Global fit of unpolarized Transverse Momentum Distributions

XXXI International Workshop on Deep Inelastic Scattering (DIS2024)

Lorenzo Rossi

MAP Collaboration

April 10th

INFN
Istituto Nazionale di Fisica Nucleare

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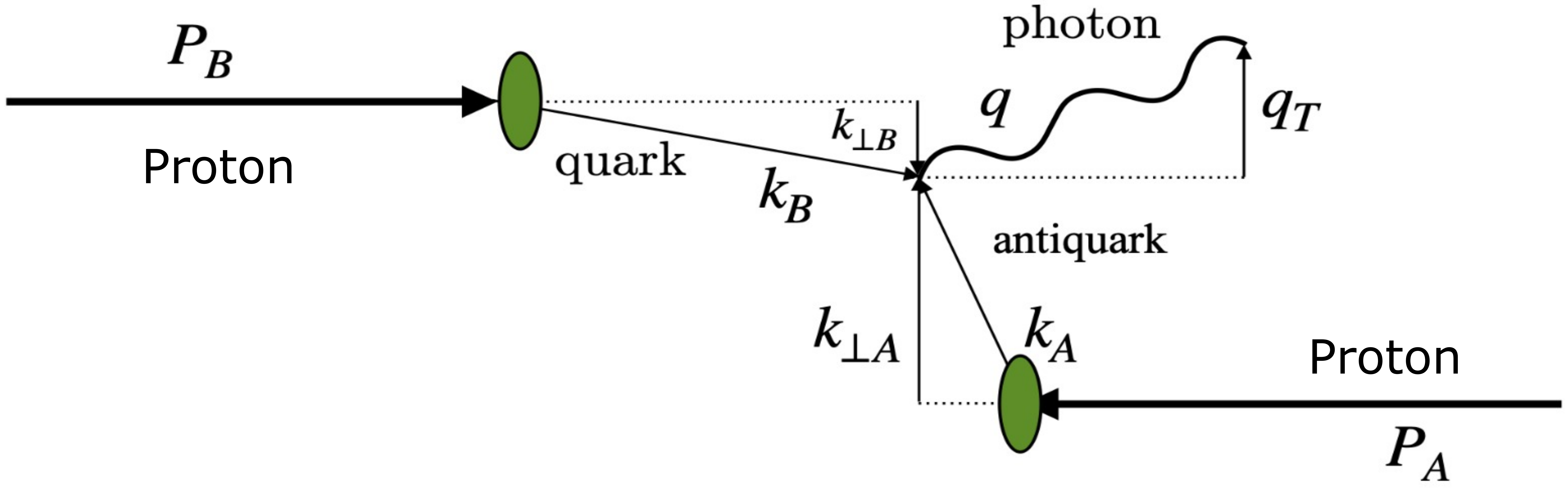
DI PAVIA

TMD factorization — Drell-Yan process

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

TMD factorization — Drell-Yan process



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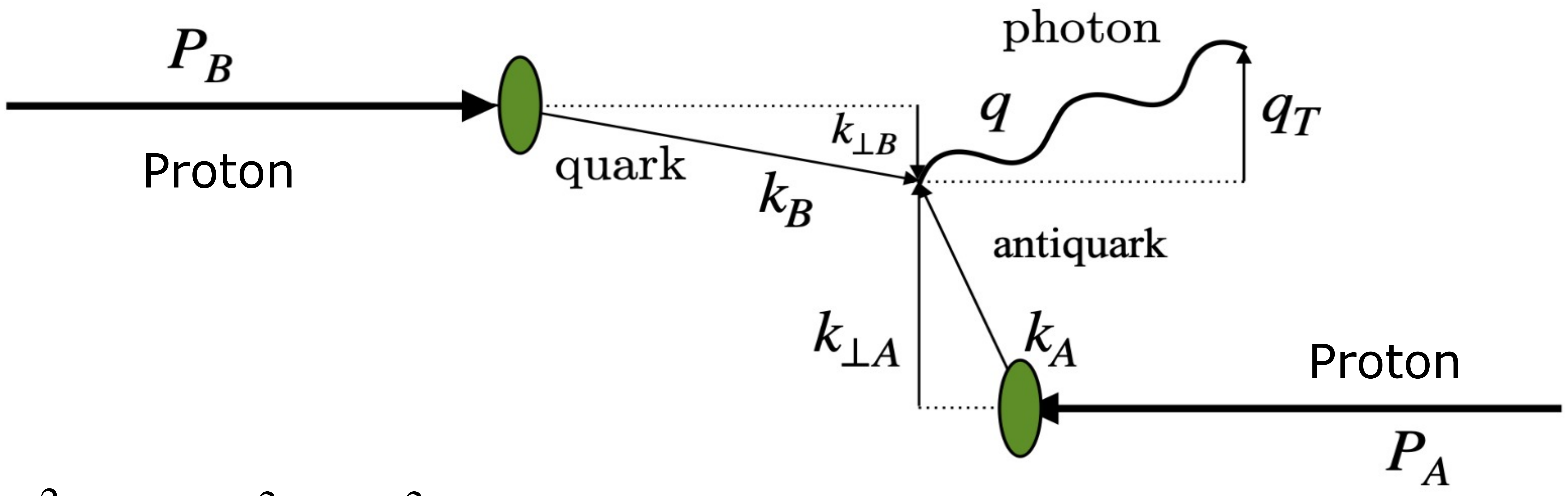
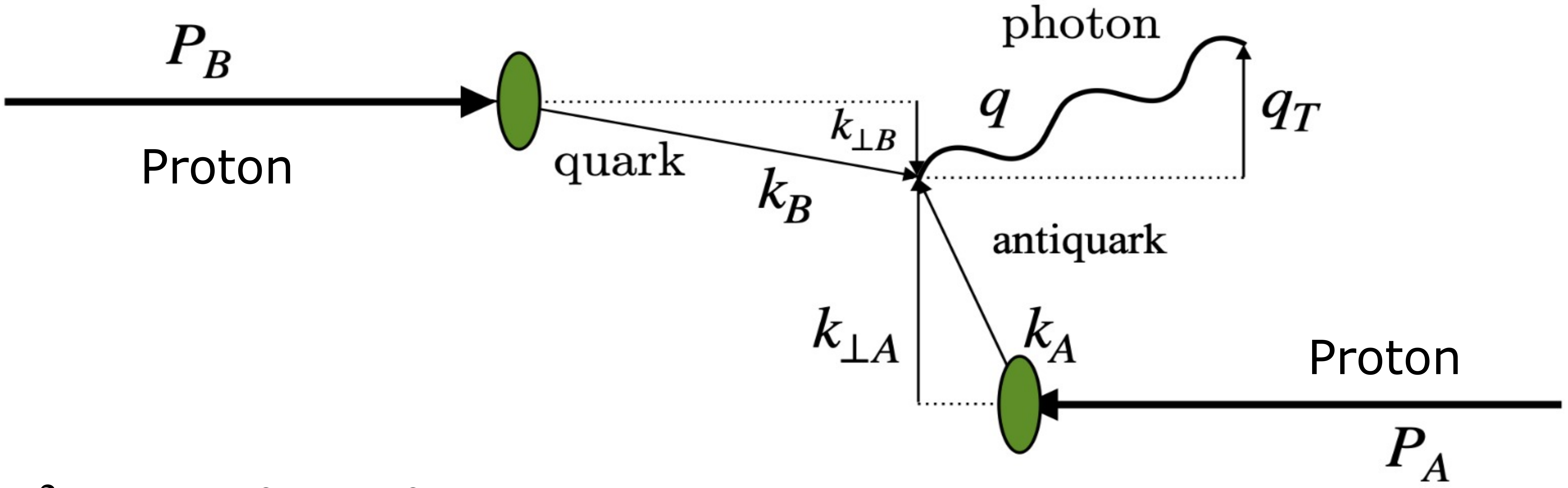


In $q_T^2 \ll Q^2$ and $M^2 \gg Q^2$ region:

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

TMD factorization — Drell-Yan process



In $q_T^2 \ll Q^2$ and $M^2 \gg Q^2$ 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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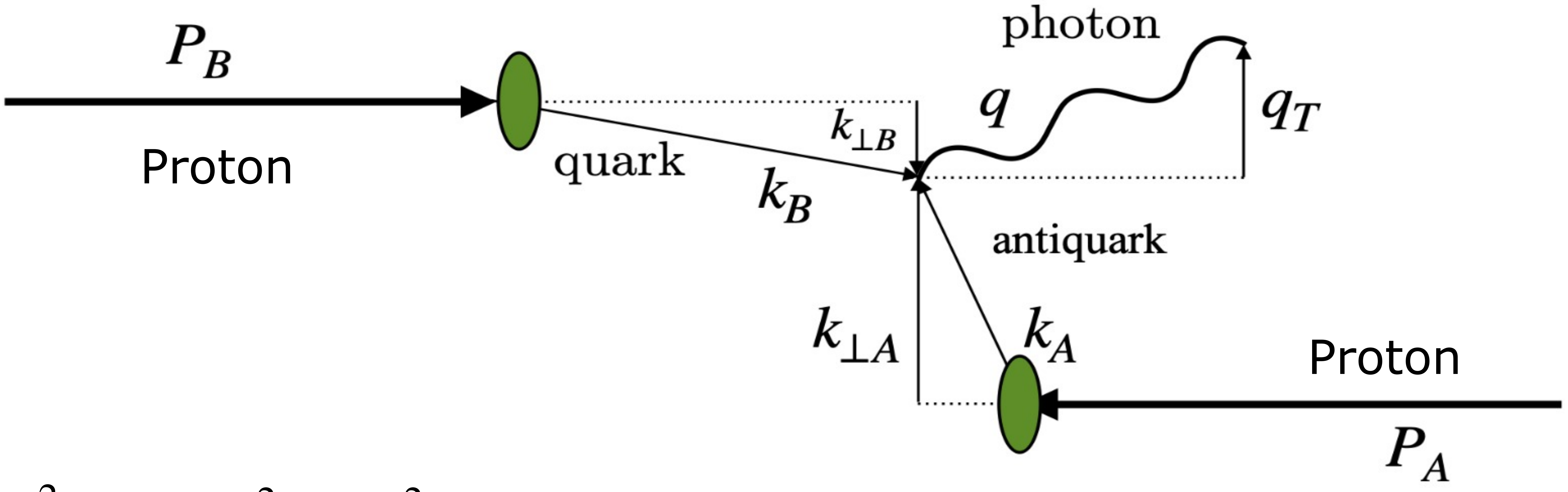

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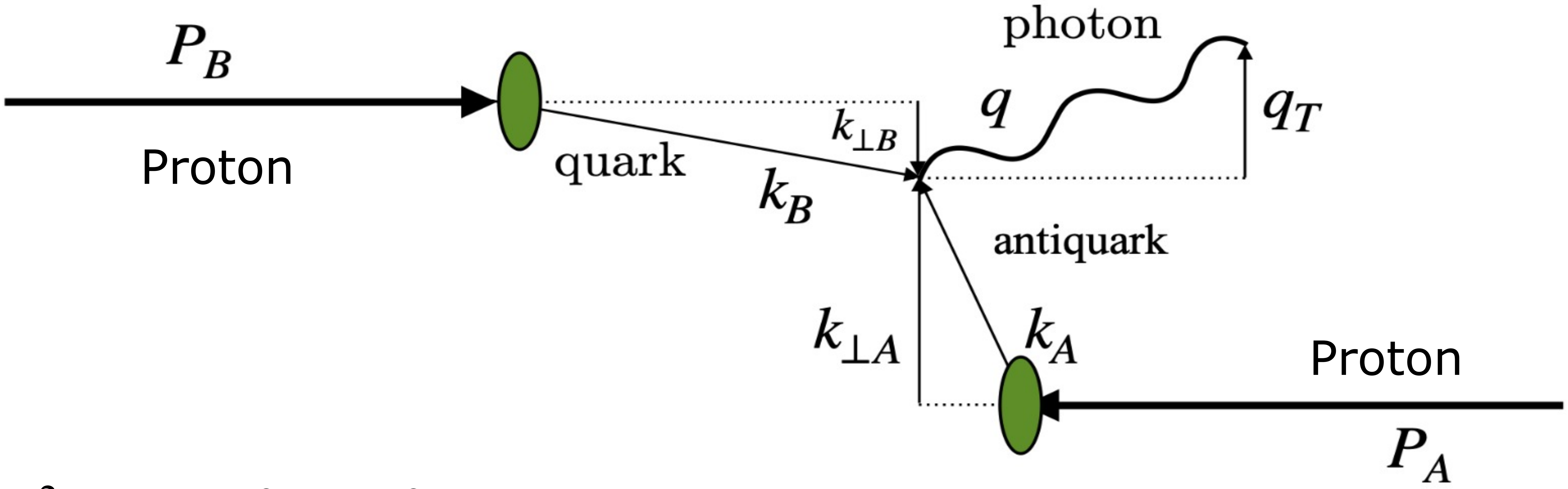

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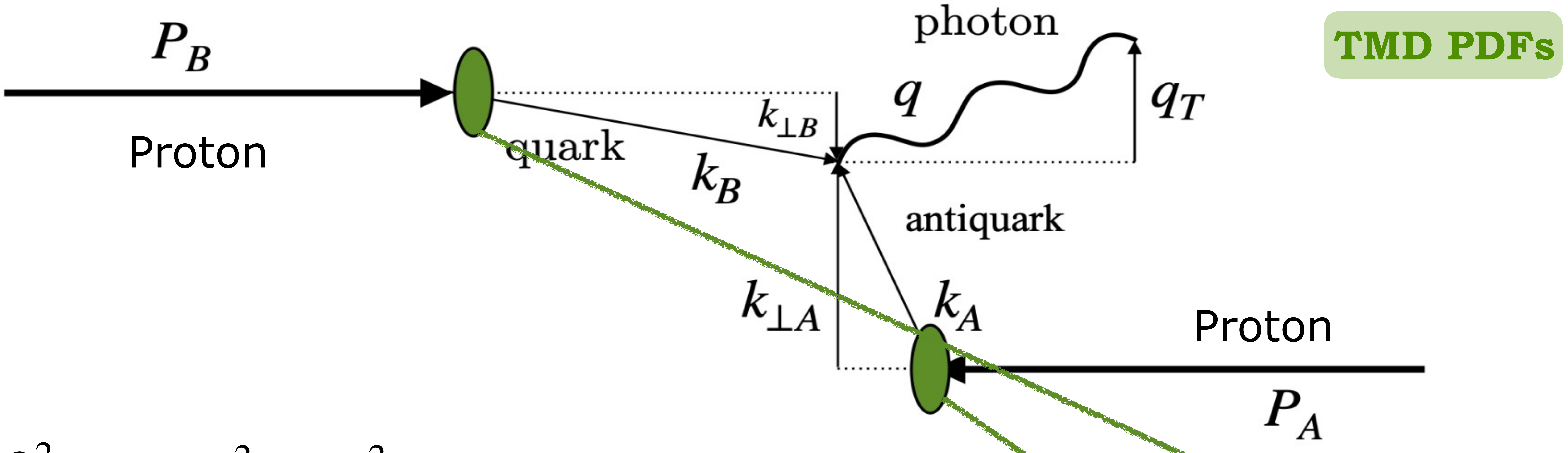

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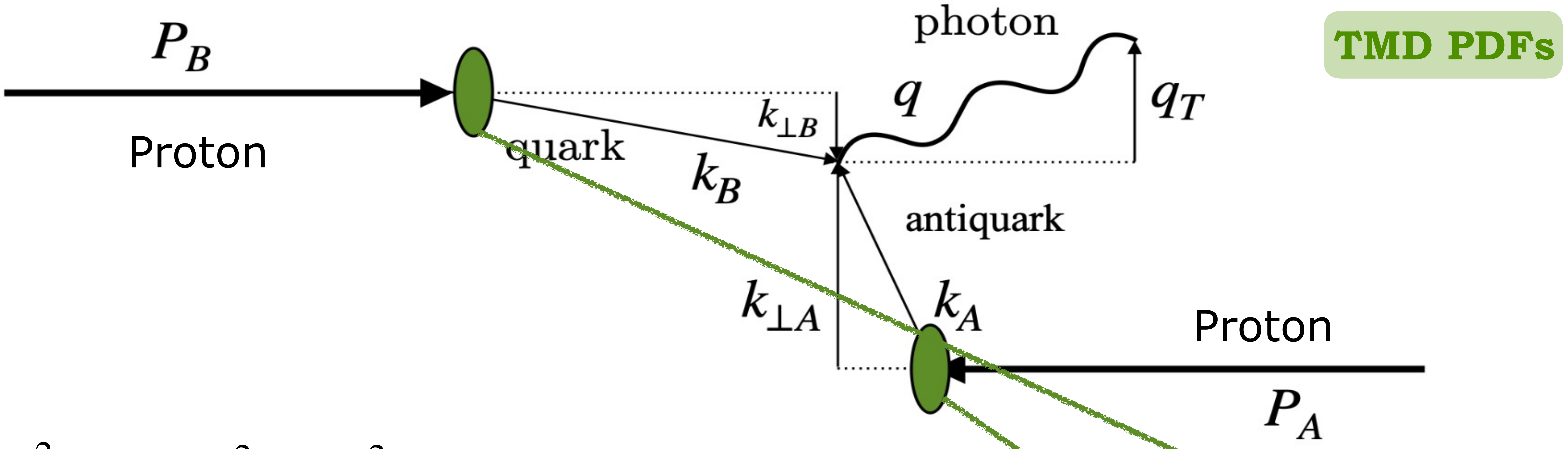

