TMDs with flavor dependence: the MAPTMD24 extraction

arXiv:2405.138833

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HAMPTON UNIVERSITY
THE STANDARD OF EXCELLENCE

Transverse-Momentum Distributions (TMDs)

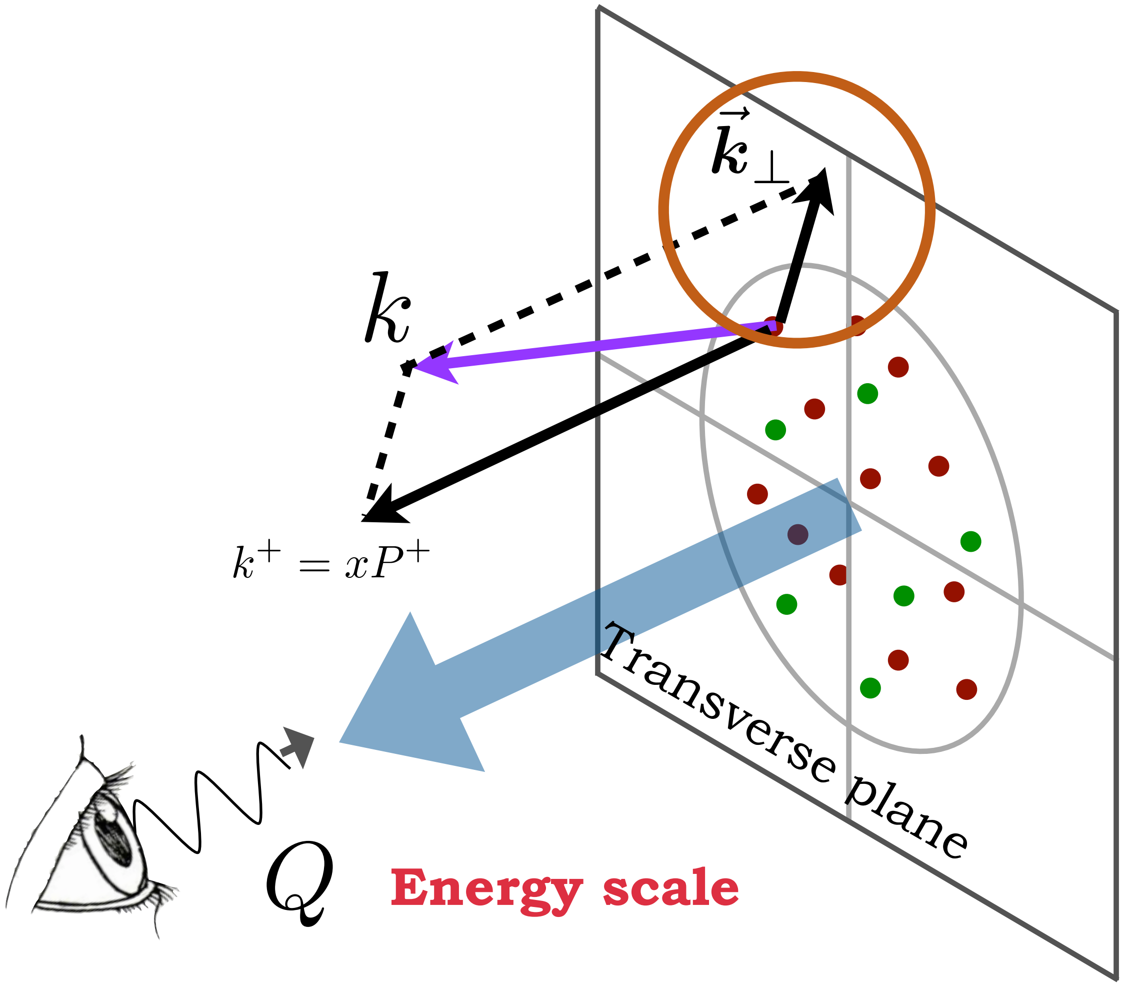
3-***dimensional*** ***map*** of the internal structure of the nucleon

Non-collinear framework

Quark Polarization

Nucleon Pol.	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	$h_1 \, h_{1T}^{\perp}$

Time-reversal odd Time-reversal even



TMD PDFs

$$F(x, \boldsymbol{k}_\perp^2, \mu, \zeta)$$

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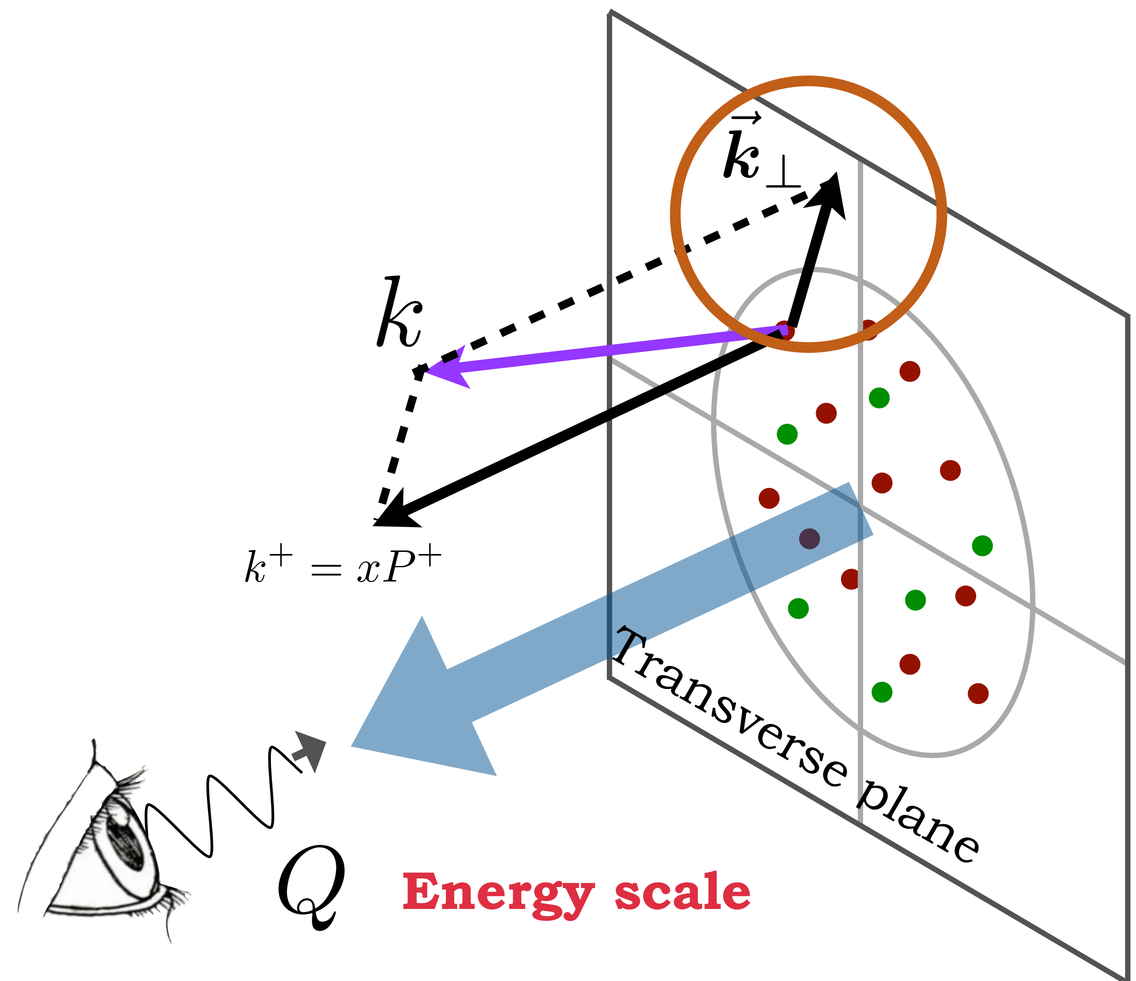

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Fraction of
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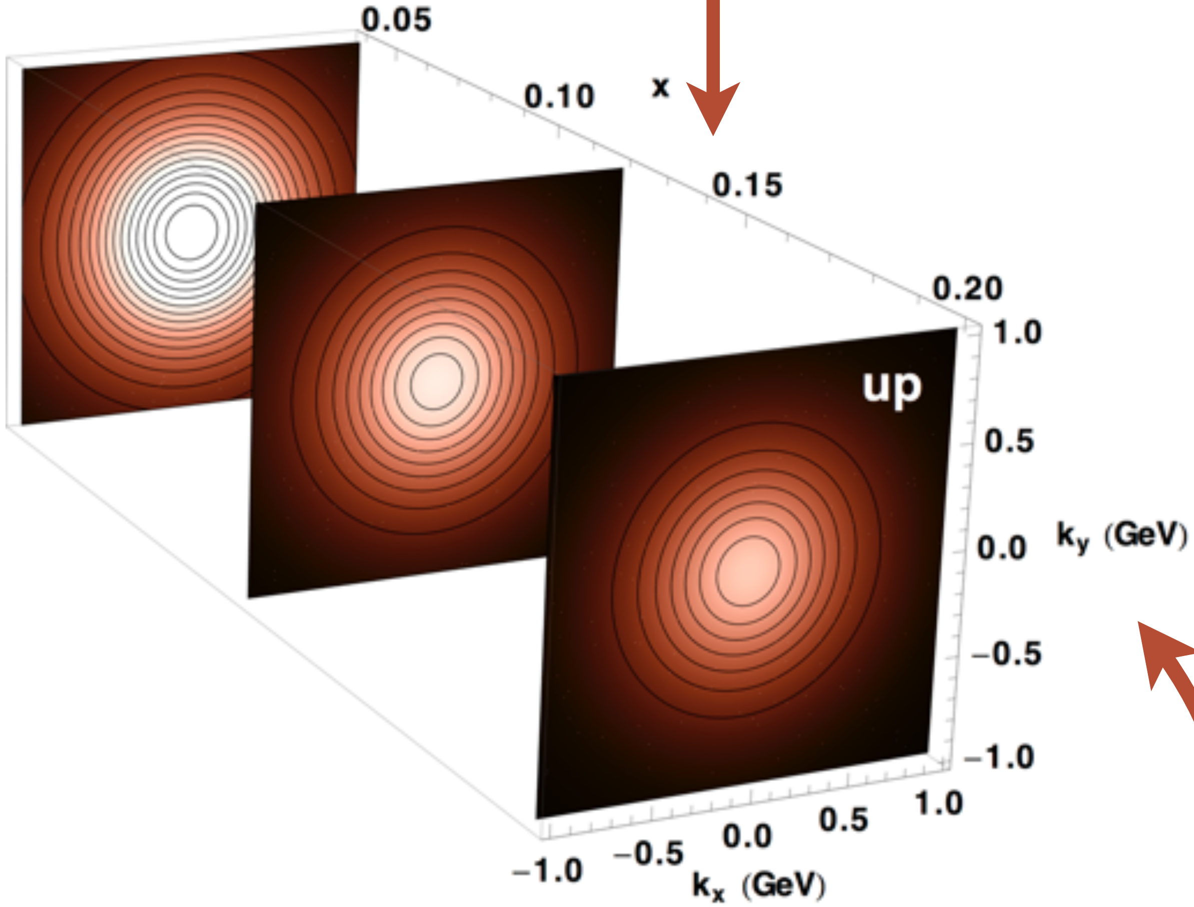
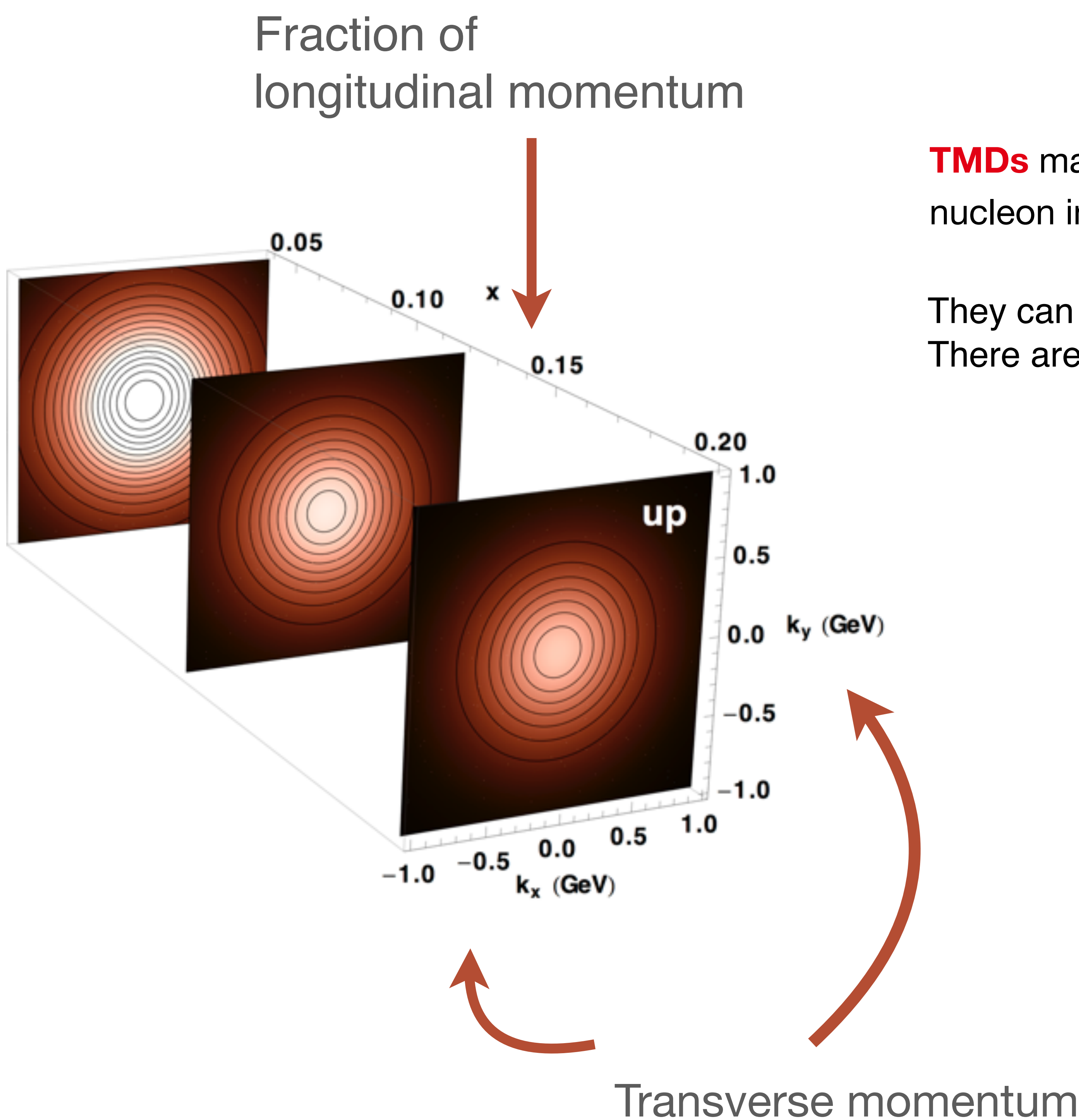


Transverse momentum

TMDs map the distribution of partons inside the nucleon in 3D in momentum space.

They can be extracted through ***global fits***
There are attempts to calculate them in lattice QCD

Transverse-Momentum Distributions (TMDs)



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Are TMDs universal?

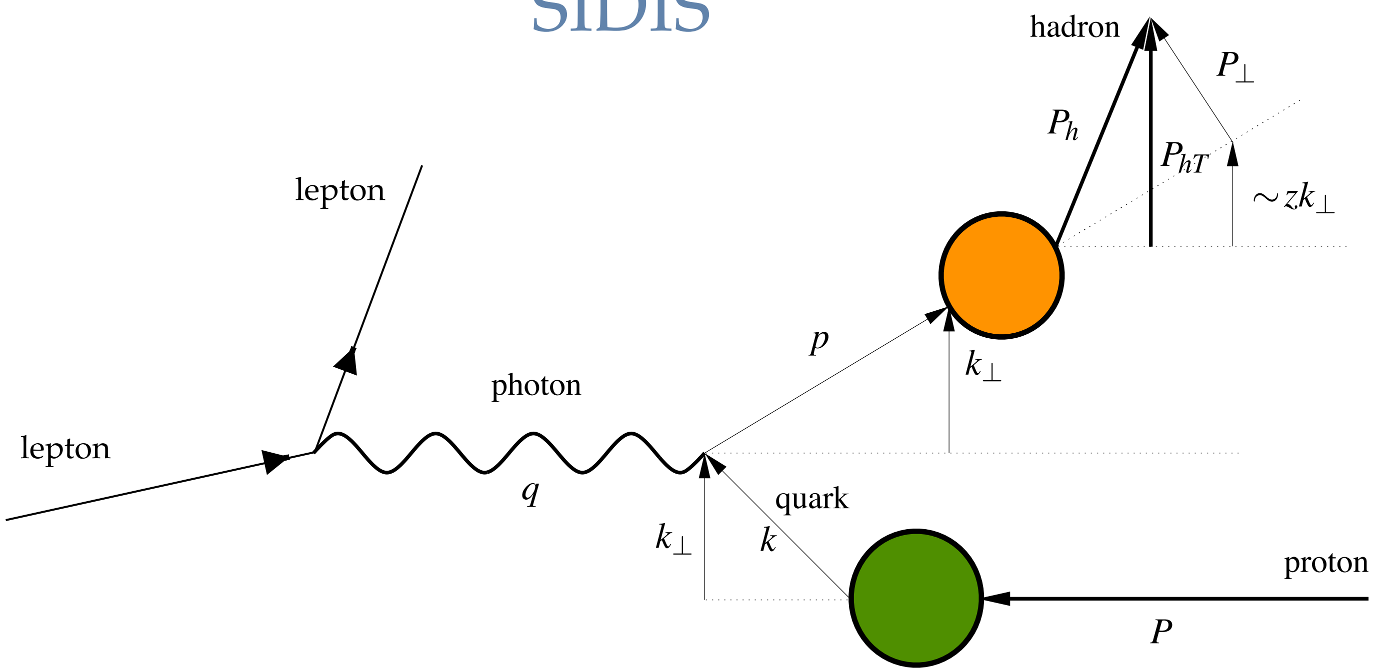
Do they depend on x?

Do they depend on the quark flavor?

