SoLID Opportunities and Challenges of Nuclear Physics at the Luminosity Frontier

TMDs and the MAPTMD24 Global Fit

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

Results with contributions from…

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MAPTMD22 $\longrightarrow$ MAPTMD24

JHEP
PUBLISHED FOR SISSA BY SPRINGER
RECEIVED: *June 23, 2022*
REVISED: *September 13, 2022*
ACCEPTED: *October 10, 2022*
PUBLISHED: *October 19, 2022*

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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JHEP10(2022)127

arXiv:2206.07598

Flavor dependence of unpolarized quark Transverse Momentum Distributions from a global fit

The **MAP** (Multi-dimensional Analyses of Partonic distributions) Collaboration

Alessandro Bacchetta,[1, 2, *] Valerio Bertone,[3, †] Chiara Bissolotti,[4, ‡] Giuseppe Bozzi,[5, 6, §] Matteo Cerutti,[7, 8, ¶] Filippo Delcarro,[1, 2, **] Marco Radici,[2, ††] Lorenzo Rossi,[1, 2, ‡‡] and Andrea Signori[9, 10, §§]
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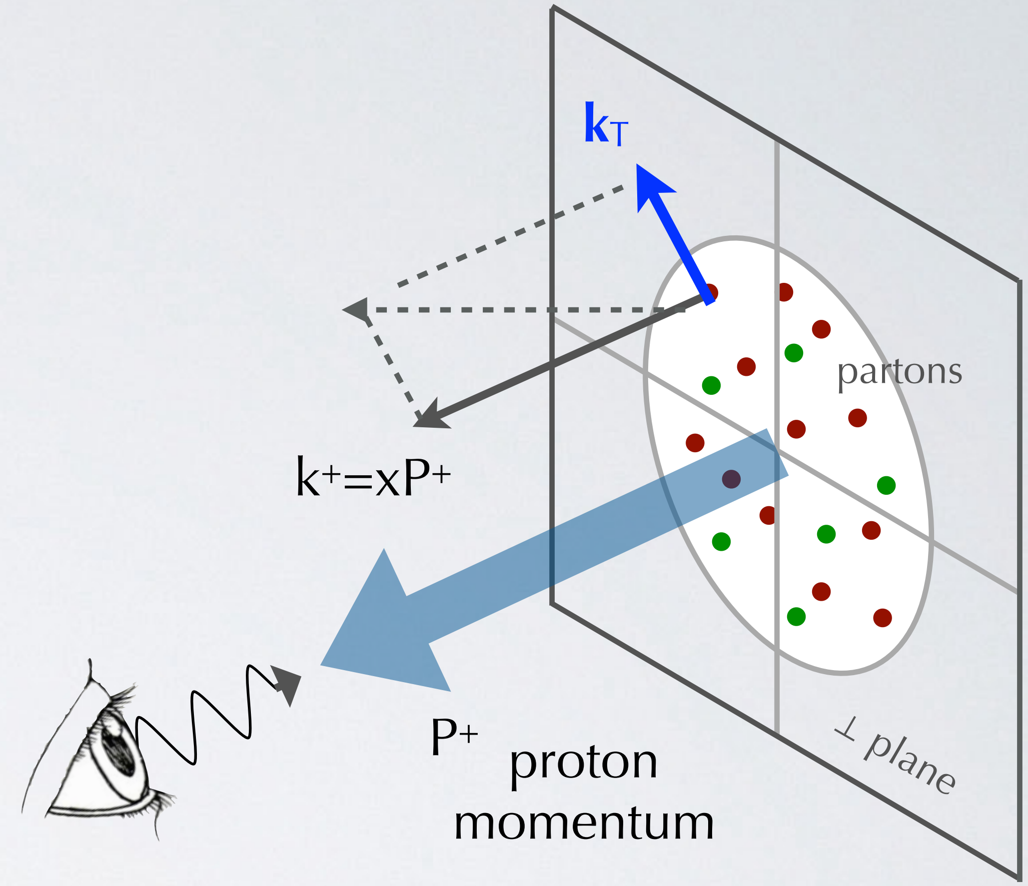
[10]*INFN, Section of Turin, via Pietro Giuria 1, I-10125 Torino, Italy*

arXiv:2405.13833

First extraction of unpolarized quark TMD f_1^q in the proton from global fit of SIDIS & Drell-Yan data including flavor sensitivity of intrinsic k_T-dependence

Transverse-Momentum Distributions (TMDs)

3D map (x, $\mathbf{k}_T$)
of internal structure of the Nucleon



		Quark polarization		
		Unpolarized (U)	**Longitudinally Polarized (L)**	**Transversely Polarized (T)**
Nucleon Polarization	U	$f_1 =$	✘	$h_1^\perp =$ -
	L	✘	$g_1 =$ -	$h_{1L}^\perp =$ -
	T	$f_{1T}^\perp =$ -	$g_{1T} =$ -	$h_1 =$ - $h_{1T}^\perp =$ -

see Gamber's talk for twist-3
Pitonyak's talk for polarized

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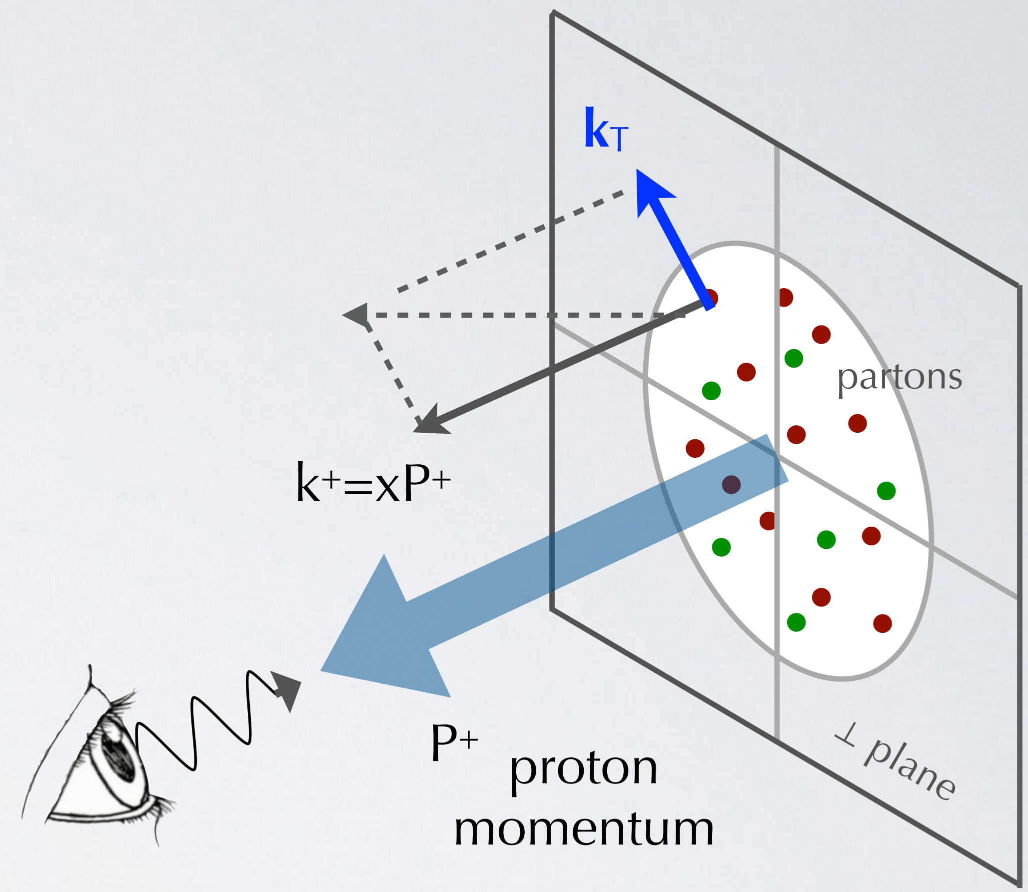

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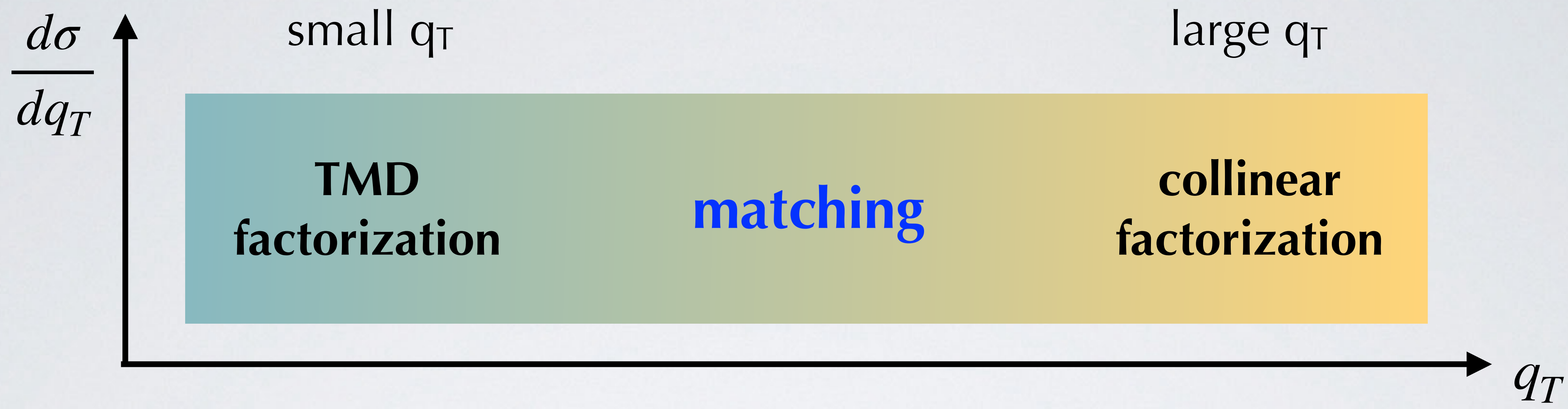
	T	$f_{1T}^\perp =$ -	$g_{1T} =$ -	$h_1 =$ - $h_{1T}^\perp =$ -

$$f_1^q(x, \mathbf{k}_T^2; \mu, \zeta)$$

depend on two scales μ, ζ

(can be chosen as $\zeta=\mu^2=Q^2$)

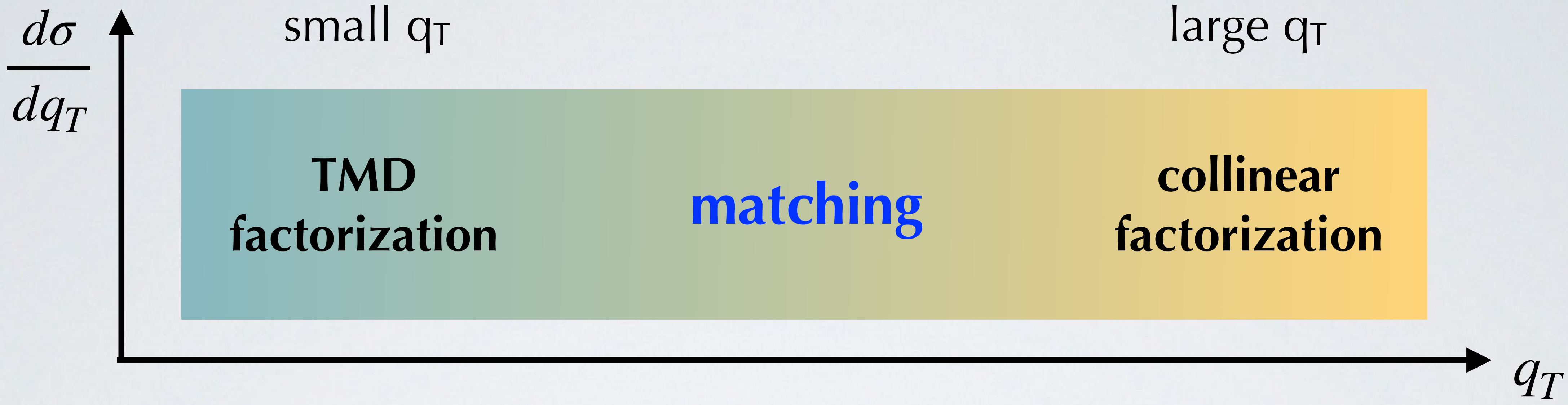
TMD factorization



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

$$0 \longleftarrow Y \longrightarrow \text{F.O.}$$

TMD factorization



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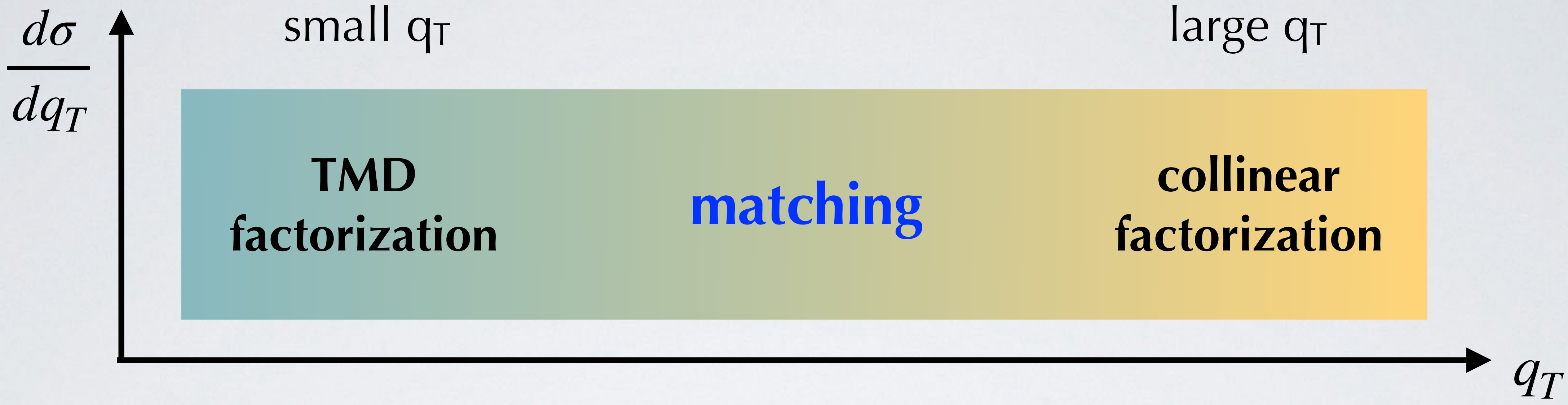
our analysis is in this regime where W-term dominates. Y-term is not included

TMD factorization



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

at low Q (SIDIS), this limit does not work....

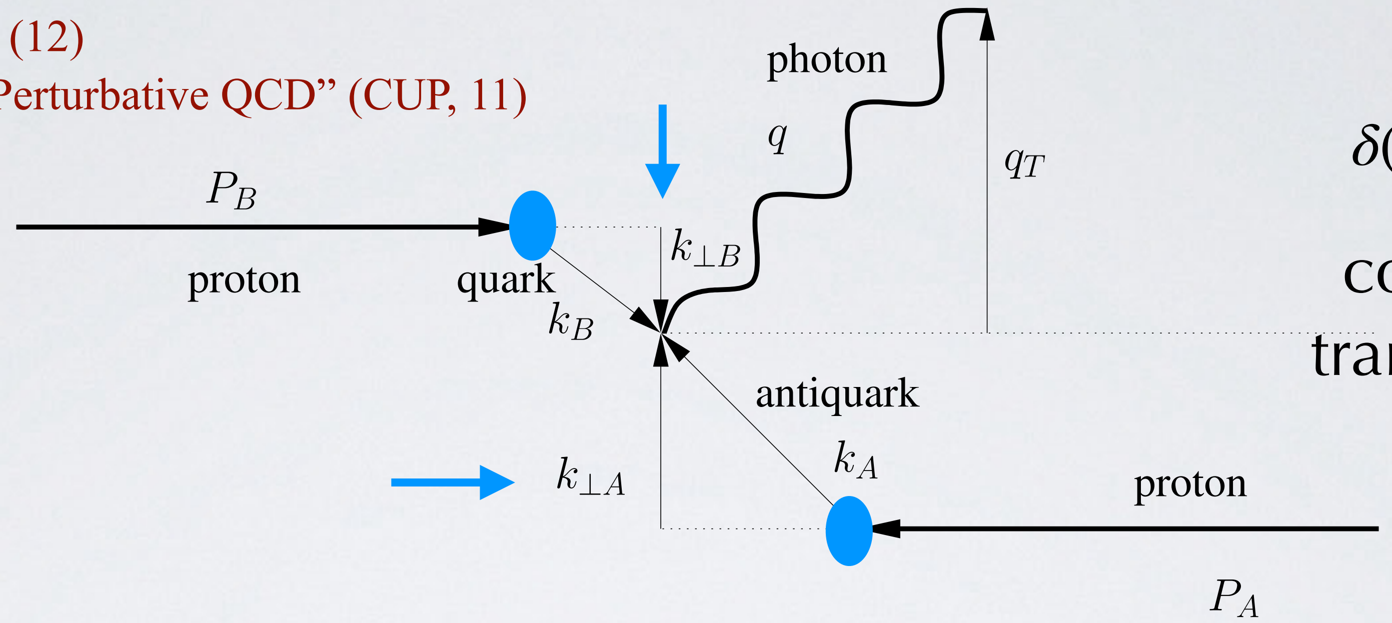
Sun *et al.*, Int.J.Mod.Phys. **A33** (18) 1841006, arXiv:1406.3073

TMD factorization: Drell-Yan

Collins & Soper, N.P. B**193** (81)
Echevarria, Idilbi, Scimemi, JHEP **07** (12)
For review, Collins, “Foundations of Perturbative QCD” (CUP, 11)

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

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 $\zeta=\mu^2=Q^2$

TMD factorization: Drell-Yan

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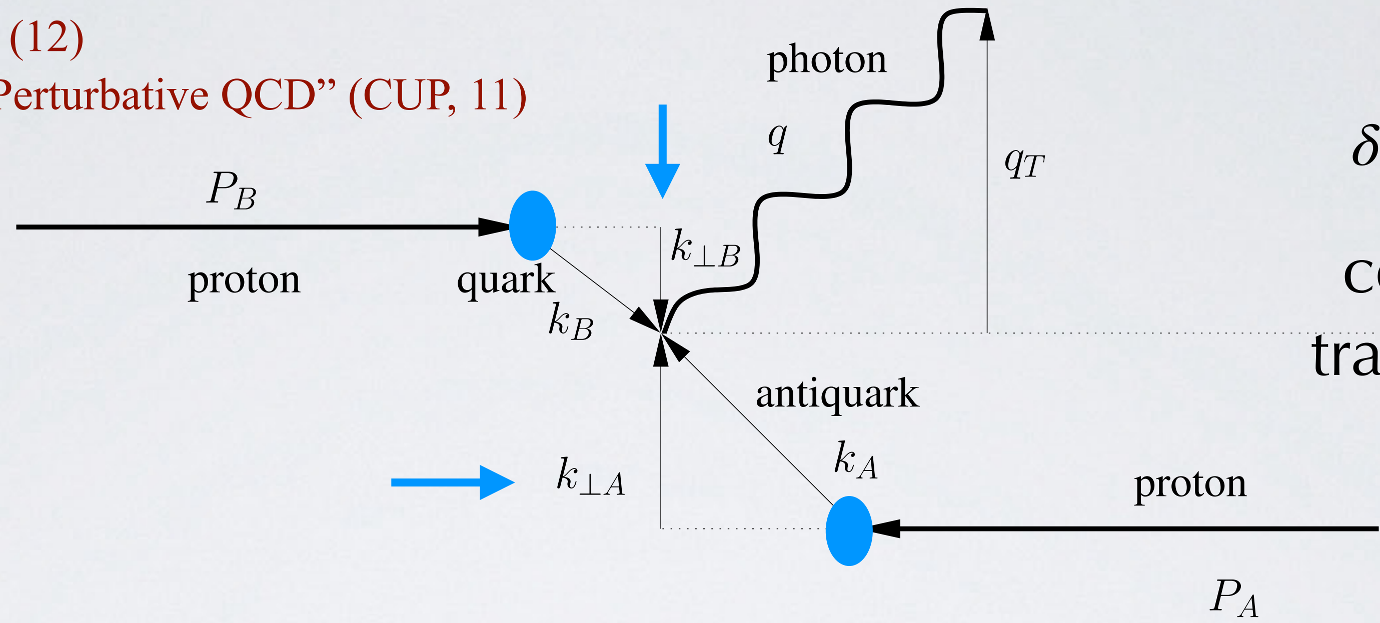

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hard factor — **TMD PDF anti-q** — **TMD PDF q**

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 $\zeta=\mu^2=Q^2$

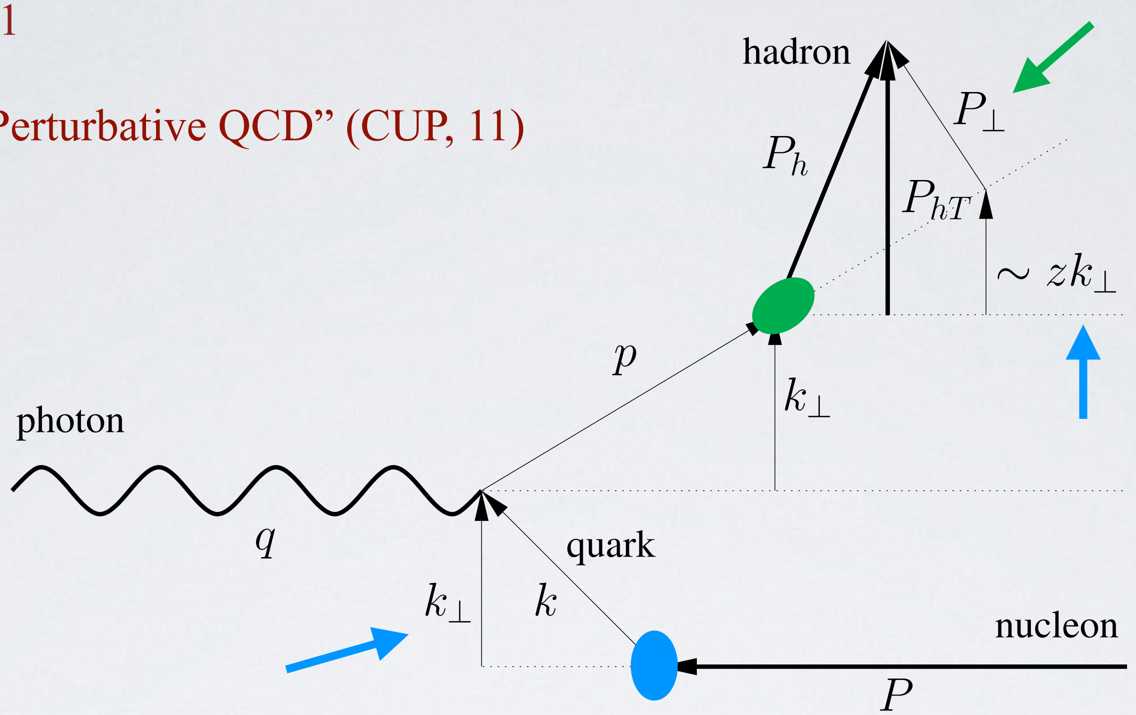
TMD factorization: SIDIS

Collins & Metz, P.R.L. **93** (04) 252001
Ji, Yuan, Ma, P.R. D**71** (05) 034005
For review, Collins, "Foundations of Perturbative QCD" (CUP, 11)

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

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

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

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

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Scale dependence of TMD: the CSS scheme

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

OPE: 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 α_S^n accuracy	$\mathscr{H}$ and C	K and γ_F	γ_K	PDF and α_S evol.	FF
LL	0	-	1	-	-
NLL	0	1	2	LO	LO
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$N^3LL(-)$	2	3	4	NNLO	NLO
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FF at NNLO only recently

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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perturbative

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

prescription to smoothly connect to large b_T, avoiding Landau pole. Introduces nonperturbative part

perturbative α_S^n accuracy	$\mathscr{H}$ and C	K and γ_F	γ_K	PDF and α_S evol.	FF
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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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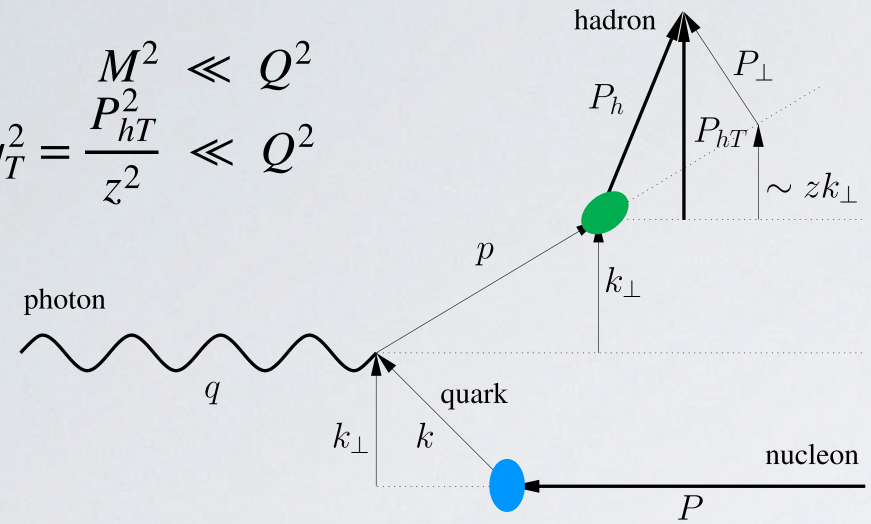
Abdul Khalek et al., P.L. **B834** (22) 137456 arXiv:2204.10331

TMD factorization → universality

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

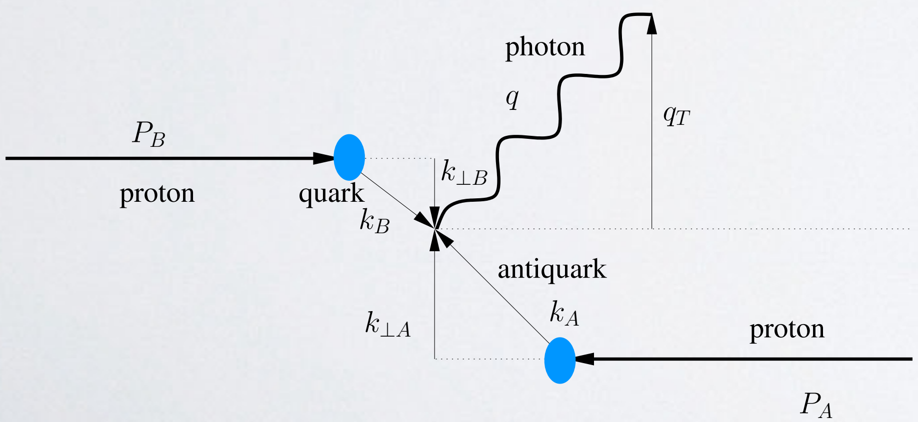


SIDIS

$$\frac{d\sigma}{dx\,dz\,dq_T\,dQ} \sim \mathcal{H}^{\rm SIDIS}(Q^2)\,\frac{1}{2\pi}\int_0^\infty db_T\,b_T\;J_0(b_T,q_T)\;\;\tilde{f}_1^q(x,b_T^2;Q^2)\;\;\tilde{D}_1^{q\to h}(z,b_T^2;Q^2)$$

same TMD PDF

$$\frac{d\sigma}{dq_T\,dy\,dQ} \sim \mathcal{H}^{\rm DY}(Q^2)\,\frac{1}{2\pi}\int_0^\infty db_T\,b_T\;J_0(b_T,q_T)\;\;\tilde{f}_1^{\bar{q}}(x_A,b_T^2;Q^2)\;\;\tilde{f}_1^q(x_B,b_T^2;Q^2)$$



