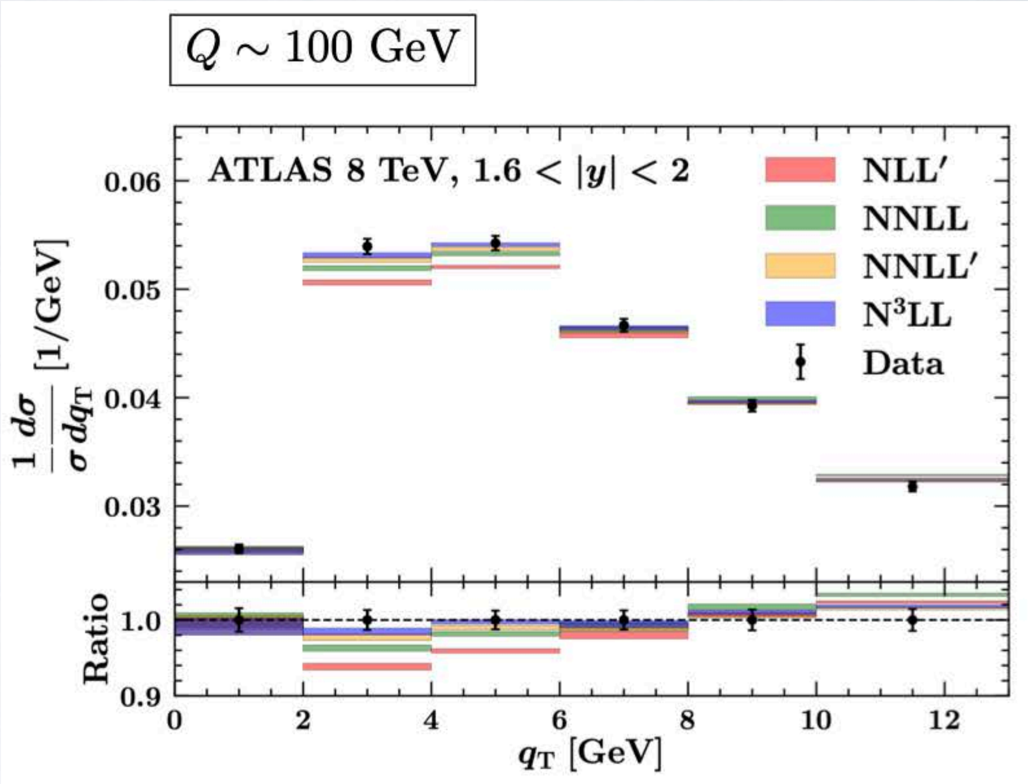
$$= \mathscr{H}^{\mathrm{SIDIS}}(Q^2)\, \frac{1}{2\pi}\int_0^\infty db_T\, b_T\, J_0(b_T,q_T)\;\; \tilde{f}_1^q(x,b_T^2;Q^2)\;\; \tilde{D}_1^{q\to h}(z,b_T^2;Q^2)$$

TMDs depend on two scales μ, ζ ; can be chosen as $\zeta=\mu^2=Q^2$

Normalization problem in SIDIS

increasing perturbative accuracy

increases agreement with Drell-Yan

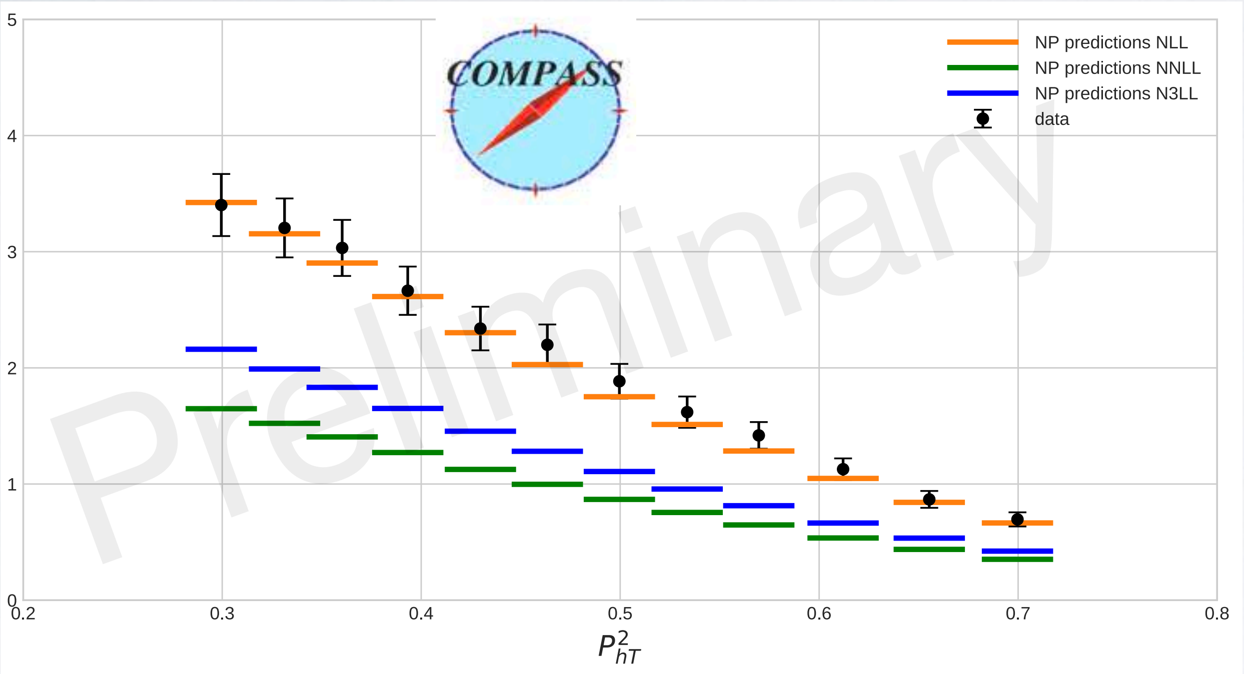


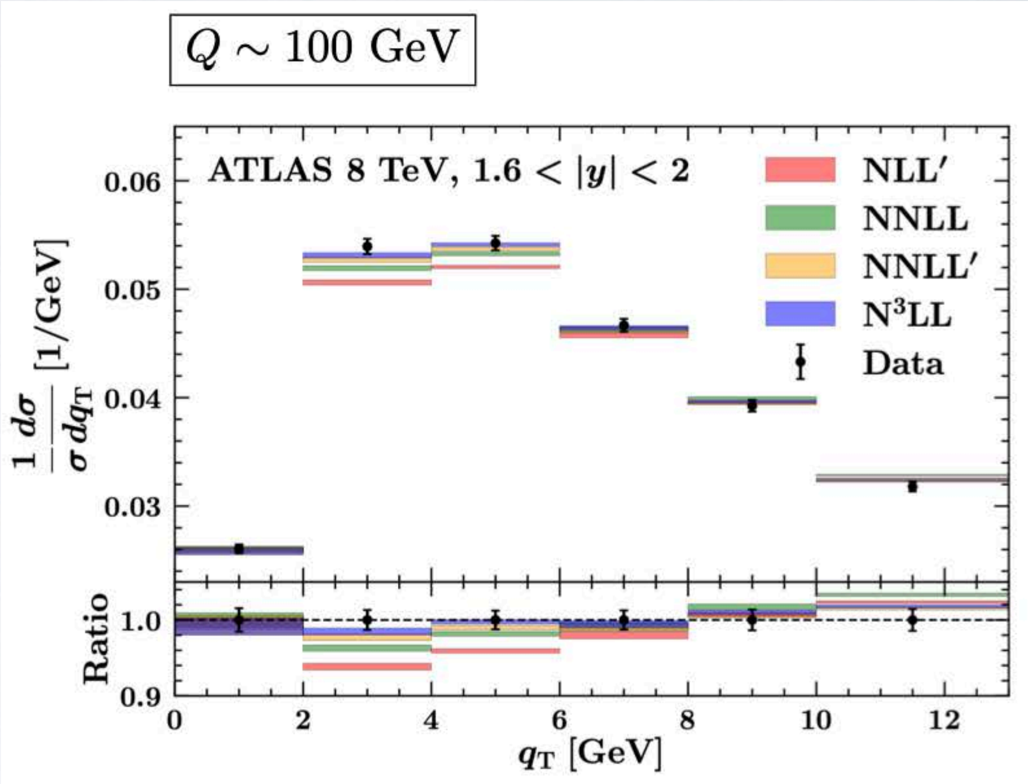
Normalization problem in SIDIS

increasing perturbative accuracy

worsens agreement with SIDIS ! increases agreement with Drell-Yan

$M^h(\bar{x}, \bar{z}, \bar{Q}, P_{hT})$ NLL NNLL N3LL





discrepancy is P_{hT}-independent: $M_{\rm NLL}/M_{\rm NNLL} \sim 2$ $M_{\rm NLL}/M_{\rm N^3LL} \sim 1.5$

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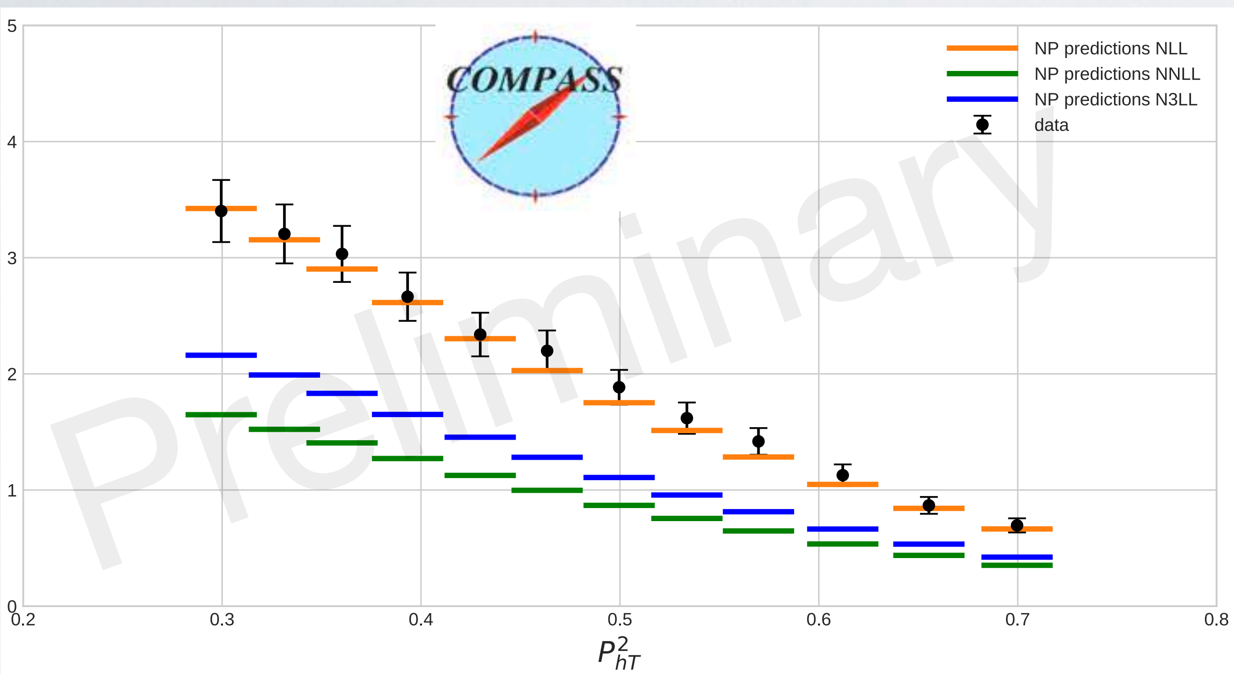
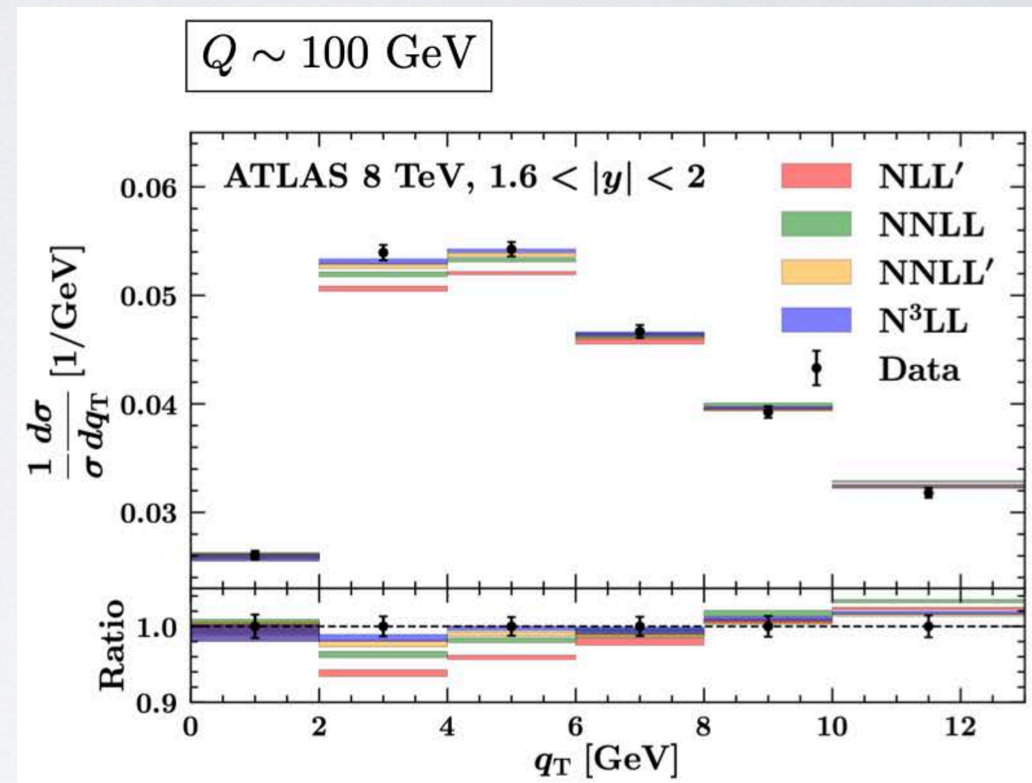
NLL NNLL N3LL





discrepancy is P_{hT}-independent: $M_{\rm NLL}/M_{\rm NNLL} \sim 2$ $M_{\rm NLL}/M_{\rm N^3LL} \sim 1.5$

tensions observed also at larger q_T
and also in Drell-Yan at low Q
and also in e+e- annihilations

Gonzalez et al., P.R. D**98** (18) 114005
Bacchetta et al., P.R. D**100** (19) 014018
Moffat et al., P.R. D**100** (19) 094014

but not in SV 2019 fit

Scimemi & Vladimirov, arXiv:1912.06532

No normalization problems for collinear SIDIS $d\sigma / dxdzdQ$:

MAPFF1.0 (Map Collaboration)

Abdul Khalek et al., arXiv:2105.08725

Normalization problem in SIDIS

at NLL, $\mathscr{H}^{\text{SIDIS}} \approx 1$

the integrated W-term reproduces the SIDIS collinear dσ at LO, which reasonably describes data

$$\int dq_T \frac{d\sigma}{dx dz dq_T dQ} = \int dq_T W\Big|_{\text{NLL}} \propto f_1^q(x,Q)\, D_1^{q\to h}(z,Q)$$

$$= \frac{d\sigma}{dx dz dQ}\Big|_{\text{LO}}$$

De Florian et al., P.R. D**75** (07) 114010

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De Florian et al., P.R. D**75** (07) 114010

at higher orders, $\mathscr{H}^{\text{SIDIS}} = 1 + c_1\alpha_S + \ldots \quad c_1 < 0$ spoils agreement

the integrated W-term contains only some terms of the SIDIS collinear dσ

$$\int dq_T W\Big|_{\text{NNLL}} \neq \frac{d\sigma}{dxdzdQ}\Big|_{\text{NLO}}$$

Y-term $\not\to 0$

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$$\int dq_T W\Big|_{\text{NNLL}} \neq \frac{d\sigma}{dxdzdQ}\Big|_{\text{NLO}}$$

Y-term $\not\to 0$

We define the normalization factor

$$\omega(x,z,Q) = \frac{d\sigma_{\text{nomix}}}{dxdzdQ} \Big/ \int d\mathbf{q}_T W \qquad = 1 \quad \text{at NLL}$$

includes all NLO terms where
x- and *z*-dependence can be factorized
→ includes W + part of the *Y* term…

Does not depend on fit parameters, precomputed

Scale dependence of TMD

$$f_1^q(x, b_T^2; \mu_f, \zeta_f) = \sum_i \left[C_{q\to i}(x, b_T^2; \mu_{b_*}) \otimes f_1^i(x, \mu_{b_*})\right]$$

matching collinear PDF at small b_T

$$\times \exp\left[S(\mu_f, \mu_{b_*})\right]$$

Sudakov: evolution in μ scale; contains anomalous dimensions γ_F , γ_K

$$\times \left[\frac{\zeta_f}{\mu_{b_*}^2}\right]^{K(b_*,\mu_{b_*})/2}$$

evolution in ζ scale; contains Collins-Soper kernel K

perturbative

perturbative accuracy	α_S^n: $\mathscr{H}$ and C	K and γ_F	γ_K	PDF and α_S evol.	FF
LL	0	-	1	-	-
NLL	0	1	2	LO	LO
NLL'	1	1	2	NLO	NLO
NNLL	1	2	3	NLO	NLO
NNLL'	2	2	3	NNLO	NNLO
N^{3}LL	2	3	4	NNLO	NNLO NLO
N^{3}LL'	3	3	4	N^{3}LO	N^{3}LO

FF at NNLO not yet implemented

Borsa et al., P.R.L. **129** (22) 012002 arXiv:2202.05060

Abdul Khalek et al., P.L. **B834** (22) 137456 arXiv:2204.10331

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nonperturbative Collins-Soper kernel (arbitrary Q_0=1 GeV)

$$\times f_{\rm NP}(x, b_T; Q_0)$$

nonperturbative TMD at initial (arbitrary) scale Q_0

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$$\mu_f \geq \mu_{b_*} = \frac{2e^{-\gamma_E}}{b_*(b_T)} \geq 1$$

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N^3LL	2	3	4	NNLO	NNLO NLO
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Most recent extractions of unpolarized TMD f_1

		SIDIS					
	Accuracy	HERMES	COMPASS	DY	Z production	N of points	χ^2/N_{points}
PV 2017 arXiv:1703.10157	NLL	✔	✔	✔	✔	8059	1.5
SV 2017 arXiv:1706.01473	NNLL'	✘	✘	✔	✔	309	1.23
BSV 2019 arXiv:1902.08474	NNLL'	✘	✘	✔	✔	457	1.17
SV 2019 arXiv:1912.06532	N^3LL	✔	✔	✔	✔	1039	1.06
PV 2019 arXiv:1912.07550	N^3LL	✘	✘	✔	✔	353	1.07
SV19 + flavor dep. arXiv:2201.07114	N^3LL	✘	✘	✔	✔	309	<1.08>
MAPTMD 2022 arXiv:2206.07598	N^3LL	✔	✔	✔	✔	2031	1.06
ART23 arXiv:2305.07473	N^4LL	✘	✘	✔	✔	627	0.96

increasing precision & accuracy

Most recent extractions of unpolarized TMD f_1

SIDIS

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SV 2019 arXiv:1912.06532	N^3LL	✔	✔	✔	✔	1039	1.06
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increasing accuracy & precision

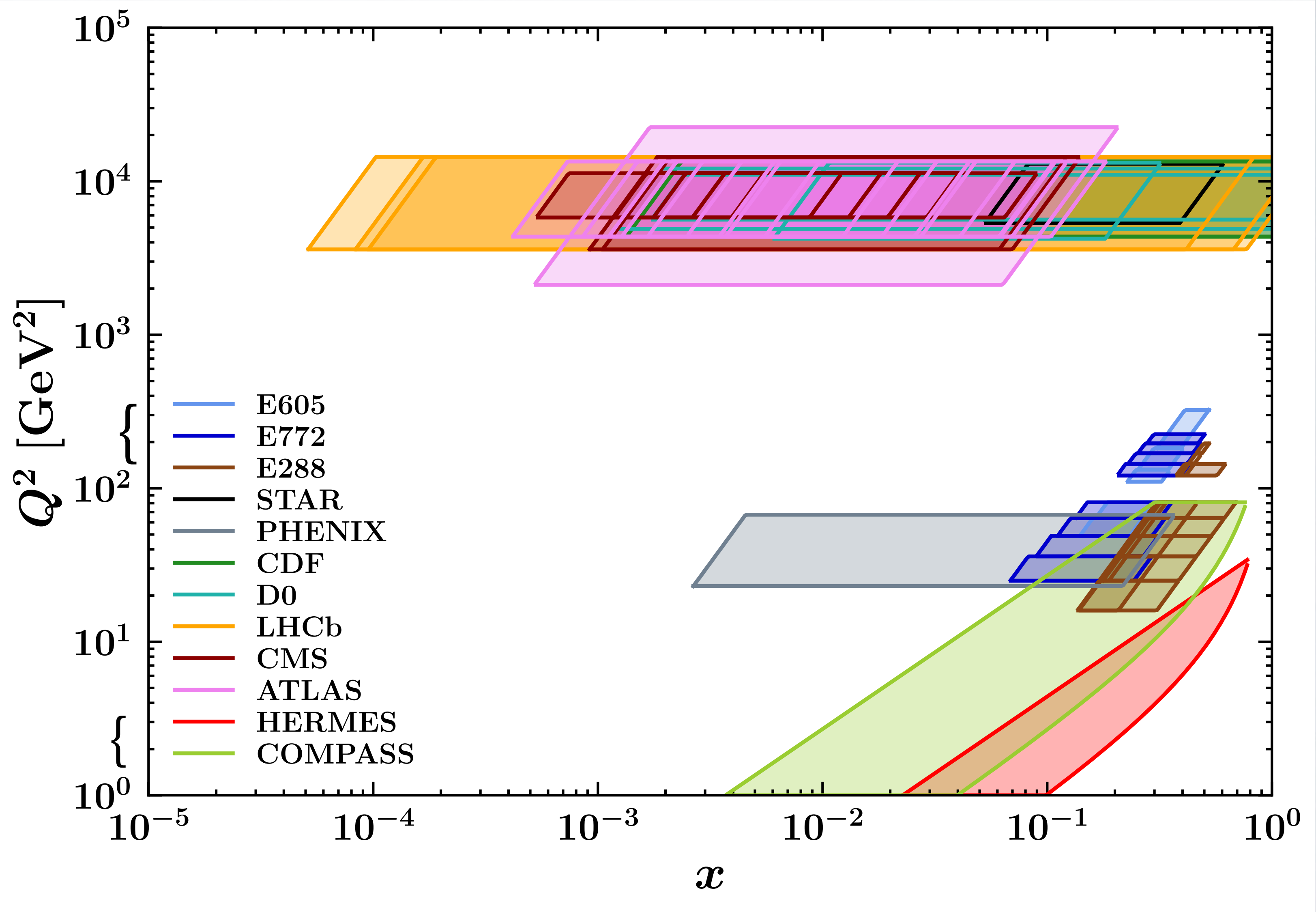
only three global fits

Main features of MAPTMD22 fit

- global fit of Drell-Yan and SIDIS data with
  - largest number of data points: **2031**
  - highest perturbative accuracy: **N³LL**
    (with FF currently only at NLO)
- prescription to fix SIDIS normalization problem beyond NLL (effectively introducing part of Y-term)
- number of fitted parameters: **21**
- extremely good description: $\chi^2 / N_{data} = 1.06$
- account of correlated (exp. and th.) errors with nuisance parameters, including PDF & FF uncertainties

PDF → MMHT2014 FF → DSS14 (π), DSS17 (K)

The MAPTMD22 data sets



N_{data} after cuts

Drell Yan { 233 fixed target
251 collider

1547 SIDIS

<u>2031 data points</u>

kinematic cuts

$\langle Q \rangle > 1.4$ GeV

$0.2 < z < 0.7$

Drell-Yan $q_T < 0.2\,Q$

SIDIS $P_{hT} < \min\left[\min\left[0.2\,Q,\, 0.5\,Qz\right] + 0.3\,\text{GeV},\, zQ\right]$

