to MAP the flavor of the 3D nucleon structure

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CFNS Postdoc Seminars
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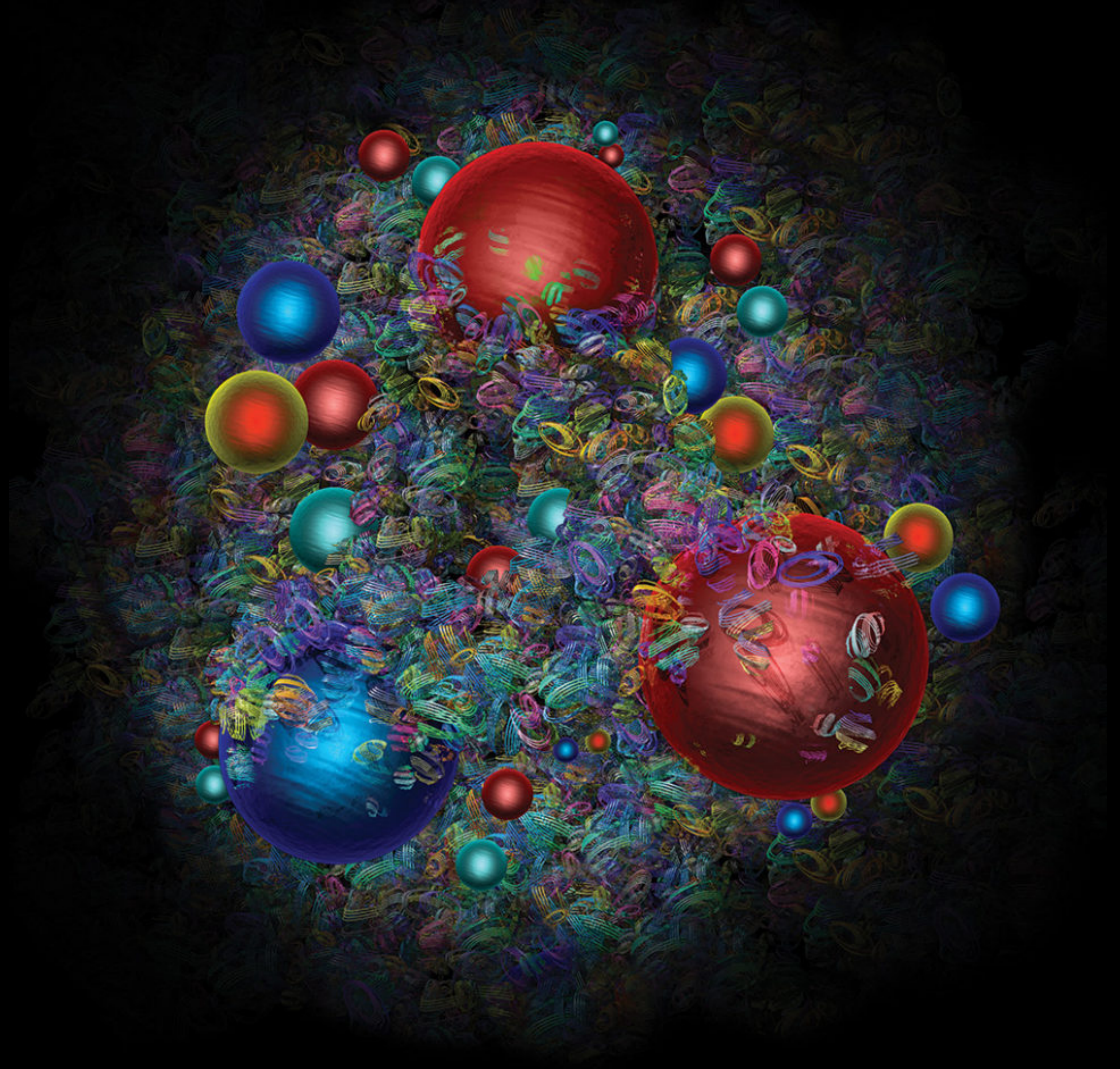
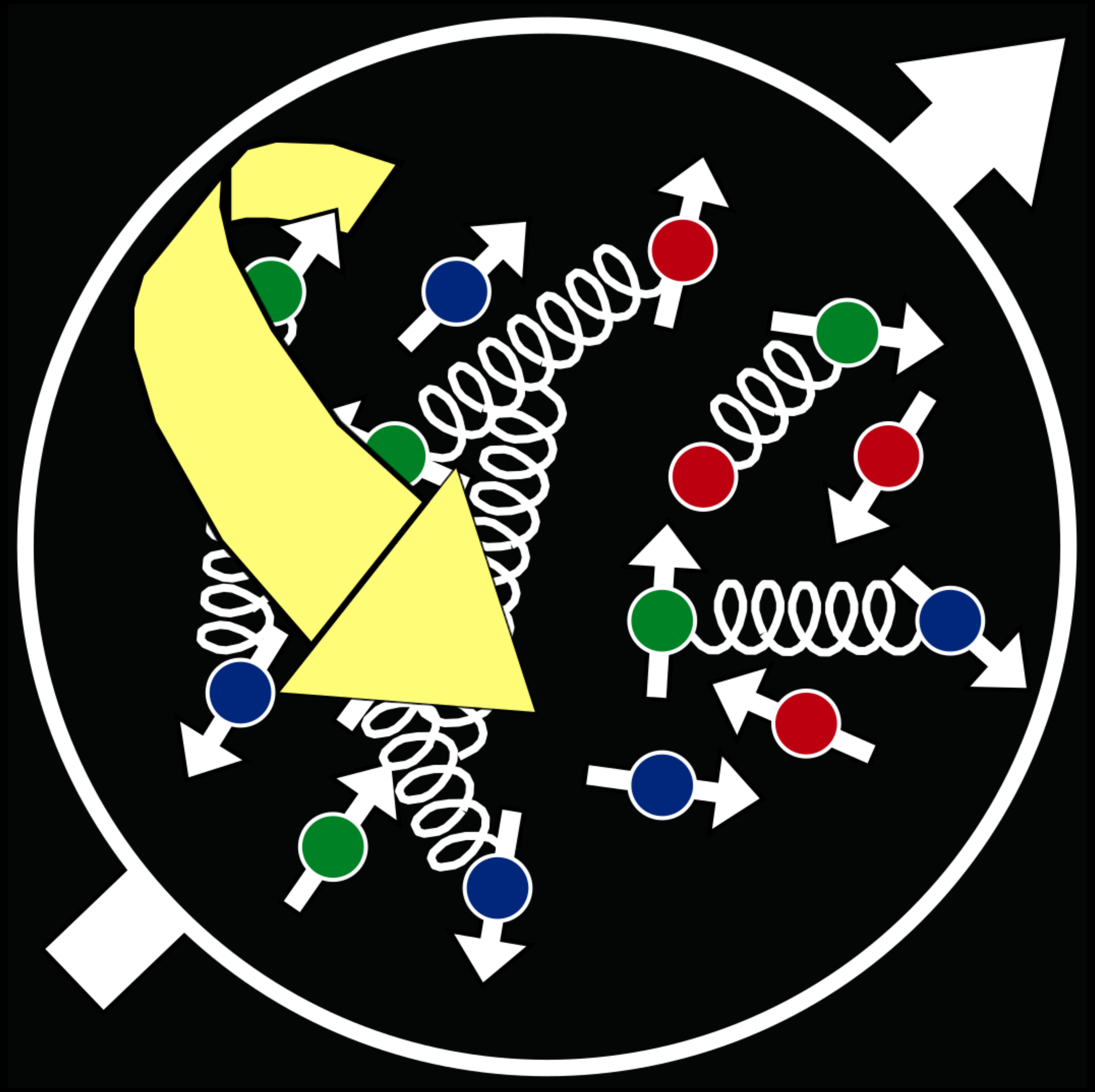
What is the structure of the nucleon?



What about the spin?



