

MAPTMD24: New insights on flavor dependence in TMD extractions

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Resummation, Evolution and Factorization 2024

Lorenzo Rossi

MAP Collaboration

October 15th



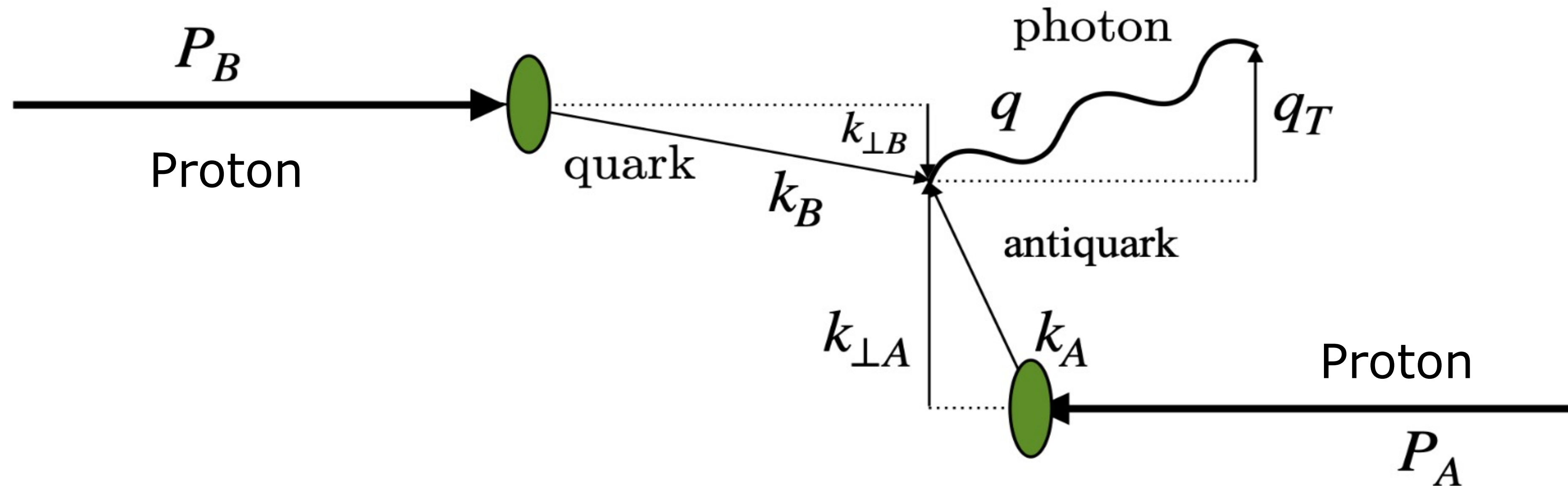
Istituto Nazionale di Fisica Nucleare



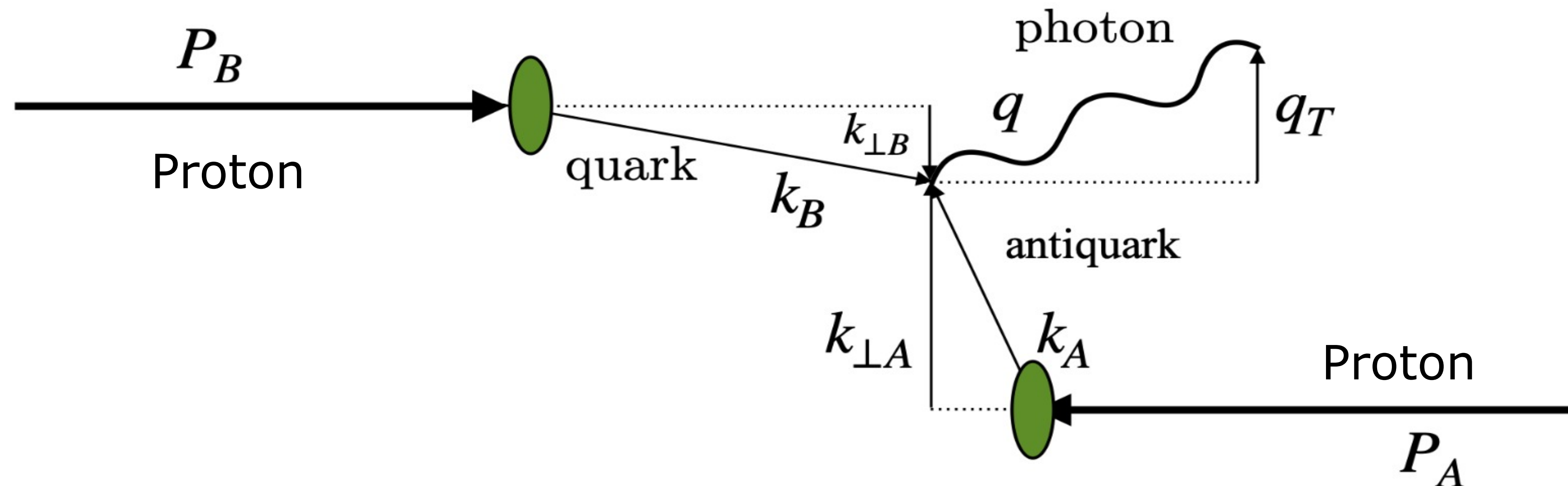
**UNIVERSITÀ
DEGLI STUDI
DI MILANO**

TMD factorization — Drell-Yan process

TMD factorization — Drell-Yan process

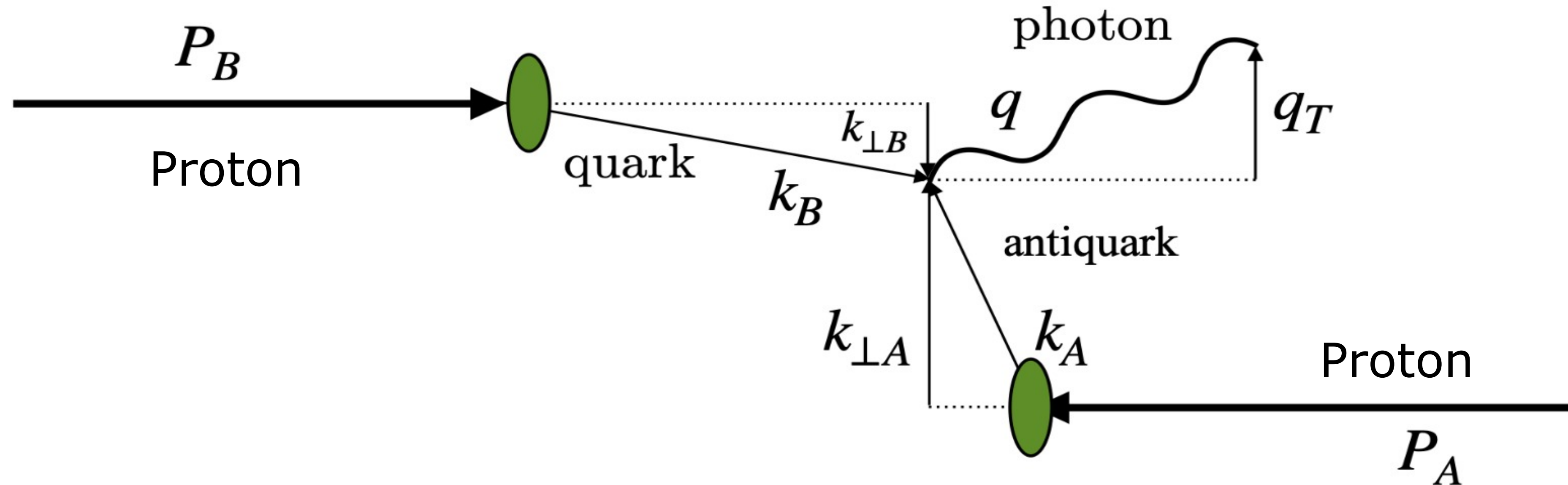


TMD factorization — Drell-Yan process



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

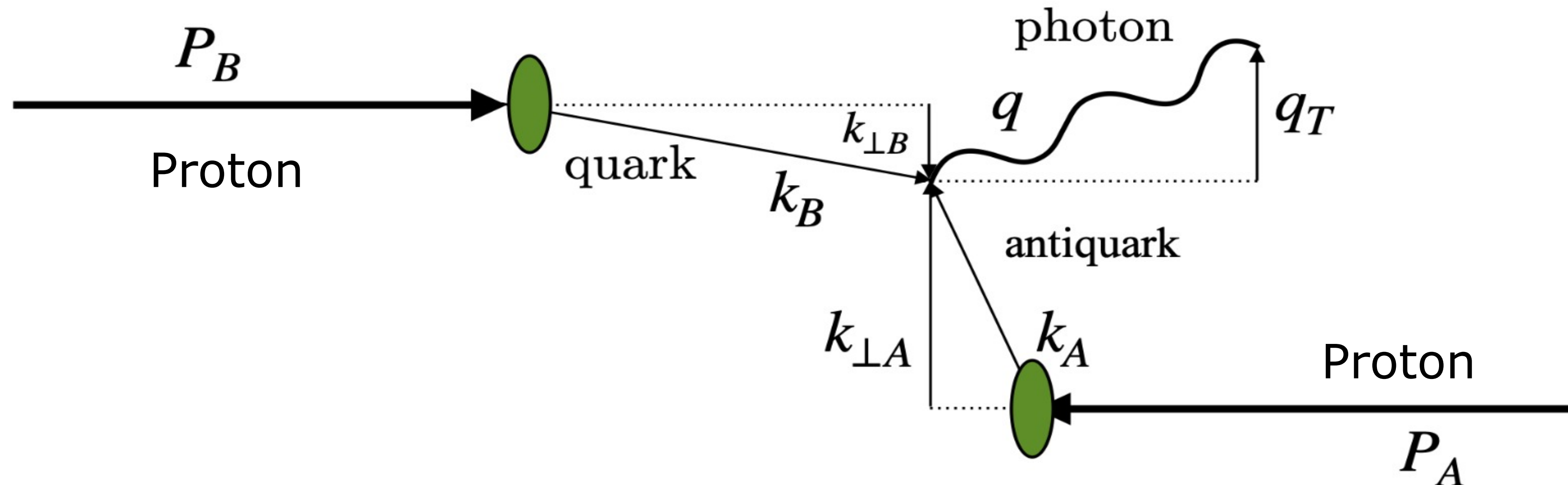
TMD factorization — Drell-Yan process



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

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

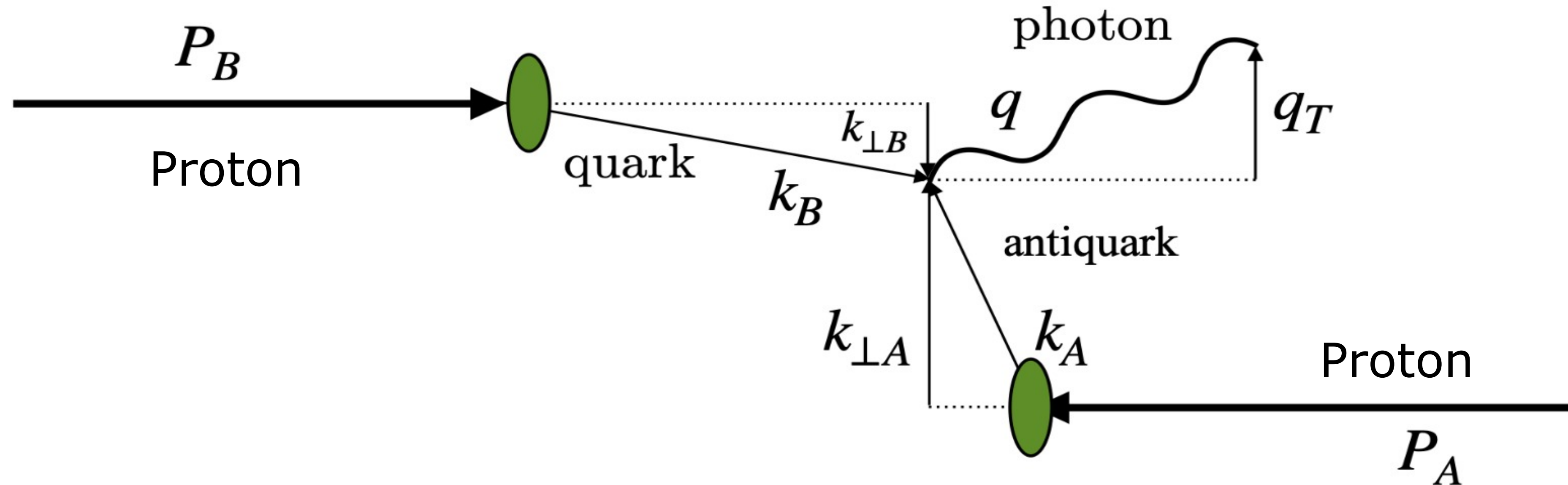
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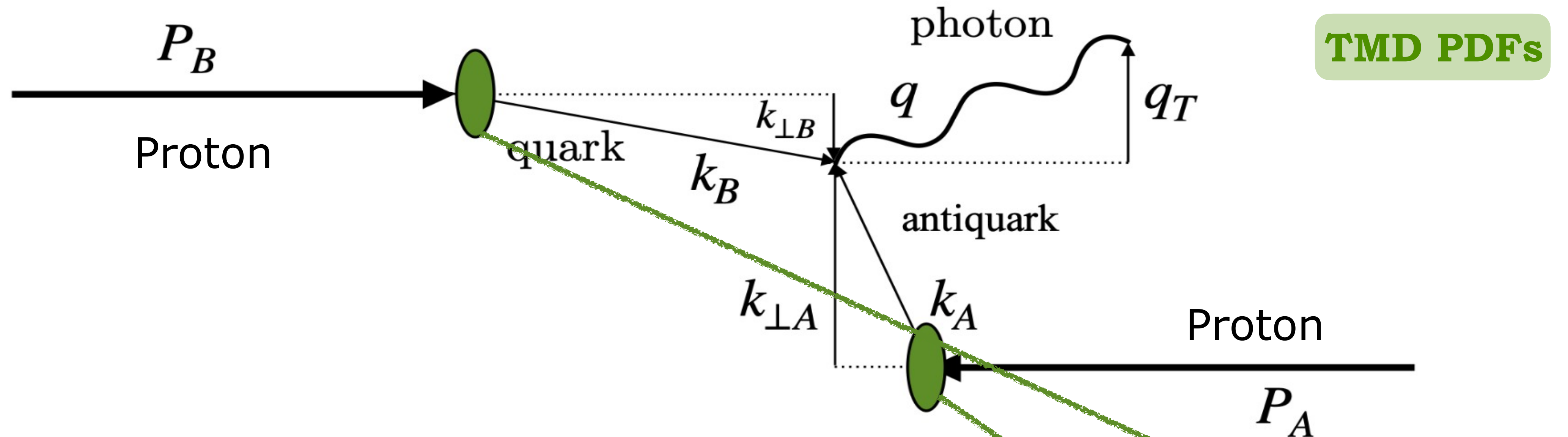
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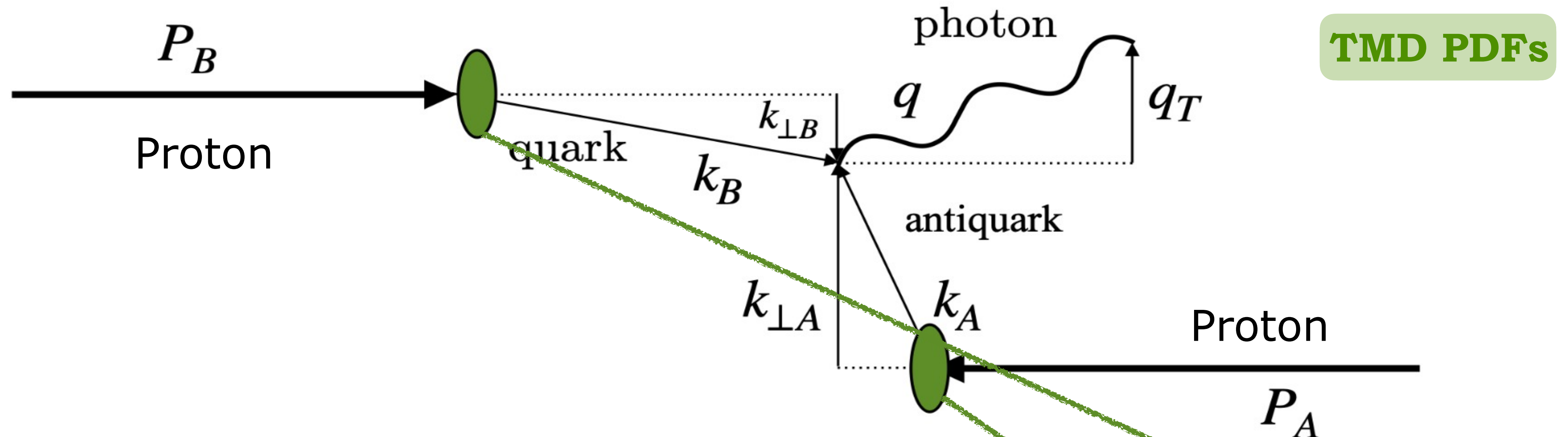
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TMD factorization — Drell-Yan process

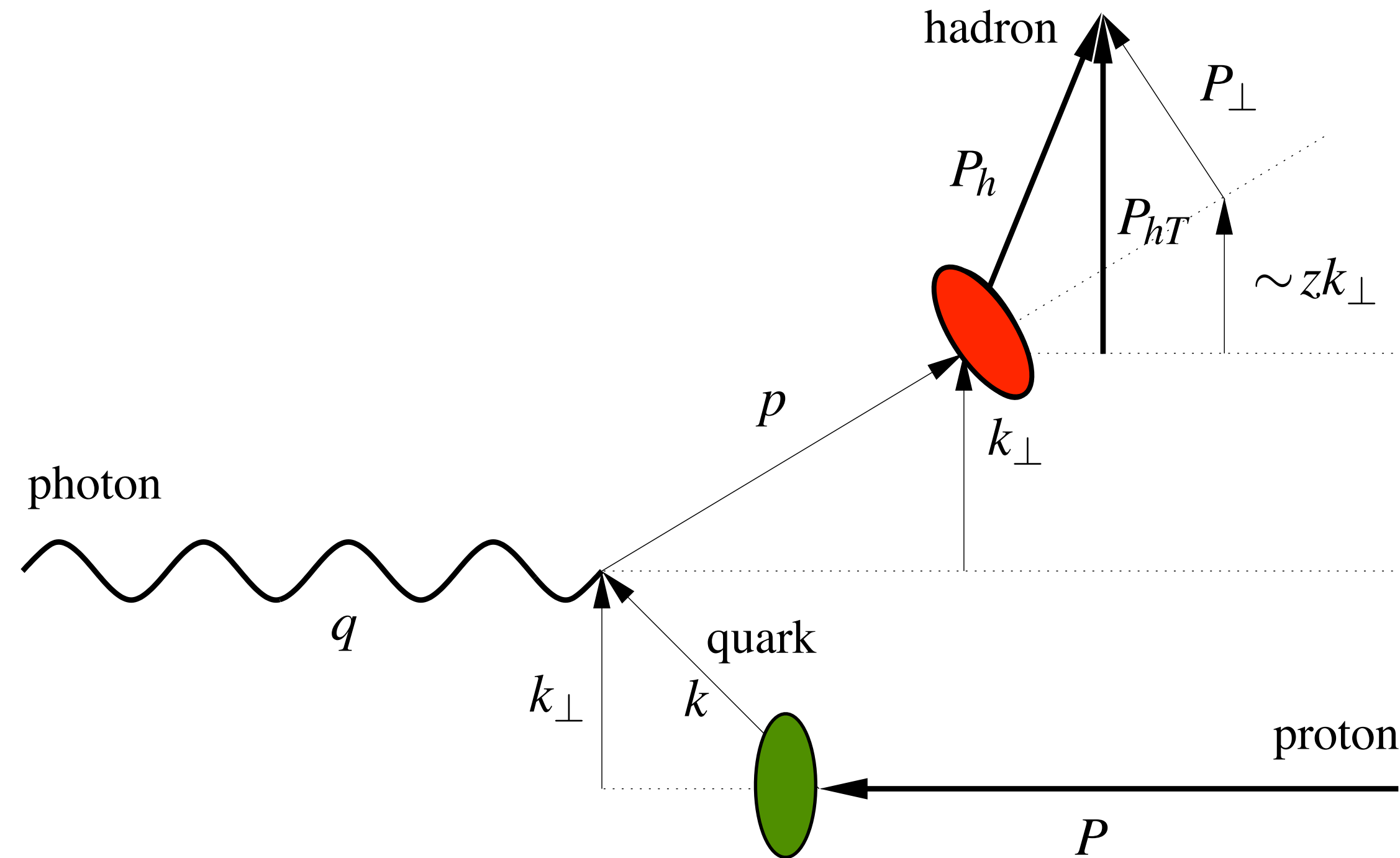


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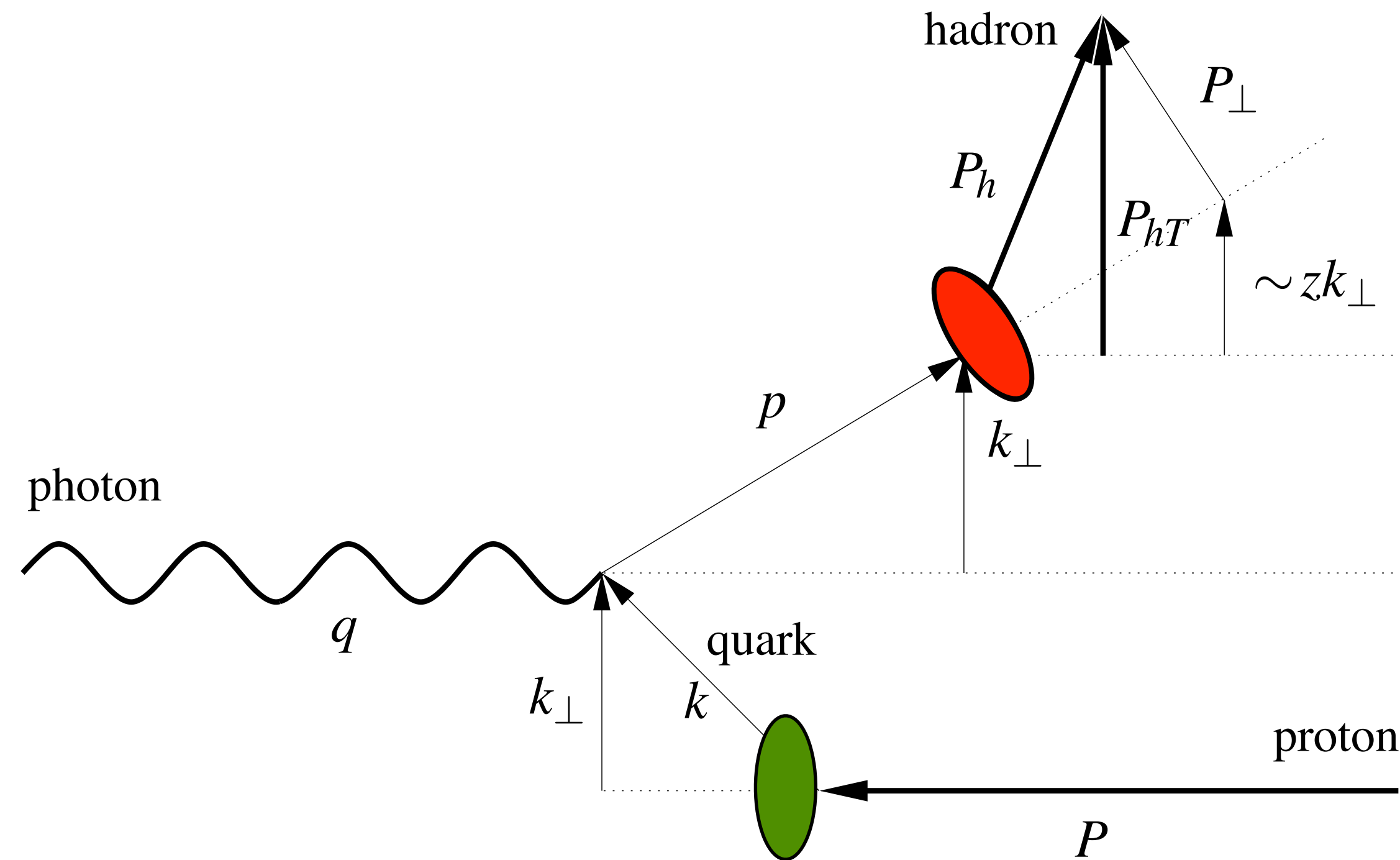
W term

TMD Factorization - SIDIS process



$$F_{UU,T}(x \cdot z; \mu_F, \mathbf{P}_{hT}^2, Q^2) = x \sum_a H_{UU,T}^a(Q^2, \mu^2) \int d^2\mathbf{k}_\perp d^2\mathbf{P}_\perp f_1^a(x, \mathbf{k}_\perp^2; \mu^2) D_1^{a \rightarrow h}(z, \mathbf{P}_\perp^2; \mu^2) \delta^{(2)}(z\mathbf{k}_\perp - \mathbf{P}_{hT} + \mathbf{P}_\perp) \\ + Y_{UU,T}(Q^2, \mathbf{P}_{hT}^2) + \mathcal{O}(M^2/Q^2)$$

TMD Factorization - SIDS process

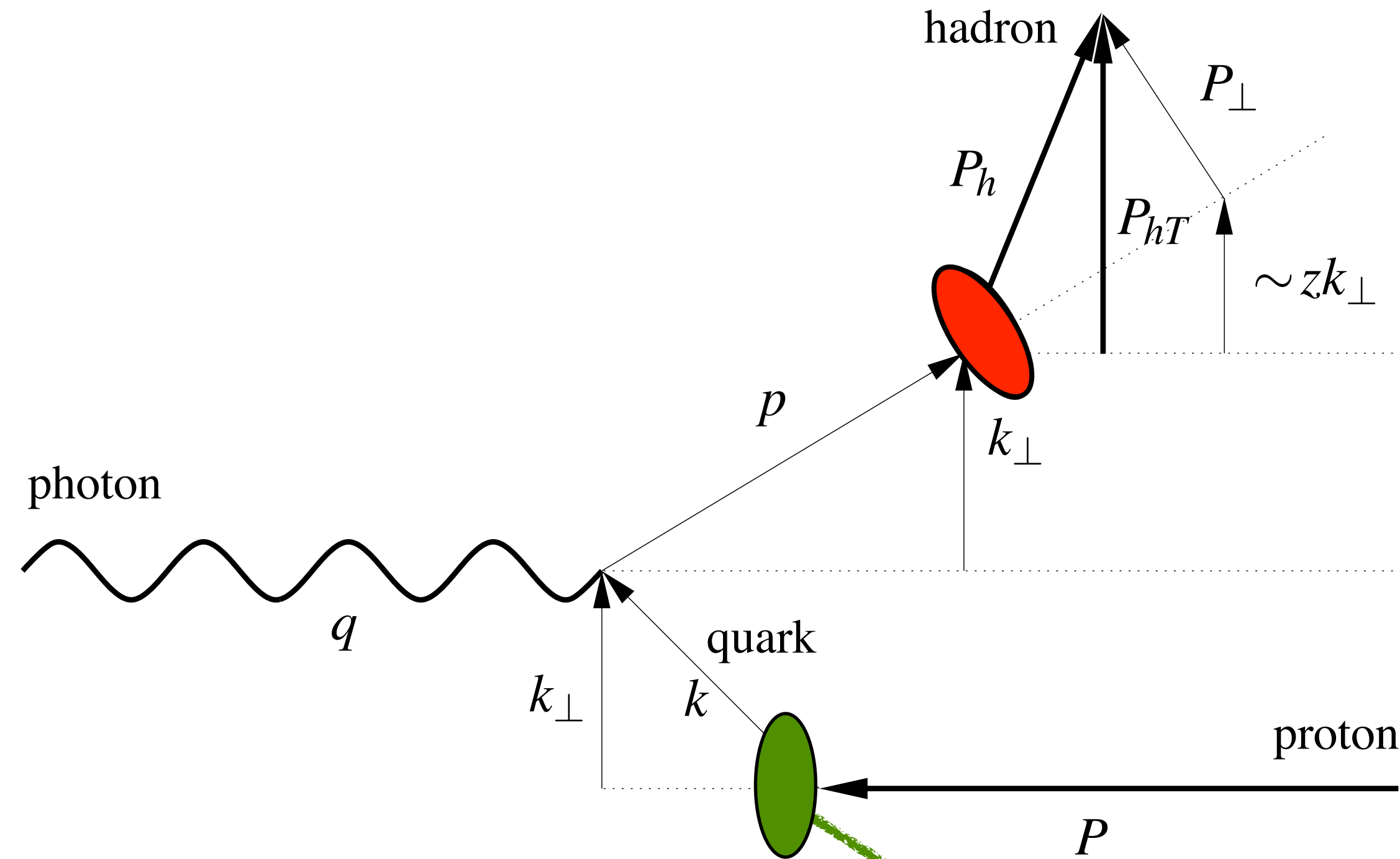


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W Term

TMD Factorization - SIDIS process

TMD PDF



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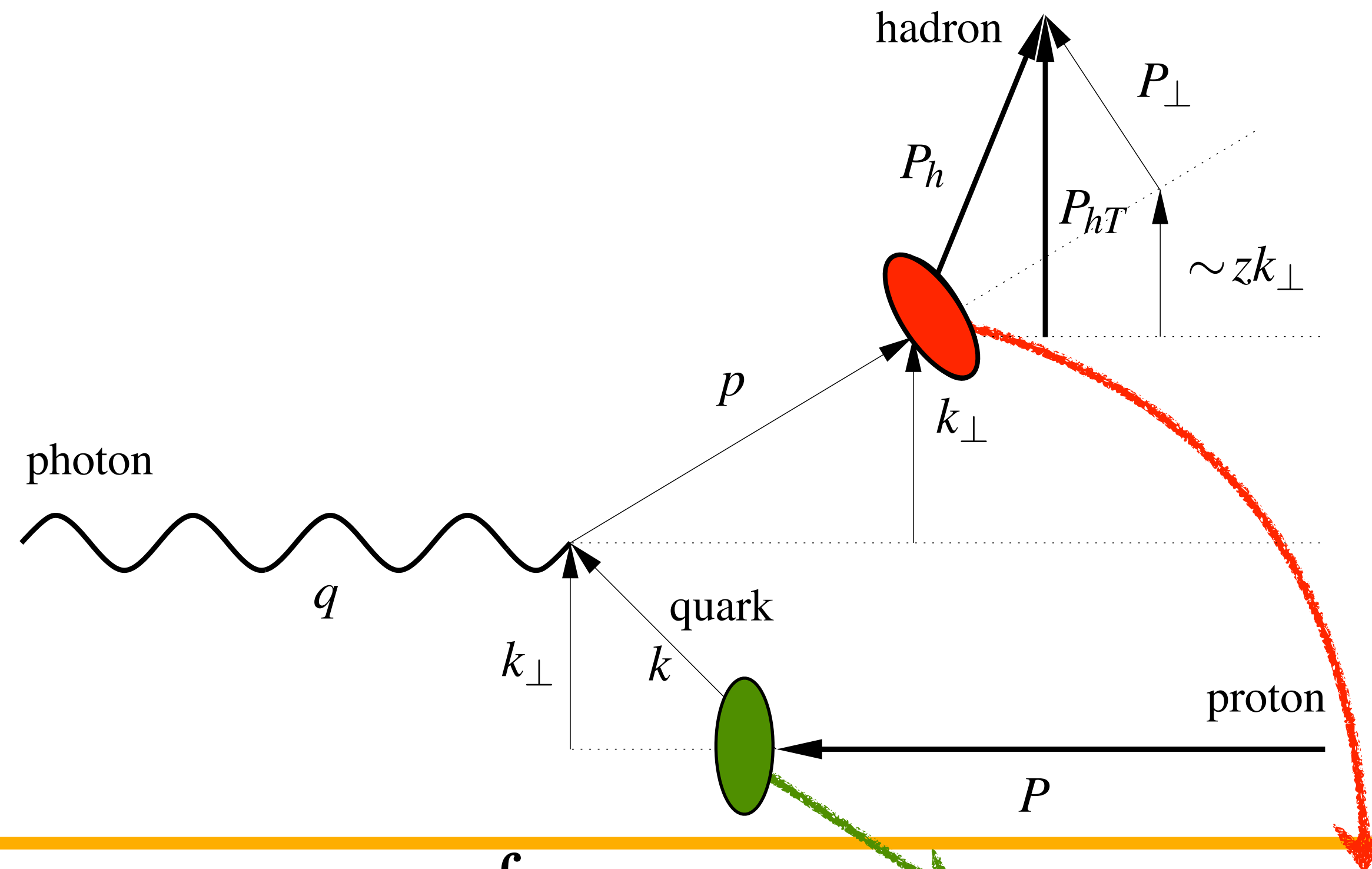
$$+ Y_{UU,T}(Q^2, \mathbf{P}_{hT}^2) + \mathcal{O}(M^2/Q^2)$$