TMD factorization: Universality

TMD factorization: Universality

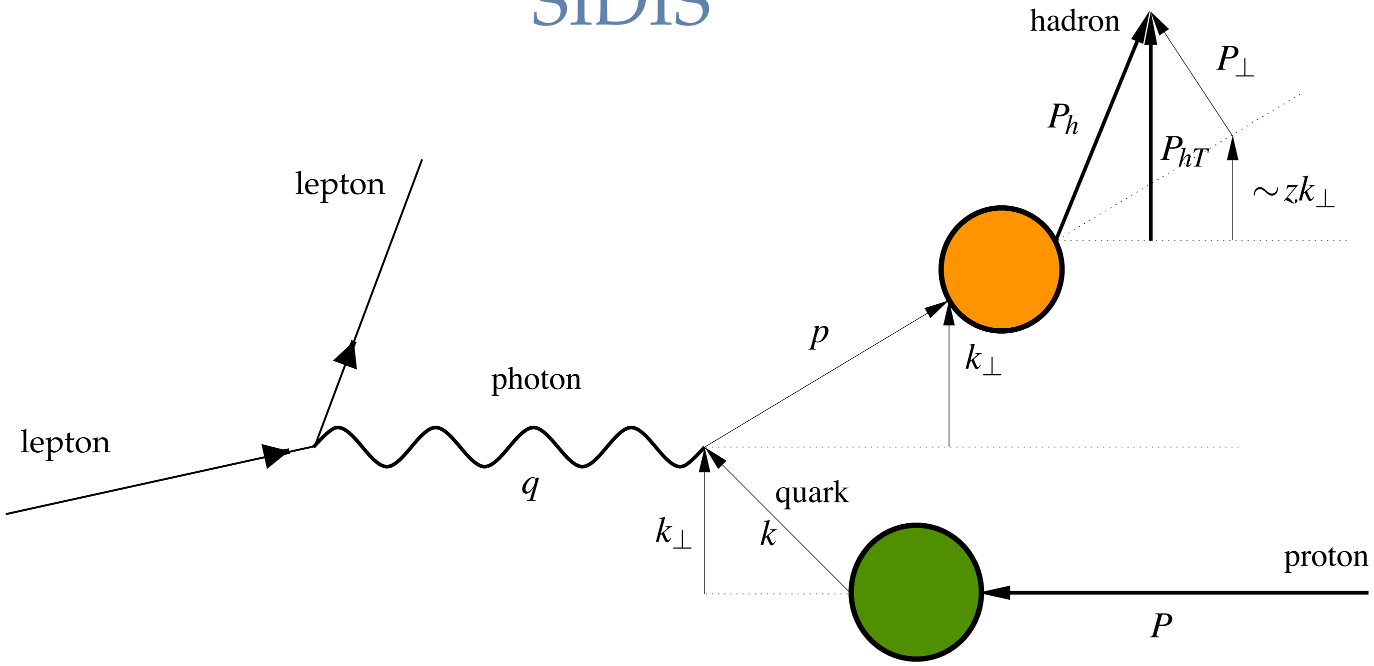
SIDIS



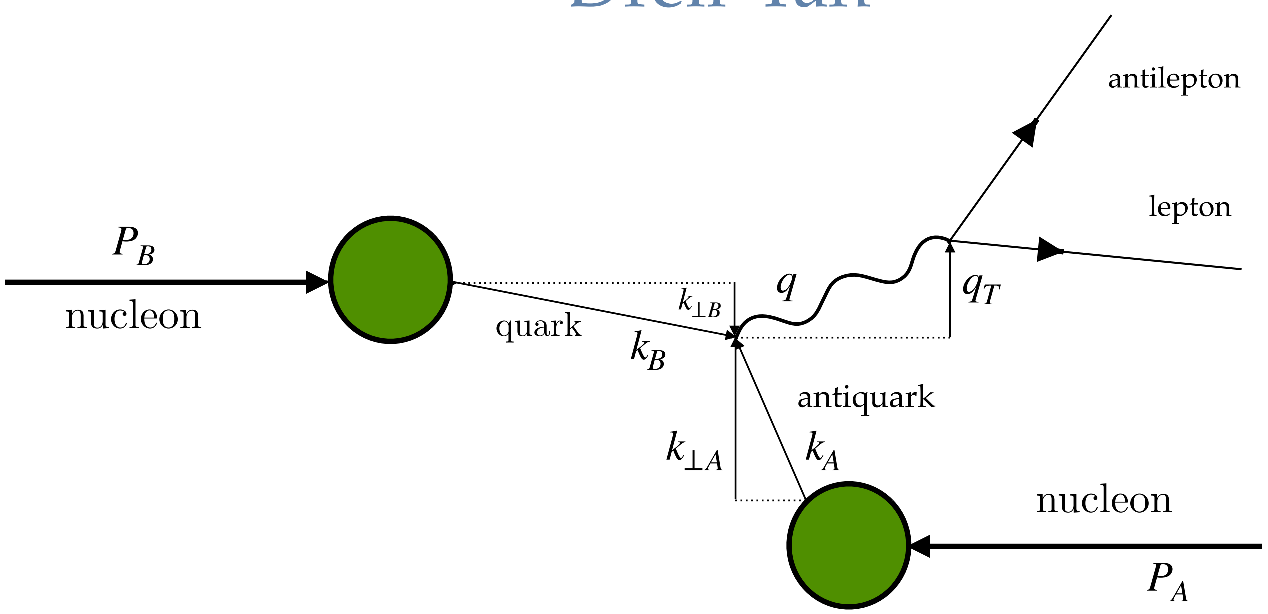
$$F_{UU,T}\big(x,z,|\boldsymbol{q}_T|,Q\big) \sim \int_0^{+\infty} d|\boldsymbol{b}_T||\boldsymbol{b}_T| J_0\big(|\boldsymbol{b}_T||\boldsymbol{q}_T|\big)\,\hat{f}_1^a(x,b_T^2;\mu,\zeta_A)\,\hat{D}_1^{a\to h}(z,b_T^2;\mu,\zeta_B)$$

TMD factorization: Universality

SIDIS



Drell-Yan



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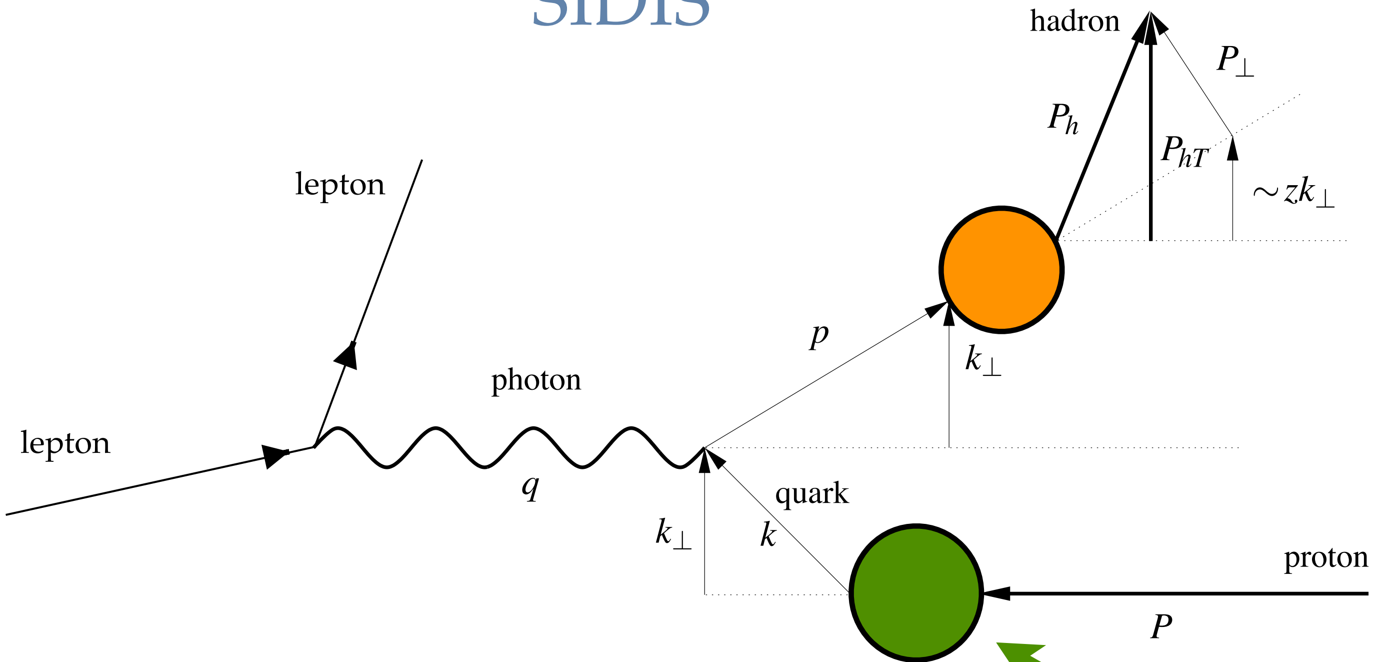

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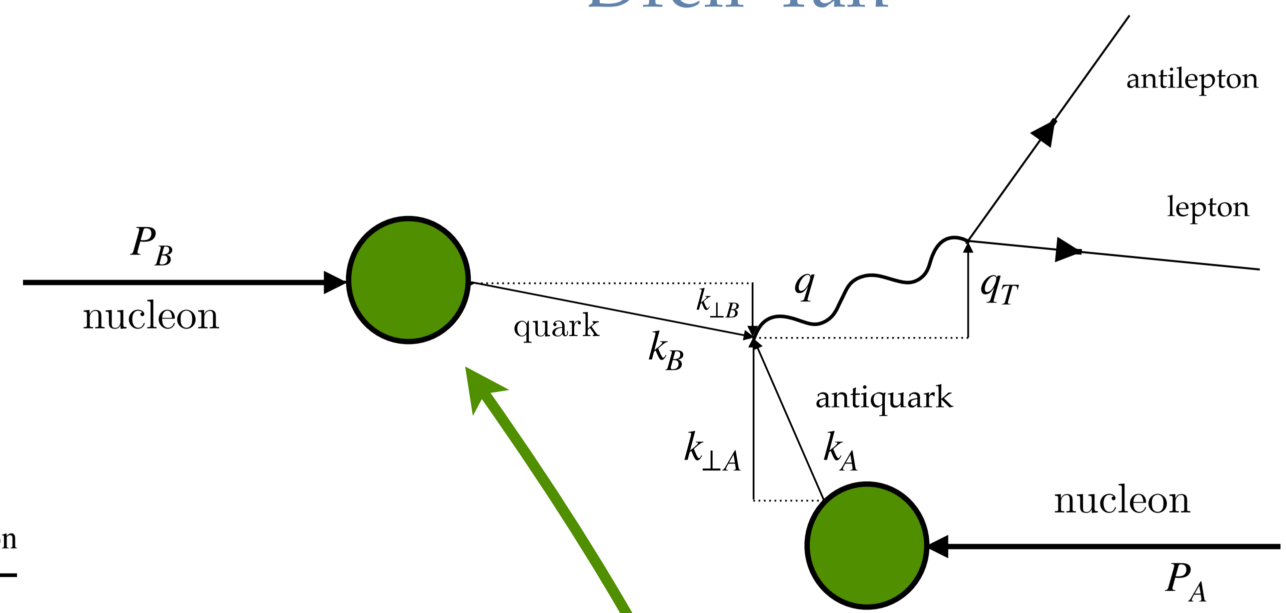

Same functions

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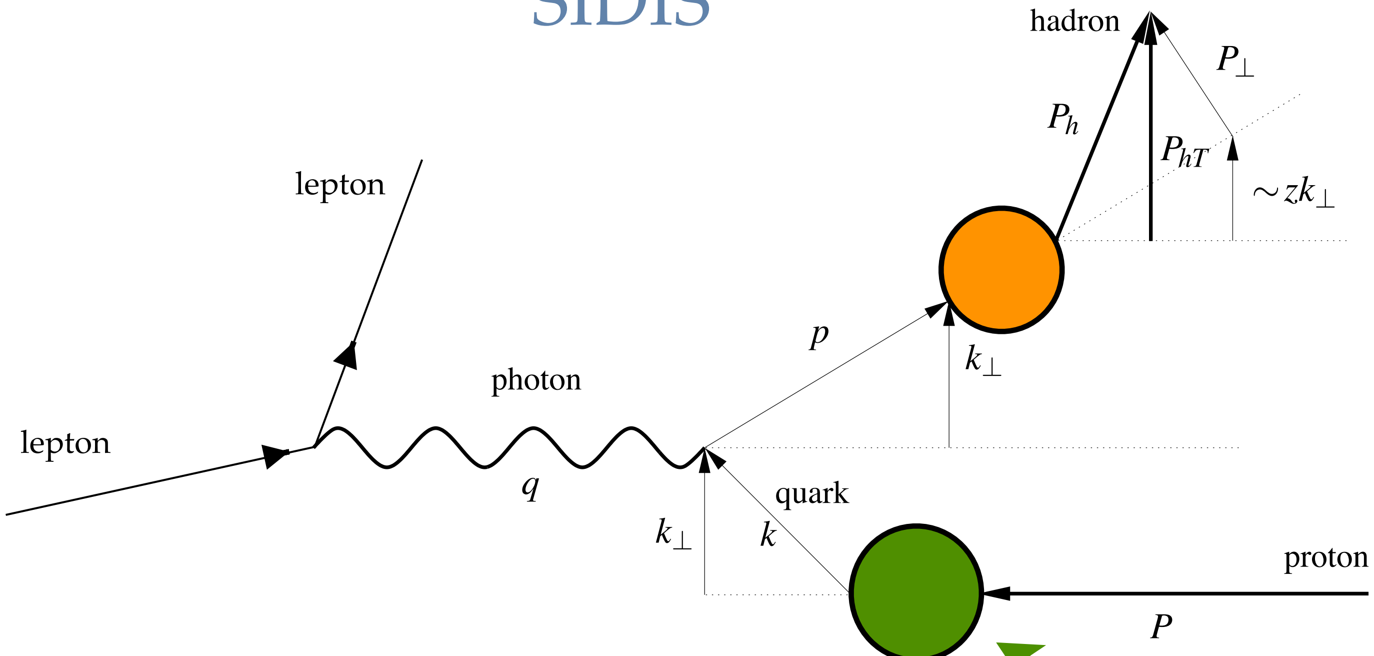

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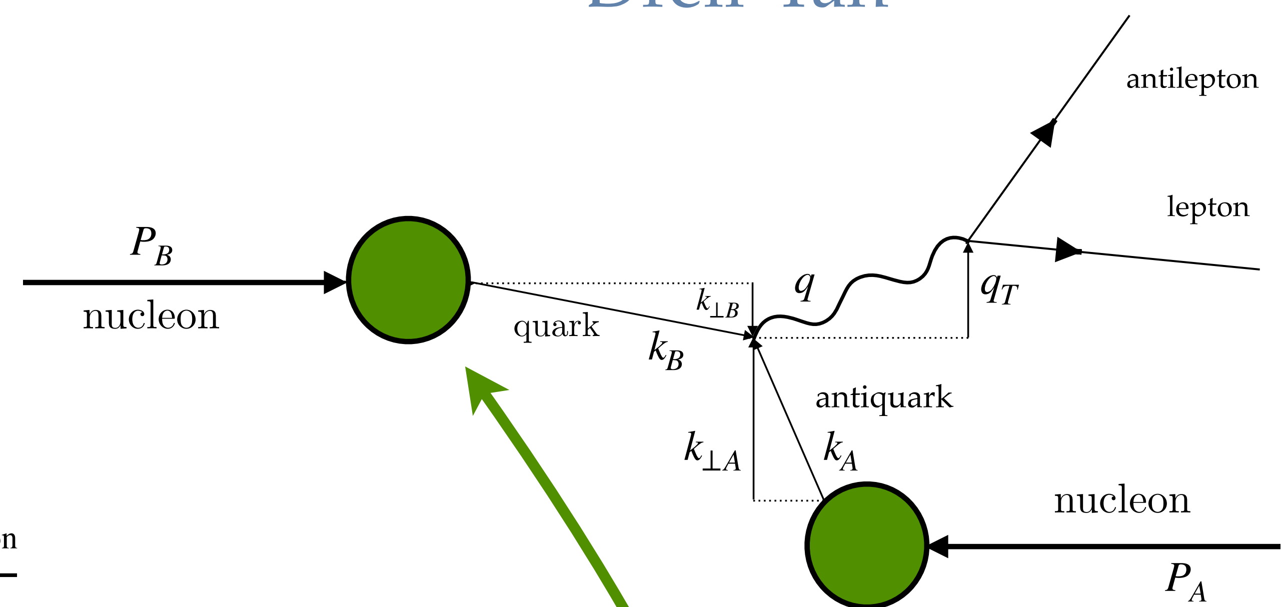

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GLOBAL FITs

Structure of a TMD

TMD in Fourier space

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

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

J. Collins, “Foundation of Perturbative QCD”

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Perturbative TMD at the initial scale

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Perturbative TMD at the initial scale

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

Evolution to final scale (of the process)

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

Non-perturbative part of the TMD

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Parameterization

Non-perturbative part of the TMD

J. Collins, "Foundation of Perturbative QCD"

MAP TMD fitting framework

https://github.com/MapCollaboration/NangaParbat

README.md

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

Download

You can obtain NangaParbat directly from the github repository:

https://github.com/MapCollaboration/NangaParbat

For the last development branch you can clone the master code:

```
git clone git@github.com:MapCollaboration/NangaParbat.git
```

Available Global Fits

	Accuracy	SIDIS	DY	N of points	χ^2/N_{data}
Pavia 2017 Bacchetta, Delcarro, et al., JHEP 06 (2017)	NLL	✔	✔	8059	1.55
SV 2019 Scimemi, Vladimirov, JHEP 06 (2020)	N^3LL^-	✔	✔	1039	1.06
MAPTMD22 Bacchetta, Bertone, et al., JHEP 10 (2022)	***N^3LL^-***	✔	✔	***2031***	***1.06***

MAPTMD22 global fit: features

MAP Collaboration, JHEP 10 (2022)

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- Global analysis of Drell-Yan and SIDIS data sets: ***2031*** data points

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MAP Collaboration, JHEP 10 (2022)

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MAP Collaboration, JHEP 10 (2022)

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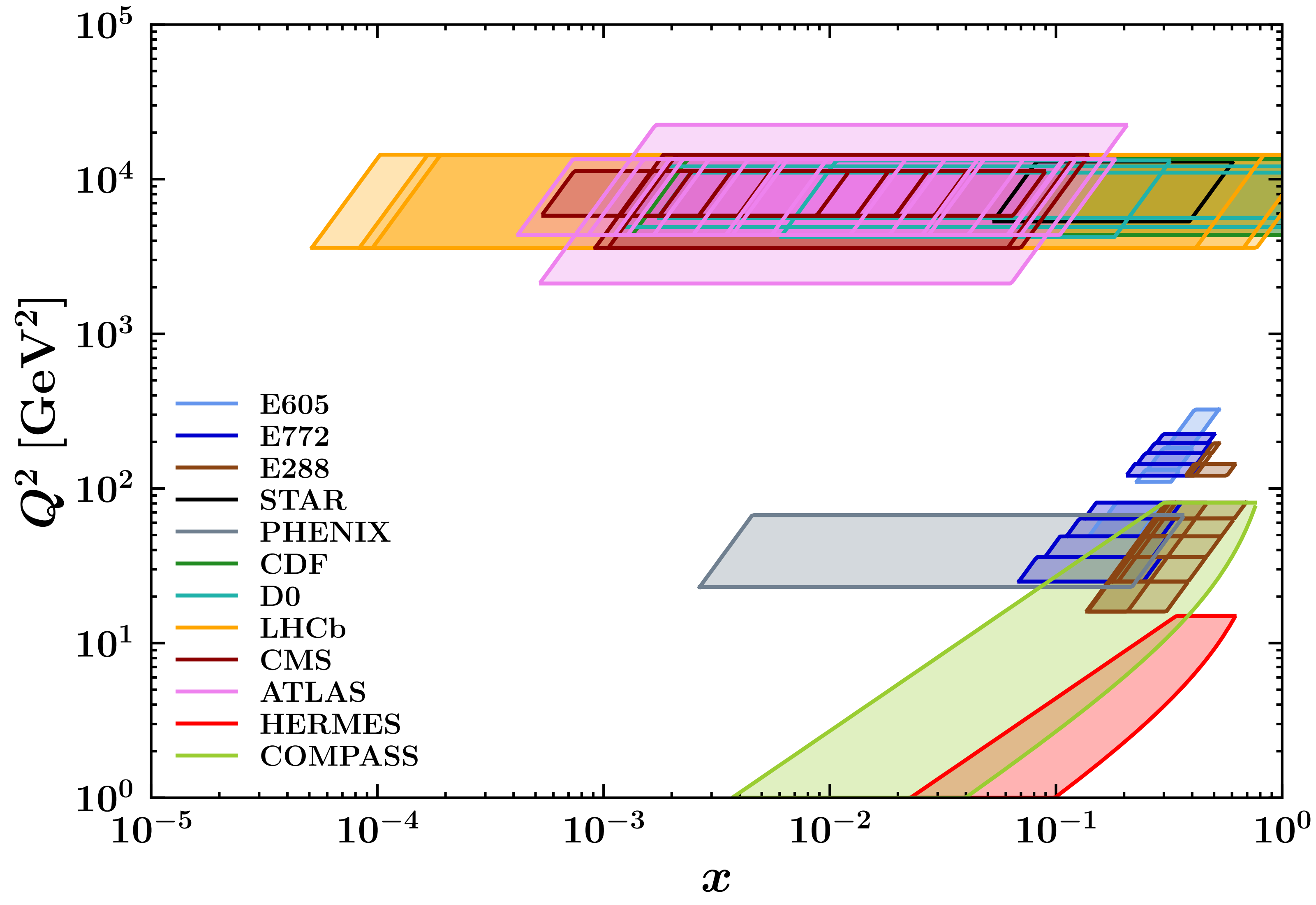
- Perturbative accuracy: N^3LL^-
- ***Normalization prefactor*** for SIDIS observables
- Number of fitted parameters: ***21***
- Agreement with data: $\chi^2/N_{data} = 1.06$