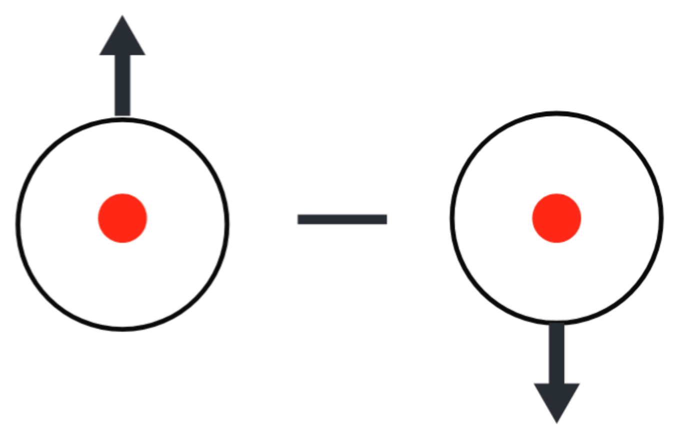
1D

3D

Collinear PDF → Transverse Momentum Dependent distributions

TMDs

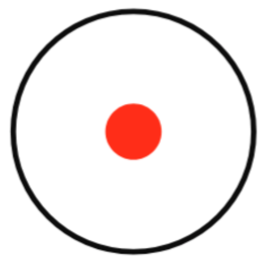
PV20Sivers



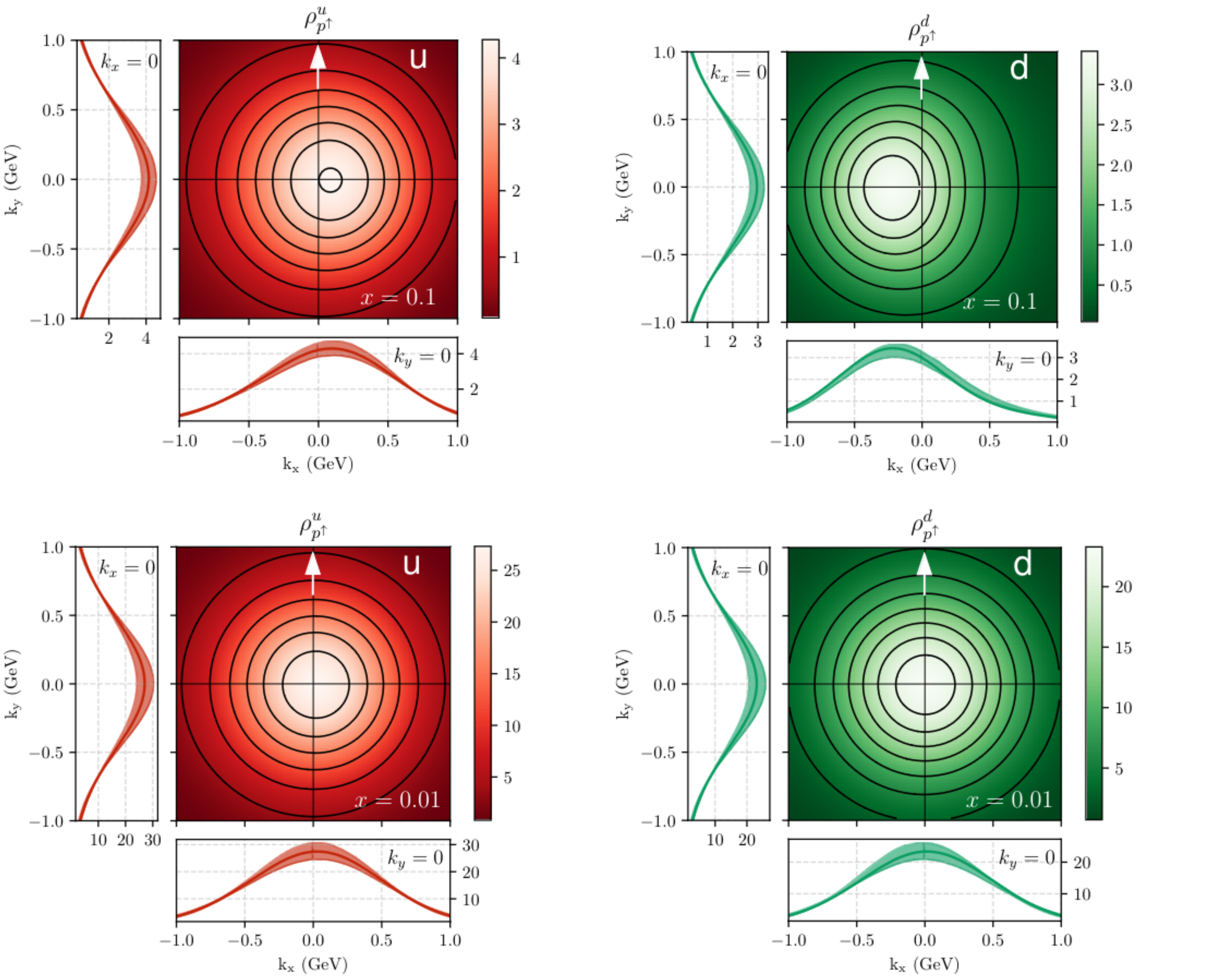
polarized

$$f_1(x, k_\perp; Q^2) - f_{1T}^{\perp}(x, k_\perp; Q^2)$$

PV17



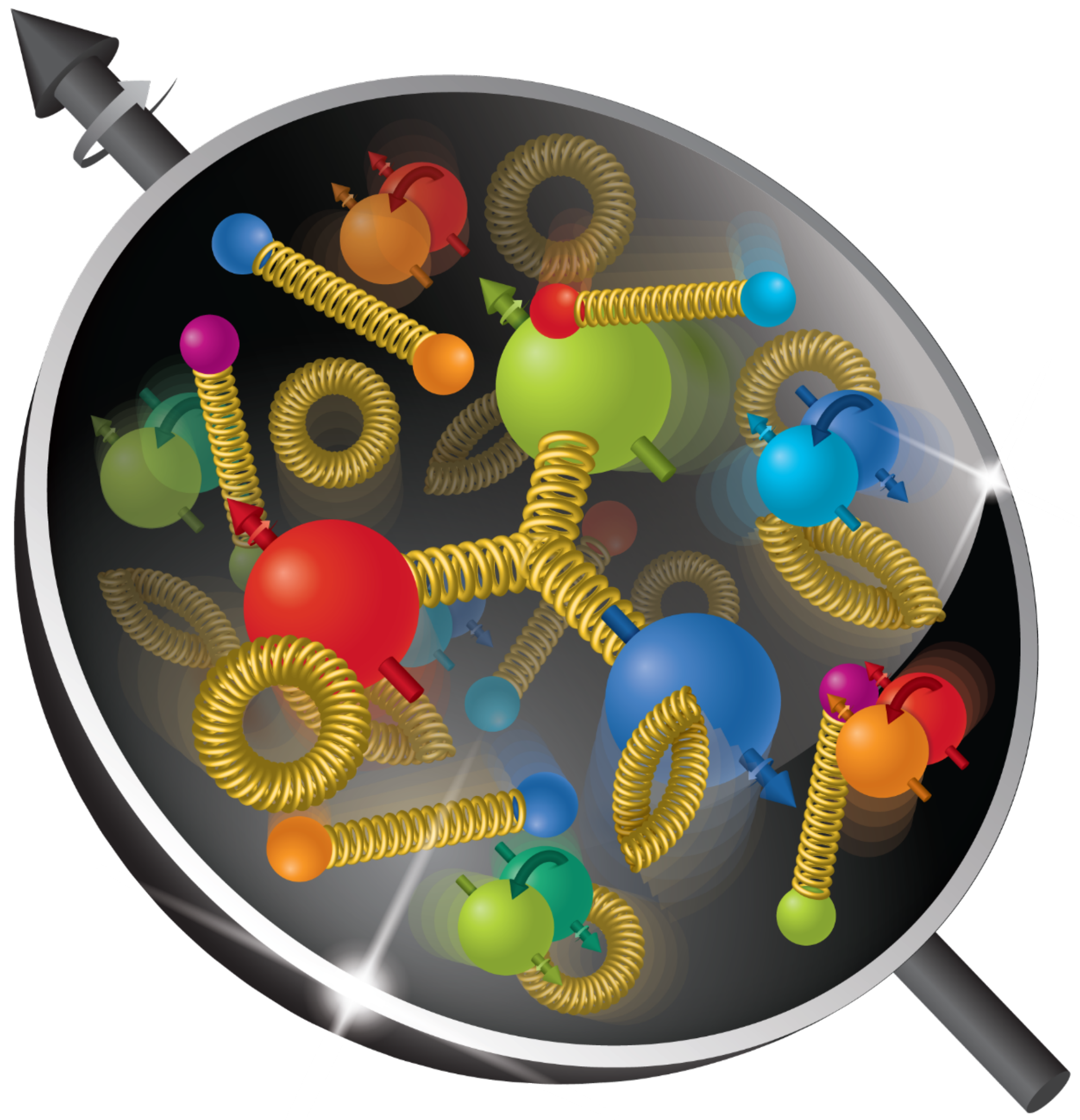
unpolarized



Unpolarized TMD extractions

	Accuracy	SIDIS	DY	Z production	N of points	χ^2/N_{data}
Pavia 2017 JHEP 06 (2017) 081	NLL	✔	✔	✔	8059	1.55
SV 2019 *JHEP* 06 (2020) 137	N^3LL^-	✔	✔	✔	1039	1.06
MAPTMD22 *JHEP* 10 (2022) 127	N^3LL^-	✔	✔	✔	2031	1.06

still missing an important ingredient…



Flavor separation is a fundamental step to fully explore nucleon structure

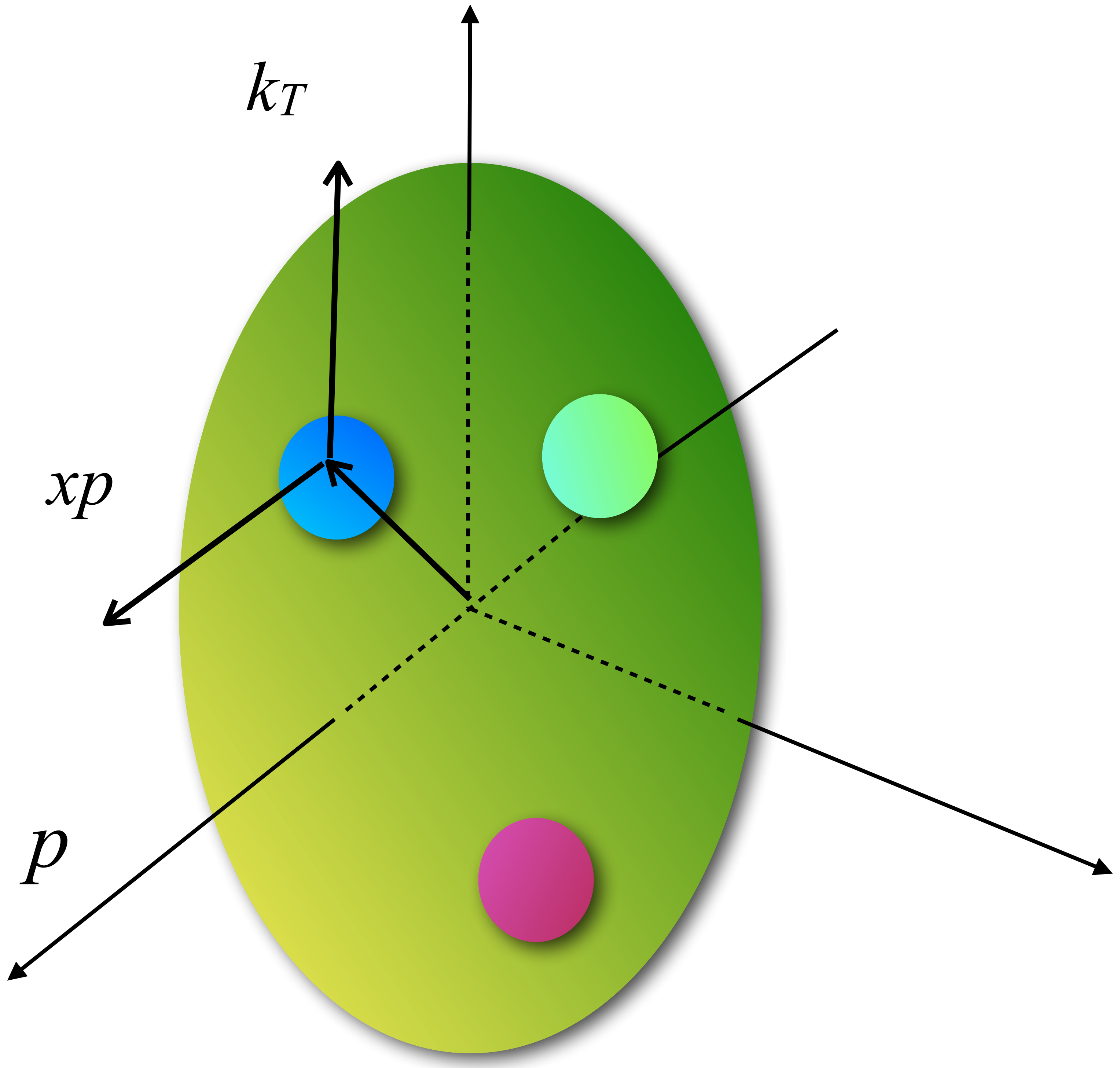
Flavor dependence of unpolarized quark Transverse Momentum Distributions from a global fit

