EXTRACTION OF FLAVOR DEPENDENCE IN UNPOLARIZED TMDs

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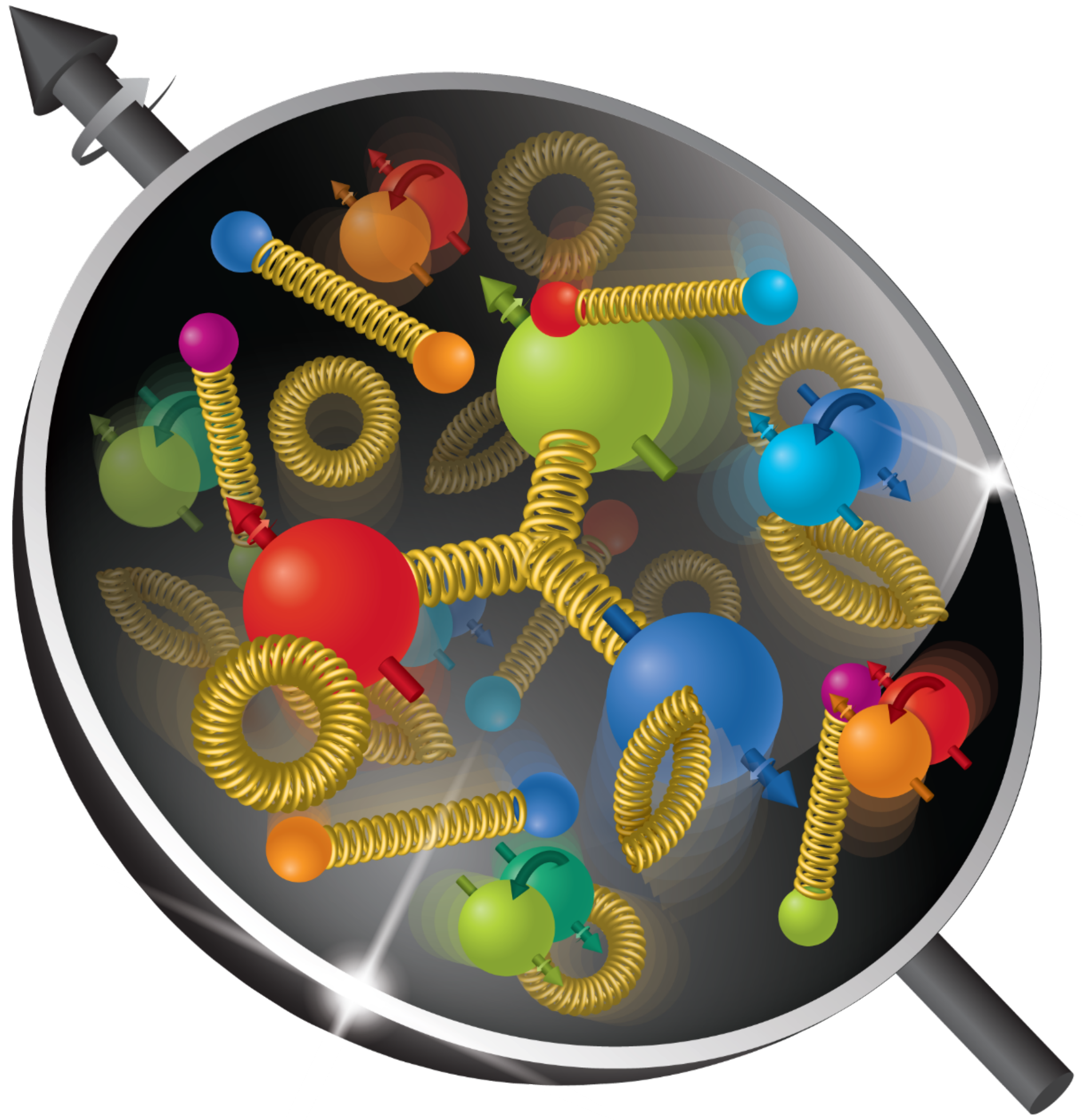
MAP Collaboration

JHEP08(2024)232

(arXiv: 2405.138833)



Flavor separation is a fundamental step to fully explore nucleon structure

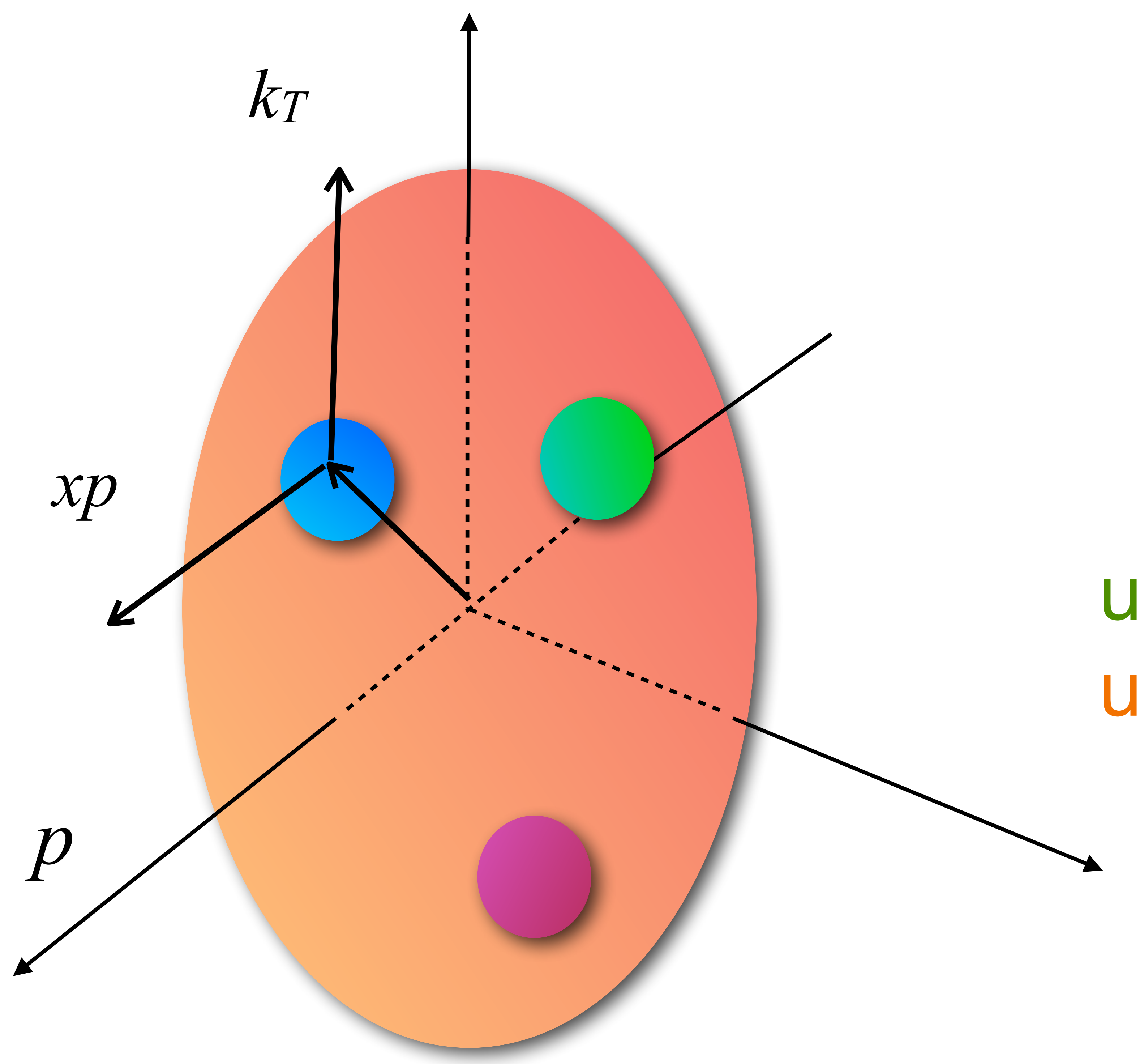
Flavor dependence of unpolarized quark Transverse Momentum Distributions from a global fit

A. Bacchetta, V. Bertone, C. Bissolotti, G. Bozzi, M. Cerutti, FD, M. Radici, L. Rossi, A. Signori

MAP Collaboration JHEP08(2024)232

Transverse Momentum Distributions

3-dimensional map of the internal structure of the nucleon



Universality: same function, multiple processes

(x, kT) dependence

Q2 energy scale evolution

flavor?

unpolarized TMD PDF
unpolarized TMD FF

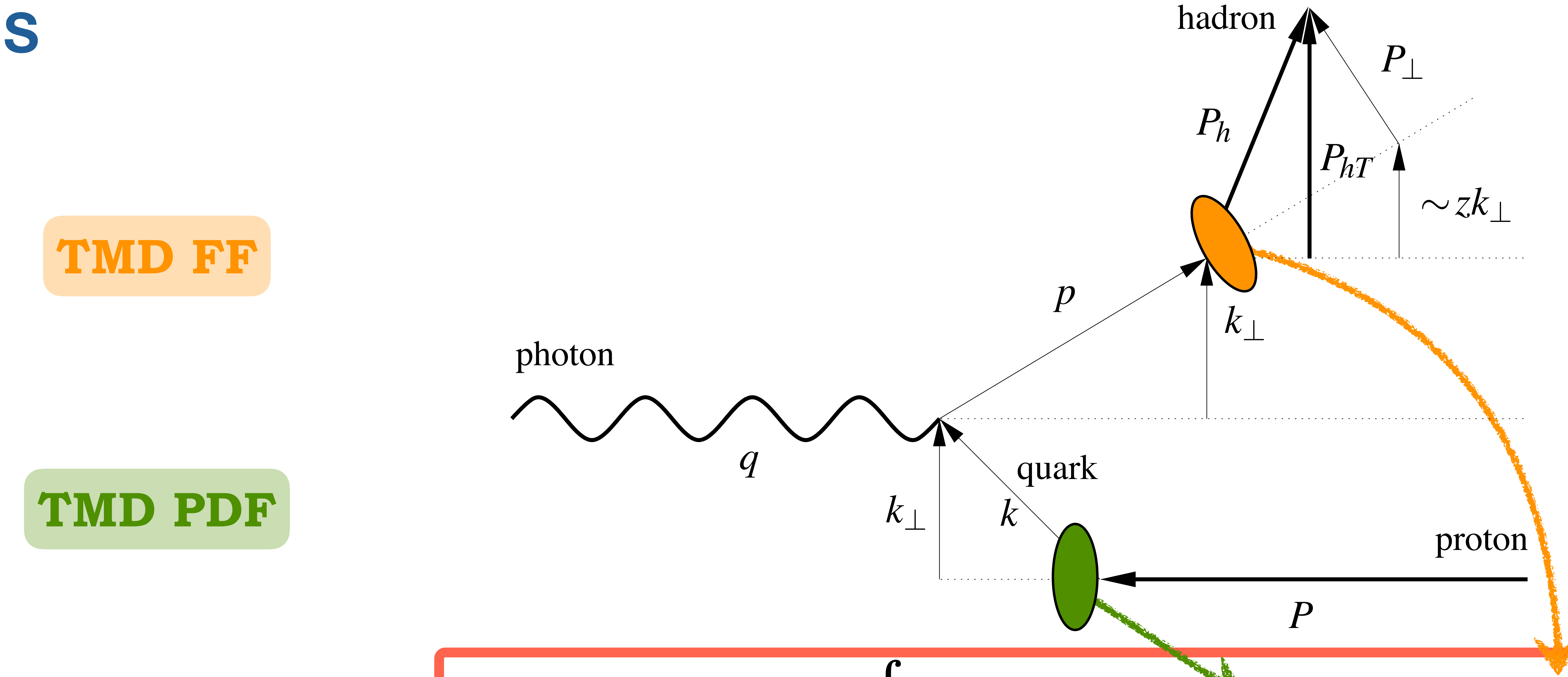
quark pol. (columns) / nucleon pol. (rows)

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

t-odd t-even

TMD formalism: factorization

SIDIS



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

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

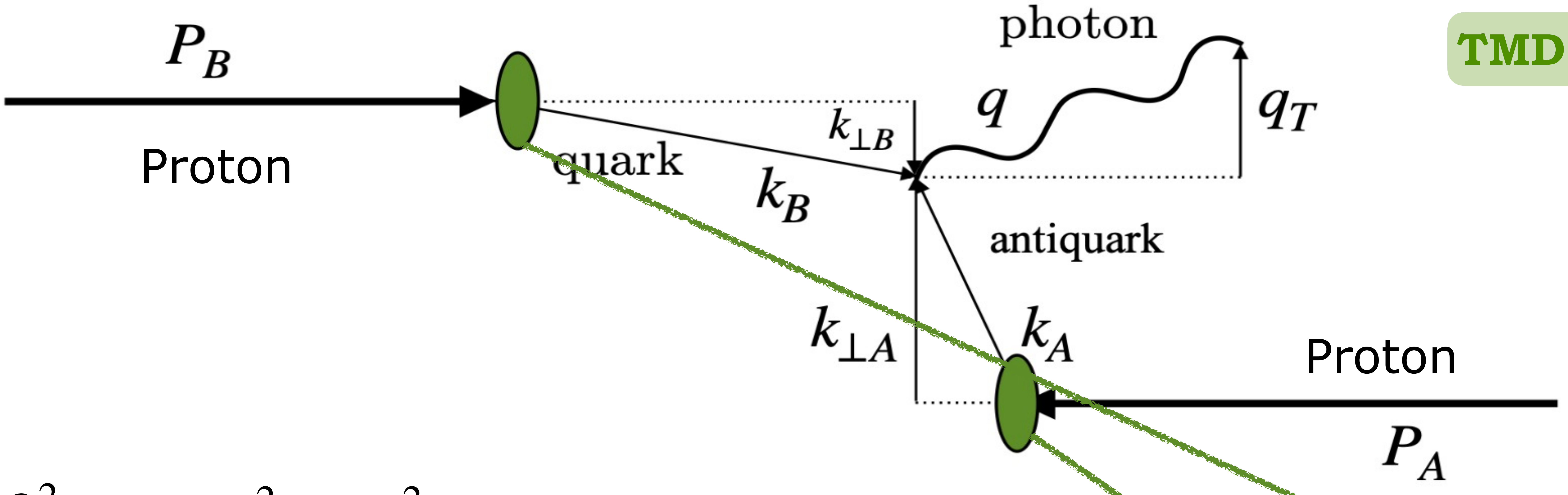
$$+Y_{UU,T}(Q^2,\mathbf{P}_{hT}^2) + \mathcal{O}(M^2/Q^2)$$