Drell-Yan

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

only three global fits

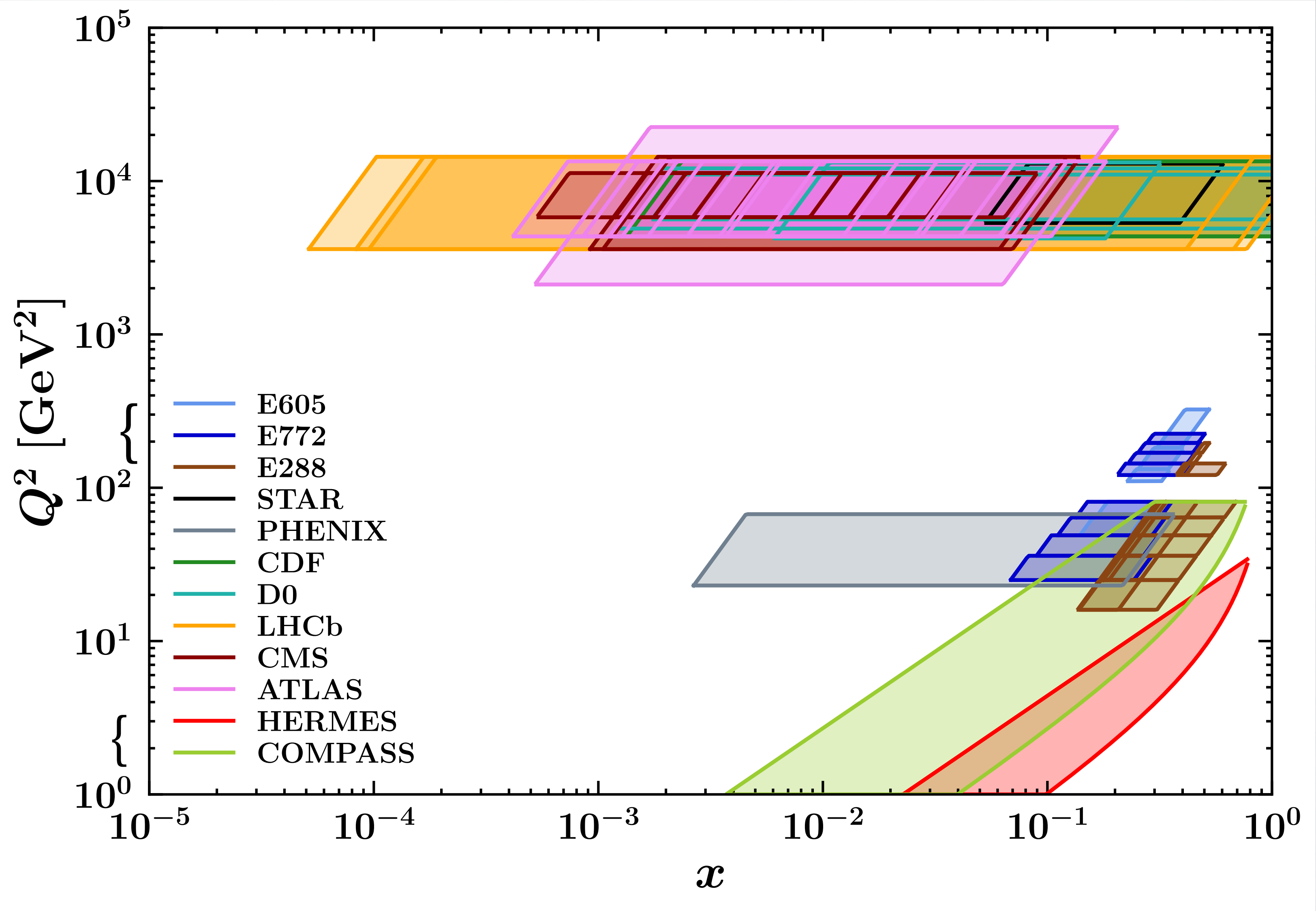
The MAPTMD22 data sets

N_{data} after cuts

Drell Yan { 233 fixed target; 251 collider

1547 SIDIS

2031 data points



kinematic cuts

$\langle Q \rangle > 1.4$ GeV

$0.2 < z < 0.7$

Drell-Yan $\quad q_T < 0.2\,Q$

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

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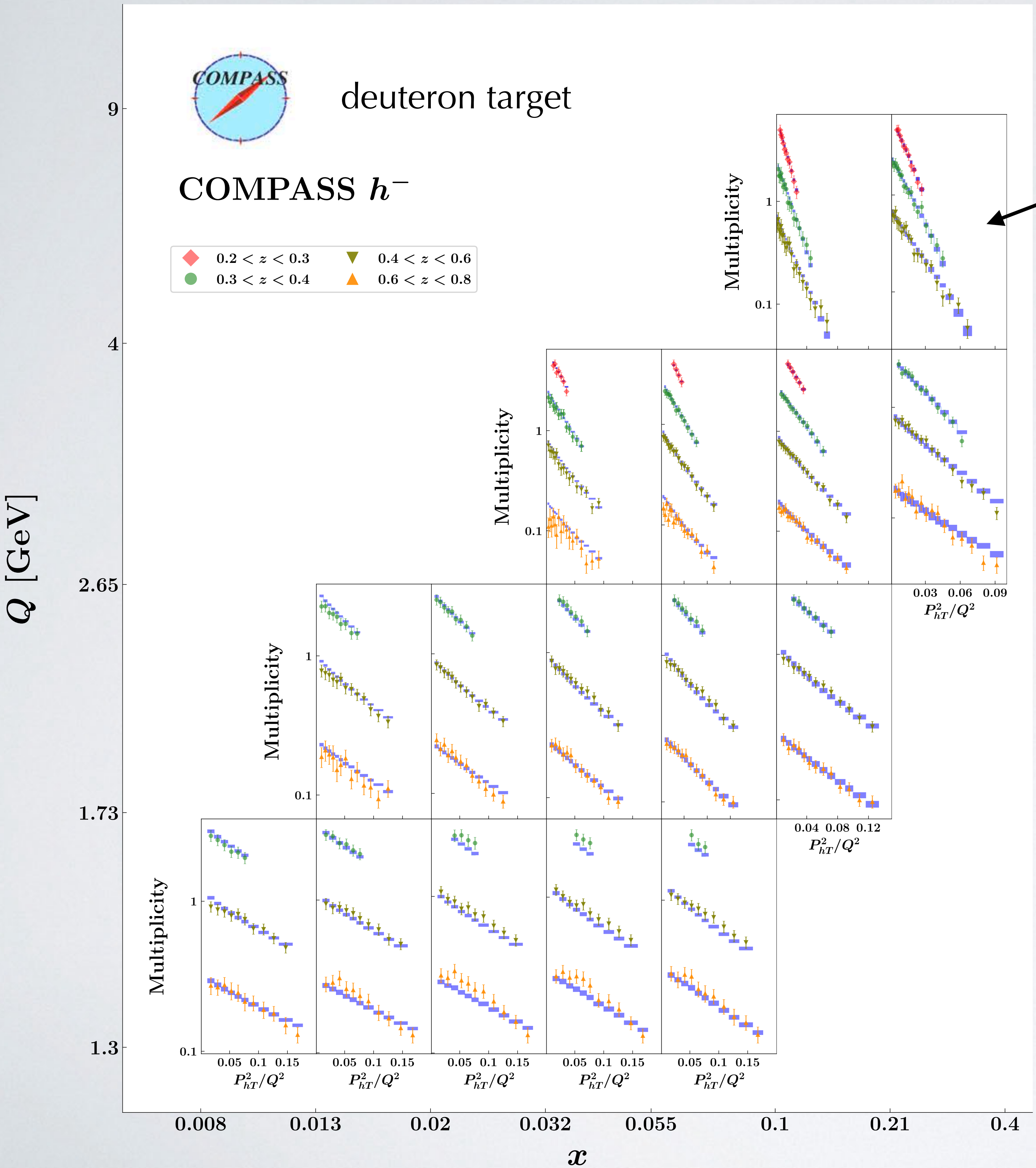
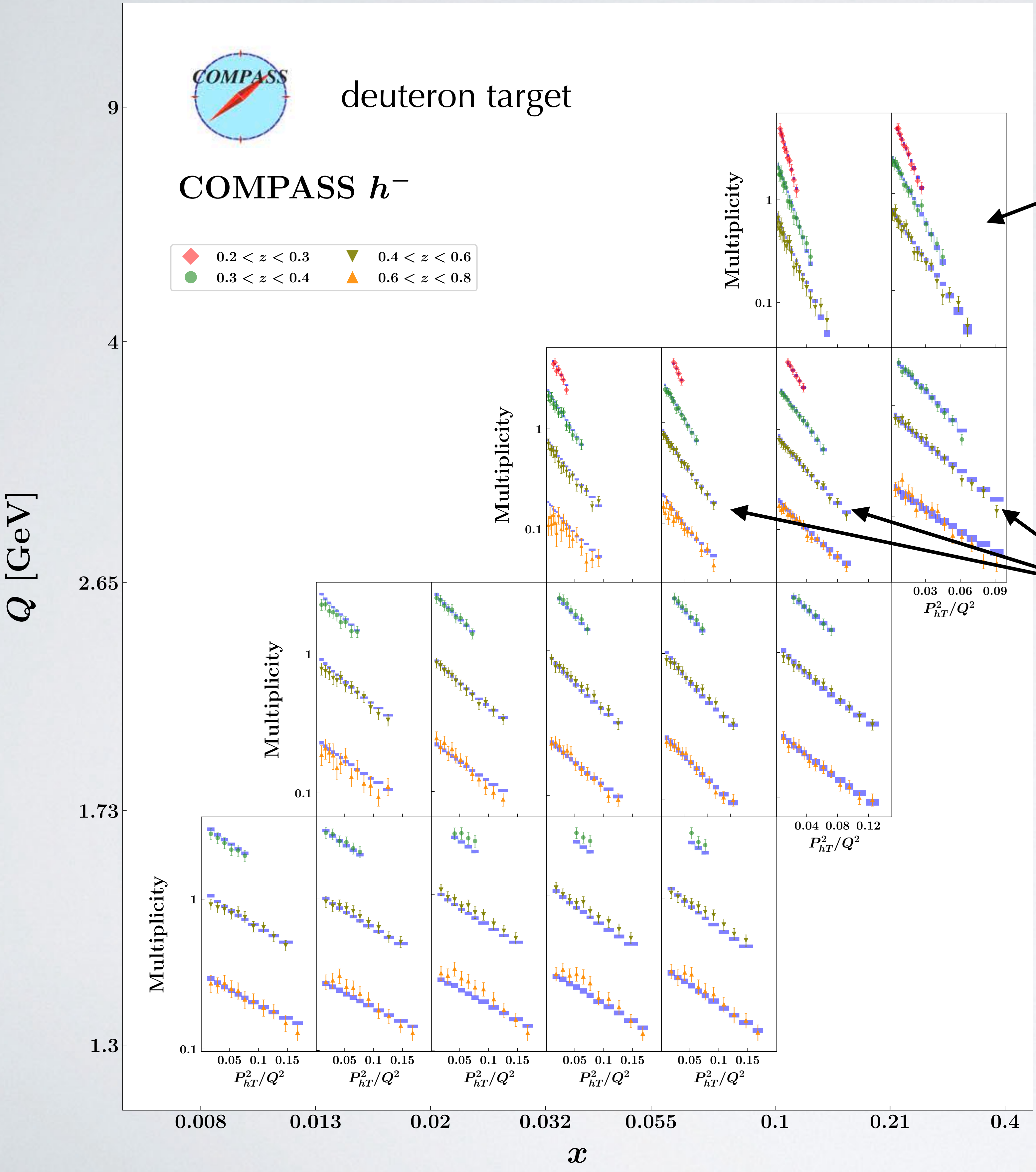
Data-driven nonperturbative TMD



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

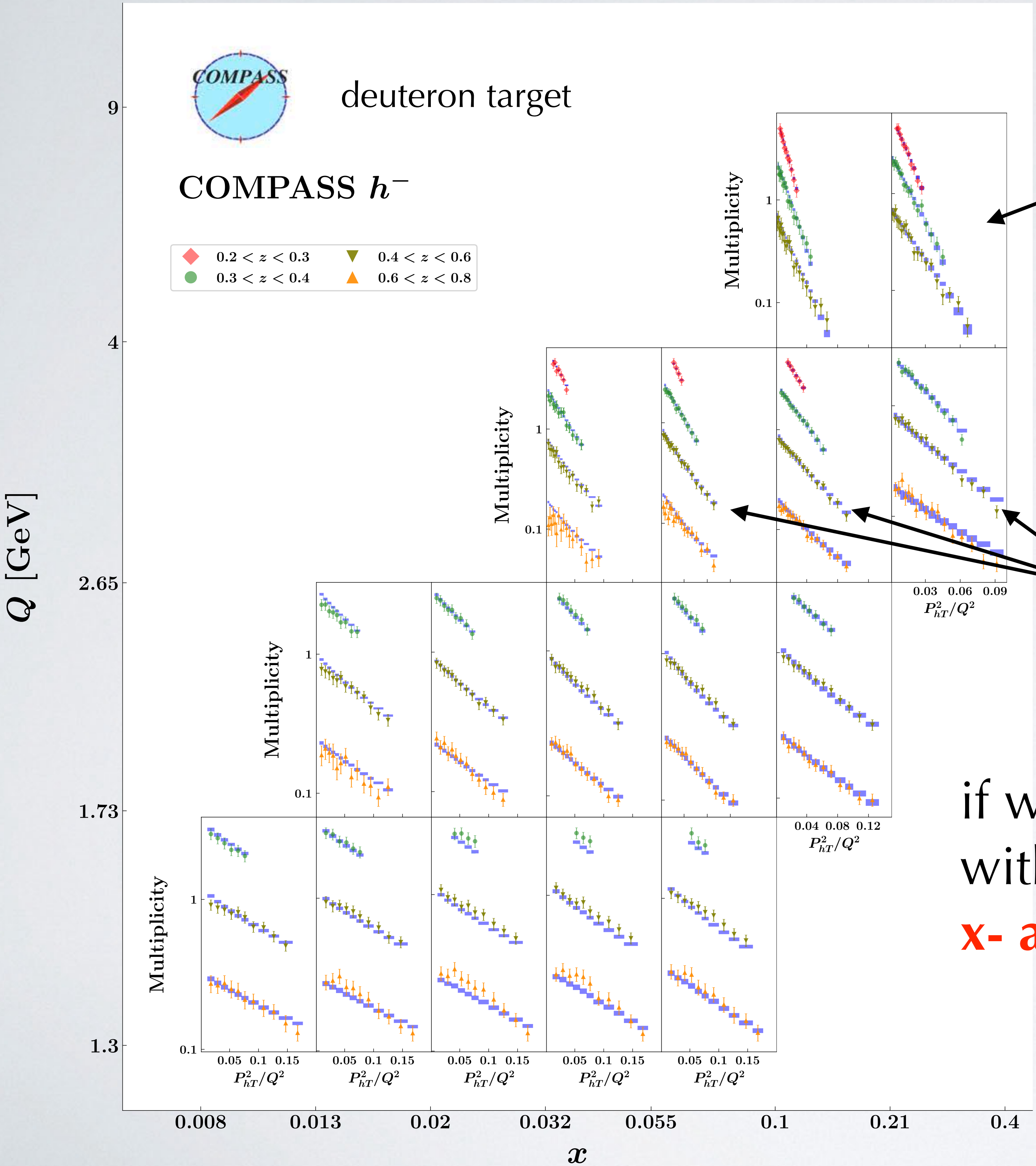
Data-driven nonperturbative TMD



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

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

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

11 param.

suggested by models

Bacchetta, Gamberg, Goldstein, et al., PLB **659** (2008)
Bacchetta, Conti, Radici, PRD **78** (2008)
Pasquini, Cazzaniga, Boffi, PRD **78** (2008)
Matevosyan, Bentz, Cloet, Thomas, PRD **85** (2012)
Burkardt, Pasquini, EPJA (2016)
Grewal, Kang, Qiu, Signori, PRD **101** (2020)

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

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

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

11 param.

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

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

9 param.

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

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.

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

9 param.

nonperturbative part of Collins-Soper kernel

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

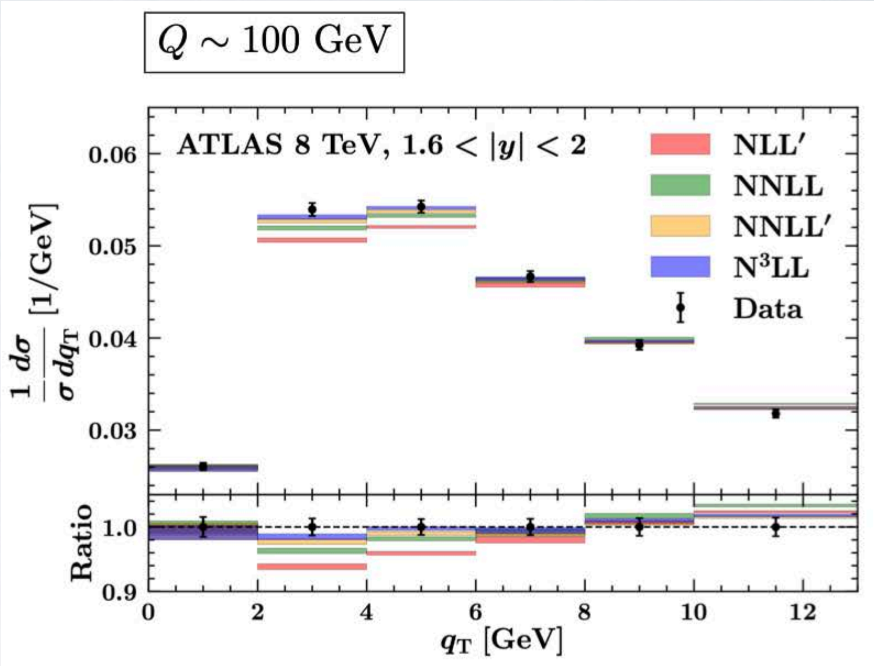
1 param.

Total 21 param.

Normalization issue in SIDIS

increasing perturbative accuracy

increases agreement with Drell-Yan

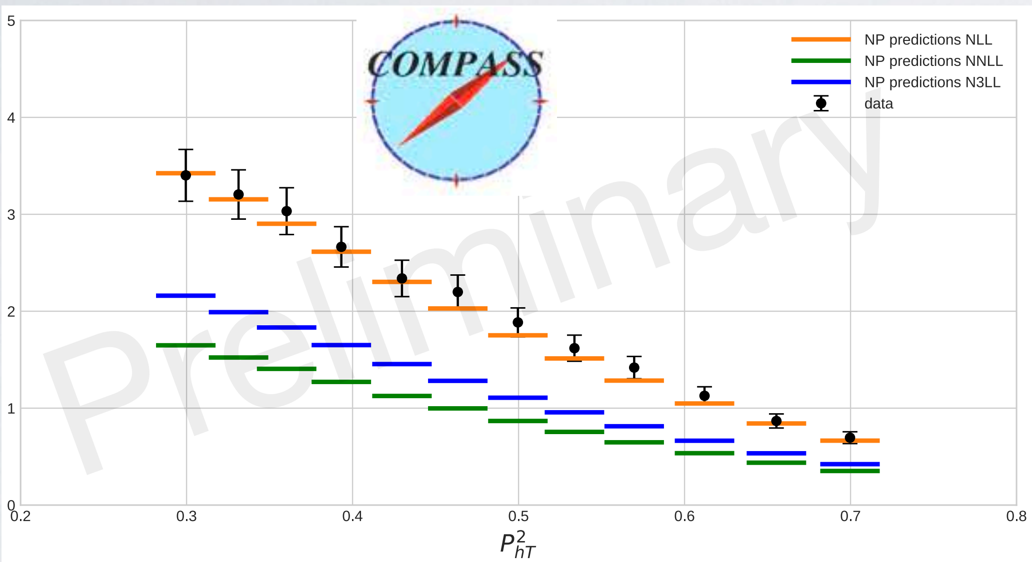


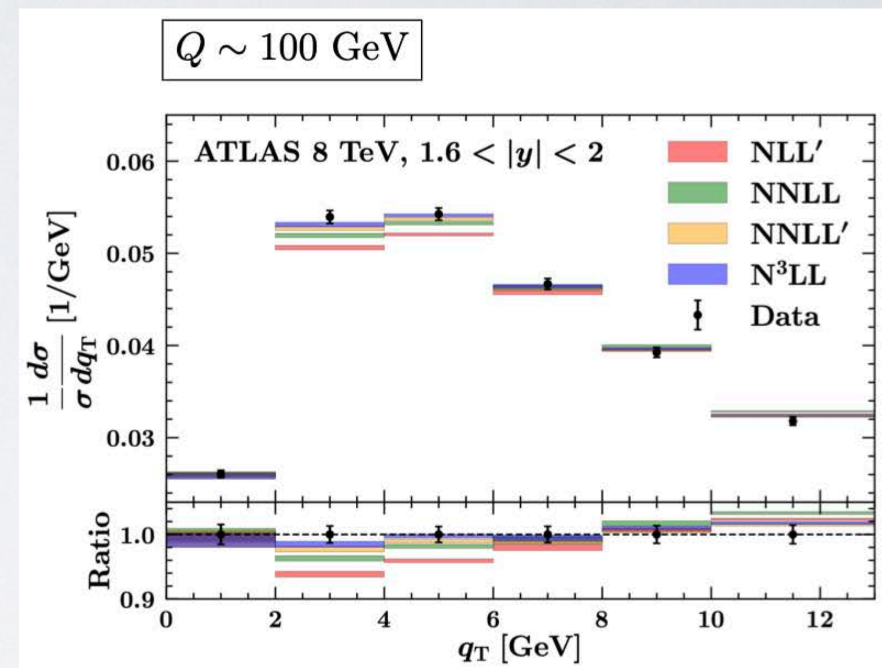
Normalization issue in SIDIS

increasing perturbative accuracy

worsens agreement with SIDIS ! increases agreement with Drell-Yan

$M^h(\bar{x}, \bar{z}, \bar{Q}, q_T)$ 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 — Gonzalez et al., P.R. D**98** (18) 114005

and also in Drell-Yan at low Q — Bacchetta et al., P.R. D**100** (19) 014018

and also in e+e- annihilations — 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)

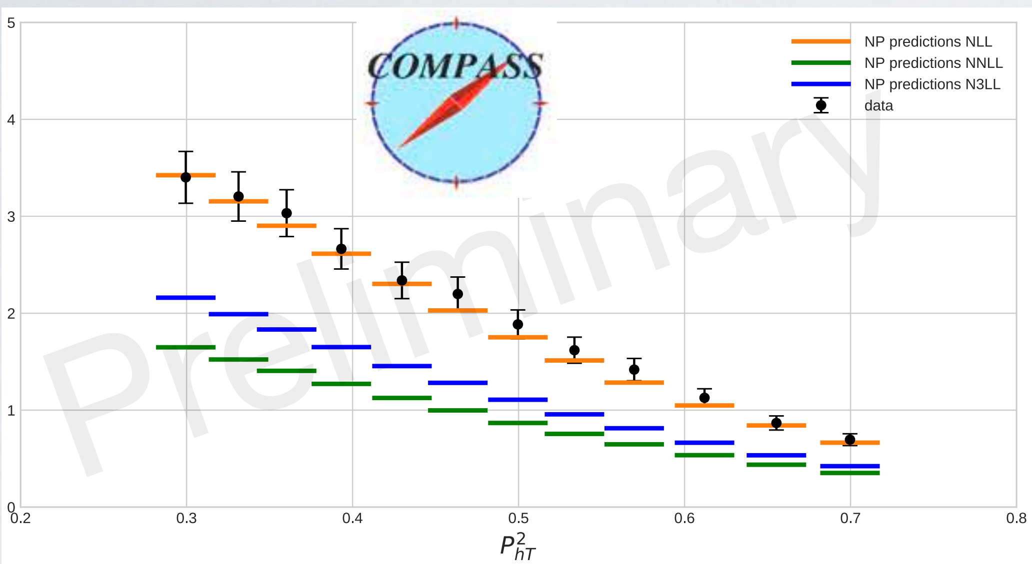
Abdul Khalek et al., arXiv:2105.08725

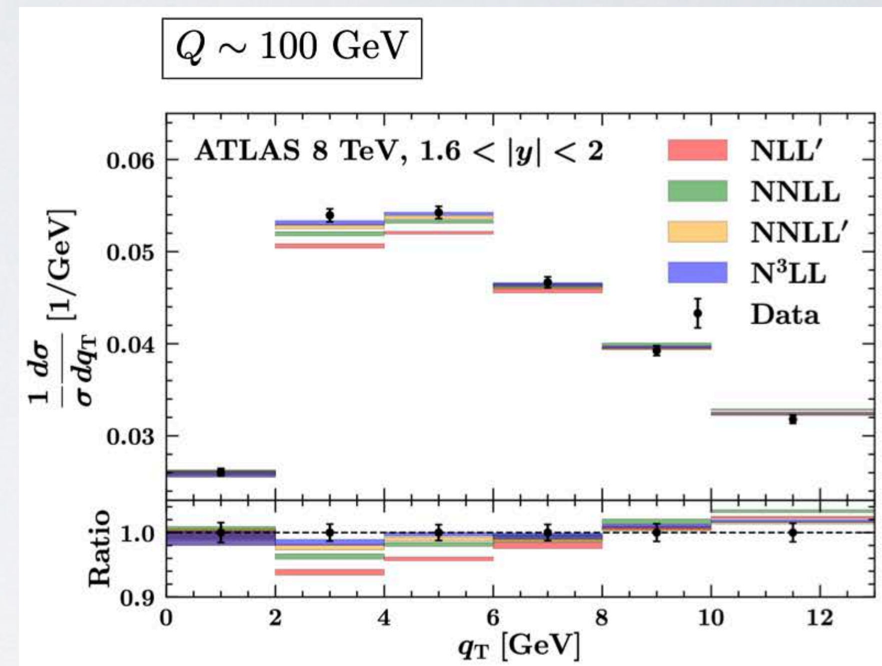
Normalization issue in SIDIS

increasing perturbative accuracy

worsens agreement with SIDIS ! increases agreement with Drell-Yan

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





SIDIS data as multiplicities M : $M(x, z, q_T, Q) = \frac{d\sigma^{\text{SIDIS}}}{dx dz dq_T dQ} \bigg/ \frac{d\sigma^{\text{DIS}}}{dx dQ}$

At **NLL** $\int dq_T \frac{d\sigma}{dx dz dq_T dQ} = \int dq_T W\Big|_{\text{NLL}} = \frac{d\sigma}{dx dz dQ}\Big|_{\text{LO}}$

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

$M(x, z, q_T, Q)$ **is ok**

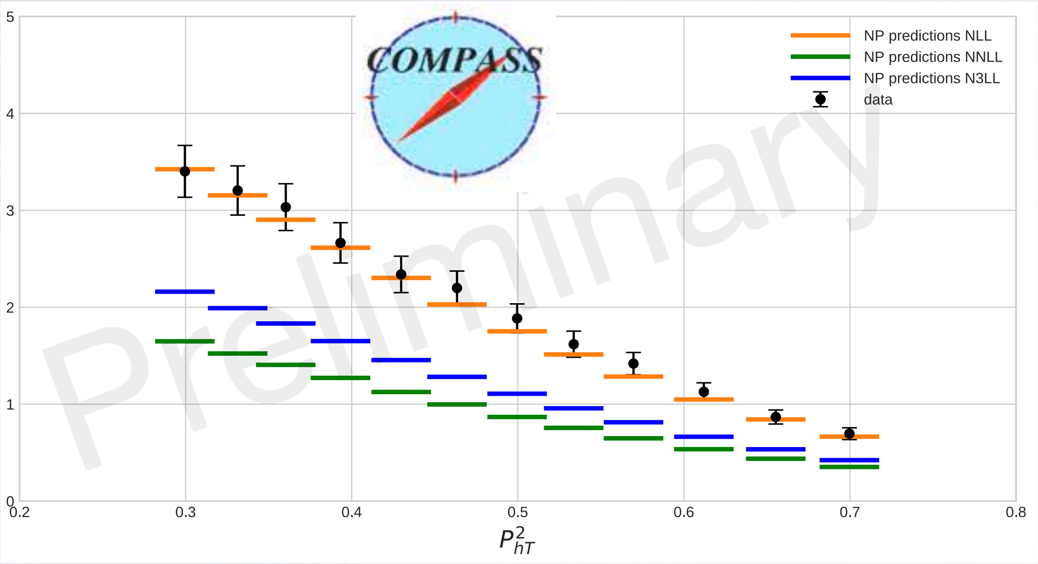
De Florian et al., P.R. D**75** (07) 114010

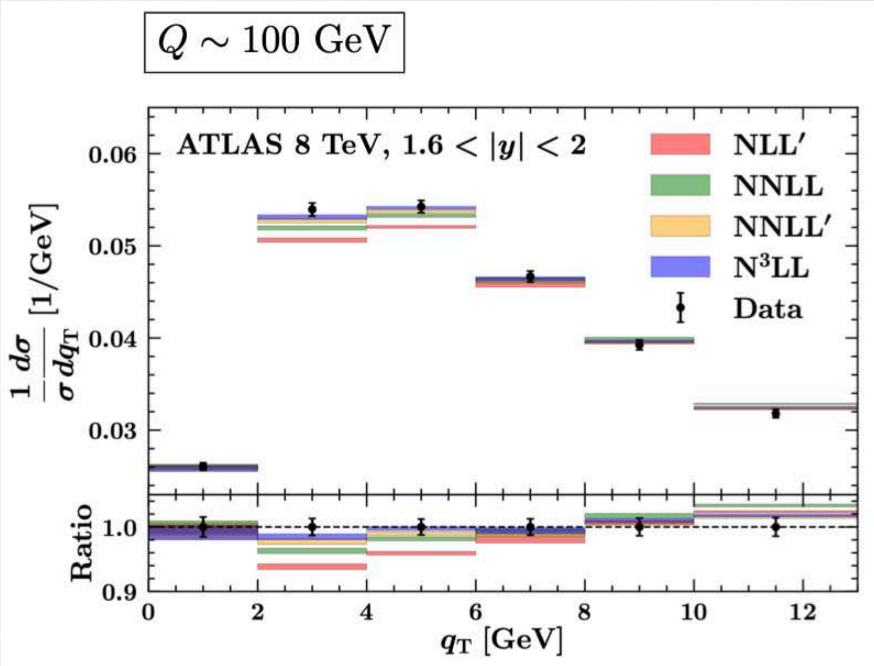
Normalization issue in SIDIS

increasing perturbative accuracy

worsens agreement with SIDIS ! increases agreement with Drell-Yan

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





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At **NNLL** $\int dq_T \, W \Big|_{\text{NNLL}} \neq \frac{d\sigma}{dx dz dQ}\Big|_{\text{NLO}}$

integrated W-term **does not** reproduce the SIDIS collinear dσ at **NLO**

Y-term contributions missing

$M(x, z, q_T, Q)$ **underestimates data**

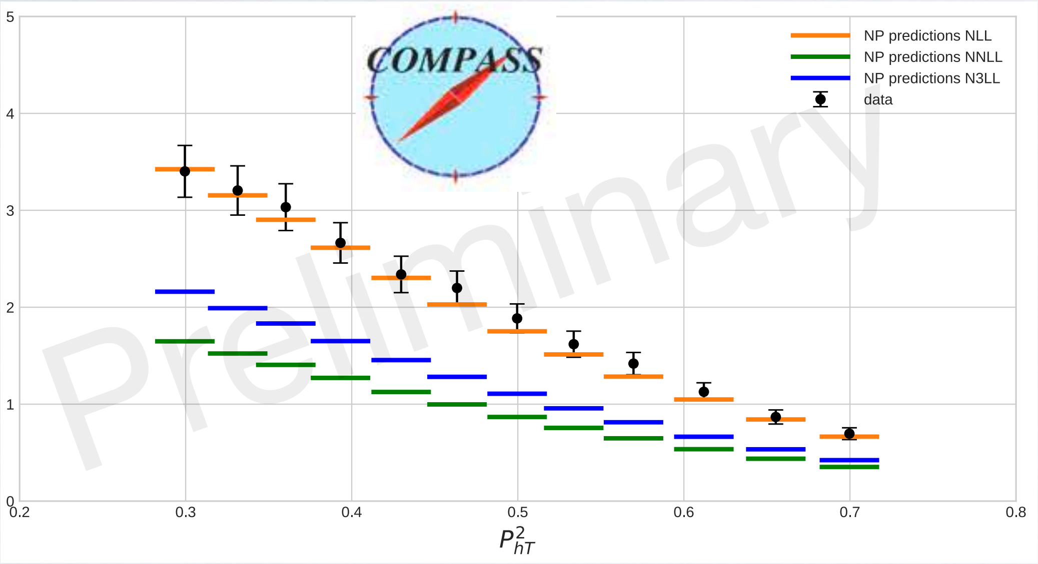
Normalization issue in SIDIS

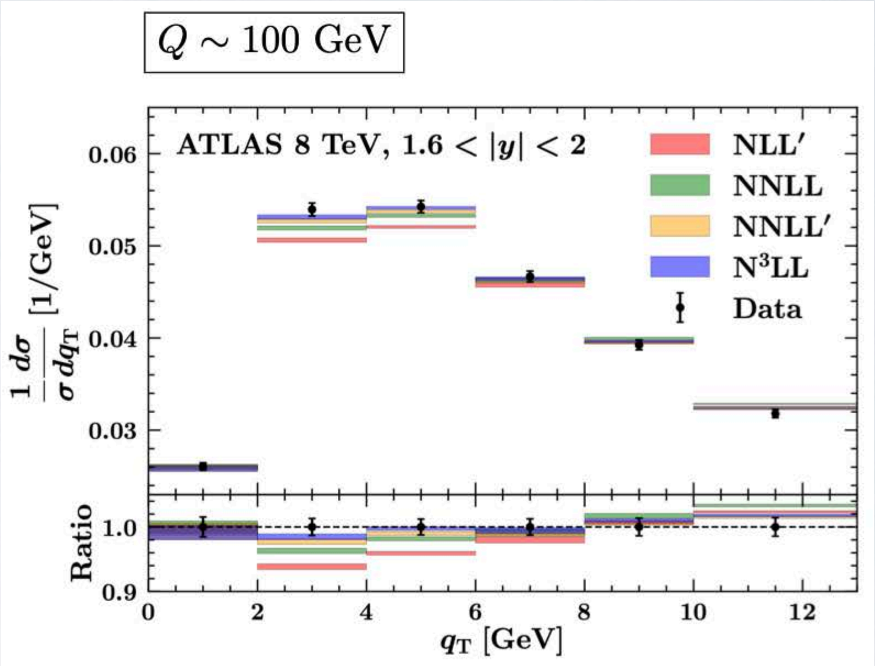
increasing perturbative accuracy

worsens agreement with SIDIS !

increases agreement with Drell-Yan

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





SIDIS data as multiplicities M : $M(x, z, q_T, Q) = \dfrac{d\sigma^{\text{SIDIS}}}{dx dz dq_T dQ} \Big/ \dfrac{d\sigma^{\text{DIS}}}{dx dQ}$

At **NNLL** $\displaystyle \int dq_T \, W \Big|_{\text{NNLL}} \neq \frac{d\sigma}{dx dz dQ}\Big|_{\text{NLO}}$

integrated W-term **does not** reproduce the SIDIS collinear dσ at **NLO**

Y-term contributions missing

$M(x, z, q_T, Q)$ **underestimates data**

Normalization factor $\omega(x, z, Q) = \dfrac{d\sigma}{dx dz dQ} \Big/ \displaystyle\int dq_T \, W$

$= 1$ at **NLL**

Bacchetta *et al.* (MAP), JHEP **10** (22) 127, arXiv:2206.07598

Does not depend on fit parameters, precomputed

Most recent extractions of unpolarized TMD f_1

	Accuracy	SIDIS HERMES	SIDIS 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
MAPTMD 2024 arXiv:2405.13833	N^3LL	✔	✔	✔	✔	2031	1.08

