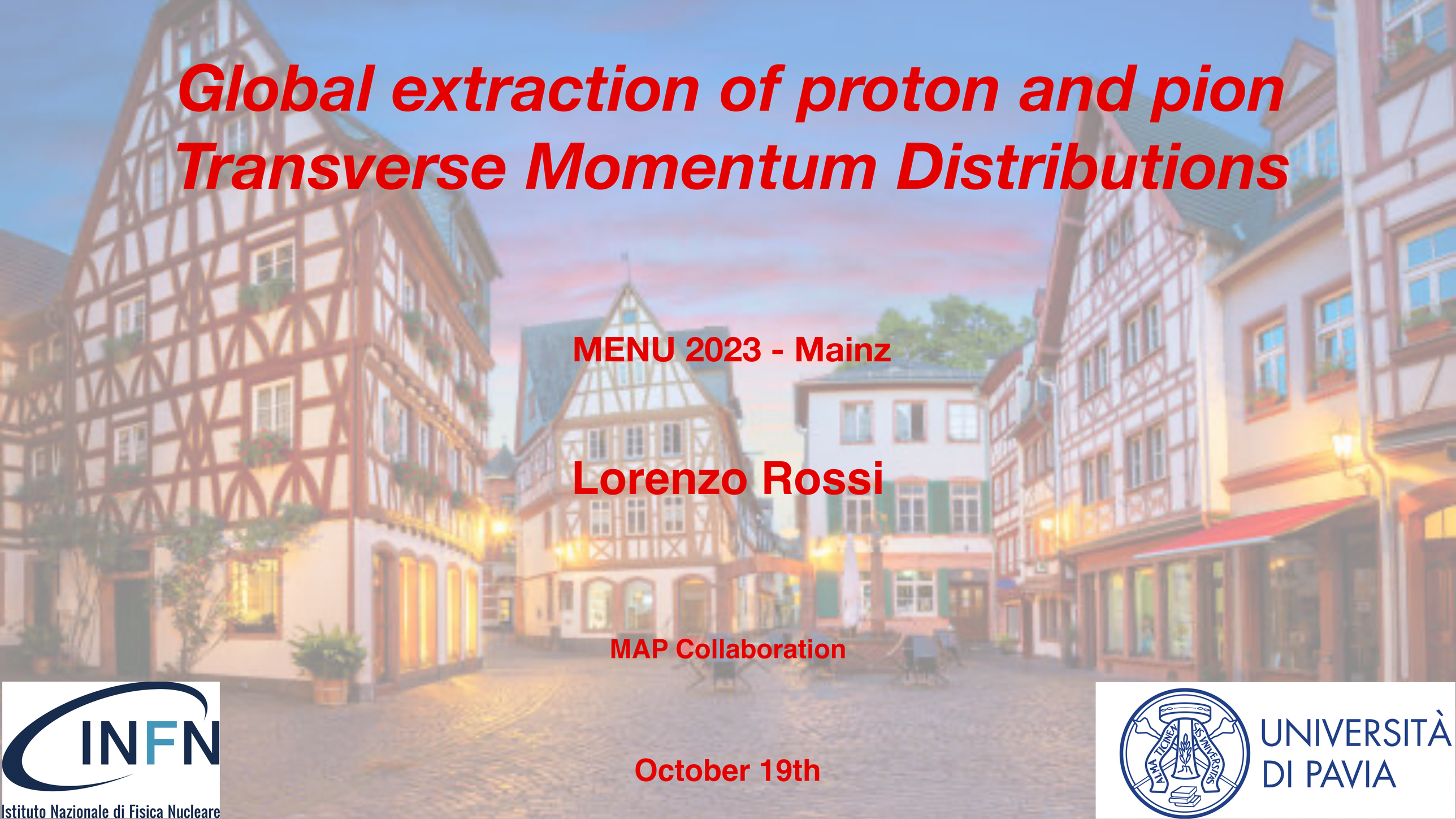


Global extraction of proton and pion Transverse Momentum Distributions

MENU 2023 - Mainz

Lorenzo Rossi

MAP Collaboration

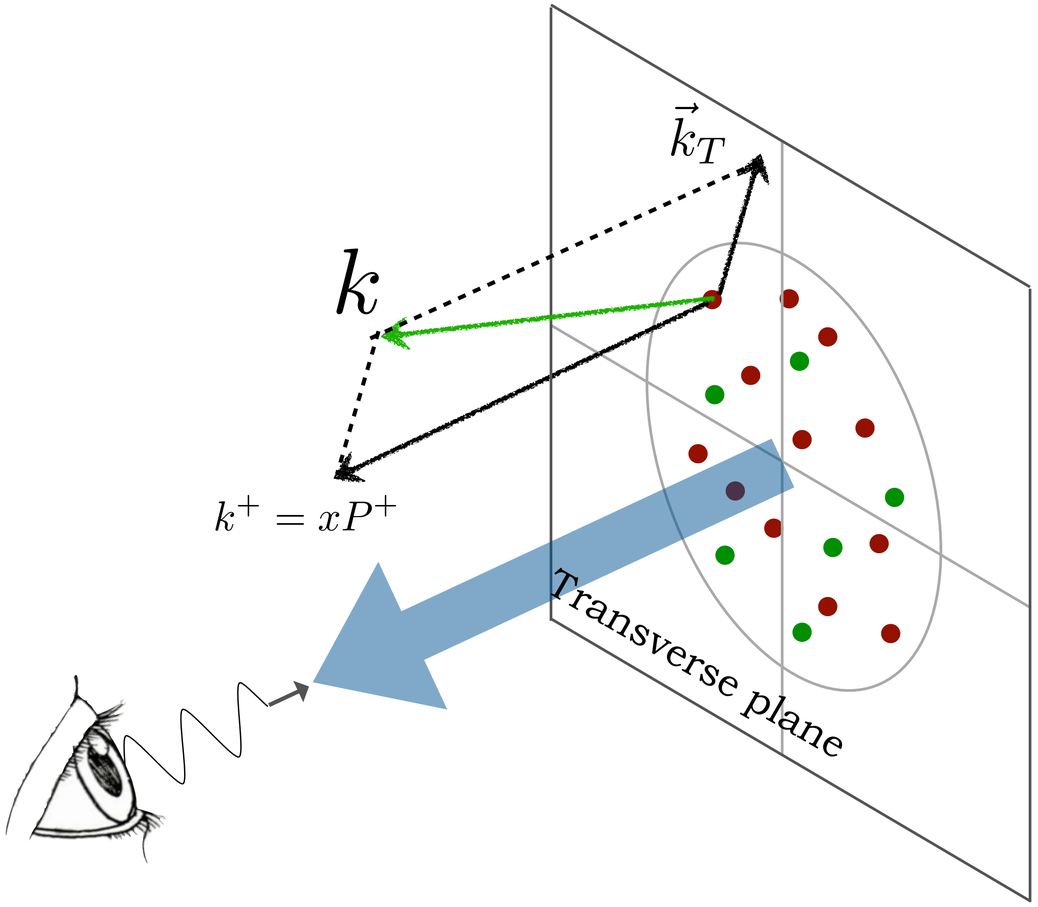
October 19th

INFN
Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ DI PAVIA

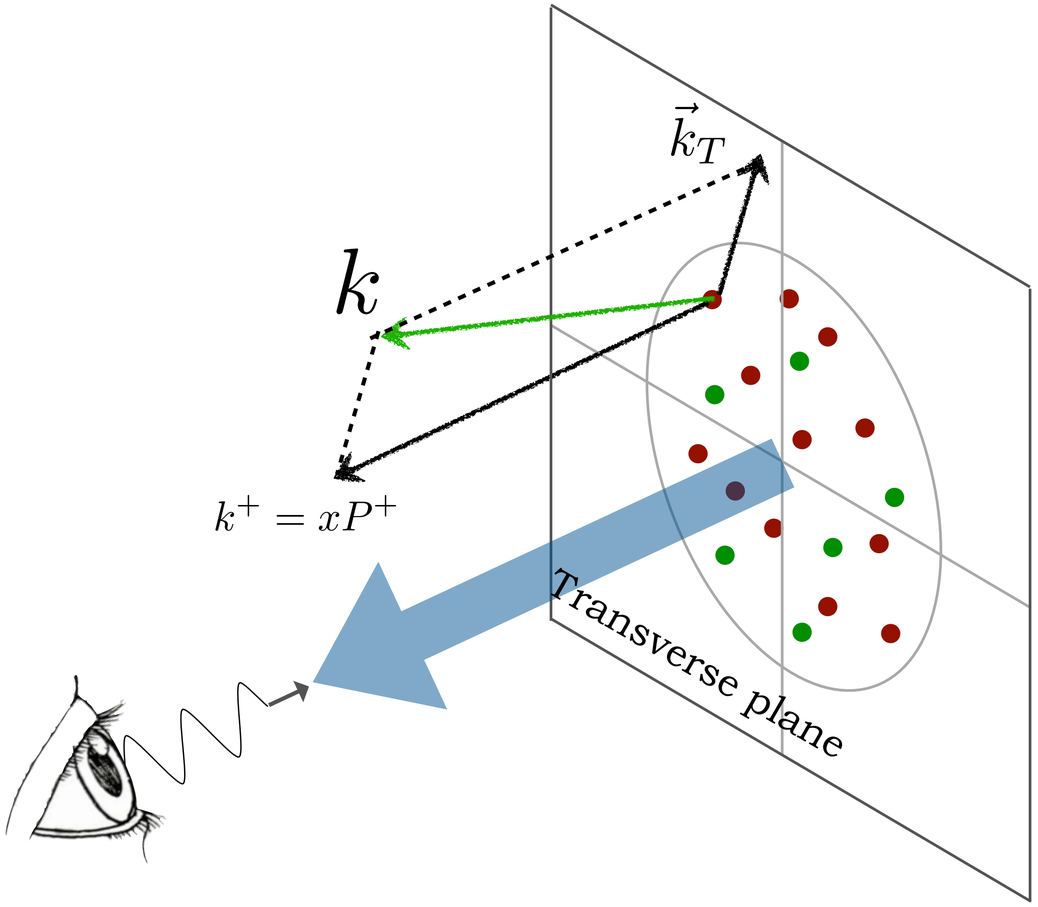
Transverse Momentum Distribution PDFs

Transverse Momentum Distribution PDFs



Transverse Momentum Distribution PDFs

3-***dimensional map*** of the
internal structure of the nucleon $f(x, \vec{k}_T)$



