MAPTMD24: First Global Flavor Dependent TMD extractions

JHEP 08 (2024) 232

Science at the Luminosity Frontier: Jefferson Lab at 22 GeV

Lorenzo Rossi

MAP Collaboration

December 10th

Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DEGLI STUDI DI MILANO

MAPTMD24: First Global Flavor Dependent TMD extractions

JHEP 08 (2024) 232

Science at the Luminosity Frontier: Jefferson Lab at 22 GeV

Lorenzo Rossi

MAP Collaboration

December 10th

INFN
Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DEGLI STUDI DI MILANO

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)

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

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

Collins, “Foundations of Perturbative QCD”

TMD Factorization - structure of TMDs

Matching coeff. (perturbative calculable)

Collinear PDFs (previous fit)

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

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

Collins, "Foundations of Perturbative QCD"

TMD Factorization - structure of TMDs

Matching coeff. (perturbative calculable)

Collinear PDFs (previous fit)

Perturbative Sudakov evolution factor

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

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

Collins, "Foundations of Perturbative QCD"

TMD Factorization - structure of TMDs

Matching coeff. (perturbative calculable)

Collinear PDFs (previous fit)

Perturbative Sudakov evolution factor

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

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

Collins-Soper kernel

Collins, "Foundations of Perturbative QCD"

TMD Factorization - structure of TMDs

Matching coeff. (perturbative calculable)

Collinear PDFs (previous fit)

Perturbative Sudakov evolution factor

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

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

Collins-Soper kernel

NP part of Collins-Soper Kernel

Collins, "Foundations of Perturbative QCD"

TMD Factorization - structure of TMDs

Matching coeff. (perturbative calculable)

Collinear PDFs (previous fit)

Perturbative Sudakov evolution factor

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

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

Collins-Soper kernel

NP part of Collins-Soper Kernel

Non perturbative part of TMDs

Collins, "Foundations of Perturbative QCD"

TMD Factorization - structure of TMDs

Matching coeff. (perturbative calculable)

Collinear PDFs (previous fit)

Perturbative Sudakov evolution factor

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

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

Collins-Soper kernel

NP part of Collins-Soper Kernel

Non perturbative part of TMDs

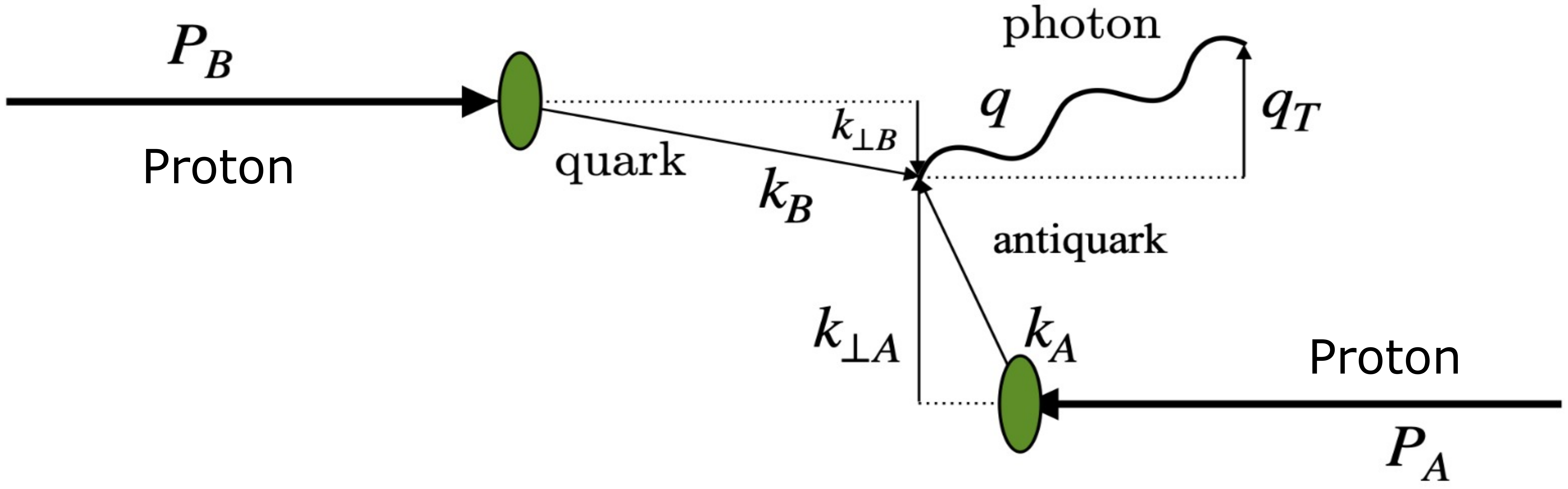
Fit extraction

Collins, "Foundations of Perturbative QCD"

TMD factorization — Drell-Yan process

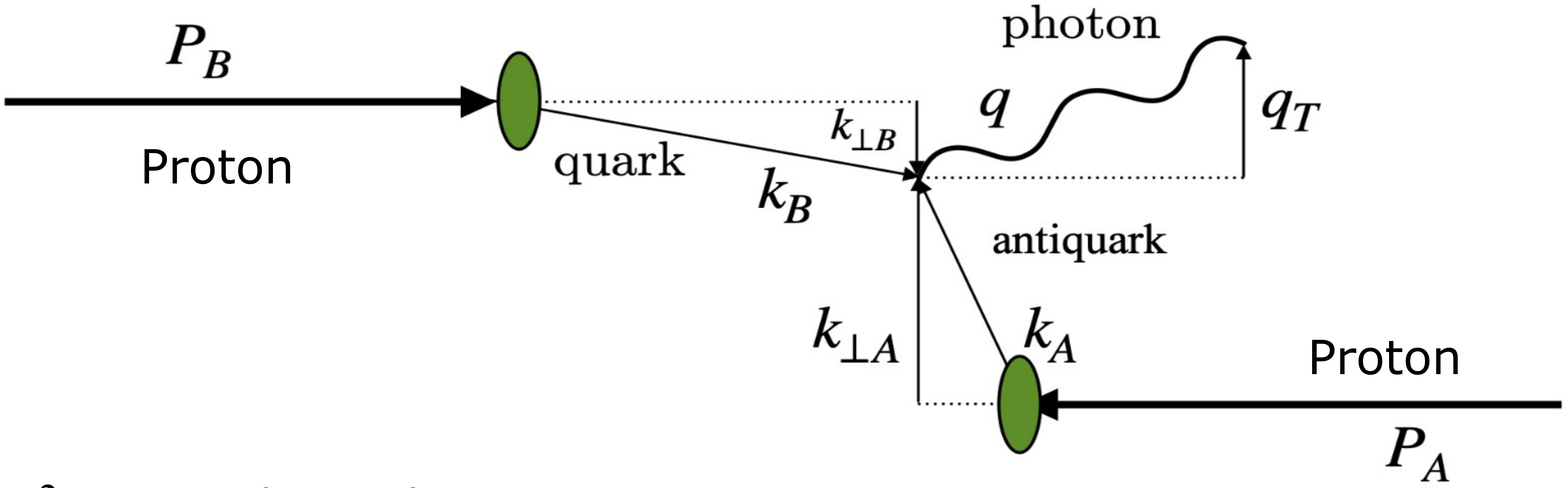
Arnold, Metz and Schlegel, Phys.Rev.D 79 (2009)

TMD factorization — Drell-Yan process



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

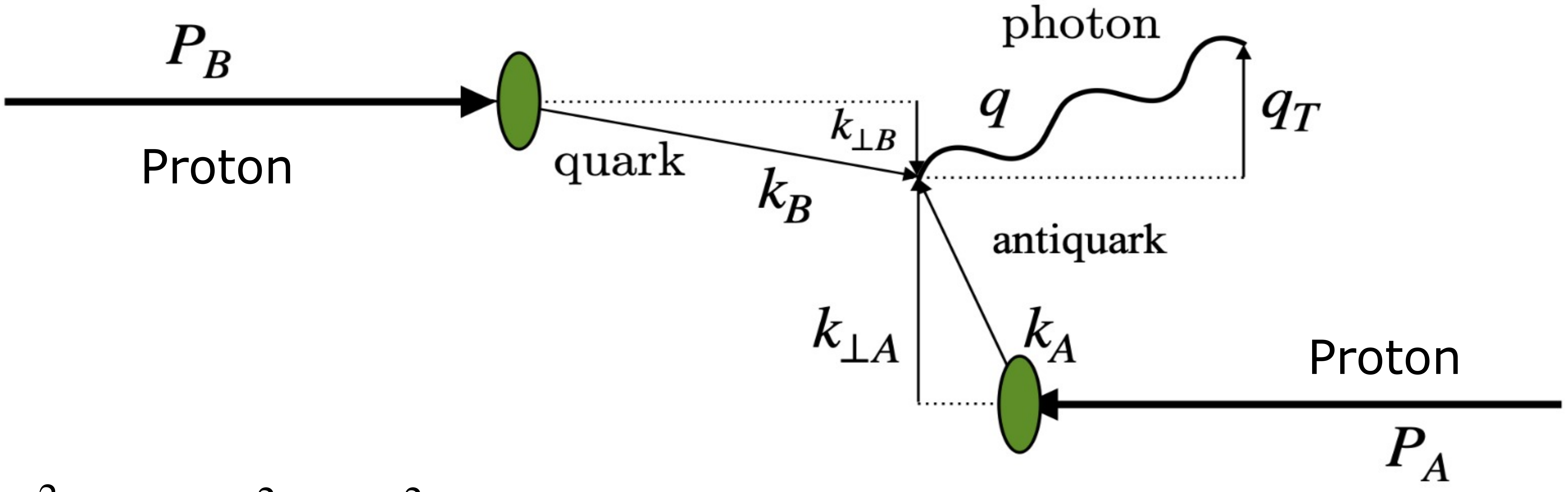
TMD factorization — Drell-Yan process



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

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

TMD factorization — Drell-Yan process

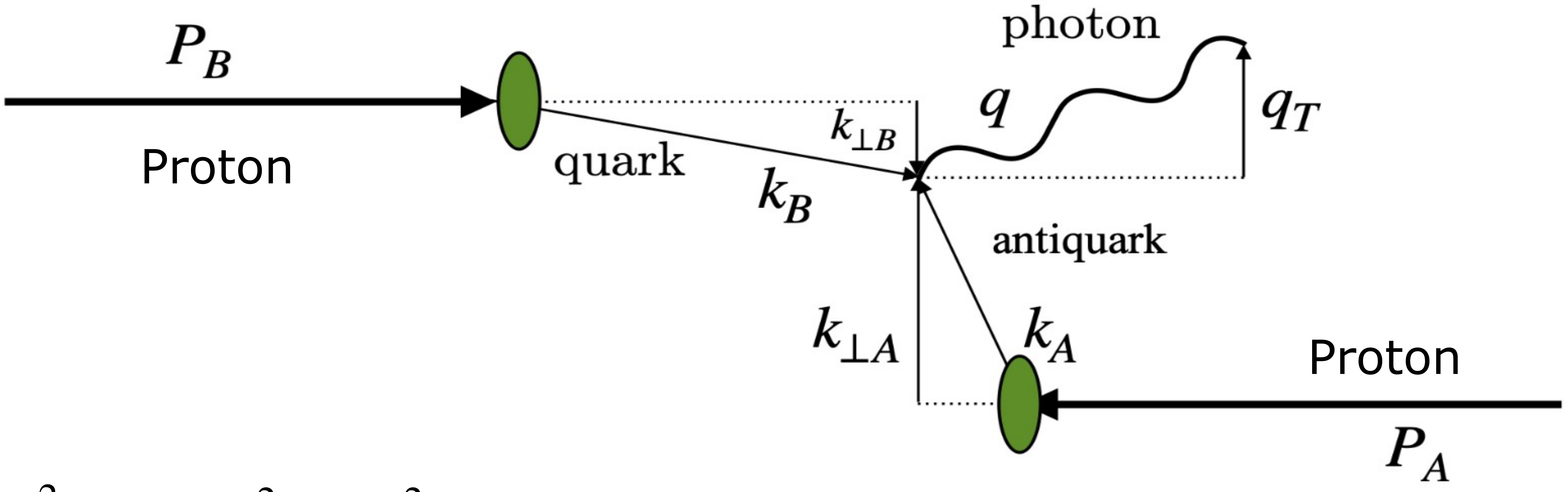


In $q_T^2 \ll Q^2$ and $M^2 \ll Q^2$ region:

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

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

TMD factorization — Drell-Yan process

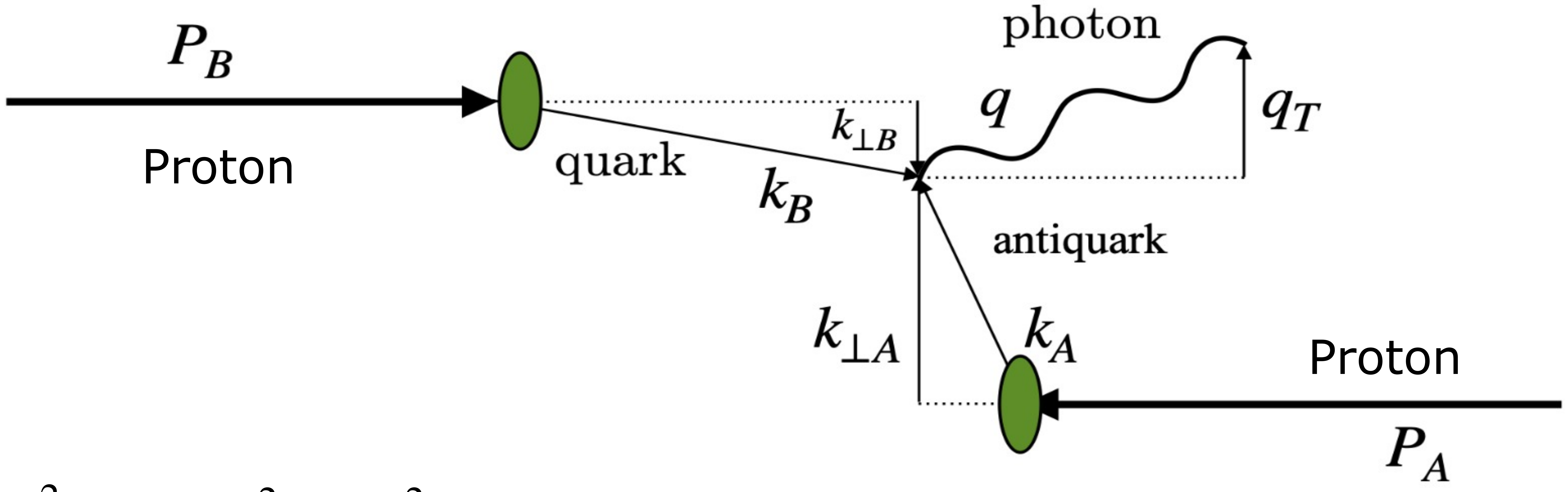


In $q_T^2 \ll Q^2$ and $M^2 \ll Q^2$ region:

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

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

TMD factorization — Drell-Yan process

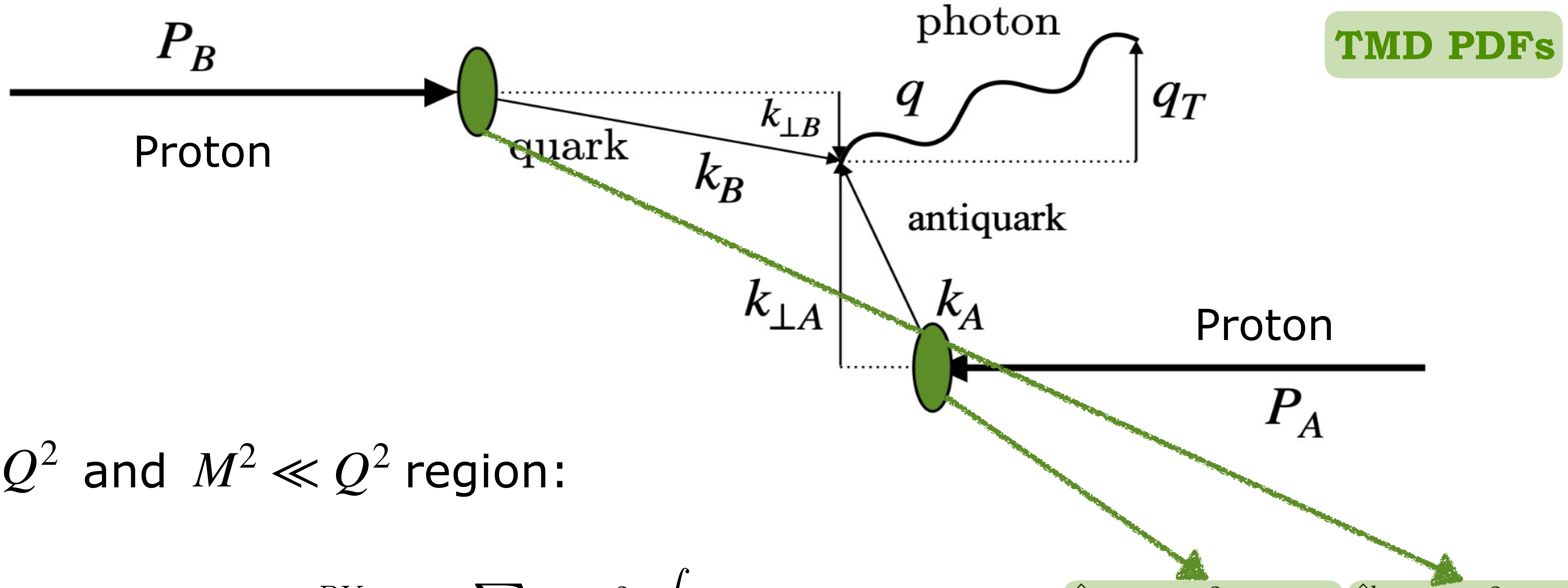


In $q_T^2 \ll Q^2$ and $M^2 \ll Q^2$ region:

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

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

TMD factorization — Drell-Yan process

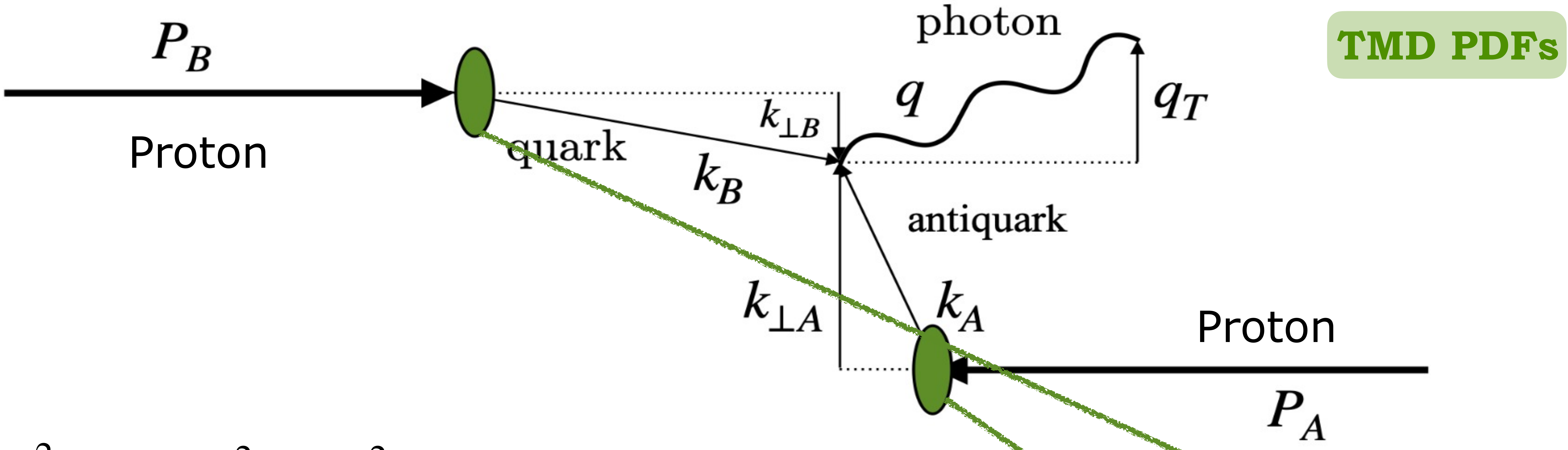


In $q_T^2 \ll Q^2$ and $M^2 \ll Q^2$ region:

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

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

TMD factorization — Drell-Yan process



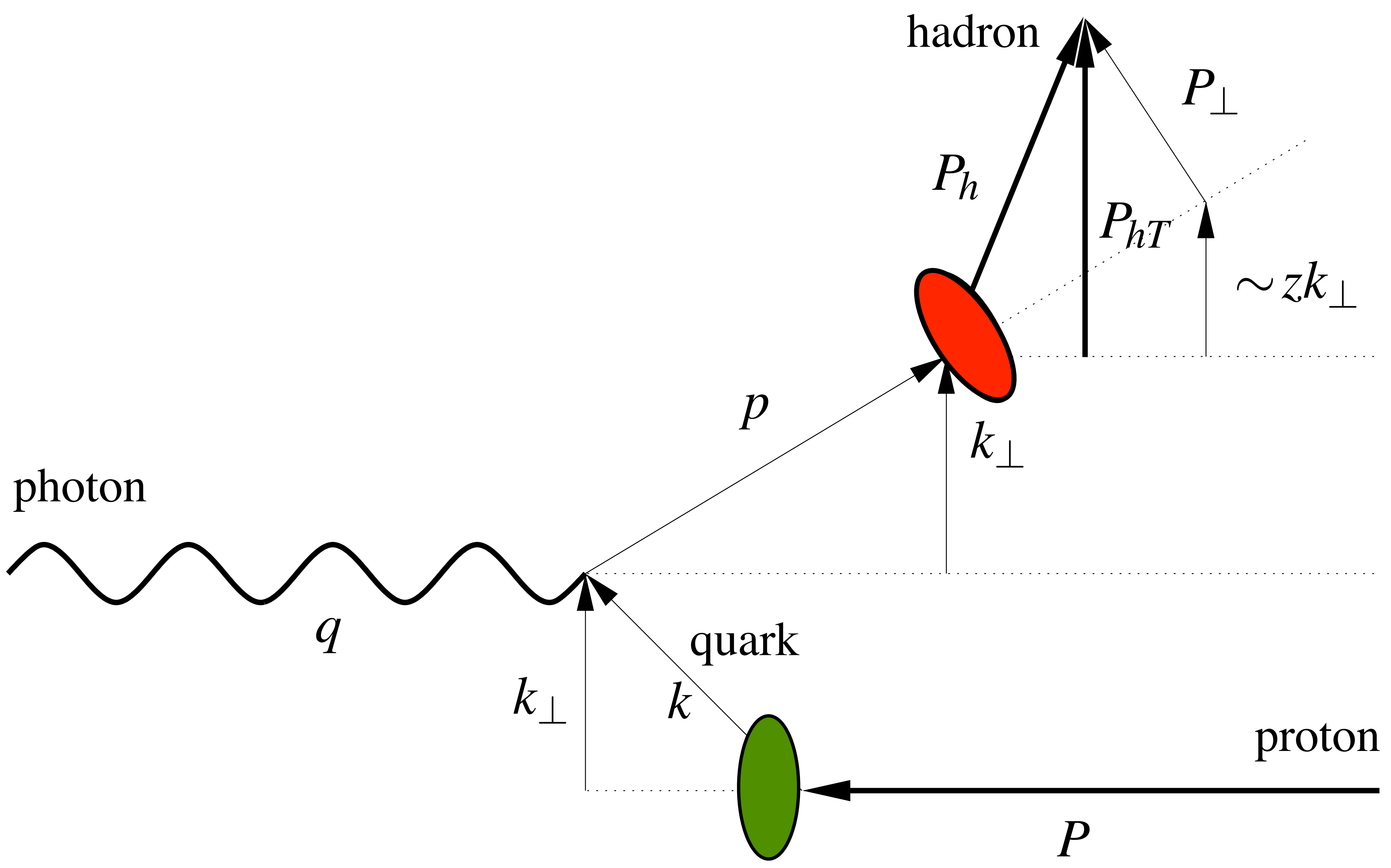
In $q_T^2 \ll Q^2$ and $M^2 \ll Q^2$ region:

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

W term

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

TMD Factorization - SIDIS process

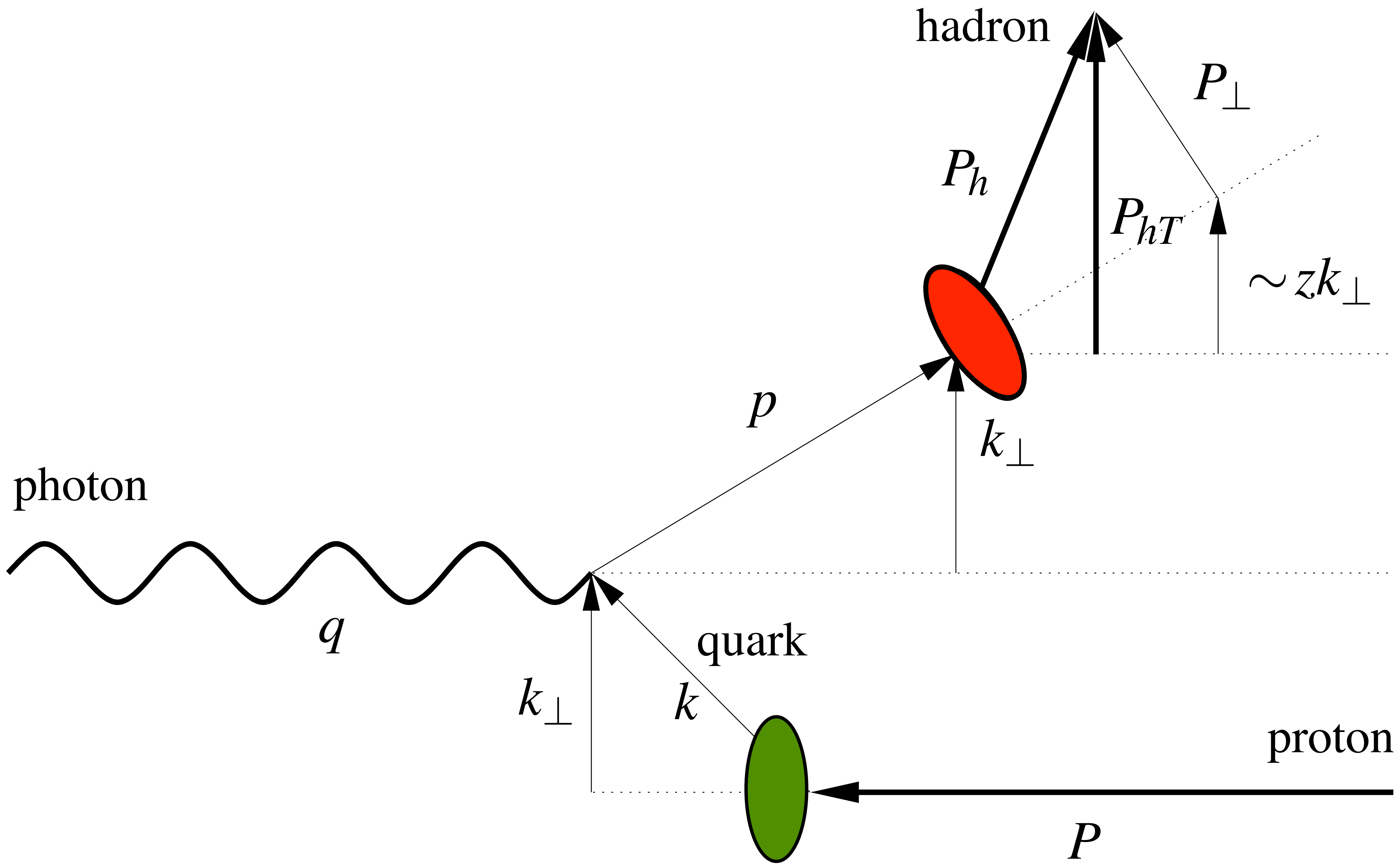


$$F_{UU,T}(x\,.\,z;\mu_F,\mathbf{P}_{hT}^2,Q^2) = x\sum_a H^a_{UU,T}(Q^2,\mu^2)\int d^2\mathbf{k}_\perp \mathbf{d}^2\mathbf{P}_\perp f_{\mathbf{1}}^{\mathbf{a}}(x,\mathbf{k}_\perp^2;\mu^2)D_{\mathbf{1}}^{\mathbf{a}\to\mathbf{h}}(z,\mathbf{P}_\perp^2;\mu^2)\delta^{(2)}(z\mathbf{k}_\perp - \mathbf{P}_{hT} + \mathbf{P}_\perp)$$