MAPTMD24: ~same as MAPTMD22 + flavor sensitivity of k_T-dependence

MAPTMD22 → MAPTMD24

- global fit of Drell-Yan and SIDIS data

  2031 data pts. → same dataset =

- prescription to fix SIDIS normalization problem

  pre-computed $\omega(x, z, Q)$ → same =

- nonperturbative parametrisation

  F.T.(combination of Gaussians) → same for each flavor ~

MAPTMD22 → MAPTMD24

- global fit of Drell-Yan and SIDIS data

  2031 data pts. → same dataset =

- prescription to fix SIDIS normalization problem

  pre-computed $\omega(x, z, Q)$ → same =

- theoretical perturbative accuracy

  $N^3LL(-)$ → N^3LL

PDF:	MMHT2014nnlo	NNPDF3.1NNLO
FF:	DSS14 (π), DSS17 (K) at NLO	MAPFF1.0NNLO

Abdul Khalek et al., arXiv:2204.10331

- nonperturbative parametrisation

  F.T.(combination of Gaussians) → same for each flavor ~

MAPTMD22 → MAPTMD24

- global fit of Drell-Yan and SIDIS data

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  N³LL(-) → N³LL

PDF: MMHT2014nnlo → NNPDF3.1NNLO

FF: DSS14 (π), DSS17 (K) at NLO → MAPFF1.0NNLO

New: using full Montecarlo sets

Abdul Khalek et al., arXiv:2204.10331

independence of results from choice of PDF cross-checked

- account of correlated (exp. & th.) errors including ΔPDF & ΔFF

  bootstrap method → replicas of PDFs & FFs

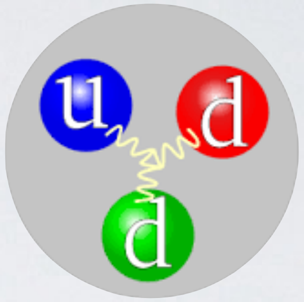
- nonperturbative parametrisation

  F.T.(combination of Gaussians) → same for each flavor ~

MAPTMD24 flavor channels

TMD PDF

$f_{NP}^{q}(x, b_T; Q_0)$ = F.T.(combination of Gaussians)



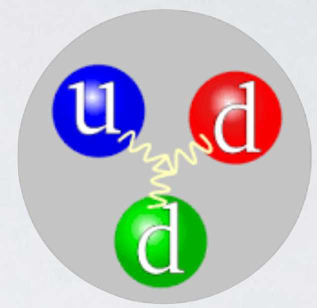
5 channels: $q = u\,,\,\bar{u}\,,\,d\,,\,\bar{d}\,,\,sea$ ("s")

MAPTMD24 flavor channels

TMD PDF

$f_{\rm NP}^{q}(x, b_T; Q_0)$ = F.T.(combination of Gaussians)

5 channels: $q = u\,,\ \bar{u}\,,\ d\,,\ \bar{d}\,,\ sea$ (“s”)



TMD FF

$D_{\rm NP}^{q}(z, b_T; Q_0)$ = F.T.(combination of Gaussians)

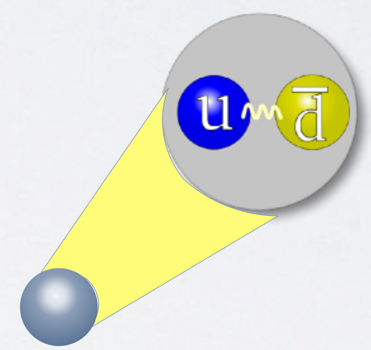
5 channels: favored pion $u \to \pi^+, \ldots$

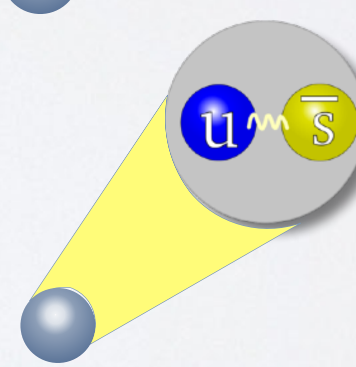
unfavored pion $d \to \pi^+, \ldots$

favored Kaon $u \to K^+, \ldots$

favored strange Kaon $\bar{s} \to K^+, \ldots$

unfavored Kaon $d, s \to K^+, \ldots$



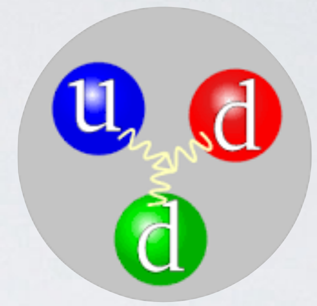


MAPTMD24 flavor channels

TMD PDF

$f_{\rm NP}^{q}(x, b_T; Q_0)$ = F.T.(combination of Gaussians)

5 channels: $q = u\,,\,\bar{u}\,,\,d\,,\,\bar{d}\,,\,sea$ (“s”)



TMD FF

$D_{\rm NP}^{q}(z, b_T; Q_0)$ = F.T.(combination of Gaussians)

5 channels: favored pion $u \to \pi^+, \ldots$

unfavored pion $d \to \pi^+, \ldots$

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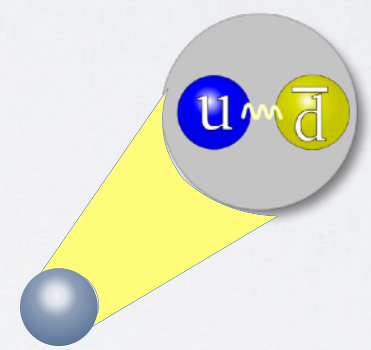
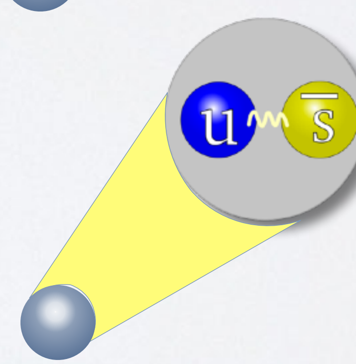




sensitivity

Hermes

target: p, D

final: $\pi^\pm$, $K^\pm$

Compass

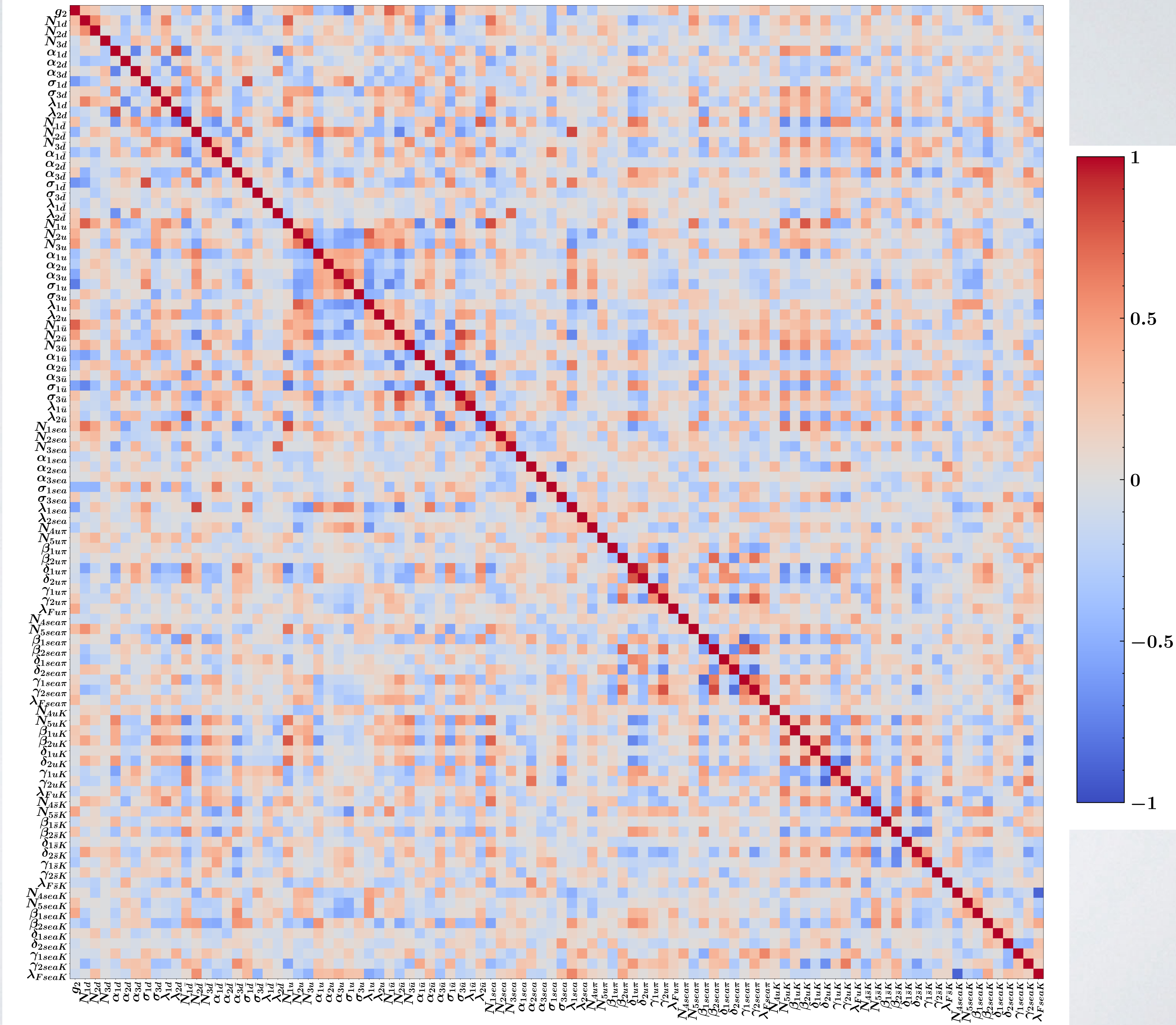
target: D

final: $h^\pm$

Drell-Yan

total of 96 parameters but with ~diagonal correlation matrix

Correlation matrix



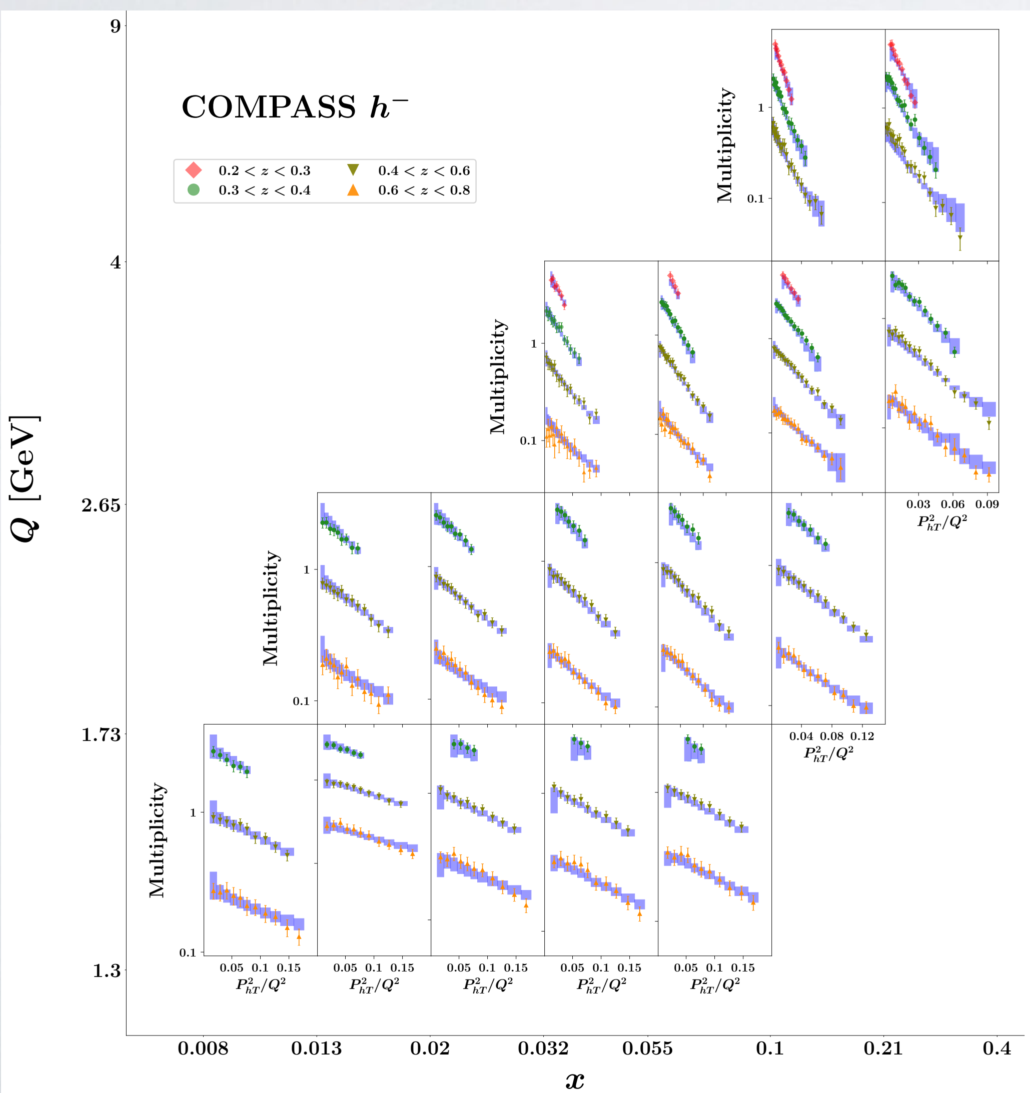
Fit results for SIDIS

data set	N_{data}	χ^2_D	χ^2_λ	χ^2
HERMES	344	0.81	0.24	1.05
COMPASS	1203	0.67	0.27	0.94
SIDIS total	1547	0.70	0.26	0.96
DY fixed target	233	0.63	0.31	0.94
DY collider	251	1.37	0.28	1.65
Total	**2031**	**0.81**	**0.27**	**1.08**

χ_D^2 = uncorrelated error

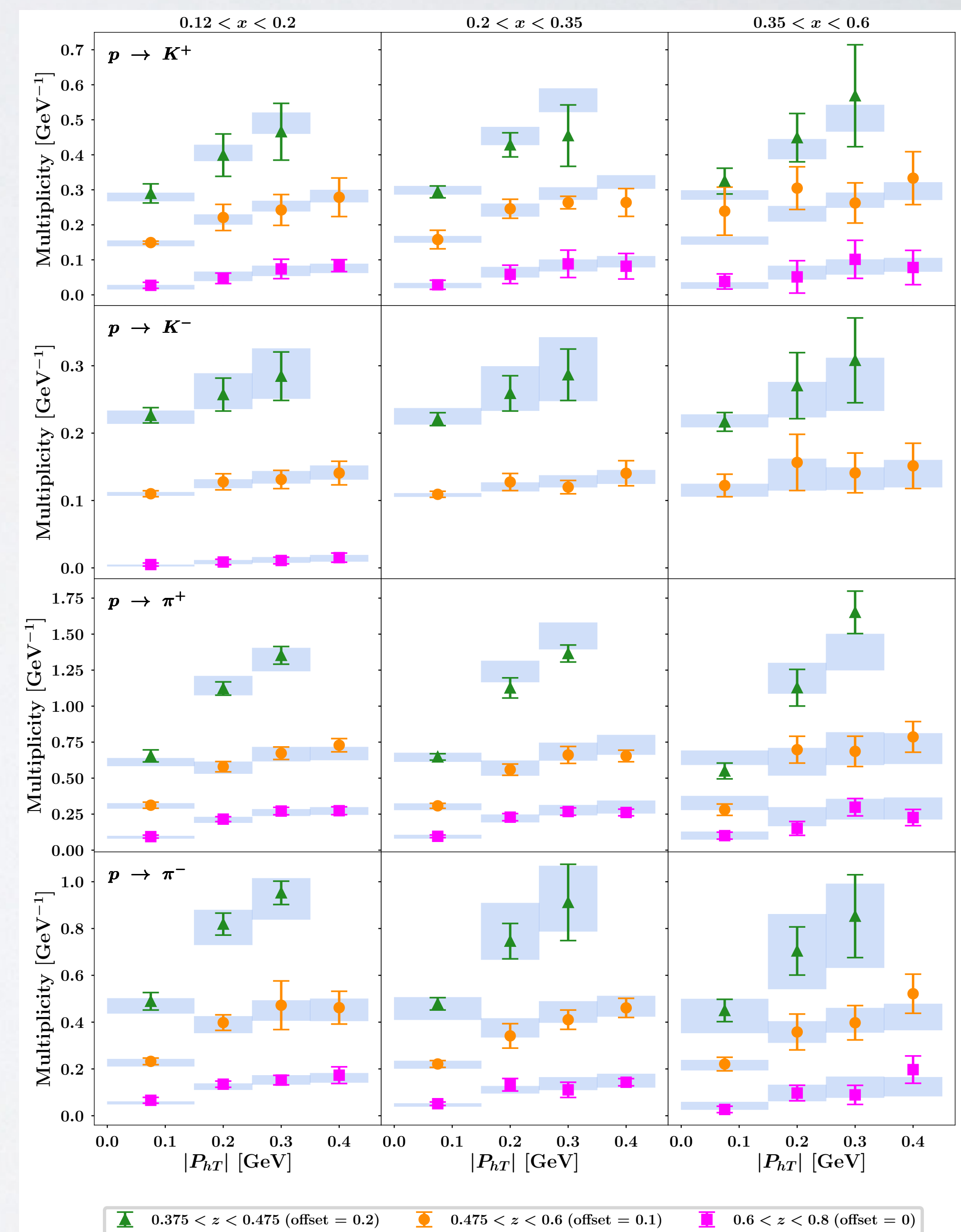
χ_λ^2 = correlated error

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



deuteron target

proton target



th. error band = 68% of all replicas

Fit results for SIDIS

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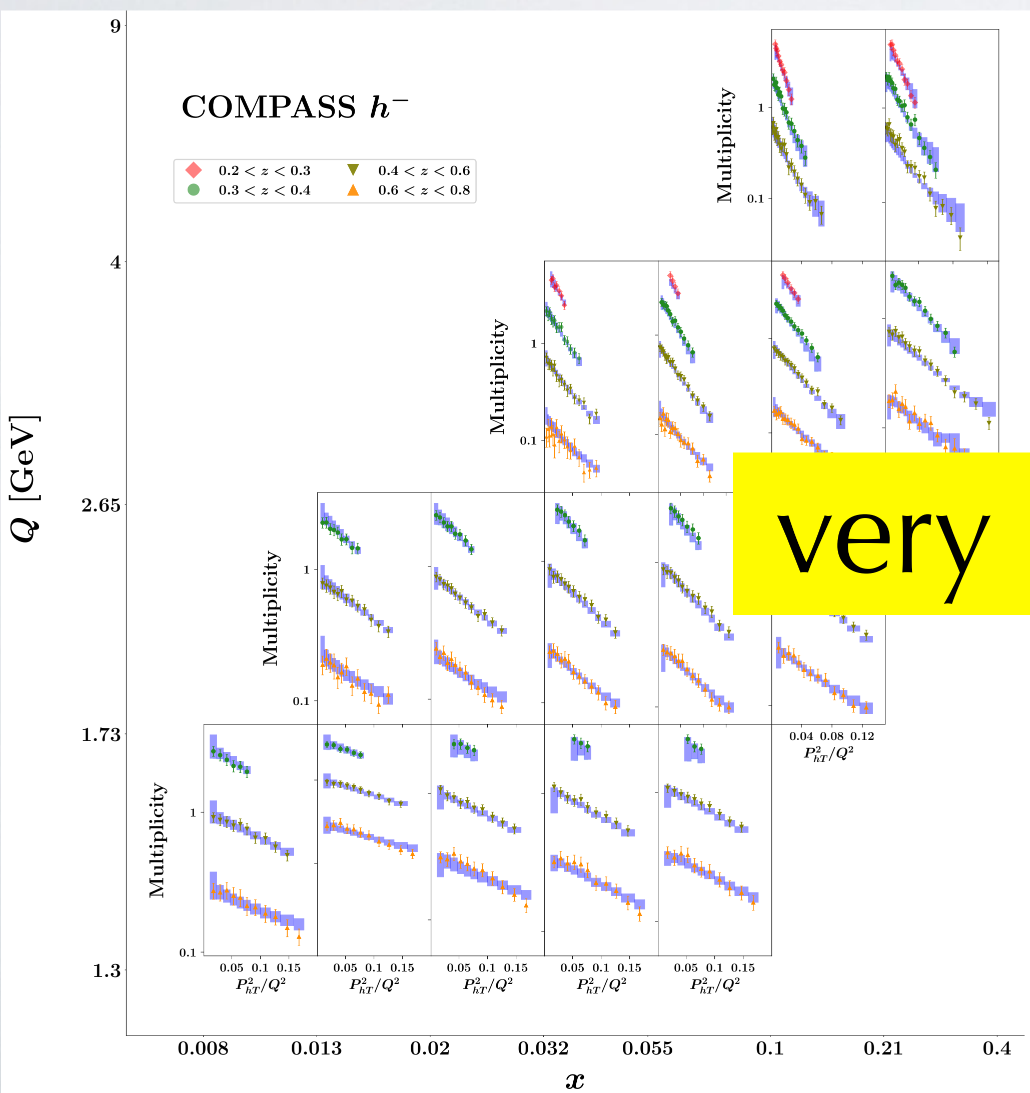
χ_D^2 = uncorrelated error

χ_λ^2 = correlated error

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

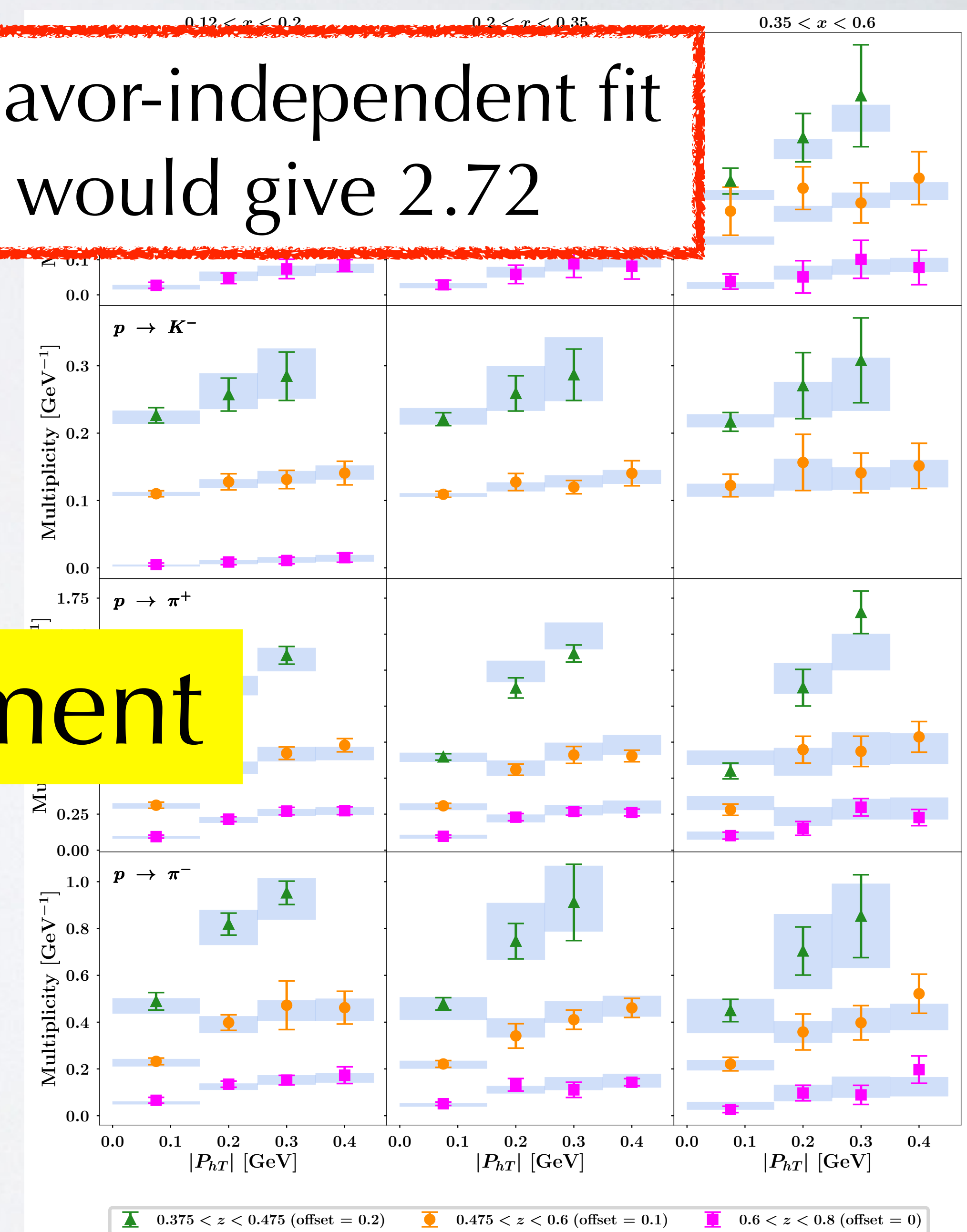
a flavor-independent fit would give 2.72

proton target



deuteron target

very good agreement



th. error band = 68% of all replicas

Fit results for Drell-Yan

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COMPASS	1203	0.67	0.27	0.94
SIDIS total	1547	0.70	0.26	0.96
DY fixed target	233	0.63	0.31	0.94
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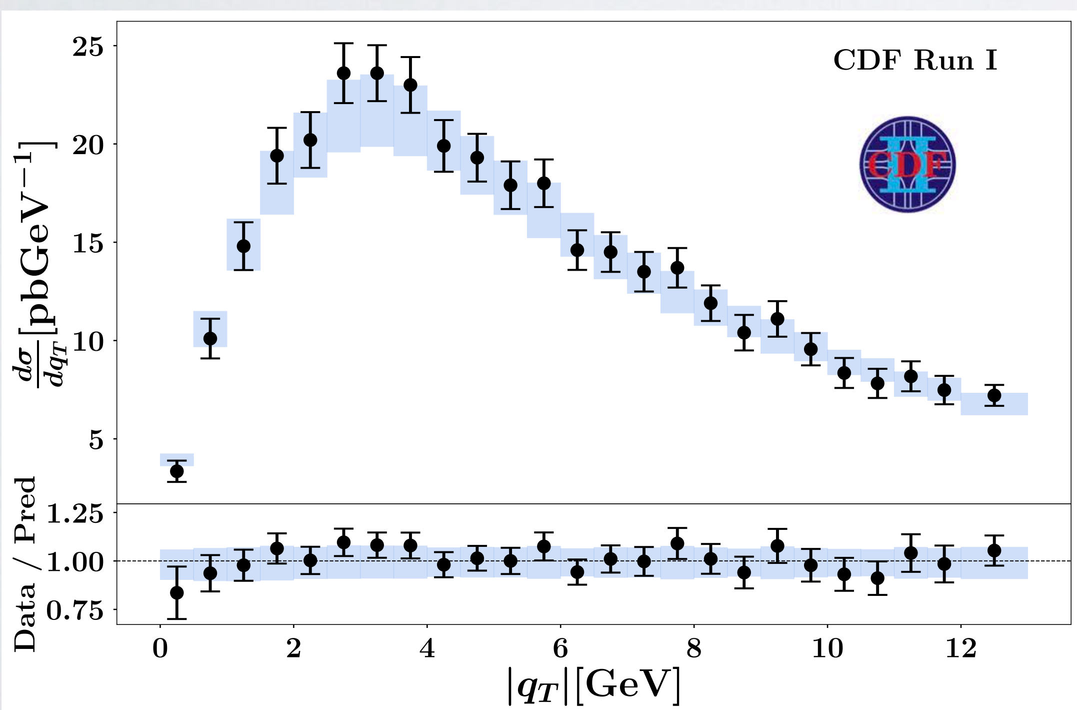
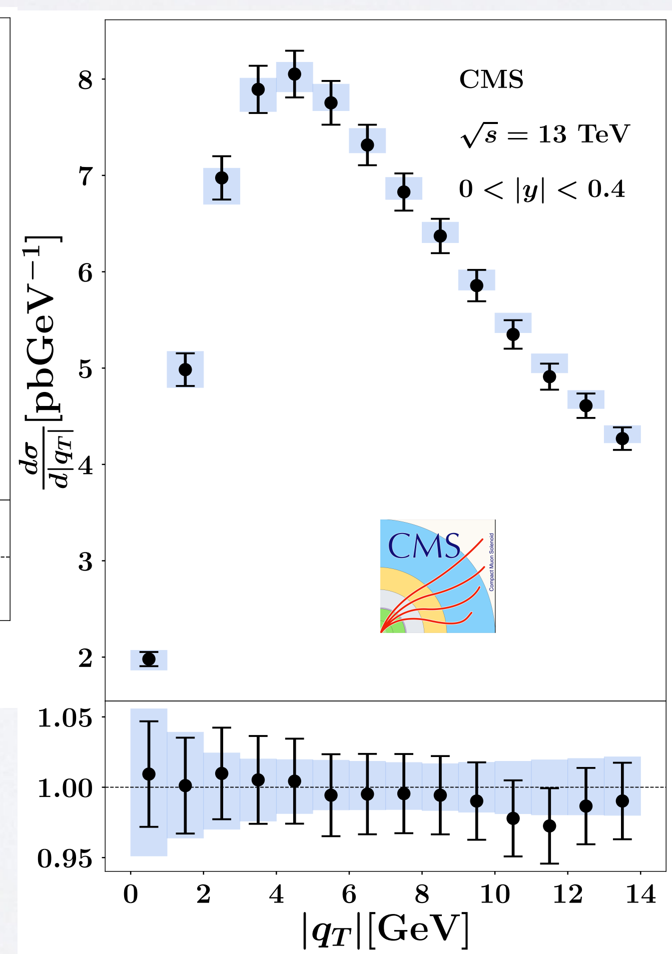
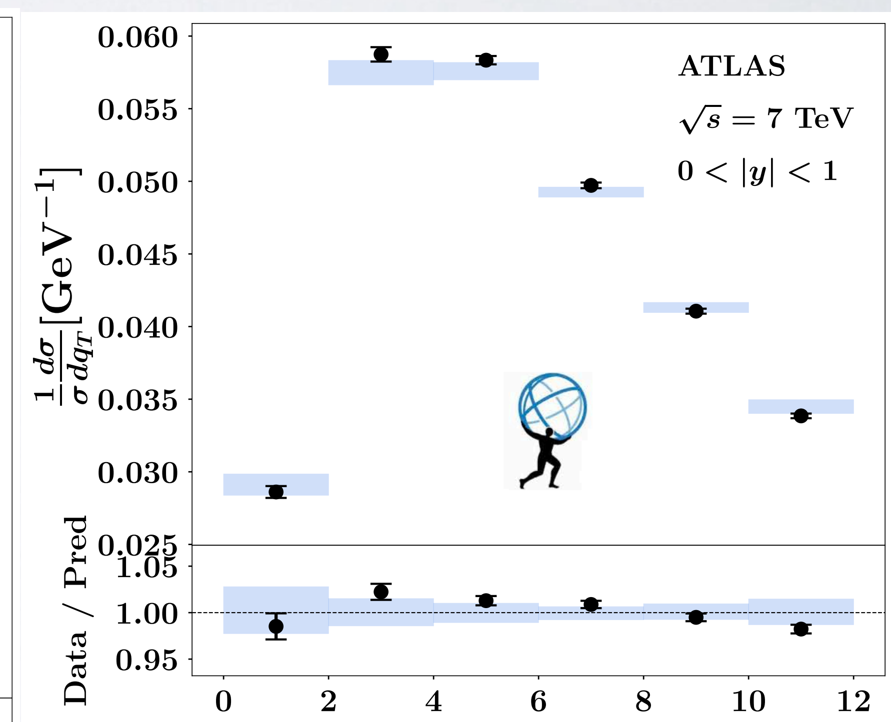
very good agreement

good agreement







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Fit results for Drell-Yan

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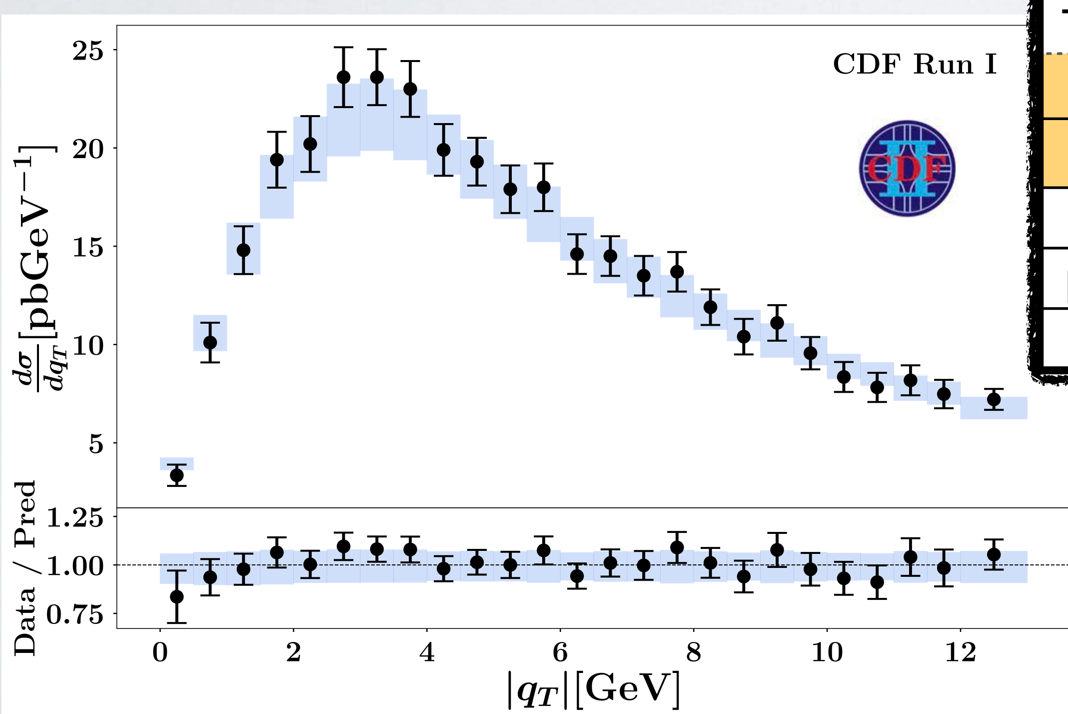
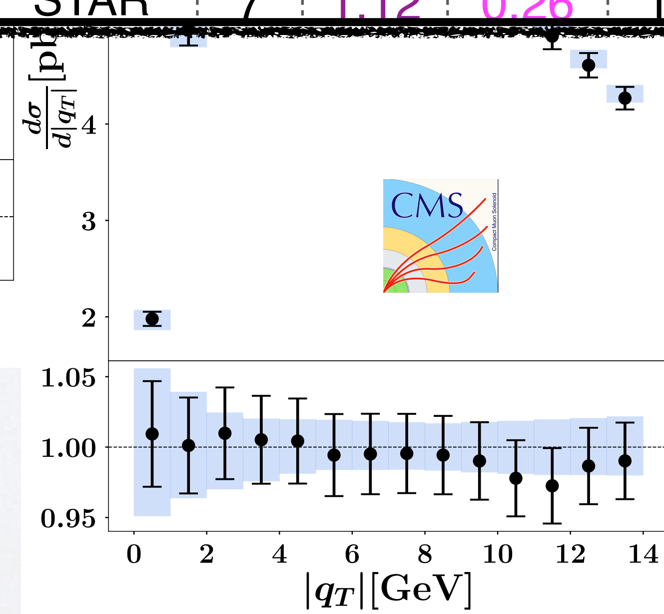
very good agreement