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

MAP **Collaboration** JHEP08(2024)232

Transverse Momentum Distributions

3-dimensional map of the internal structure of the nucleon
(in momentum space)



unpolarized TMD PDF

Features:

Universality: same function, multiple processes

(x, kT) dependence

Q2 energy scale evolution

flavor?

quark polarisation

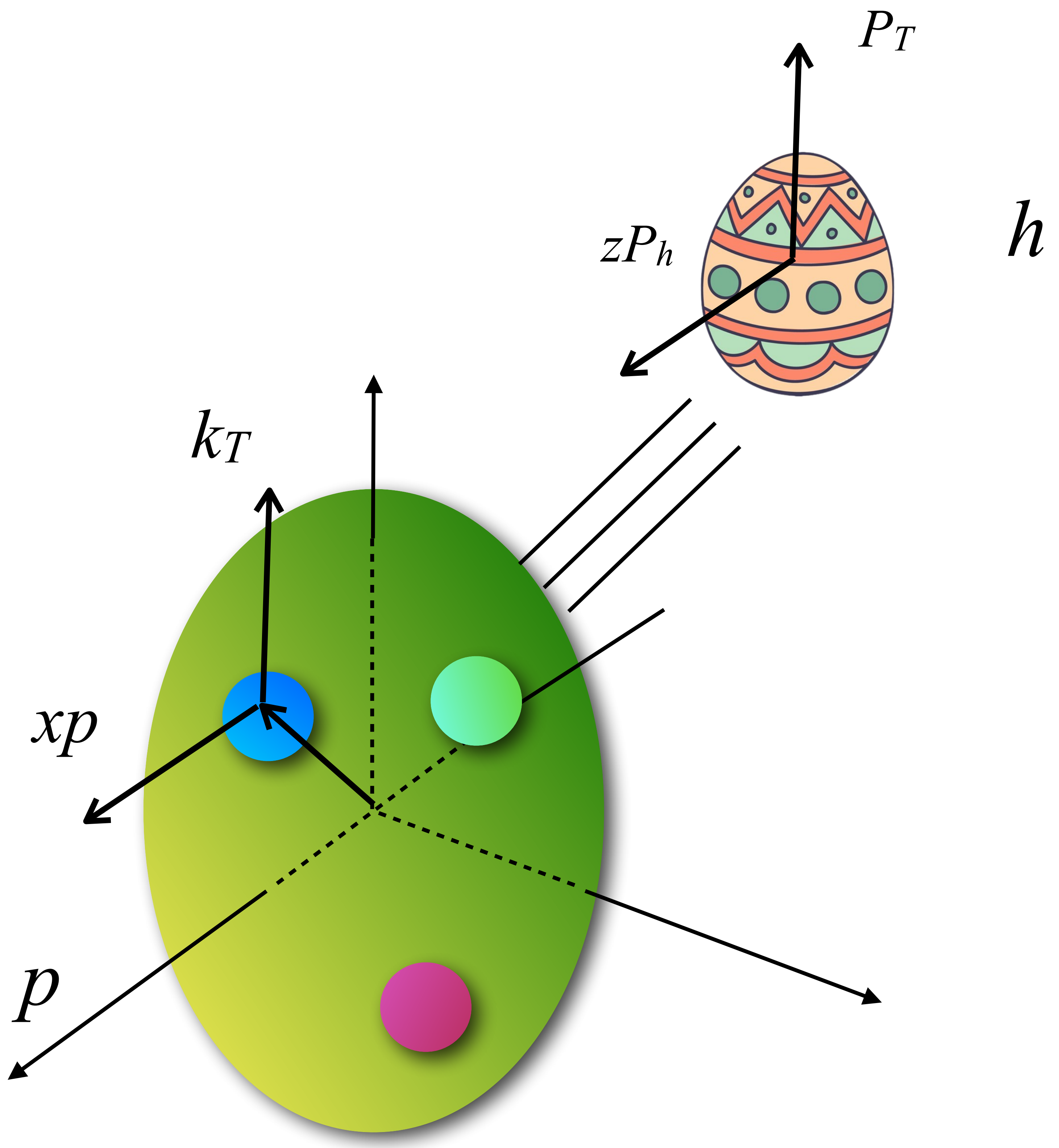
nucleon pol.

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

t-odd t-even

Transverse Momentum Distributions

3-dimensional map of the internal structure of the nucleon



unpolarized TMD FF

Features:

Universality: same function, multiple processes

(z, P_T) dependence

Q2 energy scale evolution

flavor?

quark polarisation

Hadron pol.

leading twist	U	L	T
U	D_1		$D_1^{\perp}$
L		G_{1L}	$H_{1L}^{\perp}$
T	$D_{1T}^{\perp}$	$G_{1T}^{\perp}$	$H_1, H_{1T}^{\perp}$

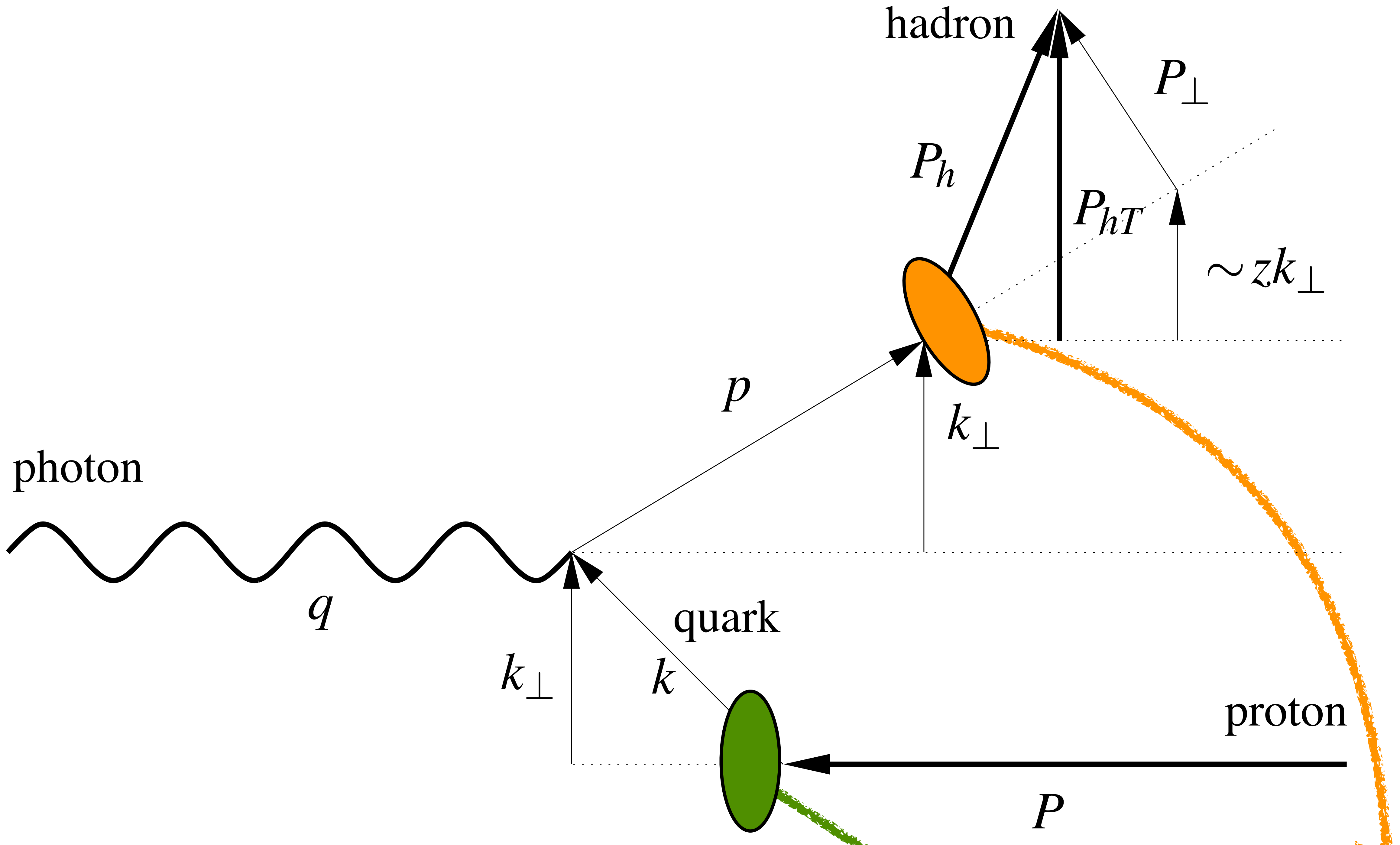
t-odd t-even

TMD formalism: factorization

SIDIS multiplicities

TMD FF

TMD PDF



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

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

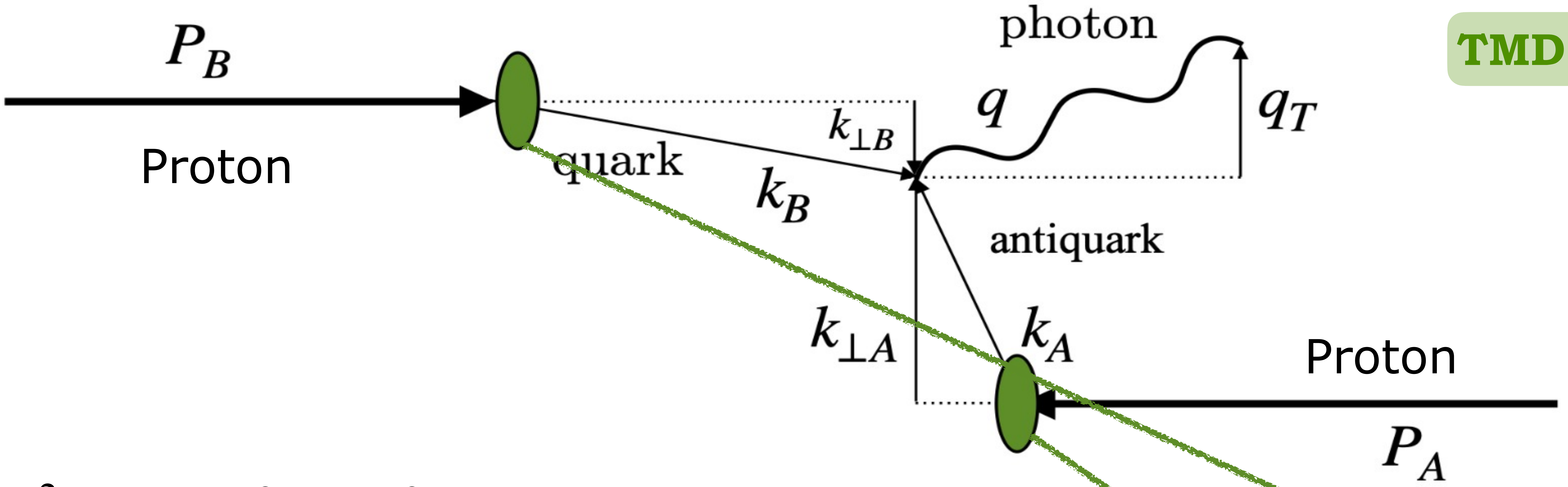
$$+Y_{UU,T}(Q^2,\mathbf{P}_{hT}^2)+\mathcal{O}(M^2/Q^2)$$