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

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

TMD Factorization - SIDIS process



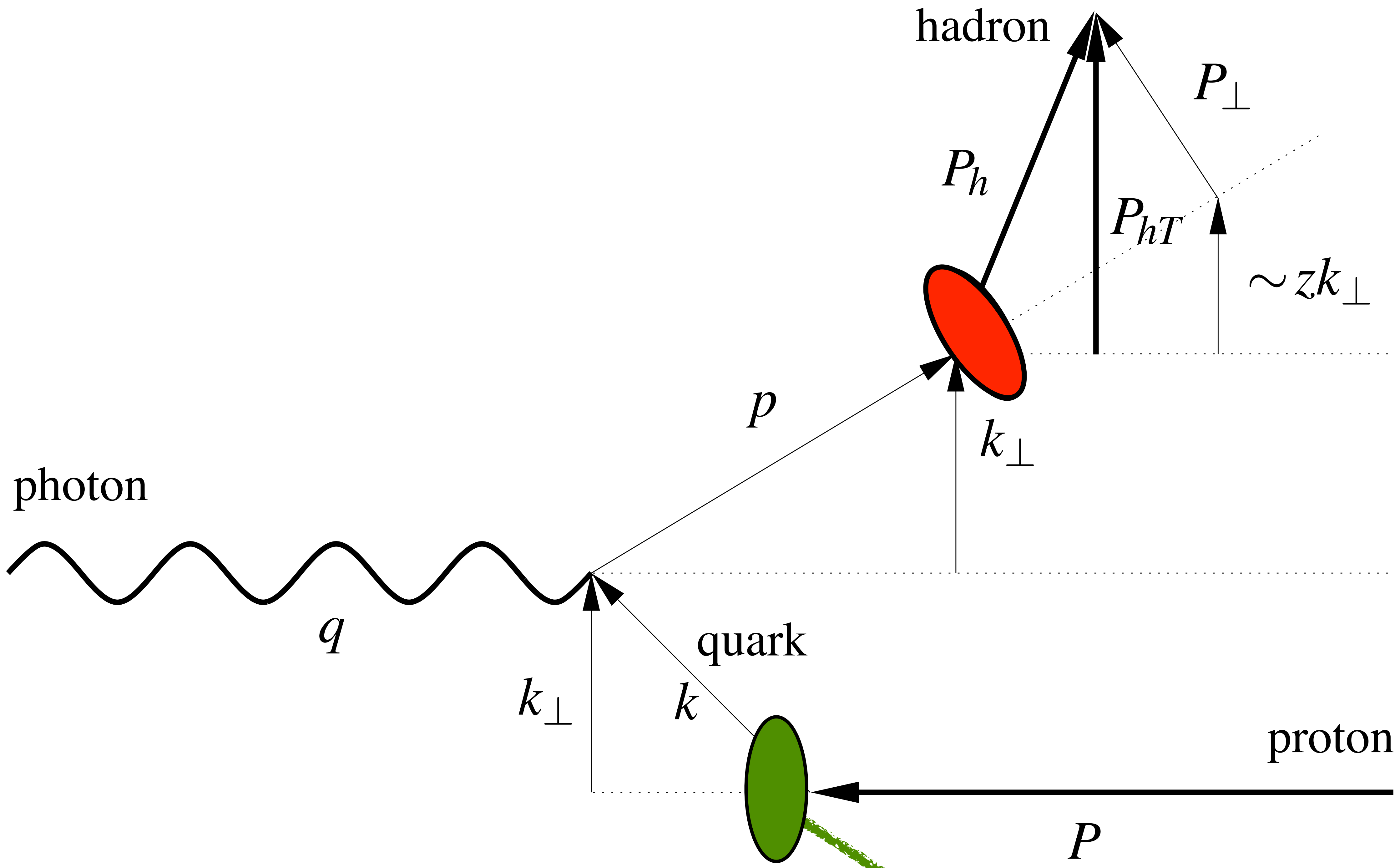
$$F_{UU,T}(x\,.\,z;\mu_F,\mathbf{P}_{hT}^2,Q^2)=x\sum_a H^a_{UU,T}(Q^2,\mu^2)\int d^2\mathbf{k}_\perp \mathbf{d^2P}_\perp f_{\mathbf{1}}^{\mathbf{a}}(x,\mathbf{k}_\perp^2;\mu^2)D_{\mathbf{1}}^{\mathbf{a\to h}}(z,\mathbf{P}_\perp^2;\mu^2)\delta^{(2)}(z\mathbf{k}_\perp-\mathbf{P}_{hT}+\mathbf{P}_\perp)$$

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

W Term

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

TMD Factorization - SIDIS process



TMD PDF

$$F_{UU,T}(x\,.\,z;\mu_F,\mathbf{P}_{hT}^2,Q^2) = x\sum_a H^a_{UU,T}(Q^2,\mu^2)\int d^2\mathbf{k}_\perp \mathbf{d^2P}_\perp f_1^{\mathbf{a}}(x,\mathbf{k}_\perp^2;\mu^2) D_{\mathbf{1}}^{\mathbf{a\to h}}(z,\mathbf{P}_\perp^2;\mu^2)\delta^{(2)}(z\mathbf{k}_\perp - \mathbf{P}_{hT} + \mathbf{P}_\perp)$$

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

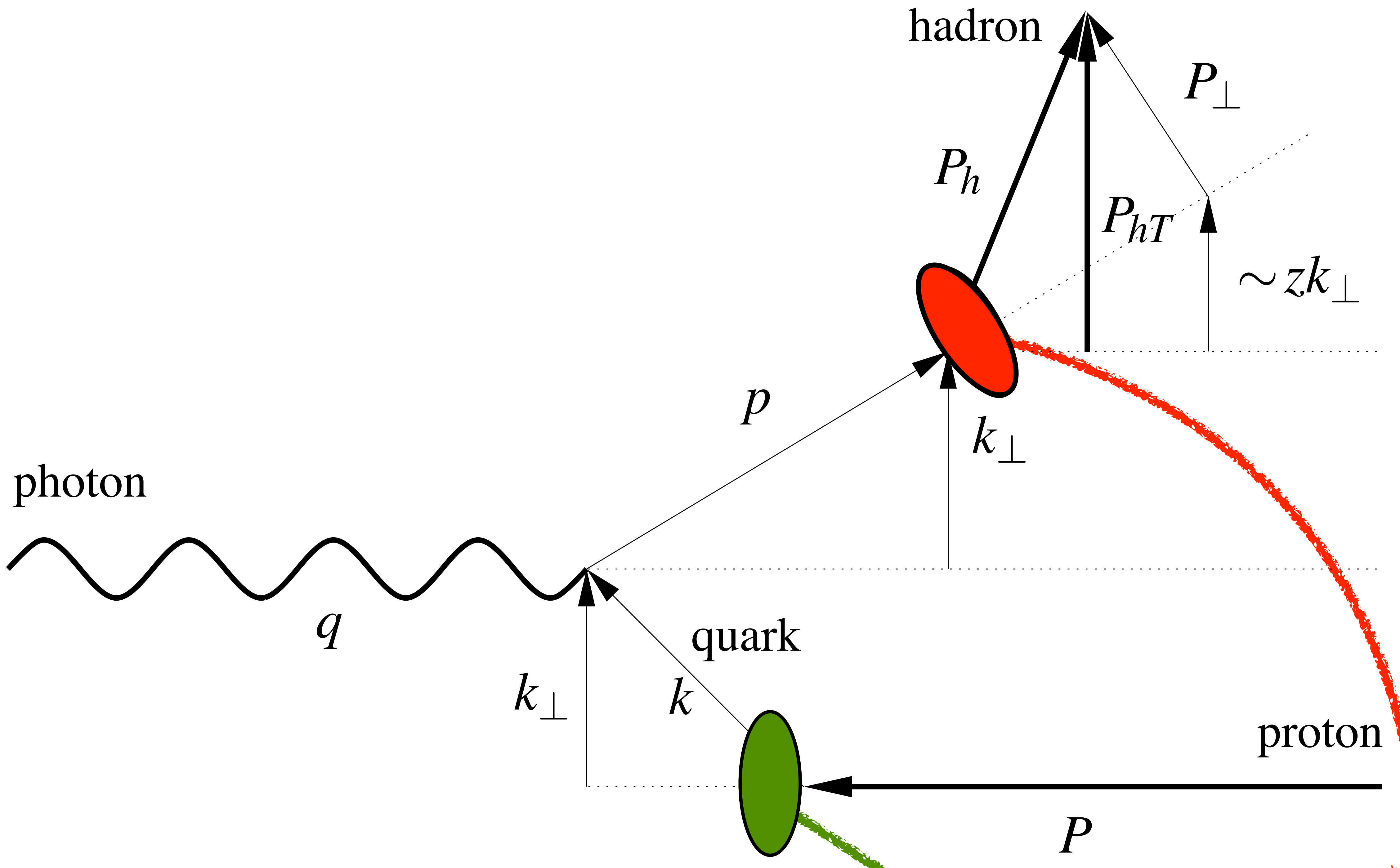
W Term

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

TMD Factorization - SIDIS process

TMD FF

TMD PDF



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

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

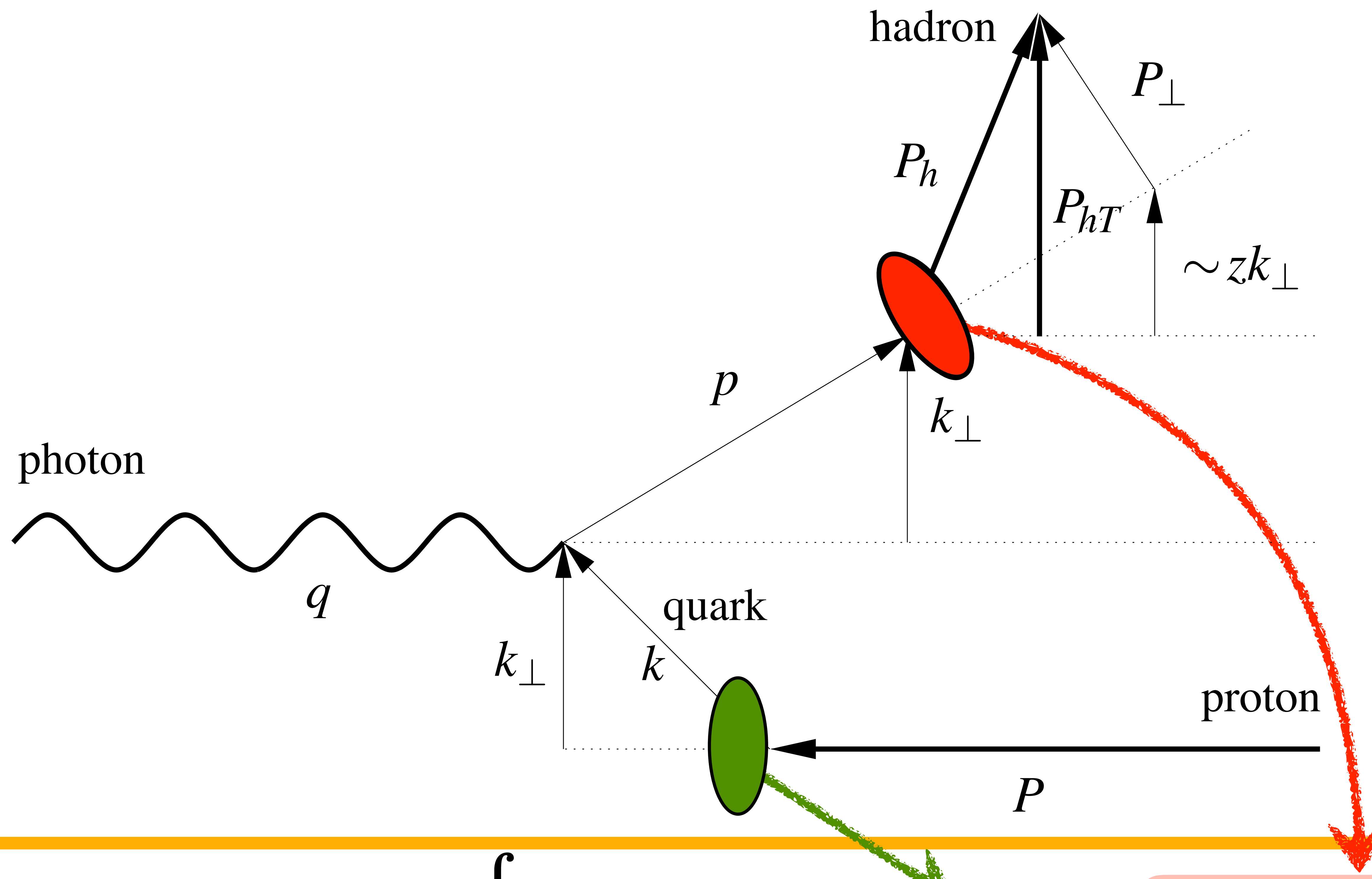
W Term

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

TMD Factorization - SIDIS process

TMD FF

TMD PDF



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

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

W Term

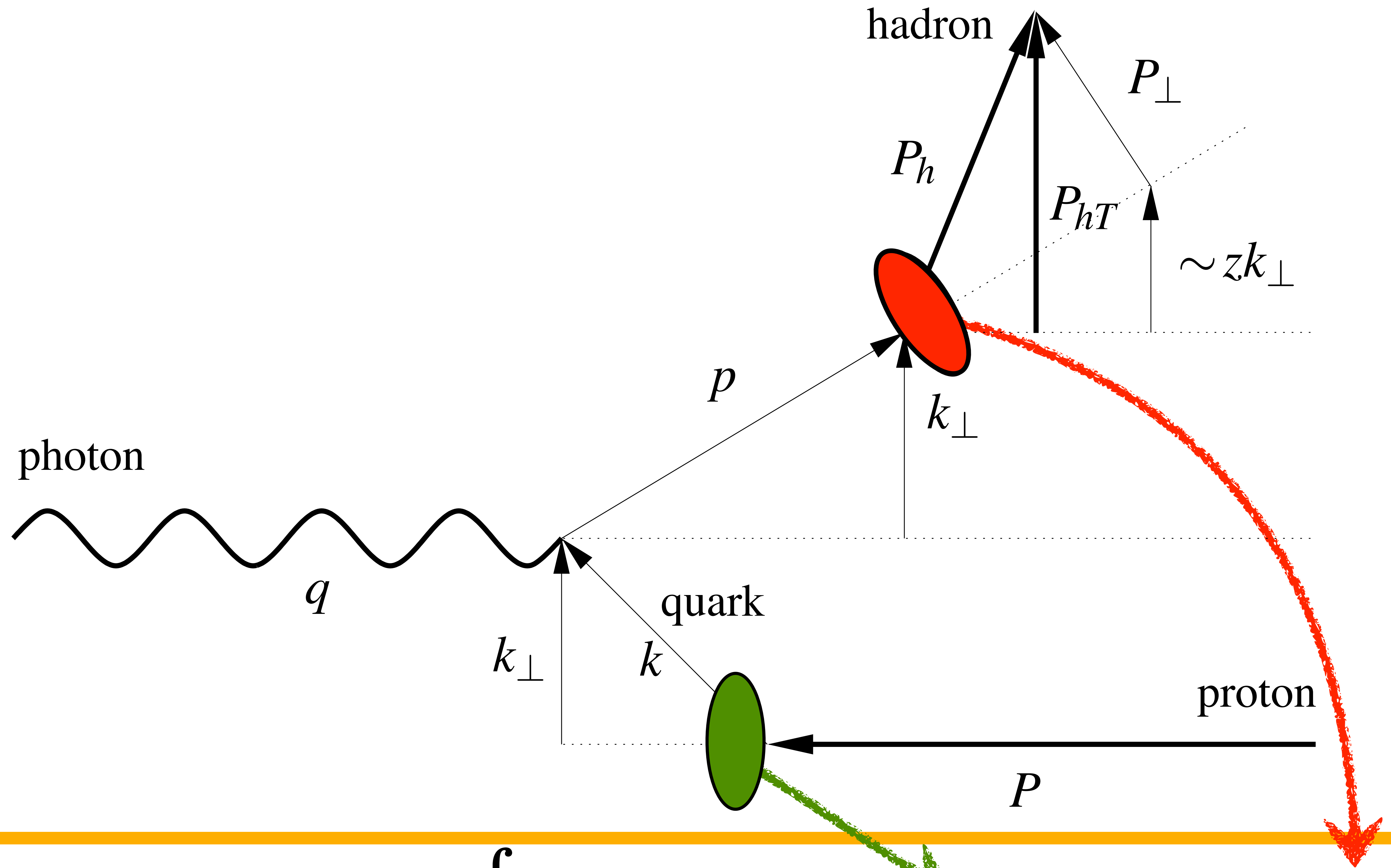
- The W term dominates in the region where $q_T \ll Q$

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

TMD Factorization - SIDIS process

TMD FF

TMD PDF



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

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

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)

(More) Recent extraction

(More) Recent extraction

	Accuracy	SIDIS	DY	Z production	N of points	χ^2/N_{data}
Pavia 2013 JHEP 11 (2013) 194	Parton Model	HERMES data	✗	✗	1538	1.63
Pavia 2017 JHEP 06 (2017) 081	NLL	✔	✔	✔	8059	1.55
Pavia 2019 JHEP 07 (2020) 117	N^{3}LL	✗	✔	✔	353	1.02
SV 2019 *JHEP* 06 (2020) 137	N^{3}LL	✔	✔	✔	1039	1.06
MAPTMD22 *JHEP* 10 (2022) 127	N^{3}LL	✔	✔	✔	2031	1.06
ART23 *JHEP* 10 (2022) 127	N^{3}LL$^+$	✗	✔	✔	627	0.96
MAPTMD24 *JHEP* 08 (2024) 232	N^{3}LL	✔	✔	✔	2031	1.08

(More) Recent extraction

	Accuracy	SIDIS	DY	Z production	N of points	χ^2/N_{data}
Pavia 2013 JHEP 11 (2013) 194	Parton Model	HERMES data	✘	✘	1538	1.63
Pavia 2017 JHEP 06 (2017) 081	NLL	✔	✔	✔	8059	1.55
Pavia 2019 JHEP 07 (2020) 117	N^3LL	✘	✔	✔	353	1.02
SV 2019 *JHEP* 06 (2020) 137	N^3LL	✔	✔	✔	1039	1.06
MAPTMD22 *JHEP* 10 (2022) 127	N^3LL	✔	✔	✔	2031	1.06
ART23 *JHEP* 10 (2022) 127	N^3LL^+	✘	✔	✔	627	0.96
MAPTMD24 *JHEP* 08 (2024) 232	N^3LL	✔	✔	✔	2031	1.08

Global Extraction

(More) Recent extraction

	Accuracy	SIDIS	DY	Z production	N of points	χ^2/N_{data}
Pavia 2013 JHEP 11 (2013) 194	Parton Model	HERMES data	✘	✘	1538	1.63
Pavia 2017 JHEP 06 (2017) 081	NLL	✔	✔	✔	8059	1.55
Pavia 2019 JHEP 07 (2020) 117	N^3LL	✘	✔	✔	353	1.02
SV 2019 *JHEP* 06 (2020) 137	N^3LL	✔	✔	✔	1039	1.06
MAPTMD22 *JHEP* 10 (2022) 127	N^3LL	✔	✔	✔	2031	1.06
ART23 *JHEP* 10 (2022) 127	N^3LL^+	✘	✔	✔	627	0.96
MAPTMD24 *JHEP* 08 (2024) 232	N^3LL	✔	✔	✔	2031	1.08

Global Extraction

Flavor Dependence

(More) Recent extraction

	Accuracy	SIDIS	DY	Z production	N of points	χ^2/N_{data}
Pavia 2013 JHEP 11 (2013) 194	Parton Model	HERMES data	✗	✗	1538	1.63
Pavia 2017 JHEP 06 (2017) 081	NLL	✔	✔	✔	8059	1.55
Pavia 2019 JHEP 07 (2020) 117	N^3LL	✗	✔	✔	353	1.02
SV 2019 *JHEP* 06 (2020) 137	N^3LL	✔	✔	✔	1039	1.06
MAPTMD22 *JHEP* 10 (2022) 127	N^3LL	✔	✔	✔	2031	1.06
ART23 *JHEP* 10 (2022) 127	N^3LL^+	✗	✔	✔	627	0.96
MAPTMD24 *JHEP* 08 (2024) 232	N^3LL	✔	✔	✔	2031	1.08

MAPTMD24 = *Global Extraction* **+** *Flavor Dependence*

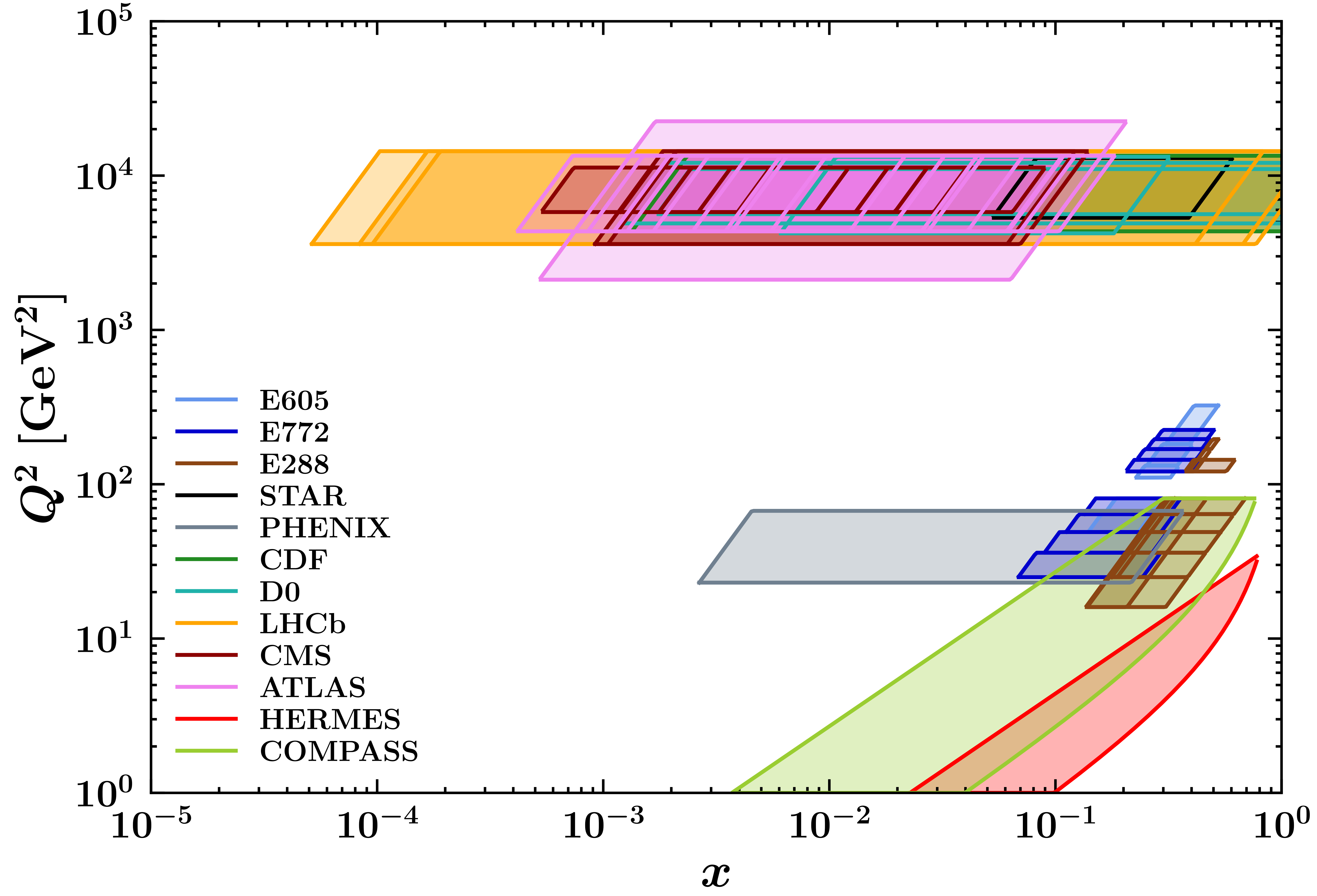
MAPTMD24 extraction

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

MAP Collaboration, JHEP 08 (2024)

MAPTMD24 extraction

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

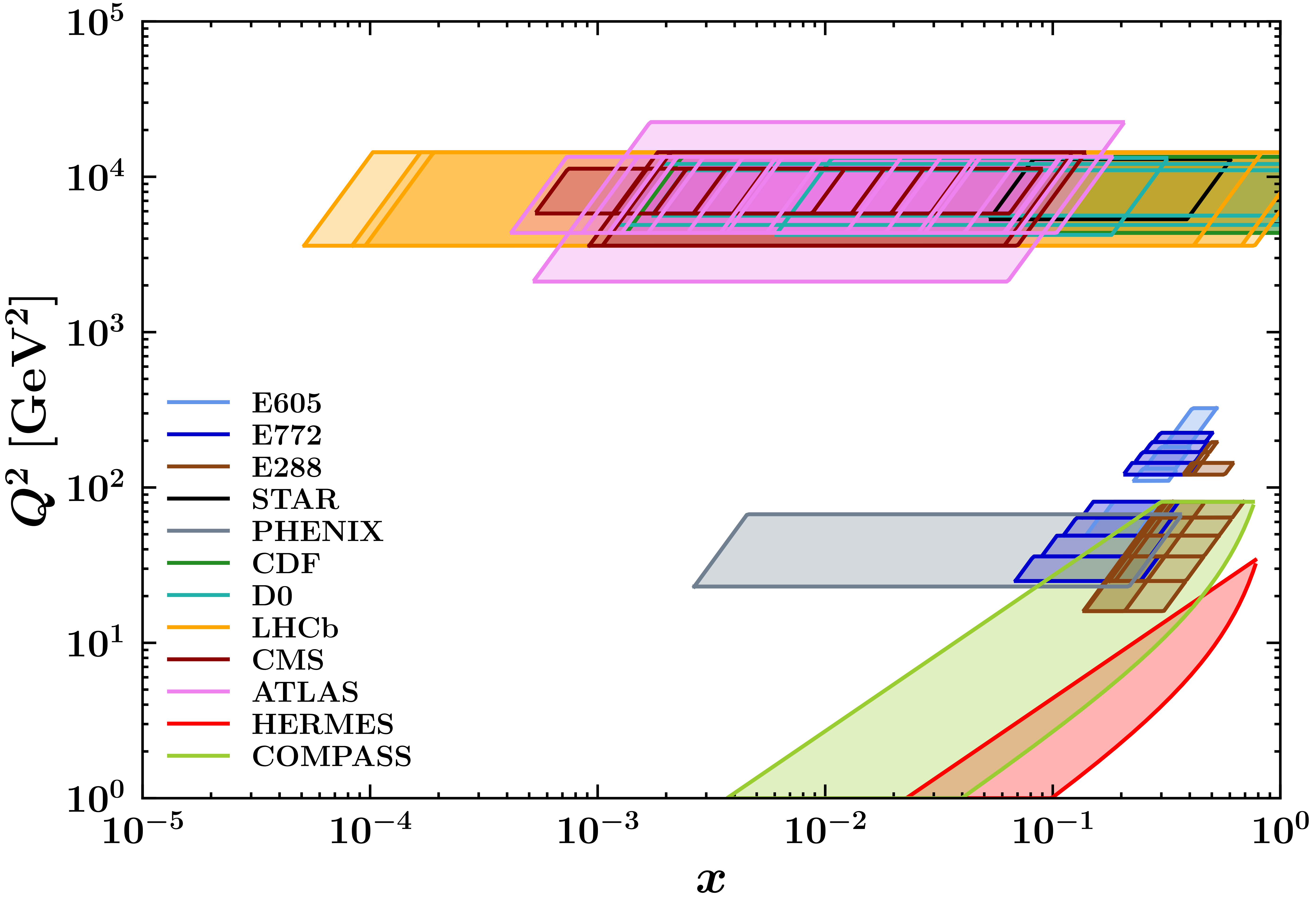


MAP Collaboration, JHEP 08 (2024)

MAPTMD24 extraction

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

Drell-Yan data
484



MAP Collaboration, JHEP 08 (2024)

MAPTMD24 extraction

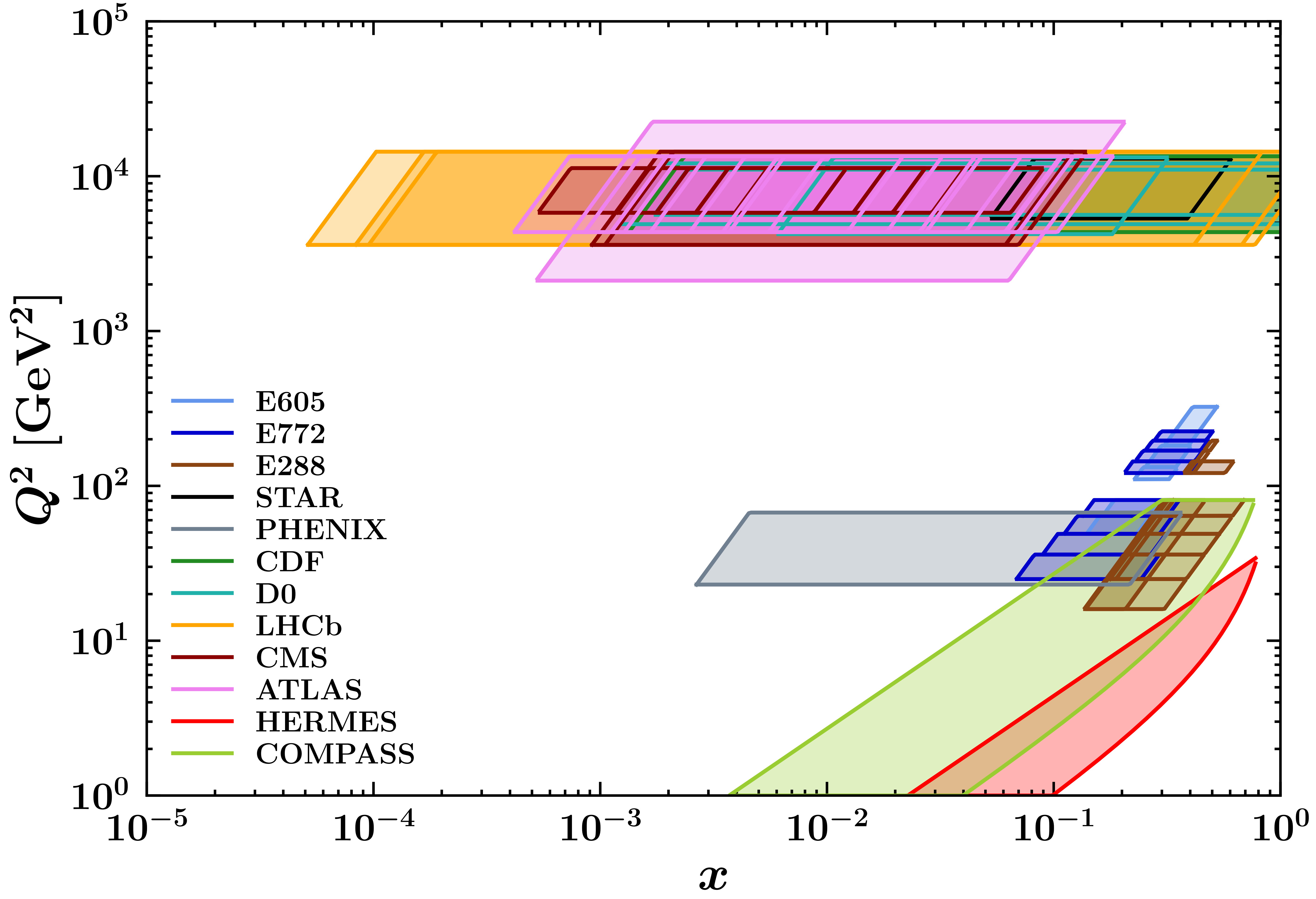
- Global analysis of Drell-Yan and Semi-Inclusive DIS data sets: ***2031*** data points

Drell-Yan data

484

SIDIS data

1547



MAP Collaboration, JHEP 08 (2024)

MAPTMD24 extraction

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

- Perturbative accuracy: $\boldsymbol{N^3LL}$

MAPTMD24 extraction

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

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

NNPDF31NNLO

MAPFF10NNLO

MAPTMD24 extraction

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

- Perturbative accuracy: $\boldsymbol{N^3LL}$

NNPDF31NNLO

MAPFF10NNLO

→ Full account of uncertainties from collinear sets

MAP Collaboration, JHEP 08 (2024)

