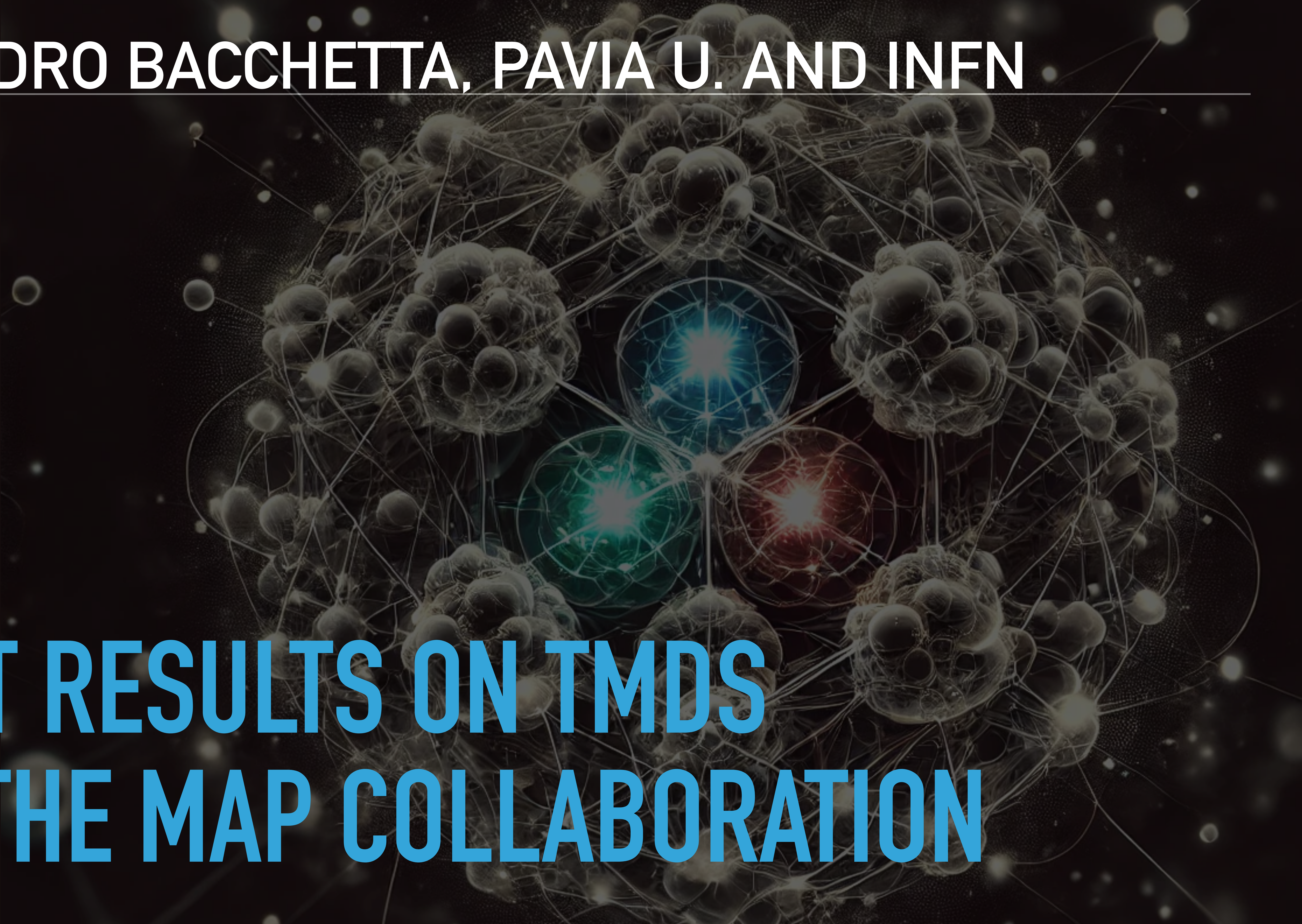
ALESSANDRO BACCHETTA, PAVIA U. AND INFN



RECENT RESULTS ON TMDS FROM THE MAP COLLABORATION


BY THE MAP COLLABORATION
https://github.com/MapCollaboration
HARVARD

MAINLY BASED ON RESULTS OBTAINED WITH

Valerio Bertone

Chiara Bissolotti

Alessia Bongallino

Giuseppe Bozzi

Matteo Cerutti

Filippo Delcarro

Fulvio Piacenza

Marco Radici

Simone Rodini

Lorenzo Rossi

Andrea Signori

Finanziato dall'Unione europea
NextGenerationEU

MUR PRIN

NEW SINCE SPIN 2023

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- MAP24: extraction of unpolarized TMDs with flavor dependence (arXiv:2405.13833)

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- MAPTMDNN: proof-of-concept extraction of unpolarized TMDs with NN (arXiv:2502.04166)

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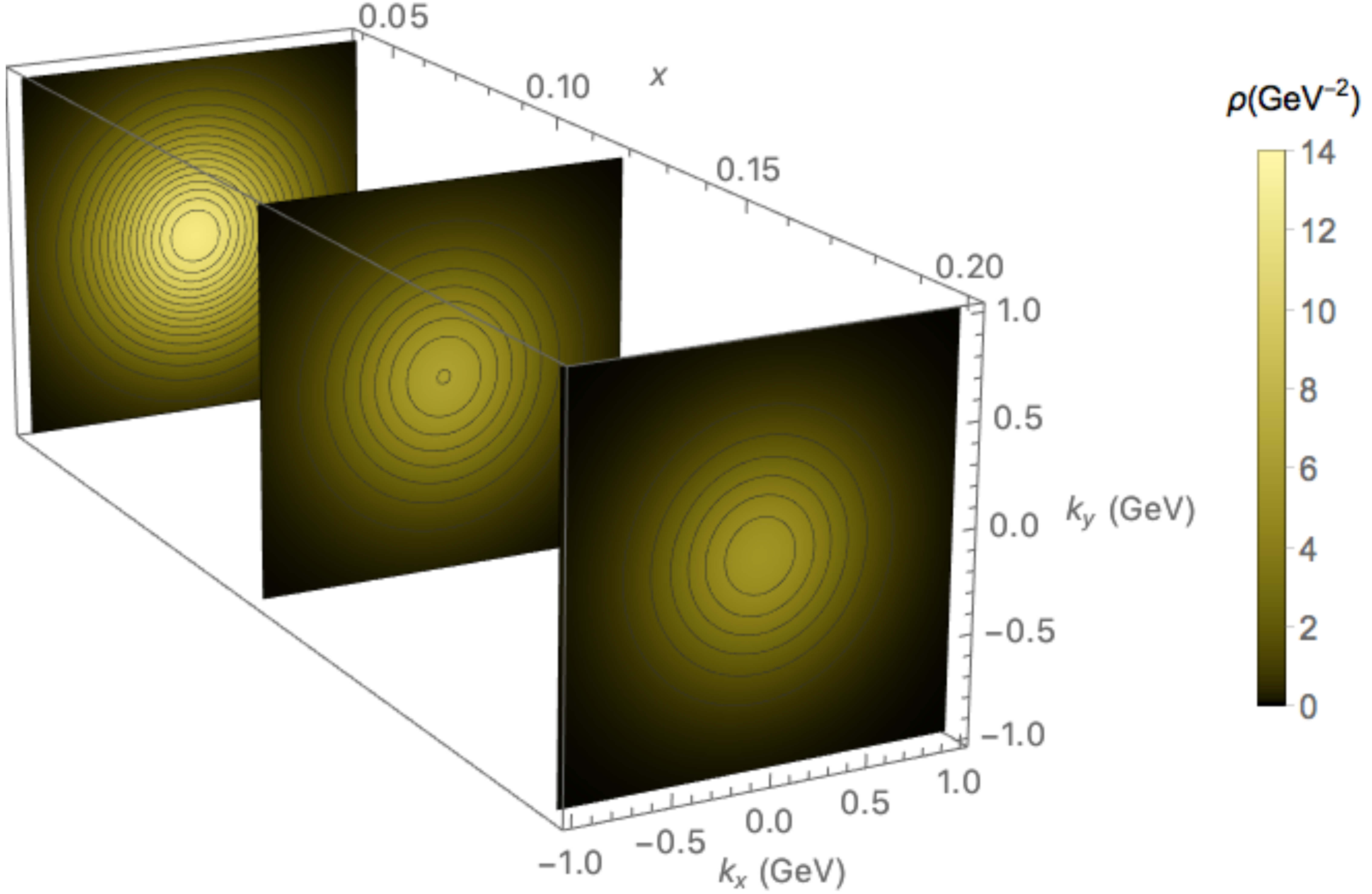
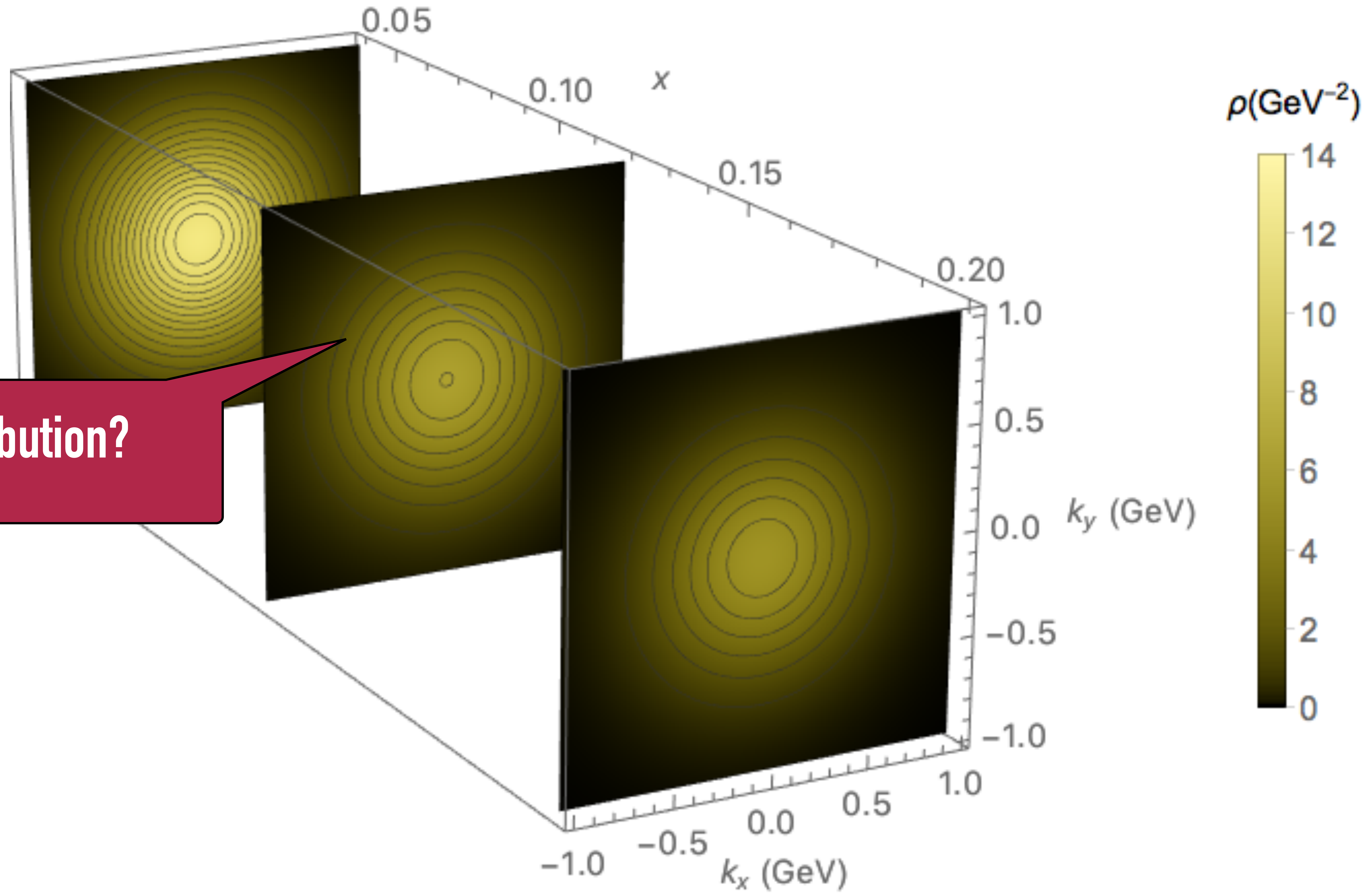
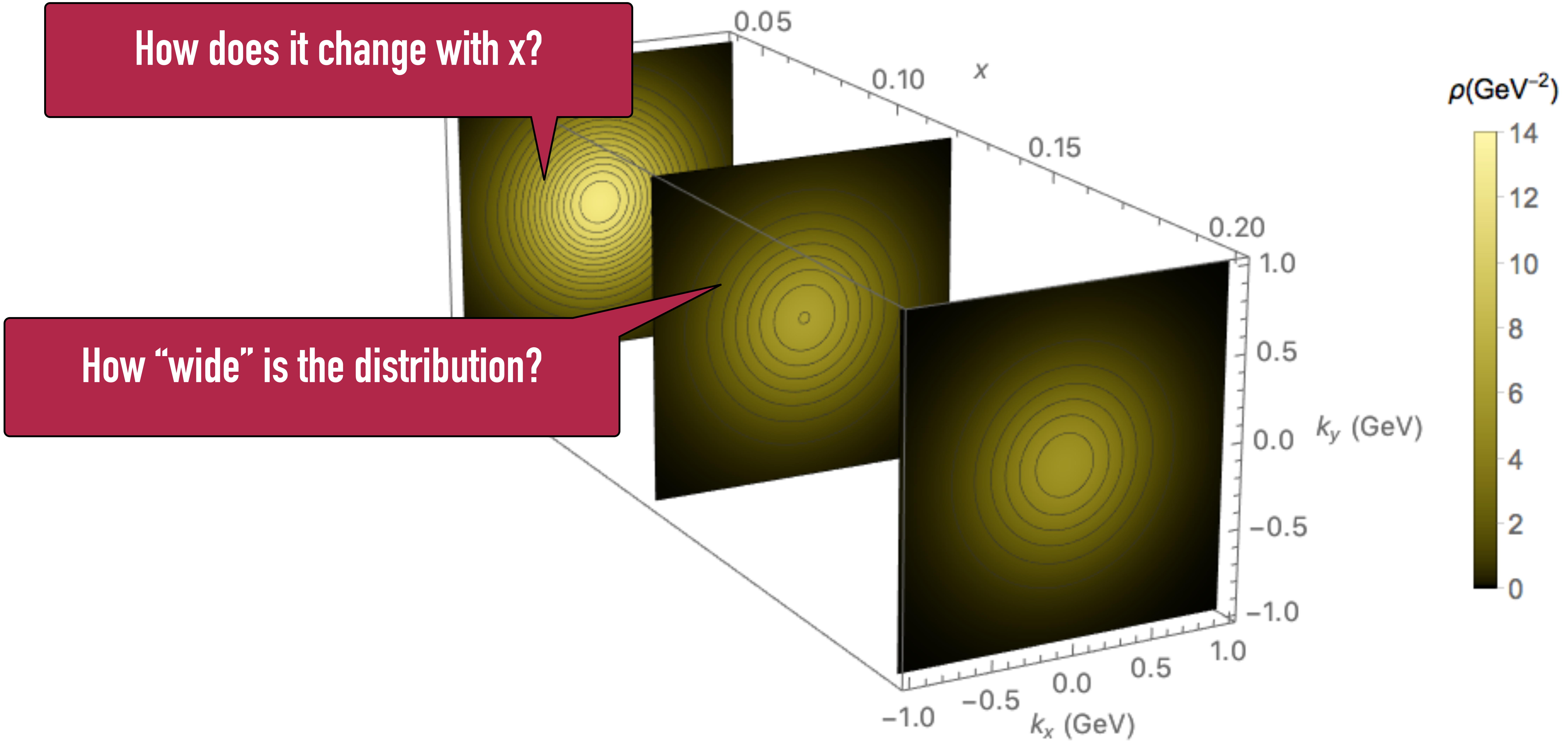
- MAPTMDpol: extraction of helicity TMDs (arXiv:2409.18078)

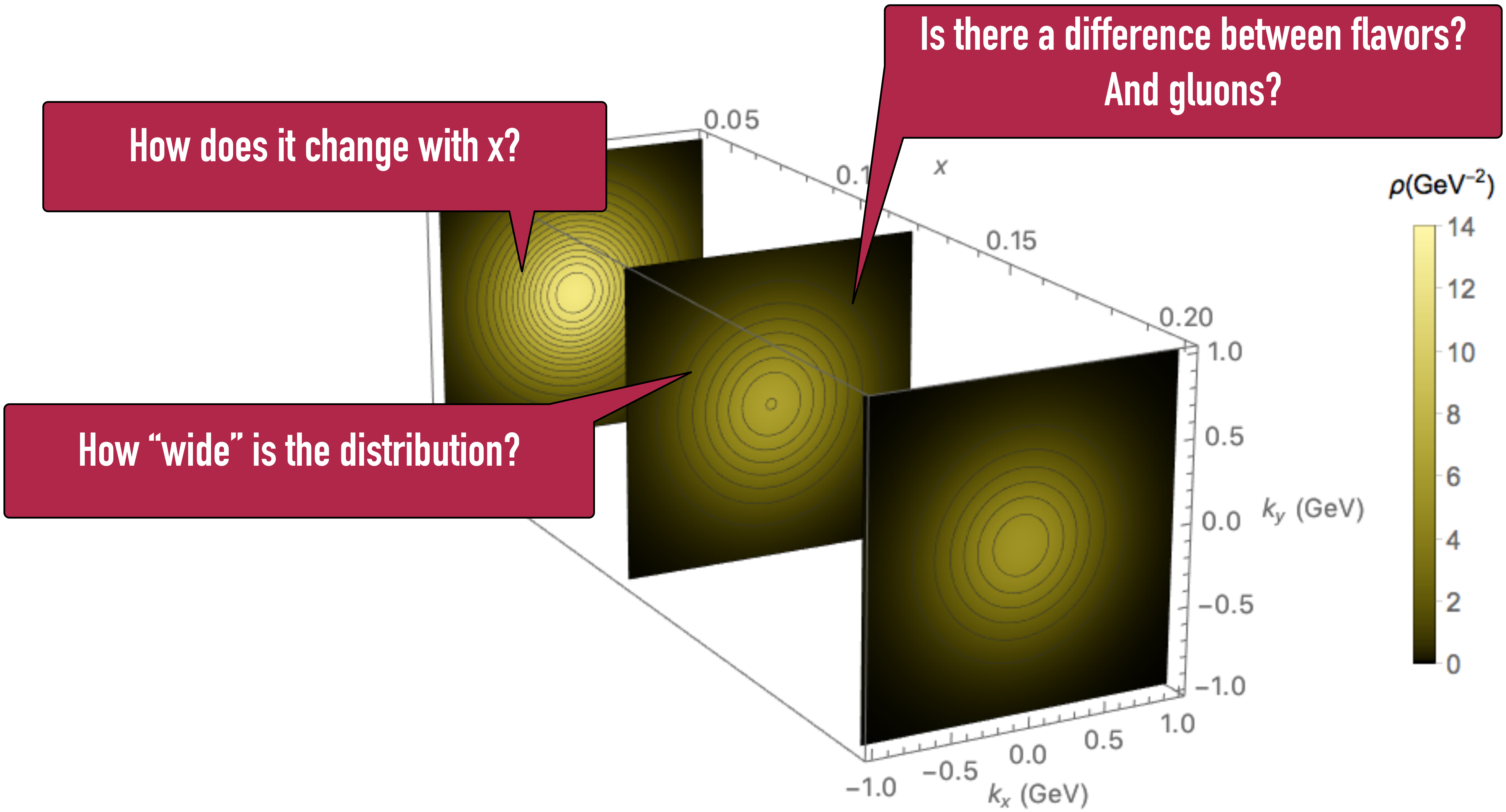


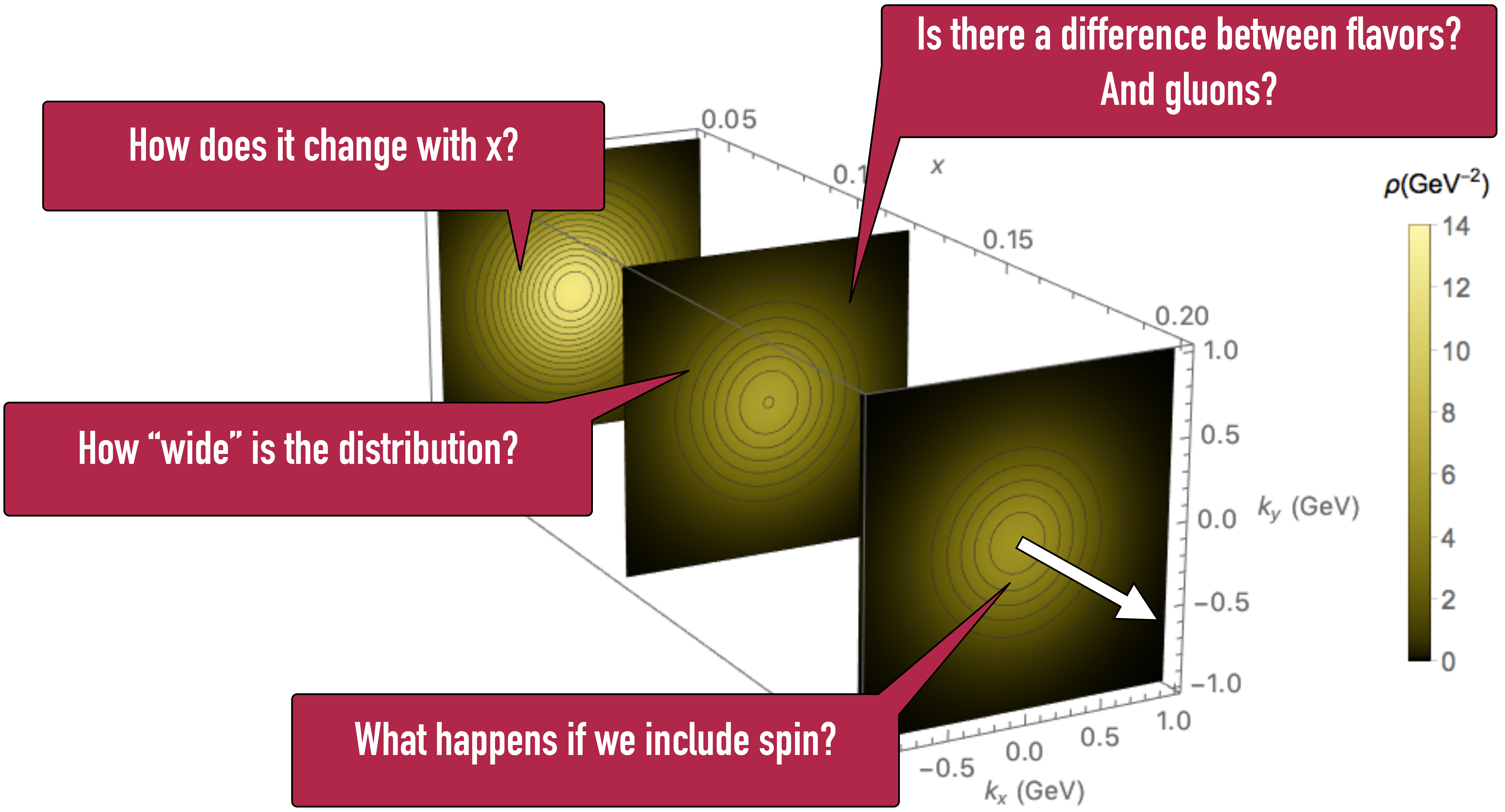
0.05
0.10
x
0.15
0.20
1.0
0.5
0.0
−0.5
−1.0
k_y (GeV)
−1.0
−0.5
0.0
0.5
1.0
k_x (GeV)
ρ(GeV^{-2})
14
12
10
8
6
4
2
0



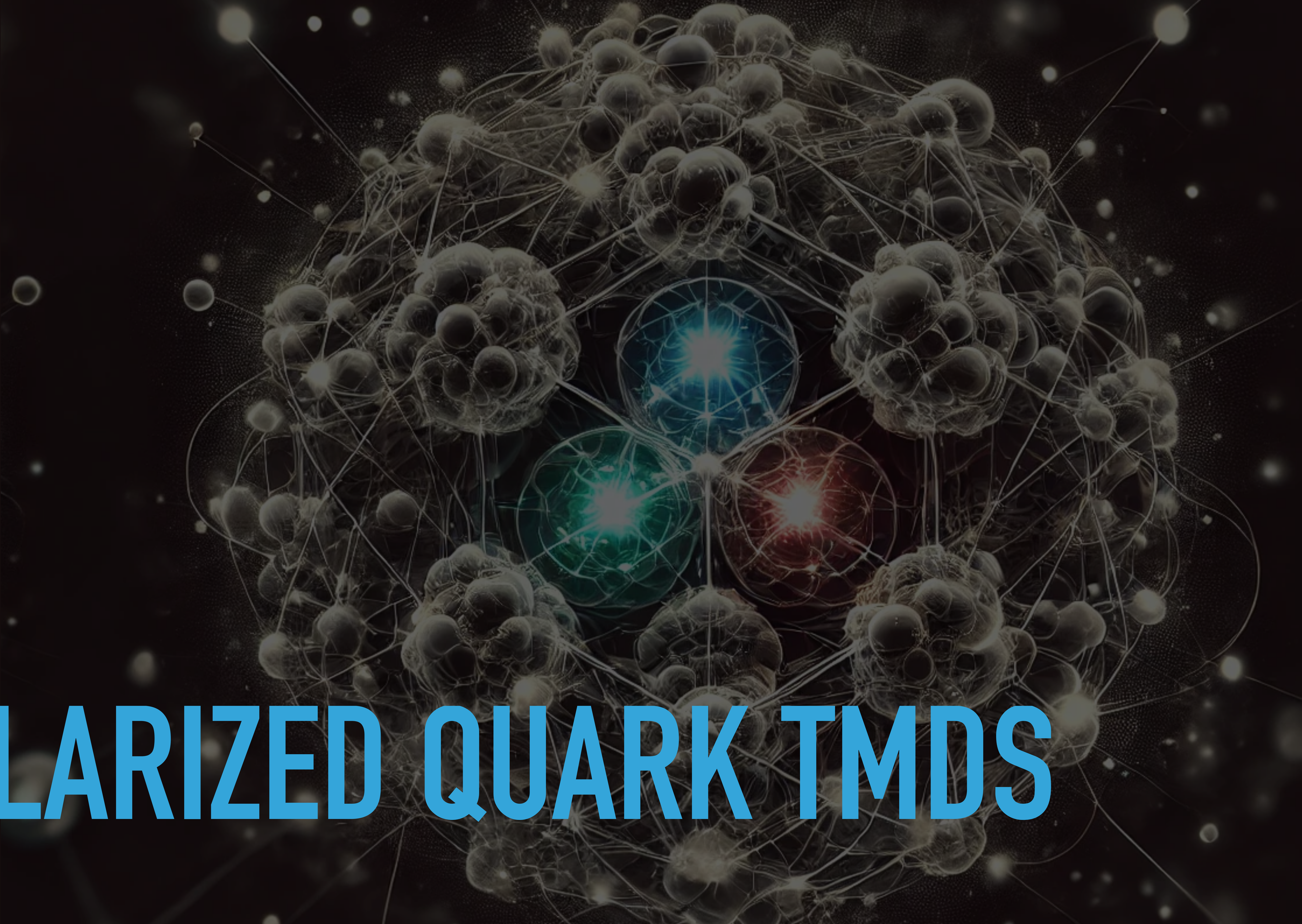
How “wide” is the distribution?


How does it change with x?
How “wide” is the distribution?
0.05
0.10
x
0.15
0.20
1.0
0.5
0.0
−0.5
−1.0
k_y (GeV)
−1.0
−0.5
0.0
0.5
1.0
k_x (GeV)
$\rho(\mathrm{GeV}^{-2})$
14
12
10
8
6
4
2
0


How does it change with x?
Is there a difference between flavors?
And gluons?
How "wide" is the distribution?
0.05
0.1
0.15
0.20
x
ρ(GeV^-2)
14
12
10
8
6
4
2
0
1.0
0.5
0.0
−0.5
−1.0
k_y (GeV)
−1.0
−0.5
0.0
0.5
1.0
k_x (GeV)

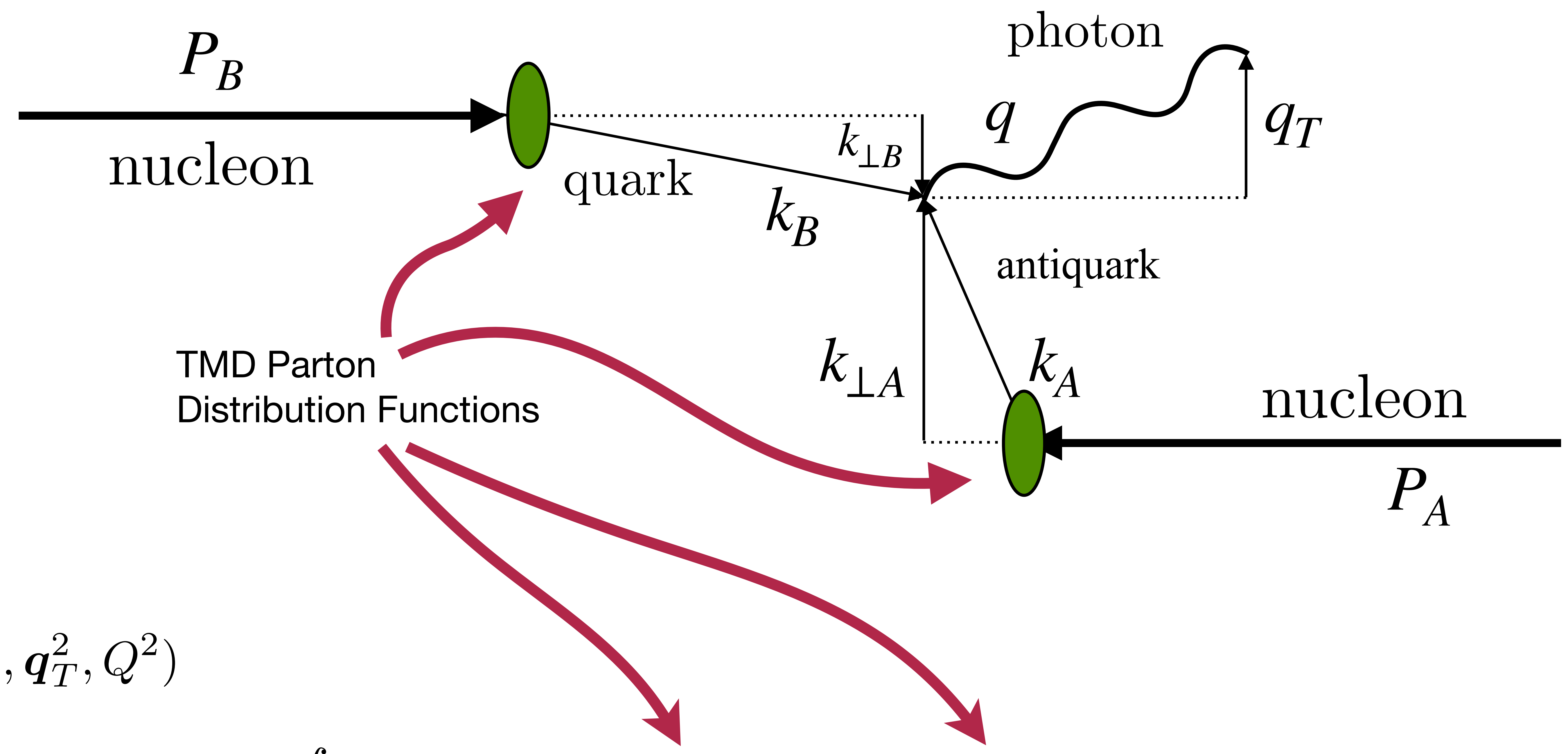


Is there a difference between flavors?
And gluons?
How does it change with x?
How "wide" is the distribution?
What happens if we include spin?
0.05
0.15
0.20
x
1.0
0.5
0.0
−0.5
−1.0
k_y (GeV)
−0.5
0.0
0.5
1.0
k_x (GeV)
ρ(GeV^{-2})
14
12
10
8
6
4
2
0



UNPOLARIZED QUARK TMDS

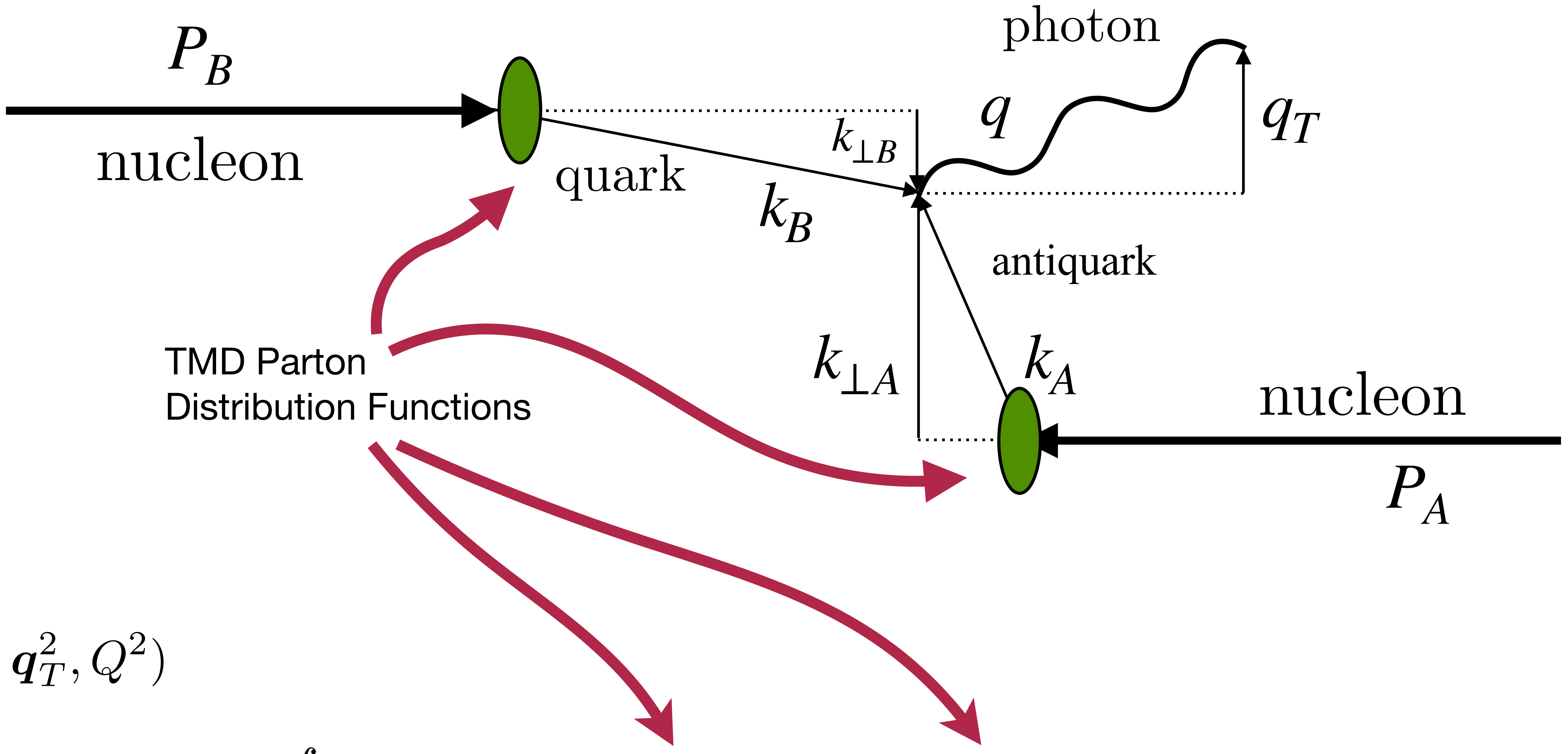
TMDS IN DRELL-YAN PROCESSES



$$F^1_{UU}(x_A, x_B, \boldsymbol{q}_T^2, Q^2)$$

$$\approx \sum_q \mathcal{H}^{1q}_{UU}(Q^2, \mu^2) \int d^2\boldsymbol{k}_{\perp A}\, d^2\boldsymbol{k}_{\perp B}\, f_1^q\big(x_A, \boldsymbol{k}^2_{\perp A}; \mu^2\big)\, f_1^{\bar{q}}\big(x_B, \boldsymbol{k}^2_{\perp B}; \mu^2\big)\, \delta^{(2)}\big(\boldsymbol{k}_{\perp A} - \boldsymbol{q}_T + \boldsymbol{k}_{\perp B}\big)$$

TMDS IN DRELL-YAN PROCESSES



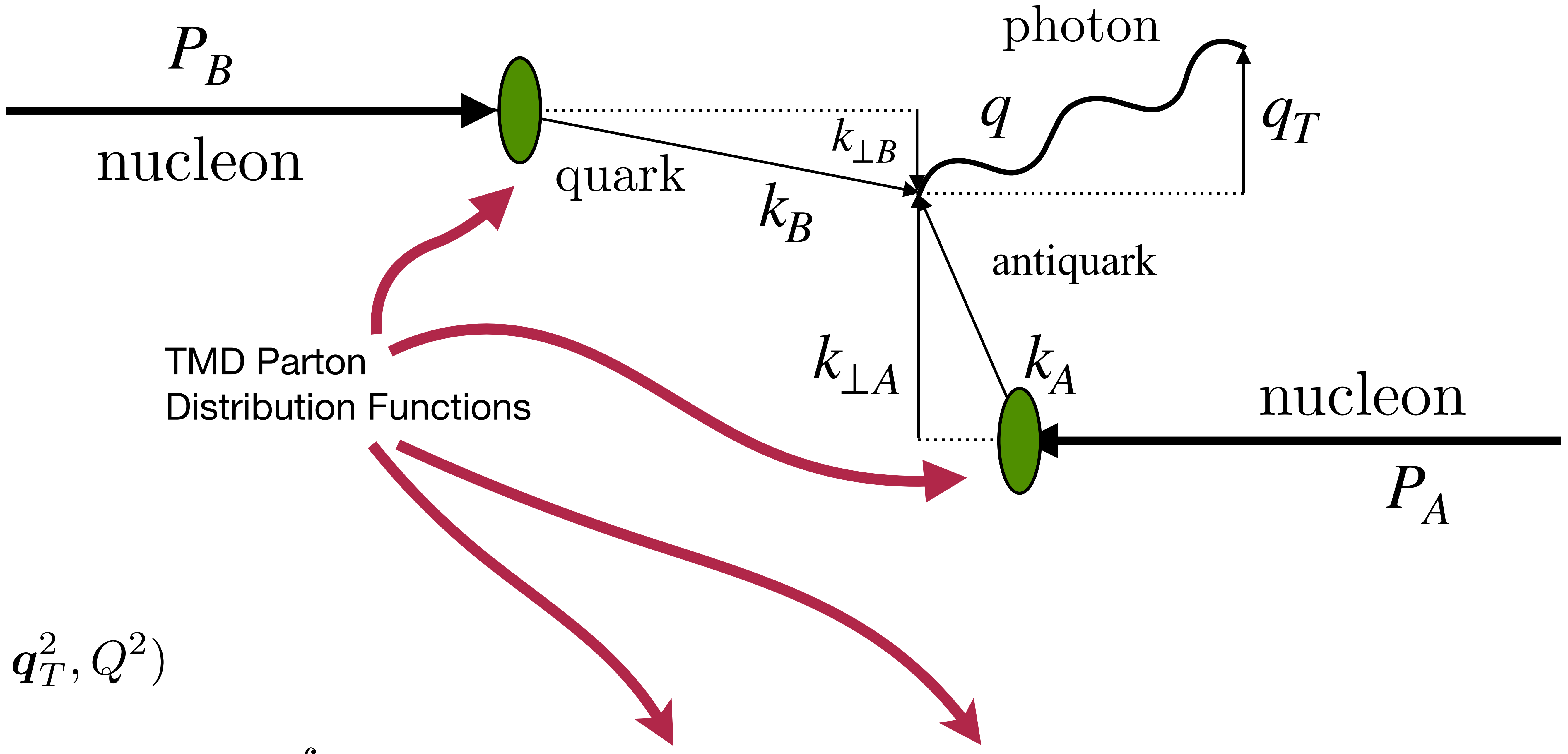
$$F^1_{UU}(x_A, x_B, \boldsymbol{q}_T^2, Q^2)$$

$$\approx \sum_q \mathcal{H}^{1q}_{UU}(Q^2,\mu^2) \int d^2\boldsymbol{k}_{\perp A}\, d^2\boldsymbol{k}_{\perp B}\, f_1^q(x_A, \boldsymbol{k}^2_{\perp A};\mu^2)\; f_1^{\bar{q}}(x_B, \boldsymbol{k}^2_{\perp B};\mu^2)\; \delta^{(2)}(\boldsymbol{k}_{\perp A} - \boldsymbol{q}_T + \boldsymbol{k}_{\perp B})$$

$$= \sum_q \mathcal{H}^{1q}_{UU}(Q^2,\mu^2) \int db_T b_T J_0(b_T|\boldsymbol{q}_T|) \hat{f}_1^q(x_A, b_T^2;\mu^2)\; \hat{f}_1^{\bar{q}}(x_B, b_T^2;\mu^2)$$

The analysis is usually done in Fourier-transformed space

TMDS IN DRELL-YAN PROCESSES



$$F^1_{UU}(x_A, x_B, \boldsymbol{q}_T^2, Q^2)$$

$$\approx \sum_q \mathcal{H}^{1q}_{UU}(Q^2, \mu^2) \int d^2\boldsymbol{k}_{\perp A}\, d^2\boldsymbol{k}_{\perp B}\, f_1^q(x_A, \boldsymbol{k}^2_{\perp A}; \mu^2)\, f_1^{\bar{q}}(x_B, \boldsymbol{k}^2_{\perp B}; \mu^2)\, \delta^{(2)}(\boldsymbol{k}_{\perp A} - \boldsymbol{q}_T + \boldsymbol{k}_{\perp B})$$

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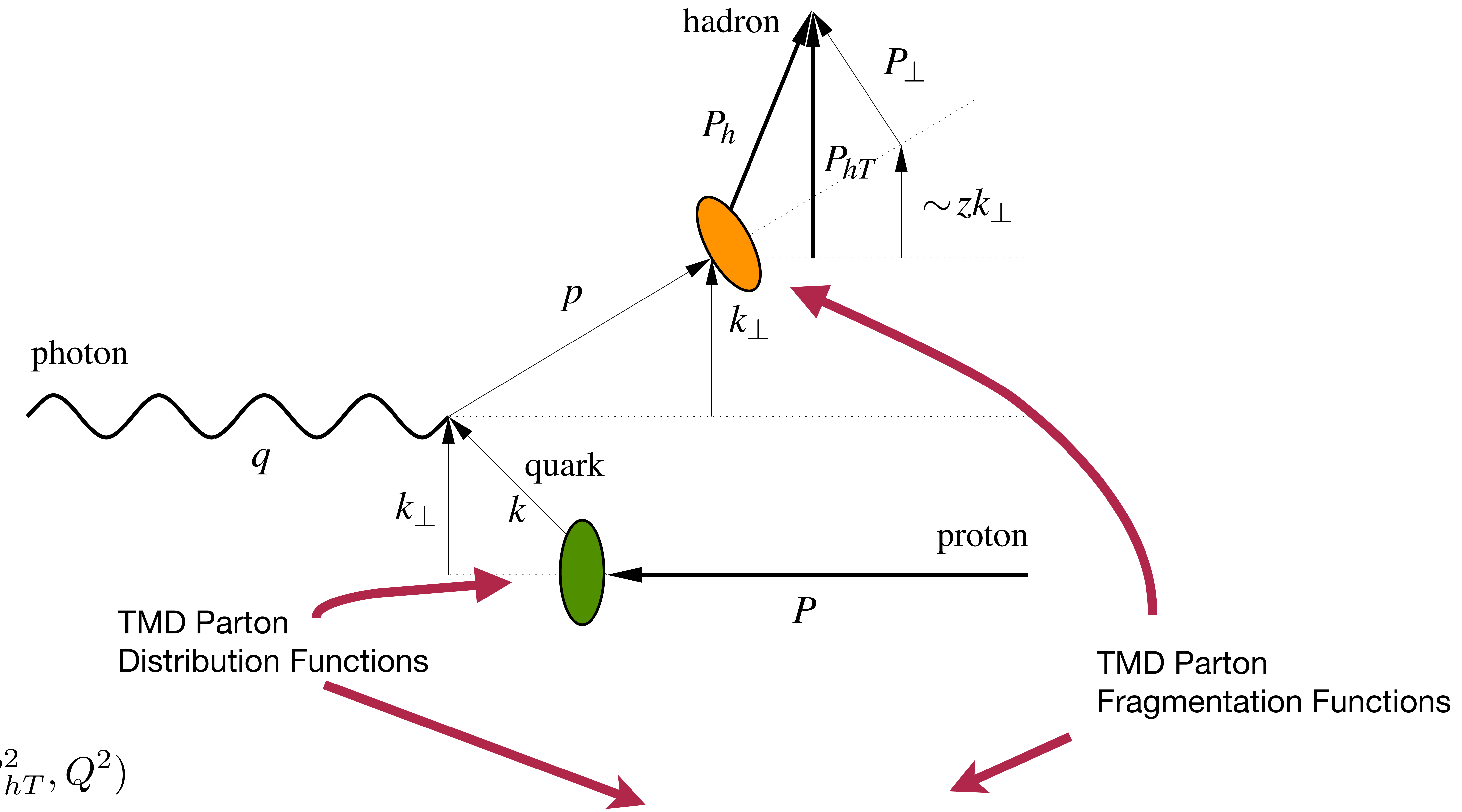
The analysis is usually done in Fourier-transformed space

TMDs formally depend on two scales, but we set them equal.