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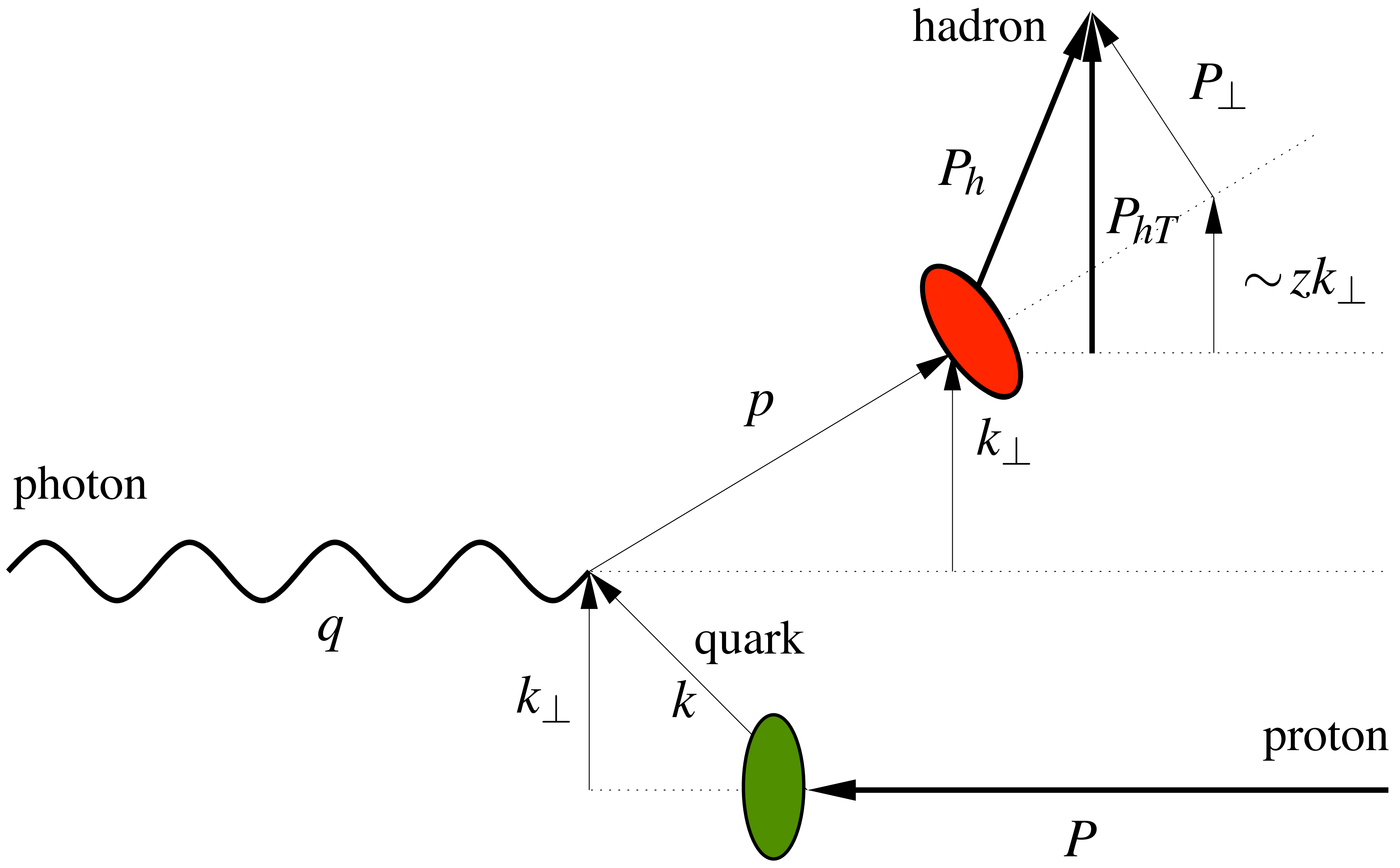
W term

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

TMD Factorization - SIDIS process



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

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

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

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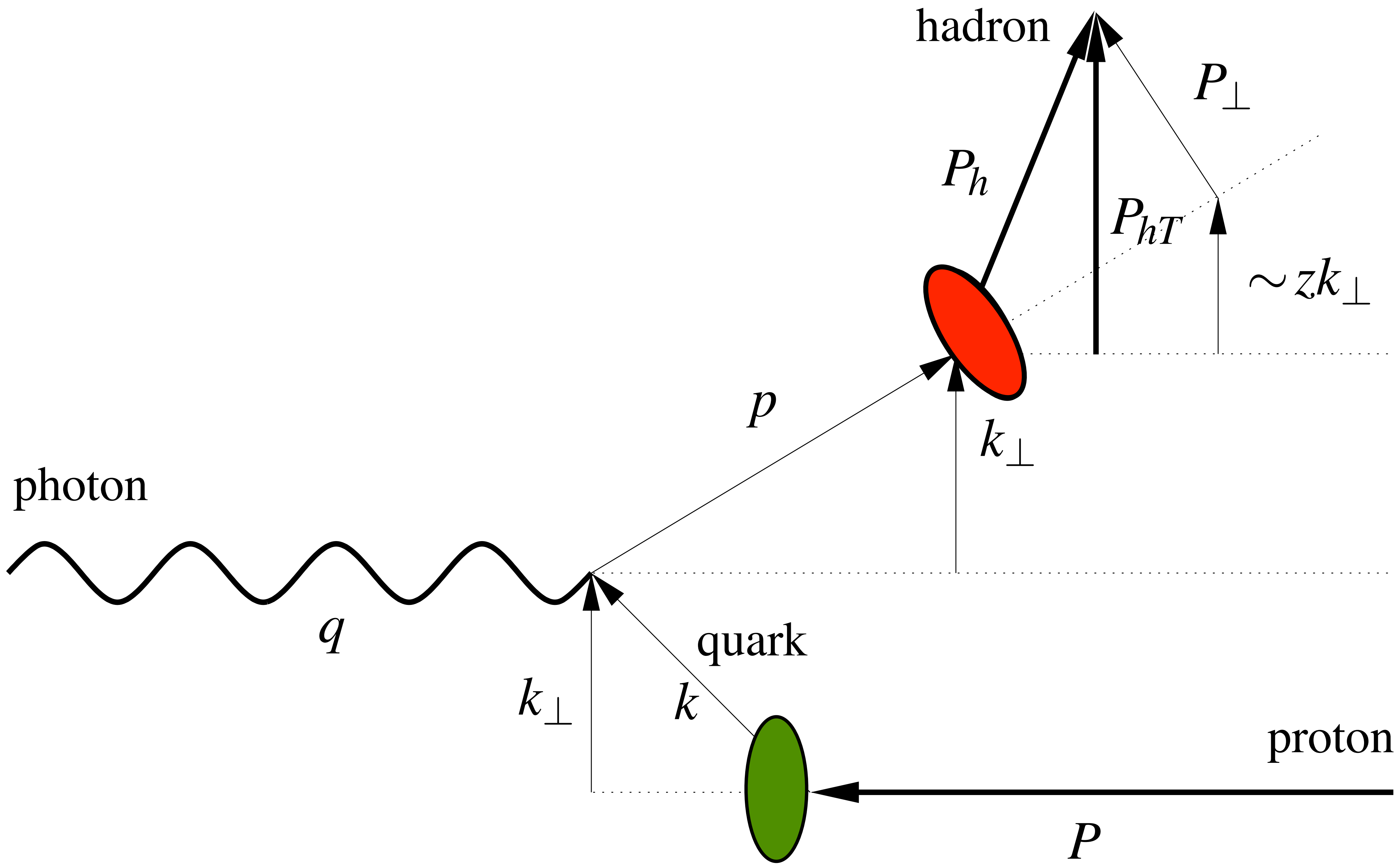

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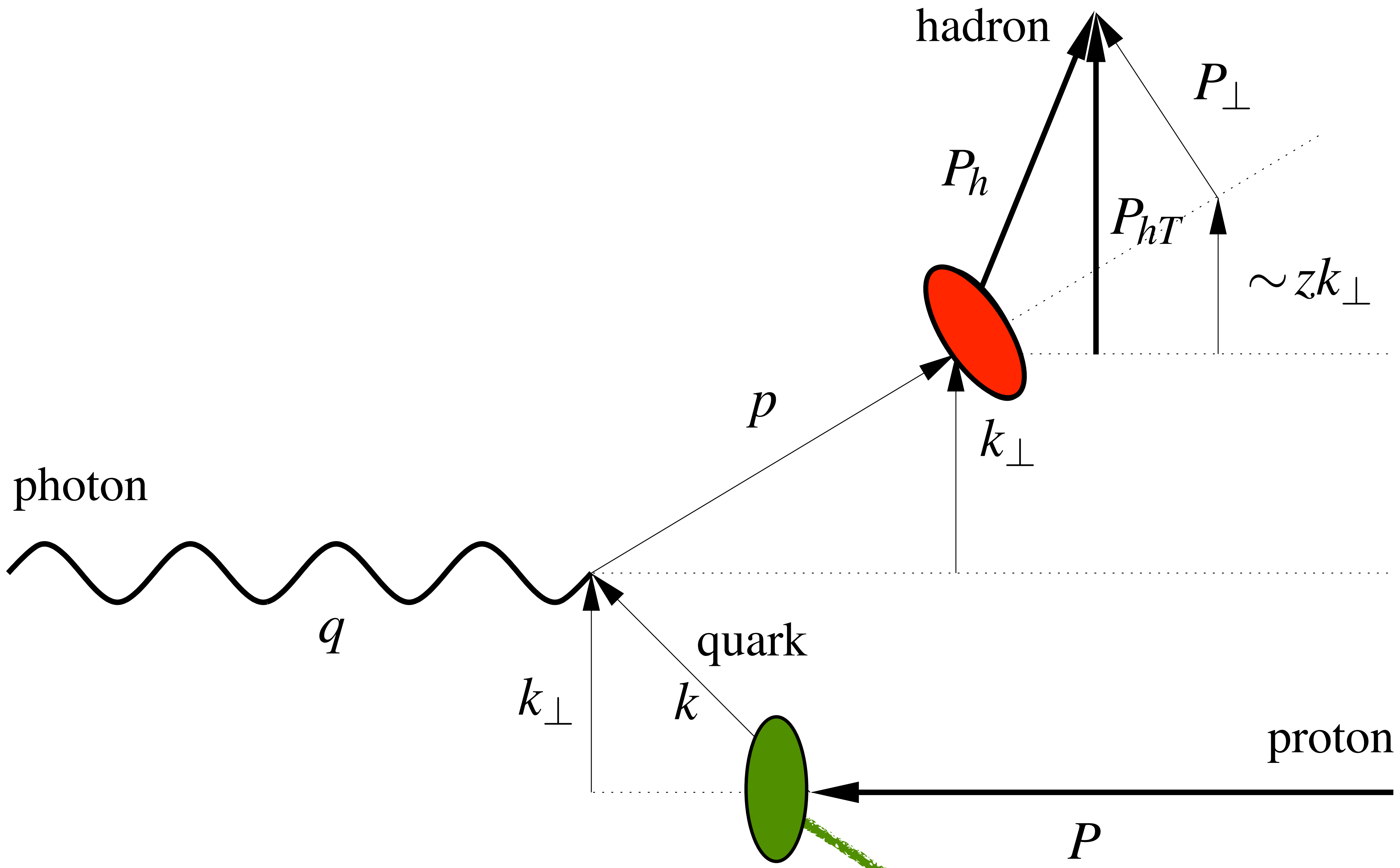

TMD PDF

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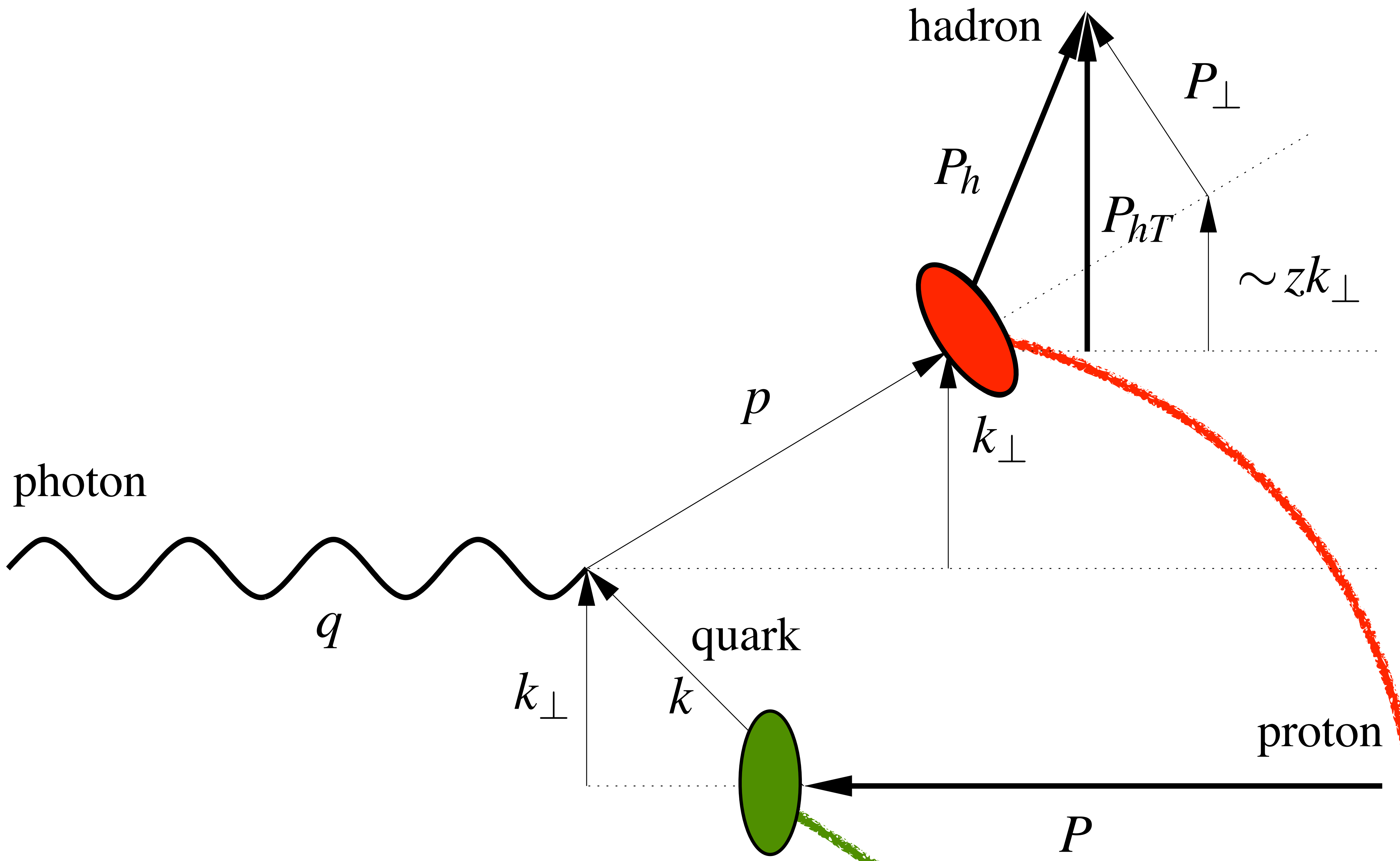
TMD FF

TMD PDF



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TMD FF

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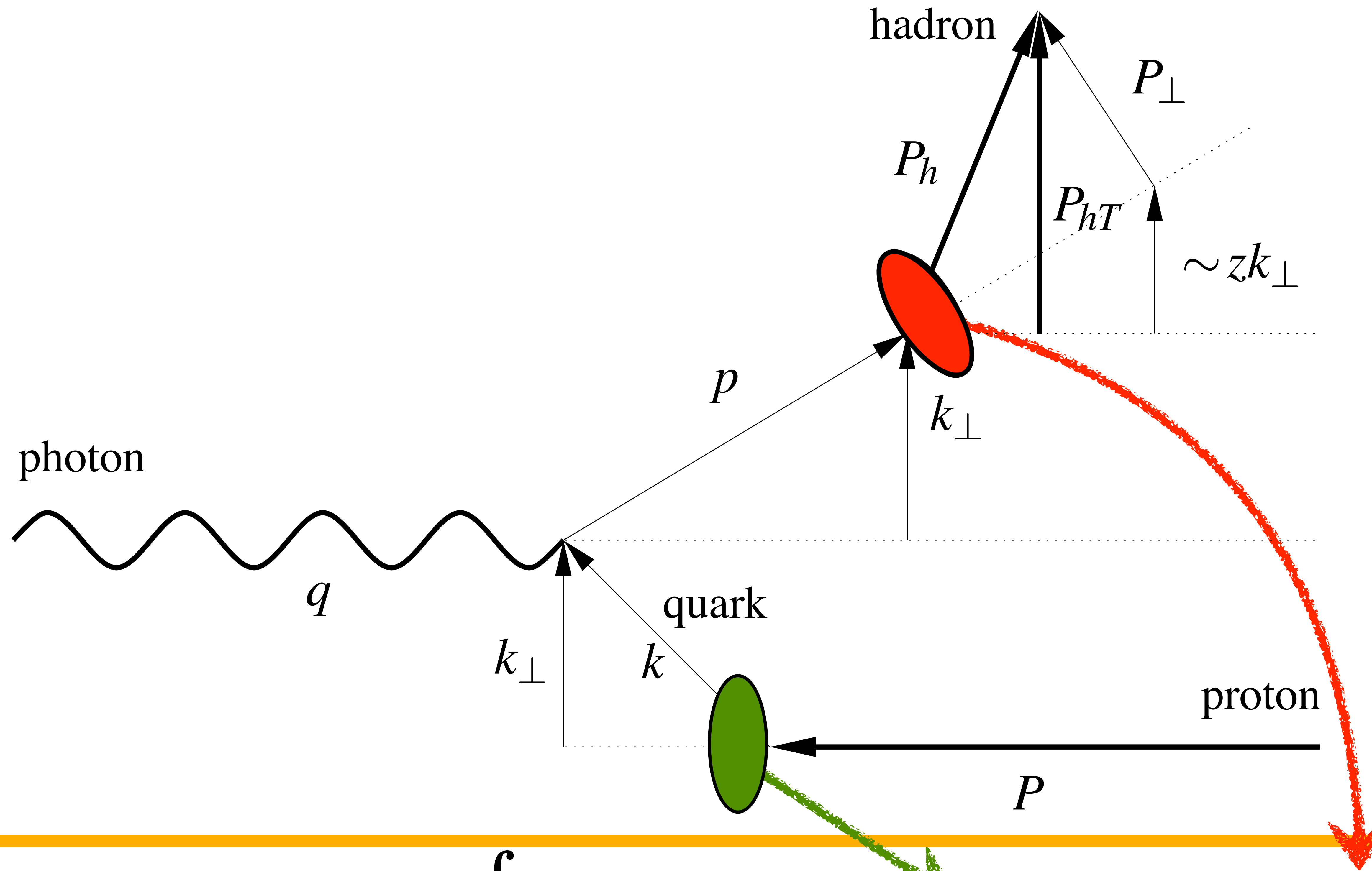