W Term

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

TMD formalism: factorization

DY



TMD PDFs

In $q_T^2 \ll Q^2$ and $M^2 \ll Q^2$ region:

$$F_{UU}^1(x_A, x_B, \mathbf{q}_T, Q) = x_A x_B \mathcal{H}^{DY}(Q;\mu) \sum_a c_a(Q^2) \int d|\mathbf{b}_T||\mathbf{b}_T| J_0(|\mathbf{q}_T||\mathbf{b}_T|) \hat{f}_1^a(x_A, \mathbf{b}_T^2; \mu, \zeta_A) \hat{f}_1^b(x_B, \mathbf{b}_T^2; \mu, \zeta_B)$$

W term

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

TMD factorization: TMD components

TMD in Fourier space

b$_*$-prescription

$$\hat{F}(x, b_T^2; \mu, \zeta) = \int \frac{d^2\boldsymbol{k}_\perp}{(2\pi)^2} e^{i\boldsymbol{b}_T \cdot \boldsymbol{k}_\perp} F(x, k_\perp^2; \mu, \zeta)$$

Collinear extractions

$$\hat{f}_1^q(x, b_T^2; \mu, \zeta) = \sum_j C_{q/j}(x, b_*; \mu_{b_*}, \mu_{b_*}^2) \otimes f_1^j(x, \mu_{b_*}) \quad : \text{A}$$

Perturbative TMD at the initial scale

Perturbative

$$\times \exp\left\{ K(b_*; \mu_{b_*}) \ln \frac{\sqrt{\zeta}}{\mu_{b_*}} + \int_{\mu_{b_*}}^{\mu} \frac{d\mu'}{\mu'} \left[\gamma_F - \gamma_K \ln \frac{\sqrt{\zeta}}{\mu'} \right] \right\} \quad : \text{B}$$

Evolution to final energy scale of the process

$$\times f_{NP}(x, b_T^2) \exp\left\{ g_K(b_T^2) \ln \frac{\sqrt{\zeta}}{\sqrt{\zeta_0}} \right\} \quad : \text{C}$$

Non-perturbative part of the TMD

Parametrization

TO BE FITTED

Collins, "Foundations of Perturbative QCD"

Nanga Parbat: a MAP fit framework

README GPL-3.0 license

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

Available global fits

DY + SIDIS

	Accuracy	Ndata	χ^2/Ndata
PV 17 Bacchetta, Delcarro et al. JHEP 06 (2017)	NLL	8059	1.55
SV 2019 Scimemi, Vladimirov JHEP 06 (2020)	N^3LL^-	1039	1.06
MAPTMD22 Bacchetta, Bertone et al. JHEP 10 (2022)	N^3LL^-	2031	1.06

Flavor independent

Our starting point: MAPTMD22 FI global fit

Flavor independent

Global fit: DY + SIDIS

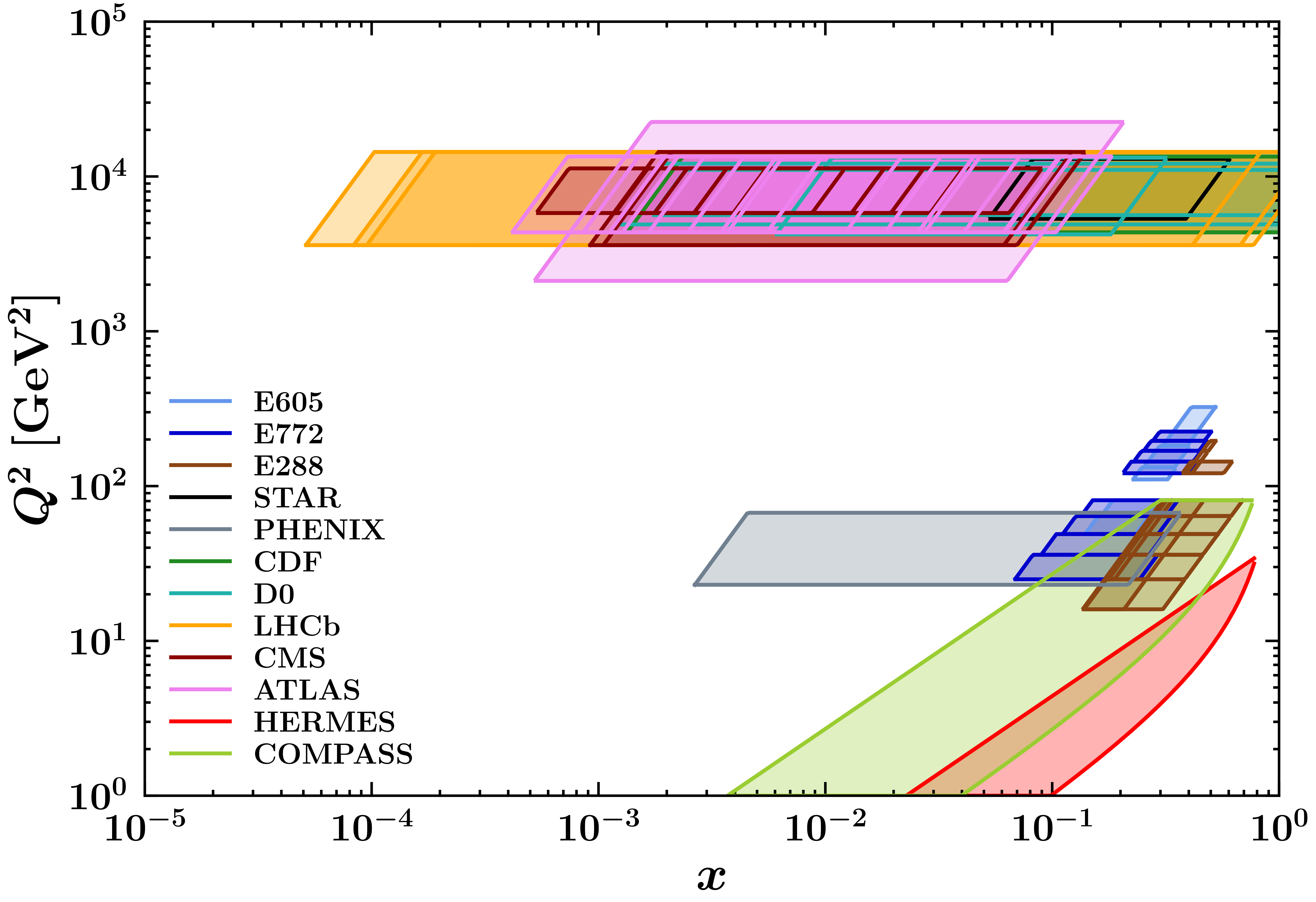
2031 data points

DY data

484

SIDIS data

1547



MAPTMD22 FI global fit

2031 data points

Perturbative accuracy: N^3LL^-

$$L = \ln\left(\frac{\mu^2}{\mu_b^2}\right)$$

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

PDF: MMHT2014nnlo

FF: DSS14-17 NLO

[Bacchetta, Bertone, Bissolotti, et al., JHEP 07 (2020)
TMD handbook, Boussarie, et al., 2023

MAPTMD22 parametrisation

$$f_{NP}(x, b_T^2) \exp\left\{ g_K(b_T^2) \ln \frac{\sqrt{\zeta}}{\sqrt{\zeta_0}} \right\}$$

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

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

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

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

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

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

MAPTMD22 summary

- Global fit of DY and SIDIS data: ***2031*** data points
- ***Normalization*** of SIDIS multiplicities beyond NLL
- Number of fitted parameters: ***21***
- Perturbative accuracy: ***N^3LL^-***

Really good description: $\chi^2/N_{\text{data}} = 1.06$

MAPTMD22 improvement: MAPTMD24

- Global fit of DY and SIDIS data: ***2031*** data points → Same data sets

- ***Normalization*** of SIDIS multiplicities beyond NLL → Same approach

- Number of fitted parameters: ***21*** → Same parametrisation (Still flavour independent)

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- Perturbative accuracy: ***full N^{3}LL***

PDF: MMHT2014nnlo → ***NNPDF31NNLO***
FF: DSS14-17 → ***MAPFF10NNLO***

R. Abdul Khalek, V. Bertone, E. R. Nocera et al., PLB 834 (2022) 137456

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- Not as good description: $\chi^2/N_{data} = 1.40$

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Improved framework but worse description. WHY?

MAPTMD* χ2 comparison

TMD extraction	collinear configuration	χ2 /Ndata		
		DY	SIDIS	Total
MAPTMD22	MMHT+DSS	1.66	0.87	1.06
MAPTMD24 FI	NNPDF+MAPFF	1.58	1.34	1.40

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SIDIS: convolution of TMD PDF x **FF**

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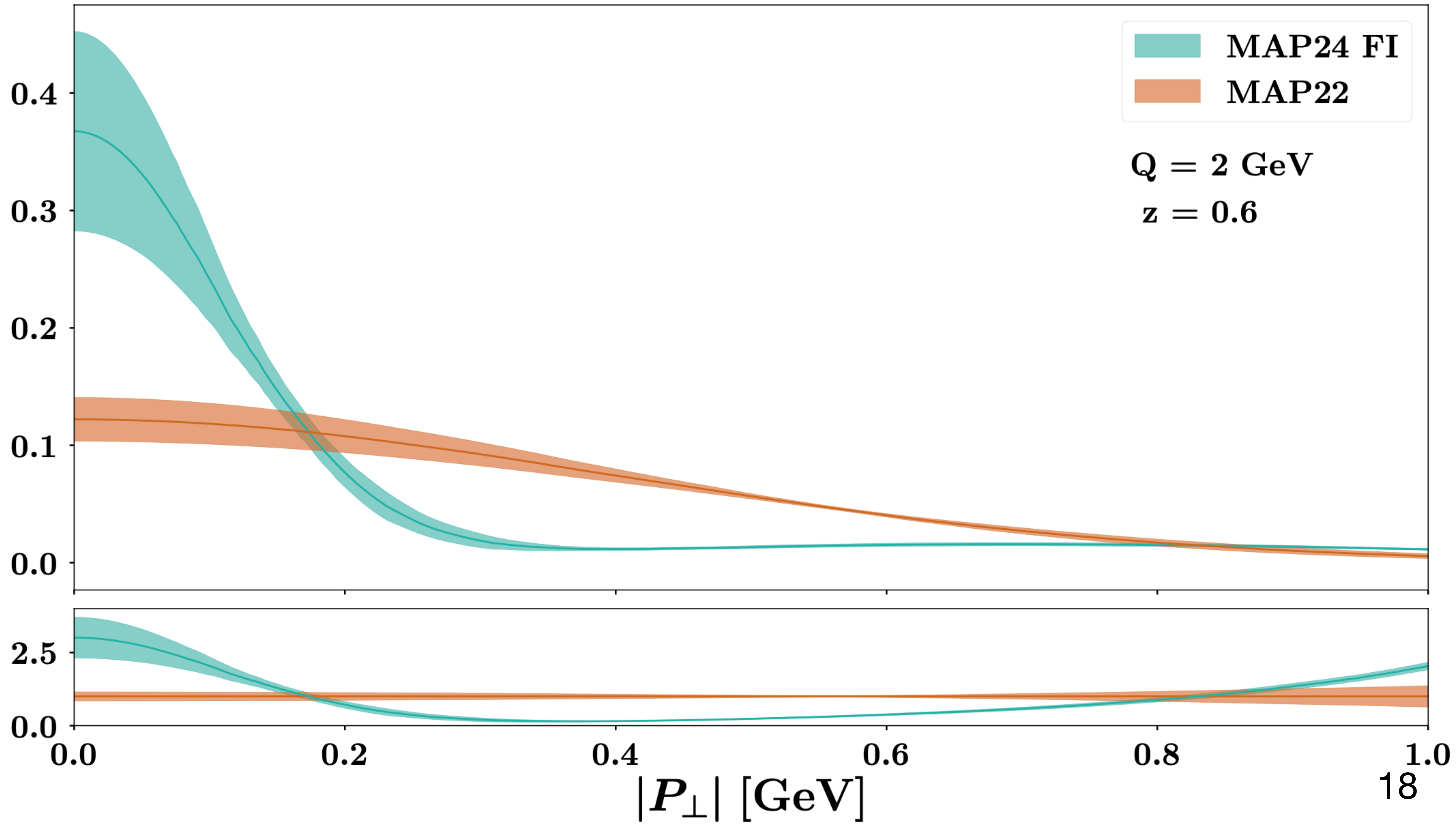