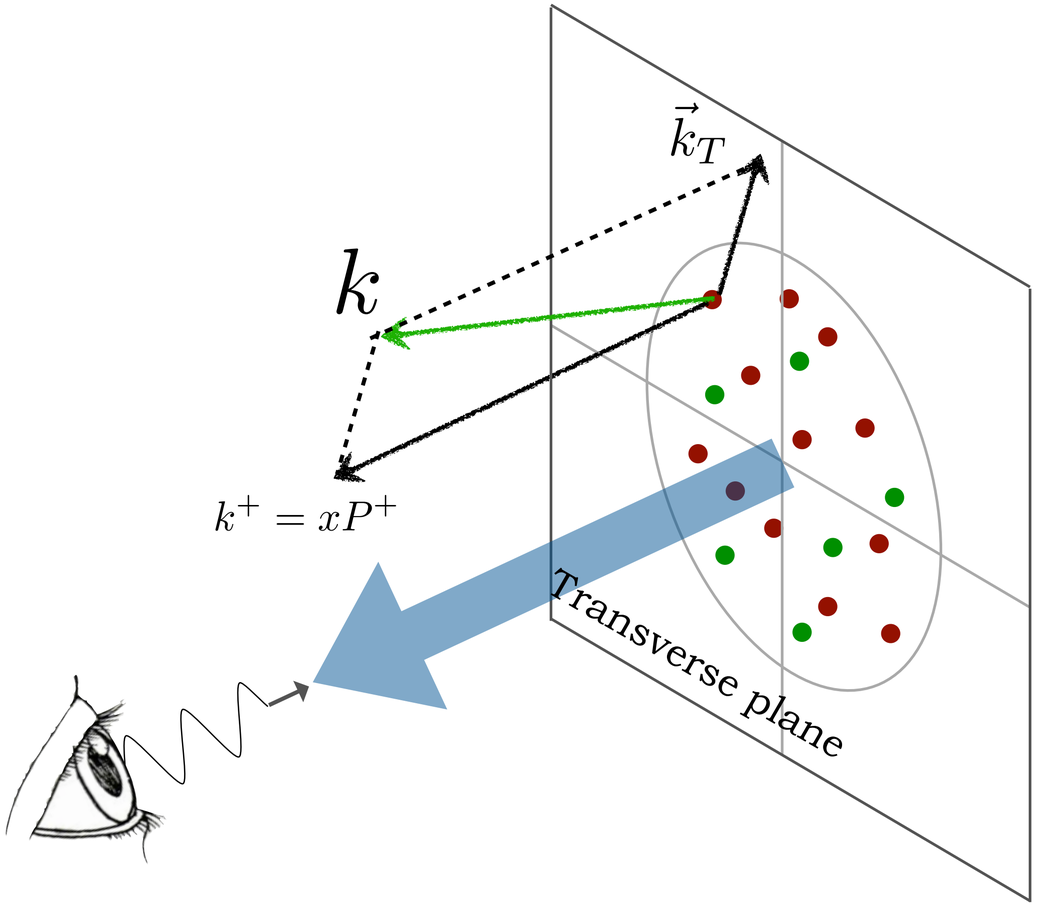
$\vec{k}_T =$ intrinsic (non-perturbative) transverse momentum of the quark

Transverse Momentum Distribution PDFs

3-***dimensional map*** of the
internal structure of the nucleon $f(x, \vec{k}_T)$

Quark Polarisation

Nucleon Pol.	U	L	T
U			
L			
T			



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Transverse Momentum Distribution PDFs

3-***dimensional map*** of the
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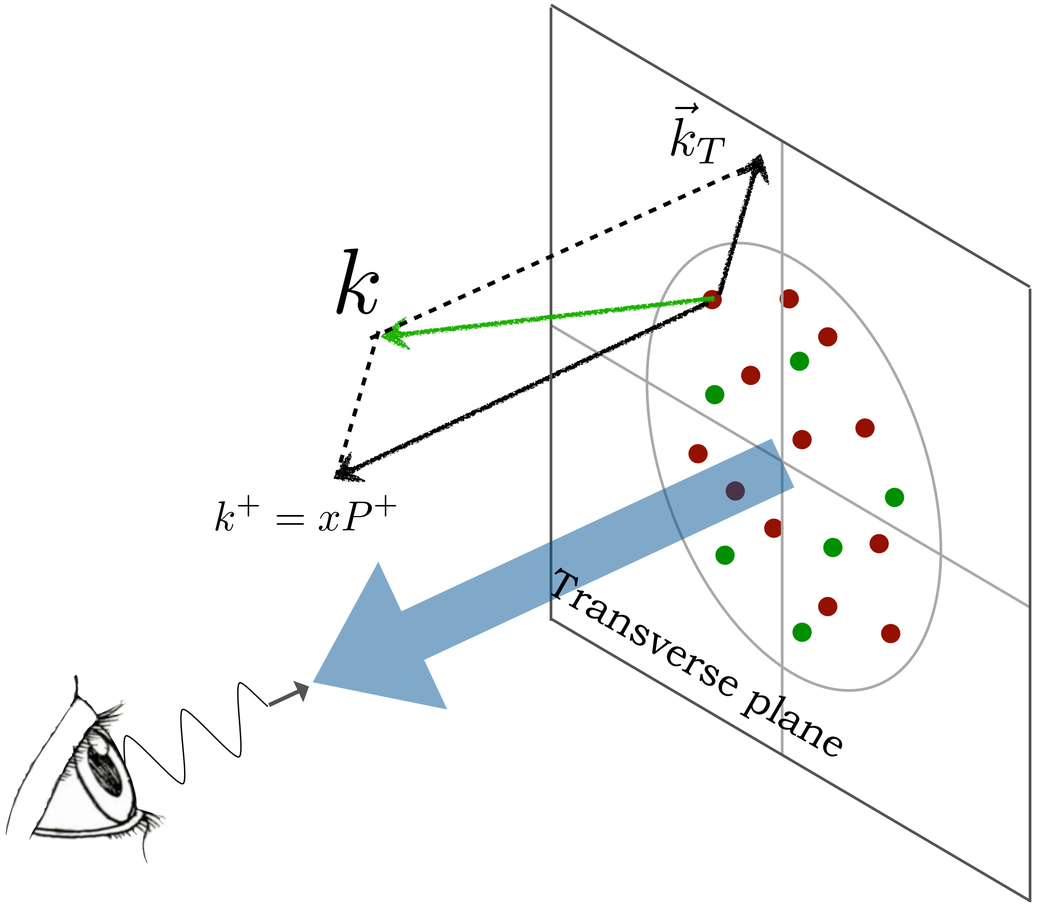
Quark Polarisation