W Term

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

TMD formalism: factorization

DY cross section



TMD PDFs

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

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

W term

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

TMD factorization: TMD components

TMD in Fourier space

b$_*$-prescription

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

Collinear extractions

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

Perturbative TMD at the initial scale

Perturbative

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

Evolution to final energy scale of the process

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

Non-perturbative part of the TMD

Parametrization

TO BE FITTED

Collins, "Foundations of Perturbative QCD"

Nanga Parbat: a MAP fit framework

README GPL-3.0 license

Nanga Parbat: a TMD fitting framework

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

Download

You can obtain NangaParbat directly from the github repository:

https://github.com/MapCollaboration/NangaParbat

Our starting point: MAPTMD22 FI global fit

flavor independent

Global fit: DY + SIDIS

2031 data points

DY data

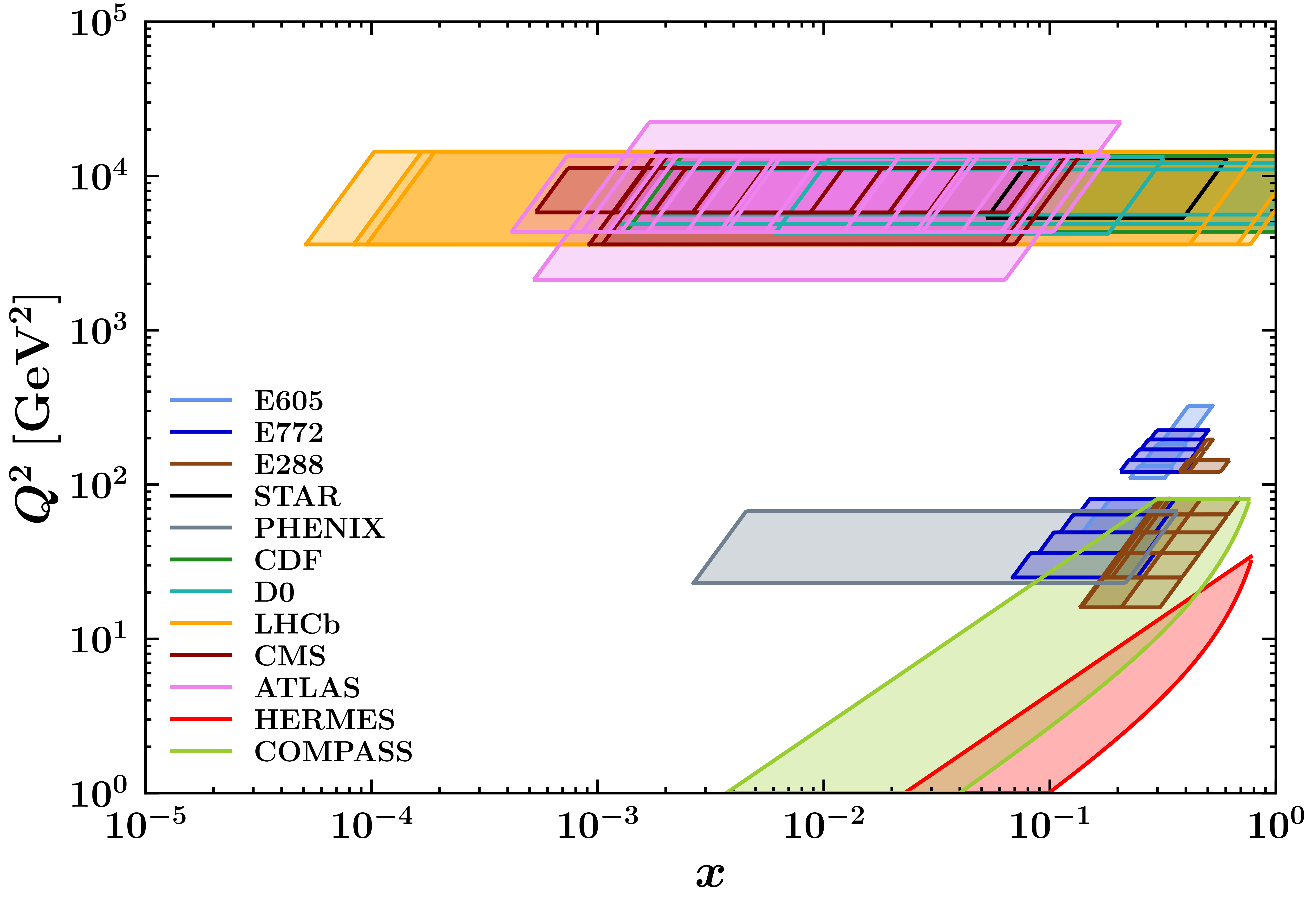
484

SIDIS data

1547

Perturbative accuracy: N³LL⁻

SIDIS
DY fixed target
DY collider



MAPTMD22 parametrisation

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

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

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

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

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

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

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

MAPTMD22 summary

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

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

MAPTMD22 improvement: MAPTMD24

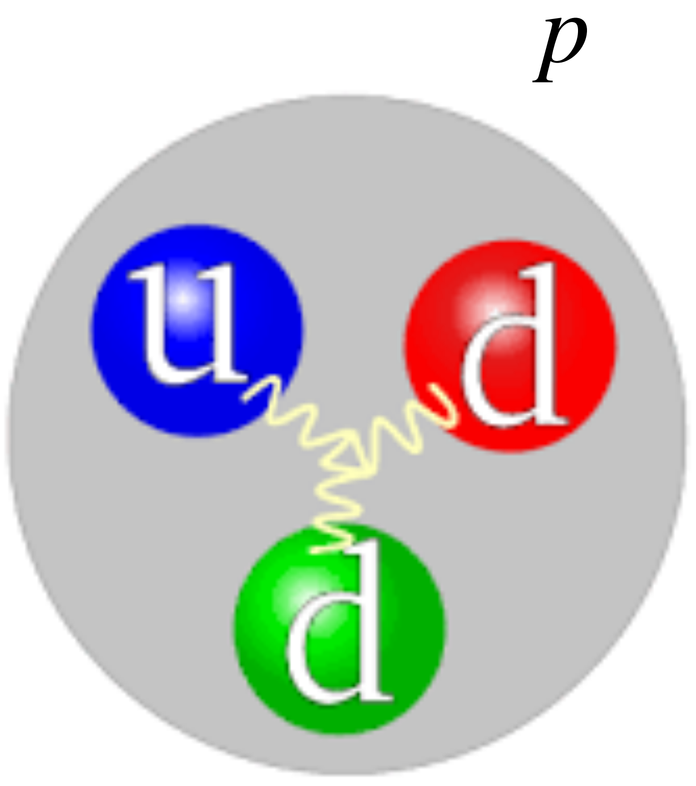
- Global fit of DY and SIDIS data: ***2031*** data points → Same data sets

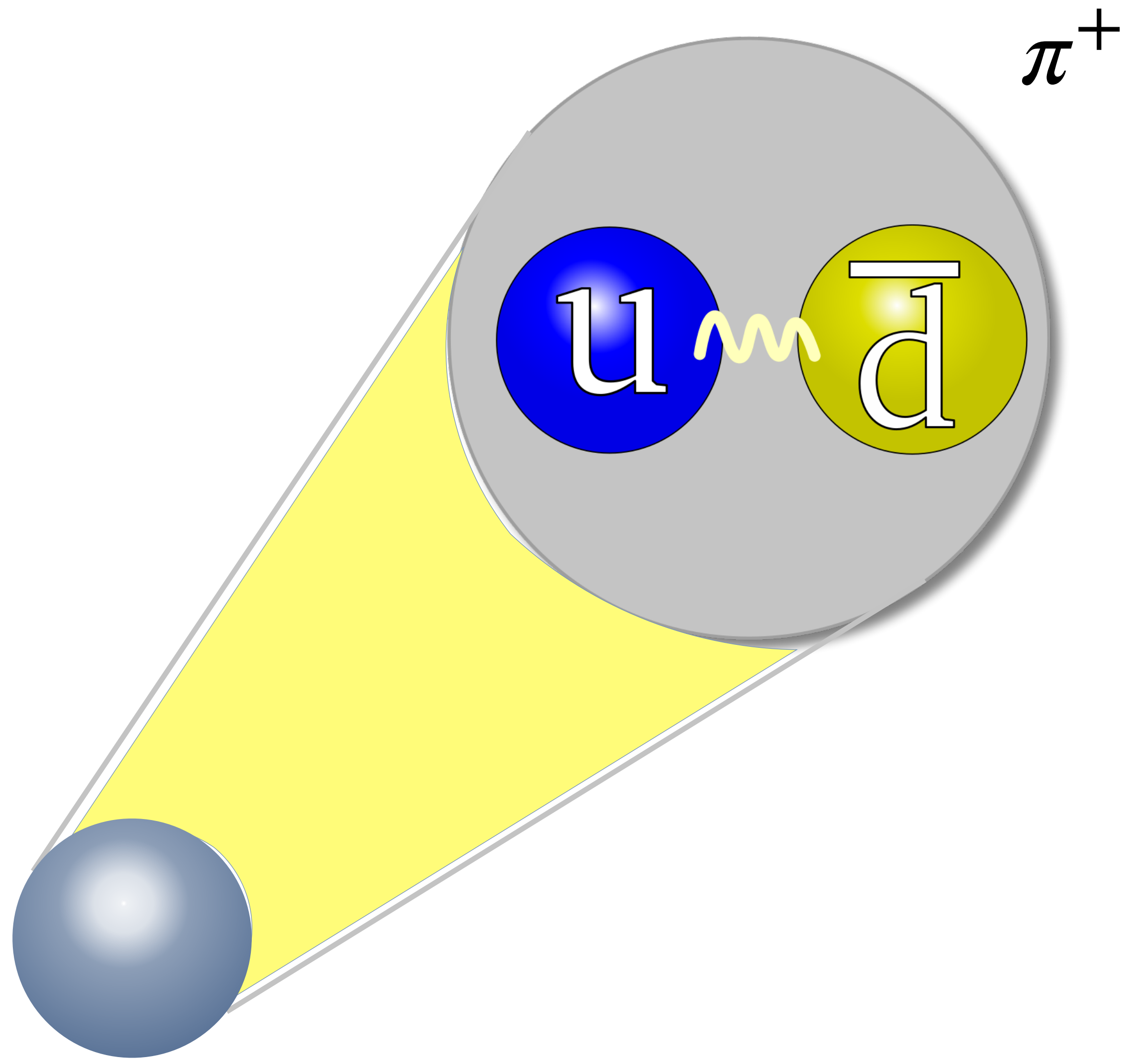
- ***Normalization*** of SIDIS multiplicities beyond NLL → Same approach