MAPTMD24 extraction

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

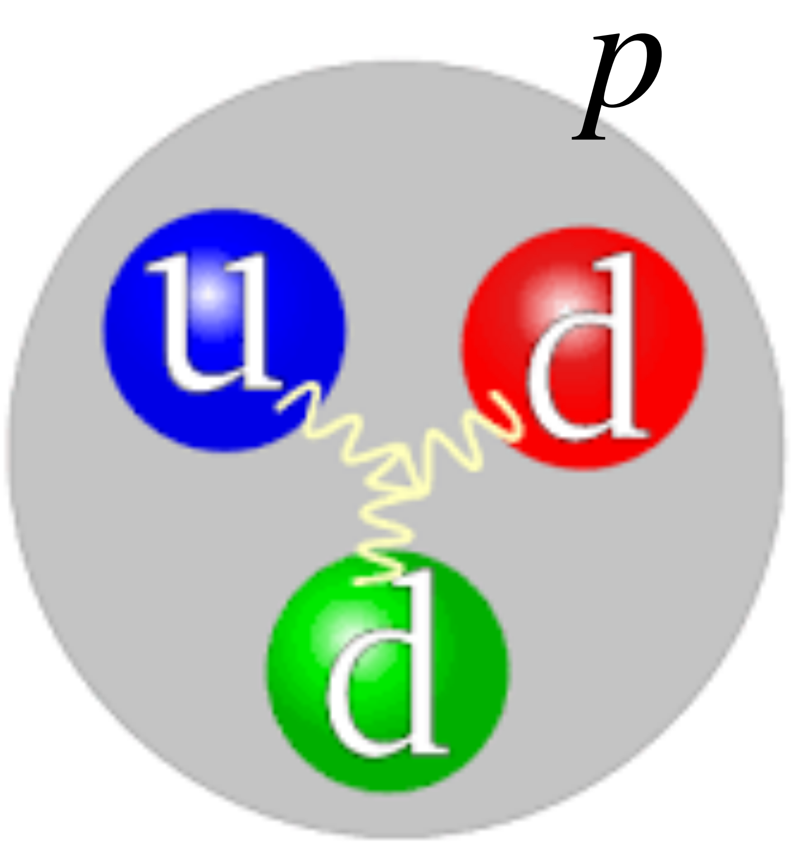
MAP Collaboration, JHEP 08 (2024)

MAPTMD24 extraction

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

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

- Flavor Dependence



u, d

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

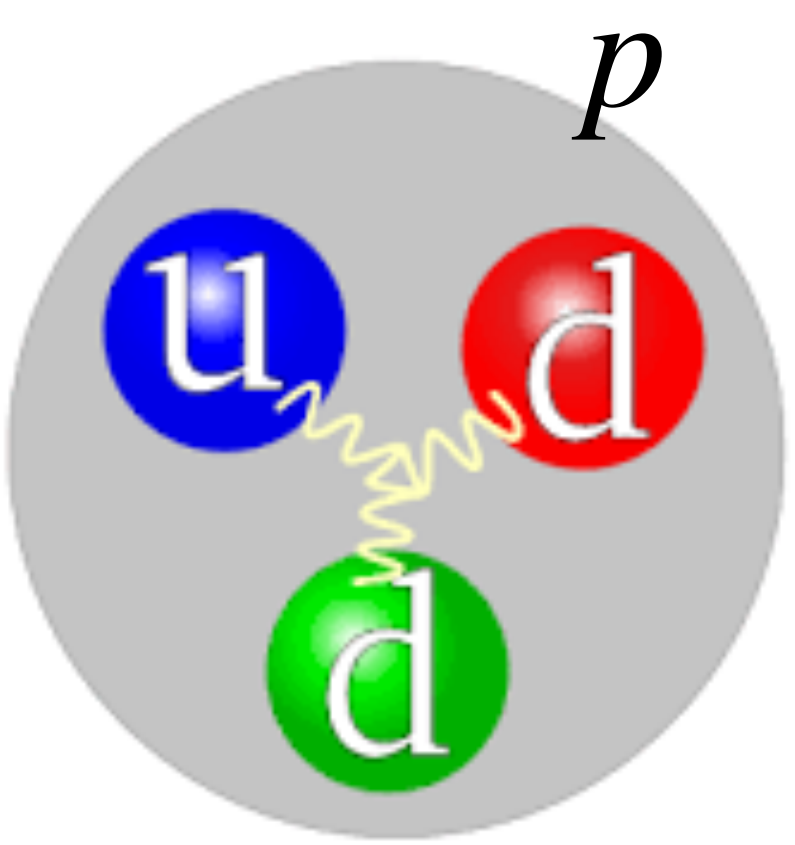
$s\,(sea)$

MAP Collaboration, JHEP 08 (2024)

MAPTMD24 extraction

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

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

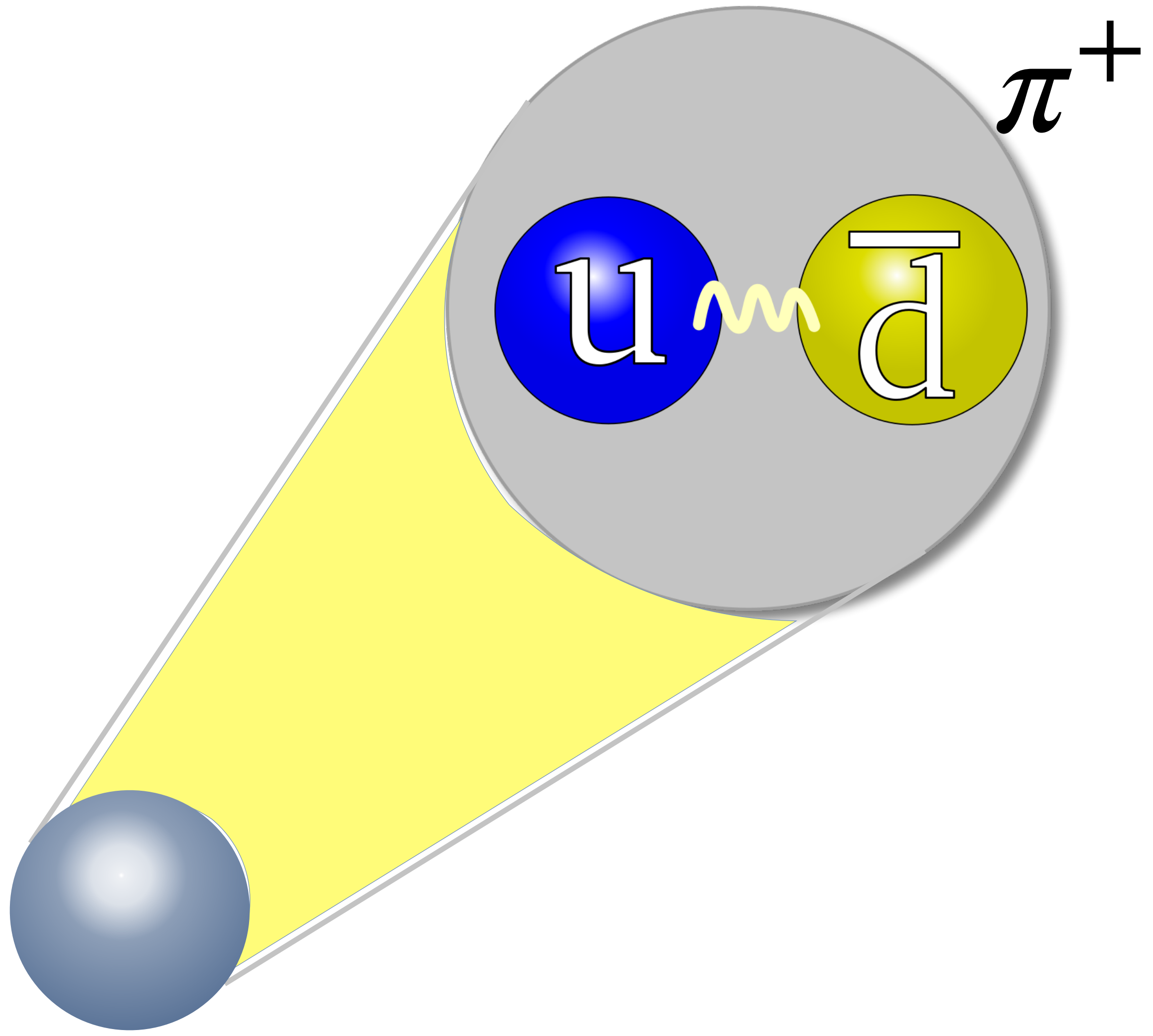


u, d

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

$s\,(sea)$

- Flavor Dependence



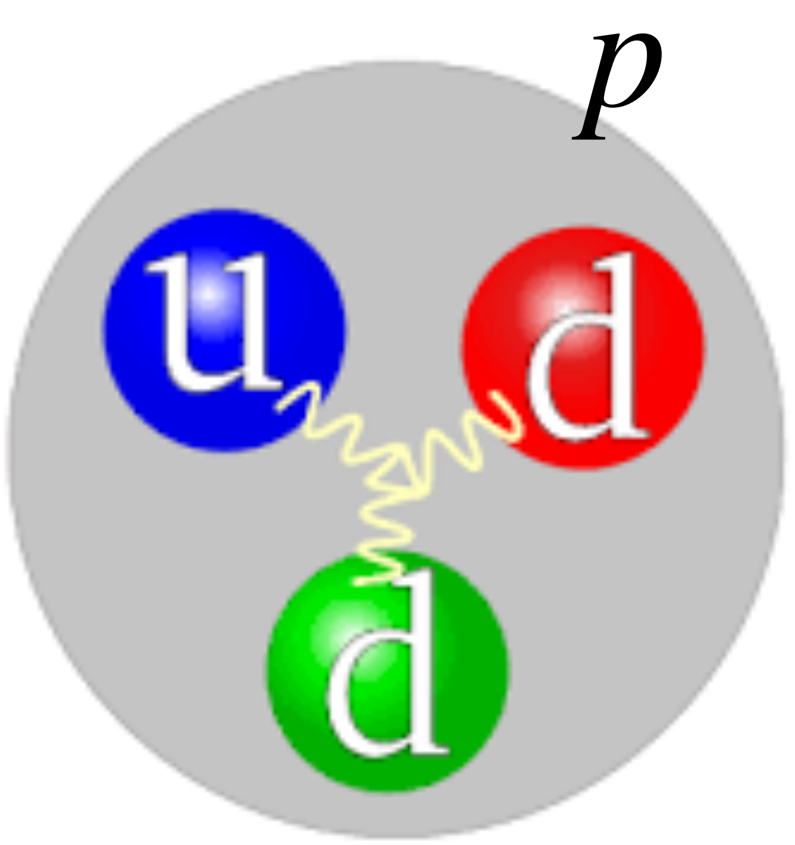
$u \rightarrow \pi^+, \ldots$

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

MAP Collaboration, JHEP 08 (2024)

MAPTMD24 extraction

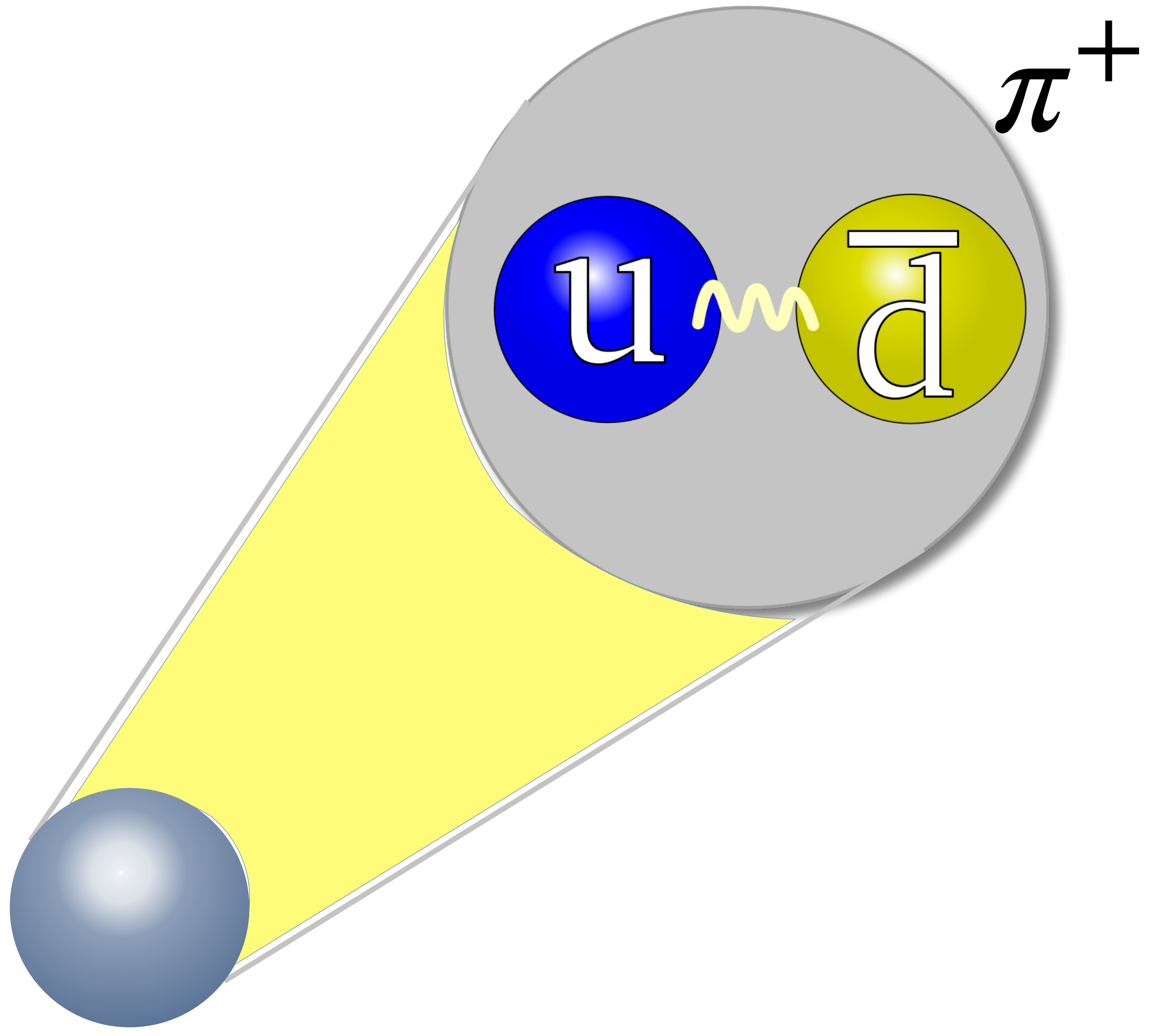
- Global analysis of Drell-Yan and Semi-Inclusive DIS data sets: **2031** data points
- Perturbative accuracy: ***N^{3}LL***
- Flavor Dependence



u, d

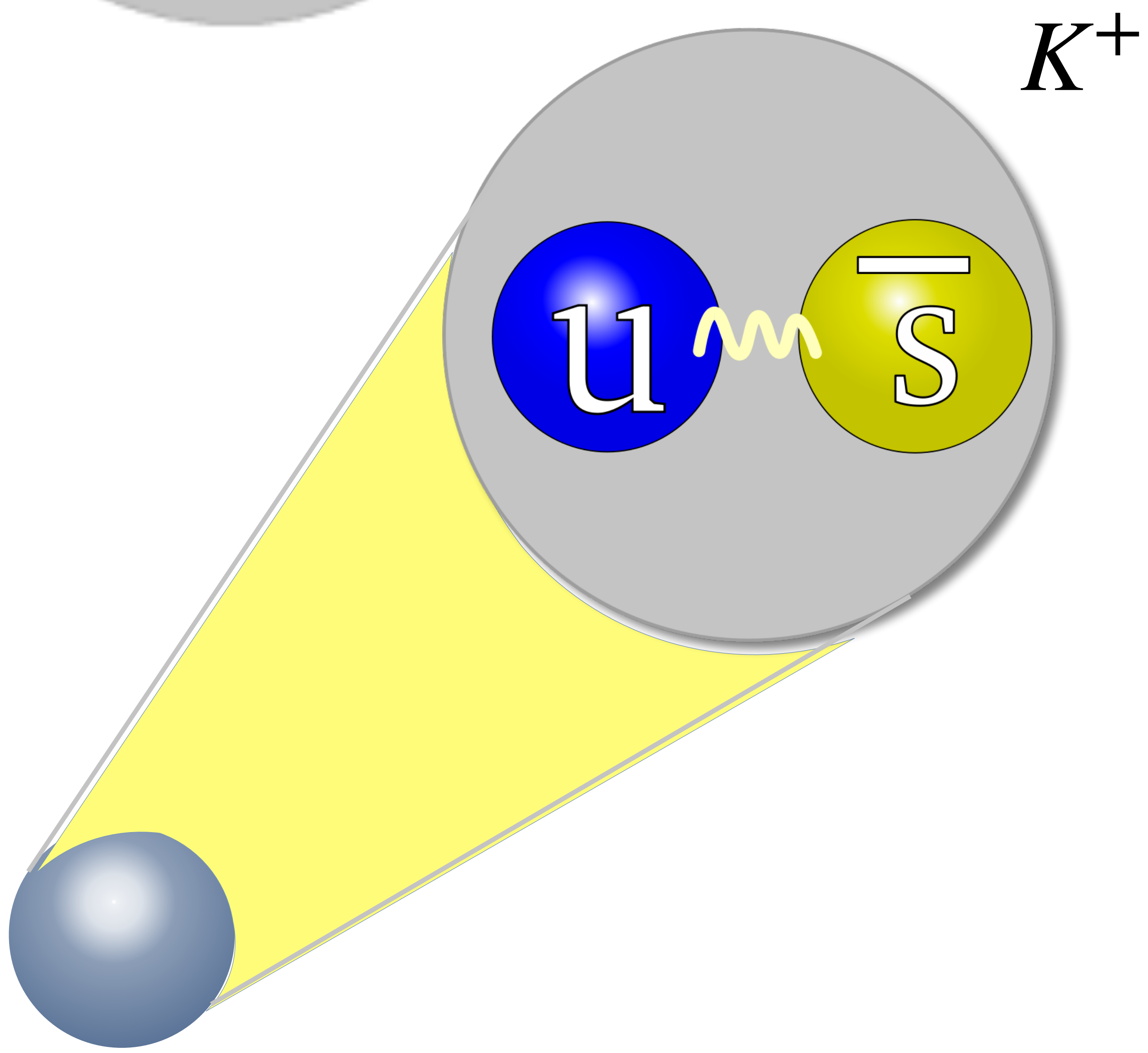
$\bar{u}, \bar{d}$

$s\,(sea)$



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

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



$u \to K^+, \ldots$

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

$d \to K^+, \ldots$

MAP Collaboration, JHEP 08 (2024)

MAPTMD24 extraction

MAPTMD24 extraction

HERMES

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

+ deuteron target

JHEP 08 (2024) 232

MAPTMD24 extraction

HERMES

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

+ deuteron target

high sensitivity to flavour dependence

MAPTMD24 extraction

HERMES

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

+ deuteron target

high sensitivity to flavour dependence

COMPASS deuteron target & unidentified final state hadron

MAPTMD24 extraction

HERMES

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

+ deuteron target

high sensitivity to flavour dependence

COMPASS deuteron target & unidentified final state hadron

low sensitivity to flavour dependence

JHEP 08 (2024) 232

MAPTMD24 extraction

HERMES

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

+ deuteron target

high sensitivity to flavour dependence

COMPASS deuteron target & unidentified final state hadron

low sensitivity to flavour dependence

Drell-Yan $q\bar{q}$ in the initial state

MAPTMD24 extraction

HERMES

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

+ deuteron target

high sensitivity to flavour dependence

COMPASS deuteron target & unidentified final state hadron

low sensitivity to flavour dependence

Drell-Yan $q\bar{q}$ in the initial state

lowest sensitivity to flavour dependence

MAPTMD24 extraction

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

MAP Collaboration, JHEP 08 (2024)

MAPTMD24 extraction

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

- Perturbative accuracy: N^3LL

- Flavor Dependence

- Extremely good description: $\chi^2/\mathrm{N_{data}} = 1.08$

MAP Collaboration, JHEP 08 (2024)

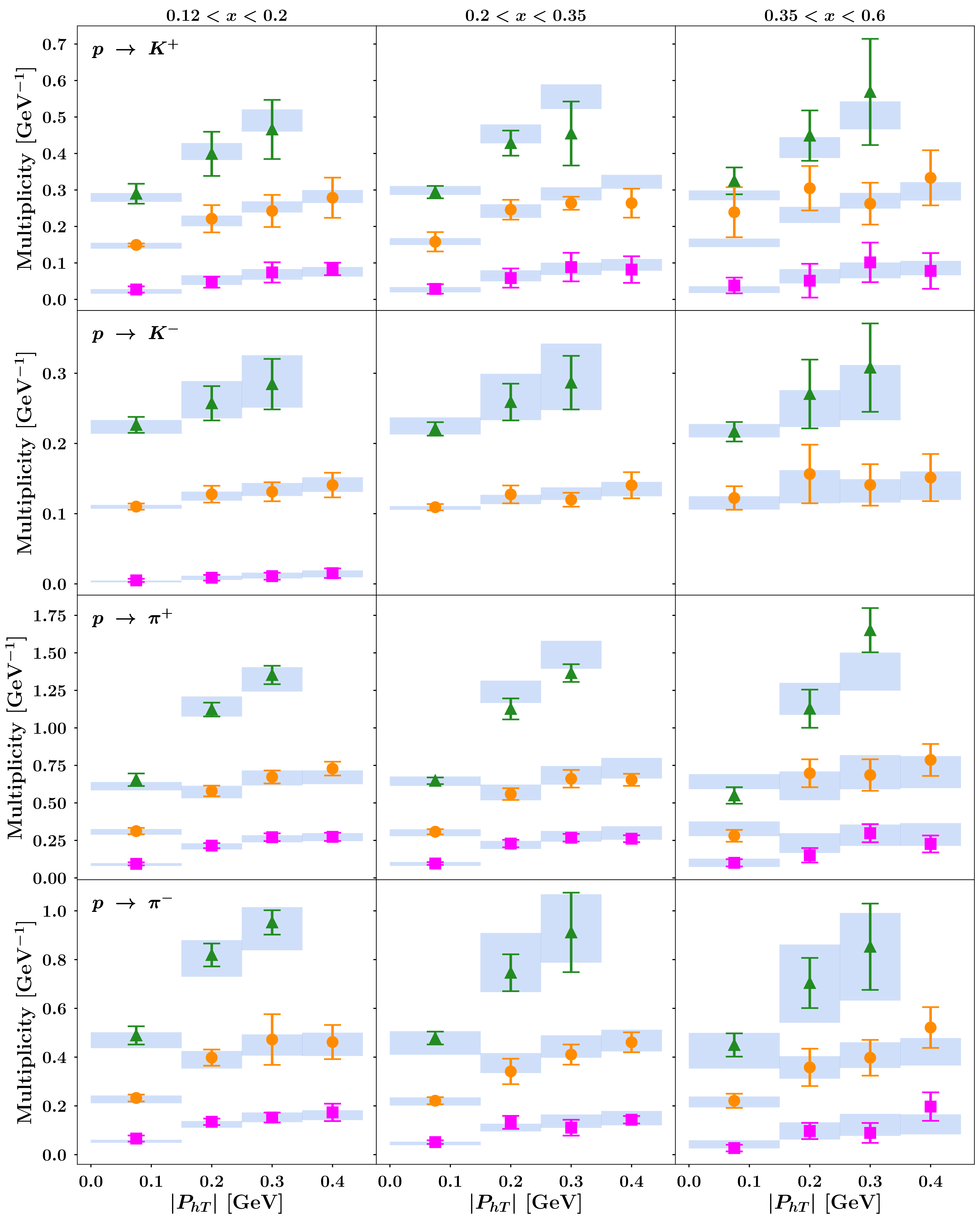
MAPTMD24 extraction - Results $\chi^2/N_{data} = 1.08$

	N^3LL			
Data set	$N_{\rm dat}$	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**

JHEP 08 (2024) 232

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

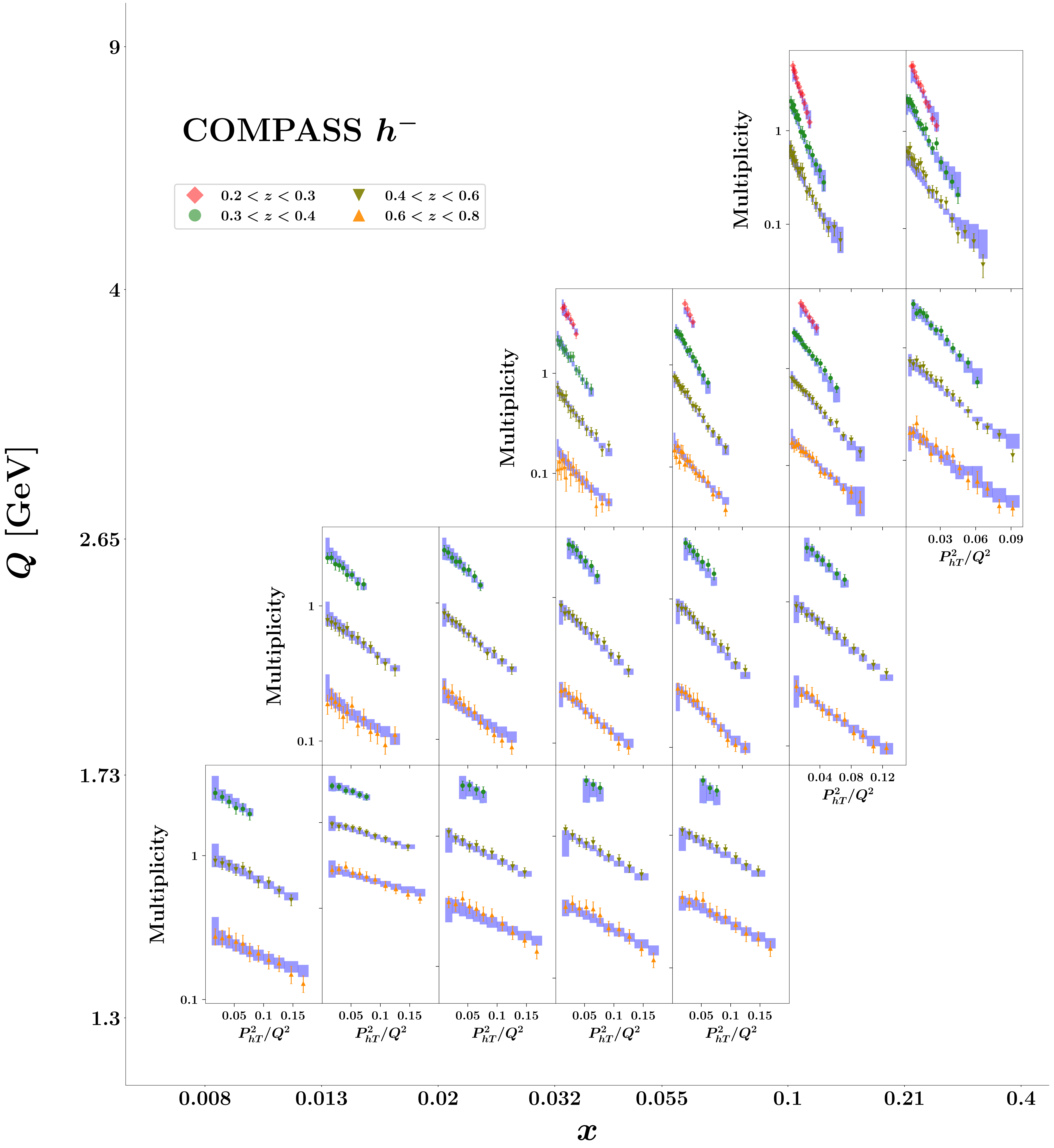
	N³LL			
Data set	N_{dat}	χ^2_D	χ^2_λ	χ^2_0
DY collider total	251	1.37	0.28	1.65
DY fixed-target total	233	0.63	0.31	0.94
HERMES total	344	0.81	0.24	1.05
COMPASS total	1203	0.67	0.27	0.94
SIDIS total	1547	0.70	0.26	0.96
Total	**2031**	**0.81**	**0.27**	**1.08**



JHEP 08 (2024) 232

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

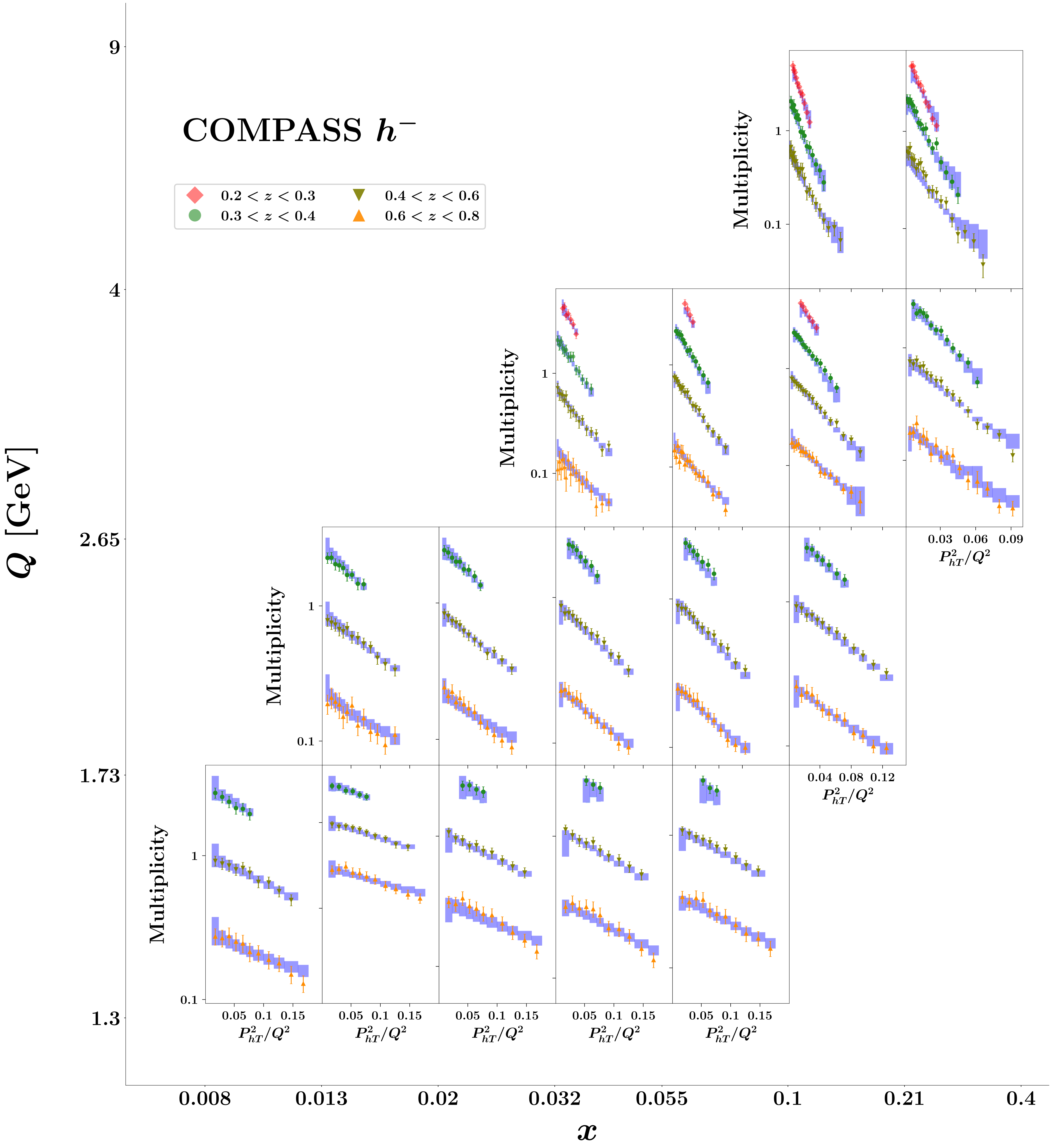
	N^{3}LL			
Data set	N_{dat}	χ^2_D	χ^2_λ	χ^2_0
DY collider total	251	1.37	0.28	1.65
DY fixed-target total	233	0.63	0.31	0.94
HERMES total	344	0.81	0.24	1.05
COMPASS total	1203	0.67	0.27	0.94
SIDIS total	1547	0.70	0.26	0.96
Total	**2031**	**0.81**	**0.27**	**1.08**