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MAPFF1.0nnlo

- NNLO
- NN approach
- new behavior
- smaller uncertainties

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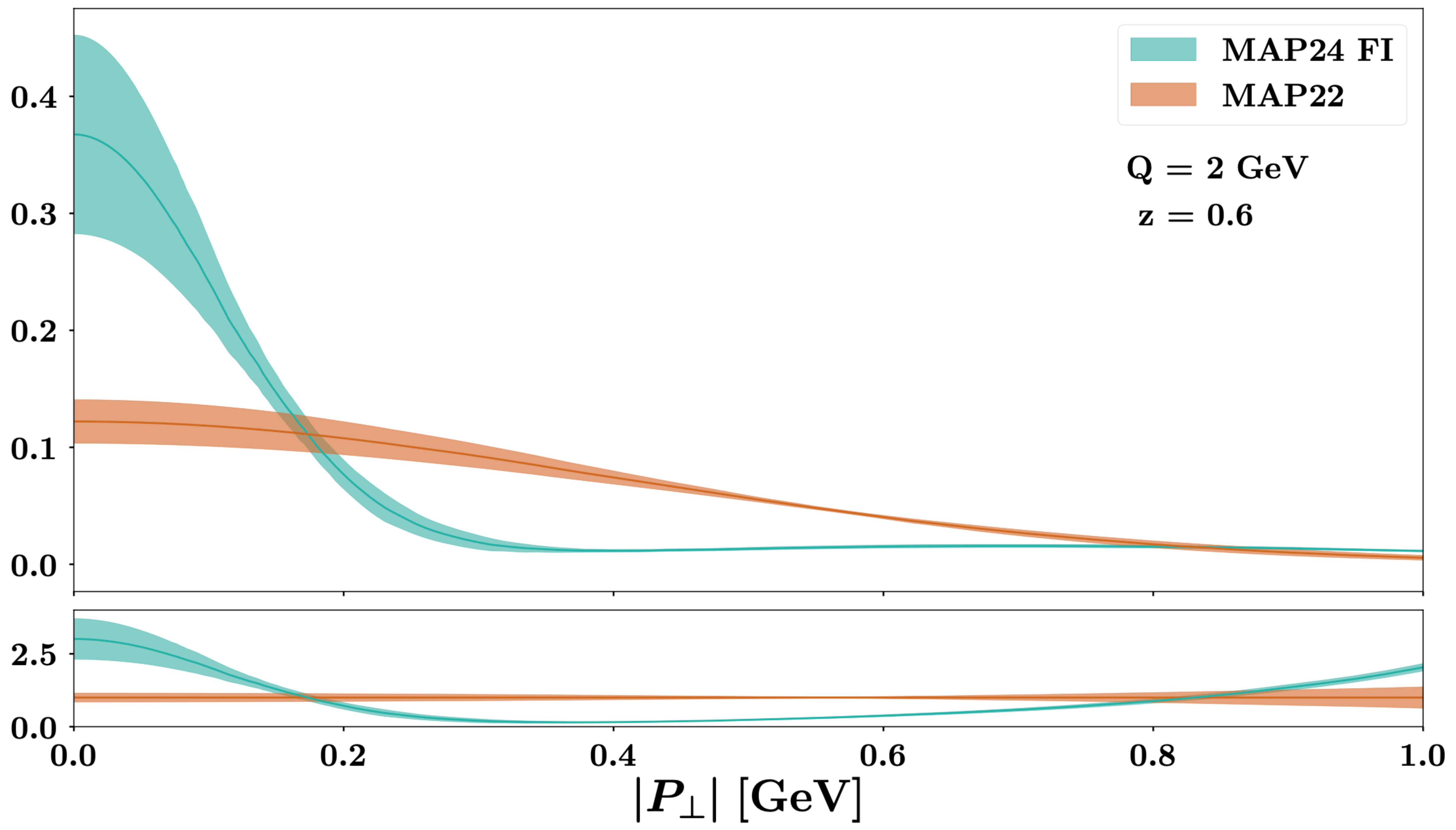

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MAPTMD24 collinear configurations

Data set	N_{dat}	$\chi_0^2/N_{\mathrm{dat}}$
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

2405.13833

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HERMES total	344	0.95
COMPASS total	1203	0.88
SIDIS total	1547	0.90
Total	2031	1.07

NNPDF + DSS

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 (MAP22)

2405.13833

MAPTMD24 collinear configurations

Data set	N_{dat}	χ_0^2/N_{dat}
DY collider total	251	2.14
Dy fixed target total	233	0.6[illegible]
HERMES total	344	2.7[illegible]
COMPASS total	1203	0.9[illegible]
SIDIS total	1547	1.3[illegible]
Total	2031	1.3[illegible]

NNPDF + MAPFF

Data set	N_{dat}	χ_0^2/N_{dat}
DY collider total	251	2.01
D[illegible] fixed target total	233	1.11
[illegible]RMES total	344	2.51
[illegible]MPASS total	1203	0.99
[illegible]IS total	1547	1.33
[illegible]al	2031	1.39

MMHT + MAPFF

Data set	N_{dat}	χ_0^2/N[illegible]
DY collider total	251	2.4[illegible]
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

[illegible]a set	N_{dat}	χ_0^2/N_{dat}
[illegible] 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 (MAP22)

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MAPTMD24: included processes

SIDIS

hermes

$$e + p \rightarrow e' + \pi^+ + X$$
$$e + p \rightarrow e' + \pi^- + X$$
$$e + p \rightarrow e' + K^+ + X$$
$$e + p \rightarrow e' + K^- + X$$

+ D target

SIDIS

COMPASS

D target, unidentified final state h

Drell-Yan

$q\bar{q}$ *in the initial state*

MAPTMD24: included processes

SIDIS

hermes

$$e + p \rightarrow e' + \pi^+ + X$$
$$e + p \rightarrow e' + \pi^- + X$$
$$e + p \rightarrow e' + K^+ + X$$
$$e + p \rightarrow e' + K^- + X$$

+ D target

HIGH sensitivity to flavor dependence

SIDIS

COMPASS 25 years 1997 - 2022

D target, unidentified final state h

LOW sensitivity to flavor dependence

Drell-Yan

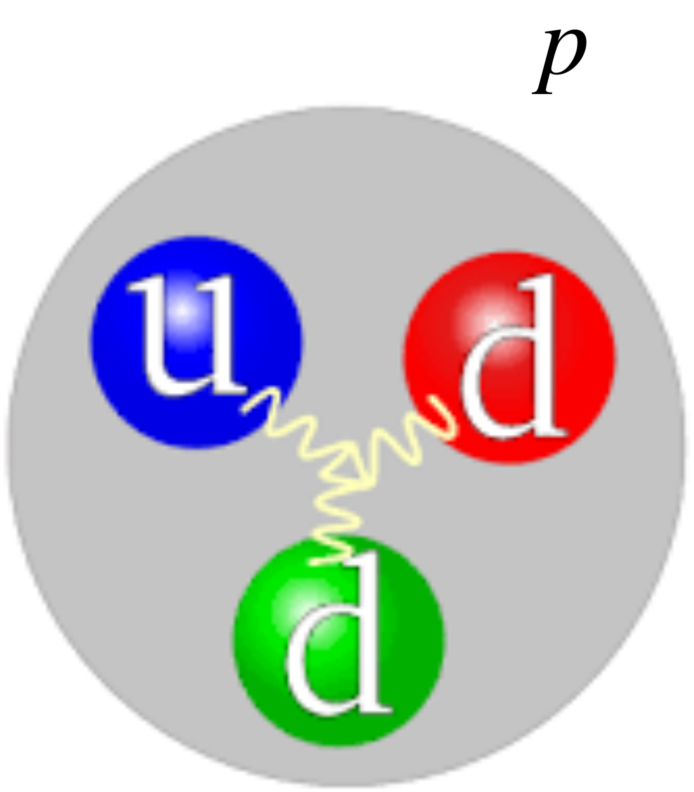
$q\bar{q}$ *in the initial state*

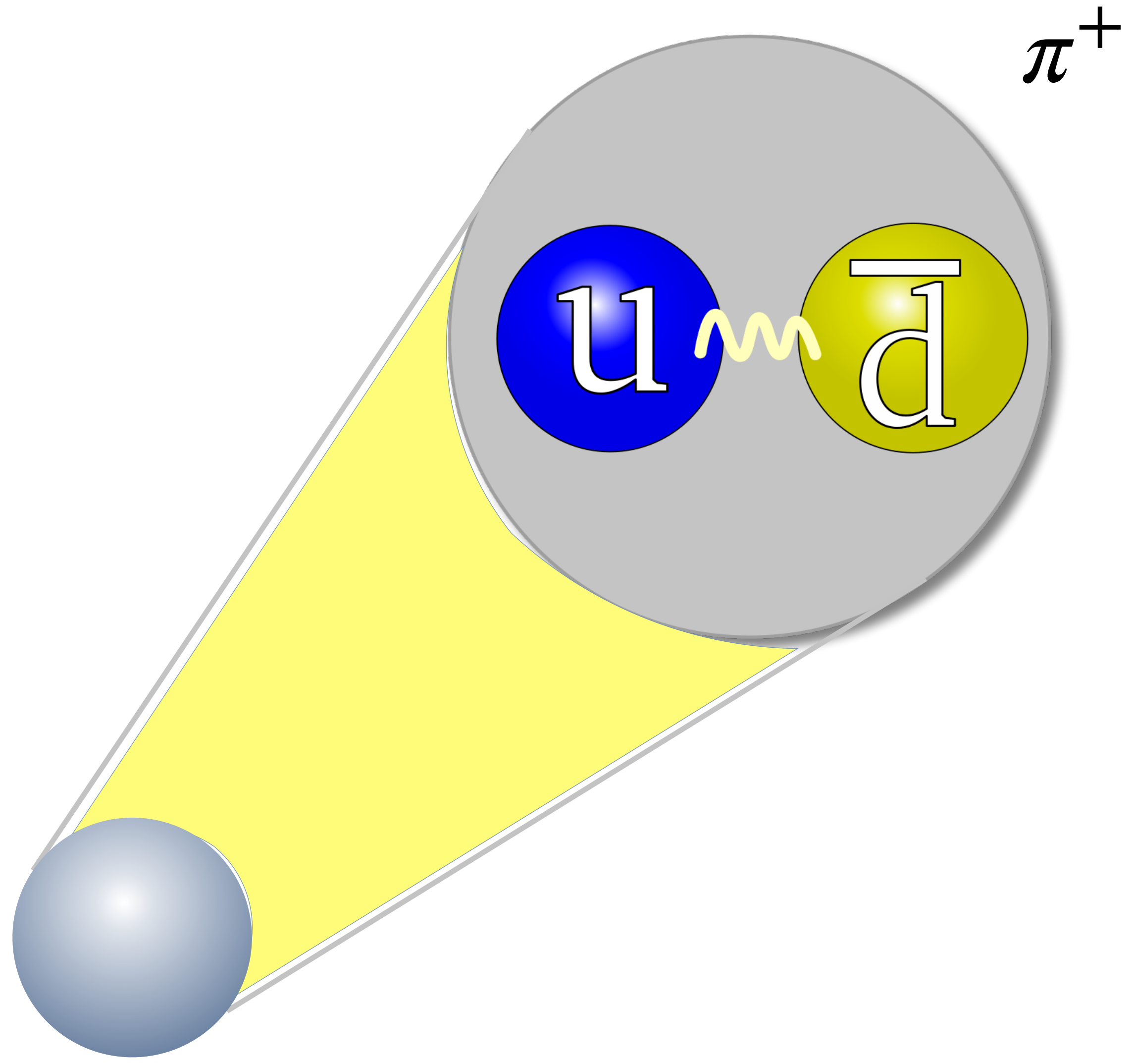
MAPTMD24: need for flavor

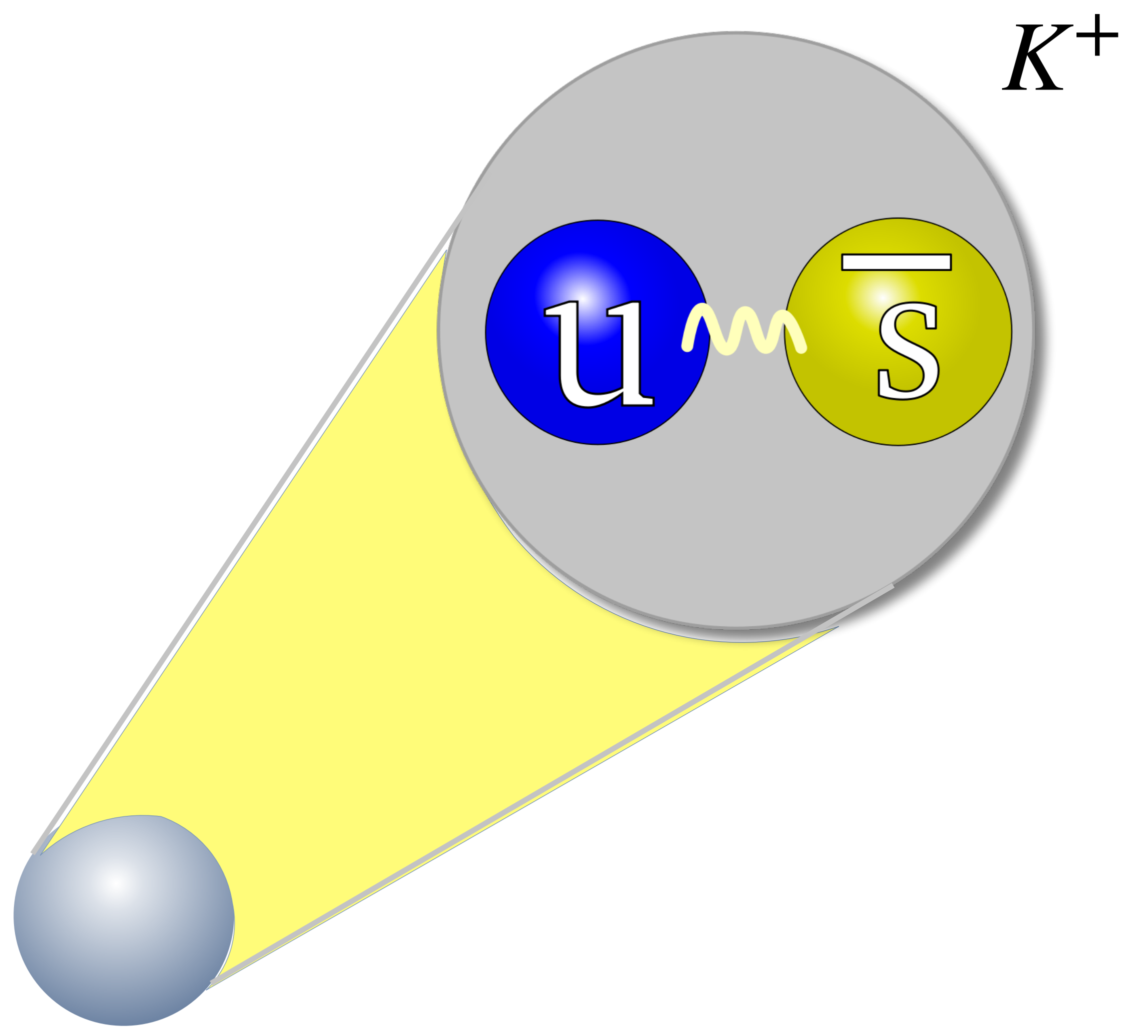
Statement: introducing new FFs highlighted a tension between theory and SIDIS data.