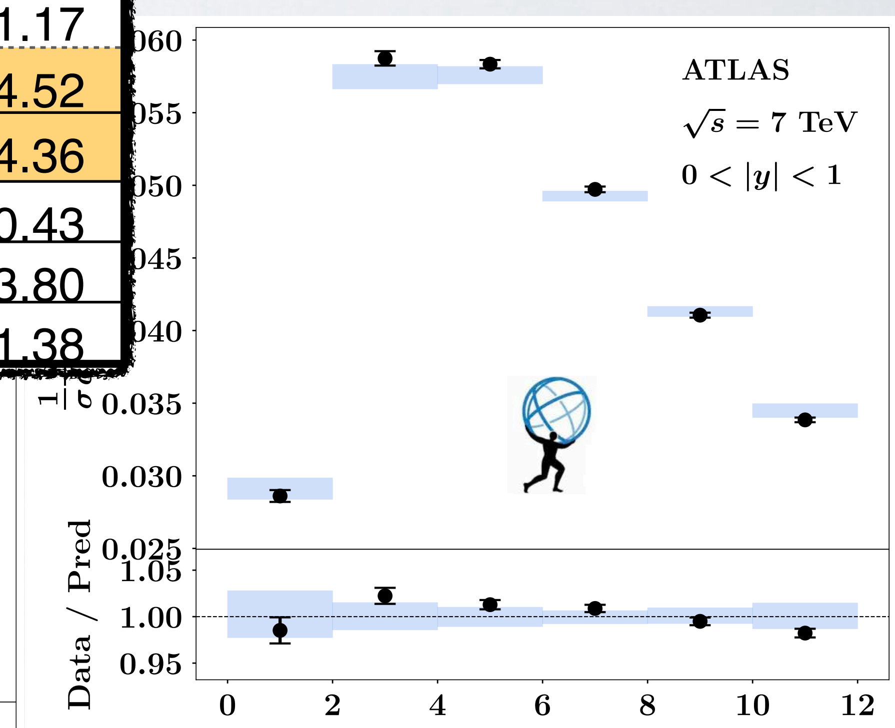
good agreement

very precise data!

data set	N_{dat}	χ^2_D	χ^2_λ	χ^2
Tevatron	71	1.10	0.07	1.17
LHCb	21	3.56	0.96	4.52
ATLAS	72	3.54	0.82	4.36
CMS	78	0.38	0.05	0.43
PHENIX	2	2.76	1.04	3.80
STAR	7	1.12	0.26	1.38

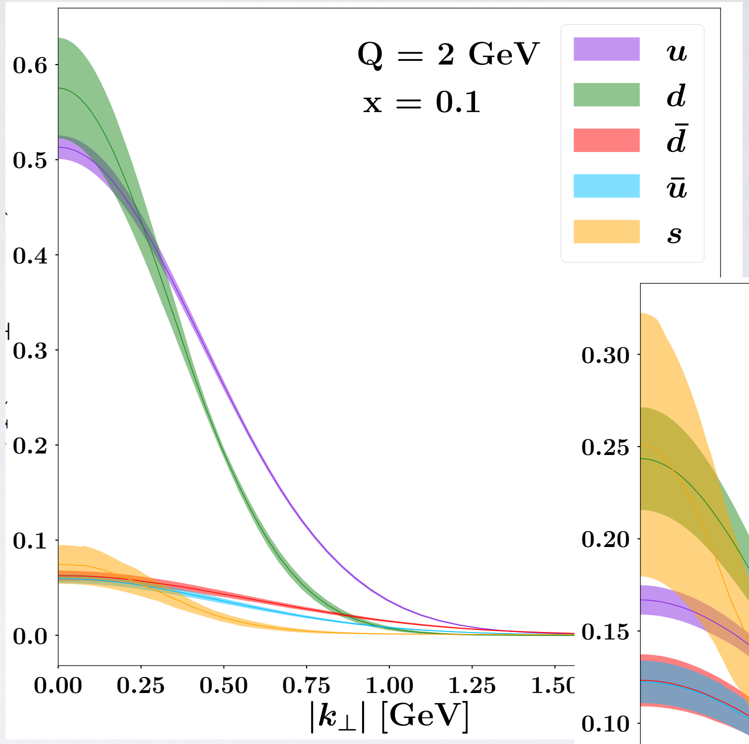




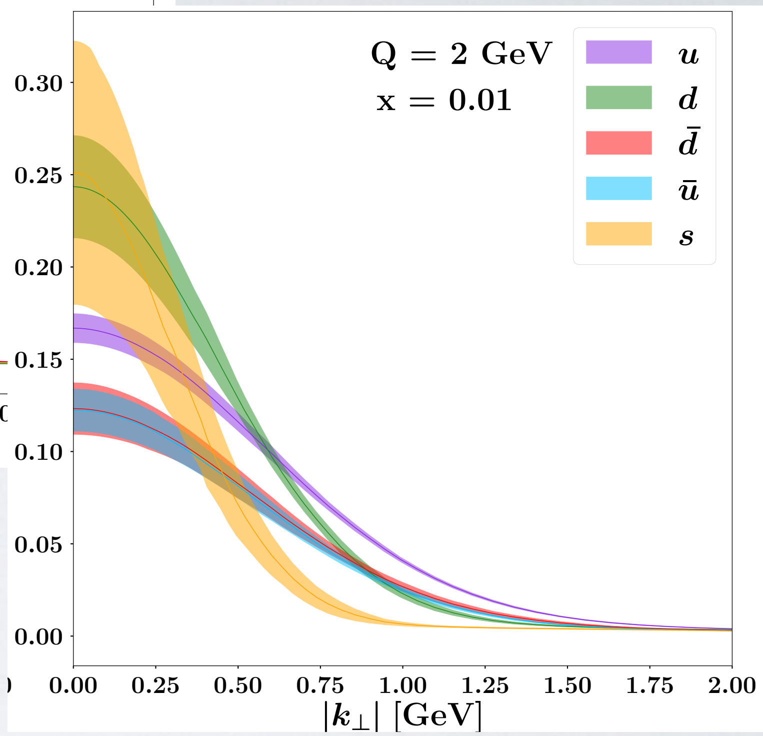


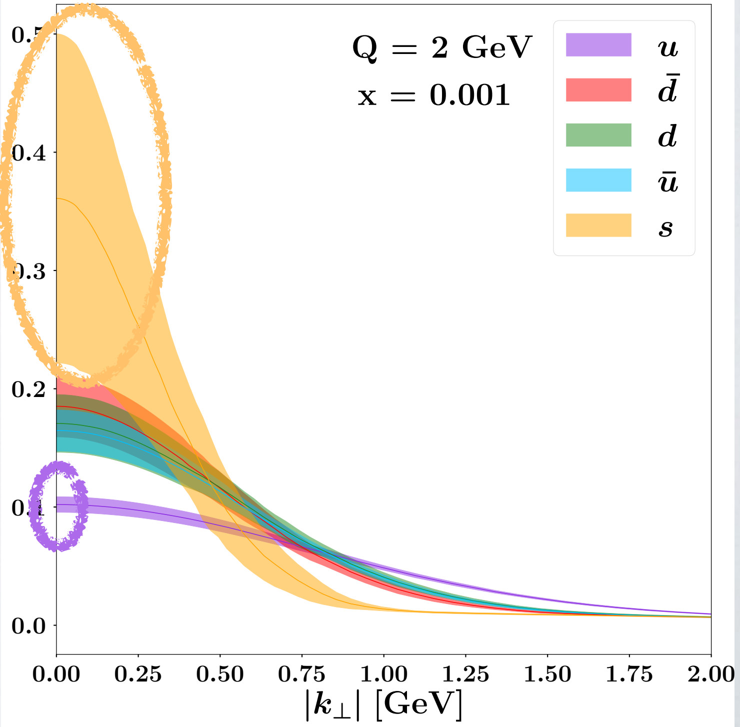
th. error band = 68% of all replicas

Visualizing MAPTMD24 TMD PDF



$x\, f_1(x, k_T; Q)$



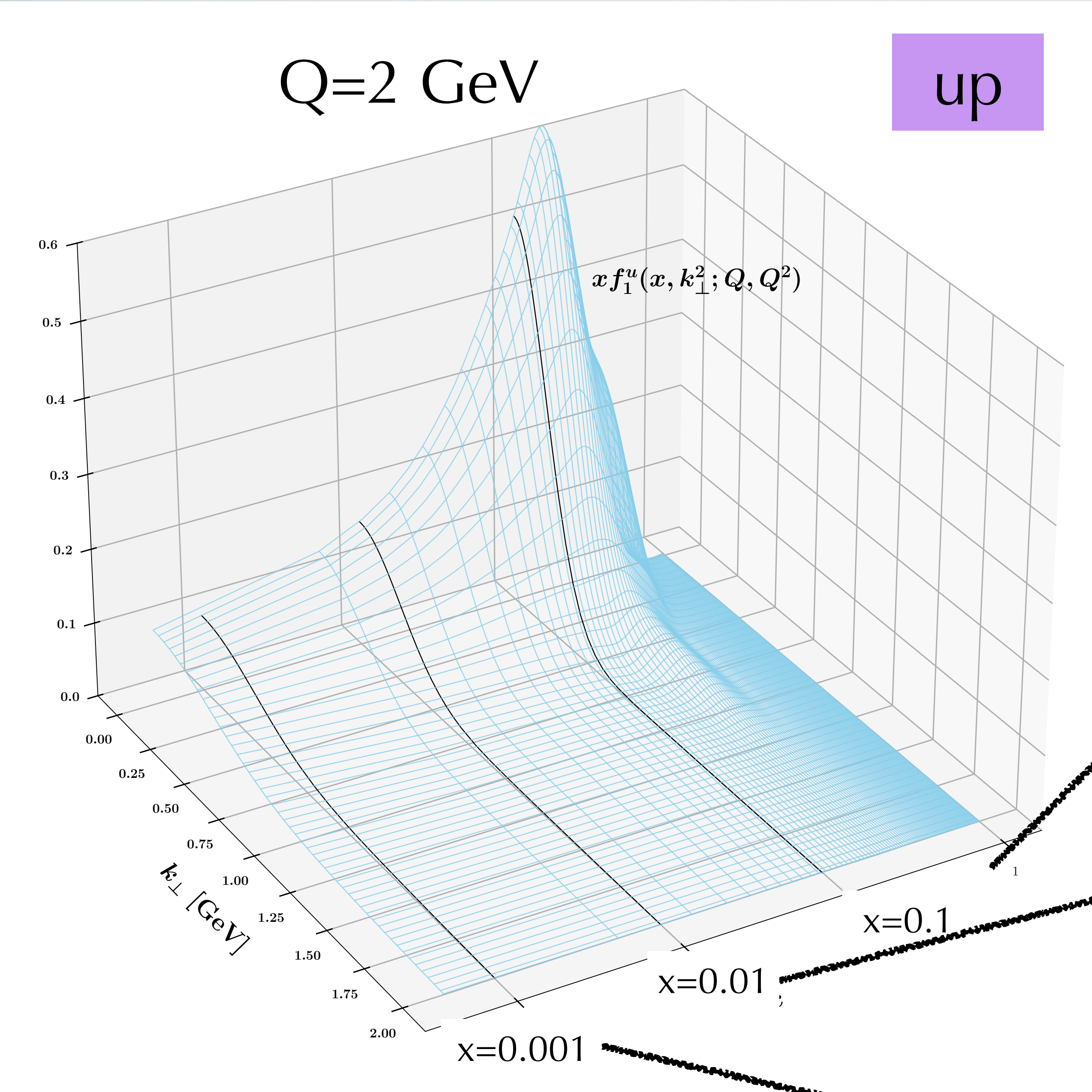


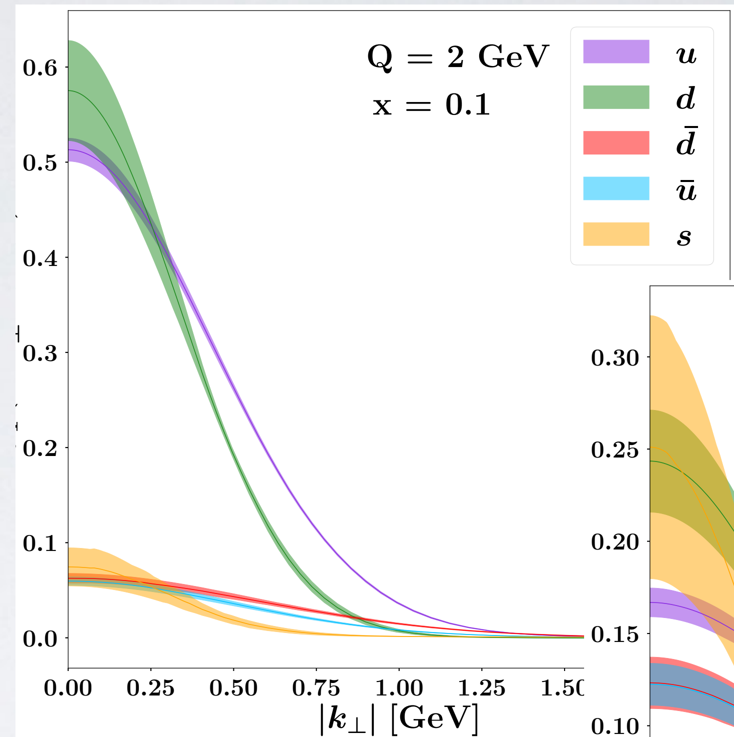
"sea" is the least constrained

up is the most constrained

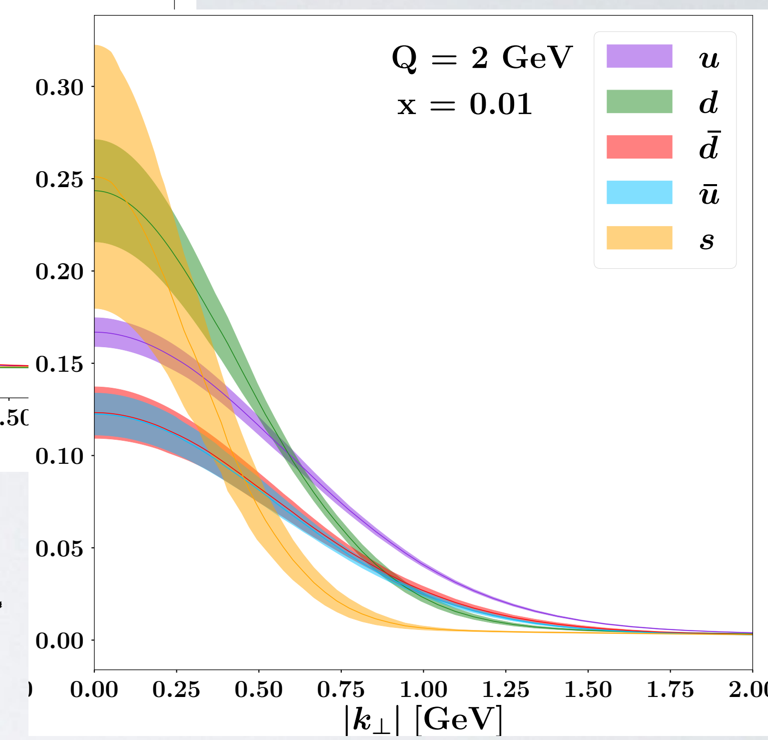
th. error band =
68% of all replicas

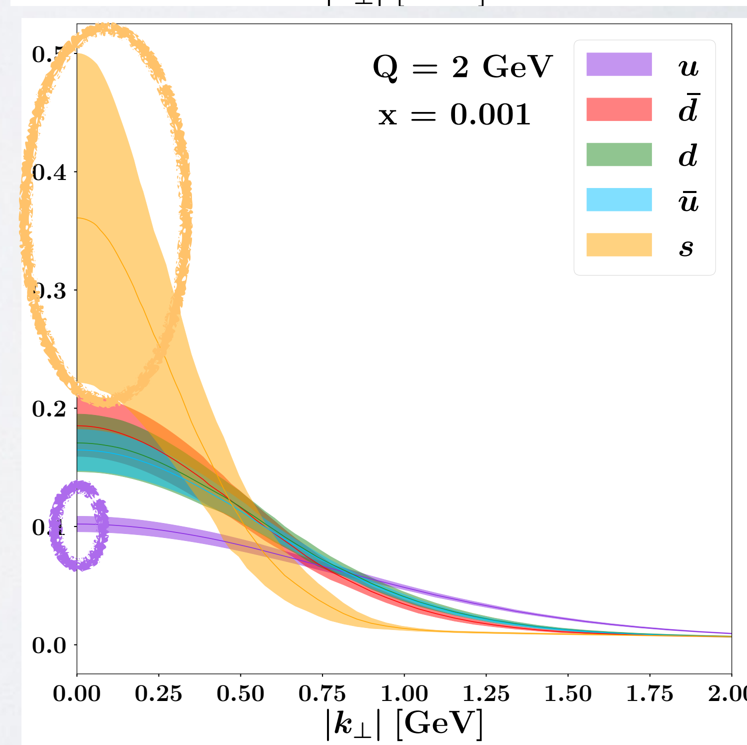
Visualizing MAPTMD24 TMD PDF





x $f_1(x,k_T;Q)$





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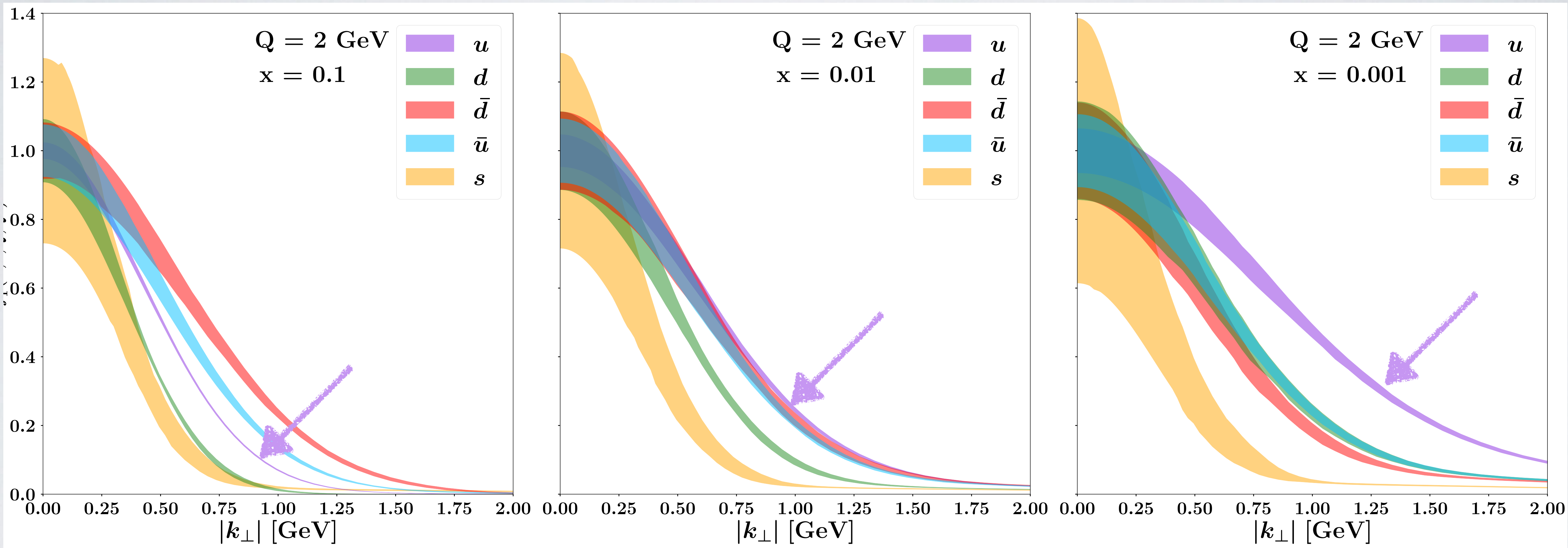
"Normalized" MAPTMD24 TMD PDF

$$\frac{f_1(x,k_T;Q)}{f_1(x,0;Q)}$$

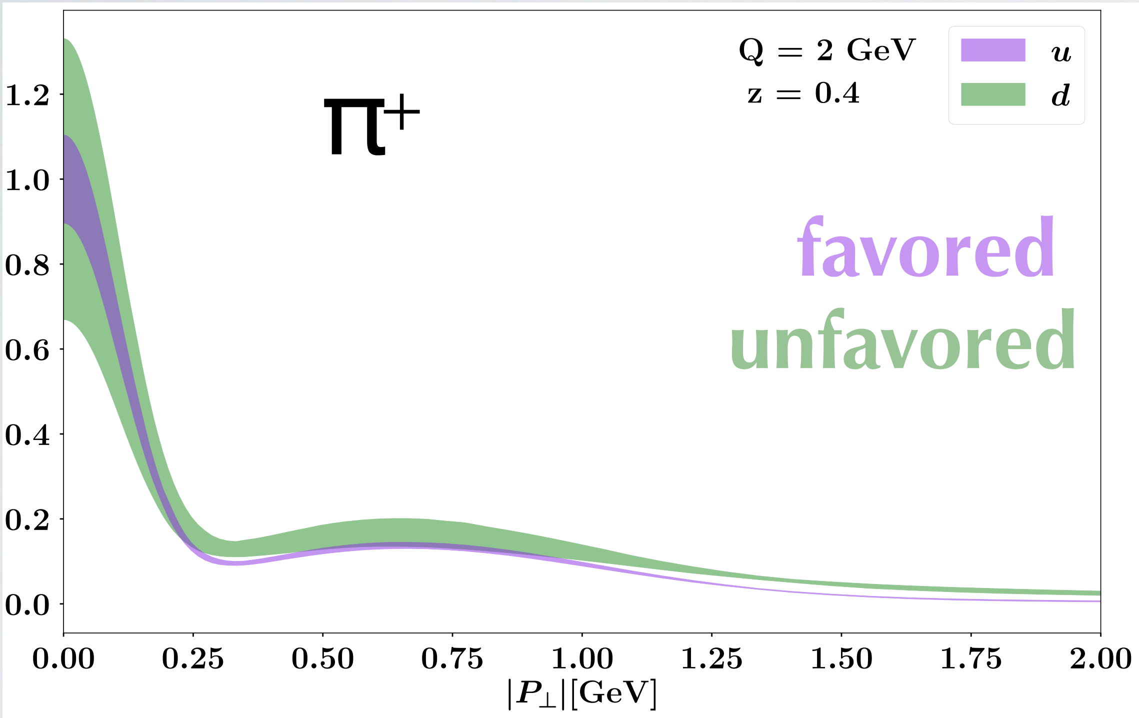


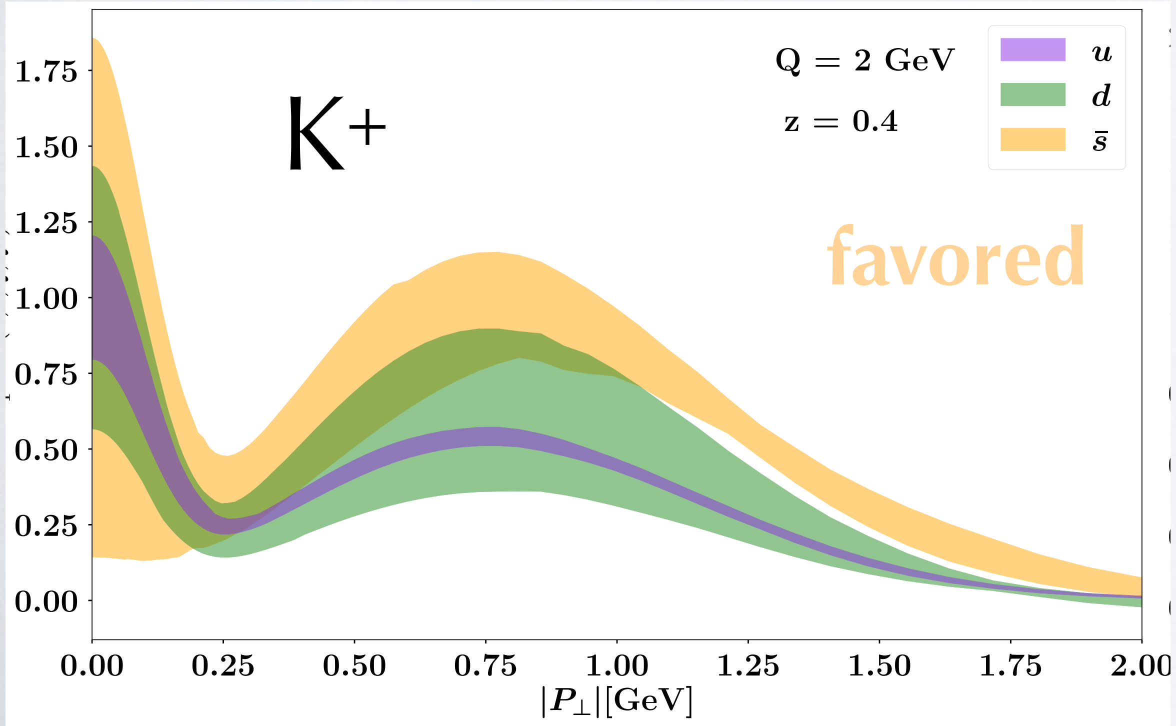
- very different k_T behavior
- it changes with x

th. error band =
68% of all replicas

“Normalized” MAPTMD24 TMD FF

$$\frac{D_1(z,P_T;Q)}{D_1(z,0;Q)}$$



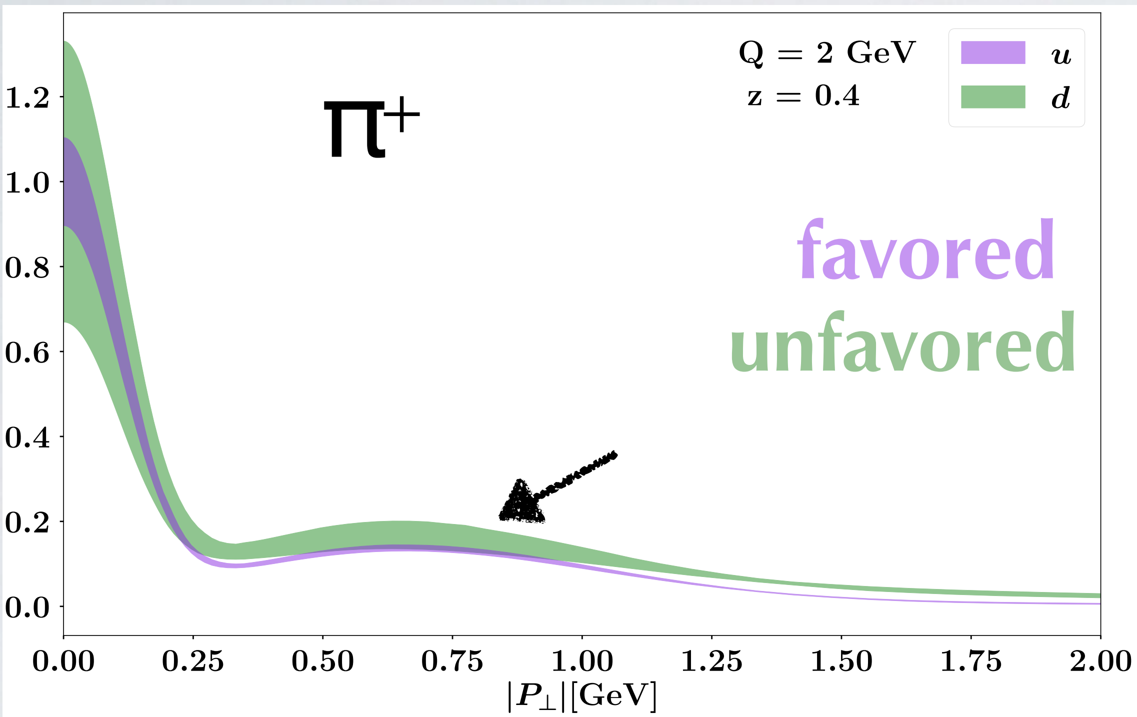


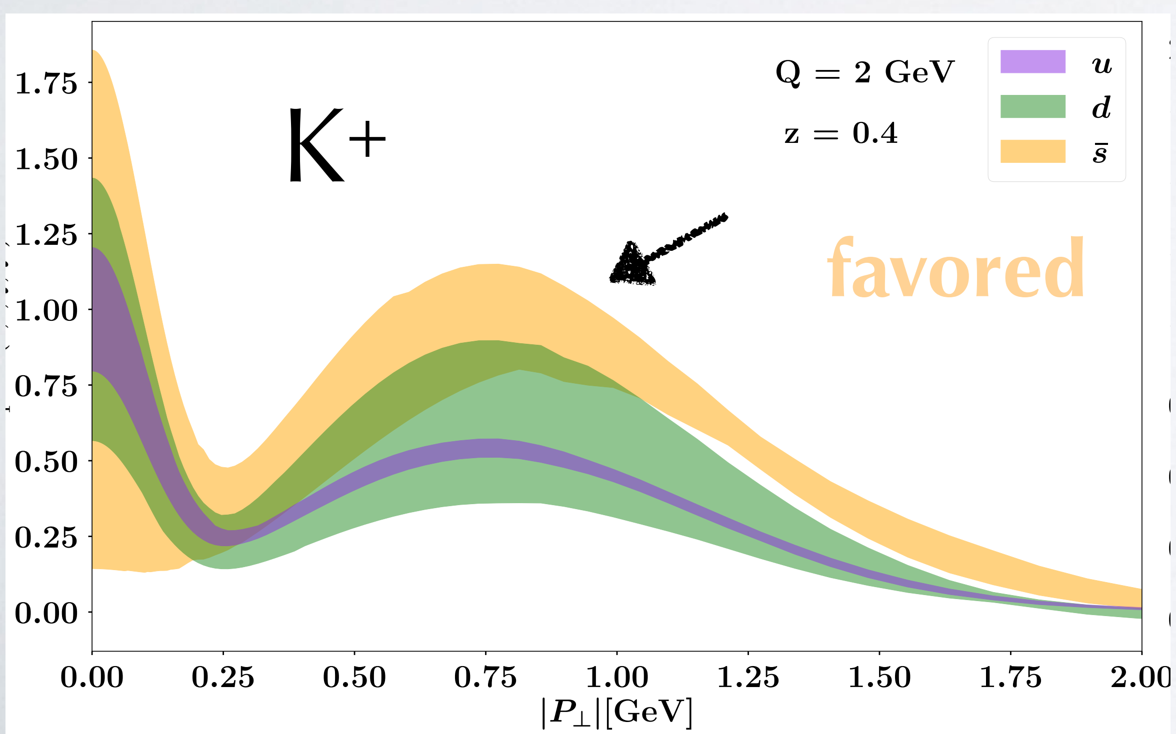
- favored better constrained than unfavored

th. error band =
68% of all replicas

"Normalized" MAPTMD24 TMD FF

$$\frac{D_1(z,P_T;Q)}{D_1(z,0;Q)}$$



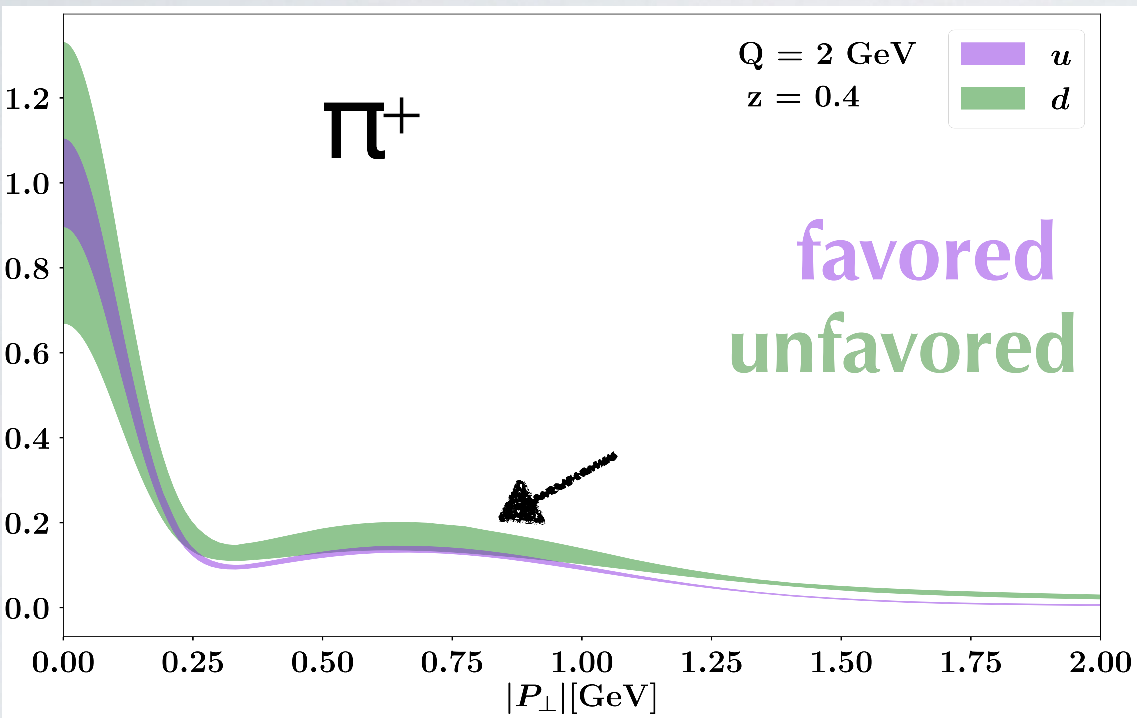


- favored better constrained than unfavored
- signs of favored ≠ unfavored
- structure from $D_{\rm NP} \sim e^{-P_\perp^2 / g_{3A}(z)} + \lambda_F \, P_\perp^2 e^{-P_\perp^2 / g_{3B}(z)}$