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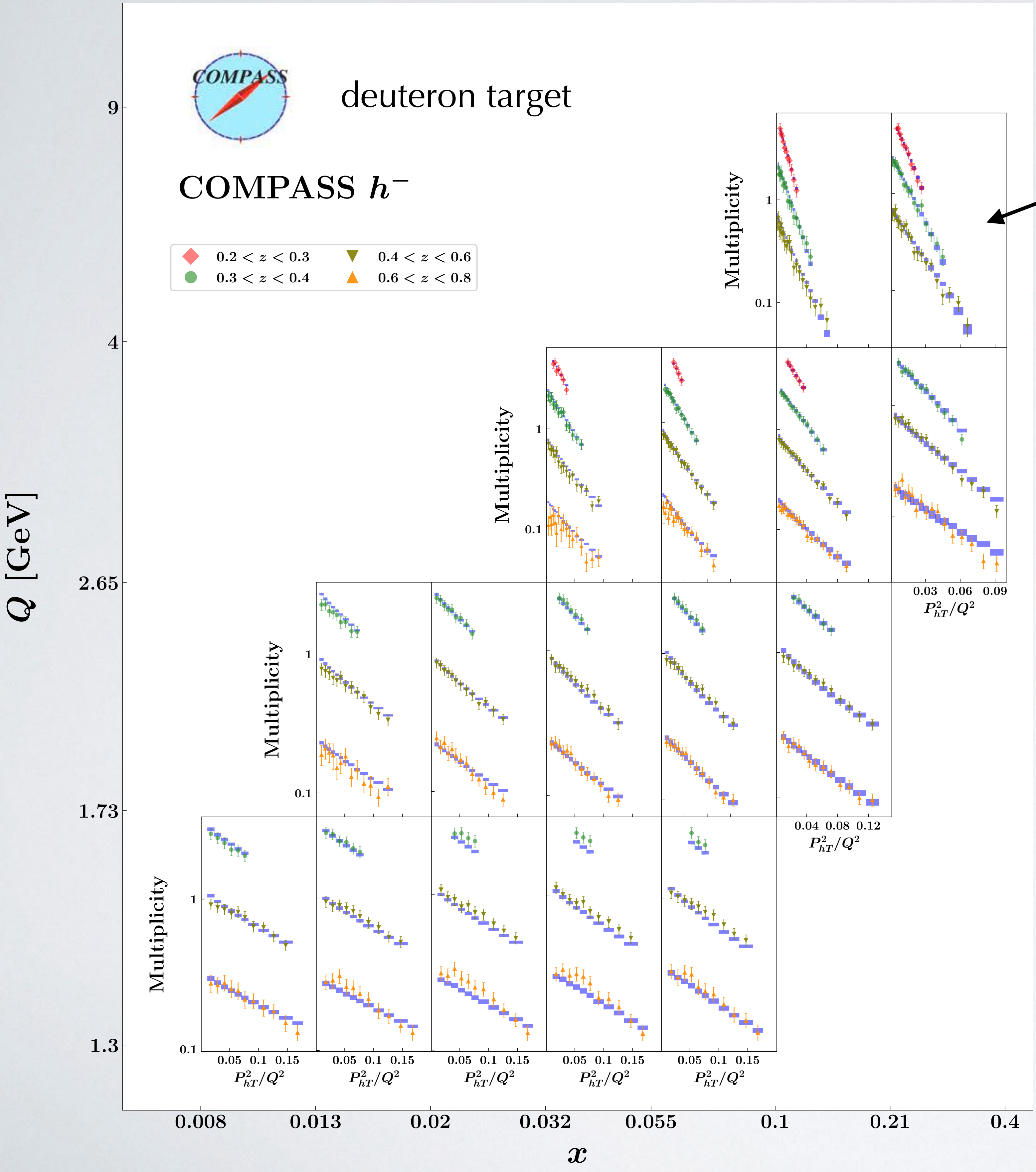
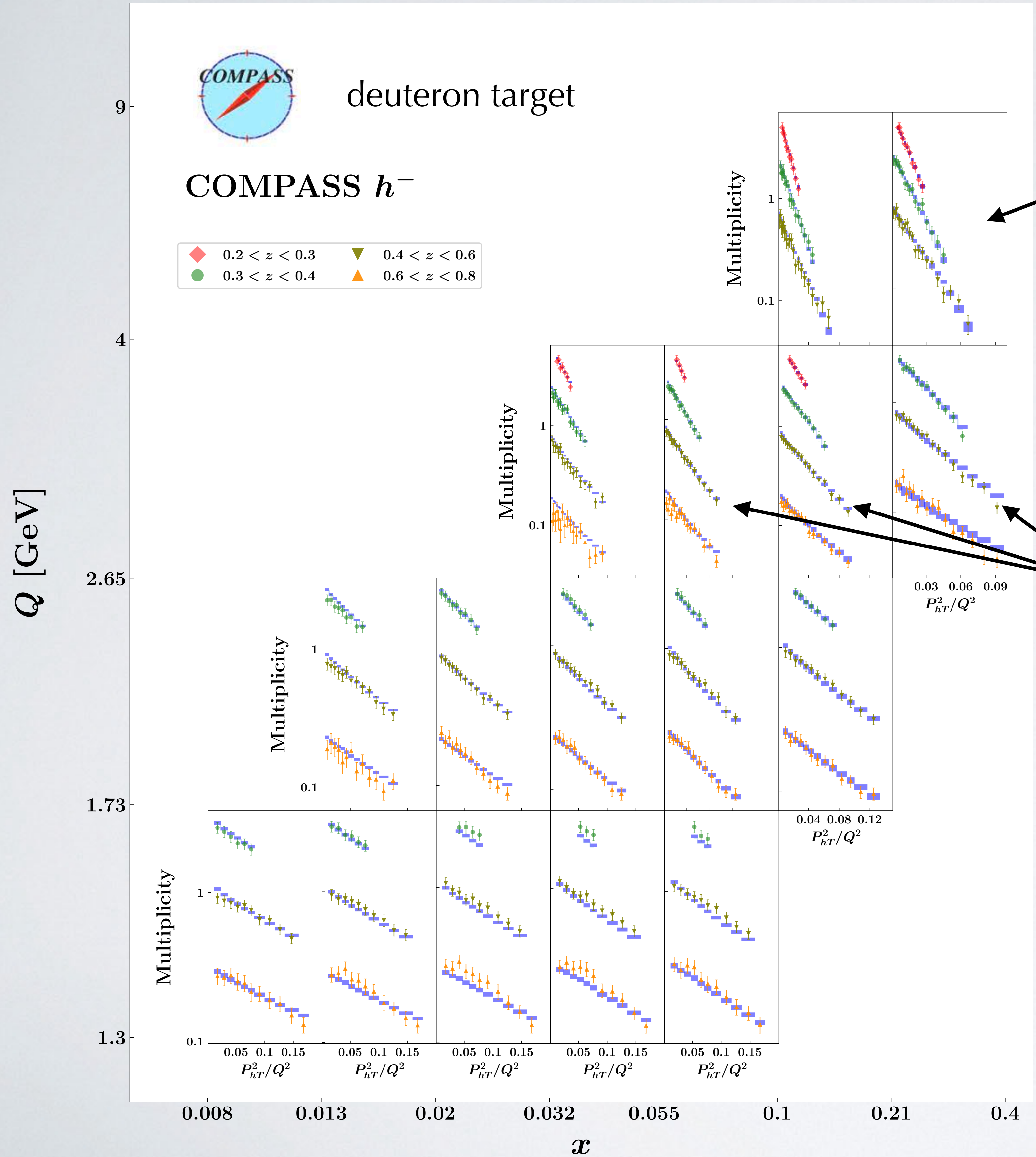
Data-driven nonperturbative TMD



at given (x,Q²), different slopes for different z

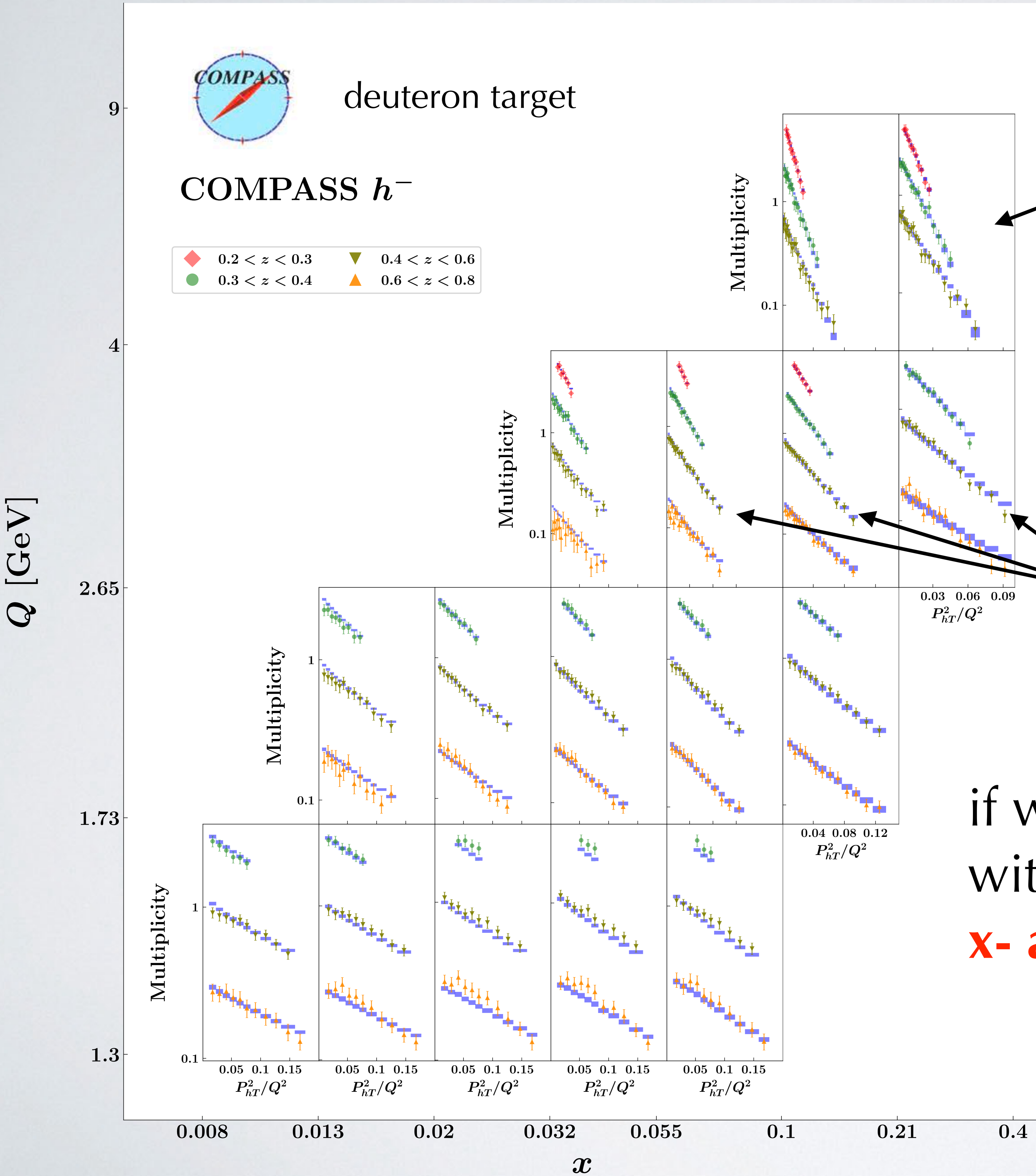
Data-driven nonperturbative TMD



at given (x,Q[2]),
different slopes for different z

at given z,
different slopes for different x

Data-driven nonperturbative TMD



at given (x,Q²),
different slopes for different z

at given z,
different slopes for different x

if we model nonperturbative TMDs with Gaussians, we need
x- and z-dependent widths!

Parametrization of non-perturbative TMD

nonperturbative TMD PDF
Fourier Transform of sum of 3 Gaussians with x-dependent widths

$$f_{\rm NP}(x, b_T; Q_0)$$
$$= {\rm F.T.}\left(e^{-k_\perp^2 / g_{1A}(x)} + \lambda_B k_\perp^2 e^{-k_\perp^2 / g_{1B}(x)} + \lambda_C e^{-k_\perp^2 / g_{1C}(x)}\right)$$

with $$g_{1X}(x) = N_{1X} \frac{(1-x)^{\alpha_X^2} x^{\sigma_X}}{(1-\hat{x})^{\alpha_X^2} \hat{x}^{\sigma_X}}$$ $\hat{x} = 0.1$

11 param.

Parametrization of non-perturbative TMD

nonperturbative TMD PDF
Fourier Transform of sum of 3 Gaussians with x-dependent widths

$$f_{\mathrm{NP}}(x, b_T; Q_0)$$
$$= \mathrm{F.T.}\left(e^{-k_\perp^2 / g_{1A}(x)} + \lambda_B\, k_\perp^2 e^{-k_\perp^2 / g_{1B}(x)} + \lambda_C e^{-k_\perp^2 / g_{1C}(x)}\right)$$

with $g_{1X}(x) = N_{1X} \dfrac{(1-x)^{\alpha_X^2}\, x^{\sigma_X}}{(1-\hat{x})^{\alpha_X^2}\, \hat{x}^{\sigma_X}}$ $\quad \hat{x} = 0.1$

11 param.

nonperturbative TMD FF
Fourier Transform of sum of 2 Gaussians with z-dependent widths

$$D_{\mathrm{NP}}(z, b_T; Q_0)$$
$$= \mathrm{F.T.}\left(e^{-P_\perp^2 / g_{3A}(z)} + \lambda_F\, P_\perp^2 e^{-P_\perp^2 / g_{3B}(z)}\right)$$

9 param.

with $g_{3X}(z) = N_{3X} \dfrac{(1-z)^{\gamma_X^2}\,(z^{\beta_X} + \delta_X^2)}{(1-\hat{z})^{\gamma_X^2}\,(\hat{z}^{\beta_X} + \delta_X^2)}$ $\quad \hat{z} = 0.5$

Parametrization of non-perturbative TMD

nonperturbative TMD PDF
Fourier Transform of sum of 3 Gaussians with x-dependent widths

$$f_{\rm NP}(x, b_T; Q_0) = {\rm F.T.}\left(e^{-k_\perp^2 / g_{1A}(x)} + \lambda_B k_\perp^2 e^{-k_\perp^2 / g_{1B}(x)} + \lambda_C e^{-k_\perp^2 / g_{1C}(x)}\right)$$

with $$g_{1X}(x) = N_{1X} \frac{(1-x)^{\alpha_X^2} x^{\sigma_X}}{(1-\hat{x})^{\alpha_X^2} \hat{x}^{\sigma_X}} \qquad \hat{x} = 0.1$$

11 param.

nonperturbative TMD FF
Fourier Transform of sum of 2 Gaussians with z-dependent widths

$$D_{\rm NP}(z, b_T; Q_0) = {\rm F.T.}\left(e^{-P_\perp^2 / g_{3A}(z)} + \lambda_F P_\perp^2 e^{-P_\perp^2 / g_{3B}(z)}\right)$$

with $$g_{3X}(z) = N_{3X} \frac{(1-z)^{\gamma_X^2} (z^{\beta_X} + \delta_X^2)}{(1-\hat{z})^{\gamma_X^2} (\hat{z}^{\beta_X} + \delta_X^2)} \qquad \hat{z} = 0.5$$

9 param.

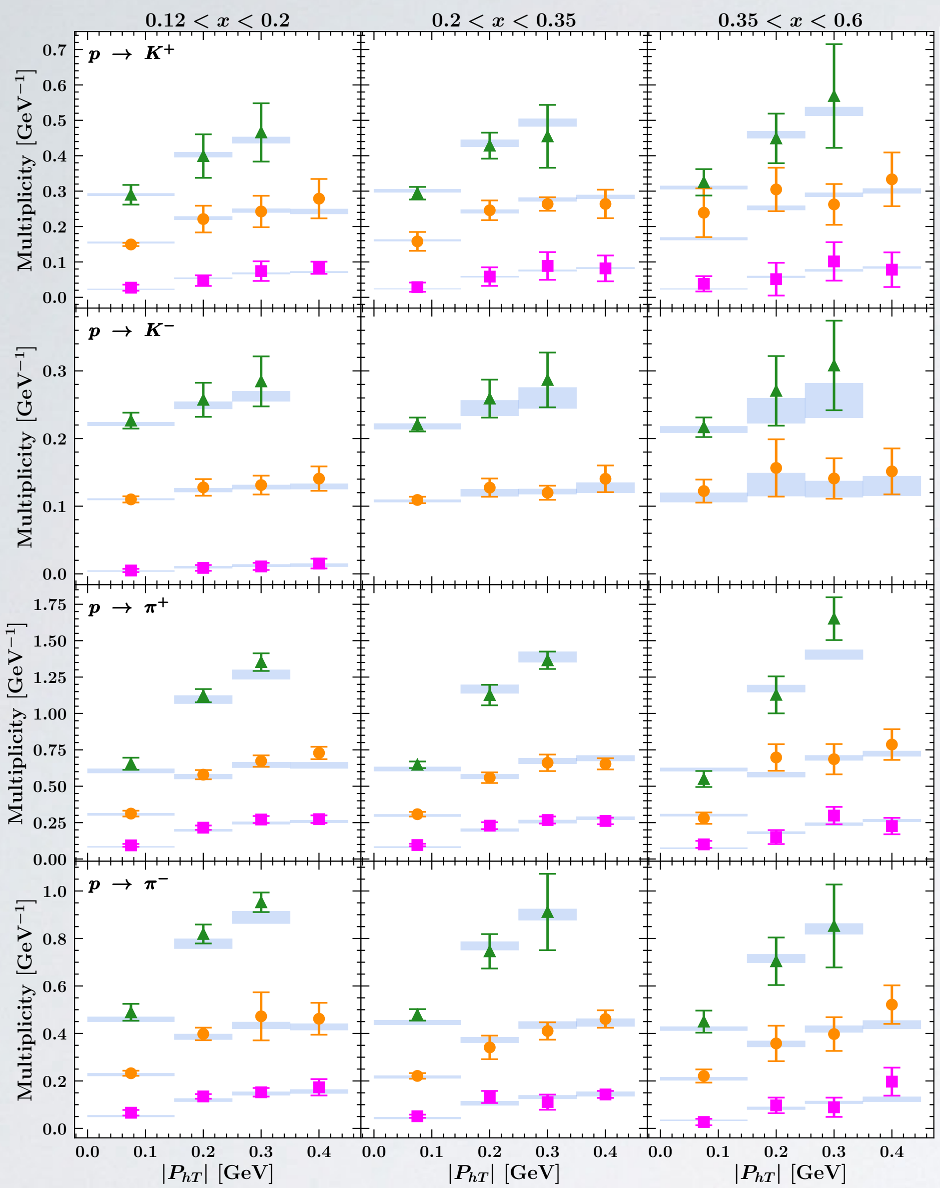
nonperturbative part of Collins-Soper kernel

$$\left[\frac{\zeta_f}{Q_0^2}\right]^{g_K(b_T)/2} \qquad g_K(b_T) = -g_2^2 \frac{b_T^2}{4}$$

1 param.

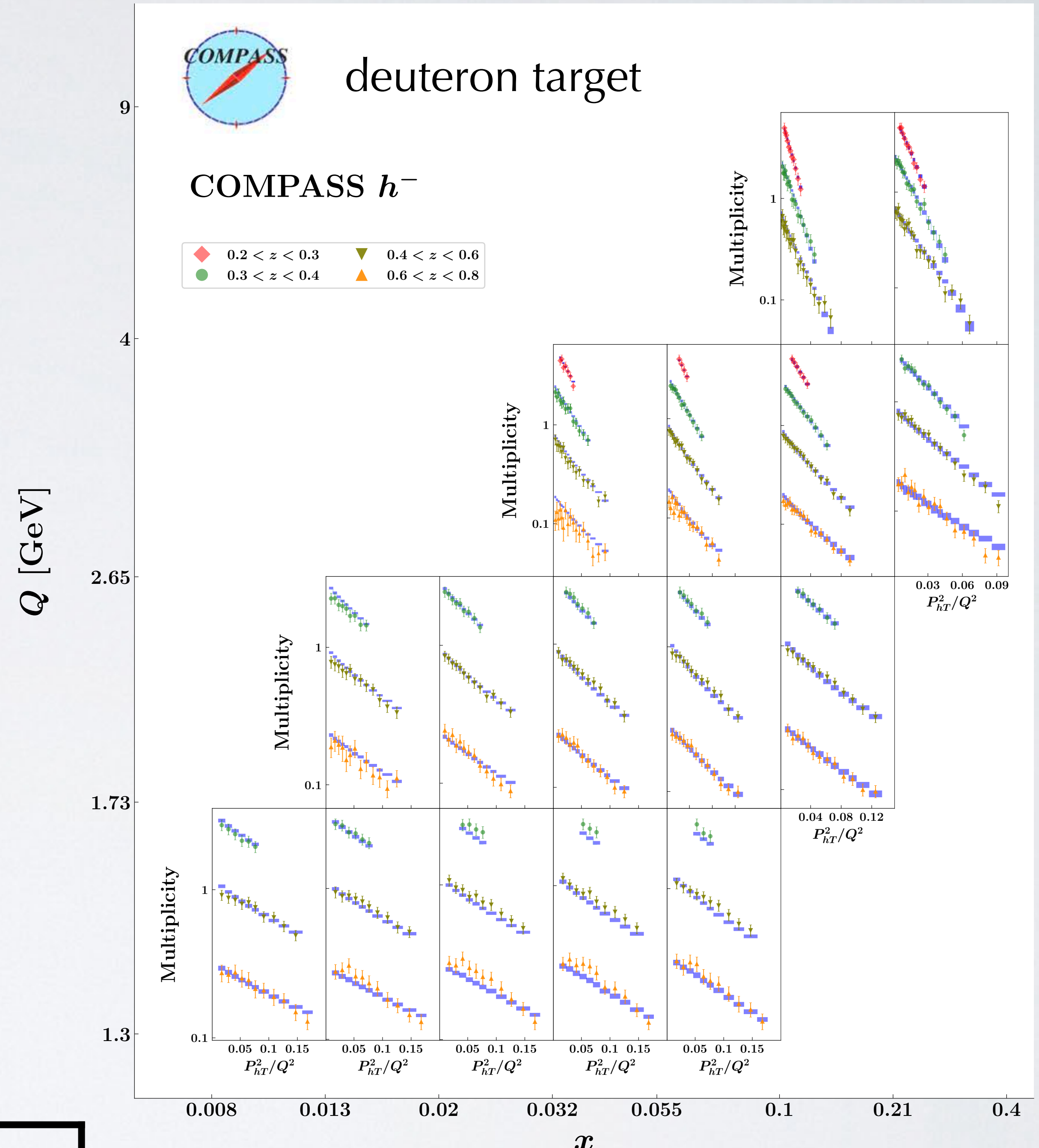
Total 21 param.

Fit results for SIDIS



proton target

0.375 < z < 0.475 (offset = 0.2) 0.475 < z < 0.6 (offset = 0.1) 0.6 < z < 0.8 (offset = 0)



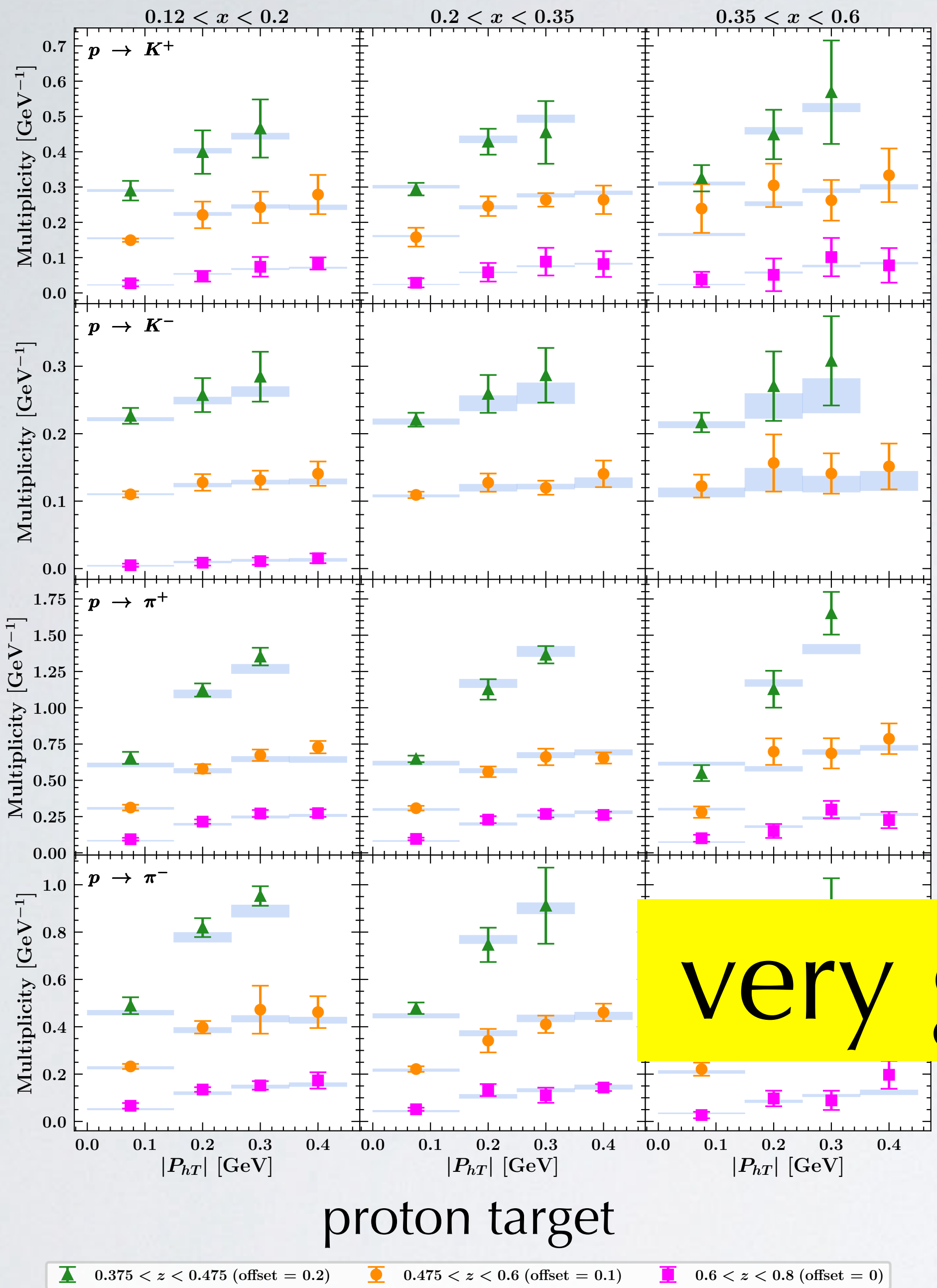
data set	N_{data}	χ^2_D	χ^2_λ	χ^2
HERMES	344	0.48	0.23	0.71
COMPASS	1203	0.62	0.3	0.92
SIDIS total	1547	0.59	0.28	0.87