A possible solution is to introduce flavor dependence

MAPTMD24 flavor parametrization







u, d

$\bar{u}, \bar{d}$

$s\ (sea)$

$u \to \pi^+, \ldots$

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

$u \to K^+, \ldots$

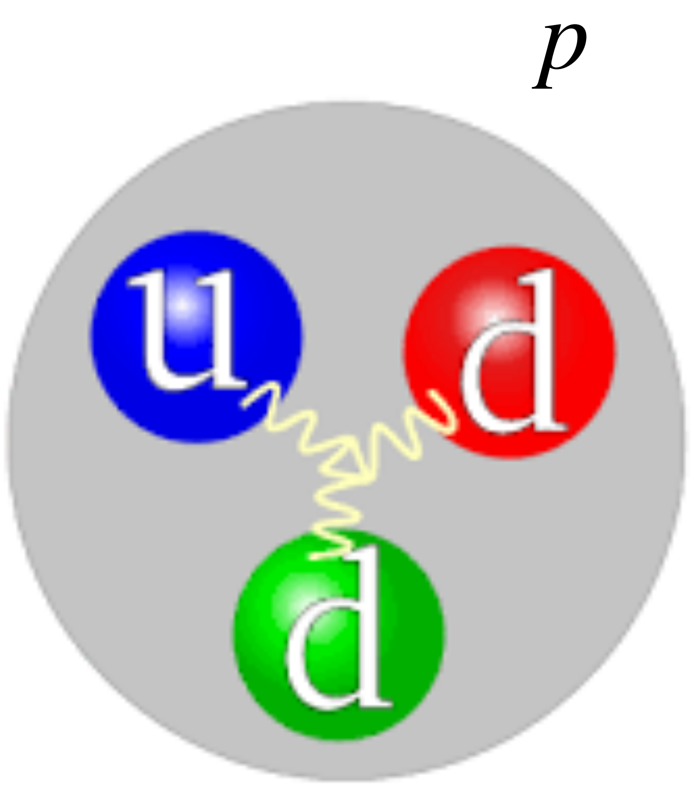
$\bar{s} \to K^+, \ldots$

$d \to K^+, \ldots$

Negative fragmenting mesons: charge conjugation

MAPTMD24 flavor parametrization

Same parametrisation as MAPTMD22 but…



PDF: 5 sets of parameters

$$u, d, \ \bar{u}, \bar{d}, sea$$

FF: 5 sets of parameters

*favored and unfavored **pion** fragmentation;*

*favored, unfavored and s-quark **kaon** fragmentation*

(10x5) parameters for TMD PDF
+ (9x5) for TMD FF
+ 1 for NP evolution
= **96** free parameters

MAPTMD24 extraction - Results

	N^3LL			
Data set	N_{dat}	χ^2_D	χ^2_λ	χ^2_0
DY collider total	251	1.37	0.28	1.65
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**

$$\chi^2/N_{data} = 1.08$$

$$\chi^2_0 = \chi^2_D + \chi^2_\lambda$$

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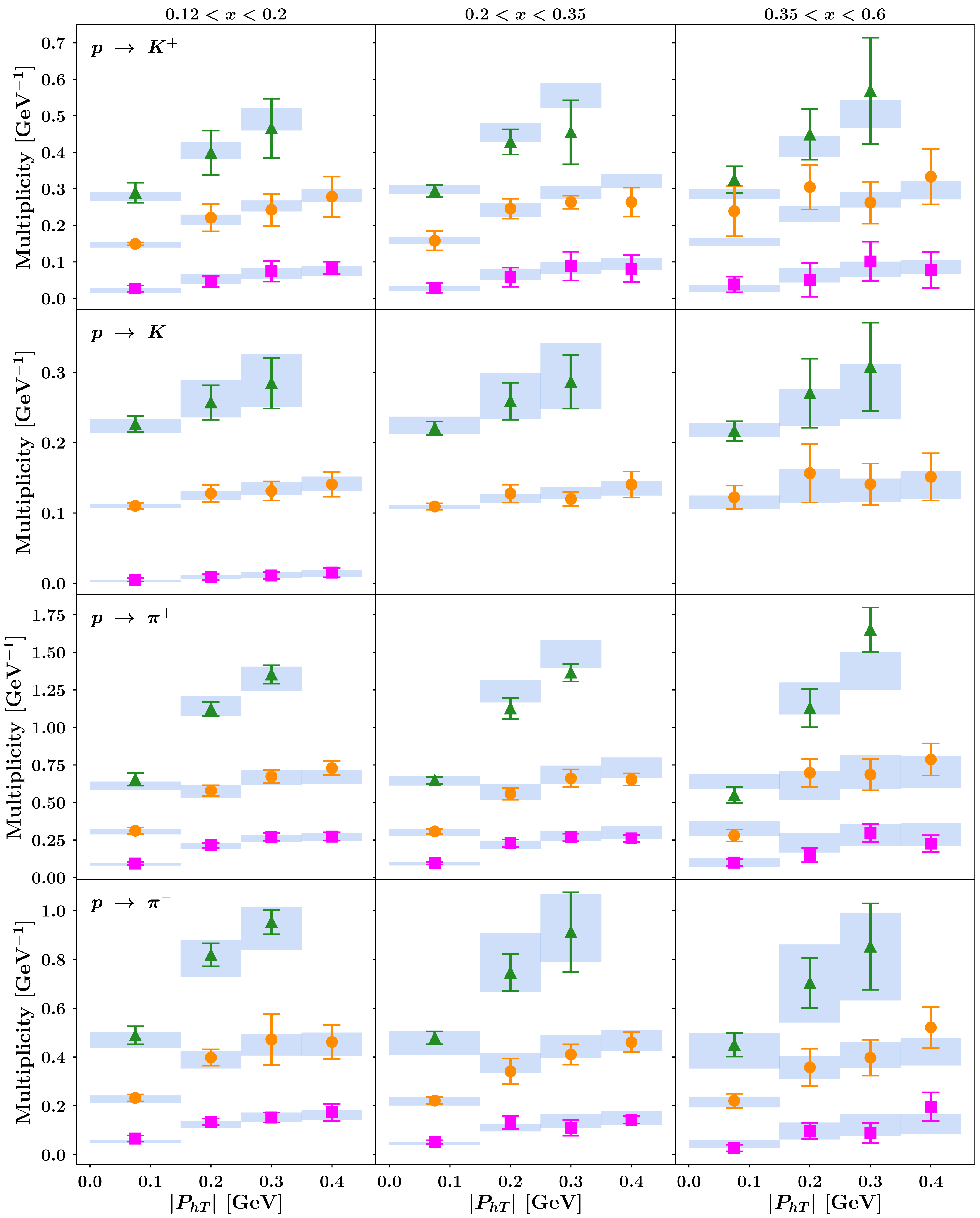
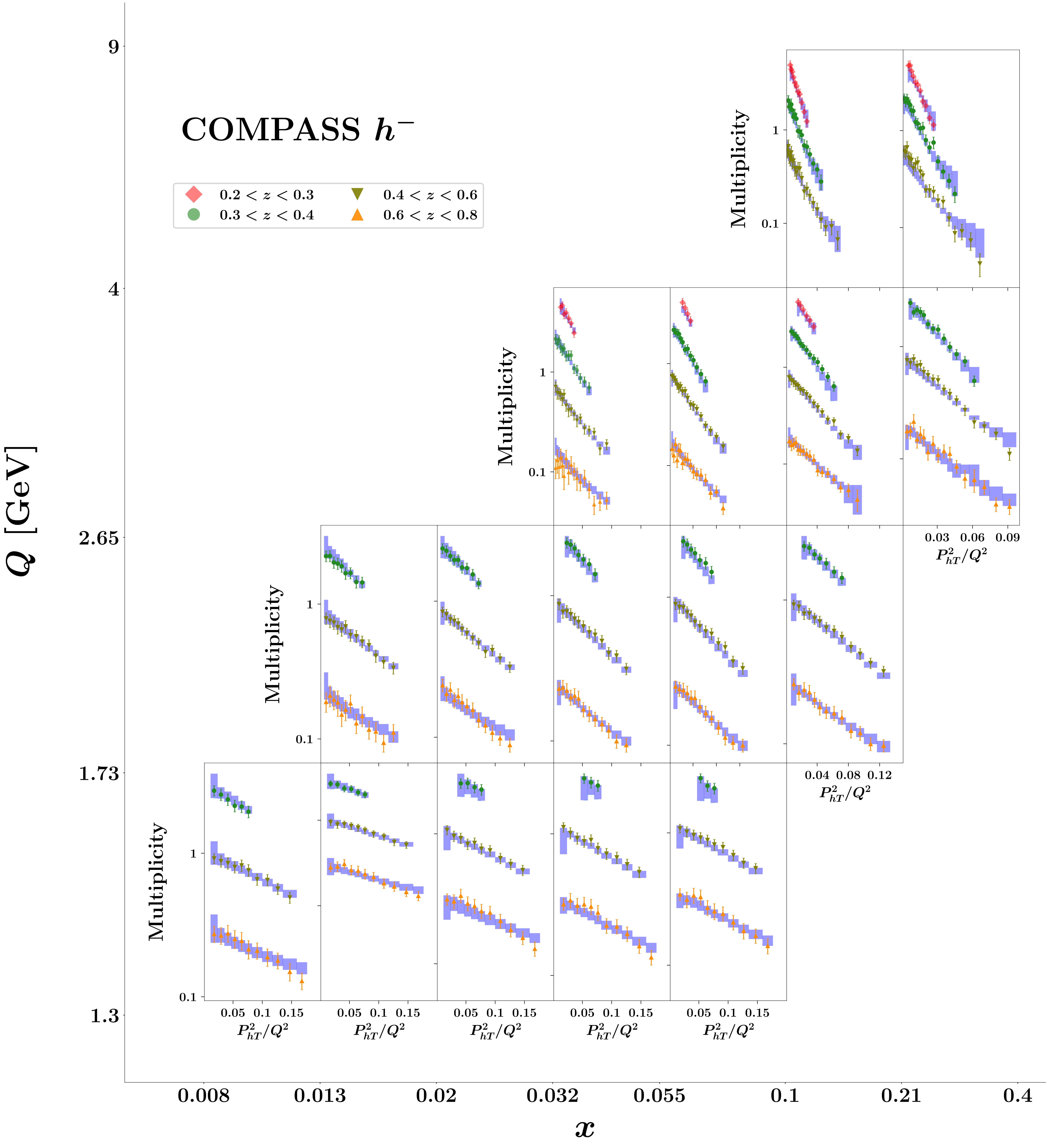
MAPTMD24 - Results

	N^3LL			
Data set	N_{dat}	χ^2_D	χ^2_λ	χ^2_0
DY collider total	251	1.37	0.28	1.65
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 - Results

	N^3LL			
Data set	N_{dat}	χ_D^2	χ_λ^2	χ_0^2
DY collider total	251	1.37	0.28	1.65
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 - Results

	N^3LL			
Data set	N_{dat}	χ^2_D	χ^2_λ	χ^2_0
DY collider total	251	1.37	0.28	1.65
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**

SIDIS data: really good agreement

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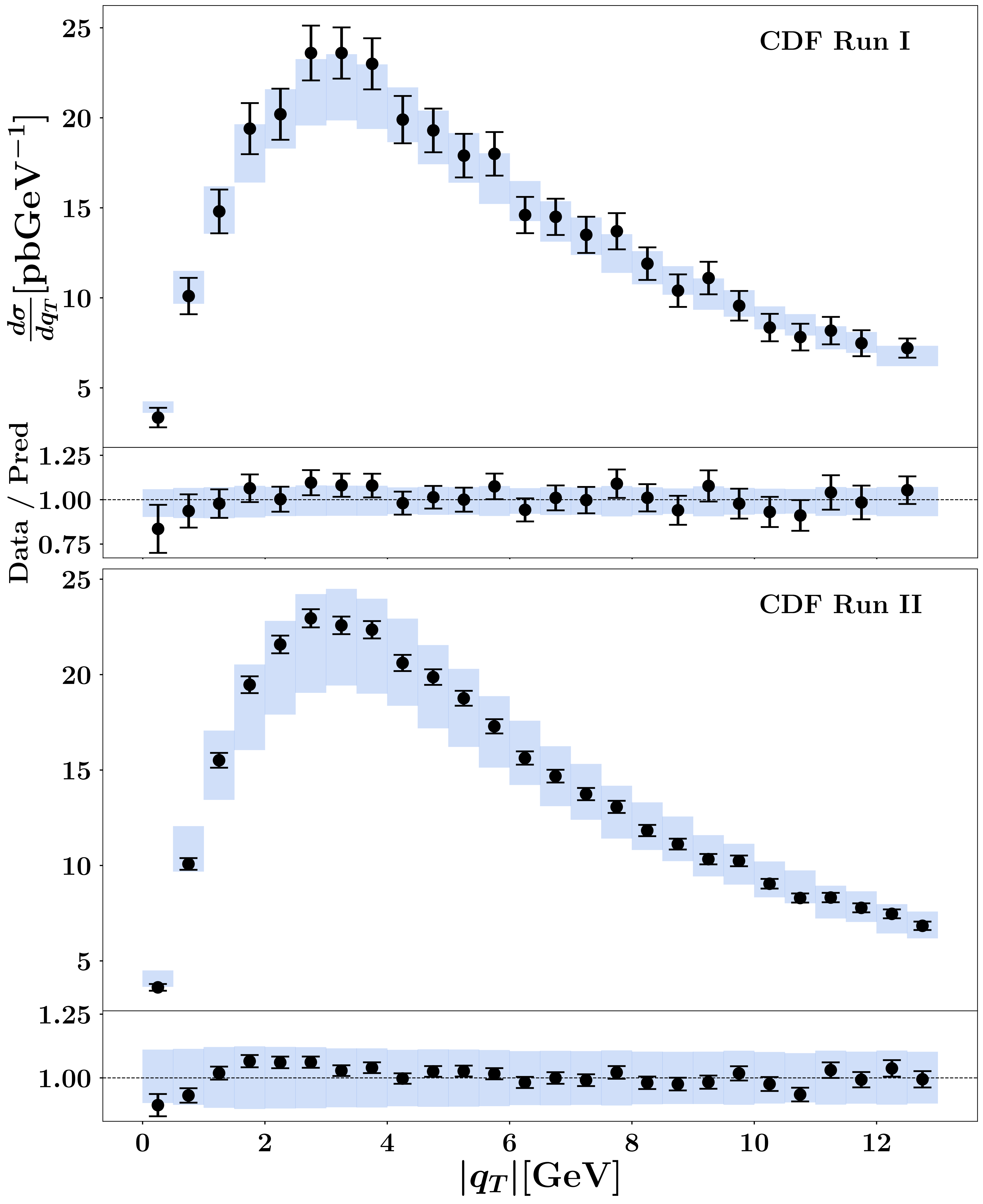
MAPTMD24 - Results