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W Term

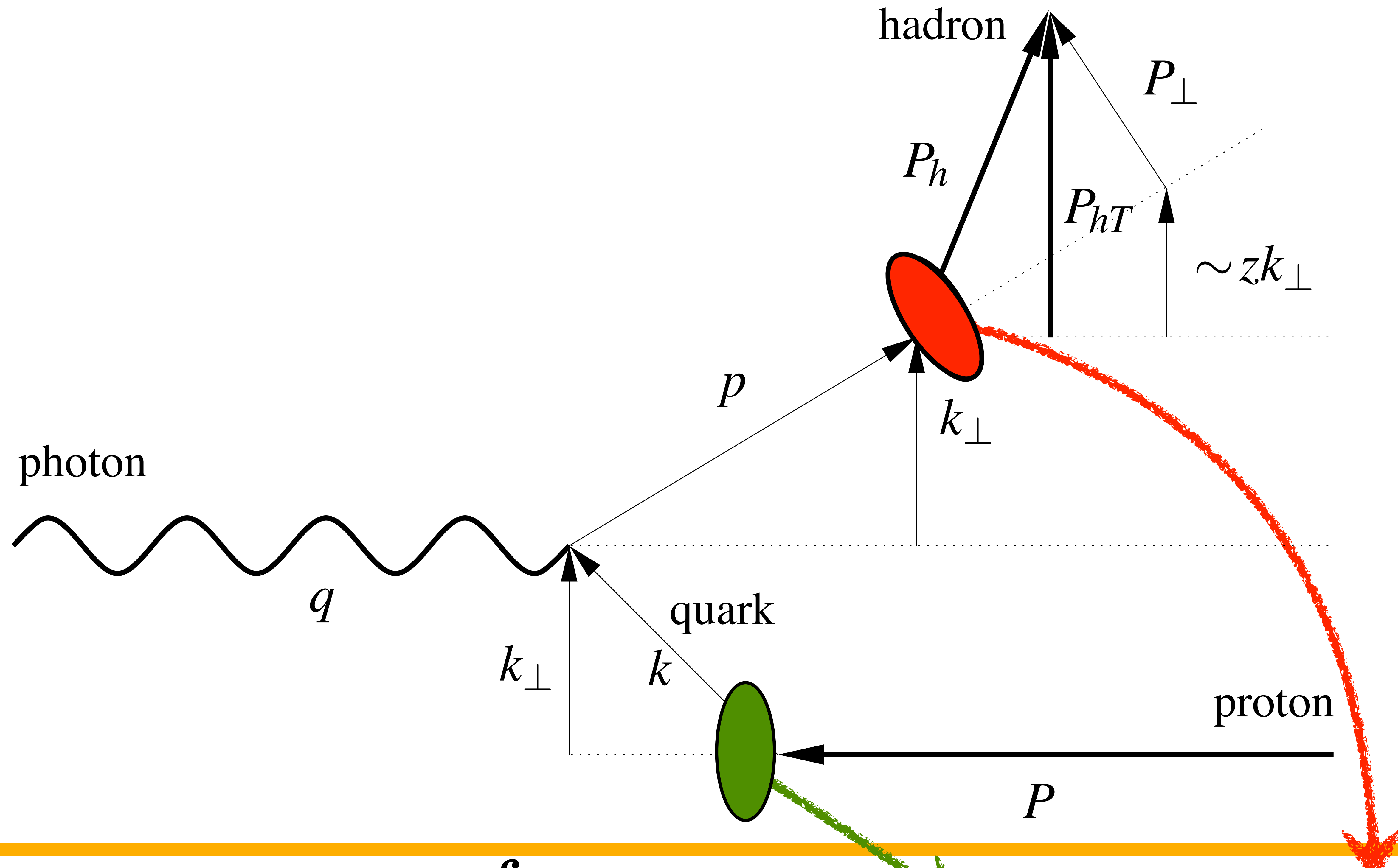
- The W term dominates in the region where $q_T \ll Q$

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

TMD Factorization - SIDIS process

TMD FF

TMD PDF



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

W Term

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

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

TMD Factorization - structure of TMDs

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

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

Collins, "Foundations of Perturbative QCD"

TMD Factorization - structure of TMDs

Matching coeff.
(perturbative calculable)

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Collins-Soper kernel

Collins, "Foundations of Perturbative QCD"

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Collins-Soper kernel

NP part of Collins-Soper Kernel

Collins, "Foundations of Perturbative QCD"

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Non perturbative part of TMDs

Collins, "Foundations of Perturbative QCD"

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Fit extraction

Collins, "Foundations of Perturbative QCD"

MAPTMD22 extraction — starting point

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

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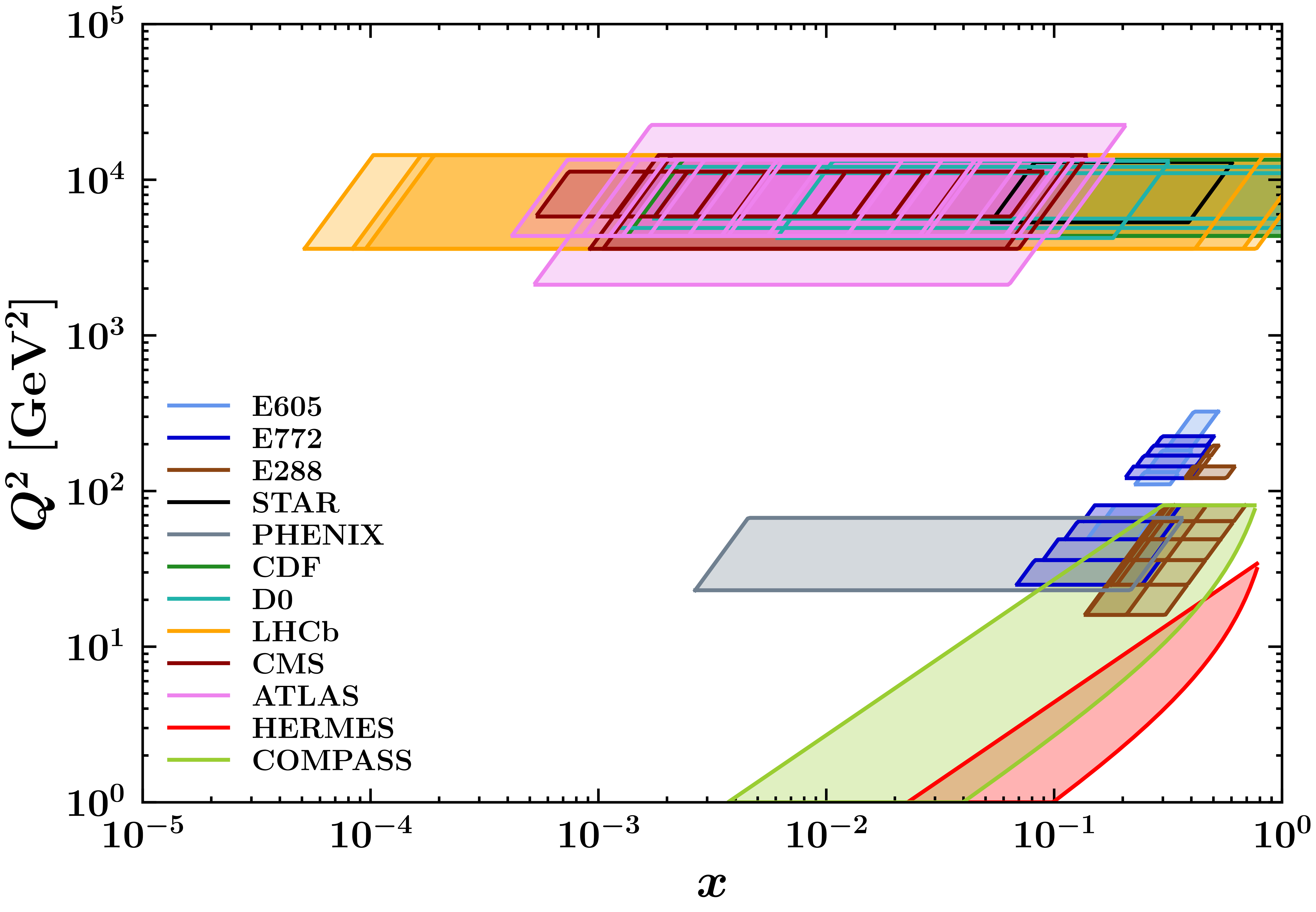

MAP Collaboration, JHEP 10 (2022)

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- Perturbative accuracy: N^3LL^-

-

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- 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^3LO

MAP Collaboration, JHEP 10 (2022)

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MMHT2014nnlo
DSS14-17 NLO

MAP Collaboration, JHEP 10 (2022)

MAPTMD22 extraction — starting point

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

- Perturbative accuracy: N^3LL^-

- Number of fitted parameters: ***21***

MAP Collaboration, JHEP 10 (2022)

MAPTMD22 extraction — starting point

- Global analysis of Drell-Yan and Semi-Inclusive DIS data sets: ***2031*** data points
- Perturbative accuracy: ***N³LL⁻***
- Number of fitted parameters: ***21***

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

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

MAP Collaboration, JHEP 10 (2022)

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

MAP Collaboration, JHEP 10 (2022)

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

MAP Collaboration, JHEP 10 (2022)

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- Perturbative accuracy: ***N^3LL^-***

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

- Number of fitted parameters: ***21***

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

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

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

MAP Collaboration, JHEP 10 (2022)

MAPTMD22 extraction ⟶ MAPTMD24

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MAP Collaboration, JHEP 10 (2022)

MAPTMD22 extraction → MAPTMD24

- Global analysis of Drell-Yan and Semi-Inclusive DIS data sets: ***2031*** data points
  Same data points
- Perturbative accuracy: N^3LL^-
- Number of fitted parameters: ***21***
- Extremely good description: $\chi^2/N_{data} = 1.06$

MAPTMD22 extraction → MAPTMD24

- Global analysis of Drell-Yan and Semi-Inclusive DIS data sets: ***2031*** data points
  Same data points
- Perturbative accuracy: N^3LL
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Why does the χ^2 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**
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PRELIMINARY

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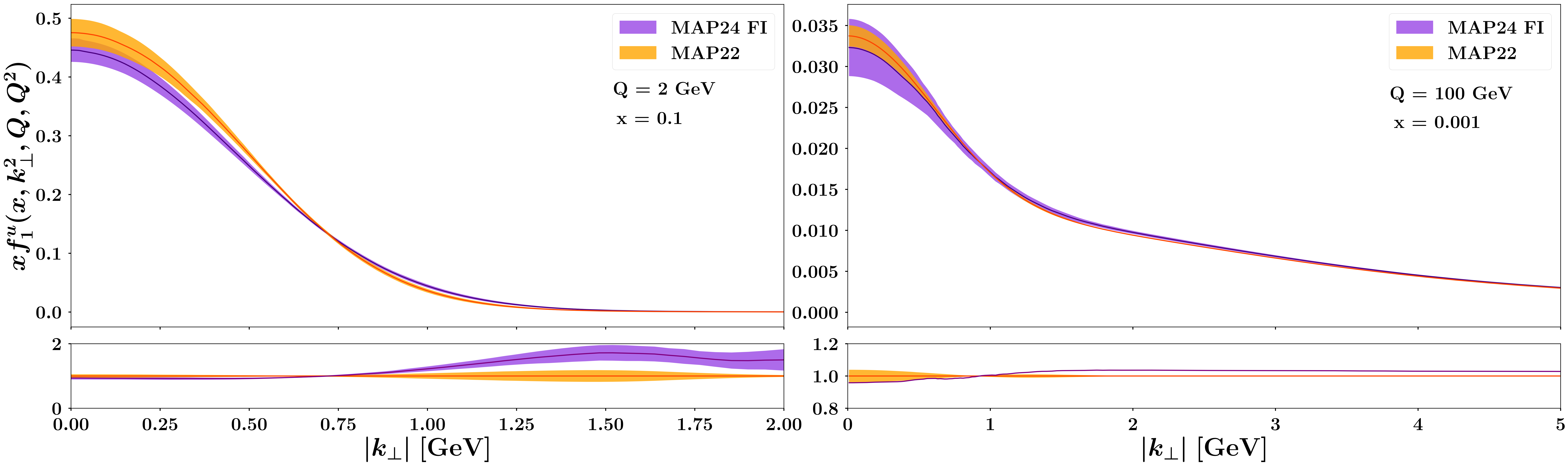

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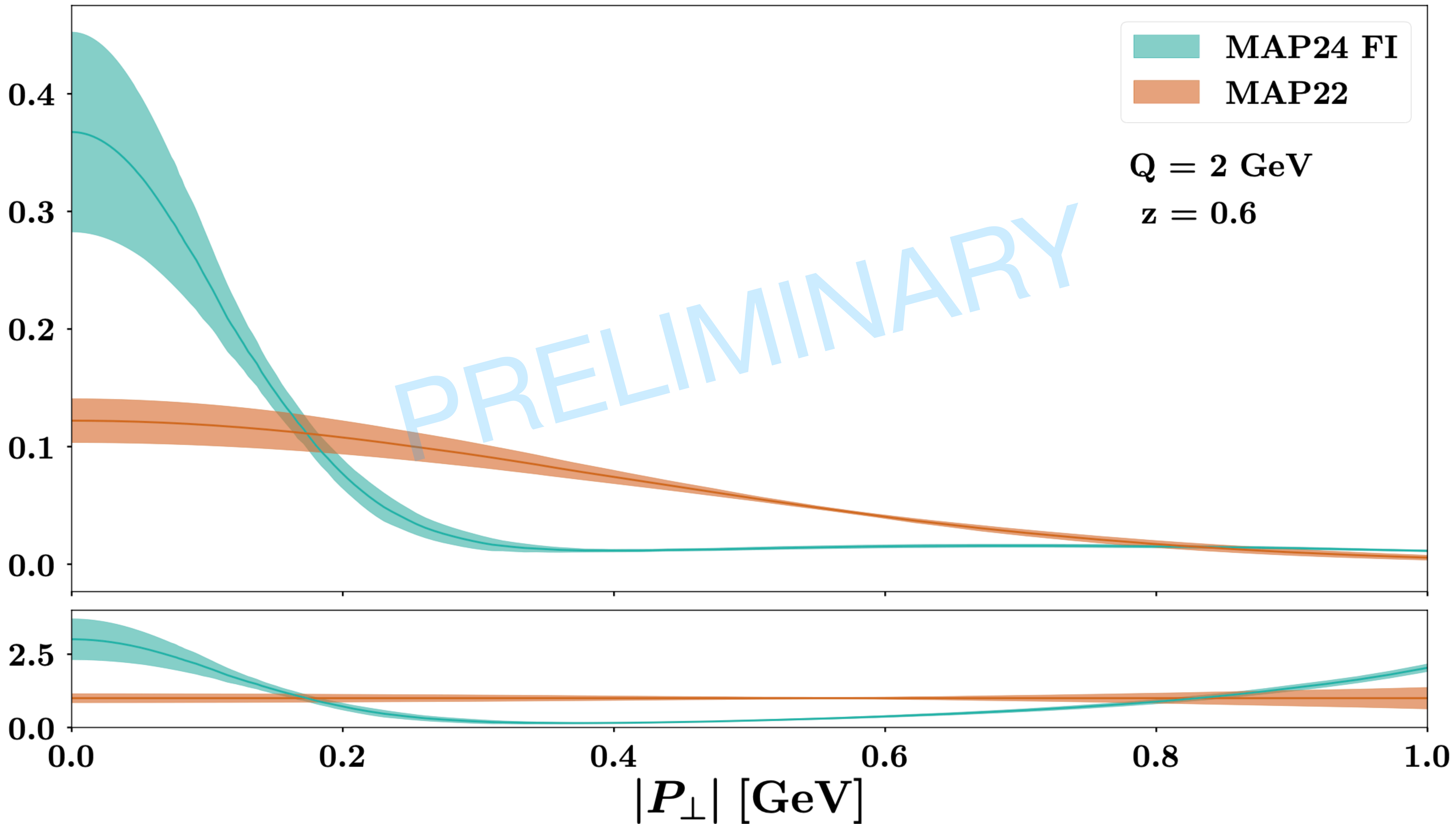