W Term

TMD Factorization - SIDS process

TMD FF

TMD PDF



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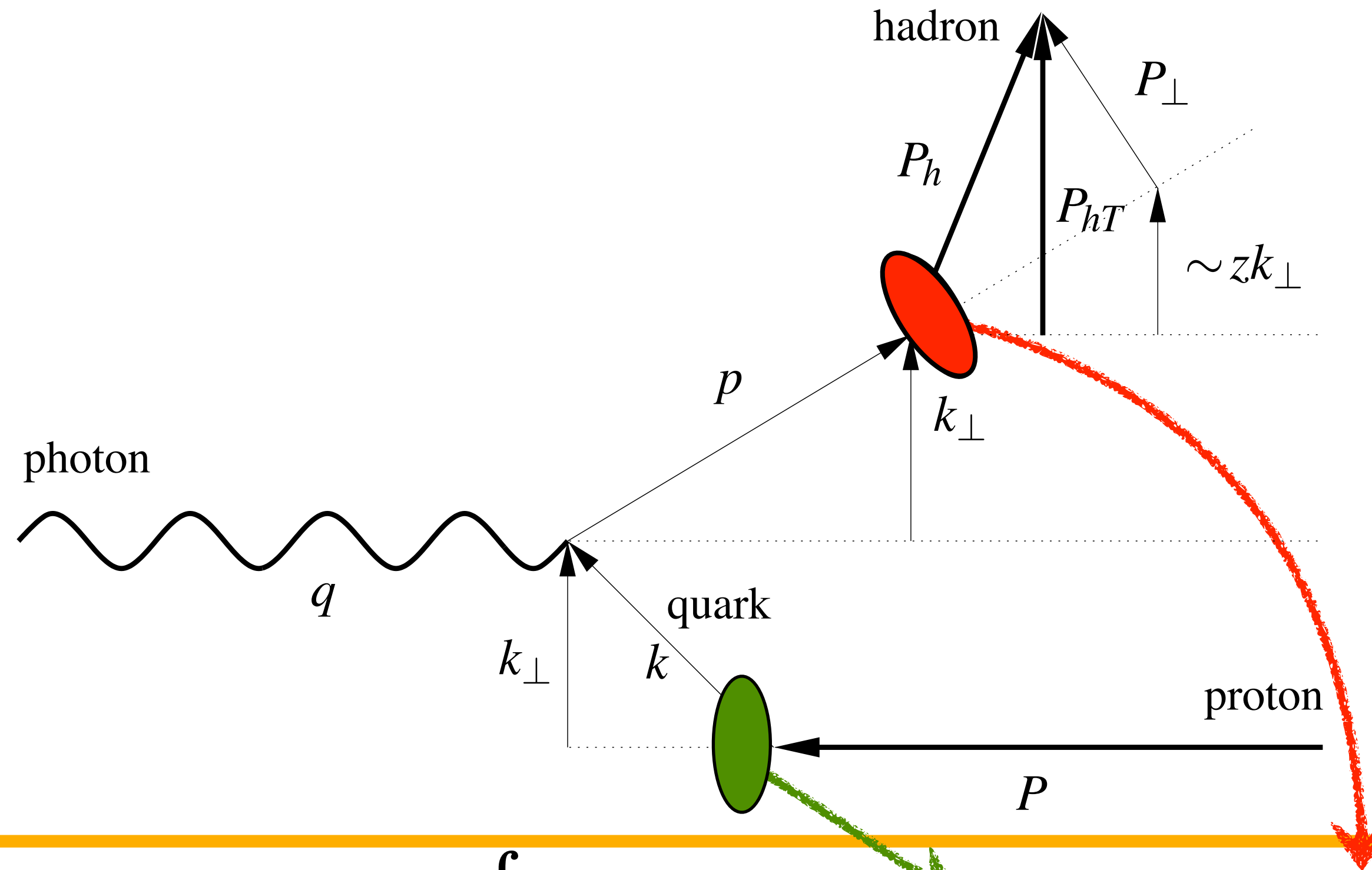
W Term

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TMD Factorization - SIDS process

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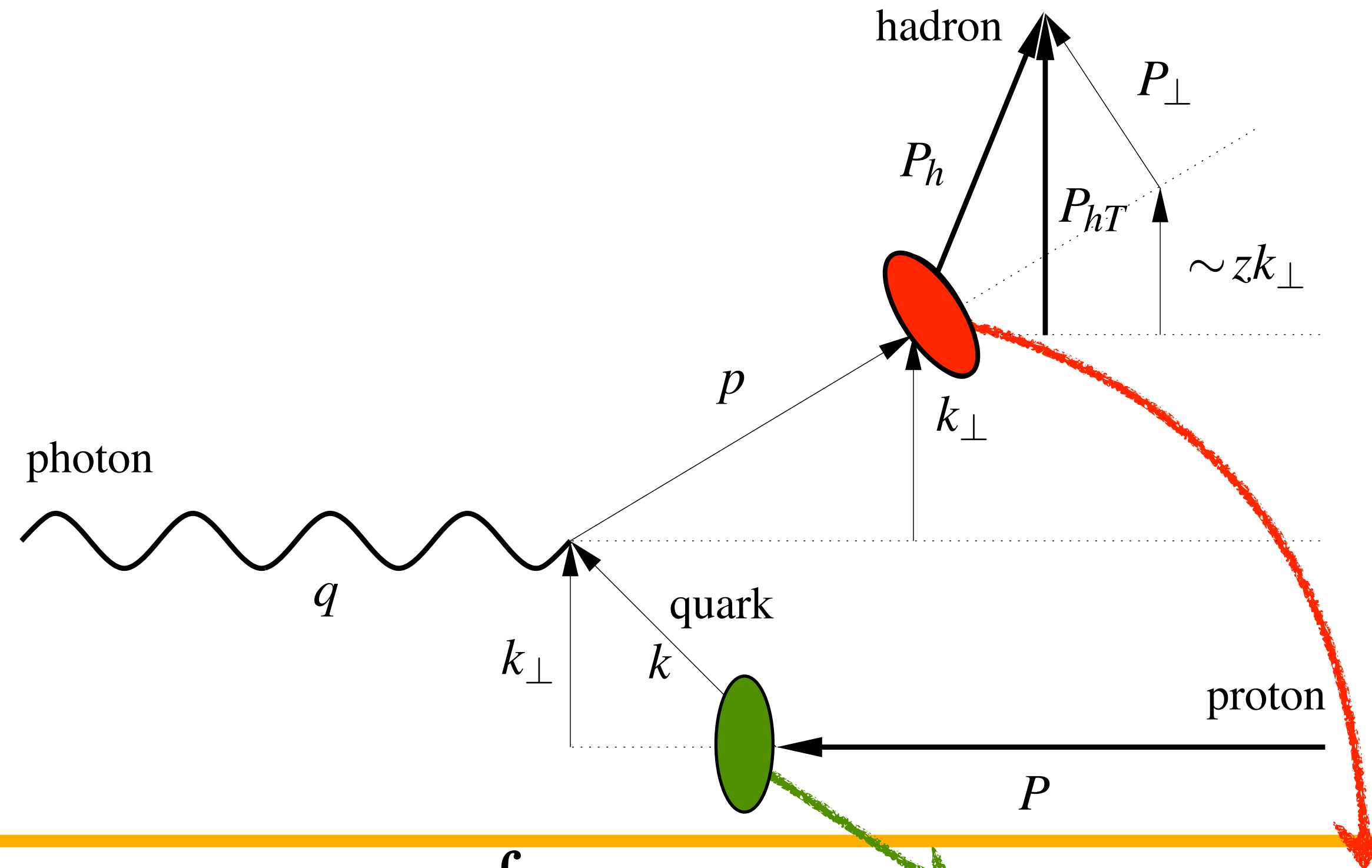
W Term

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

TMD Factorization - SIDIS process

TMD FF

TMD PDF



$$F_{UU,T}(x \cdot z; \mu_F, \mathbf{P}_{hT}^2, Q^2) = x \sum_a H_{UU,T}^a(Q^2, \mu^2) \int d^2\mathbf{k}_\perp d^2\mathbf{P}_\perp f_1^a(x, \mathbf{k}_\perp^2; \mu^2) D_1^{a \rightarrow h}(z, \mathbf{P}_\perp^2; \mu^2) \delta^{(2)}(z\mathbf{k}_\perp - \mathbf{P}_{hT} + \mathbf{P}_\perp) + Y_{UU,T}(Q^2, \mathbf{P}_{hT}^2) + \mathcal{O}(M^2/Q^2)$$

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 Factorization - structure of TMDs

$$\hat{f}_1^q(x_B, \mathbf{b}_T; \mu_F, \zeta_F) = [C \otimes f_1](x_B, b_\star; \mu_{b_\star}, \mu_{b_\star}^2) \exp \left\{ \int_{\mu_{b_\star}}^{\mu_F} \frac{d\mu'}{\mu'} \gamma(\mu', \zeta_F) \right\} \\ \times \left(\frac{\zeta}{\mu_{b_\star}^2} \right)^{K(b_\star, \mu_{b_\star})/2} \left[\frac{\zeta}{Q_0} \right]^{-g_K(\mathbf{b}_T)/2} f_1^{NP}(x, \mathbf{b}_T; \zeta, Q_0)$$

TMD Factorization - structure of TMDs

Matching coeff.
(perturbative calculable)

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TMD Factorization - structure of TMDs

Matching coeff.
(perturbative calculable)

Collinear PDFs
(previous fit)

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Perturbative Sudakov
evolution factor

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Collins-Soper
kernel

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Collins-Soper
kernel

NP part of
Collins-Soper Kernel

TMD Factorization - structure of TMDs

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Collins-Soper
kernel

NP part of
Collins-Soper Kernel

Non perturbative part
of TMDs

TMD Factorization - structure of TMDs

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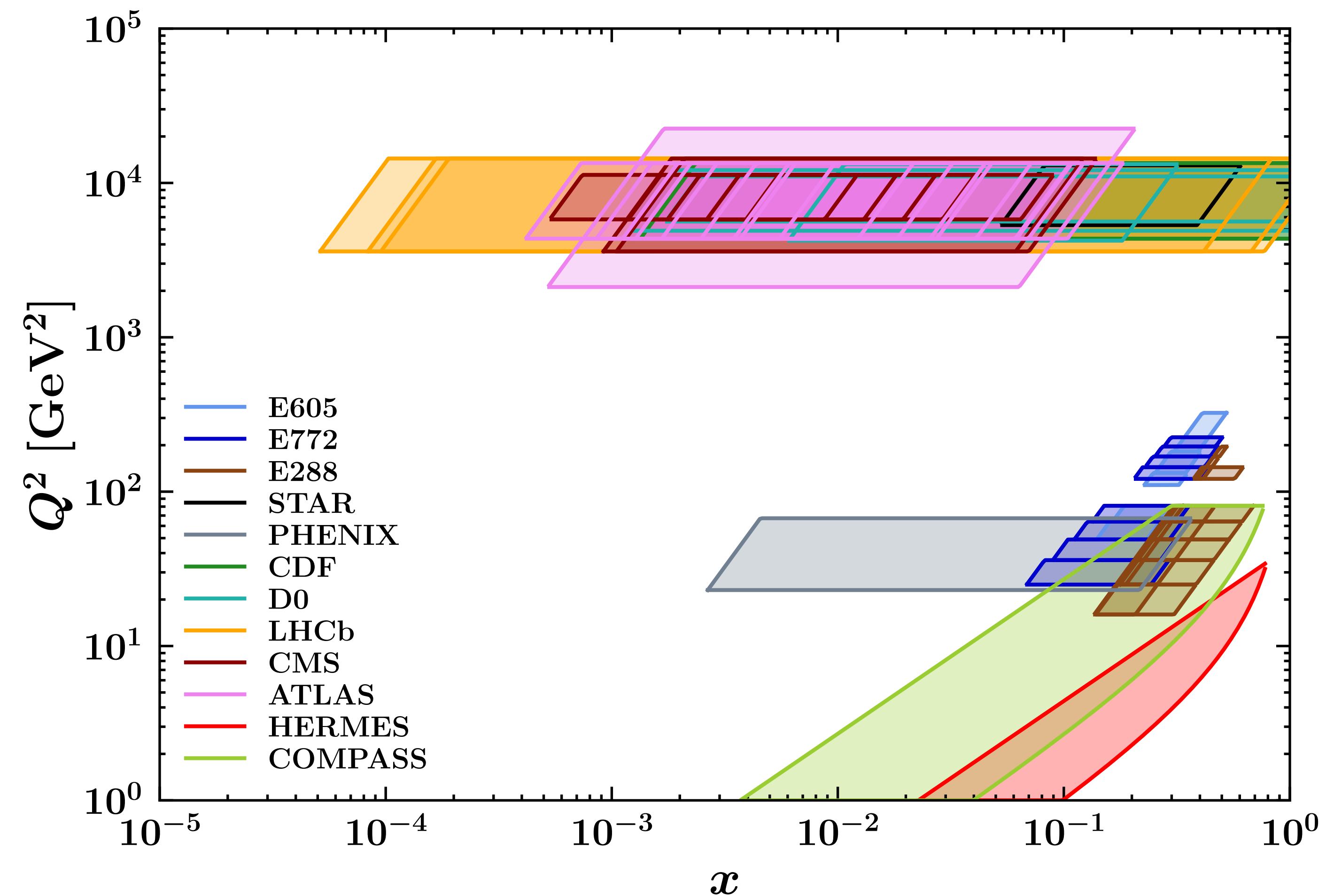
Fit extraction

MAPTMD22 extraction — starting point

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

MAPTMD22 extraction — starting point

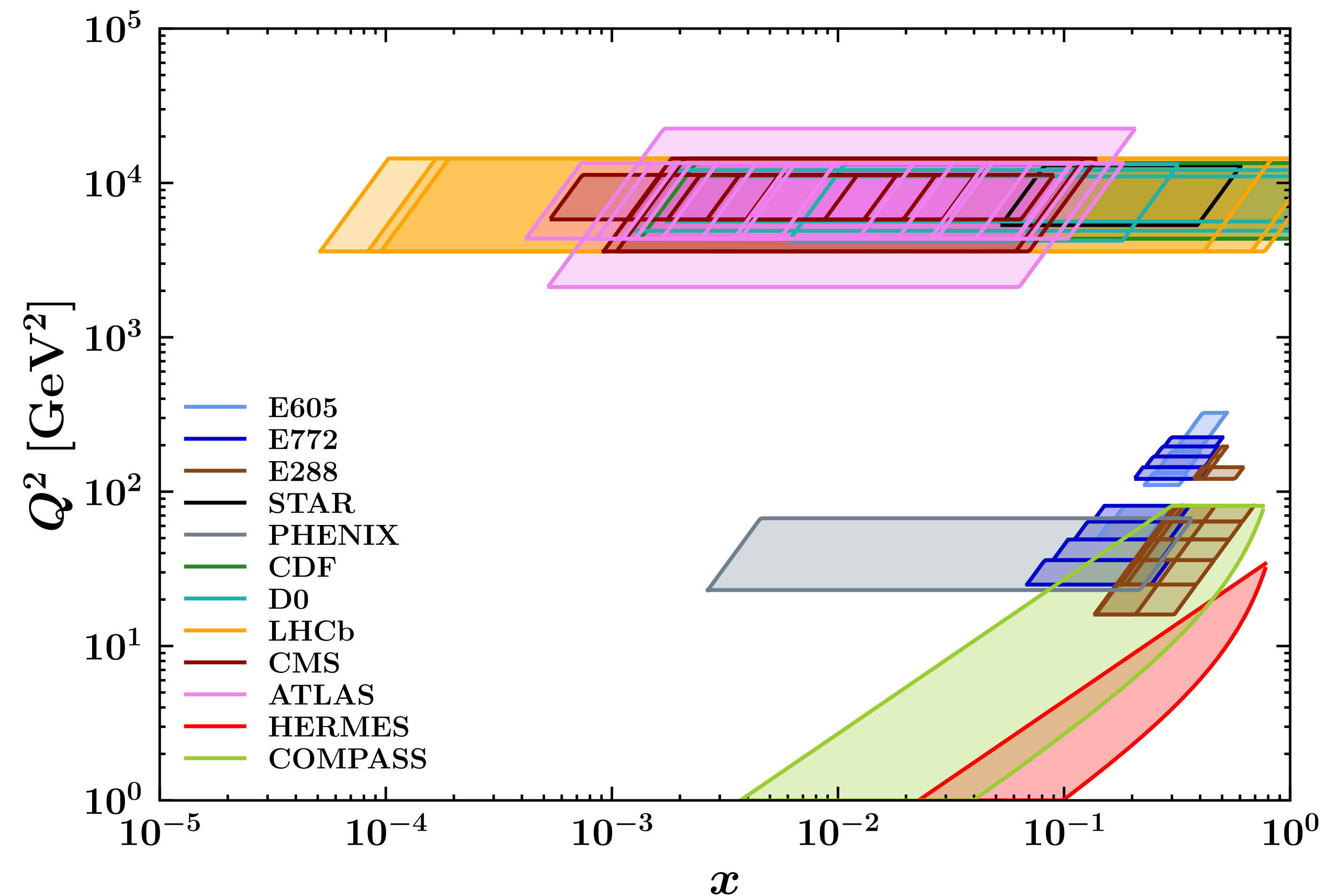
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MAPTMD22 extraction — starting point

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

Drell-Yan data
484

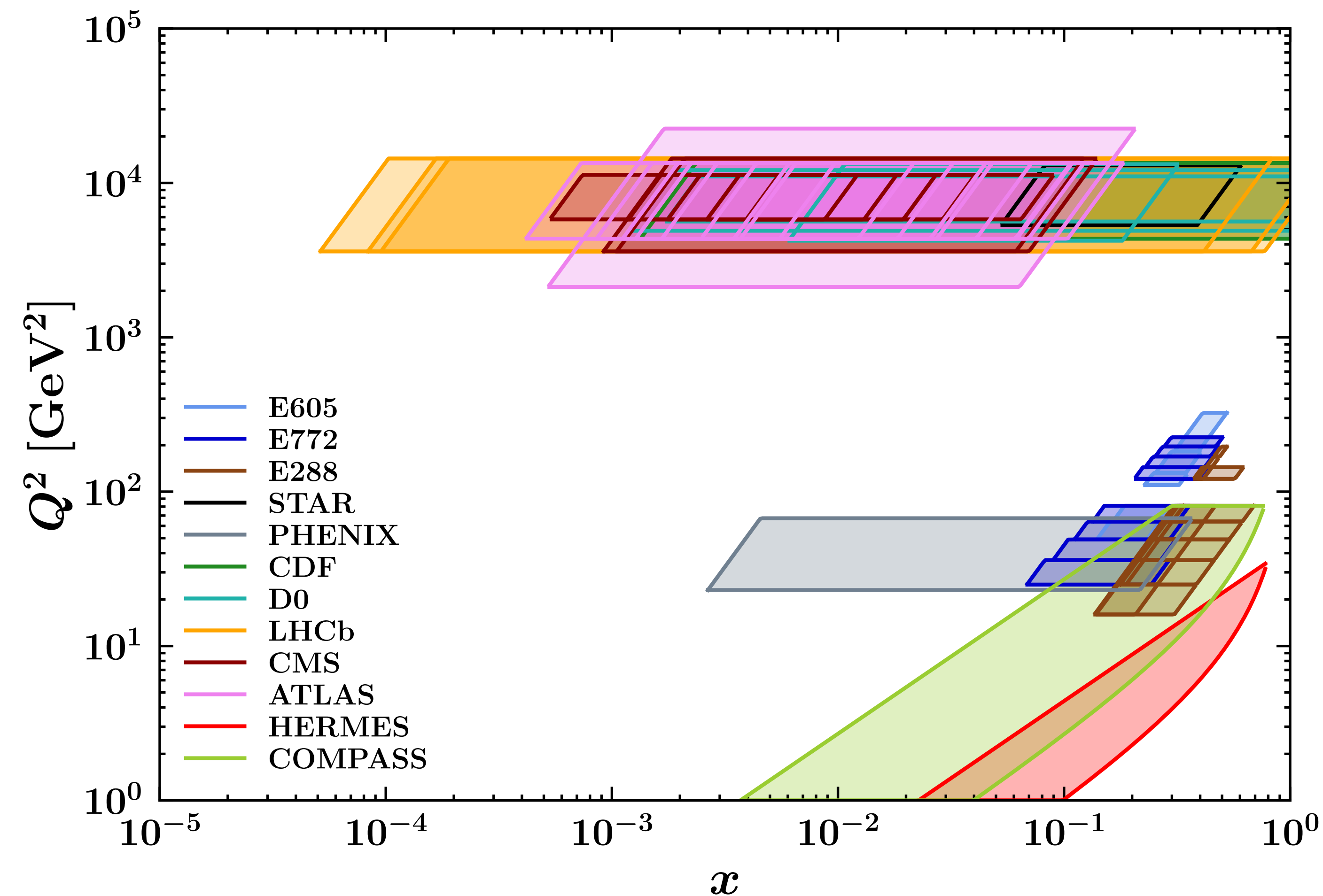


MAPTMD22 extraction — starting point

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

Drell-Yan data
484

SIDIS data
1547



MAPTMD22 extraction — starting point

- Global analysis of Drell-Yan and Semi-Inclusive DIS data sets: **2031** data points
- Perturbative accuracy: **N^3LL^-**

MAPTMD22 extraction — starting point

- Global analysis of Drell-Yan and Semi-Inclusive DIS data sets: **2031** data points
- Perturbative accuracy: **N^3LL^-**

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 ³ LO

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MMHT2014nnlo
DSS14-17 NLO

MAPTMD22 extraction — starting point

- Global analysis of Drell-Yan and Semi-Inclusive DIS data sets: **2031** data points
- Perturbative accuracy: **N^3LL^-**
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MAPTMD22 extraction — starting point

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- Number of fitted parameters: **21**

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$$\boxed{f_{1\text{NP}}}(x, b_T^2) \propto \text{F.T. of} \left(e^{-\frac{k_\perp^2}{g_{1A}}} + \lambda_B k_\perp^2 e^{-\frac{k_\perp^2}{g_{1B}}} + \lambda_C e^{-\frac{k_\perp^2}{g_{1C}}} \right) \quad g_1(x) = N_1 \frac{(1-x)^\alpha x^\sigma}{(1-\hat{x})^\alpha \hat{x}^\sigma}$$

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

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

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- **Normalization** of SIDIS multiplicities beyond NLL

11 parameters for TMD PDF
+ 1 for NP evolution + 9 for
TMD FF

- Number of fitted parameters: **21**

$$\boxed{f_{1\text{NP}}}(x, b_T^2) \propto \text{F.T. of} \left(e^{-\frac{k_\perp^2}{g_{1A}}} + \lambda_B k_\perp^2 e^{-\frac{k_\perp^2}{g_{1B}}} + \lambda_C e^{-\frac{k_\perp^2}{g_{1C}}} \right) \quad g_1(x) = N_1 \frac{(1-x)^\alpha x^\sigma}{(1-\hat{x})^\alpha \hat{x}^\sigma}$$

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

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

MAPTMD22



MAPTMD24

- Global analysis of Drell-Yan and Semi-Inclusive DIS data sets: **2031** data points
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- ***Normalization*** of SIDIS multiplicities beyond NLL
- Number of fitted parameters: **21**
- Extremely good description: **$\chi^2/N_{\text{data}} = 1.06$**

MAPTMD22



MAPTMD24

- Global analysis of Drell-Yan and Semi-Inclusive DIS data sets: **2031** data points
Same global data set
- Perturbative accuracy: **N^3LL^-**
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DSS14-17 NLO
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- **Normalization** of SIDIS multiplicities beyond NLL
Same approach
- Number of fitted parameters: **21**
Same parameterization
- Extremely good description: **$\chi^2/N_{\text{data}} = 1.40$**

***Why does the
 χ^2 get worse?***

MAPTMD24 extraction

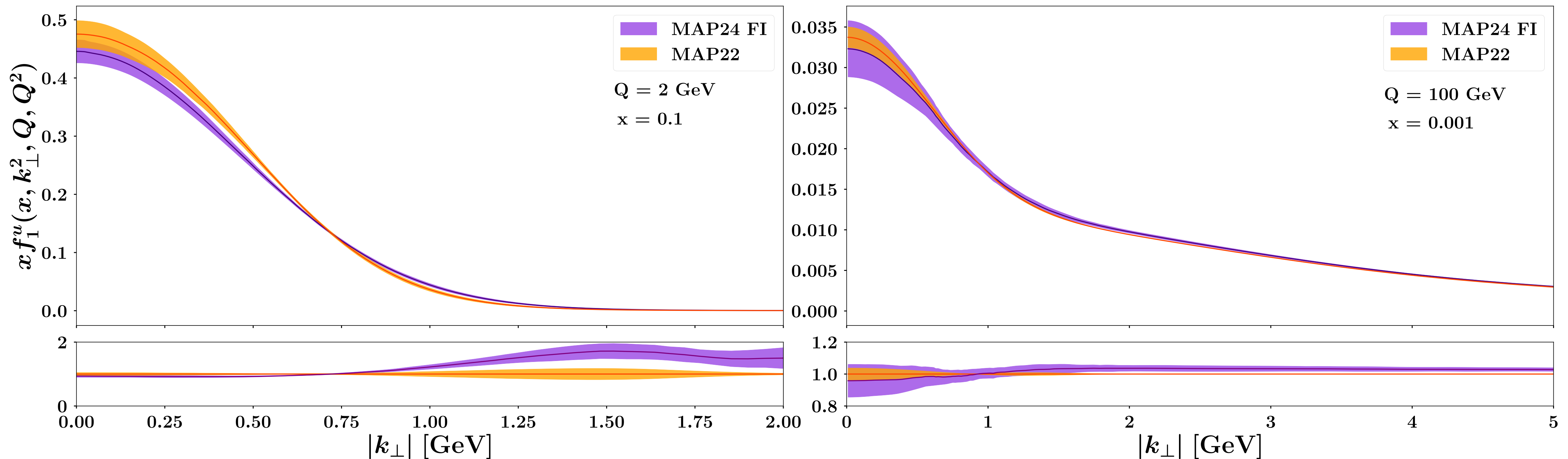
	Data set χ_0^2/N_{dat}		
Collinear sets	DY total	SIDIS total	Total
MMHT + DSS (MAP22)	1.66	0.87	1.06
NNPDF + MAPFF (MAP24 FI)	1.58	1.34	1.40