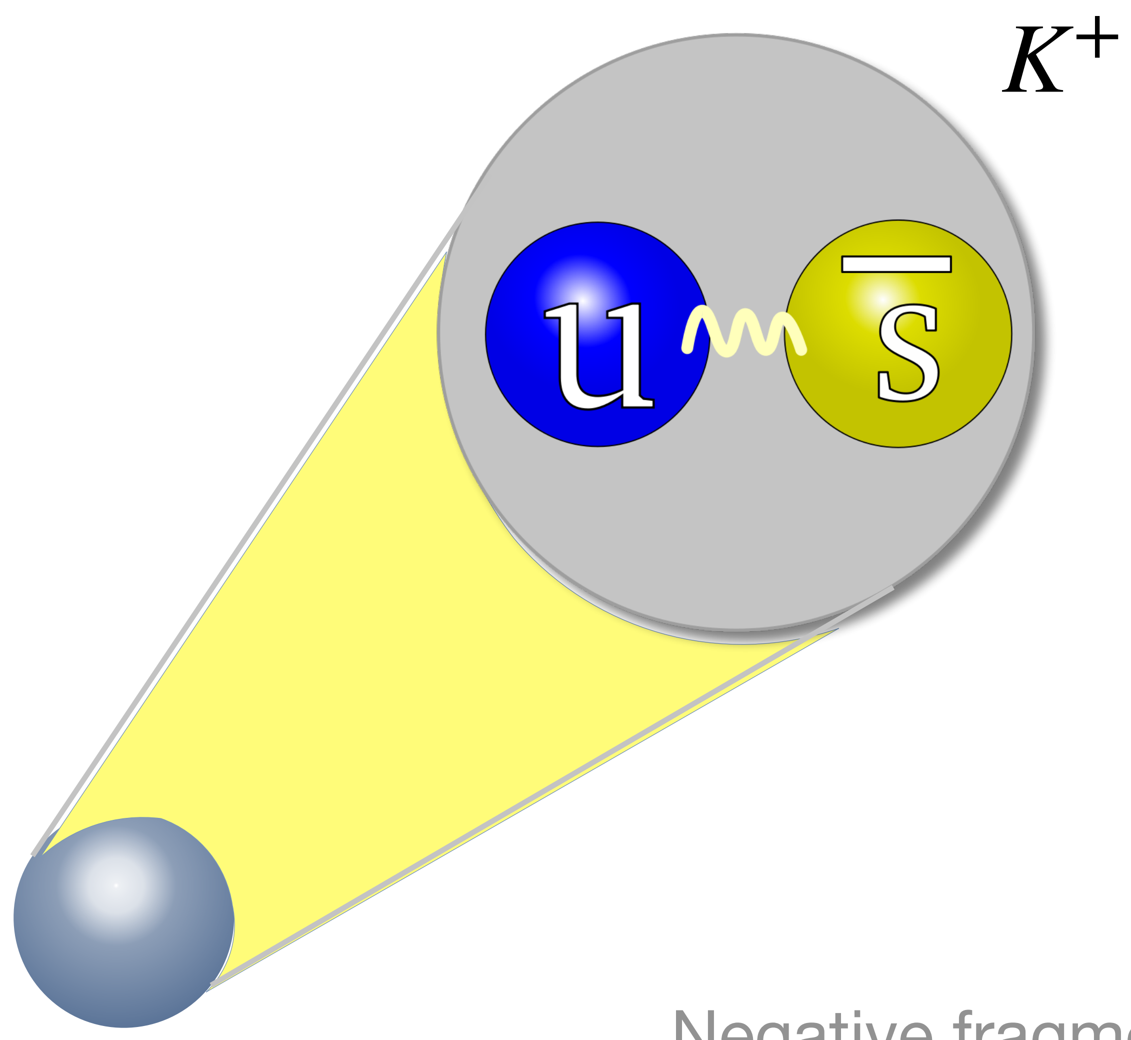
- Number of fitted parameters: ~~***21***~~ ***96*** → Same parametrisation (but flavour dependent)

JHEP08(2024)232

MAPTMD24 flavor parametrization







Negative fragmenting mesons: charge conjugation

u, d

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

$s\ (sea)$

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

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

$u \to K^+, \ldots$

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

$d \to K^+, \ldots$

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

MAPTMD24 extraction - Results

	N^{3}LL			
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**

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

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

2405.13833

MAPTMD24 - Results

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Data set	N_{dat}	χ^2_D	χ^2_λ	χ^2_0
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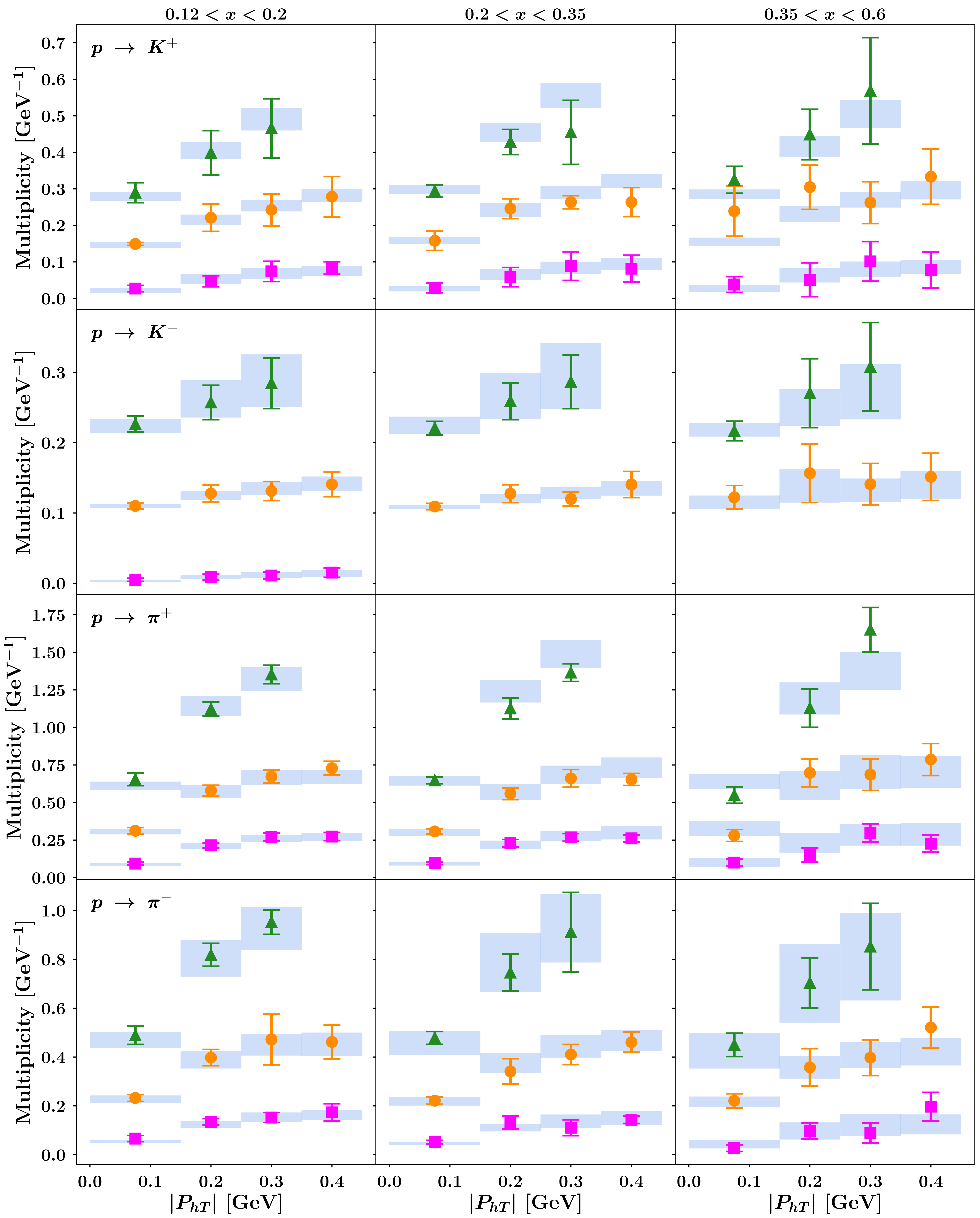