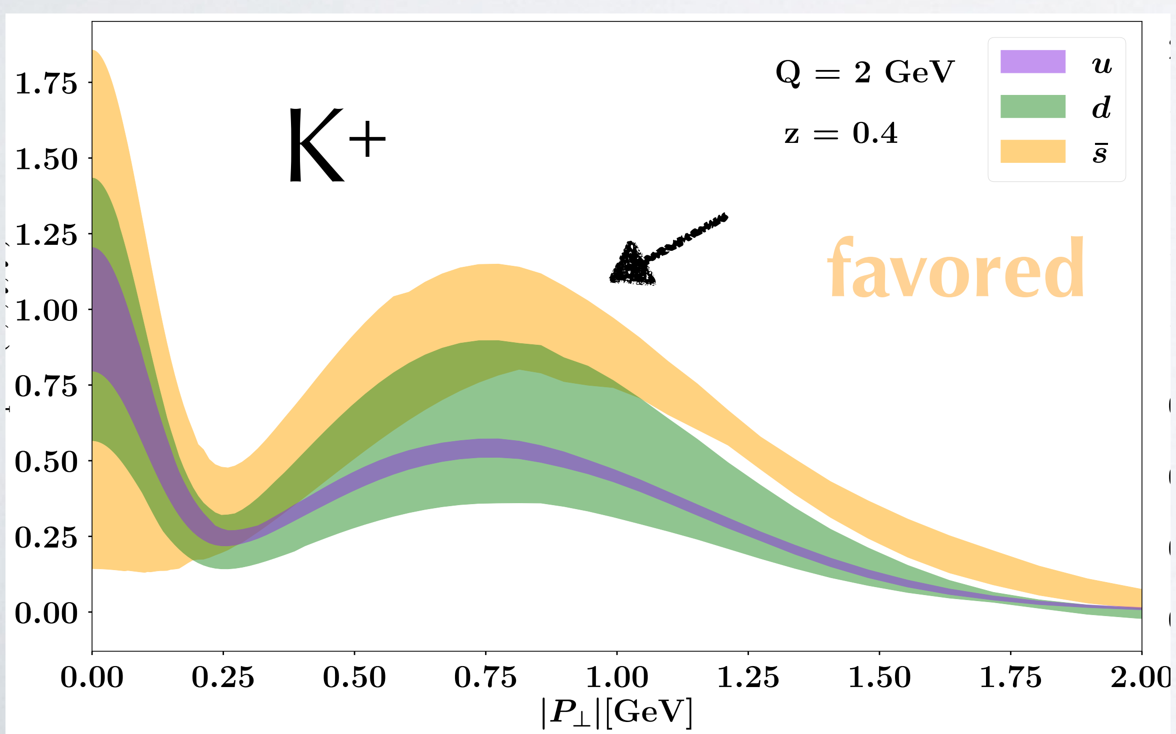
th. error band =
68% of all replicas

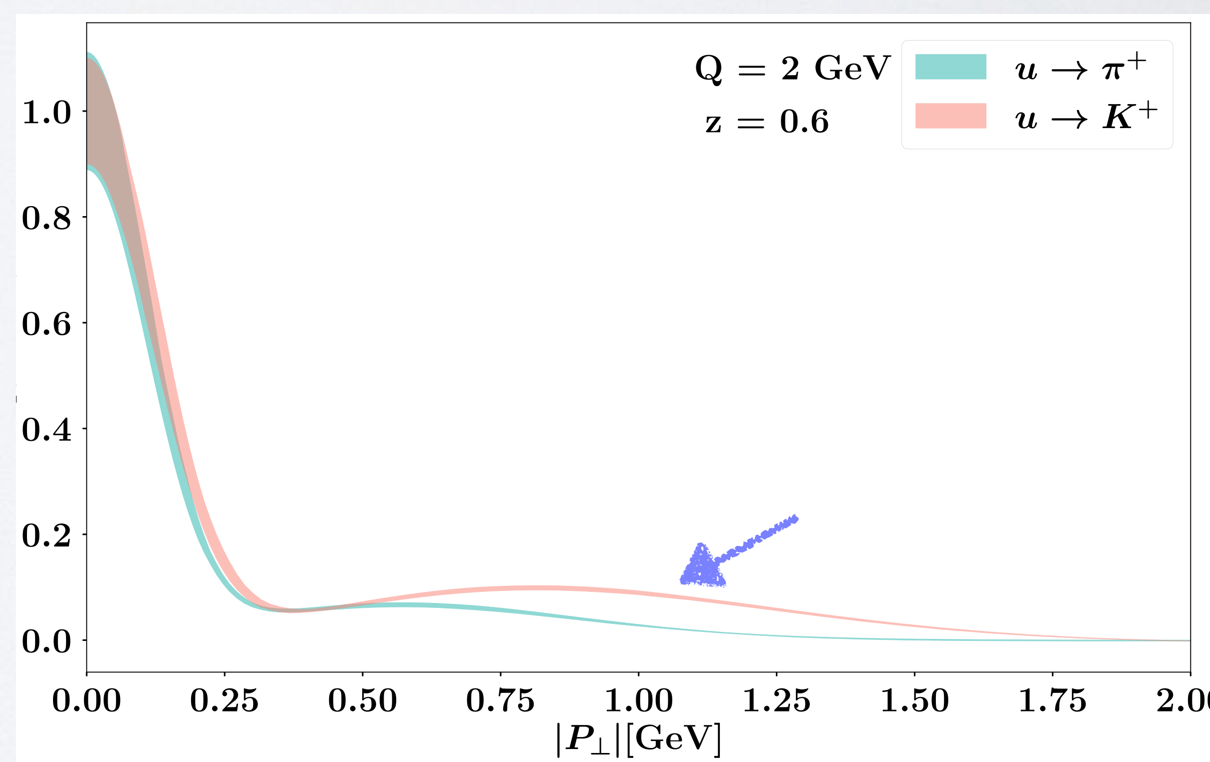
“Normalized” MAPTMD24 TMD FF

$$\frac{D_1(z,P_T;Q)}{D_1(z,0;Q)}$$

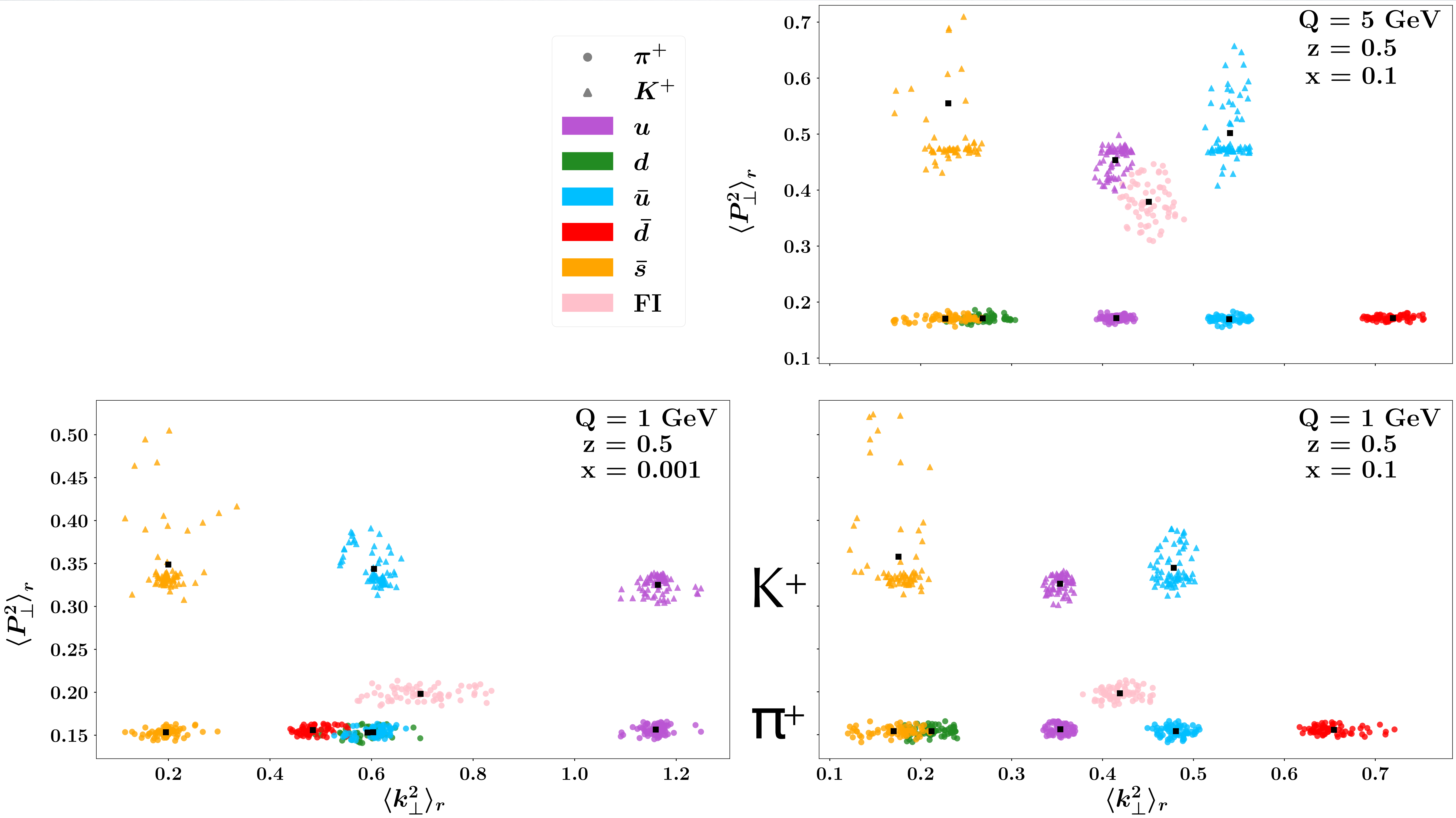


- favored better constrained than unfavored
- signs of favored ≠ unfavored
- structure from $D_{\rm NP} \sim e^{-P_\perp^2/g_{3A}(z)} + \lambda_F\, P_\perp^2 e^{-P_\perp^2/g_{3B}(z)}$
- evidence of final-hadron dependence



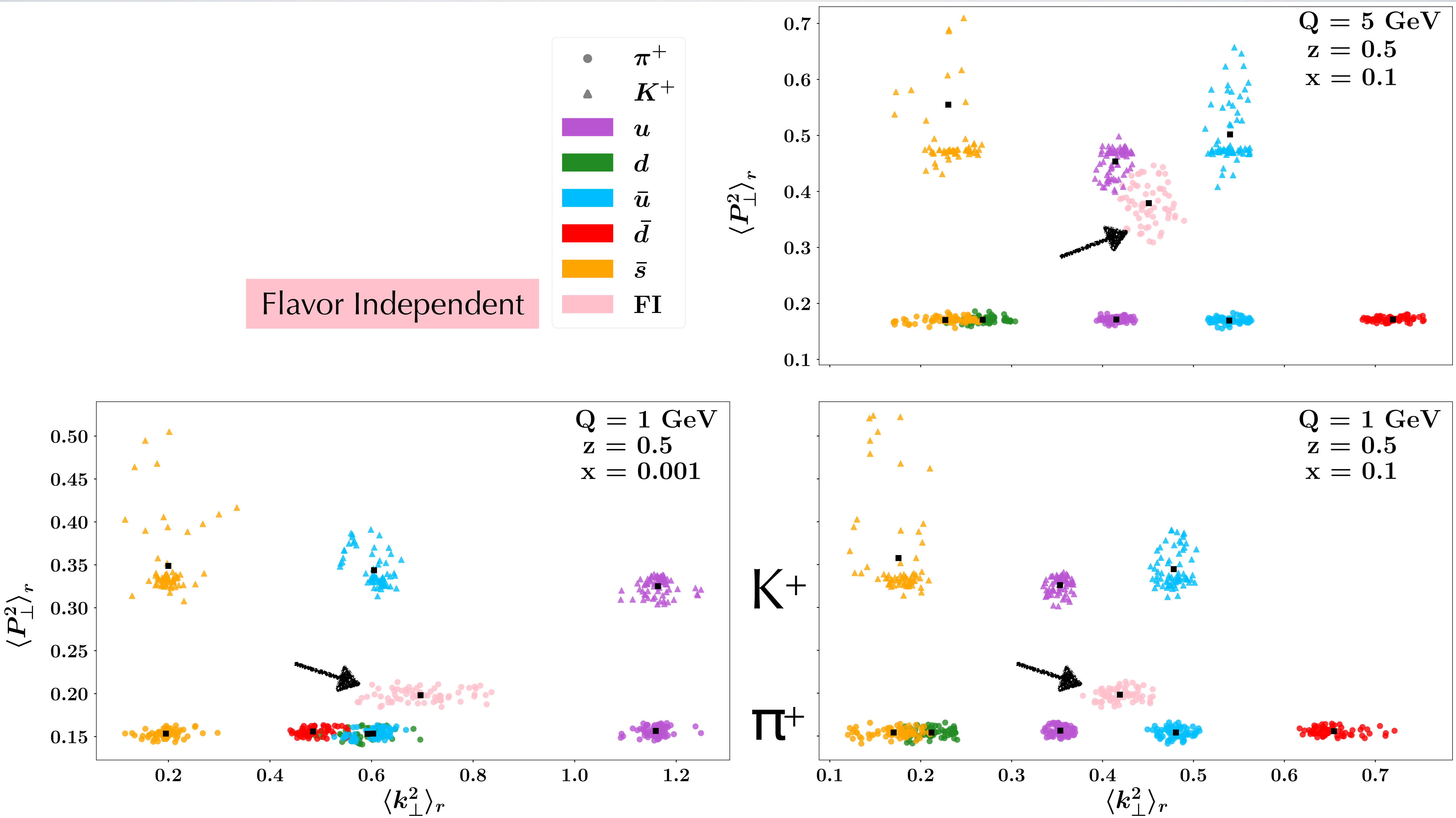


Average transverse momenta



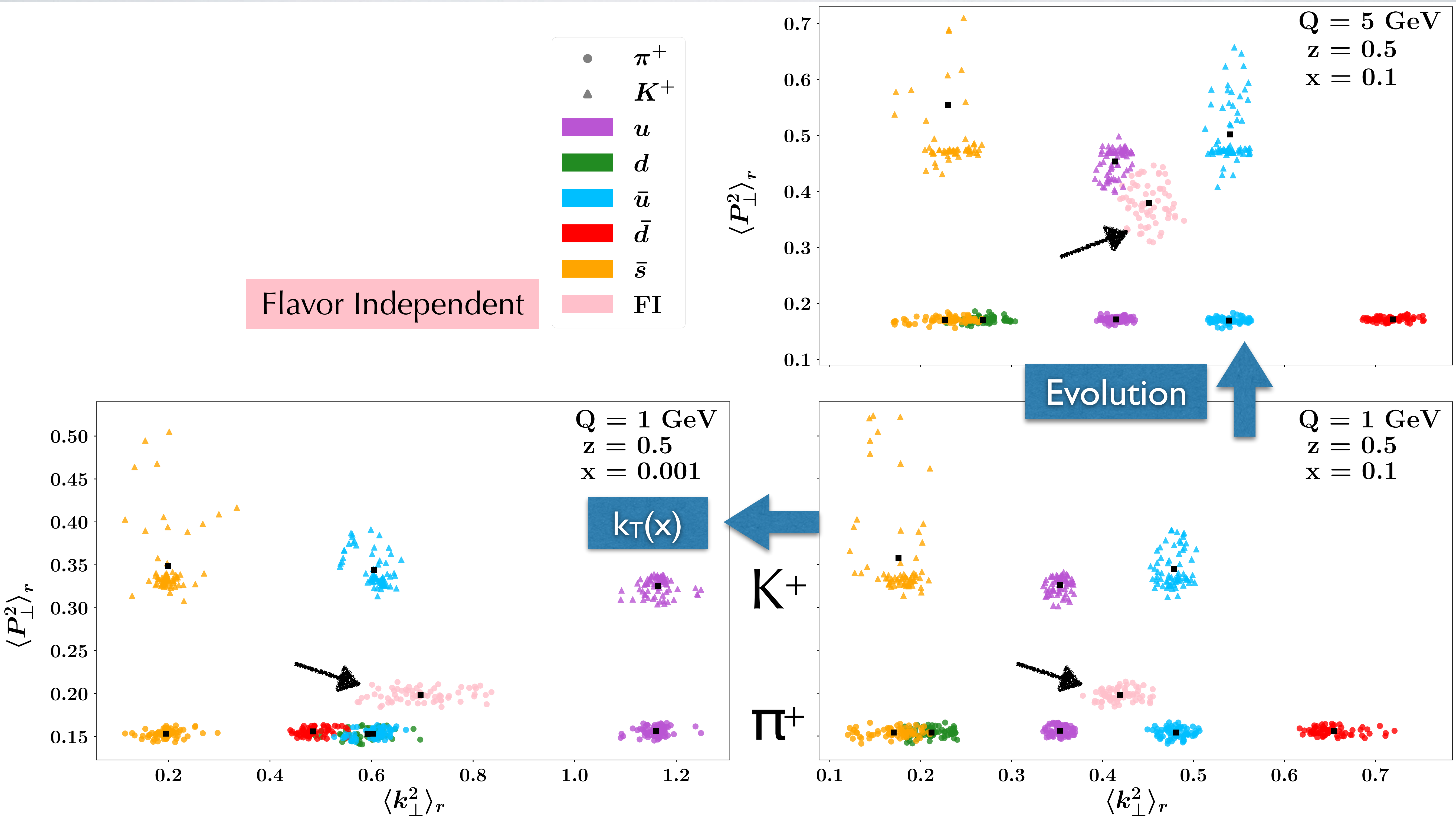
clusters = 68% of all replicas

Average transverse momenta



clusters = 68% of all replicas

Average transverse momenta



clusters = 68% of all replicas

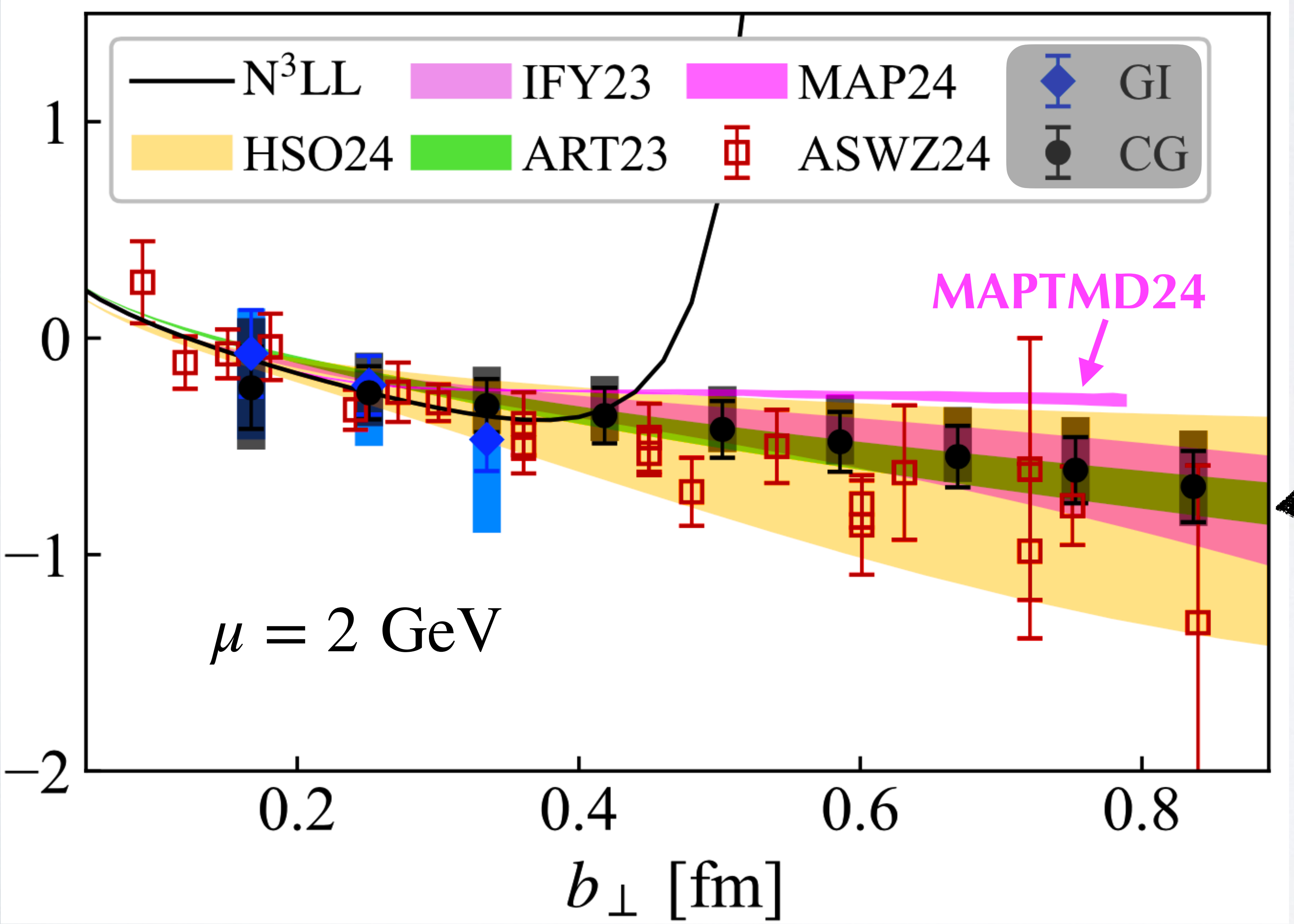
Collins-Soper kernel

universal flavor-independent

drives evolution in rapidity ζ

$$K(b_T, \mu_{b_*}) = K(b_*, \mu_{b_*}) + g_K(b_T)$$

perturbative (computed) non-perturbative (fitted)



N[3]LL Vladimirov, arXiv:1610.05791
Li&Zhu, arXiv:1604.01404

Pheno

HSO24 Aslan et al., arXiv:2401.14266

IFY23 Isaacson et al., arXiv:2311.09916

ART23 Moos et al., arXiv:2305.07473

MAPTMD22 ~ ART23

Lattice

GI, CG Bollweg et al., arXiv:2403.00664

ASWZ24 Avkhadiev et al., arXiv:2402.06725

S. Mukherjee, QCD Evolution 2024

Summary and Outlook

- **MAPTMD24**: the **first** extraction of unpolarized quark TMD from a **global fit** of SIDIS and Drell-Yan data (fixed target+collider) including **flavor sensitivity of intrinsic k_T-dependence**
- **Full N^{3}LL** perturbative th. accuracy, systematic th. error **including PDF&FF uncertainties**, **2031 data** pts., $\chi^2/N_{data} = 1.08$
- **Different flavors** → **different k_T** dependence; **non trivial x** dependence
- For a given fragmenting flavor, **different final hadron** → **different P_{hT}** dependence

---

- include more data…
- repeat study of sensitivity of M_W to flavor-dep. k_T distributions (see backup)

  Bacchetta *et al.*, P.L. **B788** (19) 542, arXiv:1807.02101

- repeat impact studies at JLab22 and EIC (see backup)


THANK YOU
for your
ATTENTION!

Backup

The Nanga Parbat fitting framework

All material available at the Nanga Parbat GitHub site

Nanga Parbat: a TMD fitting framework

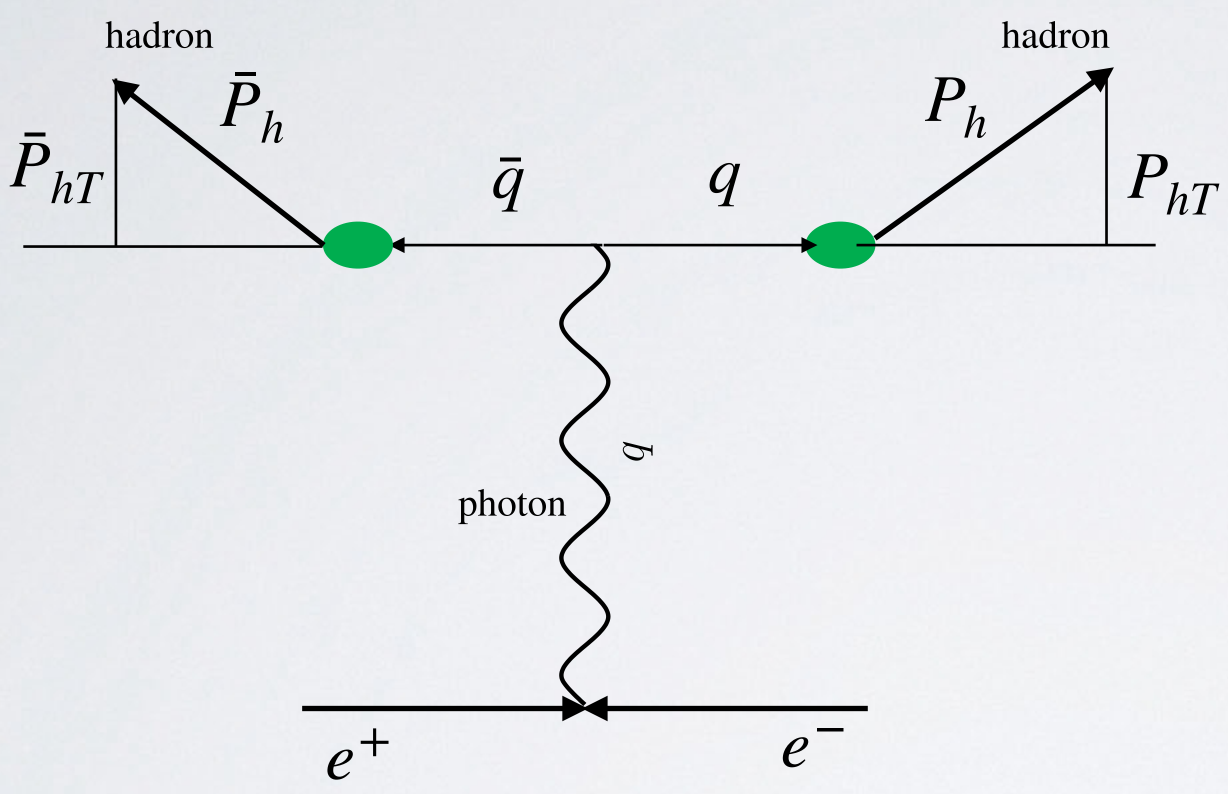
Nanga Parbat is a fitting framework aimed at the determination of the non-perturbative component of TMD distributions.