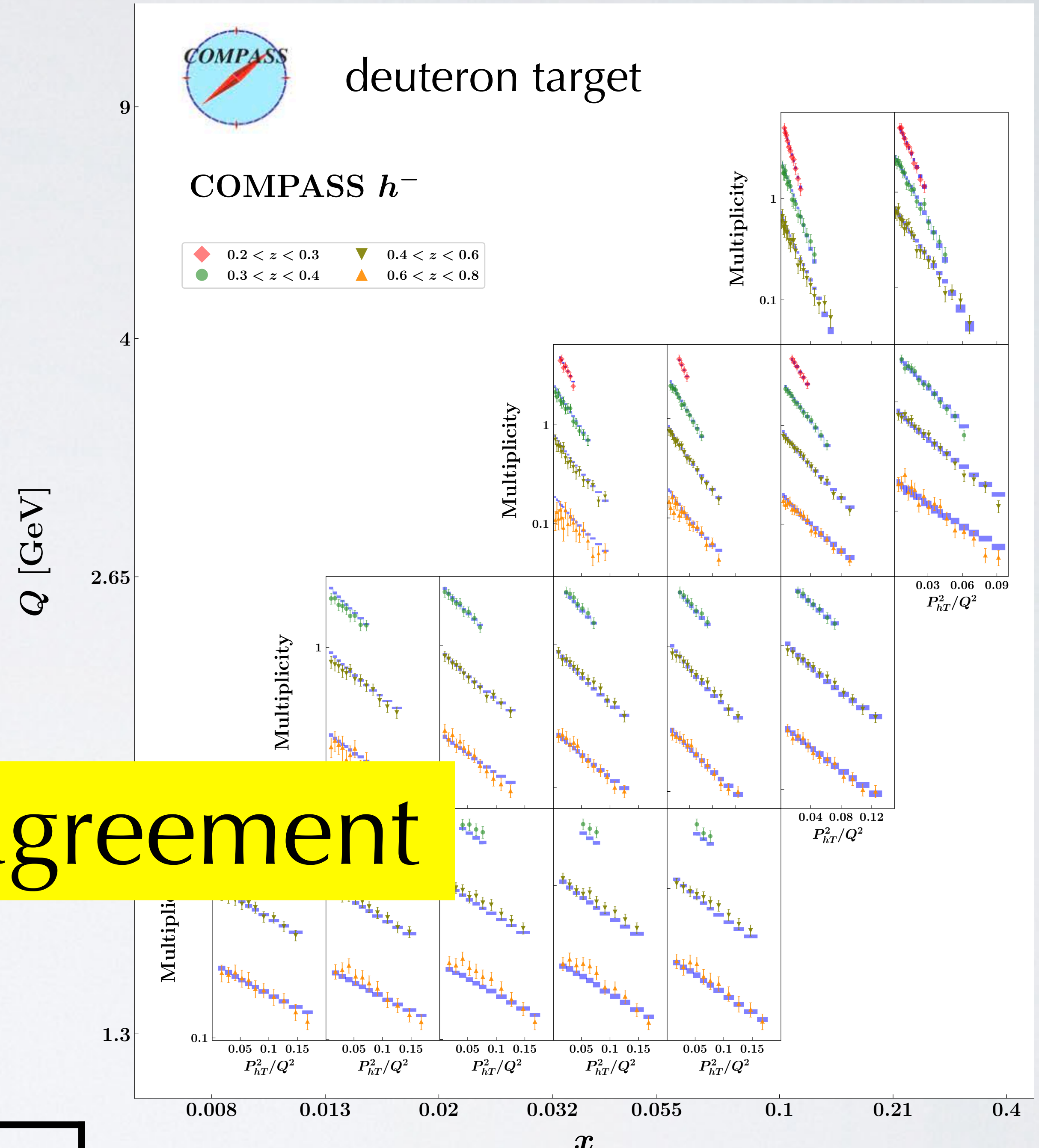
χ_D^2 = uncorrelated error

χ_λ^2 = correlated error

$\chi^2 = \chi_D^2 + \chi_\lambda^2$

Fit results for SIDIS





very good agreement

data set	$N_{\rm data}$	χ^2_D	χ^2_λ	χ^2
HERMES	344	0.48	0.23	0.71
COMPASS	1203	0.62	0.3	0.92
SIDIS total	1547	0.59	0.28	0.87

χ_D^2 = uncorrelated error

χ_λ^2 = correlated error

$\chi^2 = \chi_D^2 + \chi_\lambda^2$

Fit results for fixed-target Drell-Yan

data set	N_{data}	χ^2_D	χ^2_λ	χ^2
SIDIS total	1547	0.59	0.28	0.87
Drell-Yan fixed target tot	233	0.84	0.4	1.24
Drell-Yan collider total	251	1.86	0.2	2.06

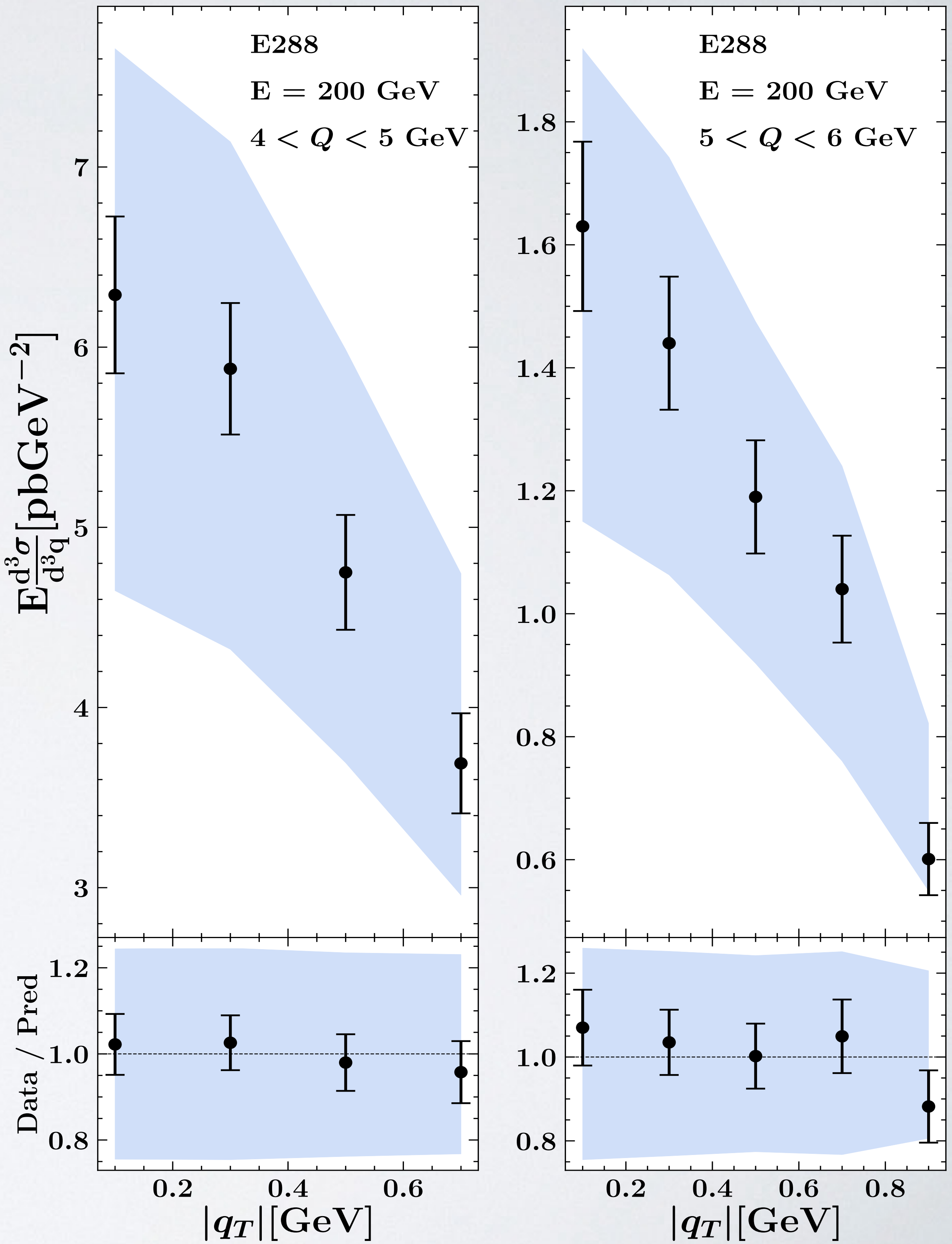
χ_D^2 = uncorrelated error

χ_λ^2 = correlated error

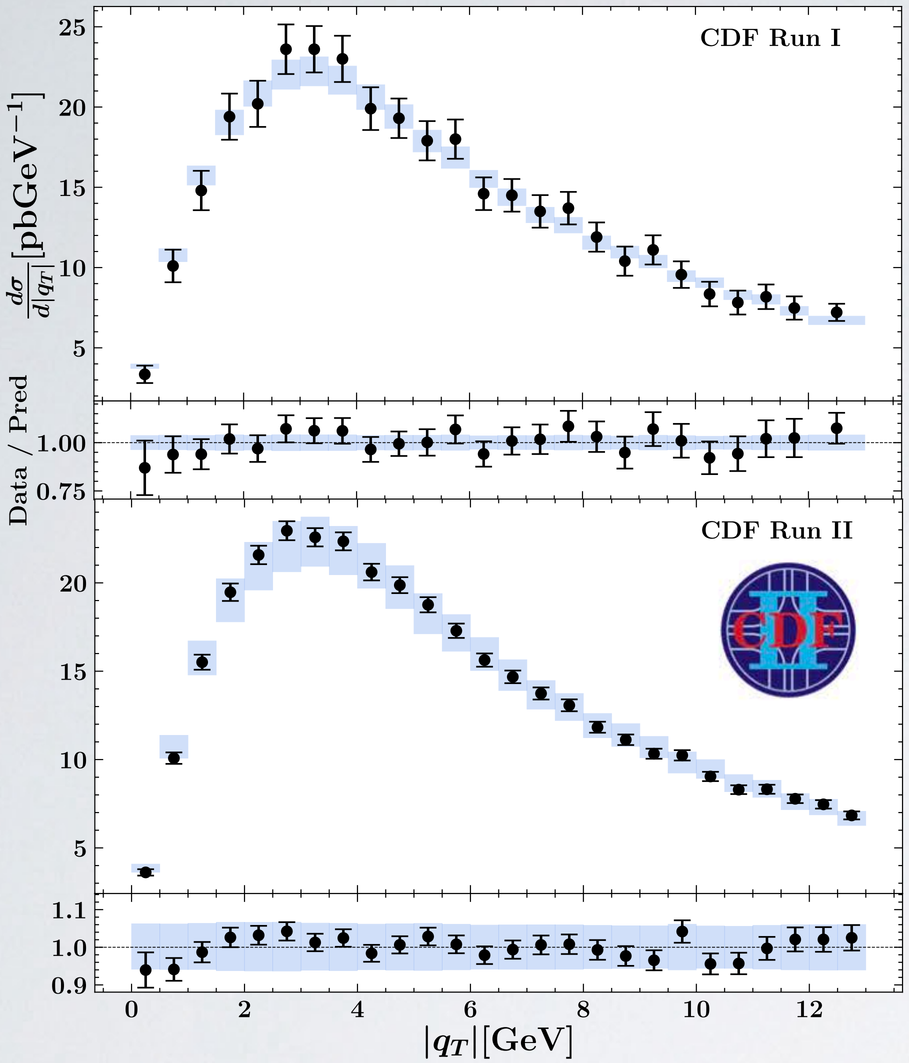
$\chi^2 = \chi_D^2 + \chi_\lambda^2$

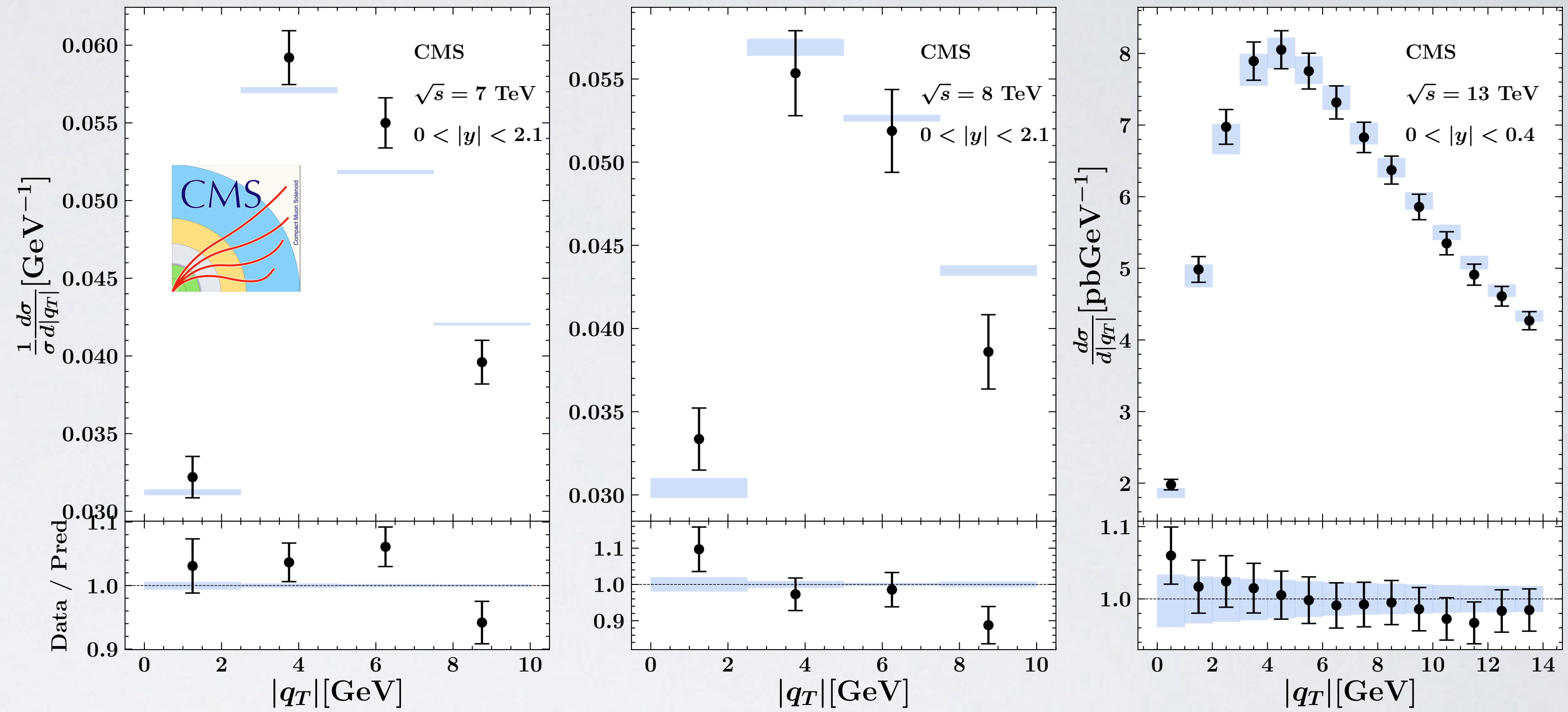
good agreement

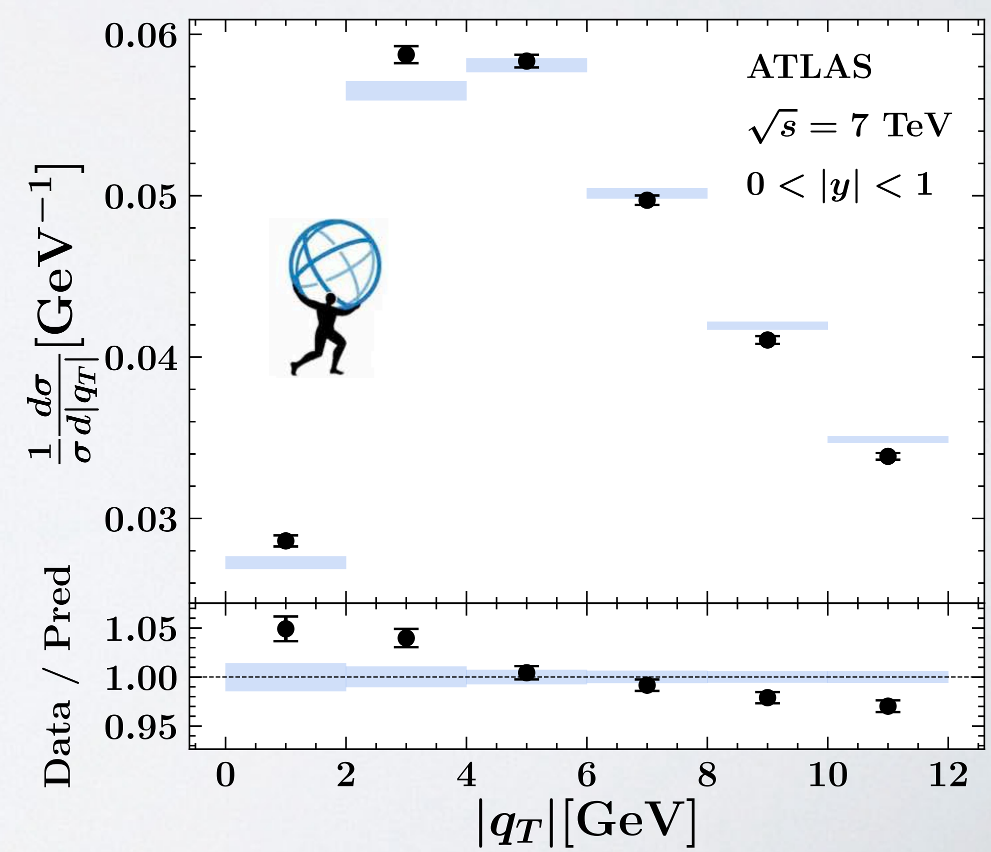
th. error band =
68% of all replicas



Fit results for collider Drell-Yan







data set	N_{data}	χ^2_D	χ^2_λ	χ^2
SIDIS total	1547	0.59	0.28	0.87
Drell-Yan fixed target tot	233	0.85	0.4	1.24
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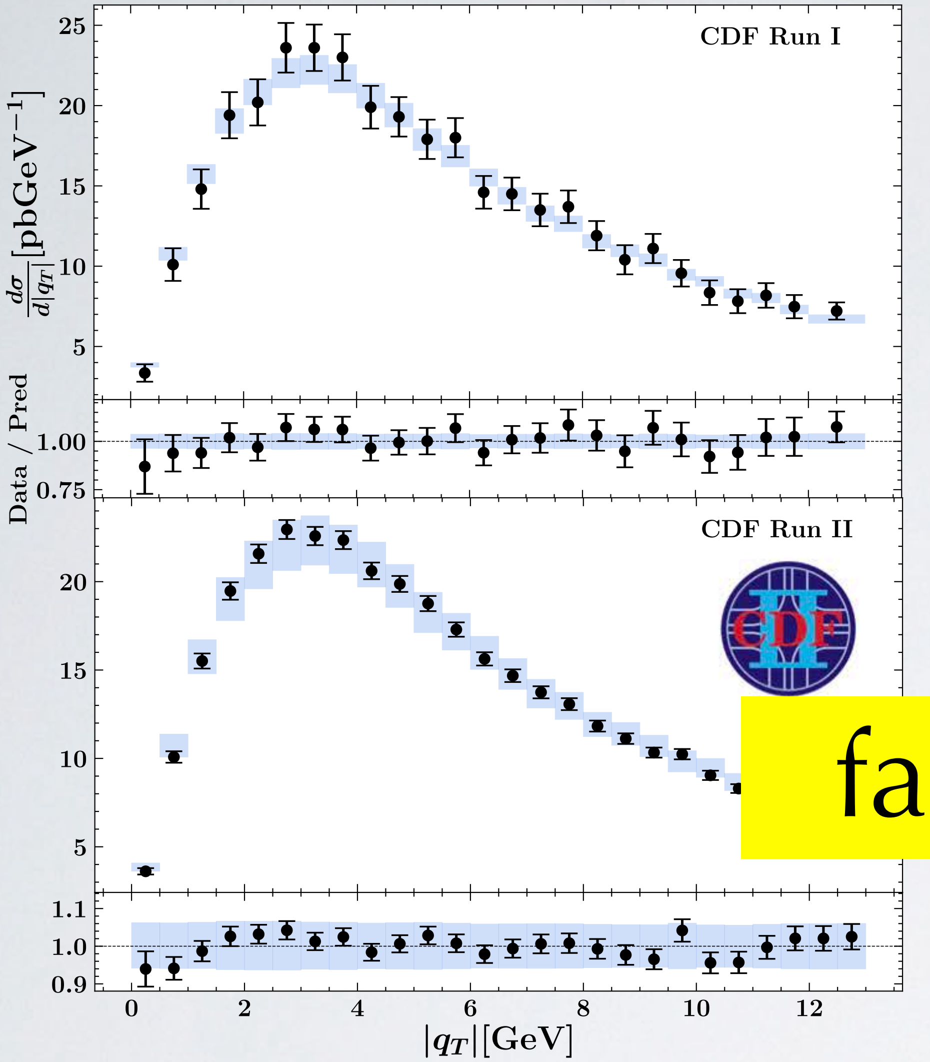
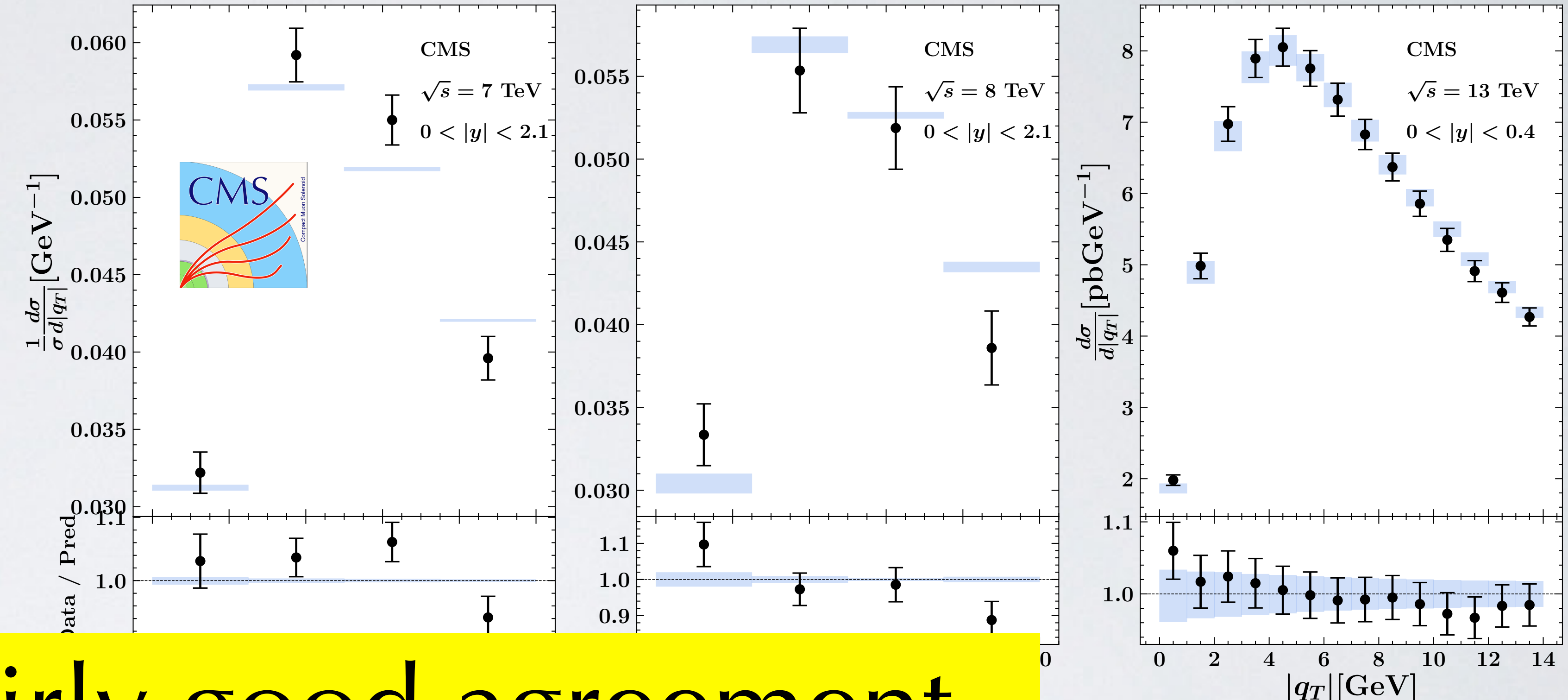
ATLAS total	72	4.56	0.48	5.05