MAPTMD24 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
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**

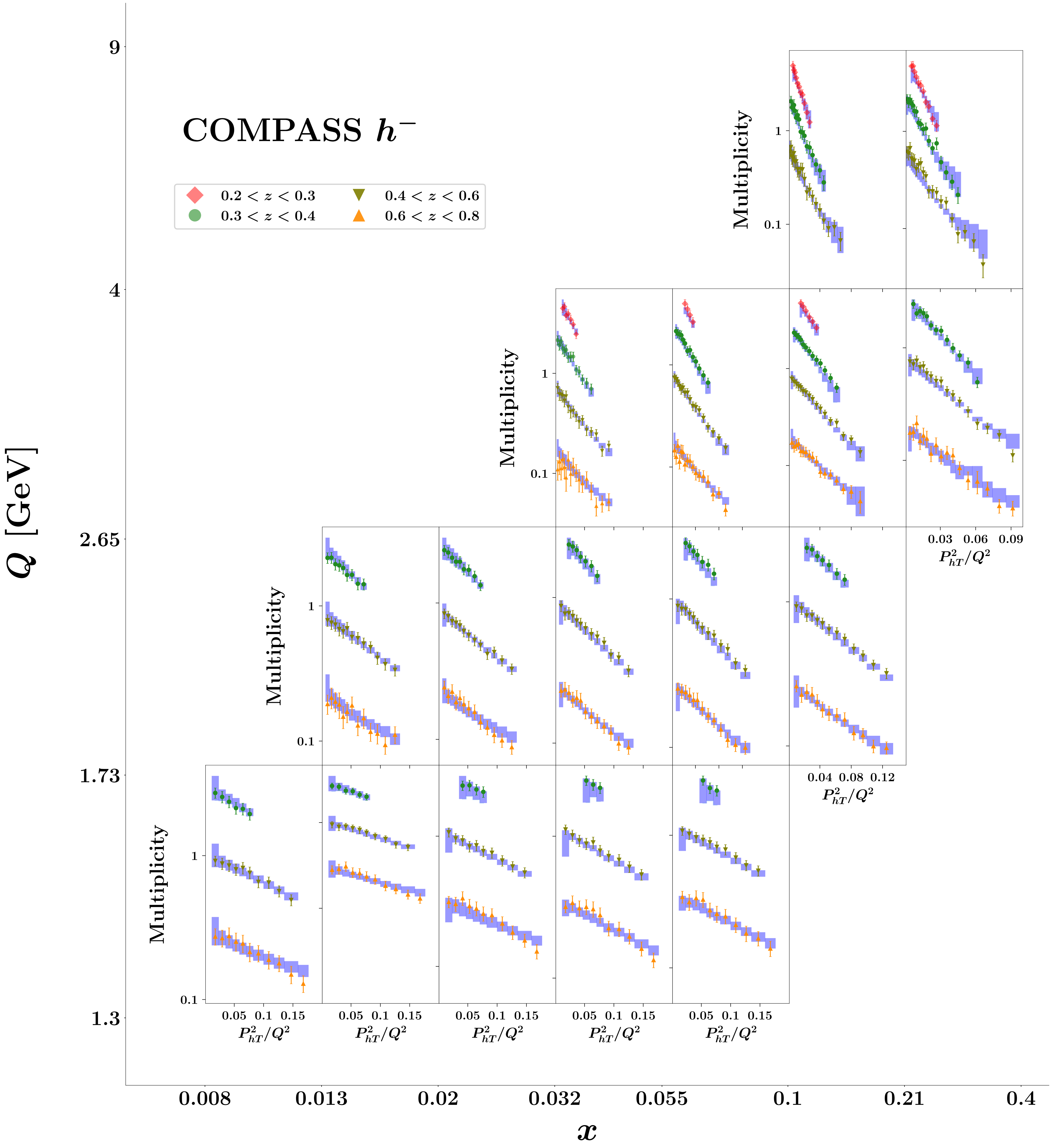
Very good agreement



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

	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**

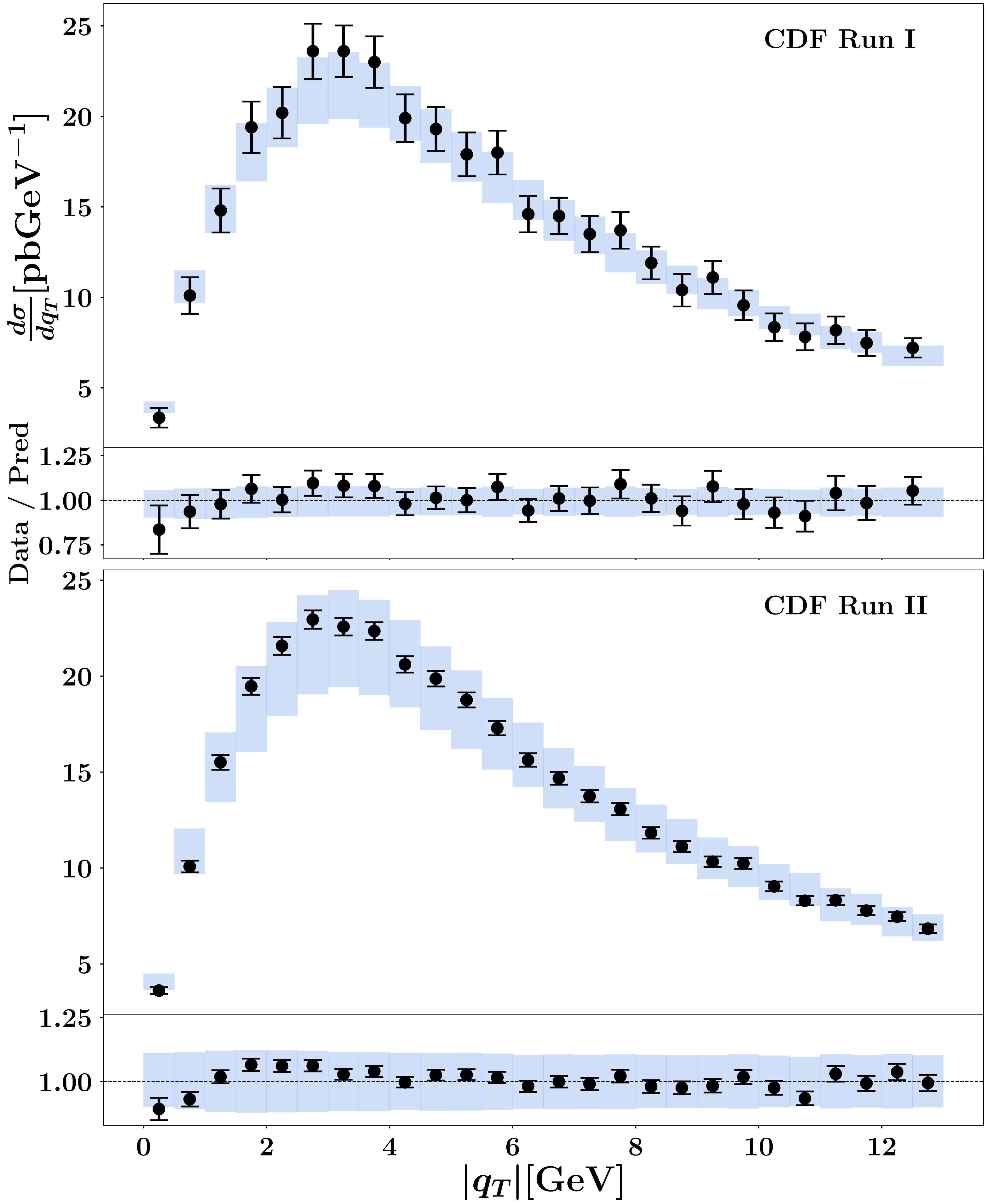
Very good agreement



JHEP 08 (2024) 232

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

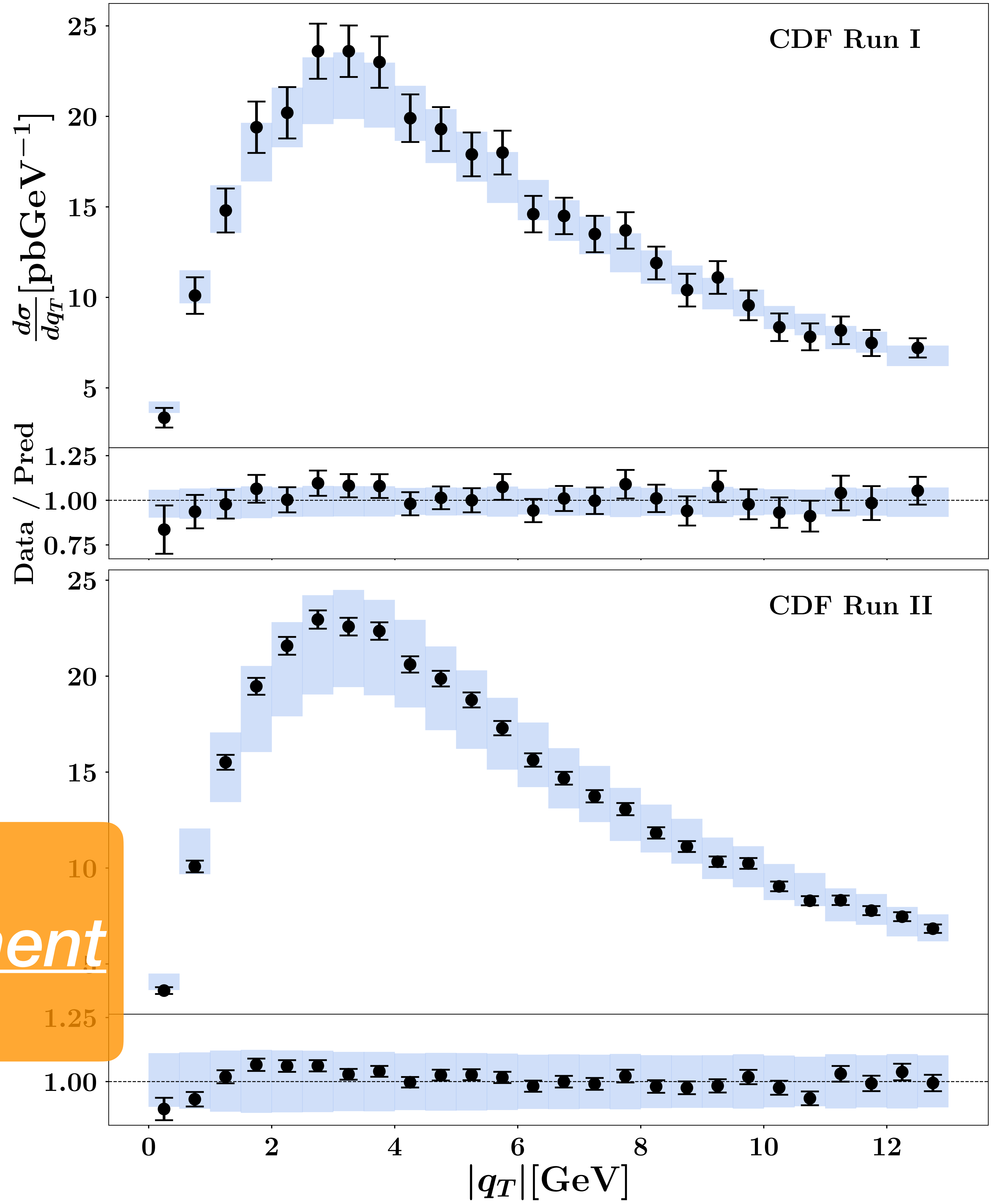
	N^3LL			
Data set	N_{dat}	χ^2_D	χ^2_λ	χ^2_0
DY collider total	251	1.37	0.28	1.65
DY fixed-target total	233	0.63	0.31	0.94
HERMES total	344	0.81	0.24	1.05
COMPASS total	1203	0.67	0.27	0.94
SIDIS total	1547	0.70	0.26	0.96
Total	**2031**	**0.81**	**0.27**	**1.08**



Very good agreement

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
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**



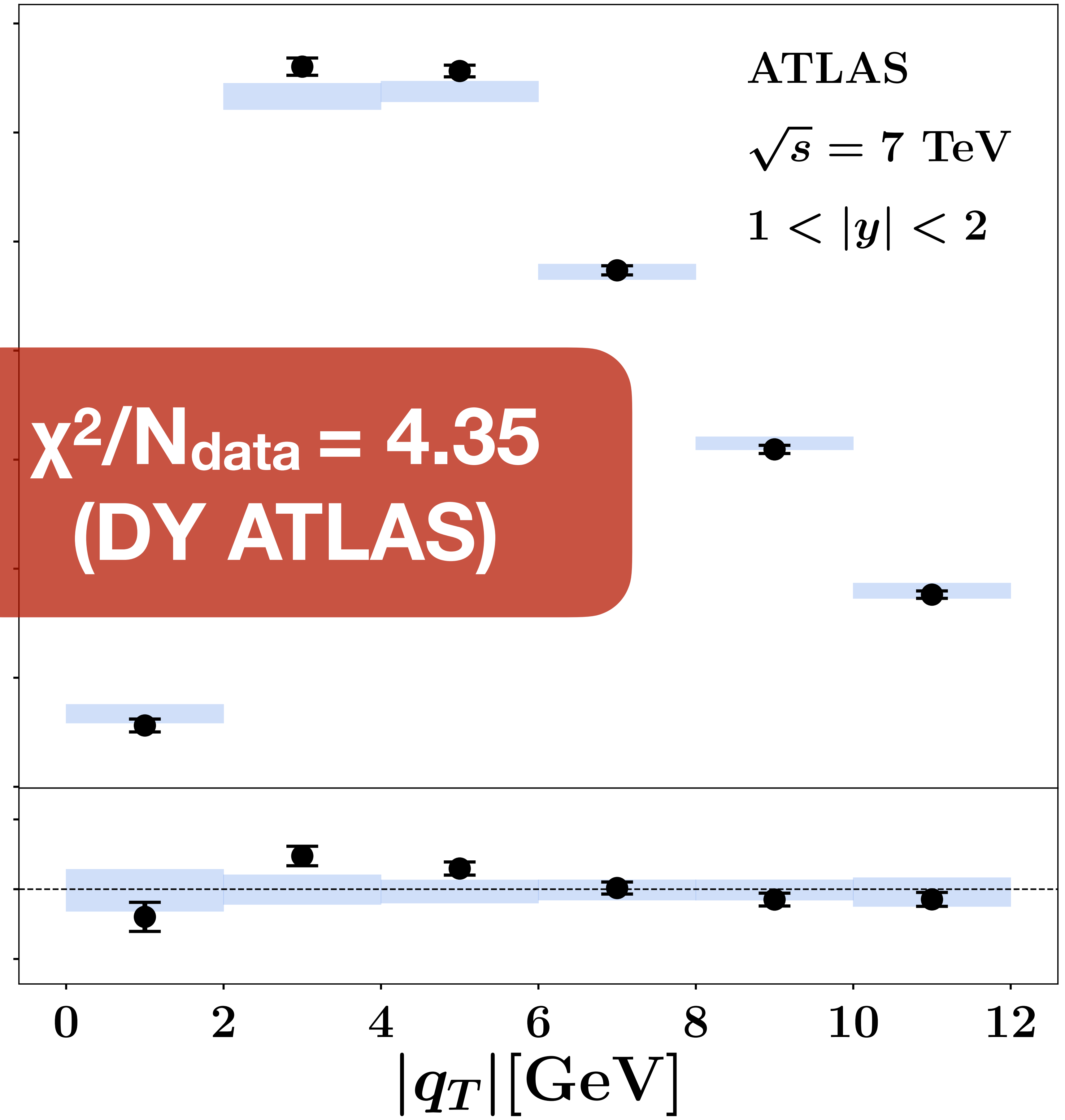
Very good agreement

Quite good agreement

JHEP 08 (2024) 232

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

	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)