Nucleon Pol.	U	L	T
U	f_1		
L		g_1	
T			h_1



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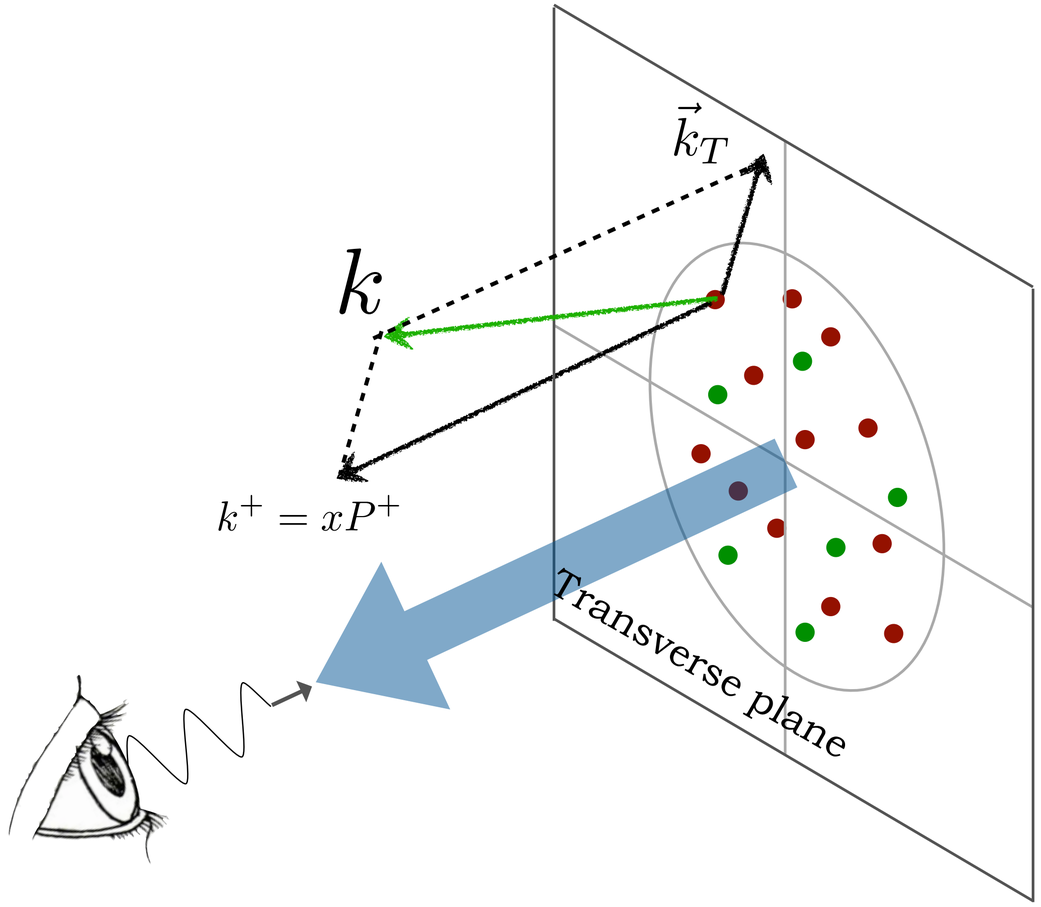
Quark Polarisation

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

Time-reversal odd



$\vec{k}_T =$ intrinsic (non-perturbative) transverse momentum of the quark

Transverse Momentum Distribution PDFs

3-***dimensional map*** of the
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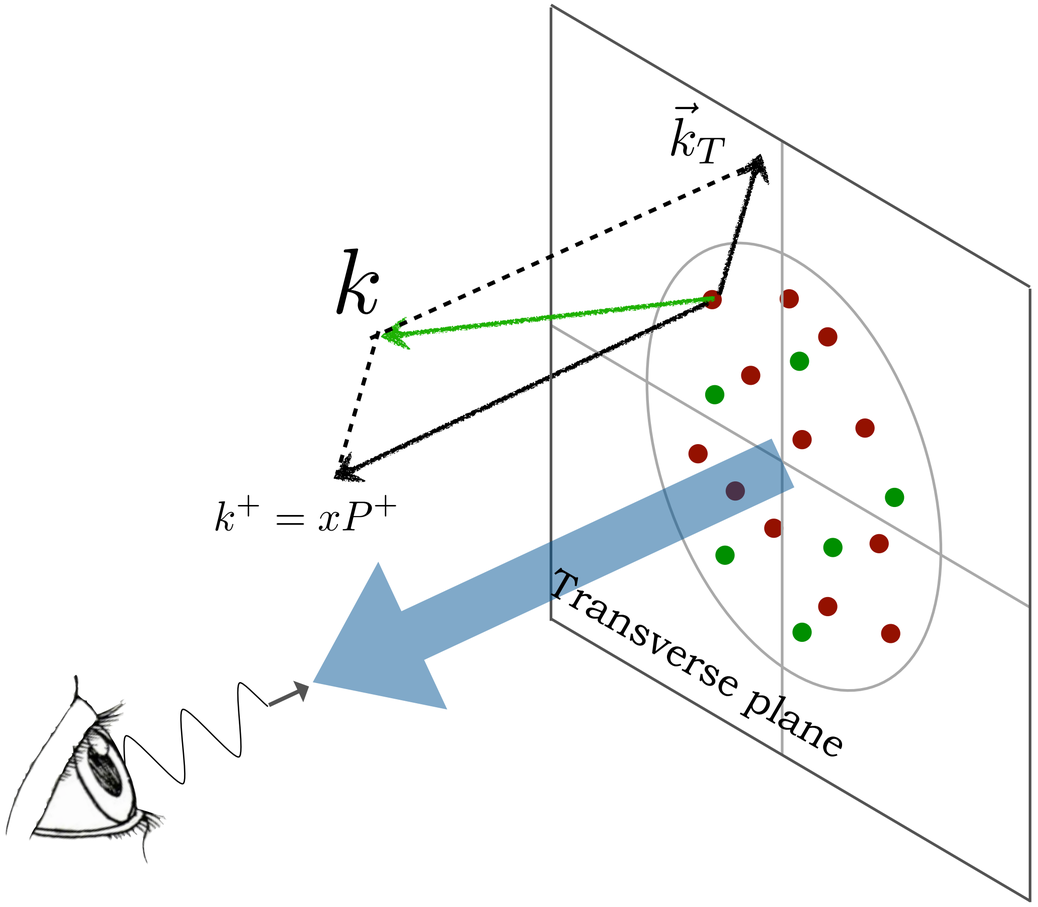
Quark Polarisation

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



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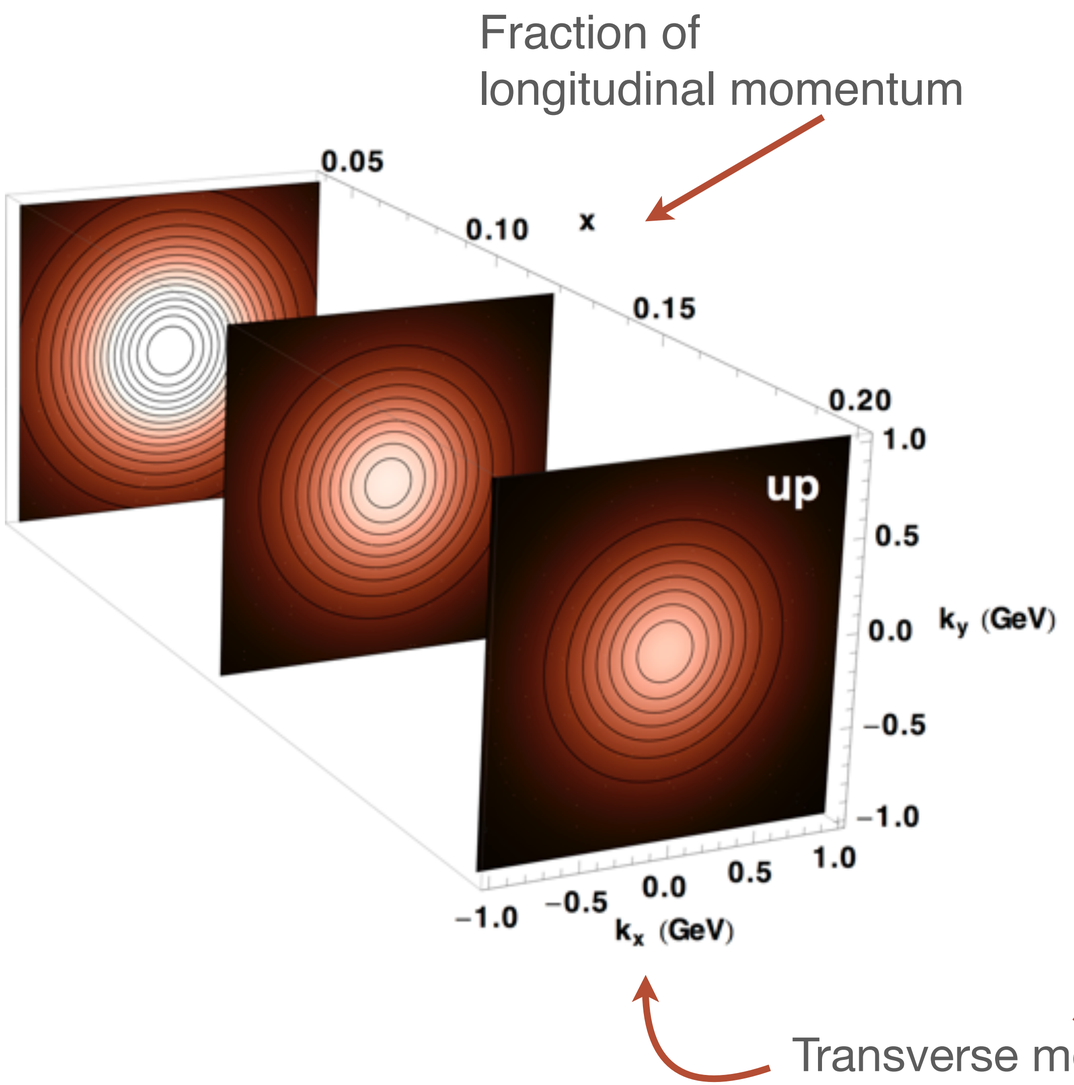
Transverse Momentum Distribution PDFs