Fit results for collider Drell-Yan





fairly good agreement

data set	N_{data}	χ^2_D	χ^2_λ	χ^2
SIDIS total	1547	0.59	0.28	0.87
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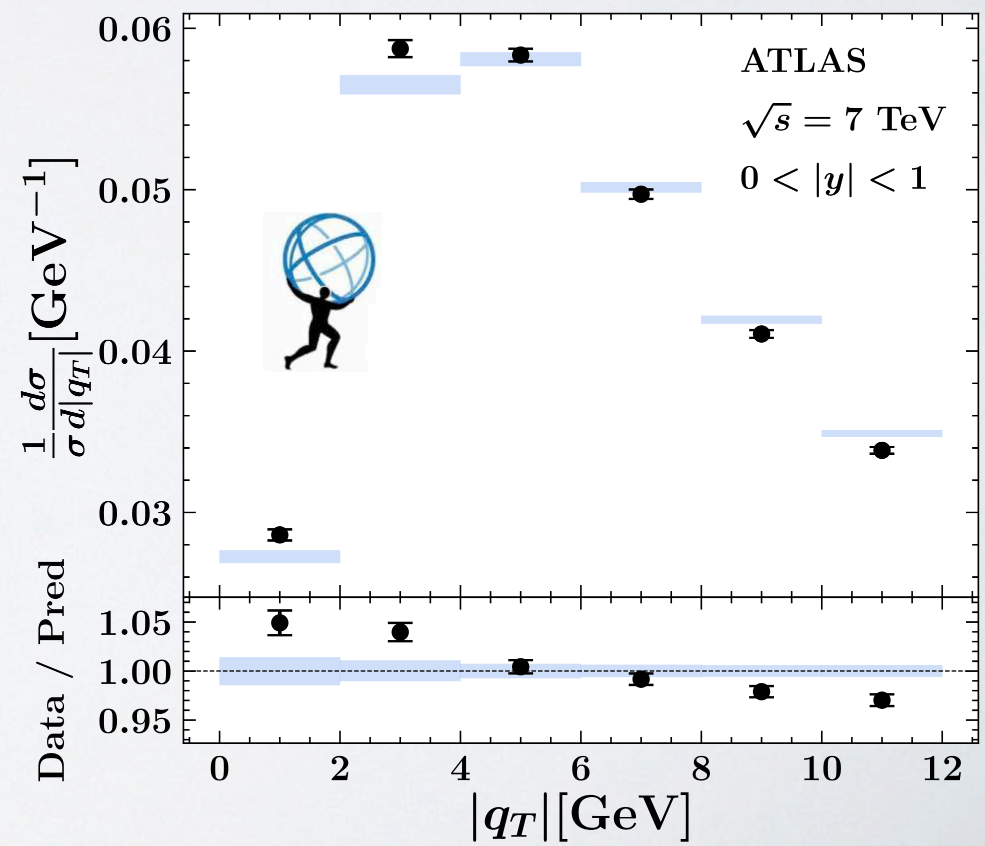
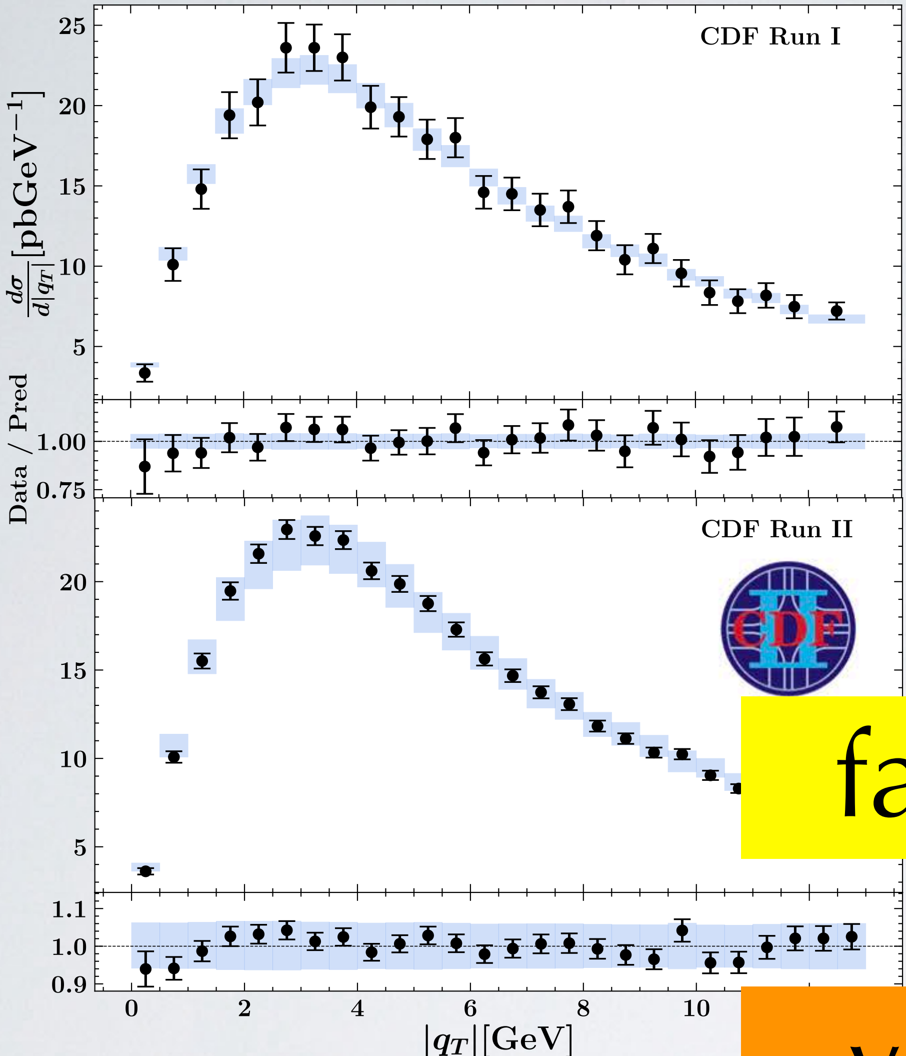
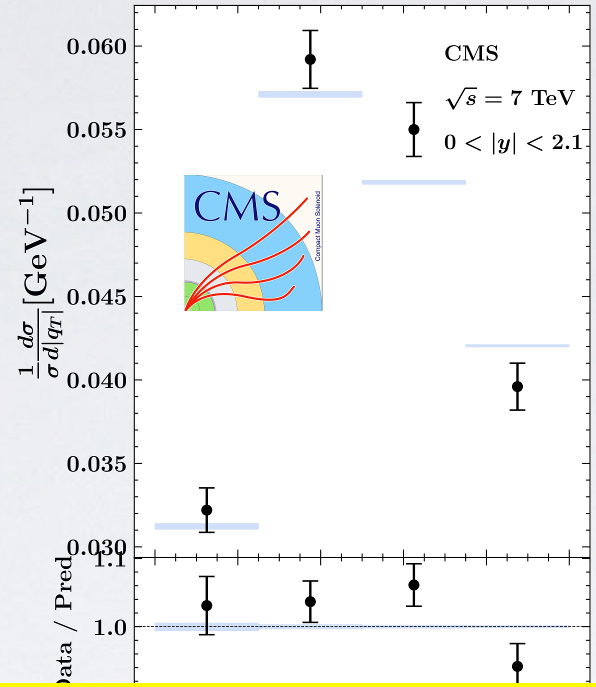
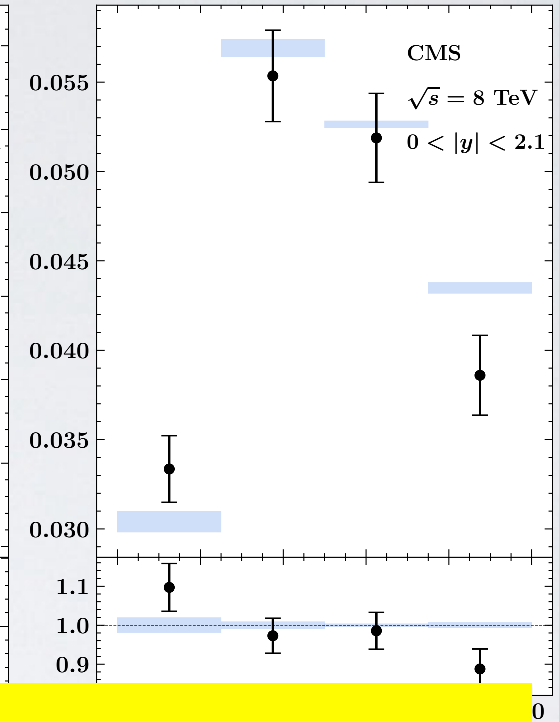
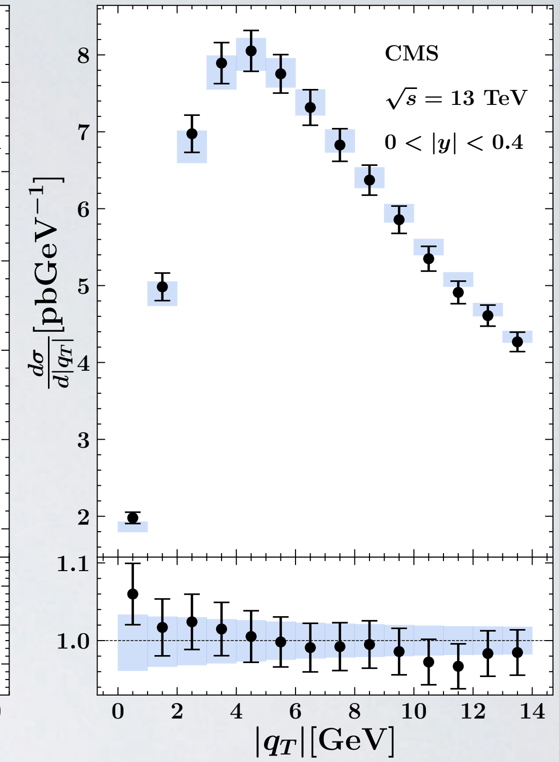


Fit results for collider Drell-Yan

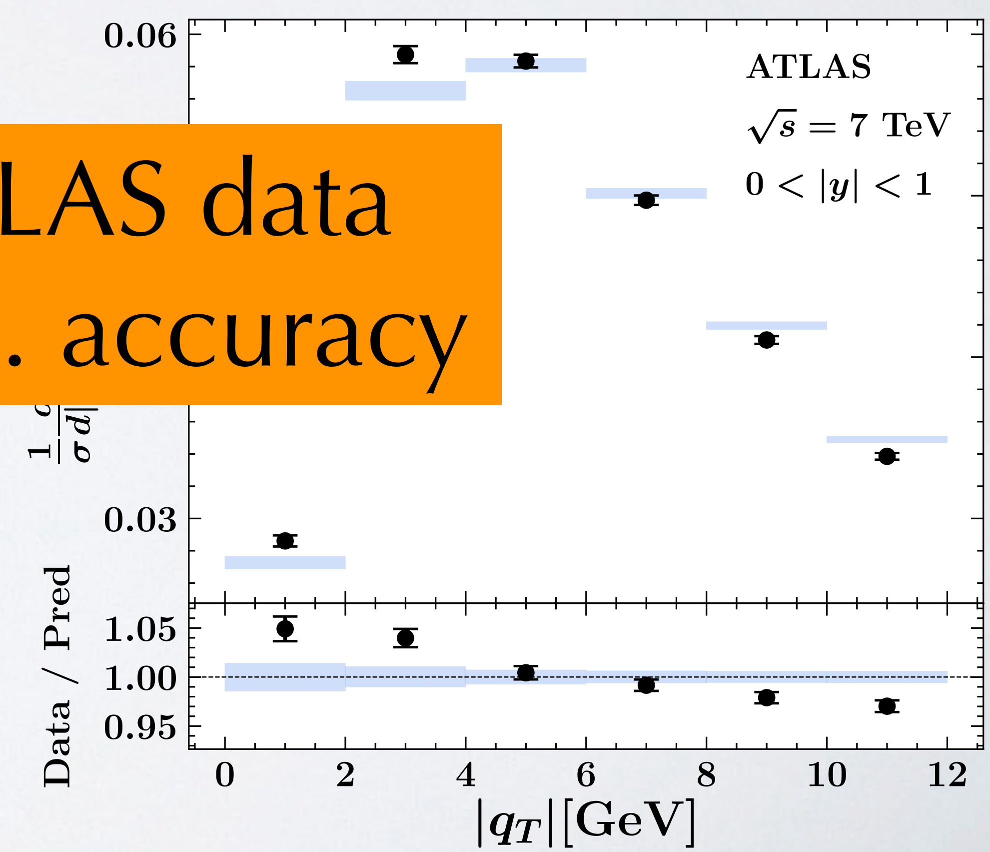








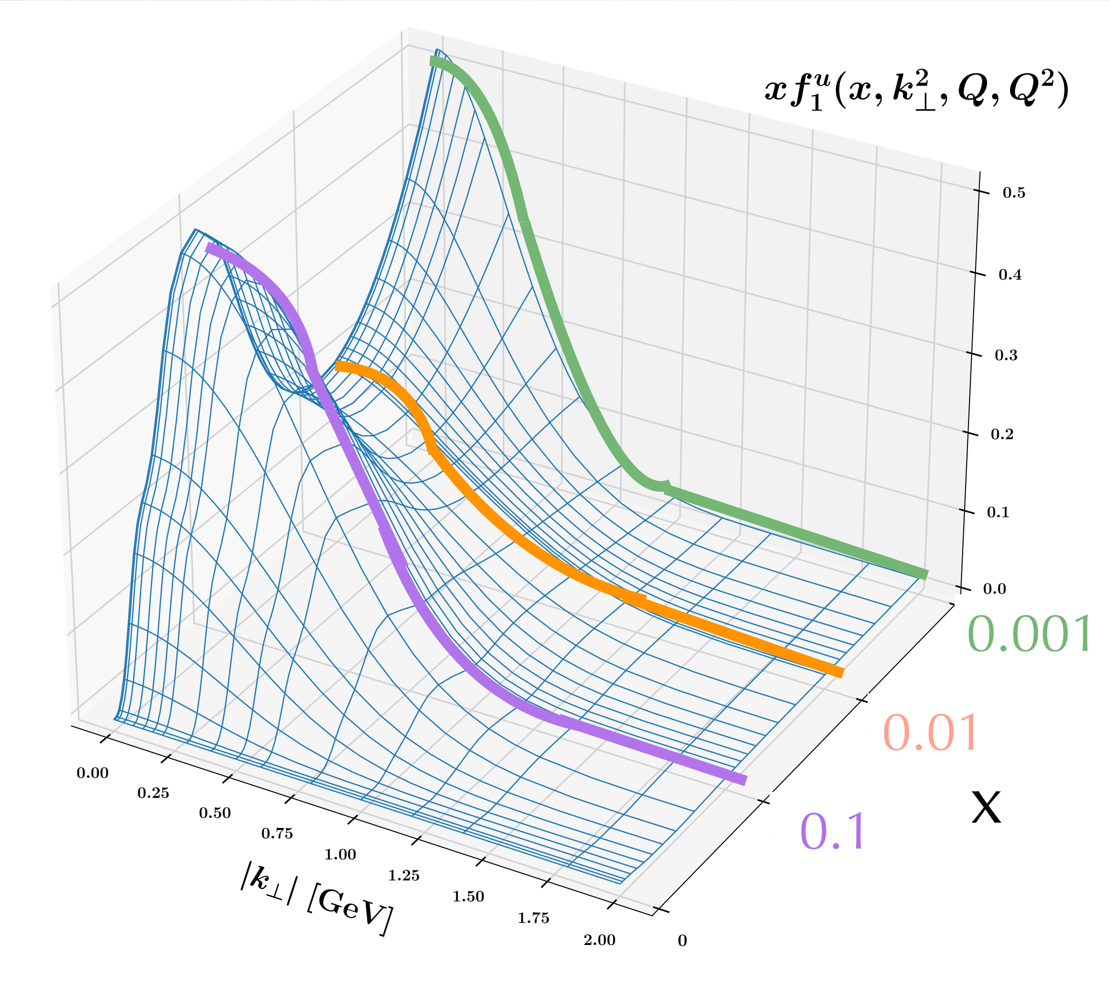
fairly good agreement



very precise ATLAS data
require higher Th. accuracy

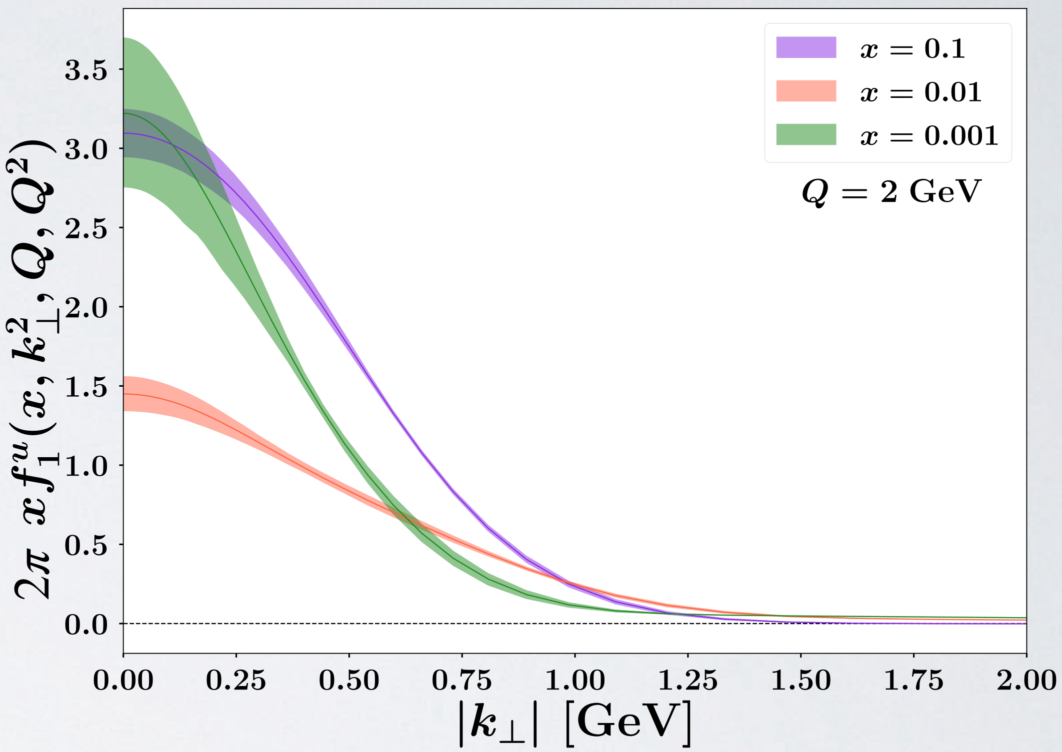
data set	N			
SIDIS total	1547	0.59	0.28	0.87
Drell-Yan fixed target tot	233	0.85	0.4	1.24
Drell-Yan collider total	251	1.86	0.2	2.06
ATLAS total	72	4.56	0.48	5.05

Visualizing MAPTMD22 TMD PDF



unpolarized up quark in the proton

Q=2 GeV

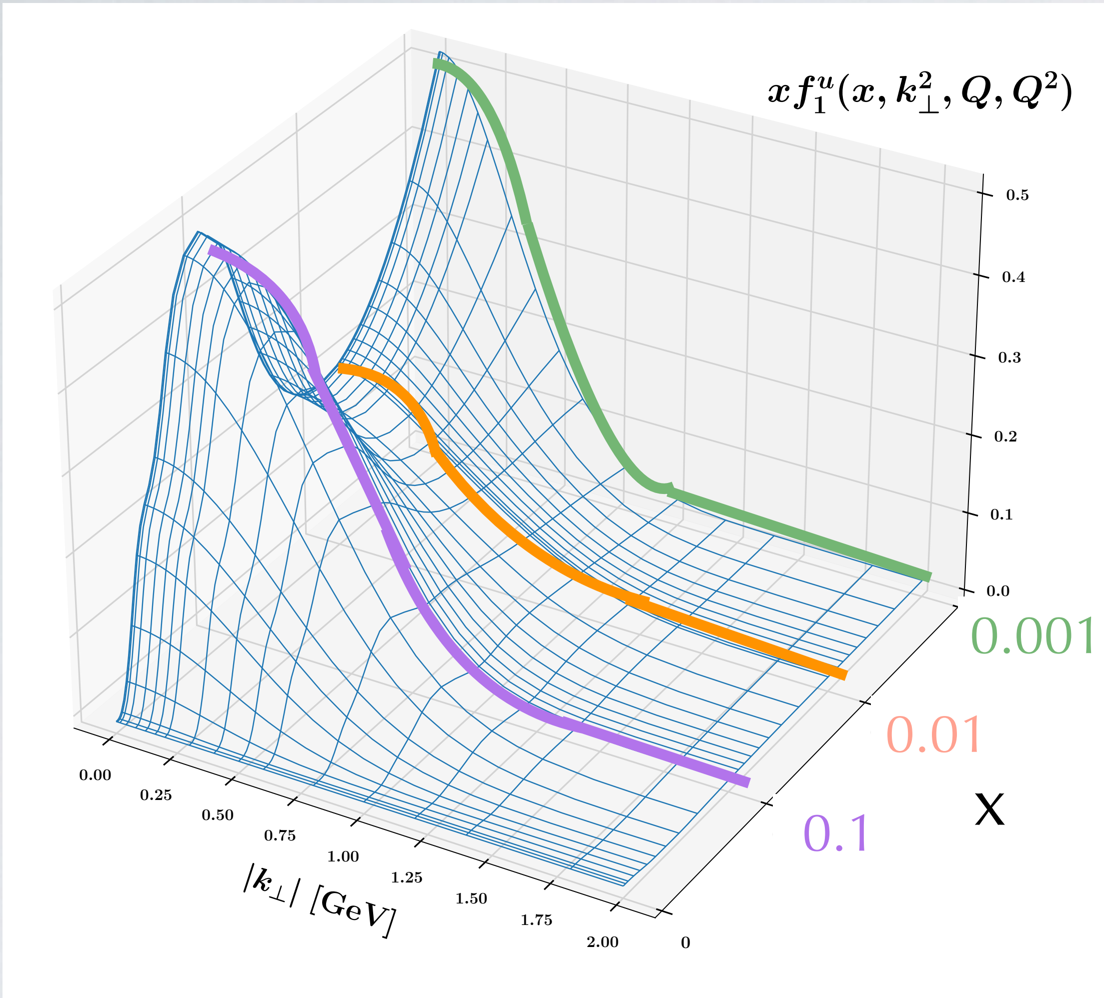


$f_{NP}(x, k_\perp; Q_0) \sim$ Gauss + $\lambda_B\, k_\perp^2$ Gauss + λ_C Gauss

effect of x-dependent widths

$\langle k_\perp^2 \rangle (x = 0.1, Q = 1) = 0.3 \pm 0.05$ GeV^2

Visualizing MAPTMD22 TMD PDF



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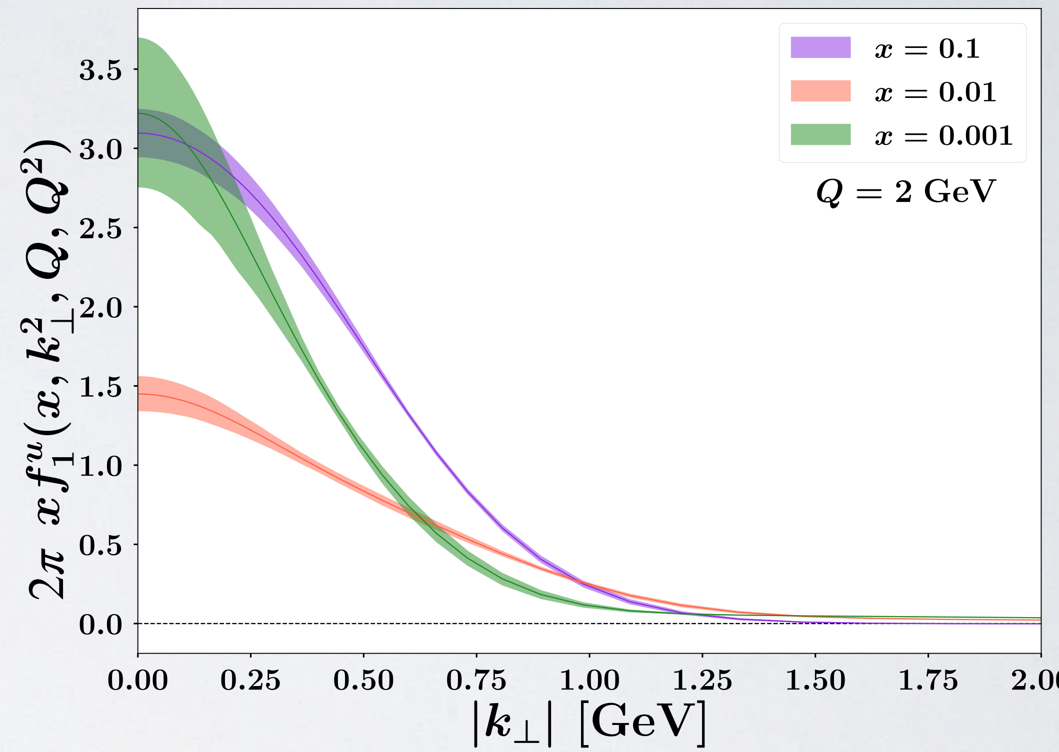