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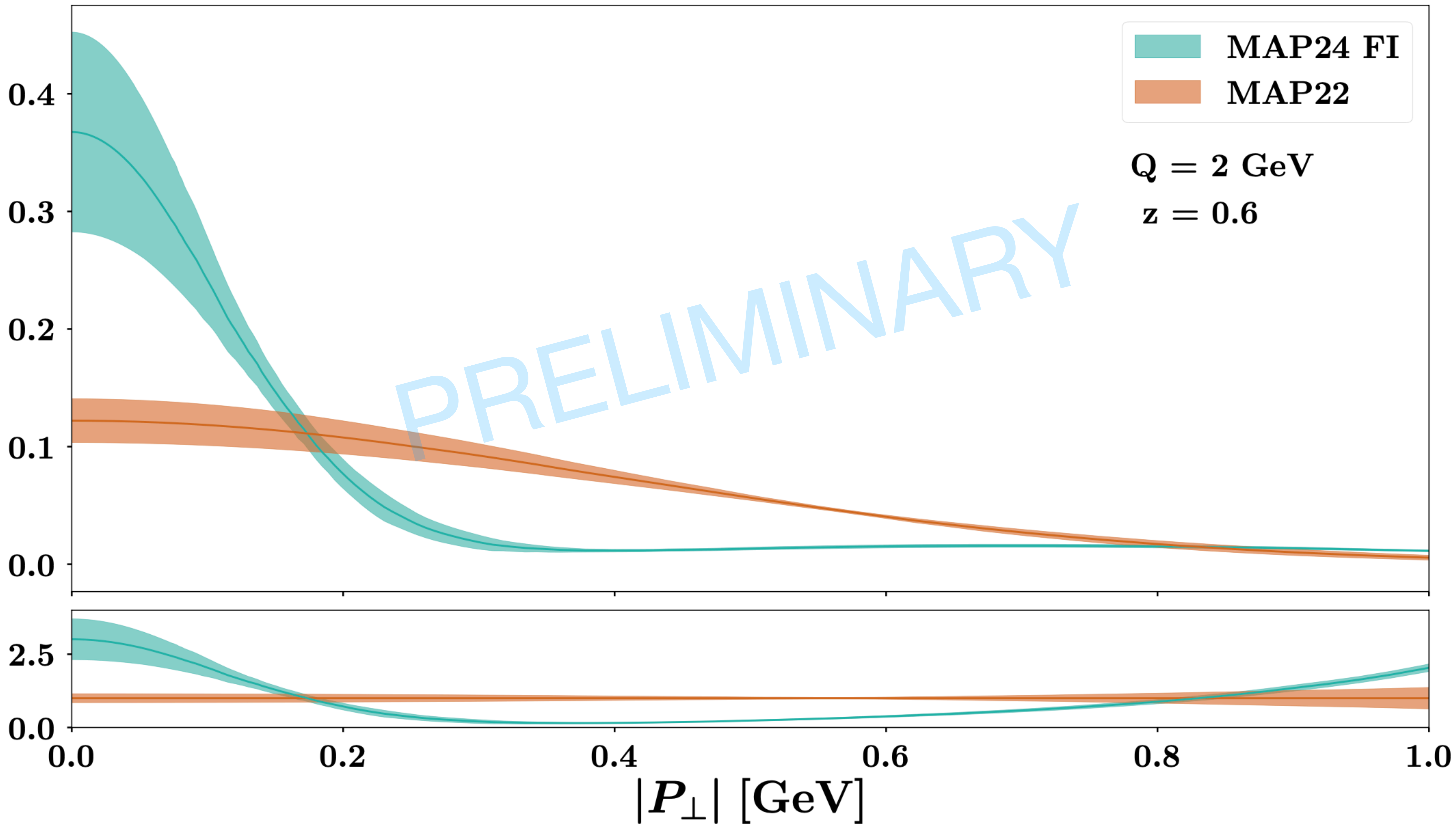

Increased order in the collinear FF extraction

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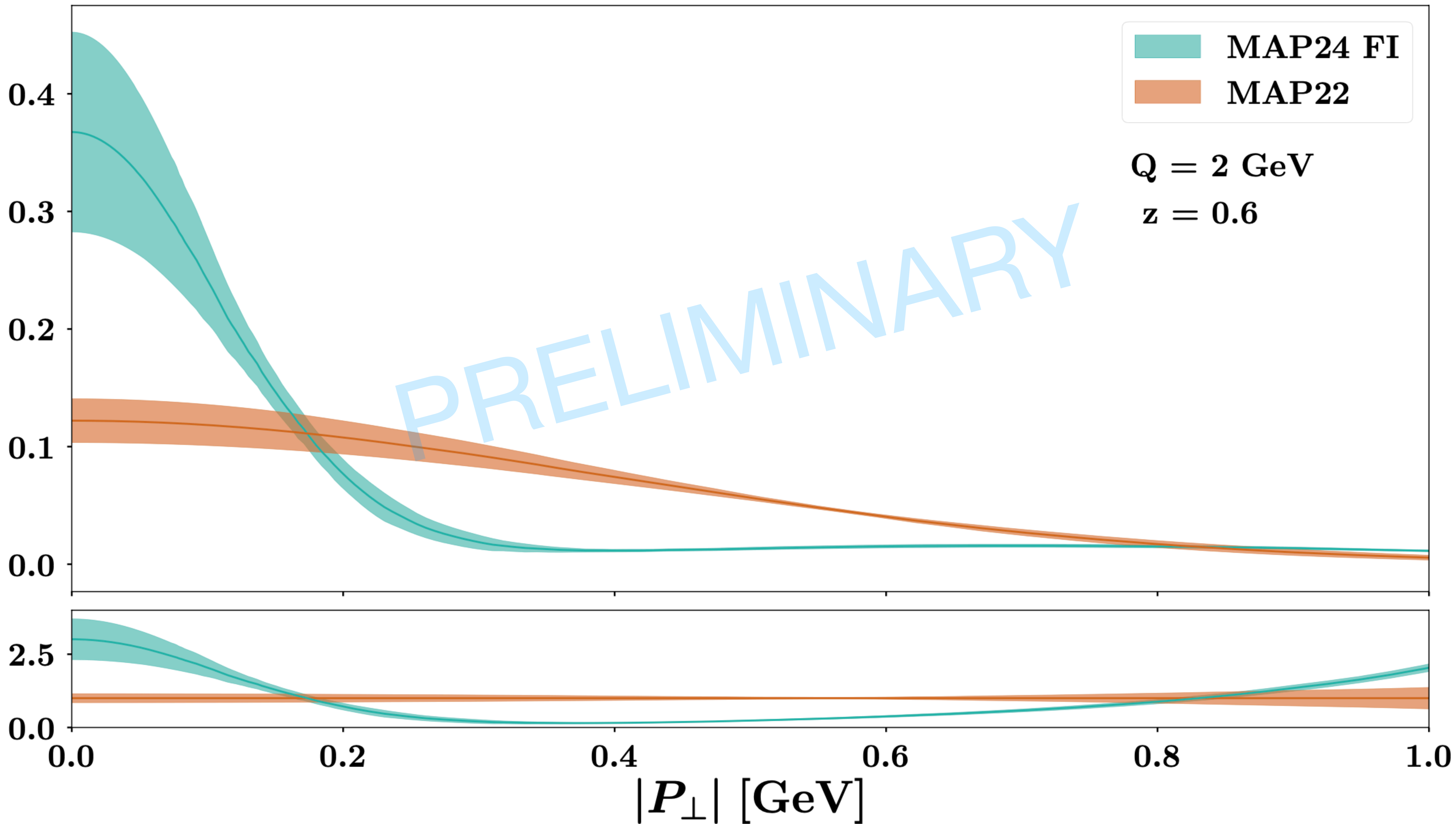

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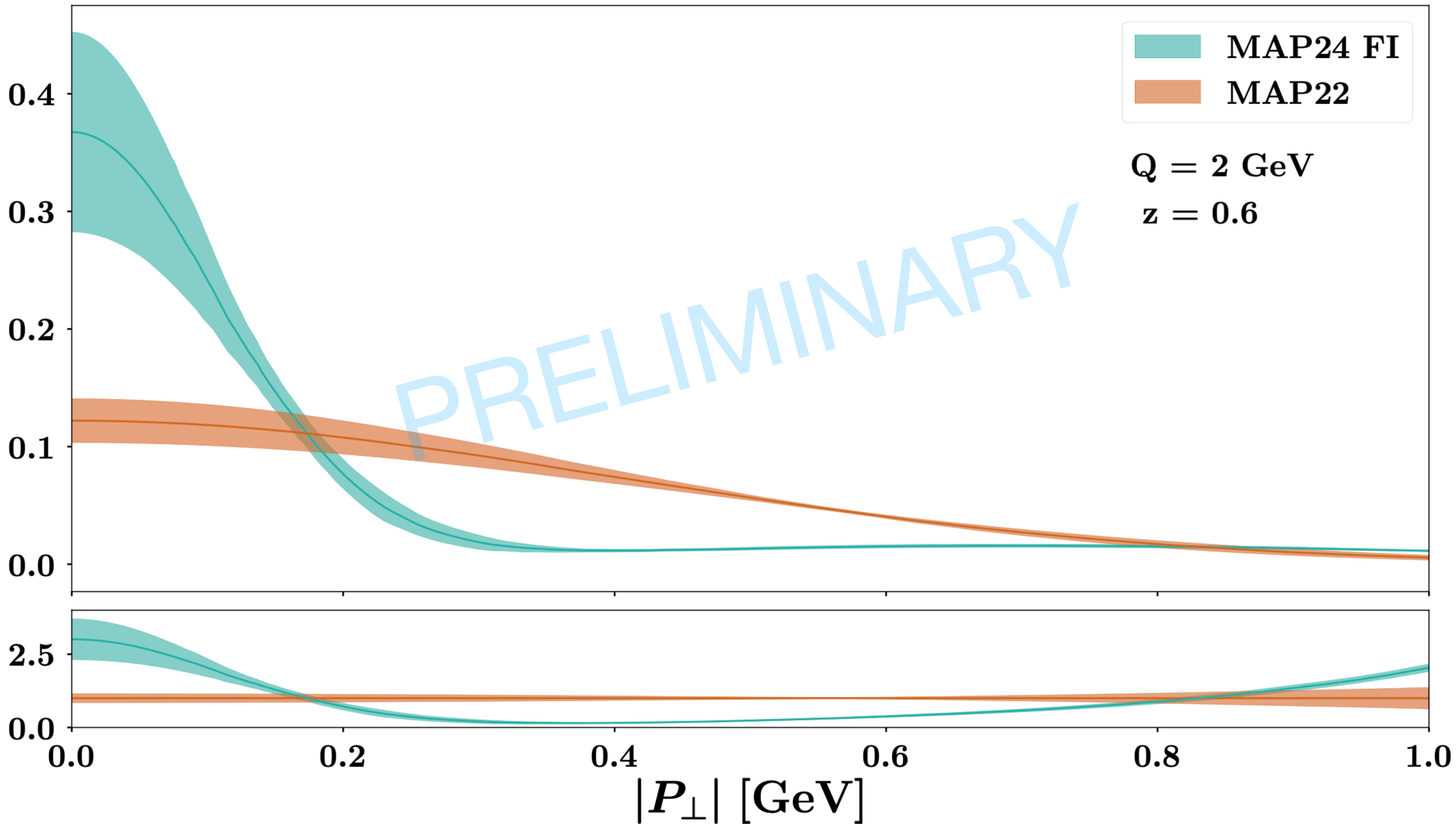

Increased order in the collinear FF extraction

- New behaviours
- Smaller uncertainties

MAPTMD24 extraction

MAPTMD24 extraction

And the next step? How do we solve it?

MAPTMD24 extraction

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$\neq \quad \neq \quad \neq$

TMD FFs: *favored* $(u \to K^+)$, *favored'* $(\bar{s} \to K^+)$, *unfavored*

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

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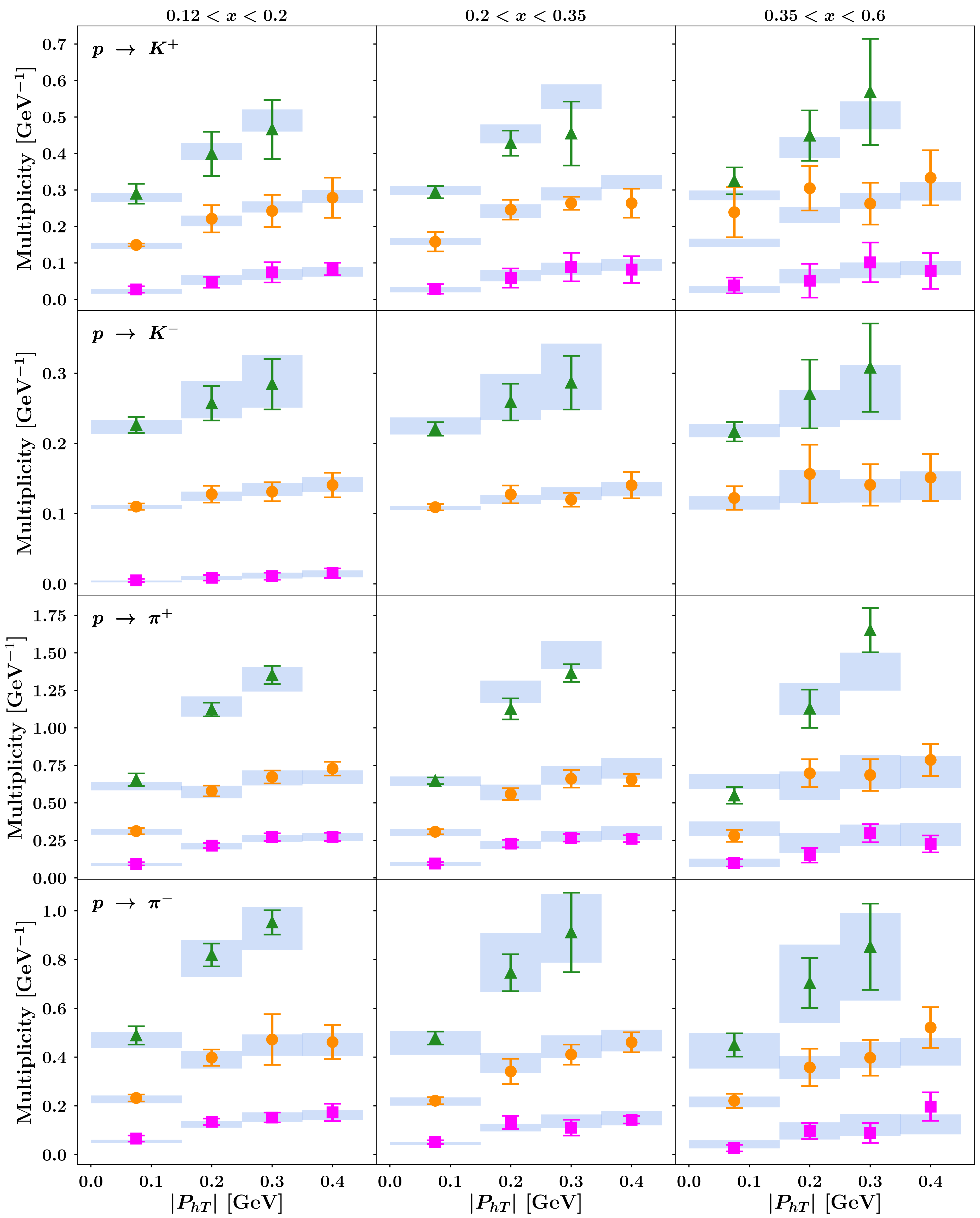