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

A. Bacchetta, F. Delcarro, C. Pisano and M. Radici, Phys. Lett. B 827 (2022) 136961

Transverse Momentum Distribution PDFs

3-***dimensional map*** of the
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Quark Polarisation

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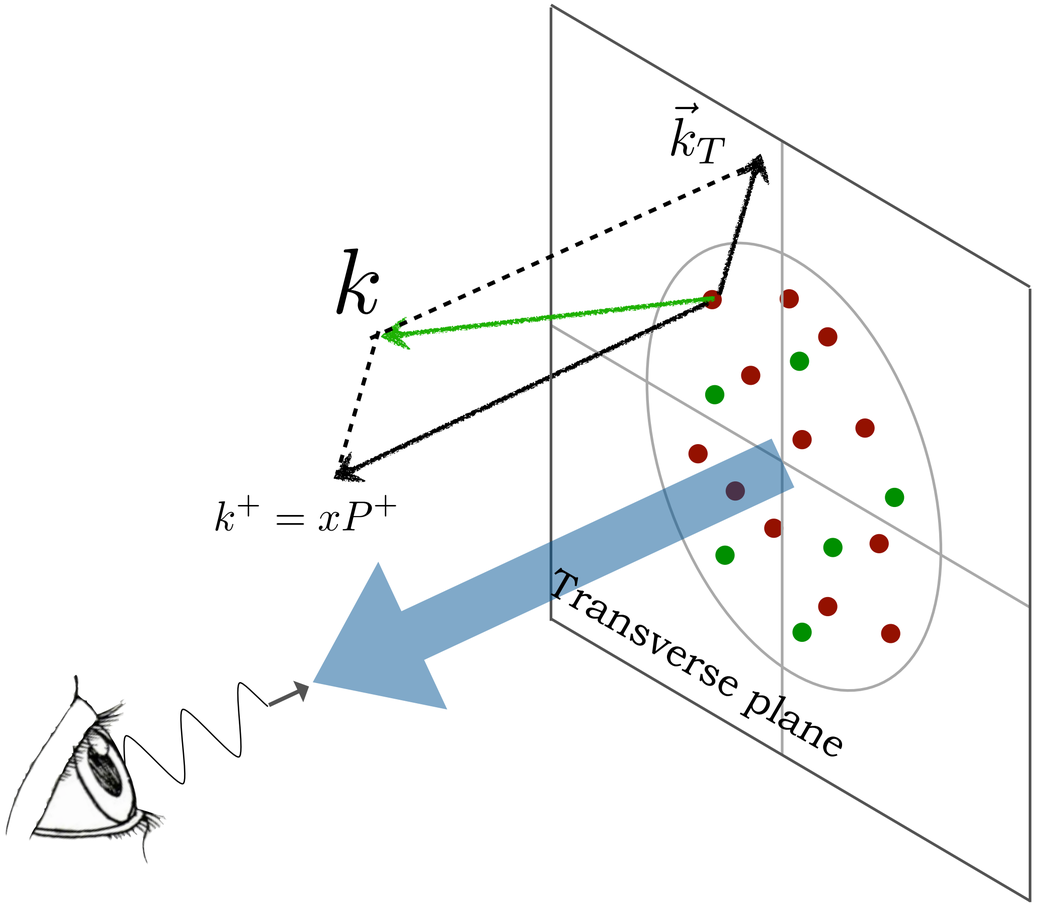


$\vec{k}_T =$ intrinsic (non-perturbative) transverse momentum of the quark

Transverse Momentum Distribution PDFs

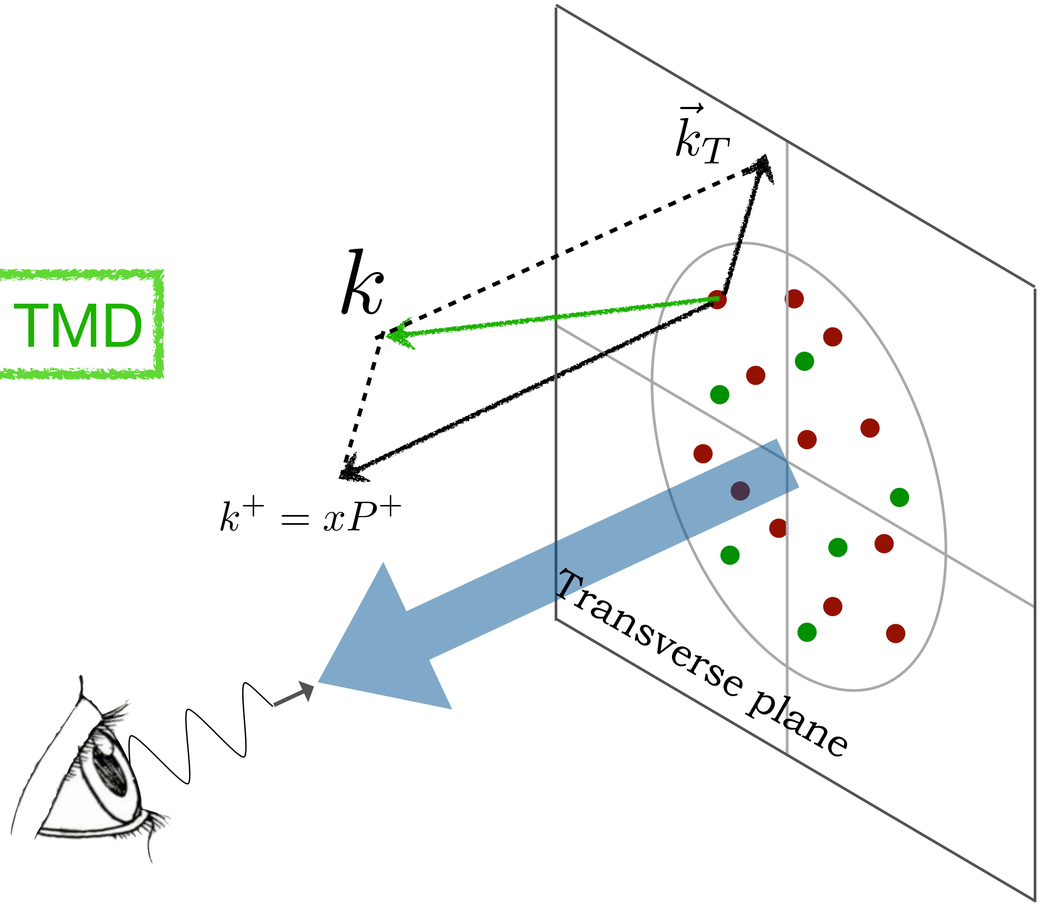
3-***dimensional map*** of the internal structure of the nucleon $f(x, \vec{k}_T)$

Unpolarized TMD

Quark Polarisation

Nucleon Pol.