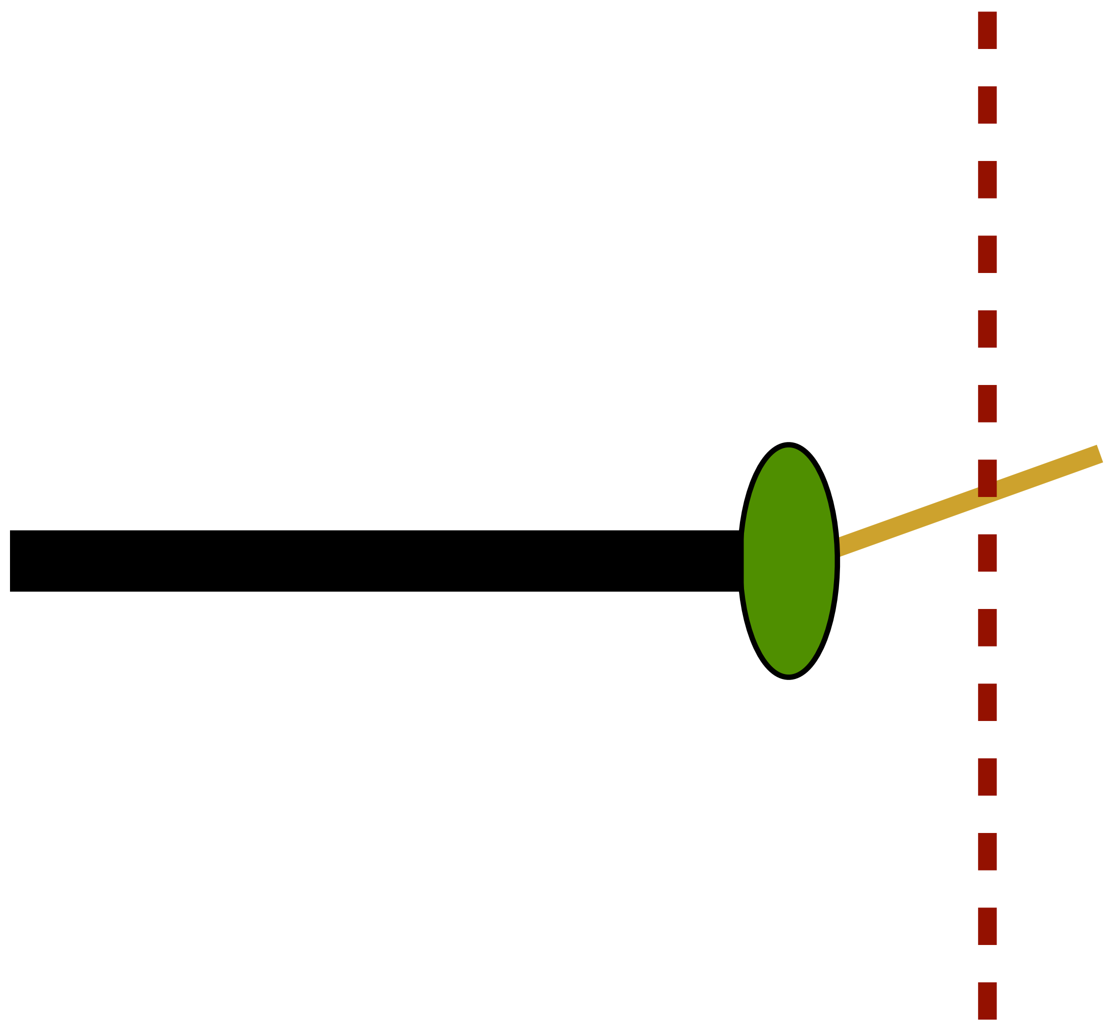
TMDS IN SEMI-INCLUSIVE DIS (SIDIS)



$$
\begin{aligned}
&F_{UU,T}(x, z, \boldsymbol{P}_{hT}^2, Q^2) \\
&\quad = x \sum_q \mathcal{H}^q_{UU,T}(Q^2, \mu^2) \int d^2\boldsymbol{k}_\perp \, d^2\boldsymbol{P}_\perp \, f_1^a(x, \boldsymbol{k}_\perp^2; \mu^2) \, D_1^{a\to h}(z, \boldsymbol{P}_\perp^2; \mu^2) \, \delta(z\boldsymbol{k}_\perp - \boldsymbol{P}_{hT} + \boldsymbol{P}_\perp) \\
&\quad = x \sum_a \mathcal{H}^q_{UU,T}(Q^2, \mu^2) \int db_T b_T J_0(b_T|\boldsymbol{P}_{h\perp}|) \hat{f}_1^q(x, z^2 b_\perp^2; \mu^2) \, \hat{D}_1^{a\to h}(z, b_\perp^2; \mu^2)
\end{aligned}
$$

CONTRIBUTIONS TO TRANSVERSE MOMENTUM

“intrinsic”
transverse
momentum

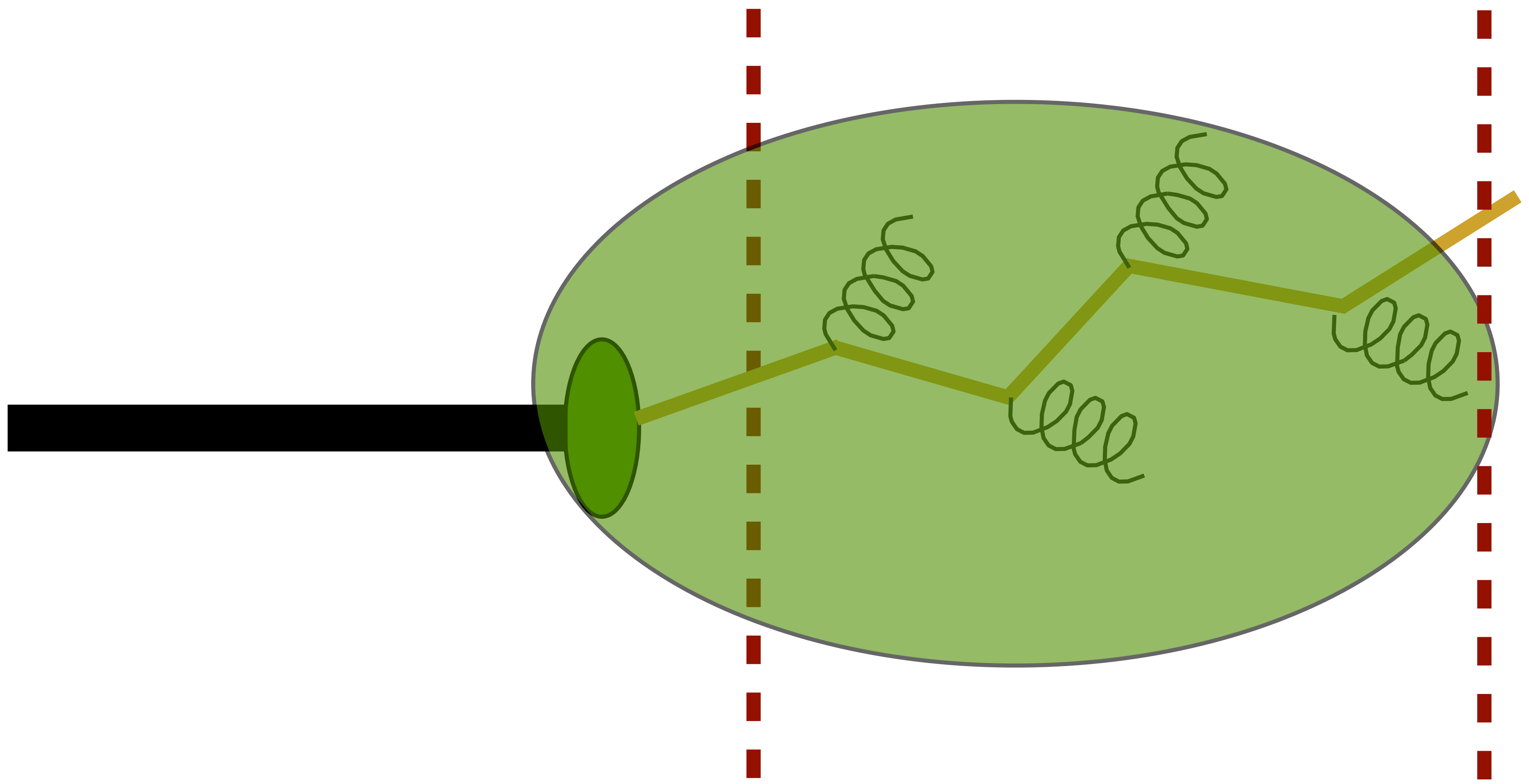


$|k_\perp| \sim \Lambda_{\mathrm{QCD}}$

CONTRIBUTIONS TO TRANSVERSE MOMENTUM

"intrinsic" transverse momentum

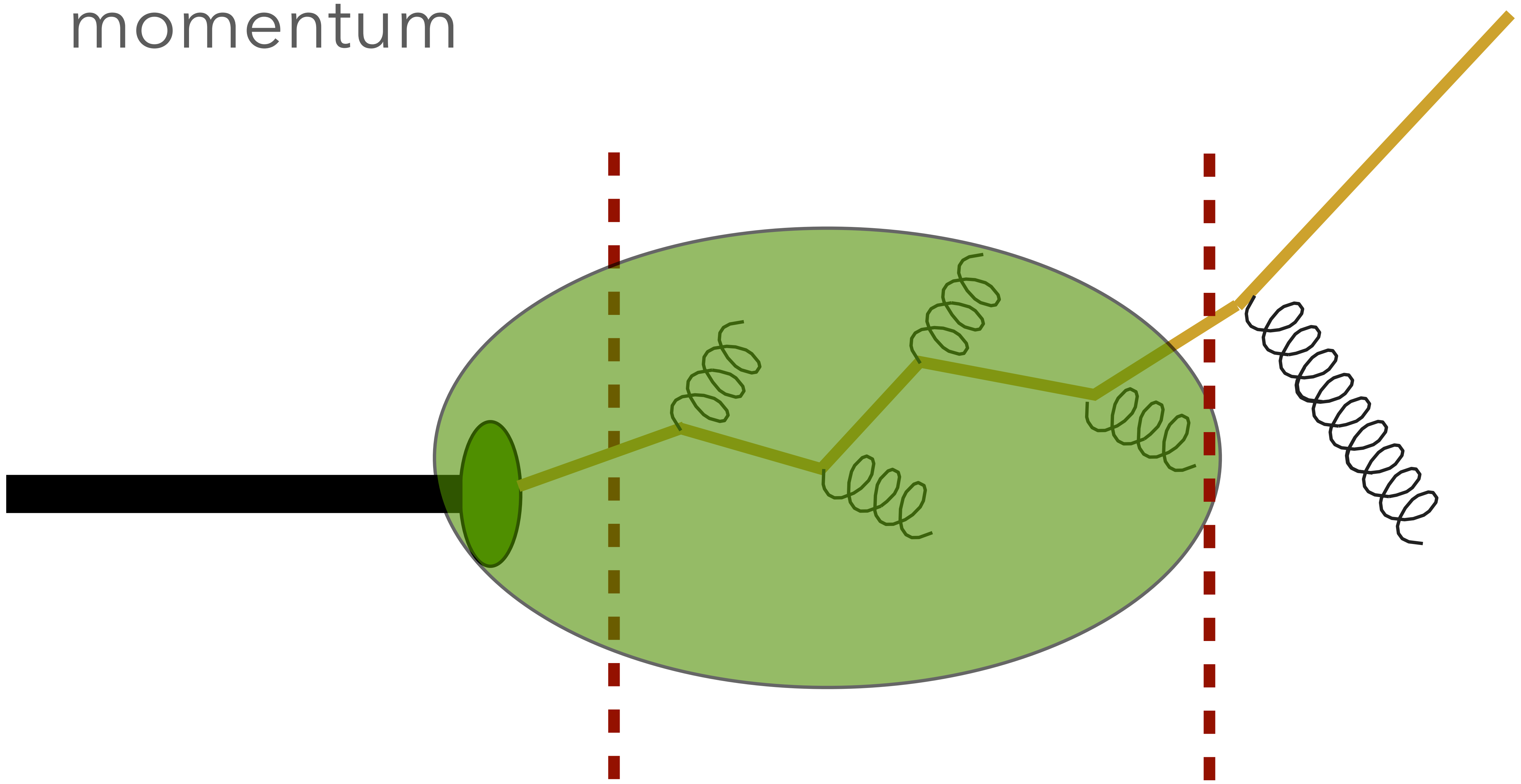
soft and collinear gluon radiation



$|k_\perp| \sim \Lambda_{\mathrm{QCD}}$

$|k_\perp| \ll Q$

CONTRIBUTIONS TO TRANSVERSE MOMENTUM



$|k_\perp| \sim \Lambda_{\rm QCD}$ $|k_\perp| \ll Q$ $|k_\perp| \sim Q$

TMD STRUCTURE

$$\hat{f}_1^a(x,|\boldsymbol{b}_T|;\mu,\zeta) = \int d^2\boldsymbol{k}_\perp\, e^{i\boldsymbol{b}_T\cdot\boldsymbol{k}_\perp}\, f_1^a(x,\boldsymbol{k}_\perp^2;\mu,\zeta)$$

see, e.g., Collins, "Foundations of Perturbative QCD" (11)
TMD collaboration, "TMD Handbook," arXiv:2304.03302

TMD STRUCTURE

$$\hat{f}_1^a(x, |\boldsymbol{b}_T|; \mu, \zeta) = \int d^2\boldsymbol{k}_\perp \, e^{i\boldsymbol{b}_T \cdot \boldsymbol{k}_\perp} \, f_1^a(x, \boldsymbol{k}_\perp^2; \mu, \zeta)$$

$$\hat{f}_1^a(x, b_T^2; \mu_f, \zeta_f) = [C \otimes f_1](x, \mu_{b_*}) \; e^{\int_{\mu_{b_*}}^{\mu_f} \frac{d\mu}{\mu} \left(\gamma_F - \gamma_K \ln \frac{\sqrt{\zeta_f}}{\mu}\right)} \left(\frac{\sqrt{\zeta_f}}{\mu_{b_*}}\right)^{K_{\text{resum}}}$$

see, e.g., Collins, "Foundations of Perturbative QCD" (11)
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TMD STRUCTURE

$$\hat{f}_1^a(x, |\boldsymbol{b}_T|; \mu, \zeta) = \int d^2\boldsymbol{k}_\perp \, e^{i\boldsymbol{b}_T \cdot \boldsymbol{k}_\perp} \, f_1^a(x, \boldsymbol{k}_\perp^2; \mu, \zeta)$$

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$$\mu_b = \frac{2e^{-\gamma_E}}{b_T}$$

see, e.g., Collins, "Foundations of Perturbative QCD" (11)
TMD collaboration, "TMD Handbook," arXiv:2304.03302

TMD STRUCTURE

$$\hat{f}_1^a(x, |\boldsymbol{b}_T|; \mu, \zeta) = \int d^2\boldsymbol{k}_\perp \, e^{i\boldsymbol{b}_T\cdot\boldsymbol{k}_\perp} \, f_1^a(x, \boldsymbol{k}_\perp^2; \mu, \zeta)$$

perturbative Sudakov form factor

$$\hat{f}_1^a(x, b_T^2; \mu_f, \zeta_f) = [C \otimes f_1](x, \mu_{b_*}) \; e^{\int_{\mu_{b_*}}^{\mu_f} \frac{d\mu}{\mu}\left(\gamma_F - \gamma_K \ln \frac{\sqrt{\zeta_f}}{\mu}\right)} \left(\frac{\sqrt{\zeta_f}}{\mu_{b_*}}\right)^{K_{\text{resum}}}$$

collinear PDF

Collins-Soper kernel

$$\mu_b = \frac{2e^{-\gamma_E}}{b_T}$$

matching coefficients (perturbative)

see, e.g., Collins, "Foundations of Perturbative QCD" (11)
TMD collaboration, "TMD Handbook," arXiv:2304.03302

TMD STRUCTURE

$$\hat{f}_1^a(x, |\boldsymbol{b}_T|; \mu, \zeta) = \int d^2\boldsymbol{k}_\perp \, e^{i\boldsymbol{b}_T \cdot \boldsymbol{k}_\perp} \, f_1^a(x, \boldsymbol{k}_\perp^2; \mu, \zeta)$$

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- perturbative Sudakov form factor
- matching coefficients (perturbative)
- collinear PDF
- Collins-Soper kernel

$$\mu_b = \frac{2e^{-\gamma_E}}{b_T}$$

⬇

$$\mu_{b*} = \frac{2e^{-\gamma_E}}{\bar{b}_*}$$

see, e.g., Collins, "Foundations of Perturbative QCD" (11)
TMD collaboration, "TMD Handbook," arXiv:2304.03302

TMD STRUCTURE

$$\hat{f}_1^a(x, |\boldsymbol{b}_T|; \mu, \zeta) = \int d^2\boldsymbol{k}_\perp \, e^{i\boldsymbol{b}_T\cdot\boldsymbol{k}_\perp} \, f_1^a(x, \boldsymbol{k}_\perp^2; \mu, \zeta)$$

perturbative Sudakov form factor

$$\hat{f}_1^a(x, b_T^2; \mu_f, \zeta_f) = [C \otimes f_1](x, \mu_{b_*}) \, e^{\int_{\mu_{b_*}}^{\mu_f} \frac{d\mu}{\mu}\left(\gamma_F - \gamma_K \ln \frac{\sqrt{\zeta_f}}{\mu}\right)} \left(\frac{\sqrt{\zeta_f}}{\mu_{b_*}}\right)^{K_{\mathrm{resum}}+g_K}$$

collinear PDF

matching coefficients (perturbative)

Collins-Soper kernel (perturbative and nonperturbative)

$$\mu_b = \frac{2e^{-\gamma_E}}{b_T}$$

⬇

$$\mu_{b*} = \frac{2e^{-\gamma_E}}{\bar{b}_*}$$

see, e.g., Collins, "Foundations of Perturbative QCD" (11)
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TMD STRUCTURE

$$\hat{f}_1^a(x, |\boldsymbol{b}_T|; \mu, \zeta) = \int d^2\boldsymbol{k}_\perp \, e^{i\boldsymbol{b}_T\cdot\boldsymbol{k}_\perp} \, f_1^a(x, \boldsymbol{k}_\perp^2; \mu, \zeta)$$

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perturbative Sudakov form factor

matching coefficients (perturbative)

collinear PDF

Collins-Soper kernel (perturbative and nonperturbative)

nonperturbative part of TMD

$$\mu_b = \frac{2e^{-\gamma_E}}{b_T}$$

$$\mu_{b*} = \frac{2e^{-\gamma_E}}{\bar{b}_*}$$

[see, e.g., Collins, "Foundations of Perturbative QCD" (11)](#)

[TMD collaboration, "TMD Handbook," arXiv:2304.03302](#)

TMD GLOBAL FITS

TMD GLOBAL FITS

	Accuracy	PDF uncertainty	flavor dependence	SIDIS	DY	N of points	χ^2/N_{points}
Pavia 2017 arXiv:1703.10157	NLL	✘	✘	✔	✔	8059	1.55

TMD GLOBAL FITS

	Accuracy	PDF uncertainty	flavor dependence	SIDIS	DY	N of points	χ^2/N_{points}
Pavia 2017 arXiv:1703.10157	NLL	✘	✘	✔	✔	8059	1.55
SV 2019 arXiv:1912.06532	N^3LL^-	✘	✘	✔	✔	1039	1.06
MAP22 arXiv:2206.07598	N^3LL^-	✘	✘	✔	✔	2031	1.06

$^-$ not all ingredients are available

TMD GLOBAL FITS

	Accuracy	PDF uncertainty	flavor dependence	SIDIS	DY	N of points	χ^2/N_{points}
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MAP22 arXiv:2206.07598	N^3LL^-	✘	✘	✔	✔	2031	1.06
MAP24 arXiv:2405.13833	N^3LL	✔	✔	✔	✔	2031	1.08

$^-$ not all ingredients are available

TMD GLOBAL FITS

	Accuracy	PDF uncertainty	flavor dependence	SIDIS	DY	N of points	χ^2/N_{points}
Pavia 2017 arXiv:1703.10157	NLL	✘	✘	✔	✔	8059	1.55
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MAP24 arXiv:2405.13833	N^3LL	✔	✔	✔	✔	2031	1.08
ART25 arXiv:2503.11201	N^4LL^-	✔	✔	✔	✔	1209	1.05

$^-$ not all ingredients are available

TMD GLOBAL FITS

	Accuracy	PDF uncertainty	flavor dependence	SIDIS	DY	N of points	χ^2/N_{points}
Pavia 2017 arXiv:1703.10157	NLL	✘	✘	✔	✔	8059	1.55
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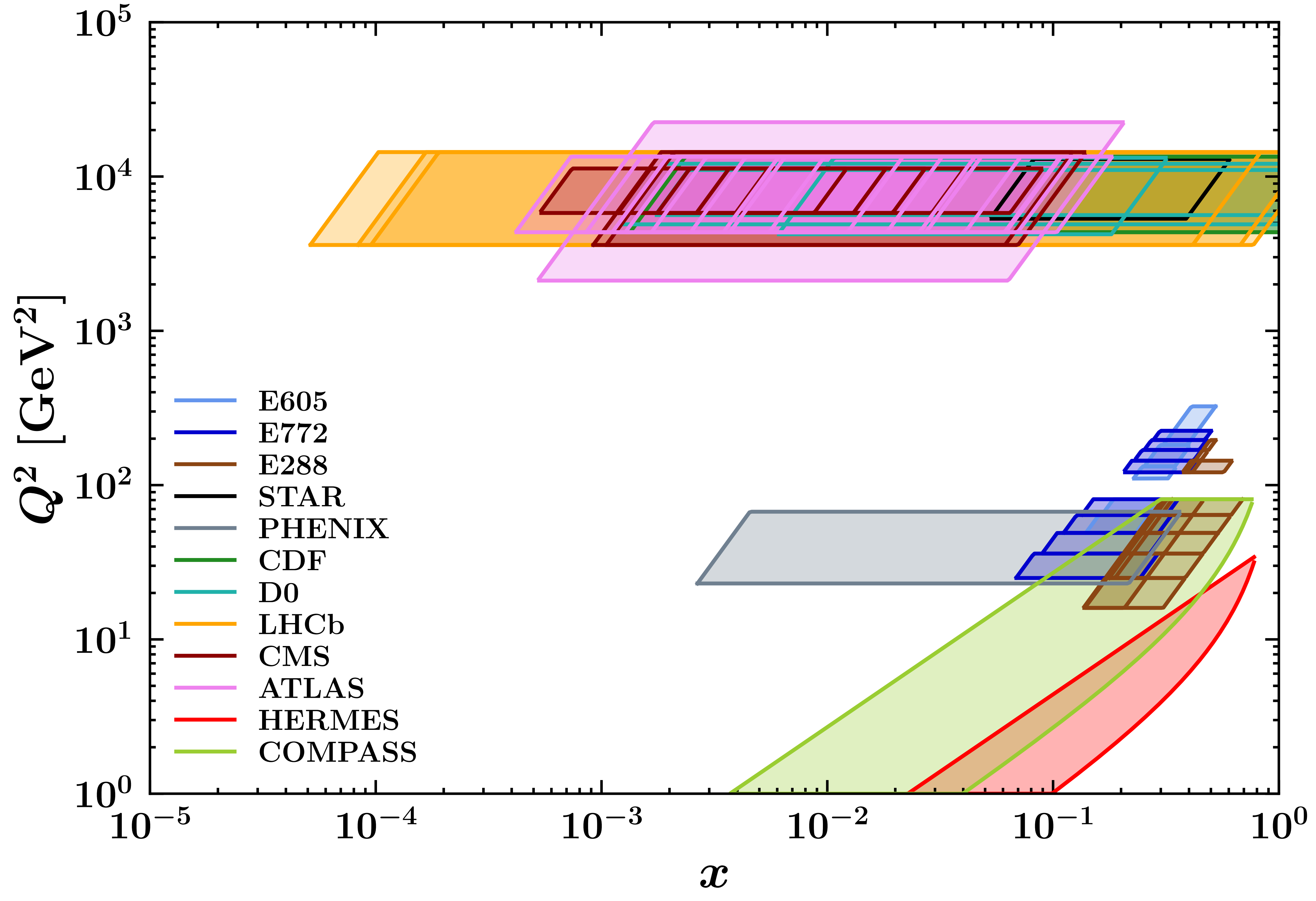
MAP24 arXiv:2405.13833	N^3LL	✔	✔	✔	✔	2031	1.08
ART25 arXiv:2503.11201	N^4LL^-	✔	✔	✔	✔	1209	1.05

$^-$ not all ingredients are available

see next talk by V. Moos

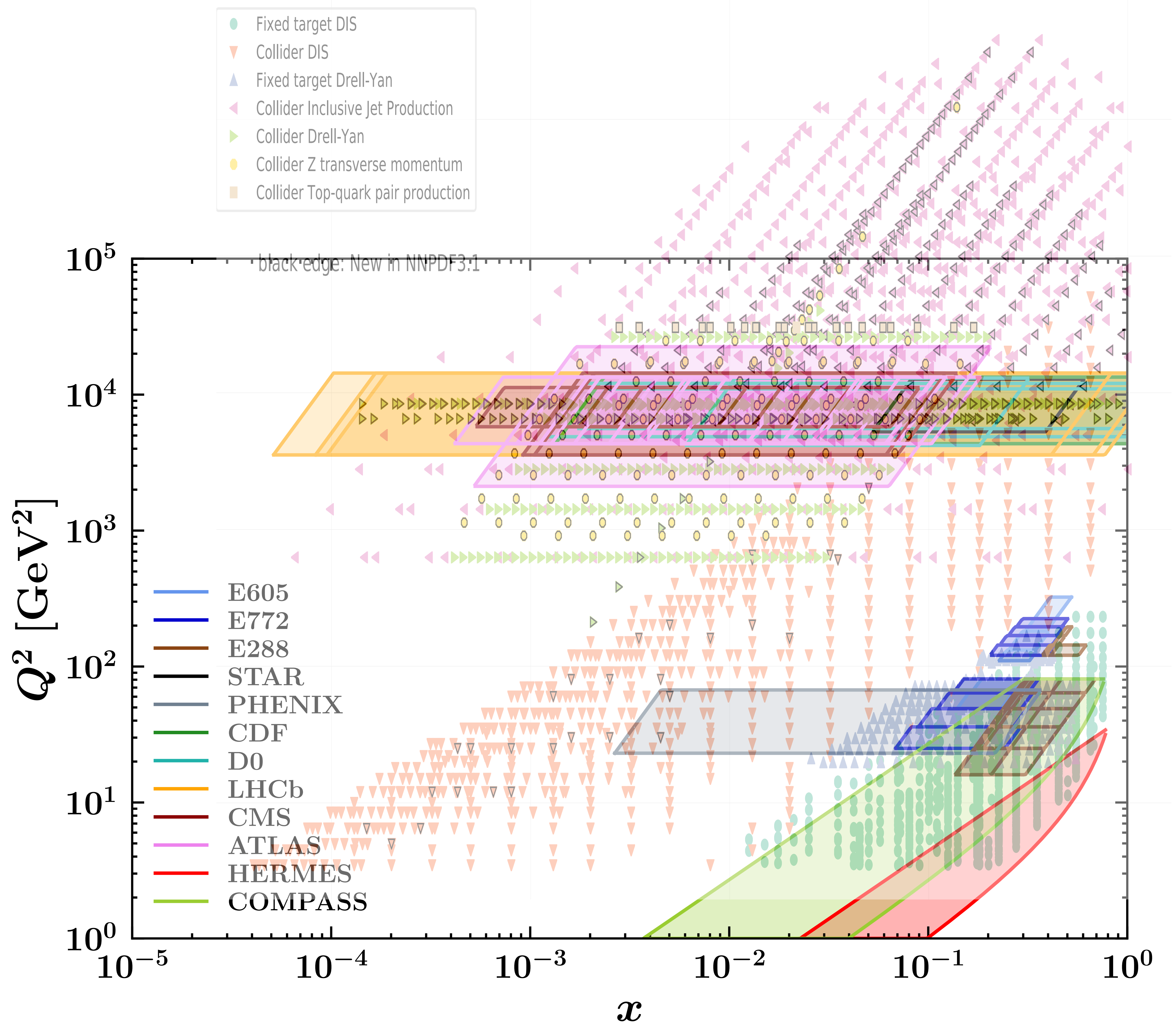
MAP24 GLOBAL FIT: x–Q² COVERAGE

MAP24 arXiv:2405.13833



MAP24 GLOBAL FIT: x–Q^2 COVERAGE

MAP24 arXiv:2405.13833

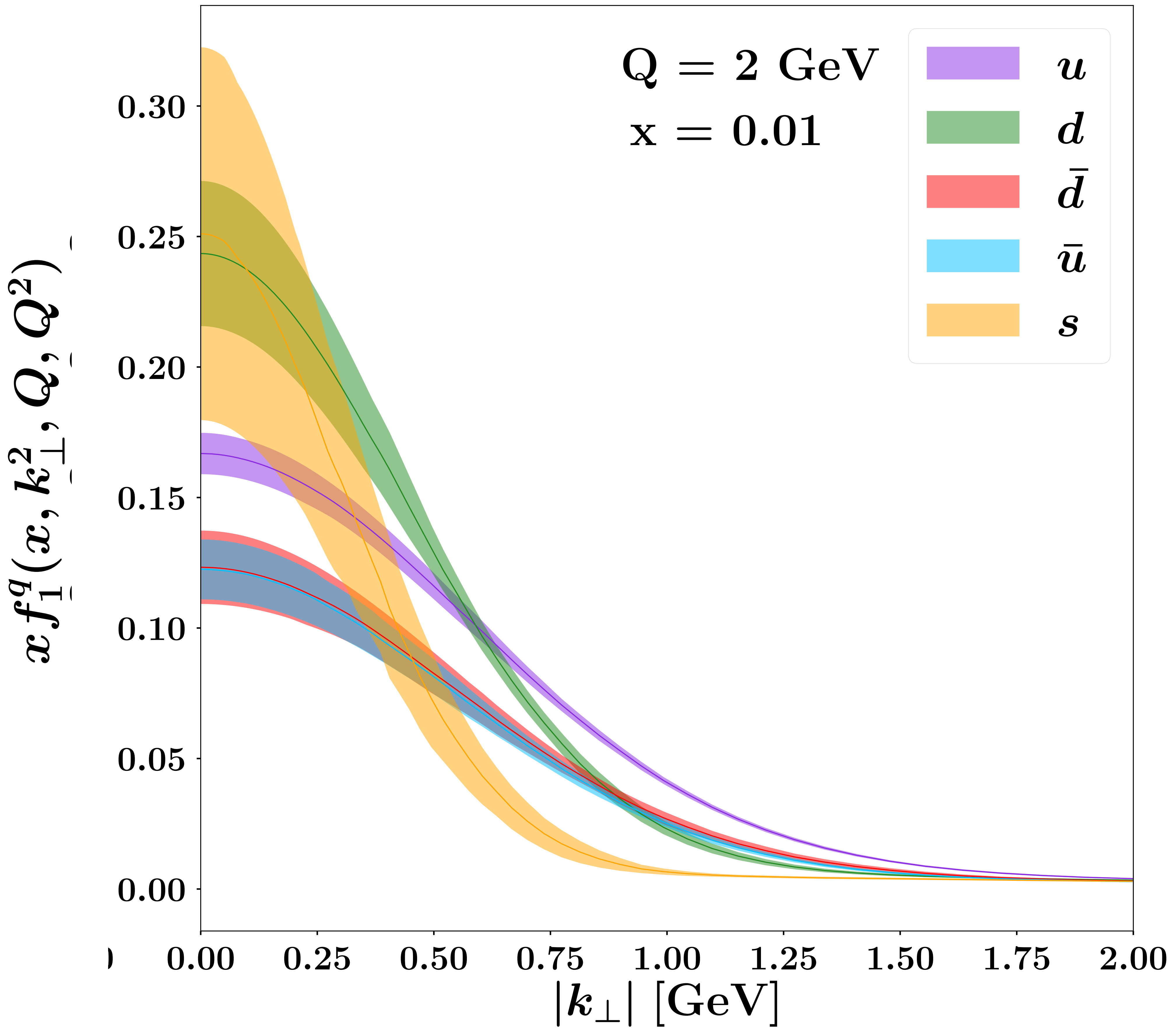


MAP24 GLOBAL FIT: DESCRIPTION OF THE DATASETS

MAP24 arXiv:2405.13833

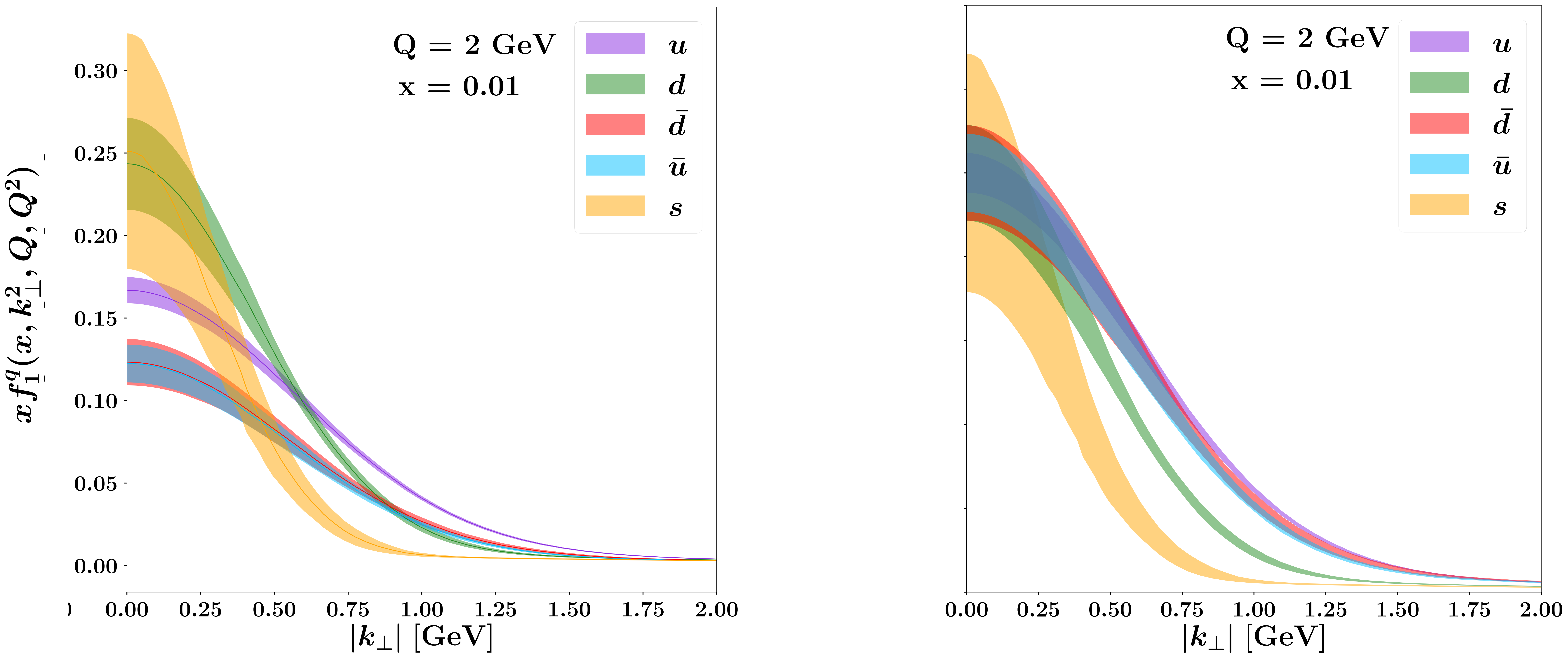
	N^{3}LL			
Data set	N_{dat}	χ_D^2	χ_λ^2	χ_0^2
Tevatron total	71	1.10	0.07	1.17
LHCb total	21	3.56	0.96	4.52
ATLAS total	72	3.54	0.82	4.36
CMS total	78	0.38	0.05	0.43
PHENIX 200	2	2.76	1.04	3.80
STAR 510	7	1.12	0.26	1.38
DY collider total	251	1.37	0.28	1.65
E288 200 GeV	30	0.13	0.40	0.53
E288 300 GeV	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**