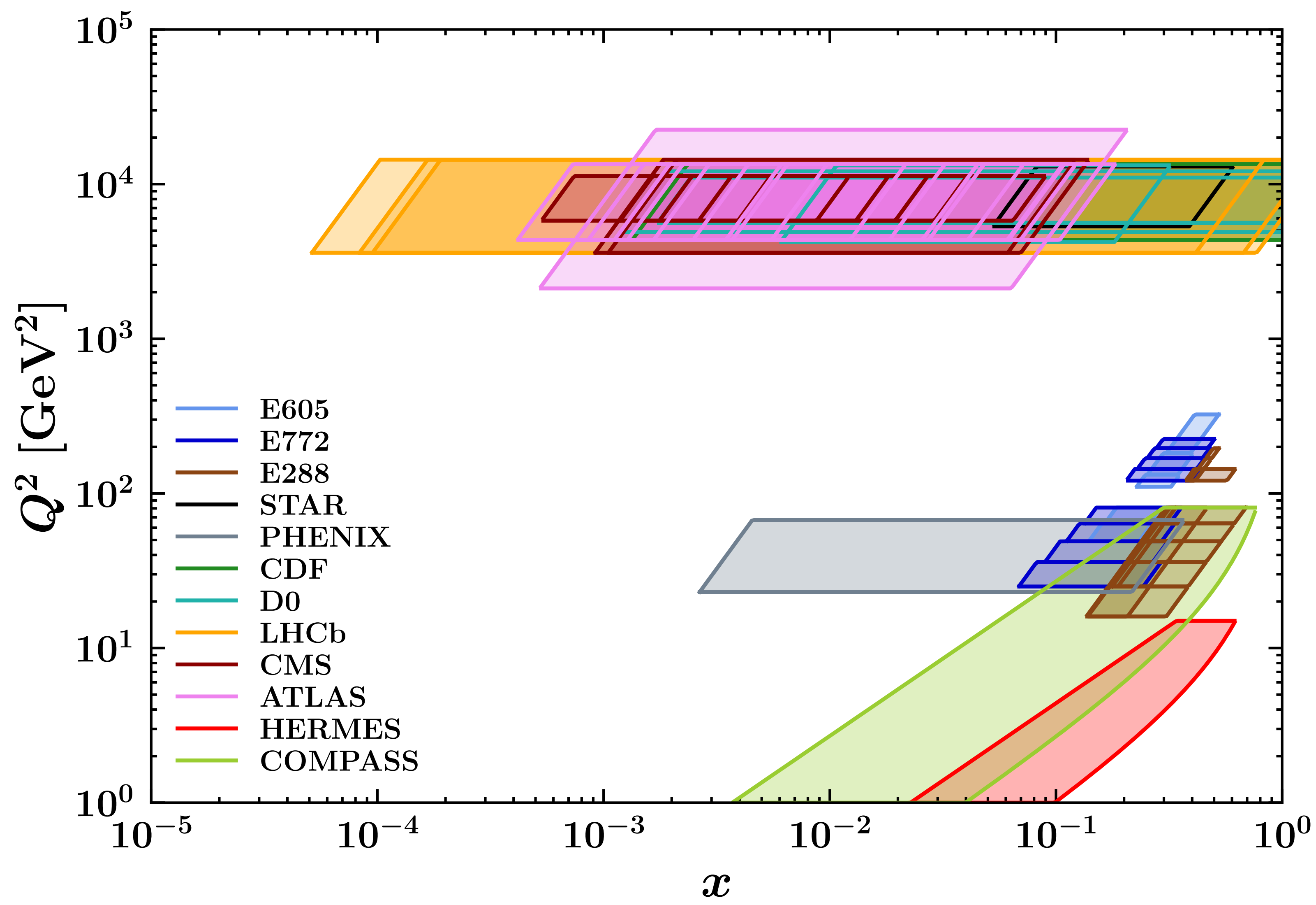
MAP Collaboration, JHEP 10 (2022)

MAP22: included data sets



MAP22: included data sets

Drell-Yan data 484



MAP22: included data sets

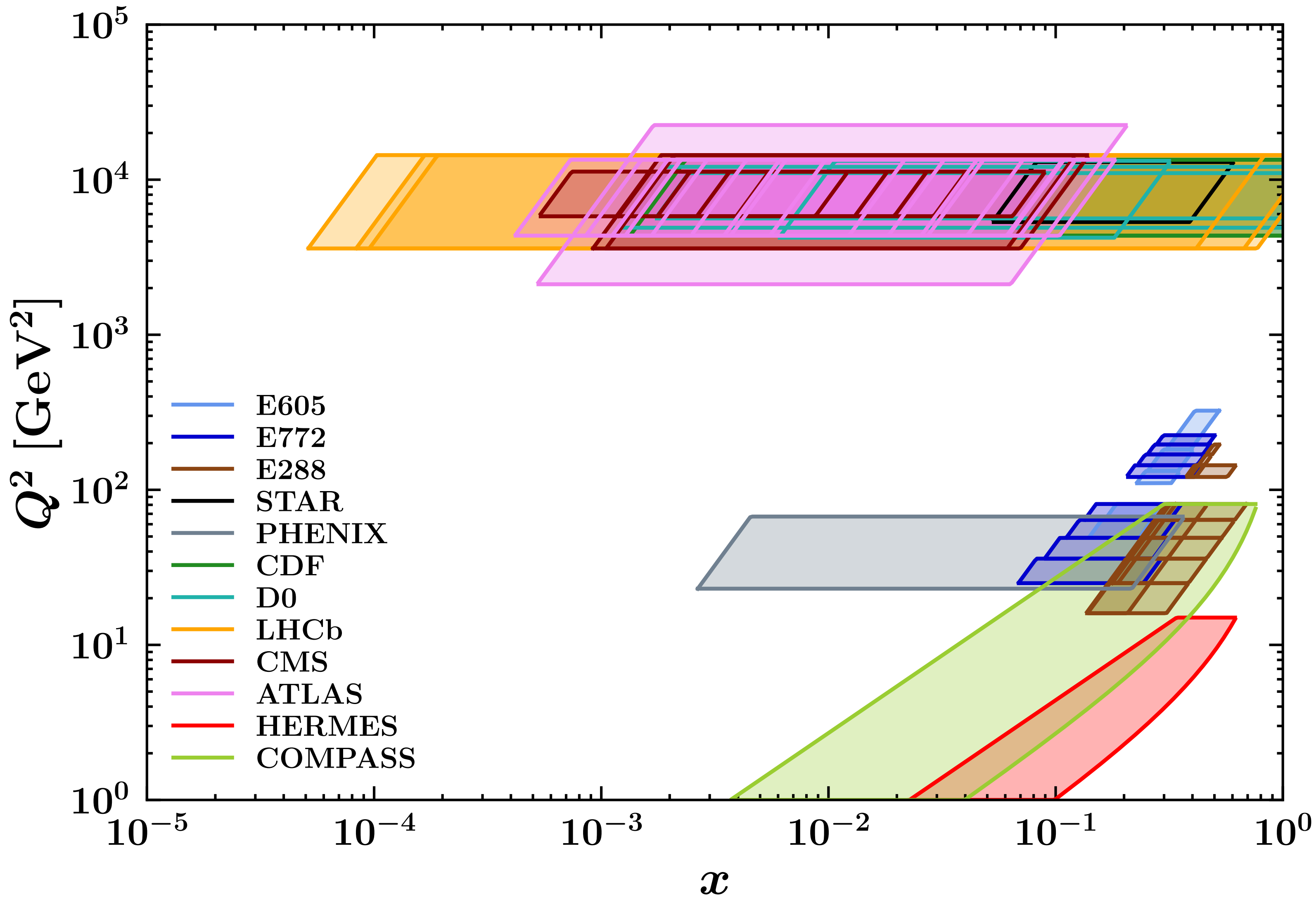
Drell-Yan data 484

Fixed-target:

E288, E605, E772

Collider mode:

RHIC, Tevatron, LHC



MAP22: included data sets

Drell-Yan data **484**

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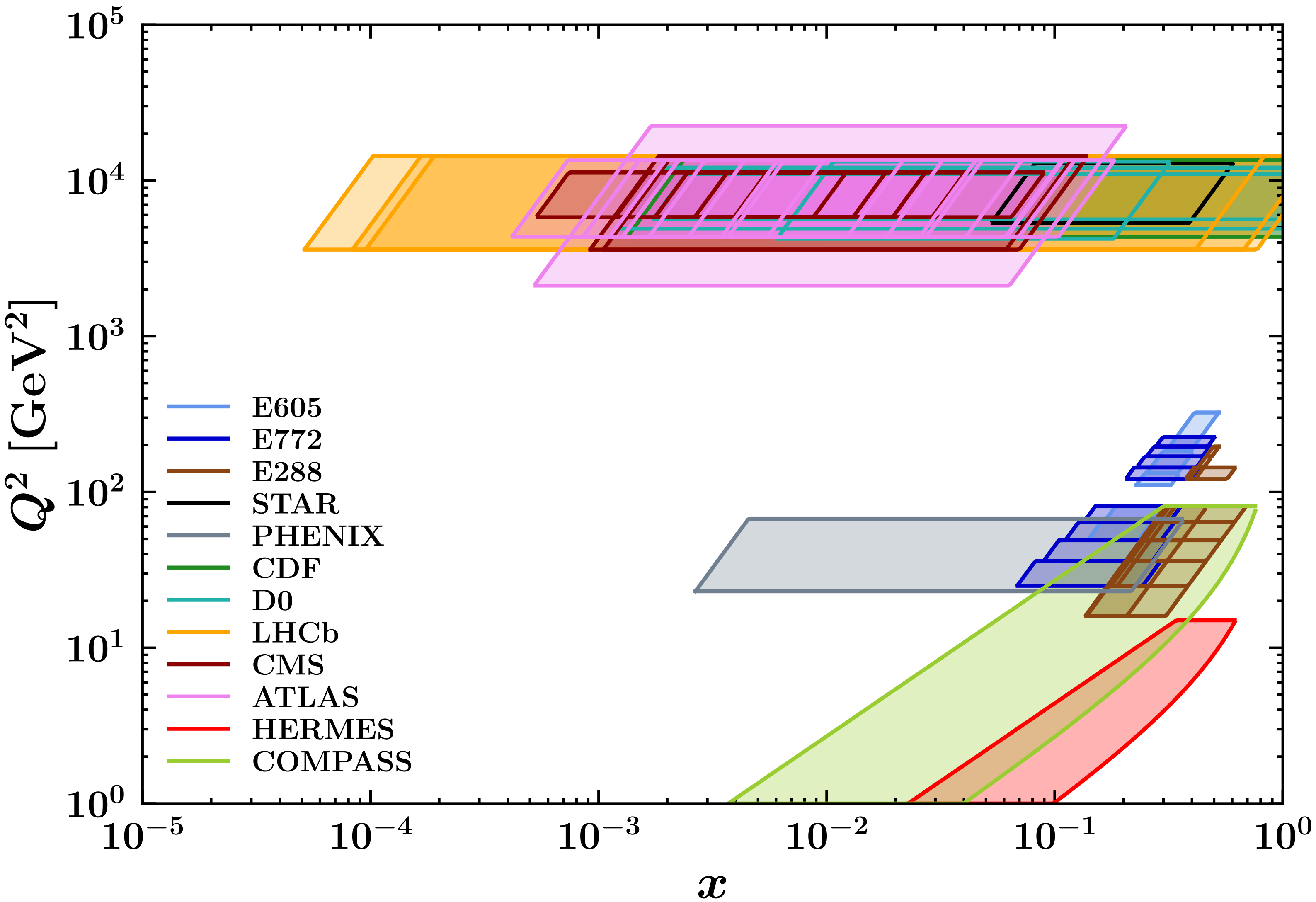
SIDIS data **1547**



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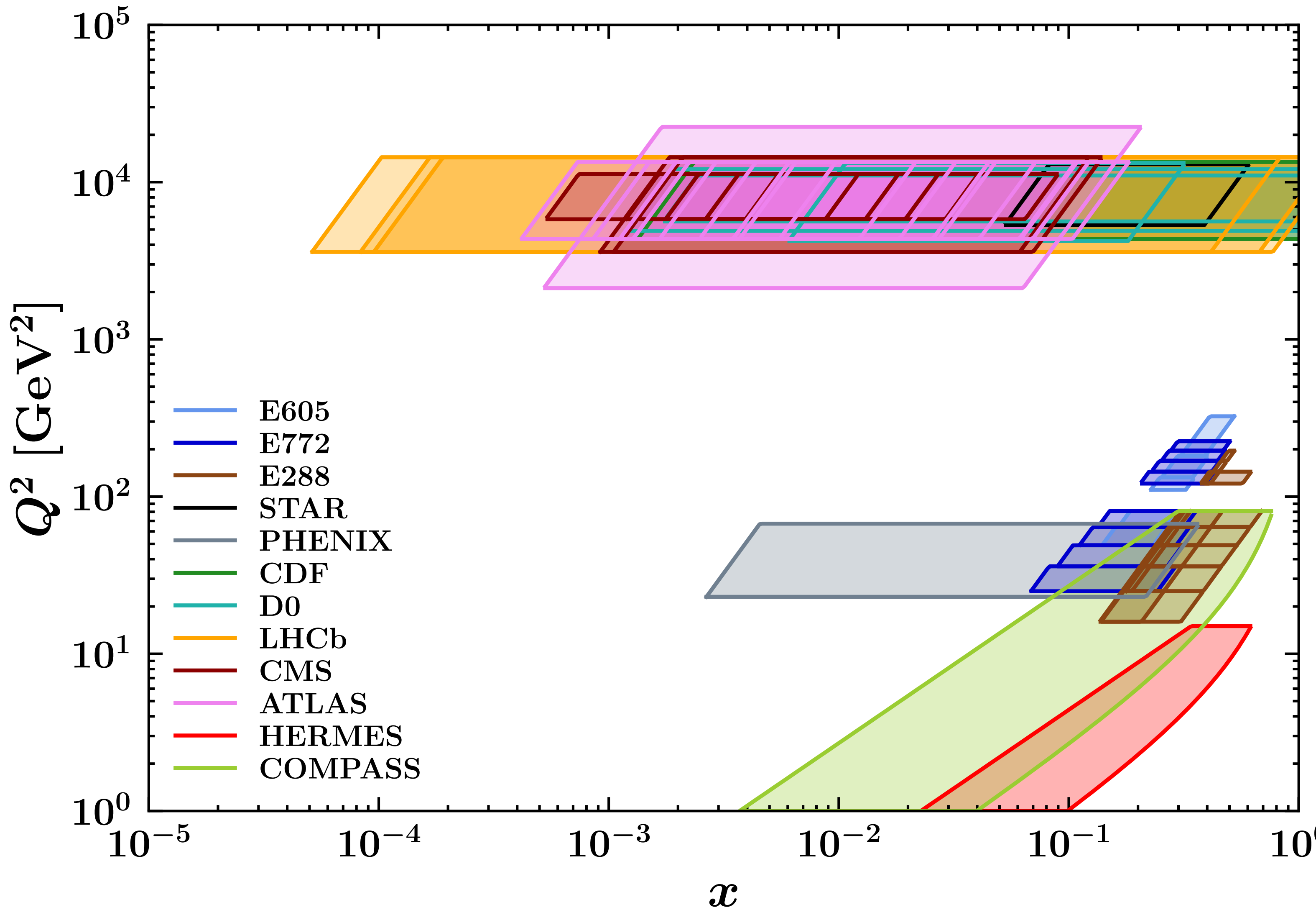
HERMES, COMPASS



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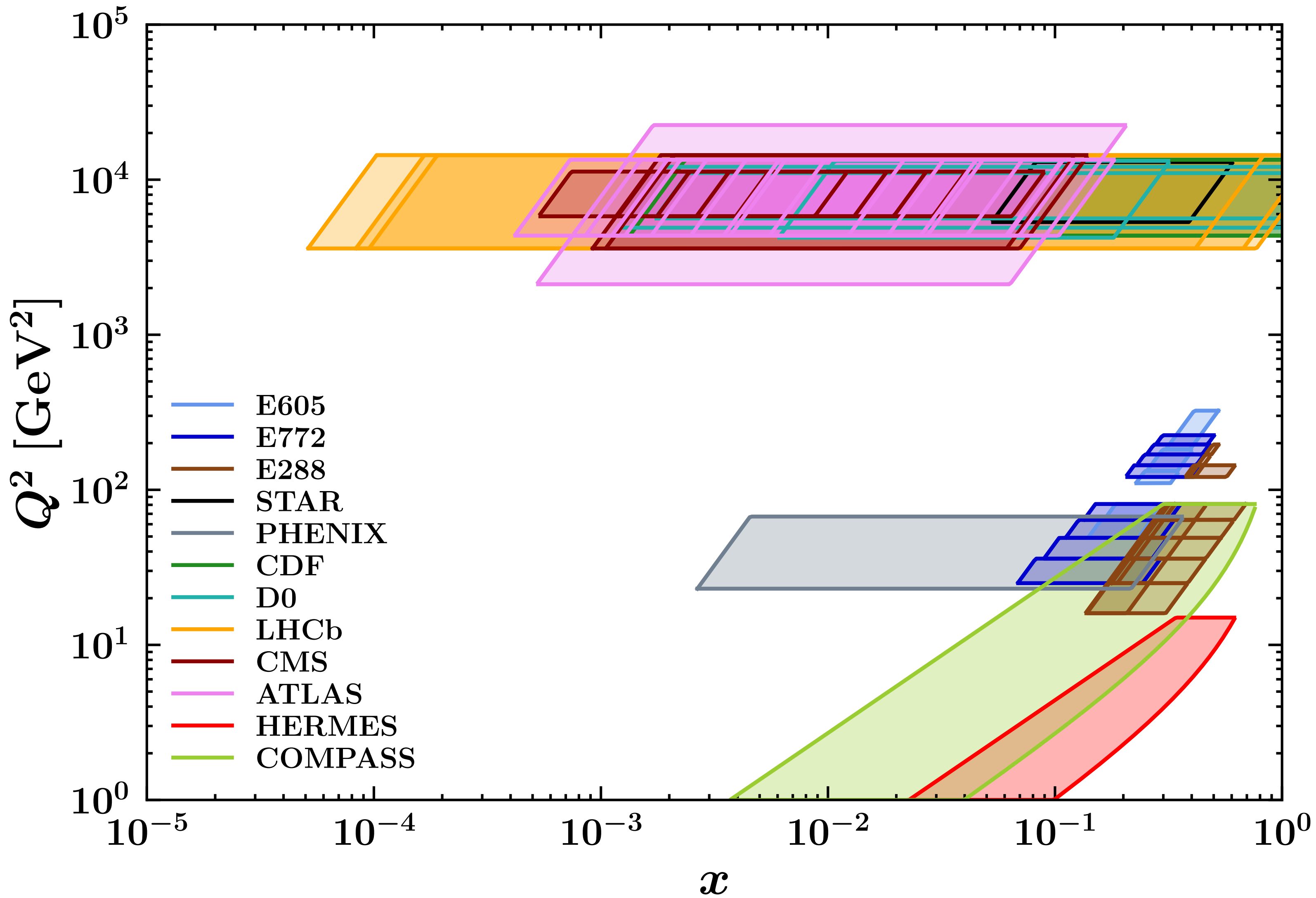

Total number of data: 2031

MAP22: NP parametrization

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

Bacchetta, Gamberg, Goldstein, et al., PLB 659 (2008)

Bacchetta, Conti, Radici, PRD 78 (2008)

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

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

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

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

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

MAP22: NP parametrization

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

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

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

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

MAPTMD22 global fit $\Rightarrow$ MAPTMD24

- Global analysis of Drell-Yan and SIDIS data sets: *2031* data points

- Perturbative accuracy: N^3LL^-

- *Normalization prefactor* for SIDIS observables

- Number of fitted parameters: *21*

- Agreement with data: $\chi^2/N_{data} = 1.06$

MAP Collaboration, JHEP 10 (2022)

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MAP Collaboration, JHEP 10 (2022)

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MAP Collaboration, JHEP 10 (2022)

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MMHT DSS	$\Rightarrow$	**NNPDF** **MAPFF**

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- Number of fitted parameters: *21*
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MAP Collaboration, JHEP 10 (2022)

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

MAP Collaboration, JHEP 10 (2022)