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

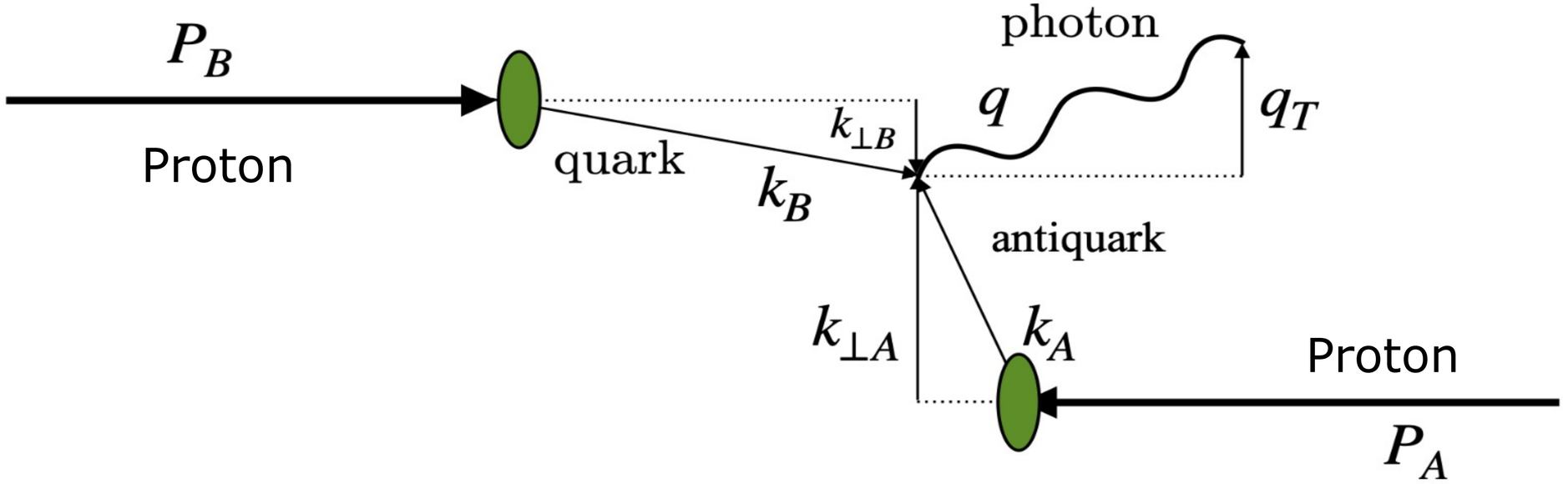


$\vec{k}_T =$ intrinsic (non-perturbative) transverse momentum of the quark

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)

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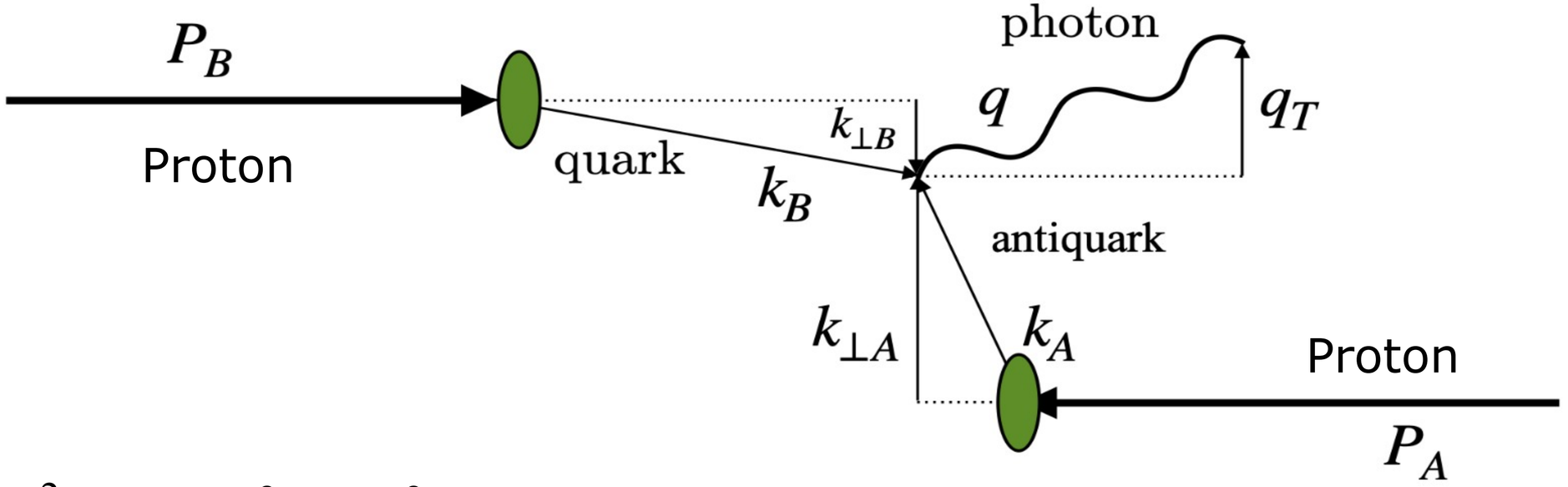
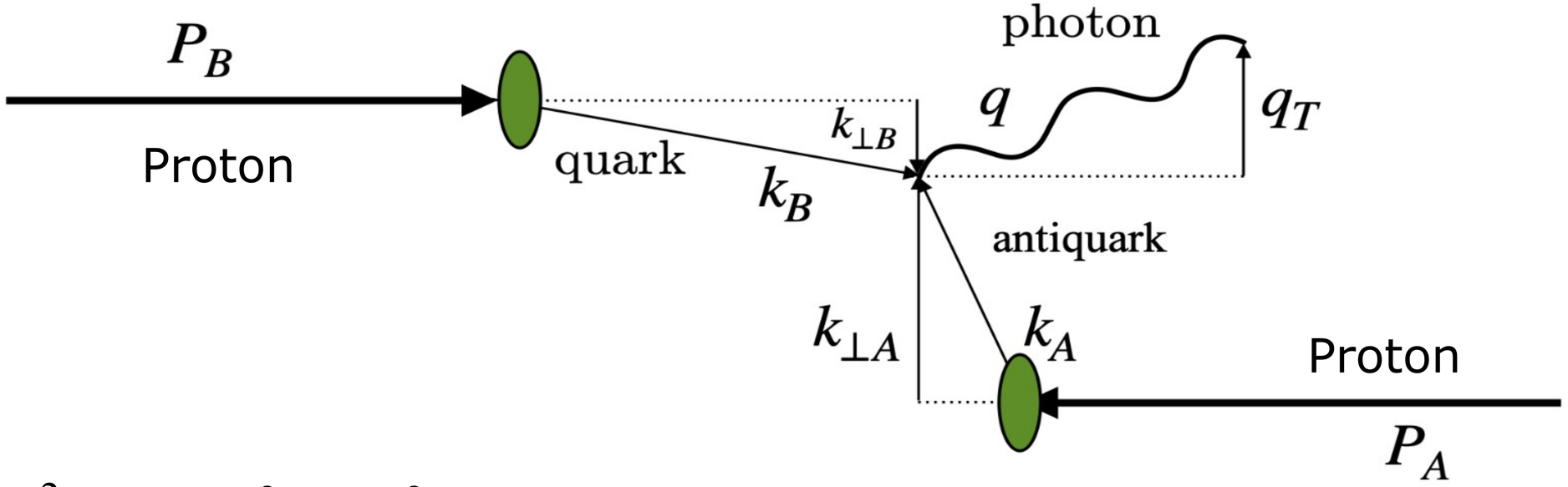


In $q_T^2 \ll Q^2$ and $M^2 \gg Q^2$ region:

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

TMD factorization — Drell-Yan process

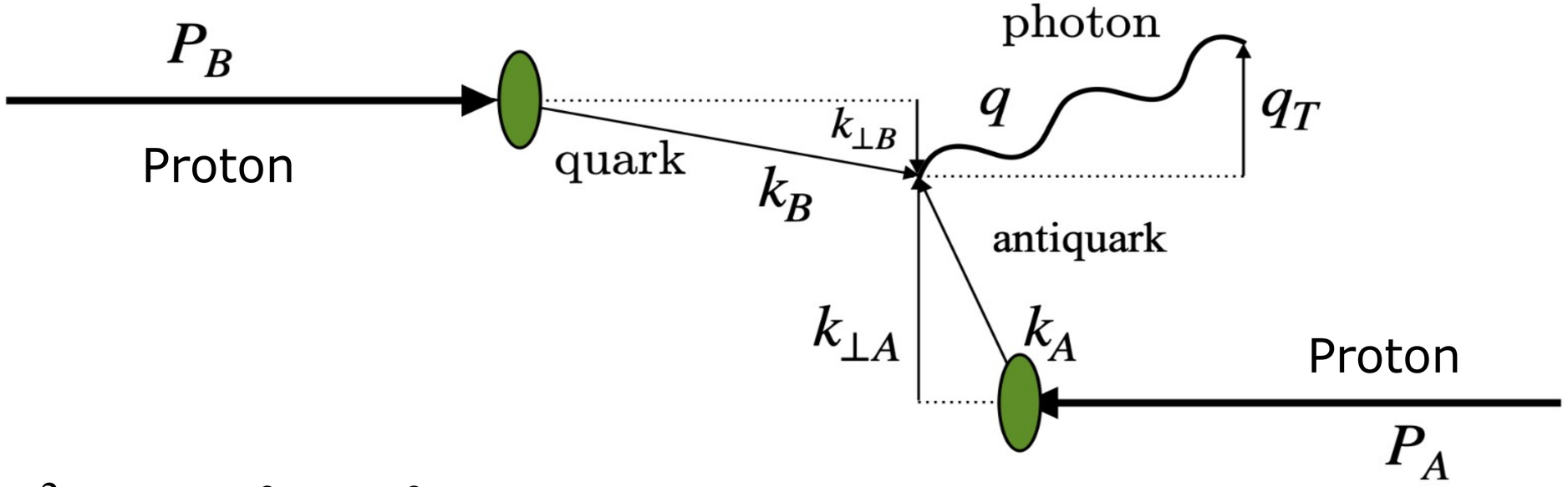


In $q_T^2 \ll Q^2$ and $M^2 \gg Q^2$ region:

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

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

TMD factorization — Drell-Yan process



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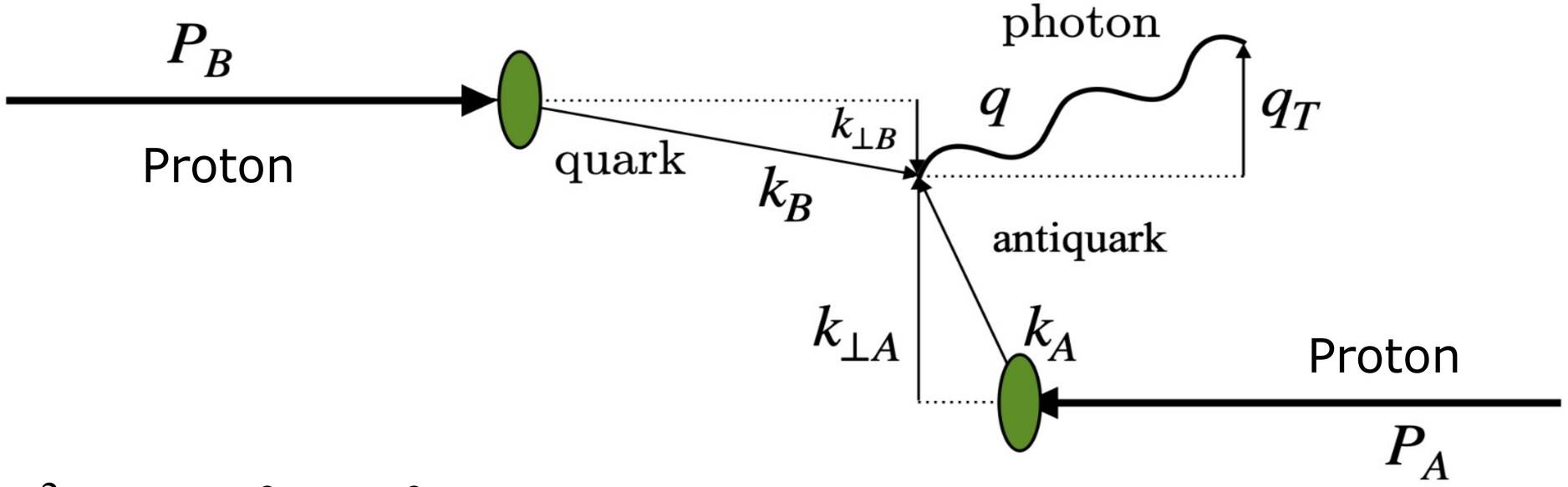

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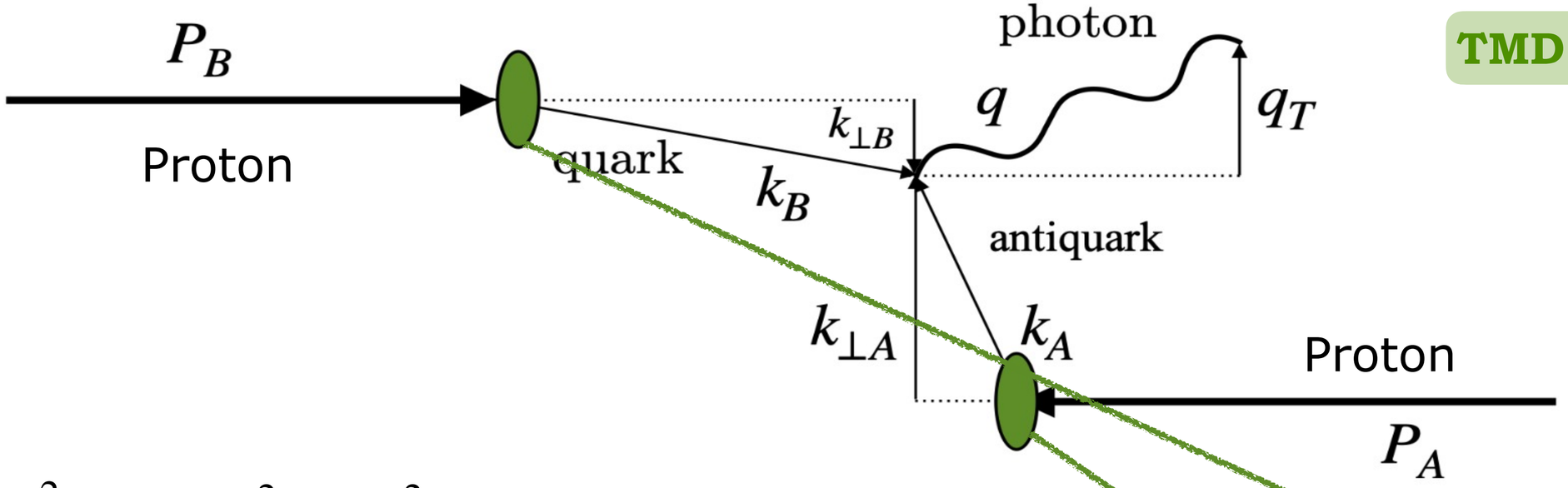

TMD PDFs

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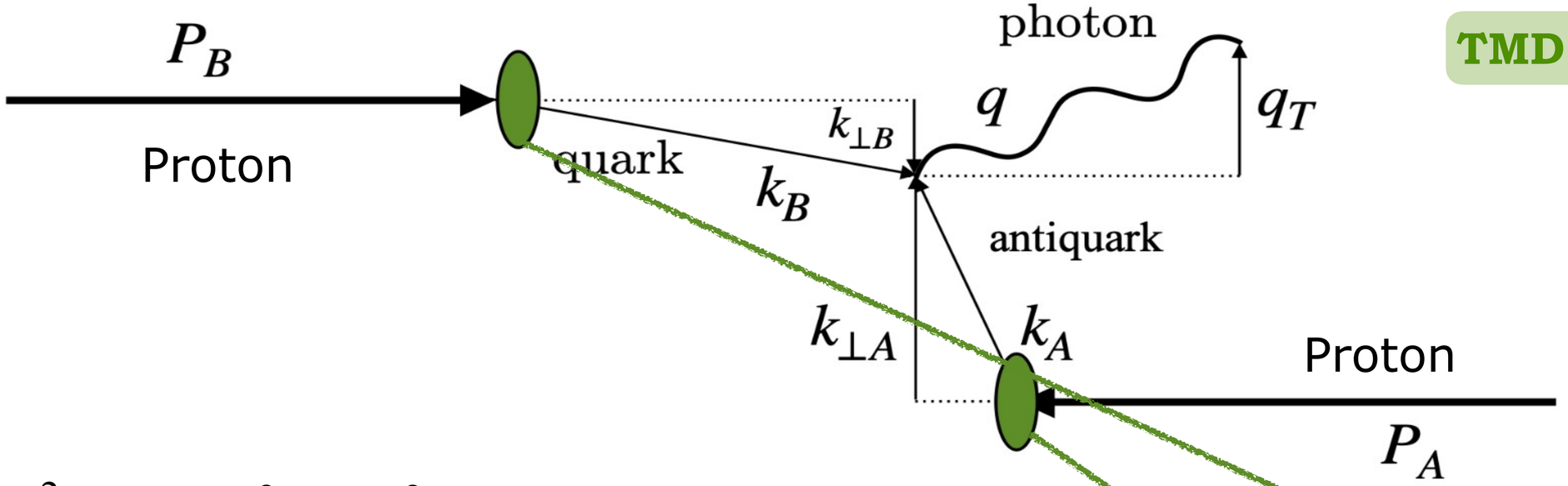