MAPTMD24 extraction

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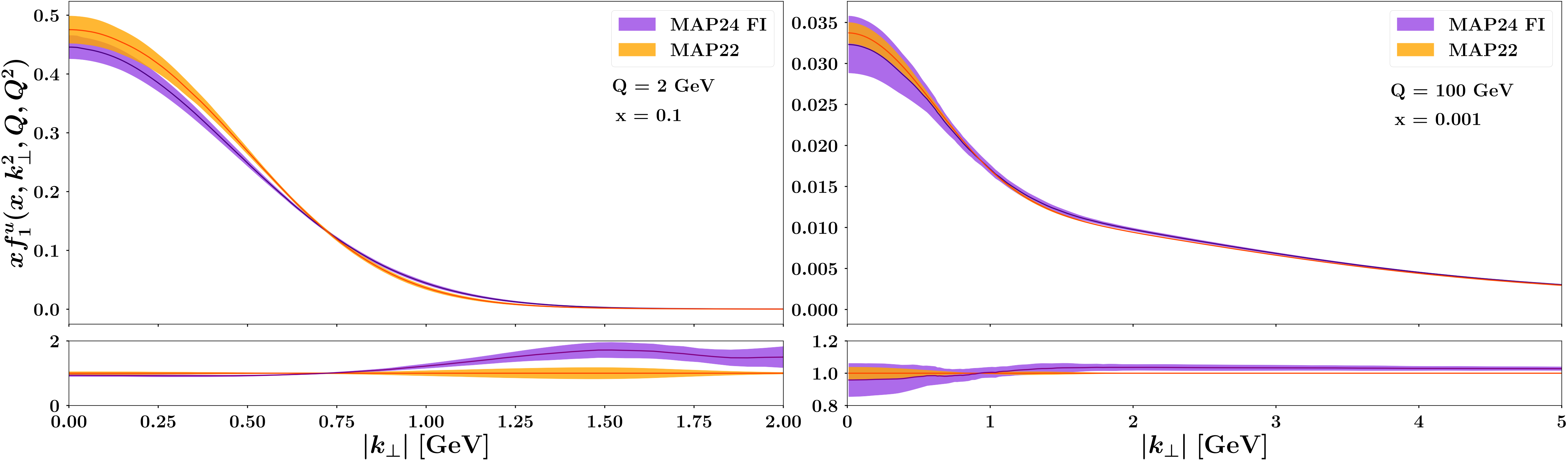
MAPTMD24 extraction

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MAPTMD24 extraction

	Data set χ^2_0/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



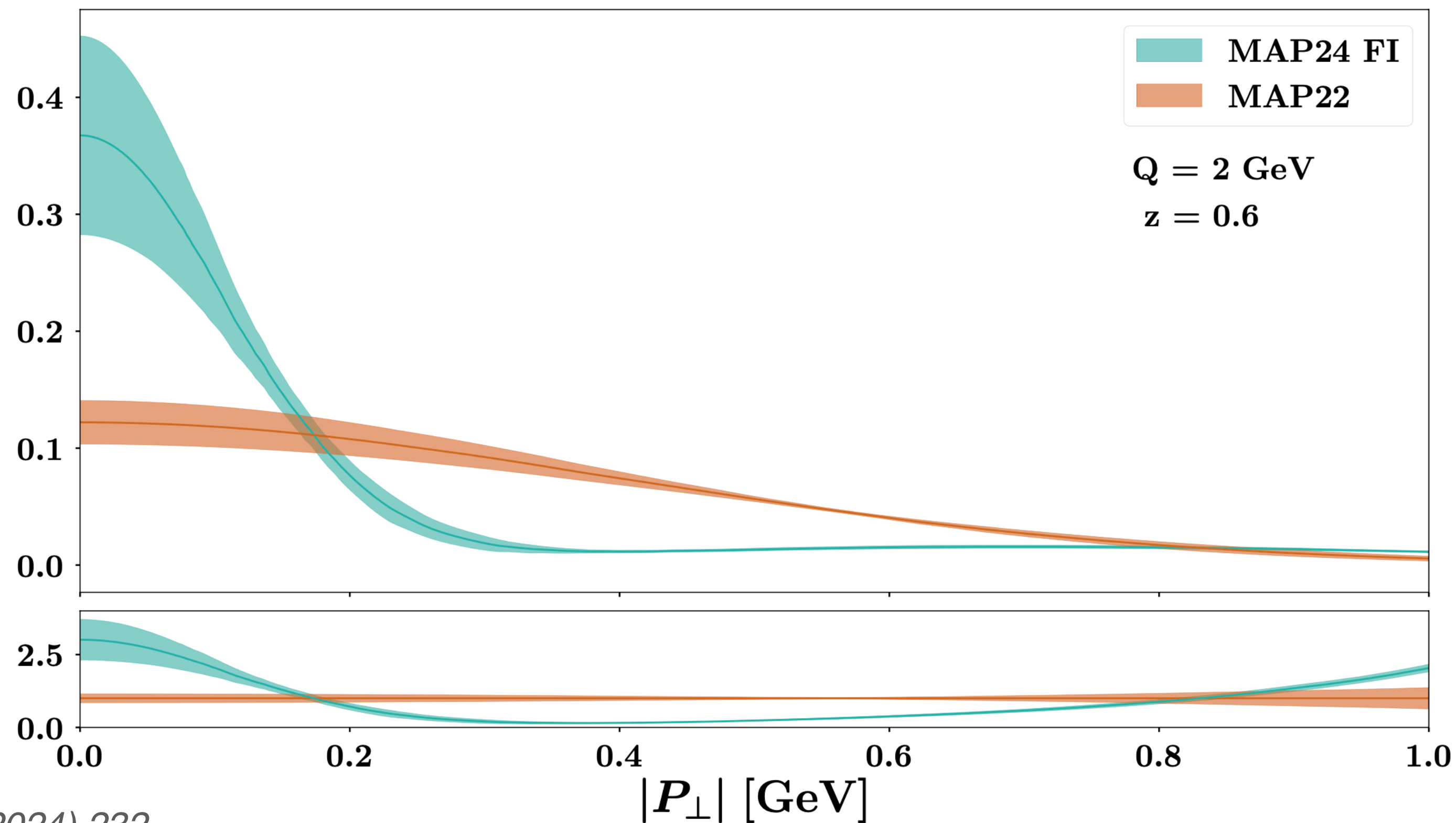
TMD PDFs are compatible with MAP22

MAPTMD24 extraction

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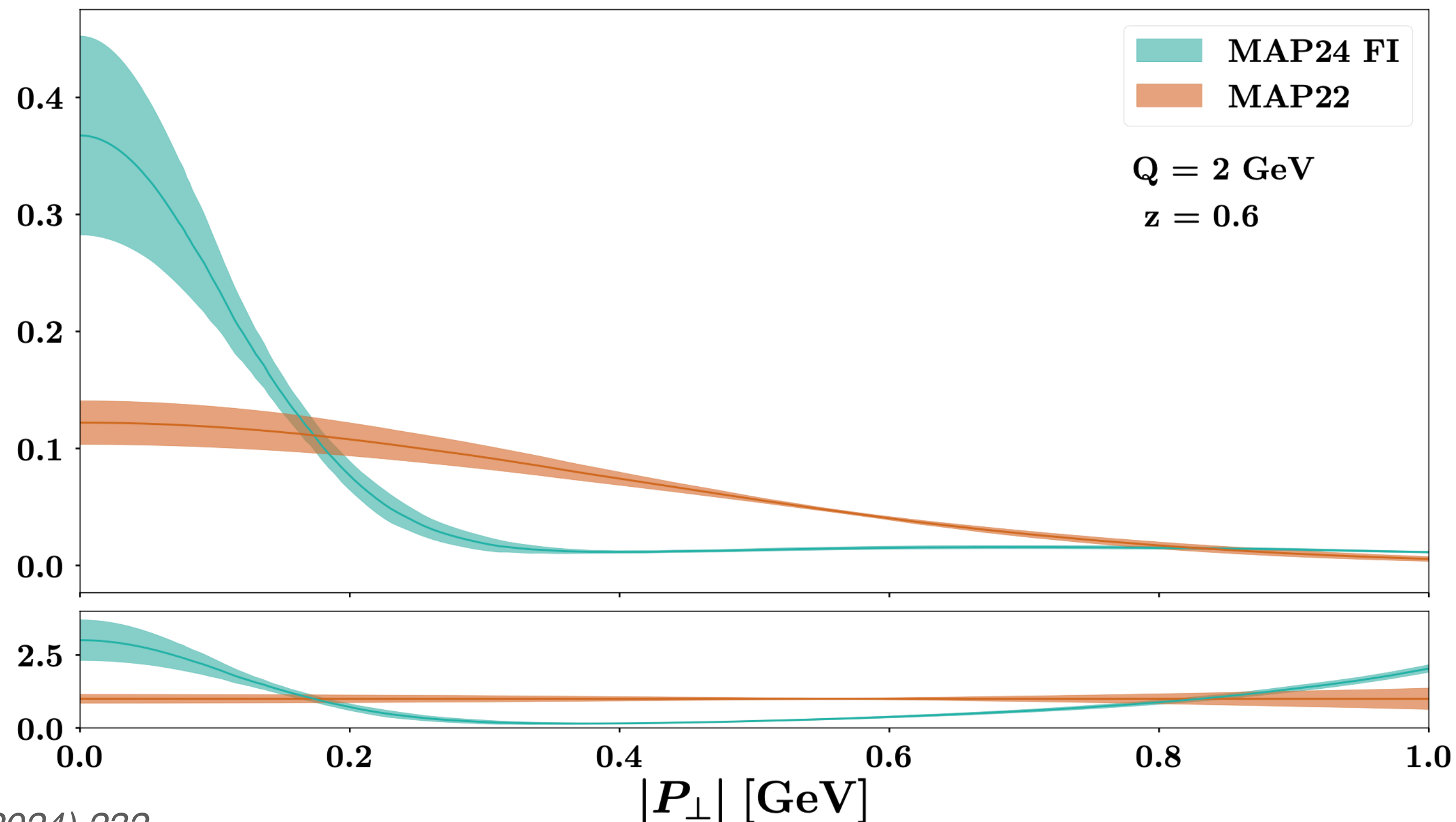
MAPTMD24 extraction

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MAPFF1.0nnlo

- Approx NNLO
- NN approach
- New behaviors
- Smaller uncertainties

MAPTMD24 extraction

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

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Data set	N_{dat}	χ_0^2/N_{dat}
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MMHT + DSS (MAP22)

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DY collider total	251	2.43
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COMPASS total	1203	0.88
SIDIS total	1547	0.90
Total	2031	1.07

NNPDF + DSS

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MMHT + DSS (MAP22)

Good agreement



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Data set	N_{dat}	χ_0^2/N_{dat}
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MMHT + DSS (MAP22)

Agreement



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MMHT + MAPFF

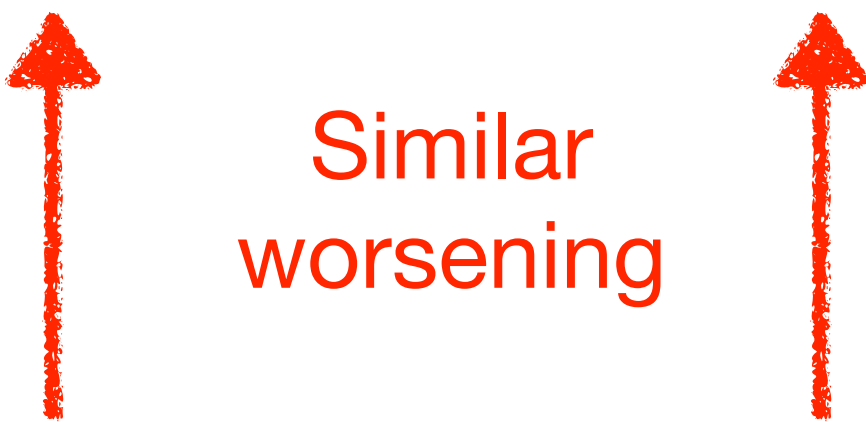
Data set	N_{dat}	χ_0^2/N_{dat}
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MMHT + DSS (MAP22)

Agreement



Similar
worsening



Good agreement



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MMHT + DSS (MAP22)

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NNPDF + MAPFF

MMHT + MAPFF

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NNPDF + DSS

MMHT + DSS (MAP22)

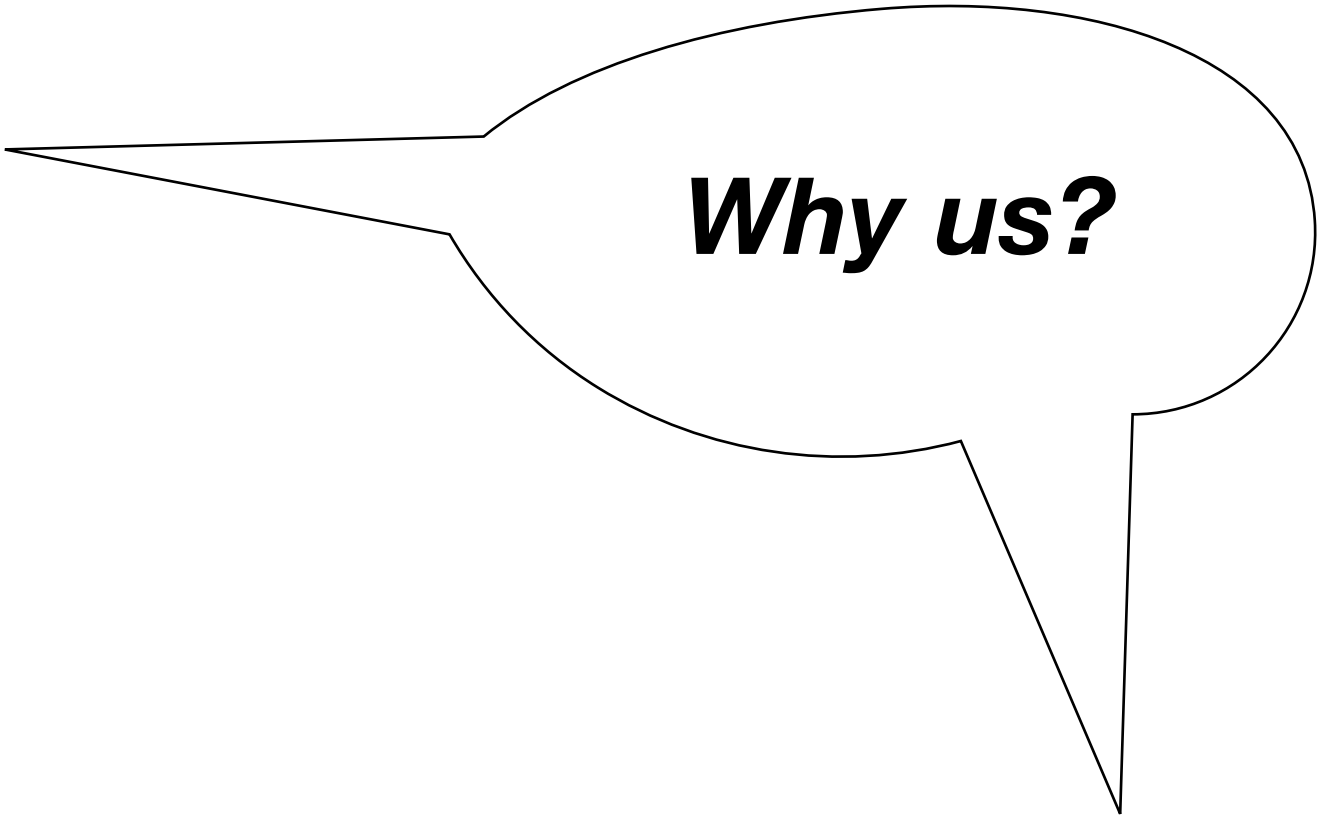
MAPTMD24 extraction

Data set
DY collider tot
Dy fixed targ
HERMES tot
COMPASS to
SIDIS total
Total

NNF

Data set	N_{dat}	χ^2_0/N_{dat}
DY collider tot		
Dy fixed targ		
HERMES tot		
COMPASS to		
SIDIS total		
Total	2031	1.07

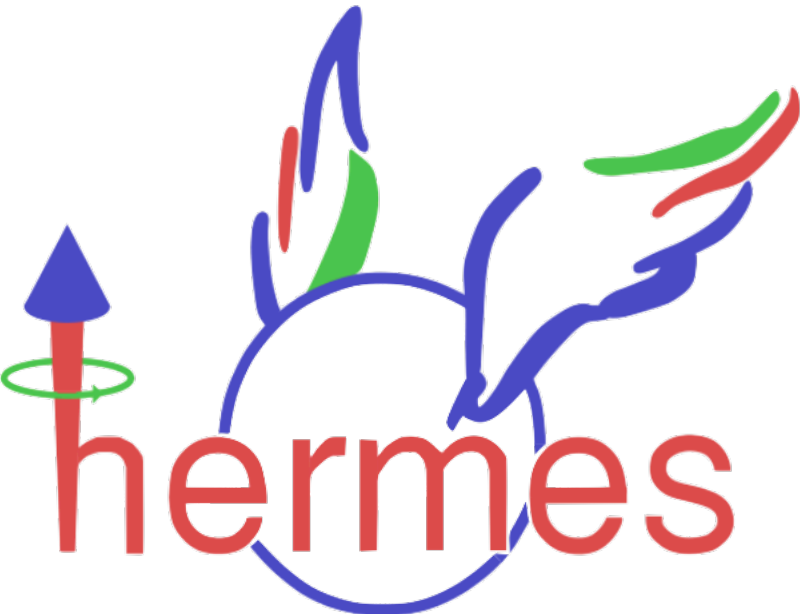
NNPDF + DSS



Data. set.	N_{dat}	χ^2_0/N_{dat}
	251	2.01
	233	1.11
	344	2.51
	1203	0.99
	1547	1.33
	2031	1.39

APFF

	N_{dat}	χ^2_0/N_{dat}
	251	2.06
	233	1.24
	344	0.71
	1203	0.92
	1547	0.87
Total	2031	1.06



MMHT + DSS (MAP22)

MAPTMD24 extraction

MAPTMD24 extraction

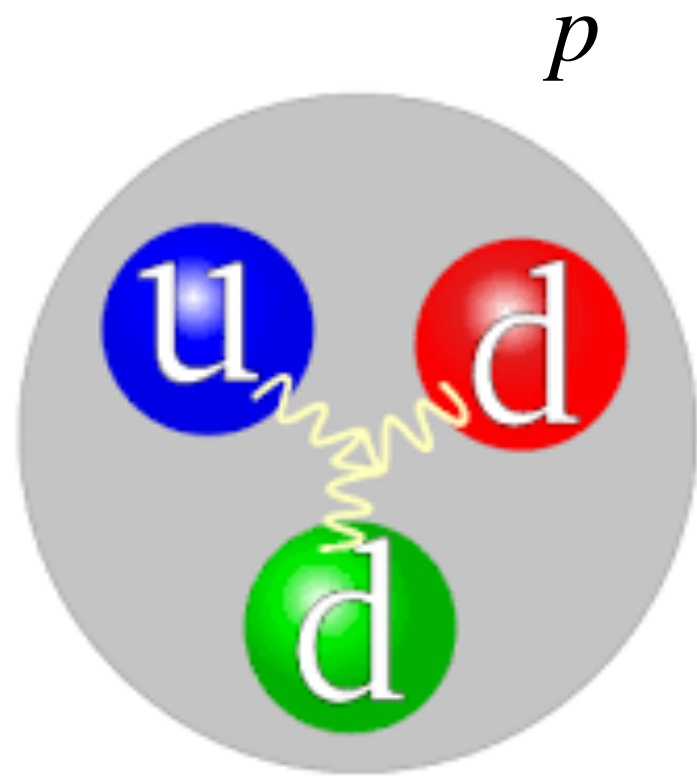
Solution:

MAPTMD24 extraction

Solution: *Flavour dependence*

MAPTMD24 extraction

Solution: *Flavour dependence*



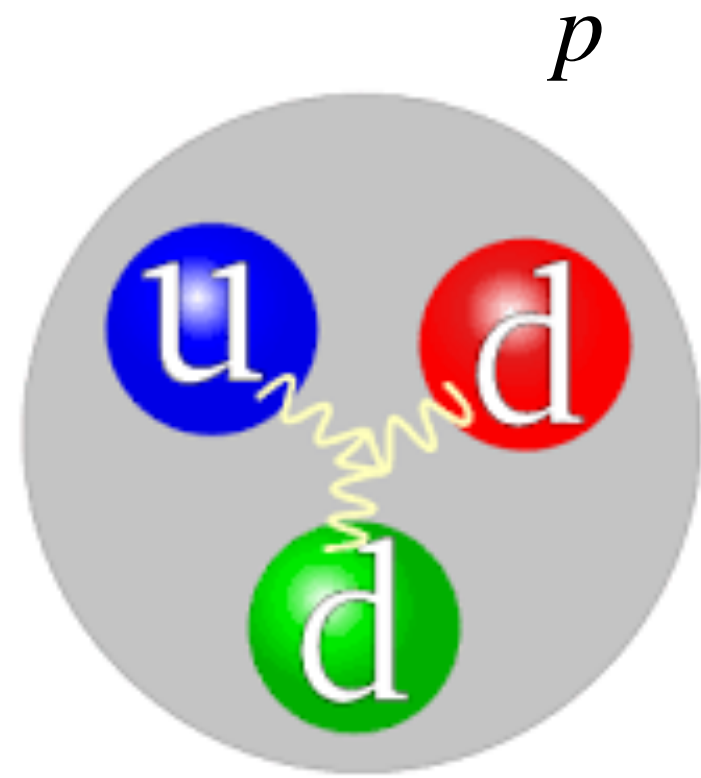
u, d

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

s (*sea*)

MAPTMD24 extraction

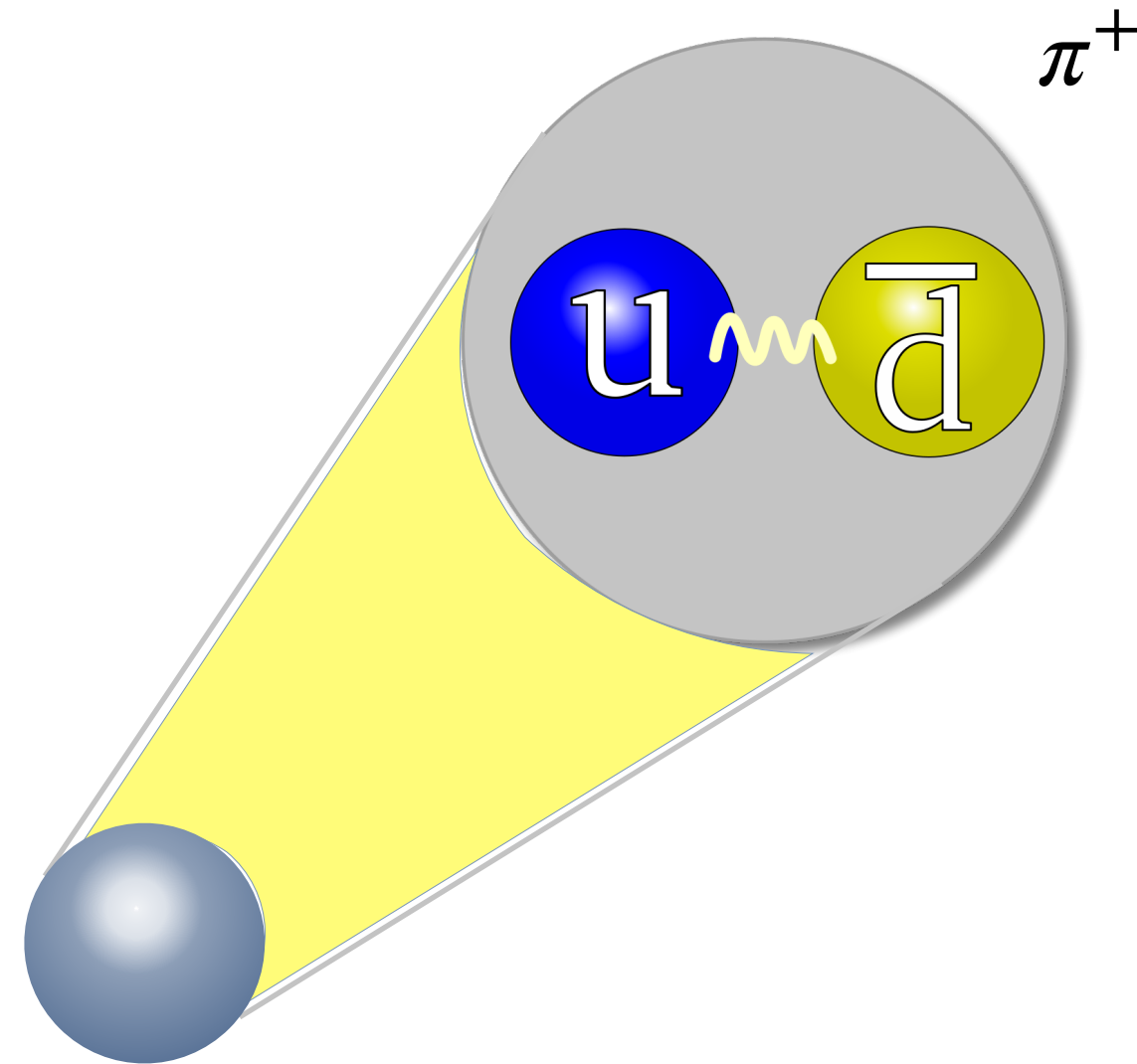
Solution: **Flavour dependence**



u, d

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

s (*sea*)