EXAMPLE OF RESULTING TMDS



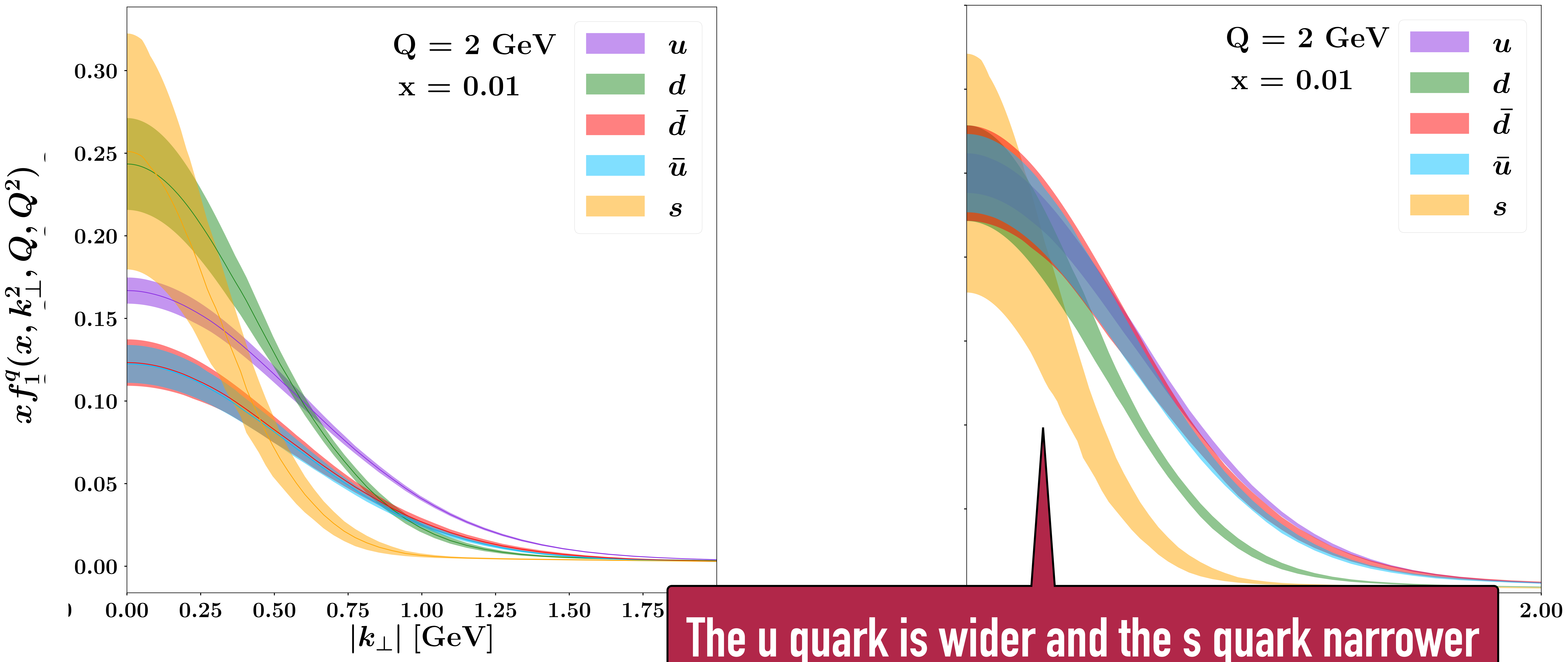
EXAMPLE OF RESULTING TMDS

normalized to the same value at $k_\perp = 0$



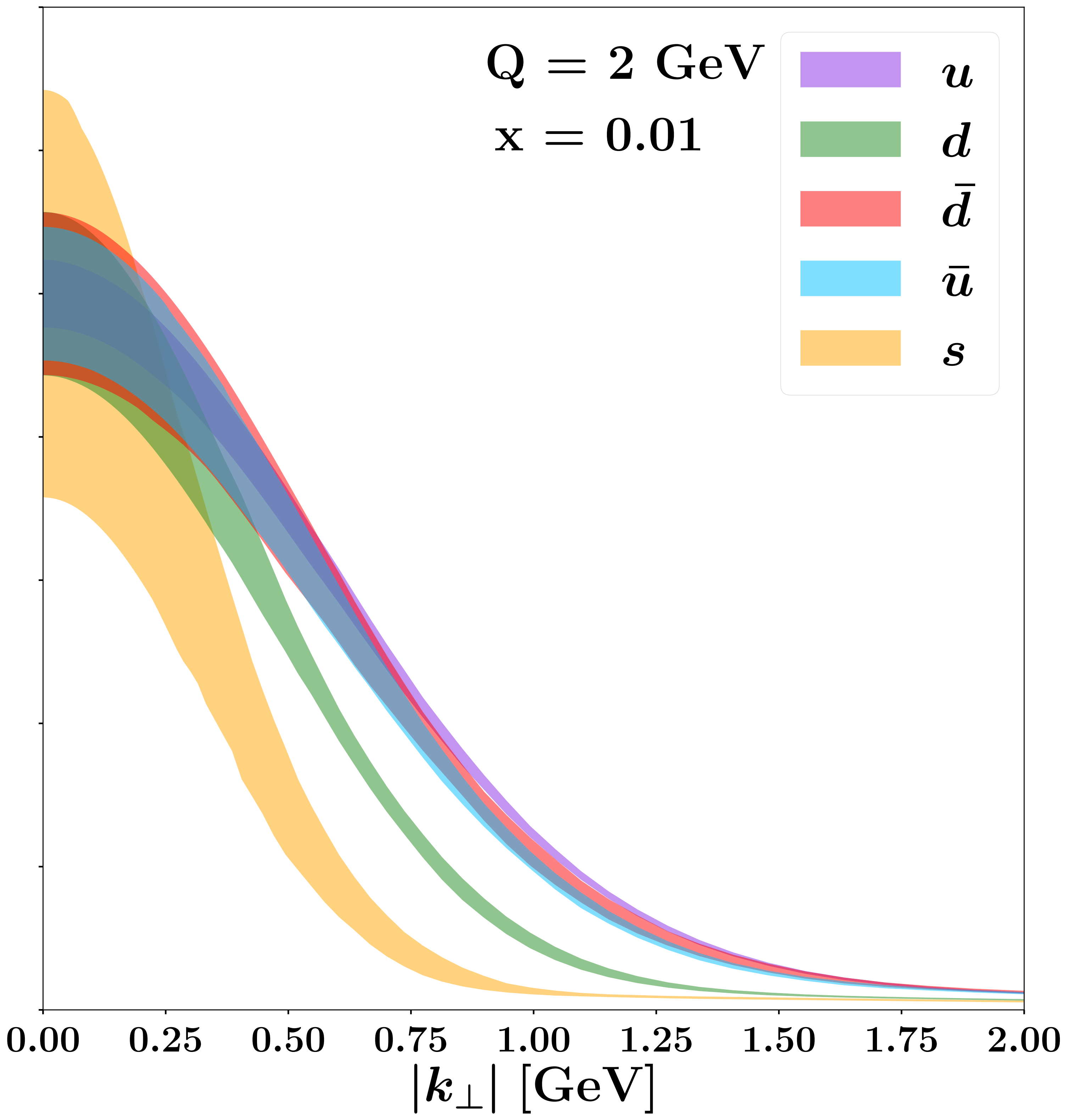
EXAMPLE OF RESULTING TMDS

normalized to the same value at $k_\perp = 0$

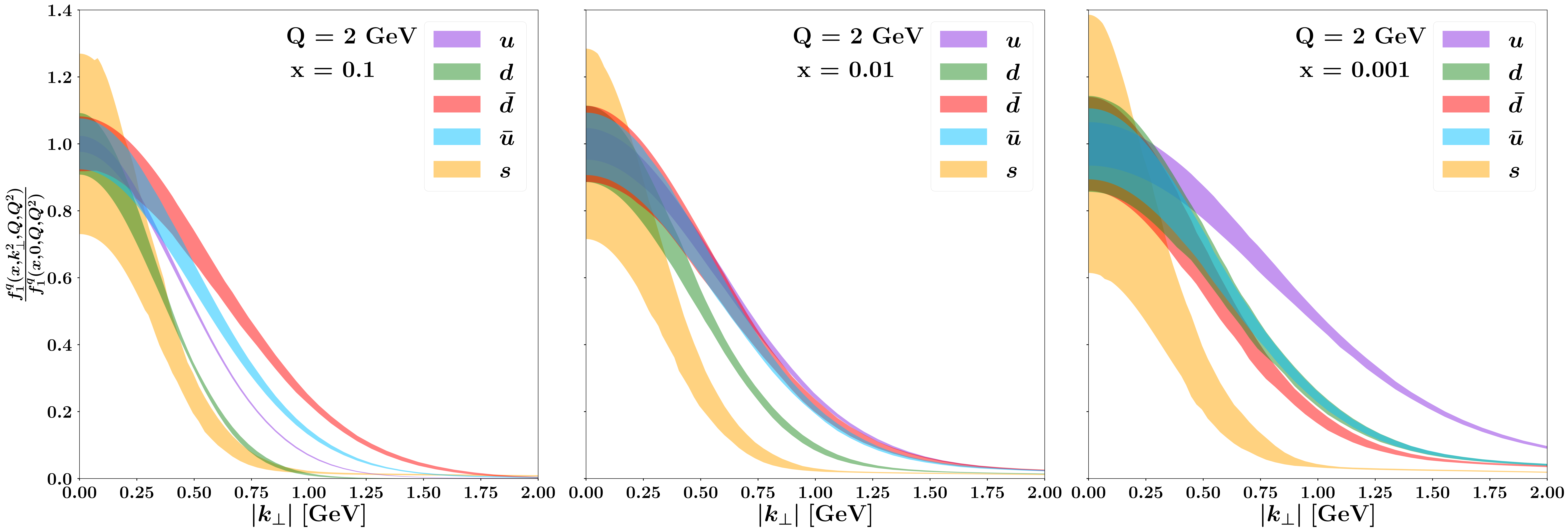


The u quark is wider and the s quark narrower

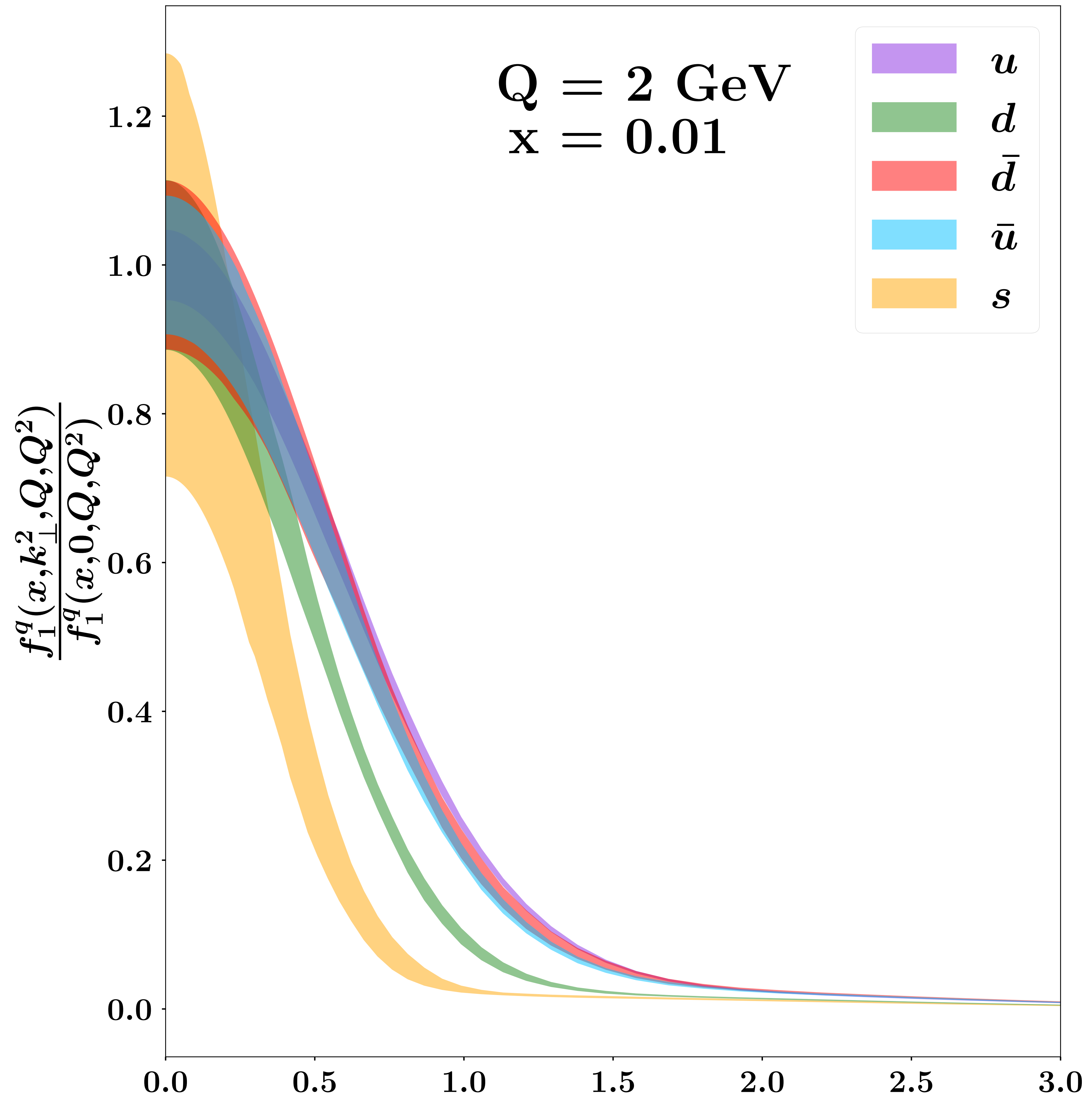
X DEPENDENCE



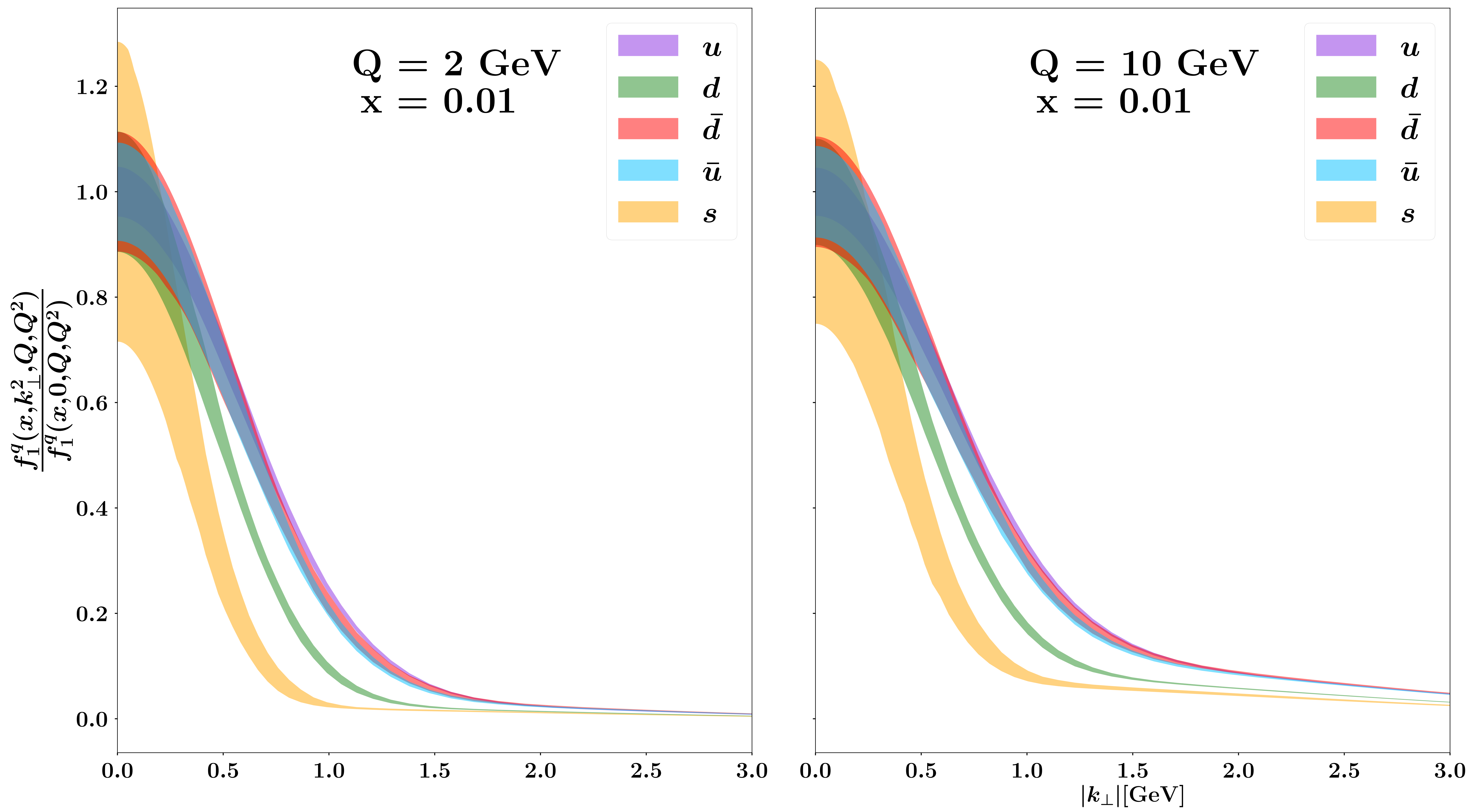
X DEPENDENCE



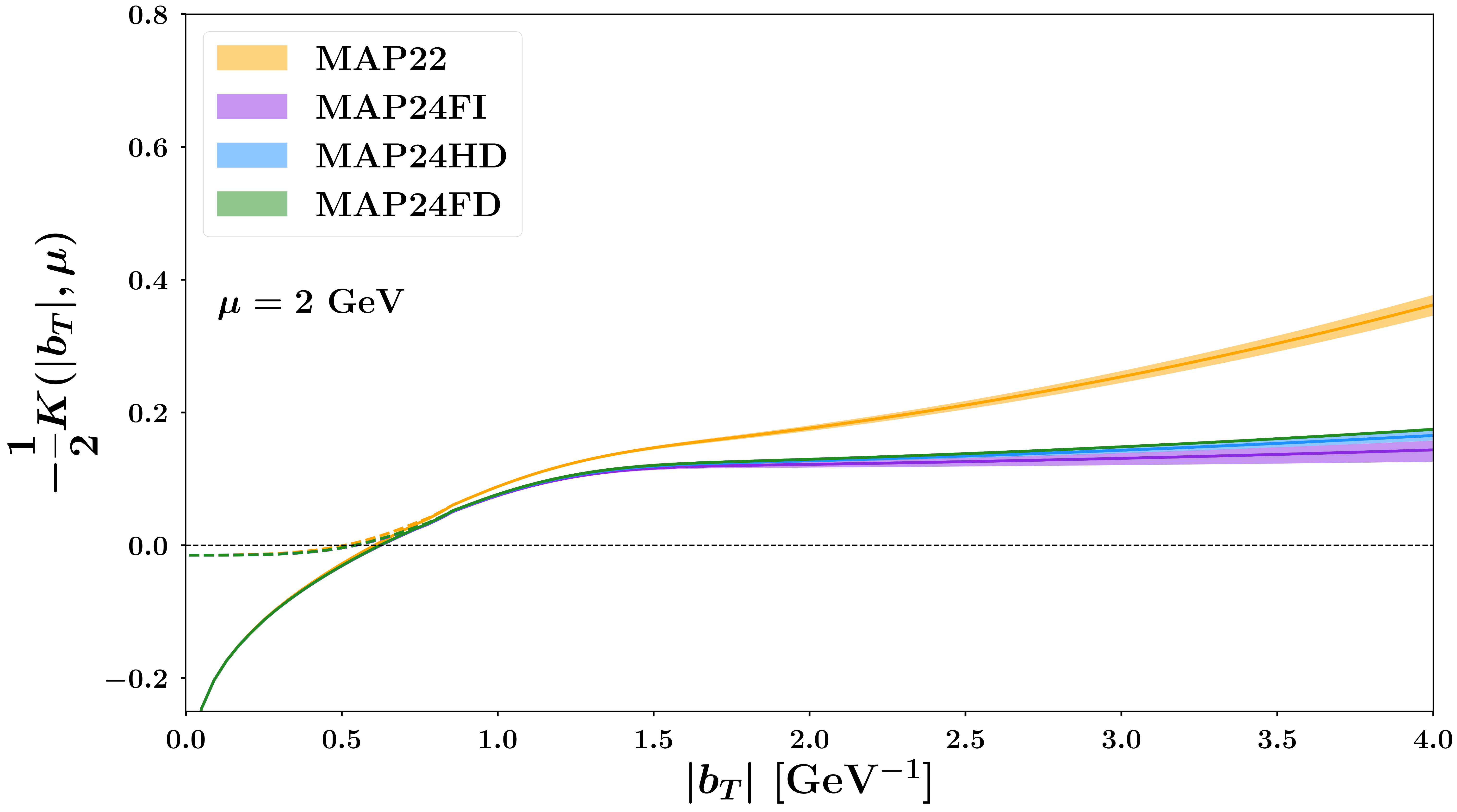
WIDENING WITH INCREASING SCALE



WIDENING WITH INCREASING SCALE



COLLINS-SOPER KERNEL



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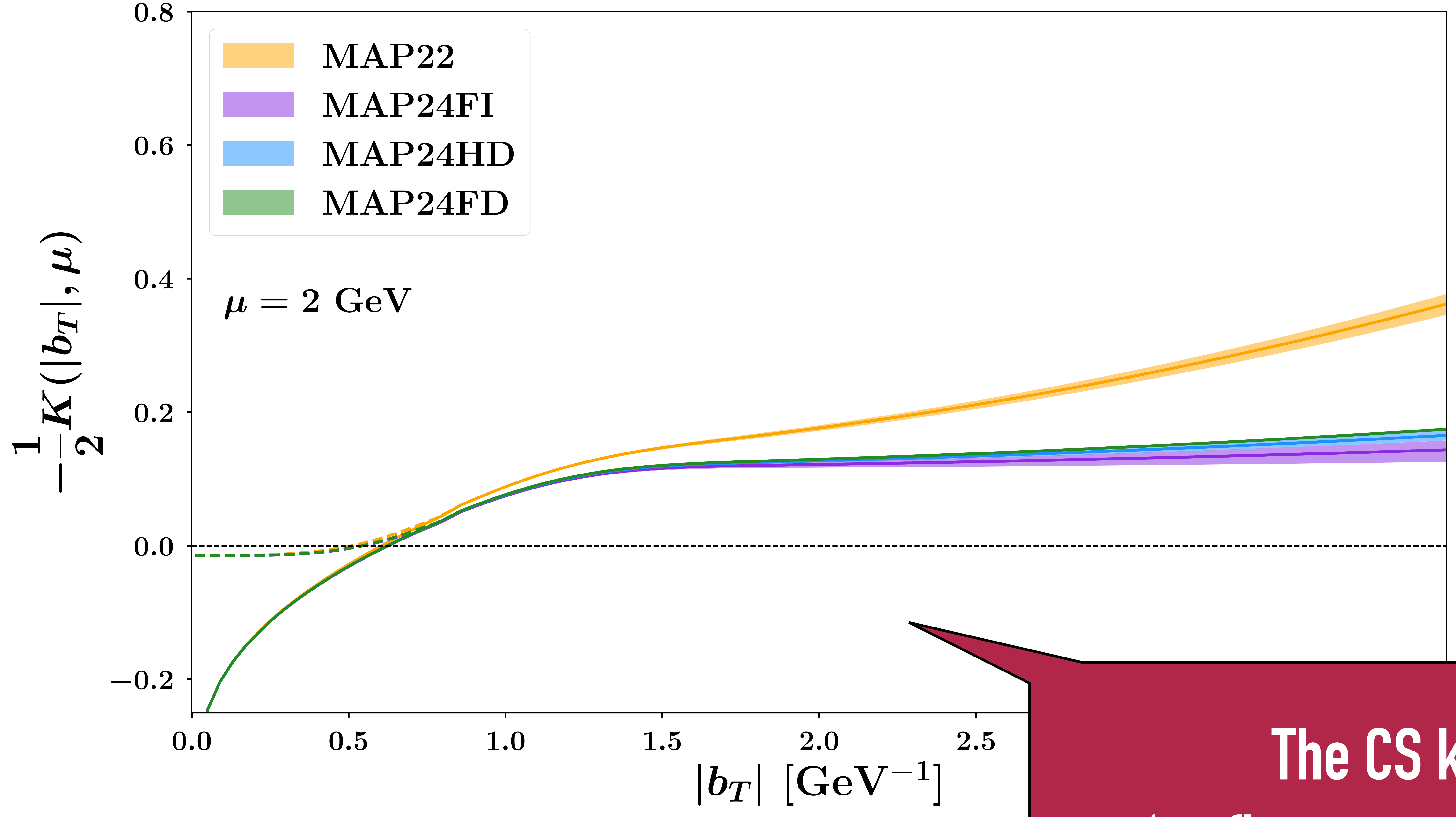
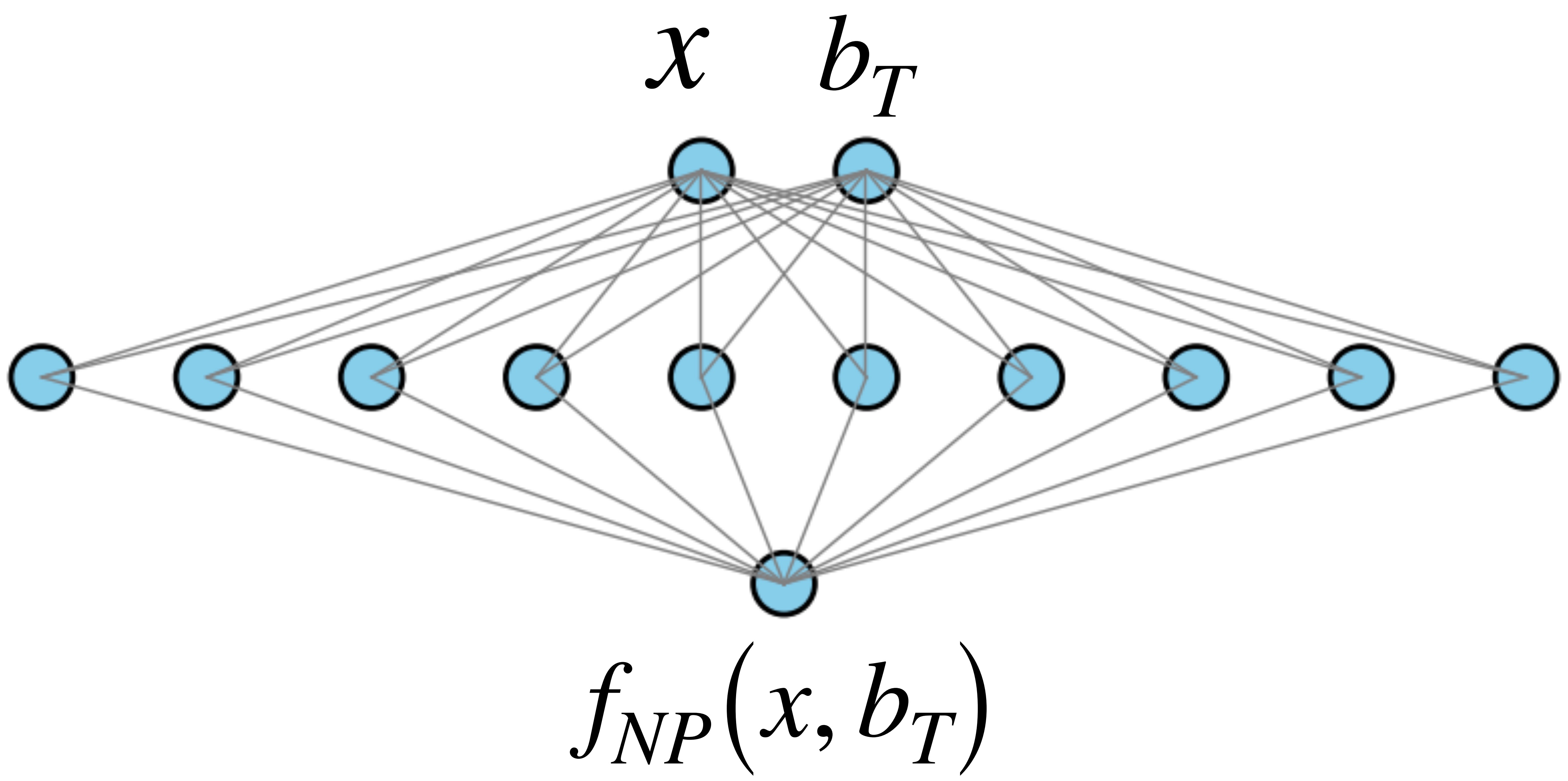


The CS kernel is "universal"
(no flavor, no x, no hadron dependence)

NEURAL NETWORK EXTRACTION

NEURAL-NETWORK FOR TMDS

MAPNN arXiv:2502.04166



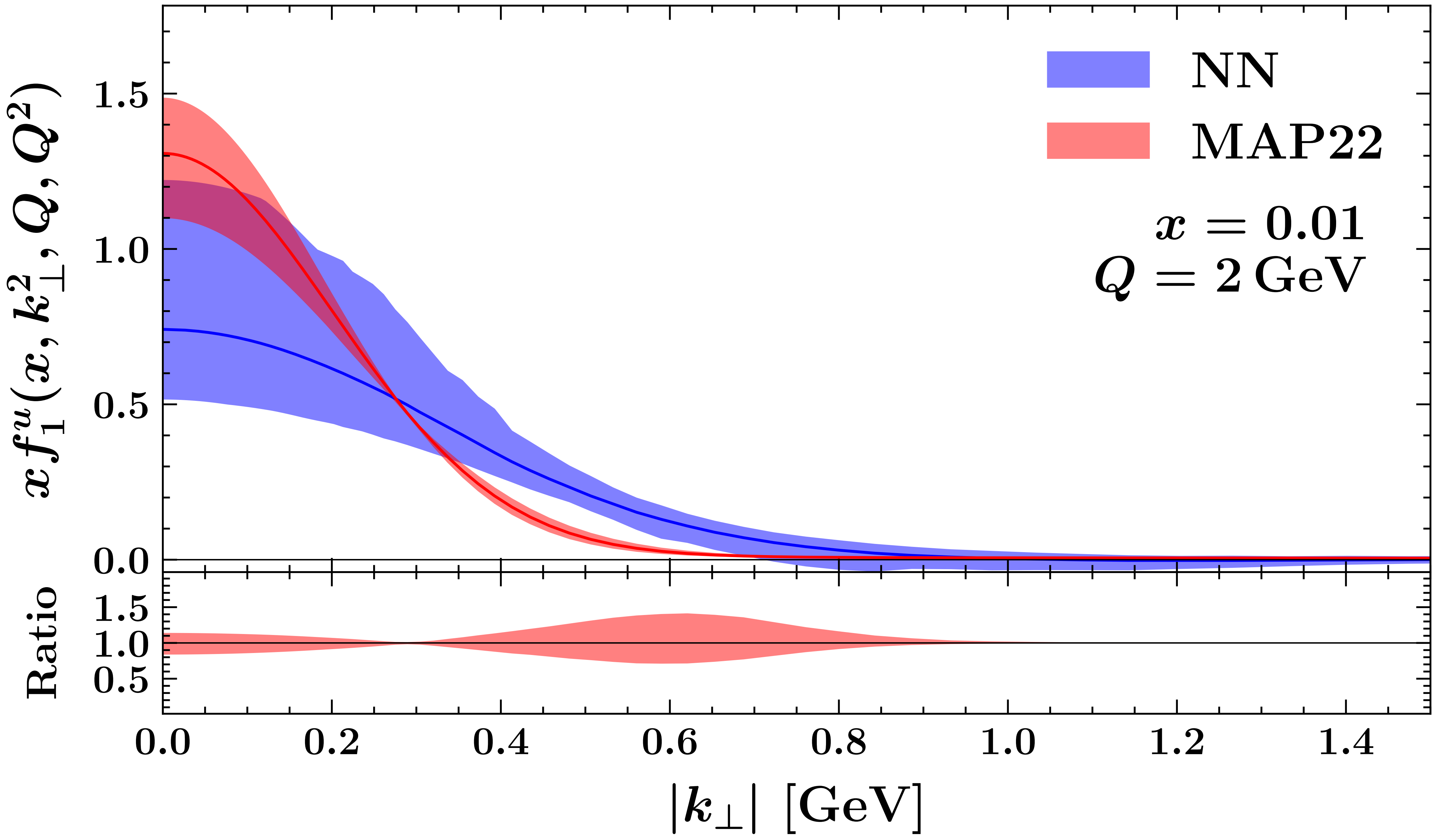
$$f_{\rm NP}(x, b_T; \zeta) = \frac{\mathbb{NN}(x, b_T)}{\mathbb{NN}(x, 0)} \exp\left[-g_2^2 b_T^2 \log\left(\frac{\zeta}{Q_0^2}\right)\right]$$

41 parameters + 1 parameter for CS kernel

PROOF-OF-CONCEPT EXTRACTION

MAPNN arXiv:2502.04166

Experiment	$N_{\rm dat}$	$\overline{\chi}^2$ $(\overline{\chi}^2_D + \overline{\chi}^2_\lambda)$ NN	MAP22
Fixed-target	233	1.08 (0.98 + 0.10)	0.91 (0.70 + 0.21)
RHIC	7	1.11 (1.03 + 0.07)	1.45 (1.37 + 0.08)
Tevatron	71	0.80 (0.73 + 0.06)	1.20 (1.17 + 0.04)
LHCb	21	0.98 (0.88 + 0.10)	1.25 (1.05 + 0.20)
CMS	78	0.40 (0.38 + 0.02)	0.41 (0.35 + 0.06)
ATLAS	72	1.38 (1.09 + 0.29)	3.51 (3.03 + 0.49)
Total	482	0.97 (0.86 + 0.11)	1.28 (1.09 + 0.20)



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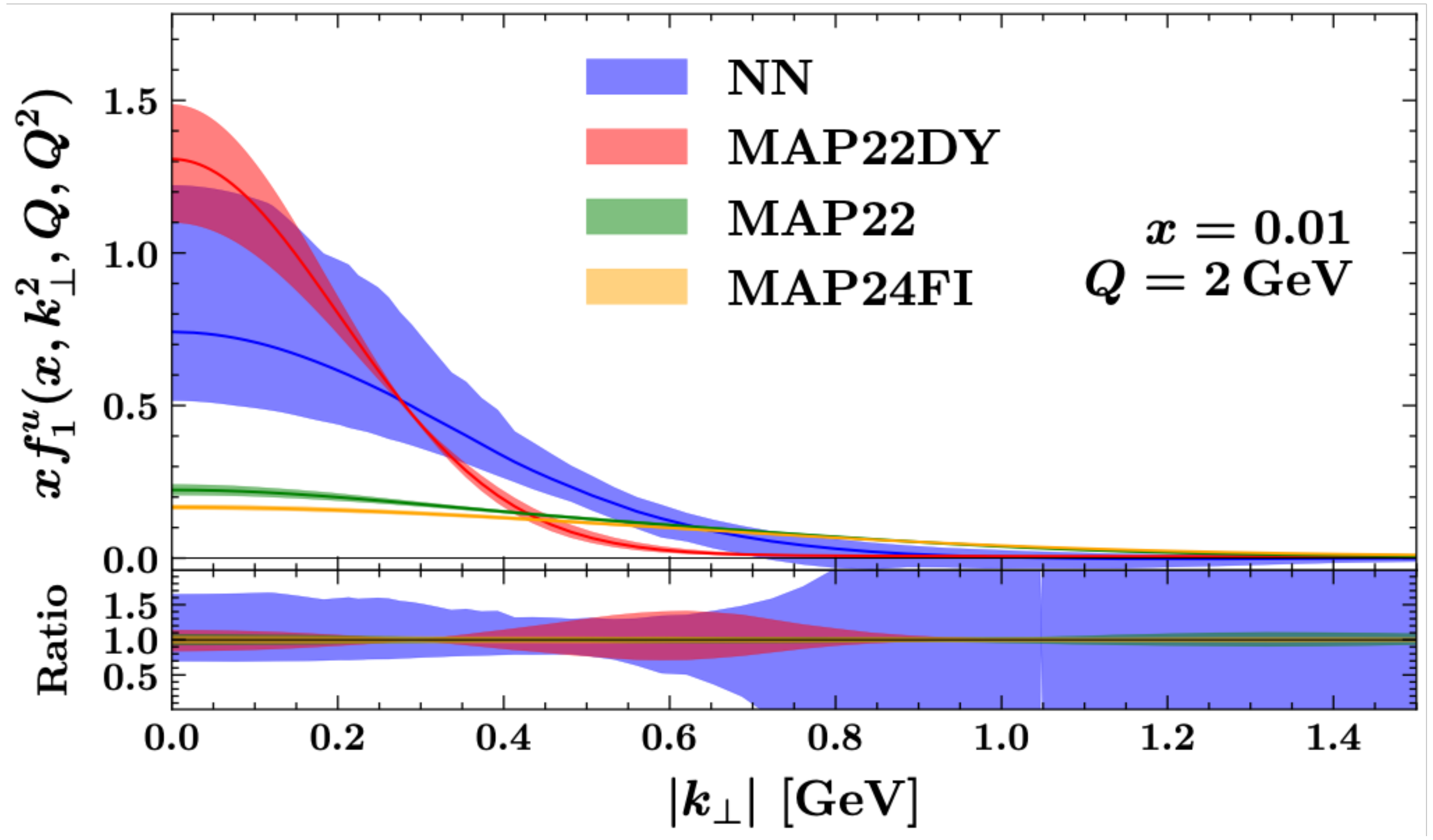
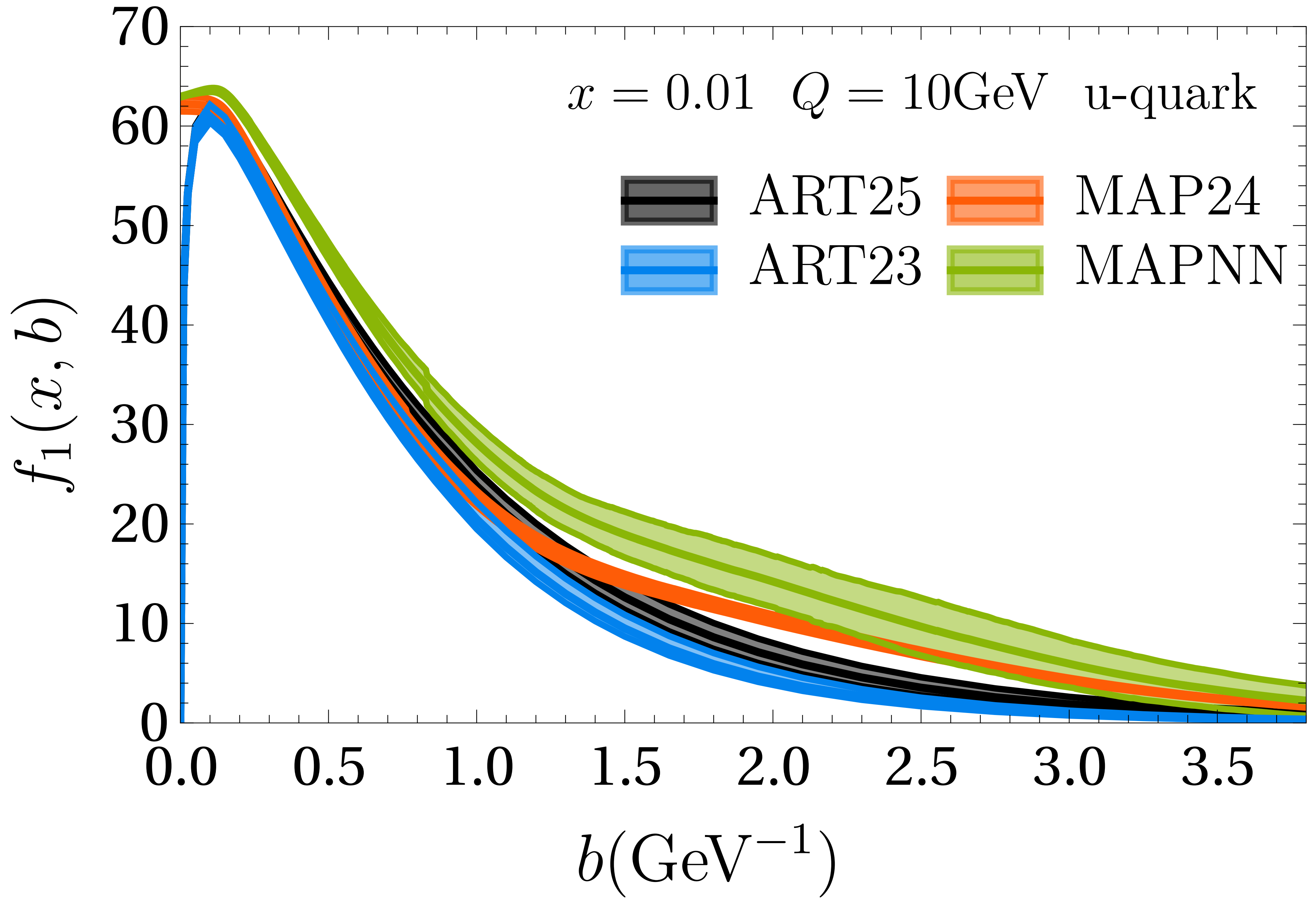


COMPARISON WITH ART25

ART25 arXiv:2503.112021, see talk by V. Moos

comparison in b_T space



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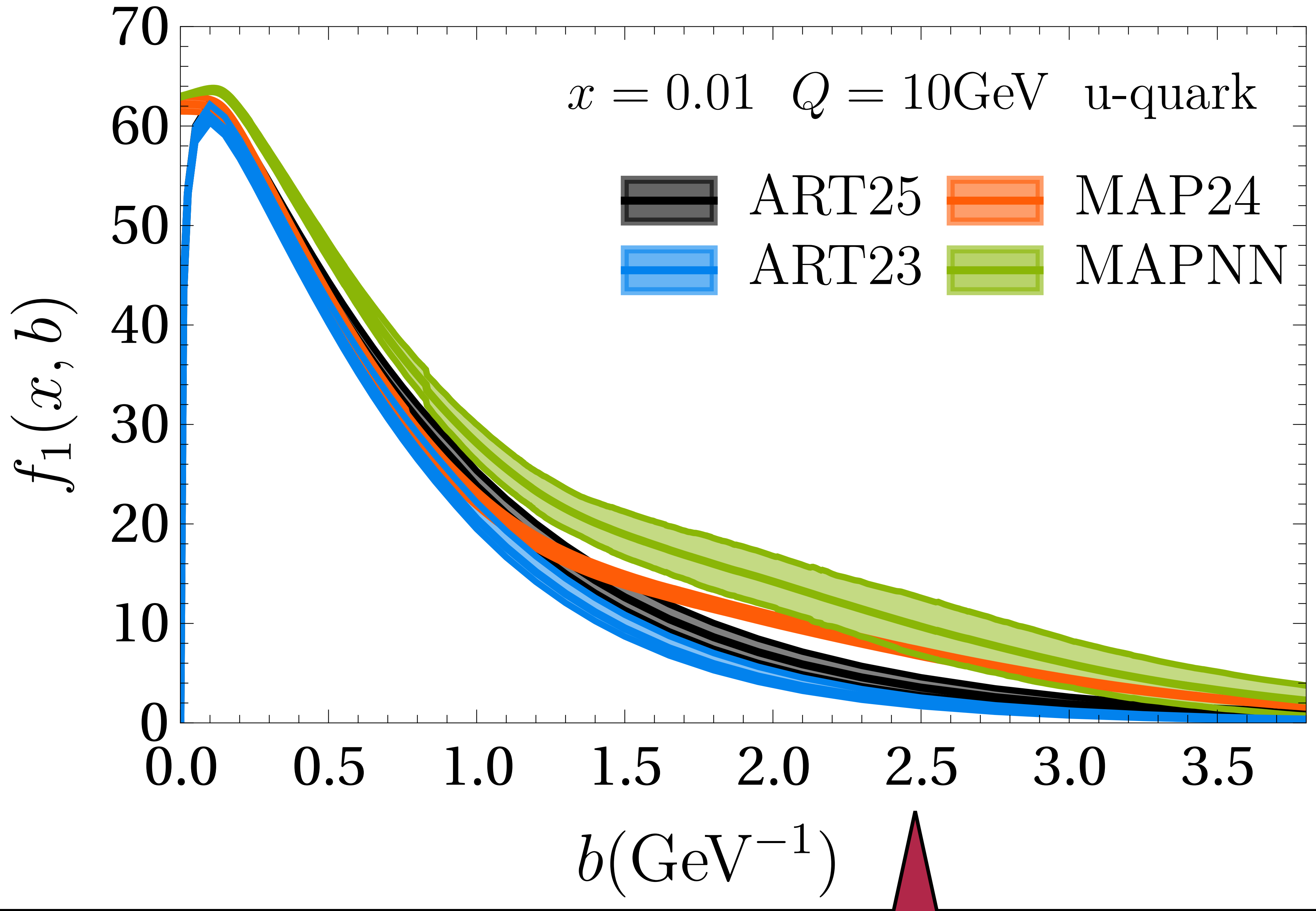

There are significant differences between different extractions.