	N^3LL			
Data set	N_{dat}	χ^2_D	χ^2_λ	χ^2_0
DY collider total	251	1.37	0.28	1.65
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**

E288 E772 E605

DY fixed: still really good agreement



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MAPTMD24 - Results

	N^3LL			
Data set	N_{dat}	χ^2_D	χ^2_λ	χ^2_0
DY collider total	251	1.37	0.28	1.65
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**

Tevatron

LHCb

CMS

STAR 510

Atlas

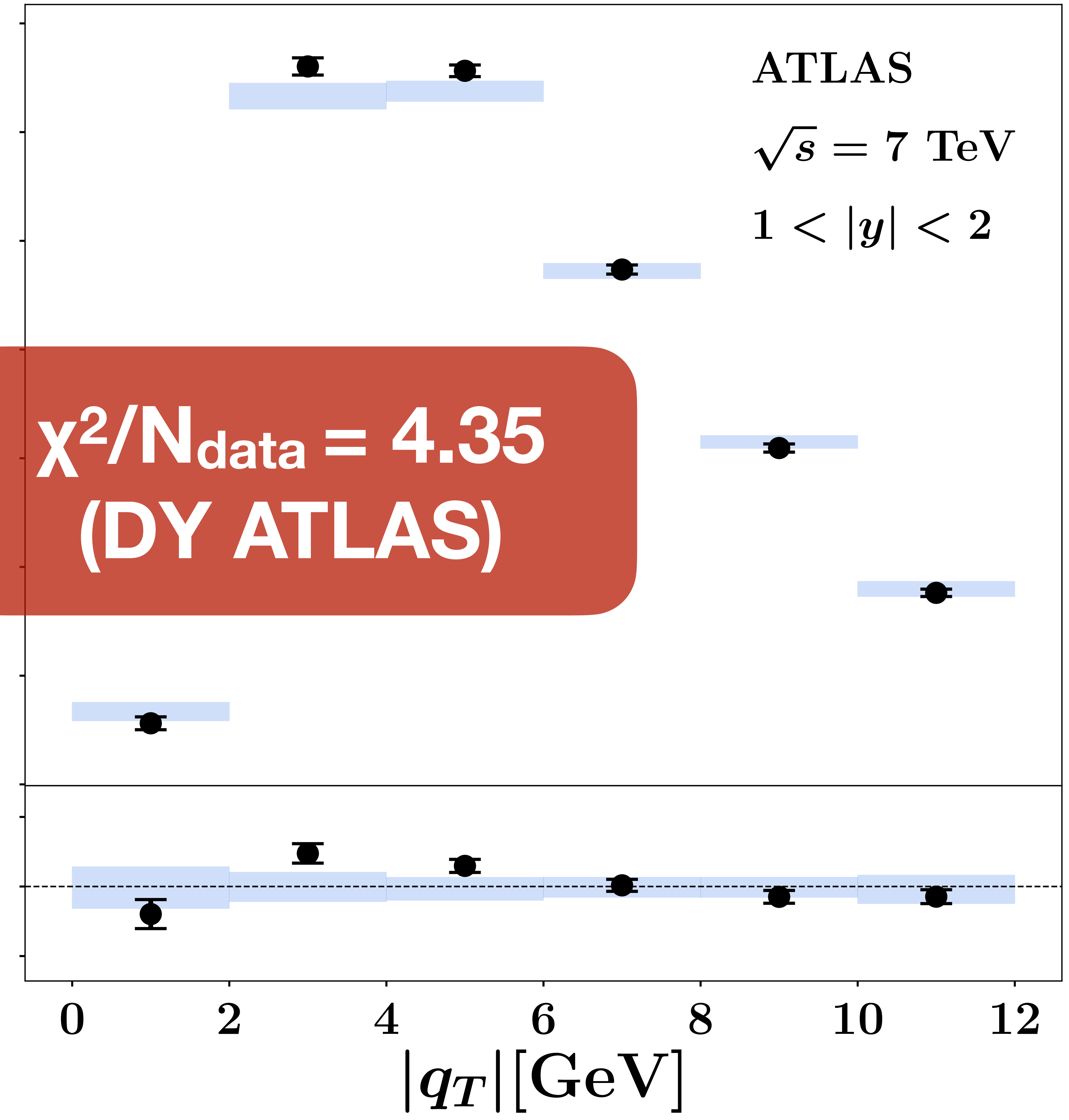
PHENIX 200

DY collider: quite good agreement

2405.13833

MAPTMD24 - Results

	N^3LL			
Data set	N_{dat}	χ^2_D	χ^2_λ	χ^2_0
DY collider total	251	1.37	0.28	1.65
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**



$\chi^2/N_{data} = 4.35$ (DY ATLAS)

DY collider: quite good agreement

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MAPTMD24 - Results

Flavor-dependent TMD PDFs

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MAPTMD24 - TMD PDF

2405.13833

MAPTMD24 - TMD PDF

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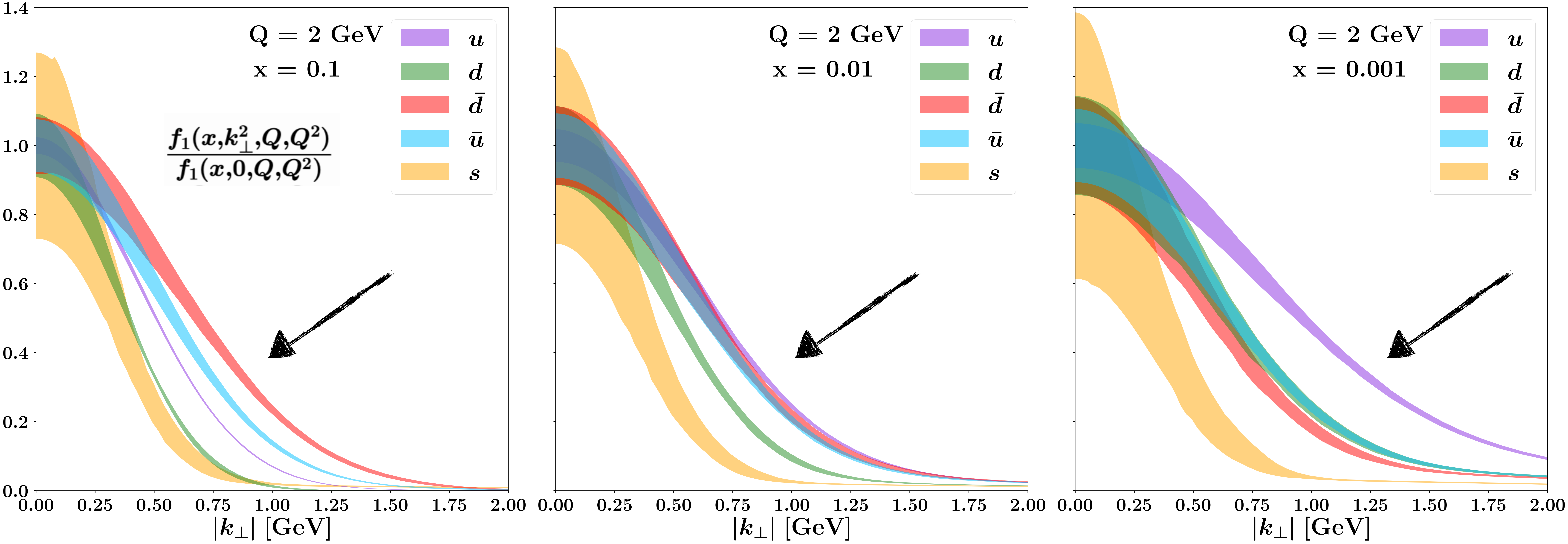
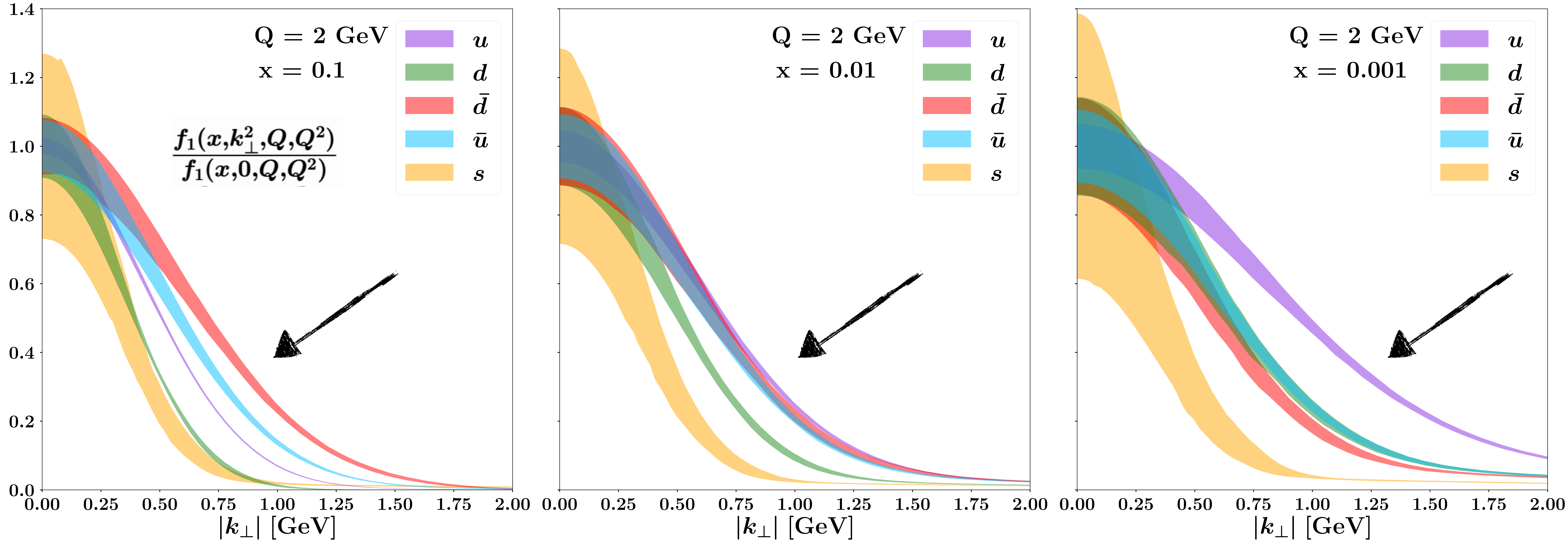
MAPTMD24 - TMD PDF



Very different $k_\perp$ - behaviours!