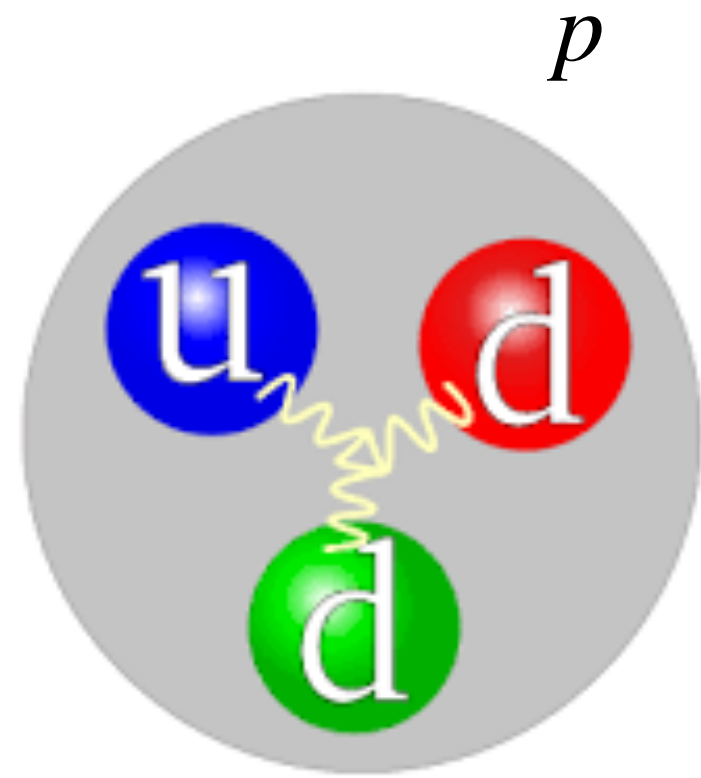


$u \rightarrow \pi^+, \dots$

$d \rightarrow \pi^+, \dots$

MAPTMD24 extraction

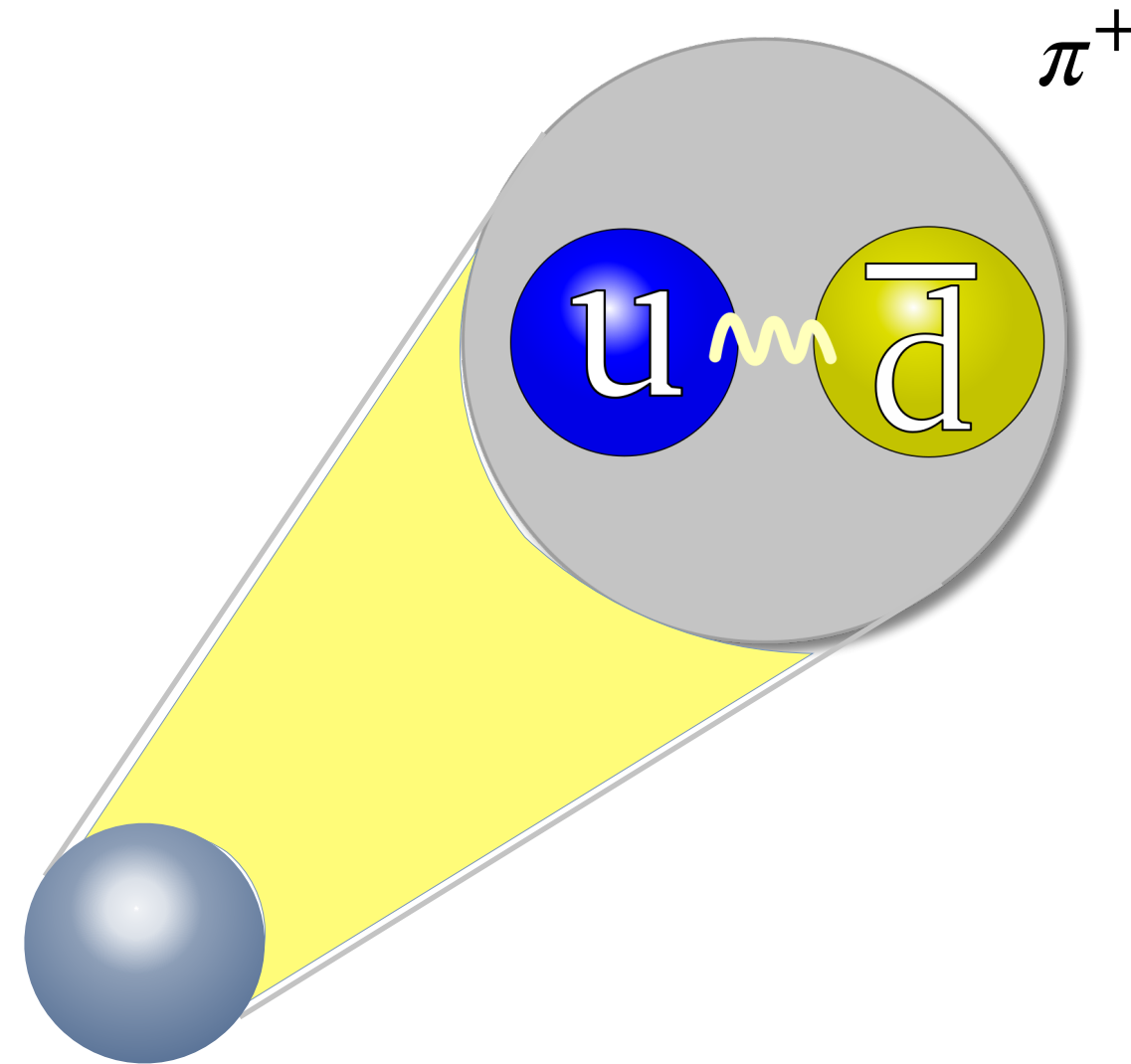
Solution: **Flavour dependence**



u, d

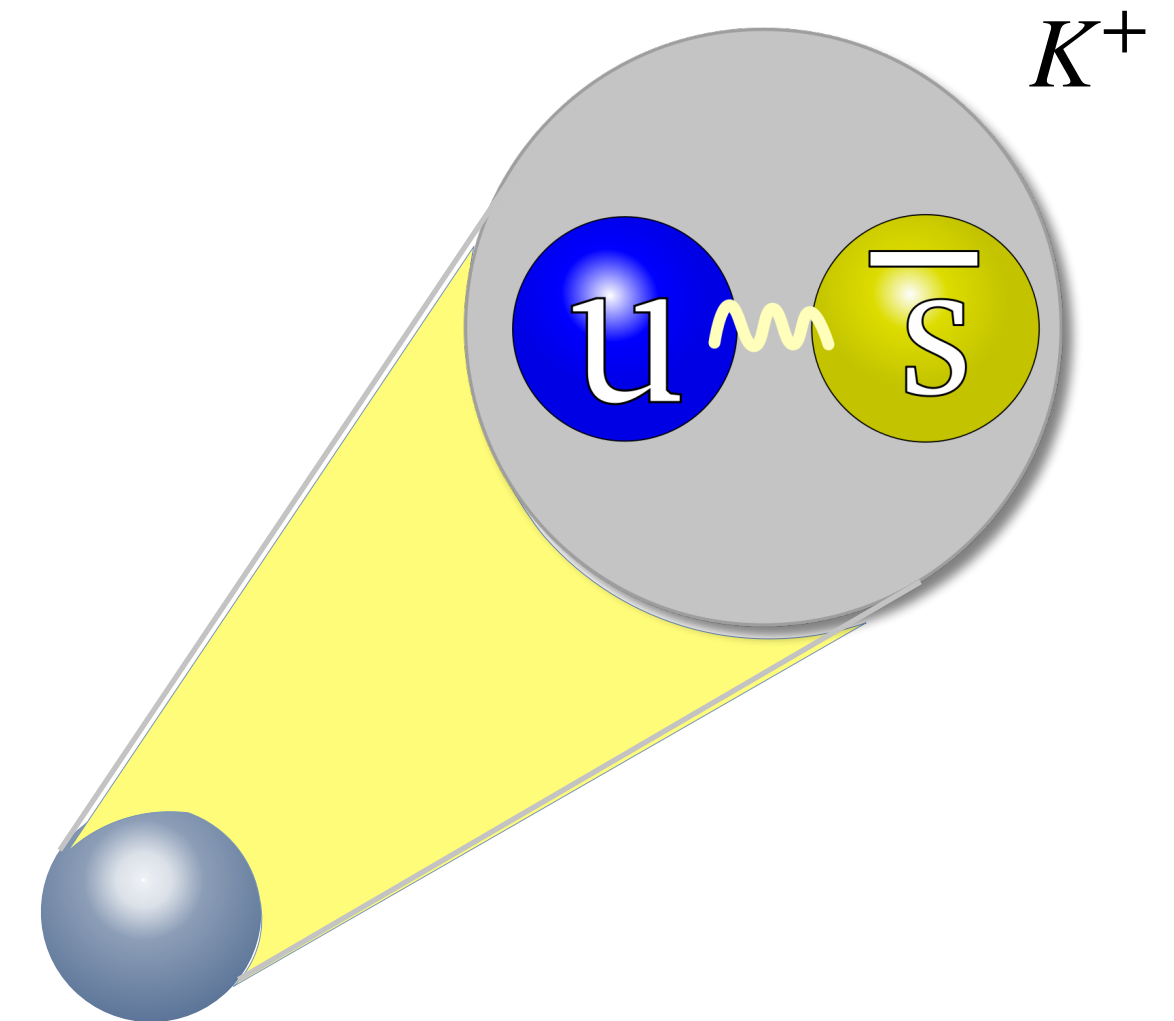
$\bar{u}, \bar{d}$

s (sea)



$u \rightarrow \pi^+, \dots$

$d \rightarrow \pi^+, \dots$



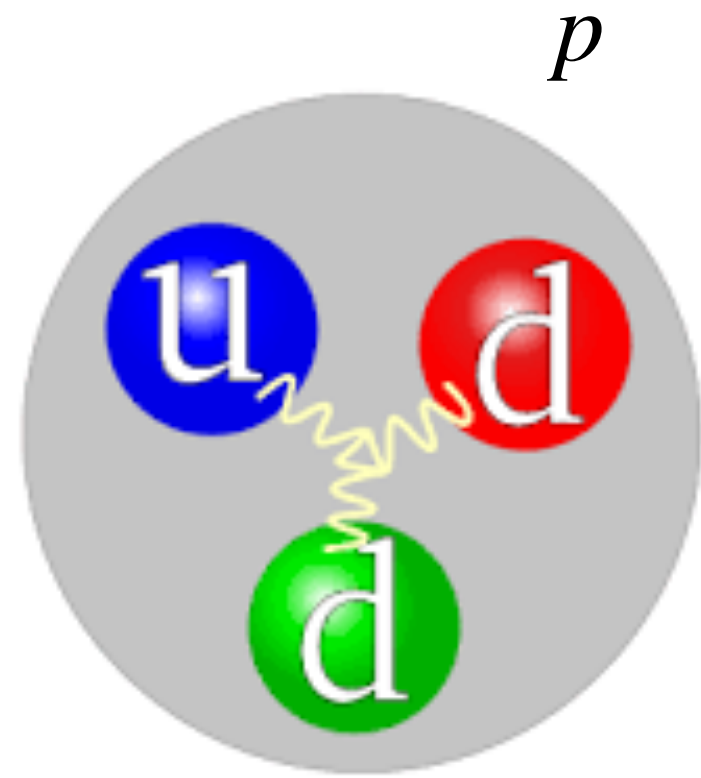
$u \rightarrow K^+, \dots$

$\bar{s} \rightarrow K^+, \dots$

$d \rightarrow K^+, \dots$

MAPTMD24 extraction

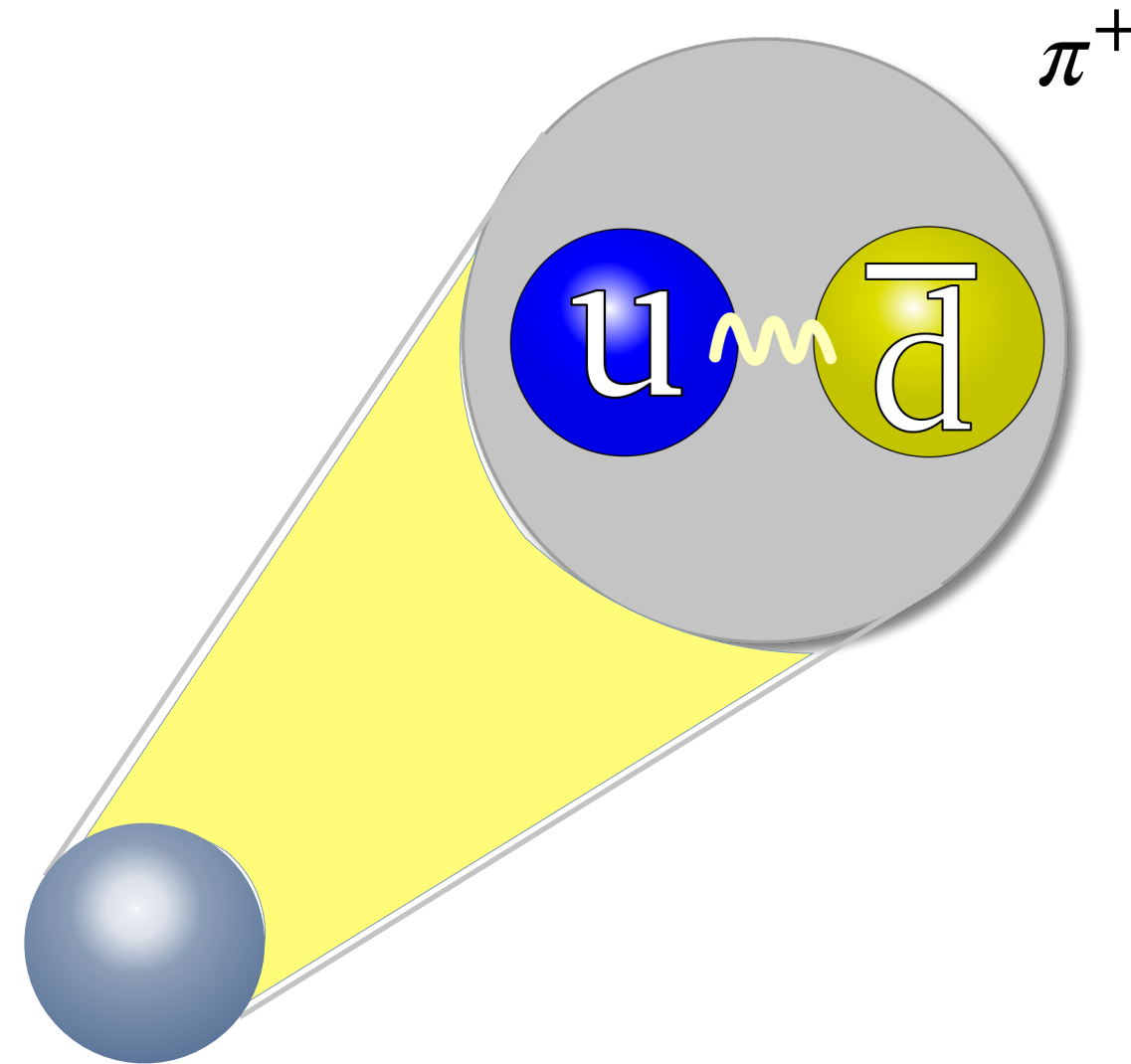
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u, d

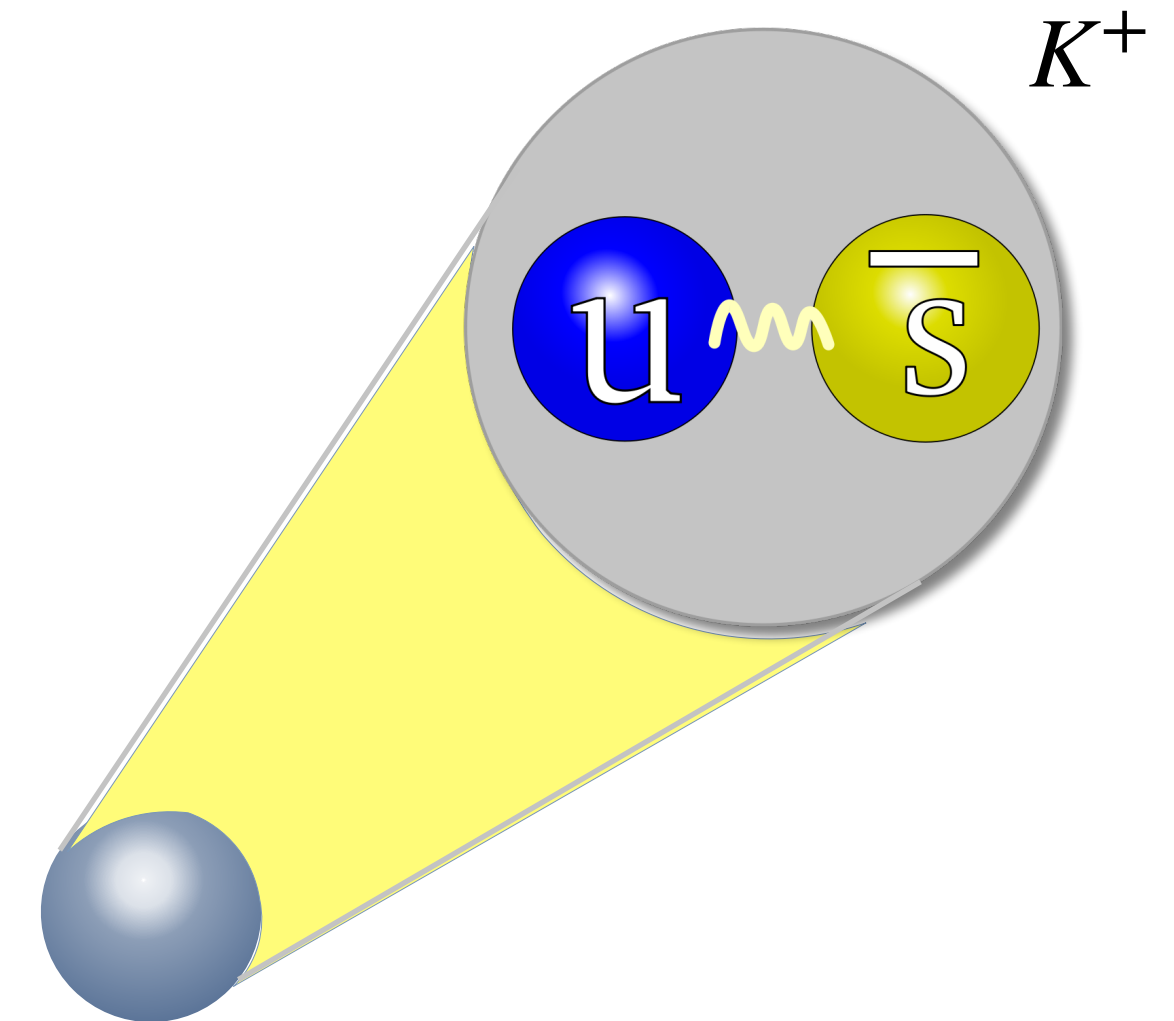
$\bar{u}, \bar{d}$

s (sea)



$u \rightarrow \pi^+, \dots$

$d \rightarrow \pi^+, \dots$



$u \rightarrow K^+, \dots$

$\bar{s} \rightarrow K^+, \dots$

$d \rightarrow K^+, \dots$

Negative fragmenting mesons: charge conjugation

MAPTMD24 extraction

MAPTMD24 extraction

HERMES

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

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

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

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

+ deuteron target

MAPTMD24 extraction

HERMES

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

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

$$e + p \rightarrow e' + K^+ + X \quad + \text{deuteron target}$$

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

high sensitivity to flavour dependence

MAPTMD24 extraction

HERMES

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

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

$$e + p \rightarrow e' + K^+ + X \quad + \text{deuteron target}$$

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

high sensitivity to flavour dependence

COMPASS

deuteron target & unidentified final state hadron

MAPTMD24 extraction

HERMES

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

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

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COMPASS

deuteron target & unidentified final state hadron

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MAPTMD24 extraction

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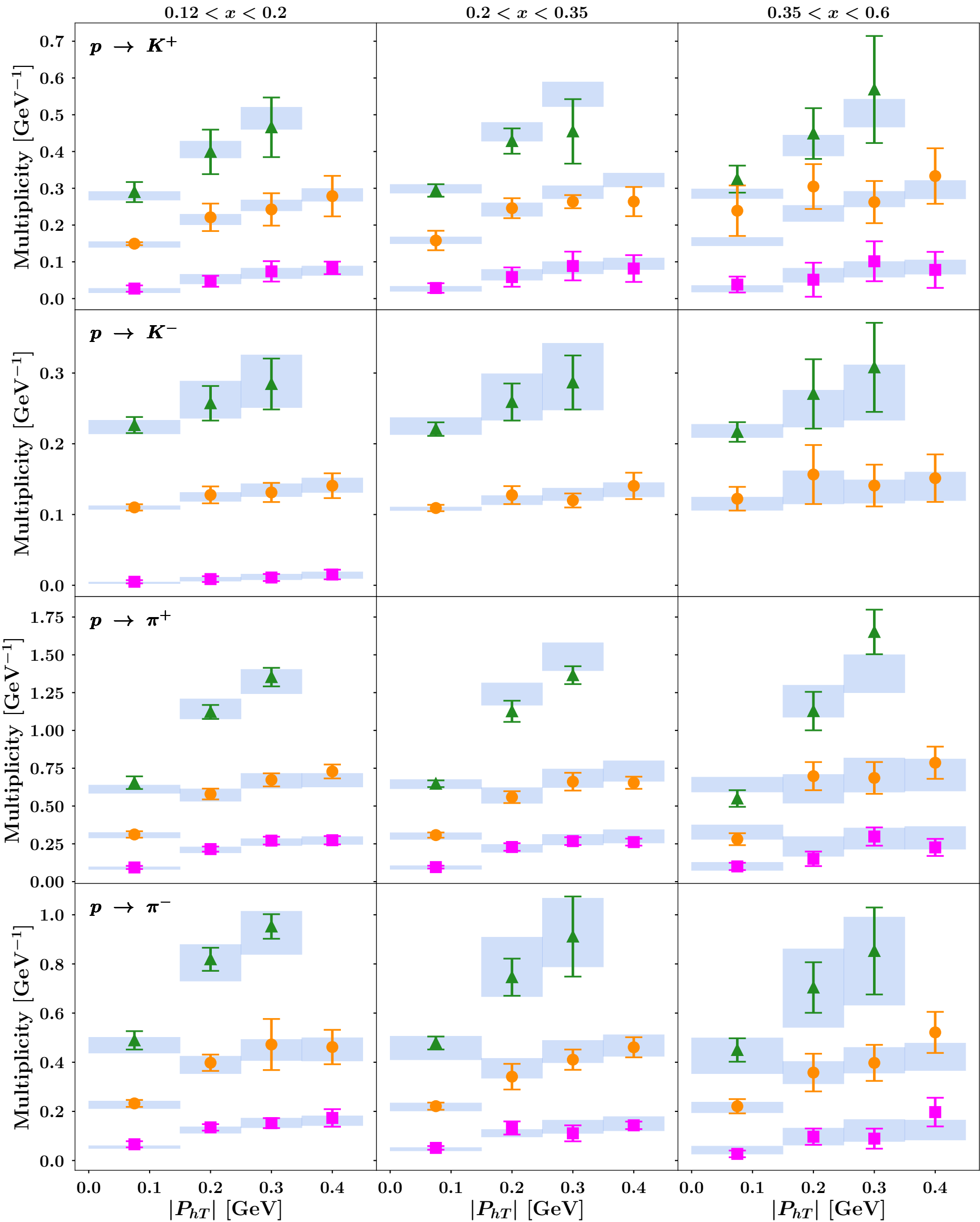
lowest sensitivity to flavour dependence

MAPTMD24 extraction - Results $\chi^2/N_{data} = 1.08$

	N ³ LL			
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
<i>HERMES total</i>	344	0.81	0.24	1.05
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SIDIS total	1547	0.70	0.26	0.96
Total	2031	0.81	0.27	1.08

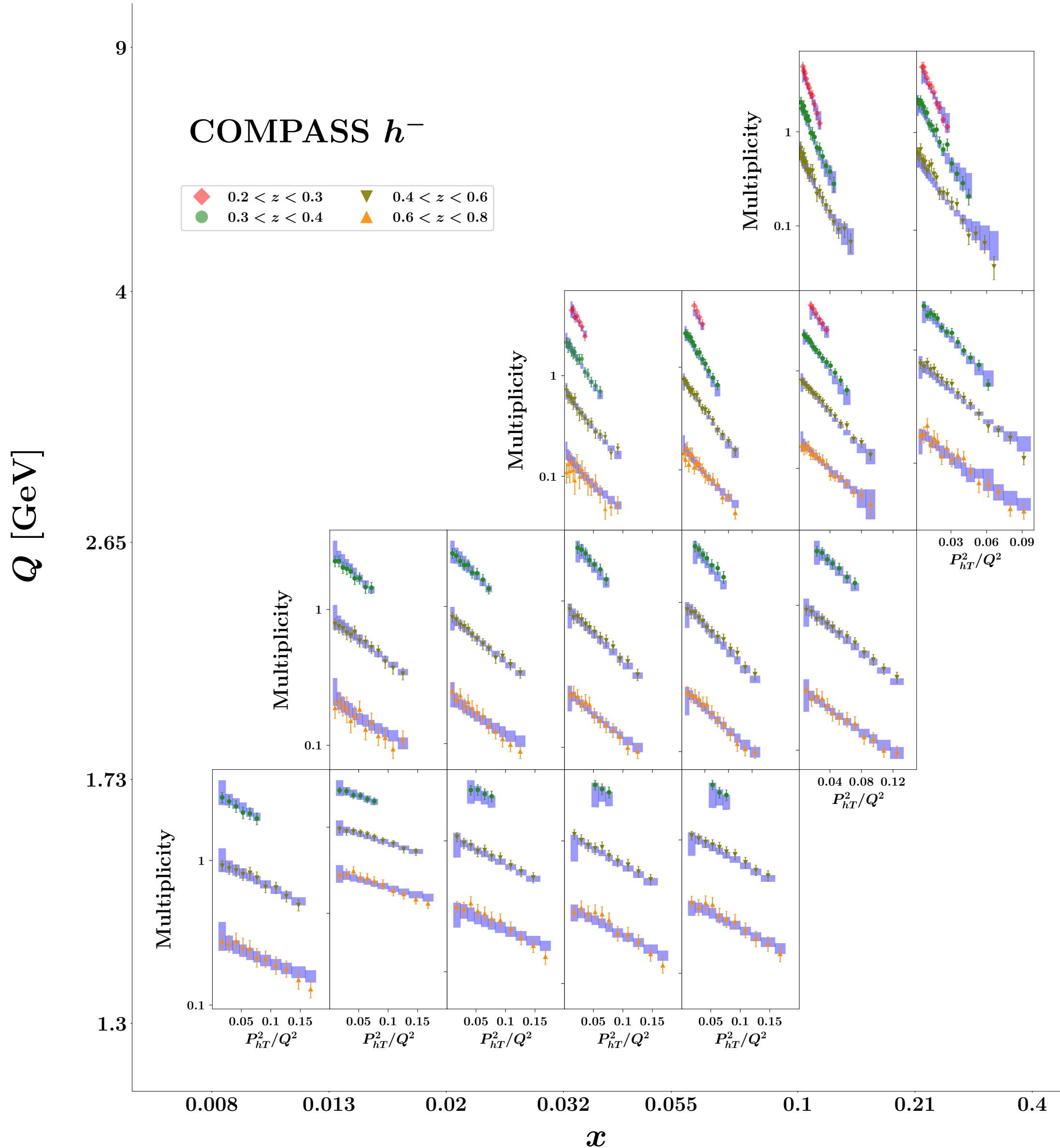
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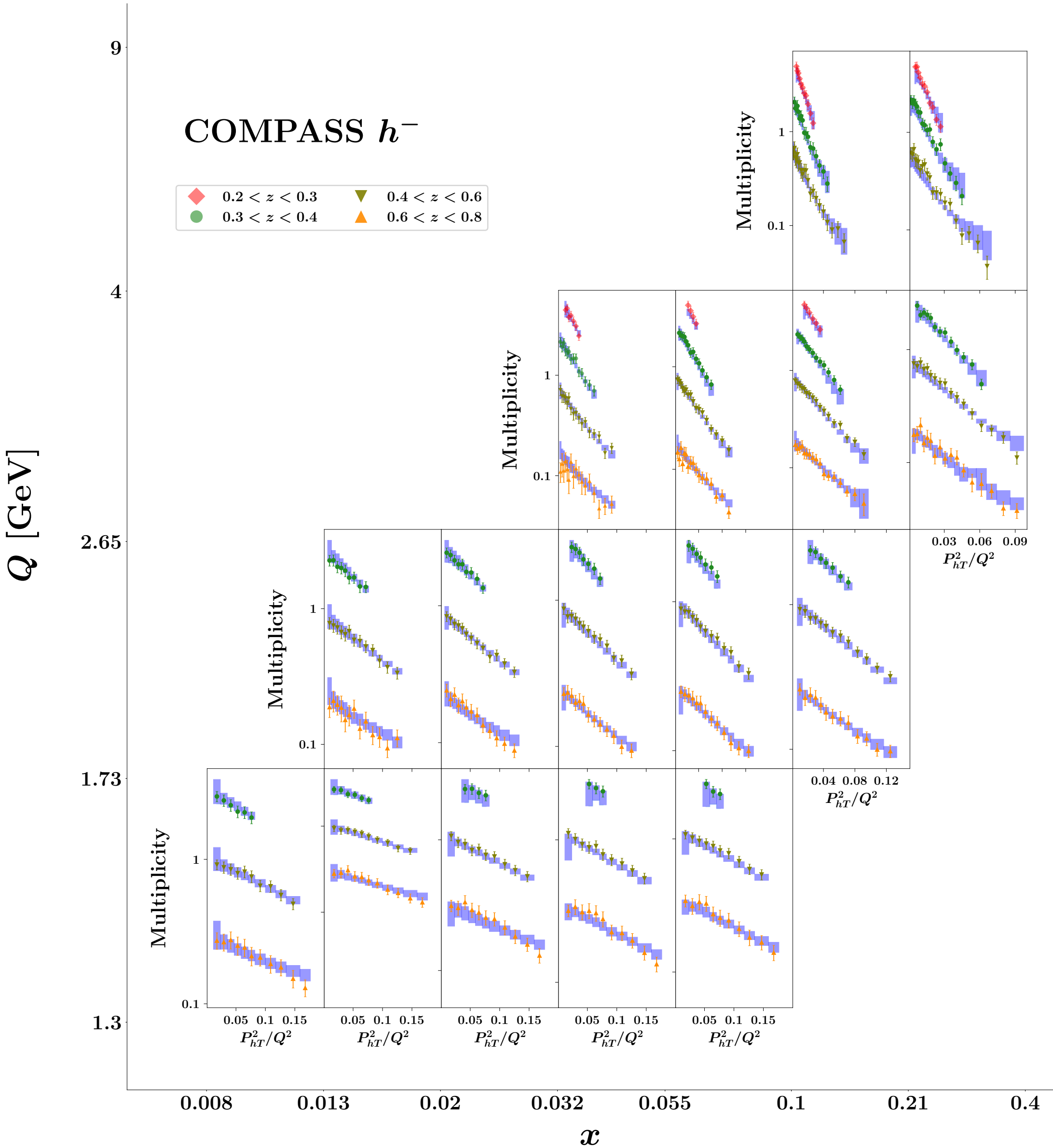
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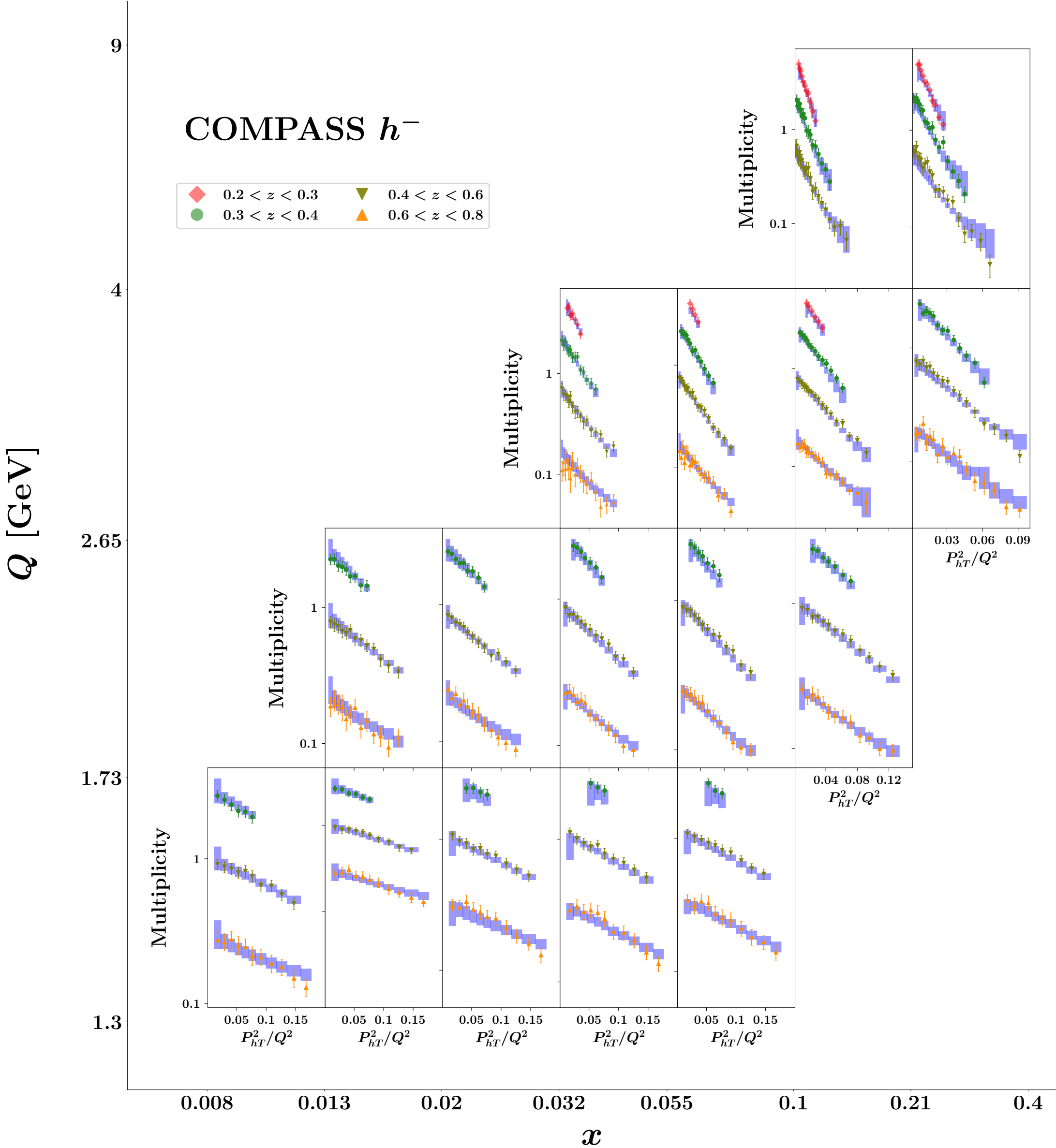
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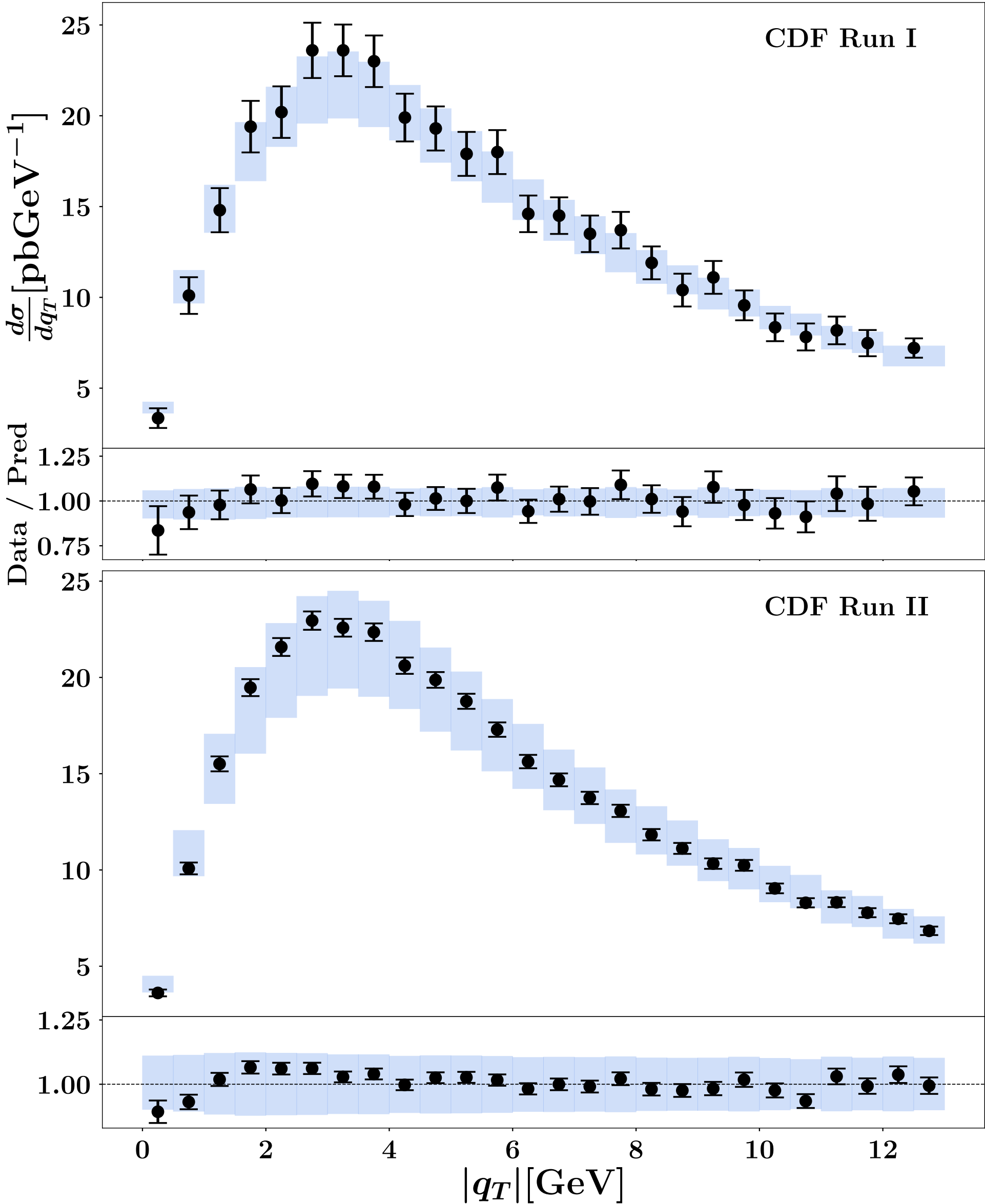
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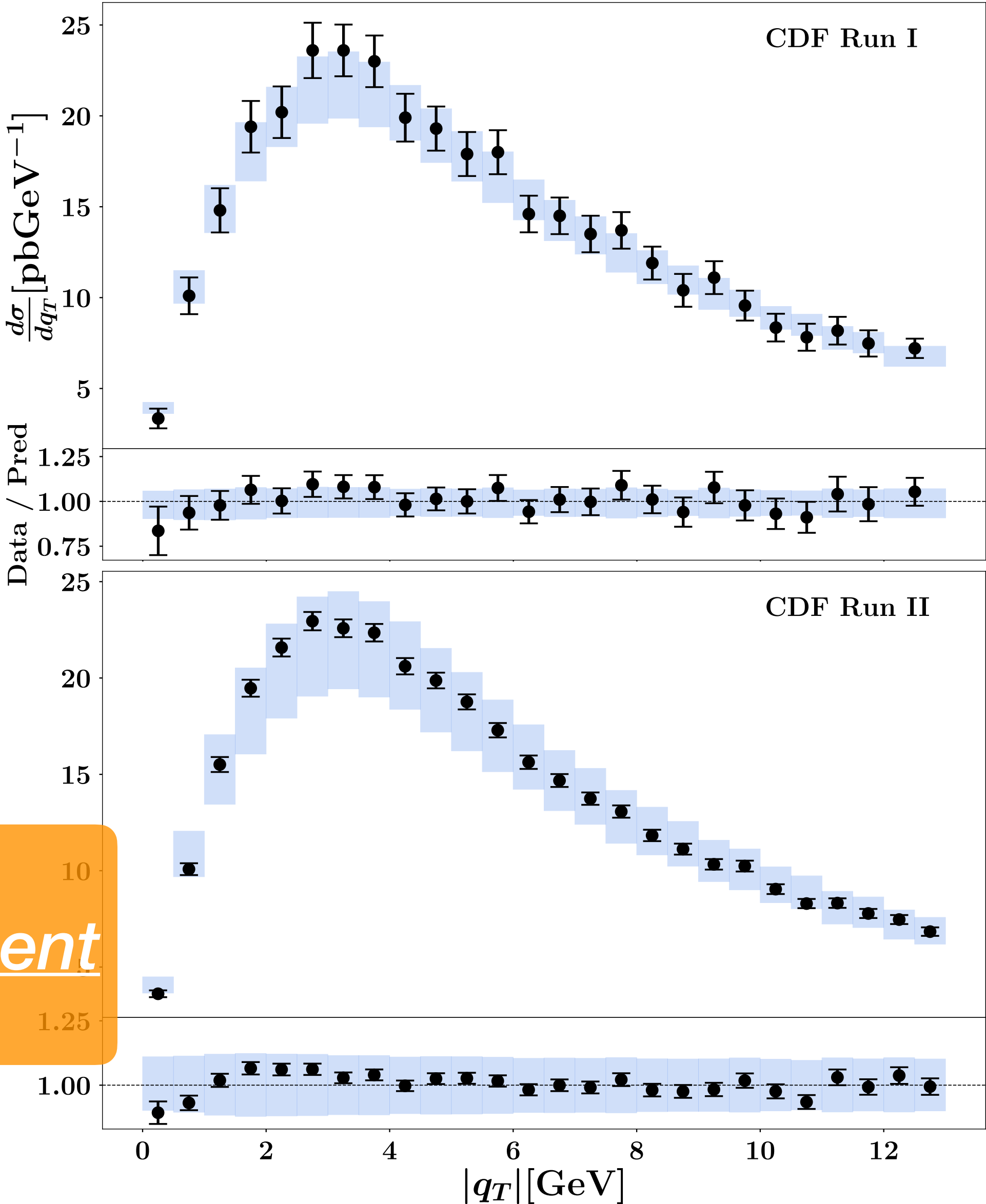