Very good agreement

Quite good agreement

MAPTMD24 extraction - TMD PDFs

MAPTMD24 extraction - TMD PDFs

JHEP 08 (2024) 232

MAPTMD24 extraction - TMD PDFs

JHEP 08 (2024) 232

MAPTMD24 extraction - TMD PDFs

Very different $k_\perp$ ***- behaviours!***

JHEP 08 (2024) 232

MAPTMD24 extraction - TMD PDFs

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

JHEP 08 (2024) 232

MAPTMD24 extraction - TMD PDFs

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

JHEP 08 (2024) 232

MAPTMD24 extraction - TMD PDFs

The sea is the least constrained

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

JHEP 08 (2024) 232

MAPTMD24 extraction - TMD PDFs

The sea is the least constrained

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

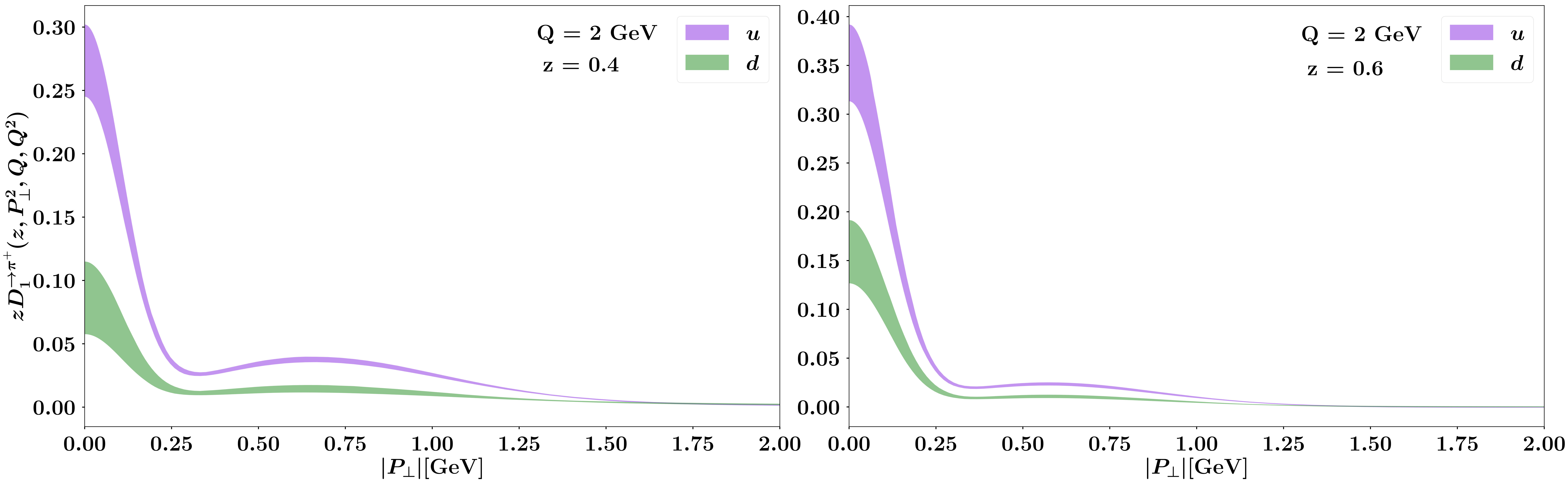
JHEP 08 (2024) 232

MAPTMD24 extraction - TMD PDFs

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



JHEP 08 (2024) 232

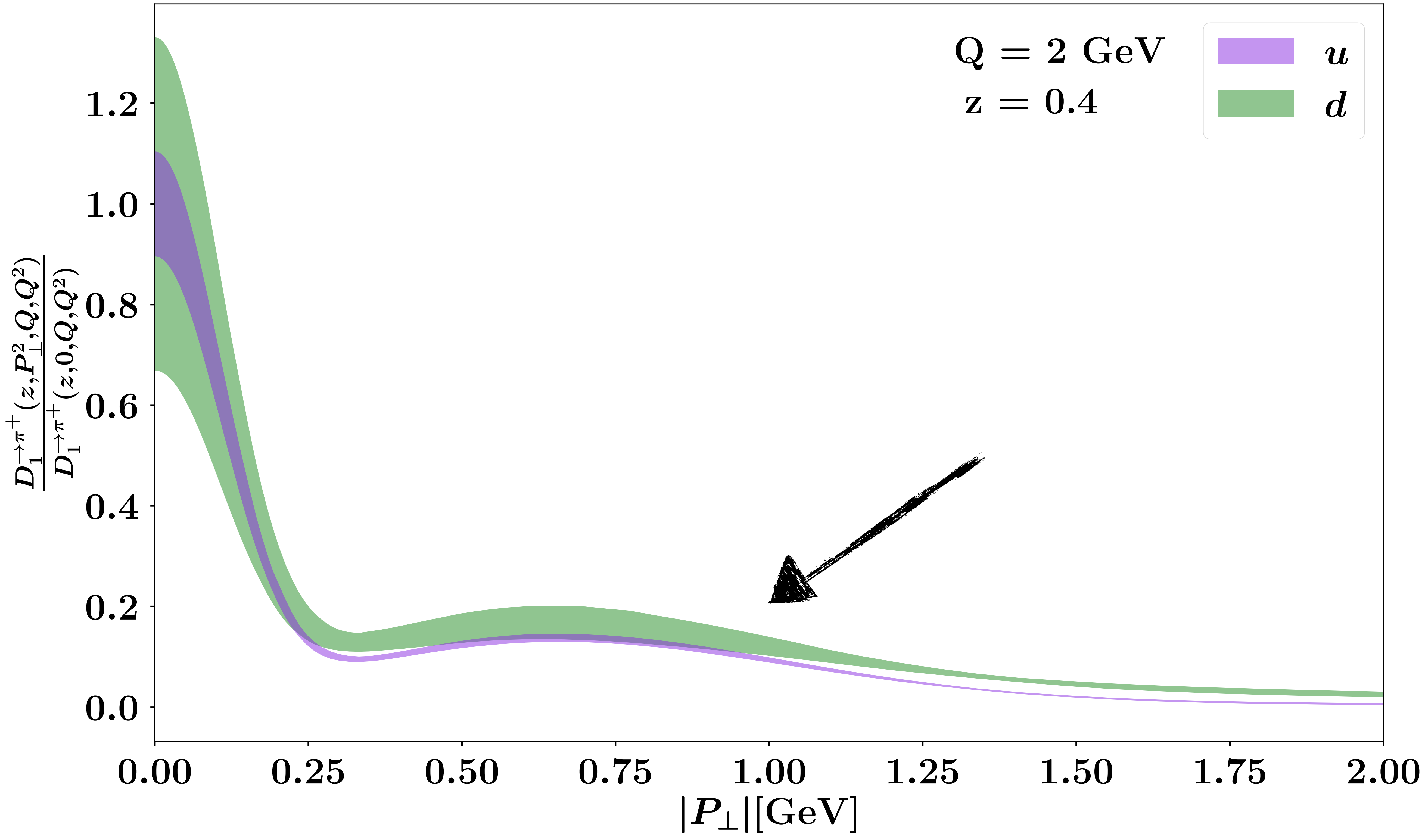
MAPTMD24 extraction - TMD FFs

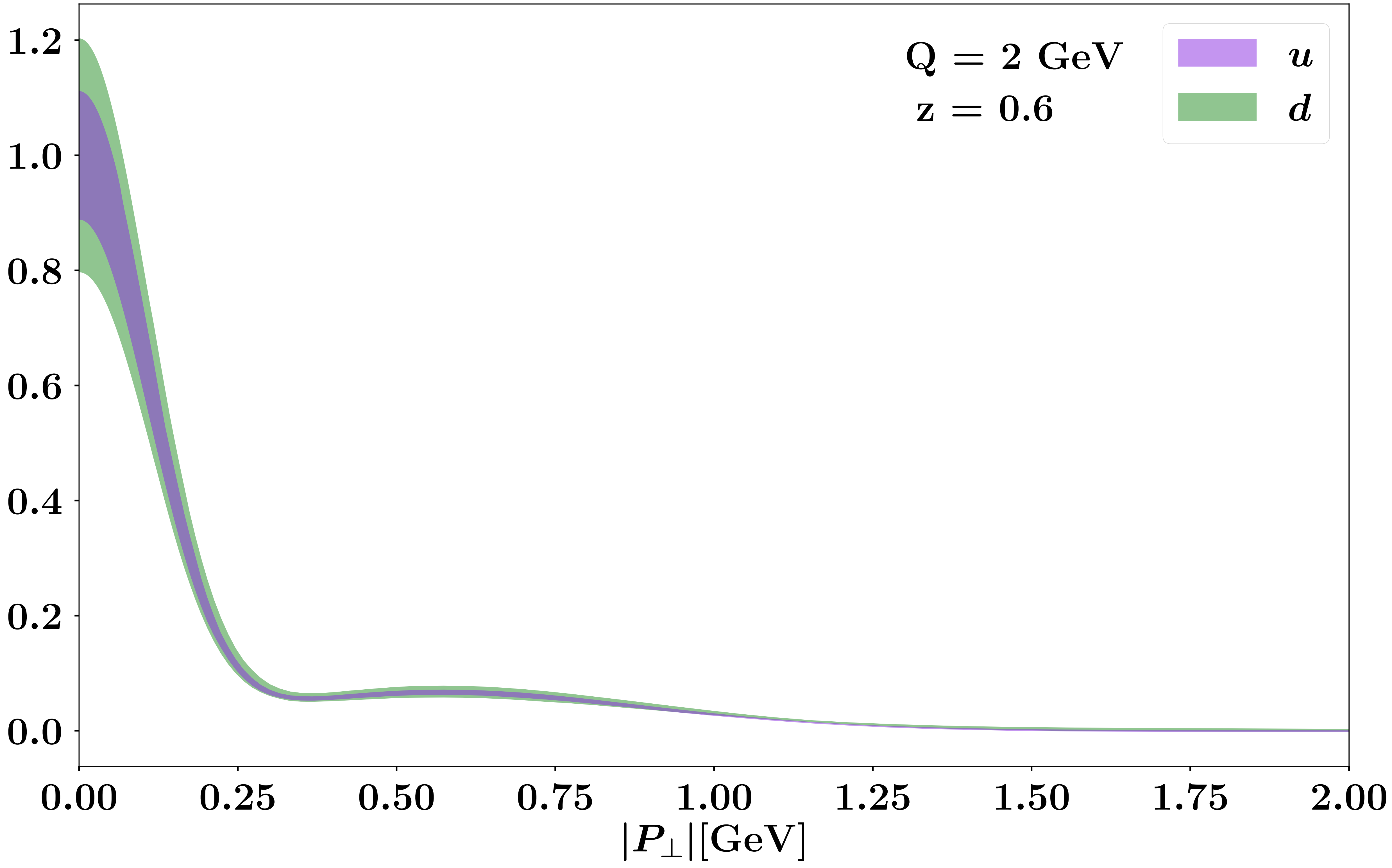
JHEP 08 (2024) 232

MAPTMD24 extraction - TMD FFs

JHEP 08 (2024) 232

MAPTMD24 extraction - TMD FFs

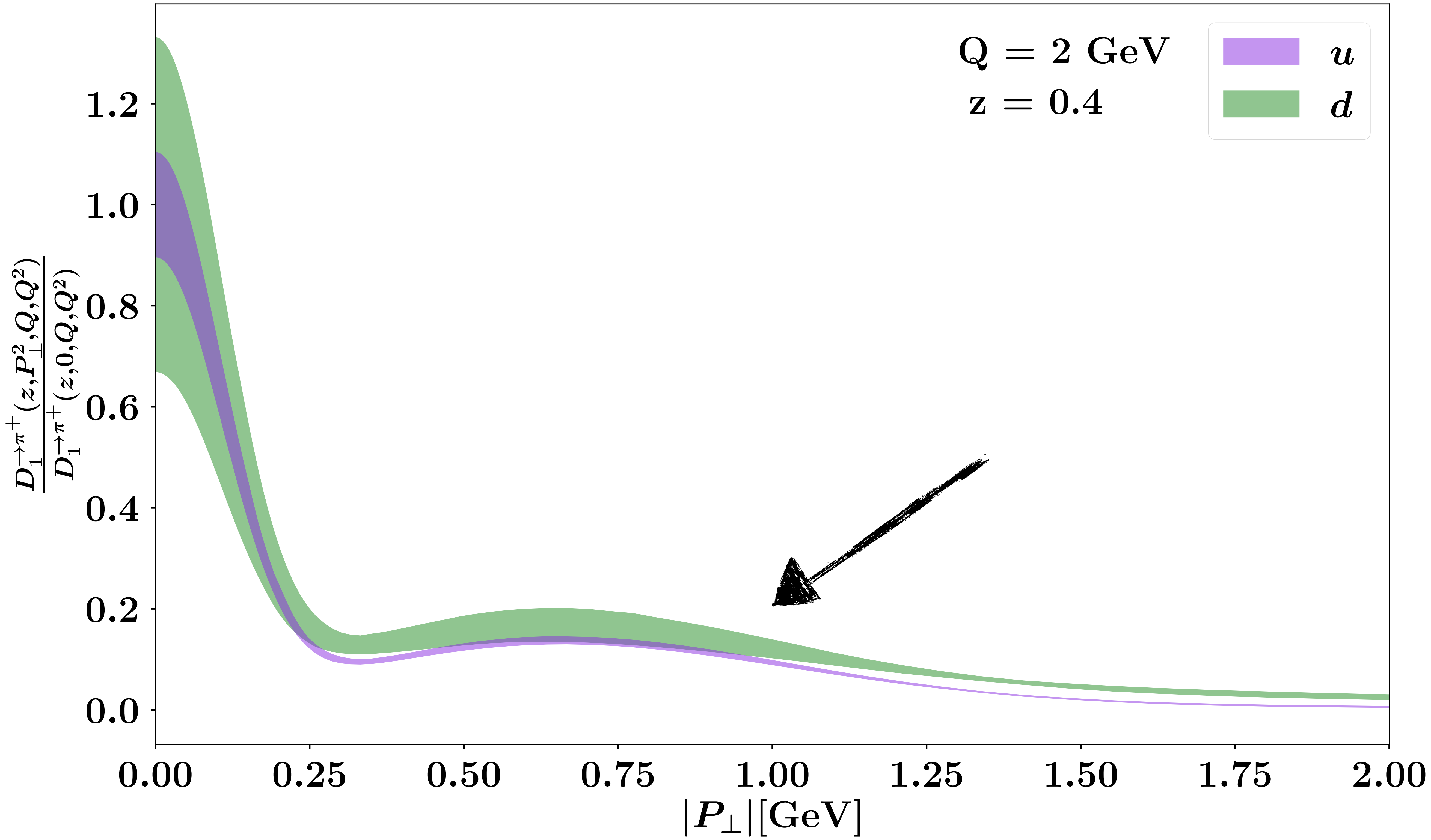


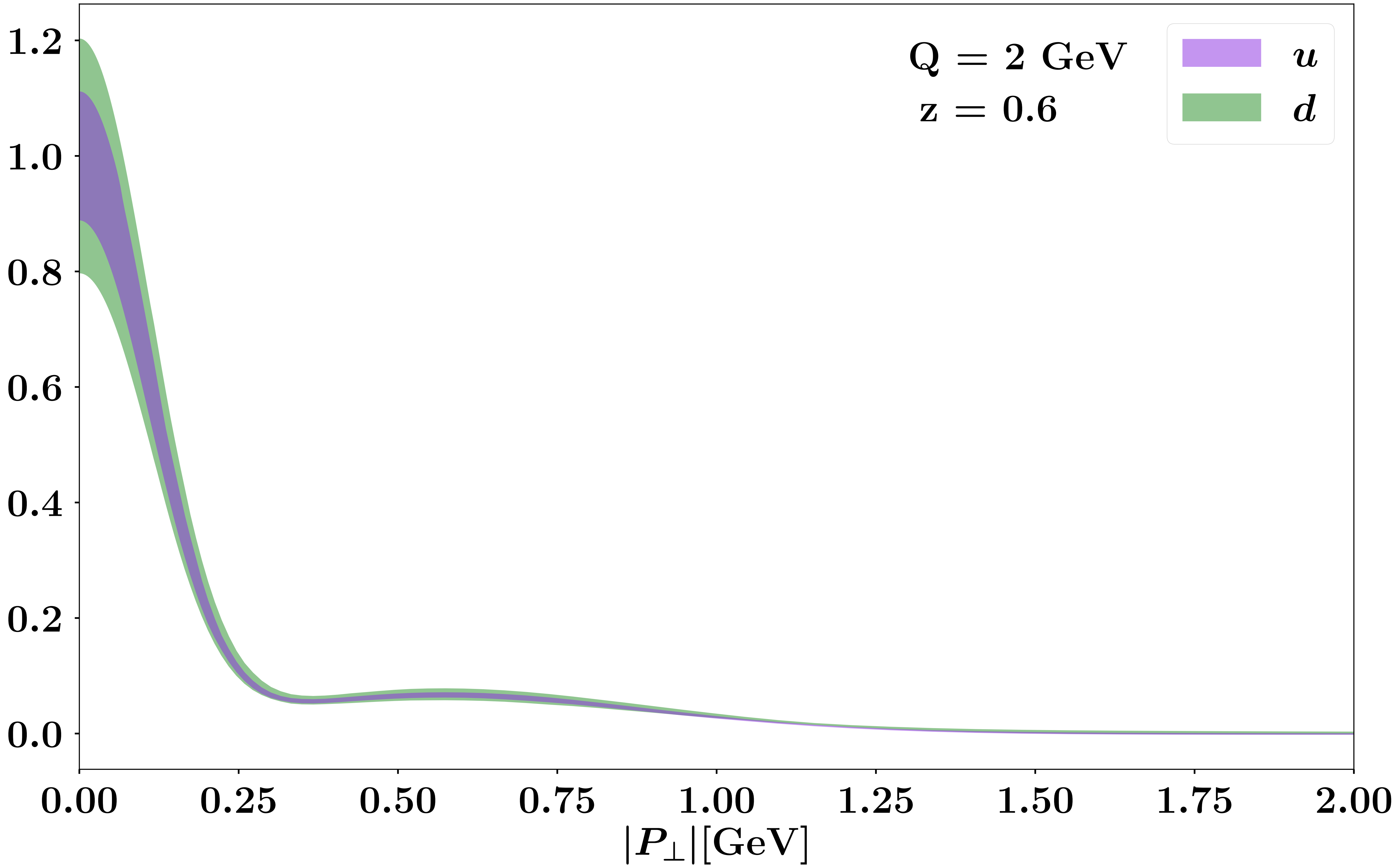


Some signals of differences between favoured and unfavoured channels

MAPTMD24 extraction - TMD FFs

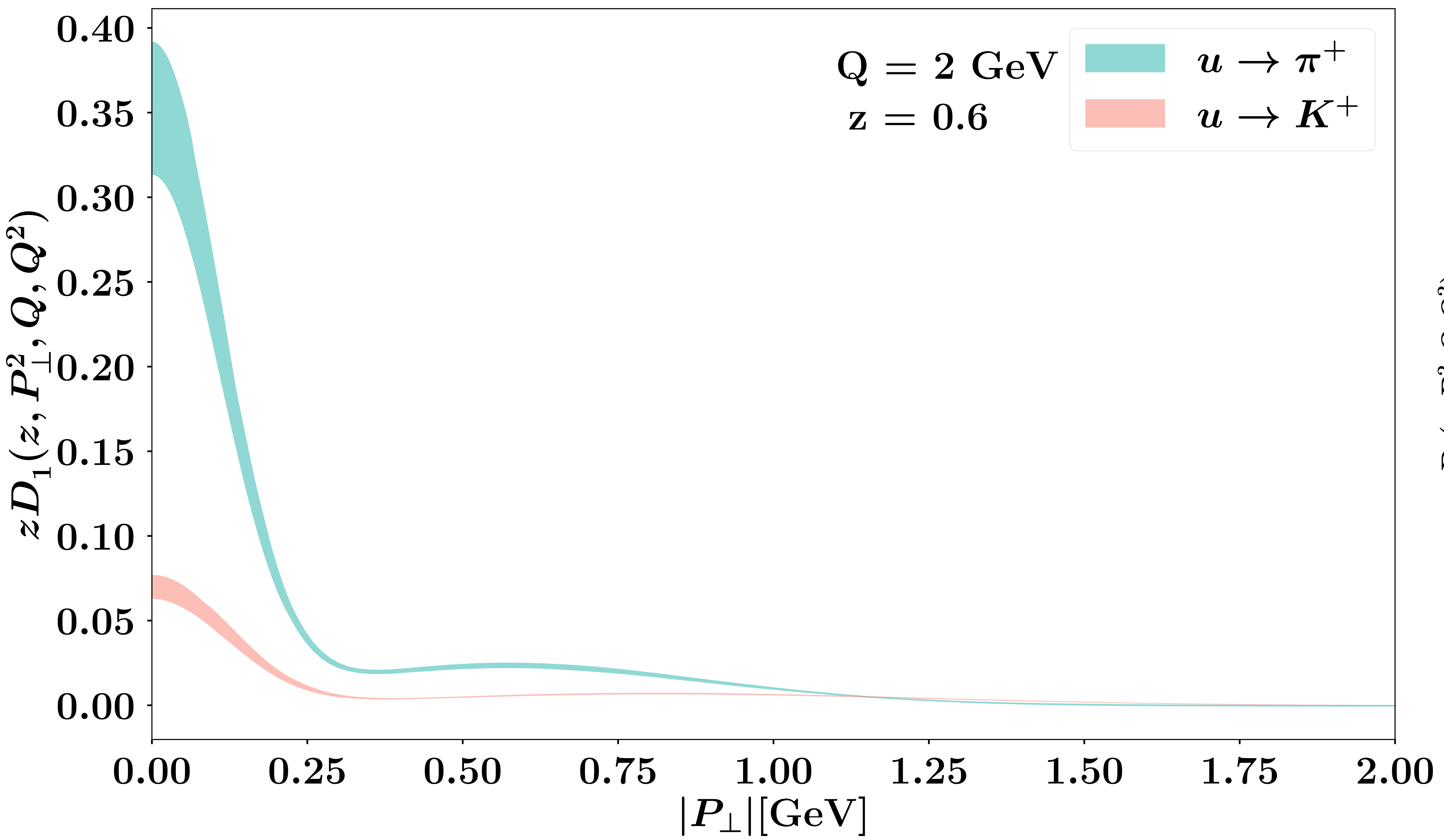
The favoured is better constrained than the unfavoured one

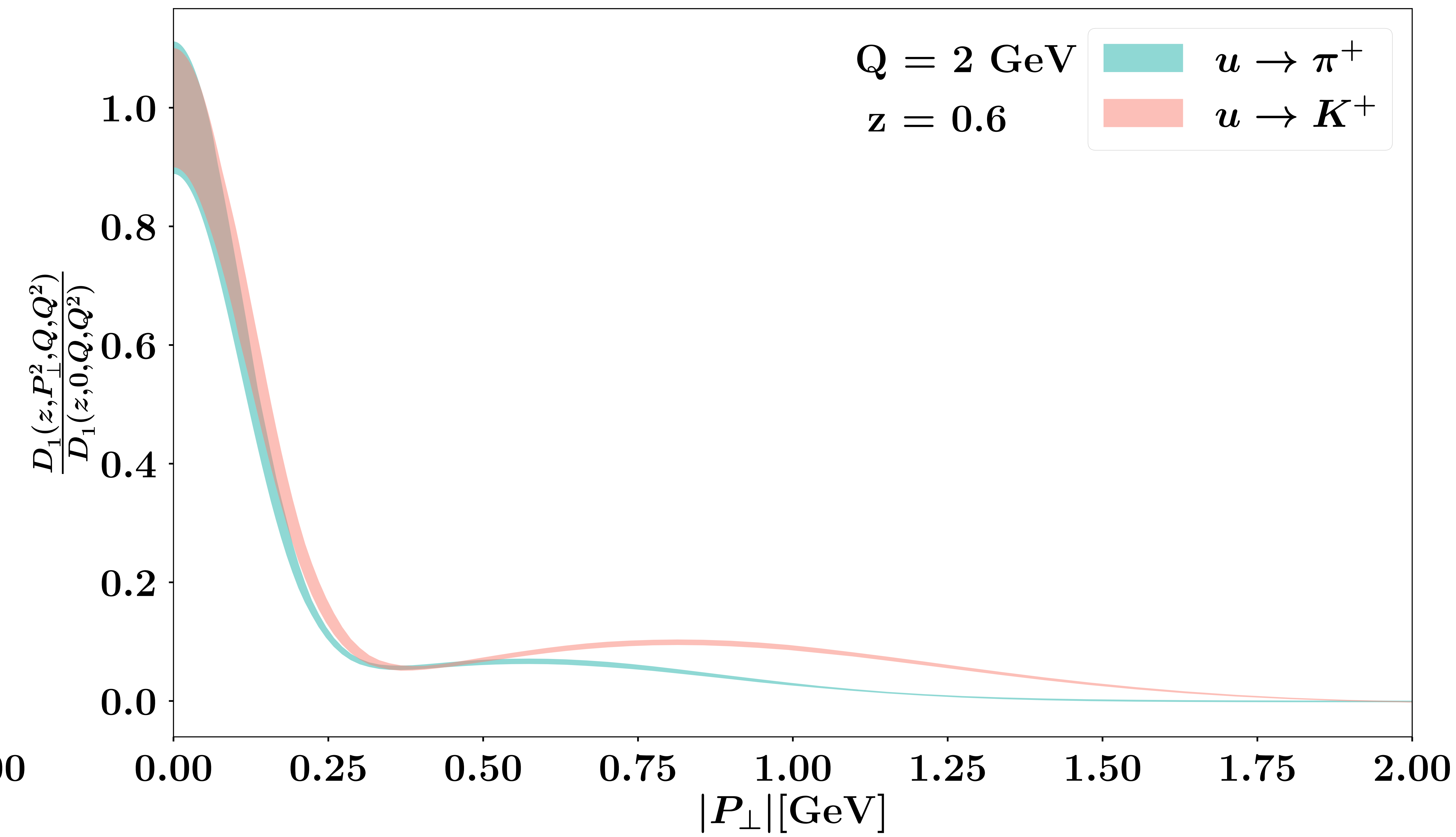




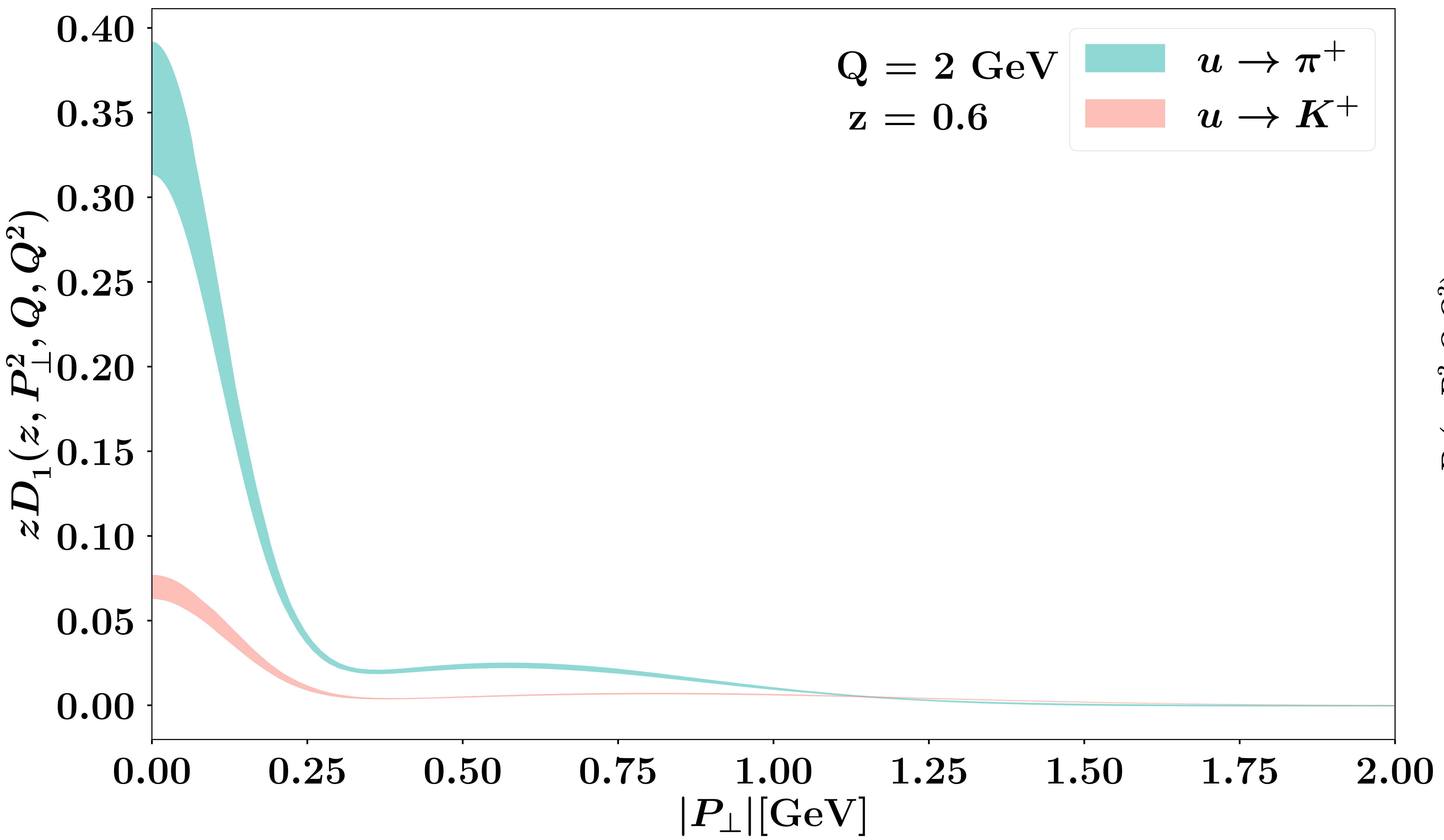
Some signals of differences between favoured and unfavoured channels

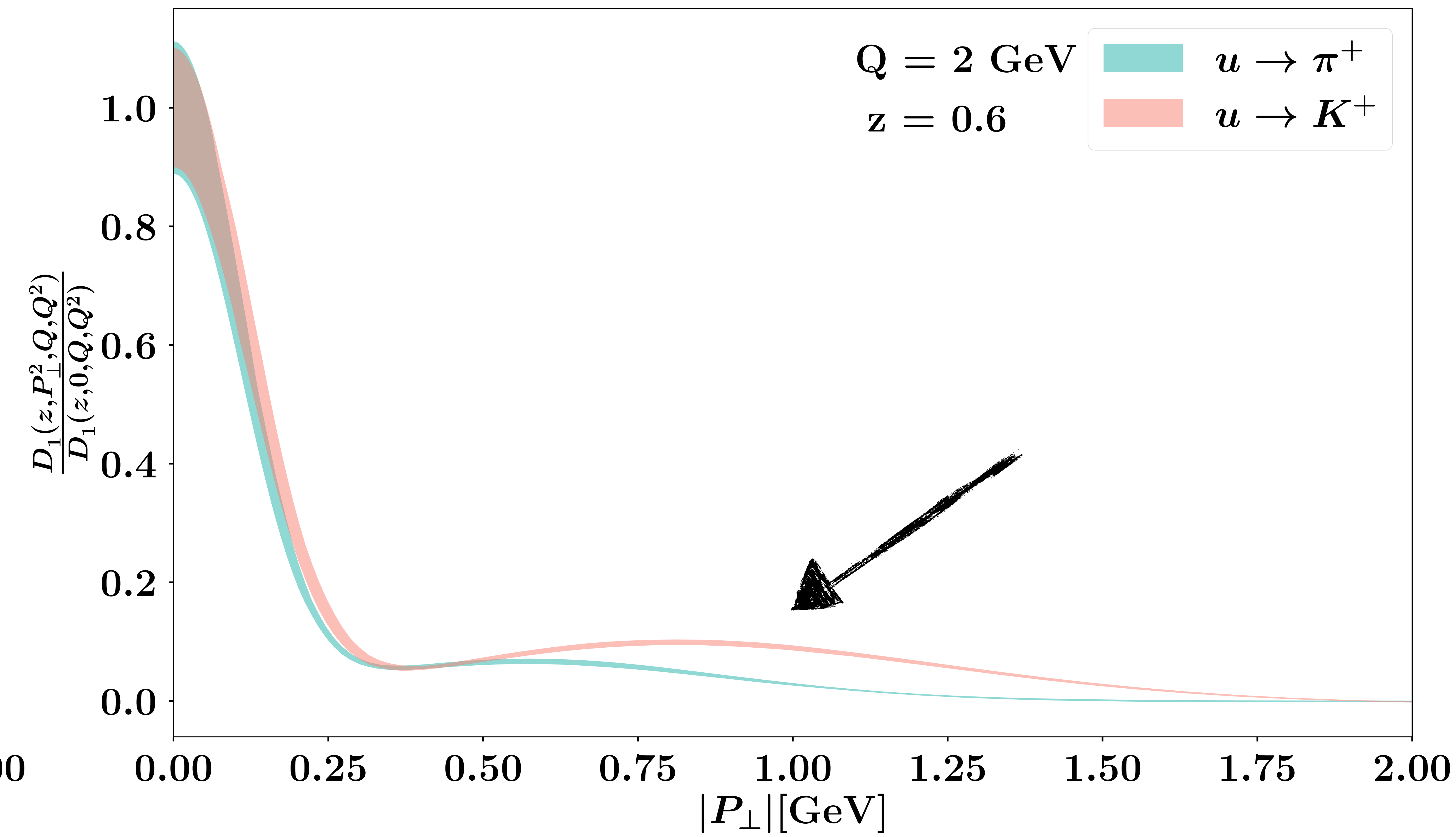
MAPTMD24 extraction - TMD FFs



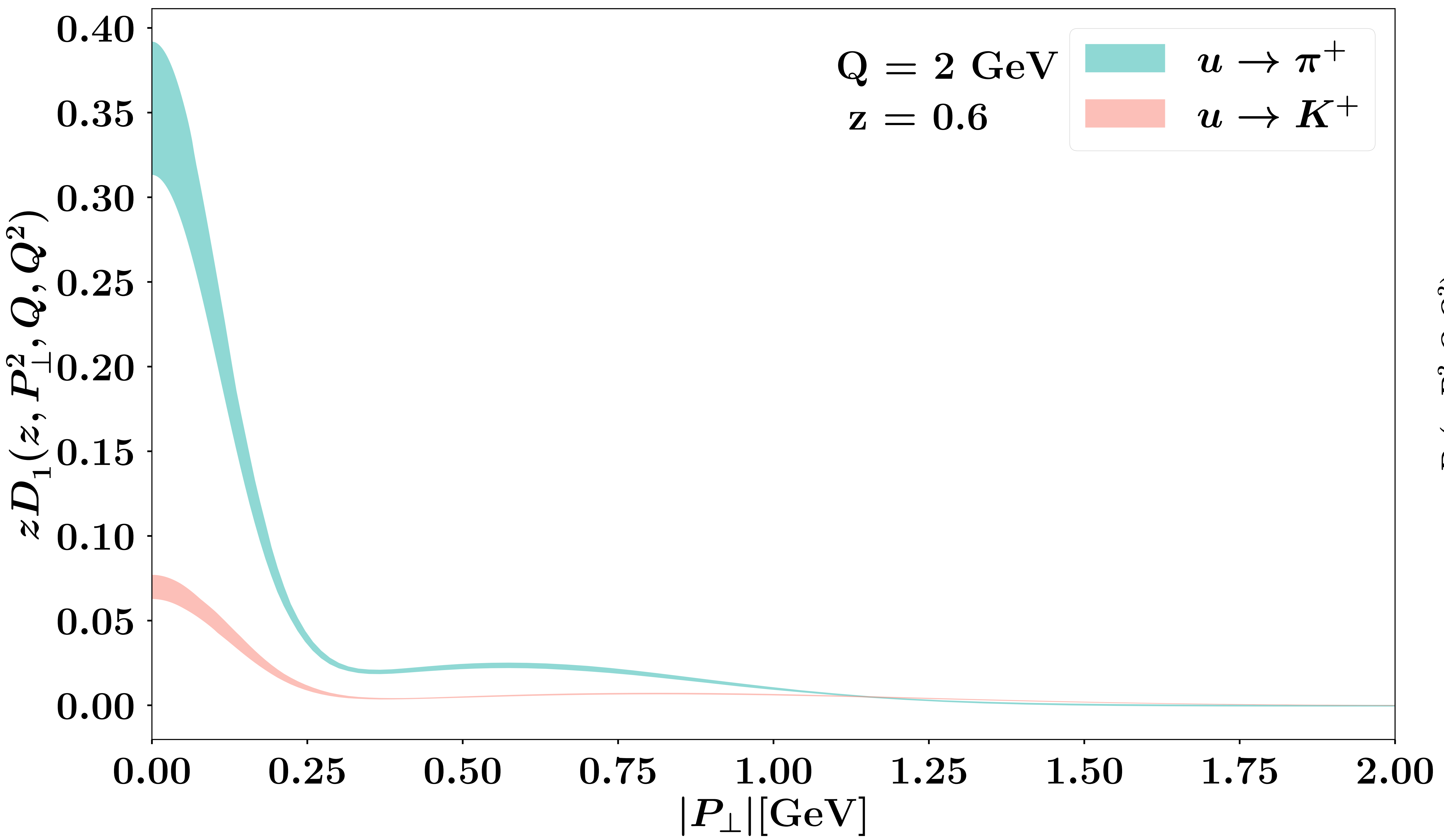


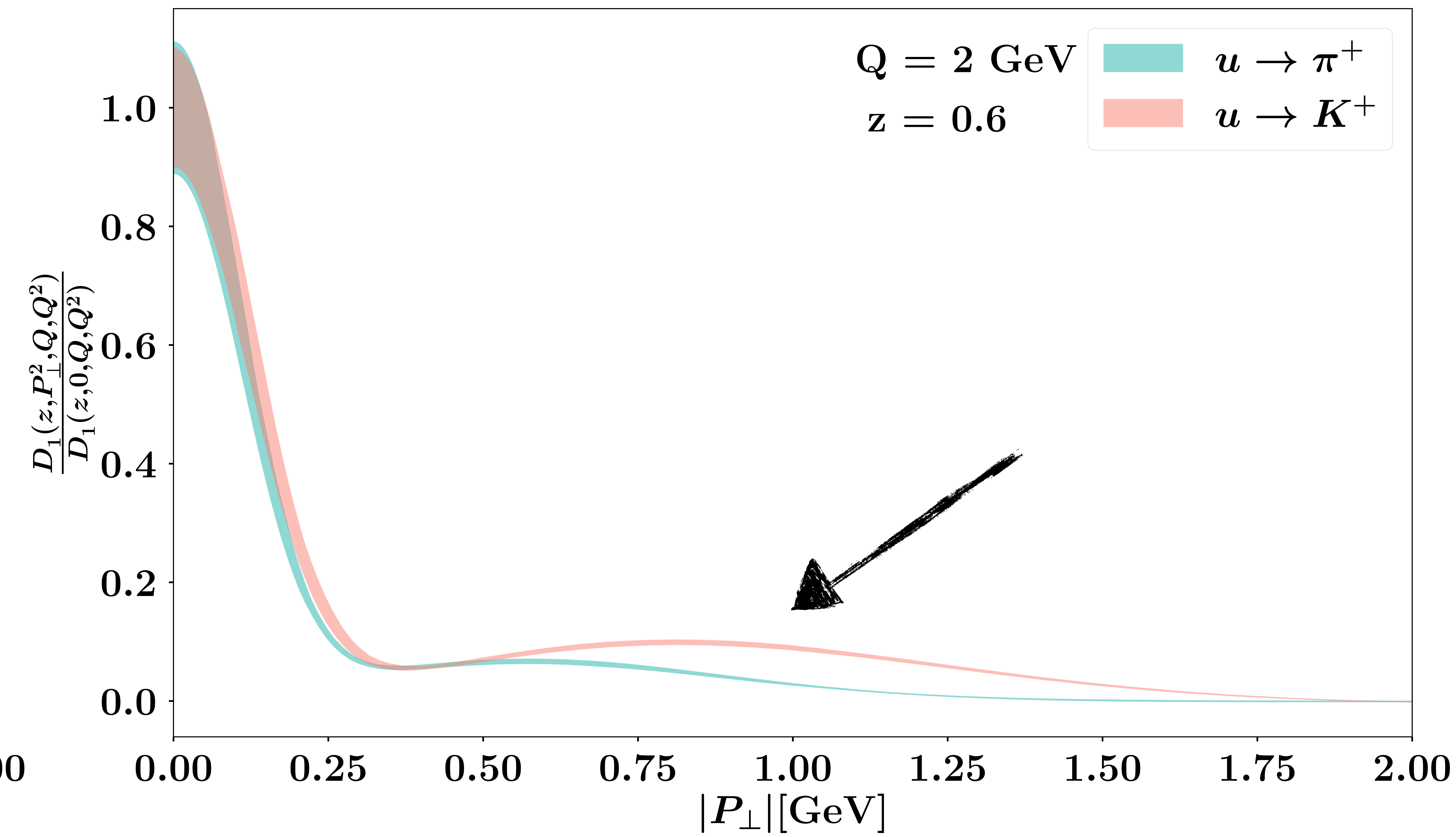
MAPTMD24 extraction - TMD FFs





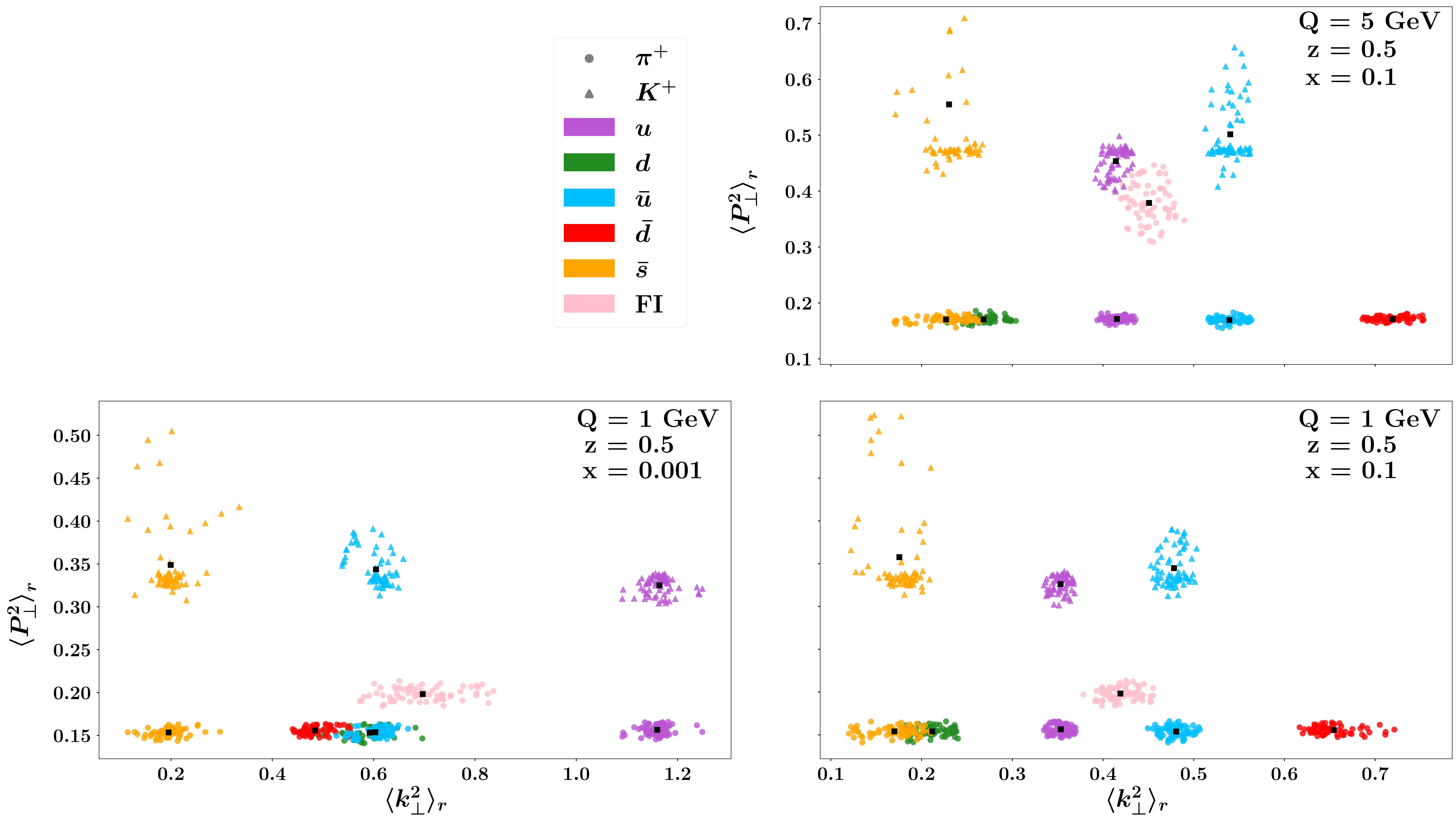
MAPTMD24 extraction - TMD FFs





Strong differences between different hadron fragmentations!