MAPTMD24

	χ^2/N_{data}		
Configuration	DY	SIDIS	Total
MMHT+DSS (MAP22)	1.66	0.87	**1.06**
NNPDF+MAPFF (MAP24 FI)	1.58	1.34	**1.40**

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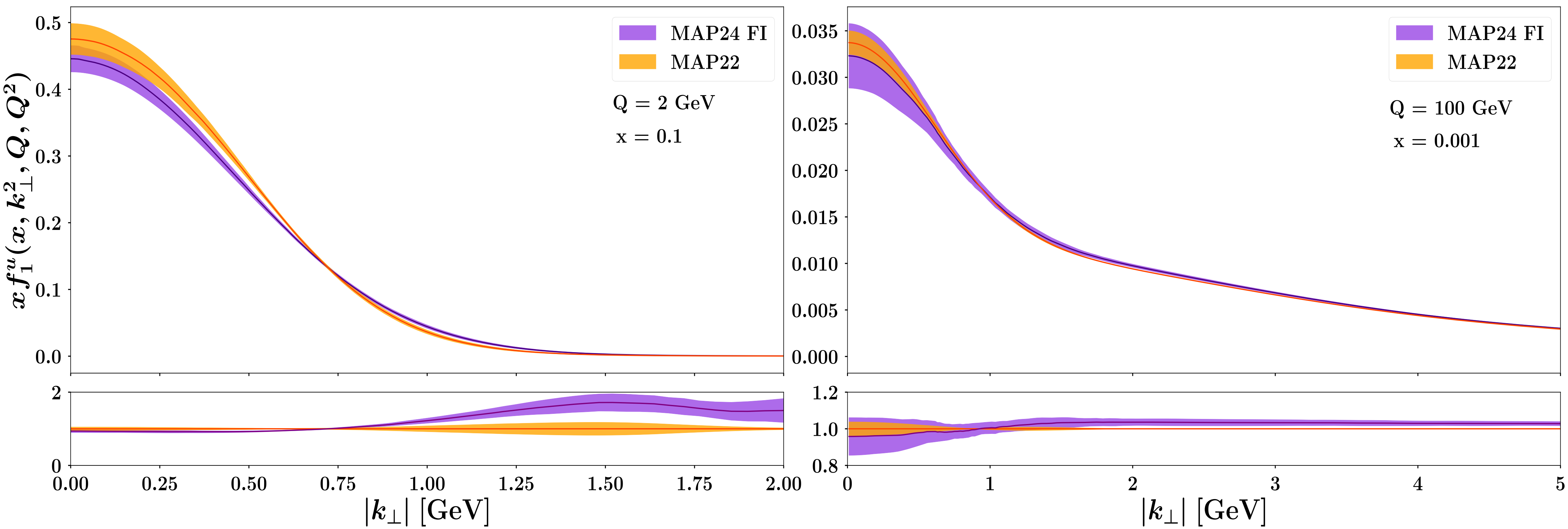

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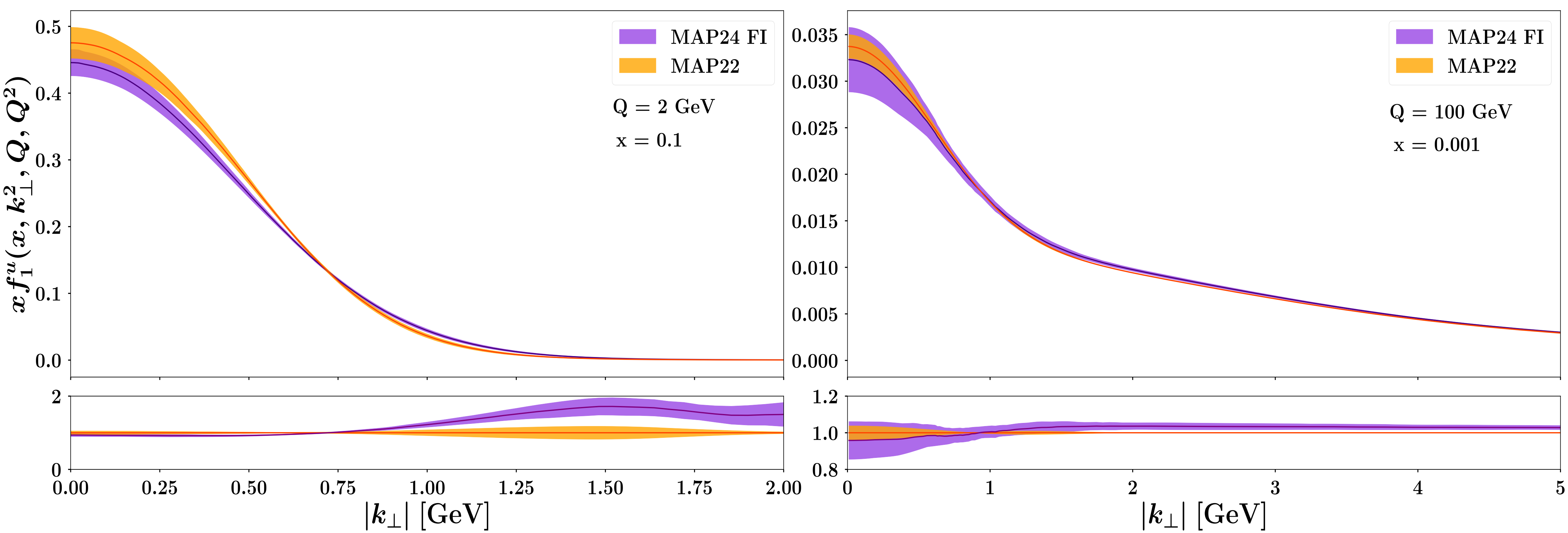

TMD PDFs are compatible with MAP22

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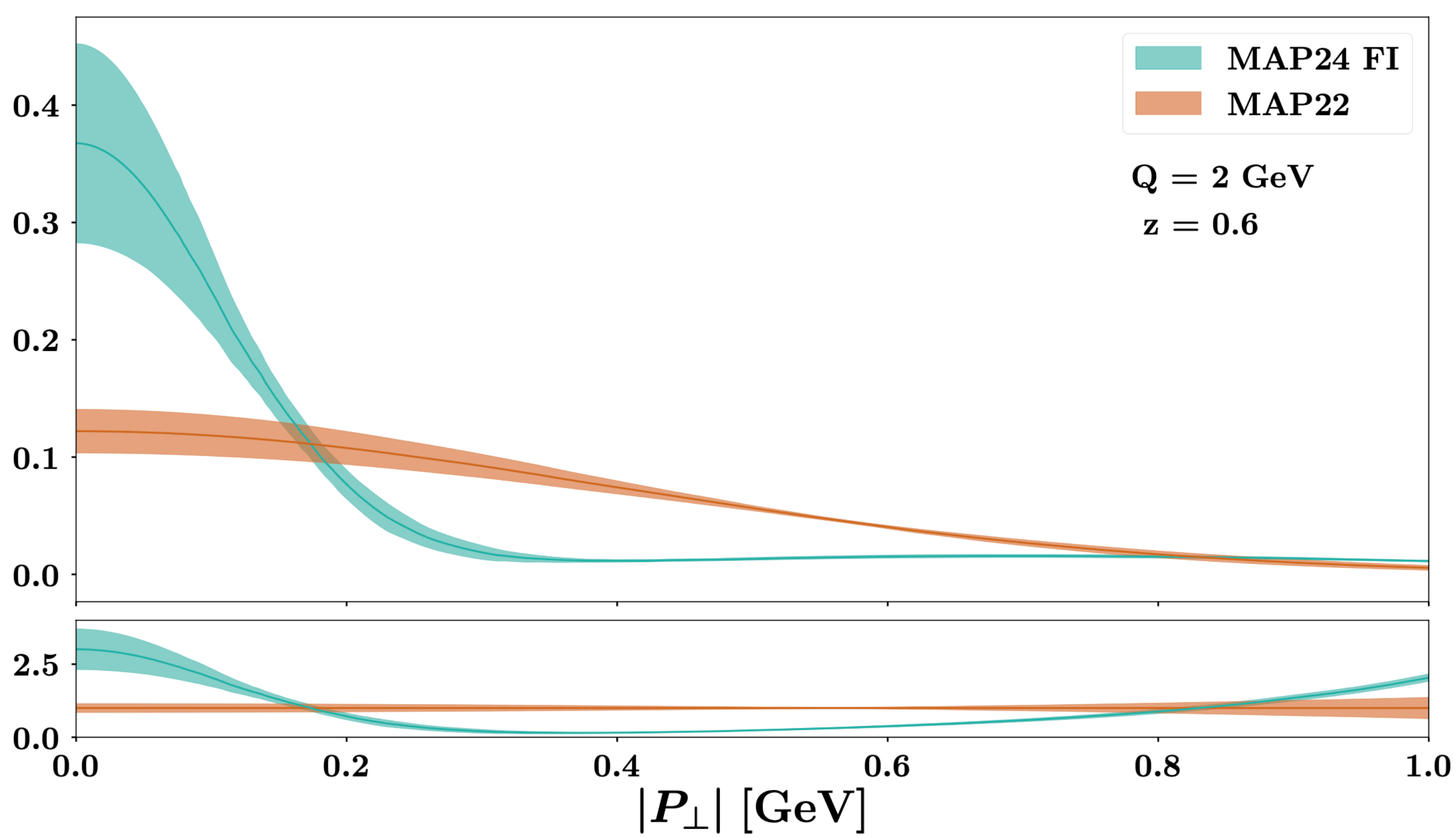

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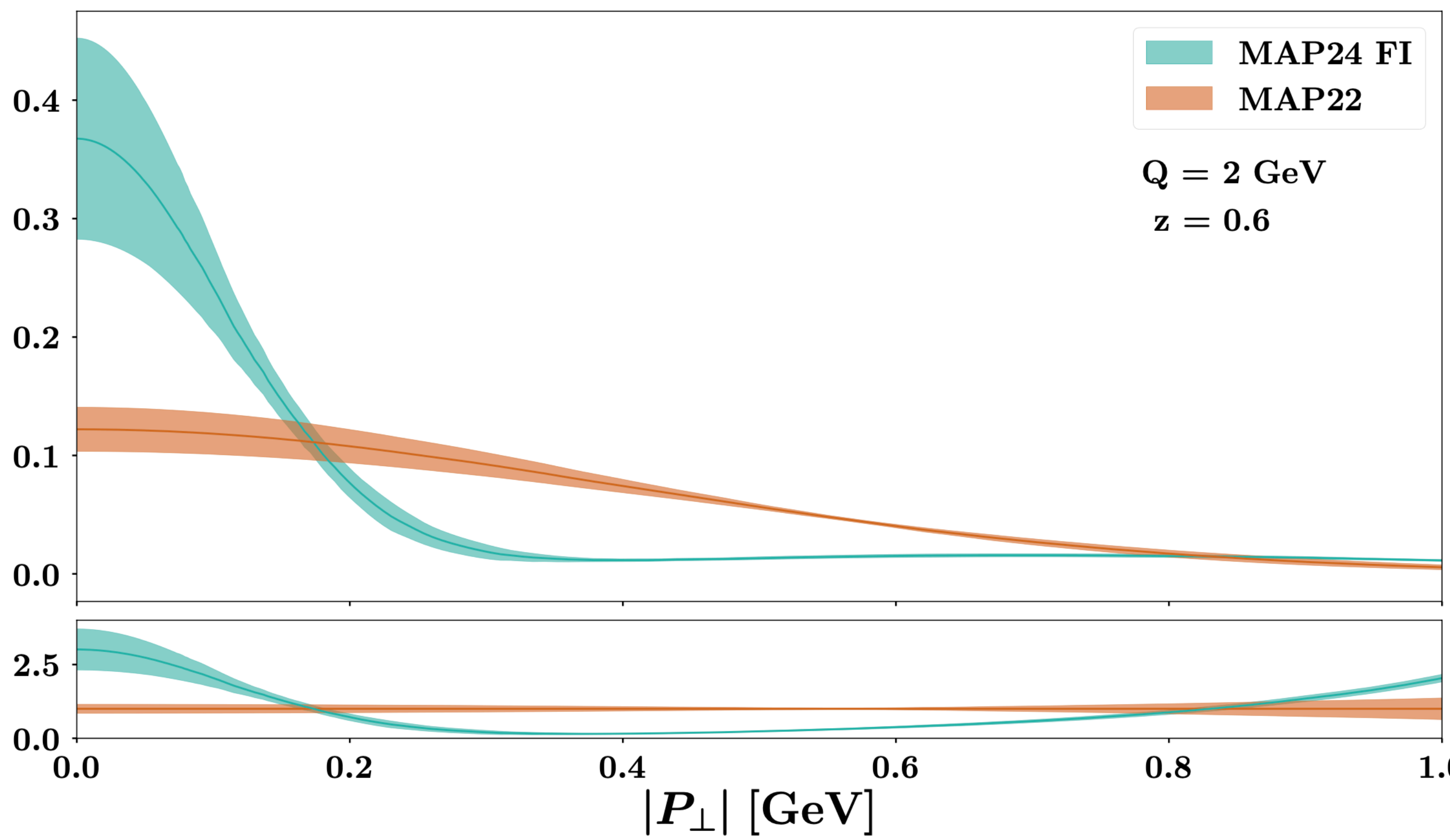

MAPFF1.0nnlo

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

MAPTMD24

NNPDF + MAPFF (MAP24 FI)

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

MMHT + MAPFF

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

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

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MAPTMD24

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MAPTMD24

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MMHT + DSS (MAP22)

TU QUOQUE,

~~BRUTE~~

HERMES

MAPTMD24: new approach

Solution: we need **flavor dependence** to obtain a good agreement between theory and experiments

MAPTMD24: new approach

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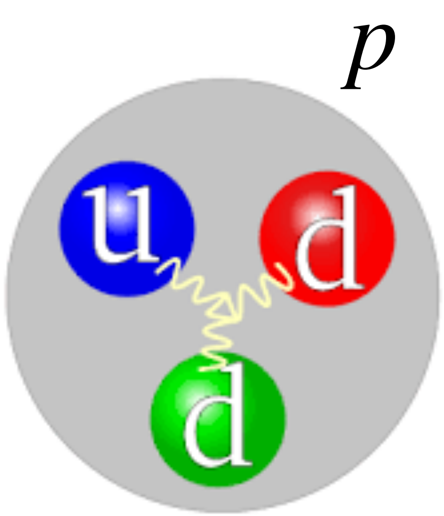

u, d

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

$s \ (sea)$

MAPTMD24: new approach

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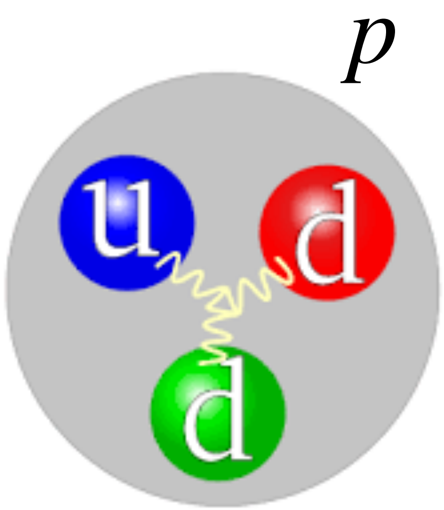

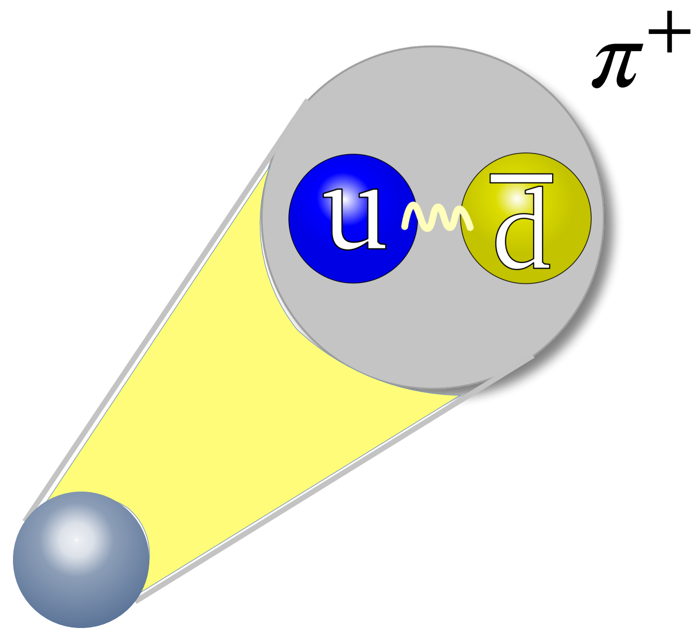

u, d

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

$s\ (sea)$

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

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

MAPTMD24: new approach

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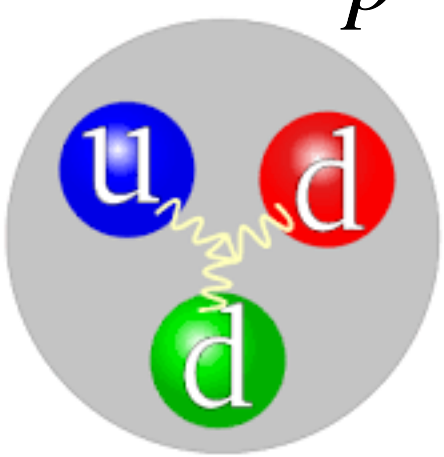
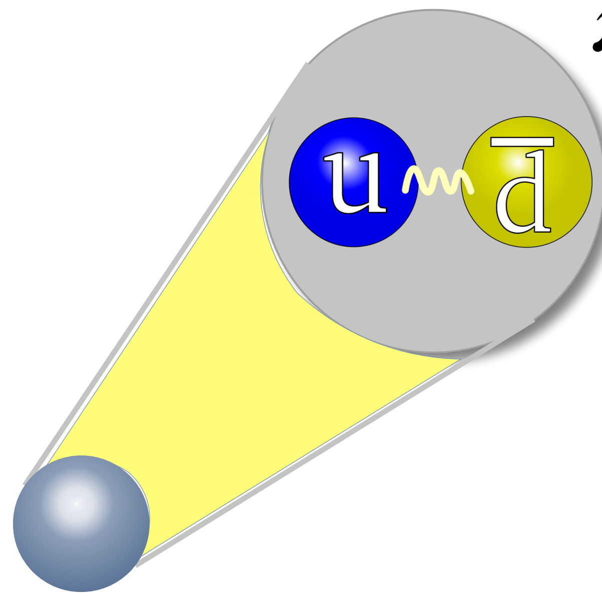
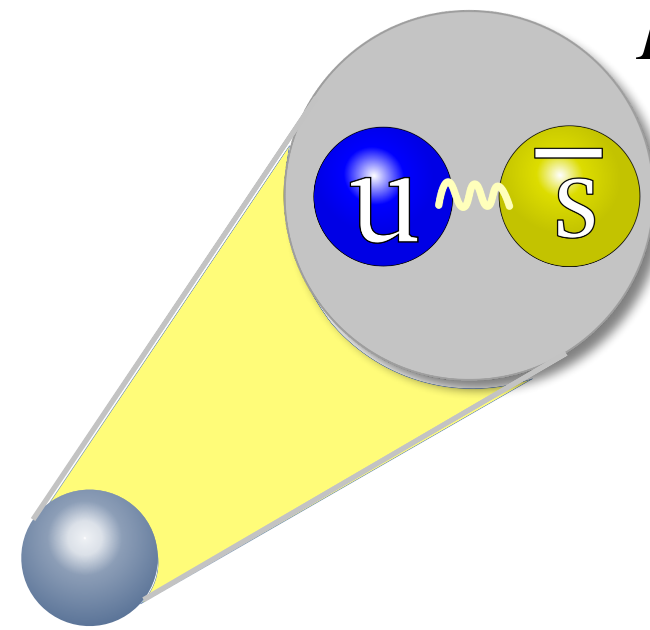
p



π^+



K^+



u, d	$u \to \pi^+, \ldots$	$u \to K^+, \ldots$
$\bar{u}, \bar{d}$	$d \to \pi^+, \ldots$	$\bar{s} \to K^+, \ldots$
$s\ (sea)$		$d \to K^+, \ldots$