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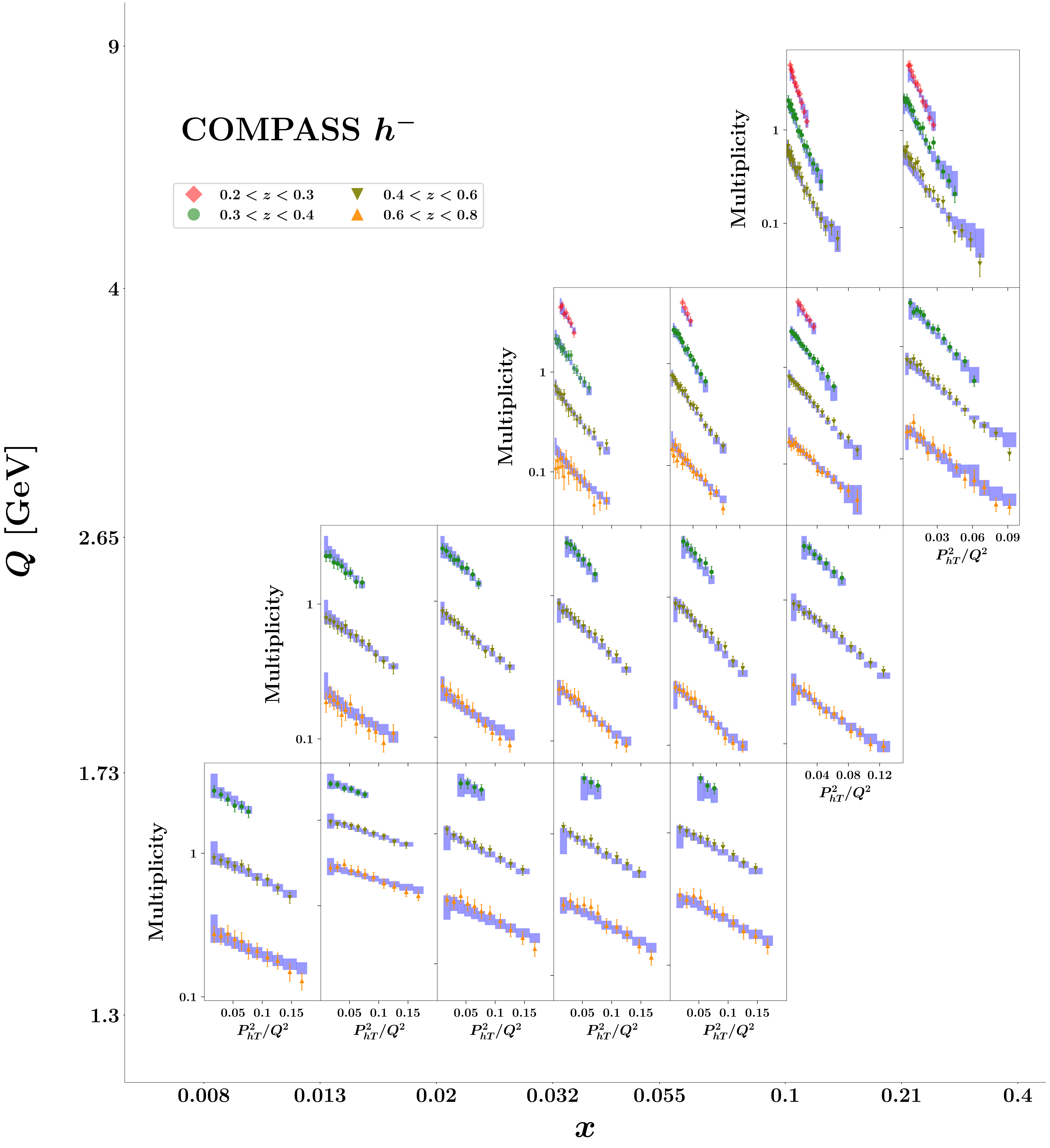

COMPASS 25 years 1997 - 2022

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MAPTMD24 - Results

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hermes

COMPASS
25 years
1997 - 2022

SIDIS data: really good agreement

2405.13833

MAPTMD24 - Results

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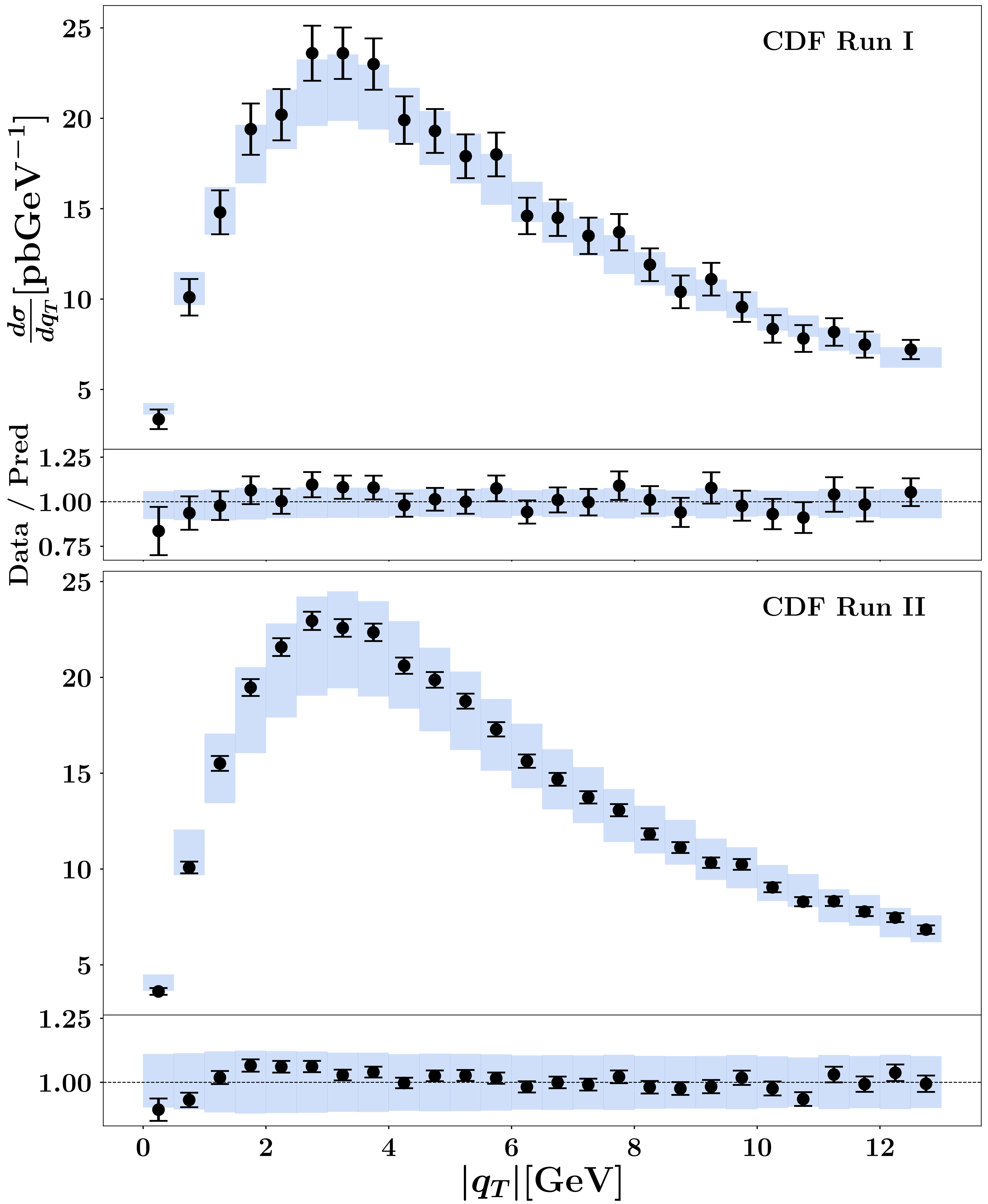
E288 E772 E605

DY fixed: still really good agreement



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MAPTMD24 - Results

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Tevatron

CMS

LHCb

STAR 510

Atlas

PHENIX 200

DY collider: quite good agreement

2405.13833

MAPTMD24 - Results

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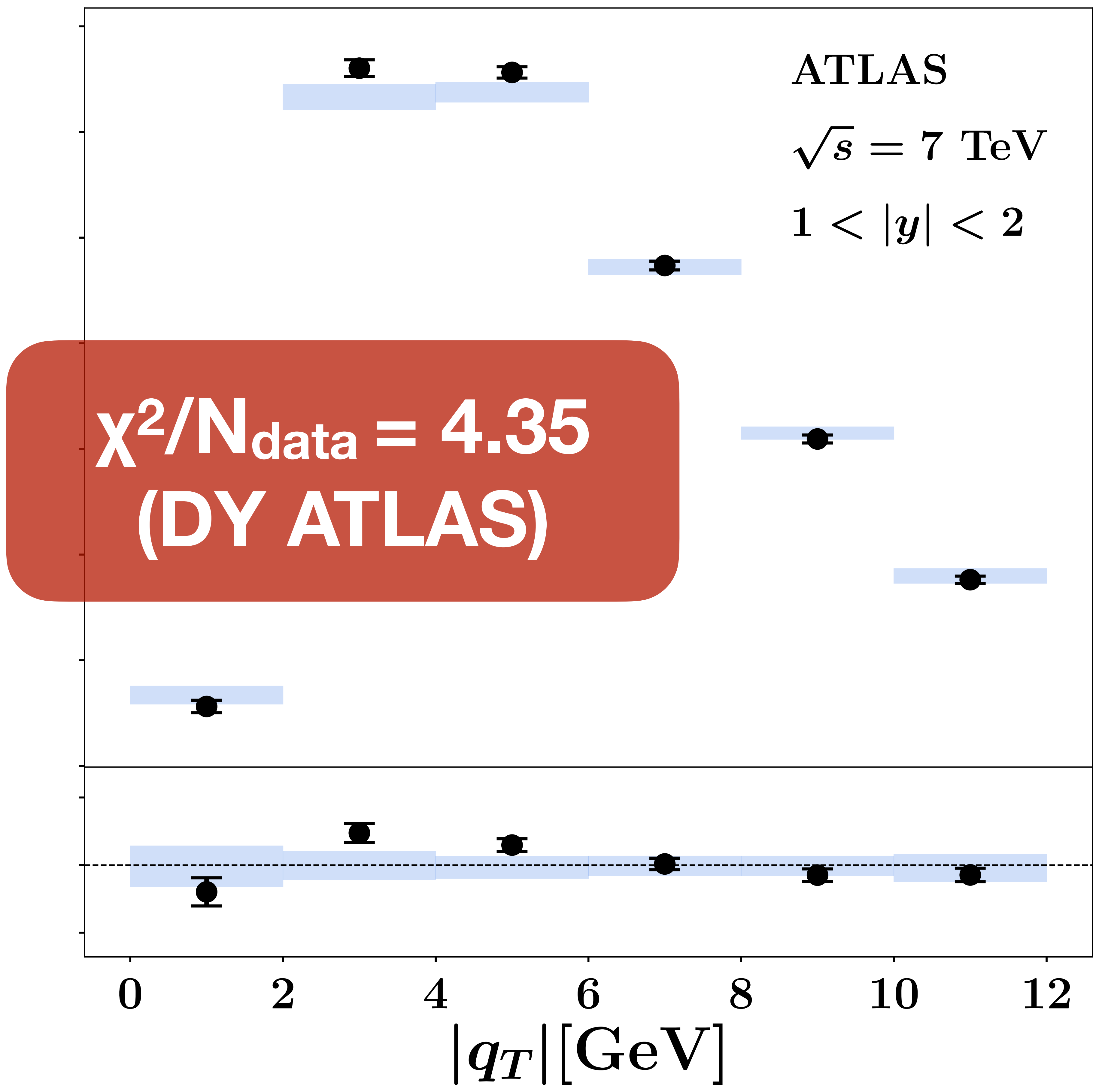