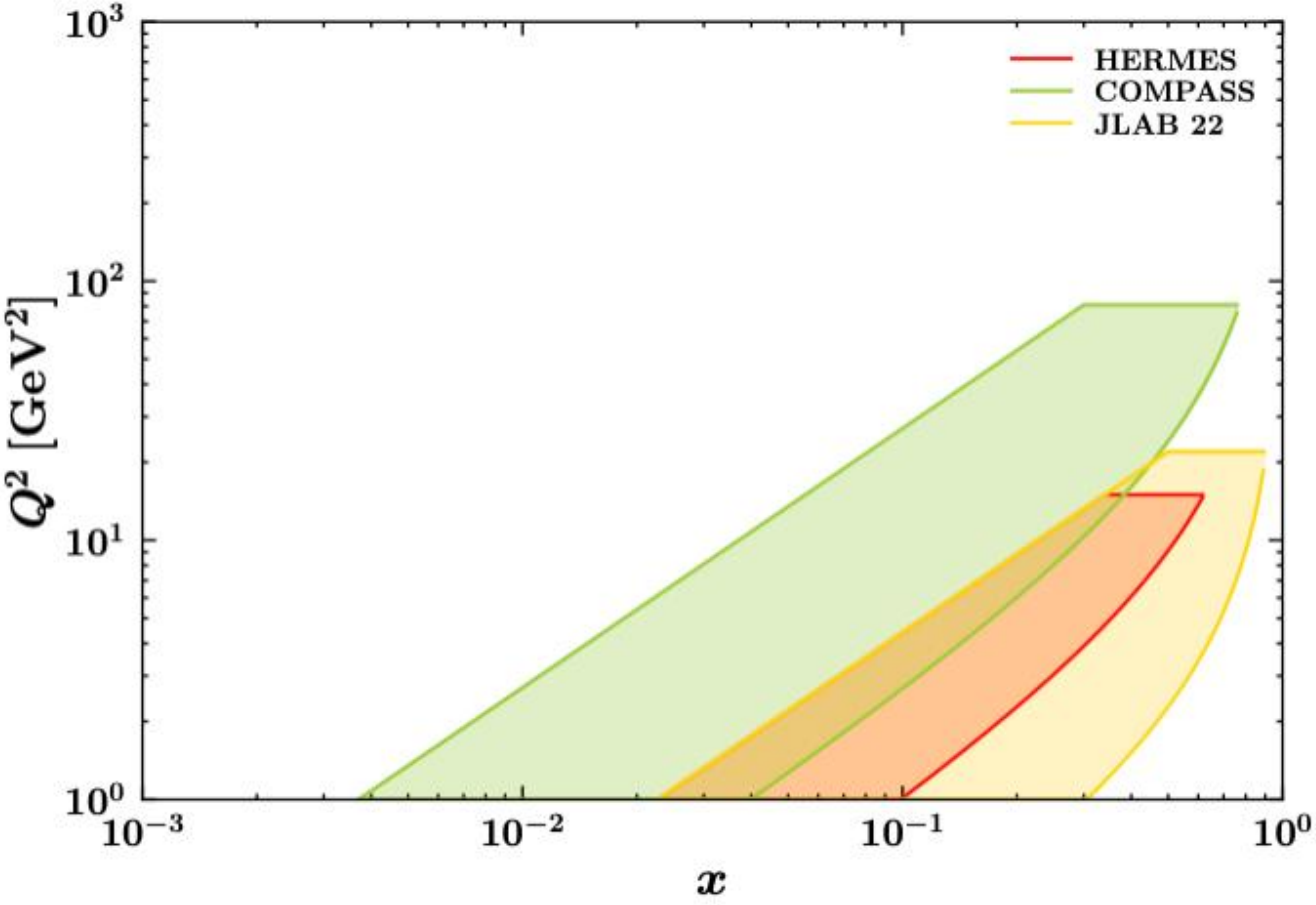
MAPTMD24 extraction - Scatter plots



JHEP 08 (2024) 232

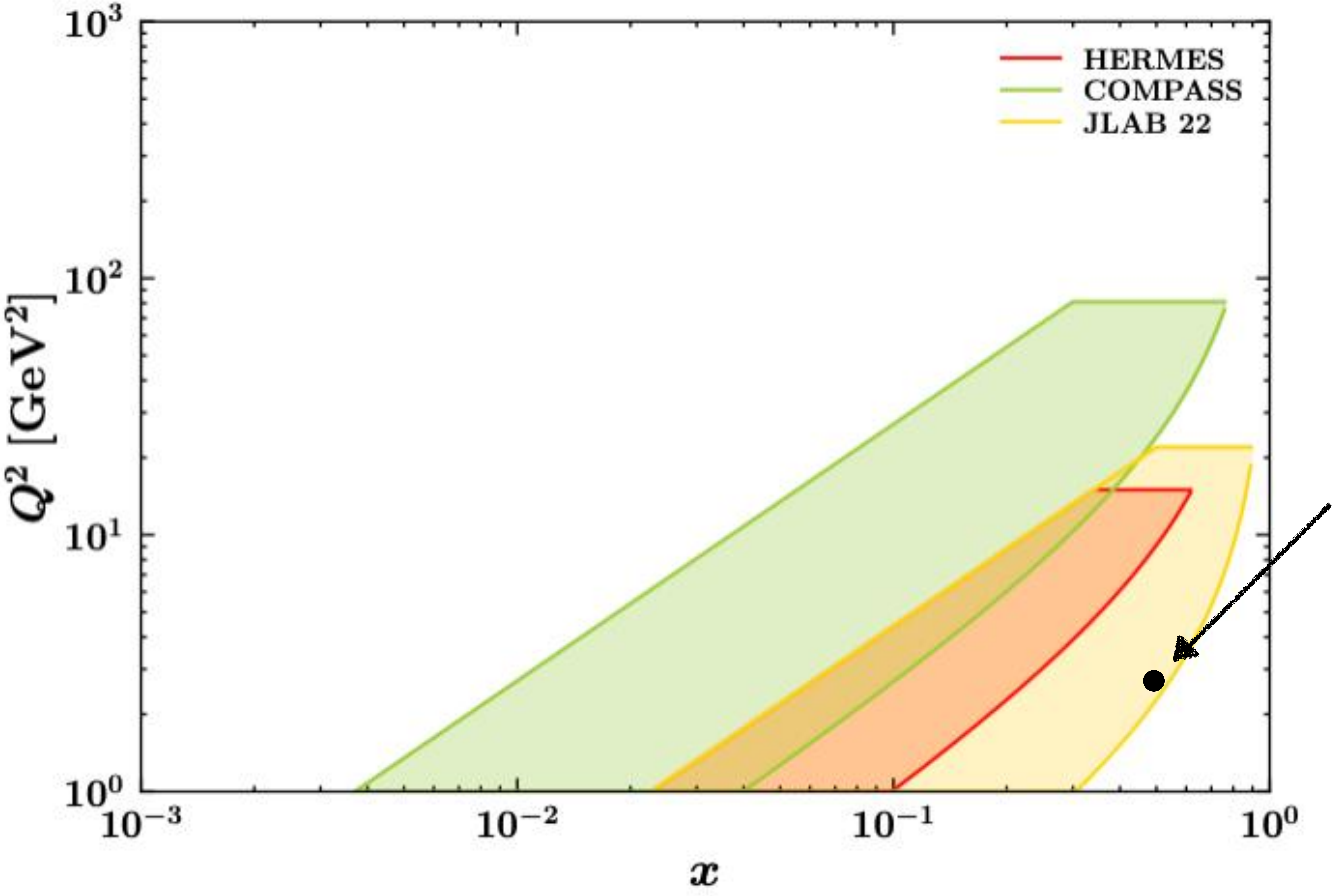
What's next?

What's next?



HERMES
COMPASS
JLAB 22
10^3
10^2
10^1
10^0
Q^2 [GeV^2]
10^{-3}
10^{-2}
10^{-1}
10^0
x

What’s next?



HERMES
COMPASS
JLAB 22
Q^2 [GeV^2]
10^3
10^2
10^1
10^0
10^{-3}
10^{-2}
10^{-1}
10^0
x

What's next?

What's next?

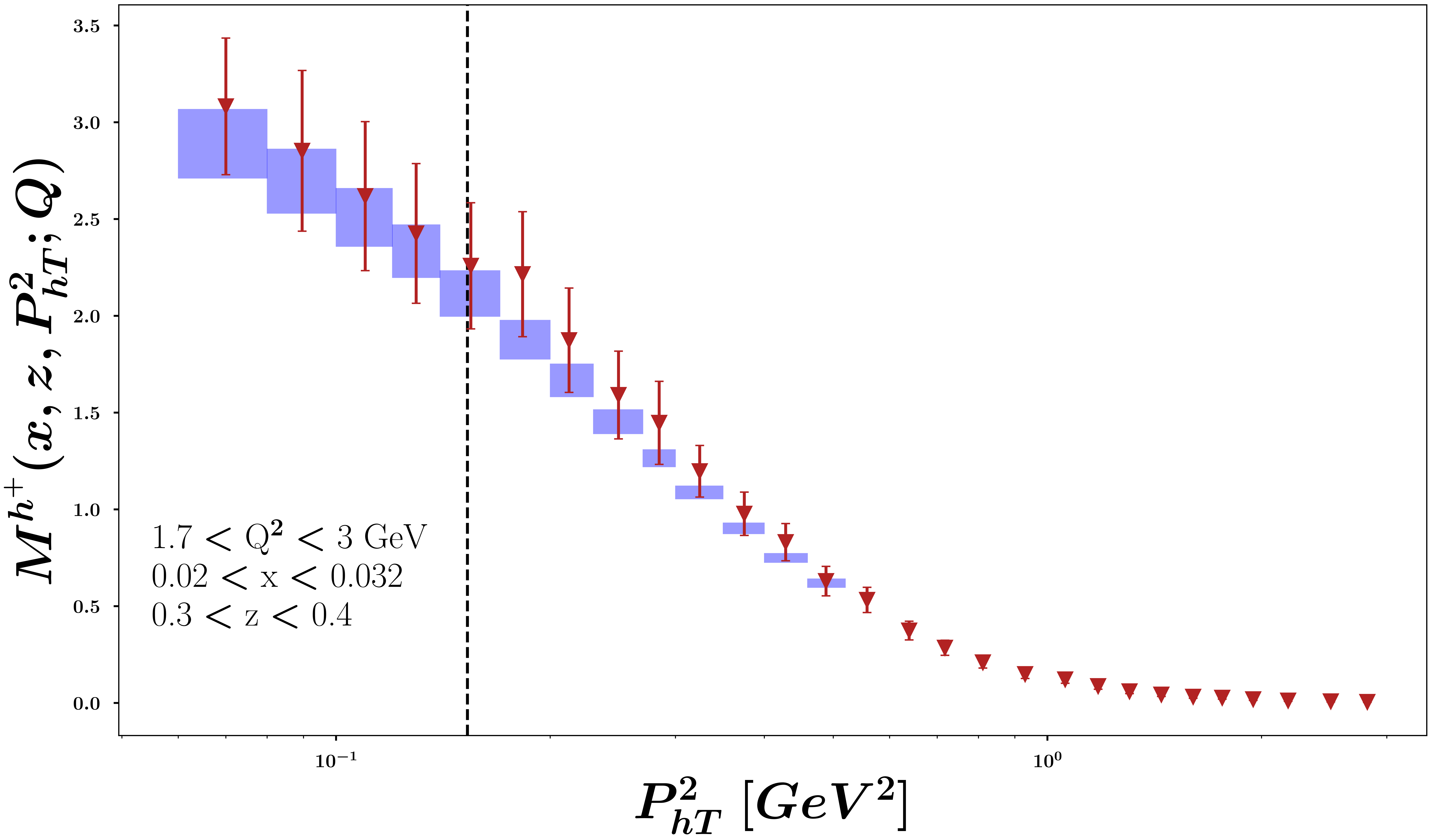
$Q = 3\,GeV\; x = 0.5$

What's next?

A lots of work still to do…

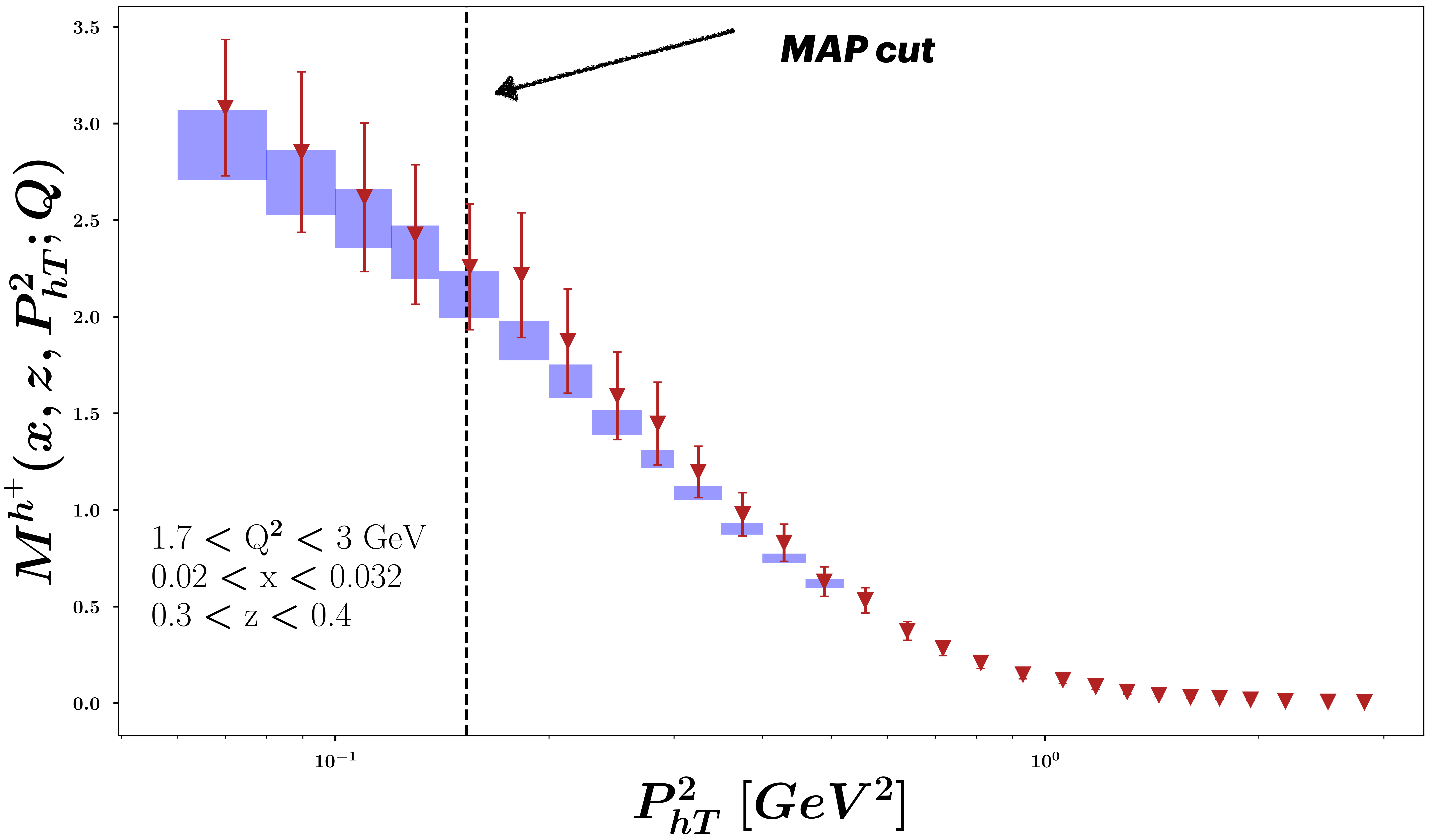
What’s next?

What's next?



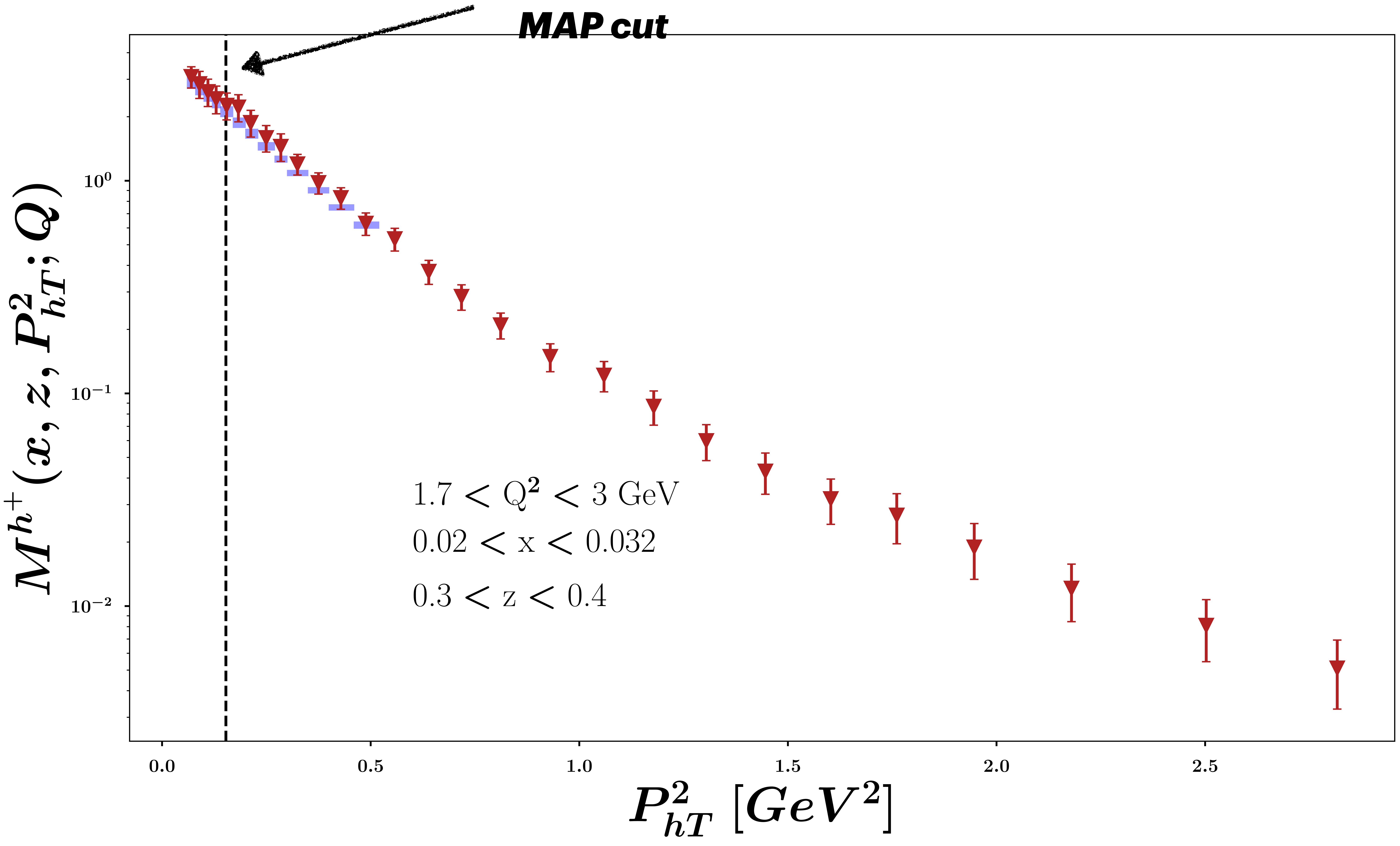
$M^{h^+}(x, z, P_{hT}^2; Q)$
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
$1.7 < Q^2 < 3$ GeV
$0.02 < x < 0.032$
$0.3 < z < 0.4$
10^{-1}
10^{0}
$P_{hT}^2\ [GeV^2]$

What's next?



MAP cut
1.7 < Q² < 3 GeV
0.02 < x < 0.032
0.3 < z < 0.4
$M^{h^+}(x, z, P_{hT}^2; Q)$
P_{hT}^2 [GeV^2]
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
10^{-1}
10^0

What’s next?



MAP cut
$1.7 < Q^2 < 3$ GeV
$0.02 < x < 0.032$
$0.3 < z < 0.4$
$M^{h^+}(x, z, P_{hT}^2; Q)$
P_{hT}^2 $[GeV^2]$
10^0
10^{-1}
10^{-2}
0.0
0.5
1.0
1.5
2.0
2.5

Conclusions and outlook

Conclusions and outlook

- ***MAPTMD24*** is the ***first flavour dependent*** extraction of unpolarized quarks TMDs in the proton from a ***global*** fit

Conclusions and outlook

- ***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***.

Conclusions and outlook

- ***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***.

Conclusions and outlook

- ***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.

Conclusions and outlook

- ***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.

- Future SIDIS data in identified hadrons will be fundamental for a full description

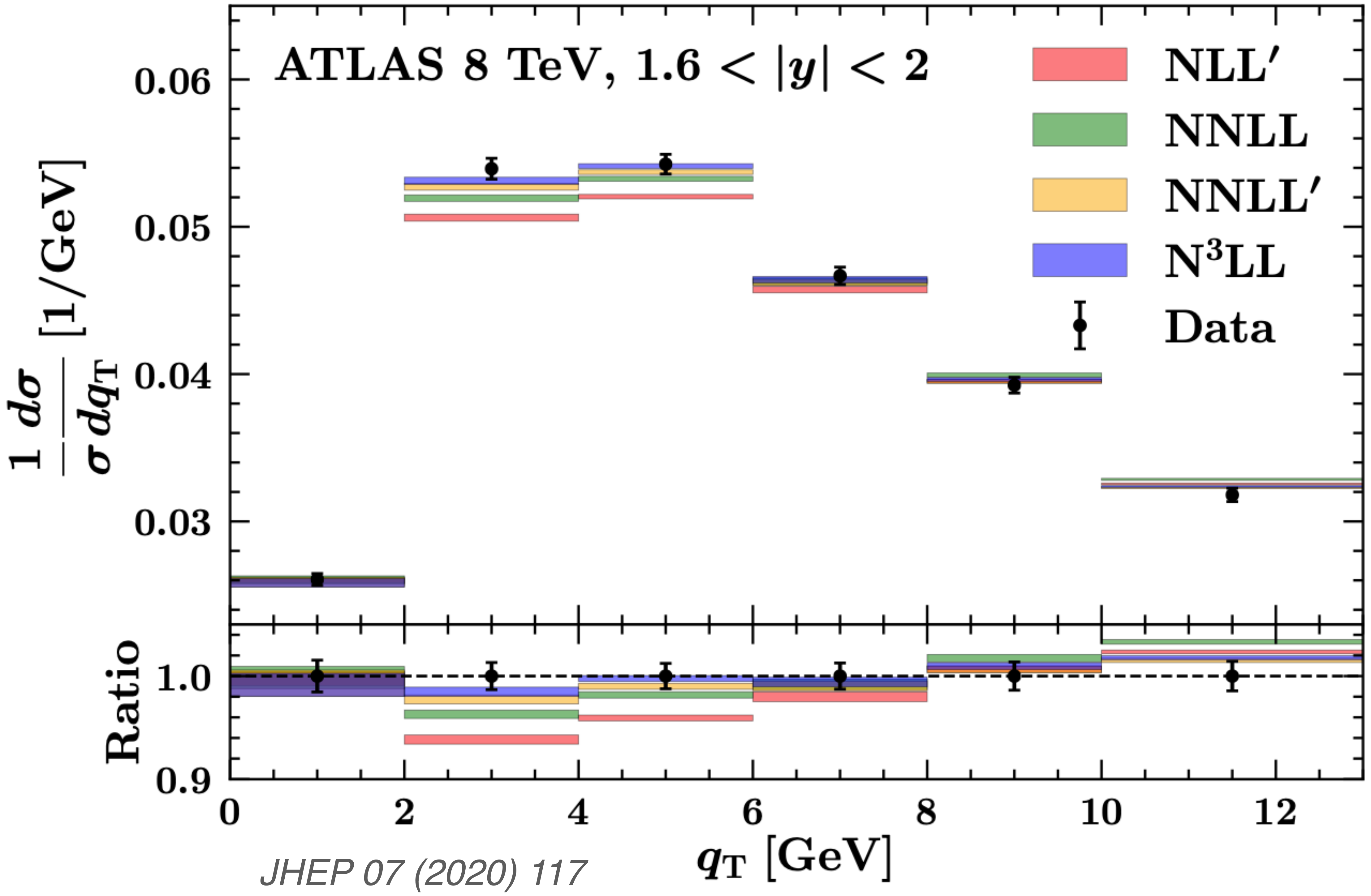
BACKUP

MAPTMD22: Normalization of SIDIS

MAP Collaboration, JHEP 10 (2022)

MAPTMD22: Normalization of SIDIS

High Energy Drell-Yan

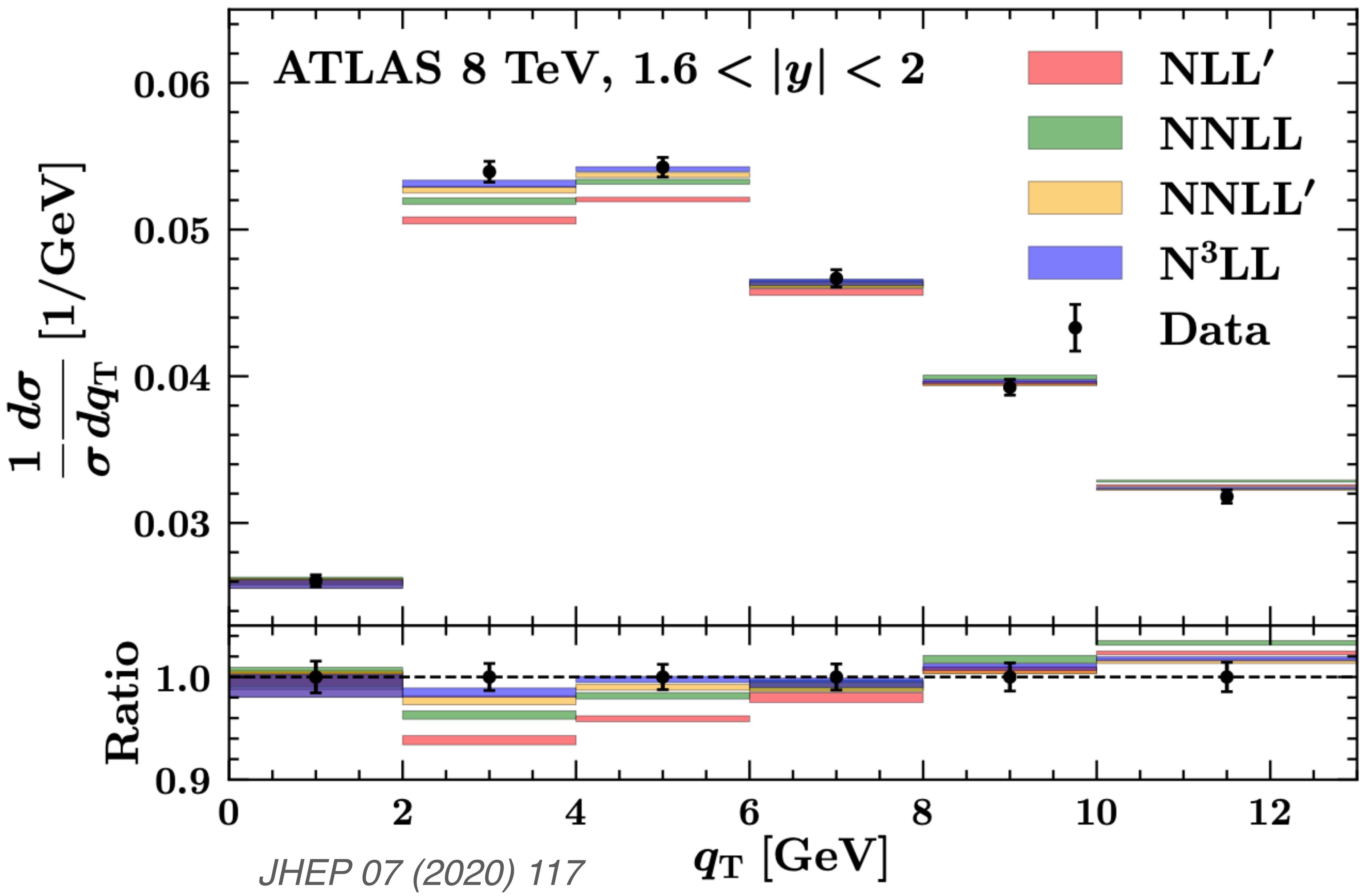


JHEP 07 (2020) 117

MAP Collaboration, JHEP 10 (2022)