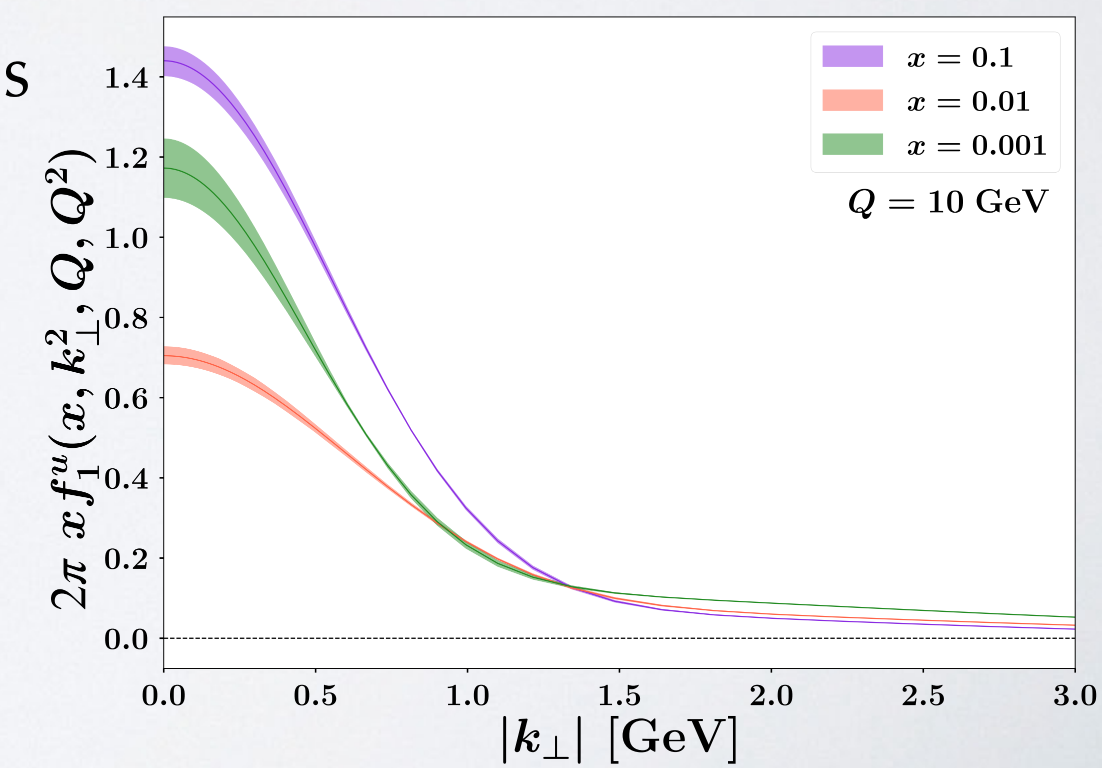
$f_{NP}(x, k_\perp; Q_0) \sim$ Gauss + $\lambda_B\, k_\perp^2$ Gauss + λ_C Gauss

effect of x-dependent widths

$\langle k_\perp^2 \rangle (x = 0.1, Q = 1) = 0.3 \pm 0.05$ GeV^2

$e^{-g_2^2\, b_T^2/4}$ $\quad g_2 = 0.248 \pm 0.008$ GeV

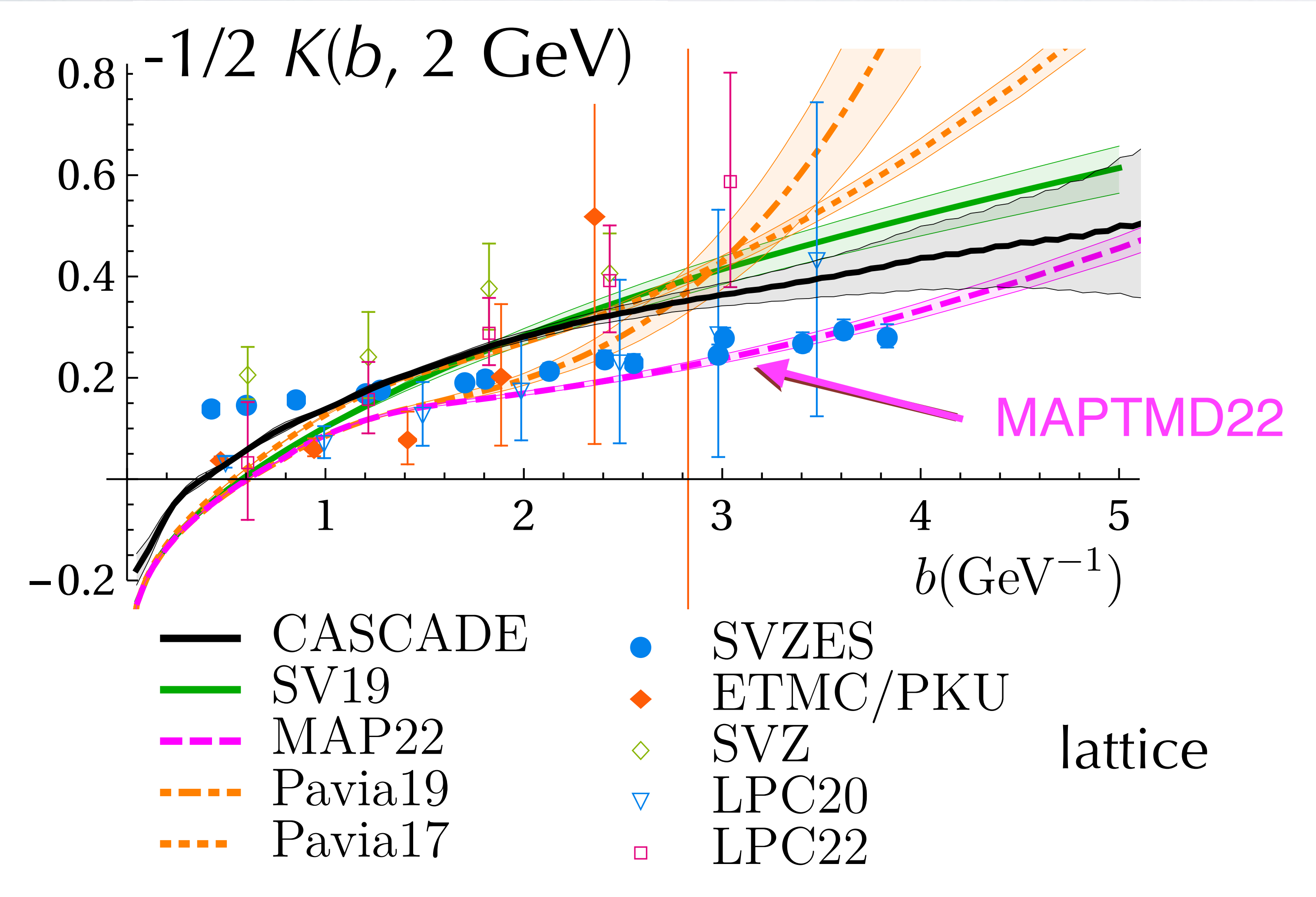
effect of nonperturbative evolution



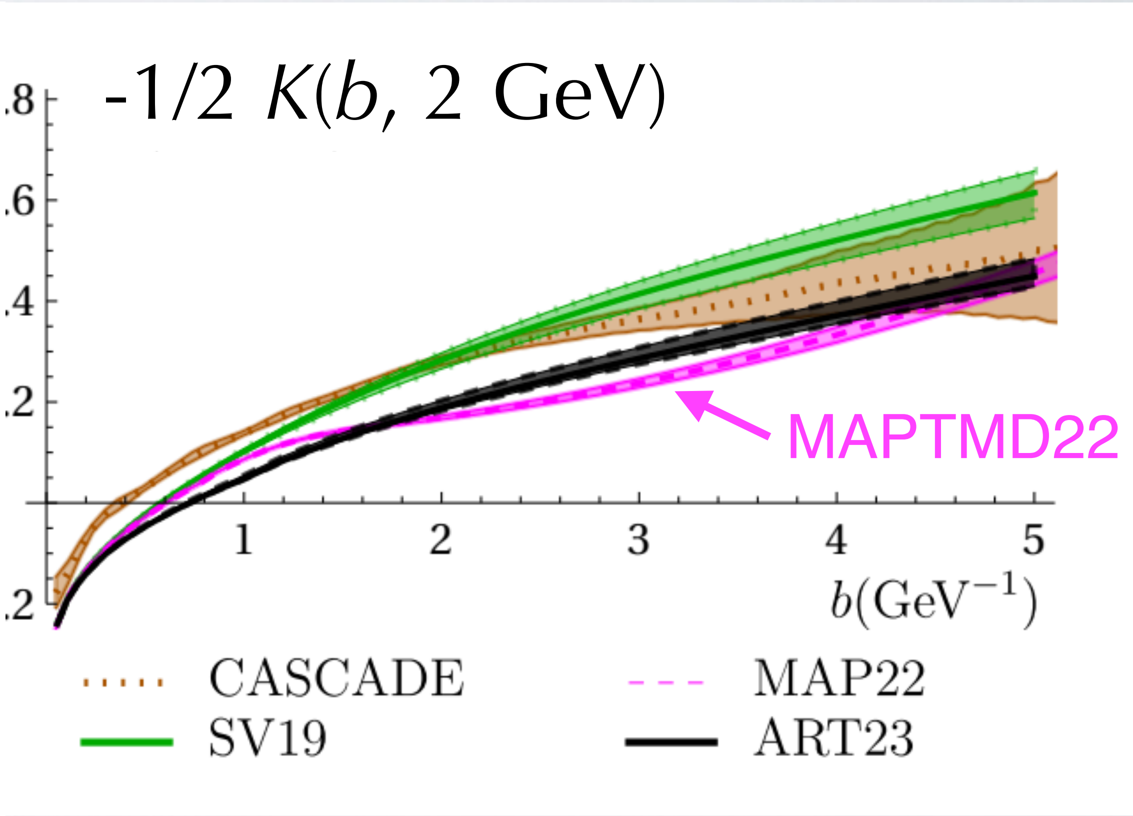
Visualizing the Collins-Soper evolution kernel

Collins-Soper kernel $K(b_T, \mu_{b_*}) = K(b_*, \mu_{b_*}) + g_K(b_T)$

drives evolution in rapidity ζ — perturbative — non-perturbative (fitted)

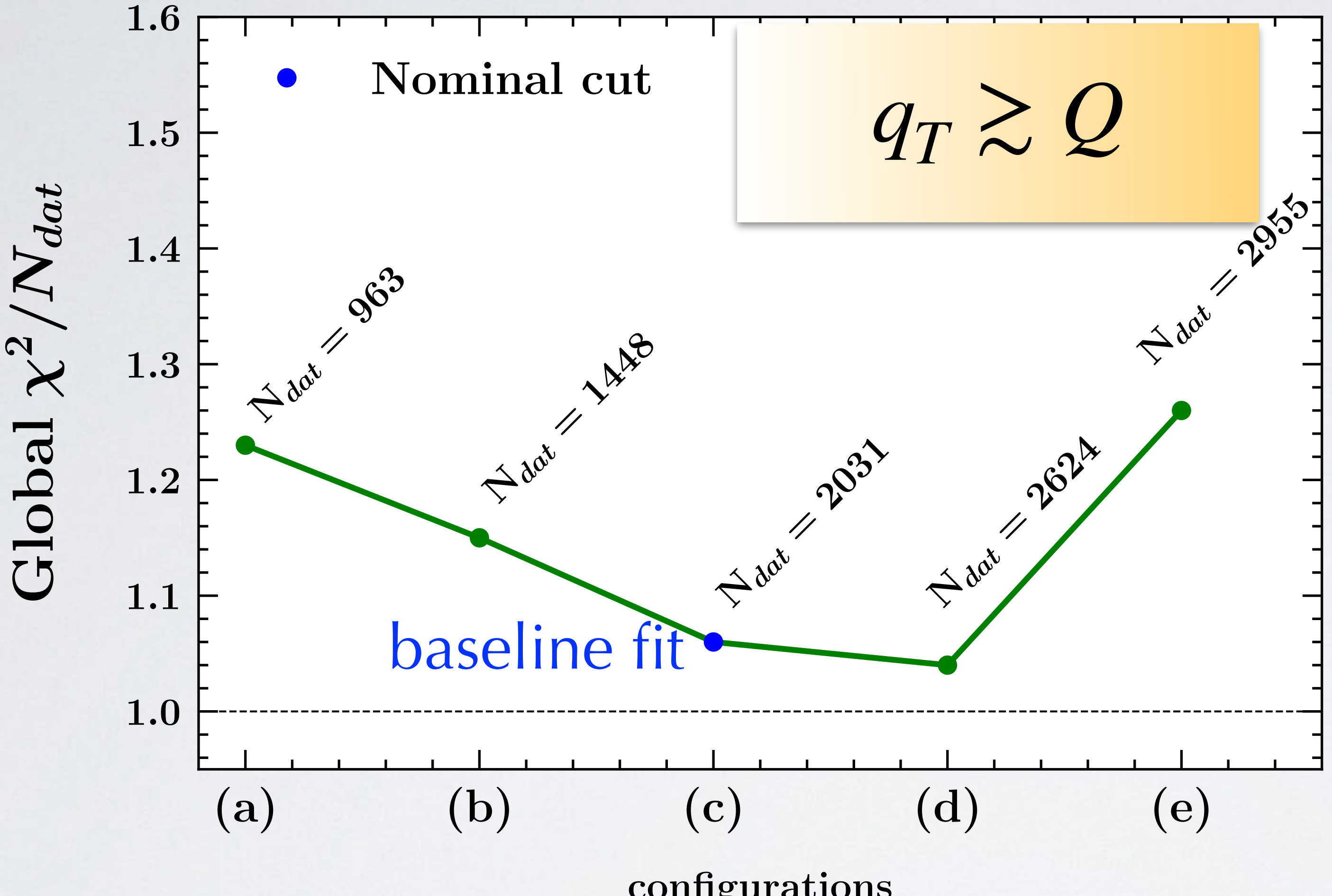


Bermudez Martinez & Vladimirov, arXiv:2206.01105



Moss et al., arXiv:2305.07473

Kinematic cuts and validity of TMD region



$$P_{hT} < \min\left[\min\left[c_1\, Q,\, c_2\, Qz\right] + c_3\,\mathrm{GeV},\, zQ\right]$$

a) $c_1=c_2=0.4$, $c_3=0$ $q_T < 0.4\, Q$

b) $c_1=0.15$, $c_2=0.4$, $c_3=0.2$

c) $c_1=0.2$, $c_2=0.5$, $c_3=0.3$ baseline fit

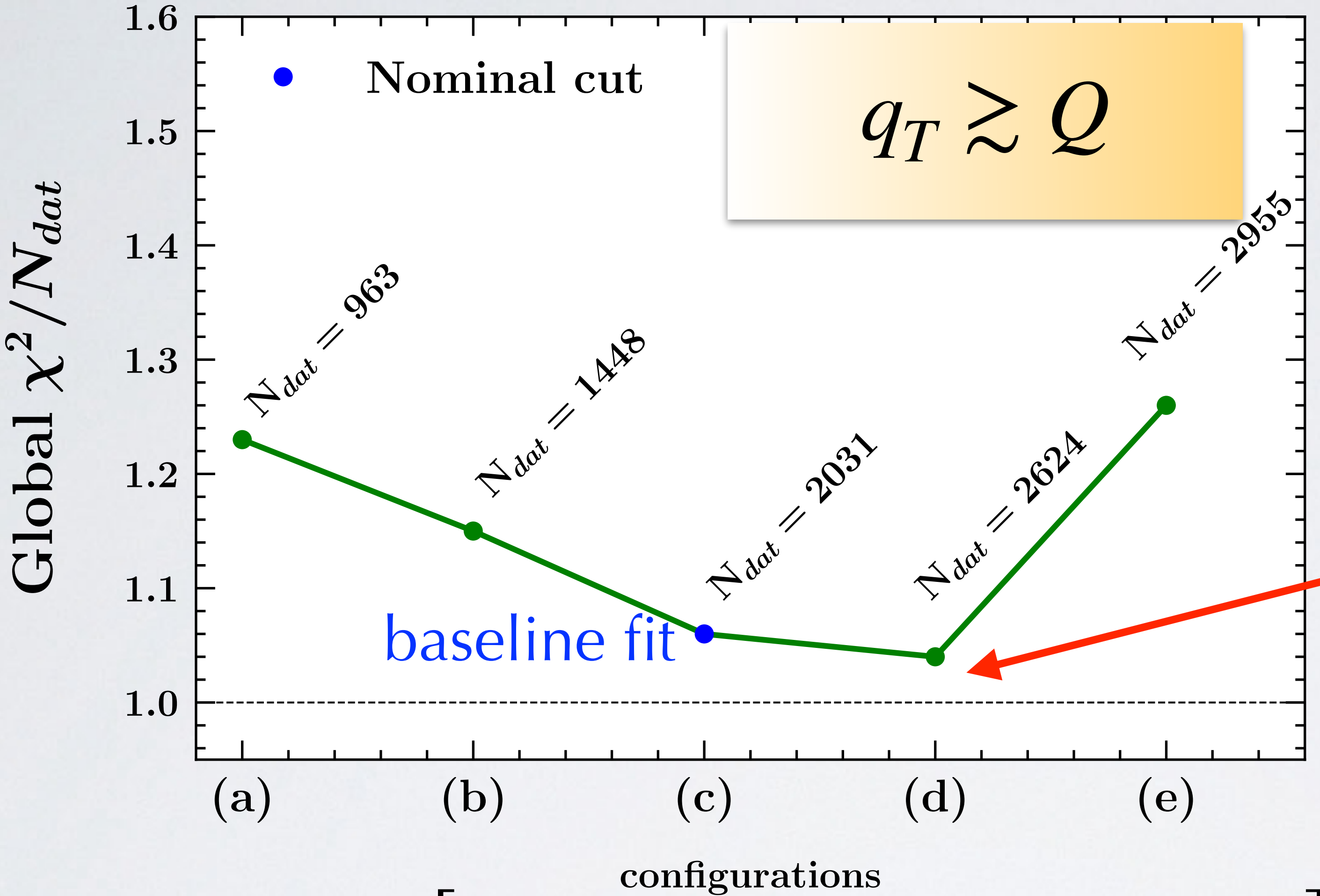
d) $c_1=0.2$, $c_2=0.6$, $c_3=0.4$ can be $q_T > Q$

e) $c_1=0.2$, $c_2=0.7$, $c_3=0.5$ can be $q_T > Q$

more conservative

less conservative

Kinematic cuts and validity of TMD region



better χ^2 with less conservative cuts allowing for $q_T > Q$

Where is the limit for TMD factorization??

$$P_{hT} < \min\left[\min\left[c_1\, Q,\, c_2\, Qz\right] + c_3\,\mathrm{GeV},\, zQ\right]$$

a) $c_1=c_2=0.4$, $c_3=0$ $q_T < 0.4\, Q$

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e) $c_1=0.2$, $c_2=0.7$, $c_3=0.5$ can be $q_T > Q$

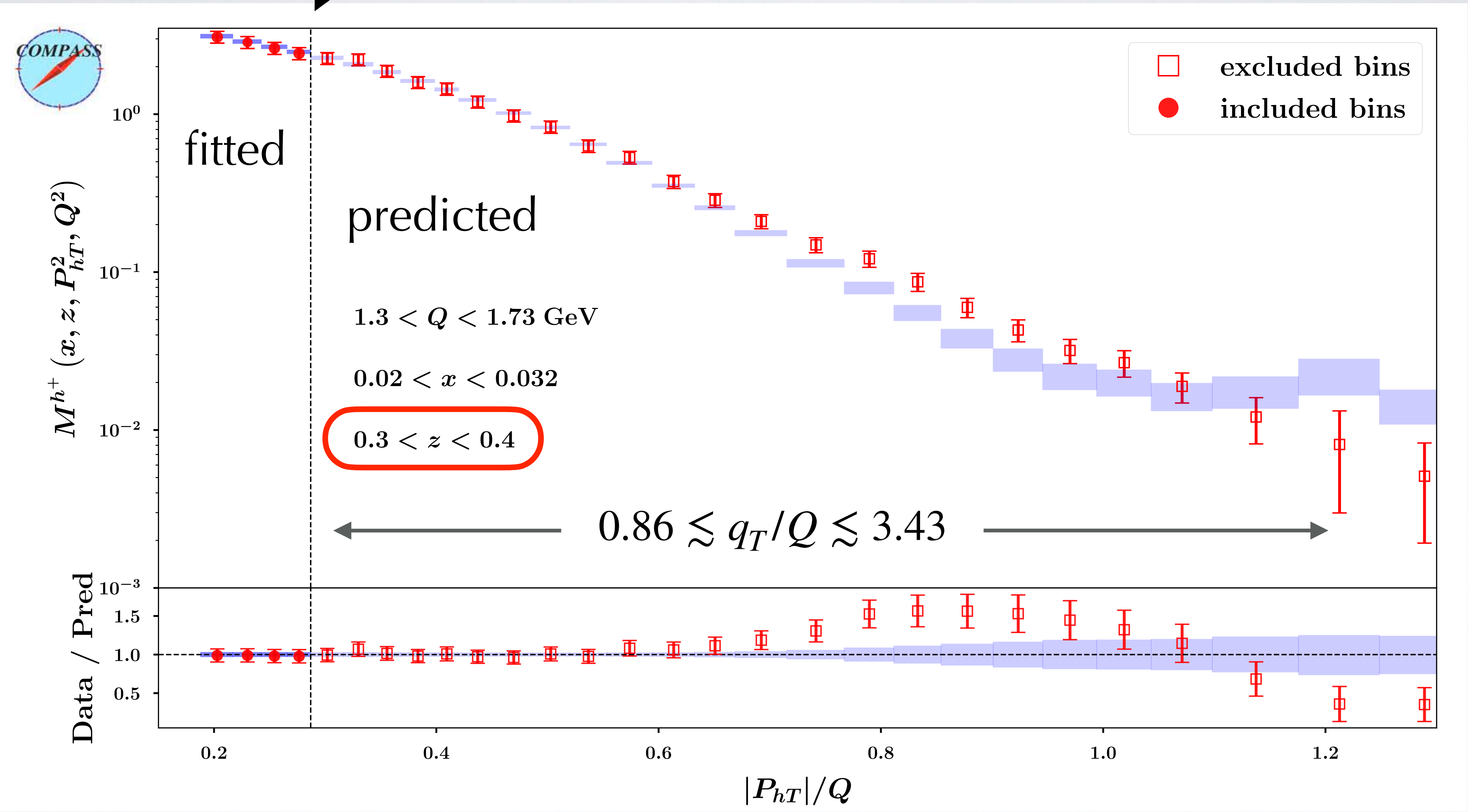
more conservative

less conservative

Kinematic cuts and validity of TMD region

cut of baseline fit

$$P_{hT} < \min\left[\min\left[0.2\,Q,\,0.5\,Qz\right] + 0.3\,\mathrm{GeV},\,zQ\right]$$



validity of TMD factorization seems to extend well beyond $P_{hT}/z << Q$!

The MAPTMDPion22 fit

Extracting TMDs for the pion

	Framework	DY	N of points	χ^2/N_{points}
Wang et al., 2017 arXiv:1707.05207	NLL	✔	96	1.61
Vladimirov, 2019 arXiv:1907.10356	NNLL'	✔	80	1.44
MAPTMDPion22, 2022 arXiv:2210.01733	N³LL	✔	138	1.54
JAM 2023 arXiv:2302.01192	NNLL	✔	93	1.37

MAPTMD**Pion**22:

arXiv:2210.01733

- best theoretical accuracy: **N³LL**
- largest number of included data: **138**
- same consistent framework of MAPTMD22

$$f_{NP}^{\pi}(x, b_T; Q_0) = e^{-g_{1\pi}(x)\, b_T^2/4} \qquad g_{1\pi}(x) = N_{1\pi} \frac{(1-x)^{\alpha_\pi^2}\, x^{\sigma_\pi}}{(1-\hat{x})^{\alpha_\pi^2}\, \hat{x}^{\sigma_\pi}}$$

3 param.

$$\hat{x} = 0.1$$

The MAPTMDPion22 data sets

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

E615: $\sqrt{s} = 21.8$ GeV $0<x_F<1$

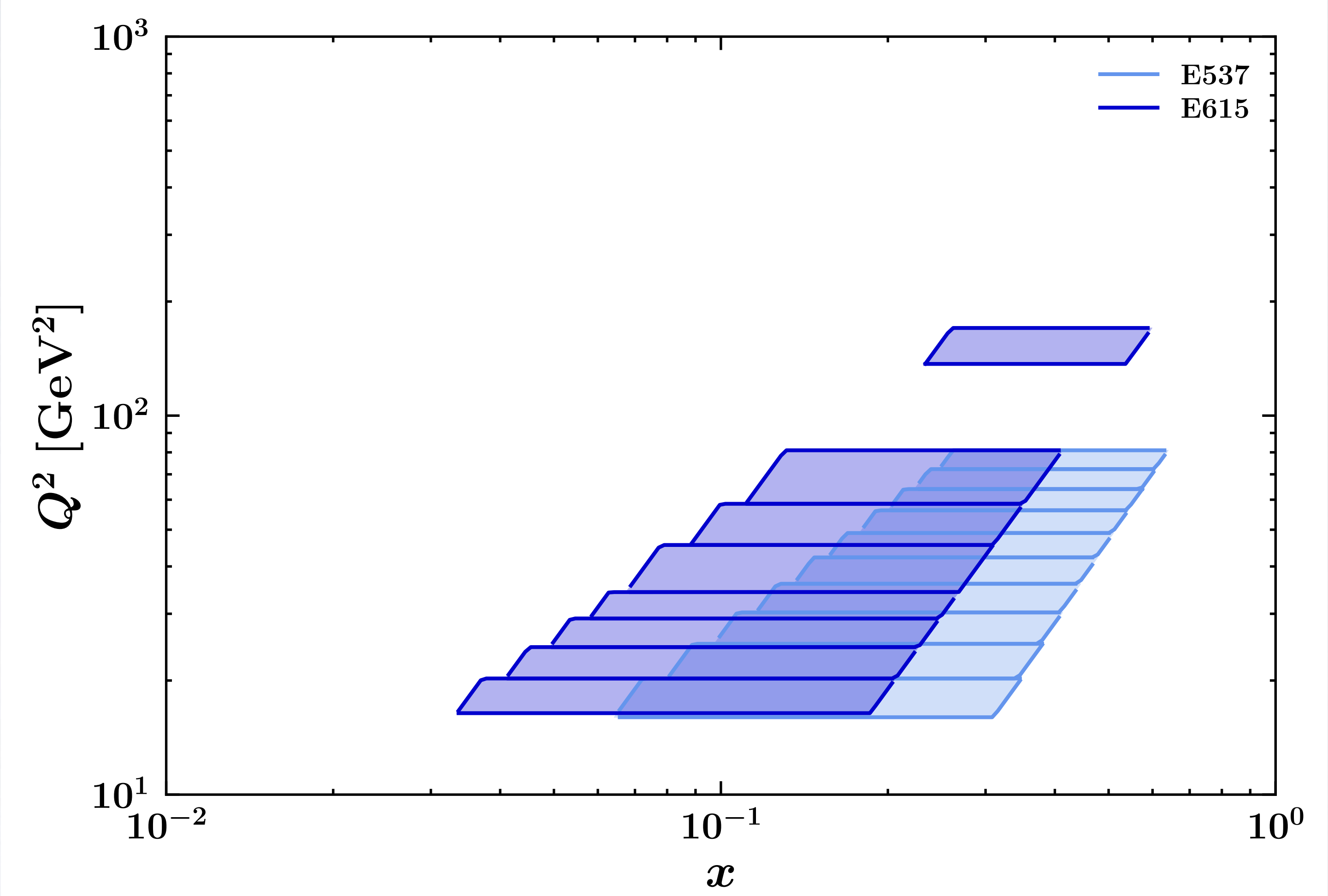
$4.05 < Q < 13.05$ GeV

Stirling et al., 1993

E537: $\sqrt{s} = 15.3$ GeV $-0.1<x_F<1$

$4 < Q < 9$ GeV

Anassontzis et al., 1988



Kinematical cut $q_T < 0.3\,Q + 0.6$

N_{data} after cut: **74** + **64**

Many sources of (large) errors:

E615: stat. 5% syst. 16% (normalization)

E537: stat. 15-20% syst. 8%

Th.: 5-8% on PDF from xFitter20

The MAPTMDPion22 data sets

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

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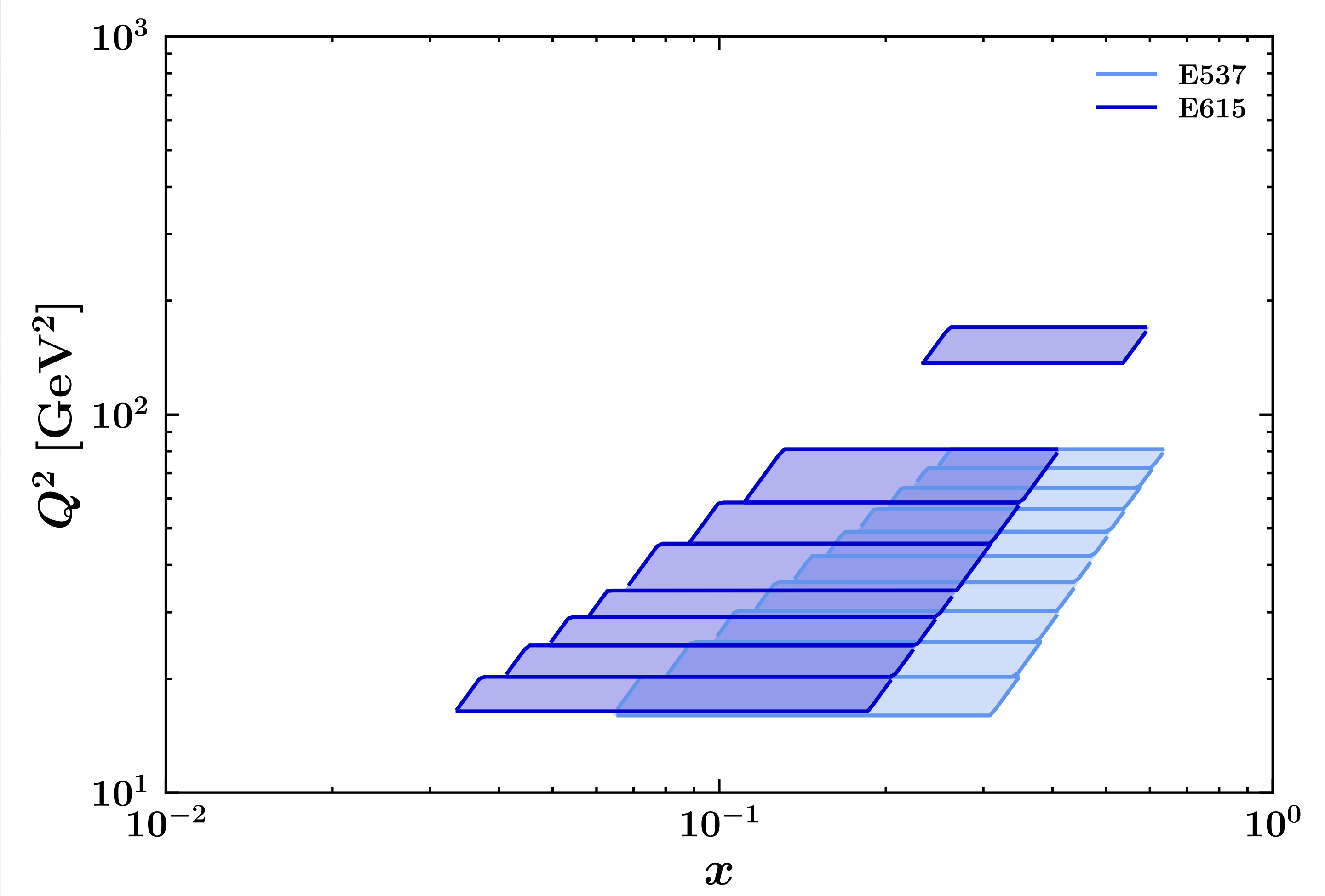


Kinematical cut $q_T < 0.2\,Q$

N_{data} after cut: **74** + **64**

Many sources of (large) errors:

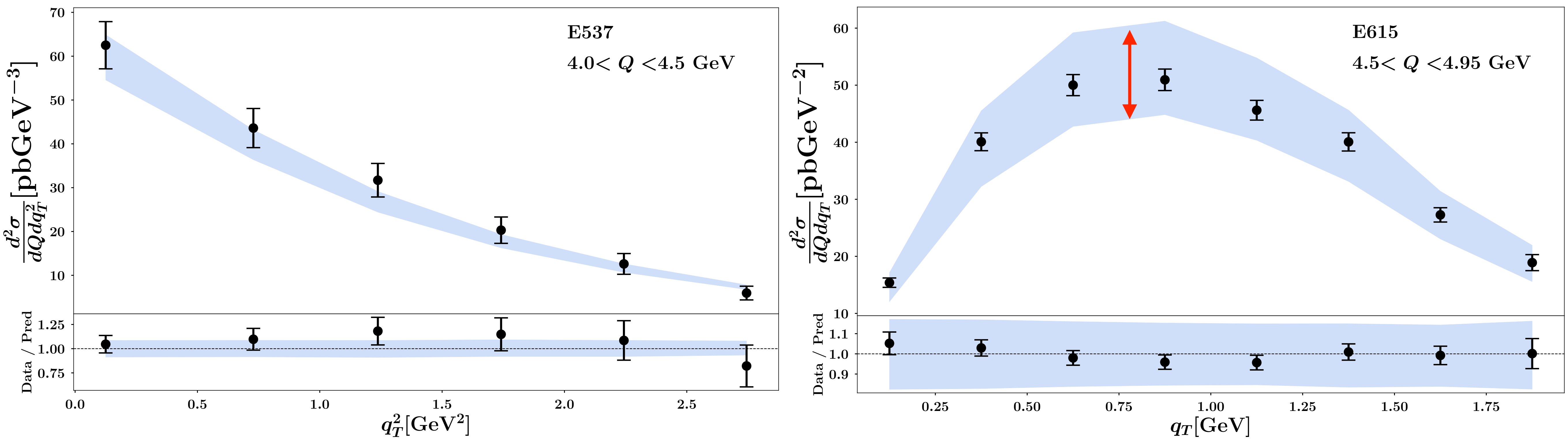
E615: stat. 5% syst. 16% (normalization)

E537: stat. 15-20% syst. 8%

Th.: 5-8% on PDF from xFitter20

Fit results

arXiv:2210.01733



MAPTMDPion22: - good agreement in shape

- large normalization errors (for E615)

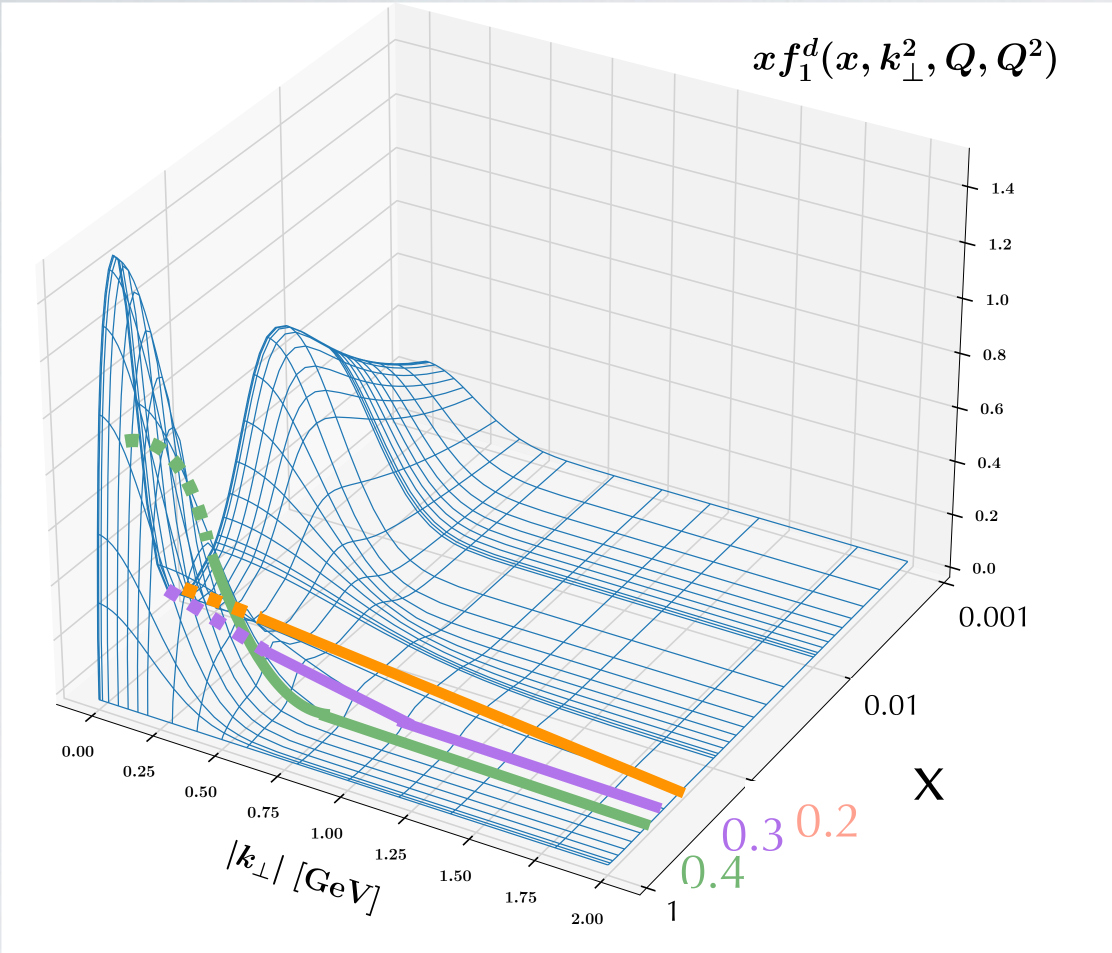
data set	N_{data}	χ_D^2	χ_λ^2	χ^2
E537	64	1.0	0.57	1.57
E615	74	0.31	1.22	1.53
total	138	0.63	0.92	1.55

χ_D^2 = uncorrelated error

χ_λ^2 = correlated error

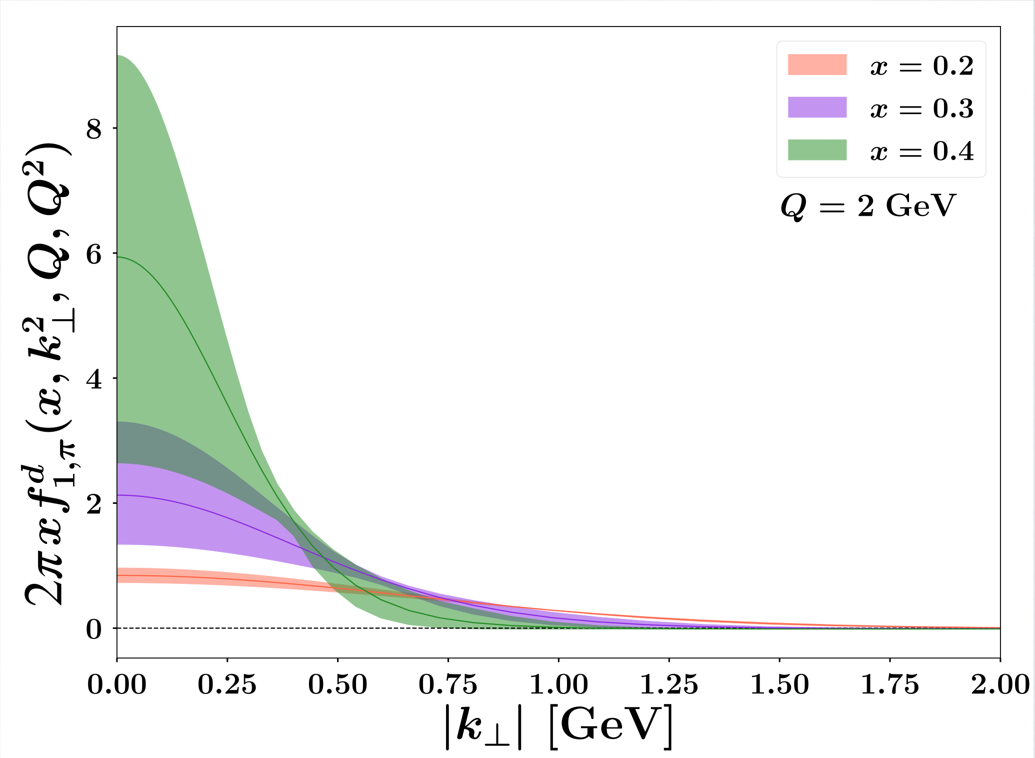
$\chi^2 = \chi_D^2 + \chi_\lambda^2$

Visualizing MAPTMDPion22 TMD PDF

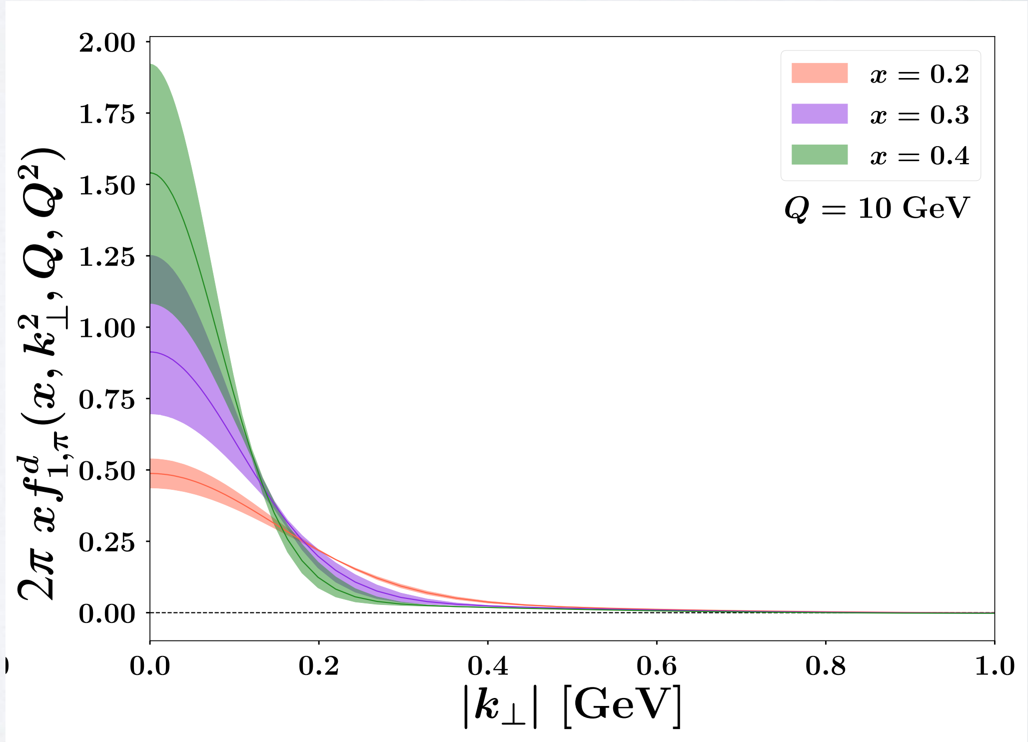


unpolarized down quark in π -

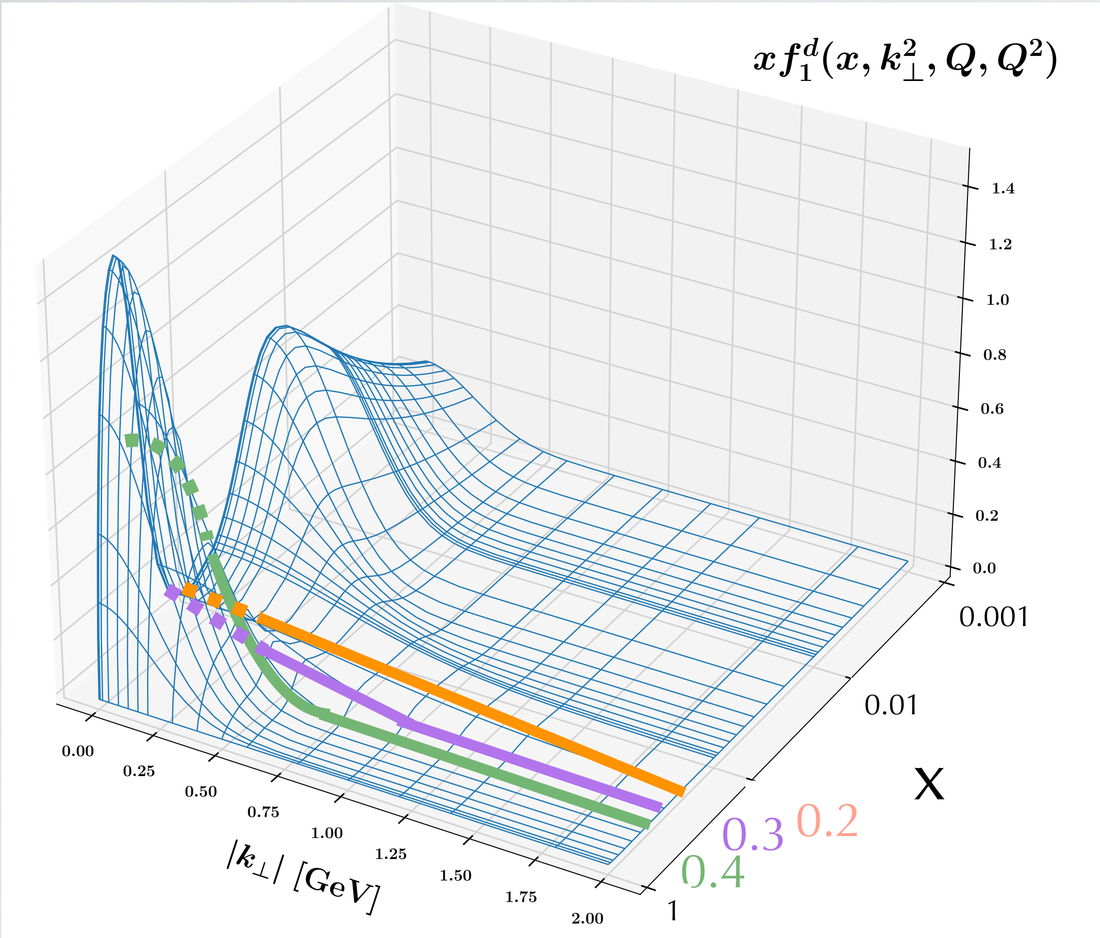
Q=2 GeV



$e^{-g_2^2 b_T^2/4}$ same nonperturbative evolution as for proton

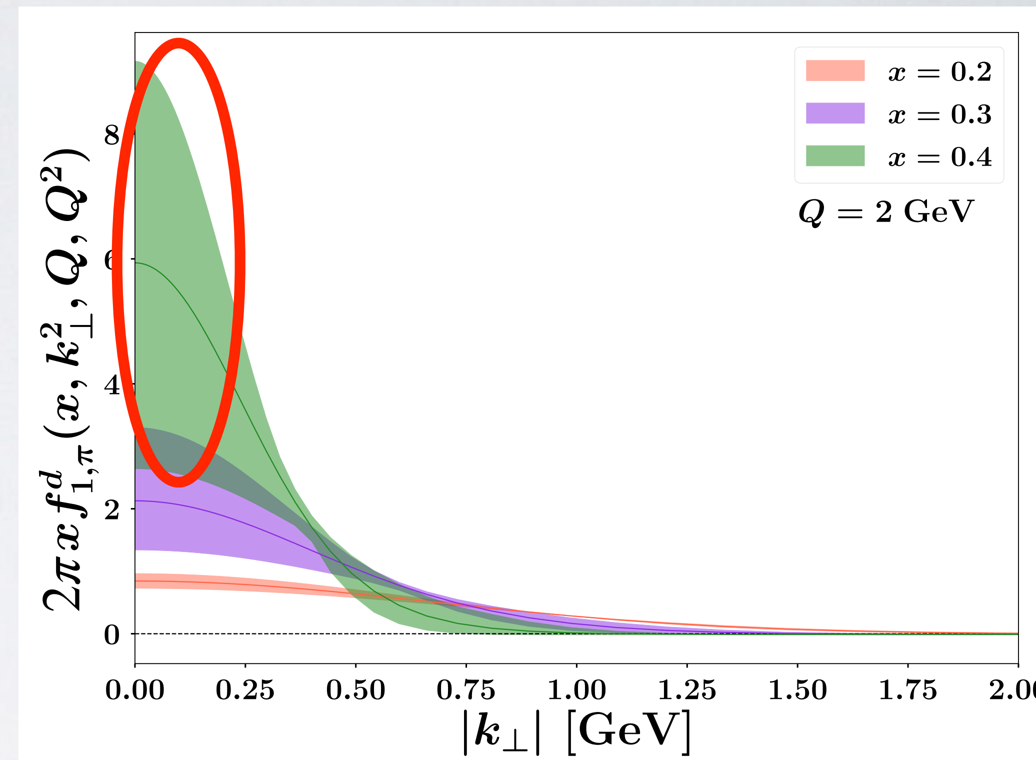


Visualizing MAPTMDPion22 TMD PDF



unpolarized down quark in π -

Q=2 GeV

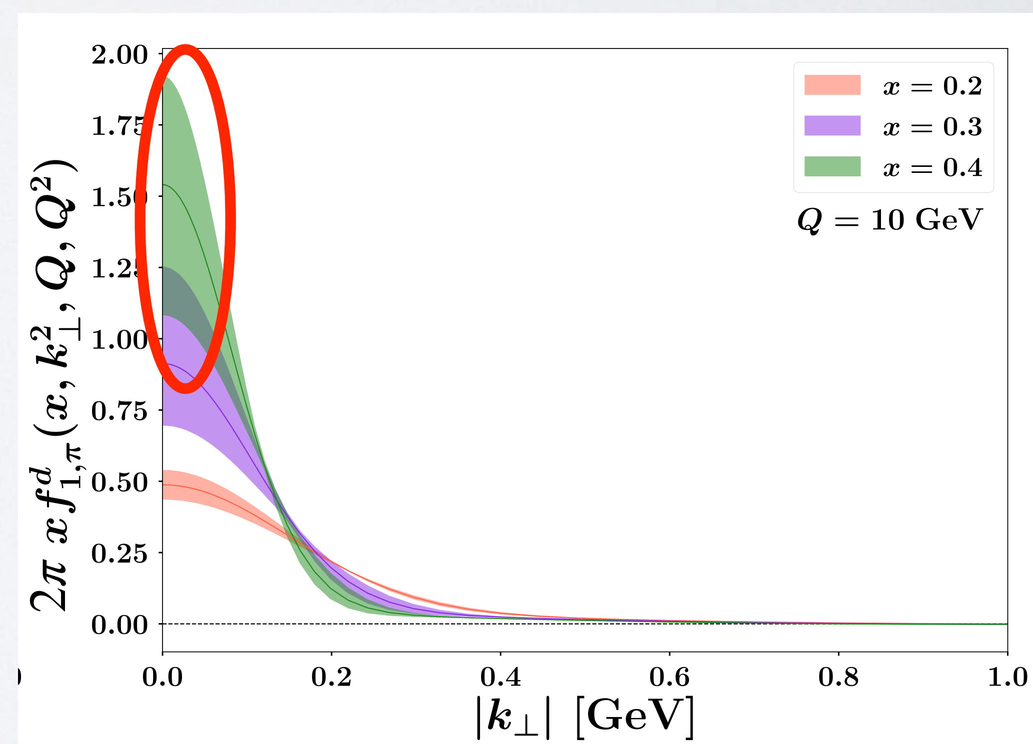


$e^{-g_2^2 b_T^2/4}$ same nonperturbative evolution as for proton

$N_{1\pi} = 0.47 \pm 0.12$ $\sigma_{1\pi} = 4.50 \pm 2.25$ $\alpha_{1\pi} = 4.40 \pm 1.34$

↓

$\langle k_\perp^2 \rangle (x = 0.1, Q = 1)$ larger than in the proton



data not very sensitive to nonperturbative parameters => **need new data!**

Summary and Outlook

- **MAPTMD22**: a **global fit** at **N^{3}LL** of SIDIS and Drell-Yan data from LHC, Tevatron, RHIC; **2031 data** pts., **21 parameters, χ^2/N_{data} = 1.06** : the current most robust and precise extraction of unpolarized quark TMDs in the proton, accuracy comparable to modern PDF fits
- surprisingly, MAPTMD22 performs **well** in SIDIS well **outside** TMD factorization limit **$q_T \ll Q$**

Summary and Outlook

- **MAPTMD22**: a **global fit** at **N^{3}LL** of SIDIS and Drell-Yan data from LHC, Tevatron, RHIC; **2031 data** pts., **21 parameters, χ^2/N_{data} = 1.06** : the current most robust and precise extraction of unpolarized quark TMDs in the proton, accuracy comparable to modern PDF fits
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- introduce flavor-dependent $k_\perp$ distributions (ongoing…)
- include upcoming Compass data for pion-induced Drell-Yan
- improve perturbative accuracy (very precise ATLAS data…)


THANK YOU
for your
ATTENTION!