Download

You can obtain NangaParbat directly from the github repository:

https://github.com/MapCollaboration/NangaParbat

TMD factorization: e+e-

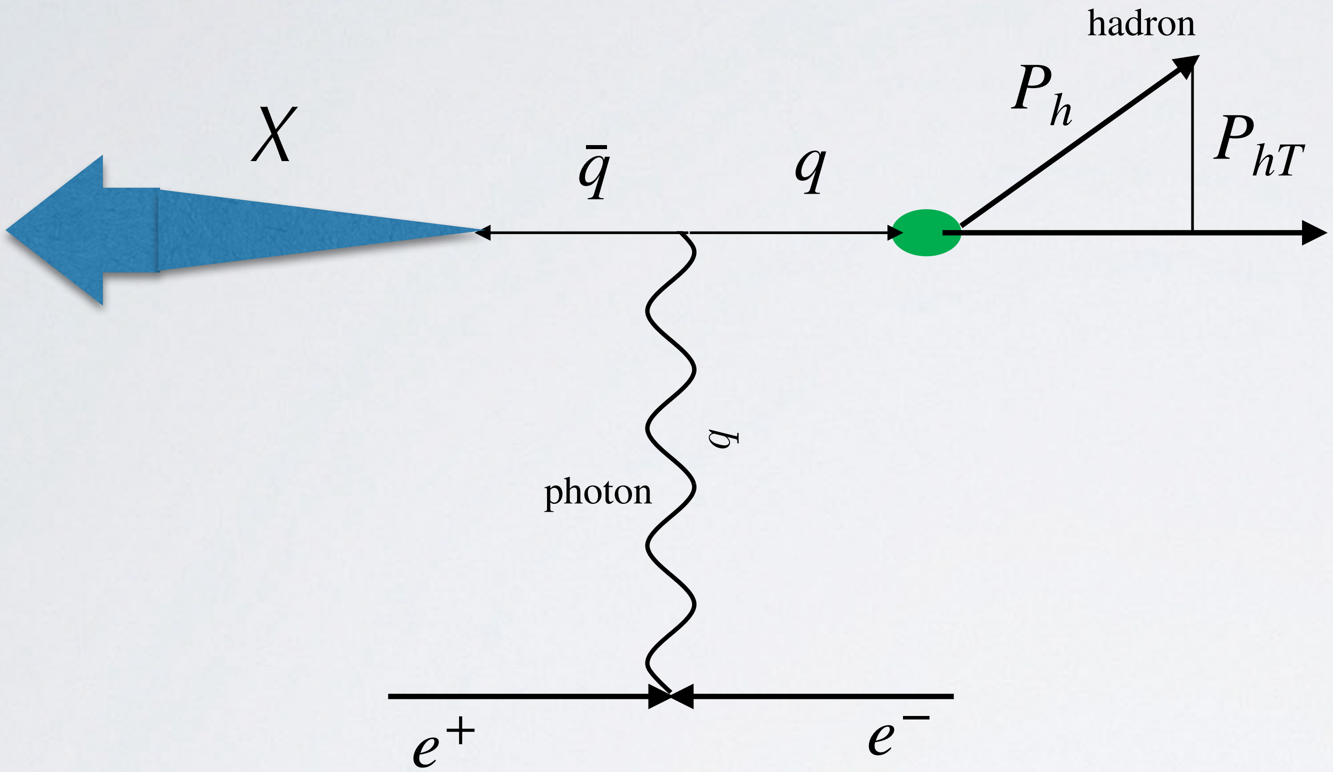


$$e^+ e^- \to h_1 + h_2 + X$$

data available only as azimuthal (spin) asymmetries

used for polarized **TMD FF**

TMD factorization: e+e-



$$e^+e^- \to h + X$$

data available

BELLE

arXiv:1902.01552

Complicated (and sometimes different) factorization theorems, depending on "distance" of hadron from thrust axis

For the moment, only Drell-Yan + SIDIS

Kang et al., arXiv:2007.14425
Makris et al., arXiv:2009.11871
Boglione & Simonelli, arXiv:2007.13674
arXiv:2011.07366
arXiv:2109.11497
arXiv:2306.02937

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

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

Multiplicity

Th: for each bin [i,f]

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

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

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

The TMD formula

- TMDs depend on two scales: renormalization μ and rapidity ζ (rapidity divergences do not cancel)
  - μ → DGLAP evolution, Sudakov form factor
  - ζ → evolution through Collins-Soper (CS) kernel K

- for small b_T, TMDs at initial scale can be OPE-expanded onto PDFs through perturbative Wilson coefficients

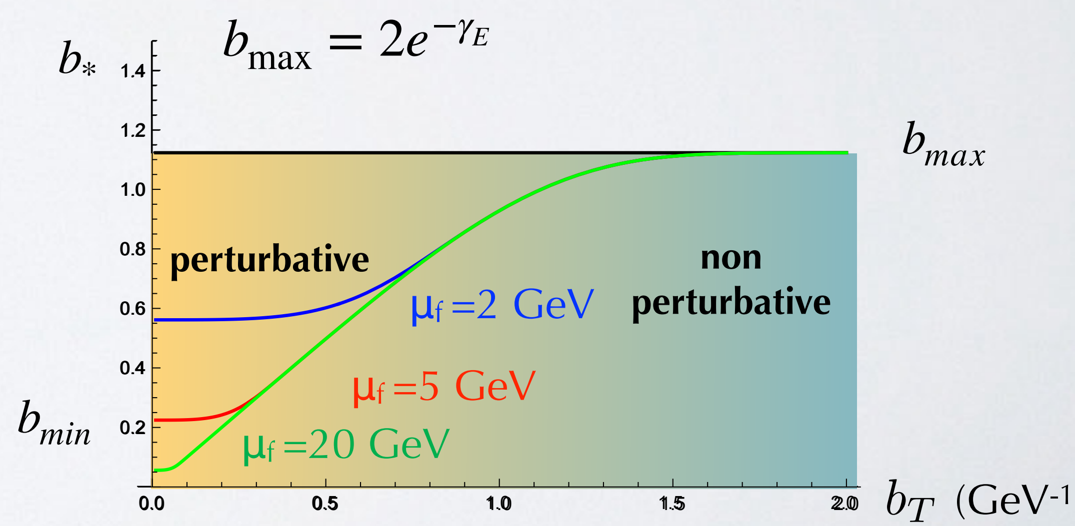
- convenient choice for initial scale is $\mu_i = \sqrt{\zeta_i} = \mu_b = \dfrac{2e^{-\gamma_E}}{b_T}$ (cancel many large logs in resummation)

- so far, approach is perturbative; but what happens at large b_T? Avoid Landau pole…

- prescription $b_*(b_T)$ such that $b_{\min} \xleftarrow{\text{small } b_T} b_*(b_T) \xrightarrow{\text{large } b_T} b_{\max}$ $\qquad \mu_f \geq \mu_{b_*} = \dfrac{2e^{-\gamma_E}}{b_*} \geq 1$

$$b_*(|\boldsymbol{b}_T|) = b_{\max} \left(\frac{1 - e^{-|\boldsymbol{b}_T|^4/b_{\max}^4}}{1 - e^{-|\boldsymbol{b}_T|^4/b_{\min}^4}} \right)^{1/4} \qquad b_{\min} = \frac{2e^{-\gamma_E}}{\mu_f}$$

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



- $b_*(b_T)$ introduces a non-perturbative component

$$f_1(x, b_T, \mu, \zeta) = f_1(x, b_*(b_T), \mu, \zeta) \, \frac{f_1(x, b_T, \mu, \zeta)}{f_1(x, b_*(b_T), \mu, \zeta)}$$

$$\equiv f_1(x, b_*(b_T), \mu, \zeta) \, f_{\rm NP}(x, b_T, \zeta, Q_0)$$

arbitrary

MAPTMD22

JHEP

PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: *June 23, 2022*
REVISED: *September 13, 2022*
ACCEPTED: *October 10, 2022*
PUBLISHED: *October 19, 2022*

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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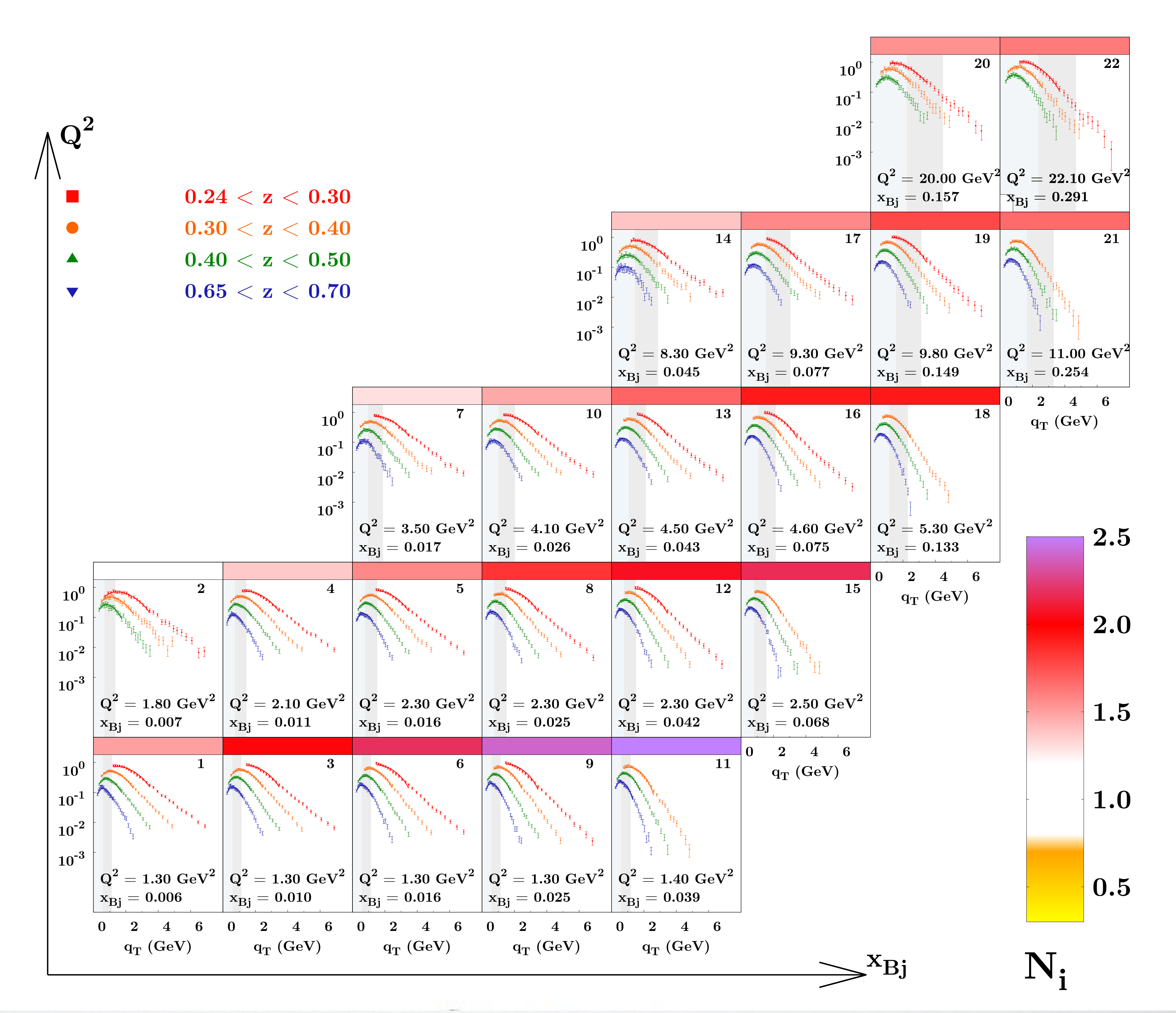
JHEP10(2022)127

MAPTMD22

arXiv:2206.07598

Normalization problem in SIDIS

Gonzalez-Hernandez, PoS DIS2019 (2019)



MAPTMD22: 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_{data}=**2031**, **21** parameters, $\chi_0^2/N_{\text{data}} = 1.06$

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

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

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

penalty for correlated errors

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

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

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

nuisance params.

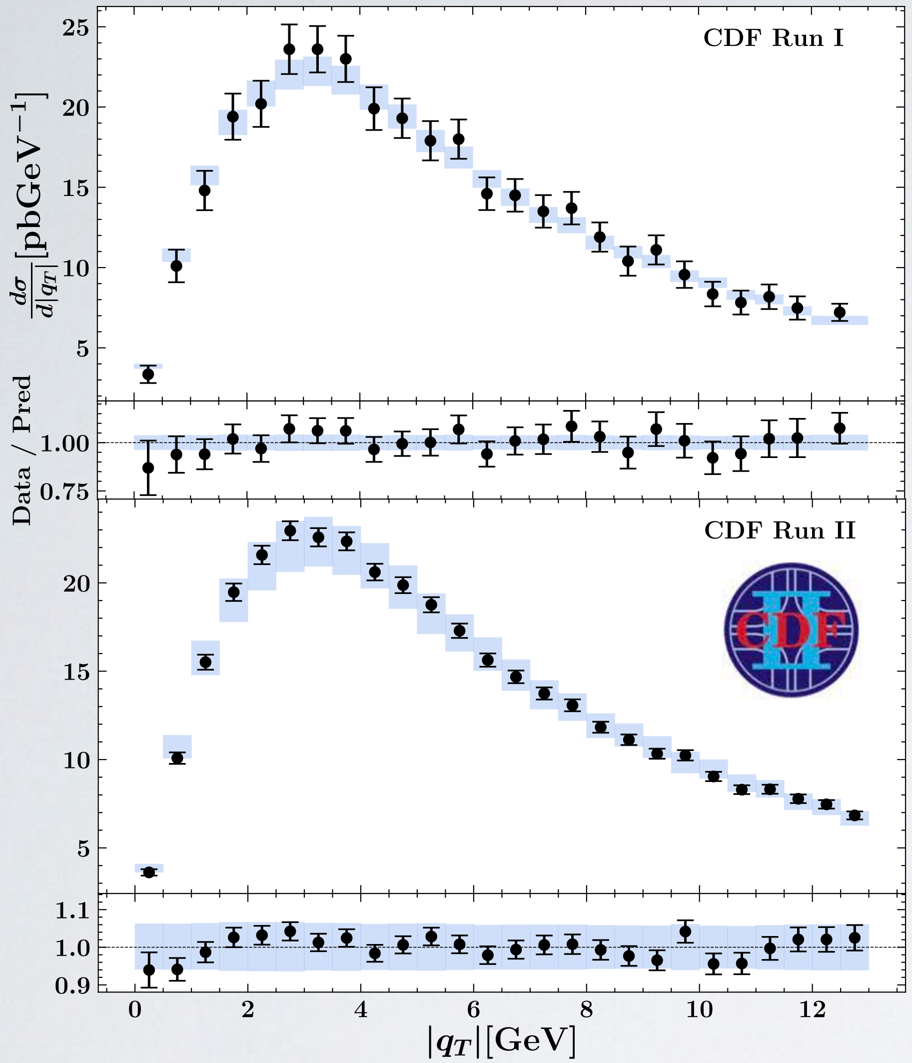
Examples of (partly) correlated errors :

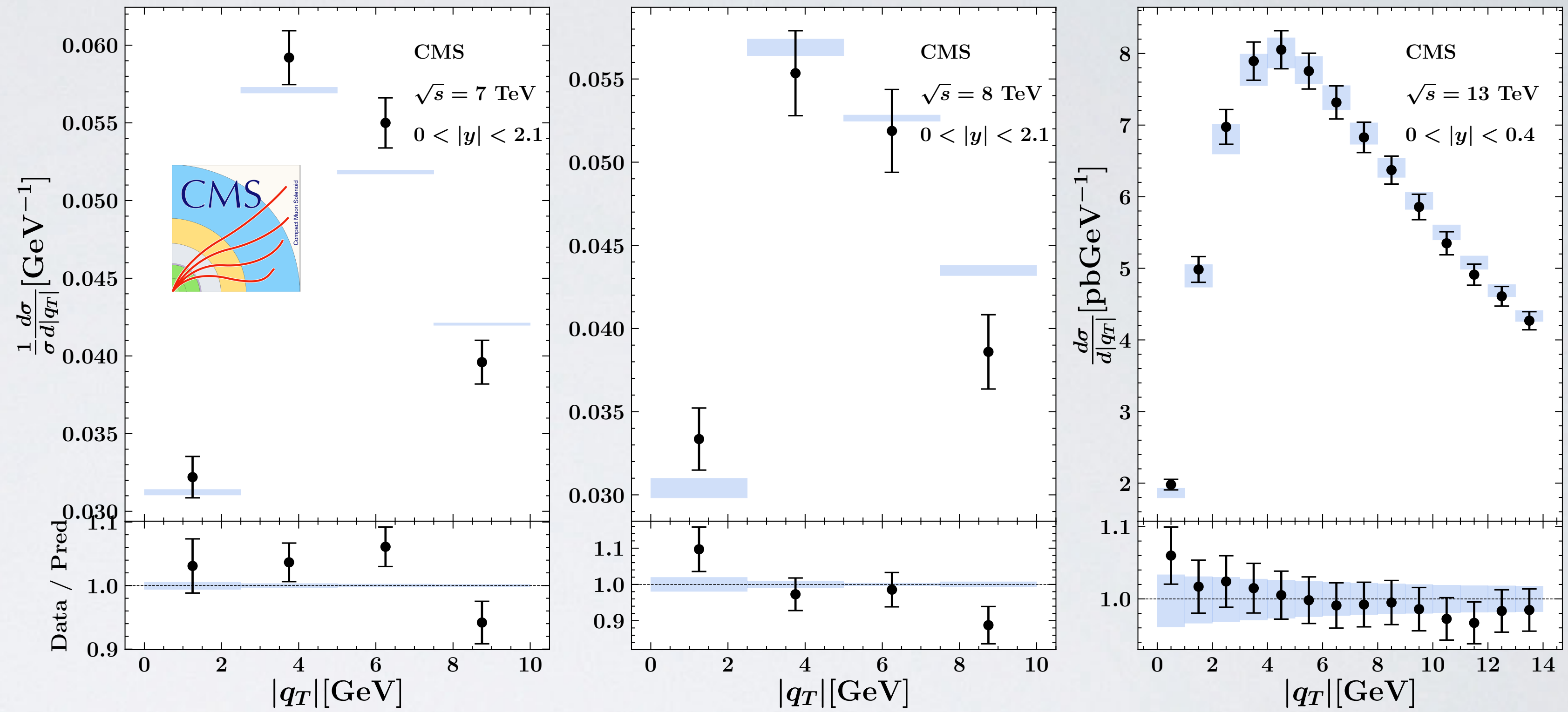
- exp.: some normalization systematic errors
- th. : uncertainties of PDFs MMHT2014

  FFs DSS14 for $\pi^\pm$

  DSS17 for $K^\pm$

MAPTMD22 N³LL⁽⁻⁾ global fit $\chi_0^2/N_{\mathrm{data}} = 1.06$





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

th. error band =
68% of all replicas

Visualizing MAPTMD22 TMD PDF

TMD PDF for unpolarized up quark

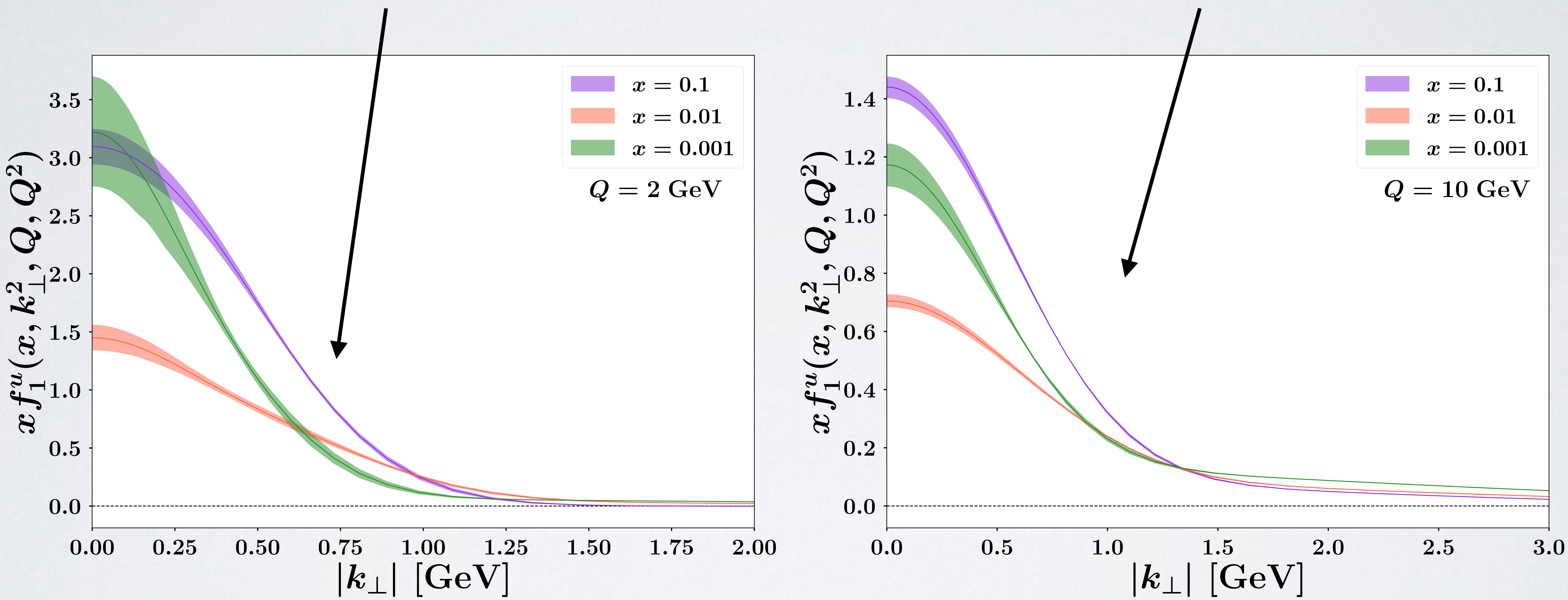
$f_{NP}(x,b_T)$

~ Gaussian + λ_B weighted Gaussian + λ_C Gaussian

$\lambda_B = 1.82 \pm 0.29\ \mathrm{GeV}^{-1}$ $\lambda_C = 0.0215 \pm 0.0058\ \mathrm{GeV}^{-1}$

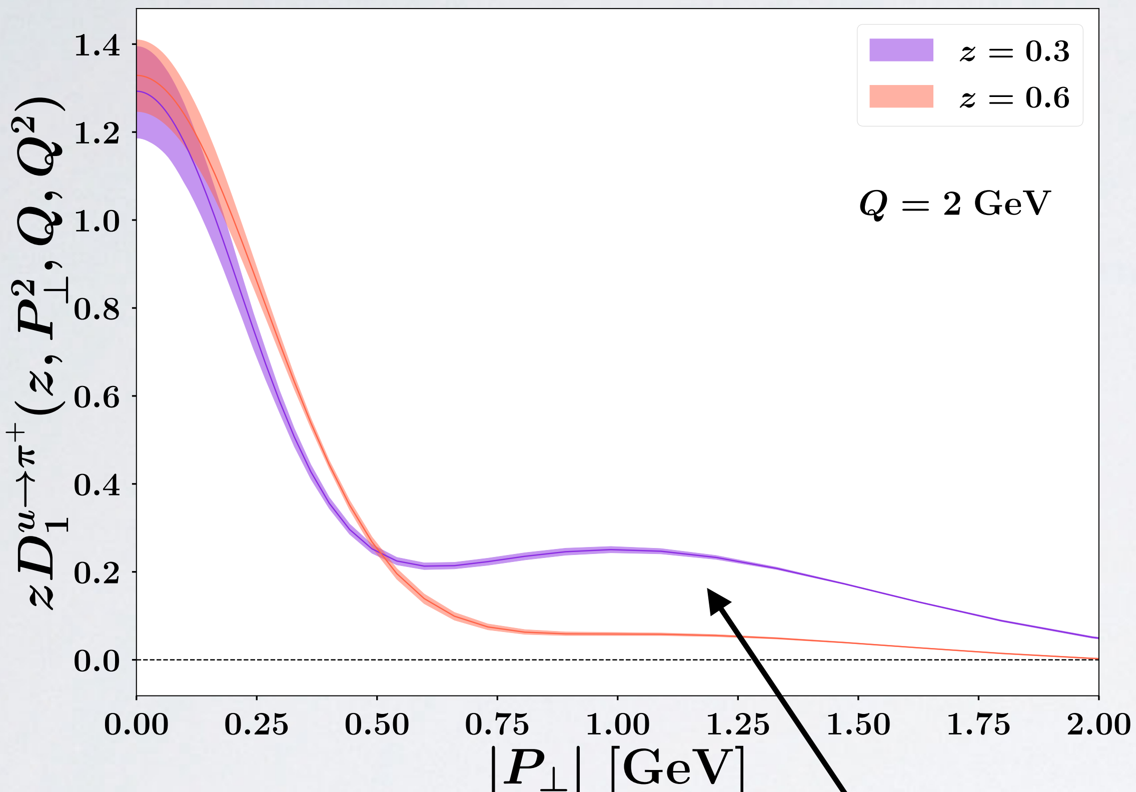
non-pert. evolution $e^{-g_2^2\, b_T^2/4}$

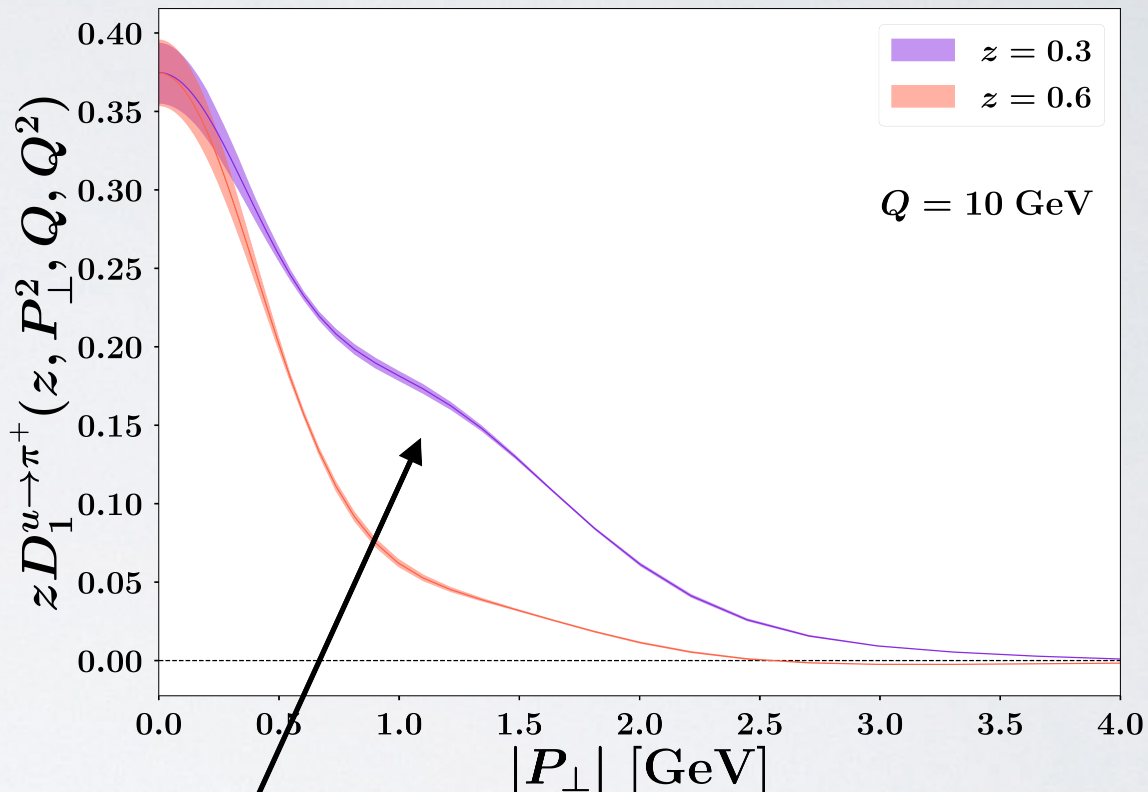
$g_2 = 0.248 \pm 0.008\ \mathrm{GeV}$



Visualizing MAPTMD22 TMD FF

up → π+





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

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

MAPTMD22: χ^2 breakout

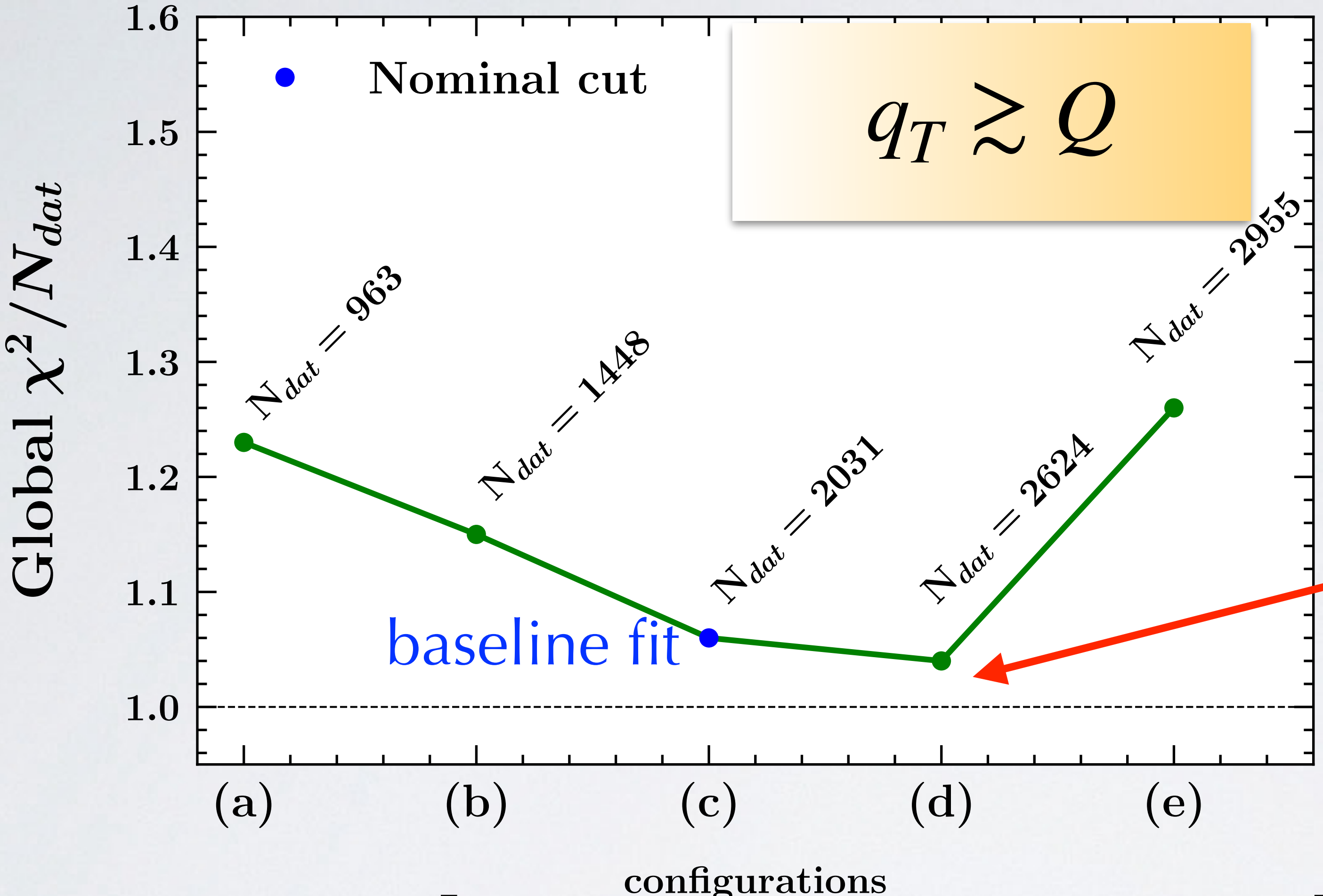
	N^{3}LL$^-$			
Data set	N_{dat}	χ^2_D	χ^2_λ	χ^2_0
CDF Run I	25	0.45	0.09	0.54
CDF Run II	26	0.995	0.004	1.0
D0 Run I	12	0.67	0.01	0.68
D0 Run II	5	0.89	0.21	1.10
D0 Run II (μ)	3	3.96	0.28	4.2
Tevatron total	71	0.87	0.06	0.93
LHCb 7 TeV	7	1.24	0.49	1.73
LHCb 8 TeV	7	0.78	0.36	1.14
LHCb 13 TeV	7	1.42	0.06	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**

MAPTMD22: 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

MAPTMD22: Kinematic cuts



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

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 $q_T > Q$

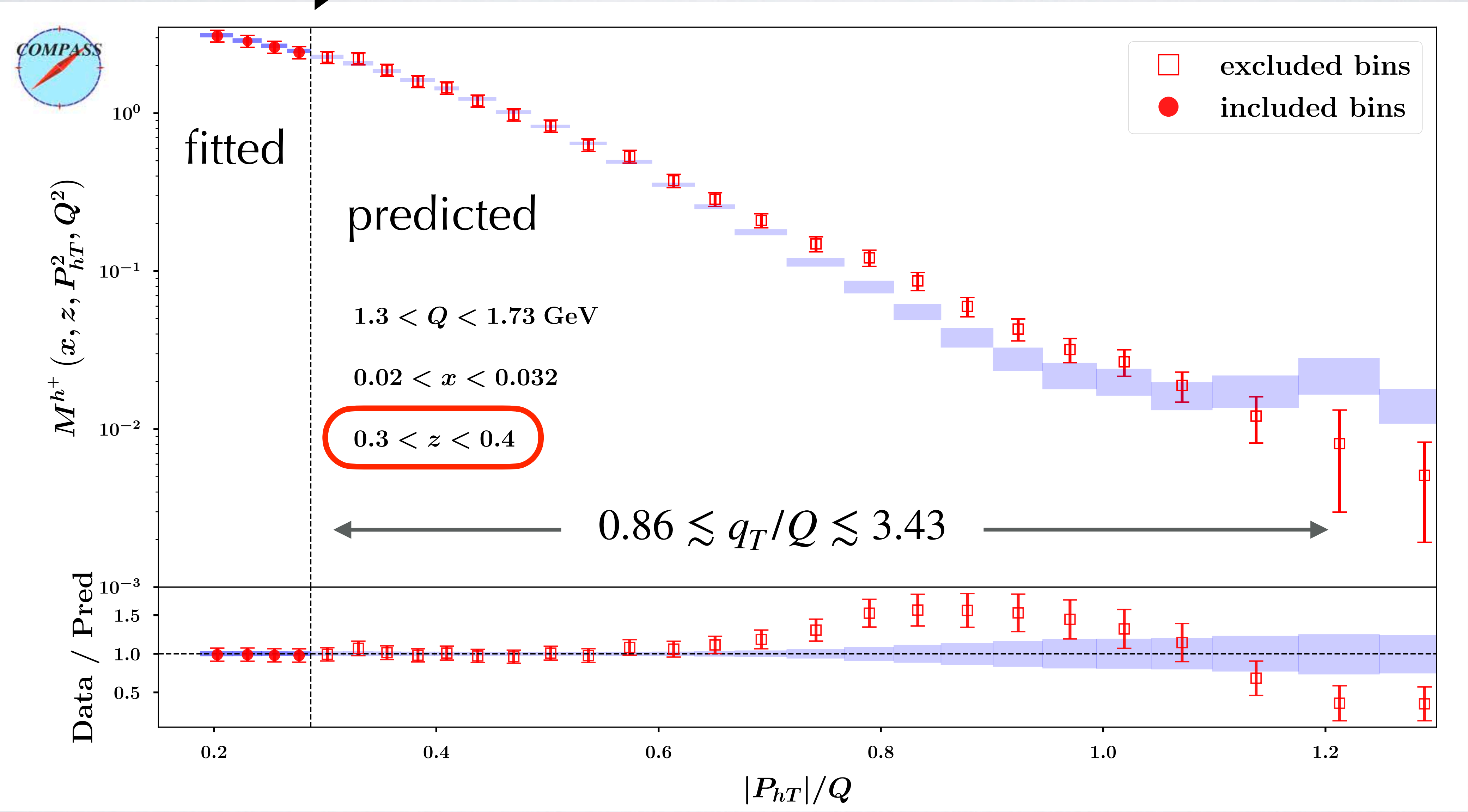
e) $c_1 = 0.2$, $c_2 = 0.7$, $c_3 = 0.5$ can be $q_T > Q$

more conservative

less conservative

MAPTMD22: validity of TMD region?