The error bands are probably underestimated

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ART25 arXiv:2503.112021, see talk by V. Moos

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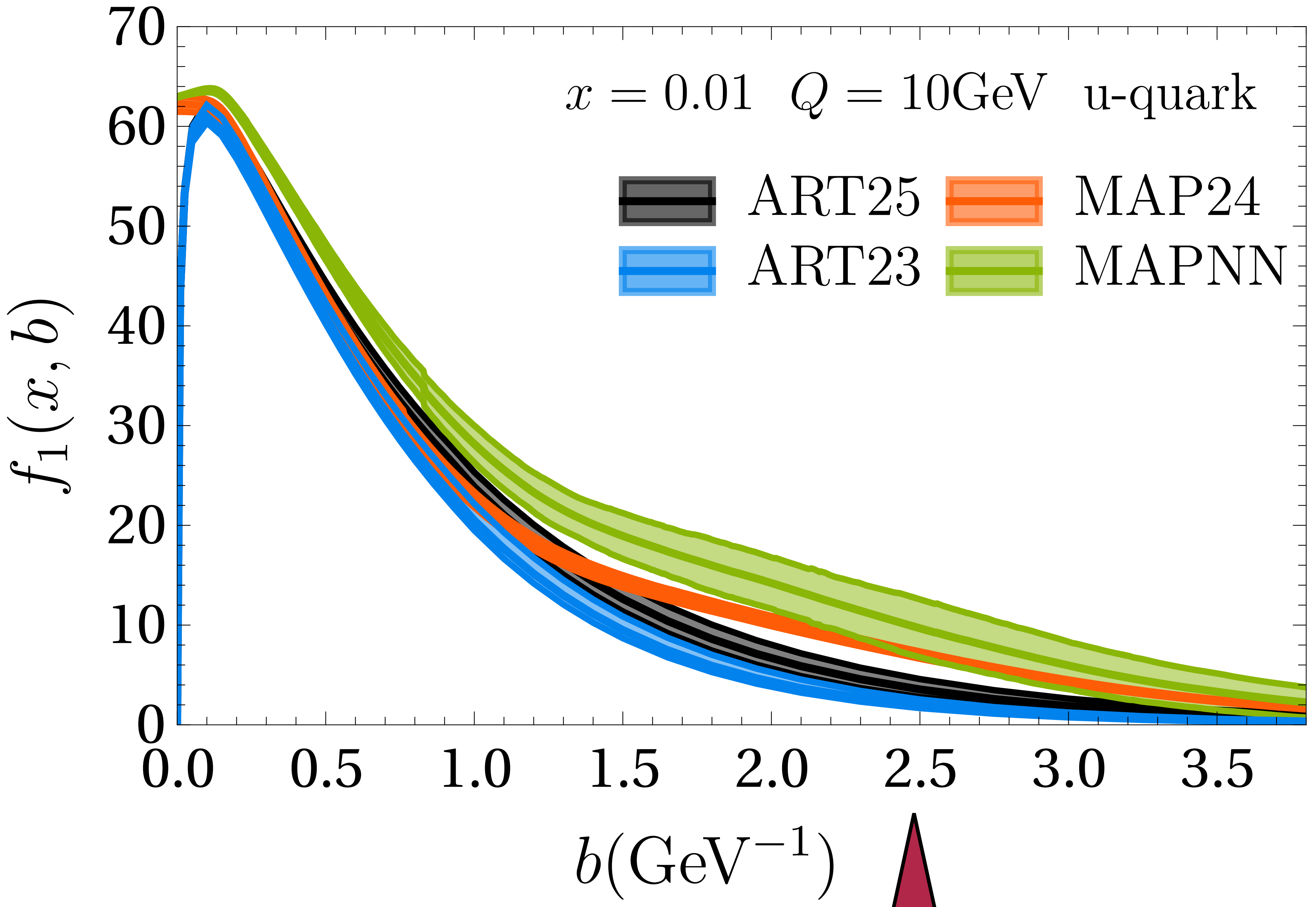

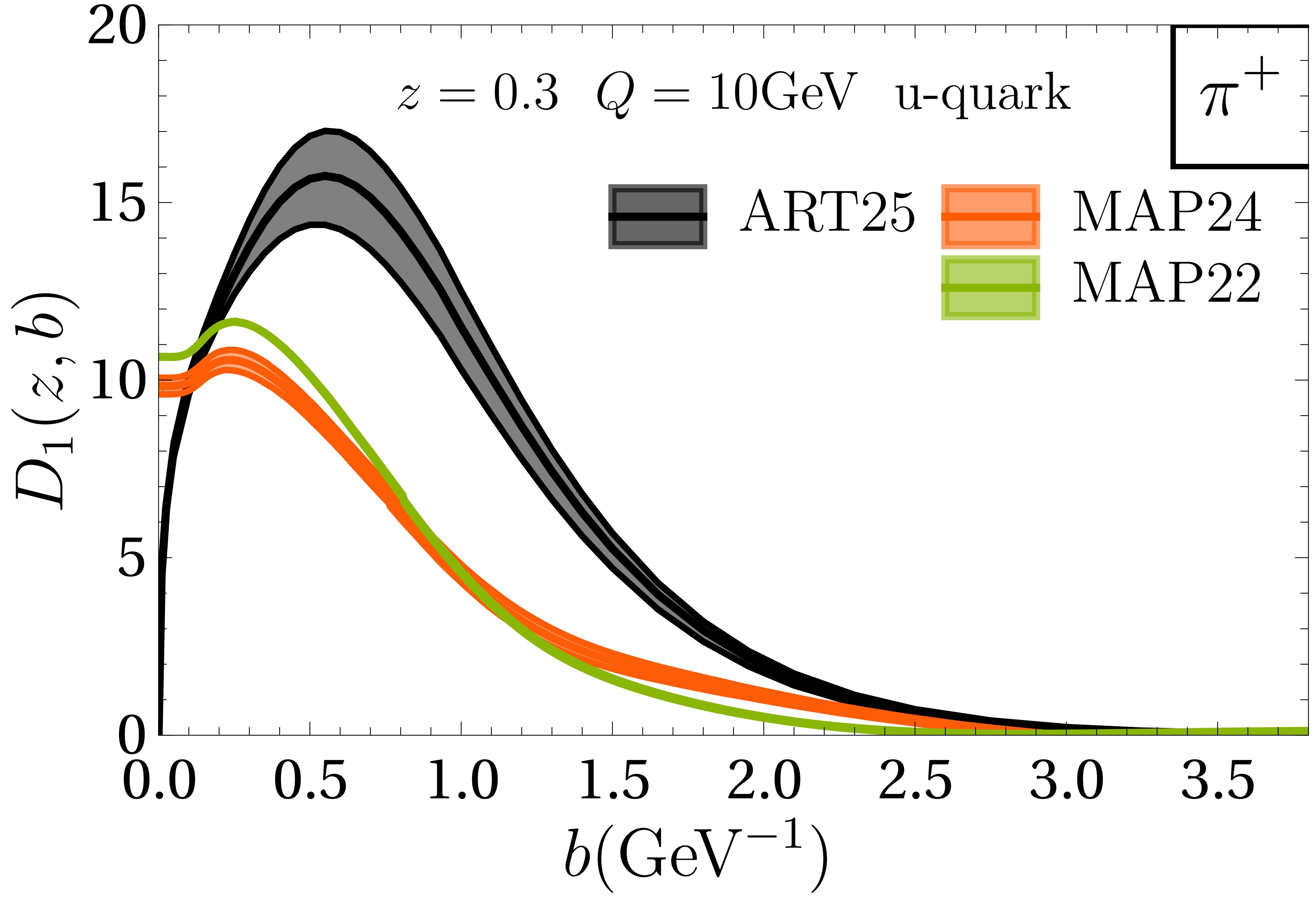

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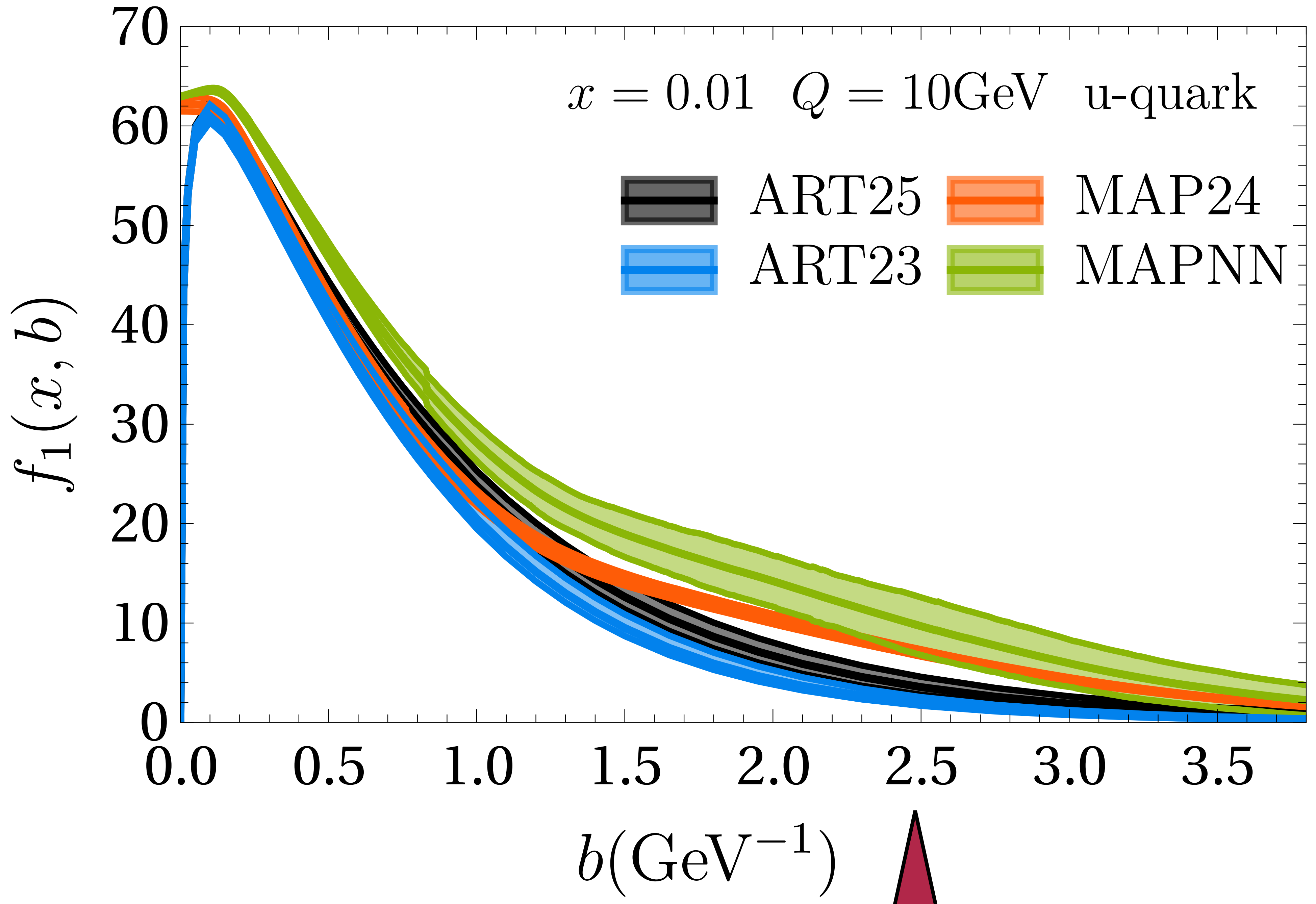
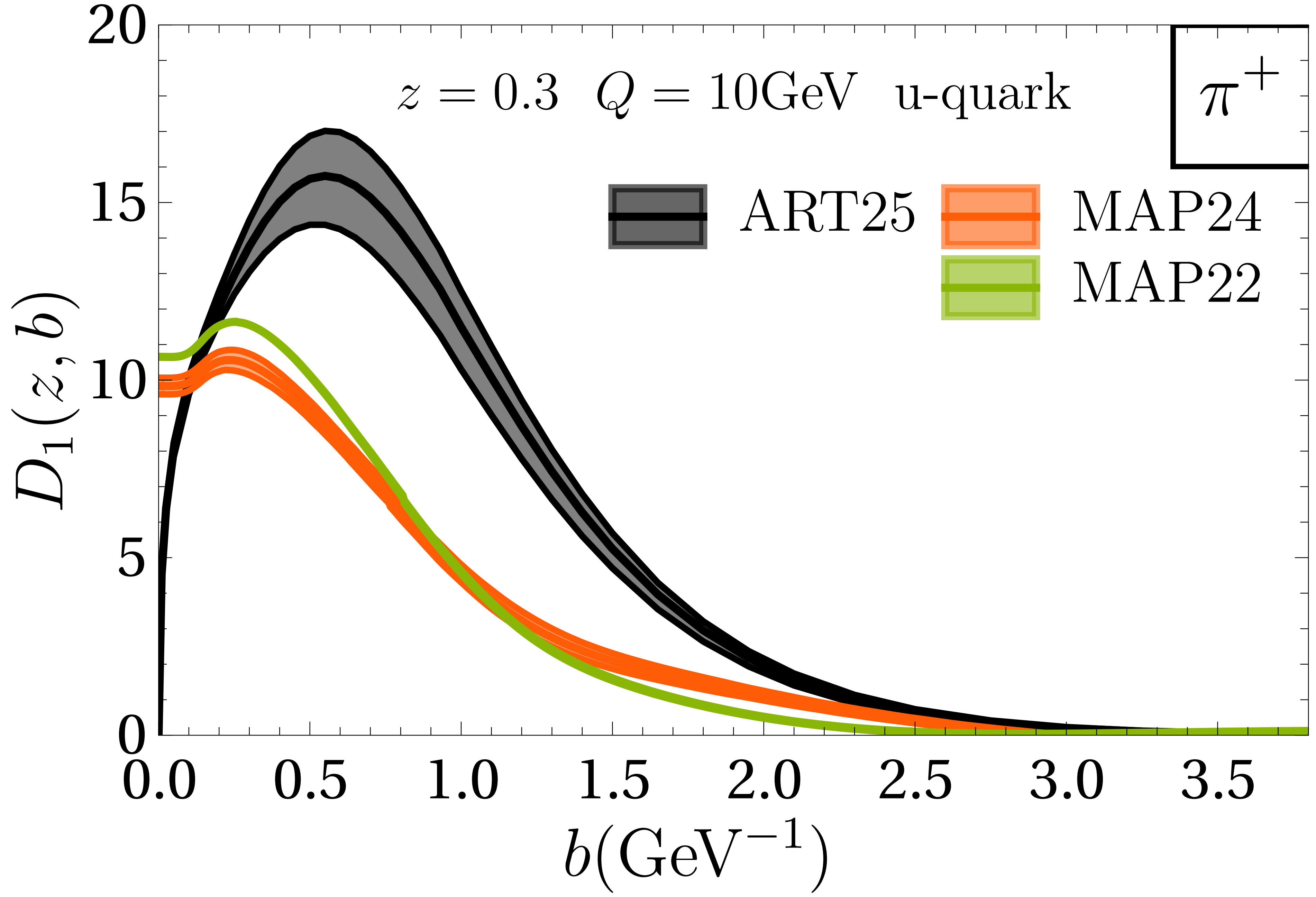
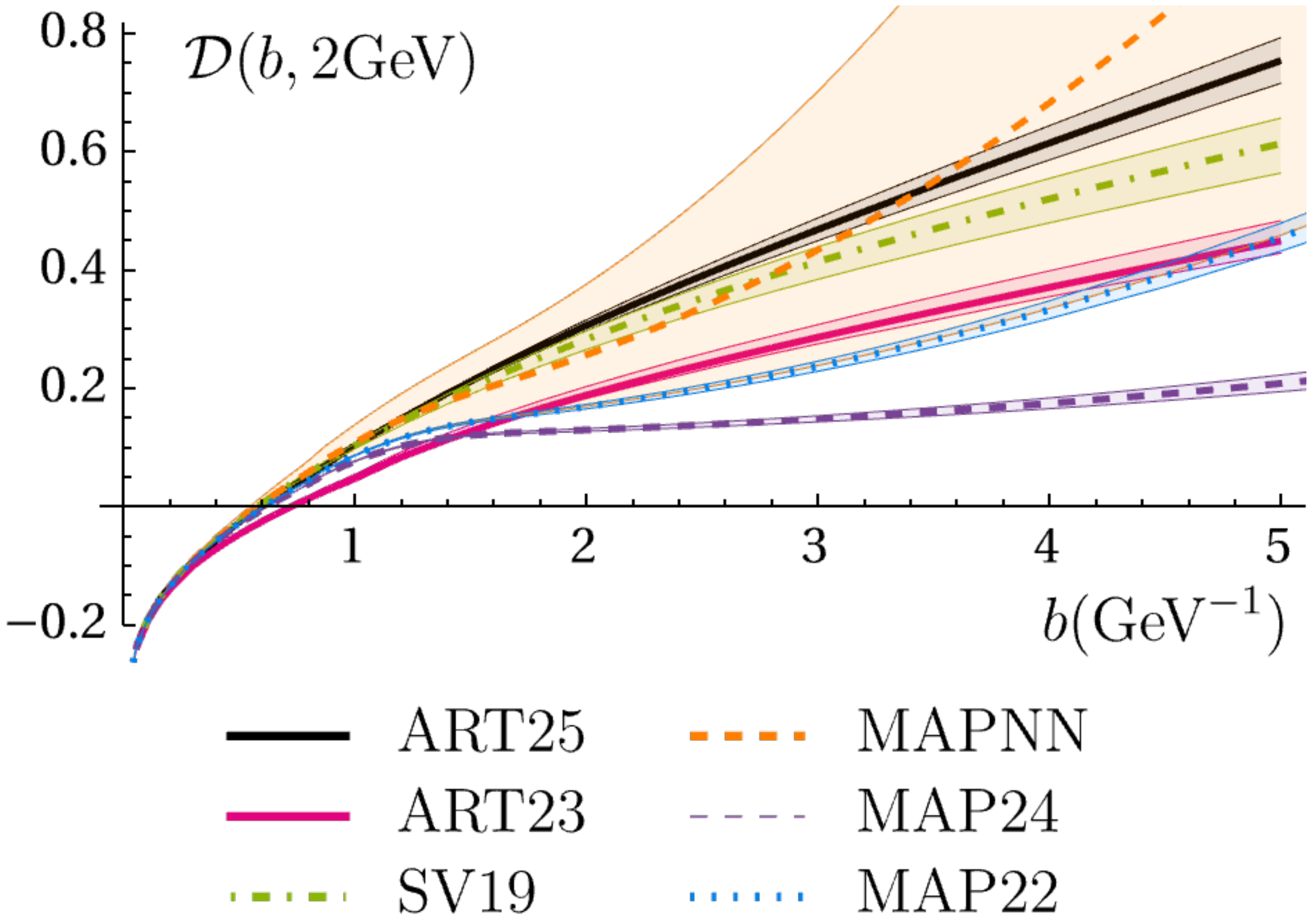




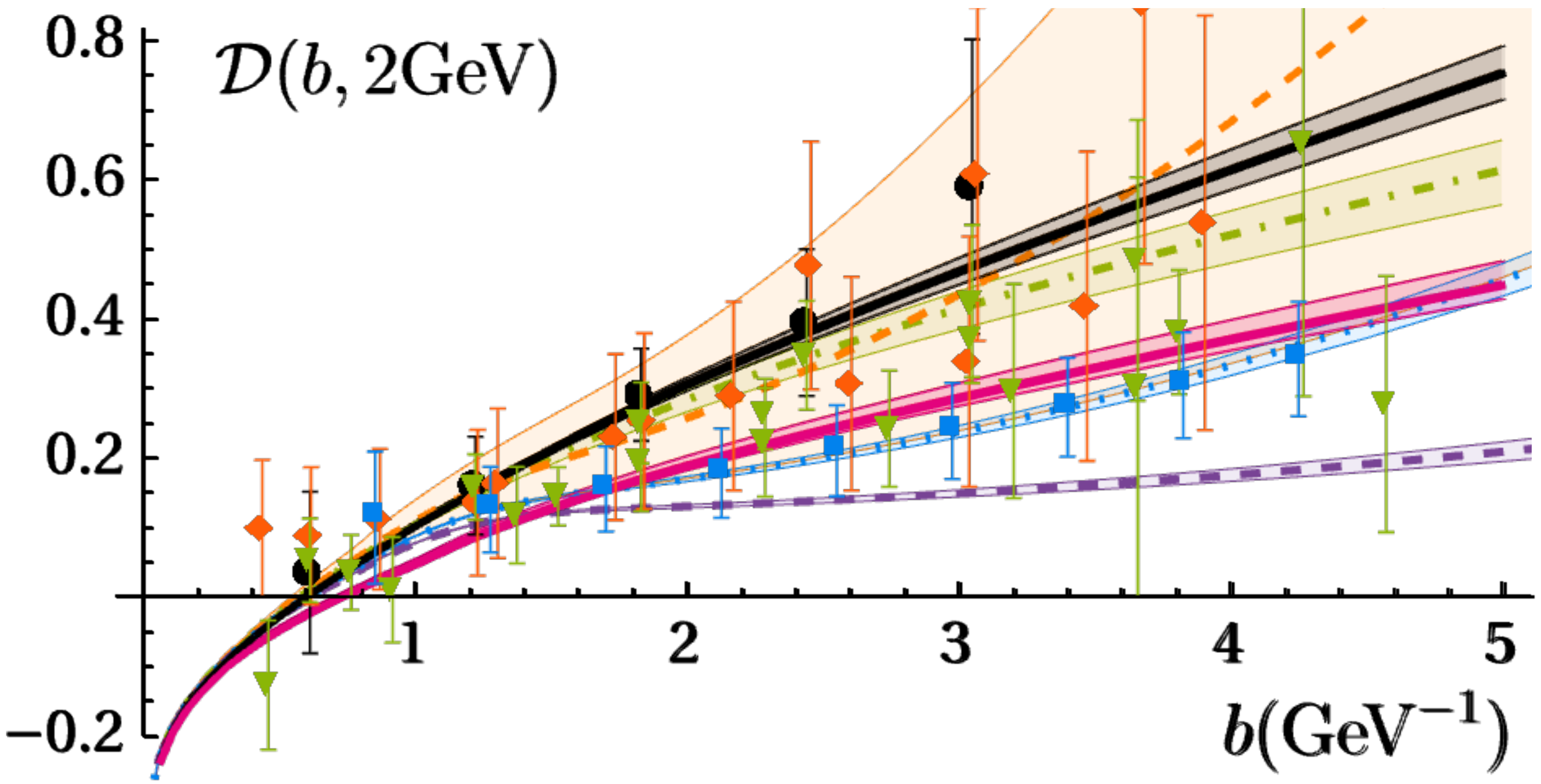
There are significant differences between different extractions.
The error bands are probably underestimated

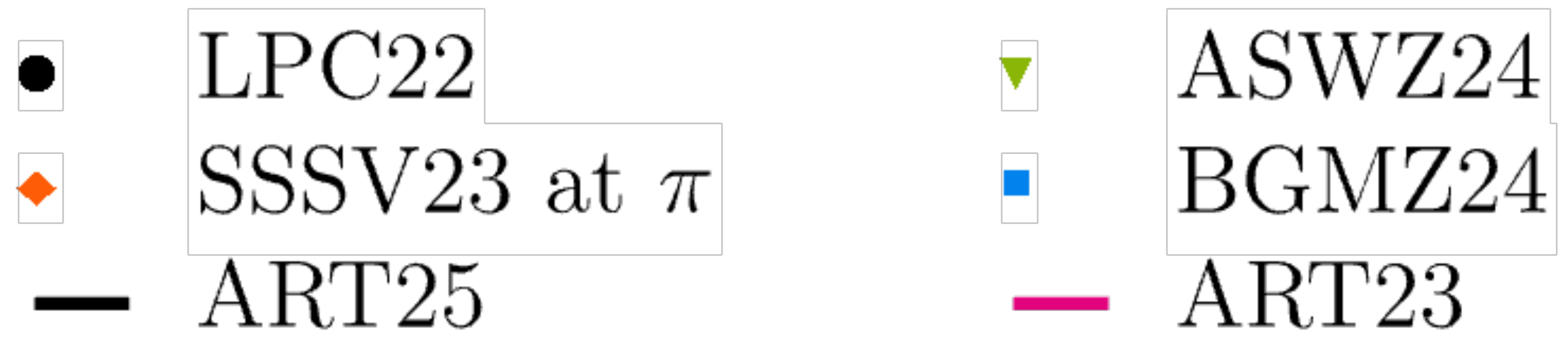
Even larger differences in the Fragmentation Functions

COMPARISON WITH ART25: CS KERNEL



COMPARISON WITH LATTICE QCD: CS KERNEL



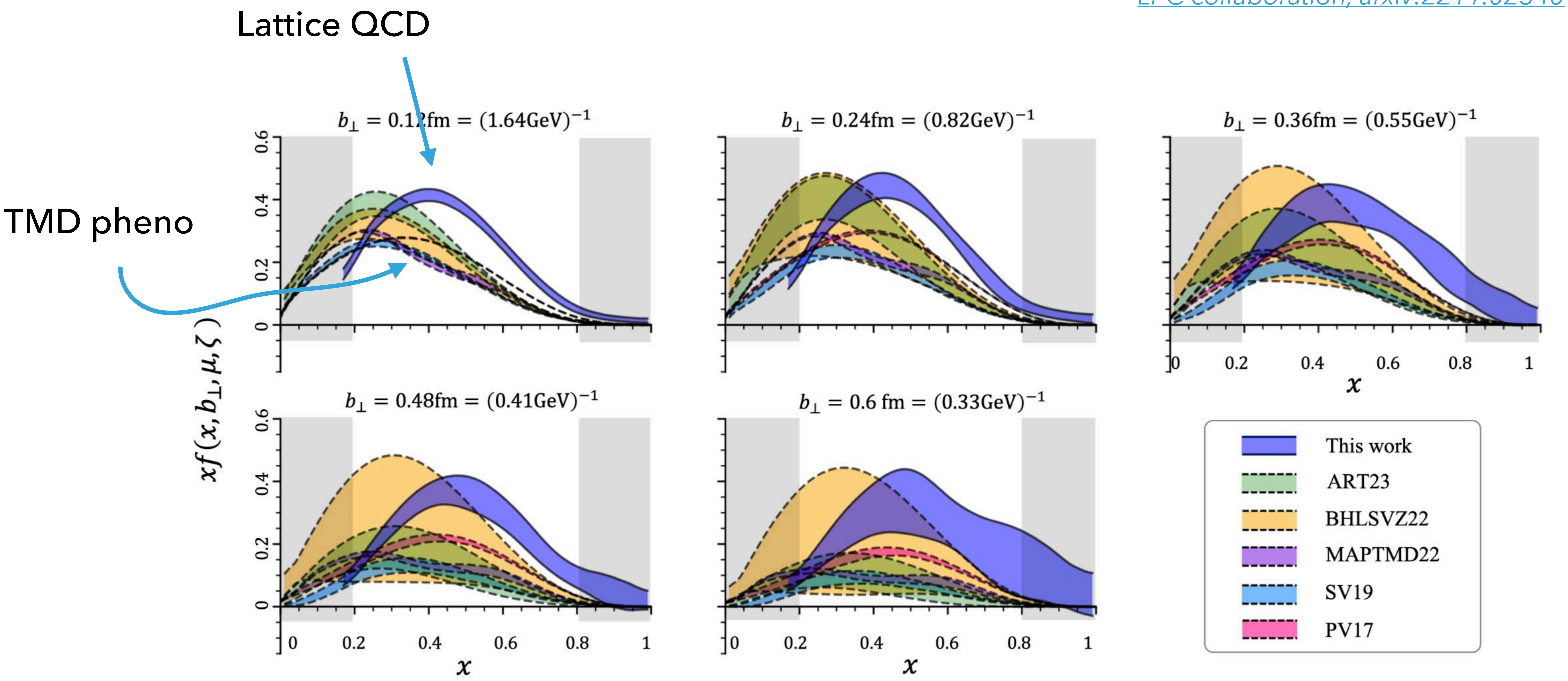


TMD phenomenology

Lattice QCD

CONNECTIONS WITH LATTICE QCD: TMDS

LPC collaboration, arxiv:2211.02340



HELICITY QUARK TMD

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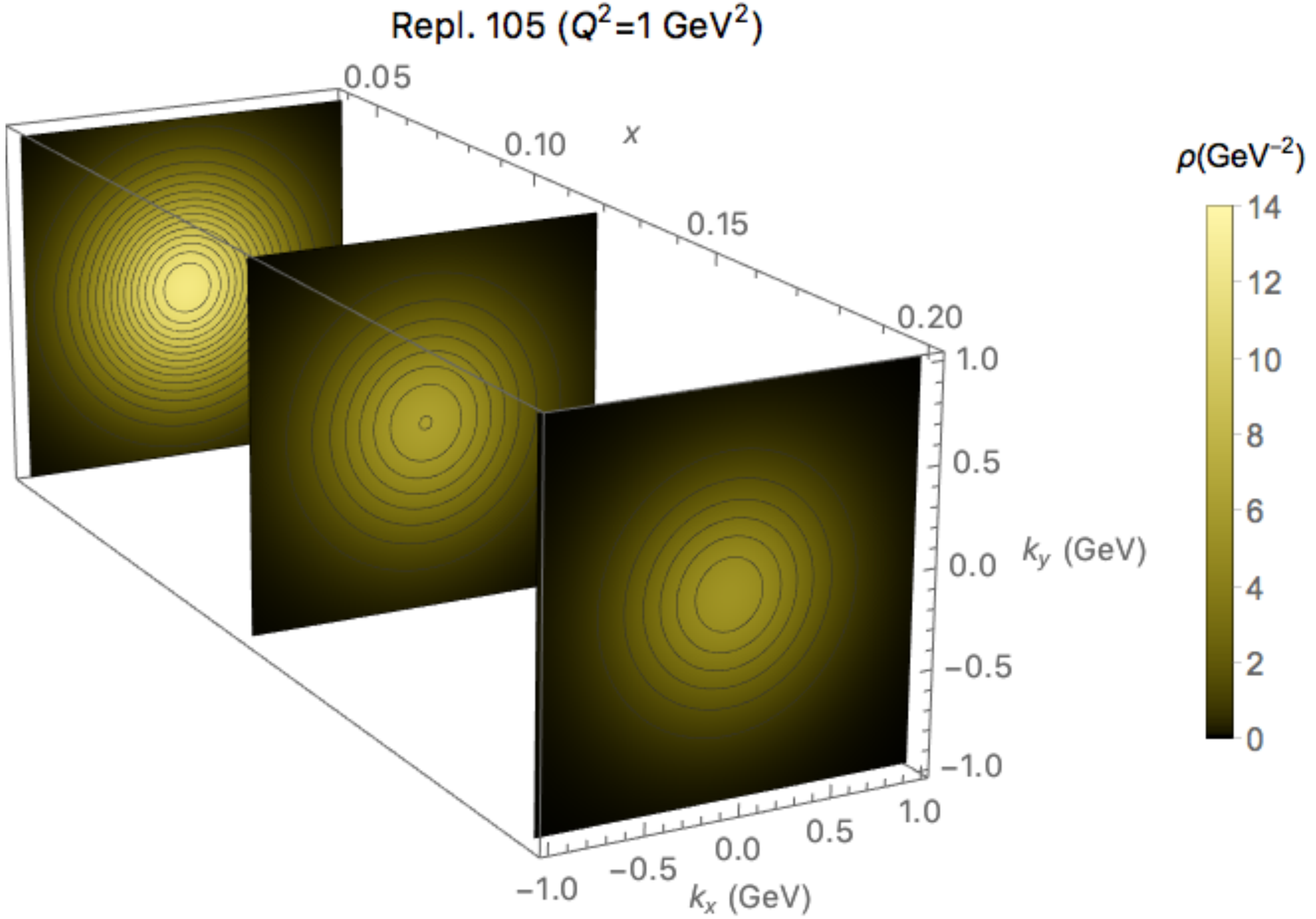
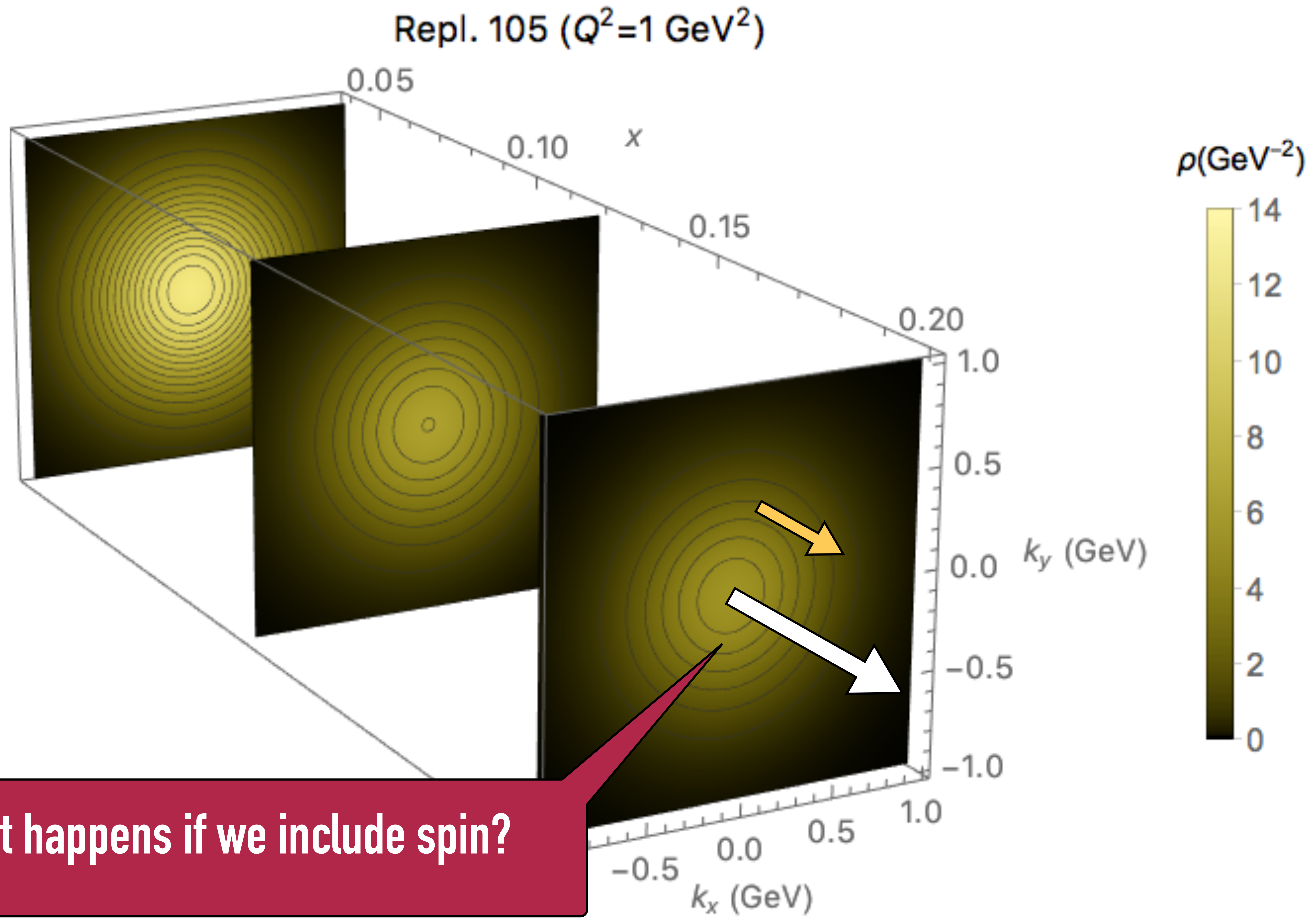
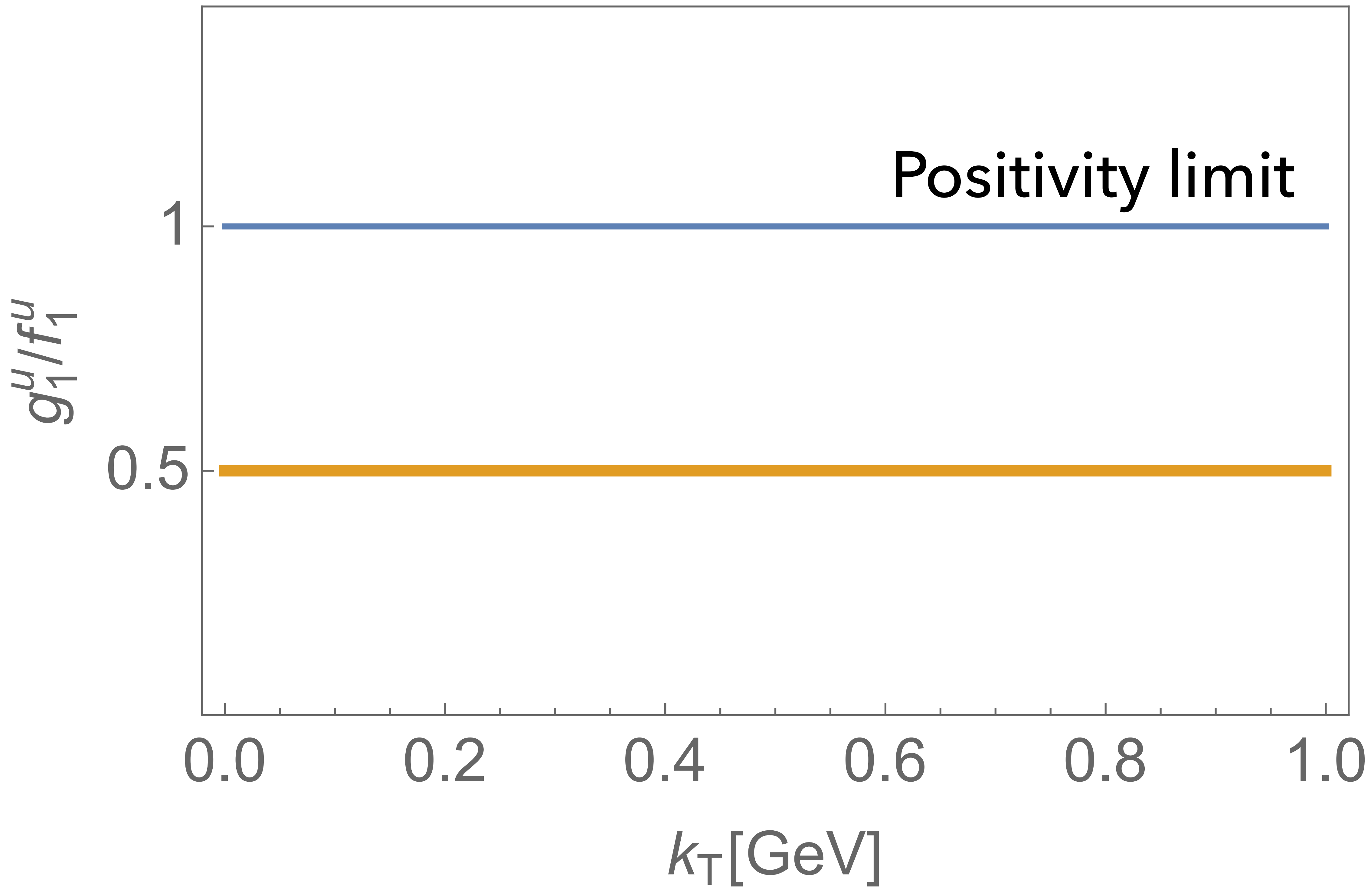