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Quite good agreement

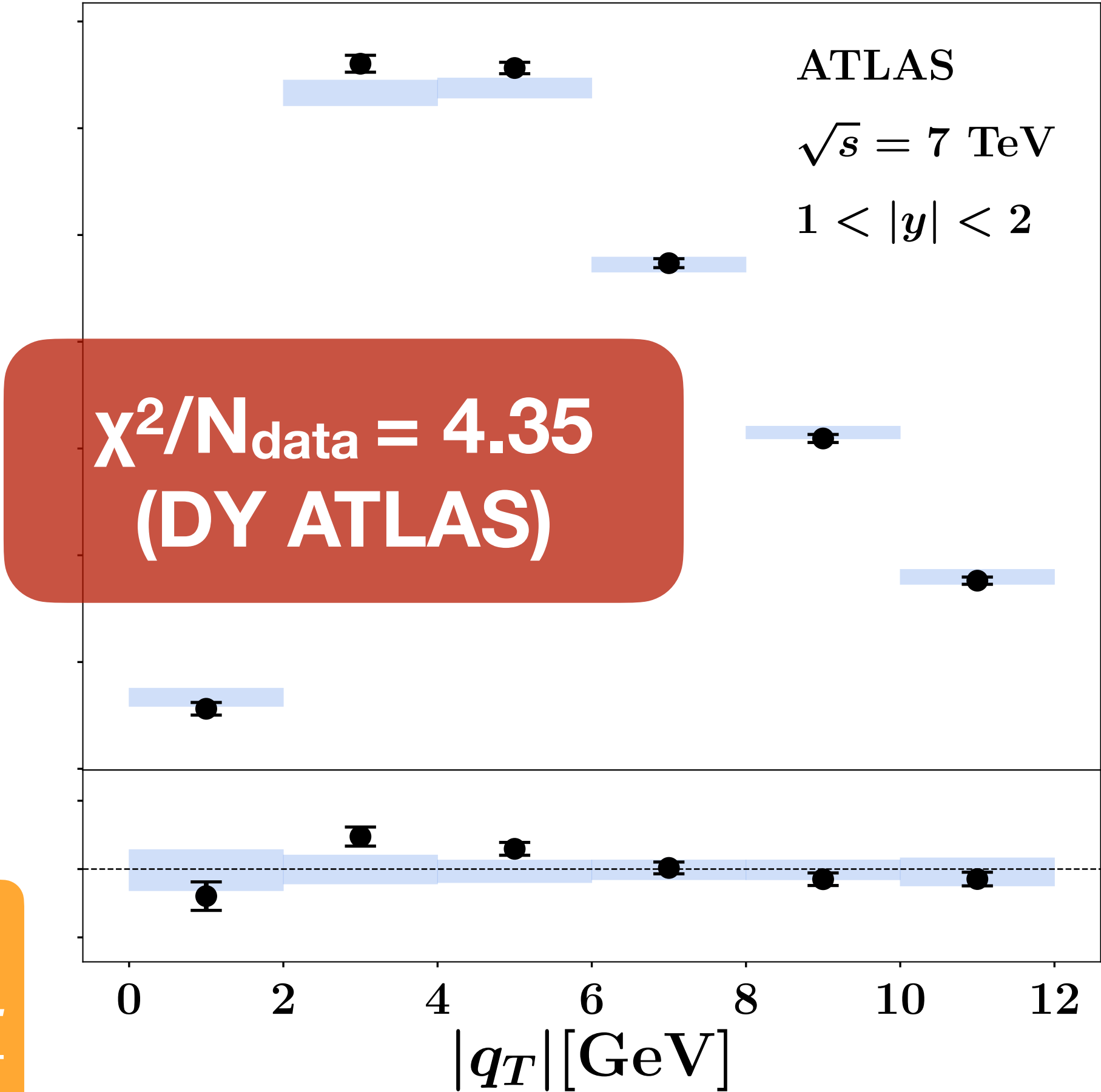


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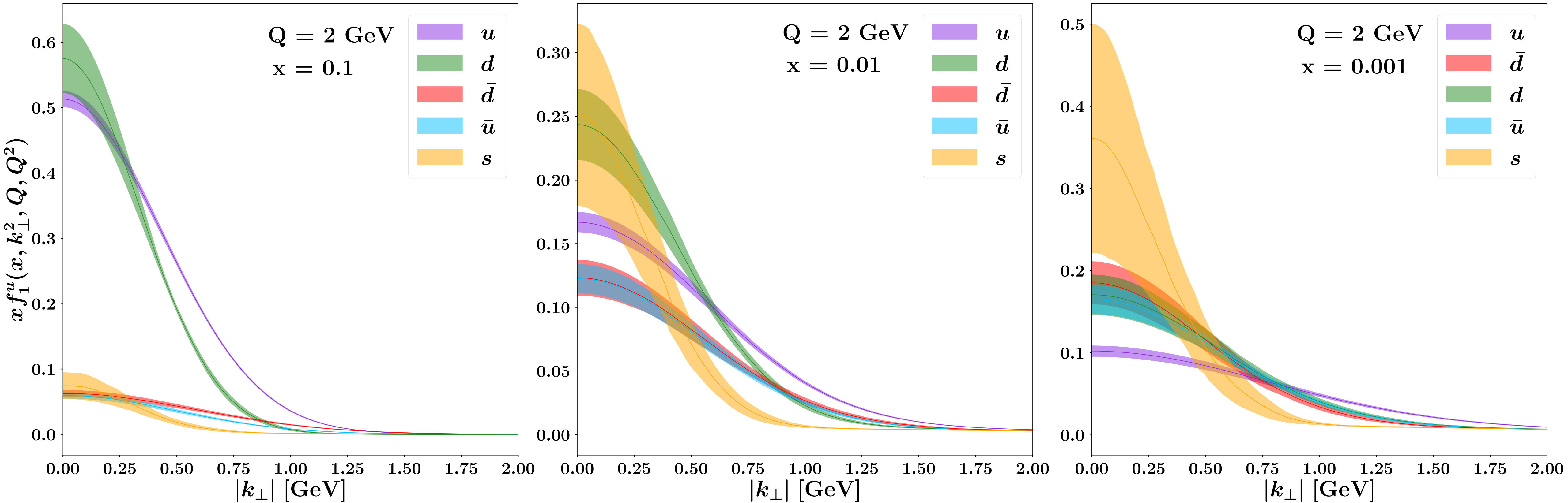
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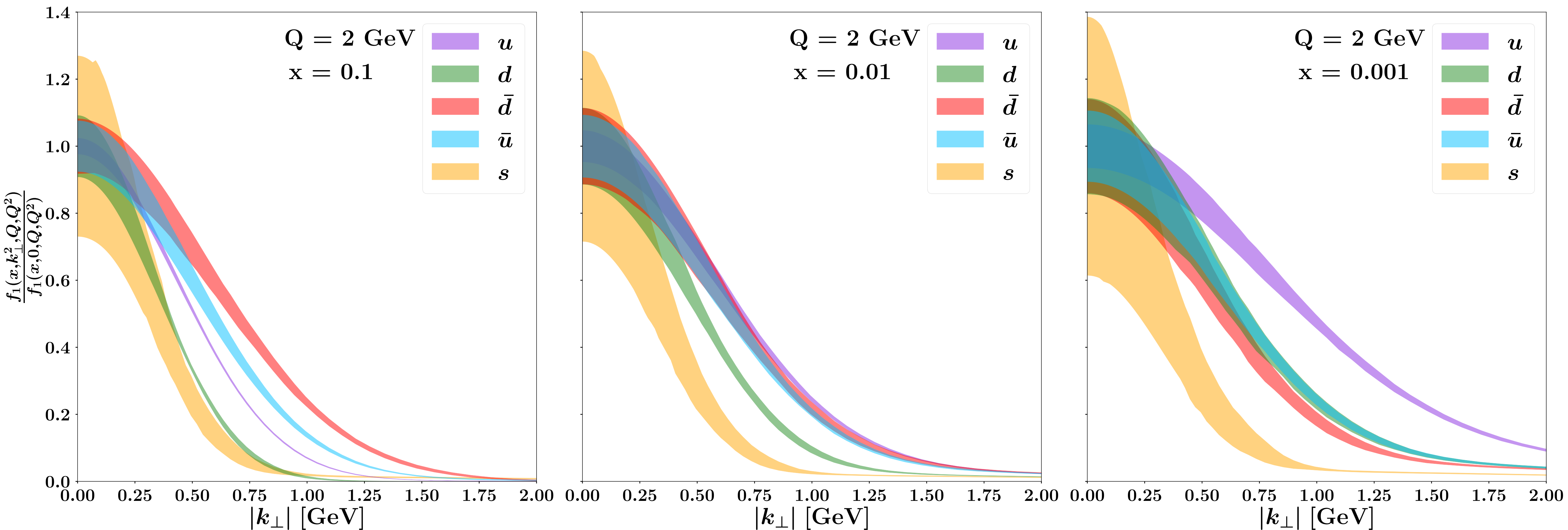
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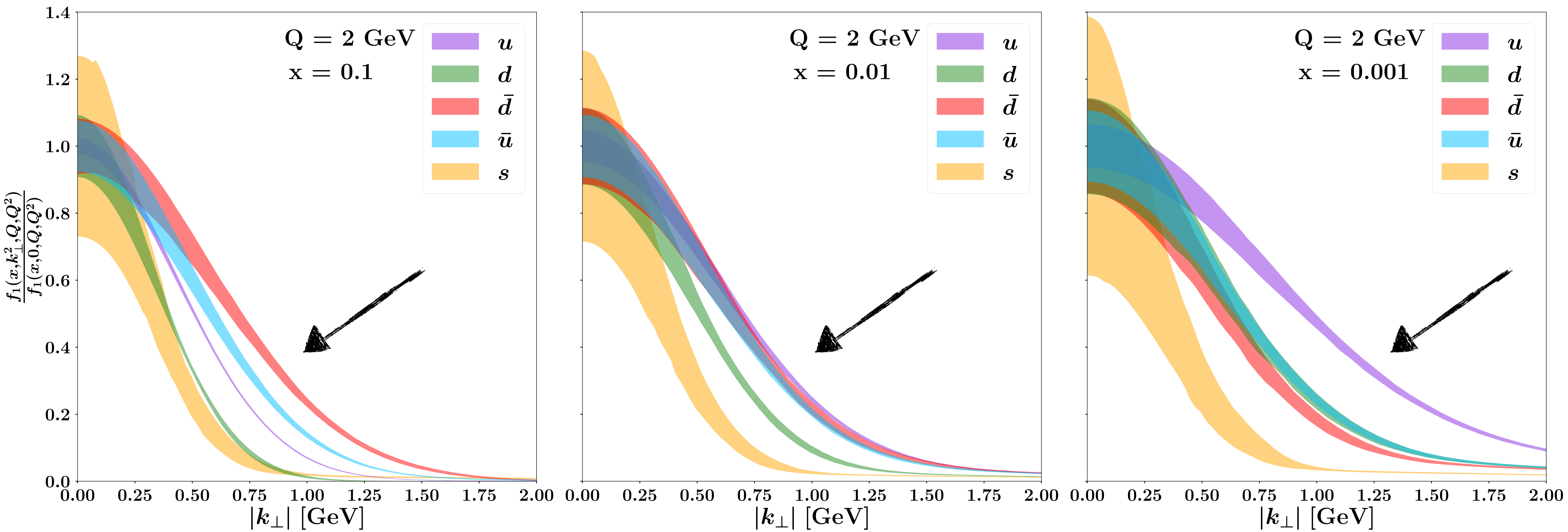
MAPTMD24 extraction - TMD PDFs



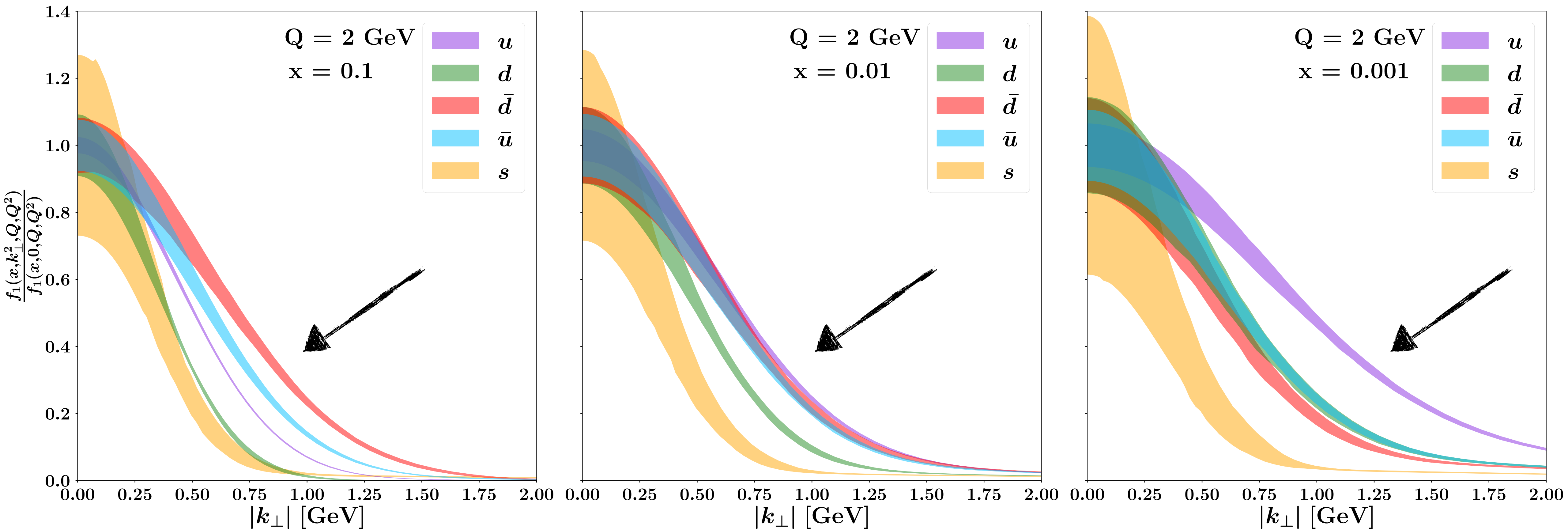
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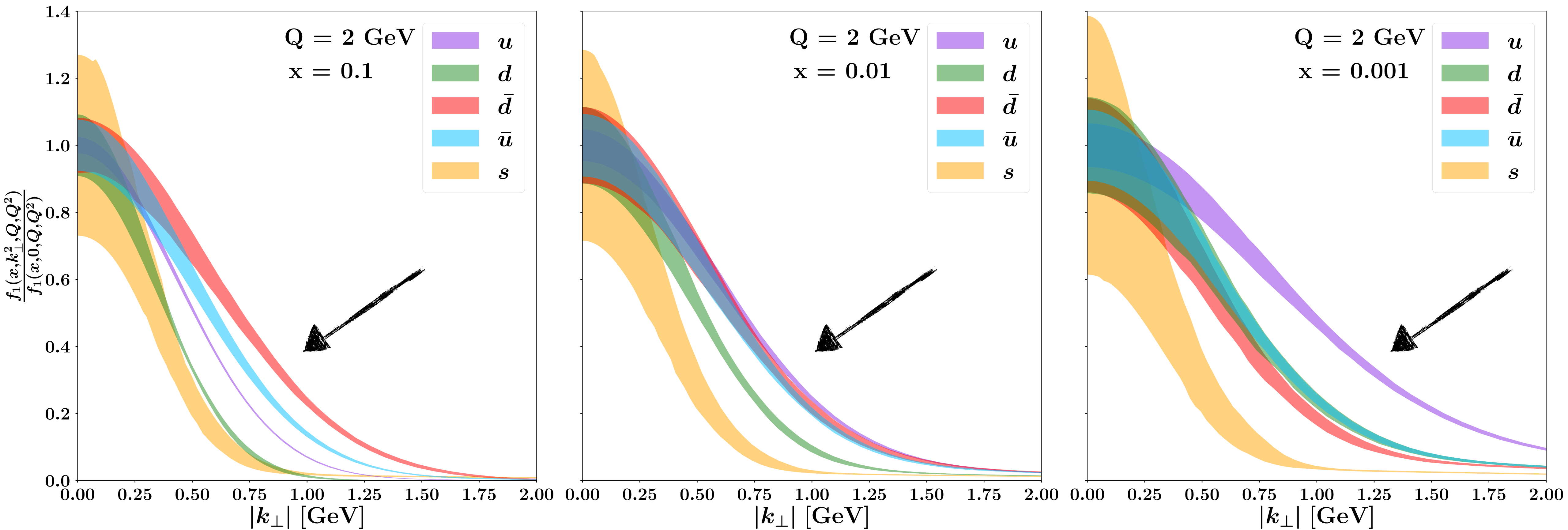


MAPTMD24 extraction - TMD PDFs



Very different $k_\perp$ - behaviours!

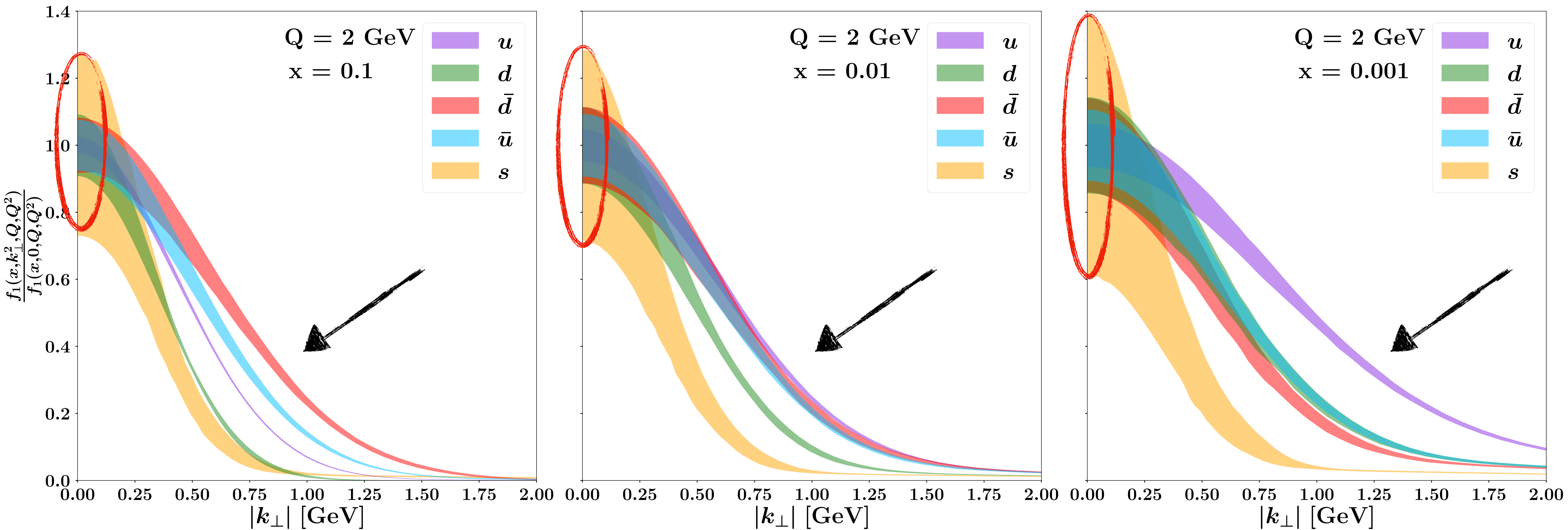
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It changes also by varying x

MAPTMD24 extraction - TMD PDFs

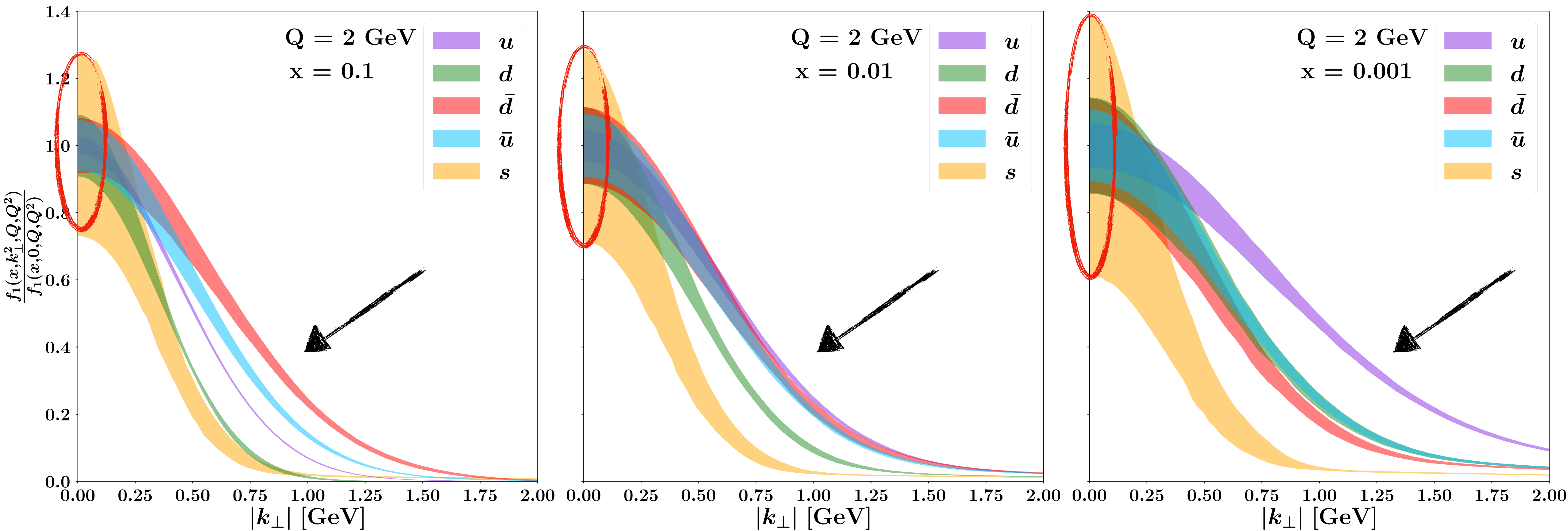


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MAPTMD24 extraction - TMD PDFs