TMD PDFs

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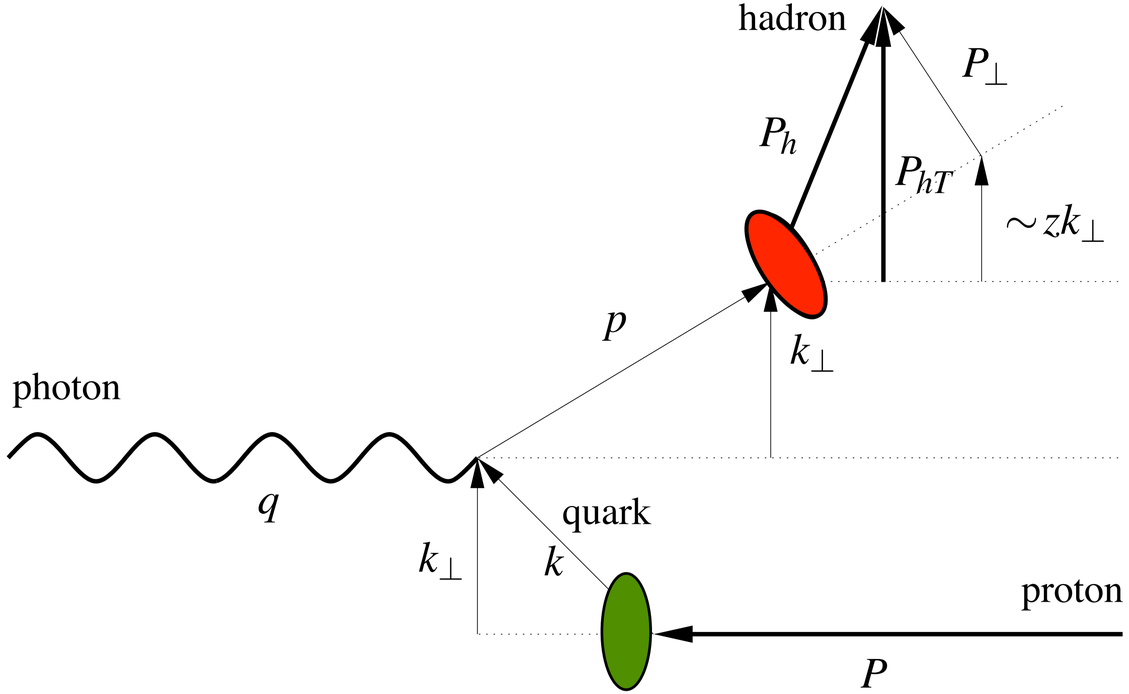
W term

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

TMD Factorization - SIDIS process

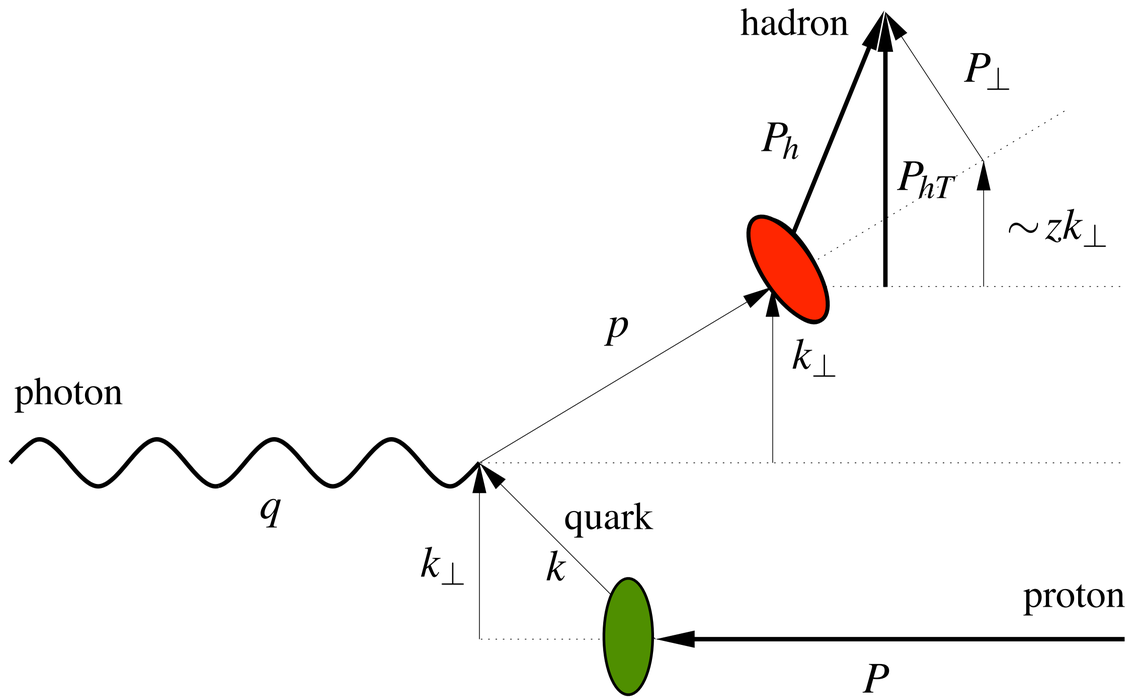


$$F_{UU,T}(x\,.\,z;\mu_F,\mathbf{P}_{hT}^2,Q^2) = x\sum_a H^a_{UU,T}(Q^2,\mu^2)\int d^2\mathbf{k}_\perp \mathbf{d^2P}_\perp f_\mathbf{1}^\mathbf{a}(x,\mathbf{k}_\perp^\mathbf{2};\mu^\mathbf{2}) D_\mathbf{1}^{\mathbf{a}\to\mathbf{h}}(z,\mathbf{P}_\perp^\mathbf{2};\mu^\mathbf{2})\delta^{(\mathbf{2})}(z\mathbf{k}_\perp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

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

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

TMD Factorization - SIDIS process



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W Term

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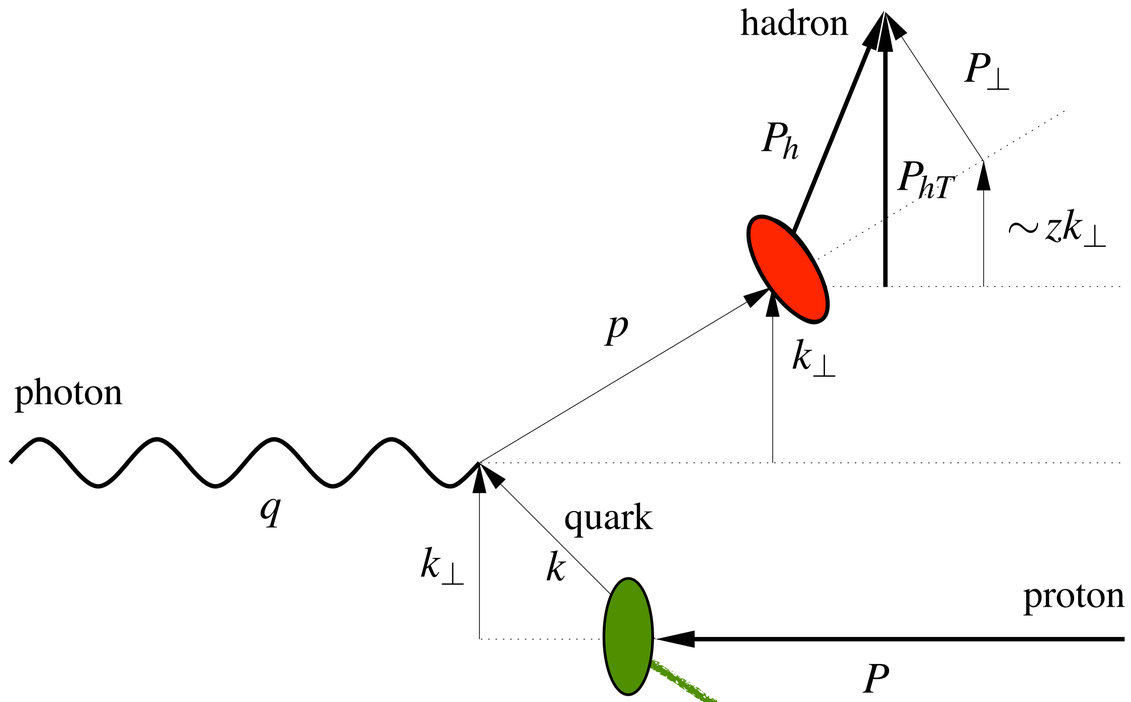