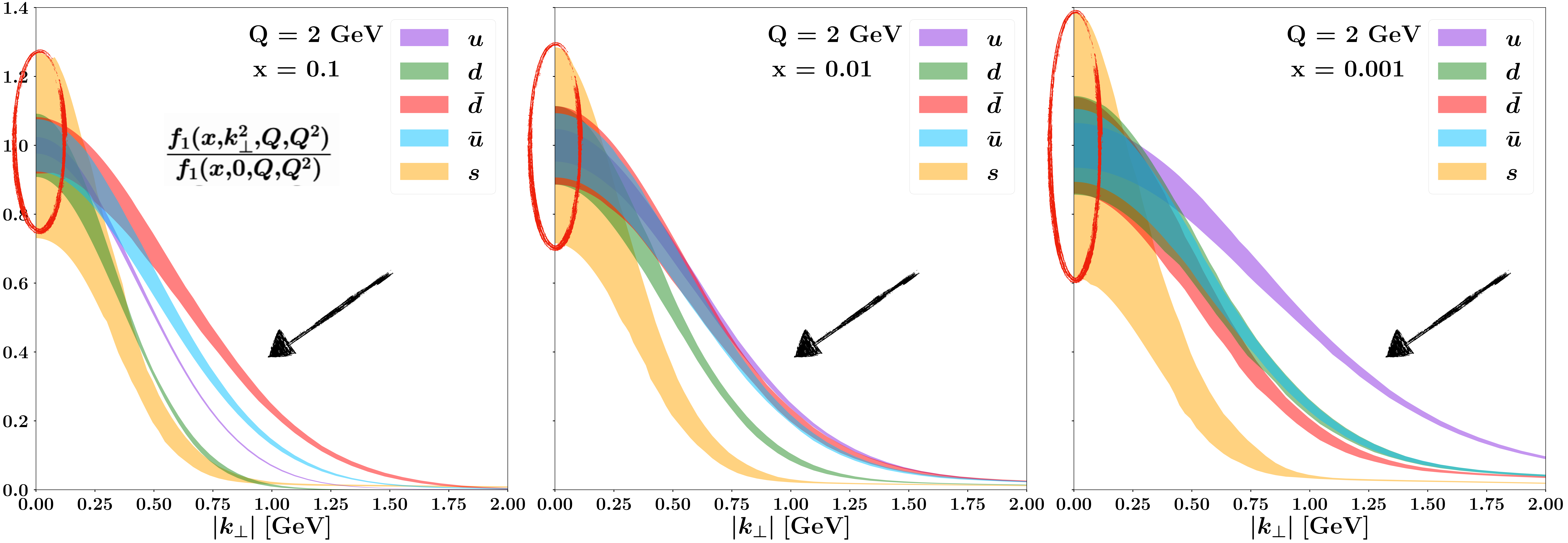
MAPTMD24 - TMD PDF



Very different $k_\perp$- behaviours! → **It also changes with x**

2405.13833

MAPTMD24 - TMD PDF

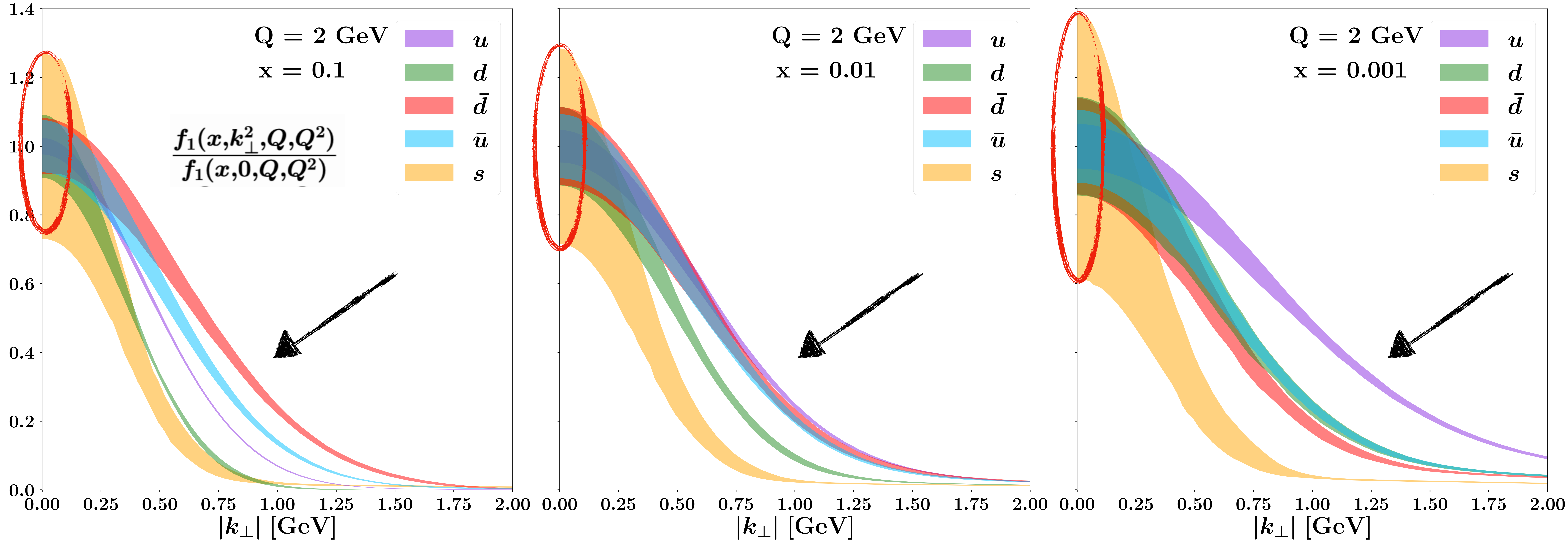


Very different $k_\perp$- behaviours! → **It also changes with x**

2405.13833

MAPTMD24 - TMD PDF

The sea is the least constrained

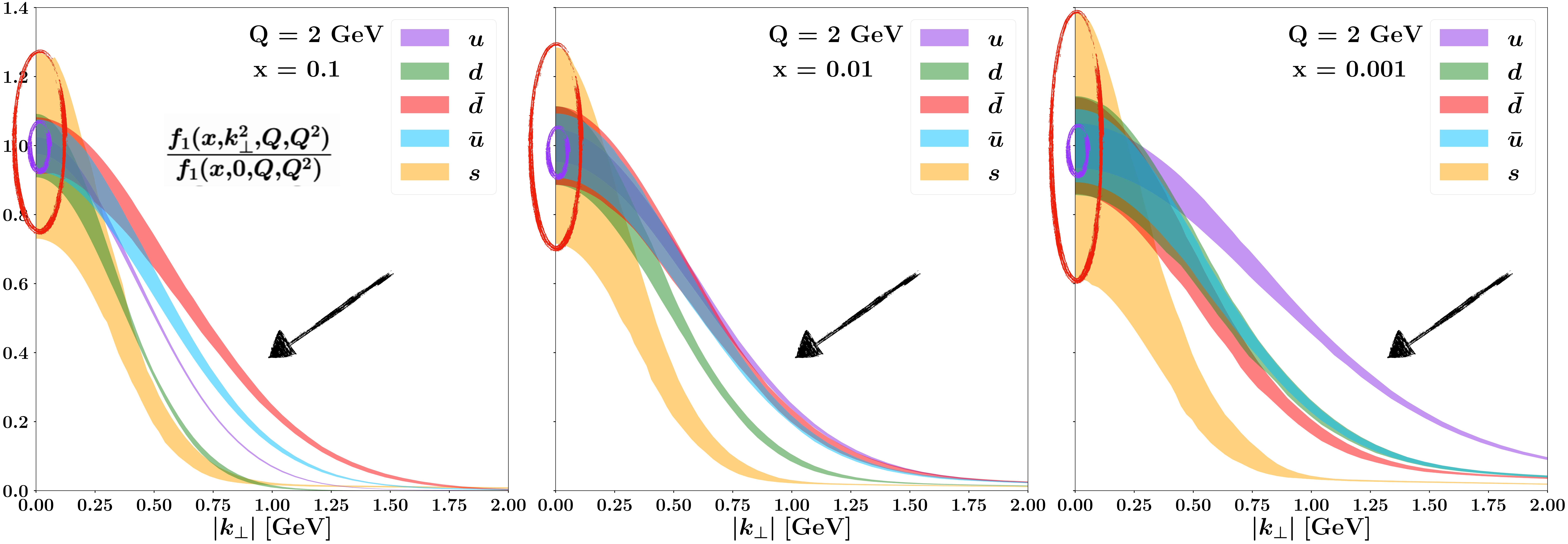


Very different $k_\perp$- behaviours! → ***It also changes with x***

2405.13833

MAPTMD24 - TMD PDF

The sea is the least constrained

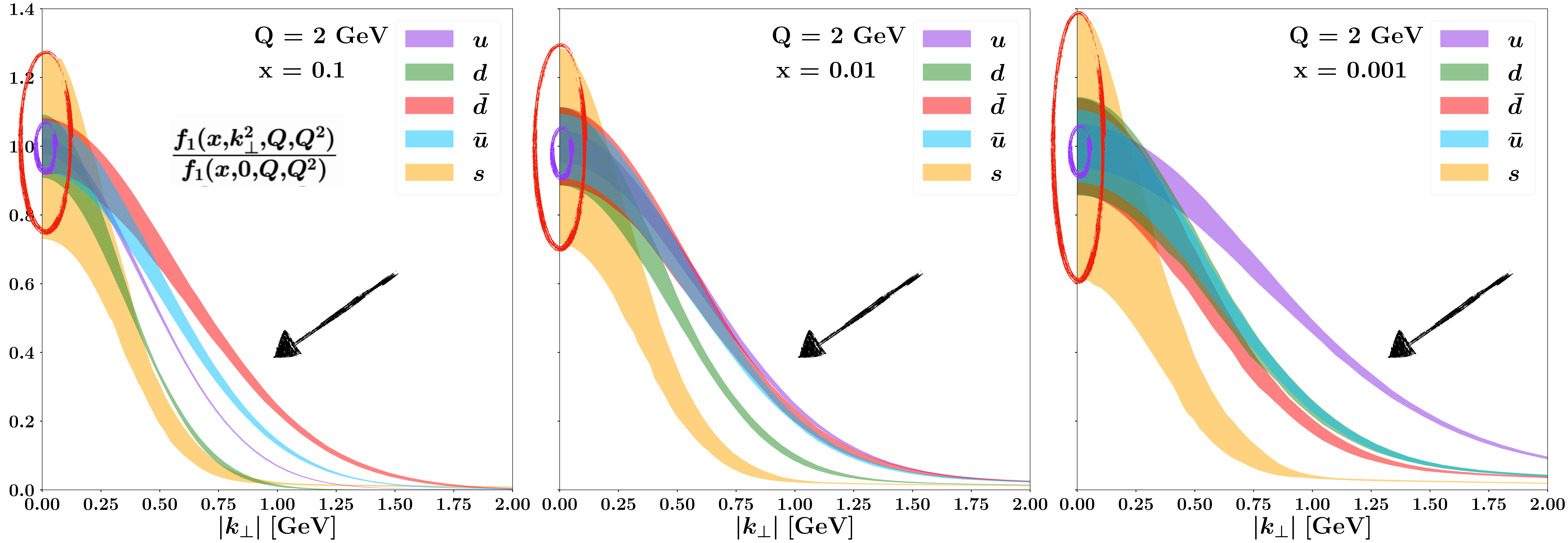


Very different $k_\perp$- behaviours! → ***It also changes with x***

2405.13833

MAPTMD24 - TMD PDF

The sea is the least constrained ↔ ***The up quark is the most constrained***



Very different $k_\perp$- behaviours! → ***It also changes with x***

2405.13833

MAPTMD24 - TMD FF

MAPTMD24 - TMD FF

MAPTMD24 - TMD FF

$$\frac{D_1^{\to\pi^+}(z,P_\perp^2,Q,Q^2)}{D_1^{\to\pi^+}(z,0,Q,Q^2)}$$

The favored is better constrained than the unfavored one

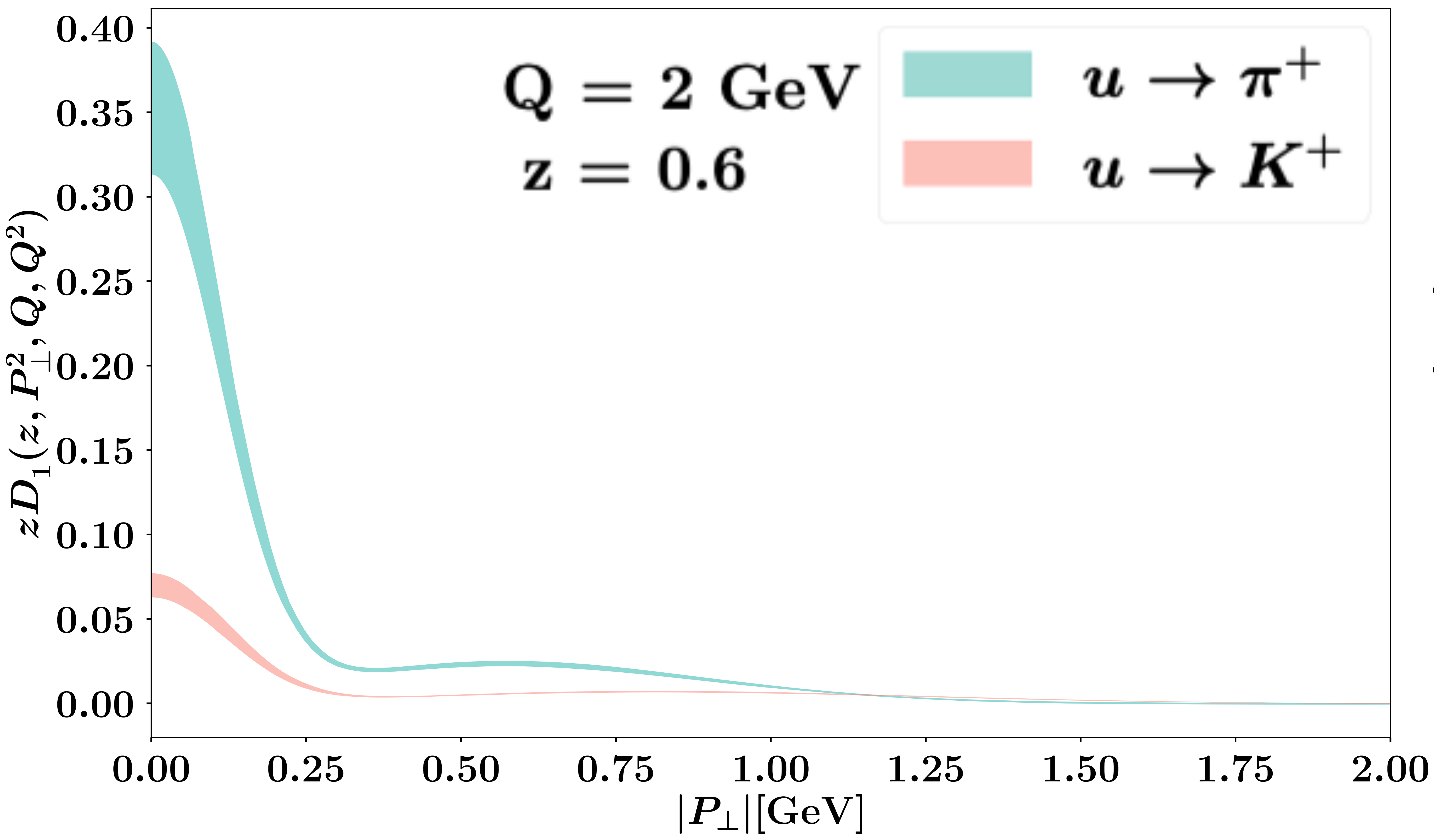
MAPTMD24 - TMD FF

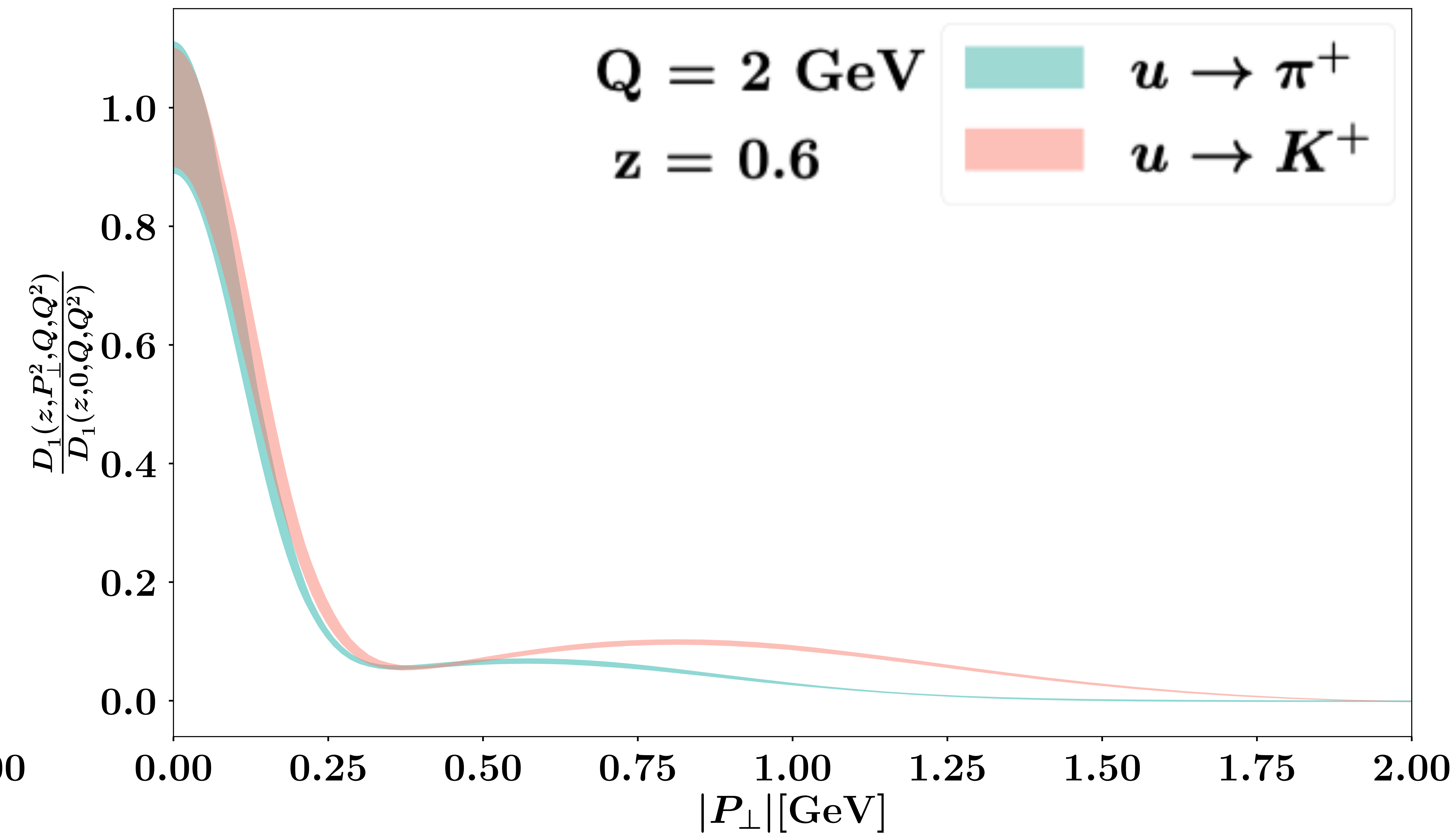
$$\frac{D_1^{\to\pi^+}(z,P_\perp^2,Q,Q^2)}{D_1^{\to\pi^+}(z,0,Q,Q^2)}$$