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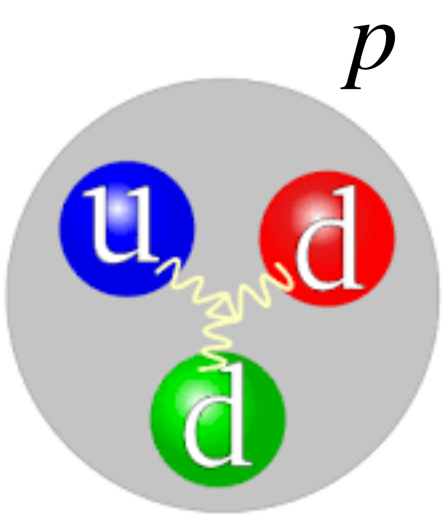
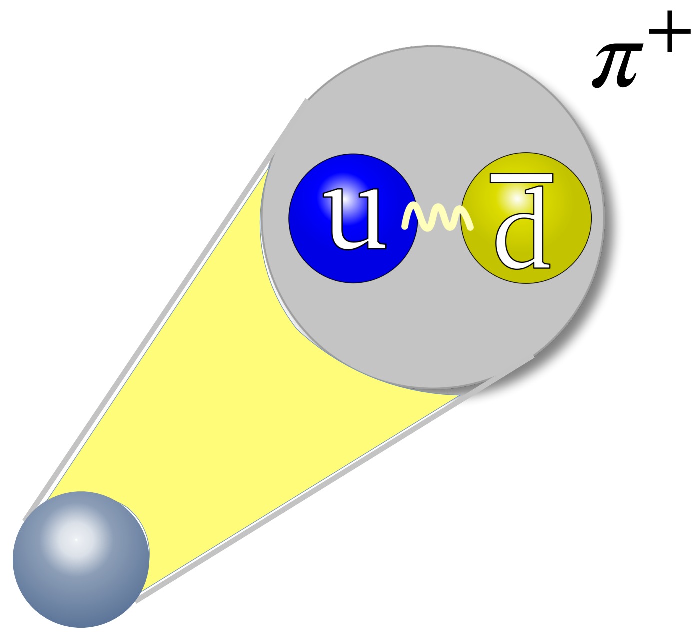
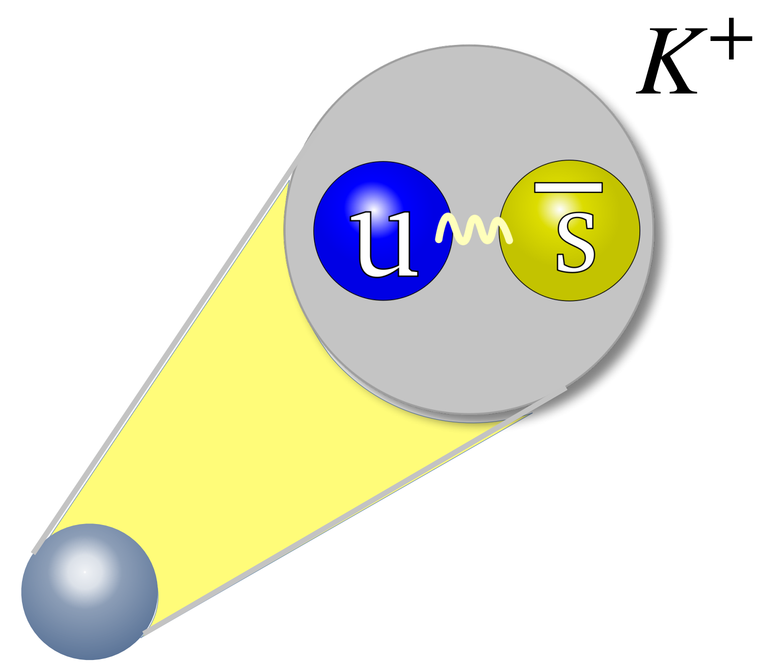
<u>*Solution*</u>: we need **flavor dependence** to obtain a good agreement between theory and experiments







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charge conjugation

MAPTMD24: new approach

high sensitivity to flavor dependence

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

+ deuteron target

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

$$p + p \to \gamma^*/Z \to l^+ + l^-$$

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

low sensitivity to flavor dependence

MAPTMD24: results

	N^3LL			
Data set	N_{dat}	χ^2_D	χ^2_λ	χ^2_0
DY collider total	251	1.37	0.28	1.65
DY fixed-target total	233	0.63	0.31	0.94
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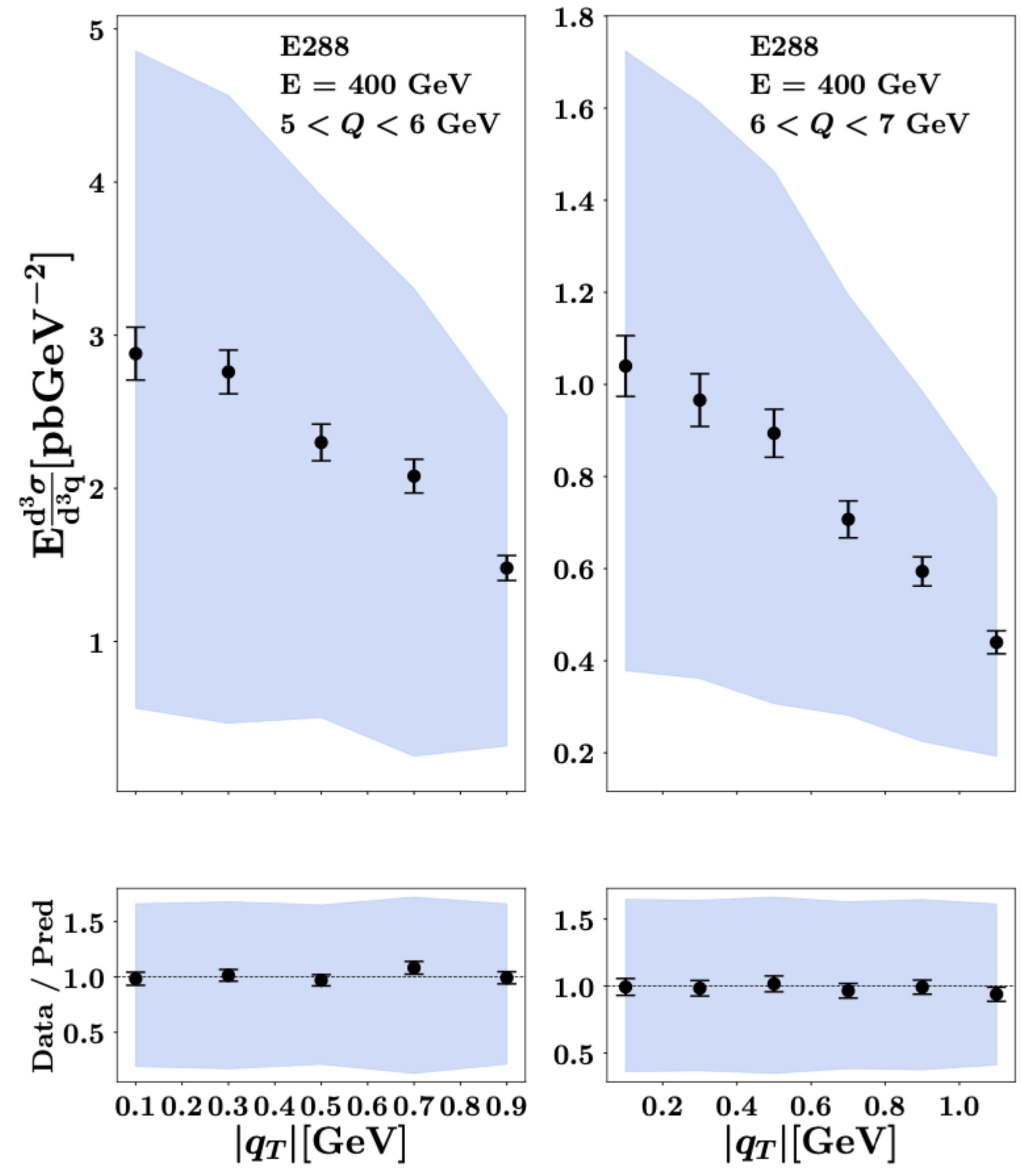

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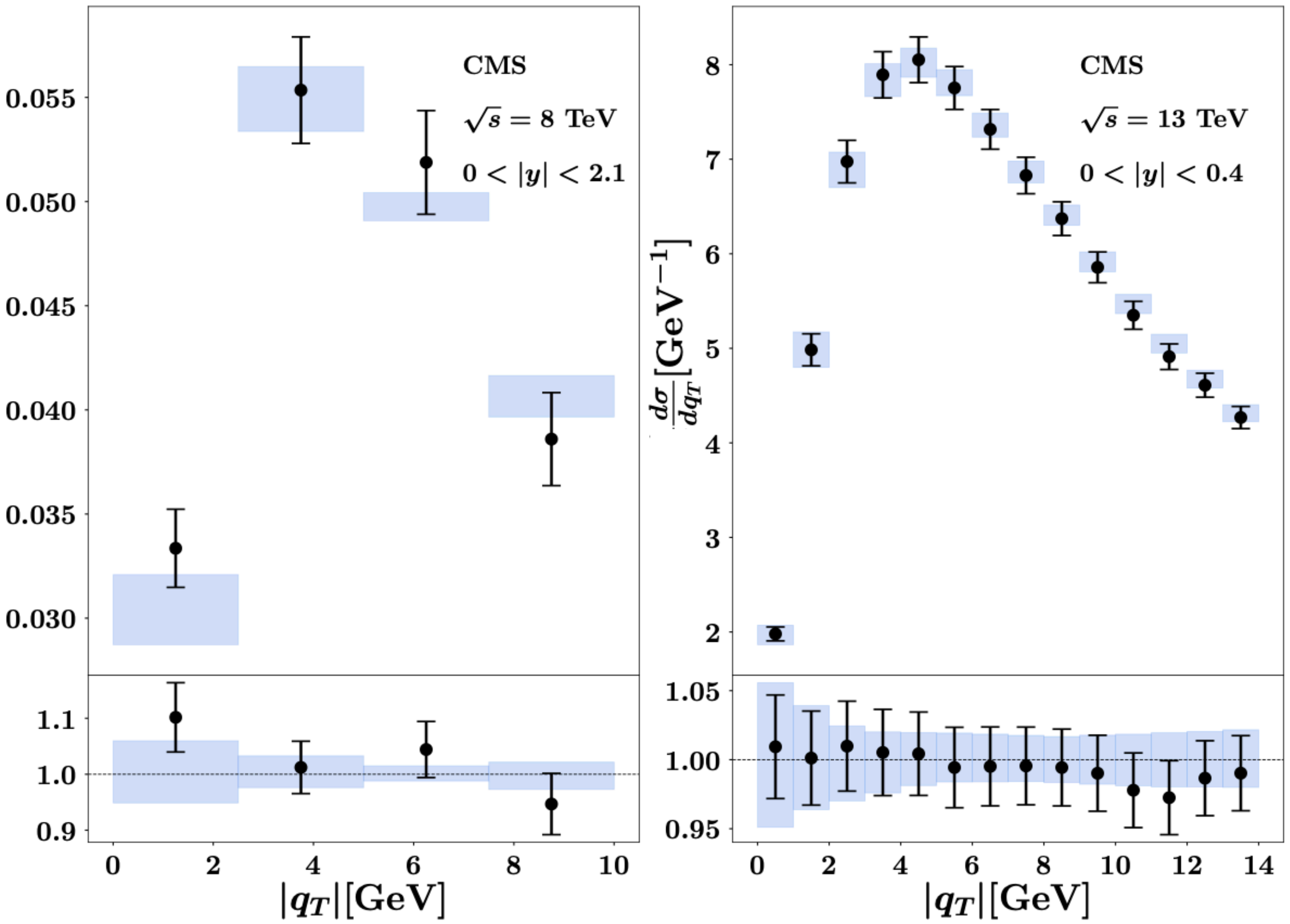

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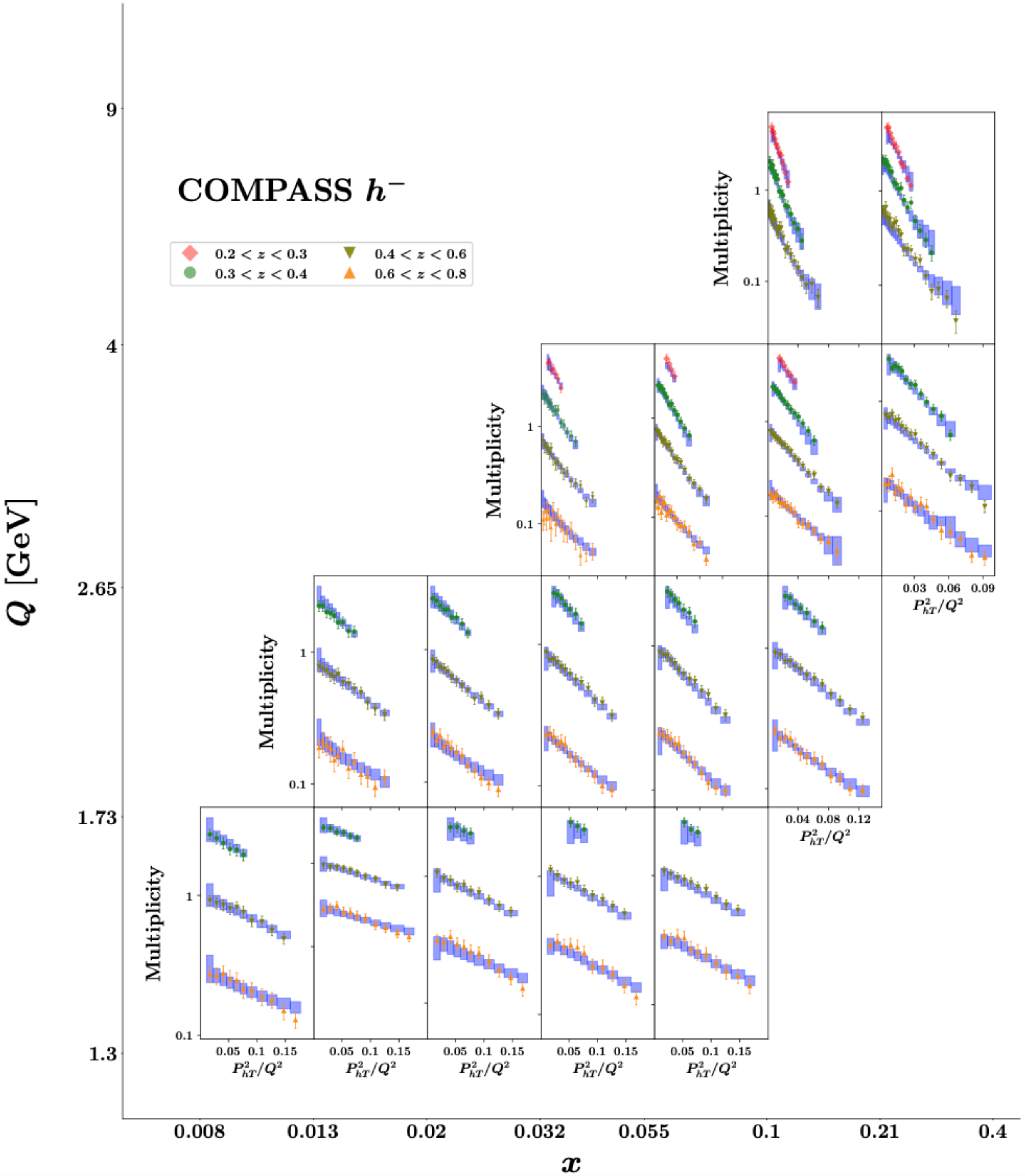

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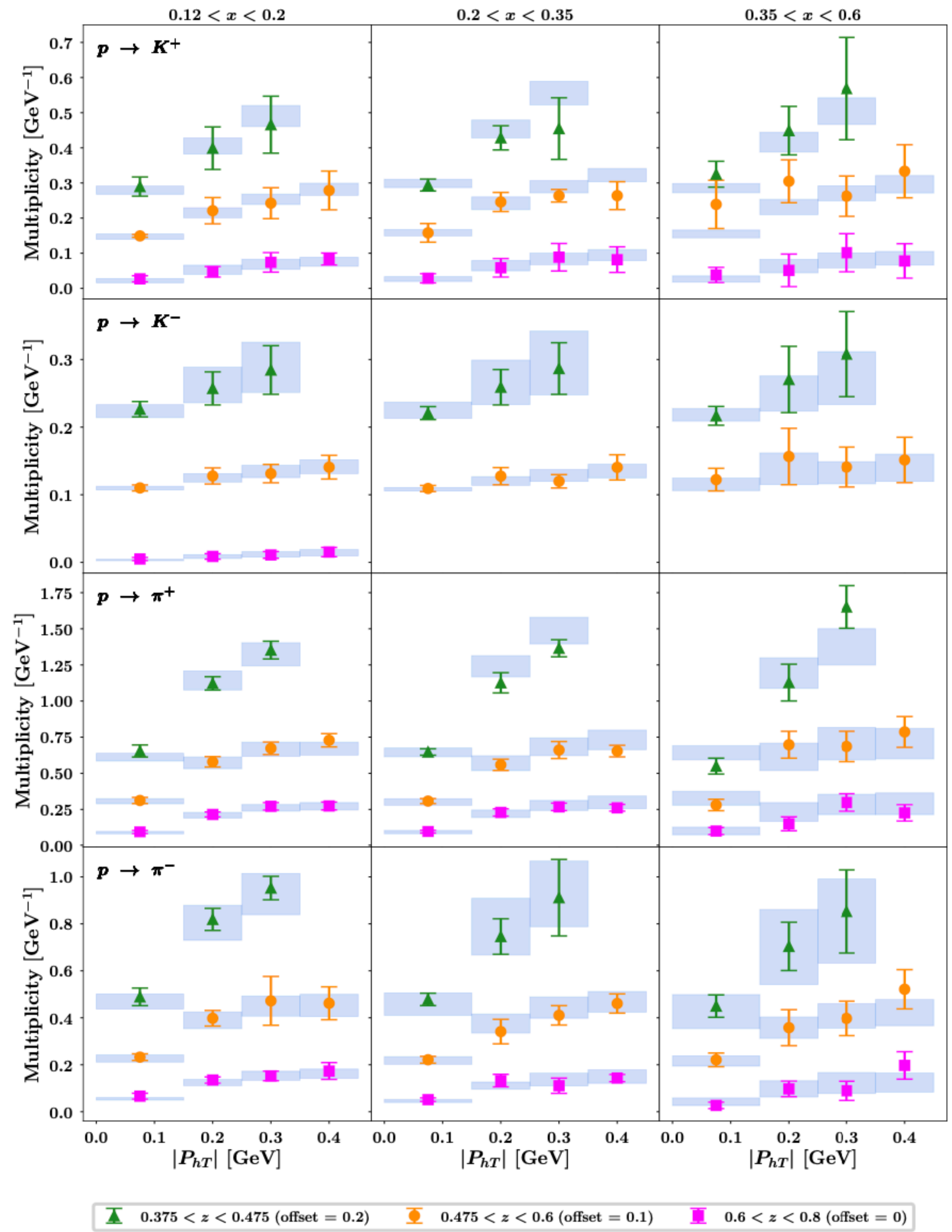