Repl. 105 (Q^2=1 GeV^2)
0.05
0.10
0.15
0.20
x
1.0
0.5
0.0
−0.5
−1.0
k_y (GeV)
−1.0
−0.5
0.0
0.5
1.0
k_x (GeV)
ρ(GeV^{-2})
14
12
10
8
6
4
2
0

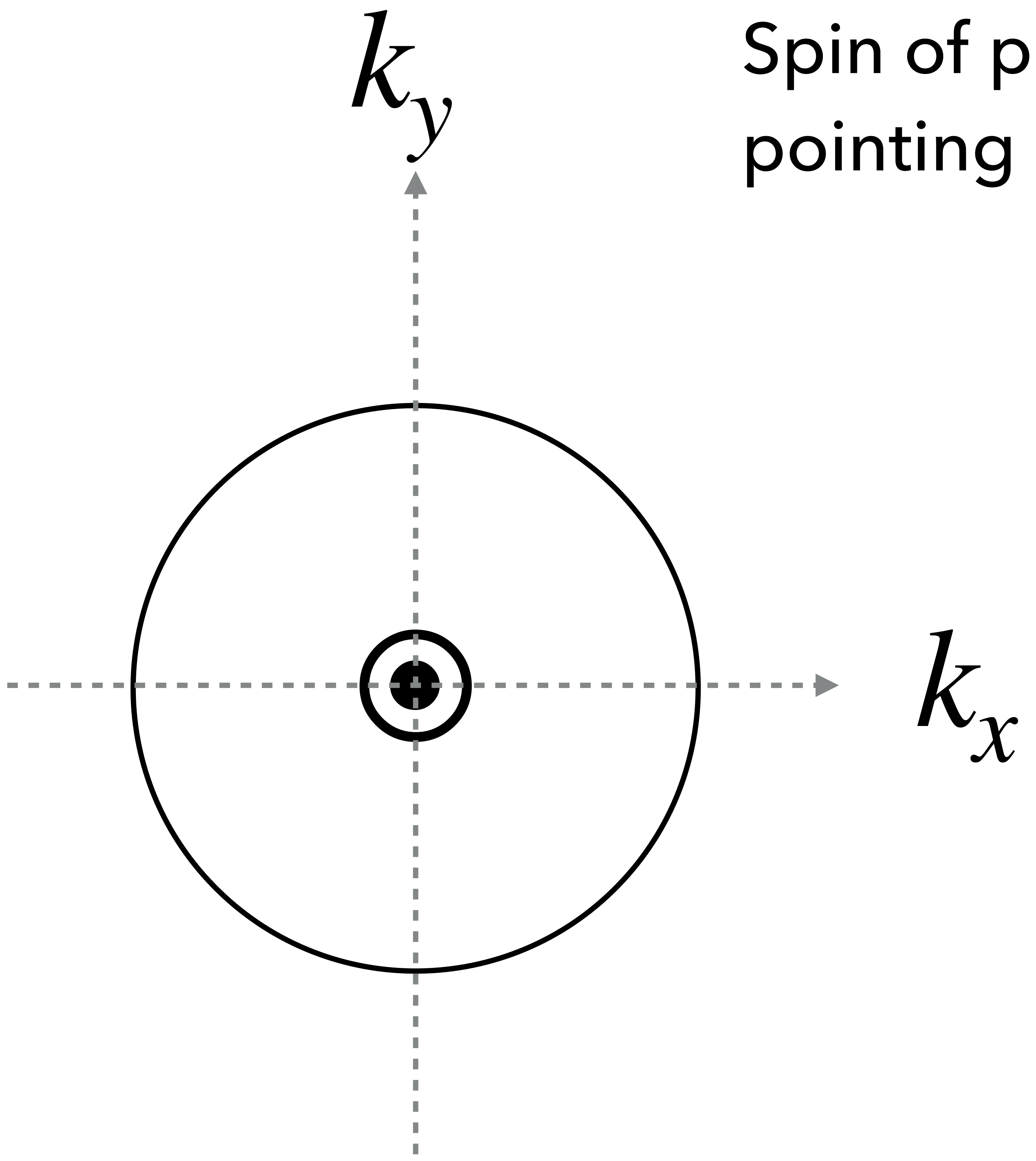


What happens if we include spin?

HELICITY TMD INTERPRETATION

At a fixed value of x





Spin of proton pointing out

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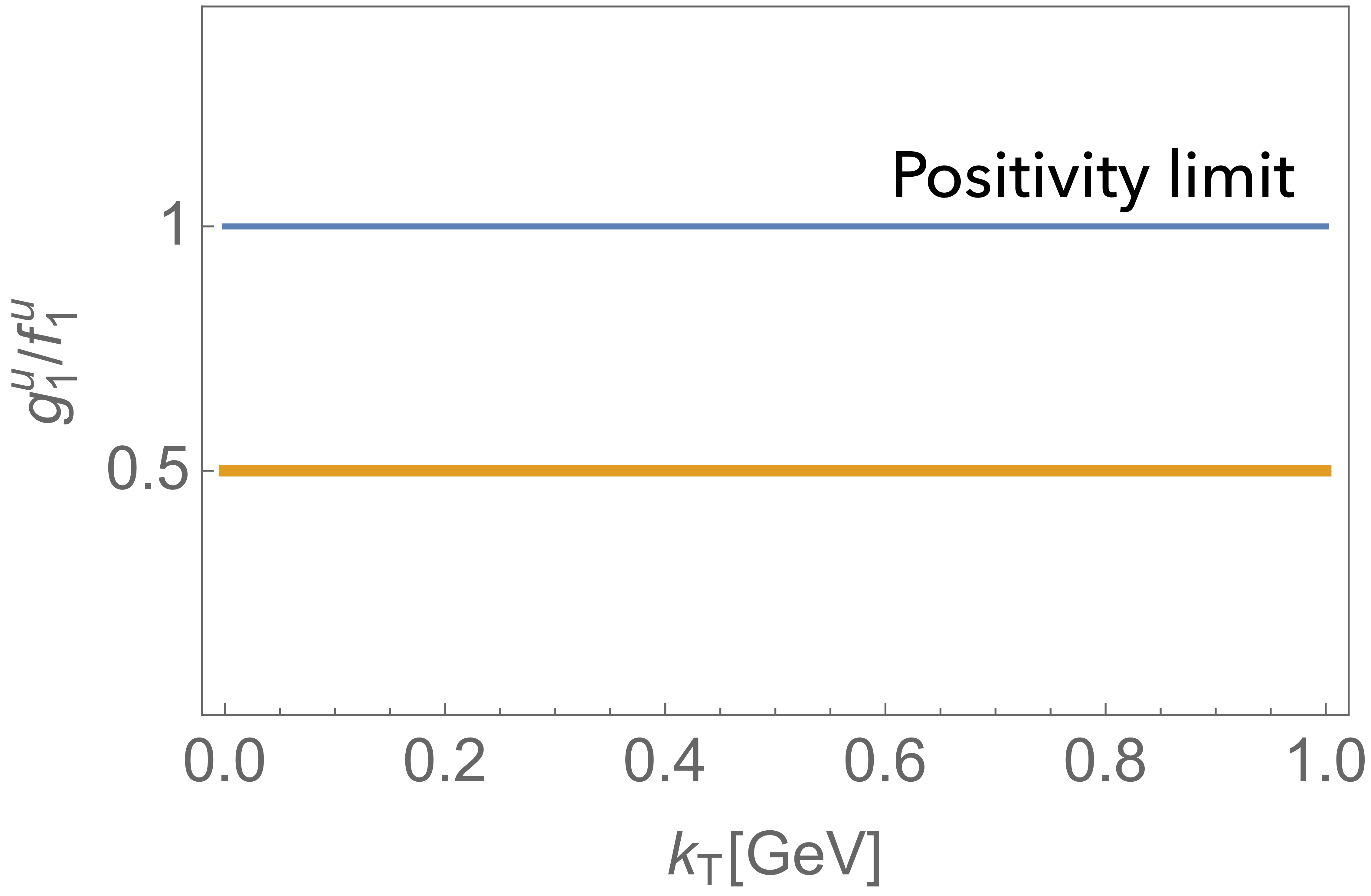
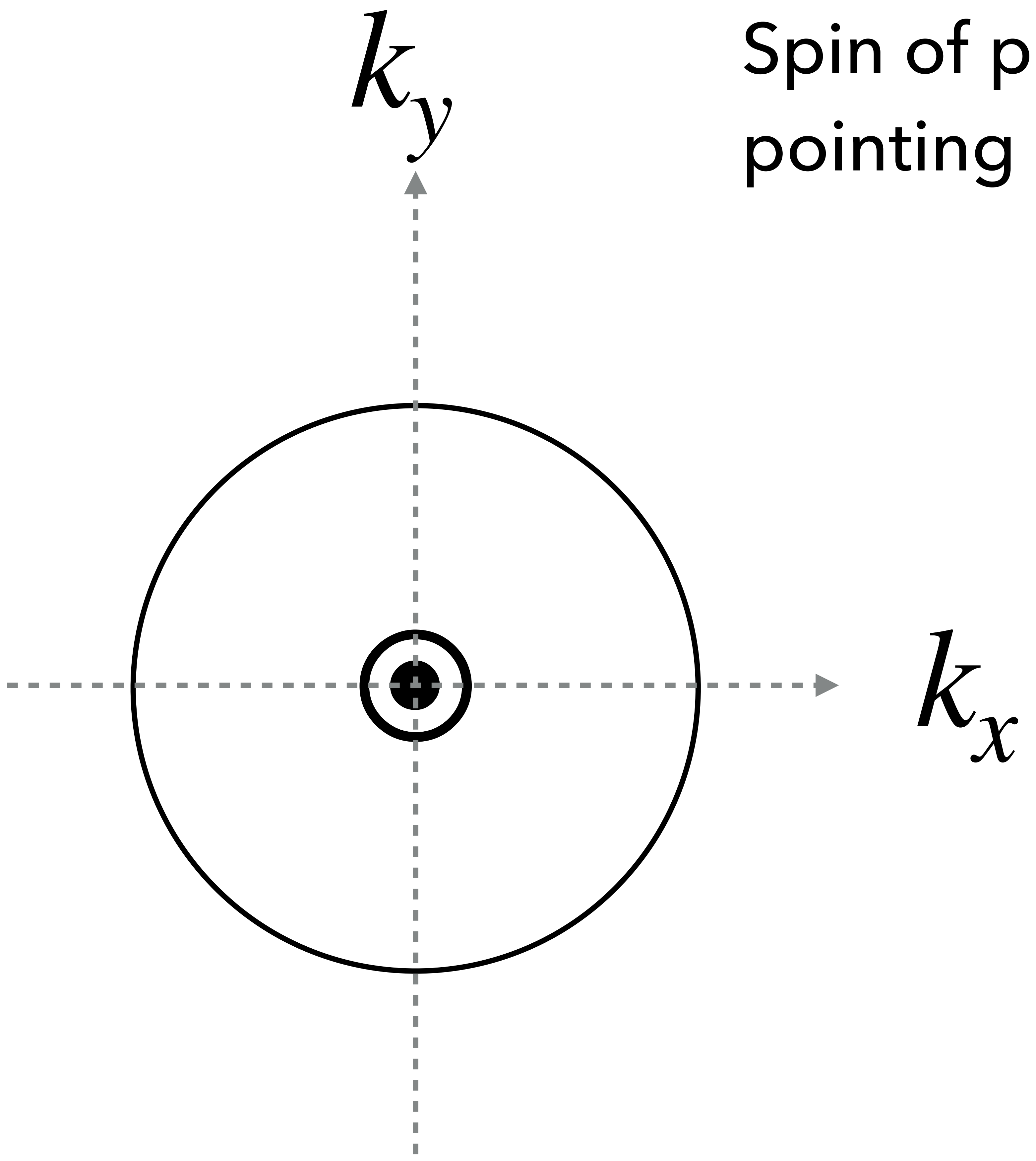
At a fixed value of x





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We try to always impose positivity limits (hep-ph/9912490).
We prefer rigid and physical to flexible and unphysical

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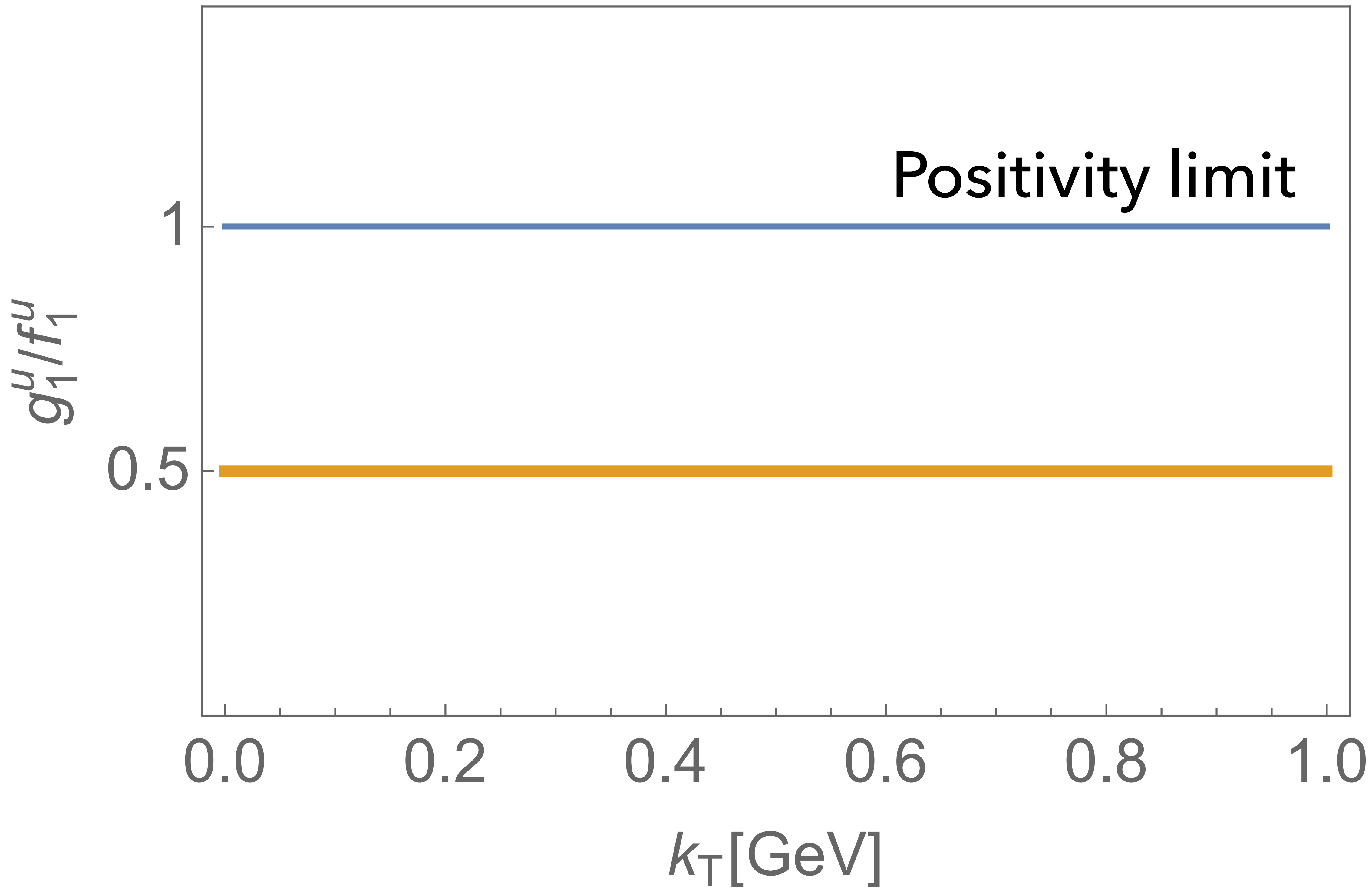

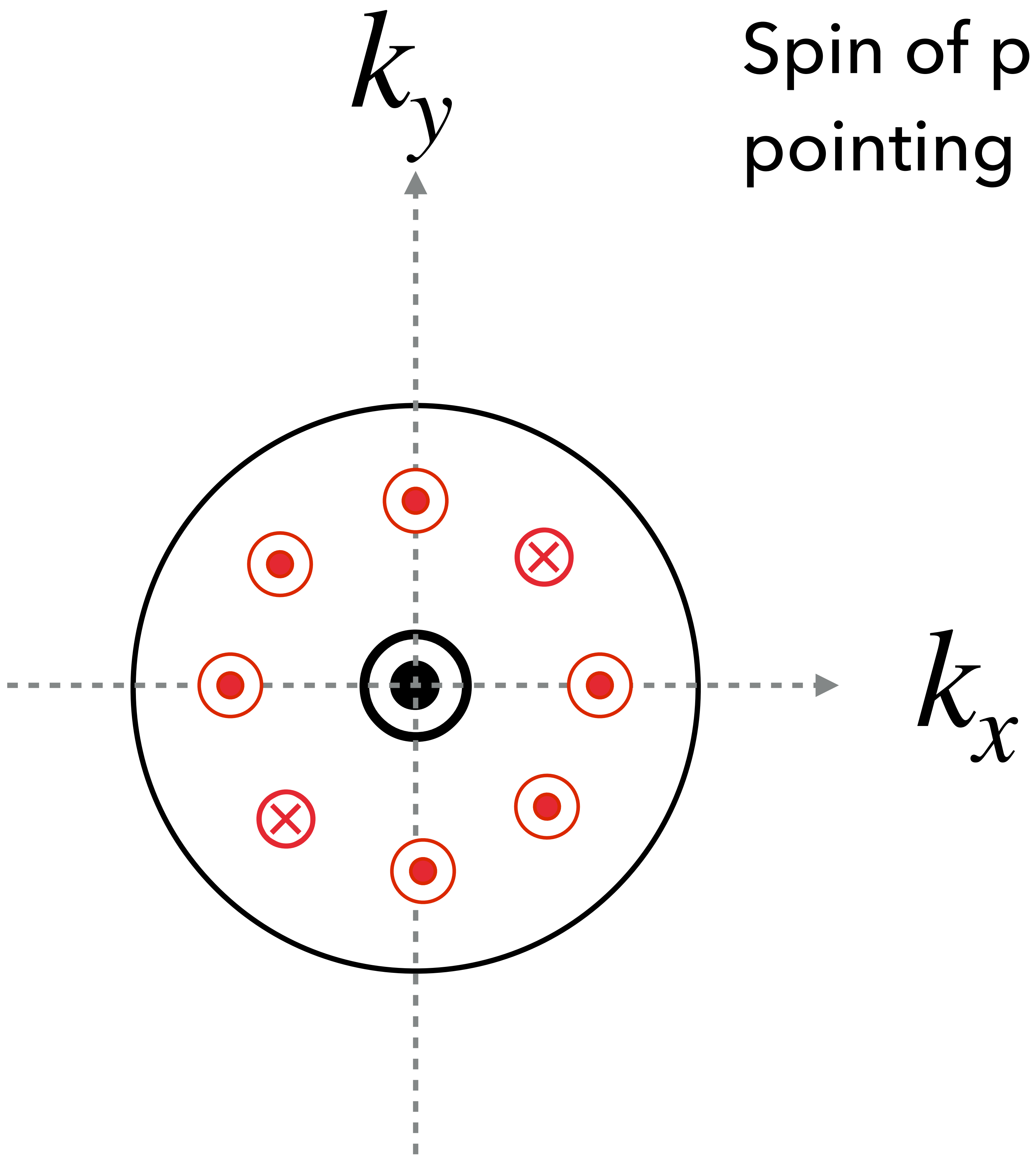

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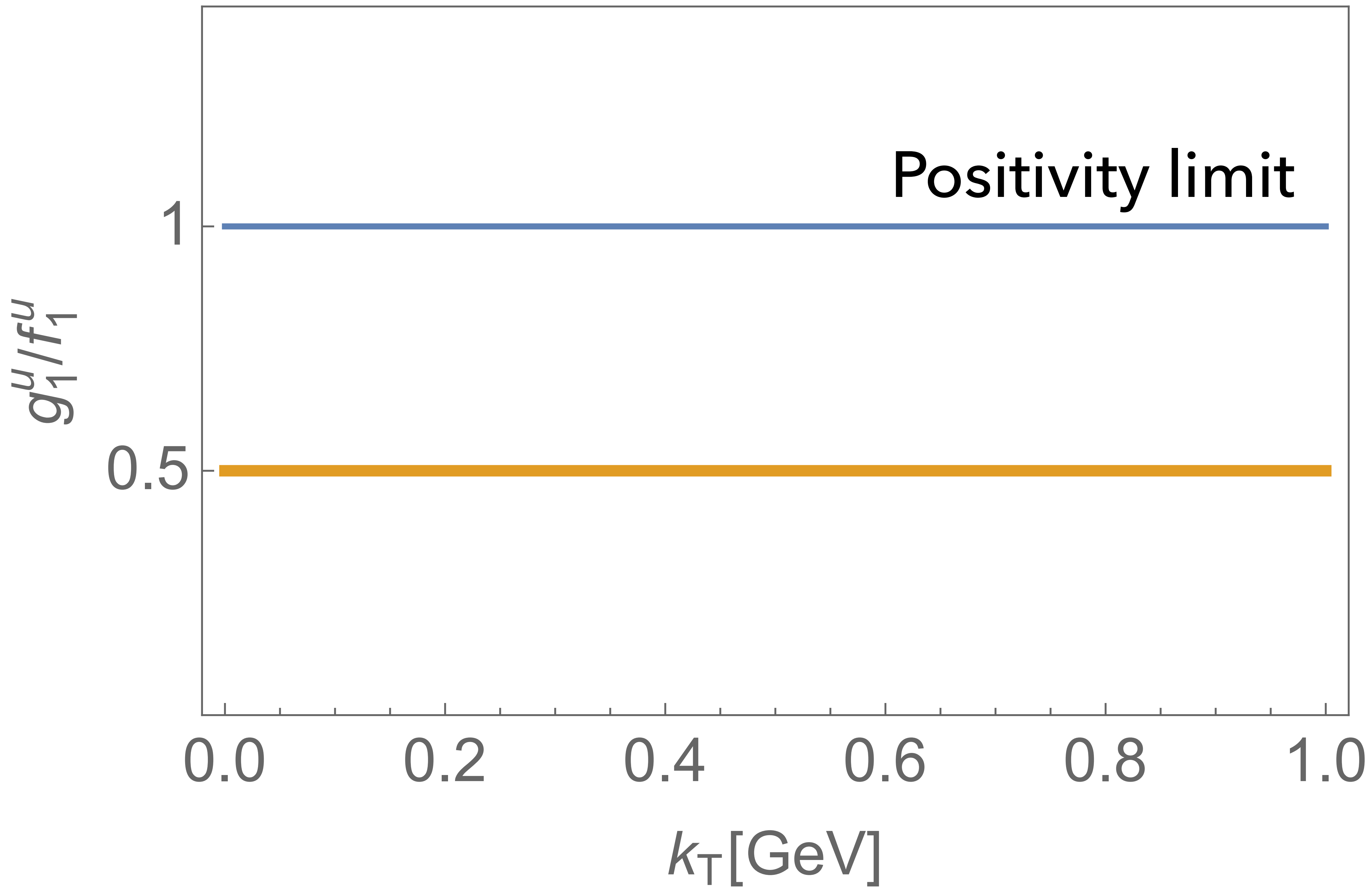

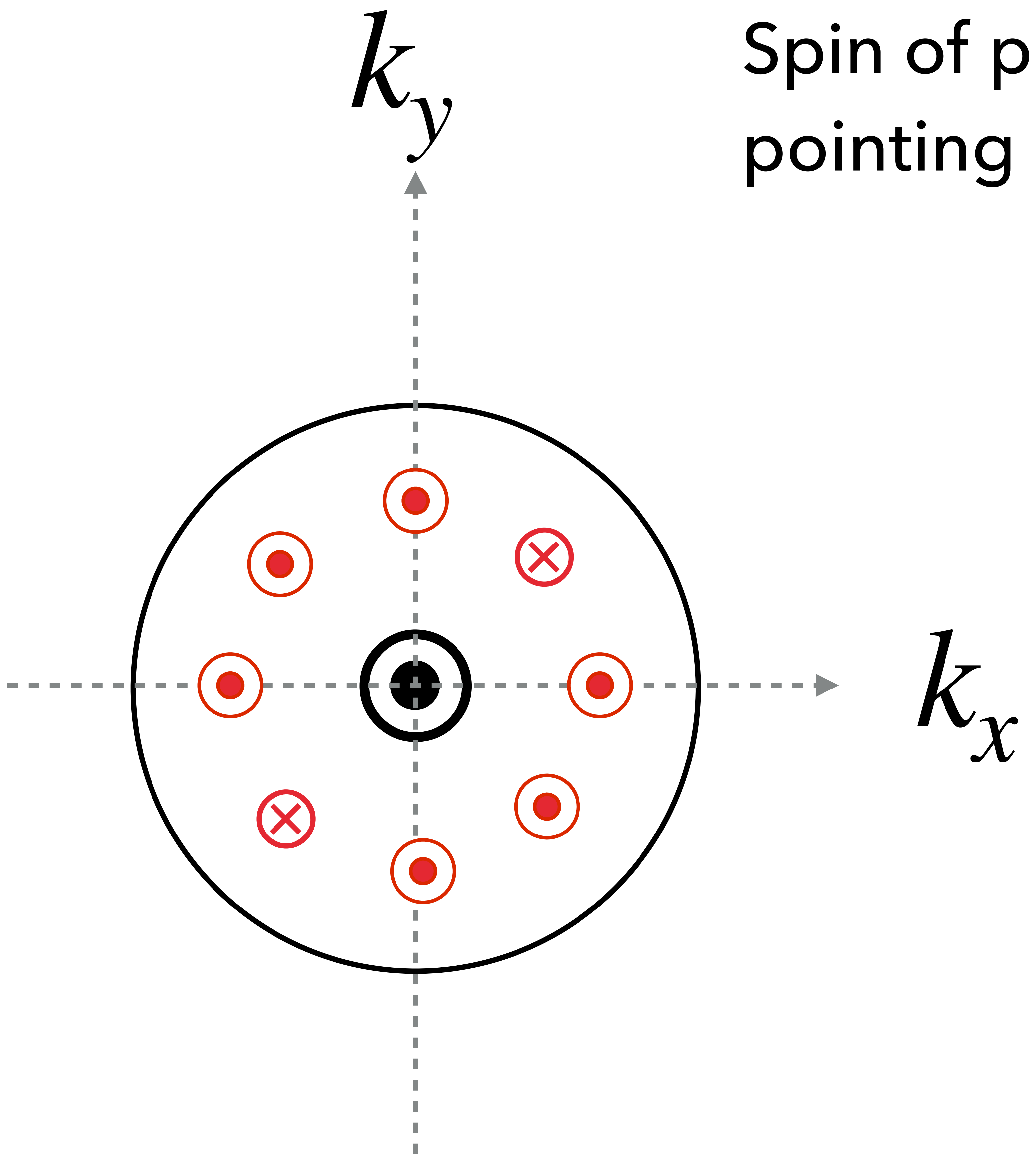

Spin of proton pointing out

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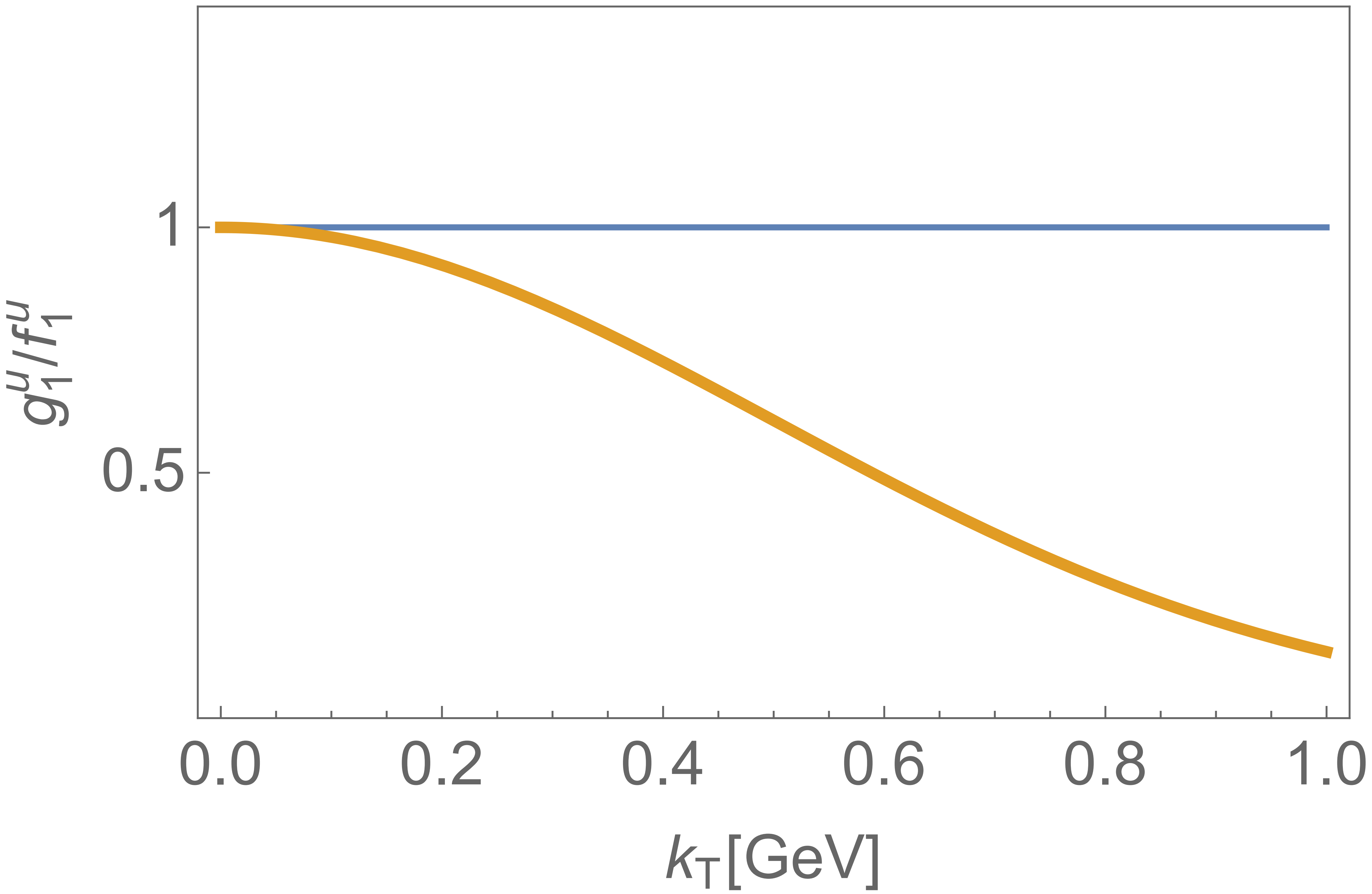
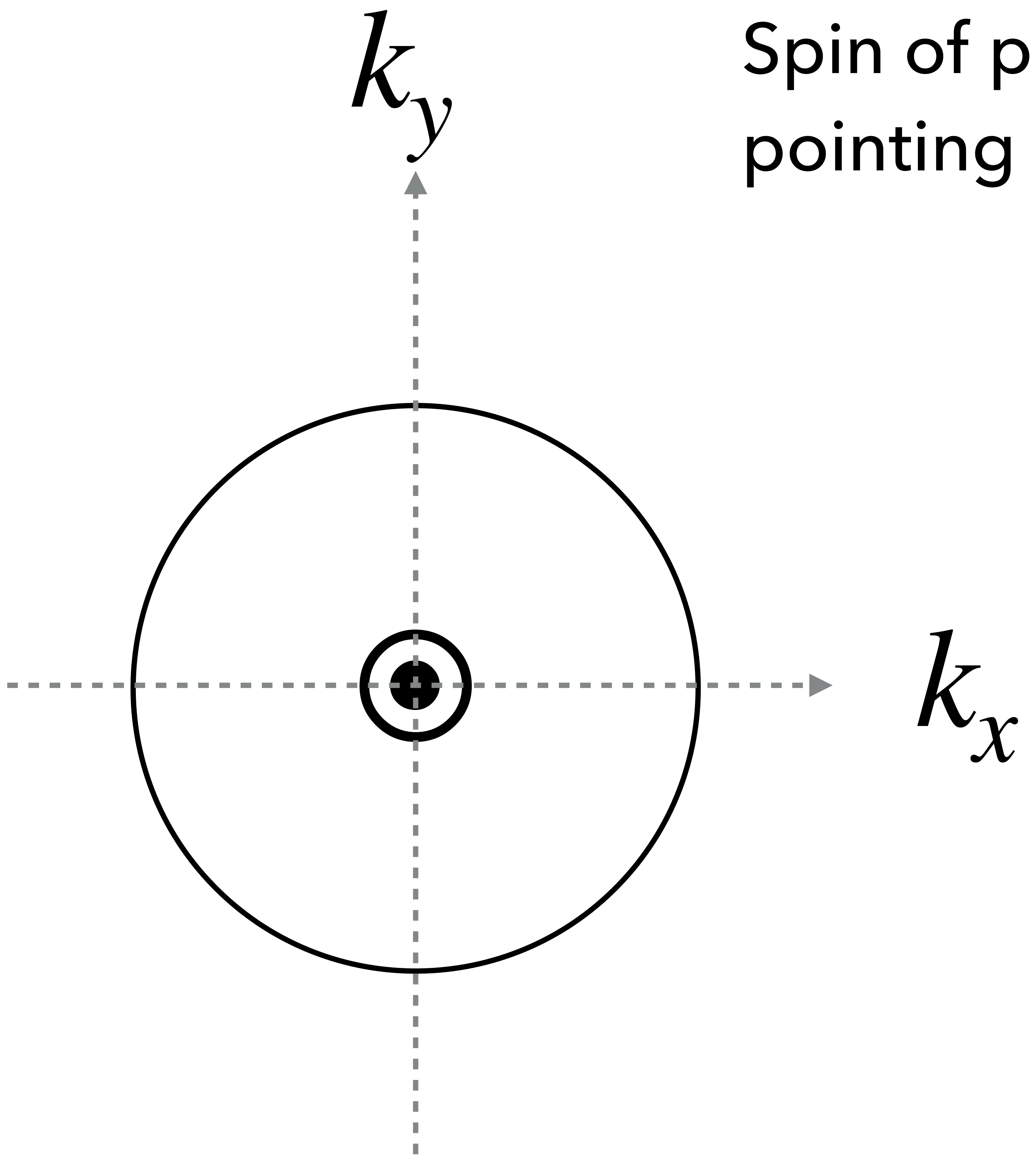
We prefer rigid and physical to flexible and unphysical