The favored is better constrained than the unfavored one

Some signals of differences between favoured and unfavored channels

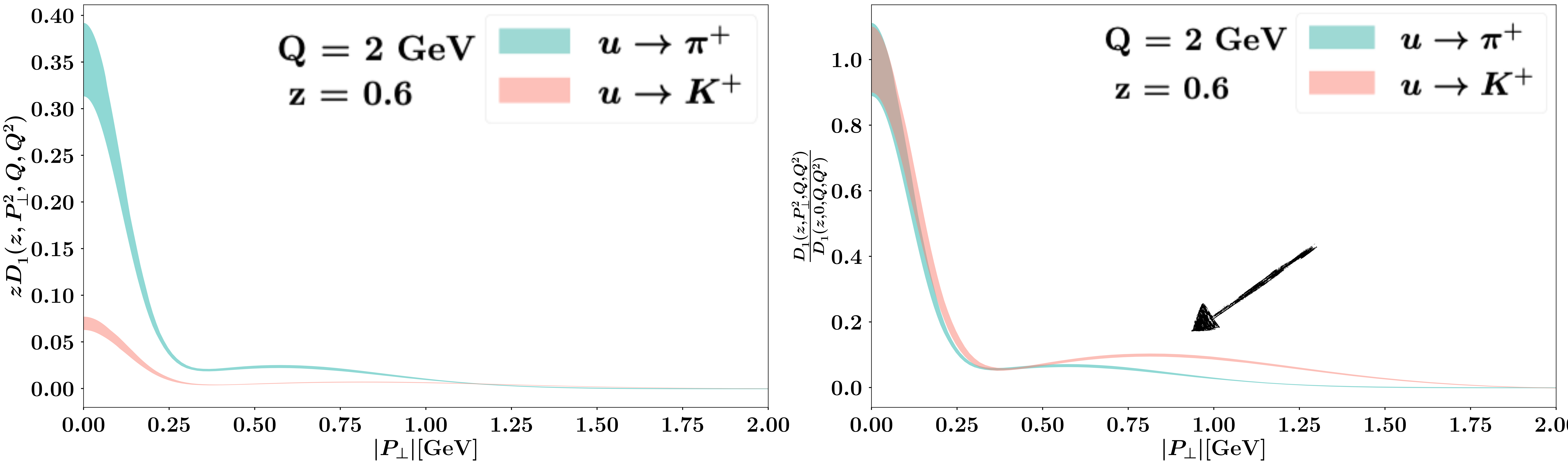
MAPTMD24 - TMD FF





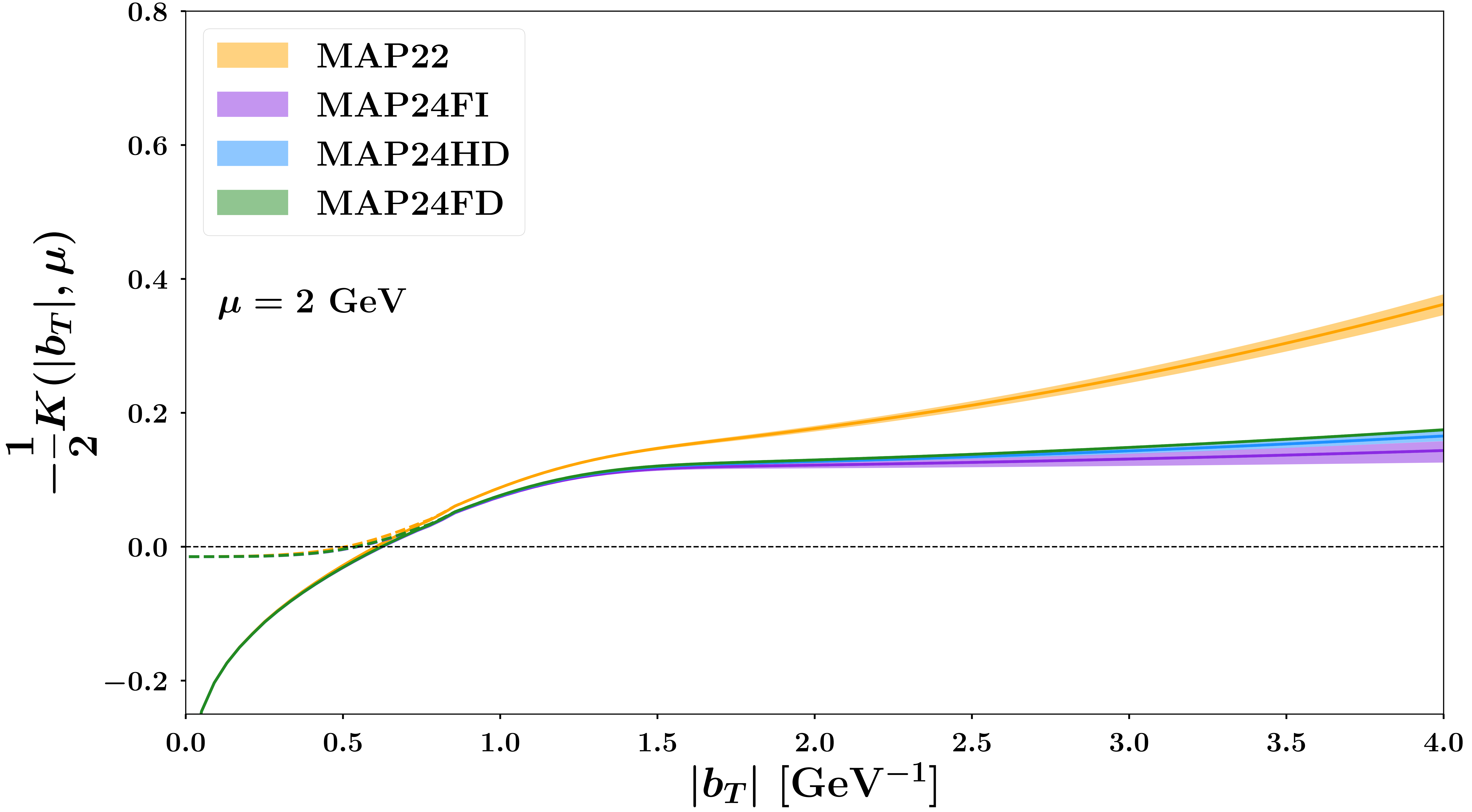
MAPTMD24 - TMD FF

MAPTMD24 - TMD FF



Strong differences between different hadron fragmentations!

MAPTMD24 evolution - Collins-Soper kernel



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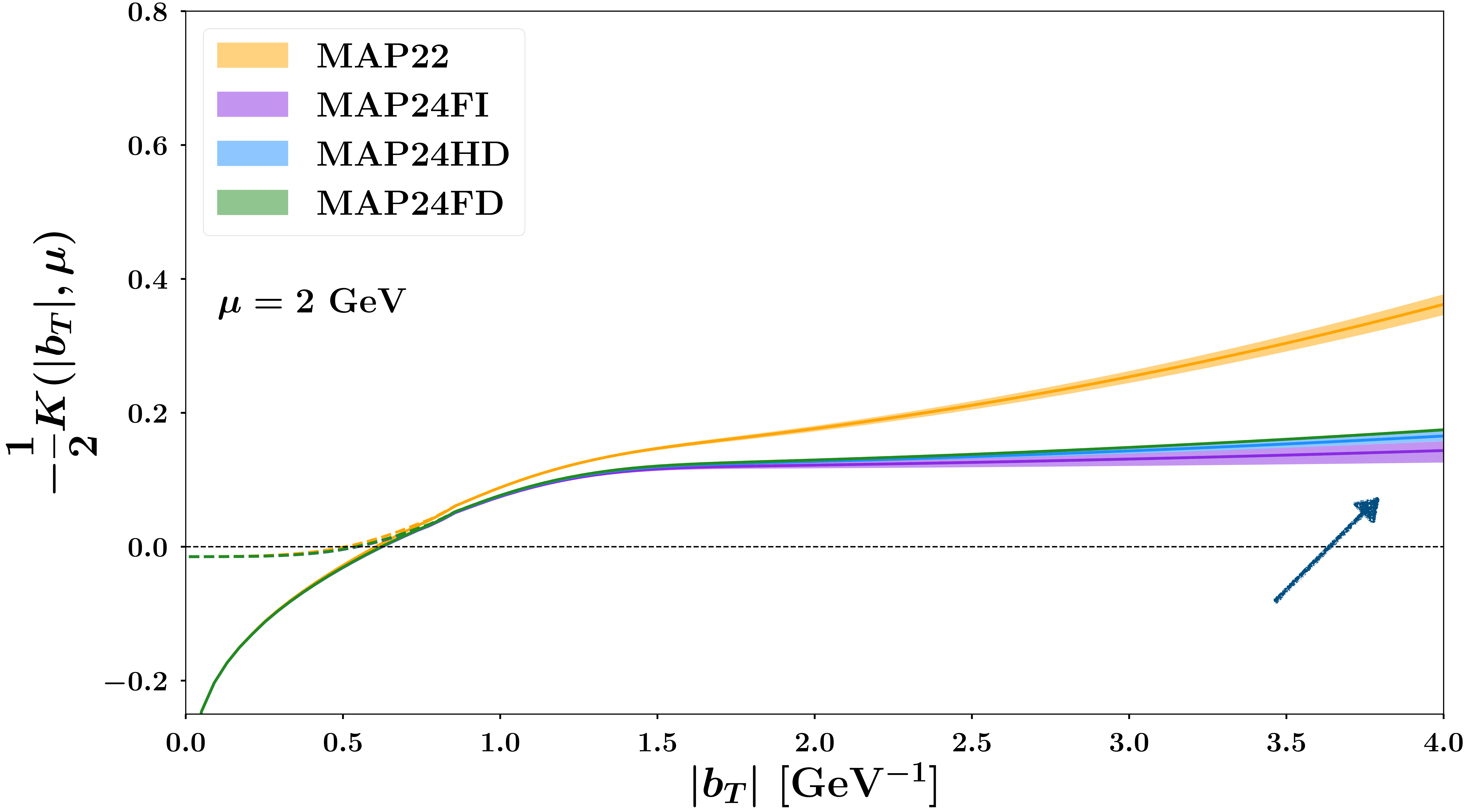
MAPTMD24 evolution - Collins-Soper kernel



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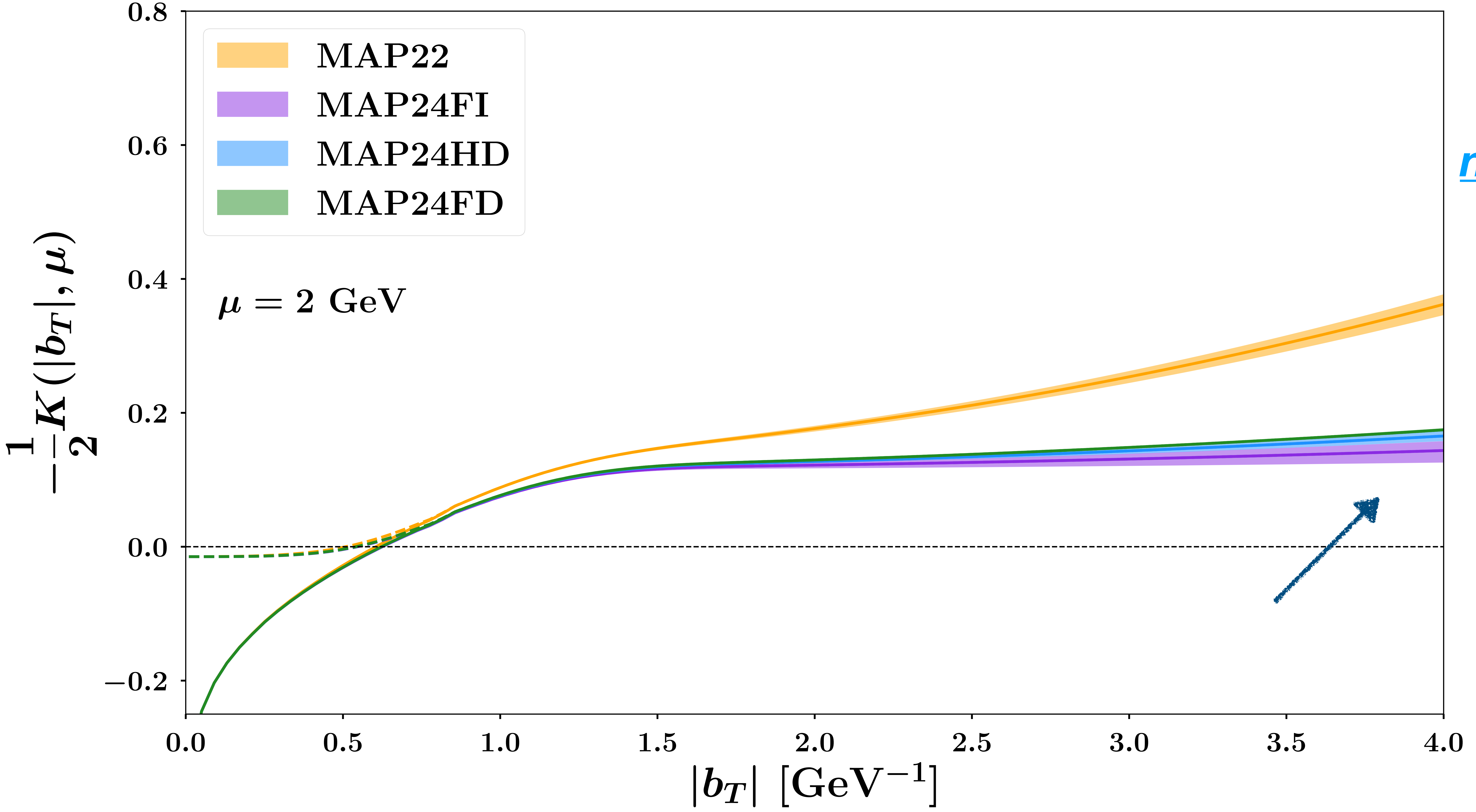
MAPTMD24 evolution - Collins-Soper kernel