The sea is the least constrained

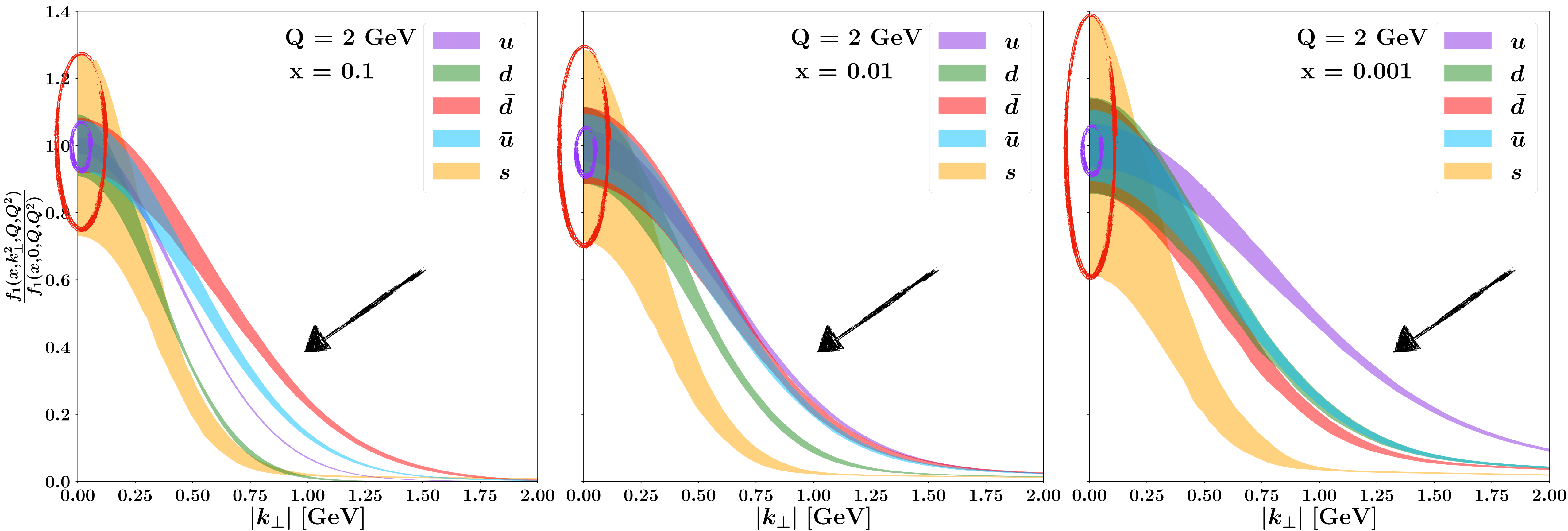


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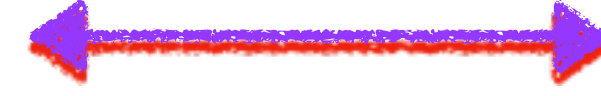


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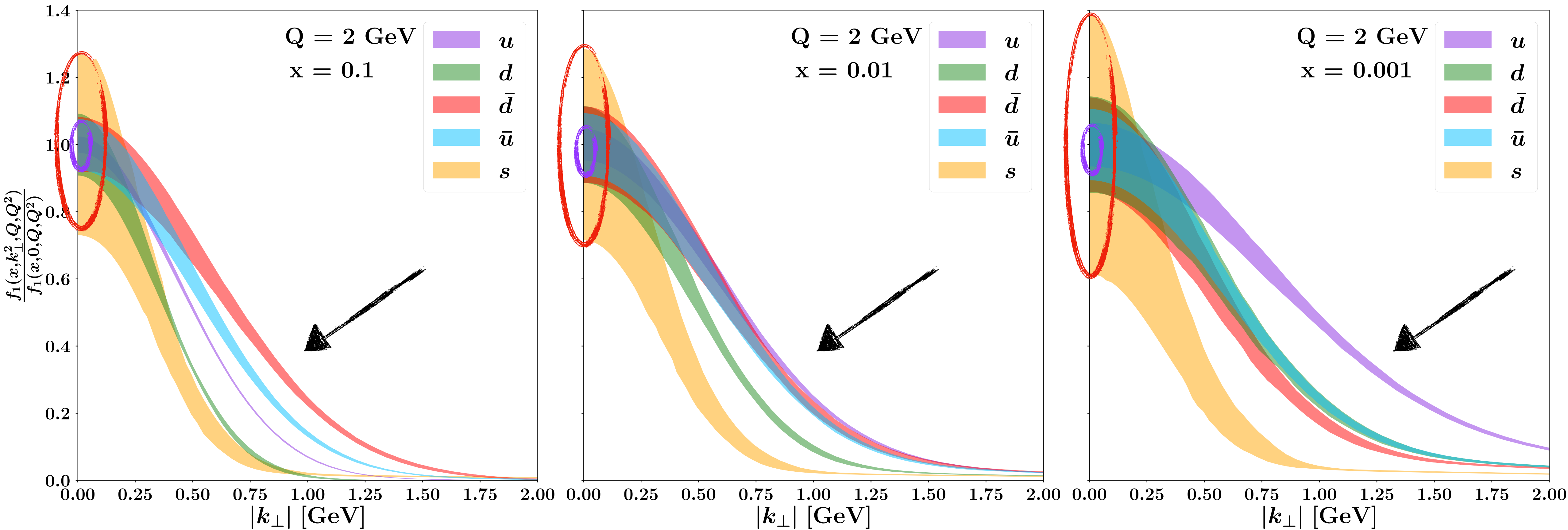
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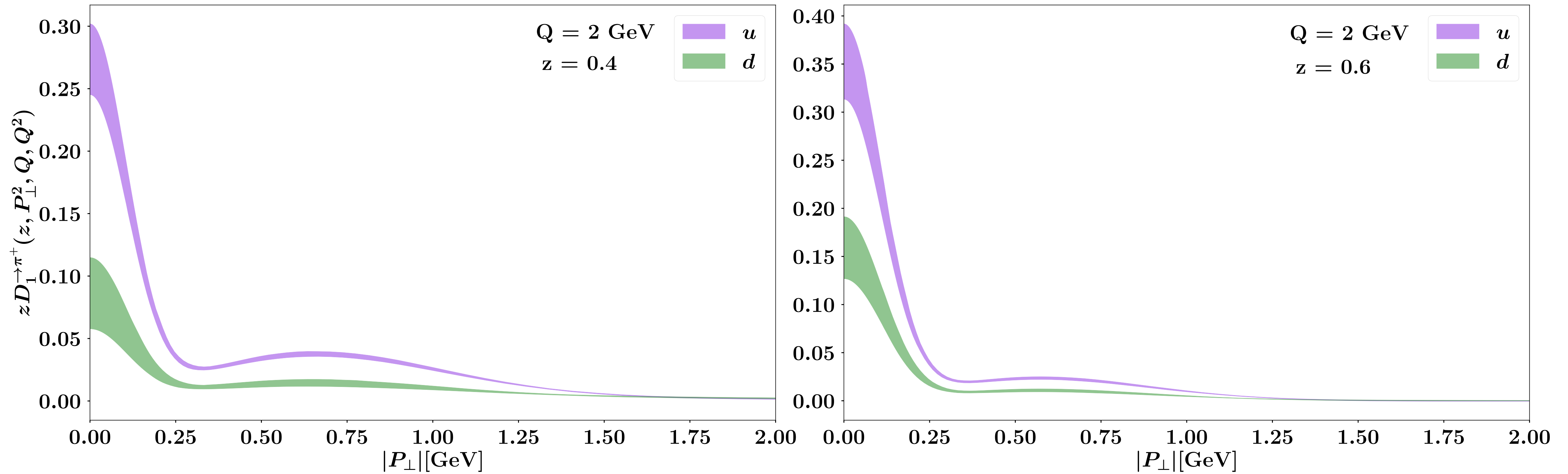
The up quark is the most one



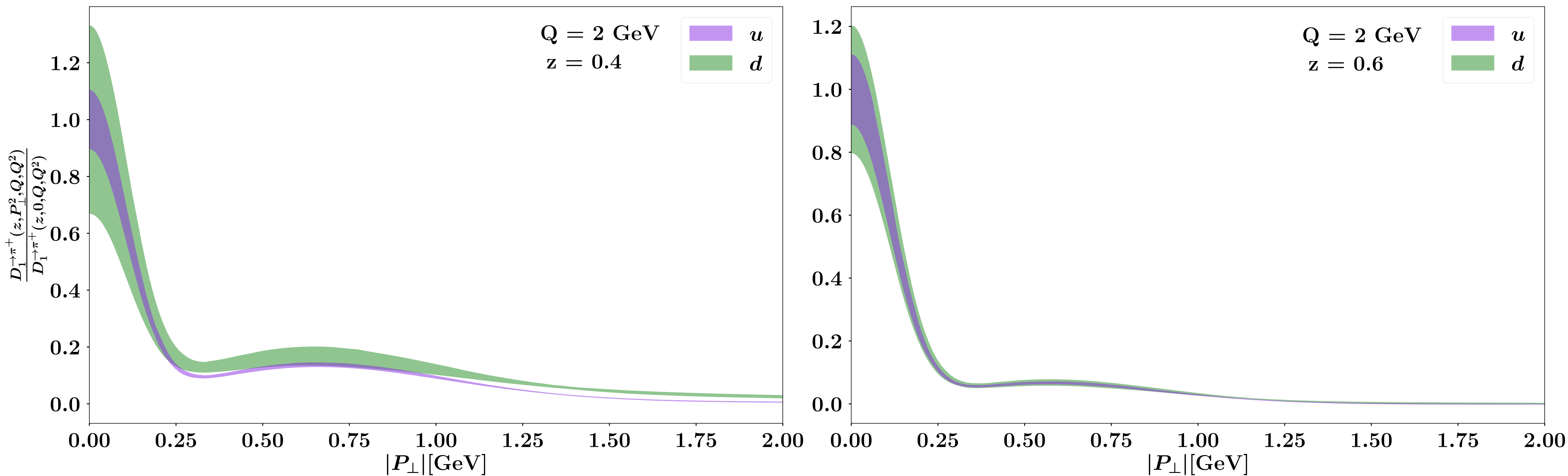
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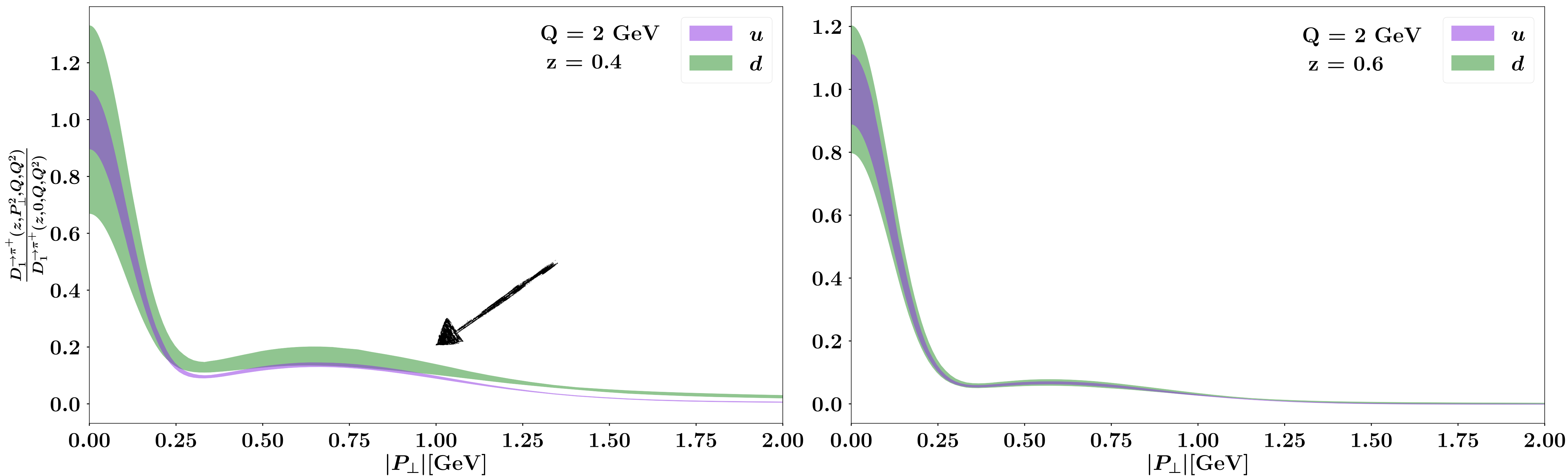
MAPTMD24 extraction - TMD FFs



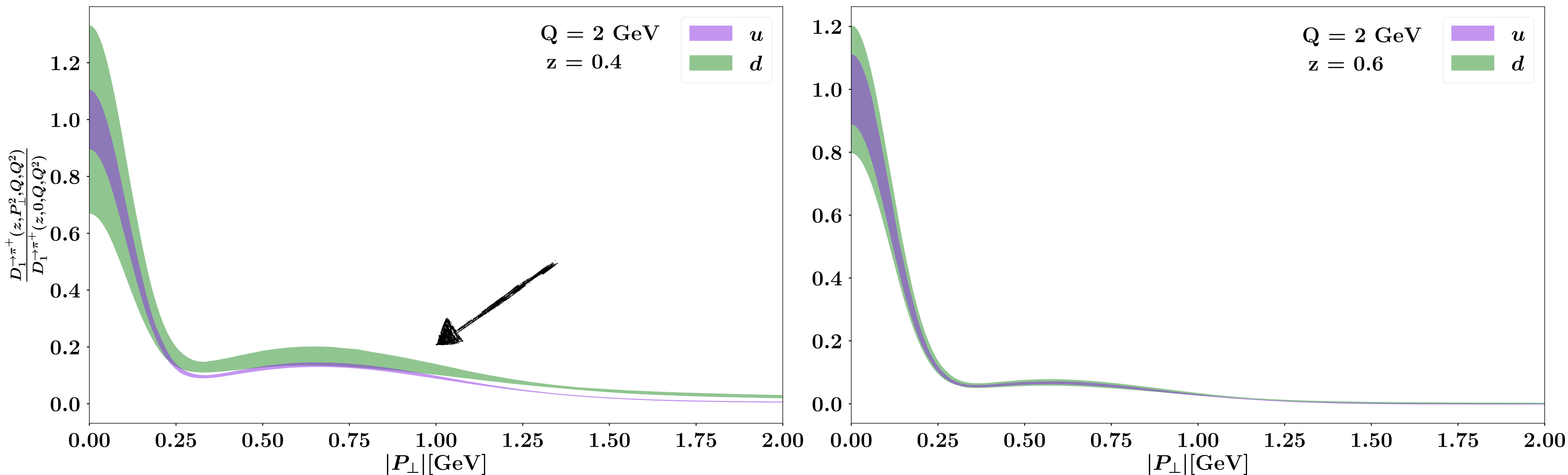
MAPTMD24 extraction - TMD FFs



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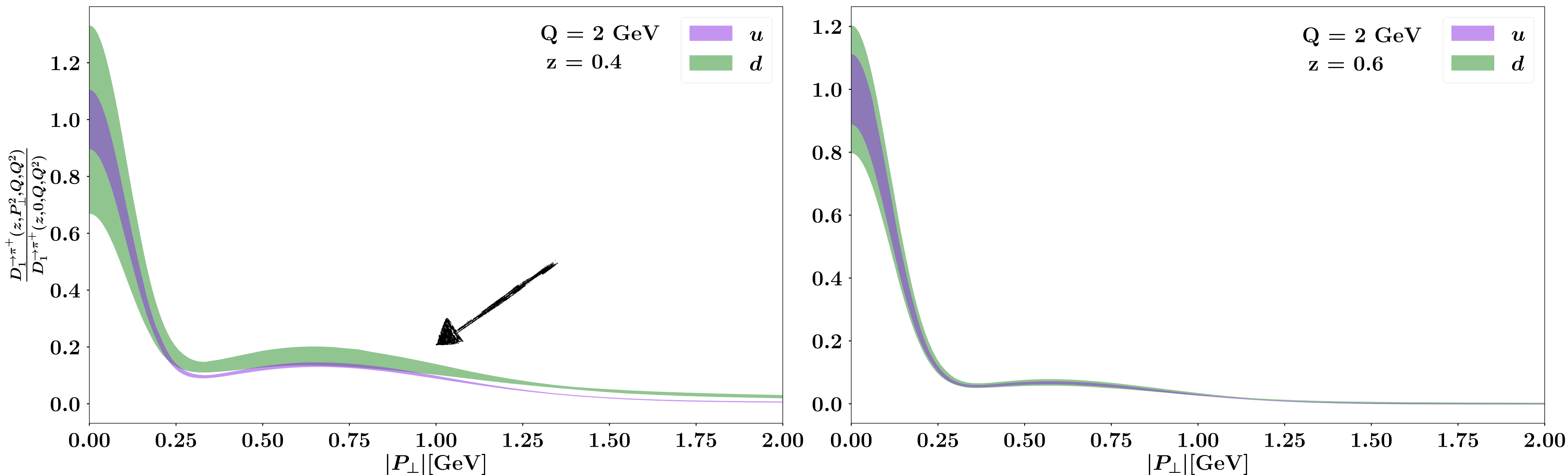
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Some signals of differences between favoured and unfavoured channels

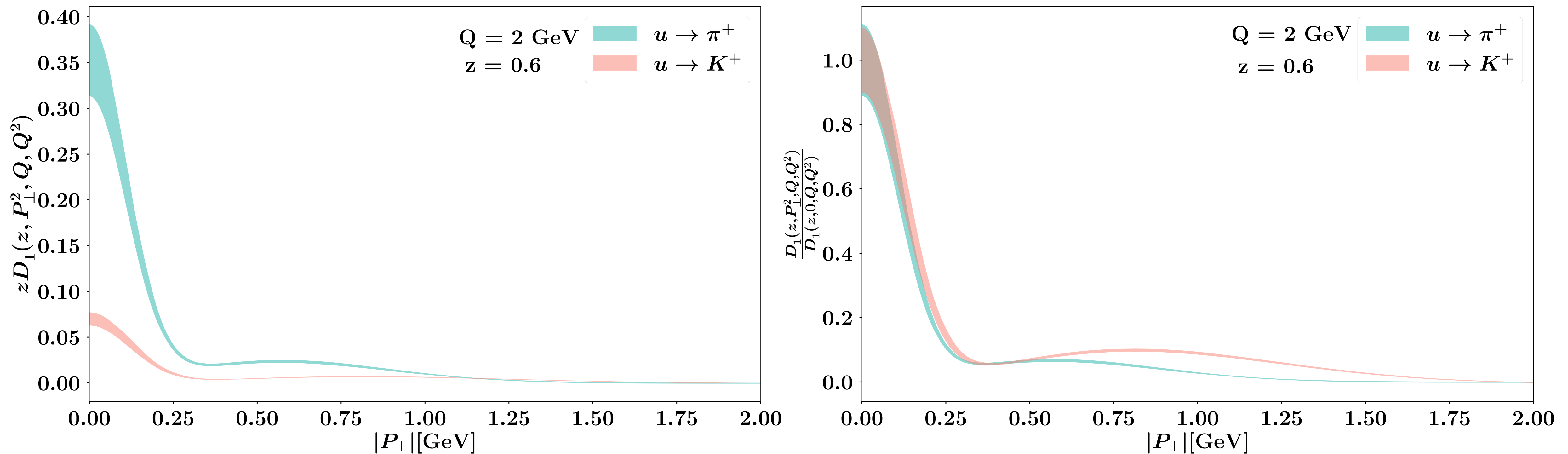
MAPTMD24 extraction - TMD FFs

The favoured is better constrained than the unfavoured one

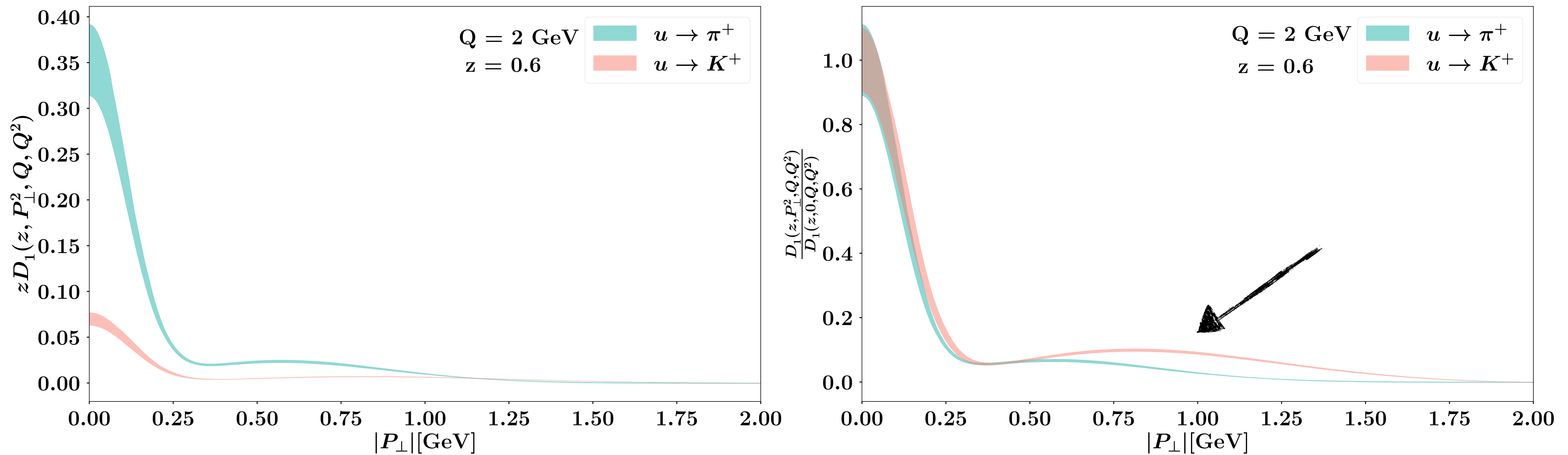


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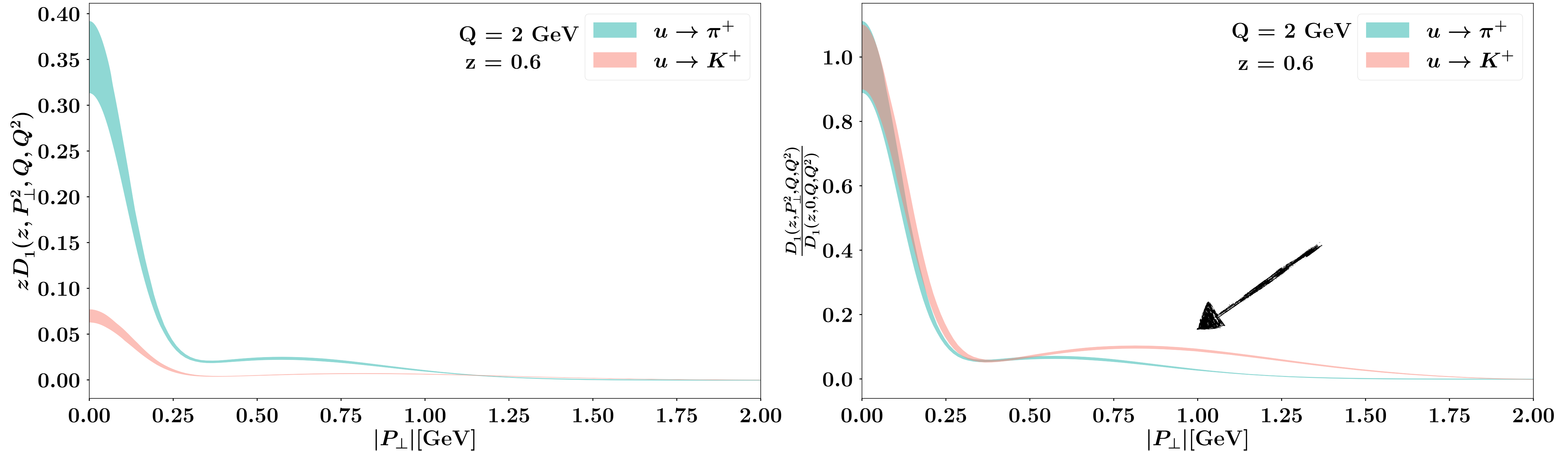
MAPTMD24 extraction - TMD FFs



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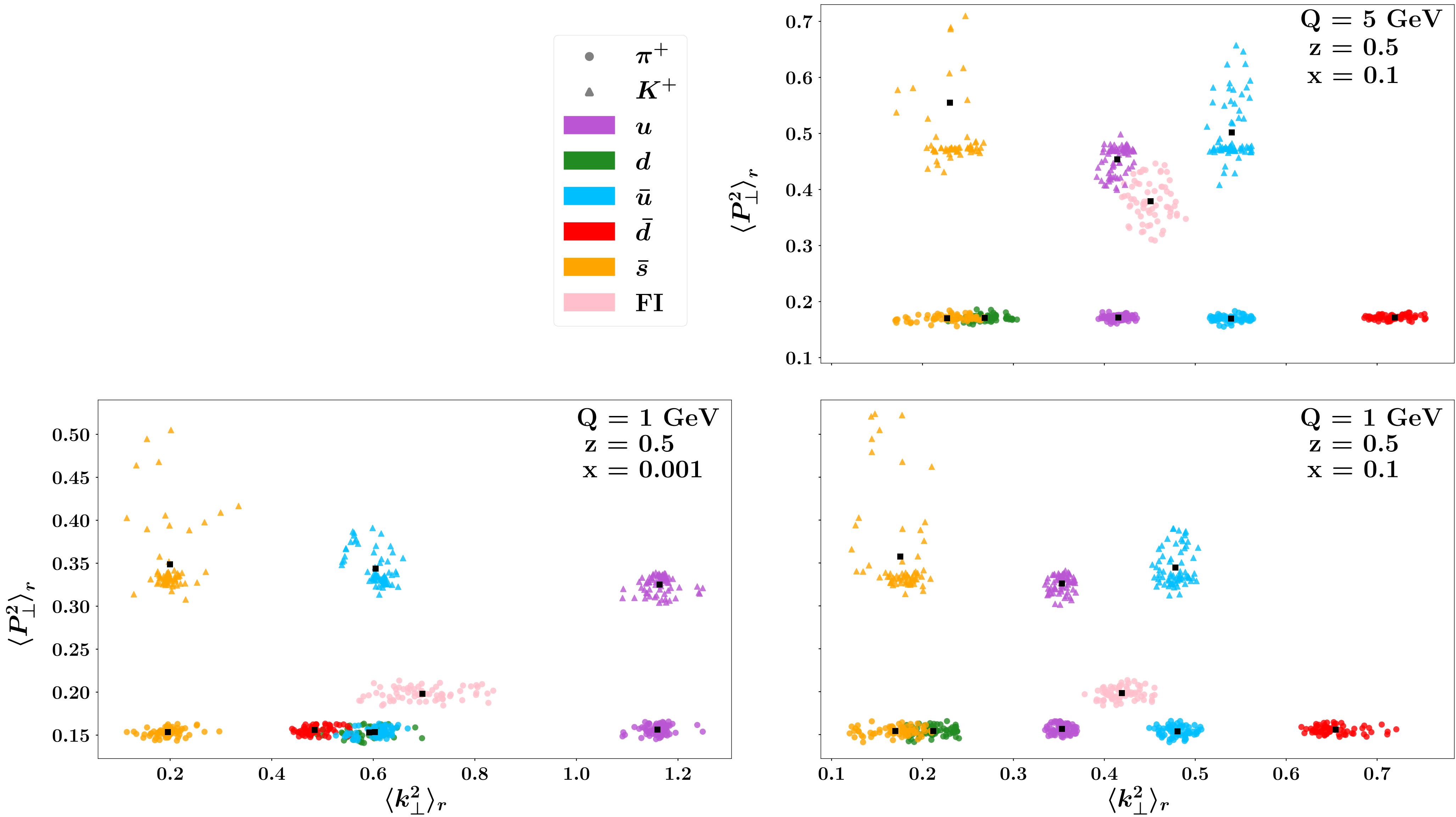


MAPTMD24 extraction - TMD FFs



Strong differences between different hadron fragmentations!