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



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

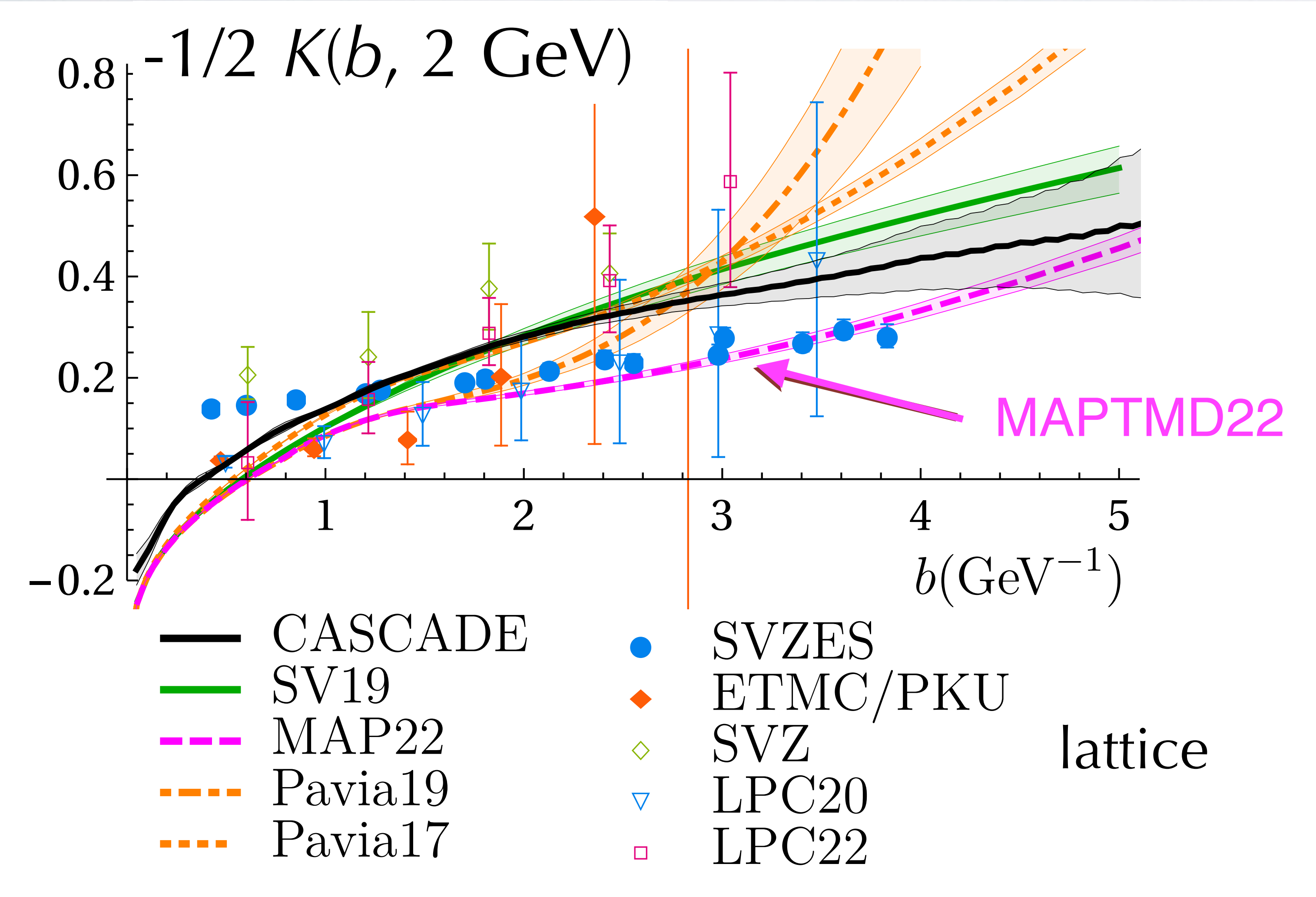
Visualizing the Collins-Soper evolution kernel

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

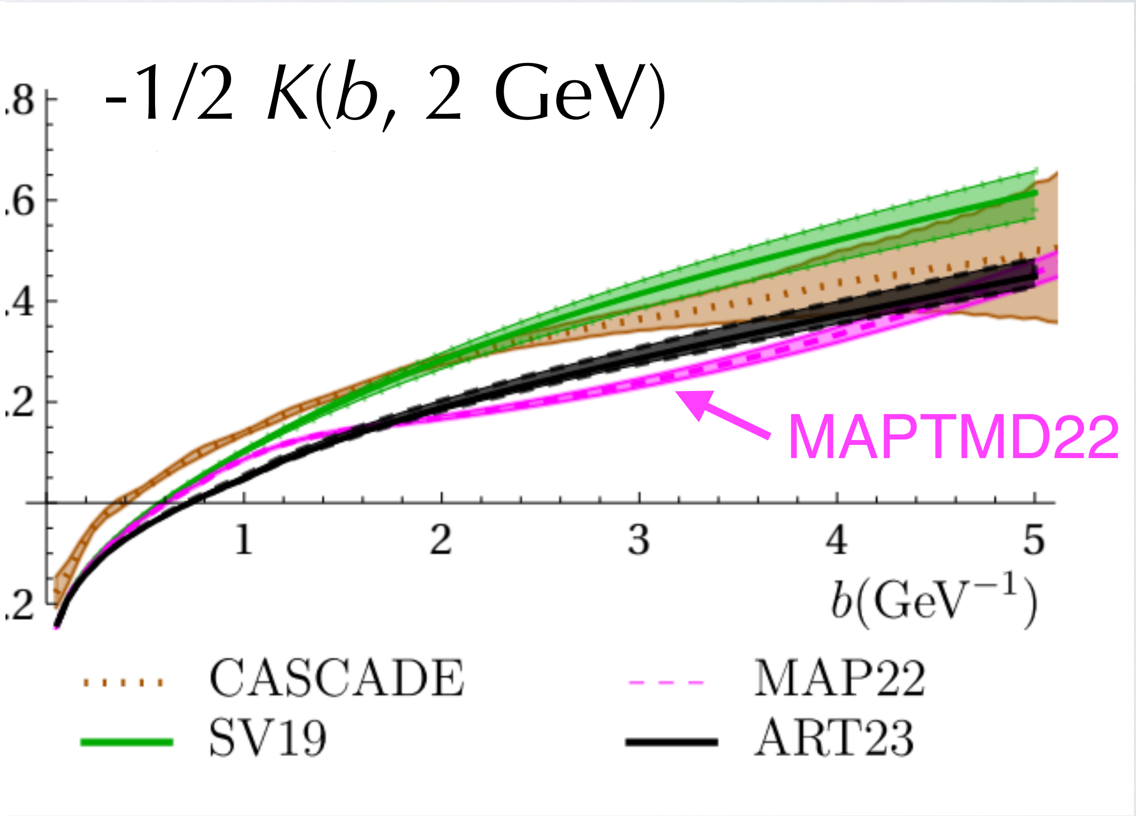
drives evolution in rapidity ζ

perturbative

non-perturbative (fitted)



Bermudez Martinez & Vladimirov, arXiv:2206.01105



Moss et al., arXiv:2305.07473

MAPTMD24

Flavor dependence of unpolarized quark Transverse Momentum Distributions from a global fit

The **MAP** (Multi-dimensional Analyses of Partonic distributions) Collaboration

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arXiv:2405.13833

MAPTMD24

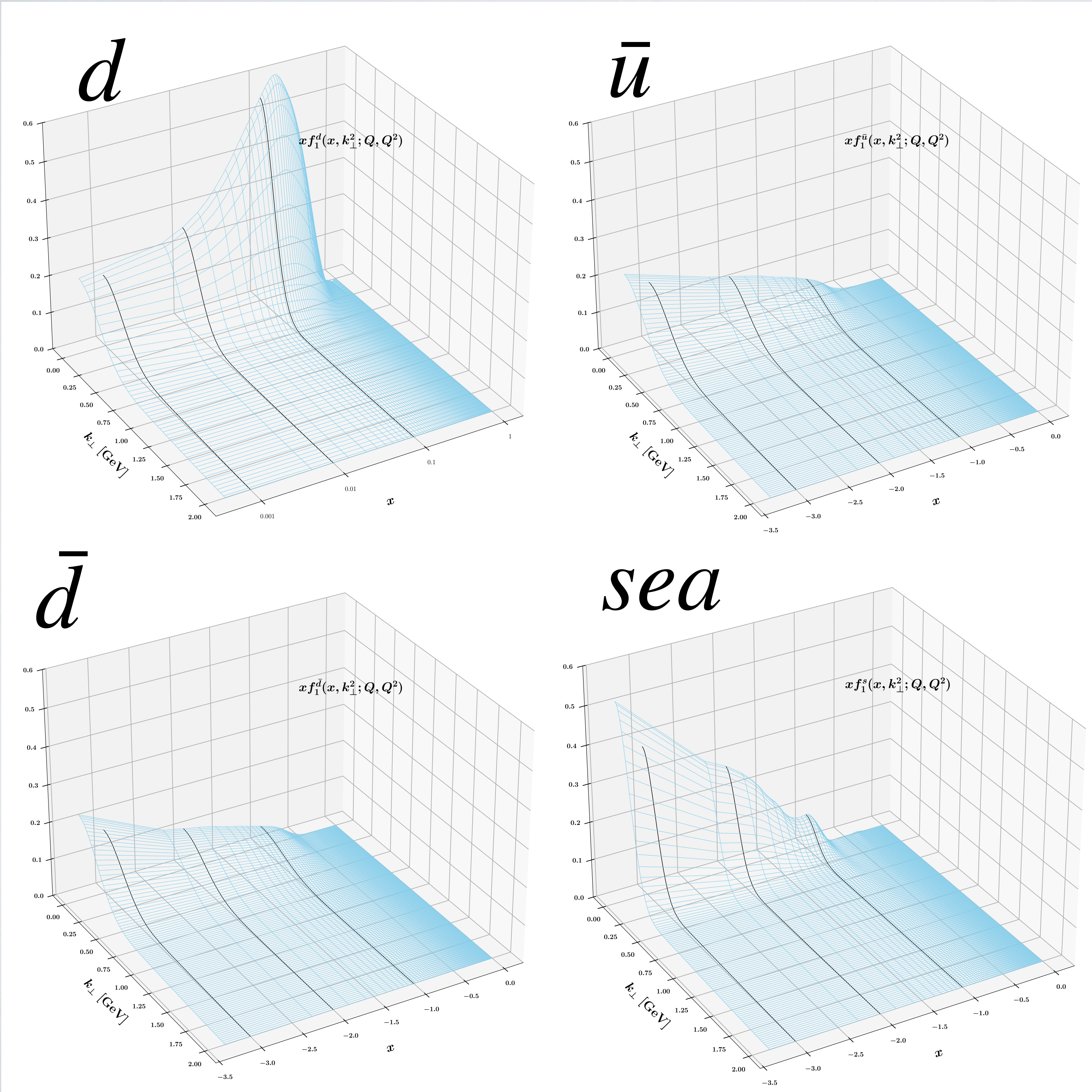
MAPTMD24: χ^2 breakout

	N^{3}LL			
Data set	N_{dat}	χ^2_D	χ^2_λ	χ^2_0
Tevatron total	71	1.10	0.07	1.17
LHCb total	21	3.56	0.96	4.52
ATLAS total	72	3.54	0.82	4.36
CMS total	78	0.38	0.05	0.43
PHENIX 200	2	2.76	1.04	3.80
STAR 510	7	1.12	0.26	1.38
DY collider total	251	1.37	0.28	1.65
E288 200 GeV	30	0.13	0.40	0.53
E288 300 GeV	39	0.16	0.26	0.42
E288 400 GeV	61	0.11	0.08	0.19
E772	53	0.88	0.20	1.08
E605	50	0.70	0.22	0.92
DY fixed-target total	233	0.63	0.31	0.94
HERMES total	344	0.81	0.24	1.05
COMPASS total	1203	0.67	0.27	0.94
SIDIS total	1547	0.70	0.26	0.96
Total	**2031**	**0.81**	**0.27**	**1.08**

MAPTMD24: fit parameters

Parameter	Value	Parameter	Value	Parameter	Value
g_2 [GeV]	0.12 ± 0.0033				
N_{1d} [GeV^2]	0.21 ± 0.017	N_{2d} [GeV^2]	0.015 ± 0.0013	N_{3d} [GeV^2]	$(40 \pm 2.2) \times 10^{-4}$
α_{1d}	0.86 ± 0.11	α_{2d}	5.5 ± 0.041	α_{3d}	2.38 ± 0.032
σ_{1d}	-0.21 ± 0.013	$\sigma_{2d} = \sigma_{3d}$	9.91 ± 0.061		
λ_{1d} [GeV^{-1}]	0.32 ± 0.038	λ_{2d} [GeV^{-1}]	0.052 ± 0.0022		
$N_{1\bar{d}}$ [GeV^2]	0.68 ± 0.038	$N_{2\bar{d}}$ [GeV^2]	0.0037 ± 0.0037	$N_{3\bar{d}}$ [GeV^2]	$(5.9 \pm 5.8) \times 10^{-5}$
$\alpha_{1\bar{d}}$	0.64 ± 0.18	$\alpha_{2\bar{d}}$	5.69 ± 0.64	$\alpha_{3\bar{d}}$	1.57 ± 0.53
$\sigma_{1\bar{d}}$	0.075 ± 0.012	$\sigma_{2\bar{d}} = \sigma_{3\bar{d}}$	10.19 ± 0.09		
$\lambda_{1\bar{d}}$ [GeV^{-1}]	0.7 ± 0.67	$\lambda_{2\bar{d}}$ [GeV^{-1}]	0.051 ± 0.0071		
N_{1u} [GeV^2]	0.35 ± 0.0063	N_{2u} [GeV^2]	0.019 ± 0.00015	N_{3u} [GeV^2]	$(355 \pm 4.5) \times 10^{-6}$
α_{1u}	0.18 ± 0.1	α_{2u}	5.42 ± 0.0037	α_{3u}	2.14 ± 0.0068
σ_{1u}	-0.26 ± 0.0079	$\sigma_{2u} = \sigma_{3u}$	10.17 ± 0.011		
λ_{1u} [GeV^{-1}]	0.49 ± 0.0037	λ_{2u} [GeV^{-1}]	0.081 ± 0.0009		
$N_{1\bar{u}}$ [GeV^2]	0.48 ± 0.0074	$N_{2\bar{u}}$ [GeV^2]	0.022 ± 0.00037	$N_{3\bar{u}}$ [GeV^2]	$(21 \pm 1.5) \times 10^{-5}$
$\alpha_{1\bar{u}}$	0.95 ± 0.077	$\alpha_{2\bar{u}}$	5.38 ± 0.0099	$\alpha_{3\bar{u}}$	1.77 ± 0.052
$\sigma_{1\bar{u}}$	-0.026 ± 0.01	$\sigma_{2\bar{u}} = \sigma_{3\bar{u}}$	10.21 ± 0.02		
$\lambda_{1\bar{u}}$ [GeV^{-1}]	0.53 ± 0.0067	$\lambda_{2\bar{u}}$ [GeV^{-1}]	0.11 ± 0.0055		
N_{1sea} [GeV^2]	0.16 ± 0.035	N_{2sea} [GeV^2]	0.029 ± 0.0027	N_{3sea} [GeV^2]	0.0039 ± 0.002
α_{1sea}	0.65 ± 0.48	α_{2sea}	5.24 ± 0.032	α_{3sea}	1.48 ± 0.74
σ_{1sea}	-0.018 ± 0.022	$\sigma_{2sea} = \sigma_{3sea}$	10.72 ± 0.037		
λ_{1sea} [GeV^{-1}]	2.43 ± 0.97	λ_{2sea} [GeV^{-1}]	0.015 ± 0.0083		
$N_{4u\pi}$ [GeV^2]	$(82 \pm 1.8) \times 10^{-5}$	$N_{5u\pi}$ [GeV^2]	0.095 ± 0.0008	$\beta_{1u\pi}$	5.19 ± 0.066
$\beta_{2u\pi}$	2.3 ± 0.041	$\delta_{1u\pi}$	0.017 ± 0.0084	$\delta_{2u\pi}$	0.19 ± 0.0049
$\gamma_{1u\pi}$	1.46 ± 0.015	$\gamma_{2u\pi}$	0.8 ± 0.0095	$\lambda_{Fu\pi}$ [GeV^{-2}]	0.089 ± 0.003
$N_{4sea\pi}$ [GeV^2]	$(83 \pm 2.4) \times 10^{-5}$	$N_{5sea\pi}$ [GeV^2]	0.094 ± 0.0012	$\beta_{1sea\pi}$	5.38 ± 0.21
$\beta_{2sea\pi}$	2.31 ± 0.072	$\delta_{1sea\pi}$	0.022 ± 0.0064	$\delta_{2sea\pi}$	0.19 ± 0.0044
$\gamma_{1sea\pi}$	1.44 ± 0.026	$\gamma_{2sea\pi}$	0.8 ± 0.012	$\lambda_{Fsea\pi}$ [GeV^{-2}]	0.086 ± 0.004
N_{4uK} [GeV^2]	$(87 \pm 5.7) \times 10^{-5}$	N_{5uK} [GeV^2]	0.14 ± 0.0026	β_{1uK}	8.52 ± 0.081
β_{2uK}	3.86 ± 0.19	δ_{1uK}	0.0061 ± 0.0035	δ_{2uK}	0.19 ± 0.0059
γ_{1uK}	1 ± 0.041	γ_{2uK}	0.19 ± 0.054	λ_{FuK} [GeV^{-2}]	0.14 ± 0.0048
$N_{4\bar{s}K}$ [GeV^2]	$(4.5 \pm 3.7) \times 10^{-4}$	$N_{5\bar{s}K}$ [GeV^2]	0.16 ± 0.016	$\beta_{1\bar{s}K}$	7.17 ± 1.4
$\beta_{2\bar{s}K}$	5.1 ± 1.04	$\delta_{1\bar{s}K}$	1.51 ± 1.51	$\delta_{2\bar{s}K}$	0.16 ± 0.033
$\gamma_{1\bar{s}K}$	0.71 ± 0.42	$\gamma_{2\bar{s}K}$	0.36 ± 0.19	$\lambda_{F\bar{s}K}$ [GeV^{-2}]	0.34 ± 0.2
N_{4seaK} [GeV^2]	$(78 \pm 2.8) \times 10^{-5}$	N_{5seaK} [GeV^2]	0.15 ± 0.0059	β_{1seaK}	8.63 ± 0.24
β_{2seaK}	4.19 ± 0.14	δ_{1seaK}	0.0075 ± 0.0051	δ_{2seaK}	0.2 ± 0.0029
γ_{1seaK}	0.96 ± 0.036	γ_{2seaK}	0.17 ± 0.092	λ_{FseaK} [GeV^{-2}]	0.15 ± 0.0055

Visualizing MAPTMD24 TMD PDFs



Q=2 GeV

MAPTMD22 → MAPTMD24

2031 data pts. → same dataset

SIDIS normalization $\omega(x, z, Q)$ → same

N^{3}LL(-) → N^{3}LL

PDF: MMHT2014nnlo → NNPDF3.1NNLO

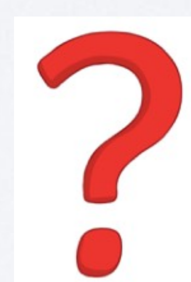
FF: DSS14 (π), DSS17 (K) at NLO → MAPFF1.0NNLO

correlated (exp. & th.) errors → same

nonperturbative parametrisation → same flavor-independent case

21 parameters → 21 parameters

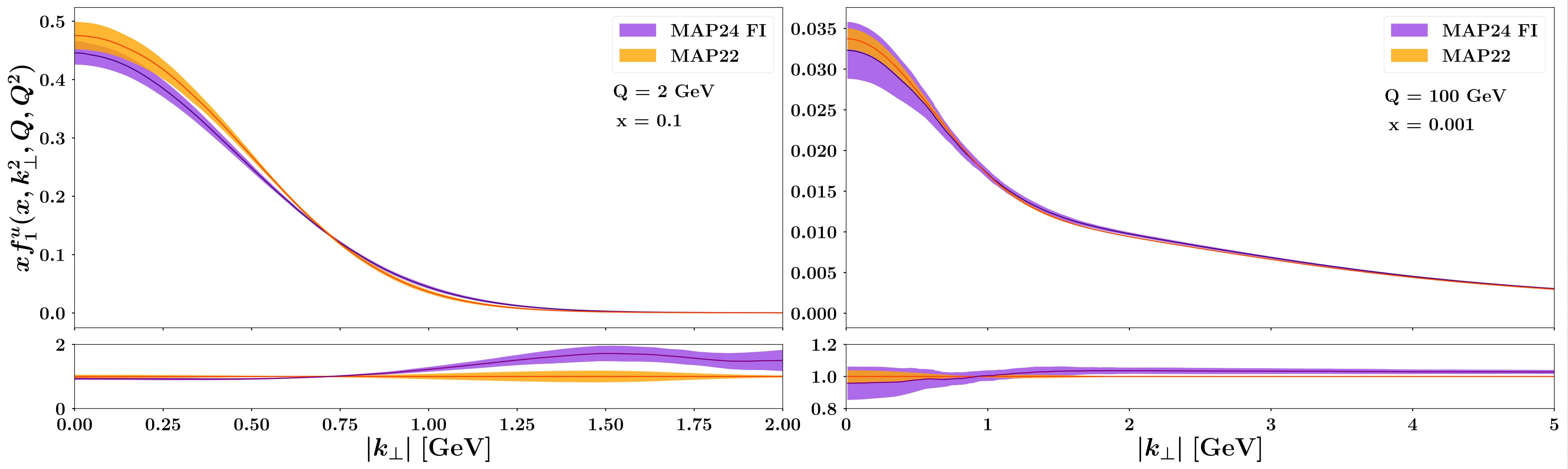
$\chi^2/N_{data} = 1.06$



$\chi^2/N_{data} = 1.40$

MAPTMD22 → MAPTMD24

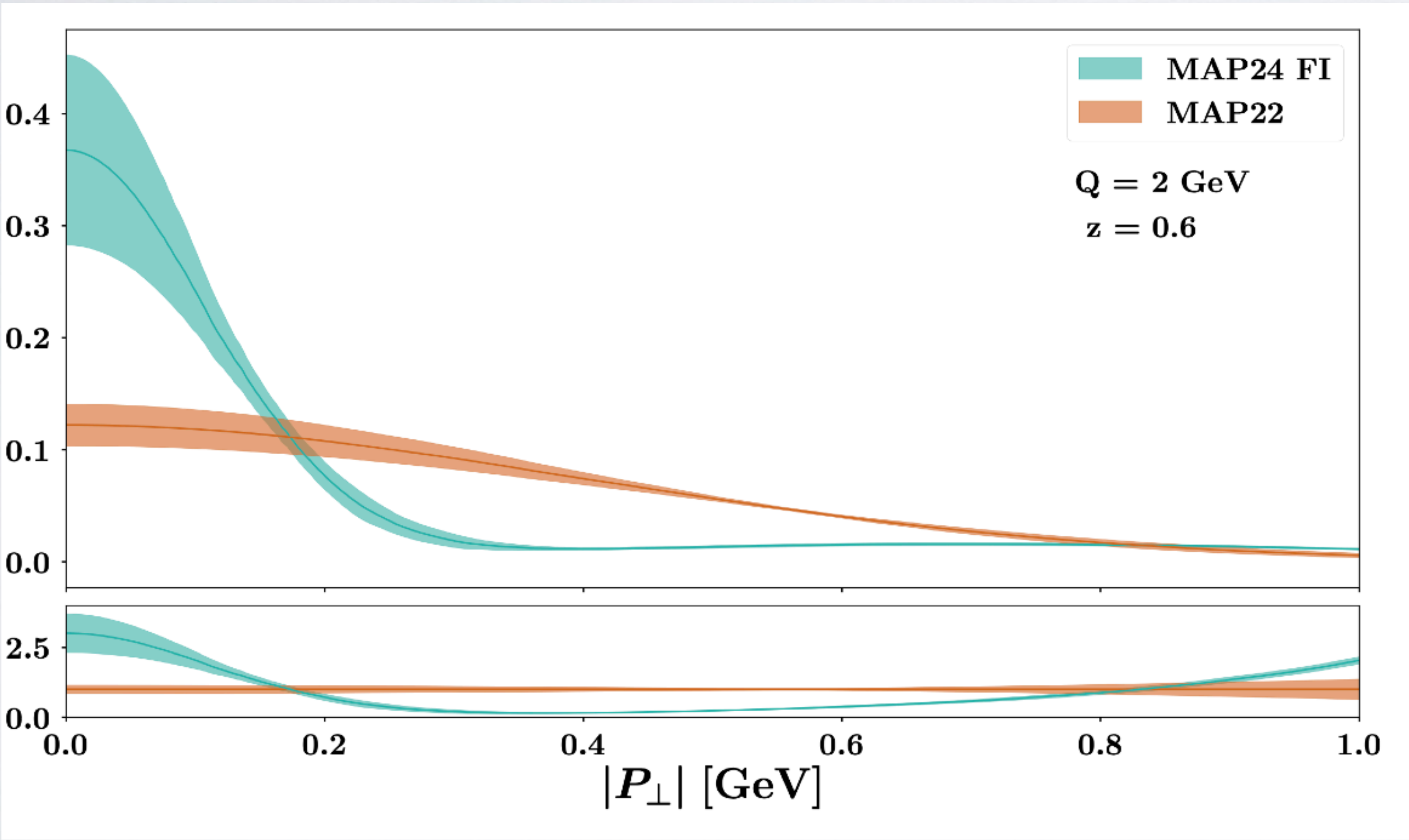
	Data set χ_0^2/N_{dat}		
Collinear sets	DY total	SIDIS total	**Total**
MMHT + DSS (MAP22)	1.66	0.87	**1.06**
NNPDF + MAPFF (MAP24 FI)	1.58	1.34	**1.40**



TMD PDFs from MAPTMD24
are compatible with MAPTMD22

MAPTMD22 → MAPTMD24

	Data set χ_0^2/N_{dat}		
Collinear sets	DY total	SIDIS total	**Total**
MMHT + DSS (MAP22)	1.66	0.87	**1.06**
NNPDF + MAPFF (MAP24 FI)	1.58	1.34	**1.40**



TMD FFs from MAPTMD24 are different from MAPTMD22

MAPFF1.0nnlo

- NNLO
- smaller uncertainties
- Neural Network approach

MAPTMD22 → MAPTMD24

Data set	N_{dat}	χ_0^2/N_{dat}
DY collider total	251	2.14
Dy fixed target total	233	0.68
HERMES total	344	2.72
COMPASS total	1203	0.99
SIDIS total	1547	1.38
Total	2031	1.40

NNPDF+MAPFF

Agreement

Data set	N_{dat}	χ_0^2/N_{dat}
DY collider total	251	2.01
Dy fixed target total	233	1.11
HERMES total	344	2.51
COMPASS total	1203	0.99
SIDIS total	1547	1.33
Total	2031	1.39

MMHT+MAPFF

Similar worsening

Data set	N_{dat}	χ_0^2/N_{dat}
DY collider total	251	2.43
Dy fixed target total	233	0.75
HERMES total	344	0.95
COMPASS total	1203	0.88
SIDIS total	1547	0.90
Total	2031	1.07

NNPDF+DSS

Good Agreement

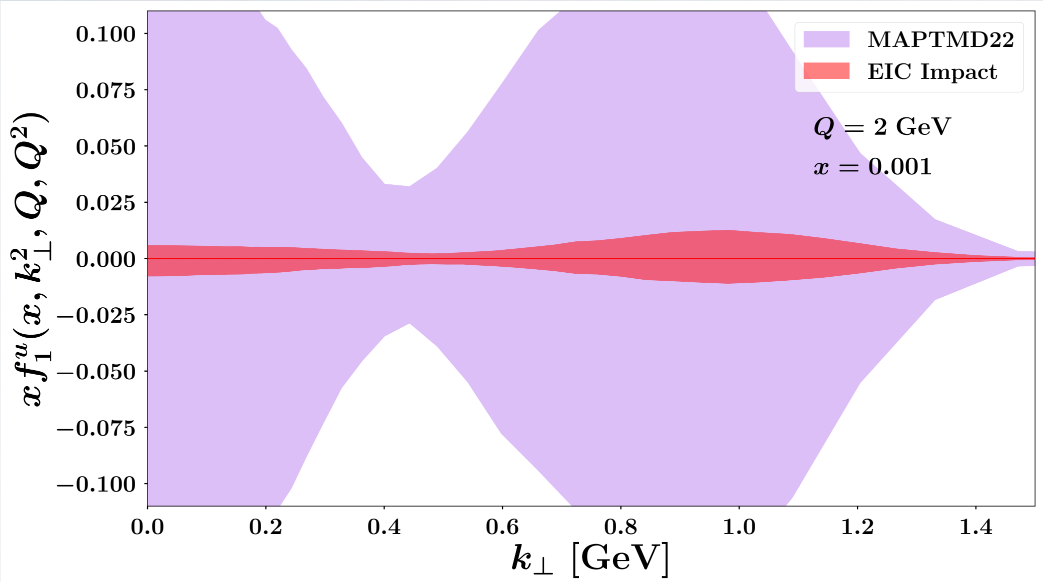
Data set	N_{dat}	χ_0^2/N_{dat}
DY collider total	251	2.06
Dy fixed target total	233	1.24
HERMES total	344	0.71
COMPASS total	1203	0.92
SIDIS total	1547	0.87
Total	2031	1.06