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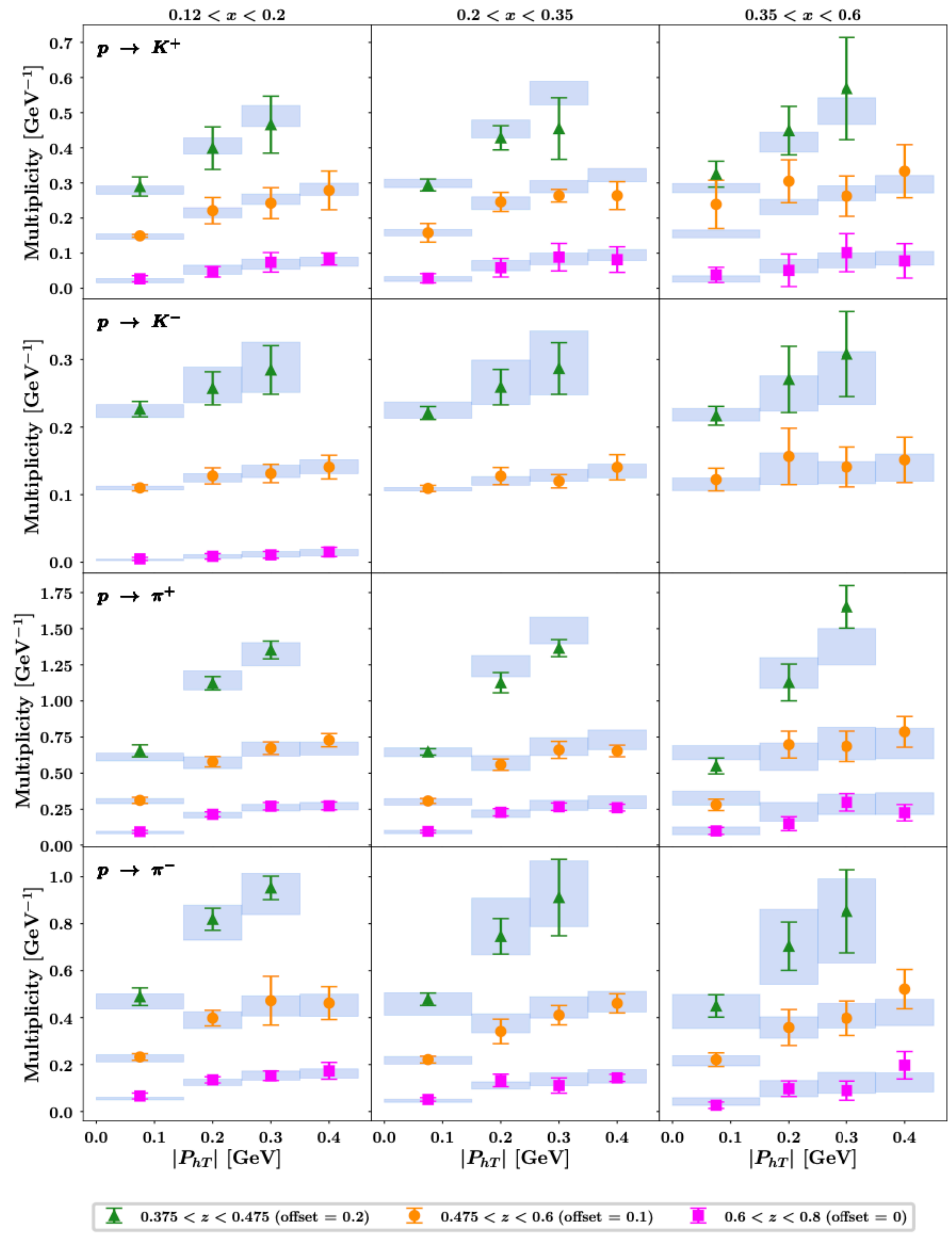
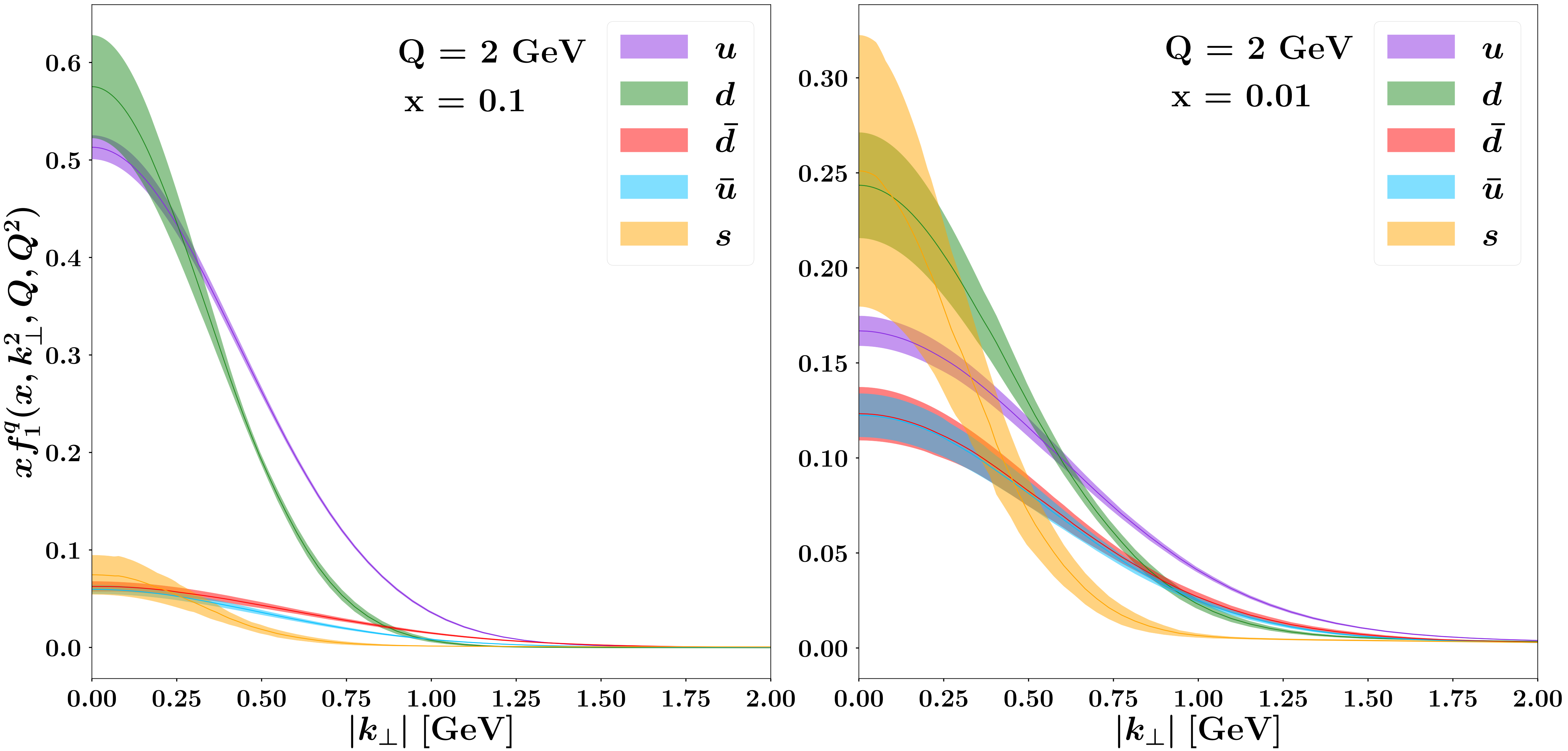


The agreement between theory and HERMES data has increased a lot!

MAPTMD24: results

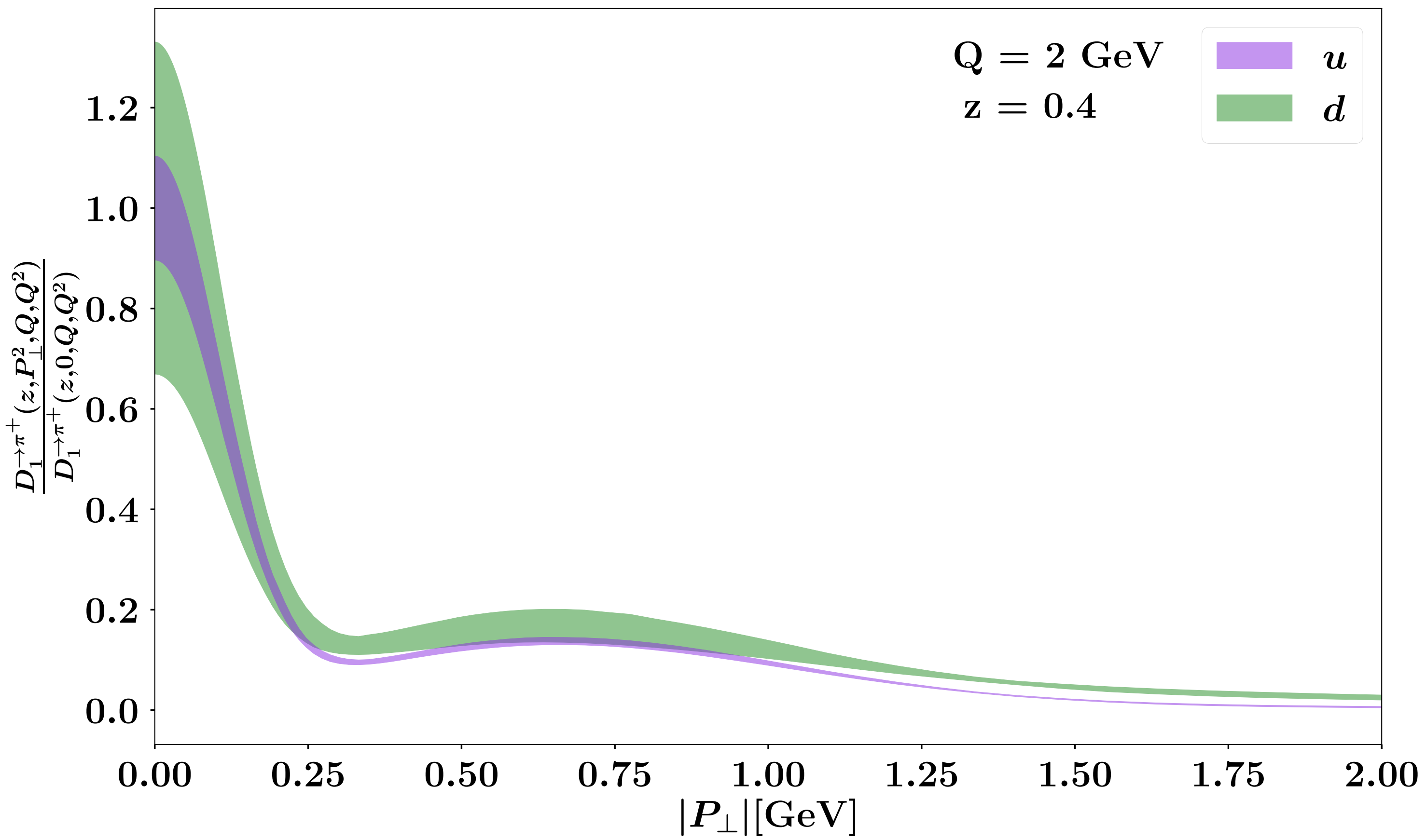
Flavor-dependent TMD PDFs



Evidence of different behaviors for different flavors

MAPTMD24: results

Flavor-dependent TMD FFs



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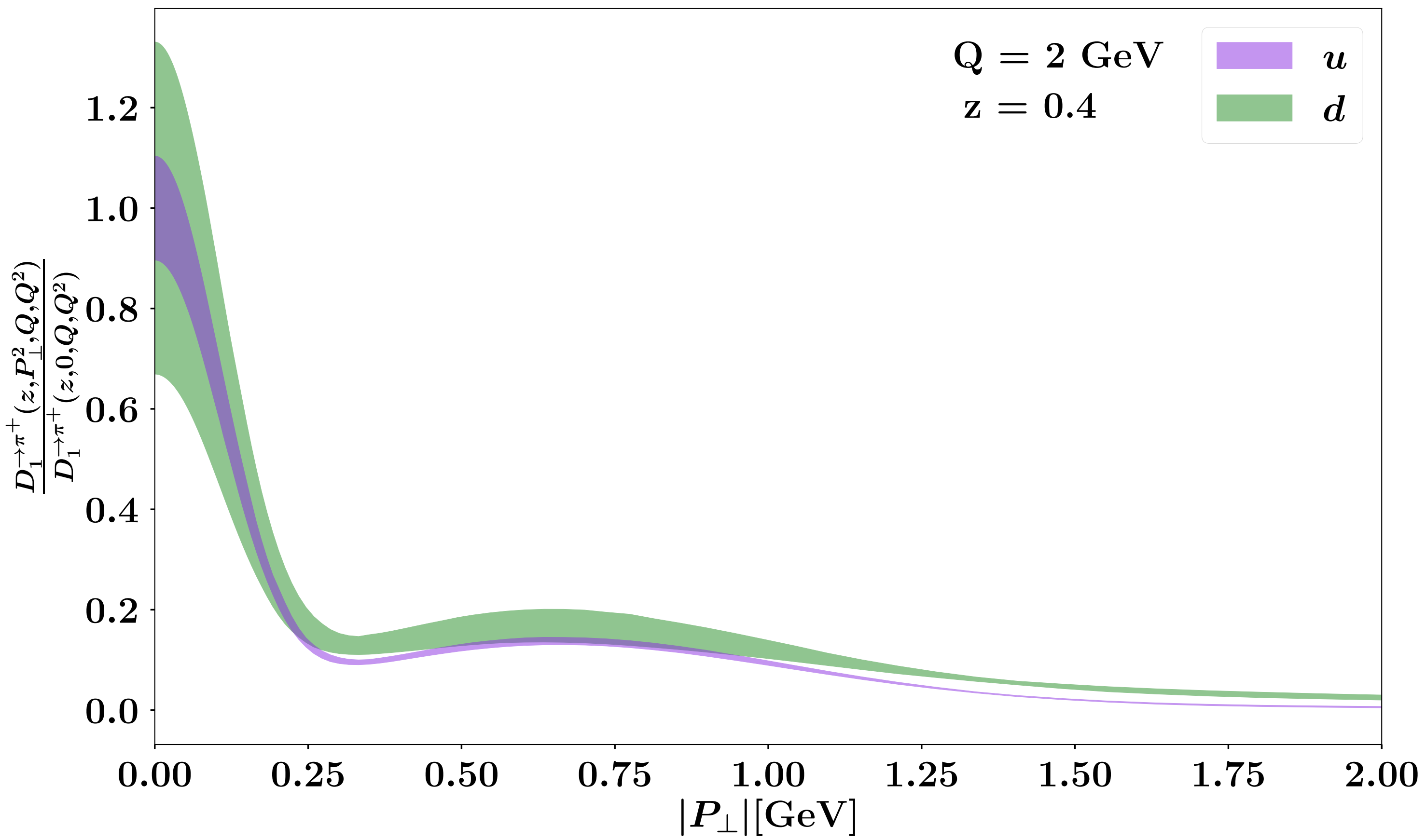

Small evidence of different behaviors for different flavors

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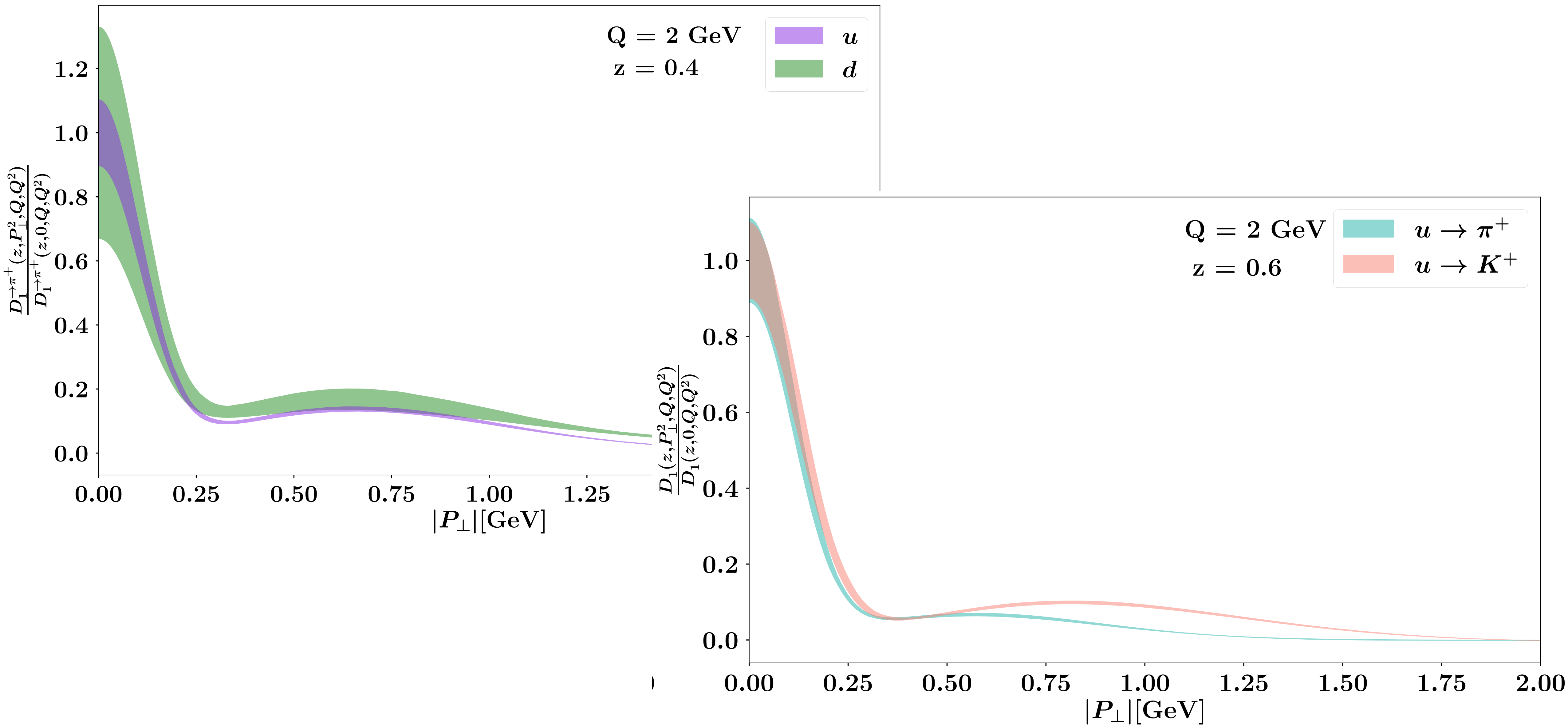