MAPTMD22: Normalization of SIDIS

High Energy Drell-Yan



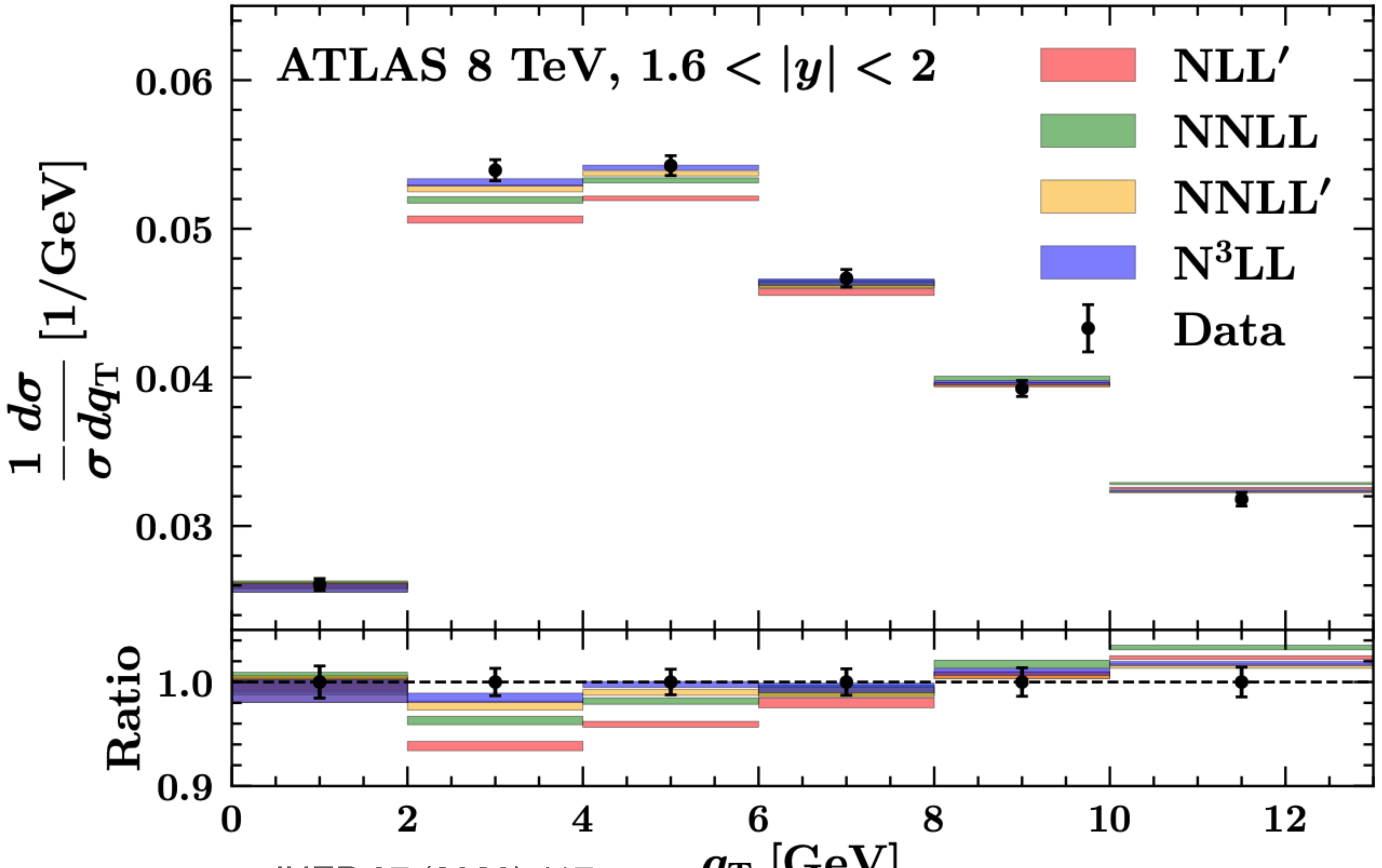
JHEP 07 (2020) 117

The description improves at high orders

MAP Collaboration, JHEP 10 (2022)

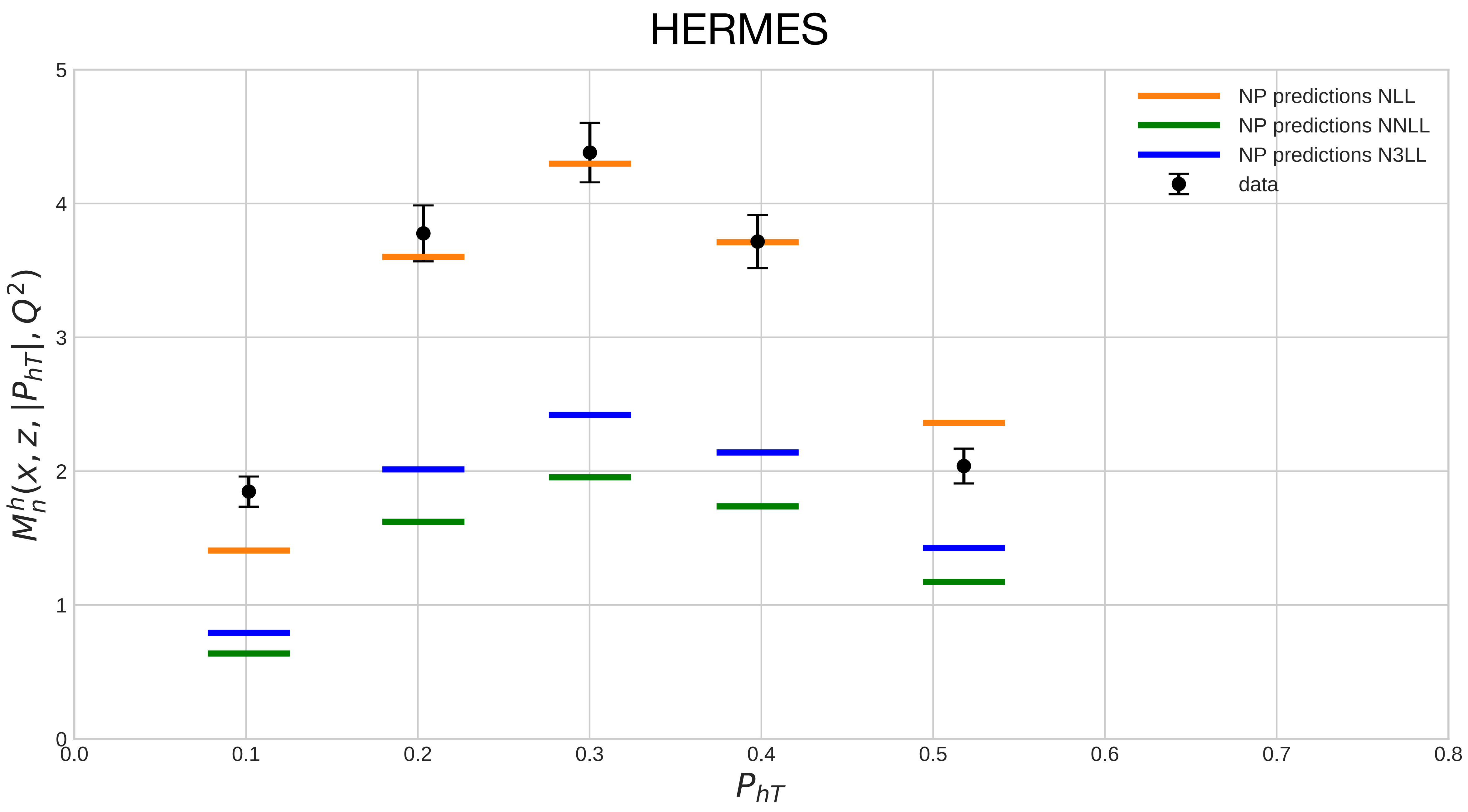
MAPTMD22: Normalization of SIDIS

High Energy Drell-Yan



JHEP 07 (2020) 117

SIDIS



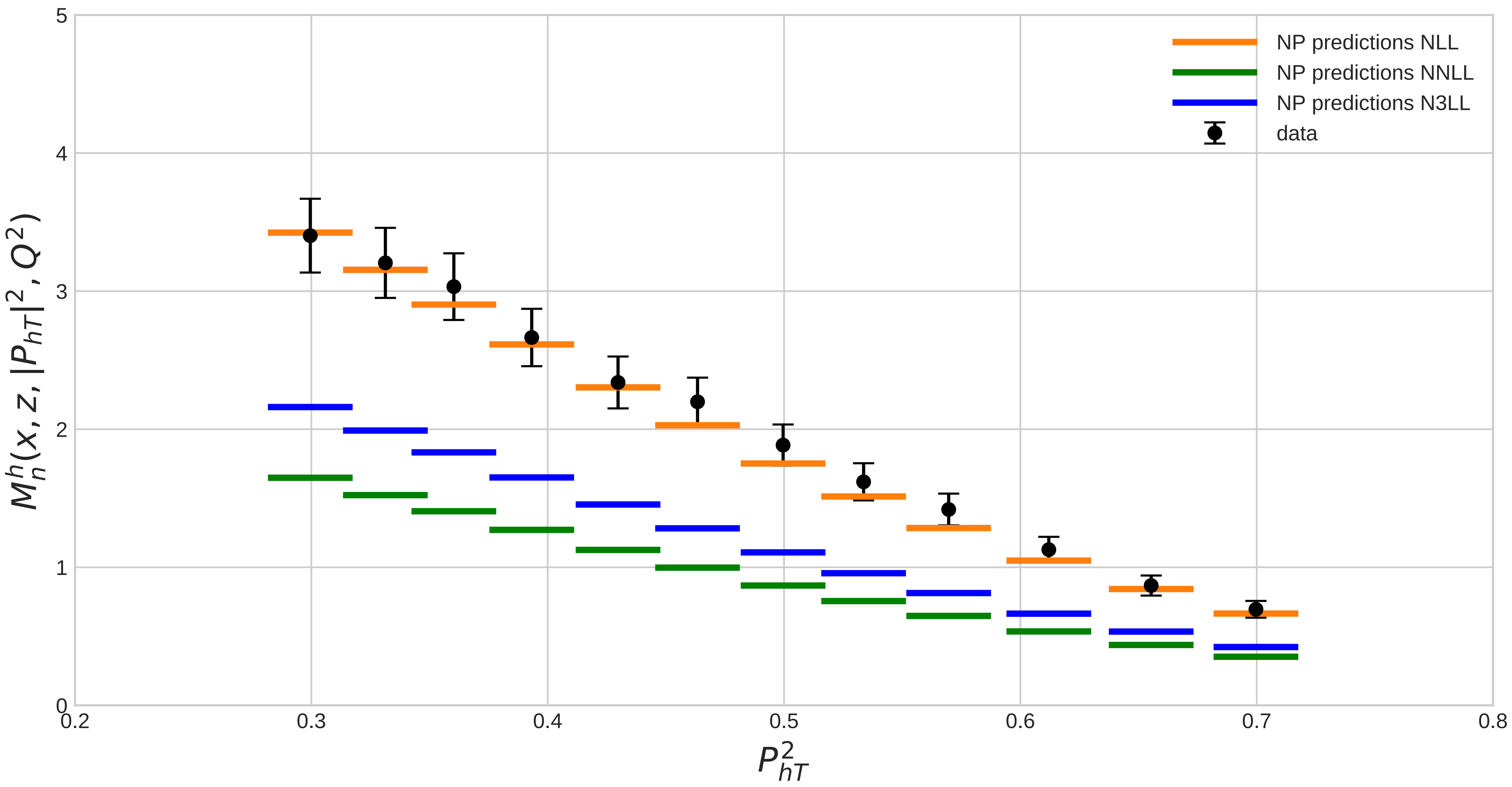
The description improves at high orders

Strange behaviors at higher orders

MAP Collaboration, JHEP 10 (2022)

MAPTMD22: Normalization of SIDIS

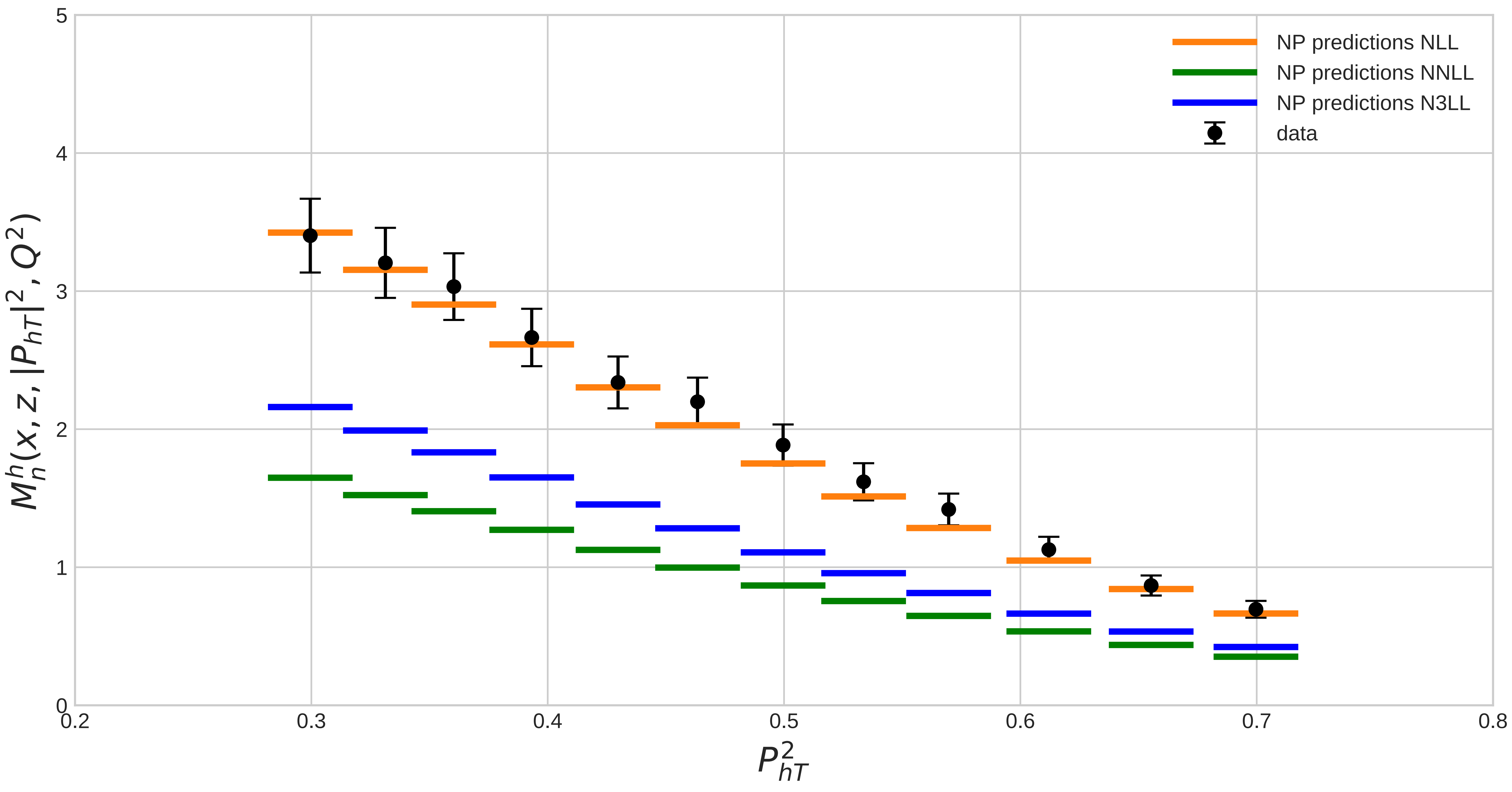
COMPASS multiplicities (one of many bins)



MAP Collaboration, JHEP 10 (2022)

MAPTMD22: Normalization of SIDIS

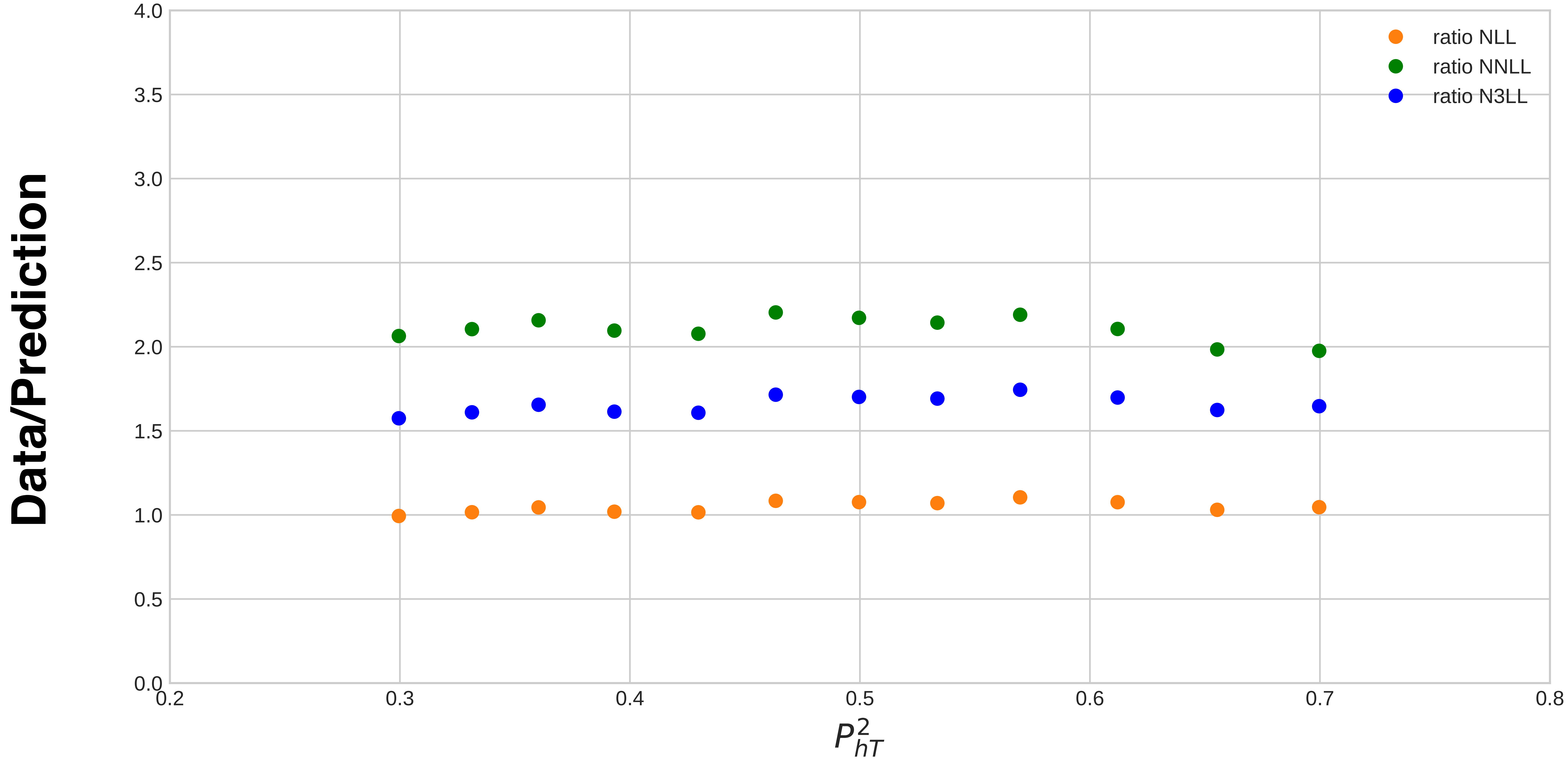
COMPASS multiplicities (one of many bins)



MAP Collaboration, JHEP 10 (2022)

MAPTMD22: Normalization of SIDIS

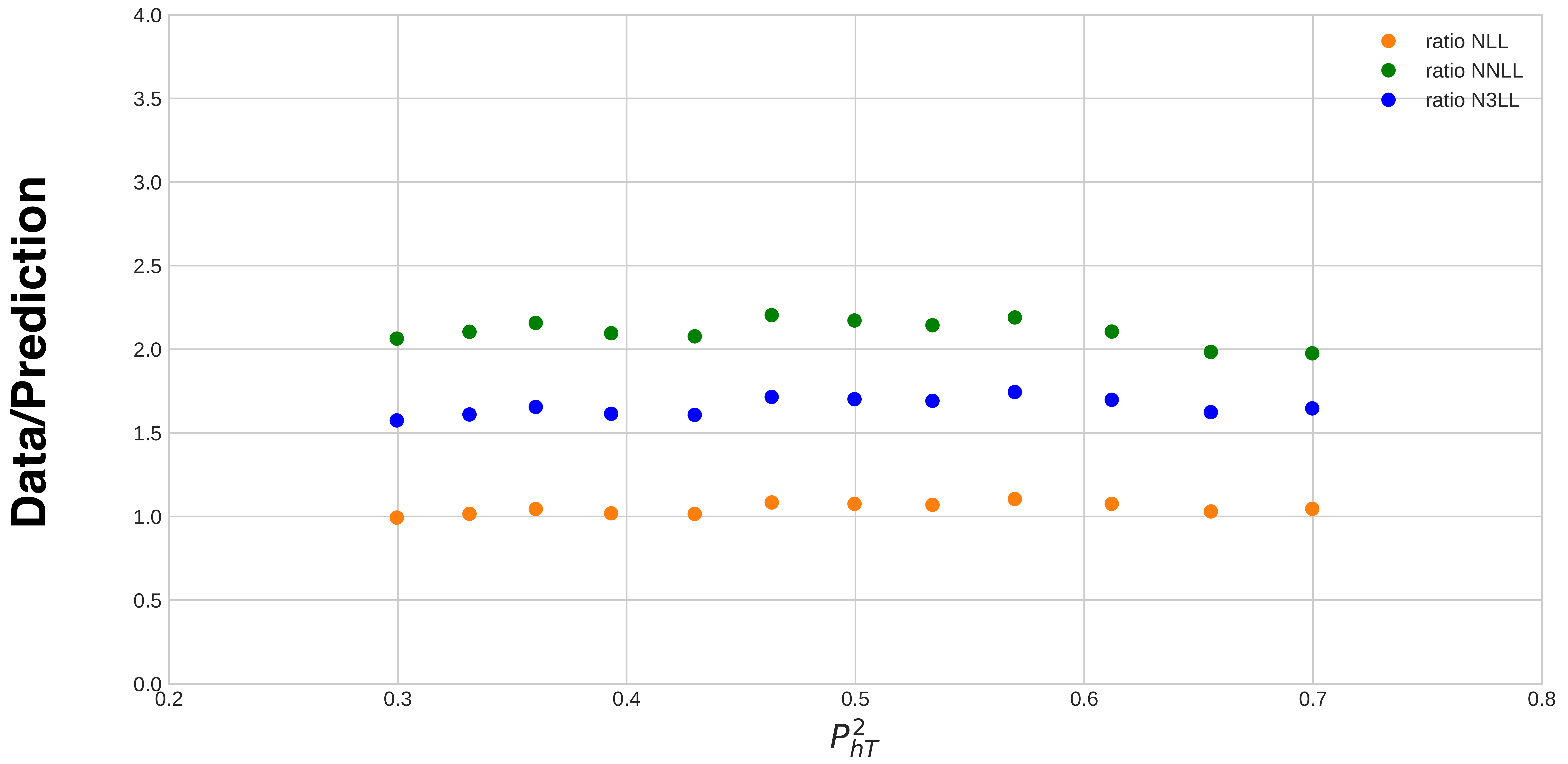
COMPASS multiplicities (one of many bins)



MAP Collaboration, JHEP 10 (2022)

MAPTMD22: Normalization of SIDIS

COMPASS multiplicities (one of many bins)



For different orders the discrepancy amounts to a nearly <u>constant</u> factor

MAP Collaboration, JHEP 10 (2022)

MAPTMD22: Normalization of SIDIS

MAP Collaboration, JHEP 10 (2022)

MAPTMD22: Normalization of SIDIS

SIDIS multiplicity

$$M(x, z, P_{hT}, Q) = \frac{d\sigma}{dxdQdzdP_{hT}} \Big/ \frac{d\sigma}{dxdQ}$$

MAP Collaboration, JHEP 10 (2022)

MAPTMD22: Normalization of SIDIS

SIDIS multiplicity $$M(x, z, P_{hT}, Q) = \frac{d\sigma}{dxdQdzdP_{hT}} \Big/ \frac{d\sigma}{dxdQ}$$

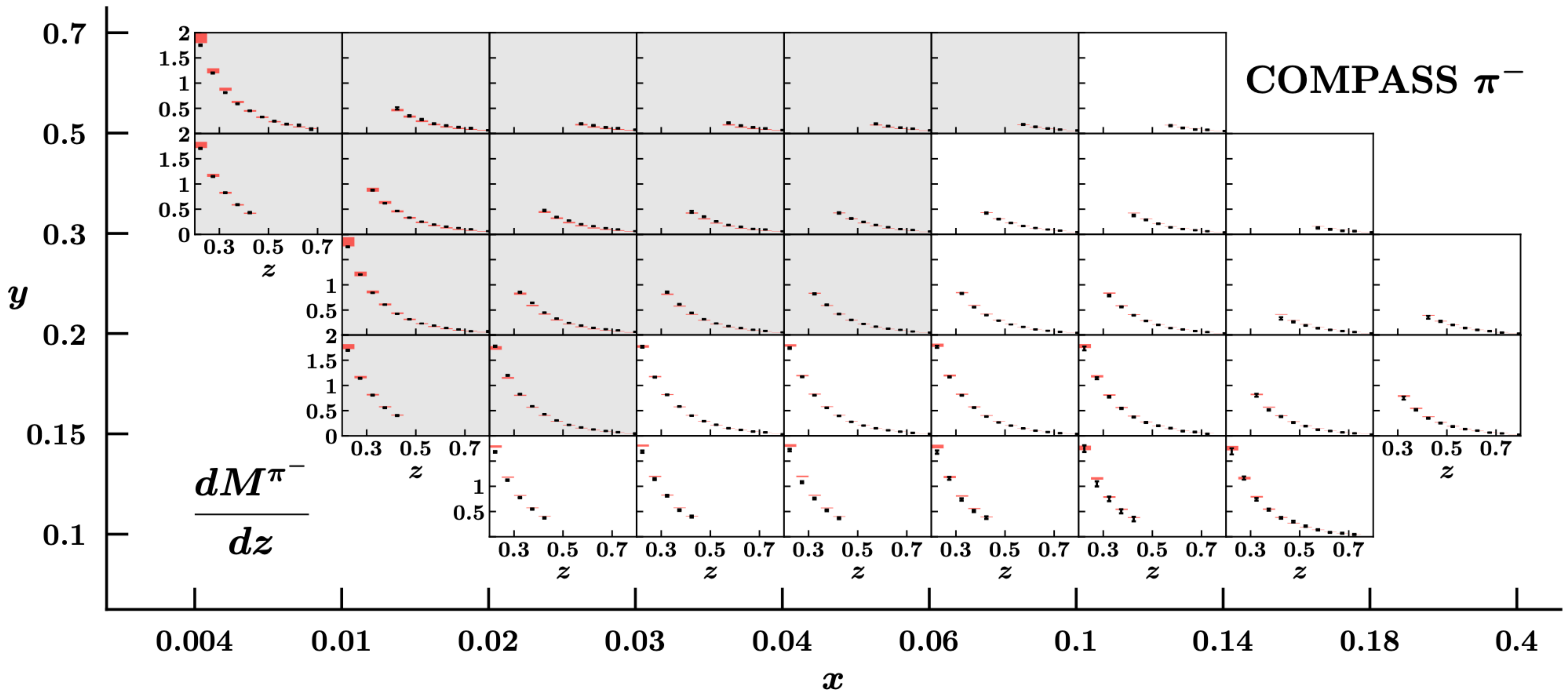
Collinear SIDIS cross section $$\frac{d\sigma}{dxdQdz}$$

MAP Collaboration, JHEP 10 (2022)

MAPTMD22: Normalization of SIDIS

SIDIS multiplicity $$M(x, z, P_{hT}, Q) = \frac{d\sigma}{dxdQdzdP_{hT}} \Big/ \frac{d\sigma}{dxdQ}$$

Collinear SIDIS cross section $$\frac{d\sigma}{dxdQdz}$$



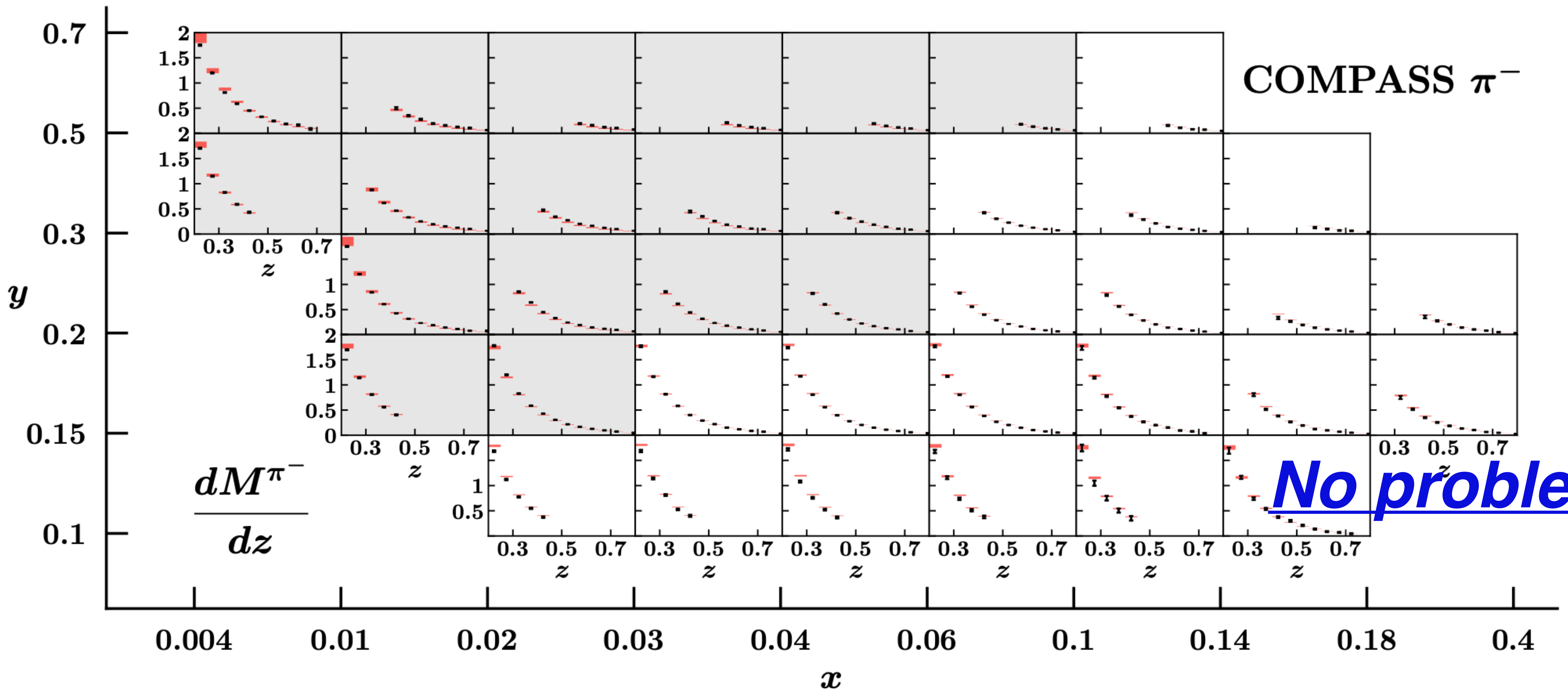
MAP Collaboration, PRD 104 (2021) 3, 034007

MAP Collaboration, JHEP 10 (2022)

MAPTMD22: Normalization of SIDIS

SIDIS multiplicity $$M(x, z, P_{hT}, Q) = \frac{d\sigma}{dxdQdzdP_{hT}} \Big/ \frac{d\sigma}{dxdQ}$$