DY collider: quite good agreement

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MAPTMD24 - Results

Flavor-dependent unpolarized TMD PDFs

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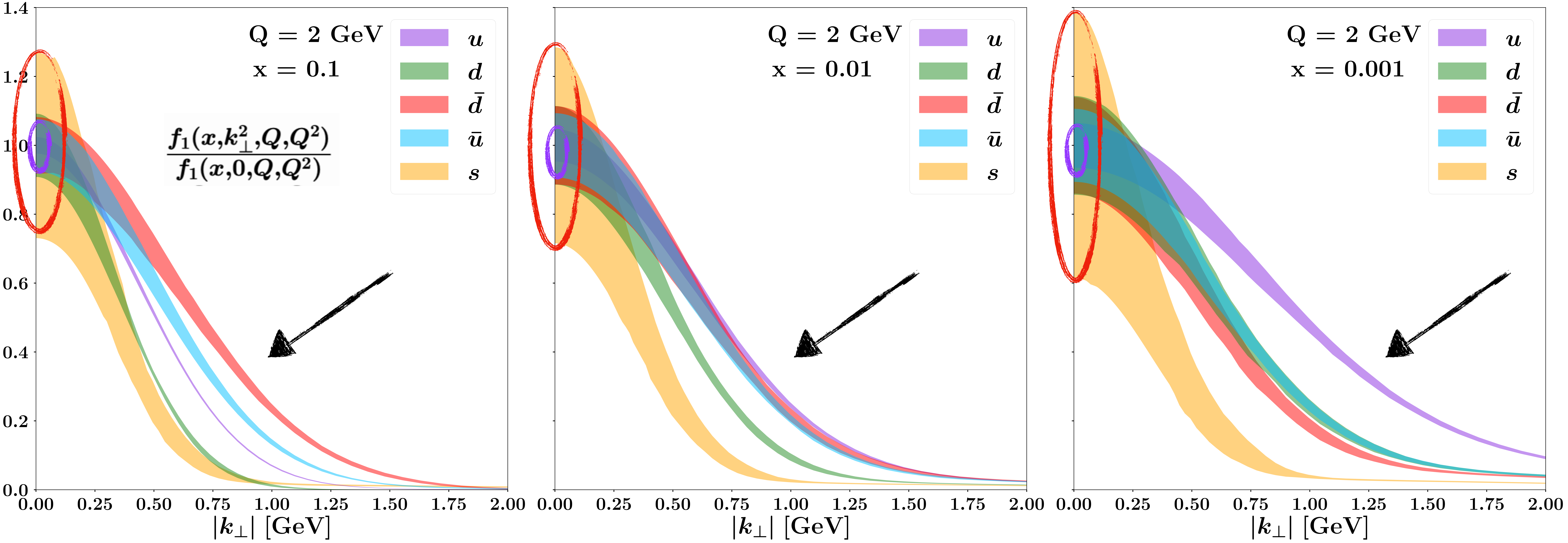
MAPTMD24 - TMD PDF

*The **sea** is the least constrained*

*The **up** quark is the most constrained*



Very different $k_\perp$- behaviours!

also x-dependent

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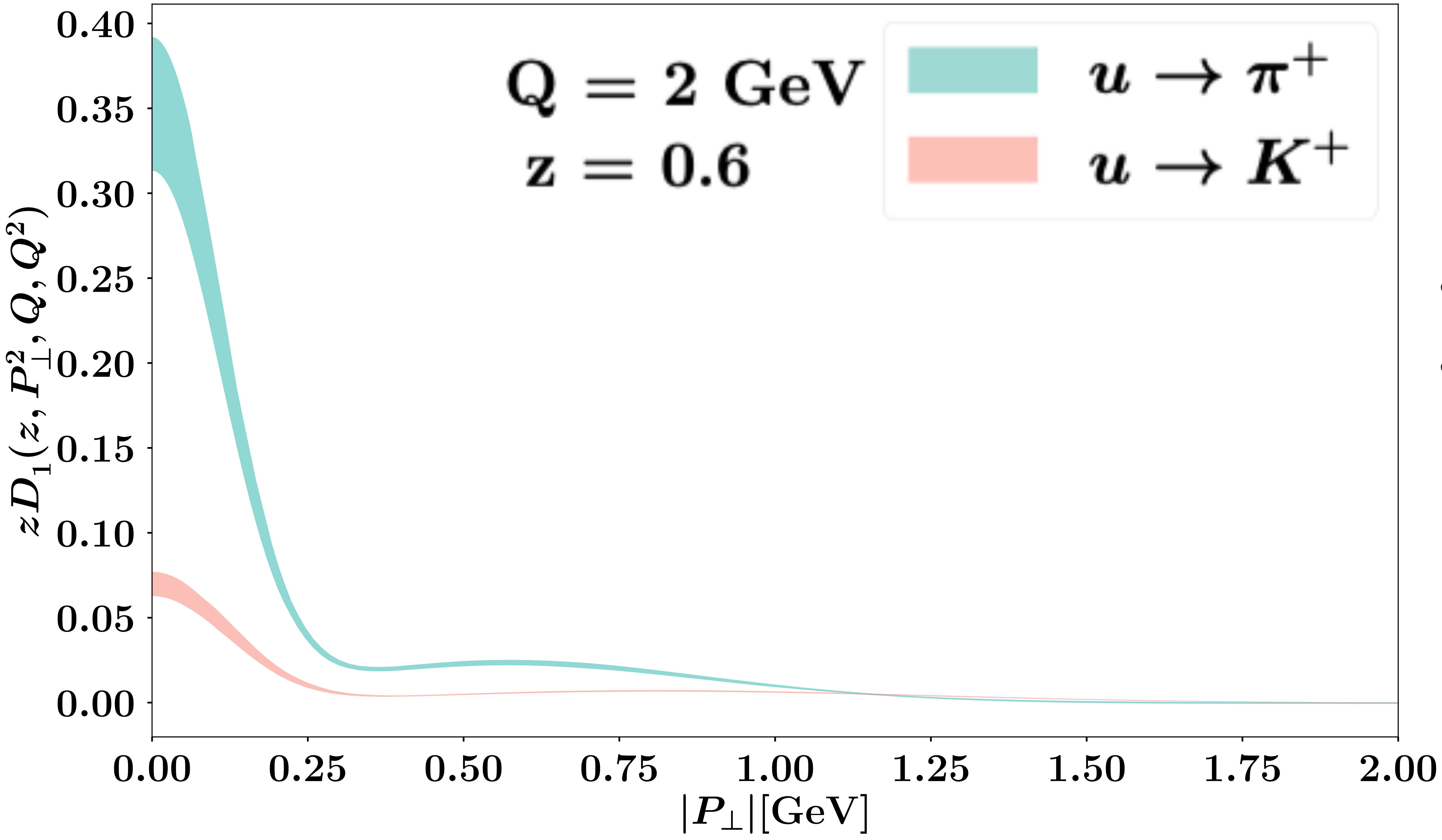
MAPTMD24 - TMD FF

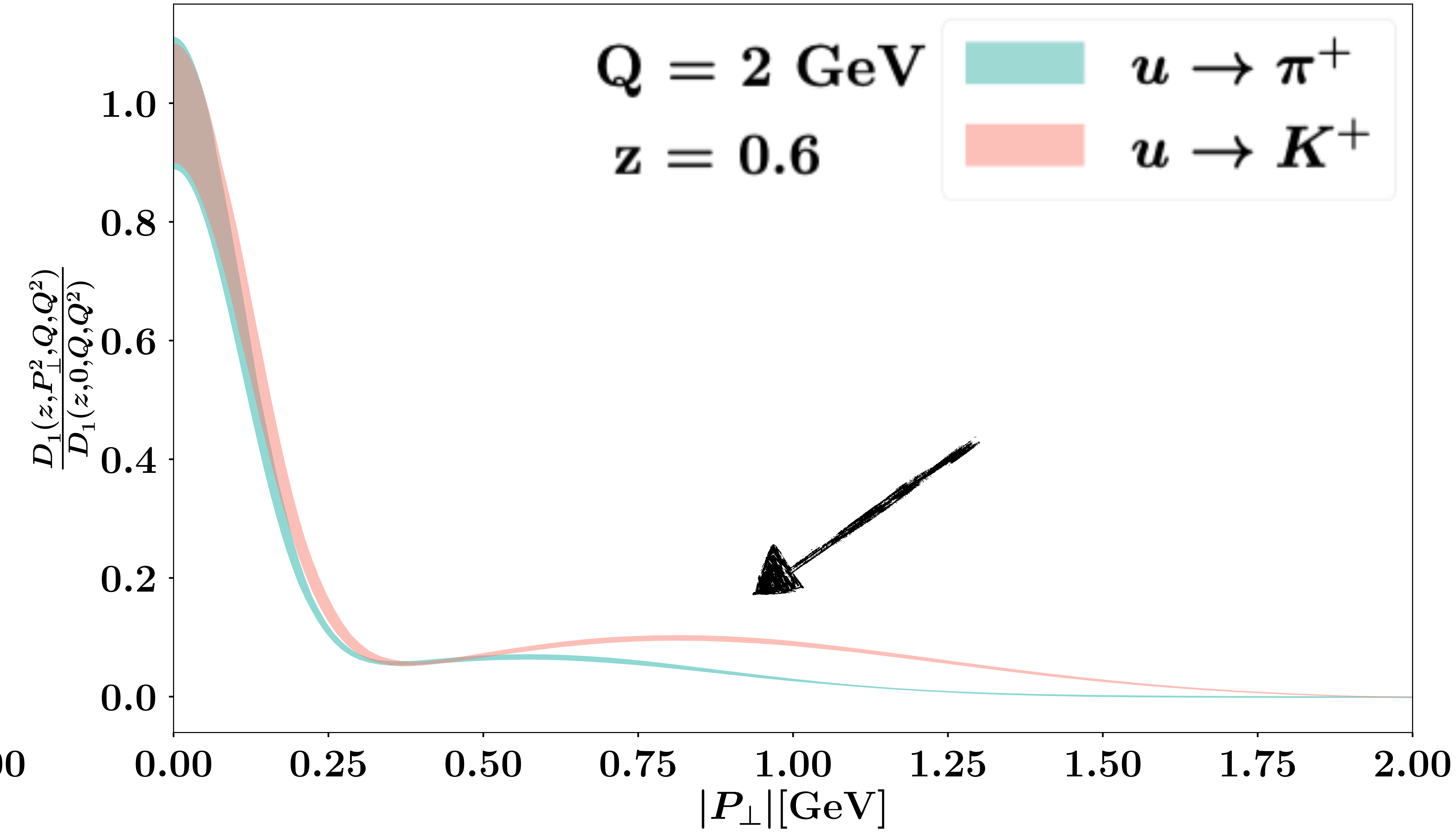
$$\frac{D_1^{\to\pi^+}(z,P_\perp^2,Q,Q^2)}{D_1^{\to\pi^+}(z,0,Q,Q^2)}$$