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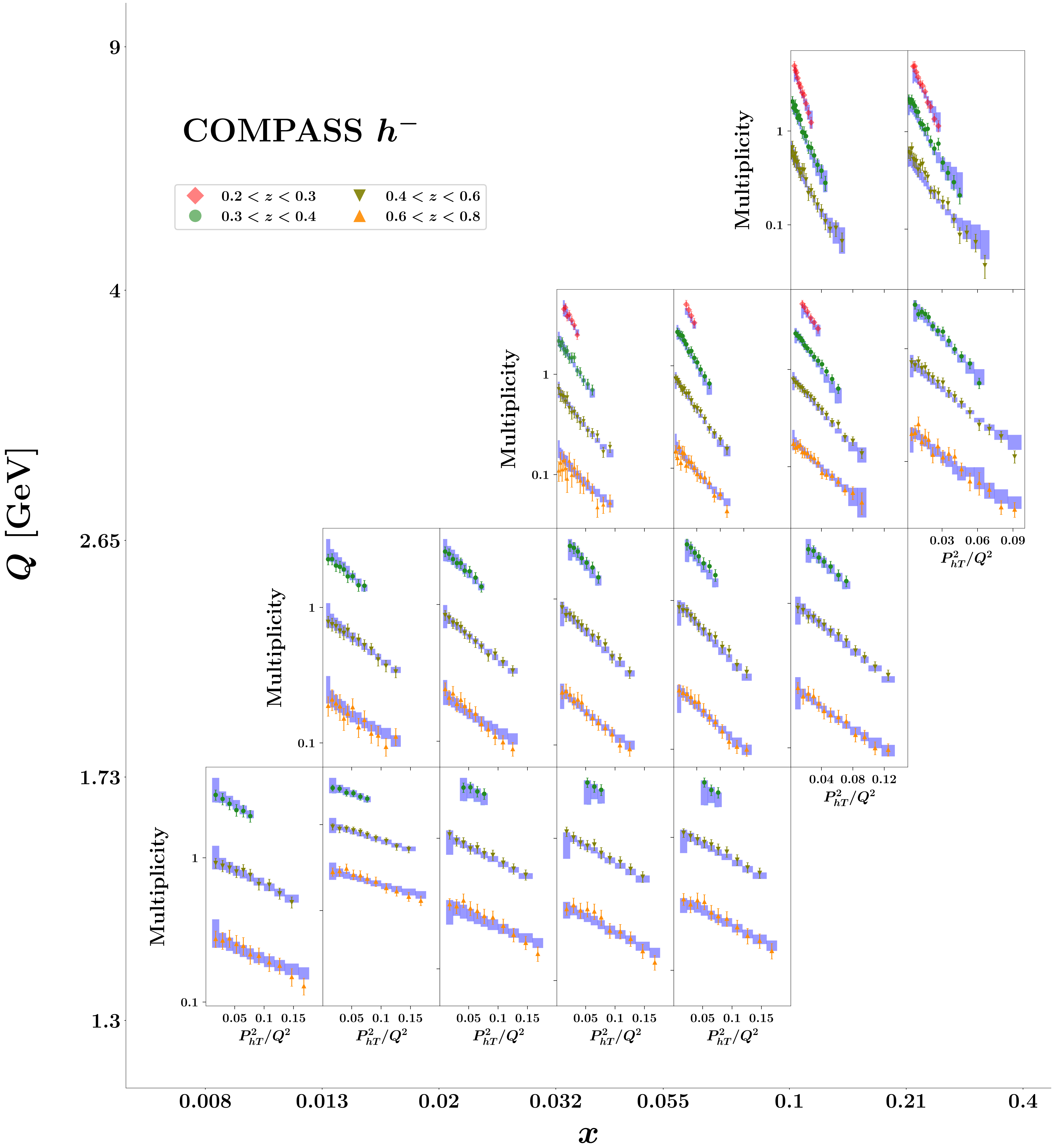

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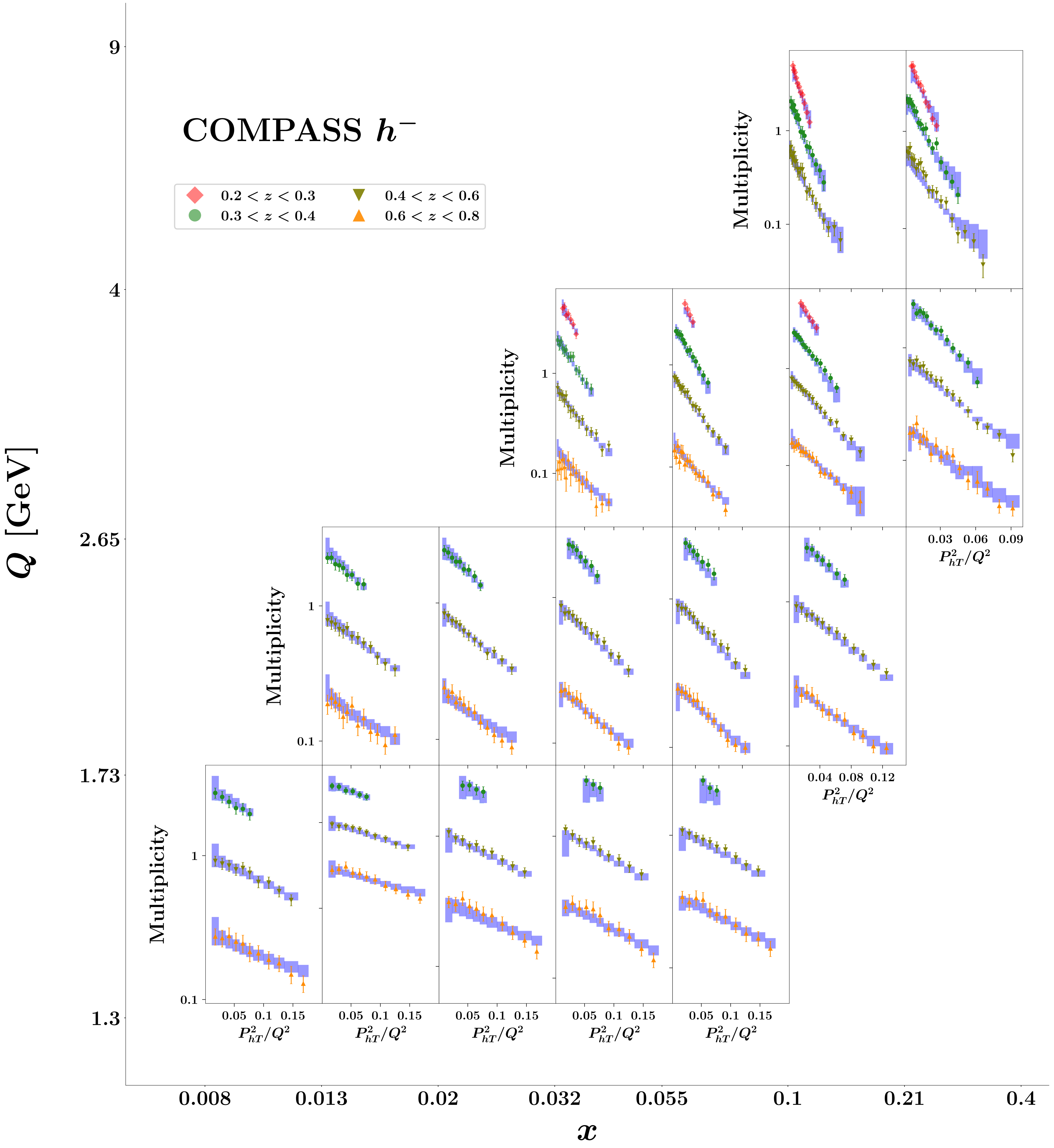

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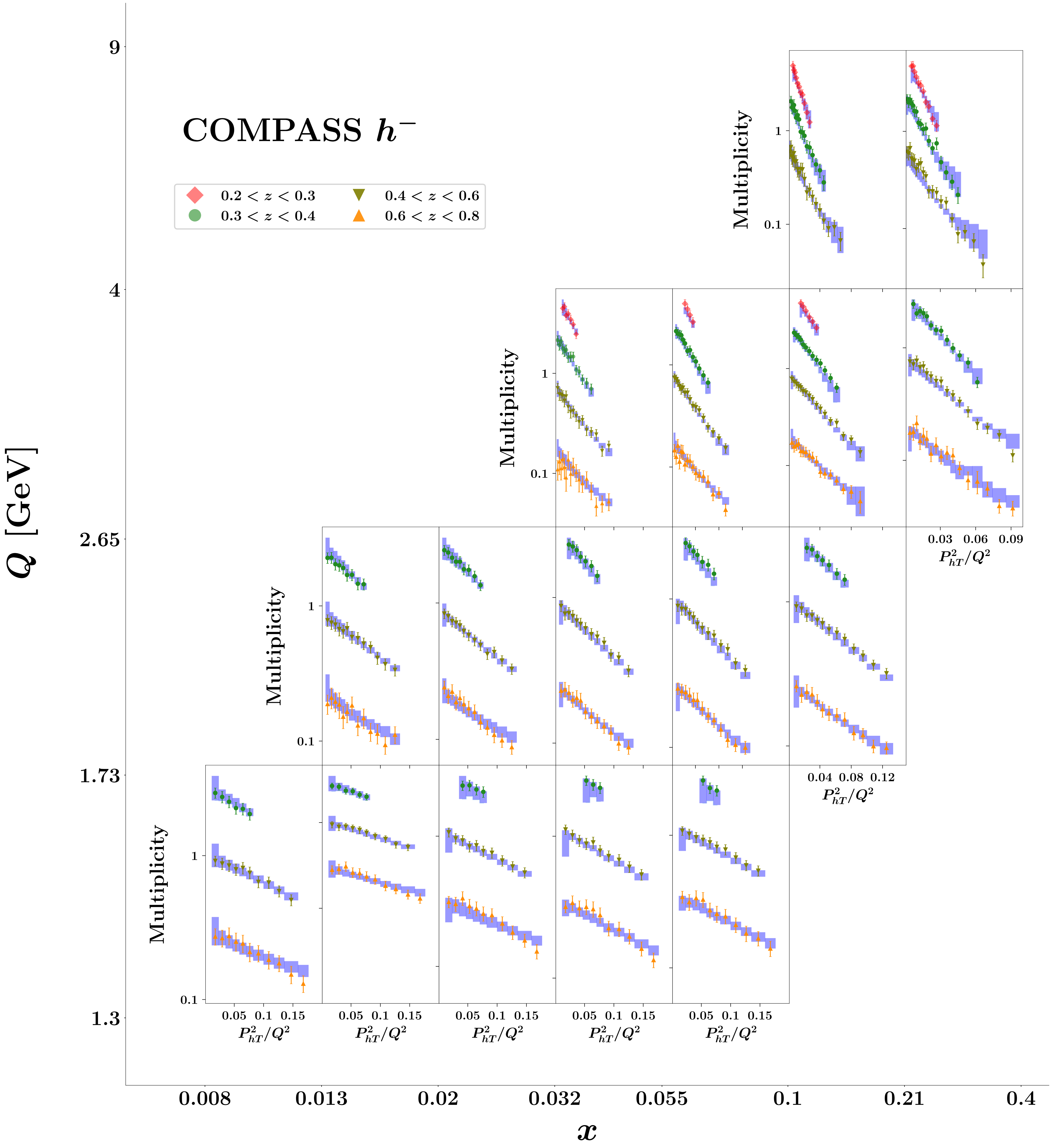

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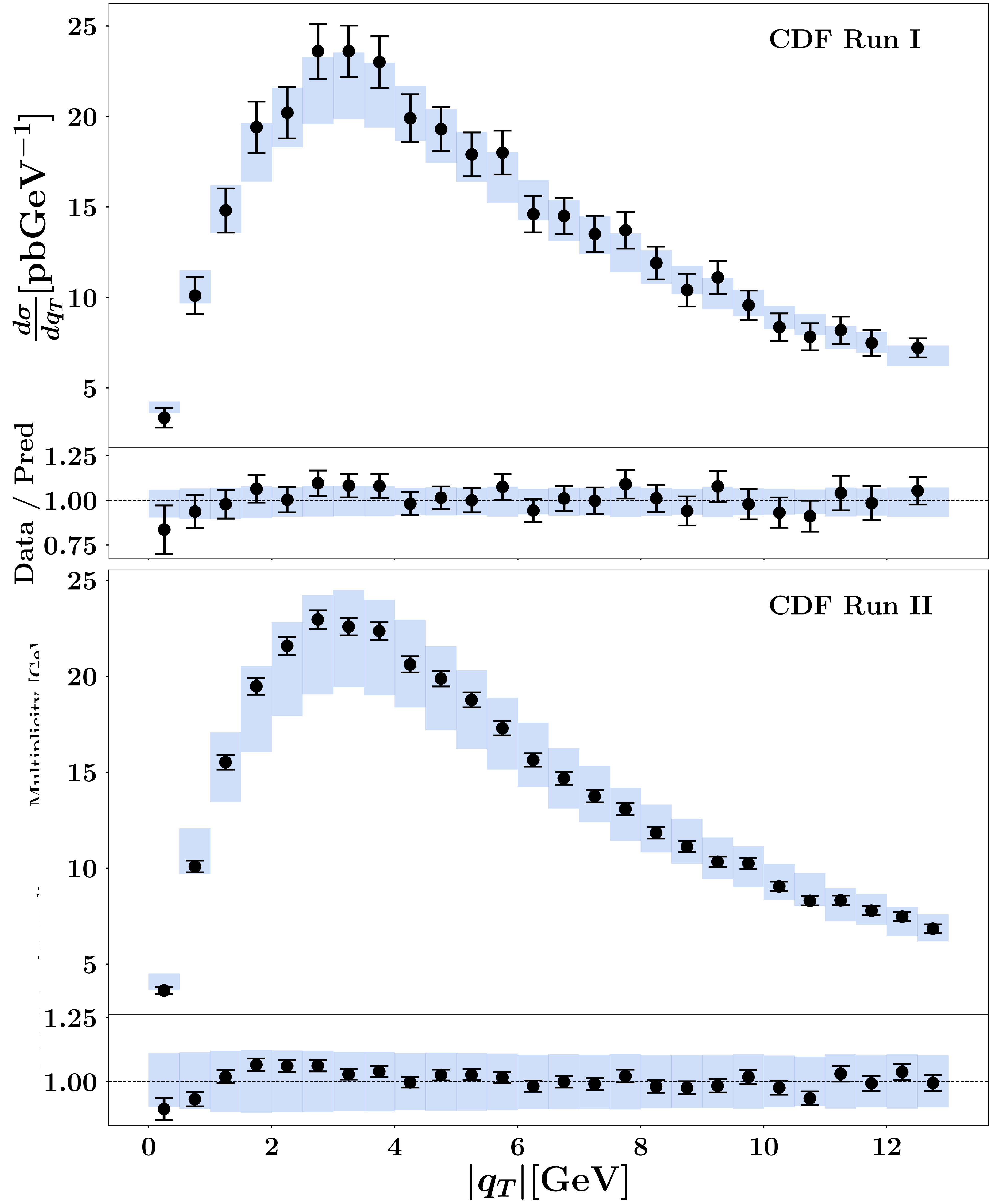

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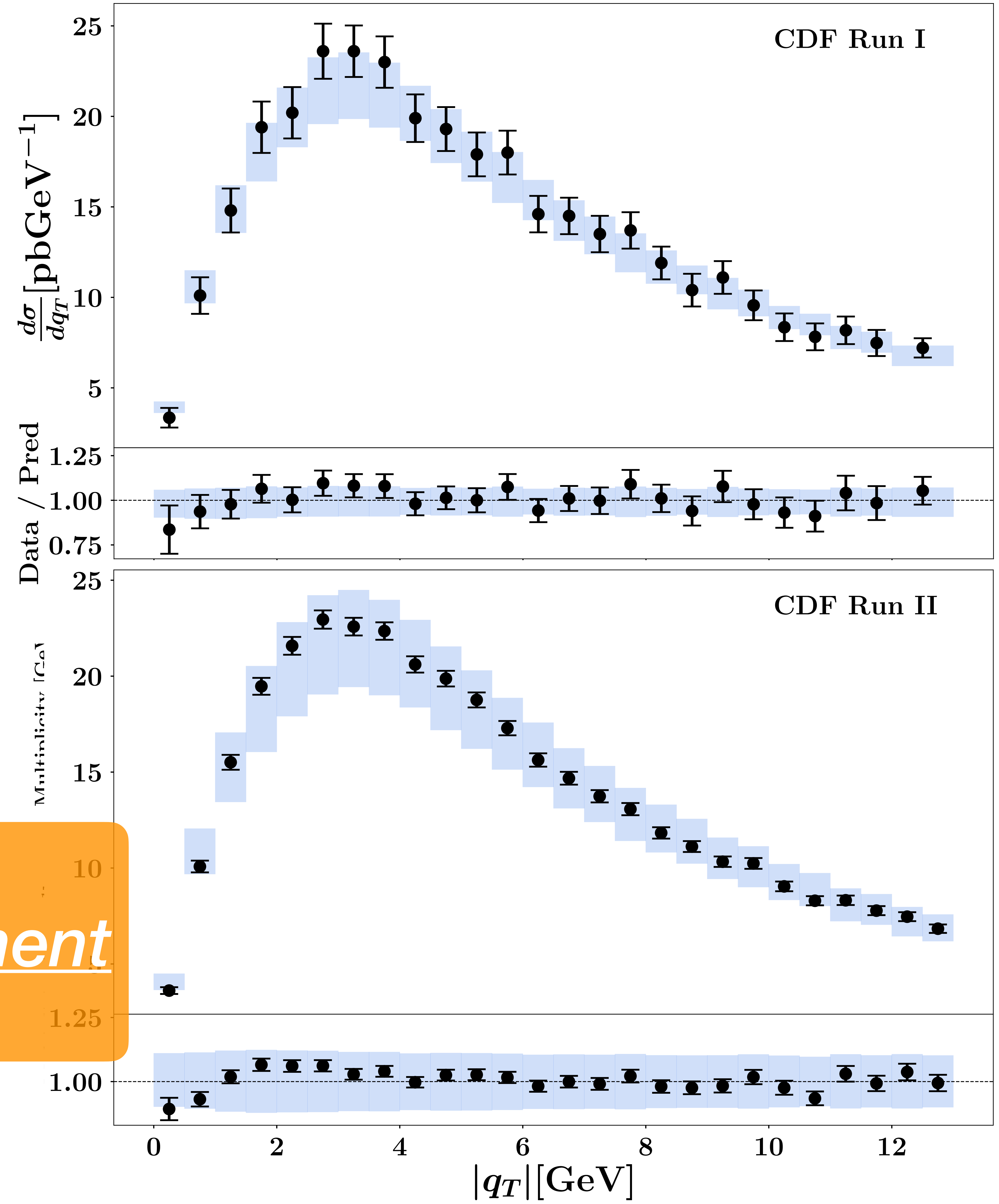

MAPTMD24 extraction - TMD PDFs

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Very different $k_\perp$ - behaviours!