MAPTMD24 extraction - Scatter plots



Conclusions and outlook

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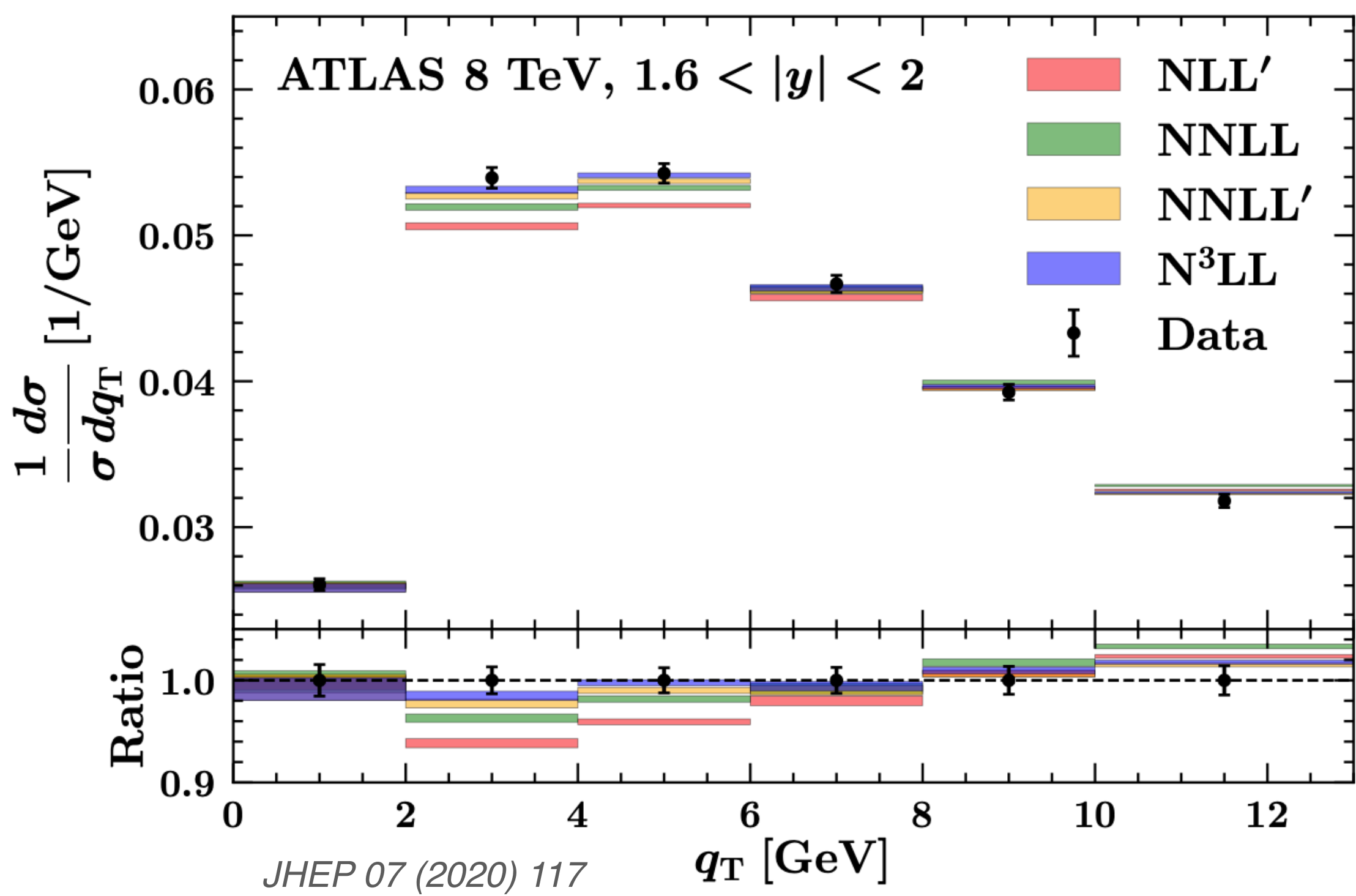
- **MAPTMD24** is the *first flavour dependent* extraction of unpolarized quarks TMDs in the proton from a *global* fit
- We find *significant* differences between the flavors in the ***TMD PDFs***.
- We find *significant* differences between different final hadrons in the ***TMD FFs***.
- We find a weak signal between different flavors in the same final hadron.

BACKUP

MAPTMD22: Normalization of SIDIS

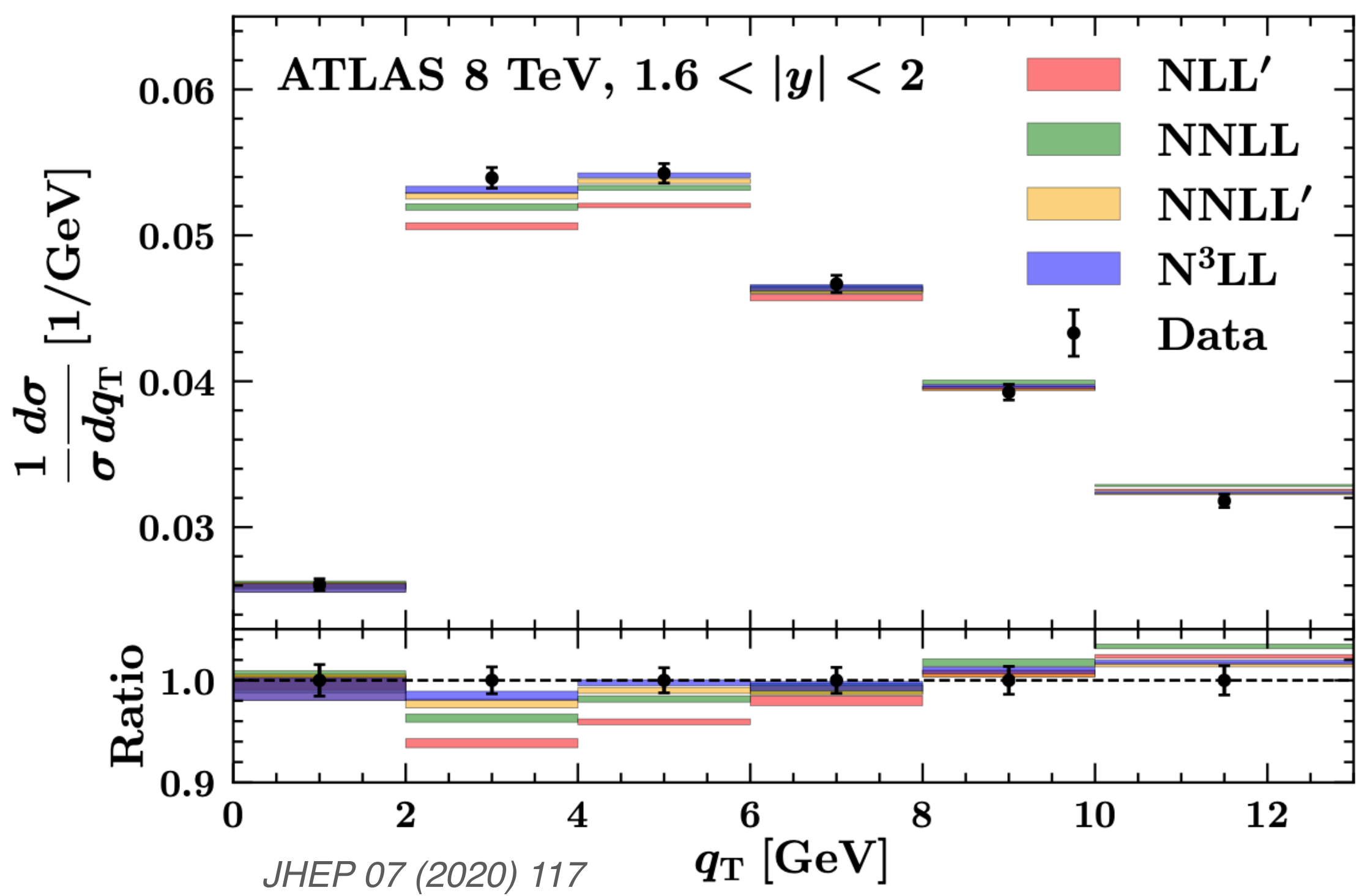
MAPTMD22: Normalization of SIDIS

High Energy Drell-Yan



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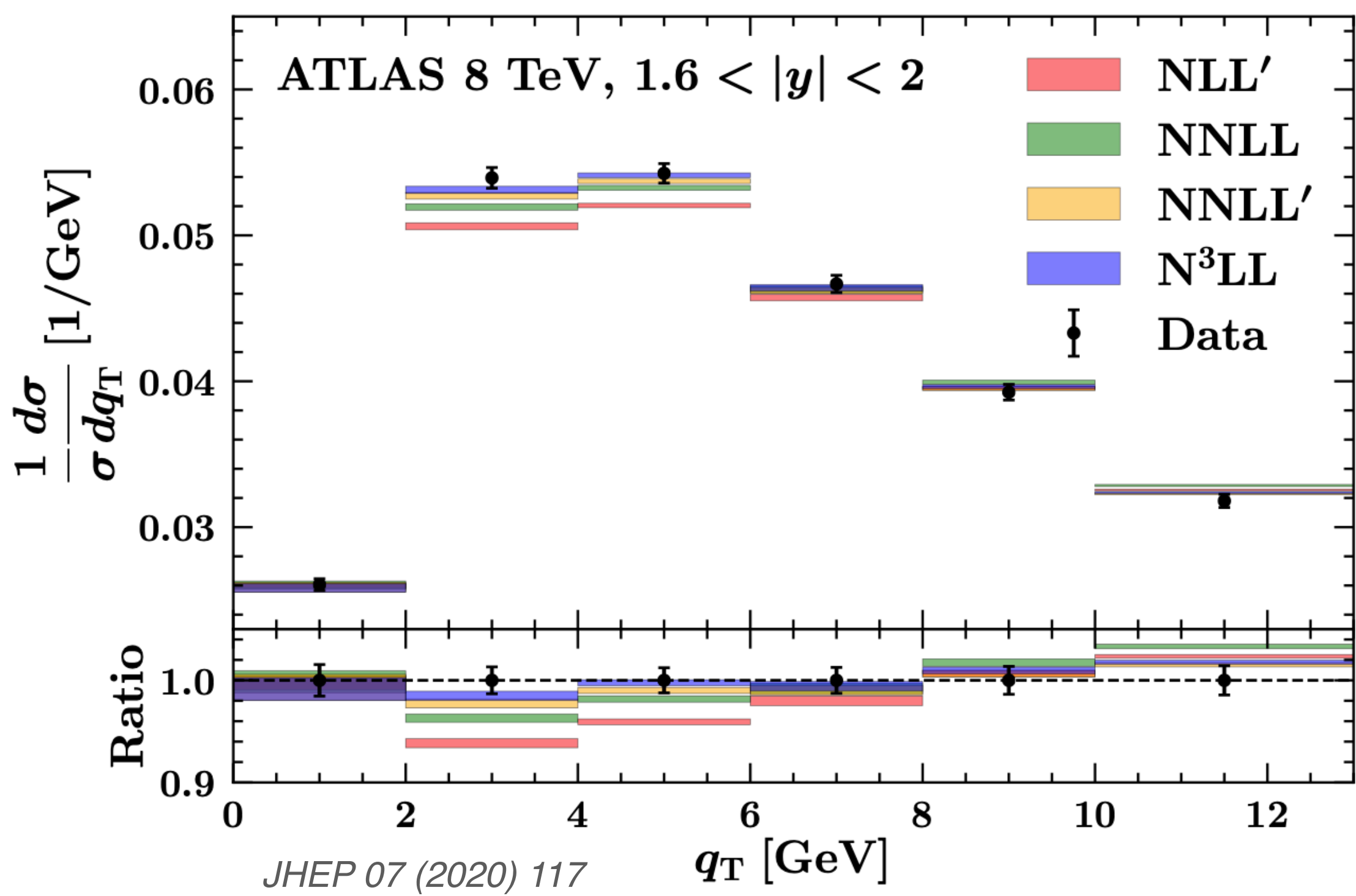
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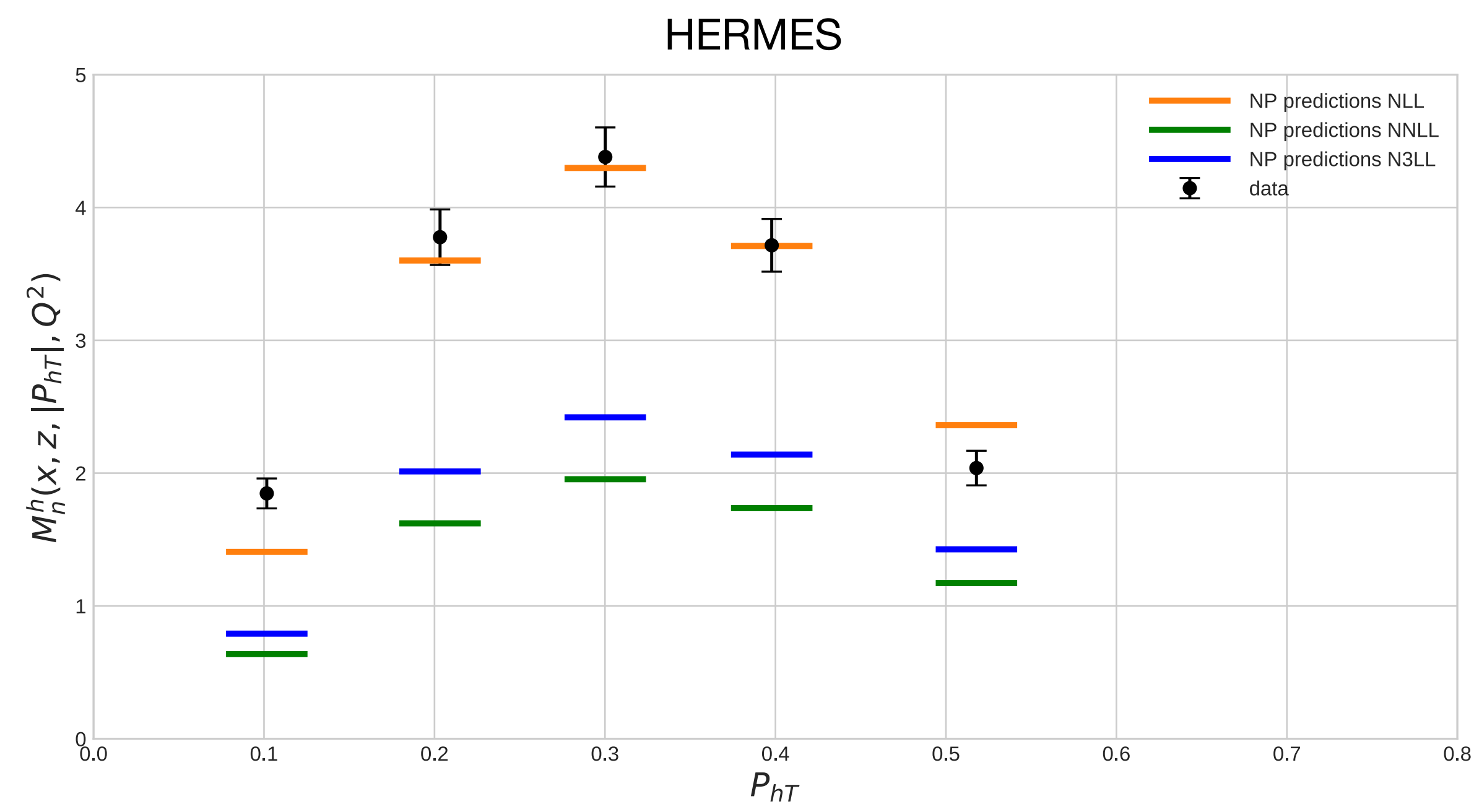
The description improves at high orders

MAPTMD22: Normalization of SIDIS

High Energy Drell-Yan



SIDIS

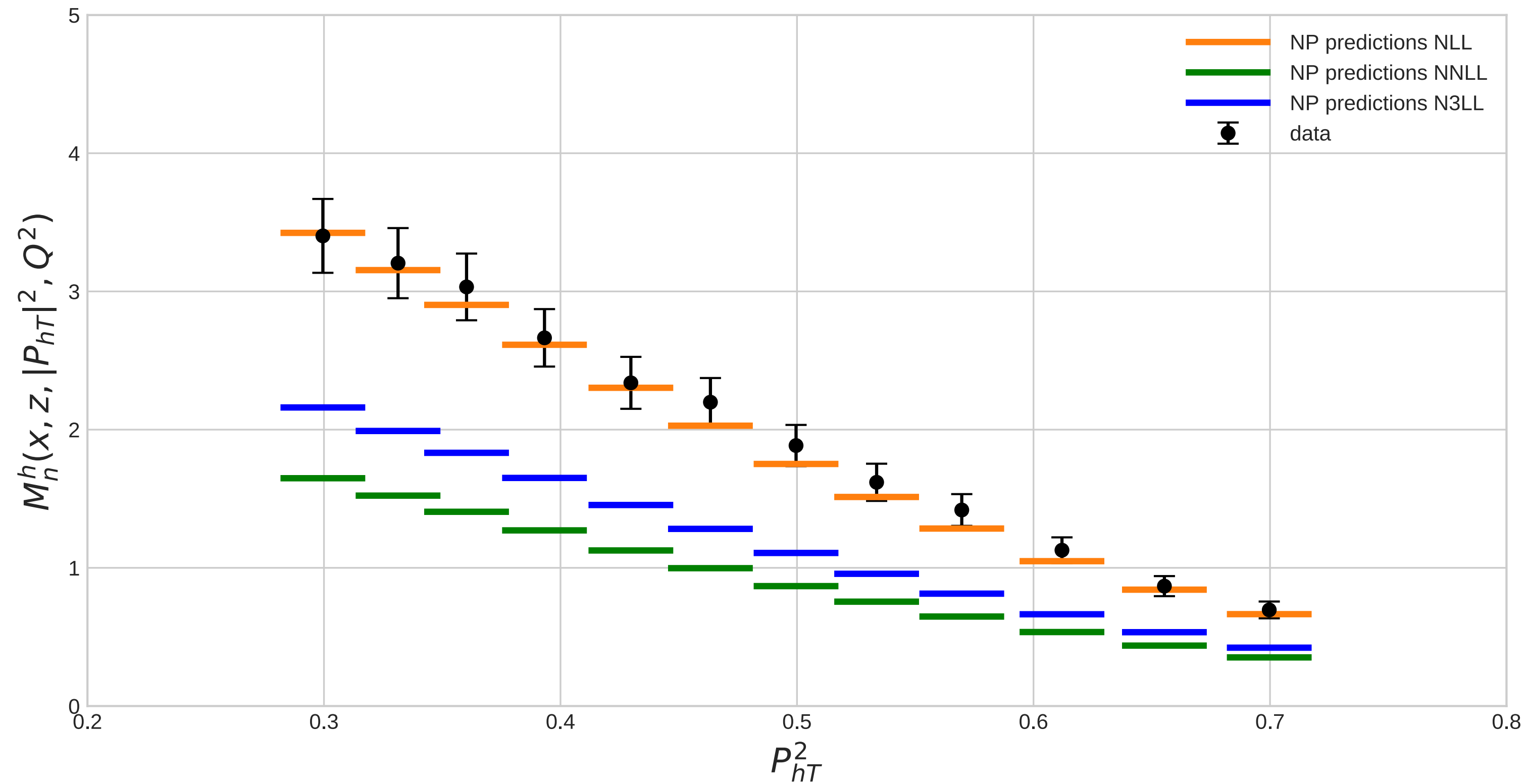


The description improves at high orders

Strange behaviors at higher orders

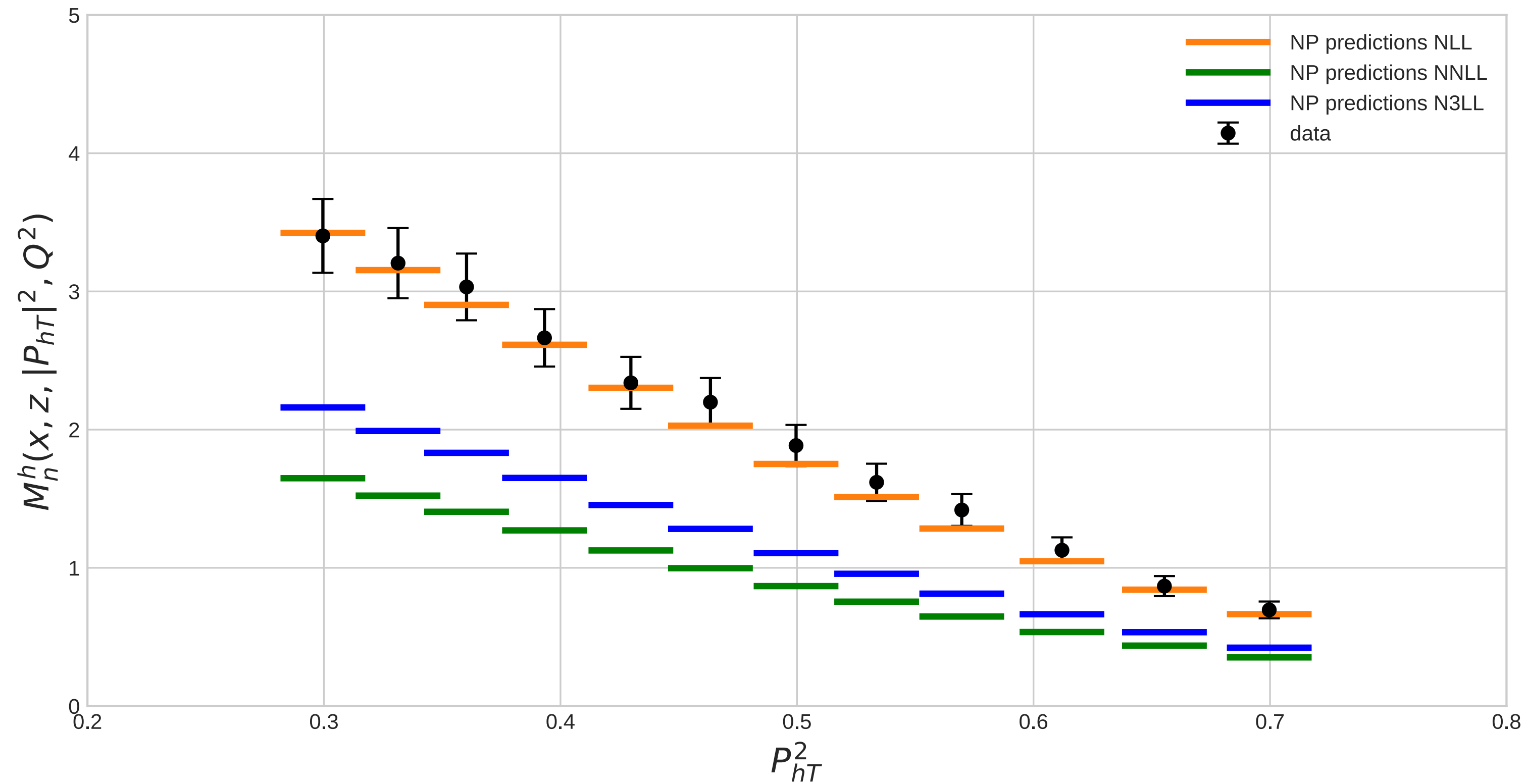
MAPTMD22: Normalization of SIDIS

COMPASS multiplicities (one of many bins)



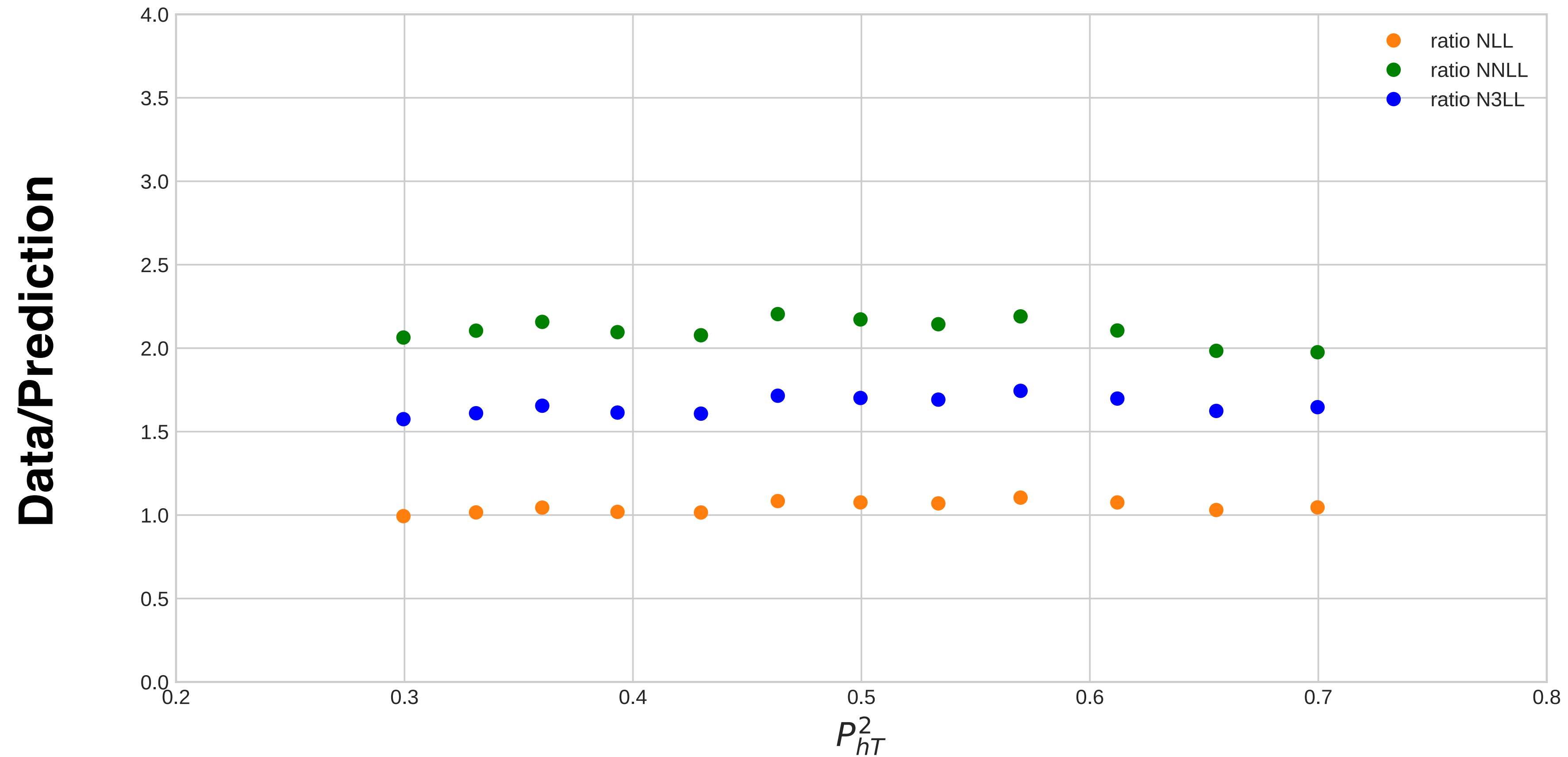
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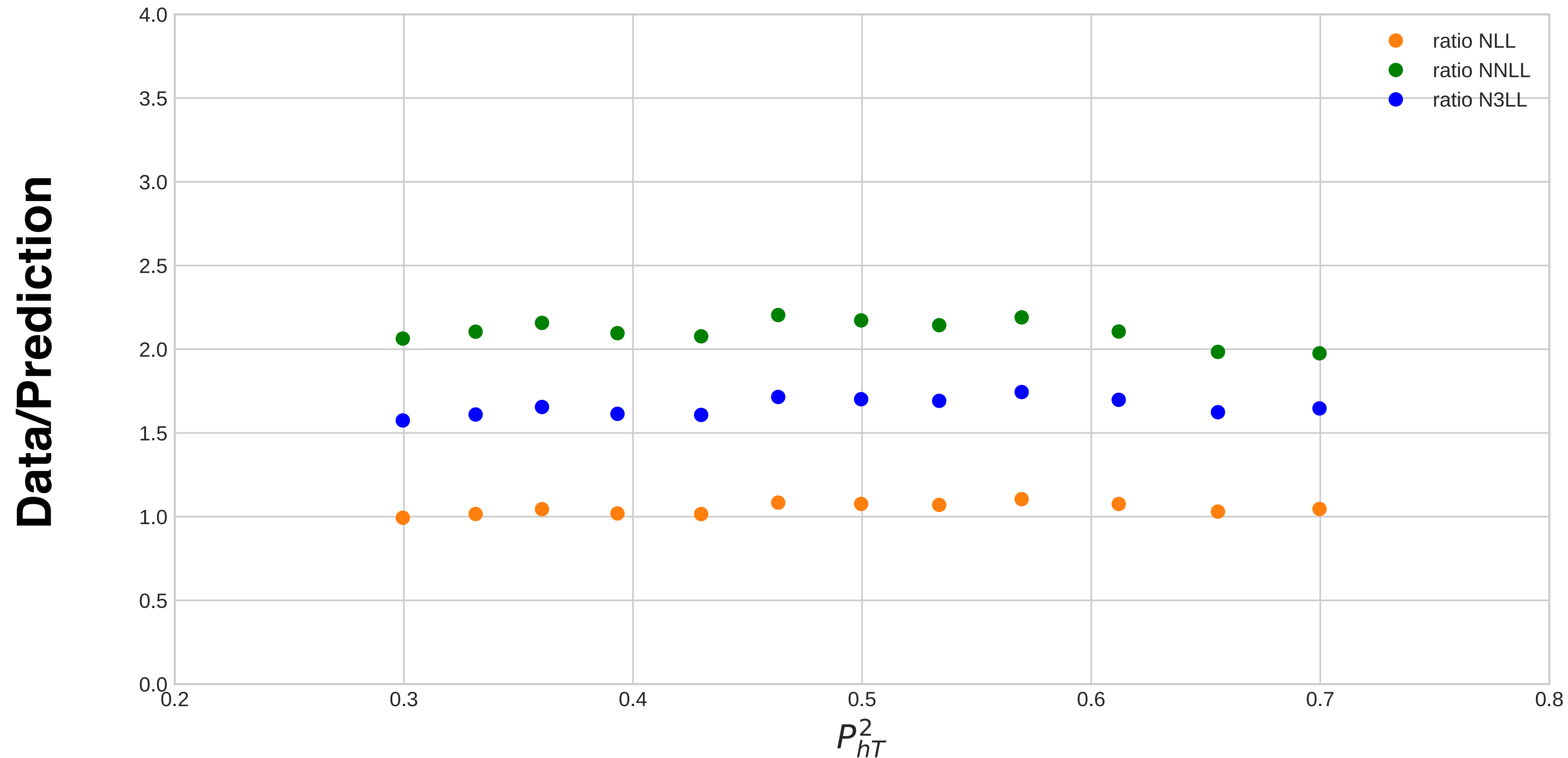
MAPTMD22: Normalization of SIDIS

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COMPASS multiplicities (one of many bins)



For different orders the discrepancy amounts to a nearly constant factor

MAPTMD22: Normalization of SIDIS

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

MAPTMD22: Normalization of SIDIS

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Collinear SIDIS cross section