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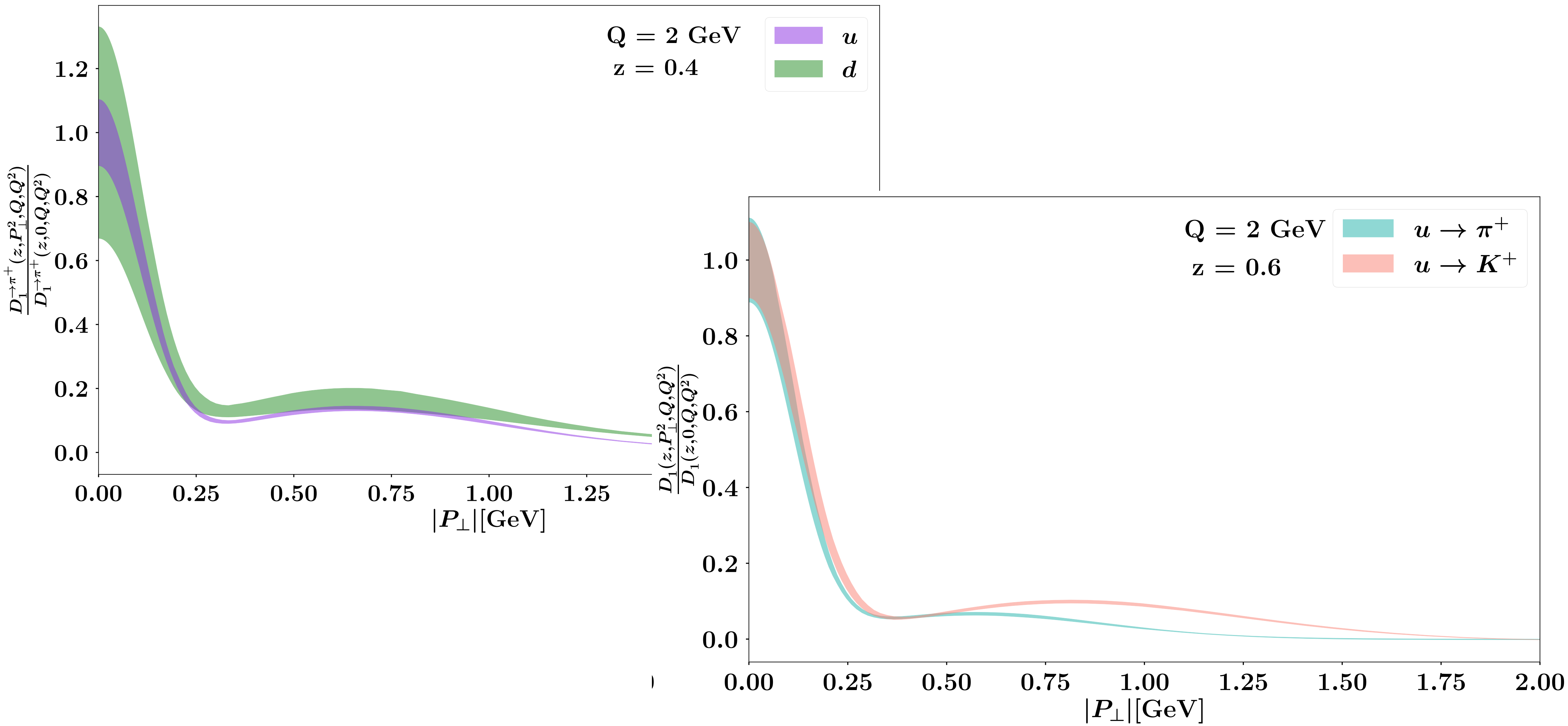
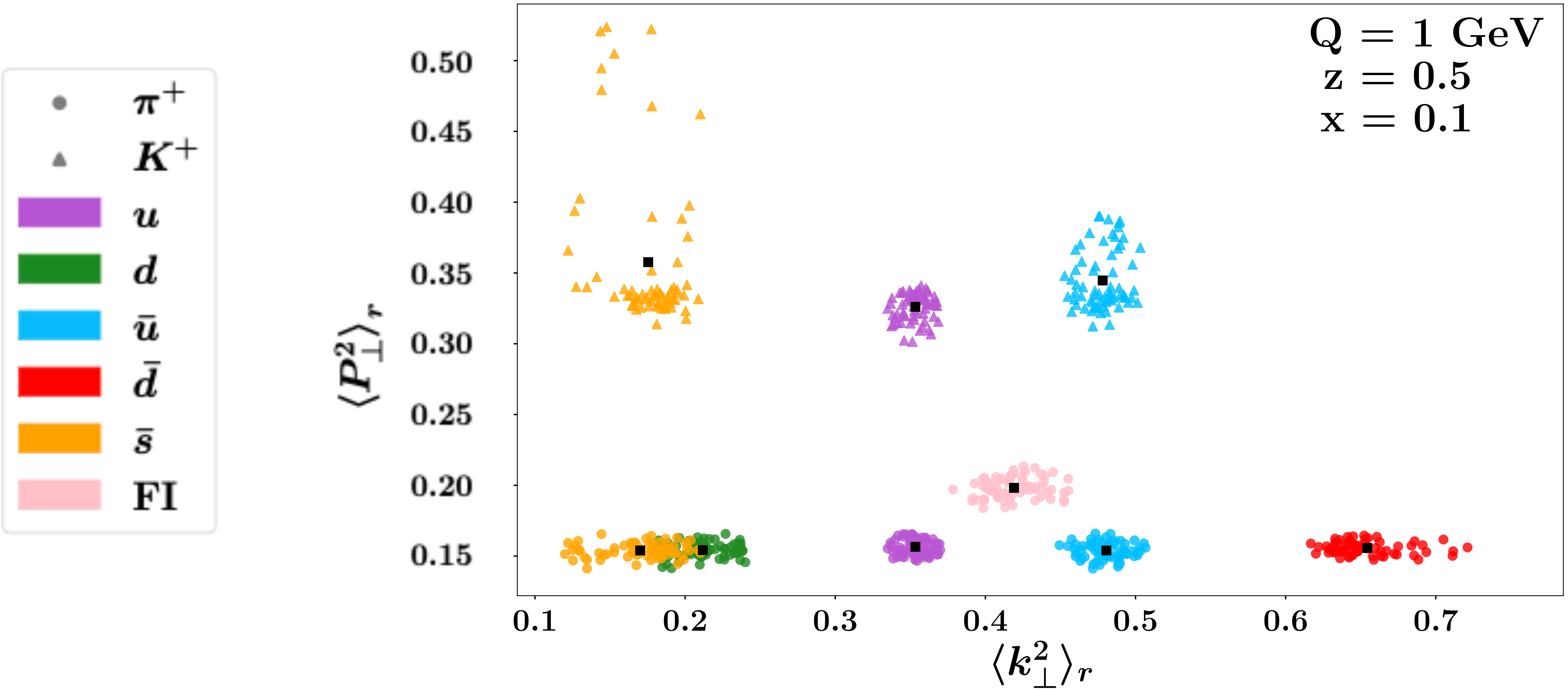


Small evidence of different behaviors for different flavors

Some evidence of different behaviors for different measured hadrons

MAPTMD24: results

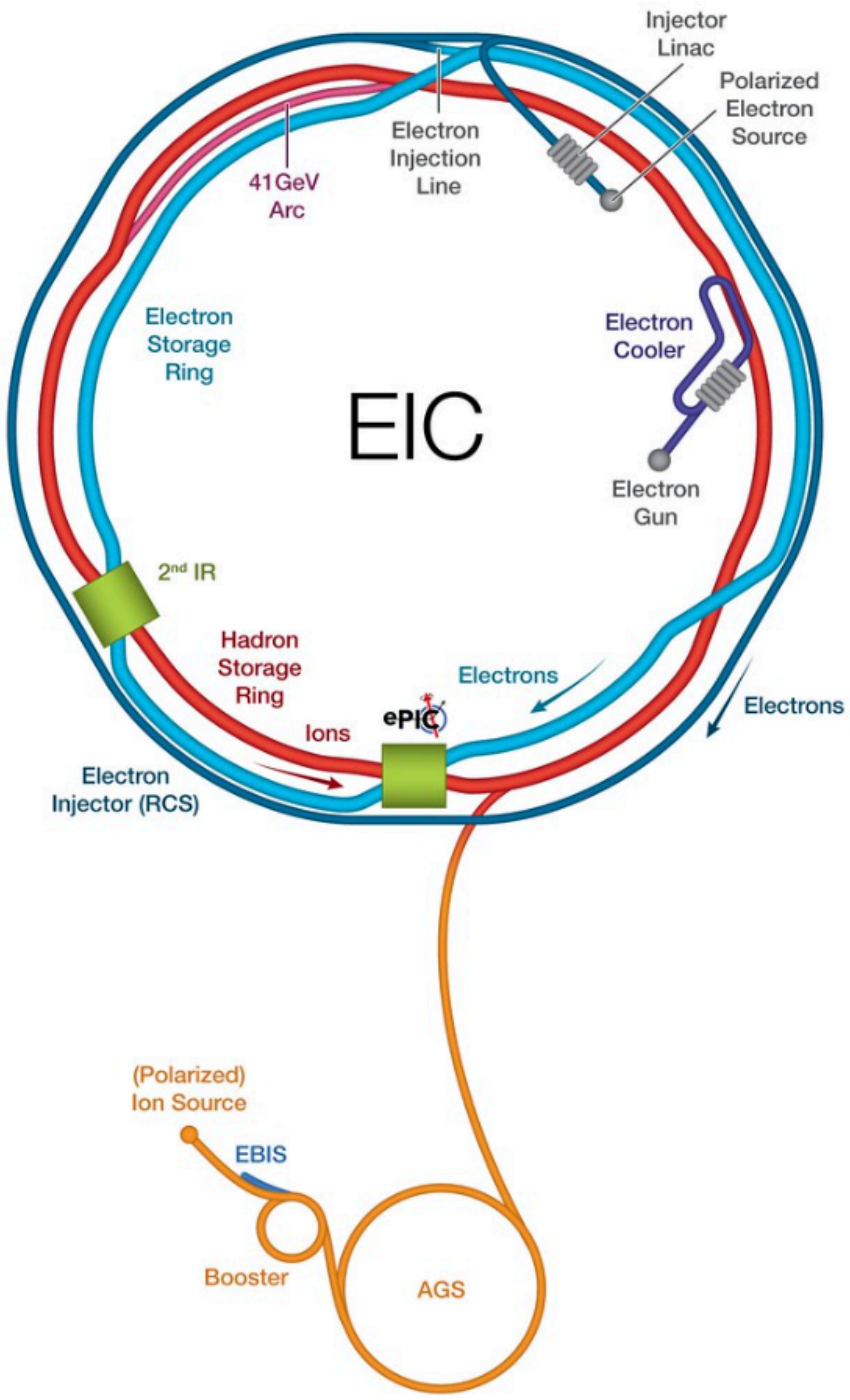
TMD's "effective width"



Evidence of different behaviors for different flavors

Evidence of different behaviors for different measured hadrons

Future perspectives



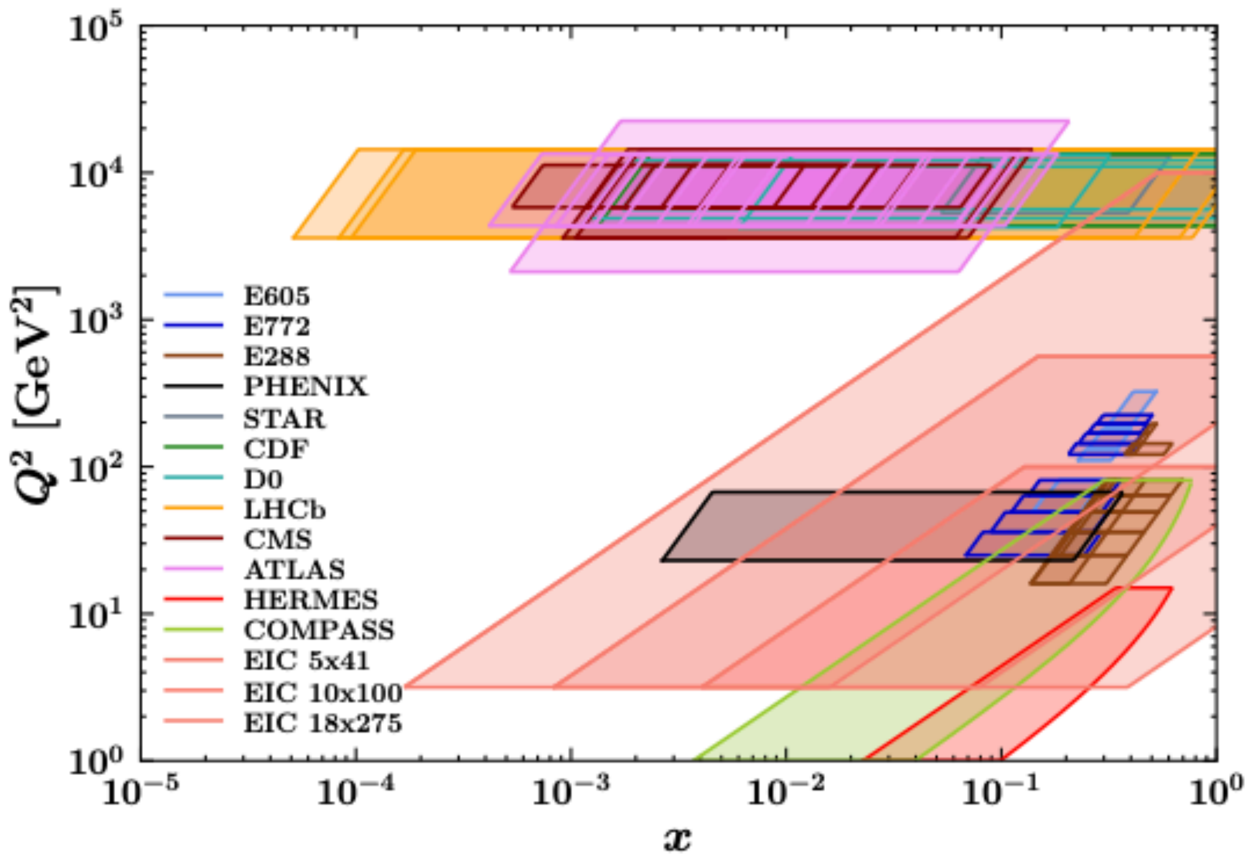
What can we learn from new experiments?

open channel with EIC SIDIS Working group

Future perspectives

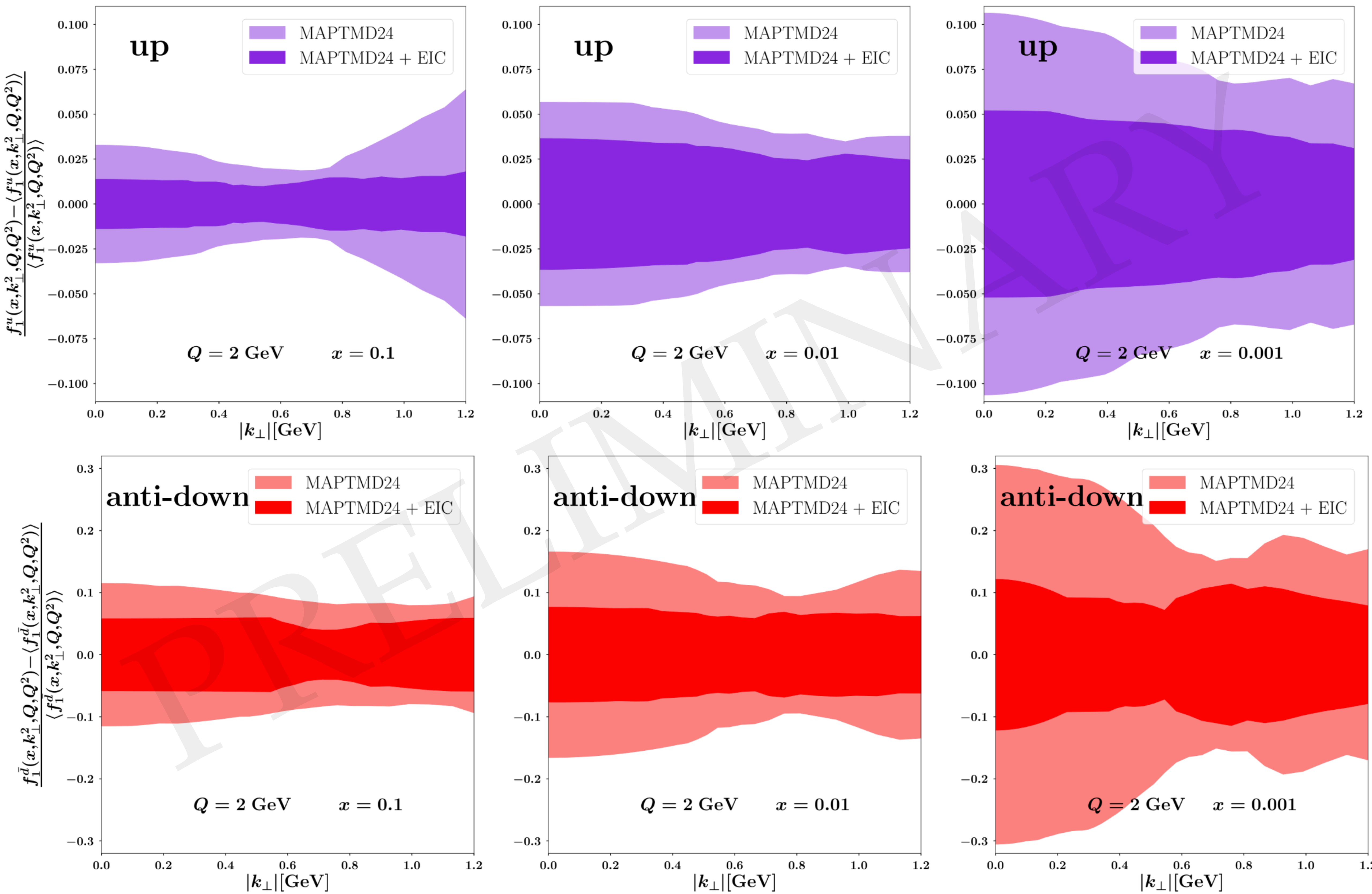
Impact of the EIC on TMDs extractions

	Data points
MAPTMD24	**2031**
5x41 π^+	*1273*
10x100 π^+	*1611*
18x275 π^+	*1648*
	6563



The number of data points has been TRIPLED

Future perspectives



Conclusions

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Conclusions

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

- We observe **non-trivial differences** in the transverse momentum distribution of partons inside hadrons

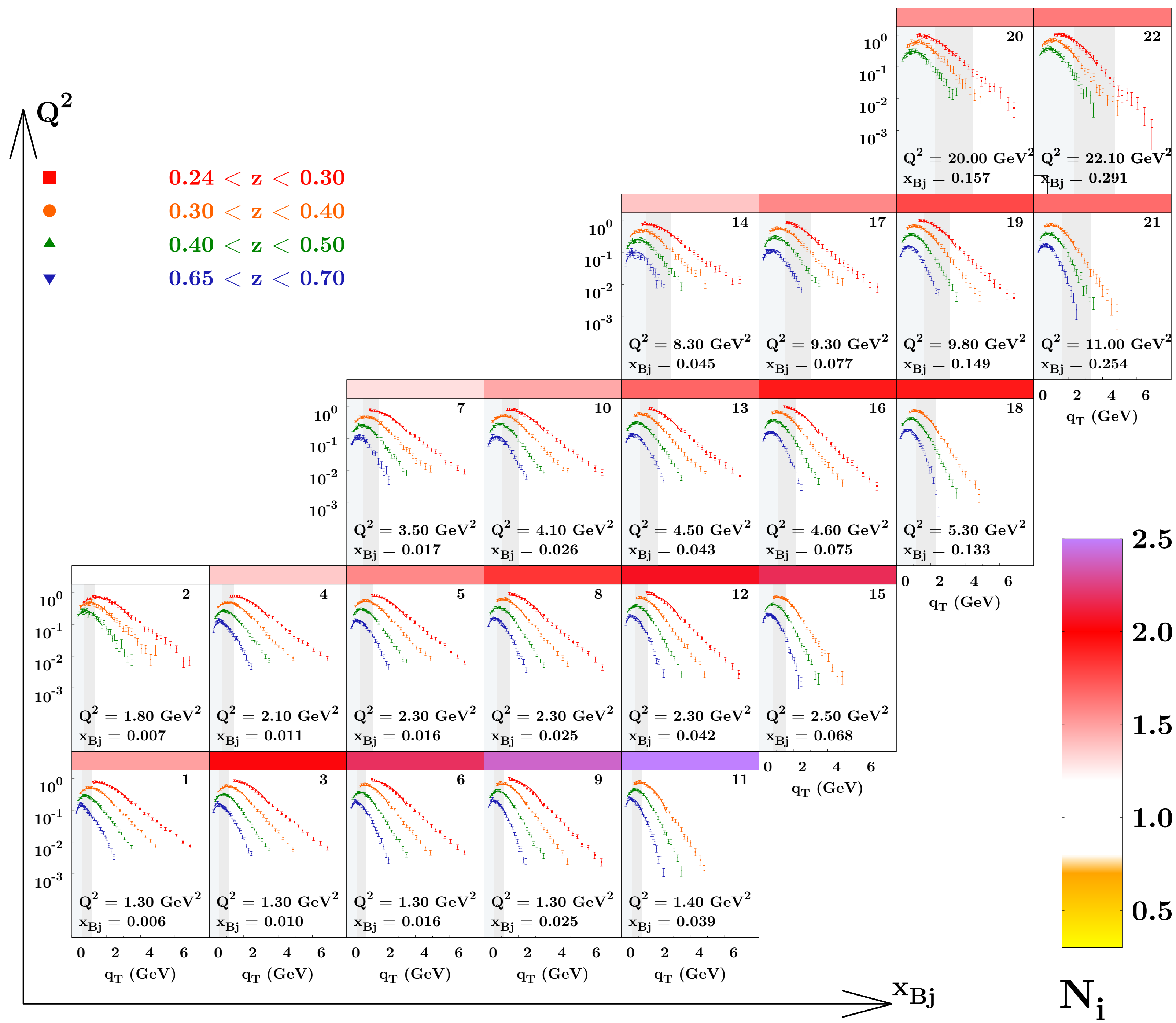
- New data from the **EIC** will be very important to **reduce the uncertainties** of extracted TMDs **by almost 50%**