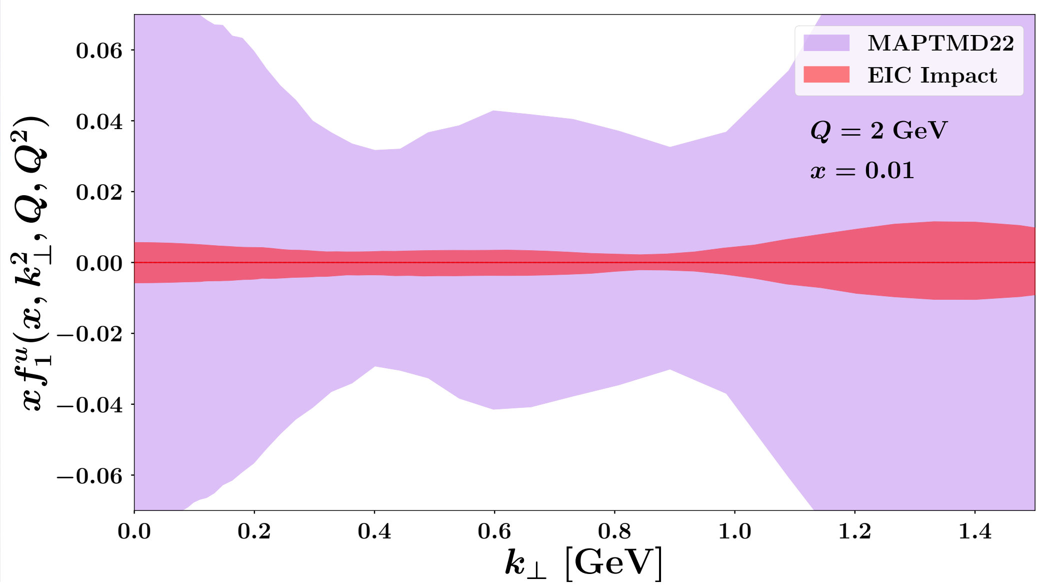
MMHT+DSS (MAPTMD22)

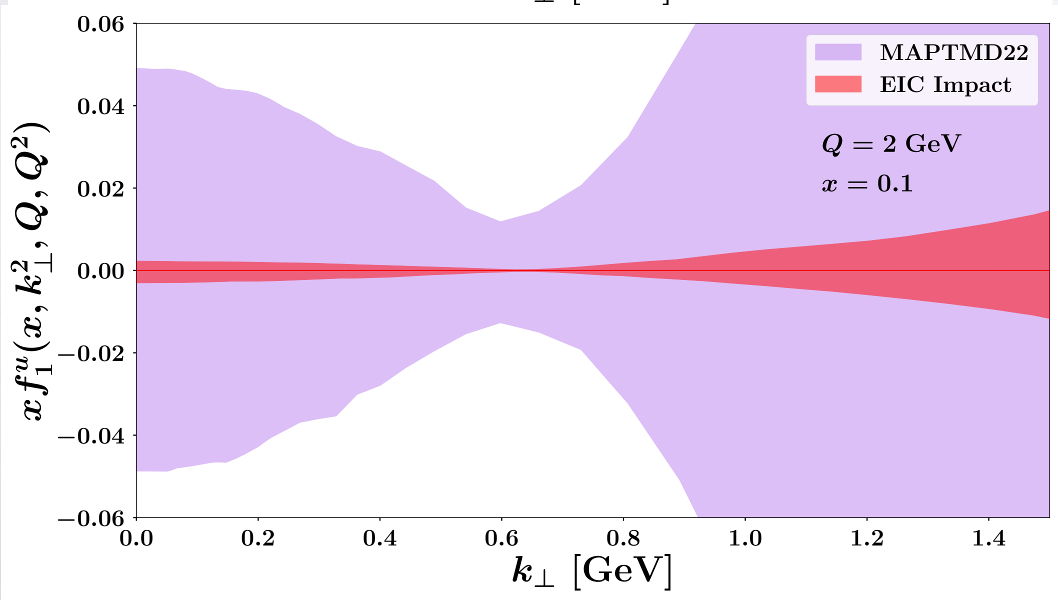
Impact studies

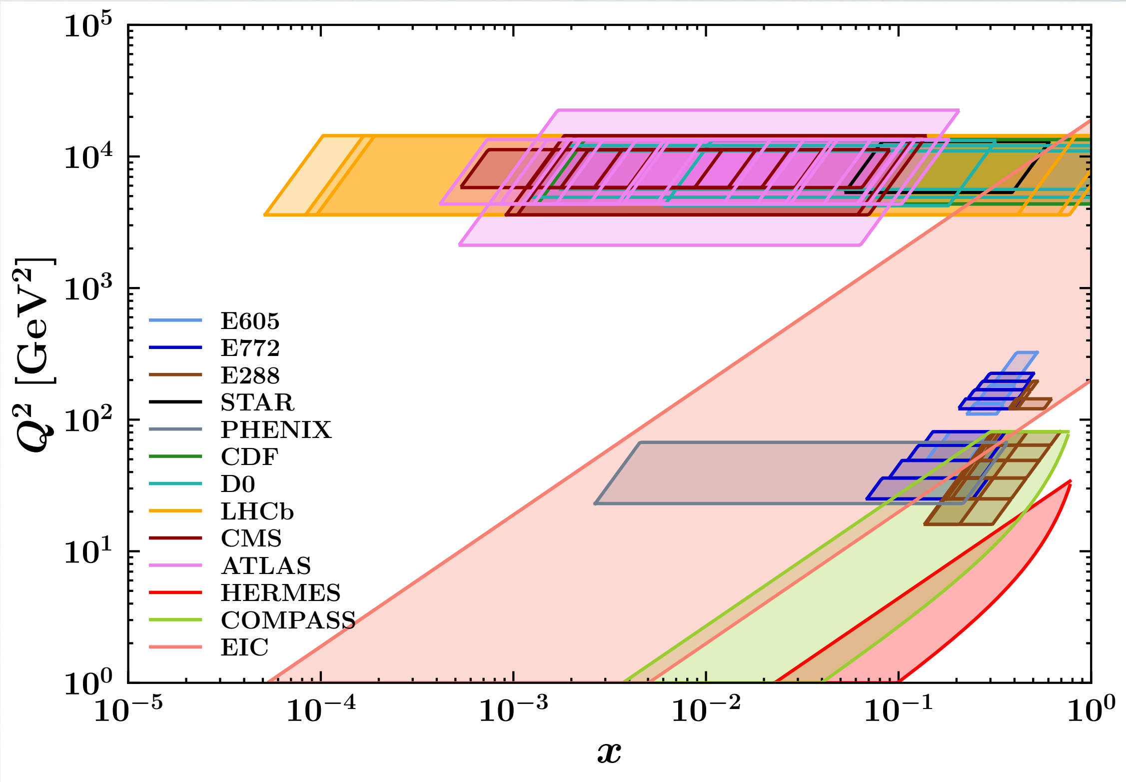
MAPTMD22 impact studies

MAPTMD22 impact on the EIC





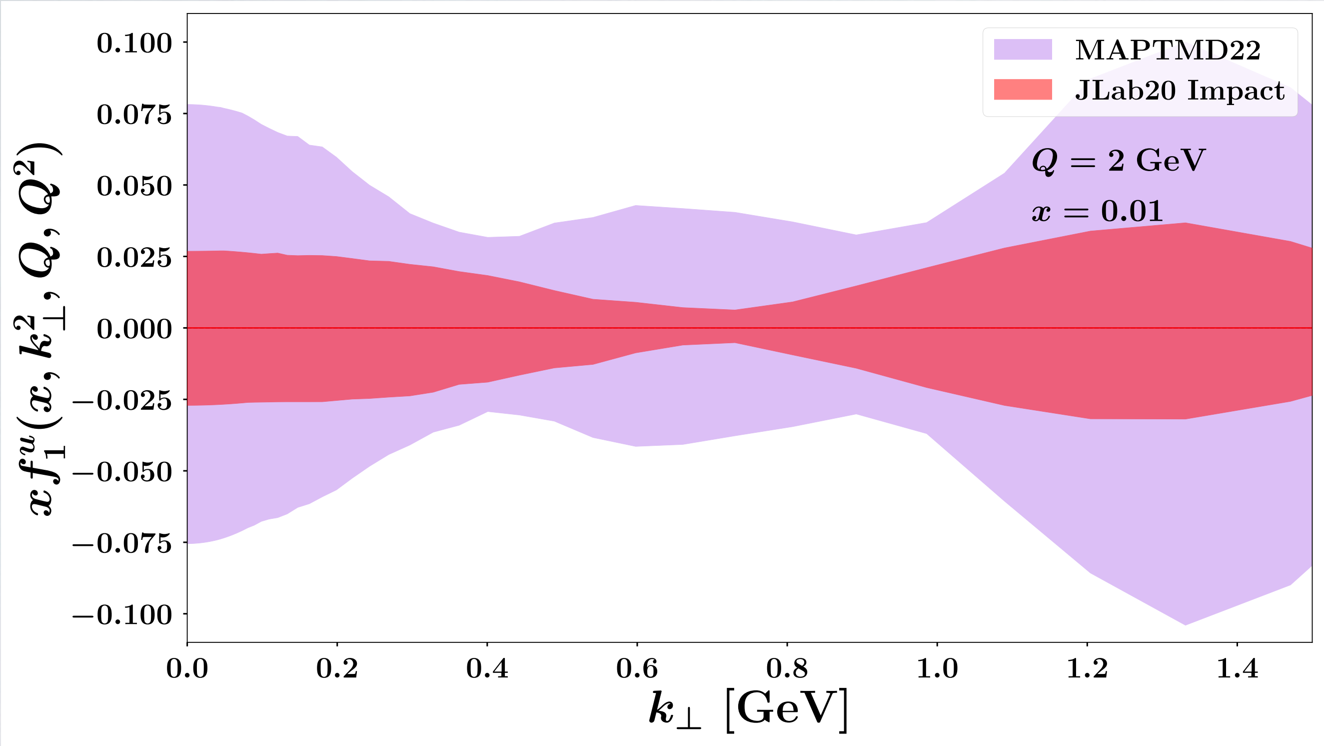


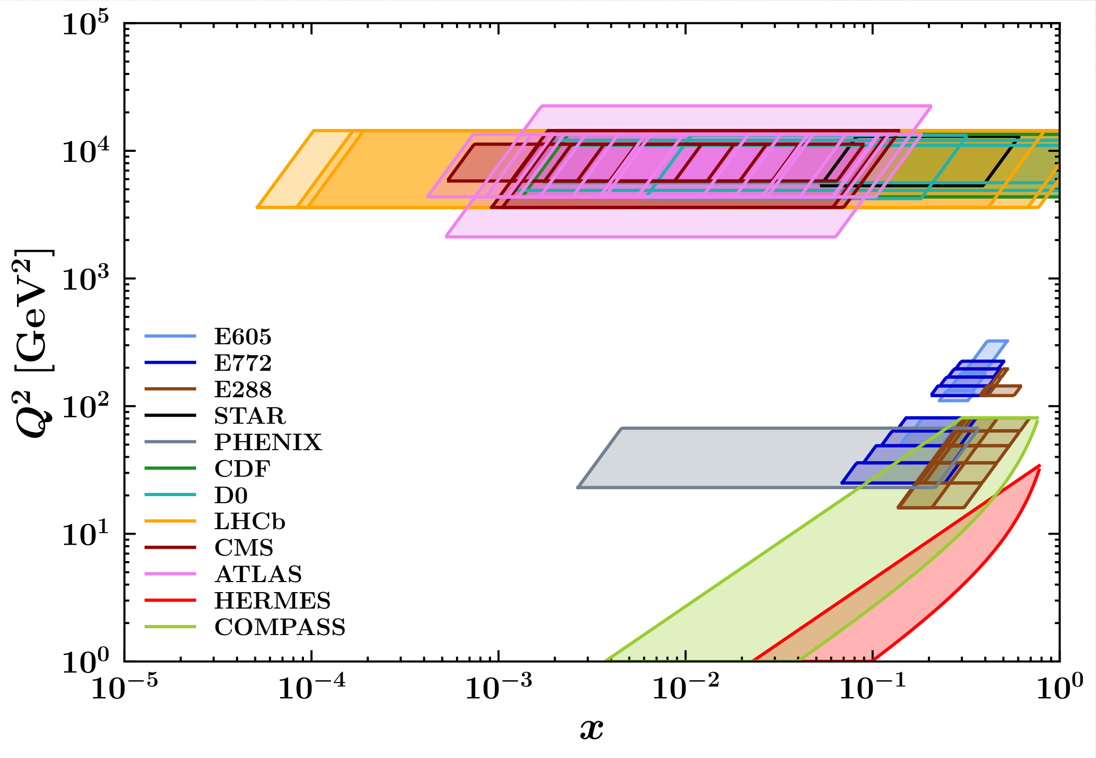


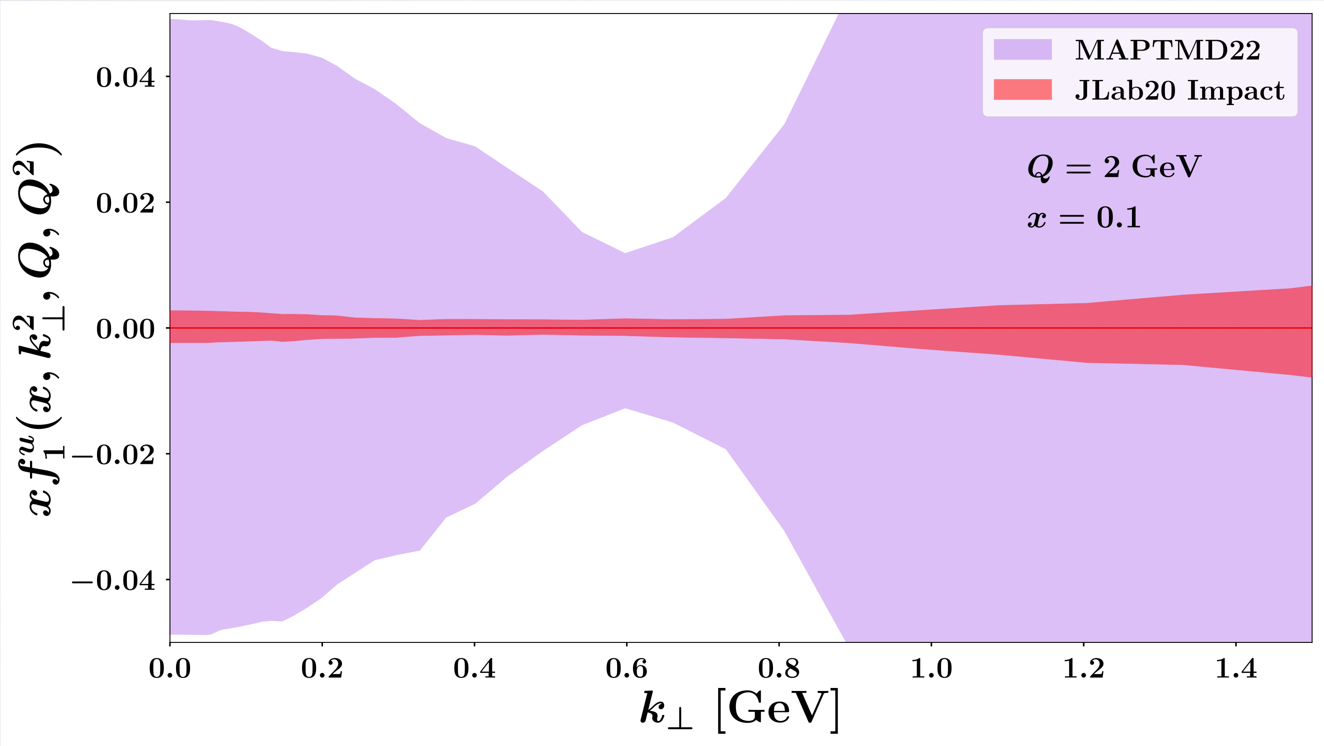
kinematics 10x100

major improvements at smaller x

MAPTMD22 impact on JLab20+







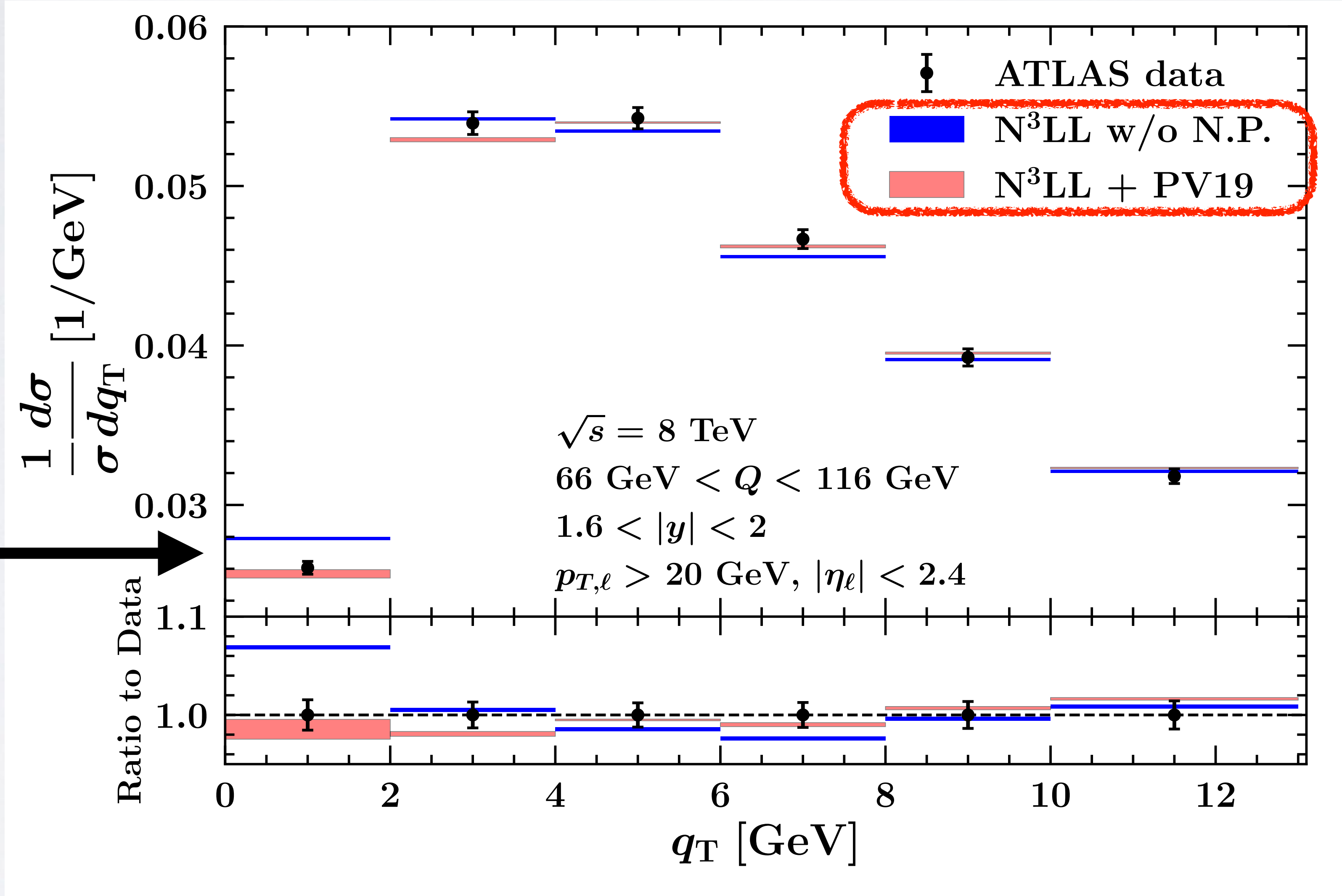
kinematics JLab20

major improvements at valence x

TMD impact at the LHC

q_T distribution of Z in ATLAS kin.

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

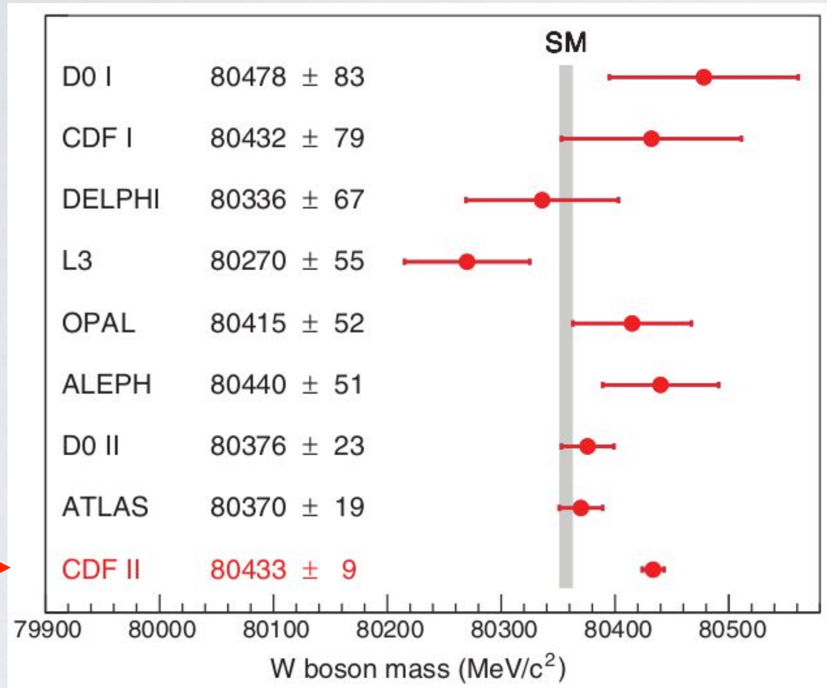


G. Bozzi, I. Scimemi (eds.) et al.,
Resummed predictions of the transverse momentum distribution of Drell-Yan lepton pairs in p-p collisions at LHC
Yellow Report of CERN EW Working Group, in preparation

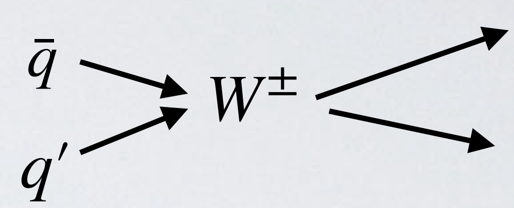
Potential impact on W mass

surprising CDF result

~ 7σ !



SM expectation: $M_W = 80357 \pm 6$ MeV



intrinsic $k_\perp$ + resummation $\rightarrow q_{TW} \rightarrow p_{T\ell}$

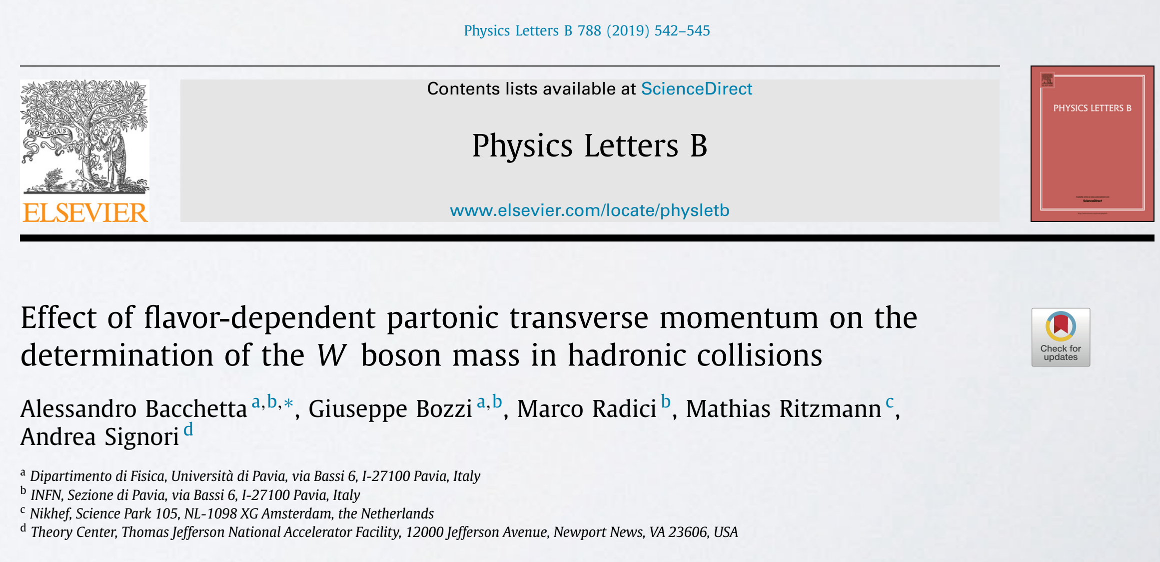
$u\bar{u}$, $d\bar{d}$ $\rightarrow$ Z^0 main channels

$u\bar{d}$ $\rightarrow$ W^+ main channel

but all analyses assume flavor-independent Gaussian $k_\perp$ distribution

our work

explore sensitivity of M_W to non-perturbative flavor-dependent $k_\perp$ distribution



Physics Letters B 788 (2019) 542–545
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ELSEVIER

Effect of flavor-dependent partonic transverse momentum on the determination of the W boson mass in hadronic collisions

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P.L. **B788** (19) 542, arXiv:1807.02101

Potential impact on W mass

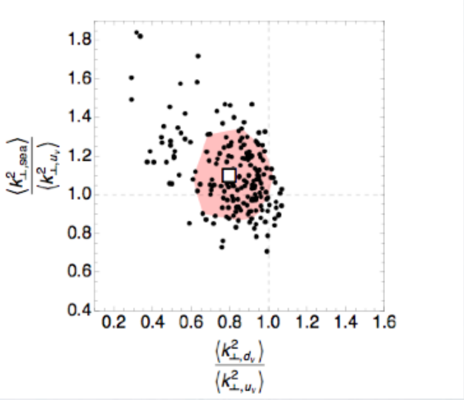
- take the DYRES code and modify the $f_{NP}(x, b_T)$

$$\exp\left[-g_2 b_T^2 \log\frac{Q^2}{Q_0^2}\right] \longrightarrow \exp\left[-\left(g_2 \log\frac{Q^2}{Q_0^2} + g^q\right) b_T^2\right]$$

flavor dependent

range of variation from

Signori et al., JHEP **11** (13) 194, arXiv:1309.3507



flavor independent, ~[0.2-0.4] GeV^2

MAPTMD22 ~ 0.25 , see also

PV 2017 Bacchetta et al., JHEP **06** (17) 081, arXiv:1703.10157

Guzzi et al., P.R. D**90** (14) 014030

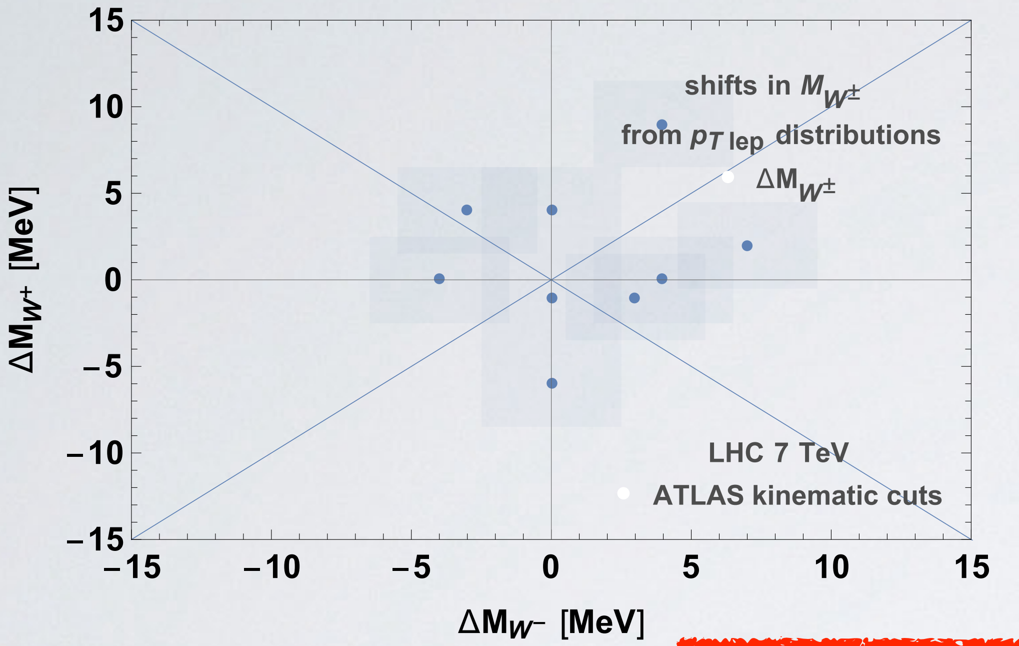
- generate p_T^Z spectrum with g_2 and assigned CDF/ATLAS errors in each bin; generate sets of p_T^Z spectra with $g^q = \{g^{u_v}, g^{d_v}, g^{u_{sea}}, g^{d_{sea}}, g^s\}$ and keep those with global χ^2/d.o.f. < 1.3

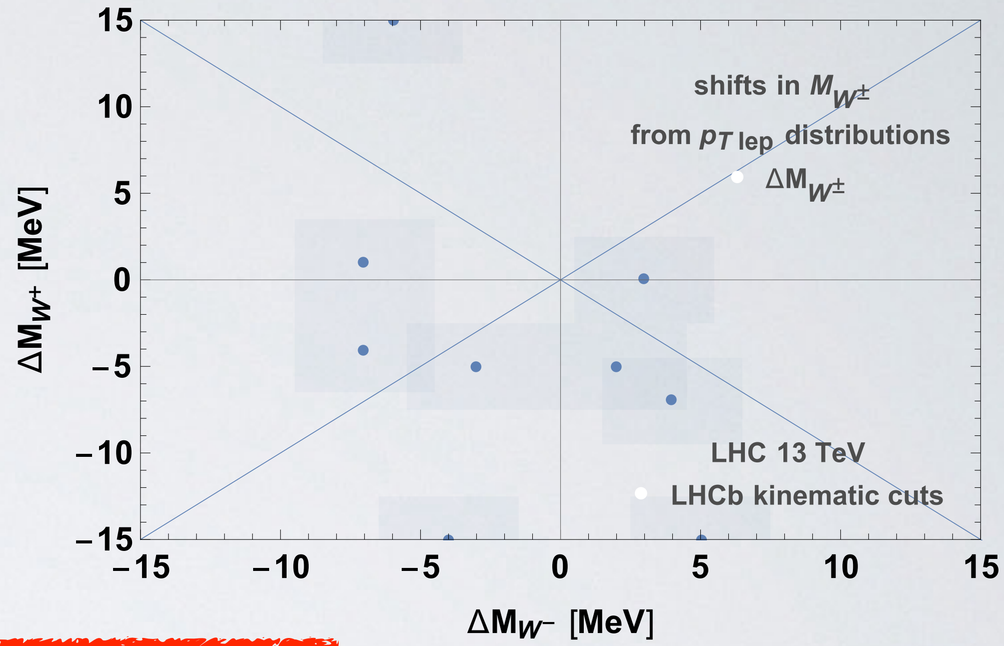
- with these "Z-equivalent" sets, generate pseudodata for lepton p_T distribution at M_W^0 = 80.370 GeV

- with g_2, generate 30 template lepton p_T distributions with M_W in $M_W^0 \pm 0.015$ GeV

- perform template fits for each pseudodata

Potential impact on W mass





$$-6 \leq \Delta M_{W^+} \leq 9$$
$$-4 \leq \Delta M_{W^-} \leq 3$$

significant shifts $\Delta M_{W^+} \neq \Delta M_{W^-}$
of nonperturbative origin

- repeat impact study on extraction of W mass using MAPTMD24 flavor-dependent k_T distributions