Backup

Drell-Yan observables

collider

Exp: normalized cross section differential in q_T in each bin

Th: for each bin [i,f]

$$\frac{1}{\sigma_{\text{fiducial}}}\frac{1}{(\Delta q_T)_{if}}\int_{q_{Ti}}^{q_{Tf}} dq_T \int_{y_i}^{y_f} dy \int_{Q_i}^{Q_f} dQ \frac{d\sigma}{dq_T dy dQ}$$

DYNNLO with MMHT14 PDFs

fixed target

E288: cross section differential in average $\overline{q_T}$ and $\overline{y}$

Th: for each bin [i,f]

$$\frac{1}{2\pi\bar{q}_T}\int_{Q_i}^{Q_f} dQ \frac{d\sigma}{dq_T dy dQ}\bigg|_{y=\bar{y},\, q_T=\bar{q}_T}$$

E772: cross section differential in average $\overline{q_T}$ and $x_F = x_A - x_B$ bins

Th: for each bin [i,f]

$$\frac{1}{(\Delta x_F)_{if}}\int_{x_{Fi}}^{x_{Ff}} dx_F \int_{Q_i}^{Q_f} dQ \frac{2E}{\pi\sqrt{s}}\frac{d\sigma}{dq_T^2 dx_F dQ}\bigg|_{q_T=\bar{q}_T}$$

E605: cross section differential in average $\overline{q_T}$ and $\overline{x_F}$

Th: for each bin [i,f]

$$\int_{Q_i}^{Q_f} dQ \frac{2E}{\pi\sqrt{s}}\frac{d\sigma}{dq_T^2 dx_F dQ}\bigg|_{x_F=\bar{x}_F,\, q_T=\bar{q}_T}$$

SIDIS observable

Exp: differential SIDIS cross section divided by DIS one

Multiplicity

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

Th: for each bin [i,f]

$$\mathcal{O}^{\text{SIDIS}} = \frac{1}{(\Delta Q)_{if}} \int_{Q_i}^{Q_f} dQ \, \frac{1}{(\Delta x)_{if}} \int_{x_i}^{x_f} dx \, \frac{1}{(\Delta z)_{if}} \int_{z_i}^{z_f} dz \, \frac{1}{(\Delta P_{hT})_{if}} \int_{P_{hTi}}^{P_{hTf}} dP_{hT} \, \frac{d\sigma^{\text{SIDIS}}}{dx\,dz\,dP_{hT}\,dQ}$$

$$\mathcal{O}^{\text{DIS}} = \frac{1}{(\Delta Q)_{if}} \int_{Q_i}^{Q_f} dQ \, \frac{1}{(\Delta x)_{if}} \int_{x_i}^{x_f} dx \, \frac{d\sigma^{\text{DIS}}}{dx\,dQ}$$

$$M^{\text{th}}(x_{if}, z_{if}, P_{hTif}, Q_{if}) = \frac{\mathcal{O}^{\text{SIDIS}}}{\mathcal{O}^{\text{DIS}}}$$

Error treatment

bootstrap method: fitting 250 replicas of fluctuated exp. data

quality indicator: χ_0^2 of *central* replica (fitting not " " ")

MAPTMD22 at N³LL⁽⁻⁾ : $N_{\rm data}$=**2031**, **21** parameters, $\chi_0^2/N_{\rm data} = 1.06$

$\chi_0^2 \sim \langle \chi^2 \rangle_{\rm replicas}$

(exp. / th.) errors can be uncorrelated or correlated

$$\chi^2 = \chi_D^2 + \chi_\lambda^2$$

penalty for correlated errors

$$\chi_D^2 = \sum_{\rm bins} \left(\frac{\exp - \overline{\rm th}}{\sigma} \right)^2 \qquad \sigma^2 = \sigma_{\rm stat}^2 + \sigma_{\rm uncorr}^2$$

$$\overline{\rm th} = {\rm th} + \sum_\alpha \lambda_\alpha \sigma_{\rm corr}^{(\alpha)}$$

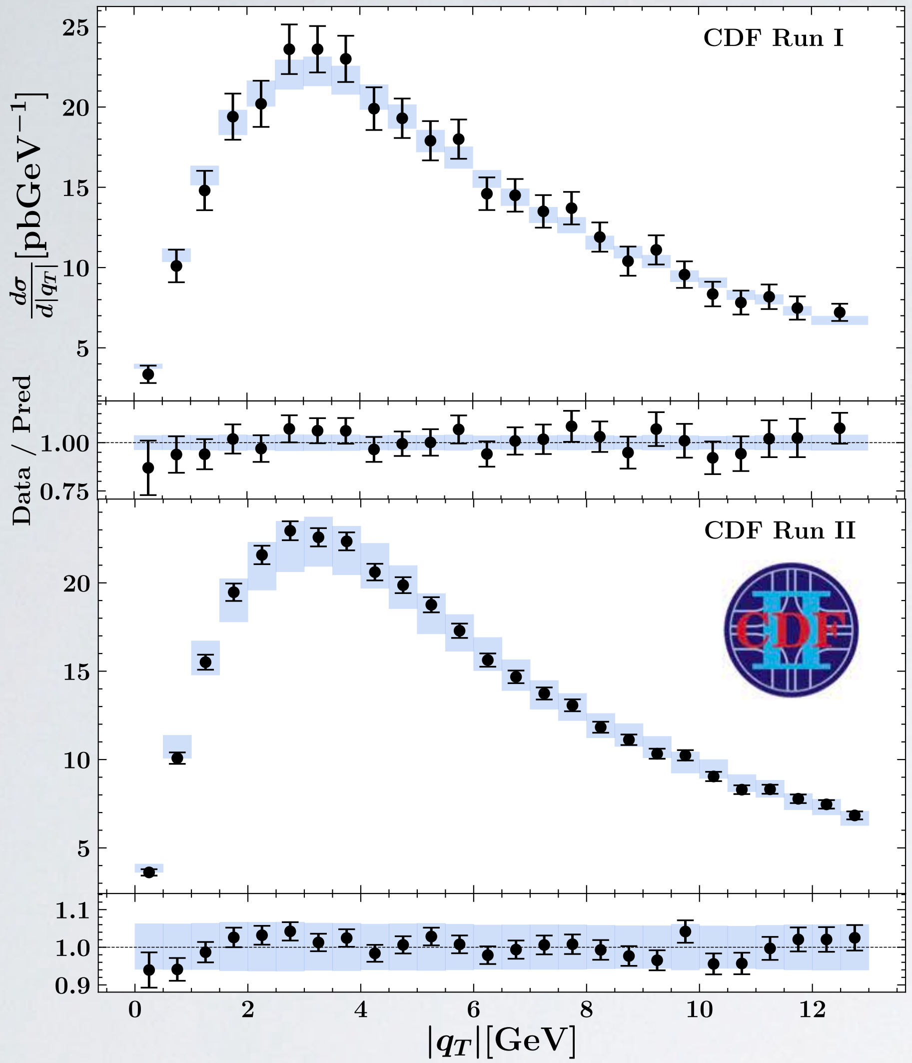
$$\chi_\lambda^2 = \sum_\alpha \lambda_\alpha^2$$

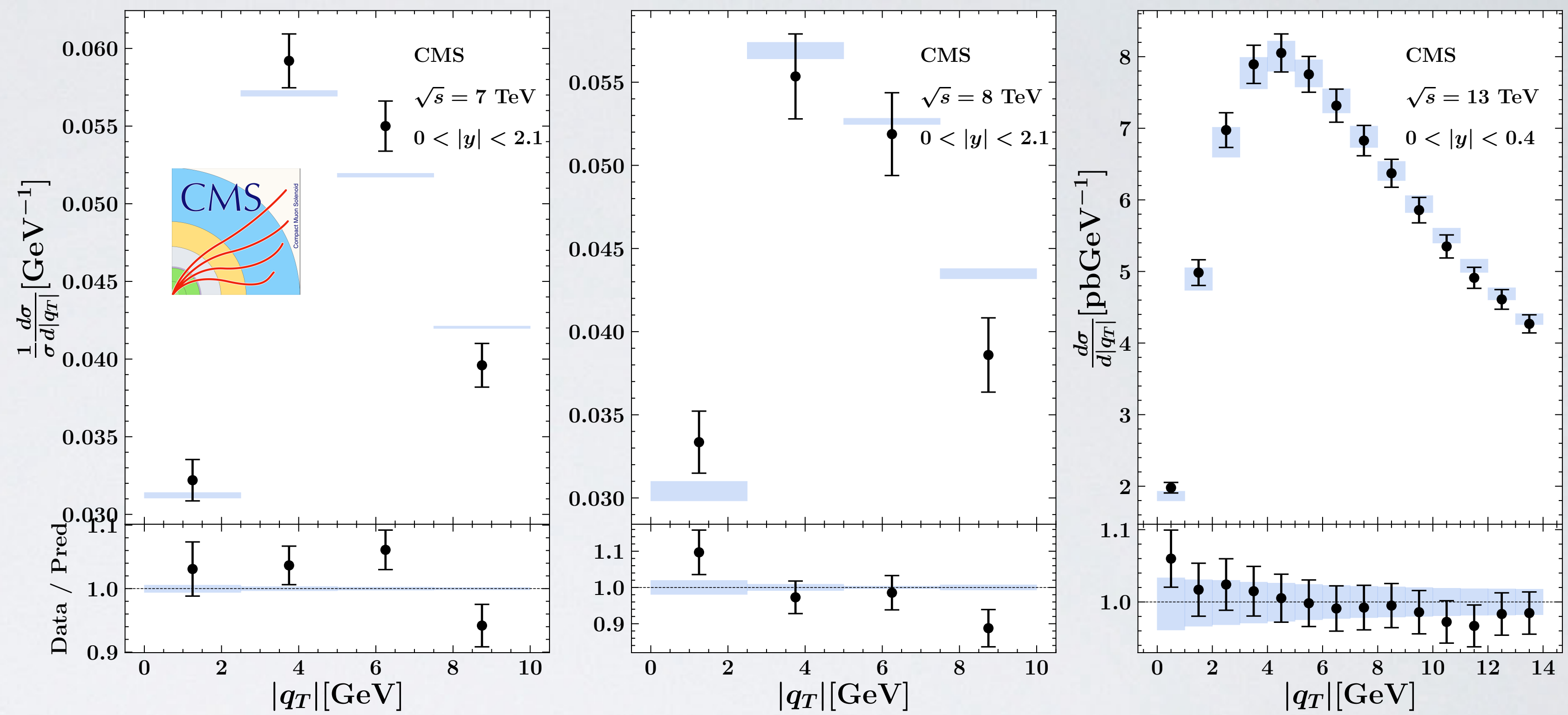
nuisance params.

Examples of (partly) correlated errors :

- exp.: some normalization systematic errors
- th. : uncertainties of PDFs MMHT2014
  - FFs DSS14 for $\pi^\pm$
  - DSS17 for $K^\pm$

MAPTMD22 N^{3}LL$^{(-)}$ global fit $\chi_0^2/N_{\mathrm{data}} = 1.06$

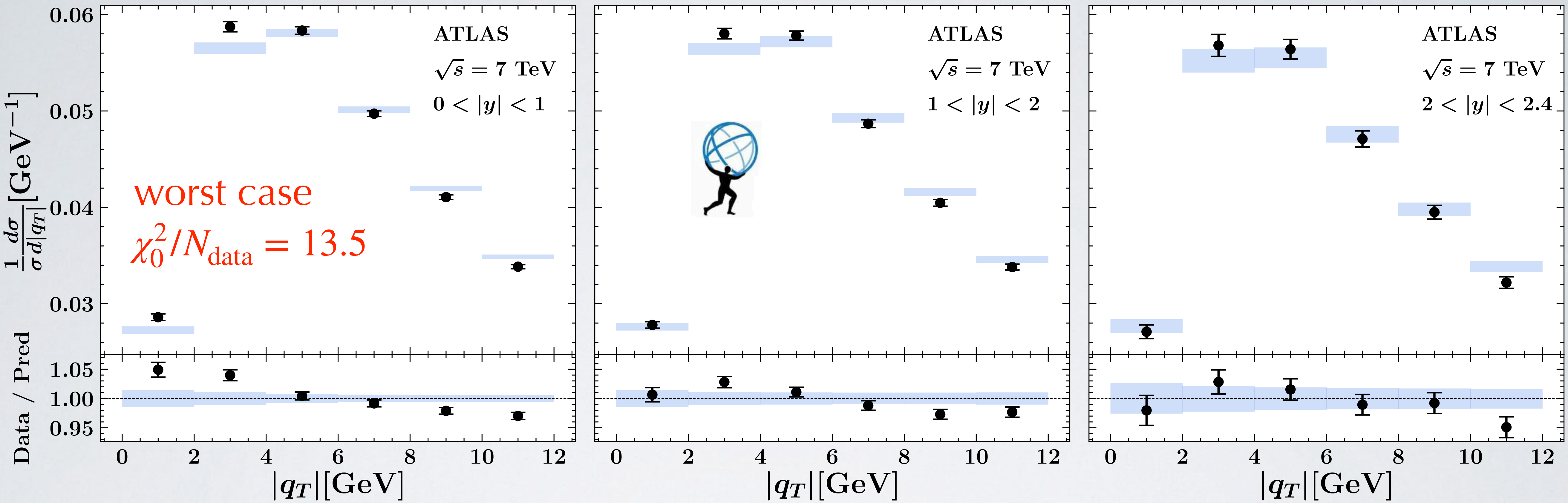




th. error band =
68% of all replicas

data set	N_{data}	χ_D^2	χ_λ^2	χ_0^2
Tevatron total	71	0.87	0.06	0.93
PHENIX 200	2	2.21	0.88	3.08
STAR 510	7	1.05	0.10	1.15
LHCb total	21	1.15	0.3	1.45
ATLAS total	72	4.56	0.48	5.05
CMS total	78	0.53	0.02	0.55
collider total	251	1.86	0.2	2.06
fixed target tot	233	0.85	0.4	1.24

MAPTMD22 N^{3}LL$^{(-)}$ global fit $\chi_0^2/N_{\text{data}} = 1.06$



extremely small exp. errors

→ very sensitive to small th. corrections

Examples:

- numerical implementation of lepton cuts
- power corrections
- effects of matching Y term

Chen et al., arXiv:2203.01565
Camarda et al., arXiv:2111.14509
Buonocore et al., arXiv:2111.13661

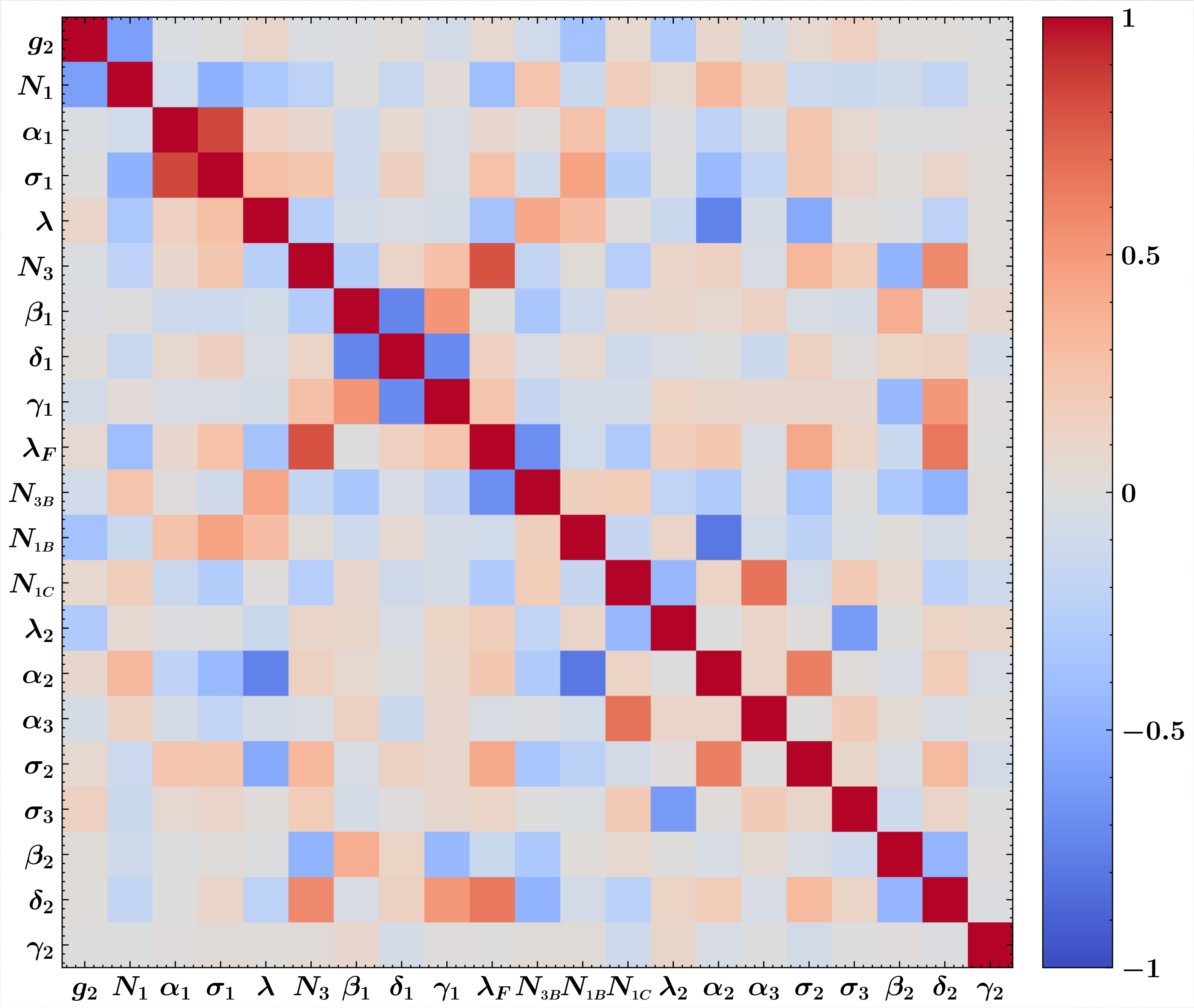
data set	N_{data}	χ_D^2	χ_λ^2	χ_0^2
ATLAS 7 TeV	18	6.43	0.92	7.35
ATLAS 8 TeV	48	3.7	0.32	4.02
ATLAS 13 TeV	6	5.09	0.5	6.4
ATLAS total	72	4.56	0.48	5.05
collider total	251	1.86	0.2	2.06

Backup: chi2 breakout

	N^3LL^-			
Data set	N_{dat}	χ^2_D	χ^2_λ	χ^2_0
CDF Run I	25	0.45	0.09	0.54
CDF Run II	26	0.995	0.004	1.0
D0 Run I	12	0.67	0.01	0.68
D0 Run II	5	0.89	0.21	1.10
D0 Run II (μ)	3	3.96	0.28	4.2
Tevatron total	71	0.87	0.06	0.93
LHCb 7 TeV	7	1.24	0.49	1.73
LHCb 8 TeV	7	0.78	0.36	1.14
LHCb 13 TeV	7	1.42	0.06	1.48
LHCb total	21	1.15	0.3	1.45
ATLAS 7 TeV	18	6.43	0.92	7.35
ATLAS 8 TeV	48	3.7	0.32	4.02
ATLAS 13 TeV	6	5.9	0.5	6.4
ATLAS total	72	4.56	0.48	5.05
CMS 7 TeV	4	2.21	0.10	2.31
CMS 8 TeV	4	1.938	0.001	1.94
CMS 13 TeV	70	0.36	0.02	0.37
CMS total	78	0.53	0.02	0.55
PHENIX 200	2	2.21	0.88	3.08
STAR 510	7	1.05	0.10	1.15
DY collider total	251	1.86	0.2	2.06
E288 200 GeV	30	0.35	0.19	0.54
E288 300 GeV	39	0.33	0.09	0.42
E288 400 GeV	61	0.5	0.11	0.61
E772	53	1.52	1.03	2.56
E605	50	1.26	0.44	1.7
DY fixed-target total	233	0.85	0.4	1.24
HERMES ($p \to \pi^+$)	45	0.86	0.42	1.28
HERMES ($p \to \pi^-$)	45	0.61	0.31	0.92
HERMES ($p \to K^+$)	45	0.49	0.04	0.53
HERMES ($p \to K^-$)	37	0.18	0.13	0.31
HERMES ($d \to \pi^+$)	41	0.68	0.45	1.13
HERMES ($d \to \pi^-$)	45	0.63	0.35	0.97
HERMES ($d \to K^+$)	45	0.2	0.02	0.22
HERMES ($d \to K^-$)	41	0.14	0.08	0.22
HERMES total	344	0.48	0.23	0.71
COMPASS ($d \to h^+$)	602	0.55	0.31	0.86
COMPASS ($d \to h^-$)	601	0.68	0.3	0.98
COMPASS total	1203	0.62	0.3	0.92
SIDIS total	1547	0.59	0.28	0.87
Total	**2031**	**0.77**	**0.29**	**1.06**

Backup: N3LL(-) fit parameters

Parameter	Average over replicas
g_2 [GeV]	0.248 ± 0.008
N_1 [GeV^2]	0.316 ± 0.025
α_1	1.29 ± 0.19
σ_1	0.68 ± 0.13
λ [GeV^{-1}]	1.82 ± 0.29
N_3 [GeV^2]	0.0055 ± 0.0006
β_1	10.23 ± 0.29
δ_1	0.0094 ± 0.0012
γ_1	1.406 ± 0.084
λ_F [GeV^{-2}]	0.078 ± 0.011
N_{3B} [GeV^2]	0.2167 ± 0.0055
N_{1B} [GeV^2]	0.134 ± 0.017
N_{1C} [GeV^2]	0.0130 ± 0.0069
λ_2 [GeV^{-1}]	0.0215 ± 0.0058
α_2	4.27 ± 0.31
α_3	4.27 ± 0.13
σ_2	0.455 ± 0.050
σ_3	12.71 ± 0.21
β_2	4.17 ± 0.13
δ_2	0.167 ± 0.006
γ_2	0.0007 ± 0.0110



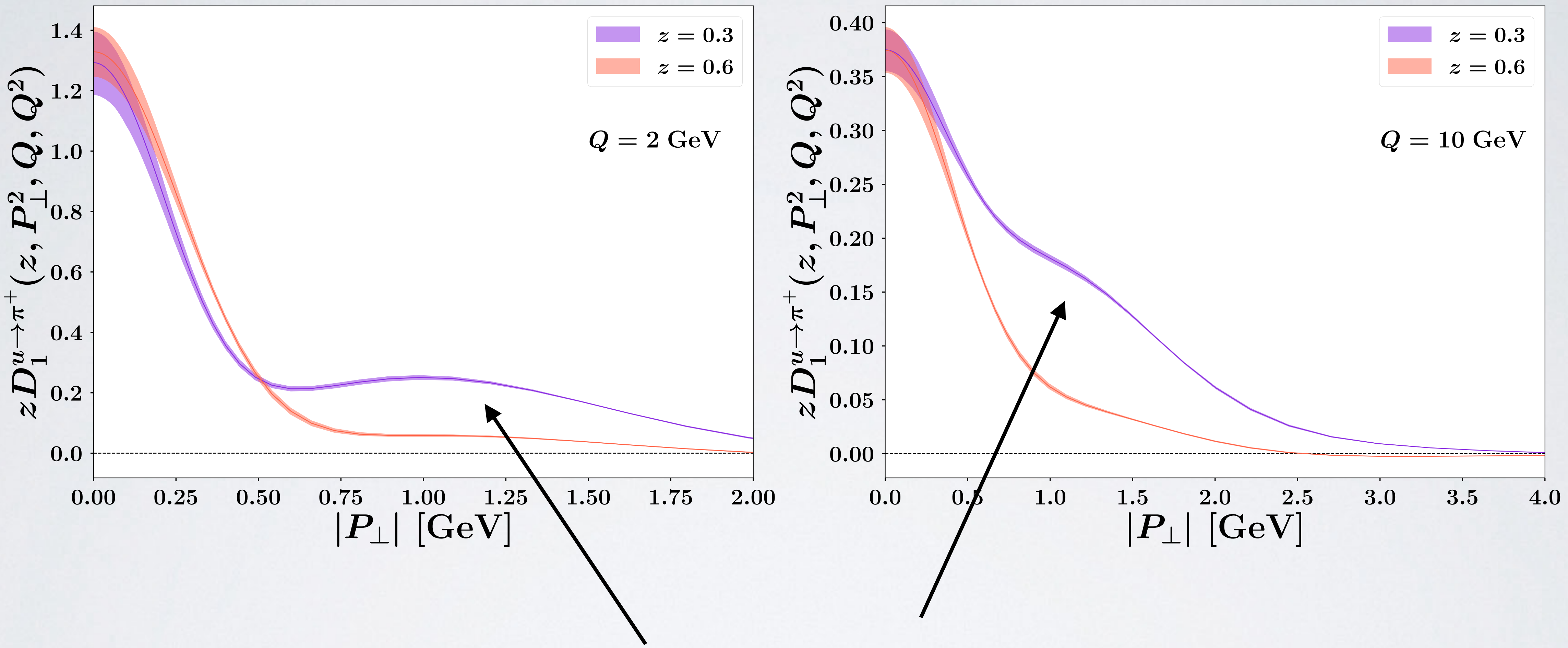
Backup: NNLL and NLL fits

	N^3LL^-		NNLL		NLL	
Data set	N_{dat}	$\langle\chi^2\rangle \pm \delta\langle\chi^2\rangle$	N_{dat}	$\langle\chi^2\rangle \pm \delta\langle\chi^2\rangle$	N_{dat}	$\langle\chi^2\rangle \pm \delta\langle\chi^2\rangle$
ATLAS	72	5.01 ± 0.26	/	/	/	/
PHENIX 200	2	3.26 ± 0.31	2	0.81 ± 0.11	/	/
STAR 510	7	1.16 ± 0.04	7	0.99 ± 0.03	/	/
Other sets	170	0.83 ± 0.01	170	2.37 ± 0.11	/	/
DY collider	251	2.06 ± 0.07	179	2.3 ± 0.1	/	/
E772	53	2.48 ± 0.12	53	2.05 ± 0.22	/	/
Other sets	180	0.87 ± 0.04	180	0.71 ± 0.04	180	0.81 ± 0.04
DY fixed-target	233	1.24 ± 0.04	233	1.01 ± 0.05	180	0.81 ± 0.04
HERMES	344	0.71 ± 0.04	344	1.1 ± 0.06	344	0.51 ± 0.02
COMPASS	1203	0.95 ± 0.02	1203	0.6 ± 0.06	1203	0.41 ± 0.01
SIDIS	1547	0.89 ± 0.02	1547	0.71 ± 0.05	1547	0.43 ± 0.01
Total	2031	1.08 ± 0.01	1959	0.89 ± 0.01	1727	0.47 ± 0.01

data sets requiring higher pert. accuracy need to be excluded.
Still, these fits useful for polarized situations with less available accuracy