The fraction of same/opposite helicities is the same at any transverse momentum

HELICITY TMD INTERPRETATION

At a certain value of x





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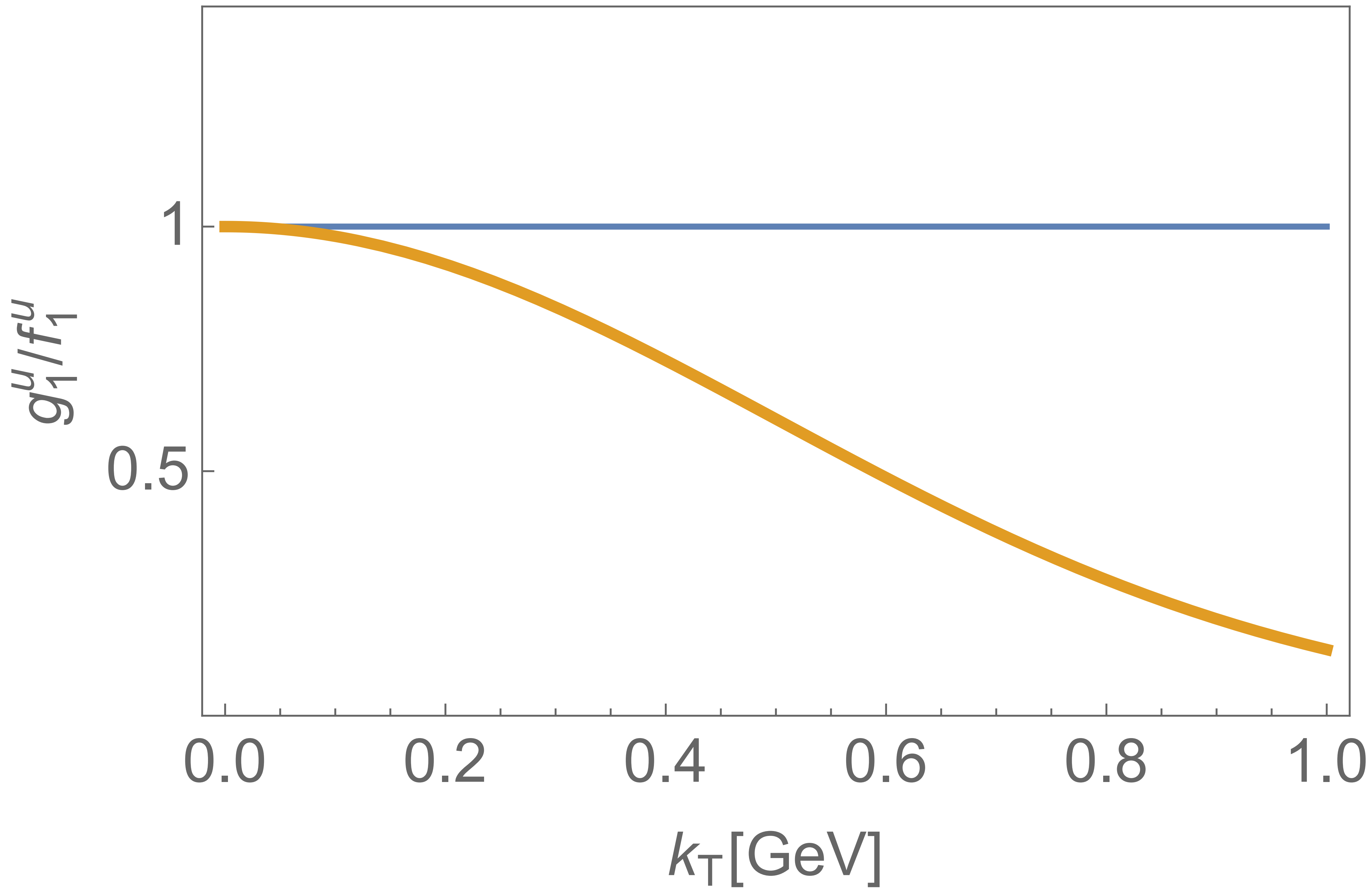

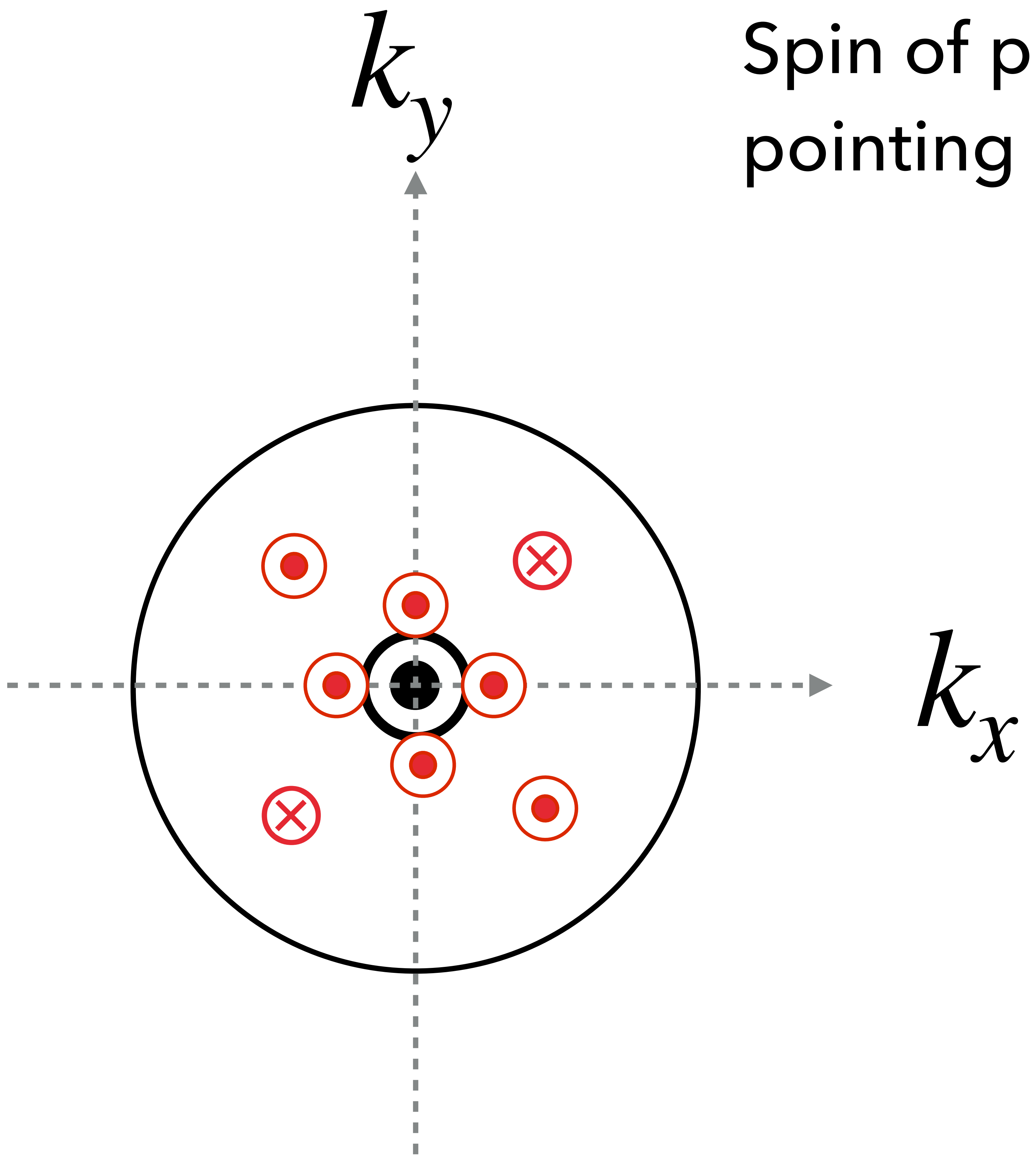

Spin of proton pointing out

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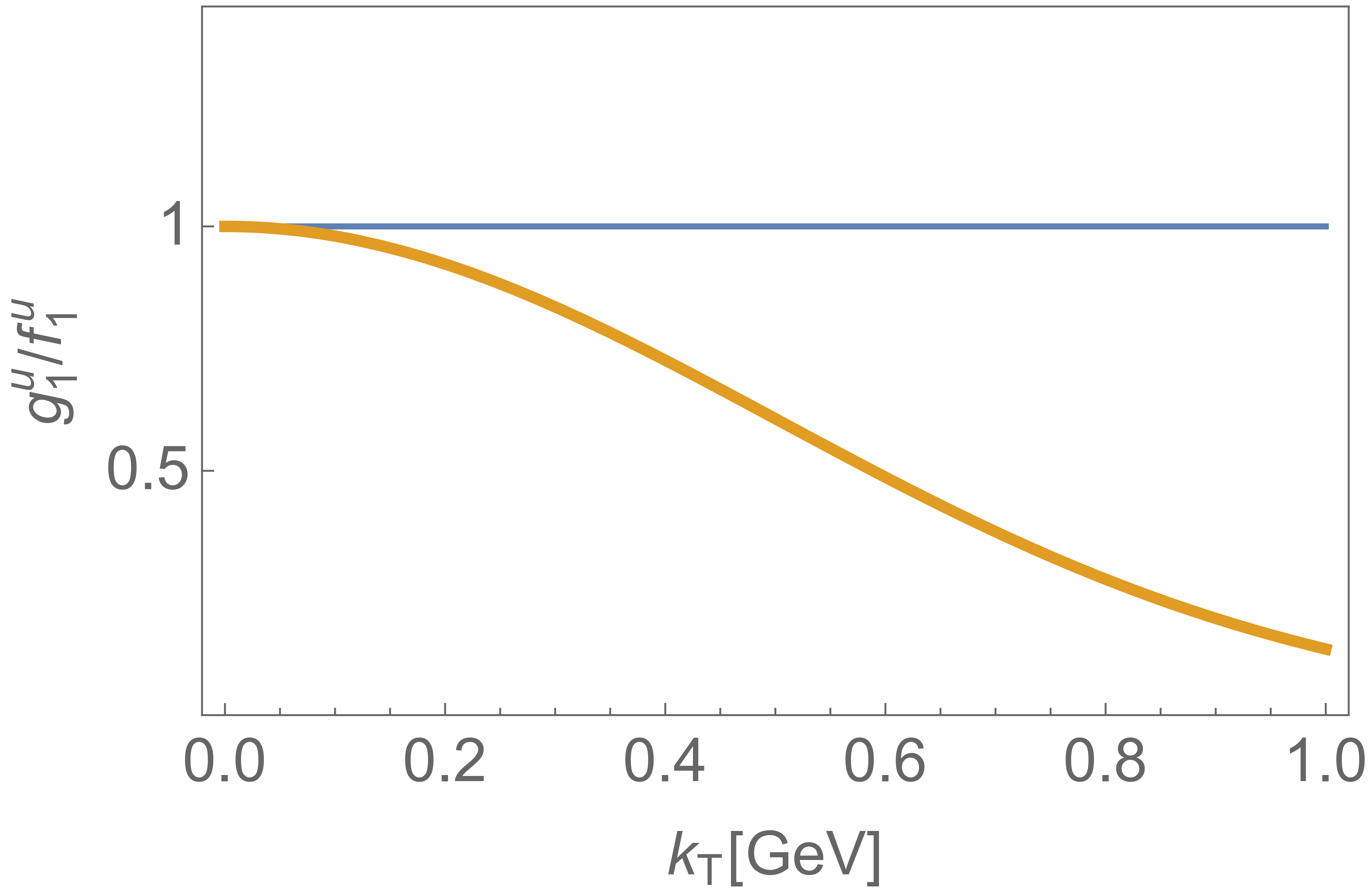
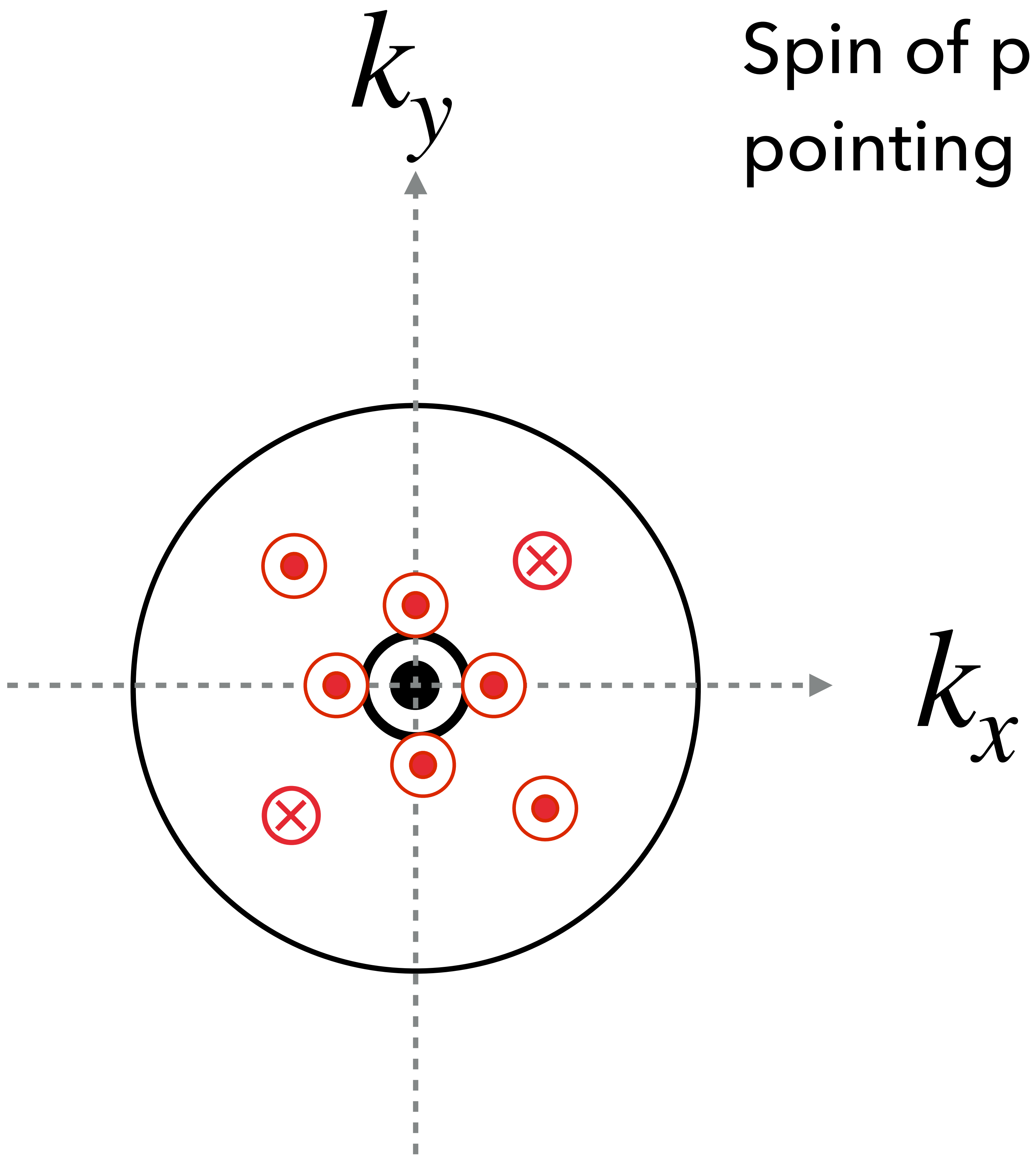


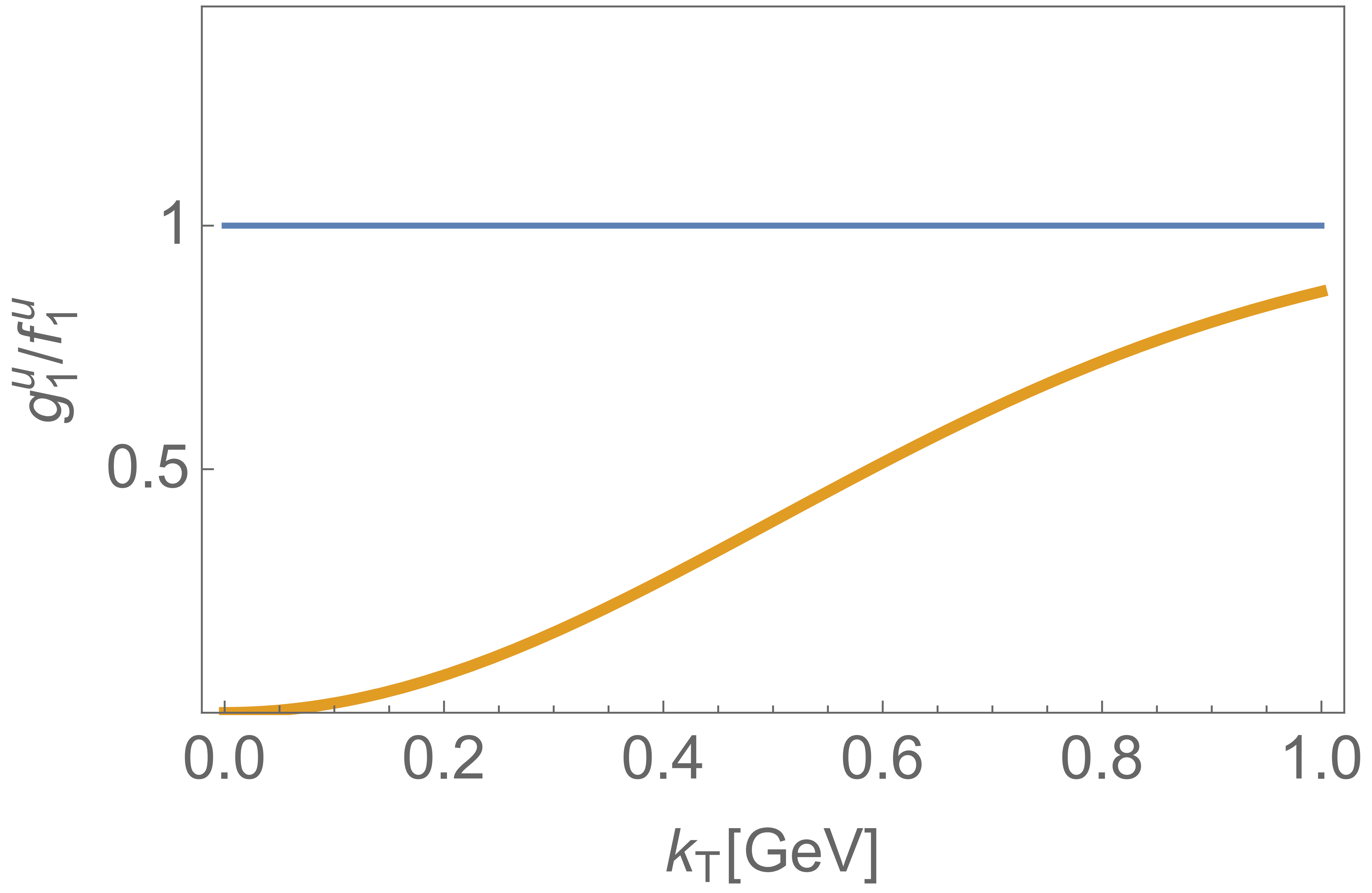


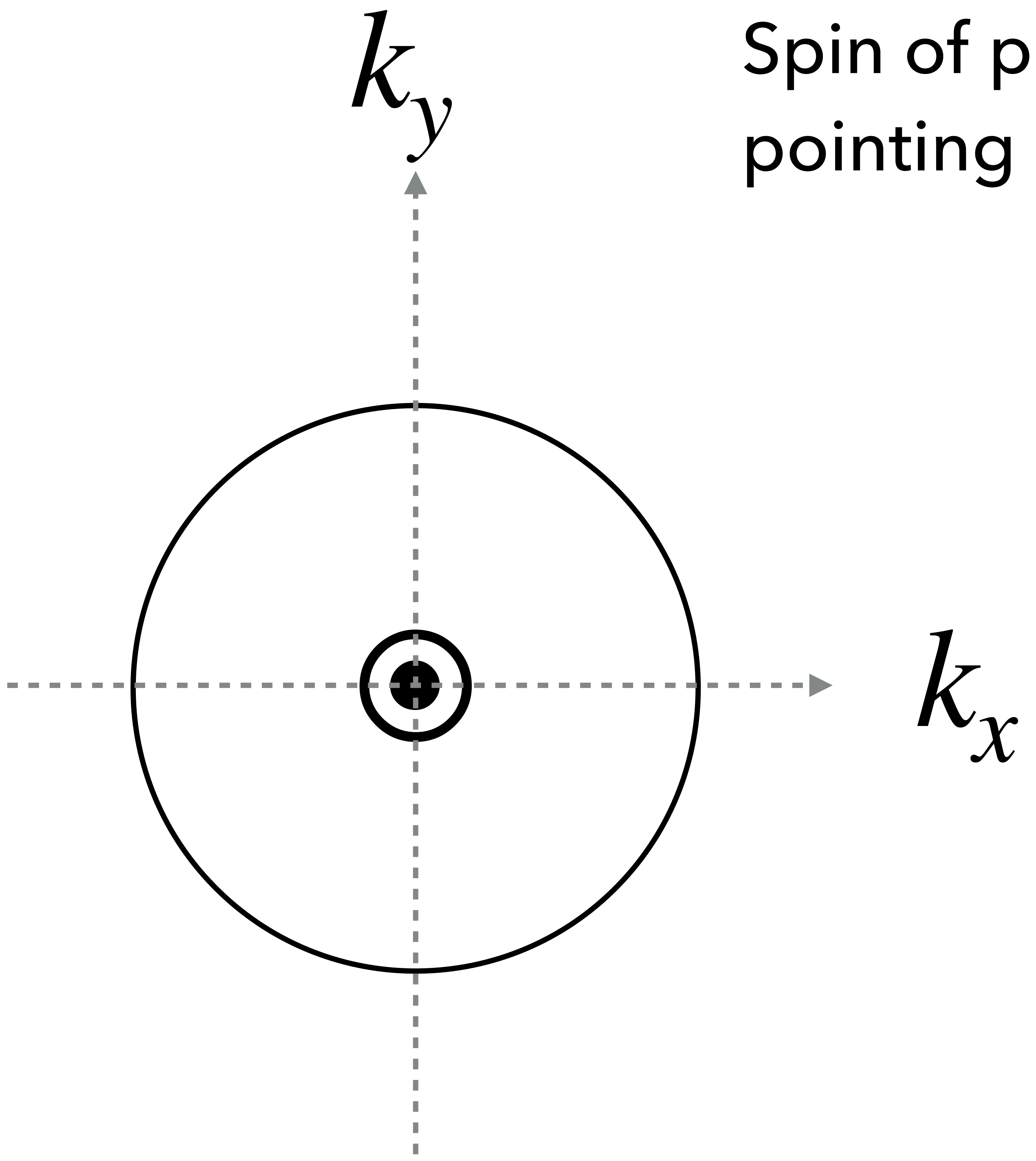
Spin of proton pointing out

The quarks with the same helicity as the proton's have less transverse momentum

HELICITY TMD INTERPRETATION

At a certain value of x





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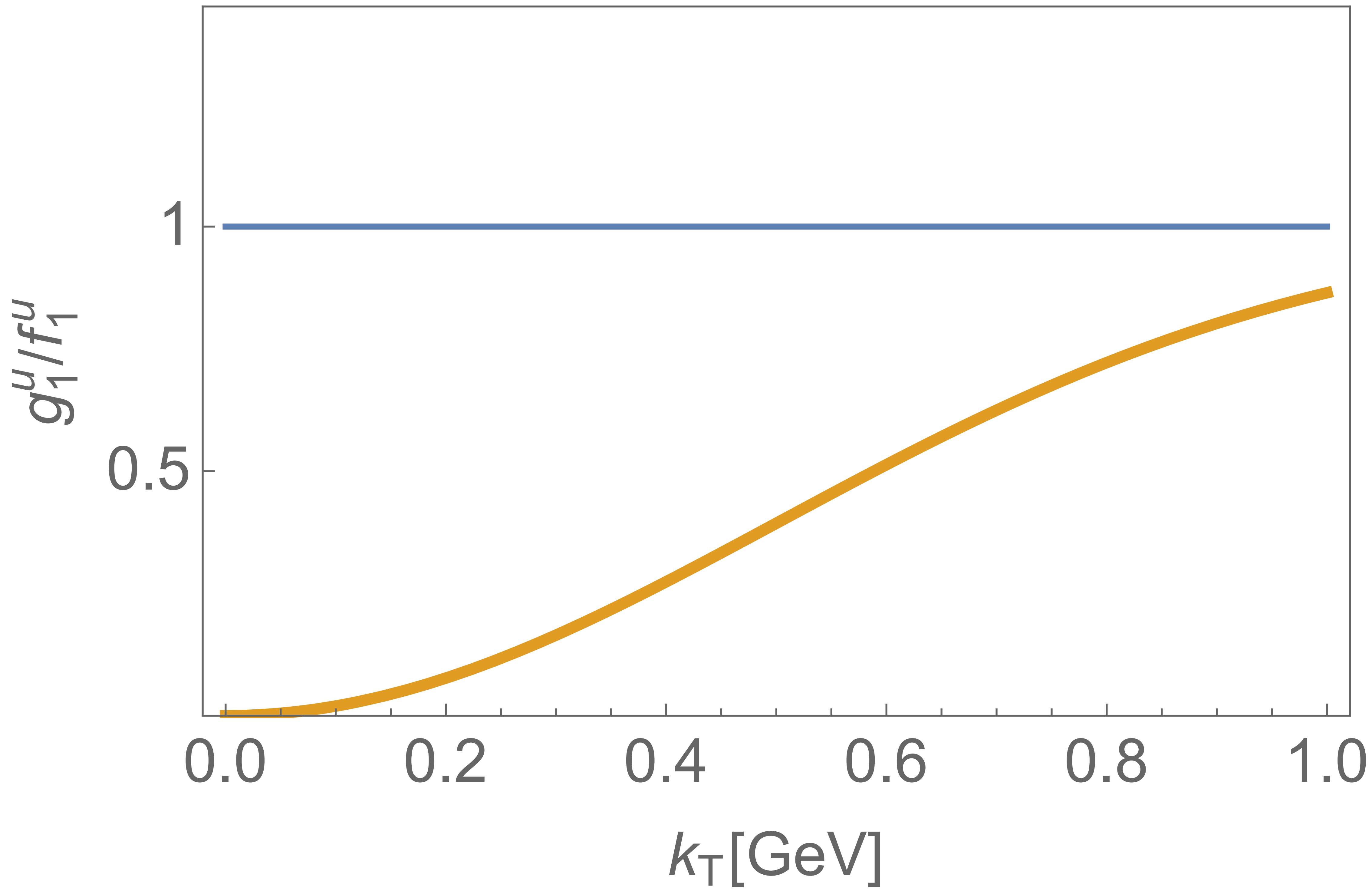

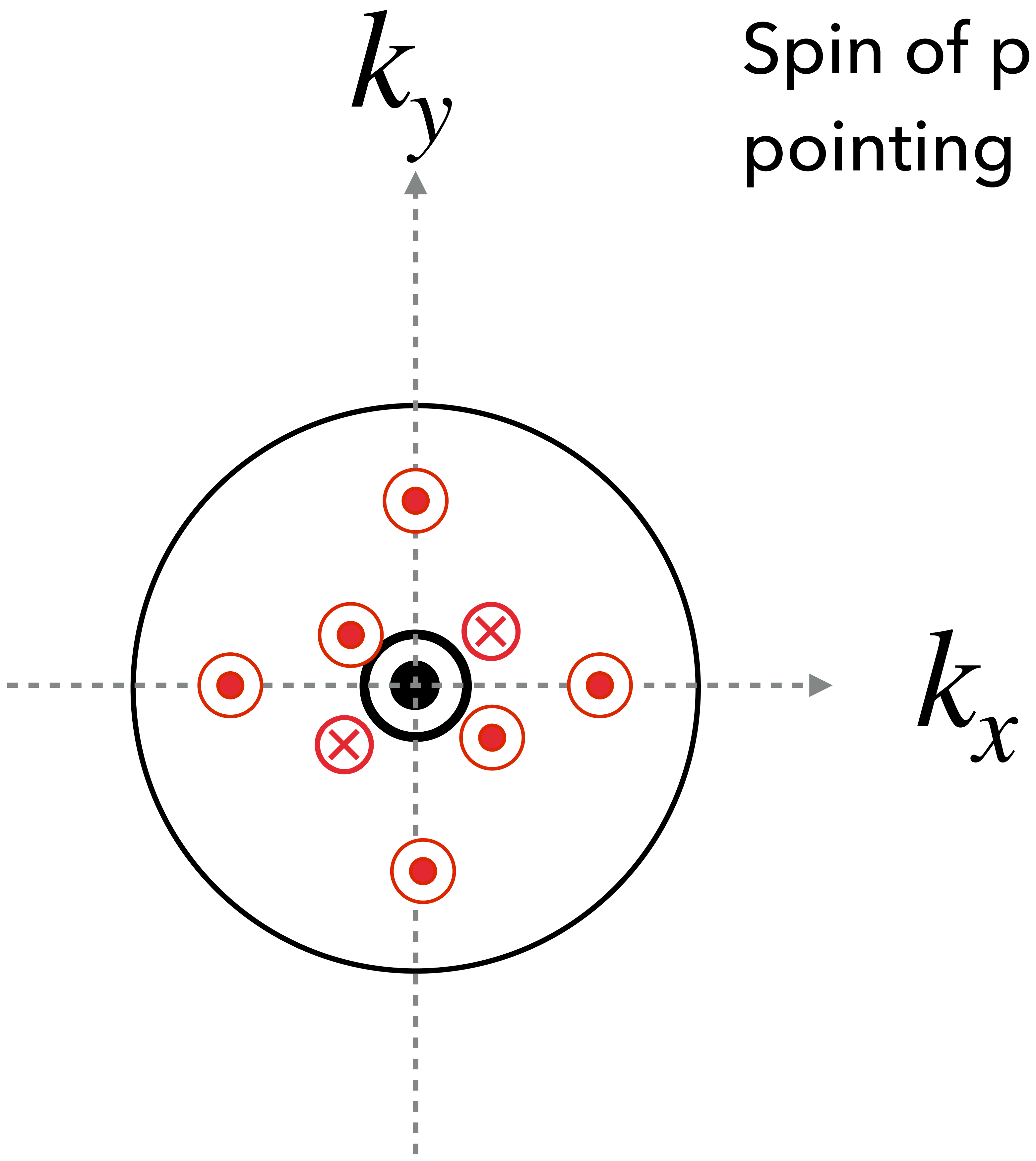

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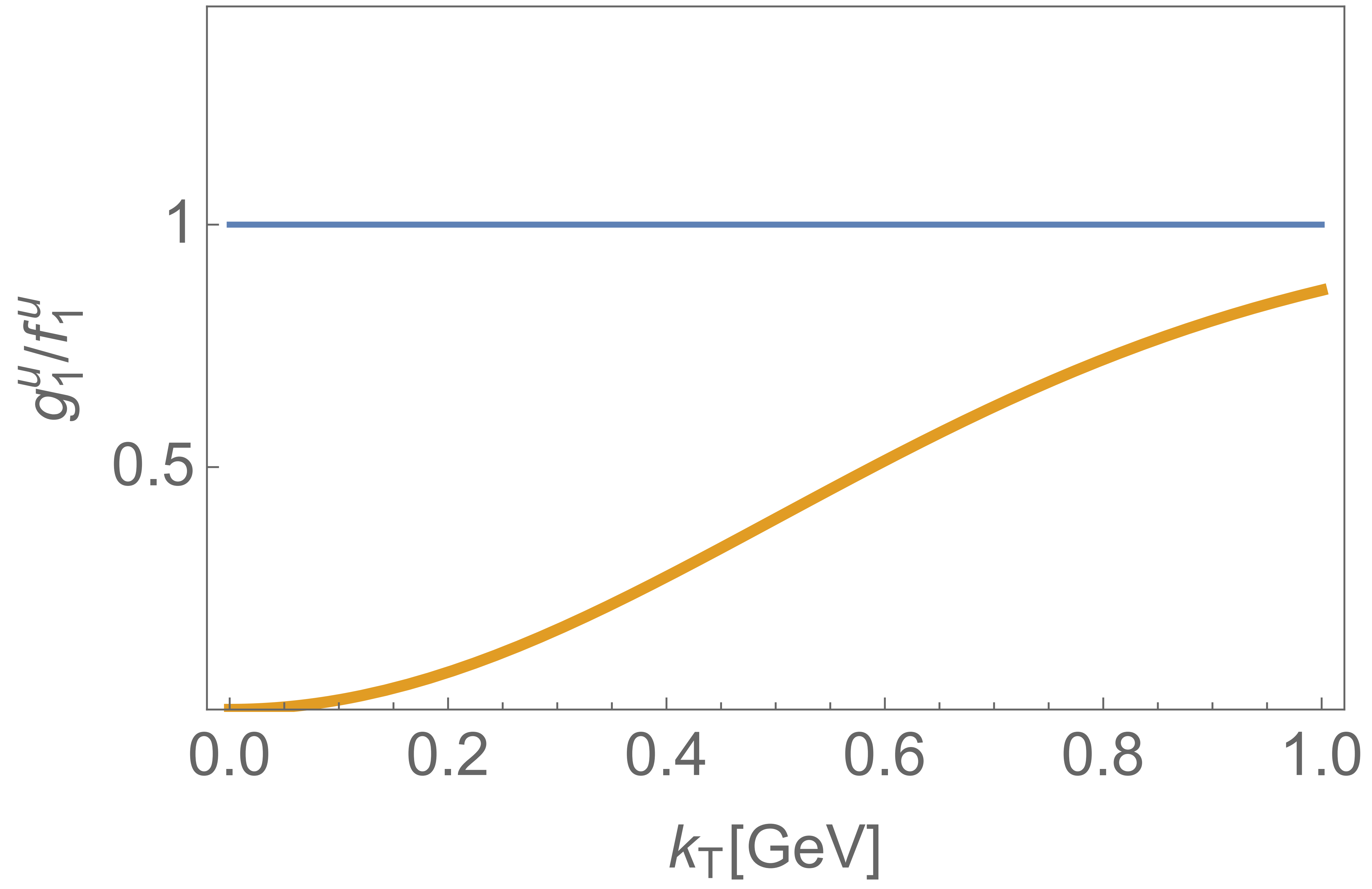
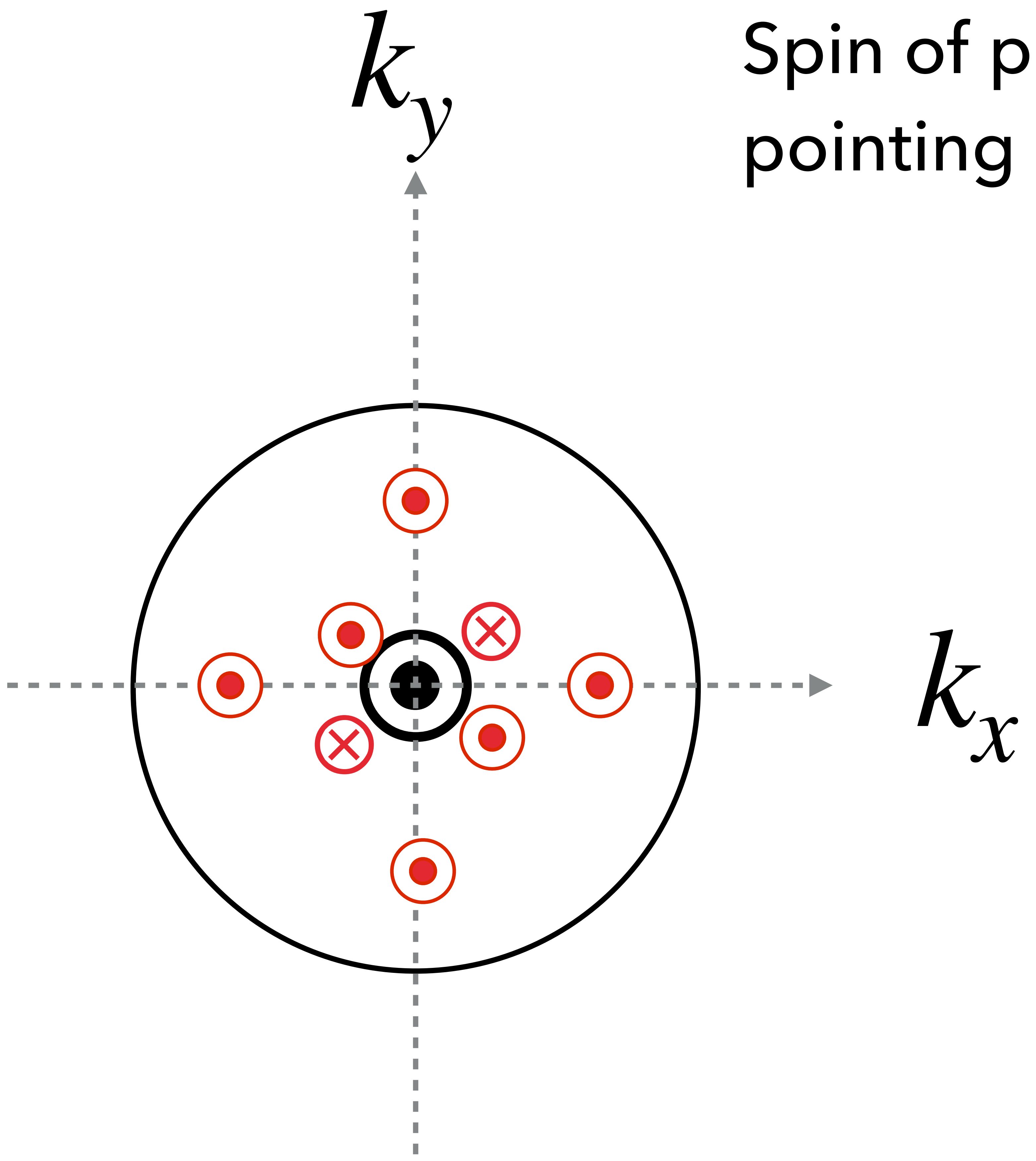
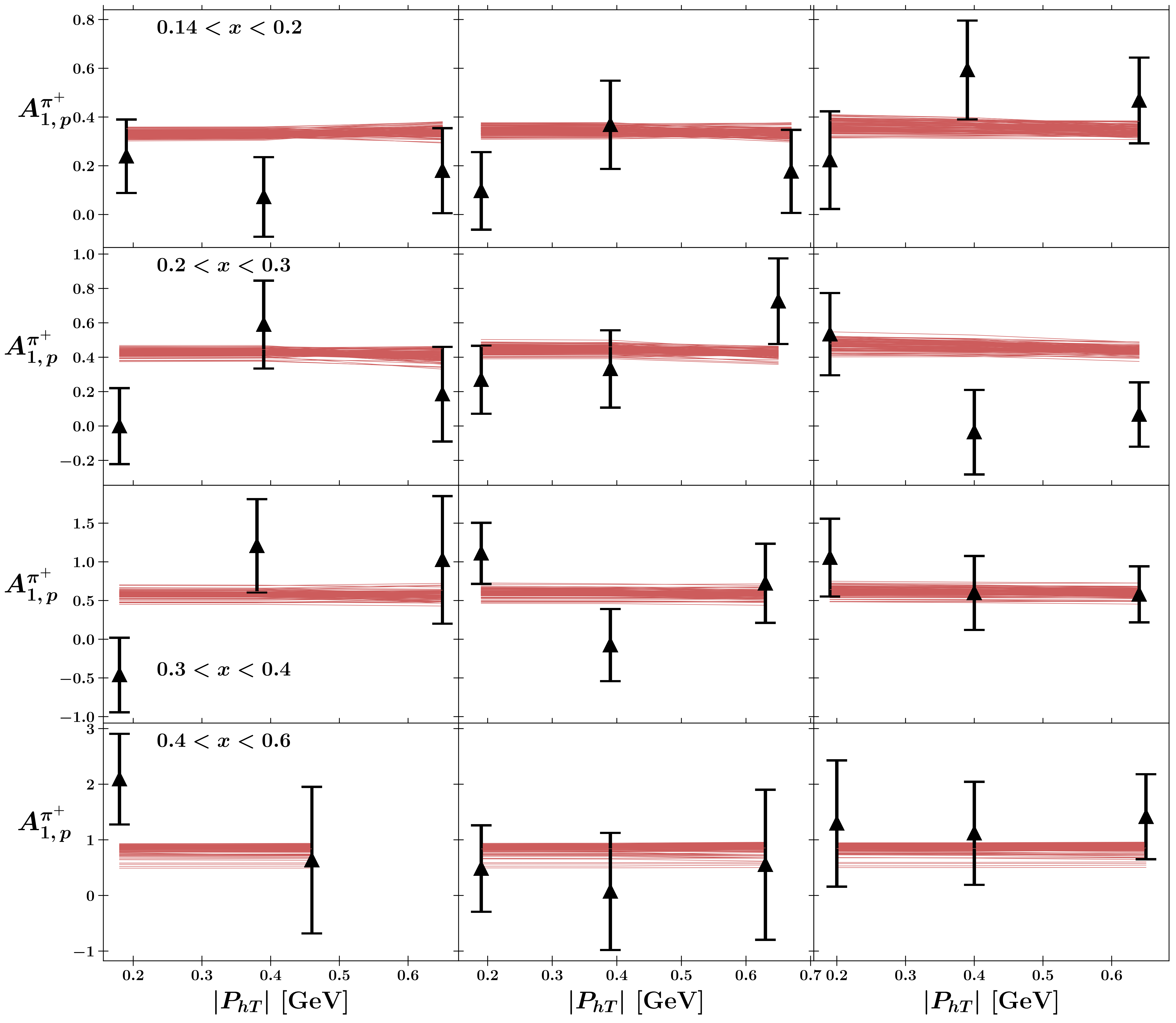