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

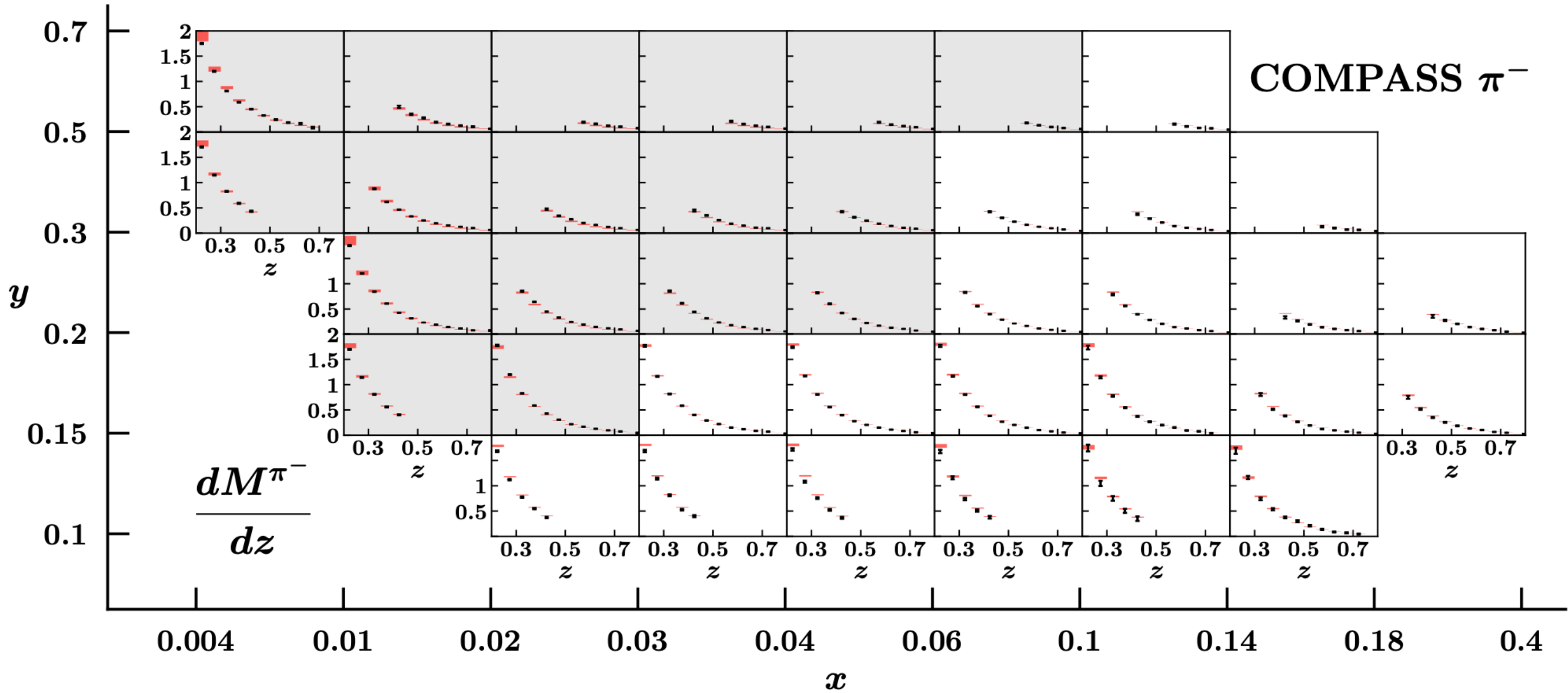
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MAP Collaboration, *PRD* 104 (2021) 3,
034007

MAP Collaboration, *JHEP* 10 (2022)

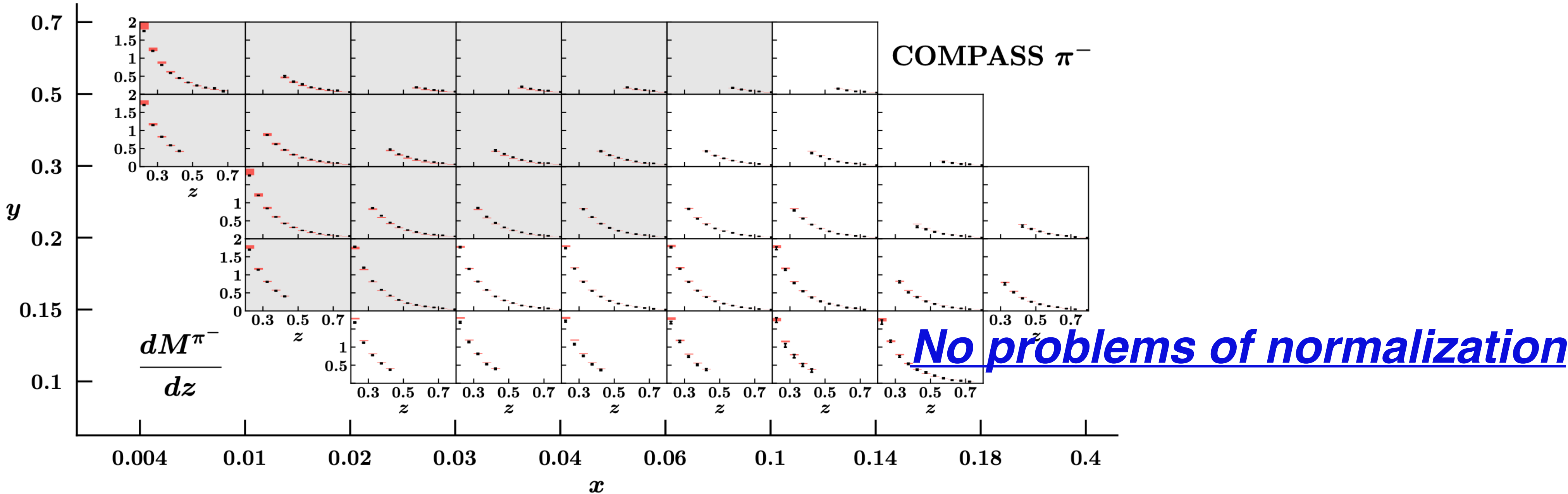
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At higher orders
something is missing
(Y-term? Power corrections?)

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

Fitting parameters independent

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

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

BACKUP

	N ³ LL			
Data set	N_{dat}	χ_D^2	χ_λ^2	χ_0^2
<i>Tevatron total</i>	71	1.10	0.07	1.17
<i>LHCb total</i>	21	3.56	0.96	4.52
<i>ATLAS total</i>	72	3.54	0.82	4.36
<i>CMS total</i>	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
<i>HERMES total</i>	344	0.81	0.24	1.05
<i>COMPASS total</i>	1203	0.67	0.27	0.94
SIDIS total	1547	0.70	0.26	0.96
Total	2031	0.81	0.27	1.08

BACKUP

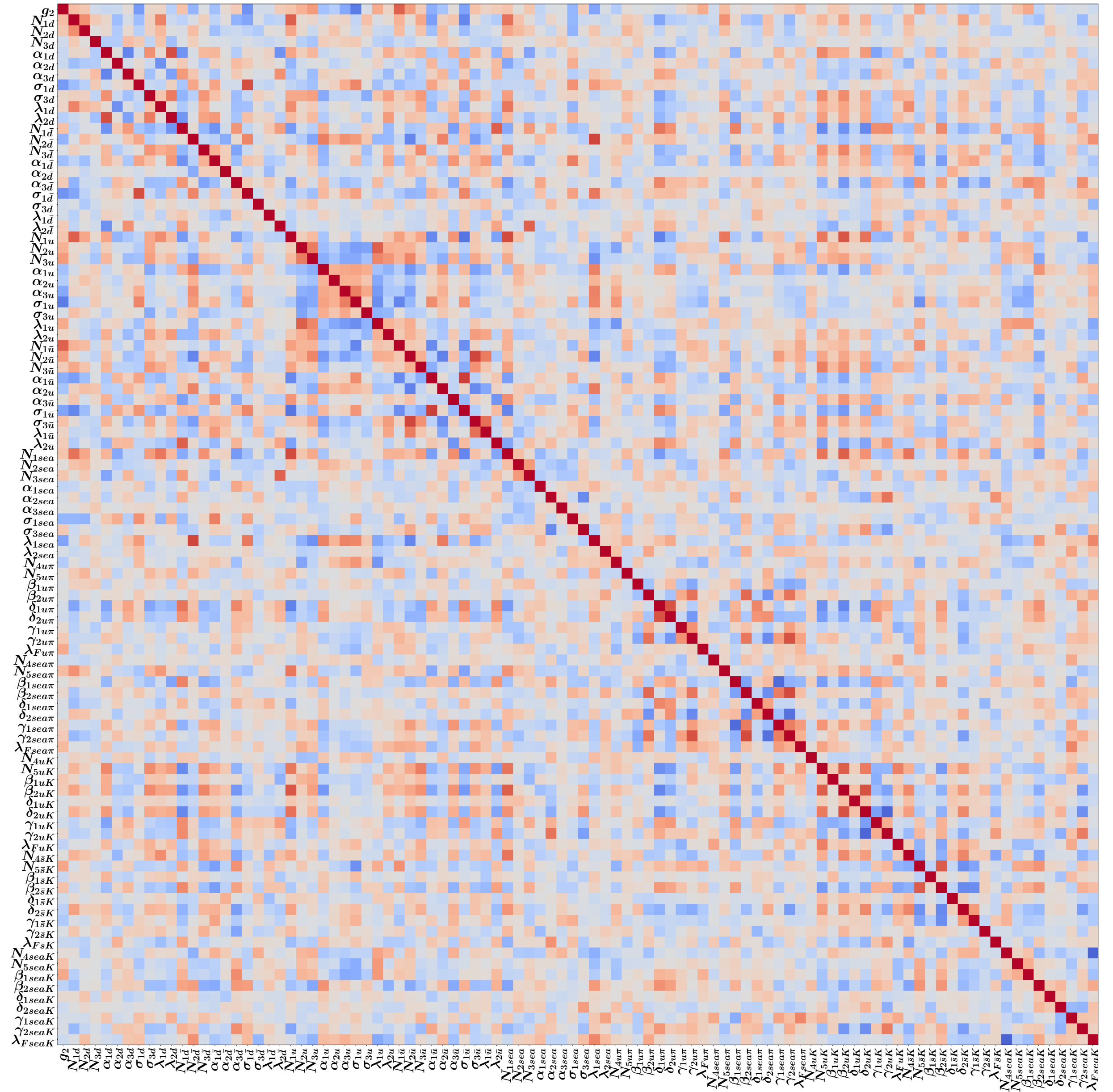
Error propagation



**100 Monte Carlo
replicas of data**

100 Monte Carlo
replicas of PDFs

100 Monte Carlo
replicas of FFs



BACKUP

Kinematic power corrections in TMD factorization theorem

#3

Alexey Vladimirov (Madrid U.) (Jul 24, 2023)

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 pdf

 DOI

 cite

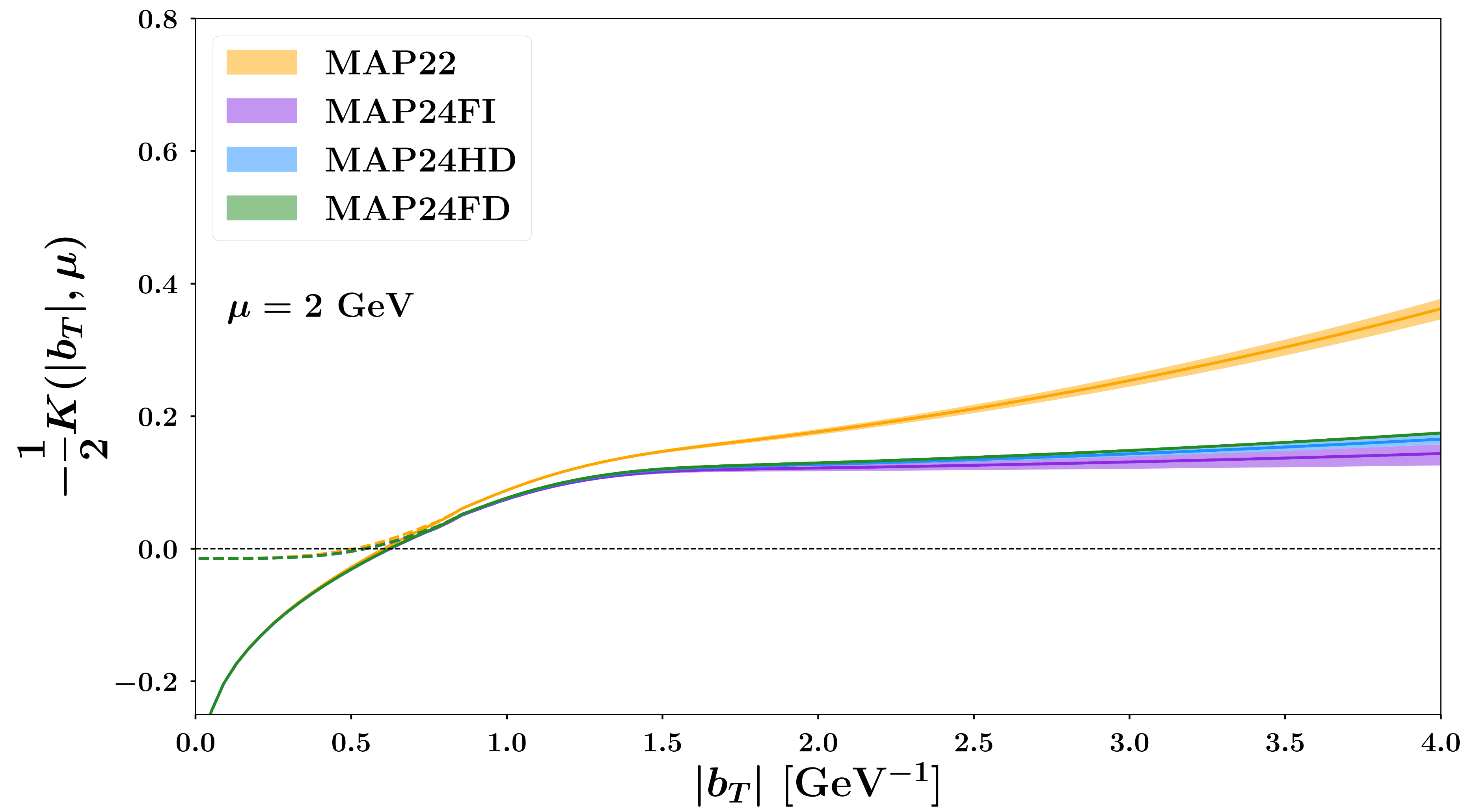
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 reference search

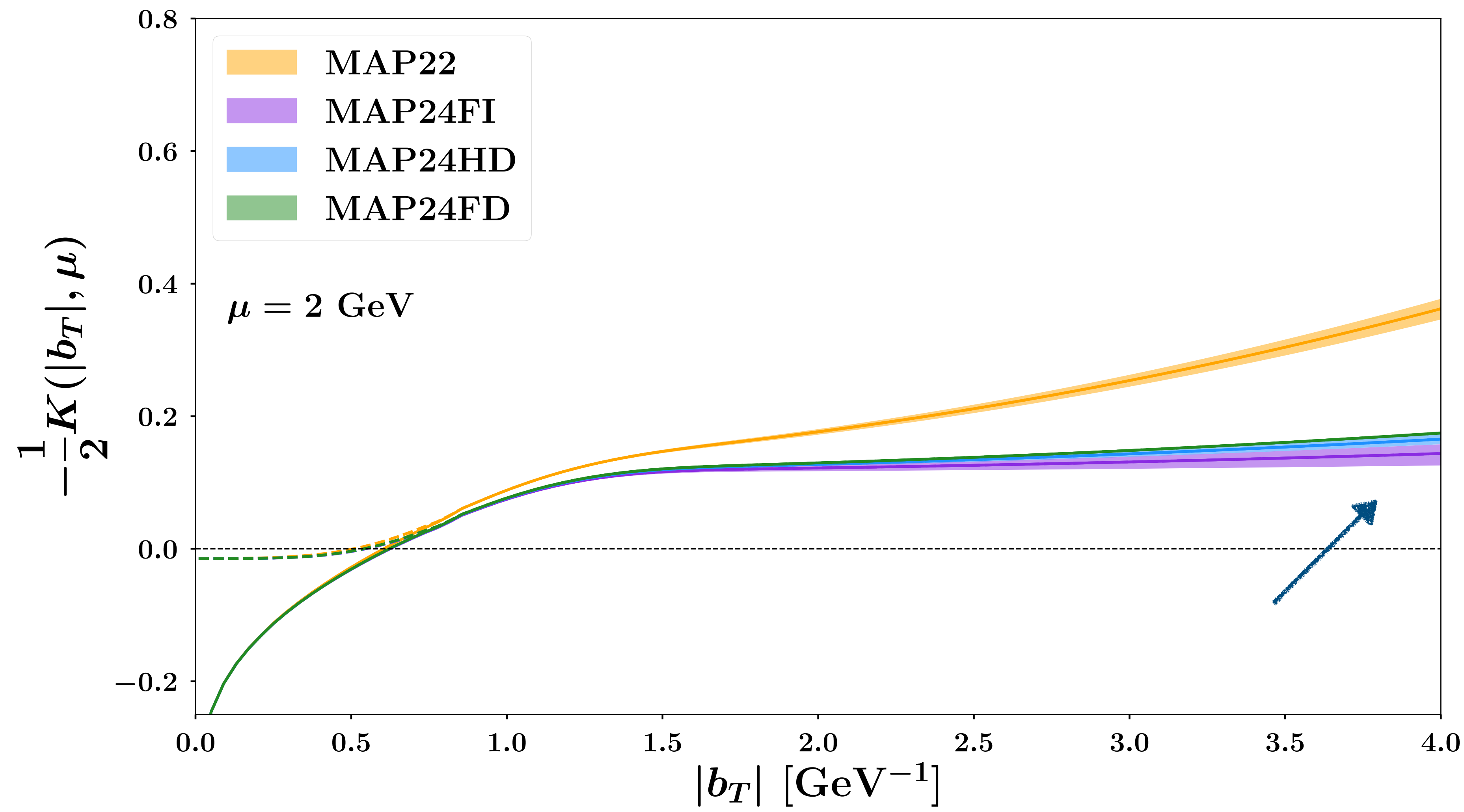
 6 citations

Estimations made in sec. 5.3 demonstrate that including KPCs results in an almost constant increment of the cross-section. The magnitude of this correction depends on Q and x . For typical LHC kinematics, the correction is around 1%, while at $Q \sim 4 - 5$ GeV, the correction can reach 100%. Interestingly, the deficiency in normalization for the TMD factorization at low energies has been reported by multiple groups. One could expect that these problems will be resolved with the inclusion of KPCs.

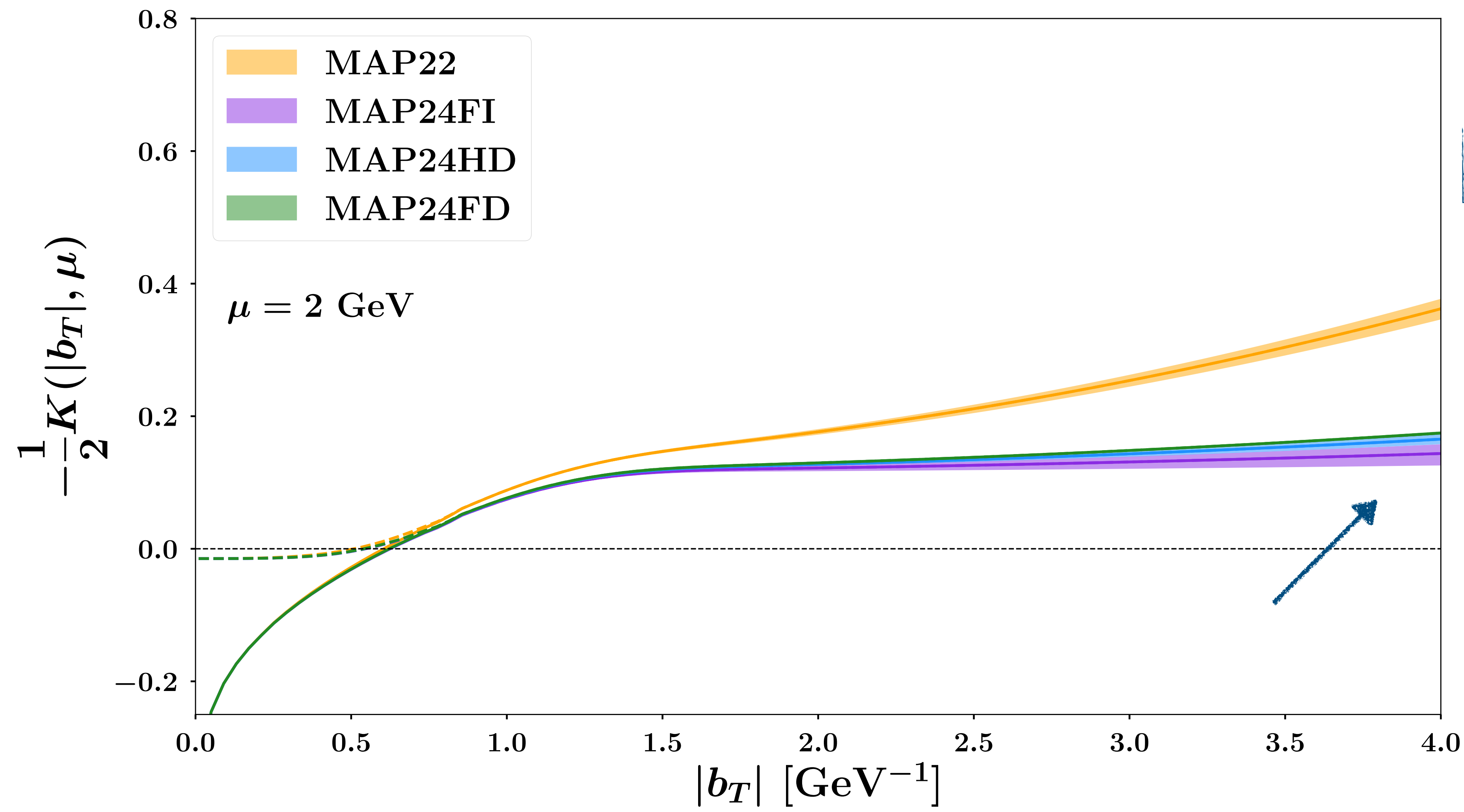
MAPTMD24 extraction - Collins Soper Kernel



MAPTMD24 extraction - Collins Soper Kernel

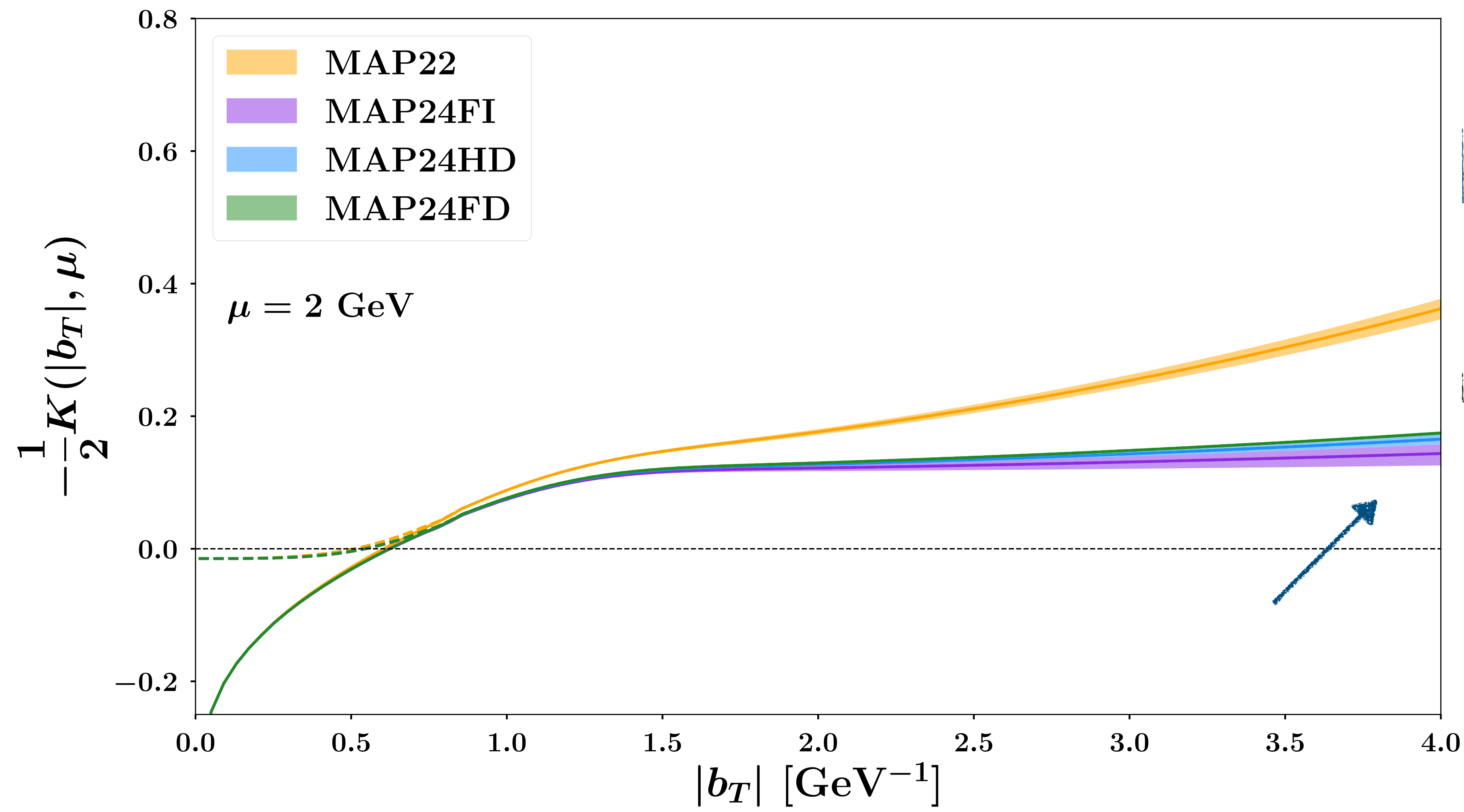


MAPTMD24 extraction - Collins Soper Kernel



*Independent of our non
perturbative choices*

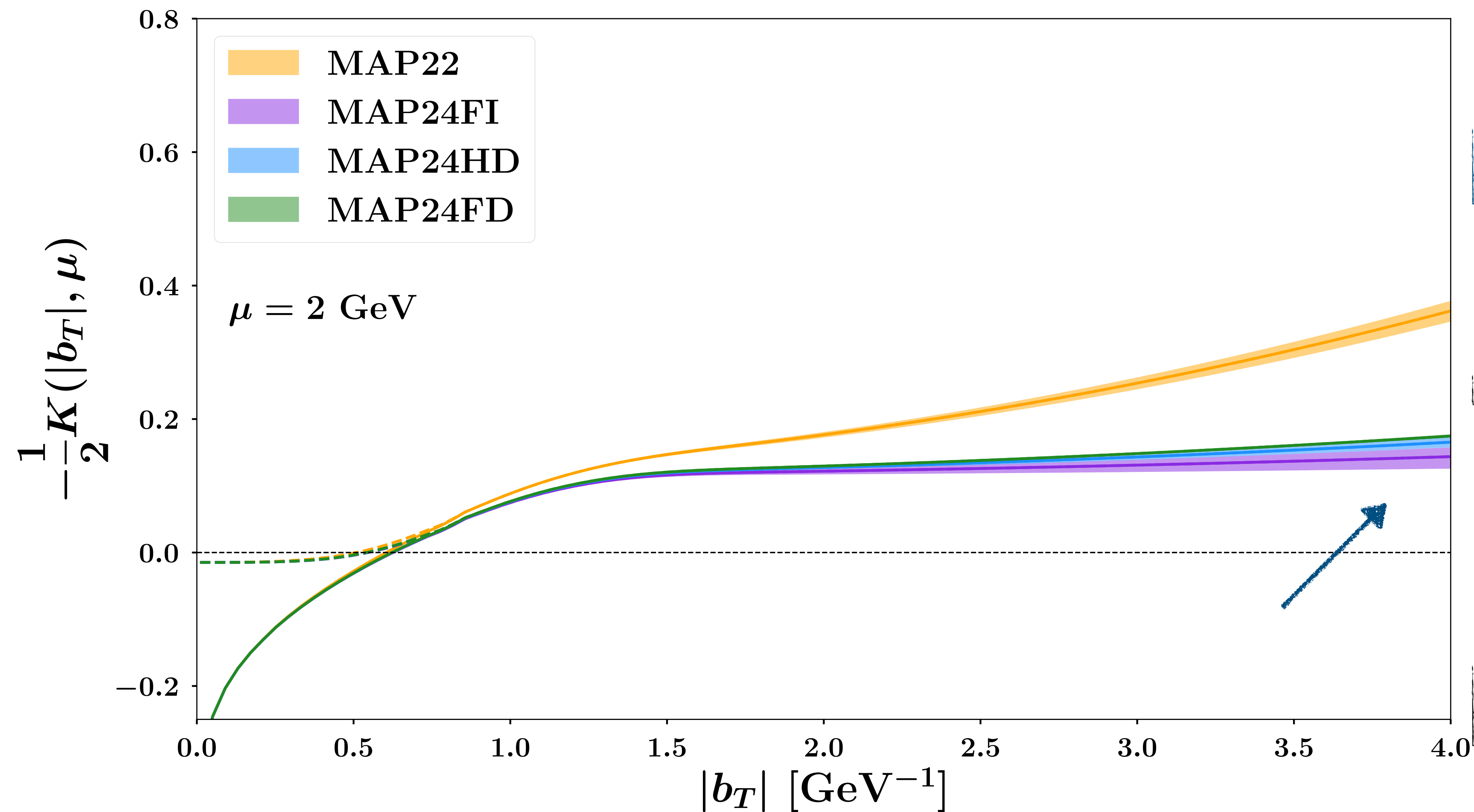
MAPTMD24 extraction - Collins Soper Kernel



Independent of our non perturbative choices

Quite flat behaviour

MAPTMD24 extraction - Collins Soper Kernel



Independent of our non perturbative choices

Quite flat behaviour

Compatible with latest lattice calculation

PLB 852 (2024) 138617