Collinear SIDIS cross section $$\frac{d\sigma}{dxdQdz}$$



No problems of normalization

MAP Collaboration, PRD 104 (2021) 3, 034007

MAP Collaboration, JHEP 10 (2022)

MAPTMD22: Normalization of SIDIS

SIDIS multiplicity $$M(x, z, P_{hT}, Q) = \frac{d\sigma}{dxdQdzdP_{hT}} \Big/ \frac{d\sigma}{dxdQ}$$

Collinear SIDIS cross section $$\frac{d\sigma}{dxdQdz}$$

MAP Collaboration, JHEP 10 (2022)

MAPTMD22: Normalization of SIDIS

SIDIS multiplicity

$$M(x, z, P_{hT}, Q) = \frac{d\sigma}{dxdQdzdP_{hT}} \Big/ \frac{d\sigma}{dxdQ}$$

Collinear SIDIS cross section

$$\frac{d\sigma}{dxdQdz}$$

MAP Collaboration, JHEP 10 (2022)

MAPTMD22: Normalization of SIDIS

SIDIS multiplicity $$M(x, z, P_{hT}, Q) = \frac{d\sigma}{dxdQdzdP_{hT}} \Big/ \frac{d\sigma}{dxdQ}$$

Collinear SIDIS cross section $$\frac{d\sigma}{dxdQdz}$$

$$\frac{d\sigma}{dxdQdz} = \int dP_{hT} \frac{d\sigma}{dxdQdzdP_{hT}}$$

MAP Collaboration, JHEP 10 (2022)

MAPTMD22: Normalization of SIDIS

SIDIS multiplicity $$M(x, z, P_{hT}, Q) = \frac{d\sigma}{dxdQdzdP_{hT}} \Big/ \frac{d\sigma}{dxdQ}$$

Collinear SIDIS cross section $$\frac{d\sigma}{dxdQdz}$$

$$\frac{d\sigma}{dxdQdz} = \int dP_{hT} \frac{d\sigma}{dxdQdzdP_{hT}} \stackrel{?}{=} \int dP_{hT} \; W\text{-term}$$

MAP Collaboration, JHEP 10 (2022)

MAPTMD22: Normalization of SIDIS

SIDIS multiplicity $M(x, z, P_{hT}, Q) = \frac{d\sigma}{dxdQdzdP_{hT}} \Big/ \frac{d\sigma}{dxdQ}$

Collinear SIDIS cross section $\frac{d\sigma}{dxdQdz}$

$$\frac{d\sigma}{dxdQdz} = \int dP_{hT} \frac{d\sigma}{dxdQdzdP_{hT}} \stackrel{?}{=} \int dP_{hT} \; \textit{W-term}$$

$$\frac{d\sigma}{dxdzdQ}\bigg|_{\mathrm{LO}} = \; \simeq \int dq_T \, W\Big|_{\mathrm{NLL}} \propto f_1^q(x, Q) \, D_1^{q\to h}(z, Q)$$

MAP Collaboration, JHEP 10 (2022)

MAPTMD22: Normalization of SIDIS

SIDIS multiplicity $$M(x, z, P_{hT}, Q) = \frac{d\sigma}{dxdQdzdP_{hT}} \Big/ \frac{d\sigma}{dxdQ}$$

Collinear SIDIS cross section $$\frac{d\sigma}{dxdQdz}$$

$$\frac{d\sigma}{dxdQdz} = \int dP_{hT} \frac{d\sigma}{dxdQdzdP_{hT}} \stackrel{?}{=} \int dP_{hT} \quad \textit{W-term}$$

$$\frac{d\sigma}{dxdzdQ}\Big|_{\mathrm{LO}} = \simeq \int dq_T \, W \Big|_{\mathrm{NLL}} \propto f_1^q(x, Q) \, D_1^{q\to h}(z, Q)$$

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

MAP Collaboration, JHEP 10 (2022)

MAPTMD22: Normalization of SIDIS

SIDIS multiplicity $M(x, z, P_{hT}, Q) = \dfrac{d\sigma}{dxdQdzdP_{hT}} \Big/ \dfrac{d\sigma}{dxdQ}$

Collinear SIDIS cross section $\dfrac{d\sigma}{dxdQdz}$

$$\frac{d\sigma}{dxdQdz} = \int dP_{hT} \frac{d\sigma}{dxdQdzdP_{hT}} \stackrel{?}{=} \int dP_{hT} \text{ W-term}$$

$$\left.\frac{d\sigma}{dxdzdQ}\right|_{\mathrm{LO}} = \simeq \int dq_T W\Big|_{\mathrm{NLL}} \propto f_1^q(x, Q)\, D_1^{q\to h}(z, Q)$$

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

$$\int dq_T W\Big|_{\mathrm{NNLL}} \neq \left.\frac{d\sigma}{dxdzdQ}\right|_{\mathrm{NLO}}$$

MAP Collaboration, JHEP 10 (2022)

MAPTMD22: Normalization of SIDIS

SIDIS multiplicity

$$M(x, z, P_{hT}, Q) = \frac{d\sigma}{dxdQdzdP_{hT}} \Big/ \frac{d\sigma}{dxdQ}$$

Collinear SIDIS cross section

$$\frac{d\sigma}{dxdQdz}$$

MAP Collaboration, JHEP 10 (2022)

MAPTMD22: Normalization of SIDIS

SIDIS multiplicity $$M(x, z, P_{hT}, Q) = \frac{d\sigma}{dxdQdzdP_{hT}} \Big/ \frac{d\sigma}{dxdQ}$$

Collinear SIDIS cross section $$\frac{d\sigma}{dxdQdz}$$

$$w(x, z, Q) = \frac{d\sigma}{dxdQdz} \Big/ \int dP_{hT} \frac{d\sigma}{dxdQdzdP_{hT}}$$

MAP Collaboration, JHEP 10 (2022)

MAPTMD22: Normalization of SIDIS

SIDIS multiplicity $$M(x, z, P_{hT}, Q) = \frac{d\sigma}{dxdQdzdP_{hT}} \Big/ \frac{d\sigma}{dxdQ}$$

Collinear SIDIS cross section $$\frac{d\sigma}{dxdQdz}$$

$$w(x, z, Q) = \frac{d\sigma}{dxdQdz} \Big/ \int dP_{hT} \frac{d\sigma}{dxdQdzdP_{hT}}$$

$$M(x, z, P_{hT}, Q) = w(x, z, Q) \frac{d\sigma}{dxdQdzdP_{hT}} \Big/ \frac{d\sigma}{dxdQ}$$

MAP Collaboration, JHEP 10 (2022)

MAPTMD22: Normalization of SIDIS

SIDIS multiplicity $$M(x, z, P_{hT}, Q) = \frac{d\sigma}{dxdQdzdP_{hT}} \Big/ \frac{d\sigma}{dxdQ}$$

Collinear SIDIS cross section $$\frac{d\sigma}{dxdQdz}$$

Fitting parameters ***independent***

$$w(x, z, Q) = \frac{d\sigma}{dxdQdz} \Big/ \int dP_{hT} \frac{d\sigma}{dxdQdzdP_{hT}}$$

$$M(x, z, P_{hT}, Q) = w(x, z, Q) \frac{d\sigma}{dxdQdzdP_{hT}} \Big/ \frac{d\sigma}{dxdQ}$$

MAP Collaboration, JHEP 10 (2022)

BACKUP

	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**

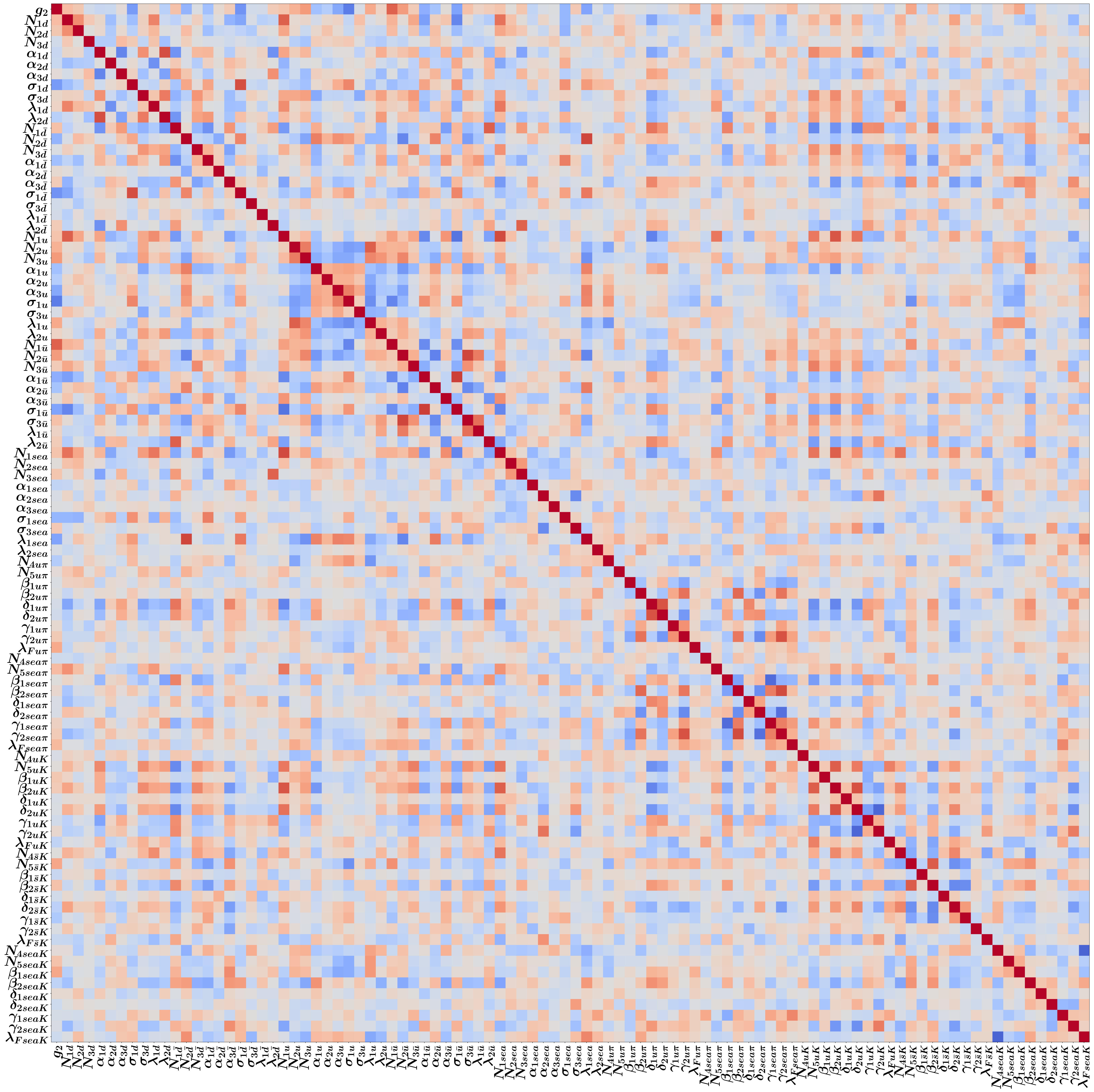
BACKUP

Error propagation

100 Monte Carlo replicas of data

100 Monte Carlo replicas of PDFs

100 Monte Carlo replicas of FFs



BACKUP

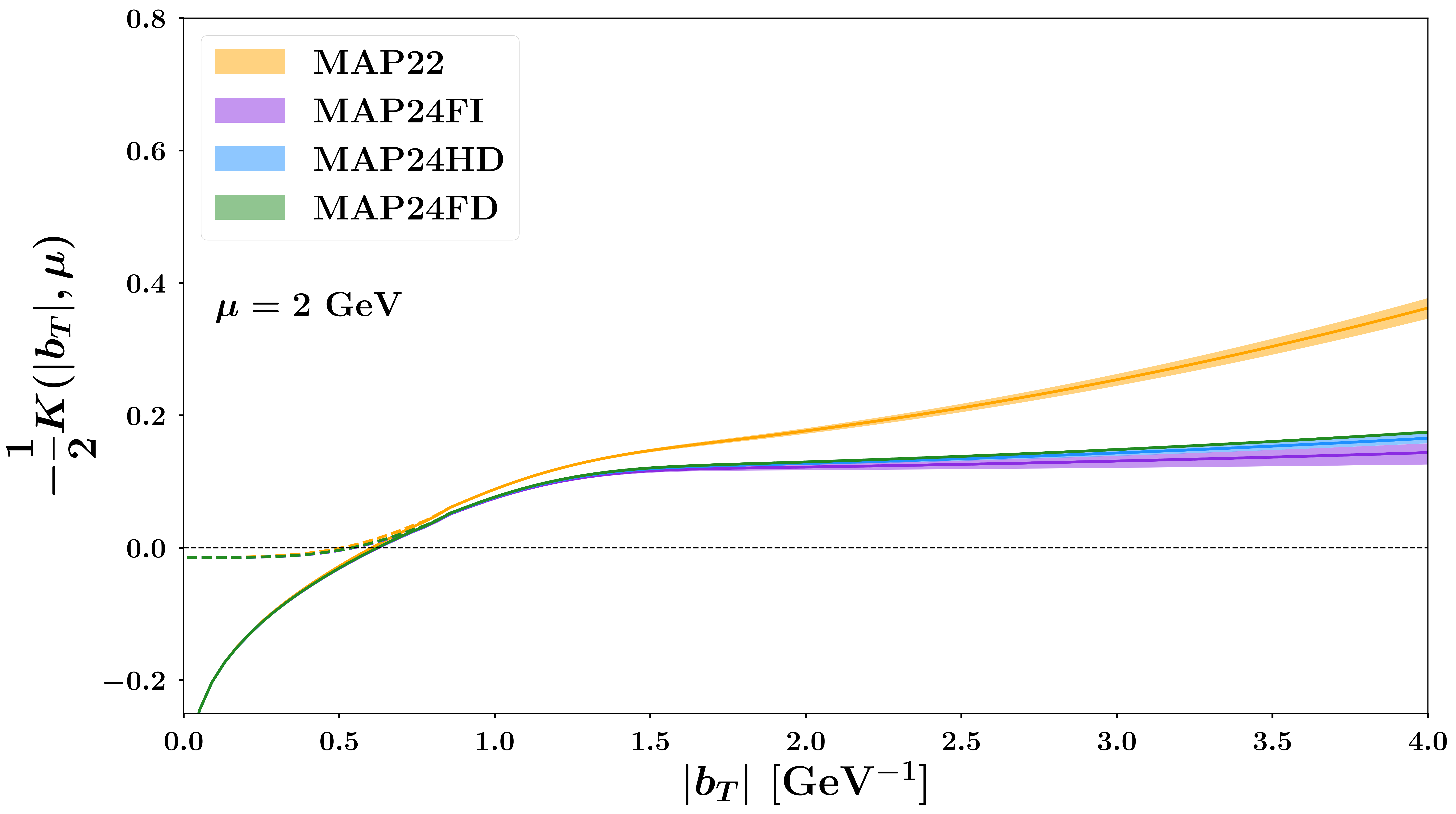
Kinematic power corrections in TMD factorization theorem

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

Published in: *JHEP* 12 (2023) 008 • e-Print: 2307.13054 [hep-ph]

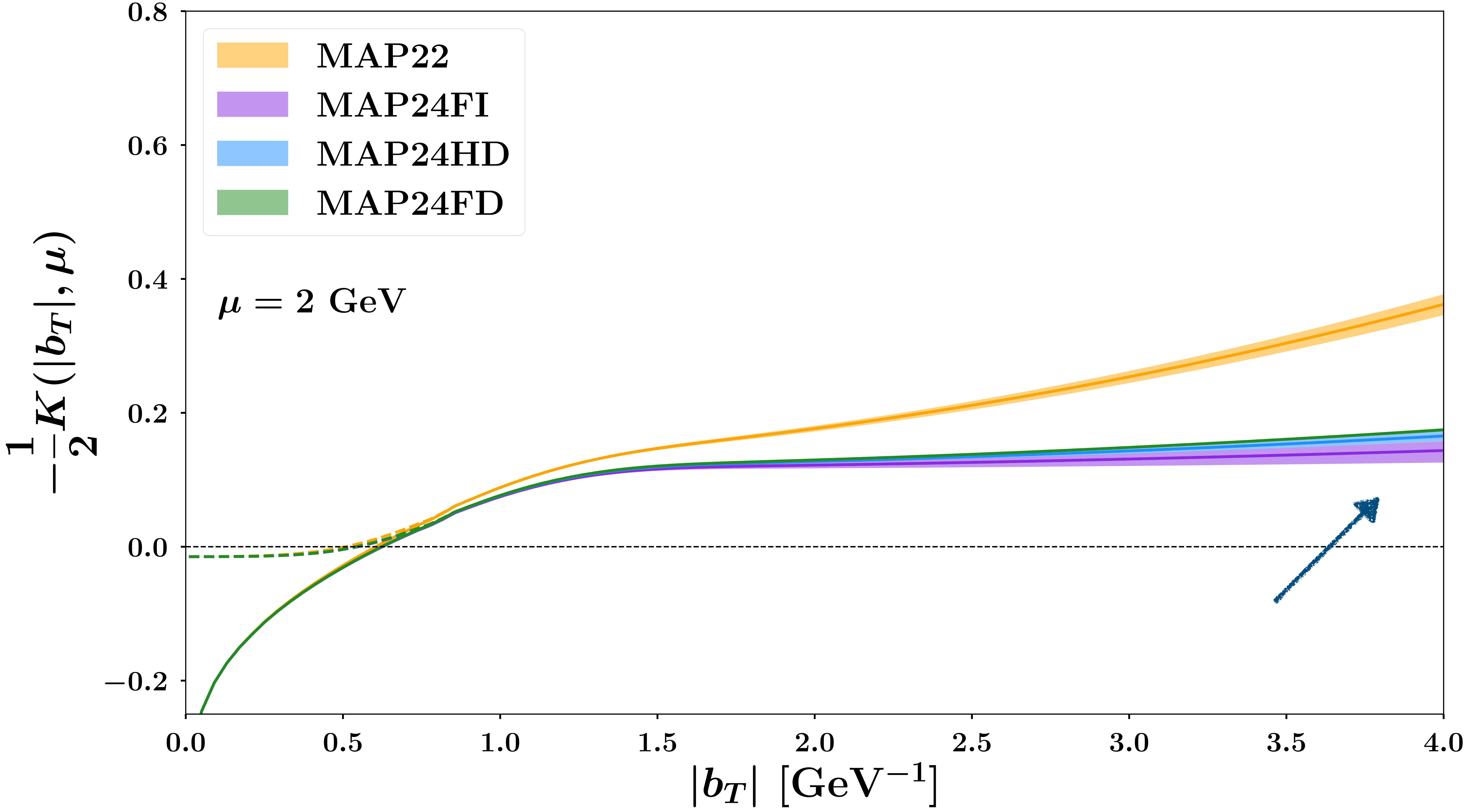
Estimations made in sec. 5.3 demonstrate that including KPCs results in an almost constant increment of the cross-section. The magnitude of this correction depends on Q and x. For typical LHC kinematics, the correction is around 1%, while at $Q \sim 4 - 5$ GeV, the correction can reach 100%. Interestingly, 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



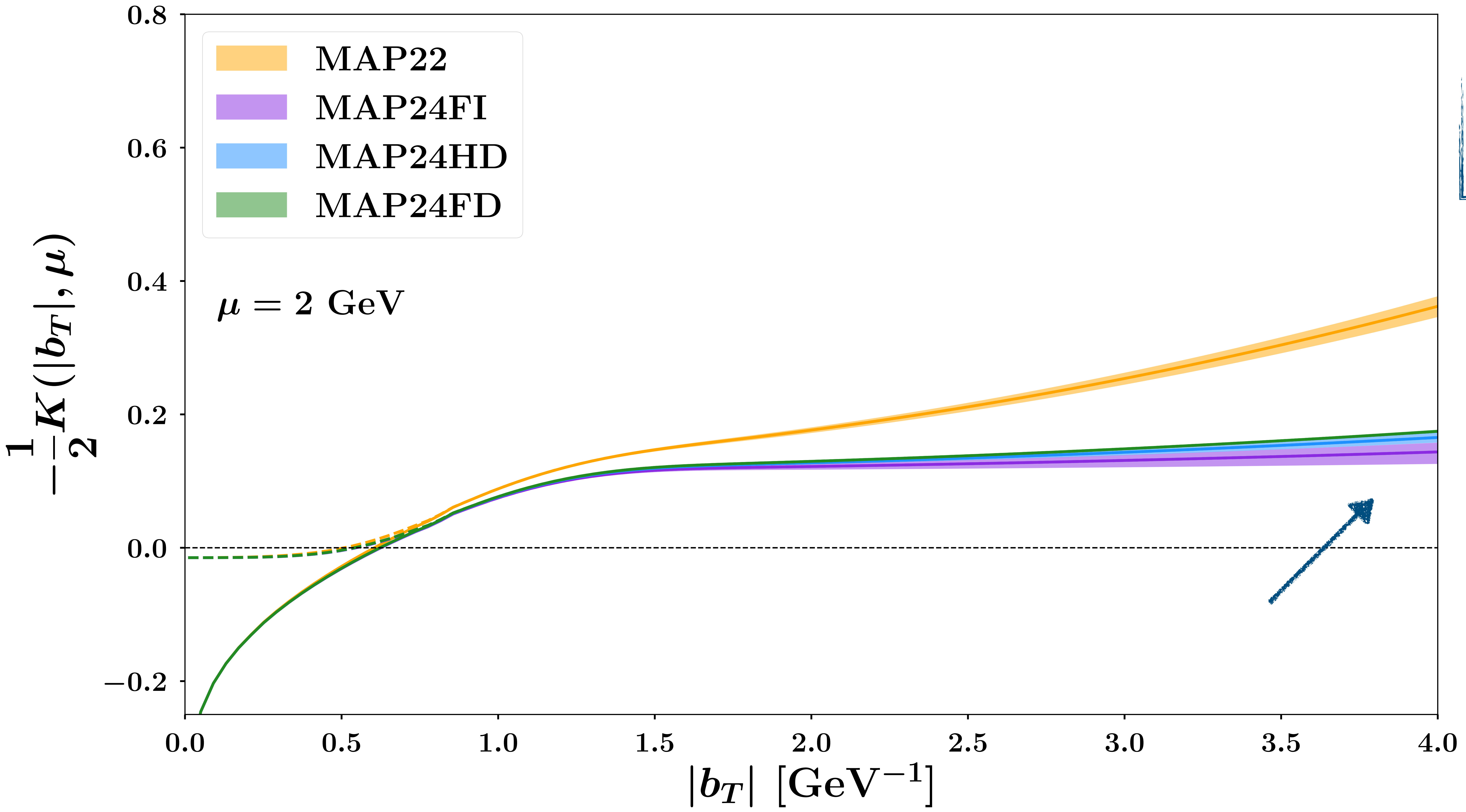
2405.13833

MAPTMD24 extraction - Collins Soper Kernel



2405.13833

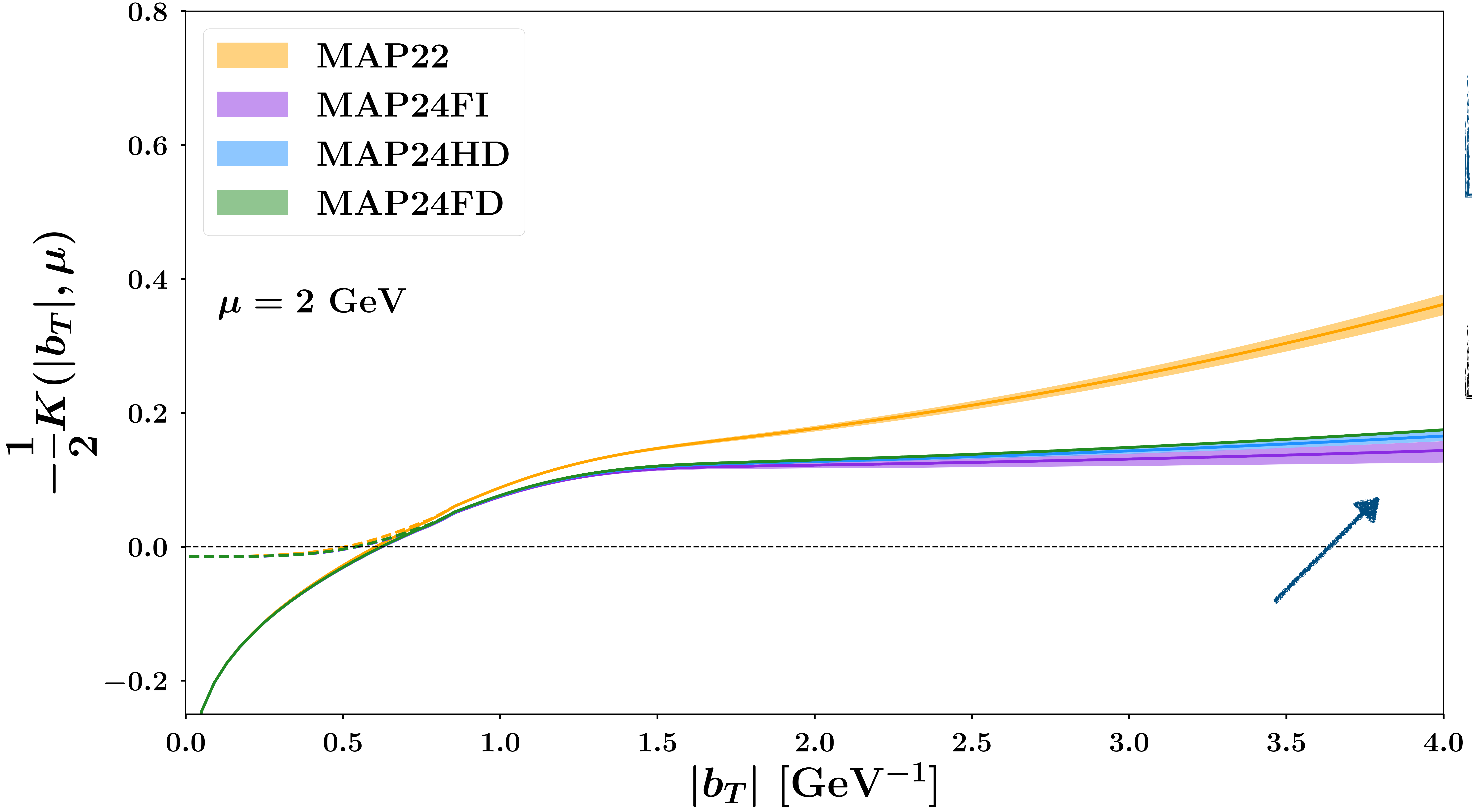
MAPTMD24 extraction - Collins Soper Kernel



Independent of our non perturbative choices

2405.13833

MAPTMD24 extraction - Collins Soper Kernel

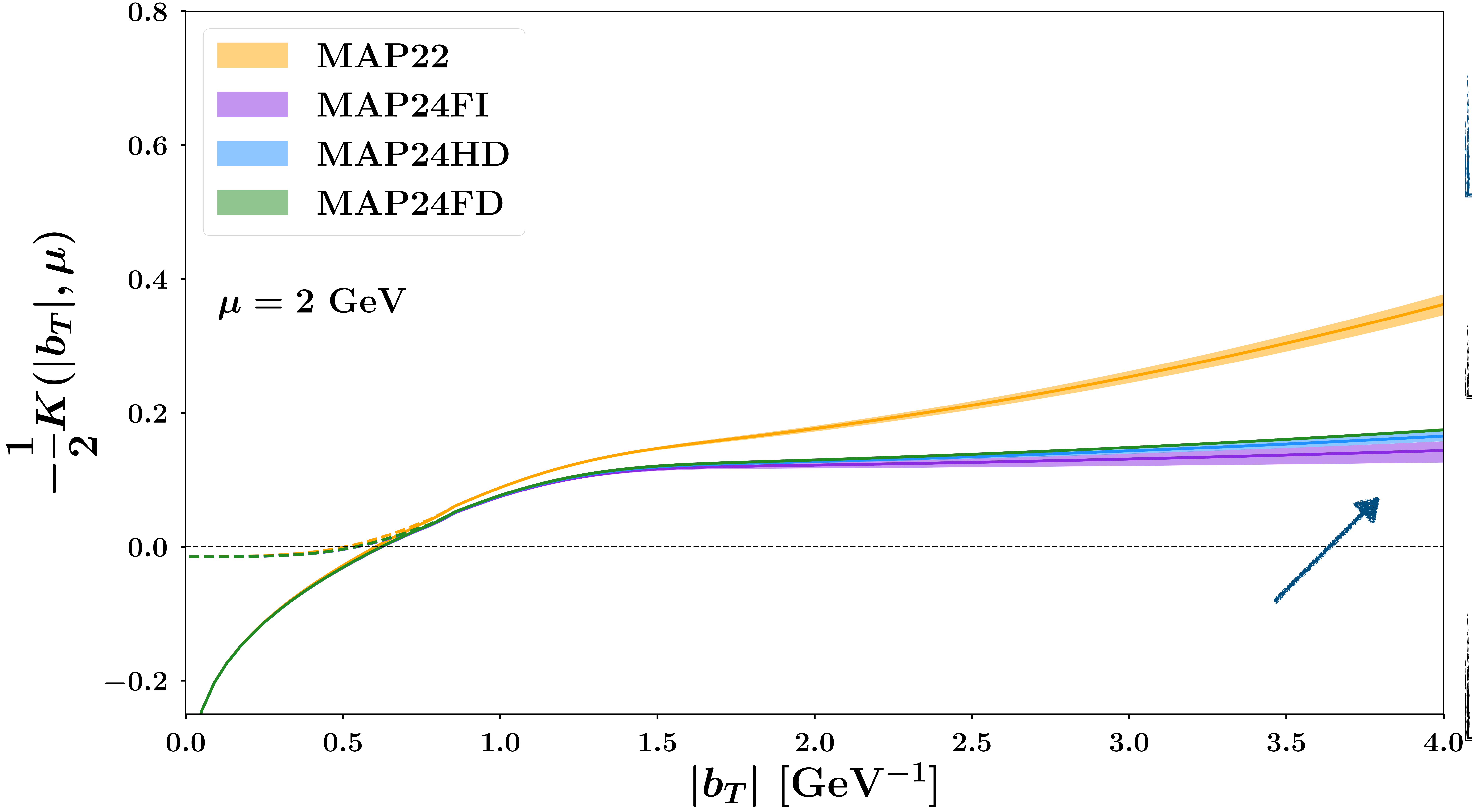


Independent of our non perturbative choices

Quite flat behaviour

2405.13833

MAPTMD24 extraction - Collins Soper Kernel



Independent of our non perturbative choices

Quite flat behaviour

Compatible with latest lattice calculation

PLB 852 (2024) 138617

2405.13833