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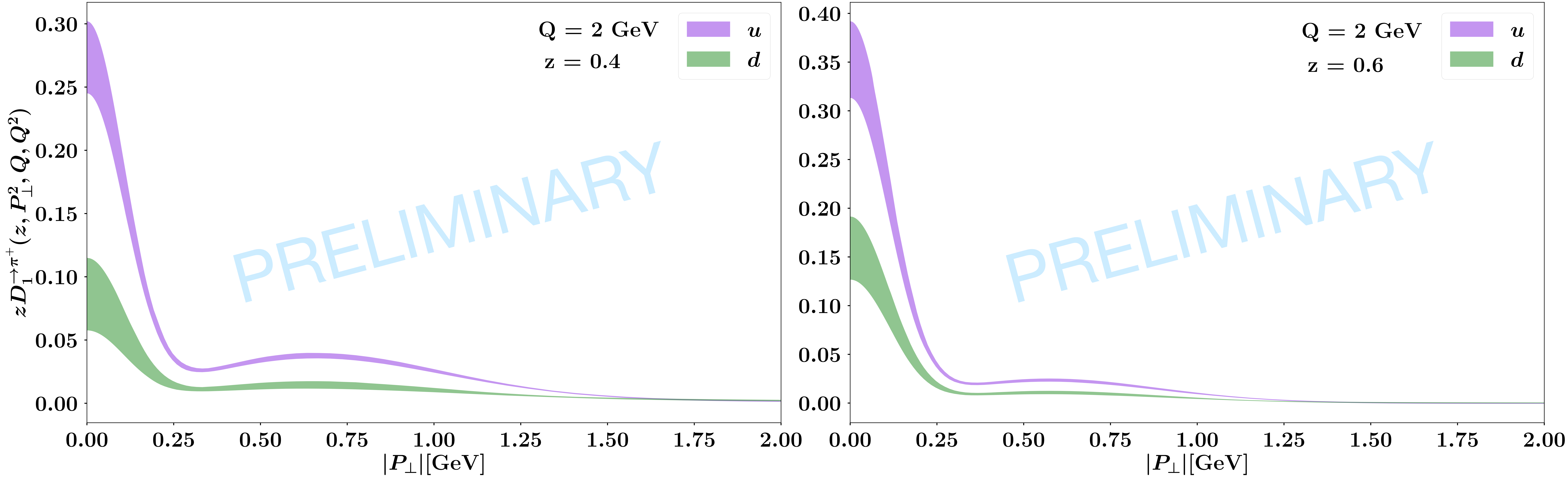
The sea is the least constrained ⟷ *The up quark is the most one*

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

MAPTMD24 extraction - TMD FFs



MAPTMD24 extraction - TMD FFs

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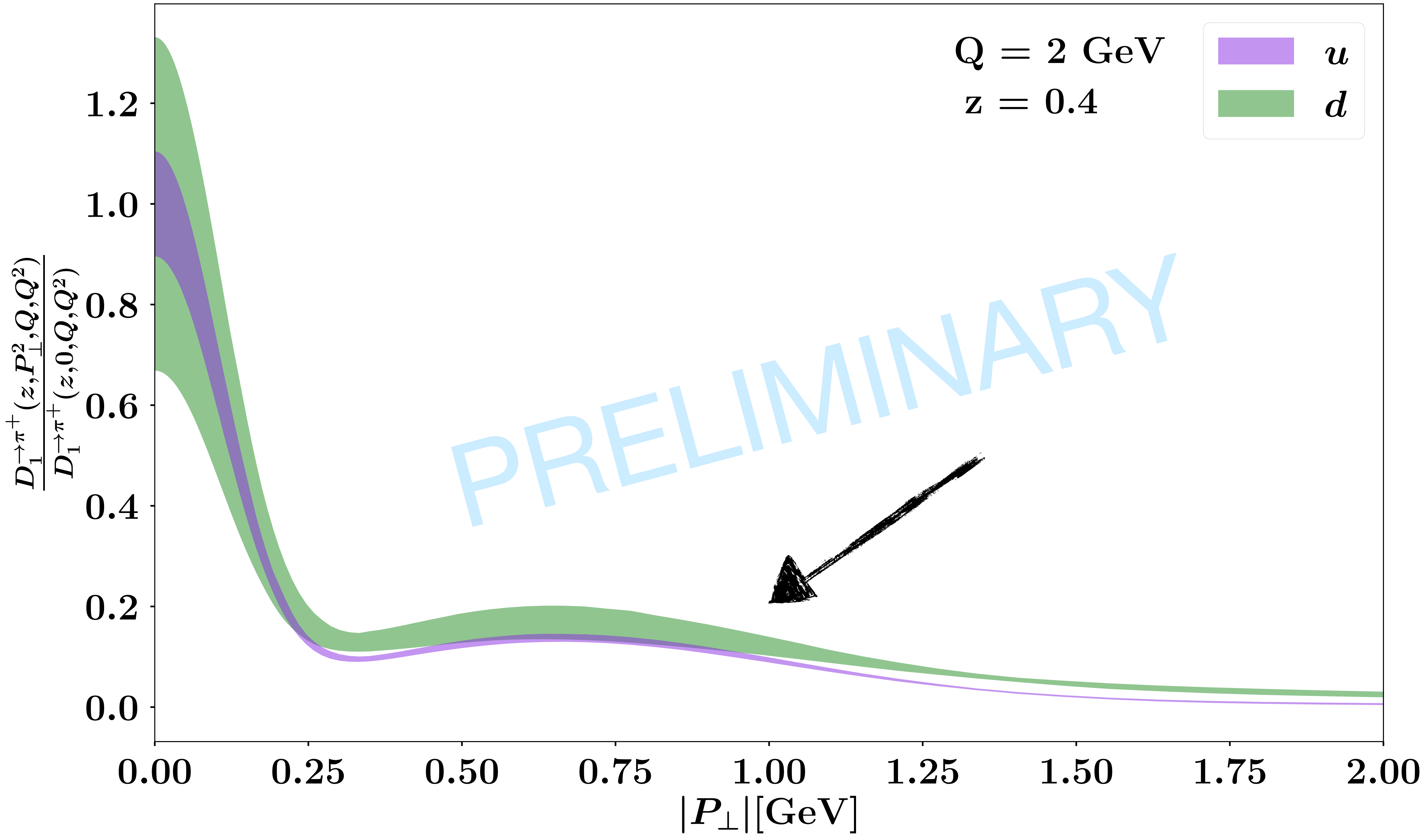
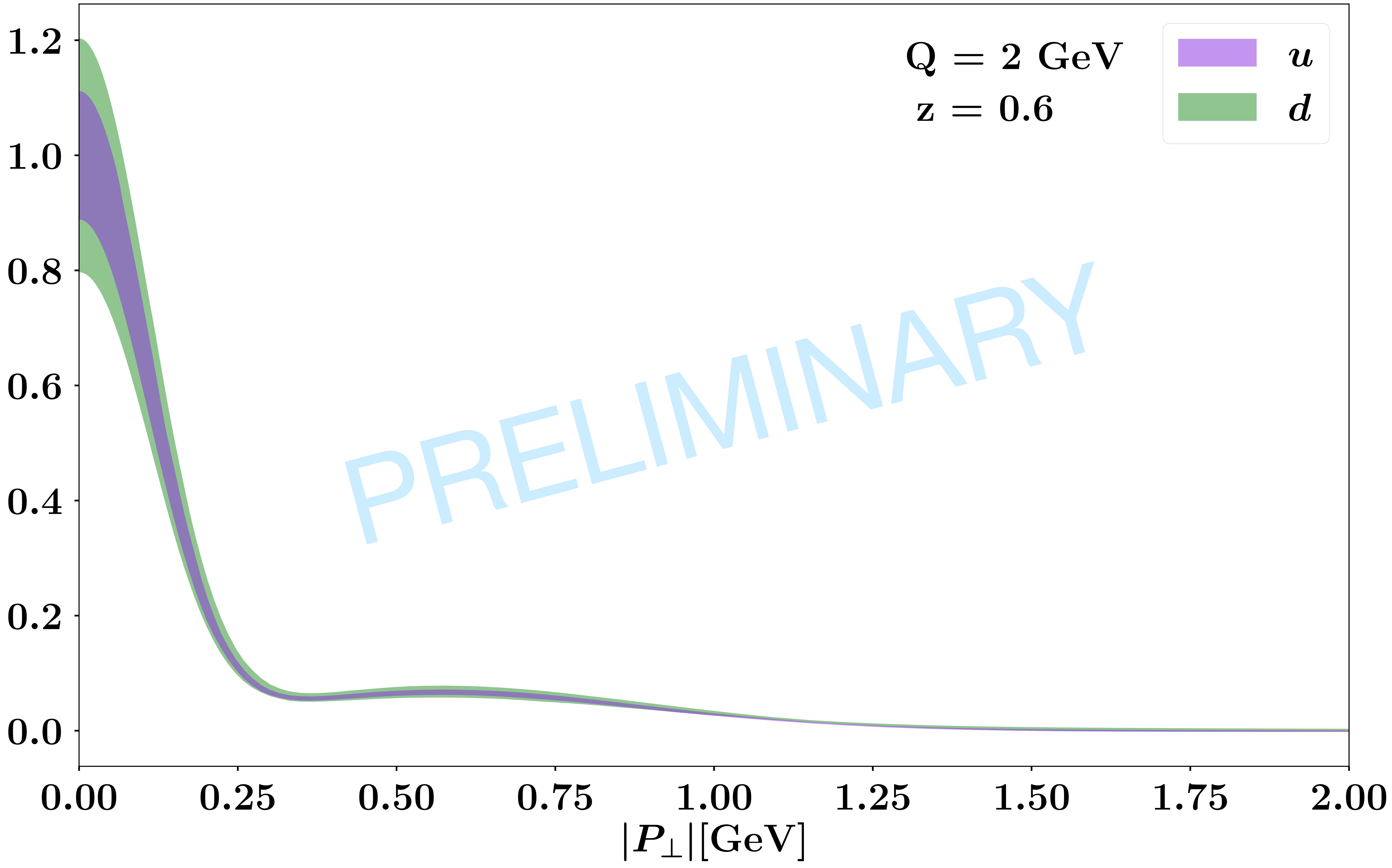
Some signals of differences between favoured and unfavoured channels

MAPTMD24 extraction - TMD FFs

The favoured is better constrained than the unfavoured one





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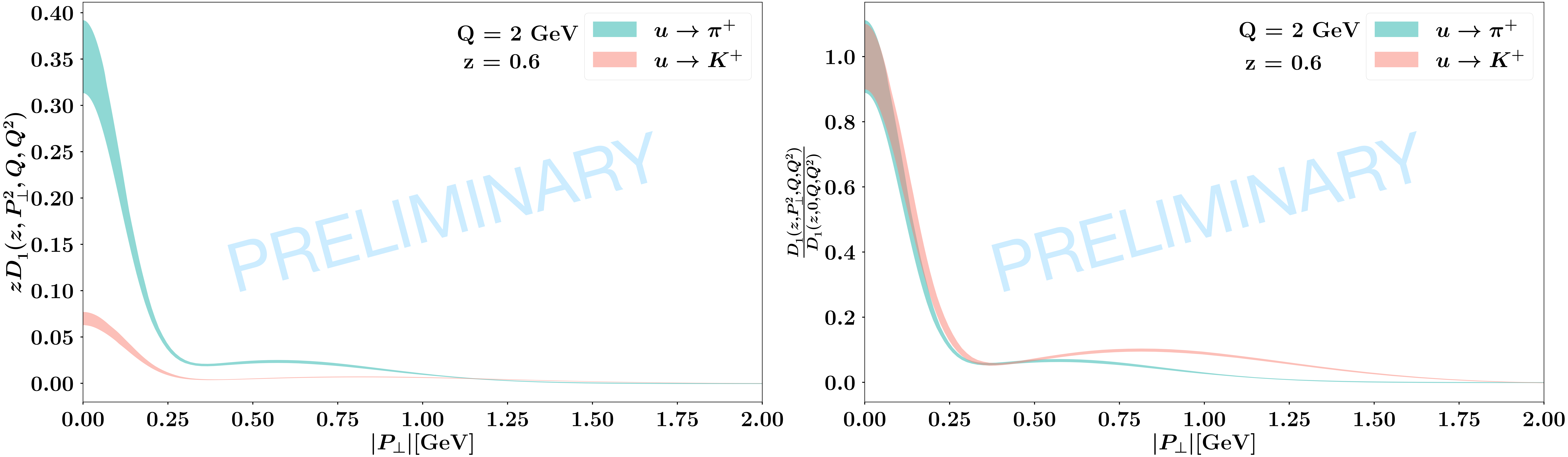

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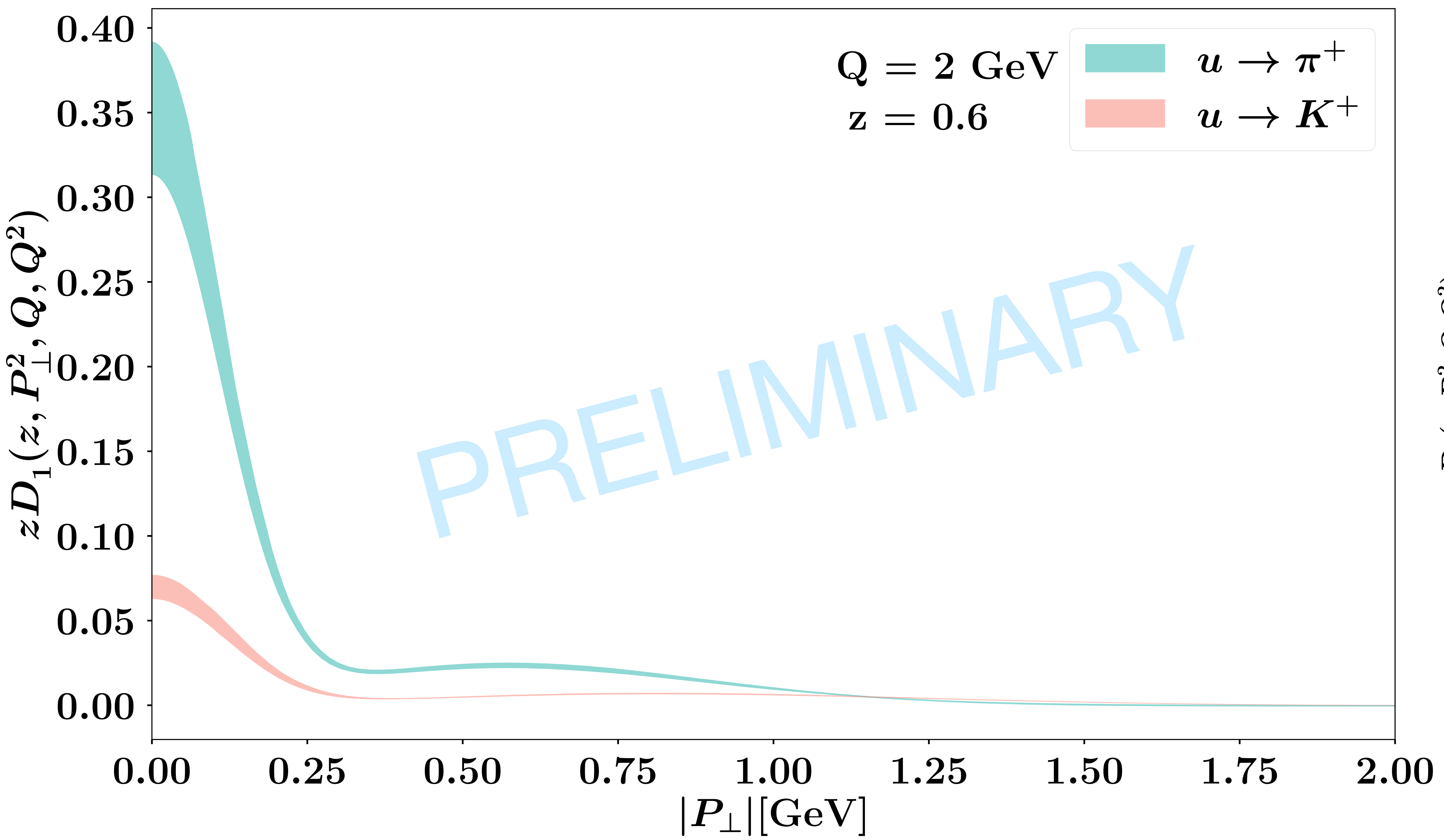