Spin of proton pointing out

The quarks with the same helicity as the proton's have more transverse momentum

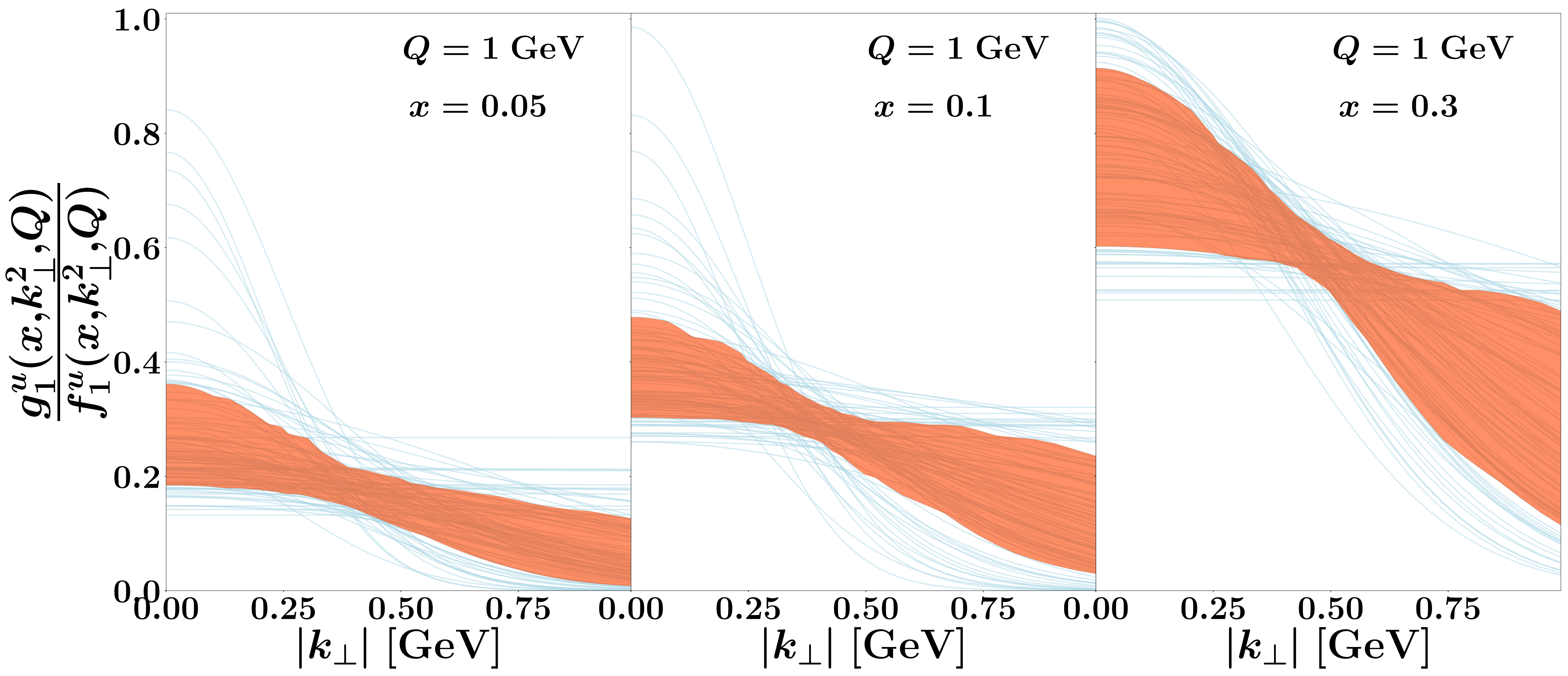
DATA FROM DOUBLE LONGITUDINAL SPIN ASYMMETRY



Airapetian et al. , arXiv:1810.07054

EXTRACTION OF TMD DEPENDENCE OF HELICITY

MAP collaboration, arXiv:2409.18078



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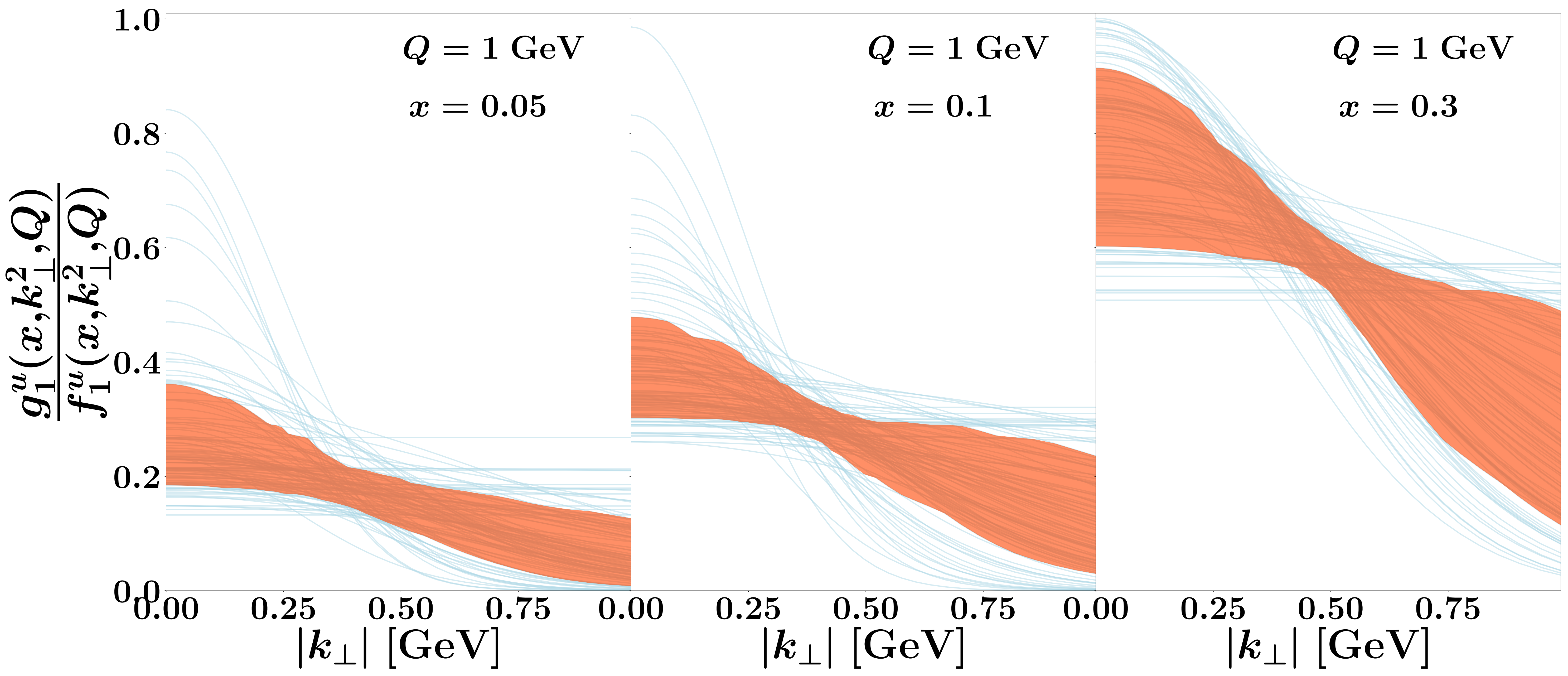
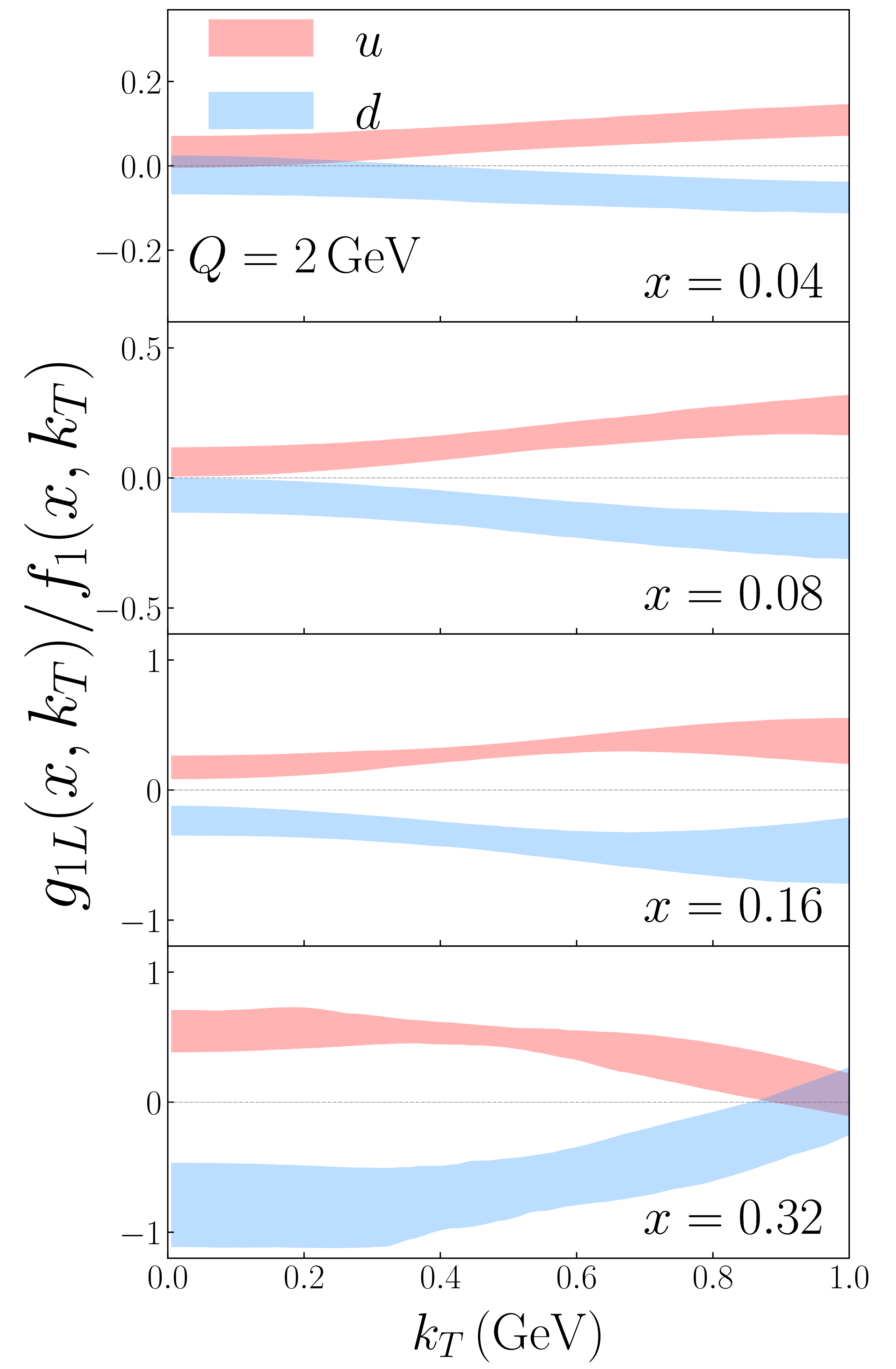
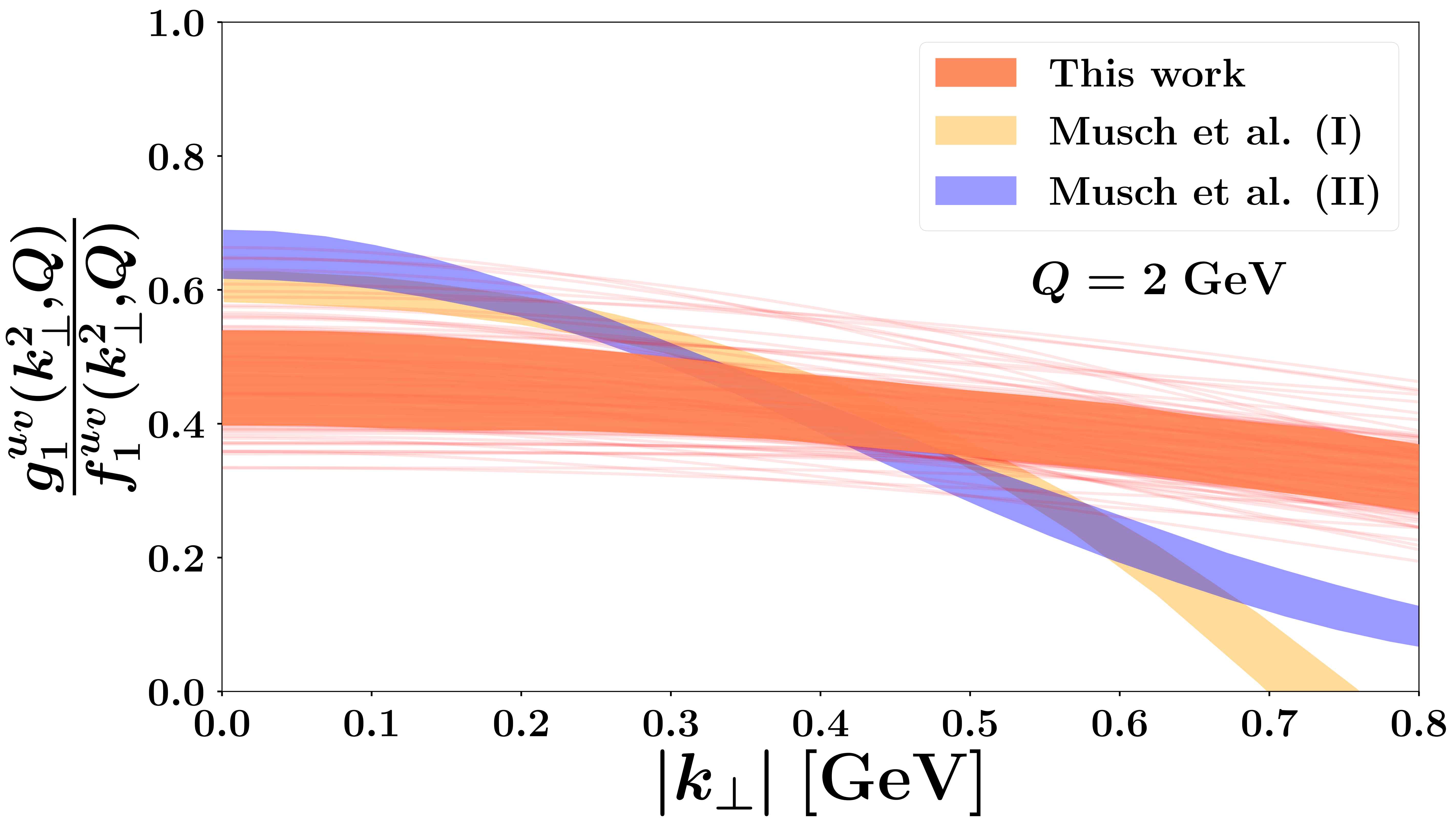
Yang, Liu, Sun, Zhao, Ma, arXiv:2409.08110, see talk by K. Yang





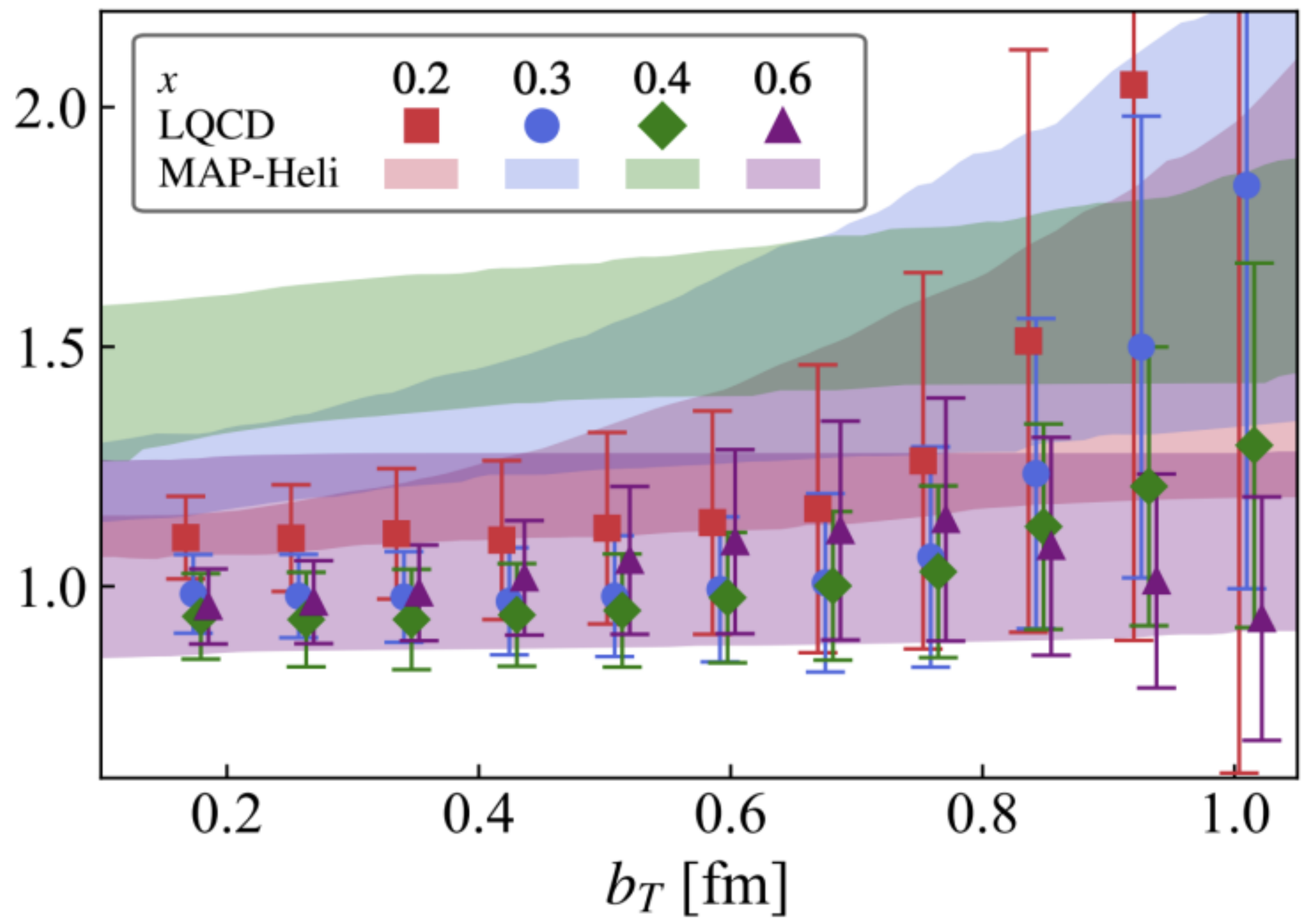
COMPARISON WITH LATTICE QCD

MAP collaboration, arXiv:2409.18078



Bollweg et al. , arXiv:2505.18430

see talk by Wei Wang



USED DATASETS

Yang, Liu, Sun, Zhao, Ma, arXiv:2409.08110

Experiment	Process	Data points	χ^2/N
HERMES[82]	$e^{\pm}p \to e^{\pm}hX$	84 (160)	0.72
HERMES[82]	$e^{\pm}d \to e^{\pm}hX$	160 (317)	0.71
CLAS[83]	$e^{-}p \to e^{-}\pi^0 X$	9 (21)	1.43
Total		253 (498)	0.74

MAP collaboration, arXiv:2409.18078

Experiment	$N_{\rm dat}$	$\chi^2_{\rm NLL}/N_{\rm dat}$	$\chi^2_{\rm NNLL}/N_{\rm dat}$
HERMES ($d \to \pi^+$)	47	1.34	1.30
HERMES ($d \to \pi^-$)	47	1.10	1.08
HERMES ($d \to K^+$)	46	1.26	1.25
HERMES ($d \to K^-$)	45	0.93	0.89
HERMES ($p \to \pi^+$)	53	1.17	1.21
HERMES ($p \to \pi^-$)	53	0.86	0.86
Total	291	1.11	1.09

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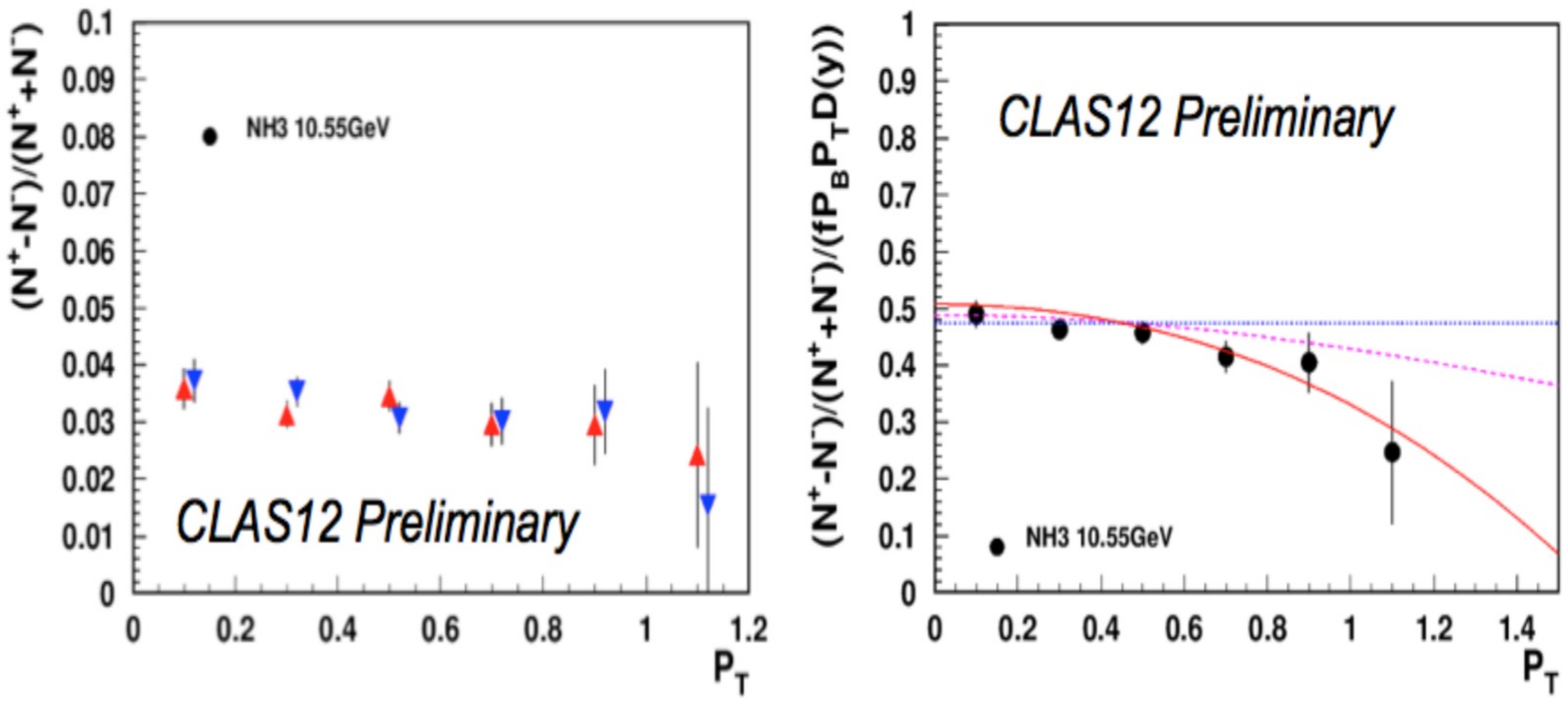
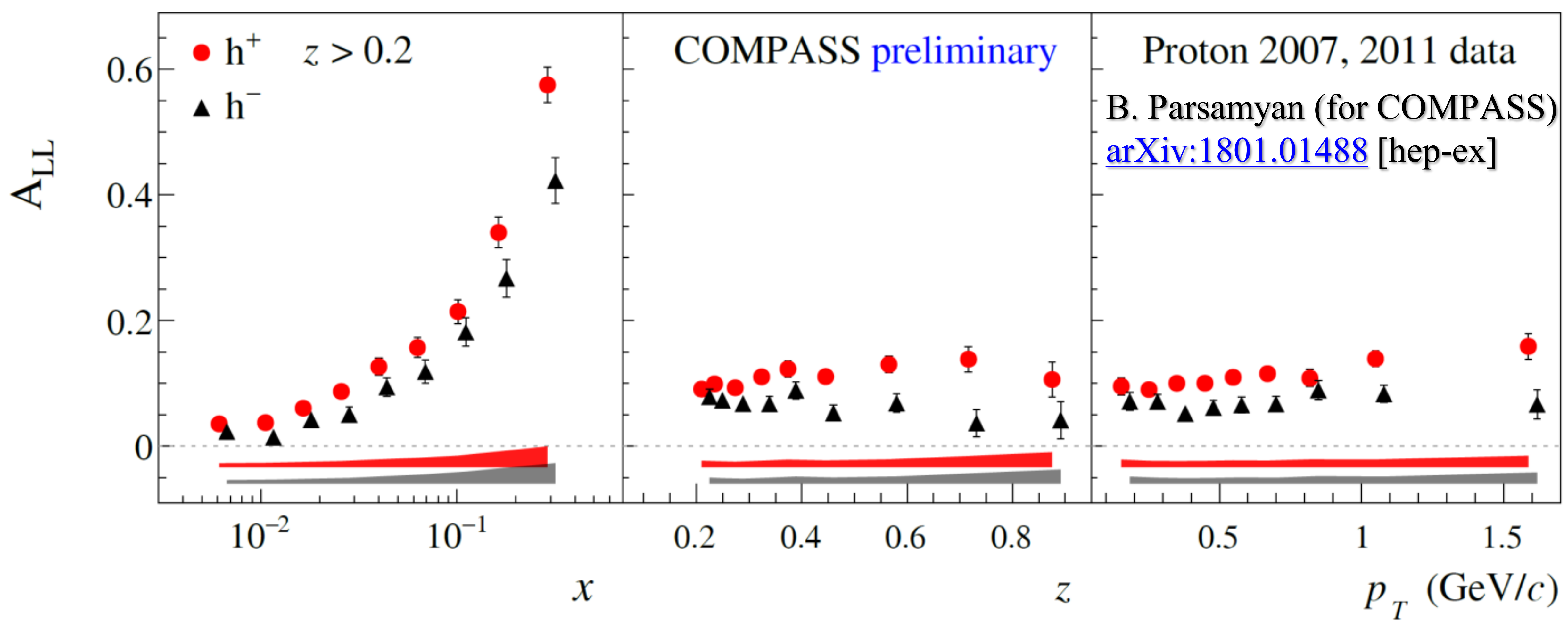
More data needed!

EXPECTED DATA

Multidimensional binning needed





CONCLUSIONS

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- There are still several sources of uncertainty to be carefully studied
- A first-ever TMD fit based on Neural Networks is available
- The transverse-momentum dependence of the helicity quark distribution has been investigated

BACKUP

CHOICES OF FUNCTIONAL FORMS

MAP24: same as MAP22, but 5 different flavors for PDFs and 5 different fragmentation function

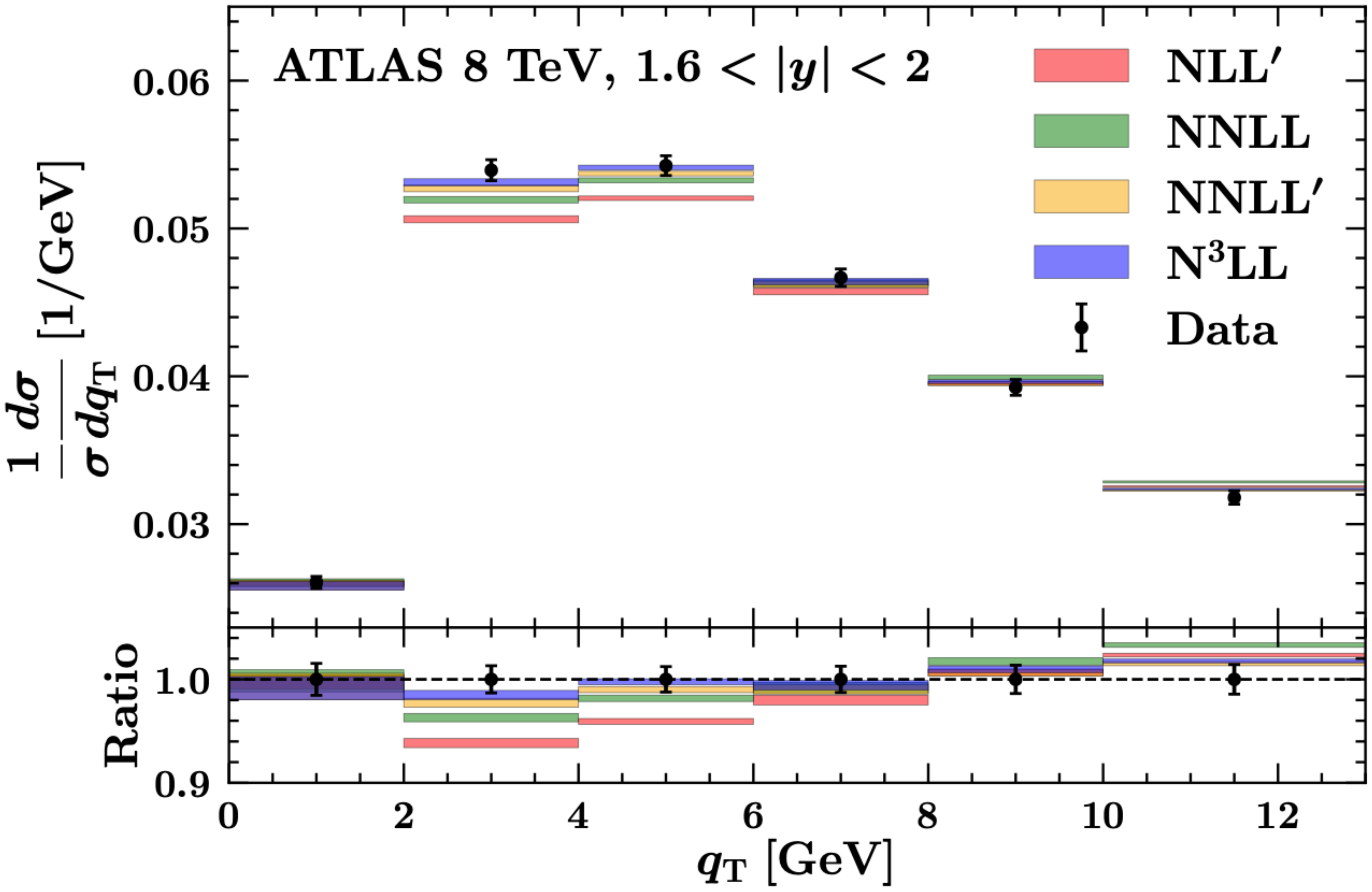
MAP22

$$f_{1\mathrm{NP}}(x, b_T^2) \propto \mathrm{F.T.\ of} \left(e^{-\frac{k_T^2}{g_1}} + \lambda^2 k_T^2 e^{-\frac{k_T^2}{g_{1B}}} + \lambda_2^2 e^{-\frac{k_T^2}{g_{1C}}} \right) \qquad g_1(x) = N_1 \frac{(1-x)^\alpha\ x^\sigma}{(1-\hat{x})^\alpha\ \hat{x}^\sigma}$$

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

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

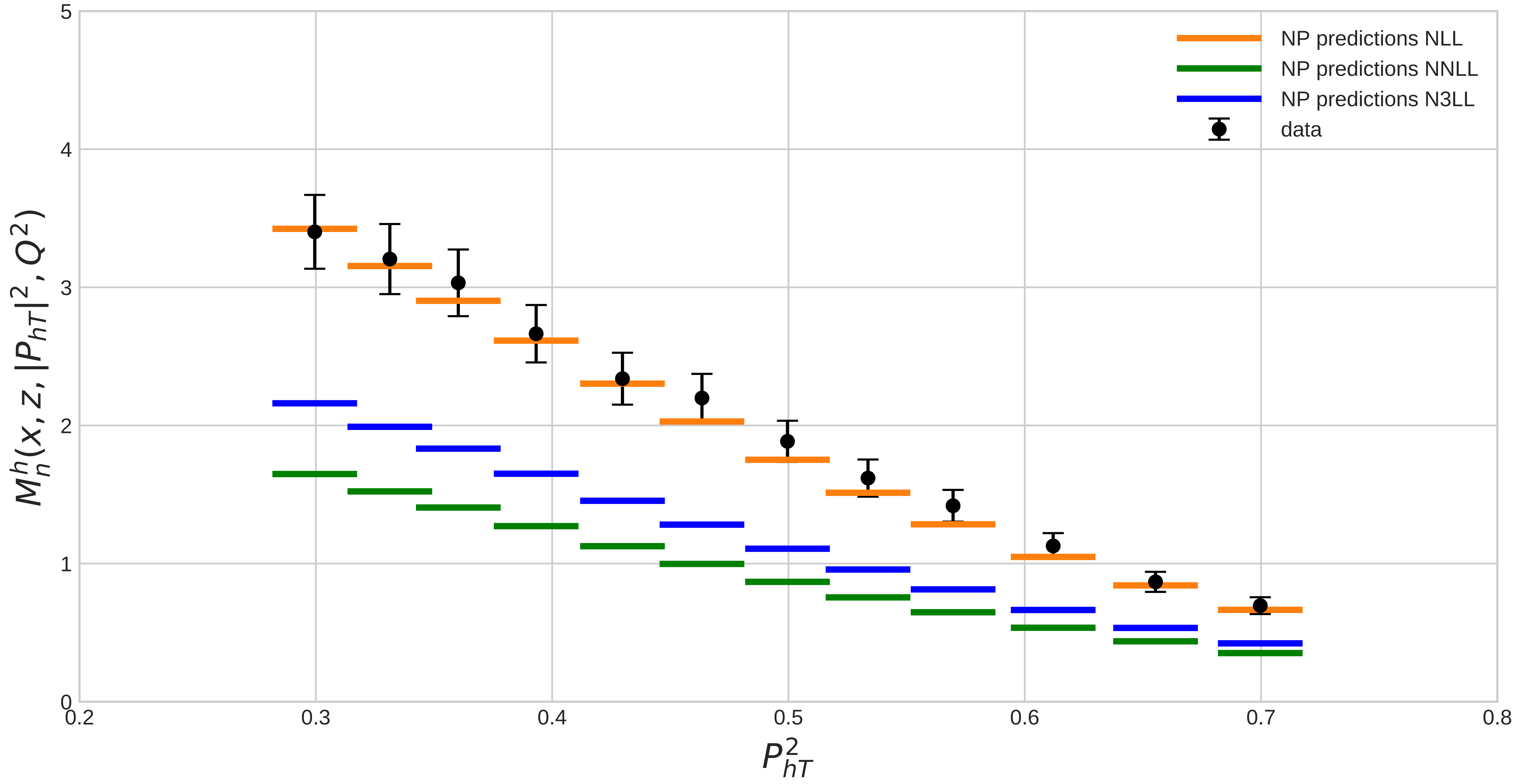
ACCURACY IMPROVEMENT AND DY



Bacchetta, Bertone, Bissolotti, Bozzi, Delcarro, Piacenza, Radici, arXiv:1912.07550

IMPROVED ACCURACY AND SIDIS

COMPASS multiplicities (one of many bins)



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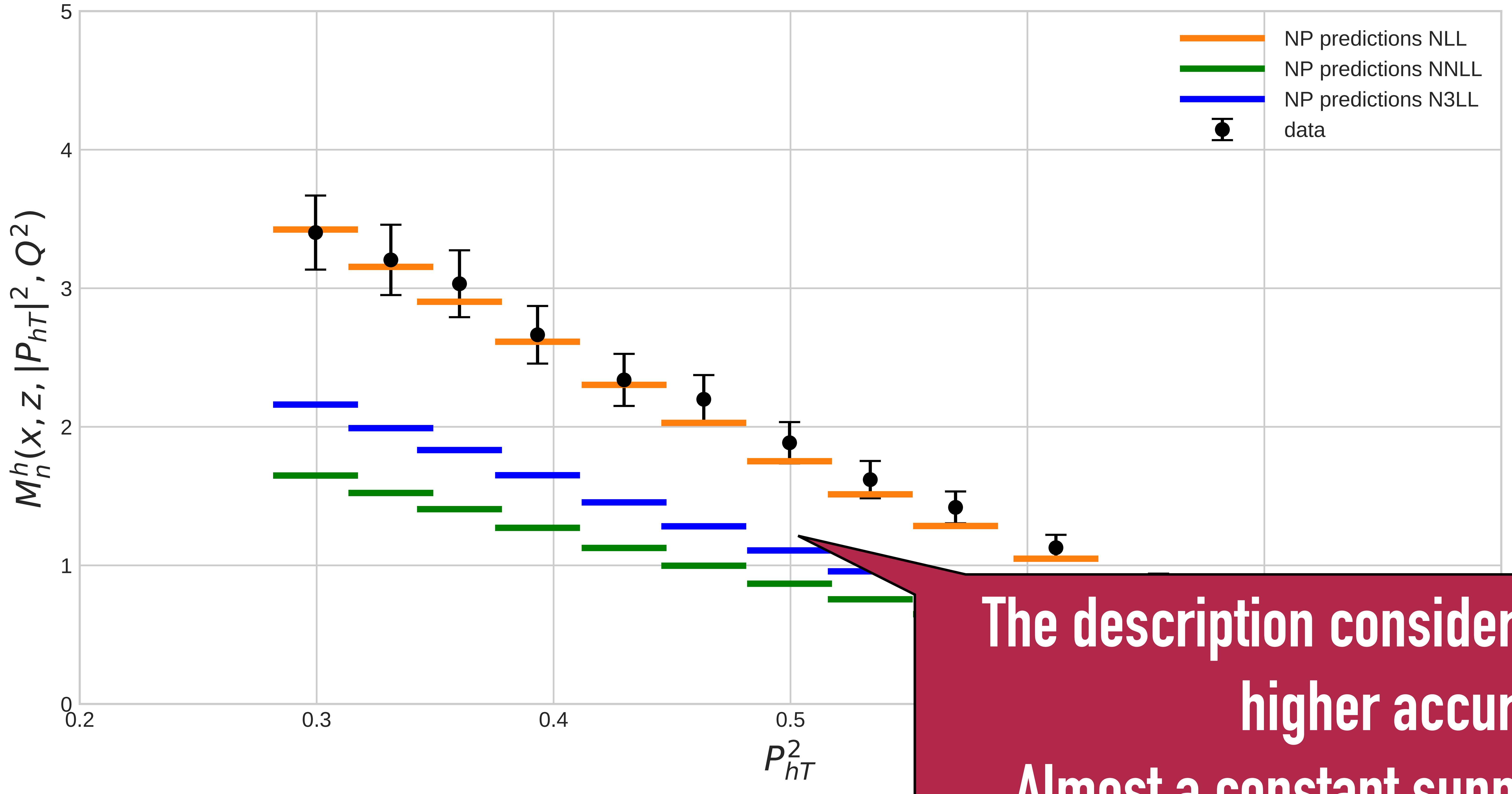
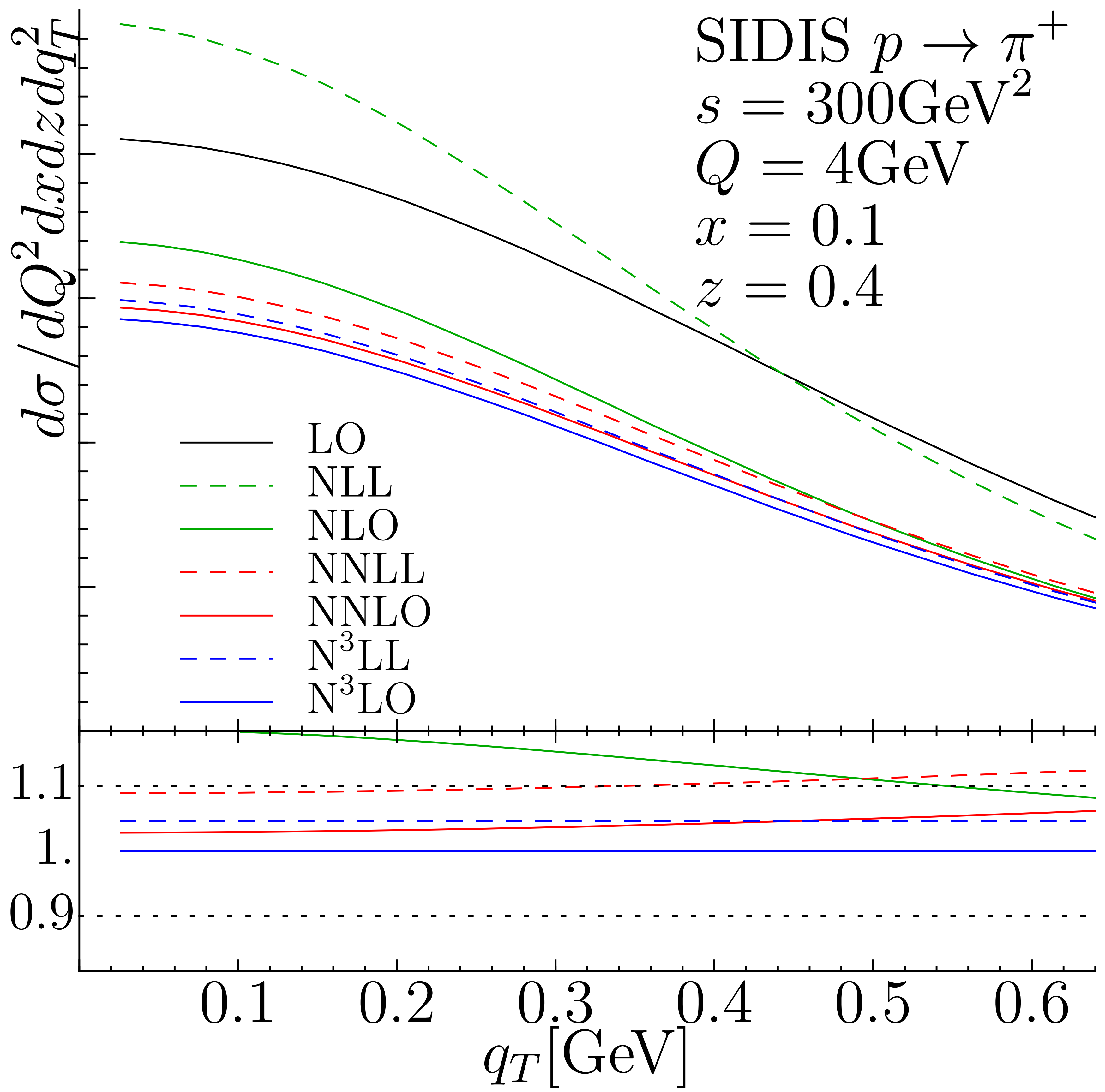


The description considerably worsens at higher accuracy.
Almost a constant suppression factor.