Visualizing MAPTMD22 TMD FF

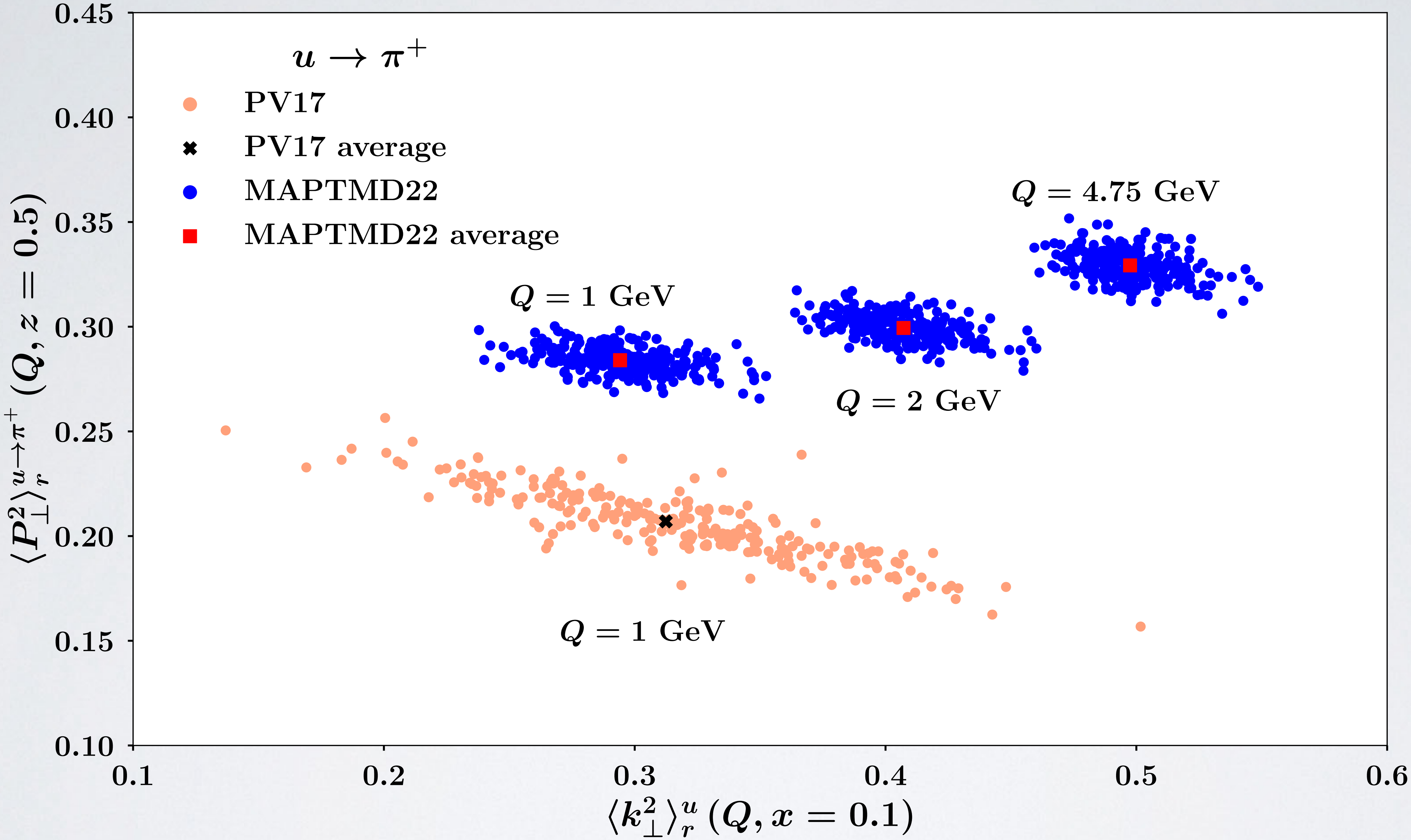
up → π^+



$D_{\mathrm{NP}}(z, P_\perp; Q_0)$ ~ Gauss + λ_F $P_\perp^2$ Gauss

$\lambda_F = 0.078 \pm 0.011\ \mathrm{GeV}^{-2}$

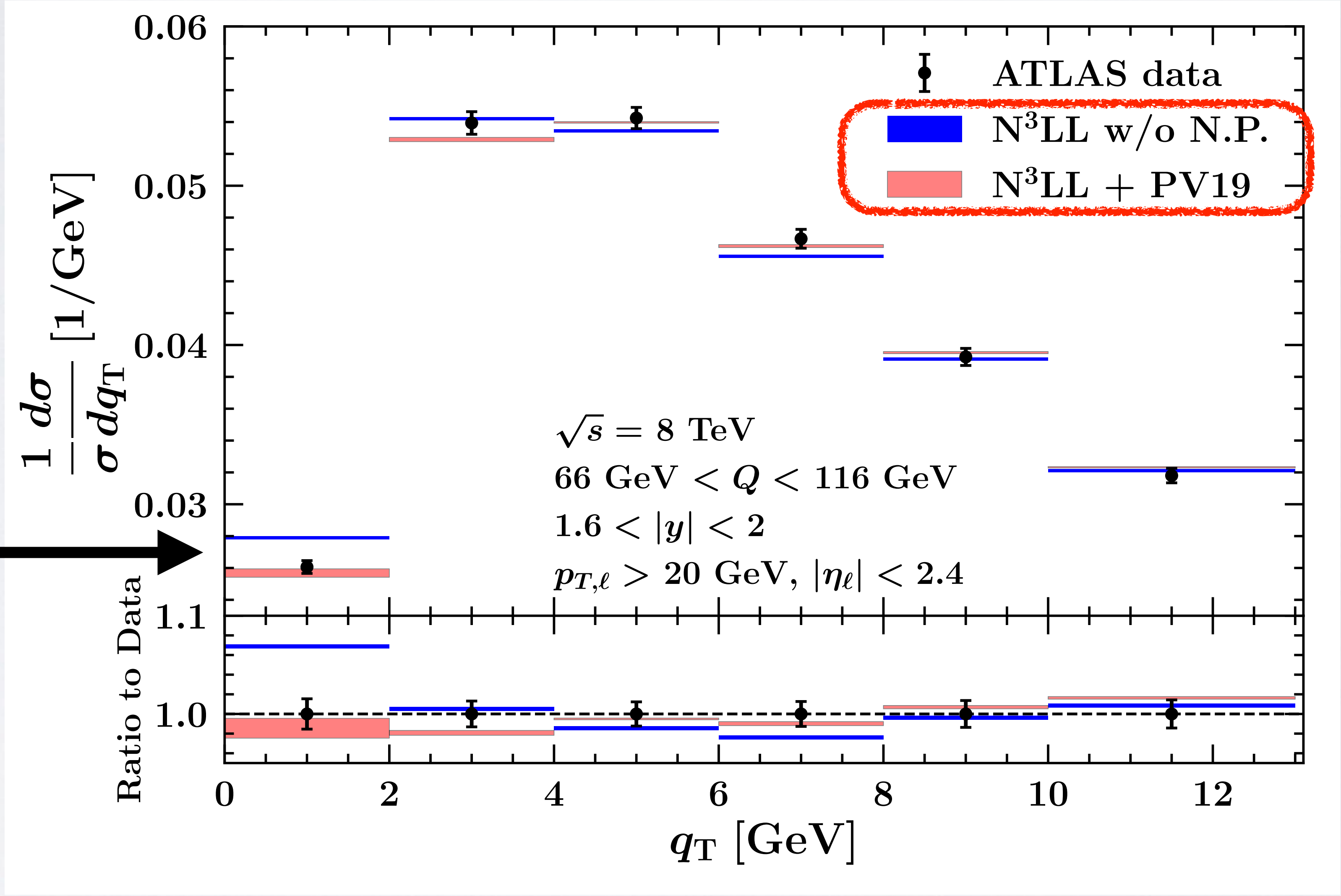
Backup: avg. transverse momenta



PV17 (NLL) ↔ MAPTMD22 (N3LL(-)) → less anticorrelation

TMD impact at the LHC

q_T distribution of Z in ATLAS kin.

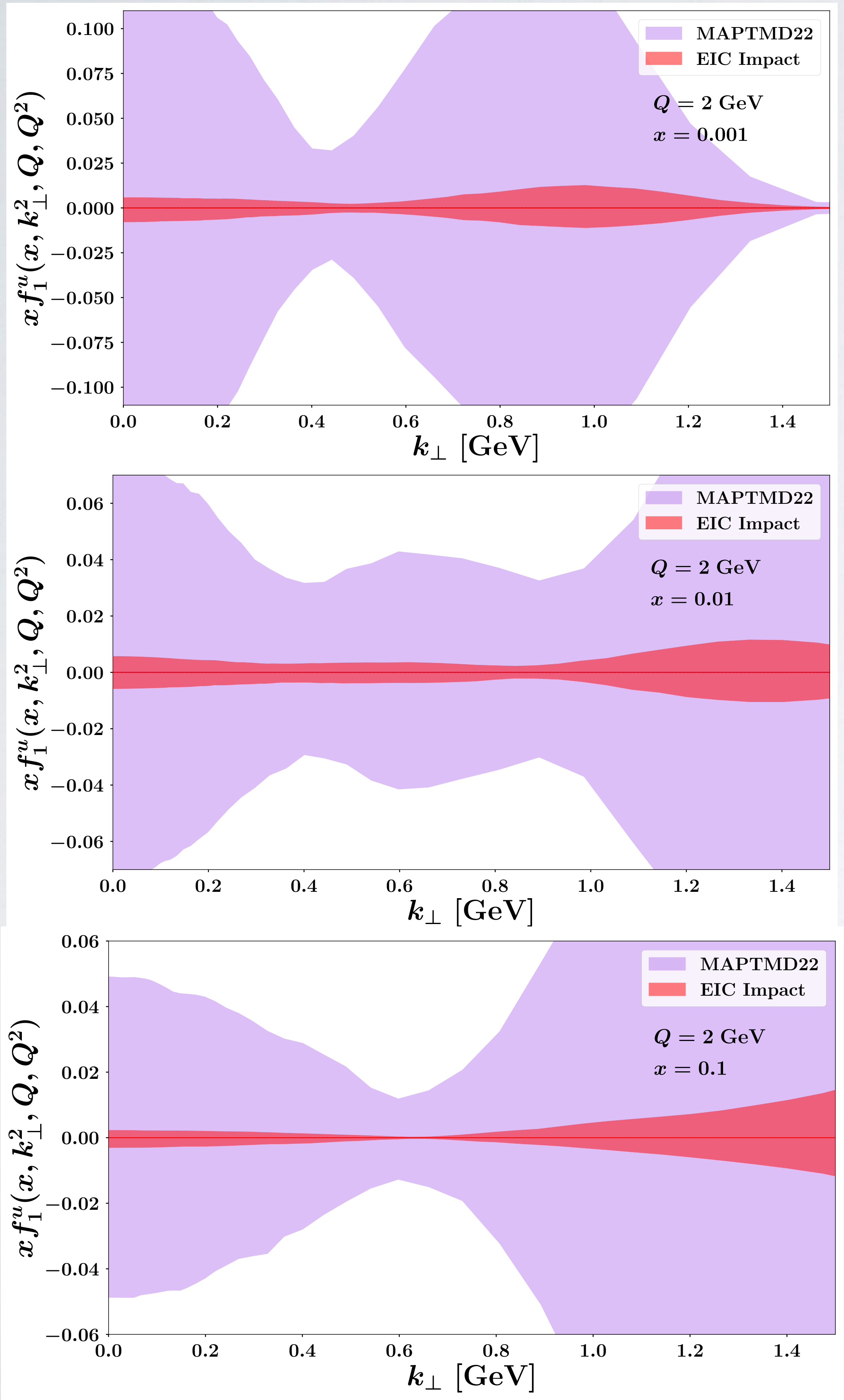


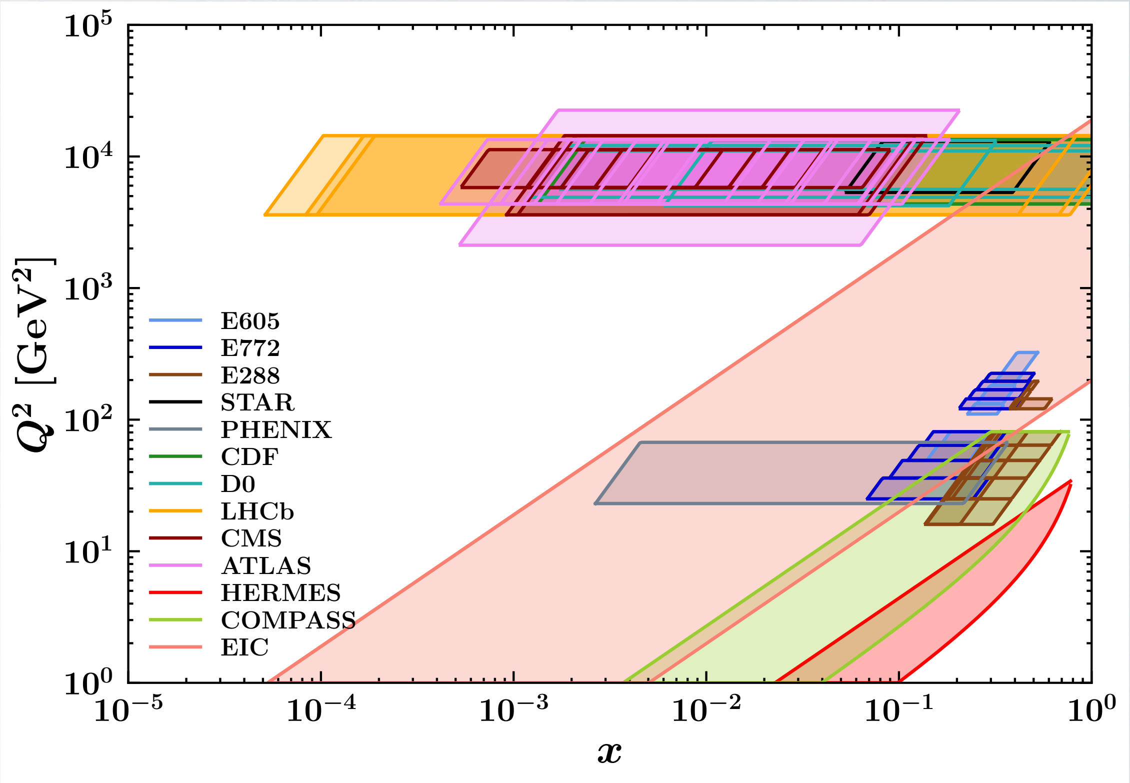
effect of intrinsic parton $k_\perp$ from PV 2019 fit

see also later for potential impact on W mass extraction

G. Bozzi, I. Scimemi (eds.) et al.,
Resummed predictions of the transverse momentum distribution of Drell-Yan lepton pairs in p-p collisions at LHC
Yellow Report of CERN EW Working Group, in preparation

The EIC impact

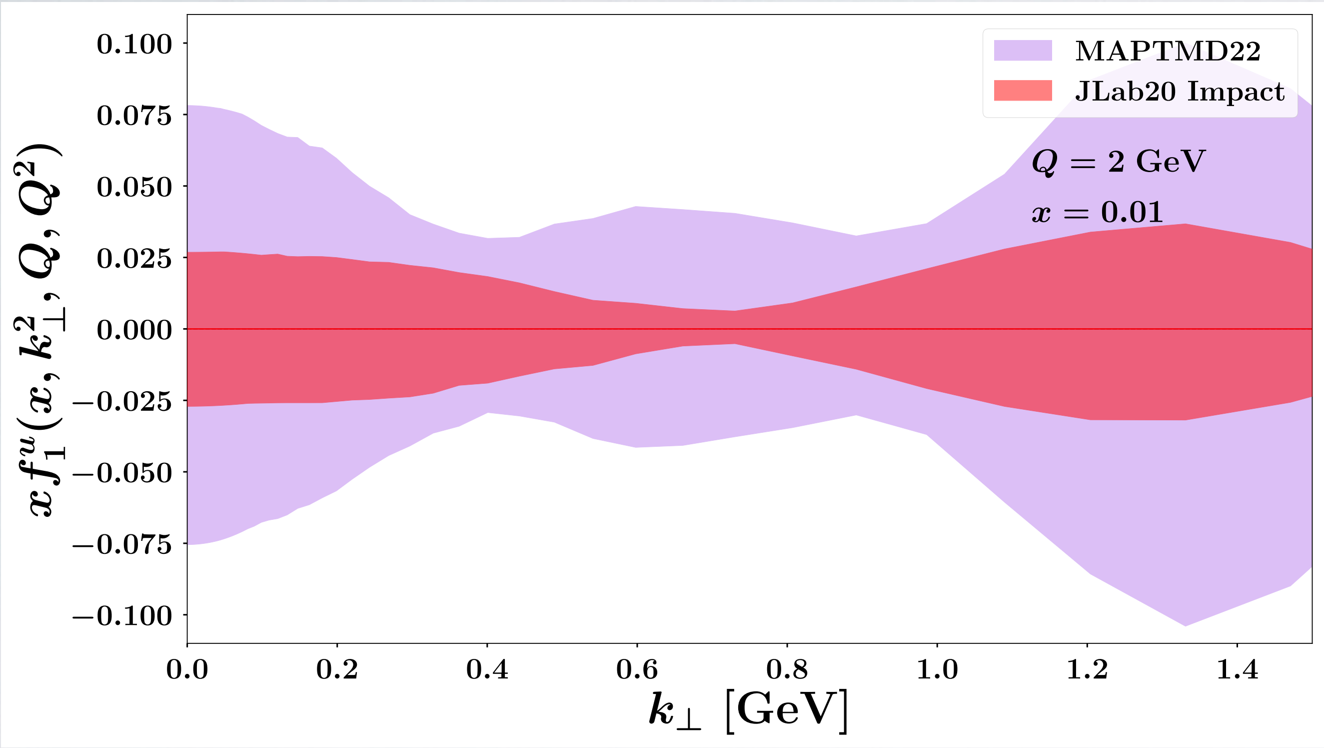


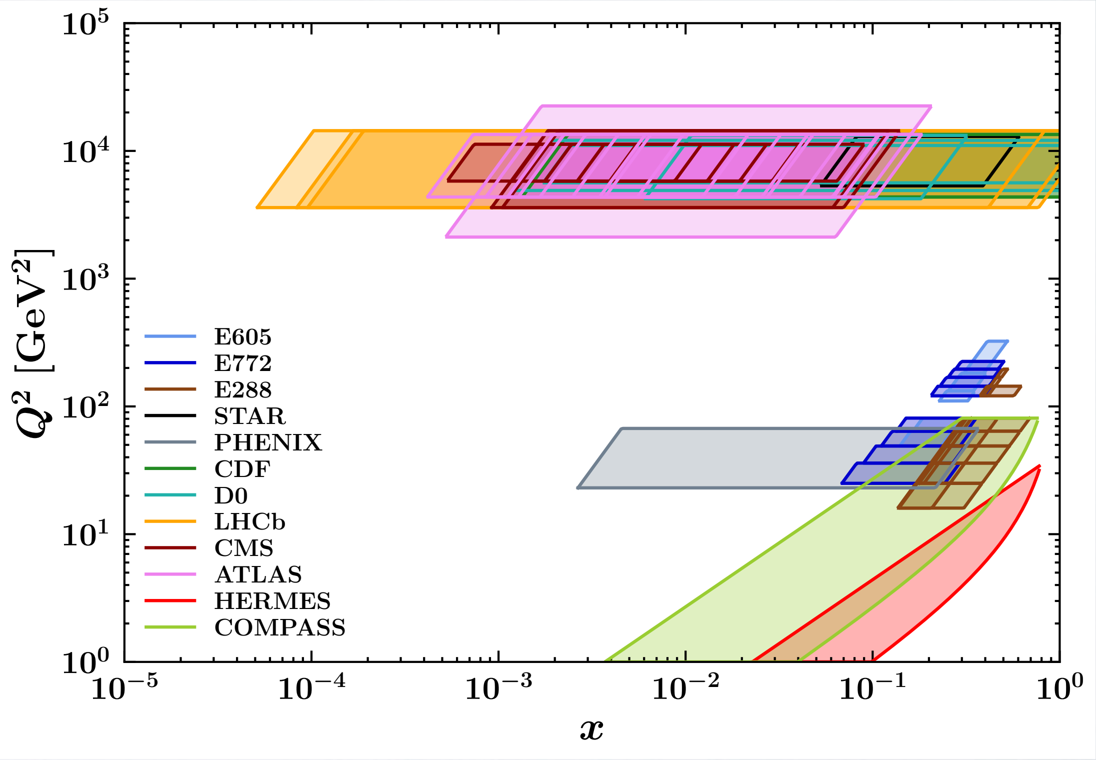


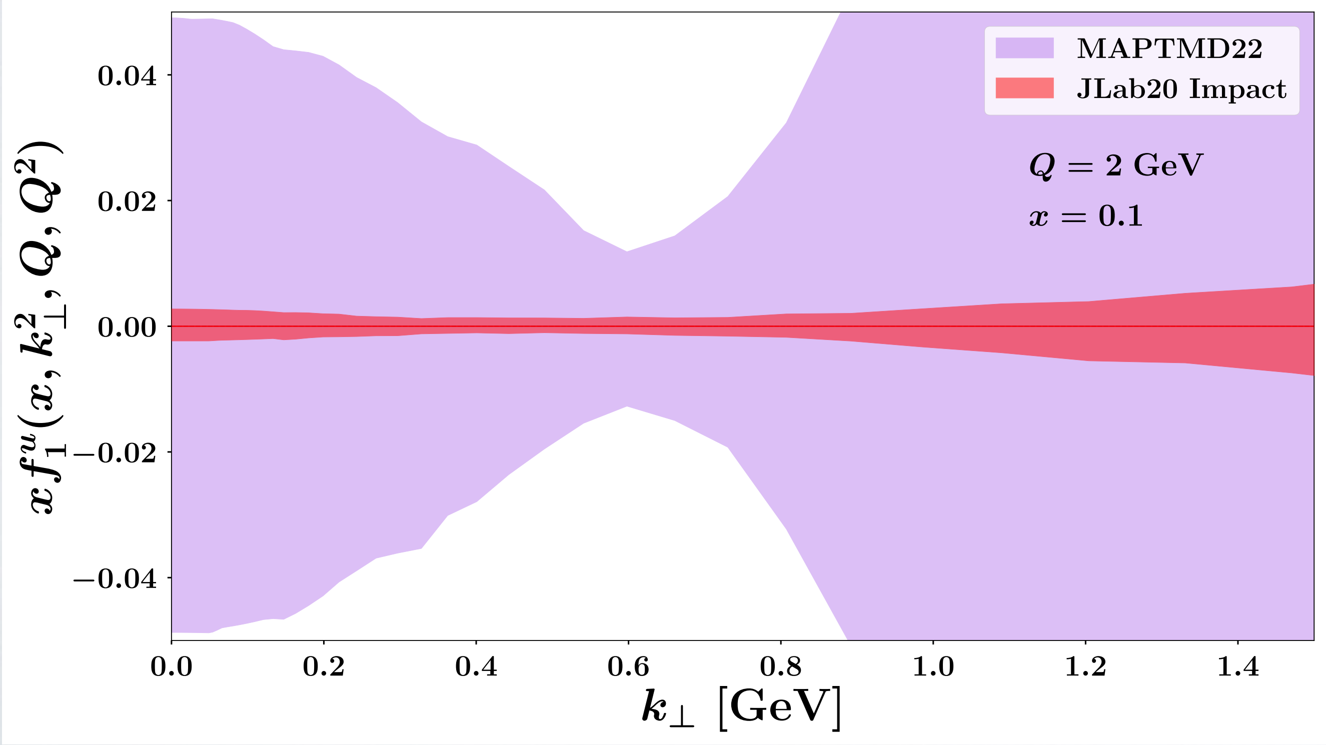
kinematics 10x100

major improvements at smaller x

The JLab20+ impact







kinematics JLab20

major improvements at valence x

The Nanga Parbat fitting framework

All material available at the Nanga Parbat github site

Nanga Parbat: a TMD fitting framework

Nanga Parbat is a fitting framework aimed at the determination of the non-perturbative component of TMD distributions.

Download

You can obtain NangaParbat directly from the github repository:

https://github.com/MapCollaboration/NangaParbat