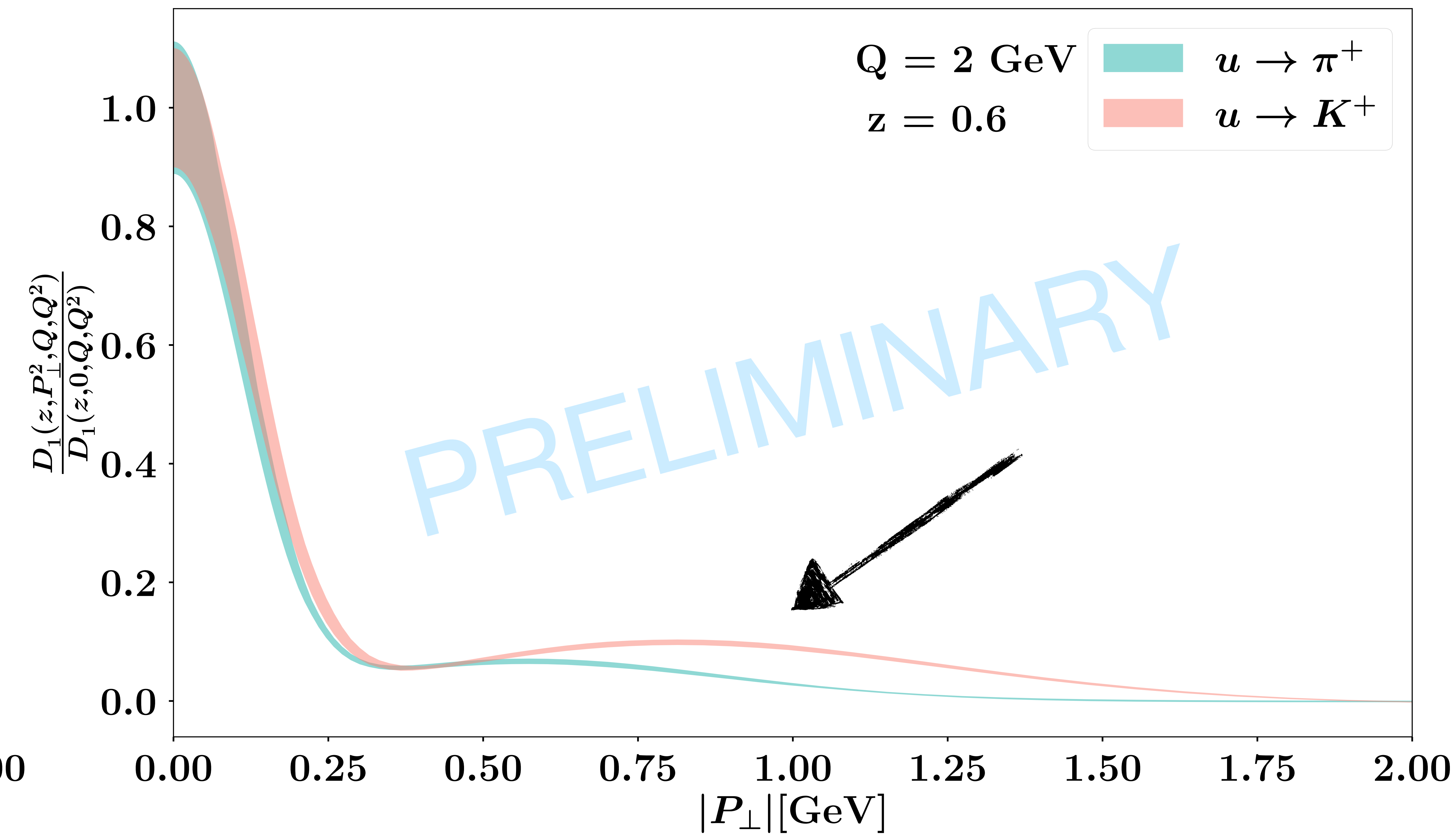

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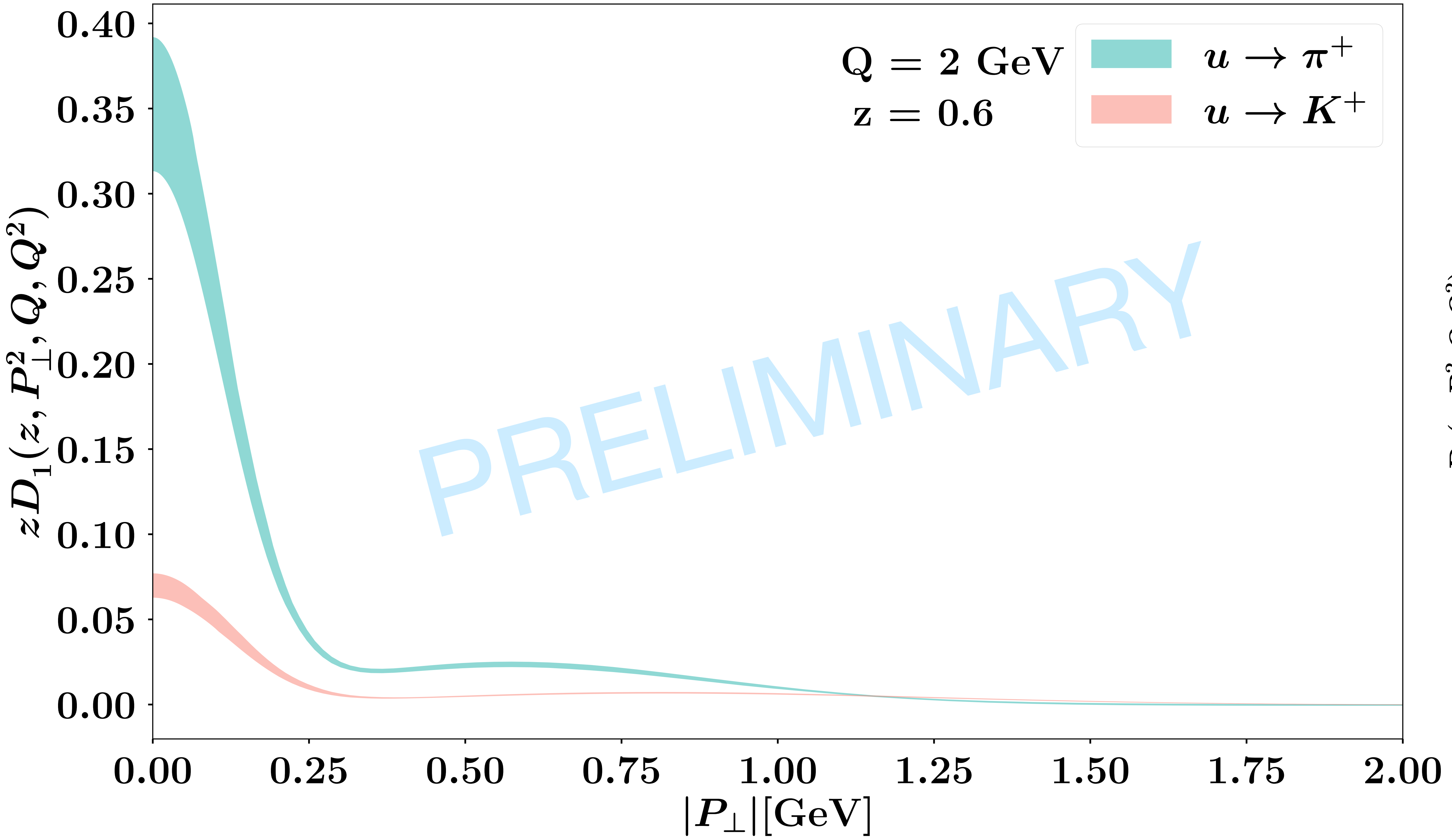
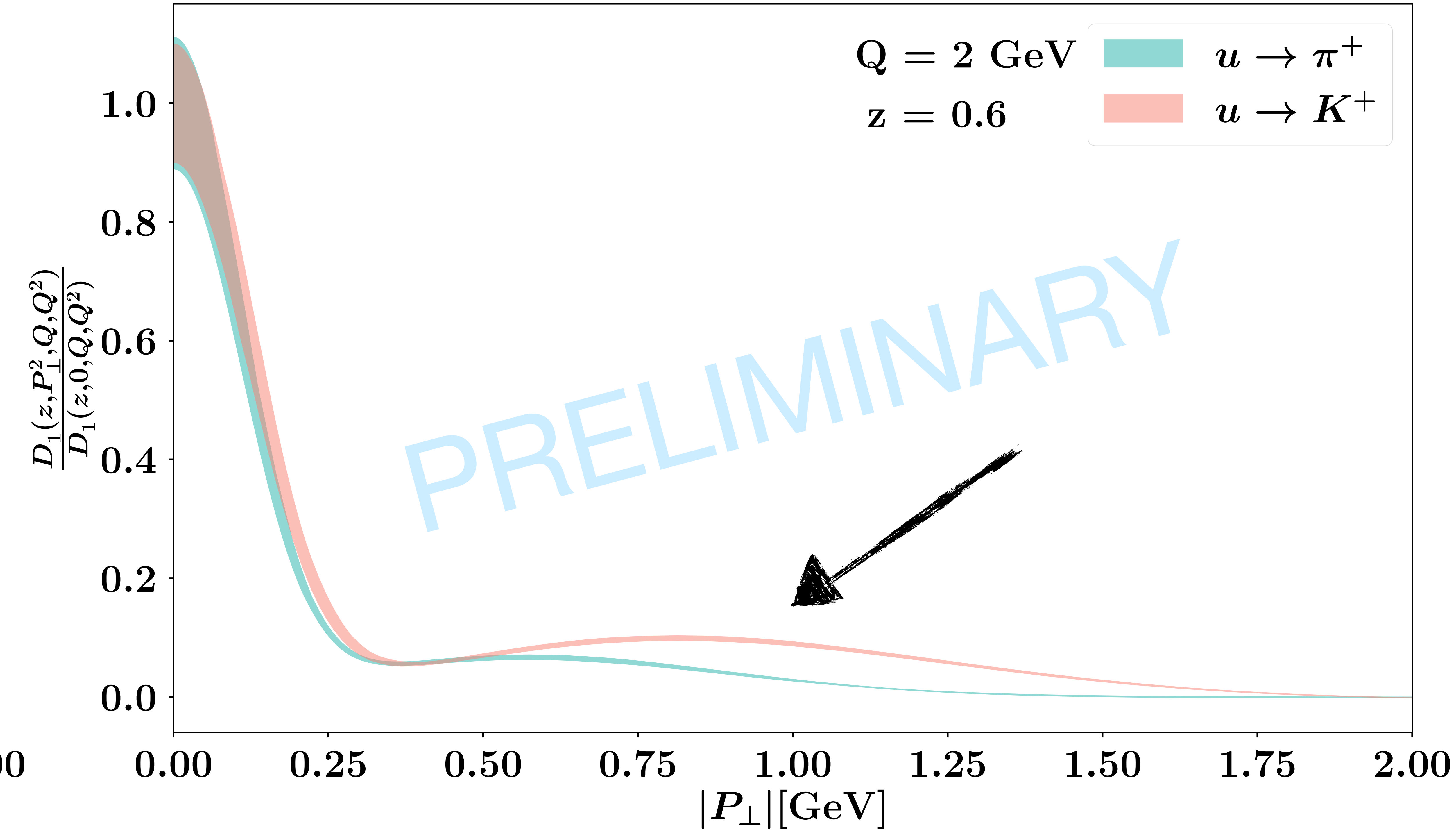
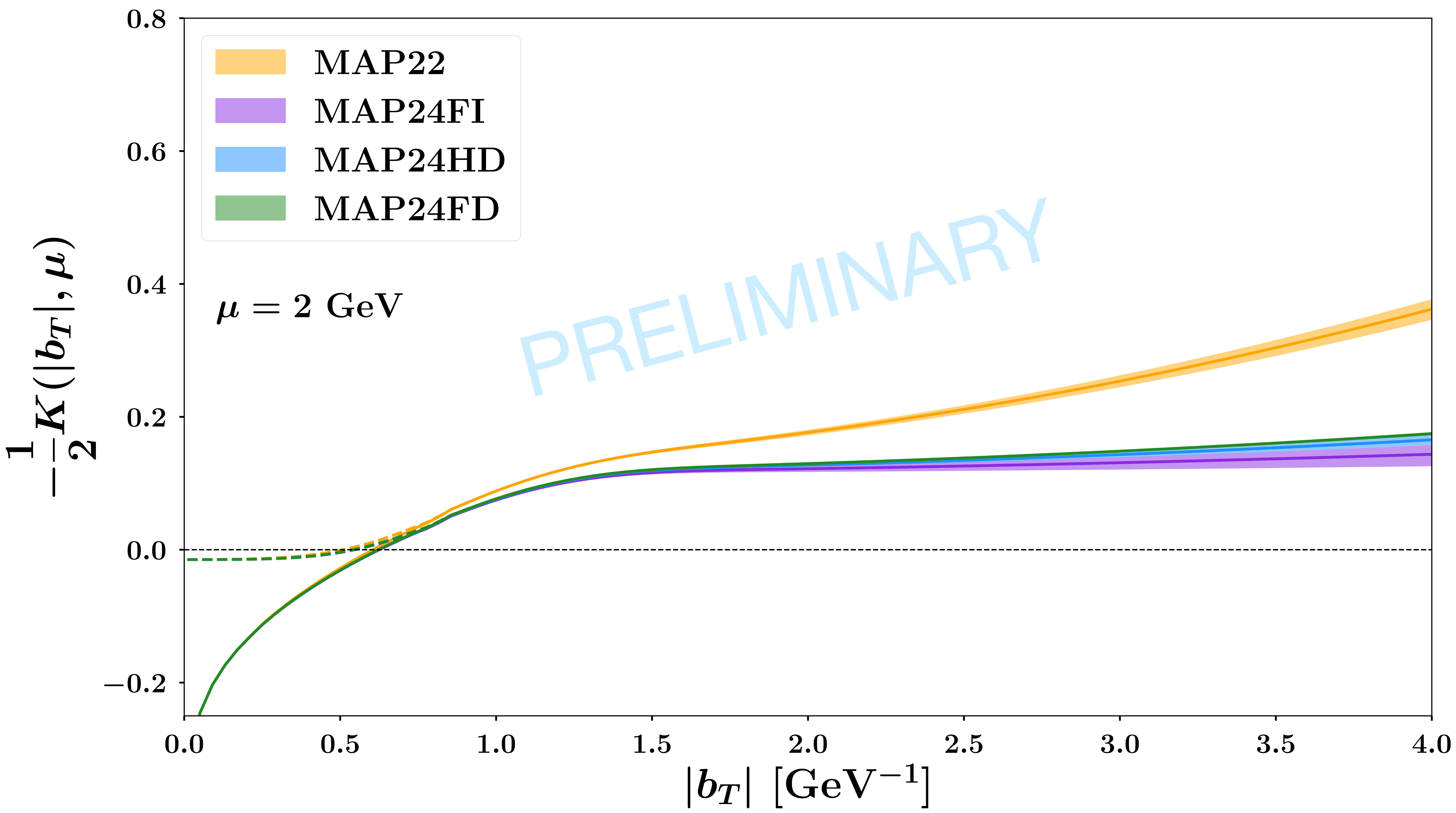




Strong differences between different hadron fragmentations!

MAPTMD24 extraction - Collins Soper Kernel



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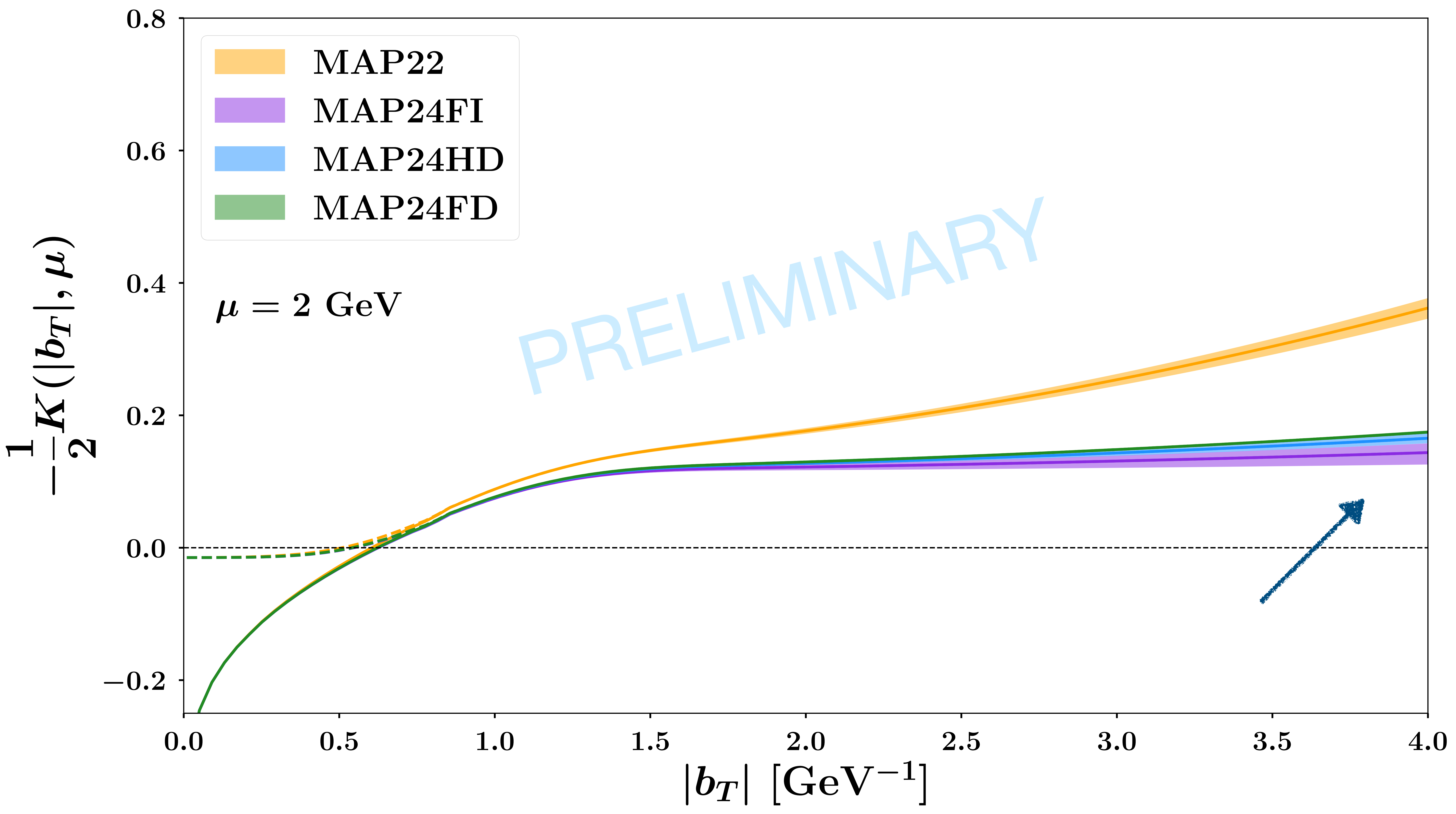