Independent of our non-perturbative choices

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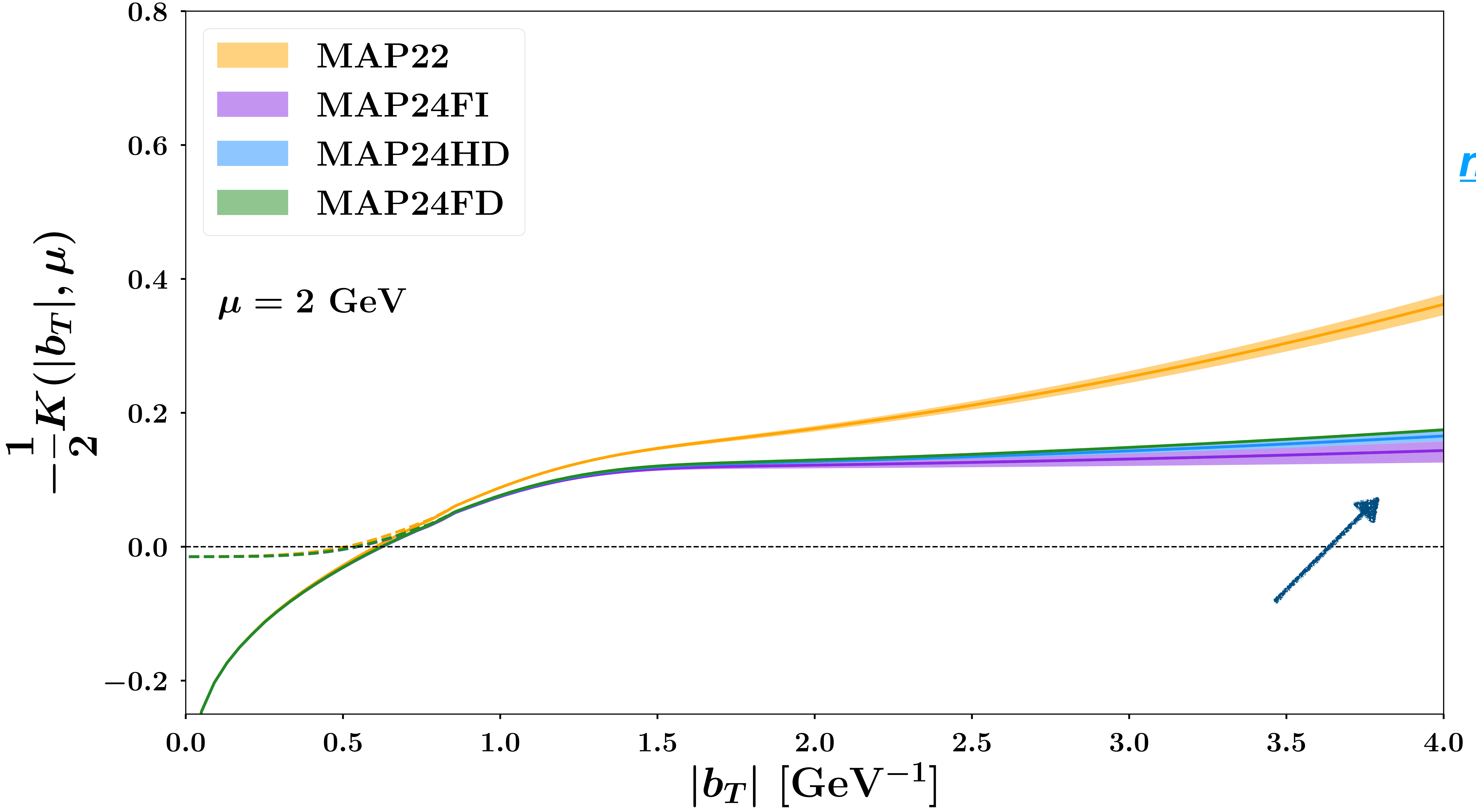
MAPTMD24 evolution - Collins-Soper kernel

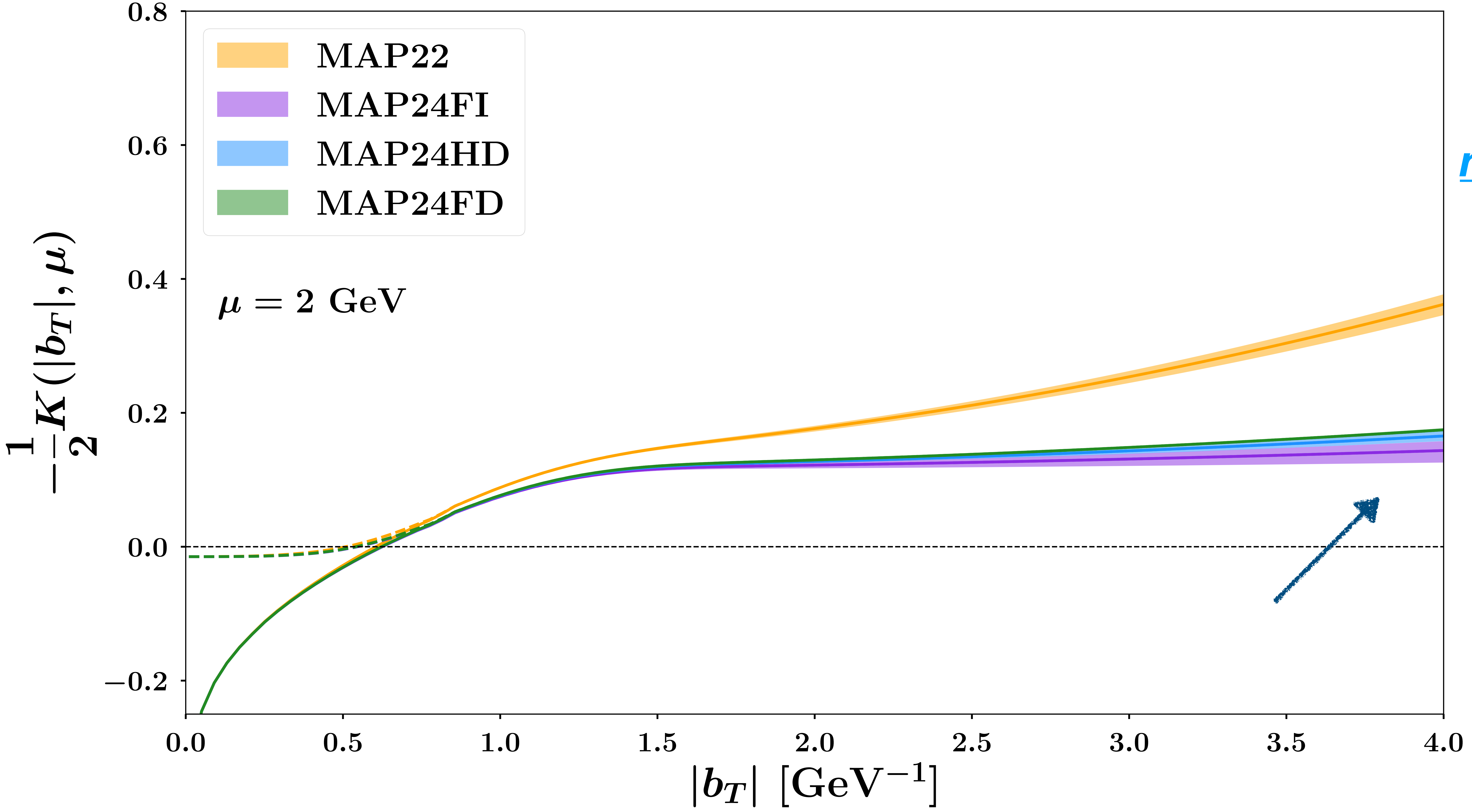


Independent of our
non-perturbative choices

Quite flat behaviour

2405.13833

MAPTMD24 evolution - Collins-Soper kernel



Independent of our
non-perturbative choices

Quite flat behaviour

Compatible with latest lattice calculation

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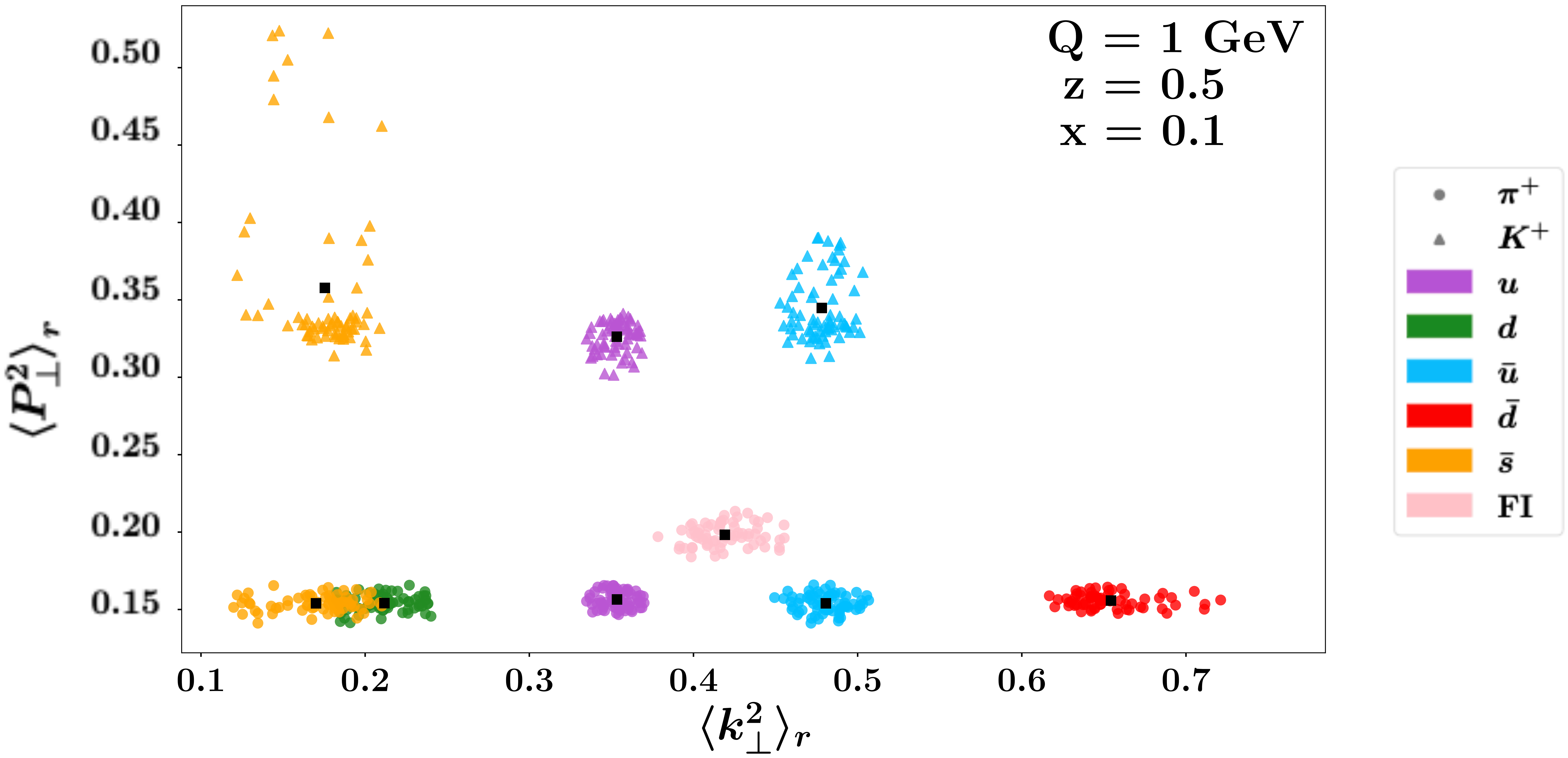
MAPTMD24 - Scatter plots



Evidence of different behaviors for different flavors
Evidence of different behaviors for different measured hadrons

Conclusions

- The extractions of **unpolarized quark TMDs** through global fits have reached very high accuracy (NNNLL), we need to introduce **flavor dependence** to obtain good theory/data agreement

- **MAPTMD24** is the **<u>first</u>** simultaneous extraction of **<u>flavor-dependent</u> unpolarized TMD PDFs and FF through a global fit**

- We observed ***significant*** differences between the flavors in the ***TMD PDFs***.

- We observed ***significant*** differences between different final hadrons in the ***TMD FFs***.

- We are finding a weak signal between different flavors in the same final hadron.