Backup

Normalization of SIDIS calculation

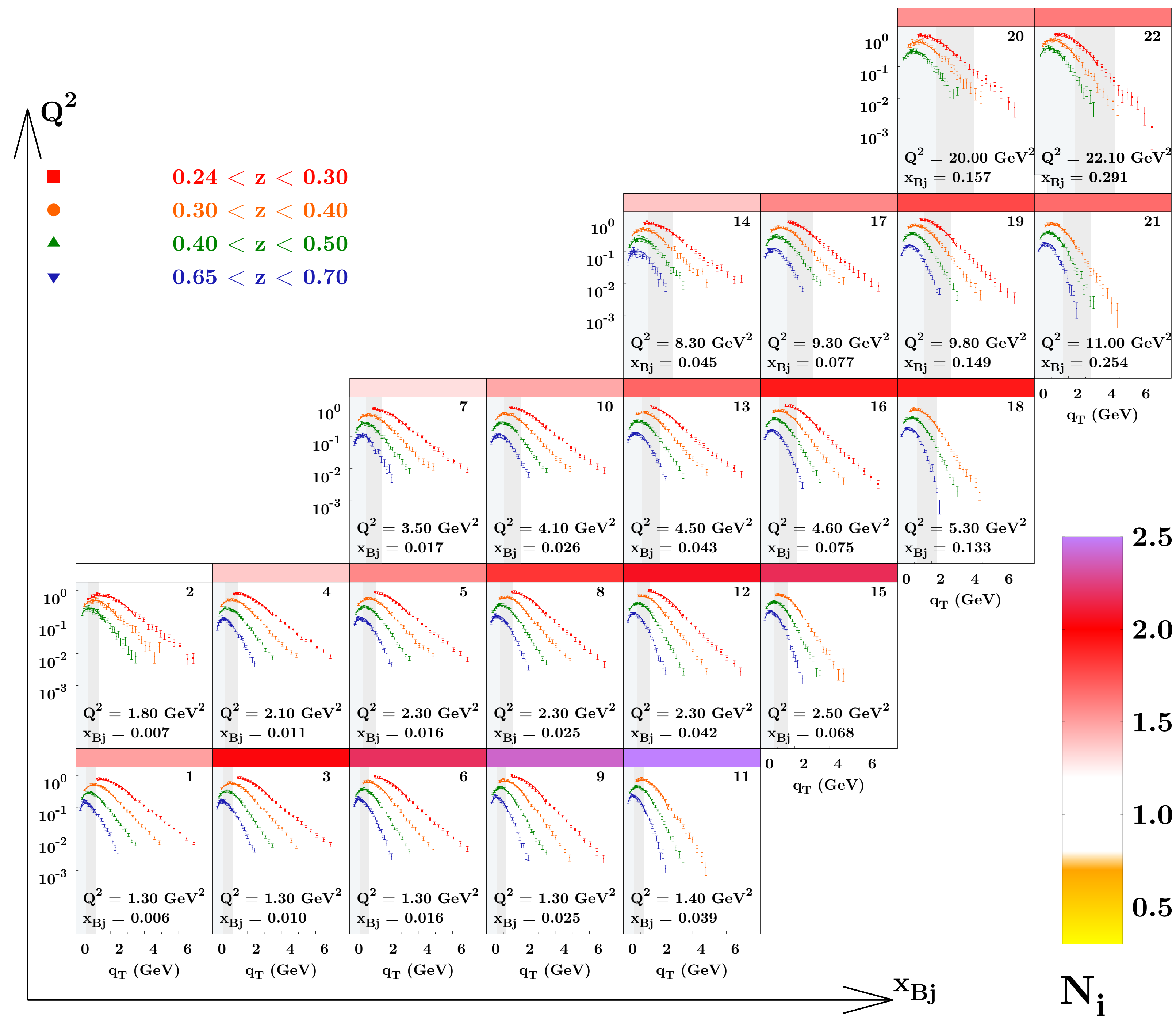
Normalization issue confirmed also in other analyses from different collaborations

Vladimirov, JHEP 12 (2023)



Gonzalez-Hernandez, PoS DIS2019 (2019)

Normalization of SIDIS calculation



Gonzalez-Hernandez, PoS DIS2019 (2019)

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Sun, Isaacson, Yuan, Yuan, IJNP A (2014)

Gonzalez-Hernandez, PoS DIS2019 (2019)

Vladimirov, JHEP 12 (2023)

Normalization of SIDIS calculation

MAP22 work solution

Good agreement for almost all bins

MAP Collaboration, JHEP 10 (2022)

Normalization of SIDIS calculation

MAP22 work solution

SIDIS multiplicity

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

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MAP Collaboration, JHEP 10 (2022)

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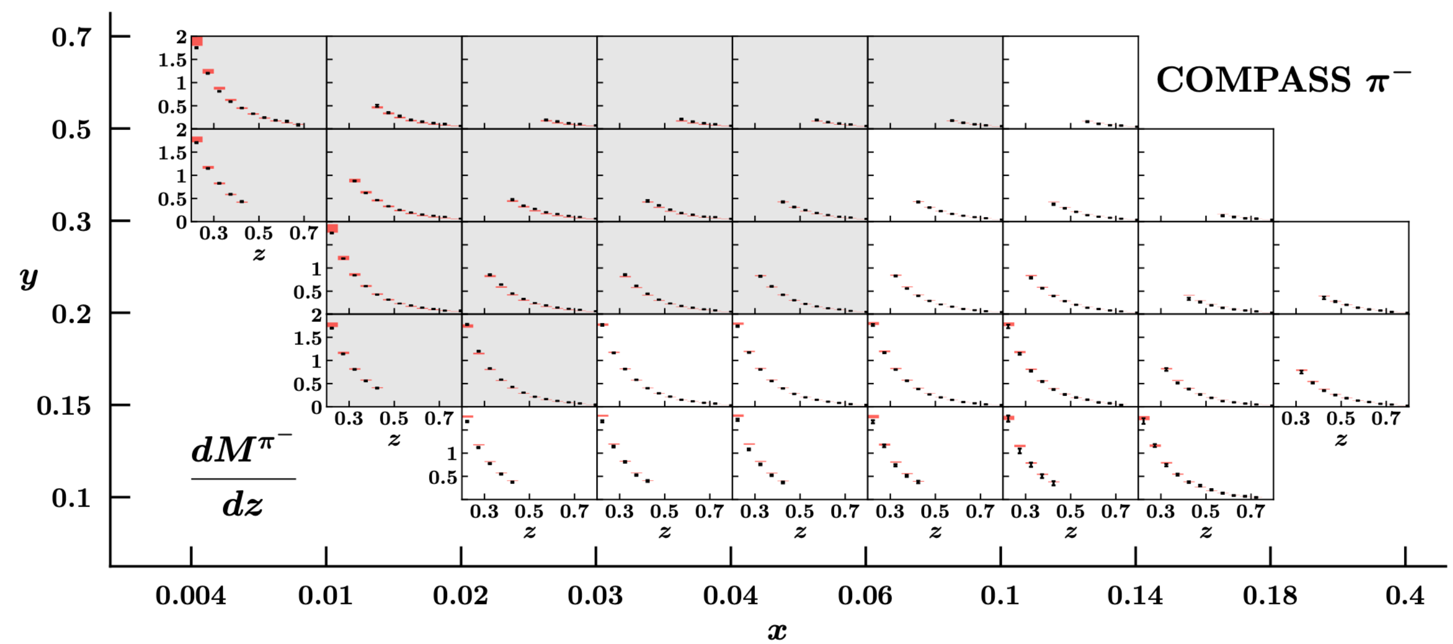

Khalek, Bertone, Nocera, et al., PRD 104 (2021)

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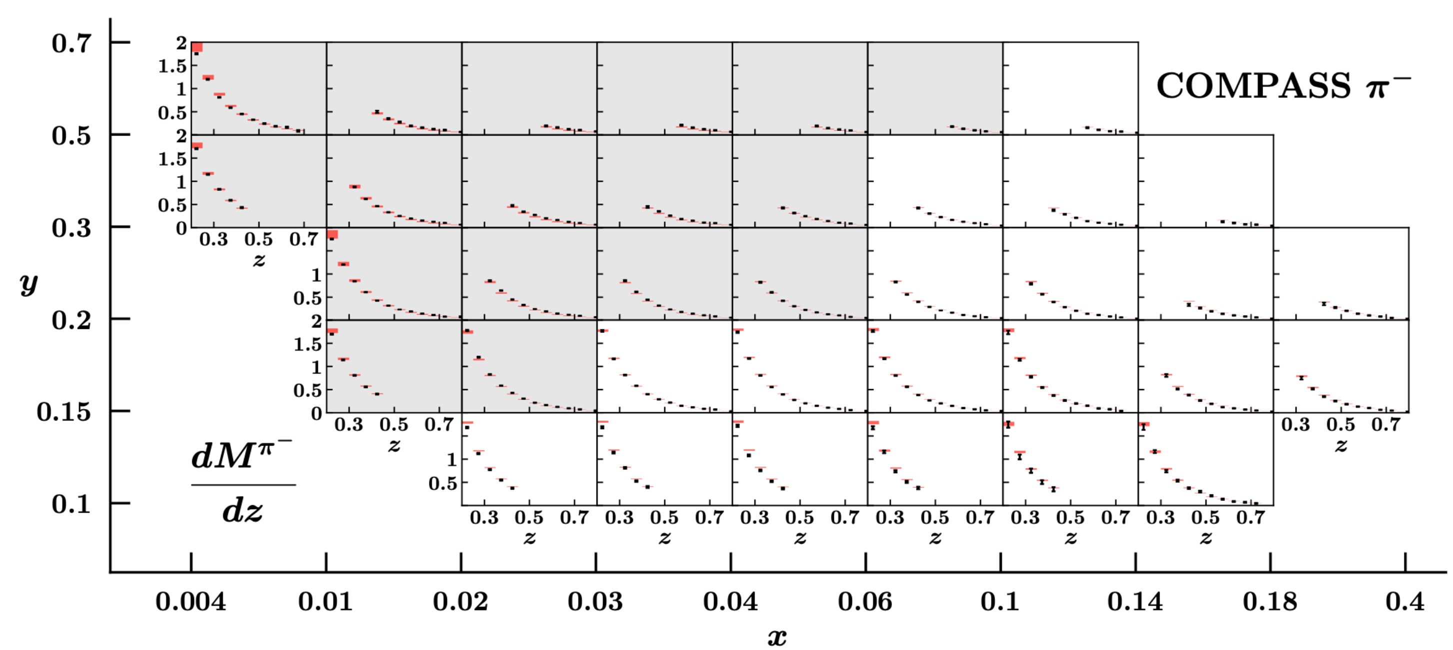
Collinear SIDIS cross section
$$\frac{d\sigma}{dx\,dQ\,dz}$$

Normalization of prediction such that

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

Piacenza, PhD thesis (2020)

Good agreement theory/data



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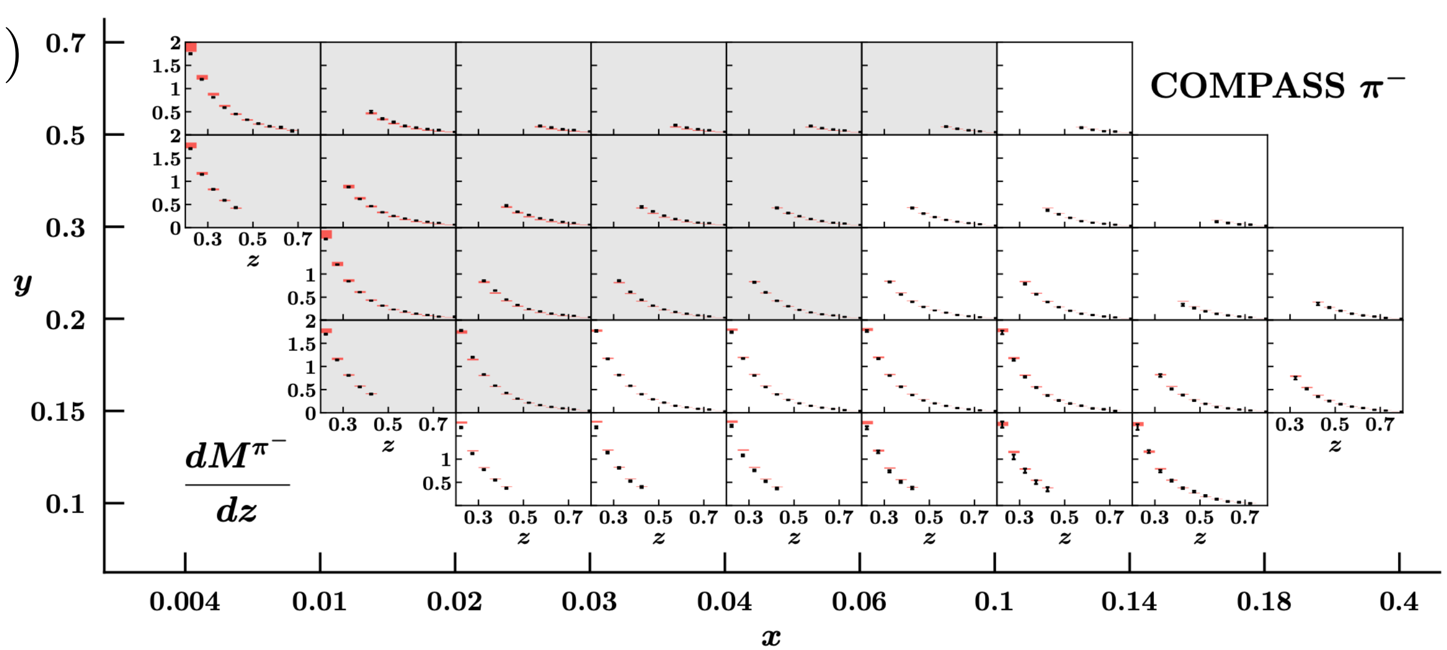

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Collinear SIDIS cross section $\frac{d\sigma}{dx\,dQ\,dz}$

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Piacenza, PhD thesis (2020)

$$M(x, z, P_{hT}, Q) = n(x, z, Q)\, W(x, z, Q, P_{hT}) \Big/ \frac{d\sigma}{dx\,dQ}$$

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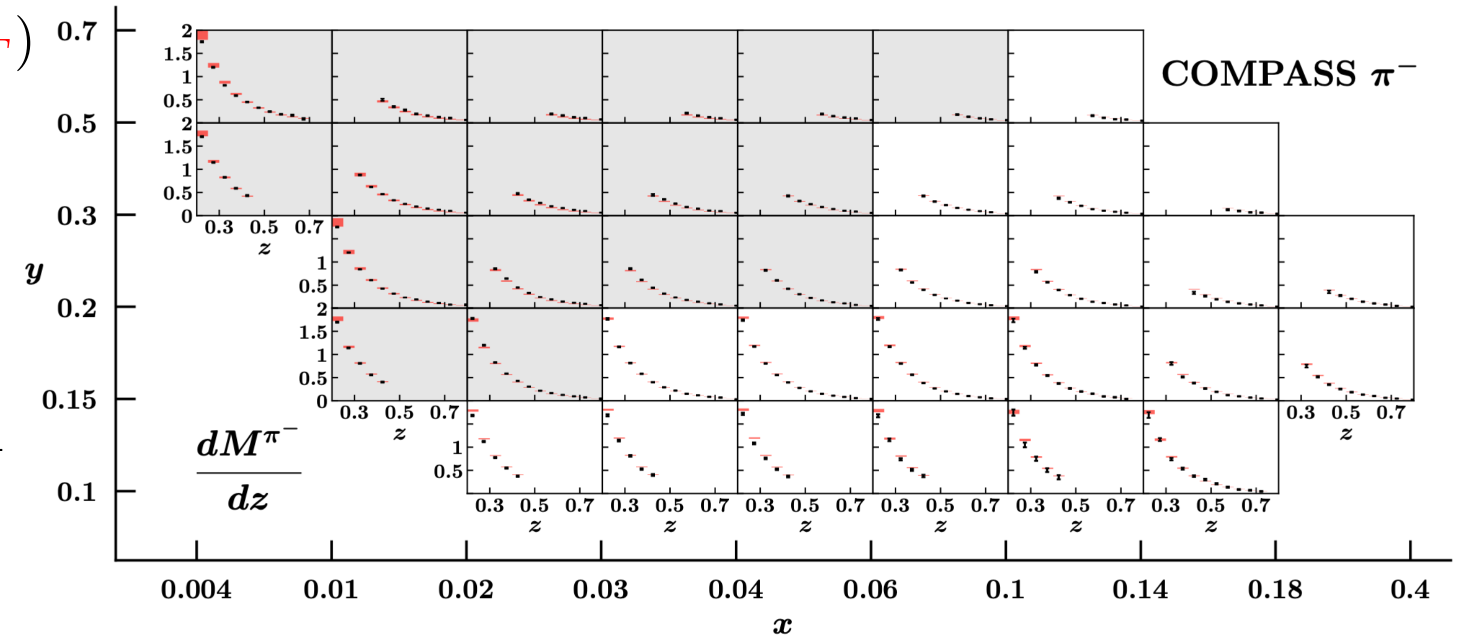

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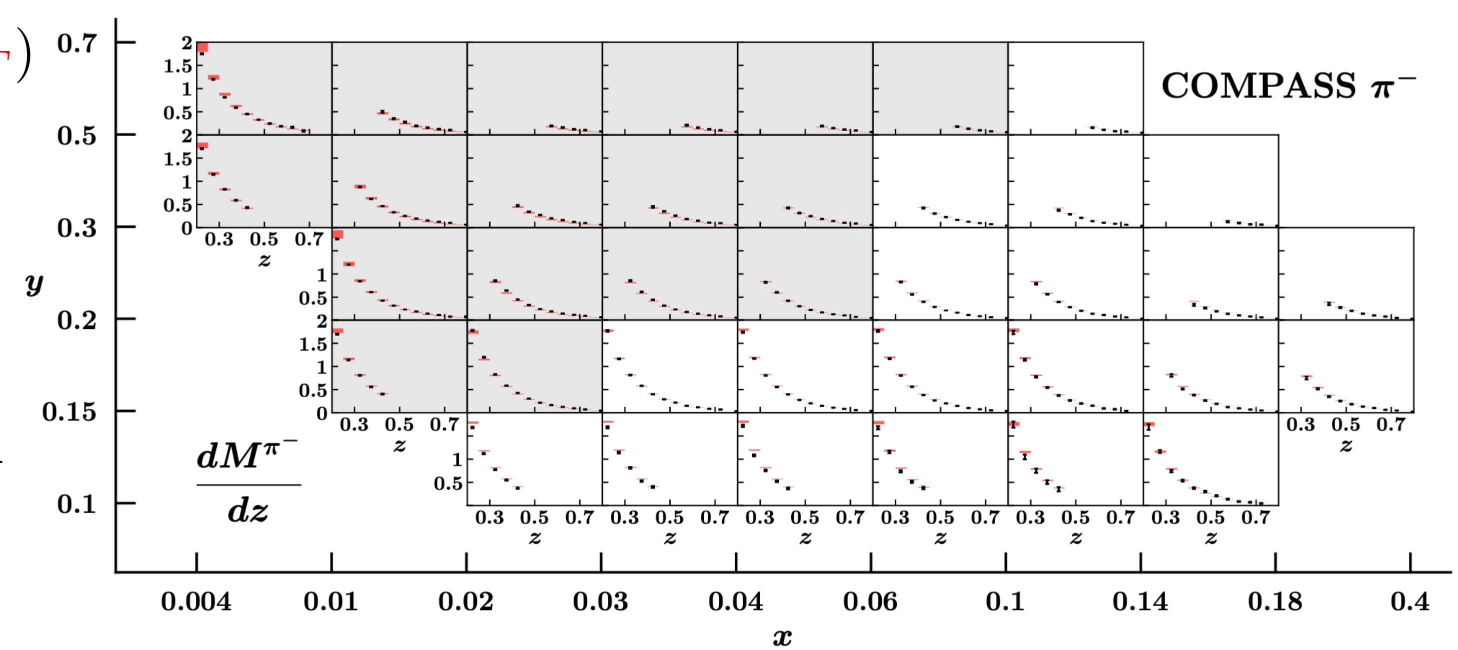
$$M(x,z,P_{hT},Q) = n(x,z,Q)\, W(x,z,Q,P_{hT}) \bigg/ \frac{d\sigma}{dx\,dQ}$$

Calculable before the fit

Good agreement theory/data



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MAPTMD22 — Error analysis

Error propagation

↓

100 Monte Carlo replicas of data

100 Monte Carlo replicas of PDFs

100 Monte Carlo replicas of FFs