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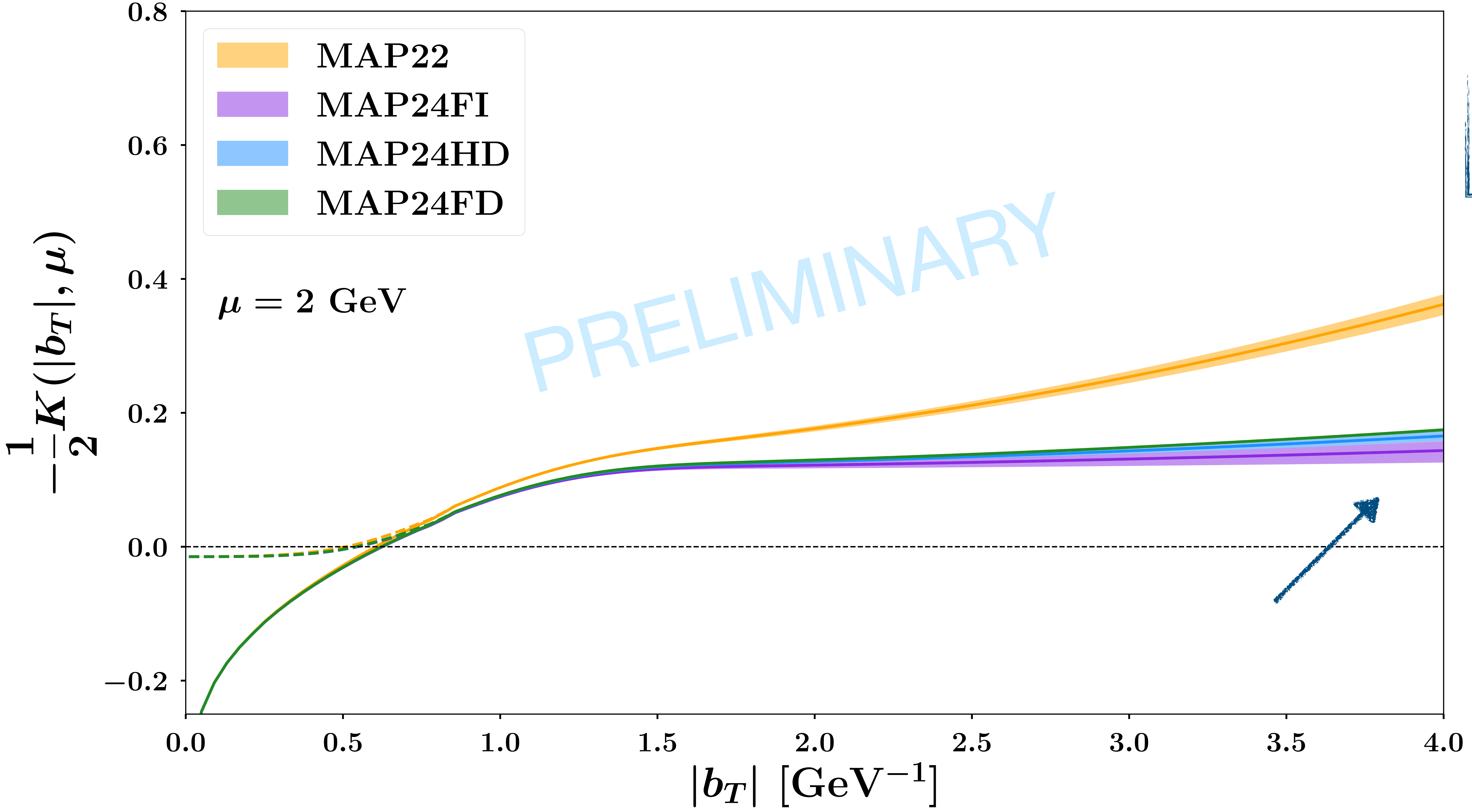

Independent of our non perturbative choices

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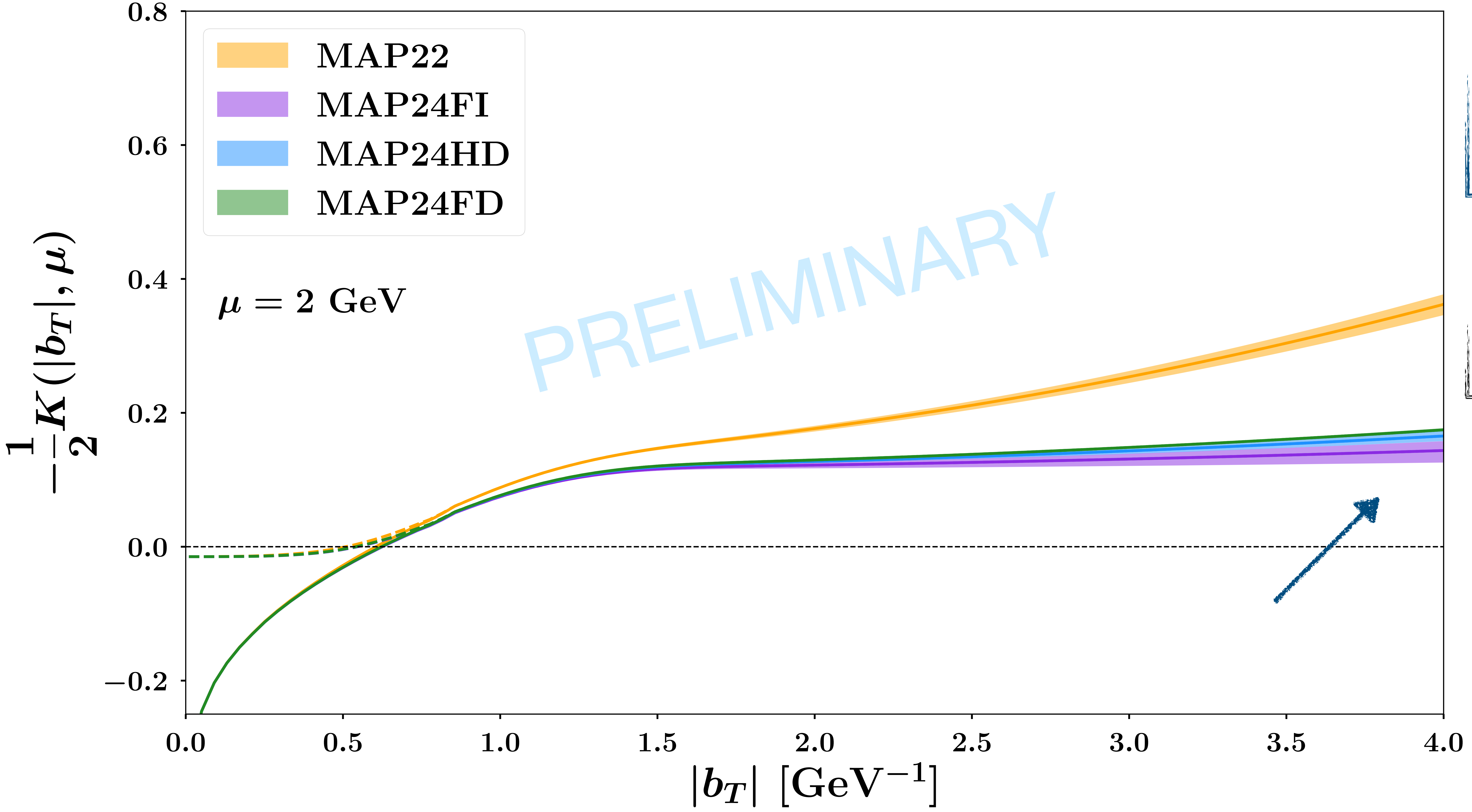

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Quite linear behaviour

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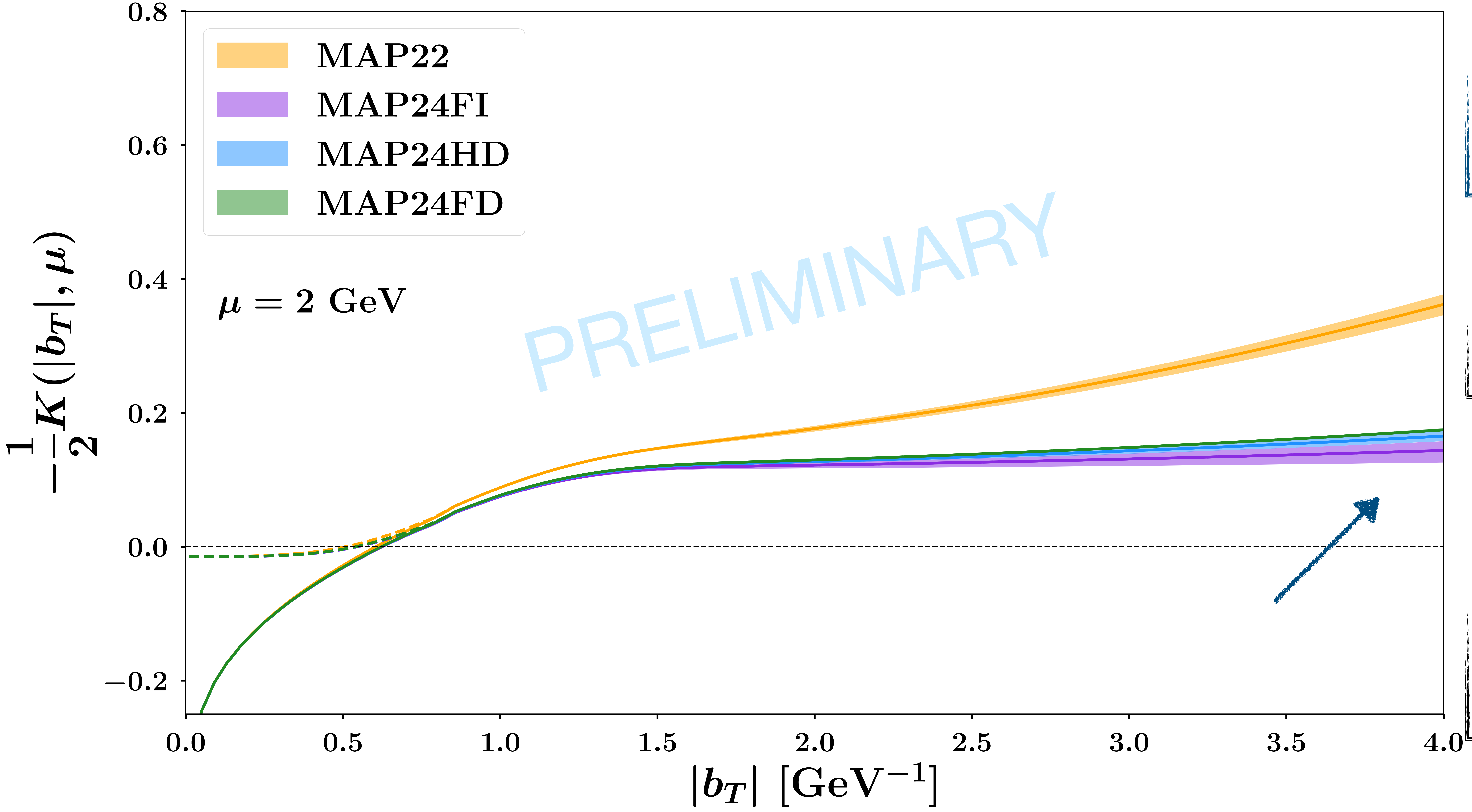

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Compatible with latest lattice calculation

2403.00664

Conclusions and outlook

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Conclusions and outlook

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

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

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

BACKUP

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
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NNPDF + MAPFF

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Data set	N_{dat}	χ_0^2/N_{dat}
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HERMES total	344	0.95
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NNPDF + MAPFF

Data set	$N_{\rm dat}$	$\chi_0^2/N_{\rm dat}$
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
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MMHT + DSS (MAP22)

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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	1.39

NNPDF + MAPFF

Data set	N_{dat}	χ_0^2/N_{dat}
DY collider total	251	2.01
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COMPASS total	1203	0.99
SIDIS total	1547	1.33
Total	2031	1.39

MMHT + MAPFF

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
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MMHT + MAPFF

Agreement

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MMHT + MAPFF

Agreement

Similar worsening

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NNPDF + DSS

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SIDIS total	1547	0.87
Total	2031	1.06

MMHT + DSS (MAP22)

Good agreement

BACKUP

	N^3LL			
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**

BACKUP - datasets included

BACKUP - datasets included

Drell-Yan

Fixed-target low-energy DY

RHIC data

LHC and Tevatron data

BACKUP - datasets included

Drell-Yan → **484 points**

Fixed-target low-energy DY

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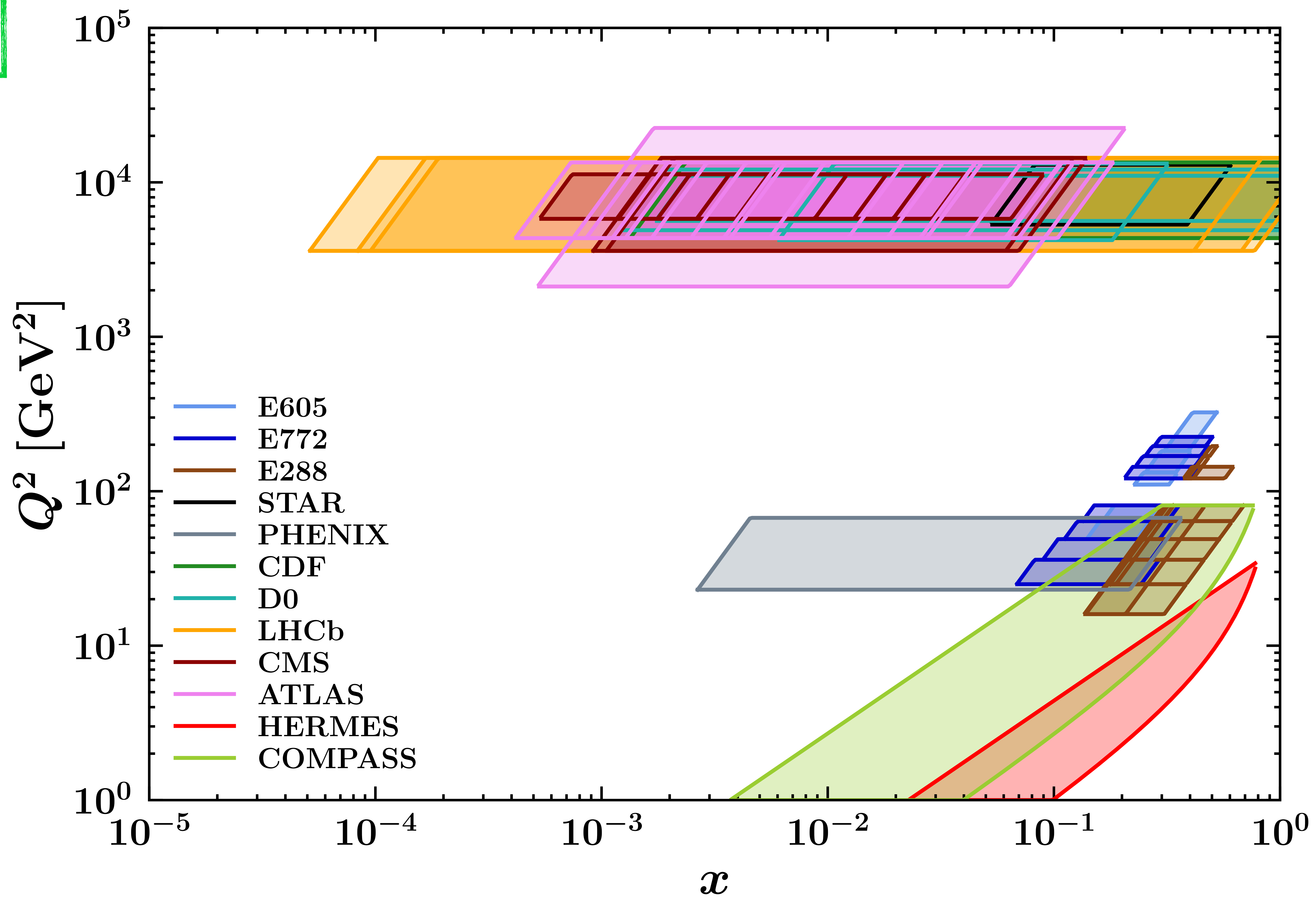
SIDIS → **1547 points**

HERMES data

COMPASS data



Total: 2031 fitted points