IMPROVED ACCURACY AND SIDIS

[Scimemi, Vladimirov, arXiv:1912.06532](https://arxiv.org/abs/1912.06532)



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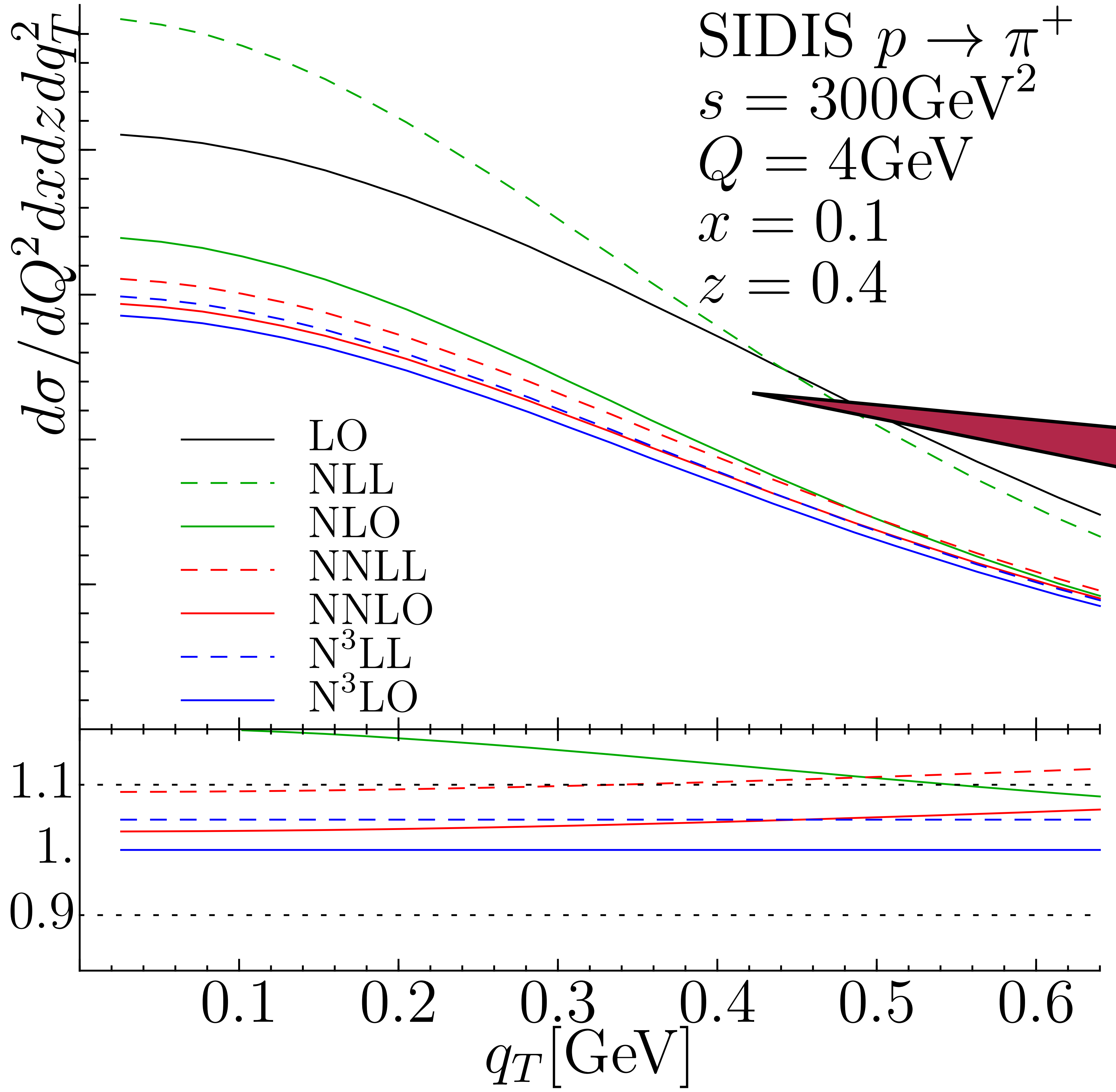

Also in the SV19 study, the overall decrease is evident, but they did not report problems with the data

MAP22 TENTATIVE SOLUTION

ENHANCEMENT PREFACTOR $= \dfrac{\left.\dfrac{d\sigma}{dxdzdQ^2}\right|_{\text{nonmix.}}}{\int \text{TMD}\ d^2P_{hT}}$

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Higher-order corrections decrease the role of the TMD region.
We need to enhance it with a prefactor.

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Sudakov form factor

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the difference between the two is formally NNLL $\quad \alpha_S^n \ln^{2n-2}\left(\frac{Q^2}{\mu_b^2}\right)$

LOW-b_T MODIFICATIONS

$$\log\left(Q^2 b_T^2\right) \to \log\left(Q^2 b_T^2 + 1\right)$$

see, e.g., Bozzi, Catani, De Florian, Grazzini
hep-ph/0302104

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$$b_*(b_c(b_\mathrm{T})) = \sqrt{\frac{b_\mathrm{T}^2 + b_0^2/(C_5^2 Q^2)}{1 + b_\mathrm{T}^2/b_\mathrm{max}^2 + b_0^2/(C_5^2 Q^2 b_\mathrm{max}^2)}}$$

$$b_\mathrm{min} \equiv b_*(b_c(0)) = \frac{b_0}{C_5 Q}\sqrt{\frac{1}{1 + b_0^2/(C_5^2 Q^2 b_\mathrm{max}^2)}}$$

Collins et al.
arXiv:1605.00671

PAVIA 2019 b_* PRESCRIPTION

$$\hat{f}_1^q(x, b_T; \mu^2) = \sum_i \big(C_{qi} \otimes f_1^i\big)(x, b_*; \mu_b) e^{\tilde{S}(b_*;\mu_b,\mu)} e^{g_K(b_T) \ln \frac{\mu}{\mu_0}} \hat{f}_{\rm NP}^q(x, b_T)$$

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These are all choices that should be at some point checked/challenged

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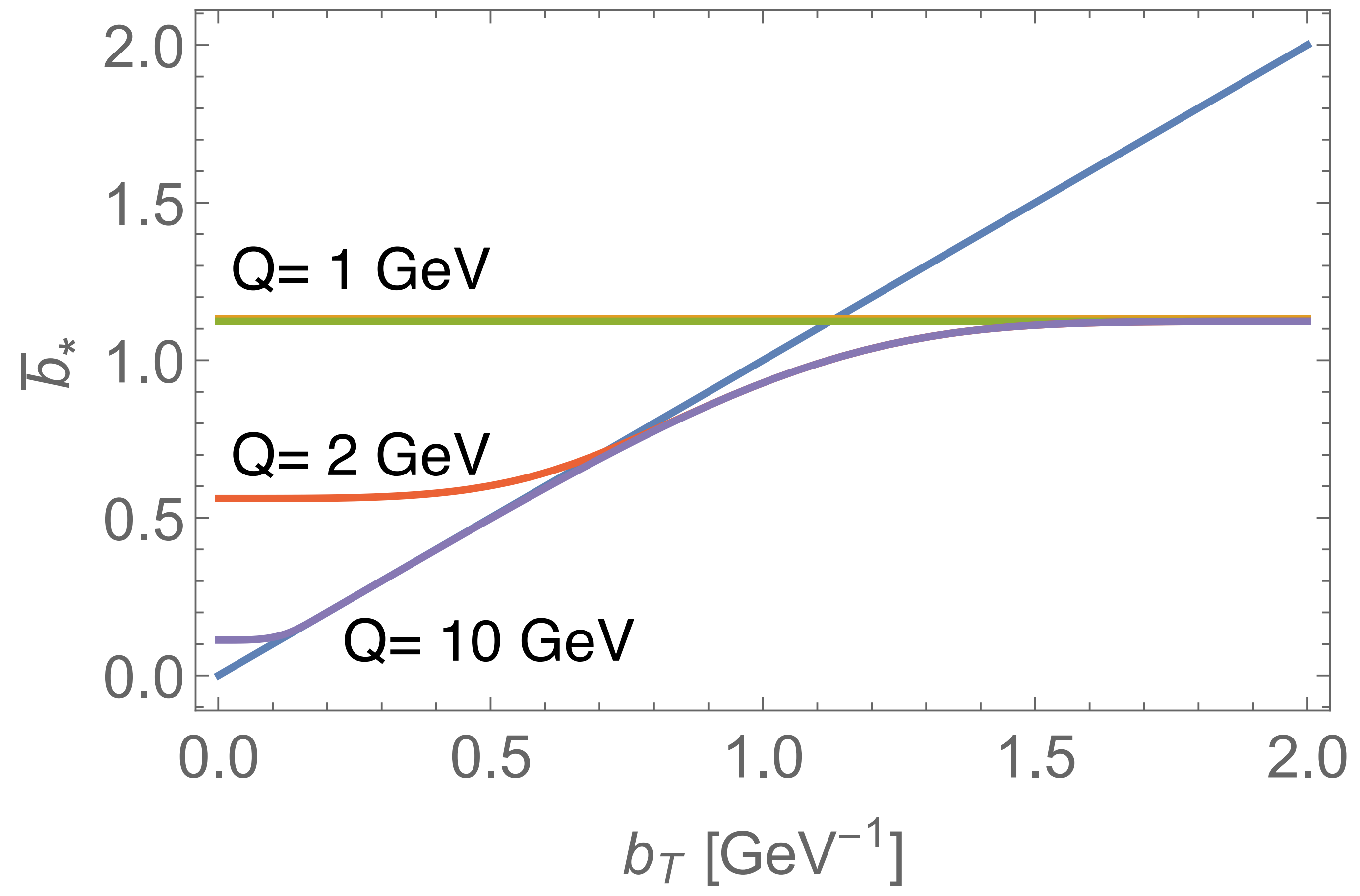

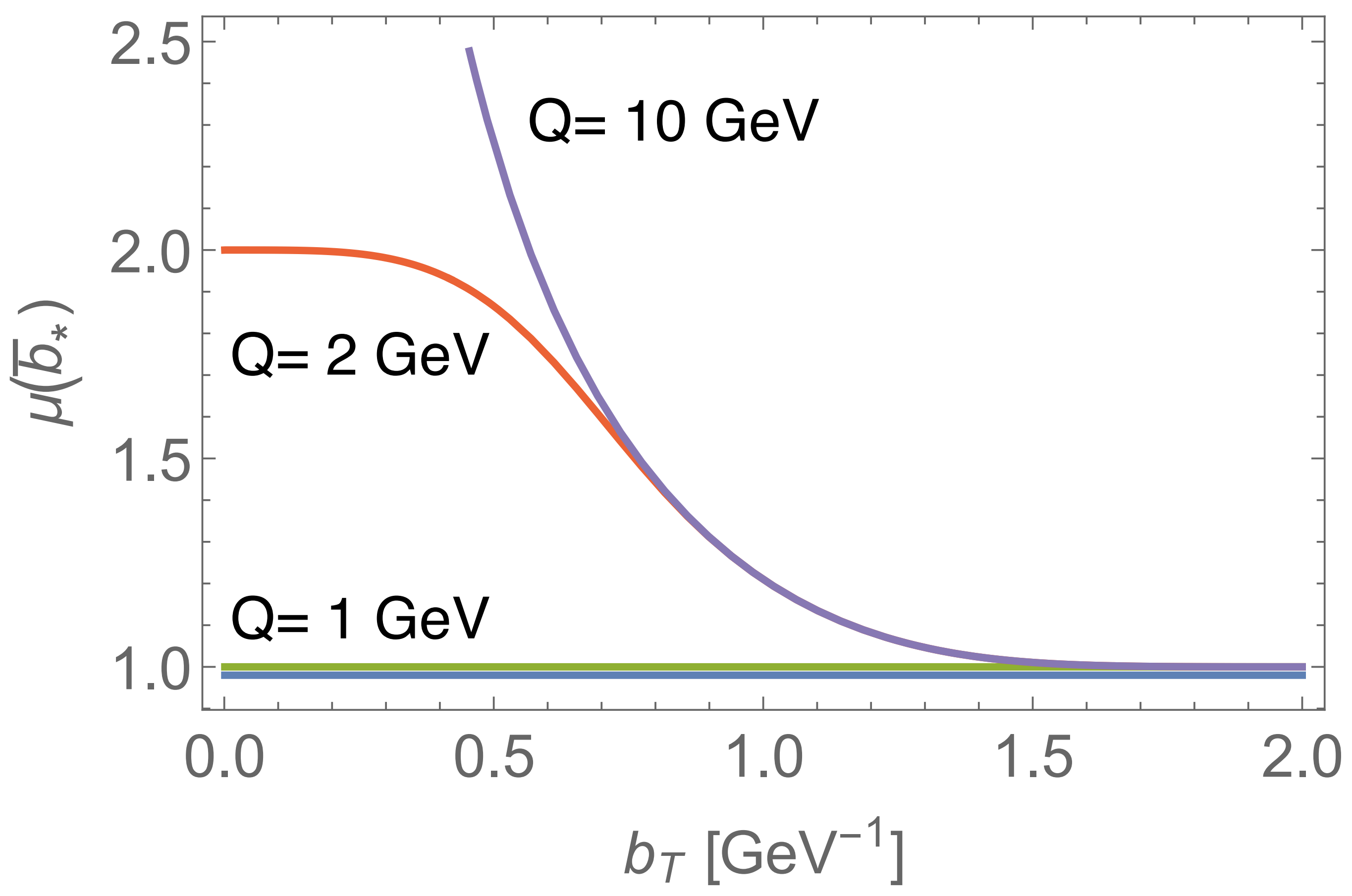

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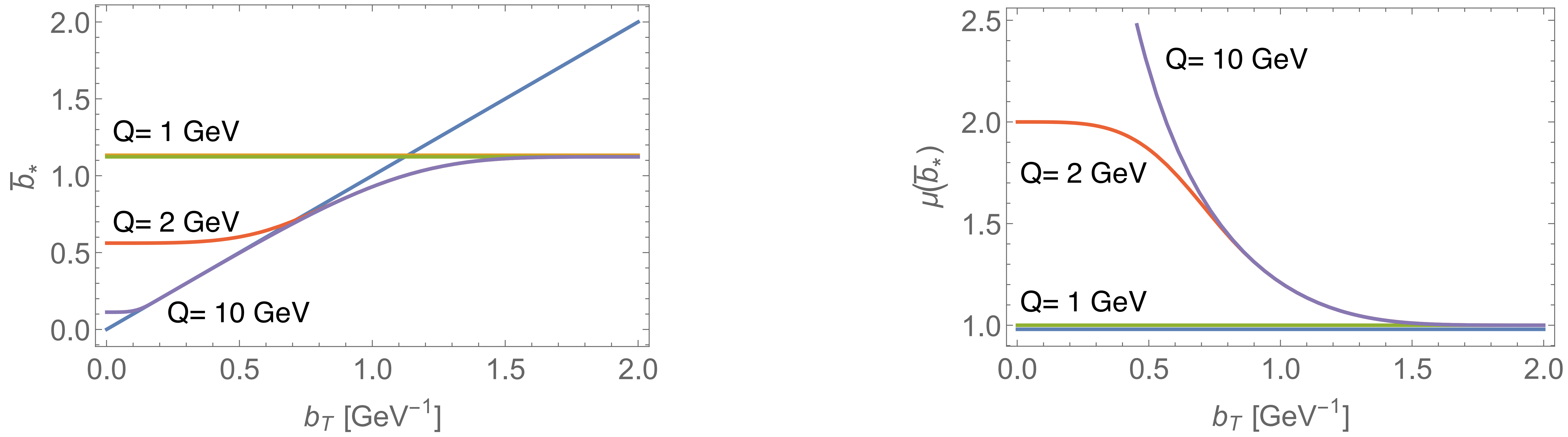
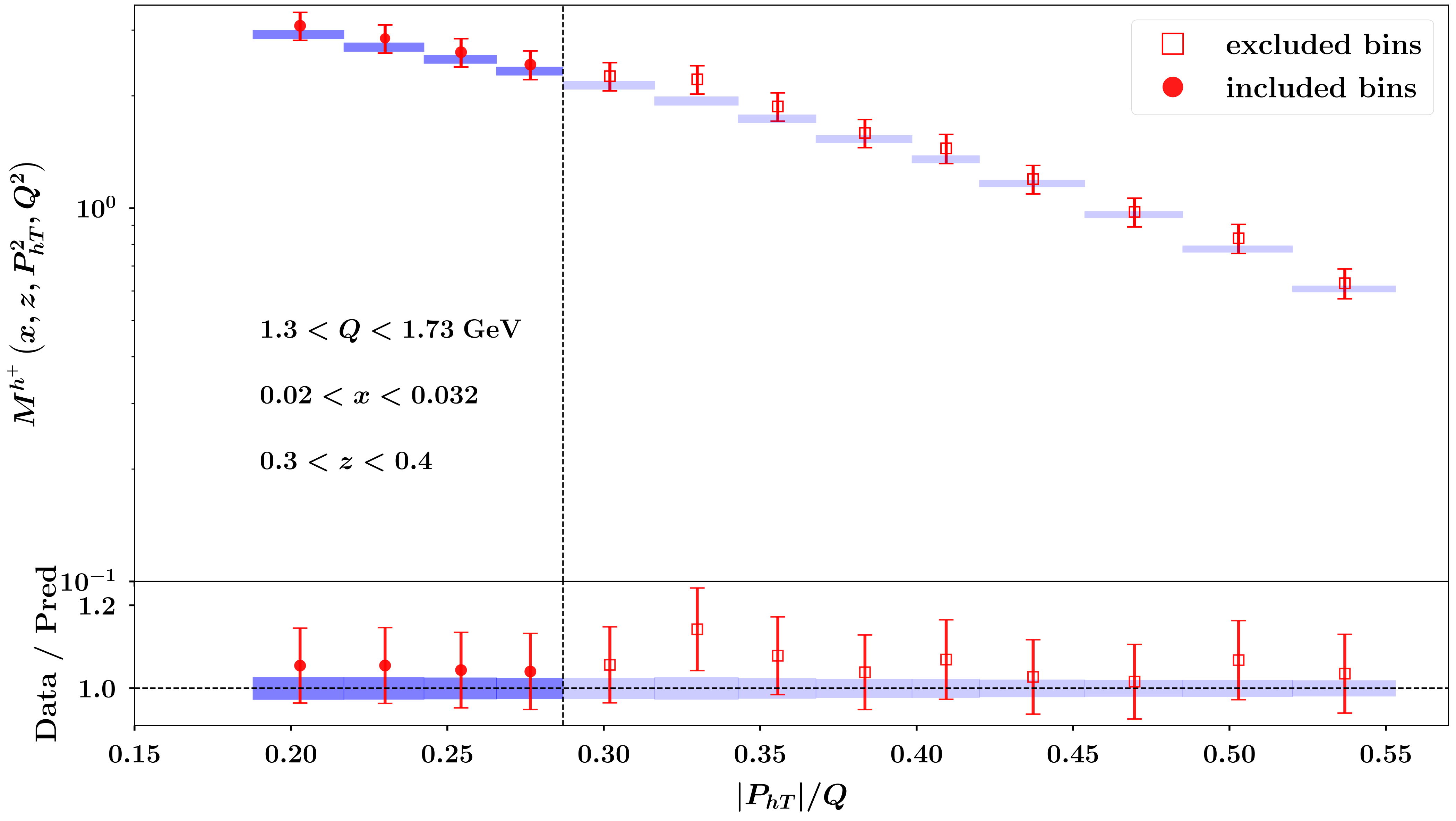


No significant effect at high Q, but large effect at low Q (inhibits perturbative contribution)

REGION OF VALIDITY OF TMD FORMALISM

$$|q_T| = |P_{hT}|/z \ll Q$$



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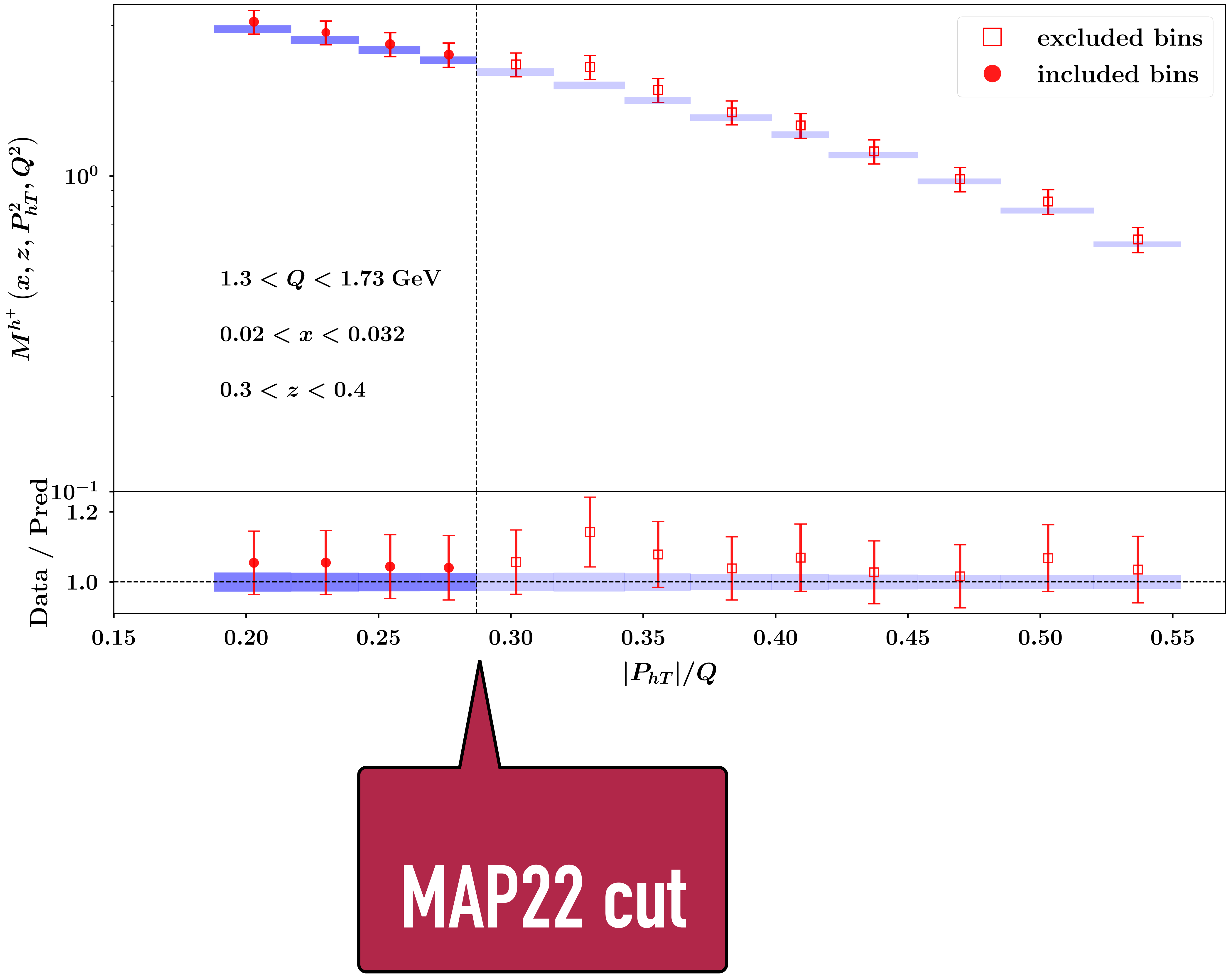

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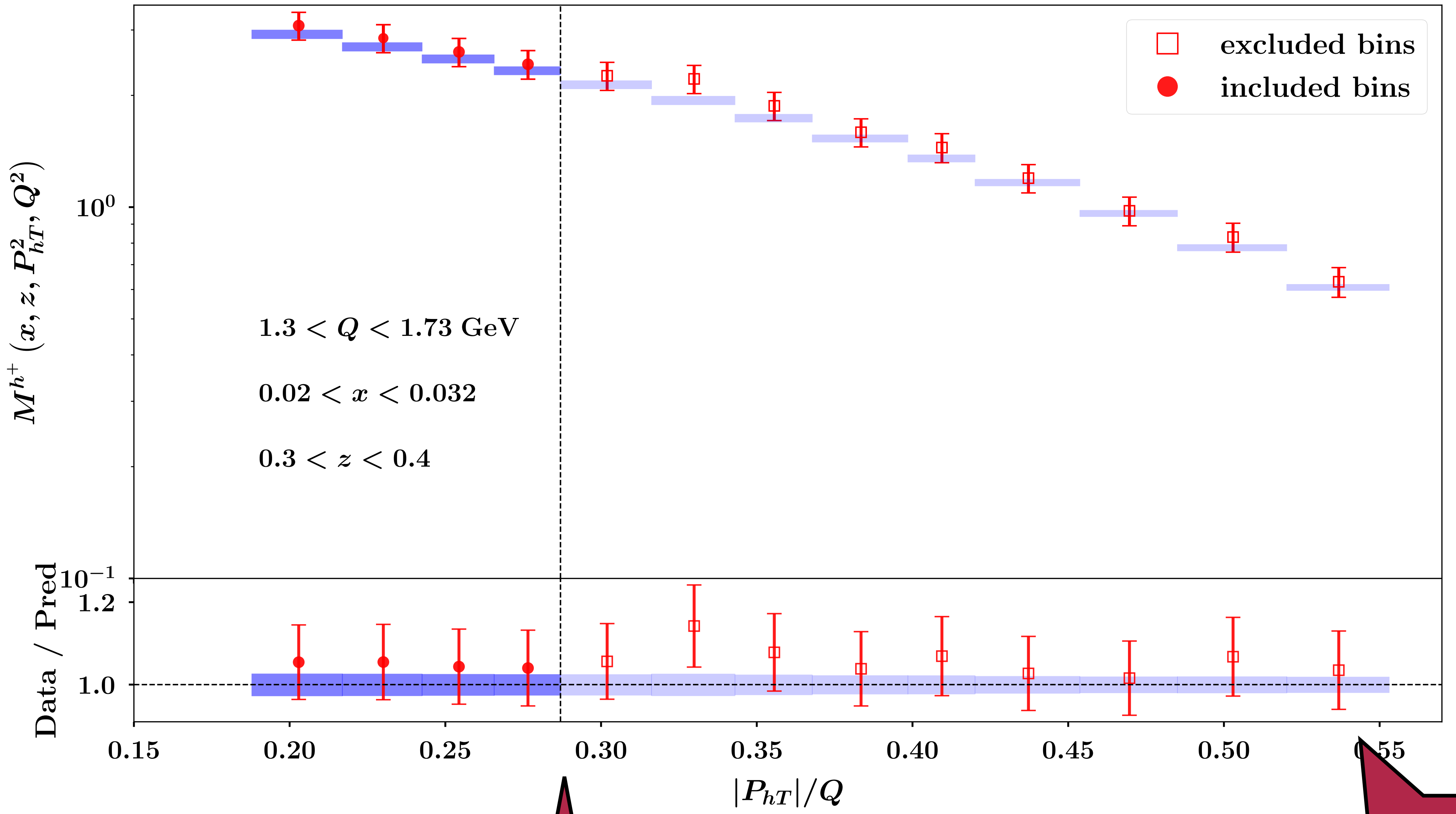

MAP22 cut

MAP22 extrapolation

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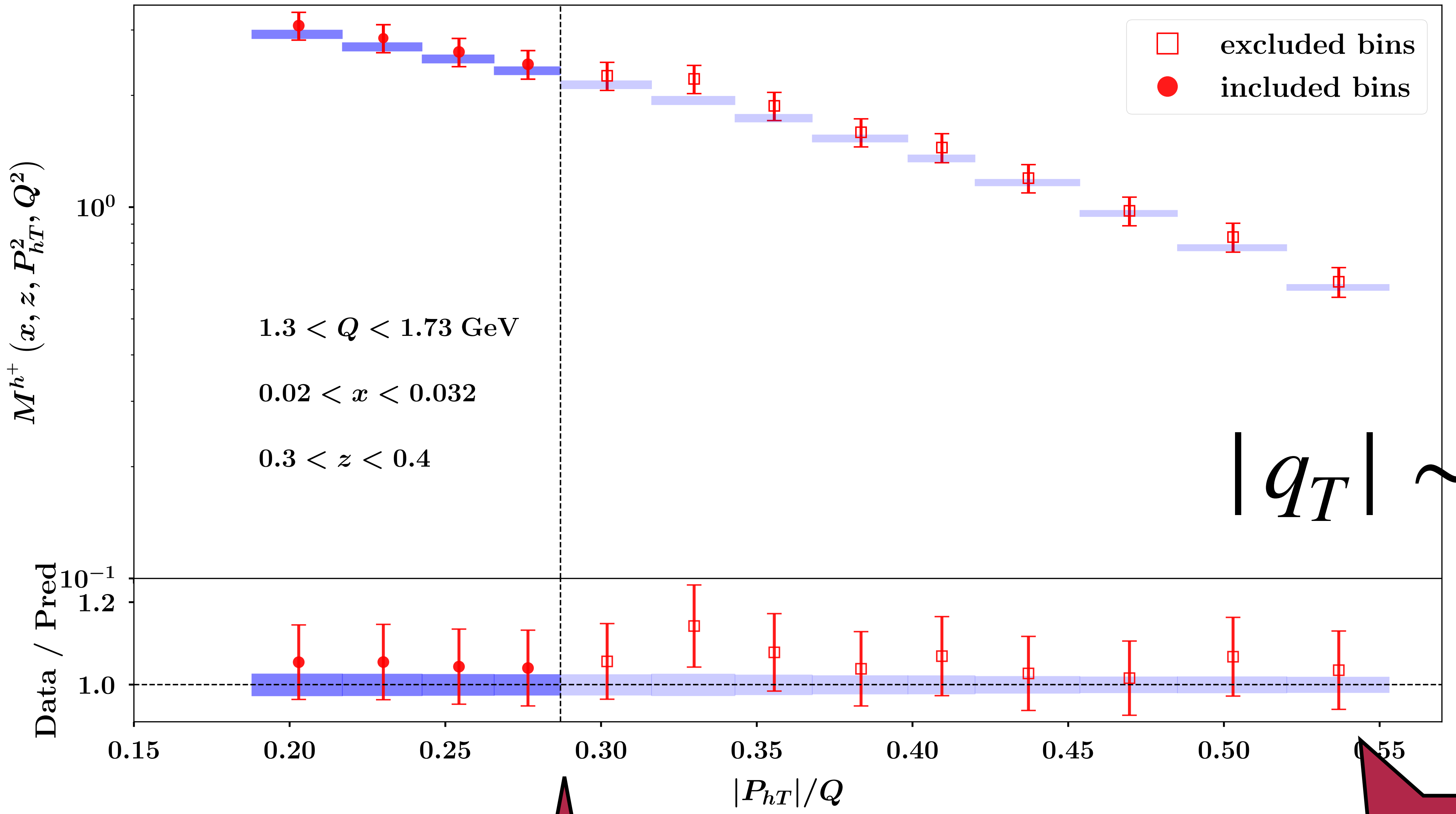

$$|q_T| \sim 1.5\ Q$$!

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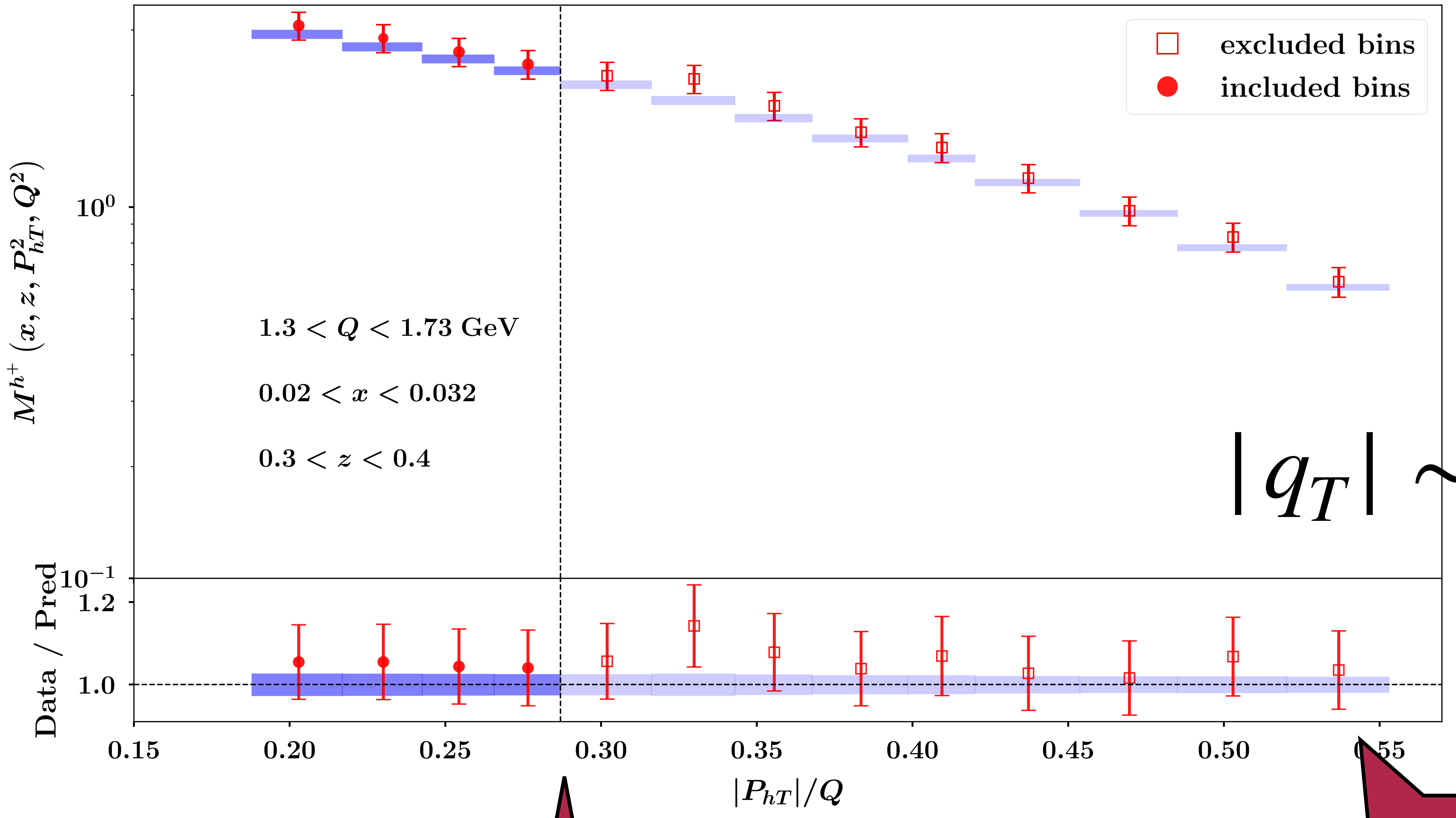

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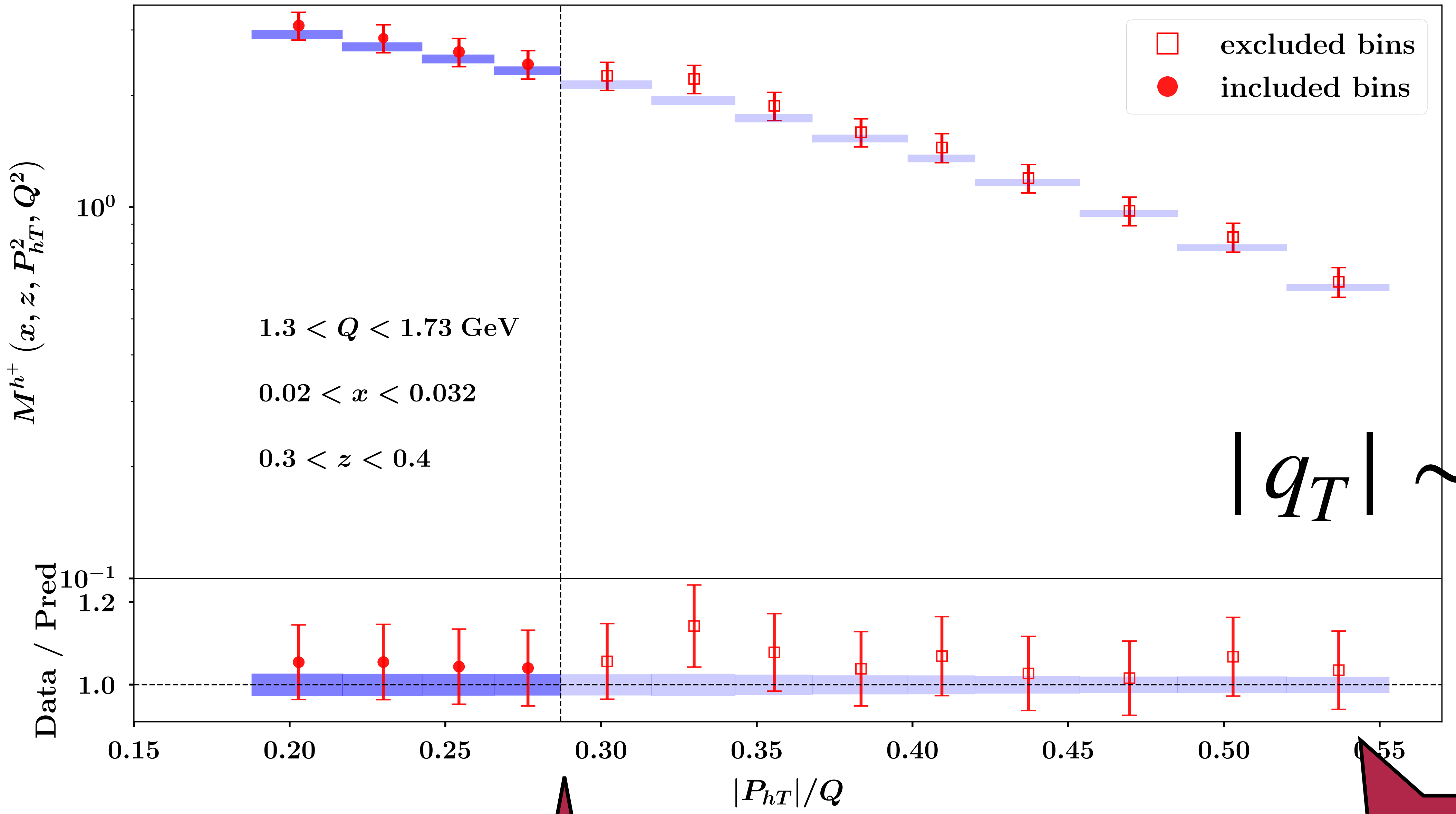

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