The favored is better constrained than the unfavored one

Some signals of differences between favored and unfavored channels

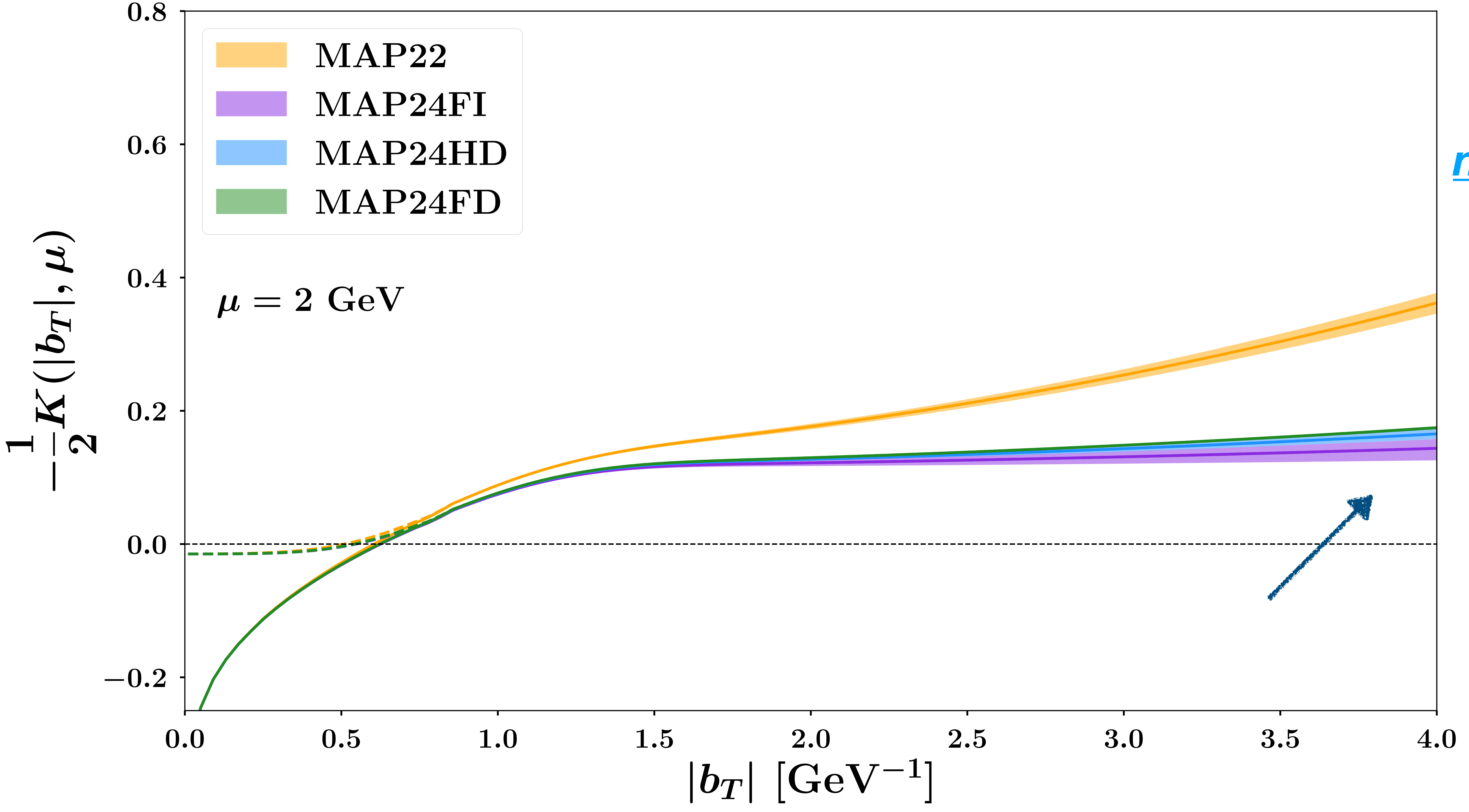
MAPTMD24 - TMD FF





Strong differences between different hadron fragmentations

MAPTMD24 evolution - Collins-Soper kernel



Independent of our ***<u>non-perturbative choices</u>***

Quite flat behaviour

Compatible with latest ***<u>lattice calculation</u>***

PLB 852 (2024) 138617

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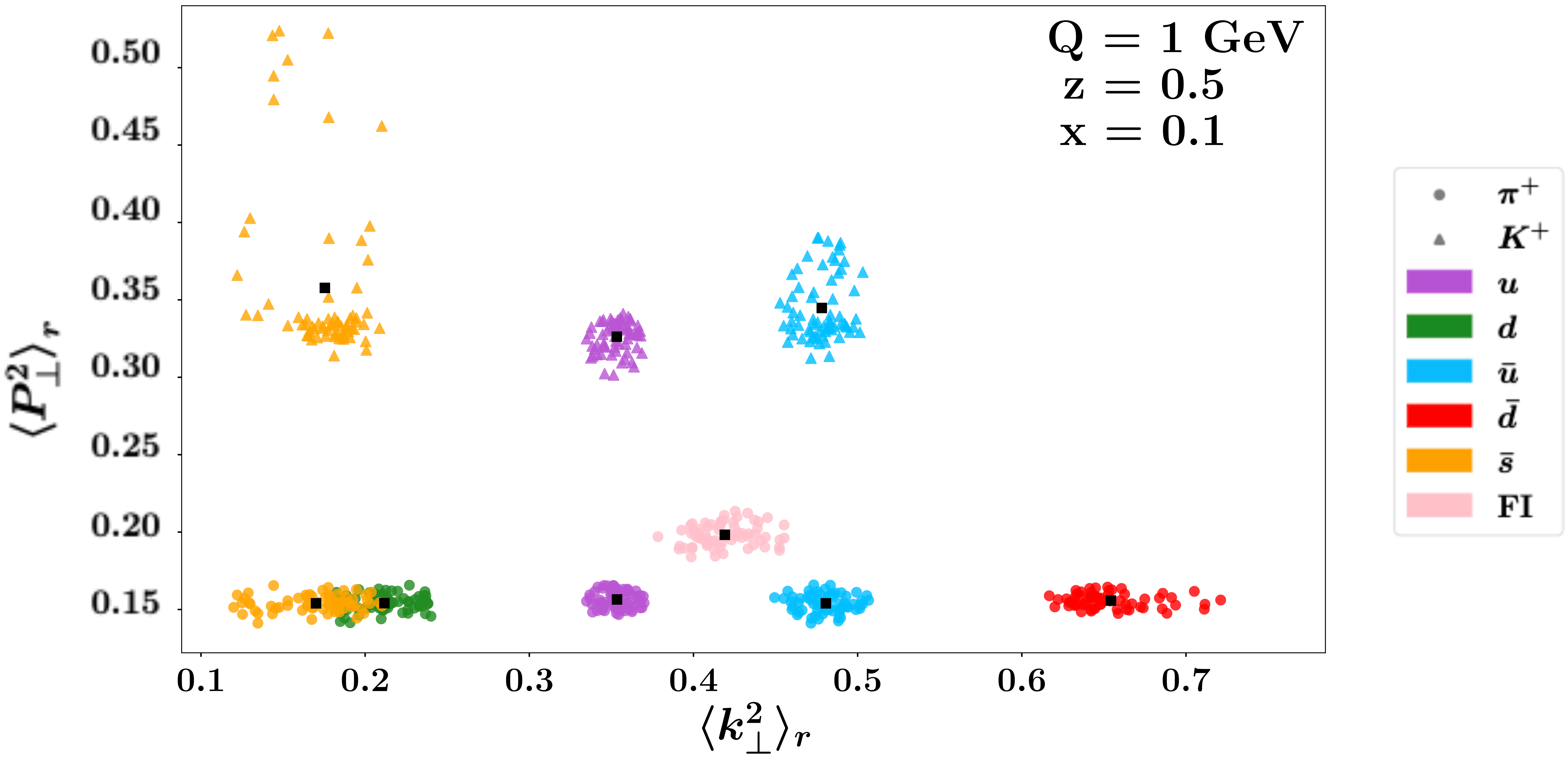
MAPTMD24 - Scatter plots



Evidence of different behaviors for different flavors

Evidence of different behaviors for different measured hadrons

Conclusions

- The extractions of **unpolarized quark TMDs** through global fits have reached very high accuracy (NNNLL), we need to introduce **flavor dependence** to obtain good theory/data agreement, especially with future, more precise experiments (EIC)
- **MAPTMD24** is the **first** simultaneous extraction of **flavor-dependent unpolarized TMD PDFs and FF through a global fit**
- We observed ***significant*** differences between the flavors in the ***TMD PDFs***.
- We observed ***significant*** differences between different final hadrons in the ***TMD FFs***.
- We are finding a weak signal between different flavors in the same final hadron.