TMD PDF

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

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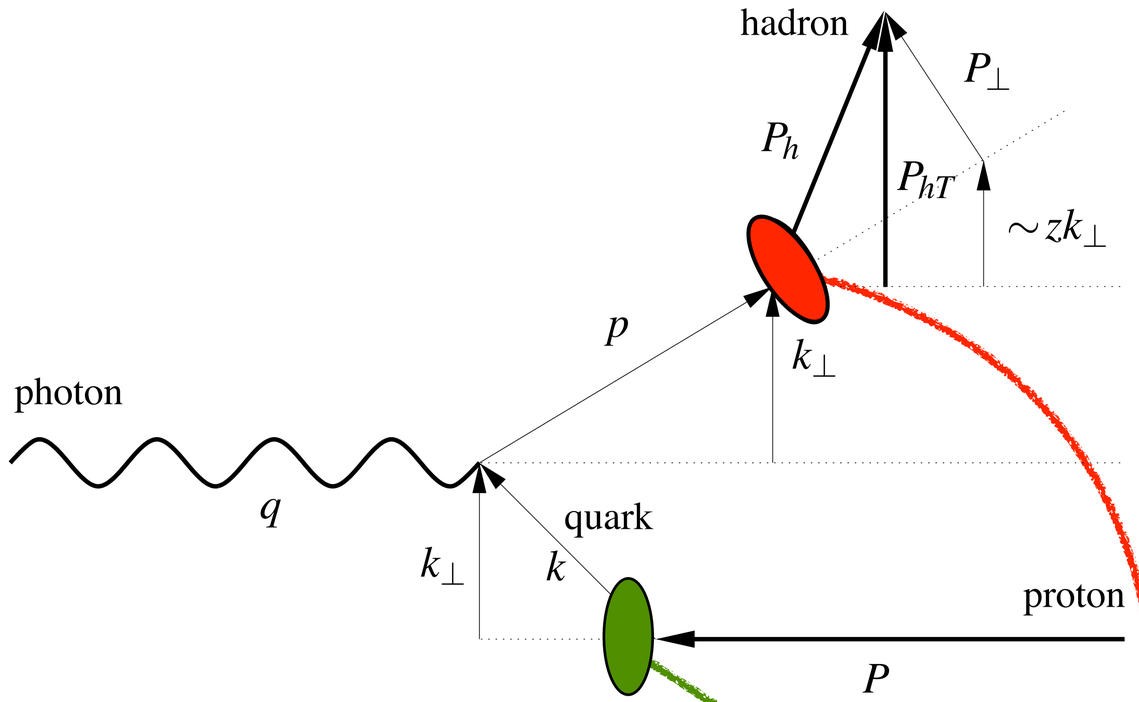
W Term

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

TMD Factorization - SIDIS process

TMD FF

TMD PDF



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

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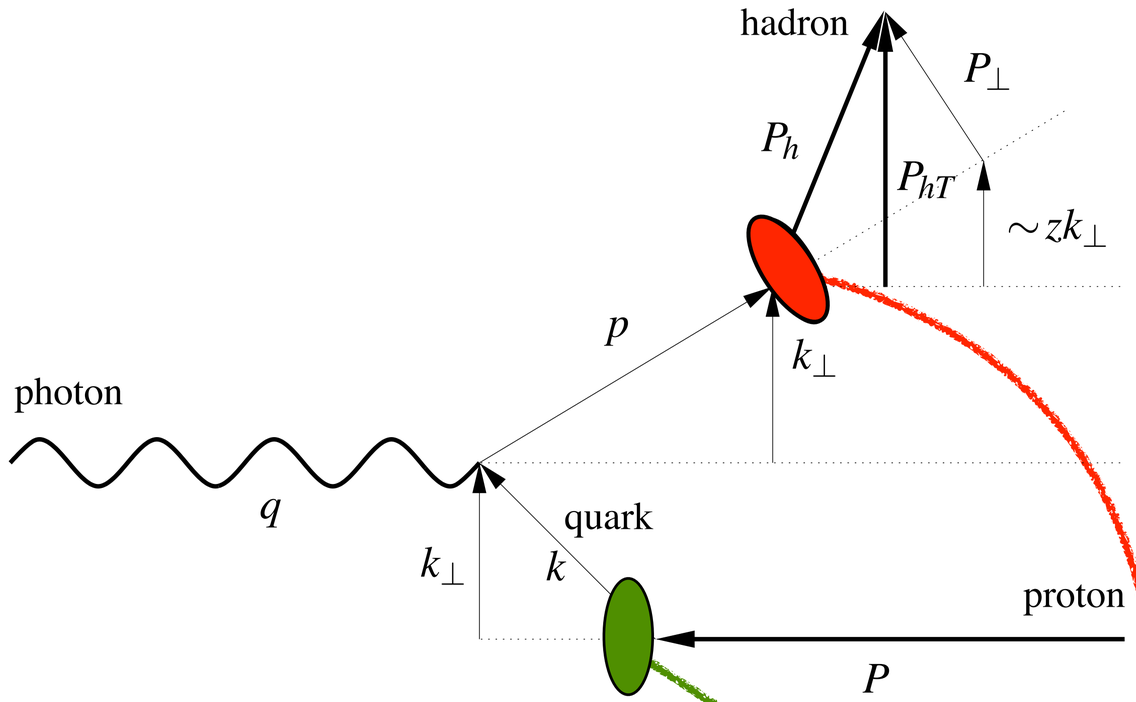
W Term

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

TMD Factorization - SIDIS process

TMD FF

TMD PDF



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

W Term

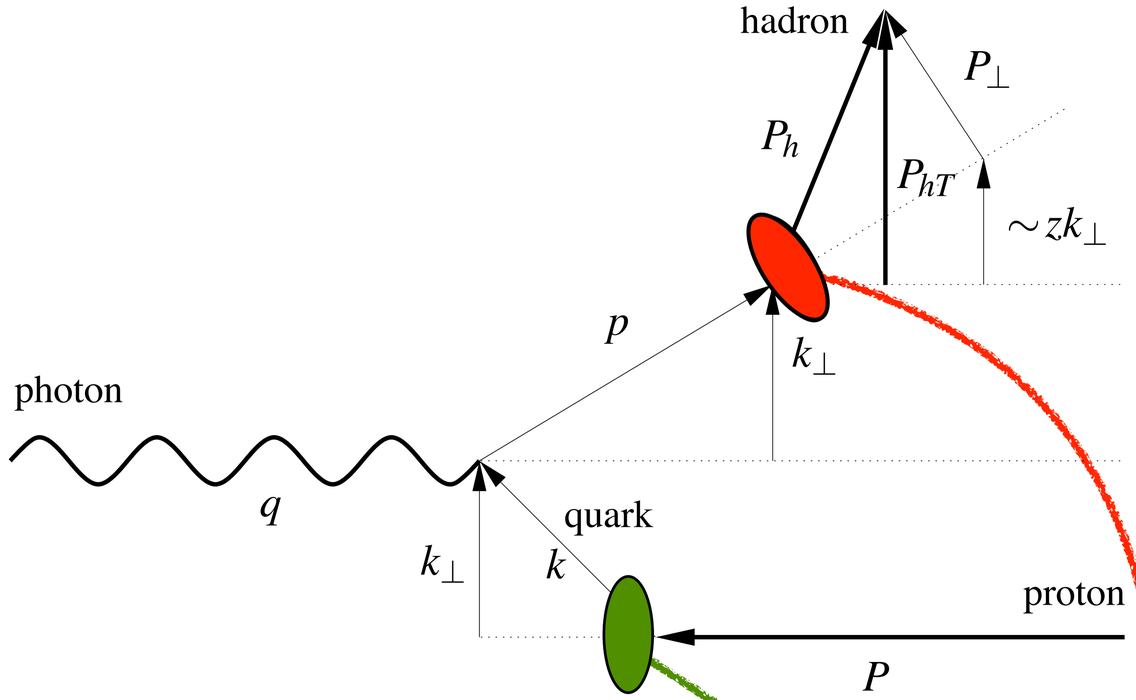
- The W term dominates in the region where $q_T \ll Q$

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 analysis

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

TMD factorization — Structure of TMDs

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

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

TMD factorization — Structure of TMDs

Matching coeff.
(perturbative calculable)

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

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TMD factorization — Structure of TMDs

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TMD factorization — Structure of TMDs

Collinear PDFs (previous fit)

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

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

TMD factorization — Structure of TMDs

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

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

$b_\star$ prescription

TMD factorization — Structure of TMDs

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

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

TMD factorization — Structure of TMDs

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Anomalous dimension: $\gamma(\mu, \zeta_F) = \gamma_F + \gamma_k \ln\left(\frac{\sqrt{\zeta_F}}{\mu} \right)$

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NP part of Collins-Soper Kernel

"Foundations of Perturbative QCD"

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Non perturbative part of TMDs

Fit extraction

Available codes

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

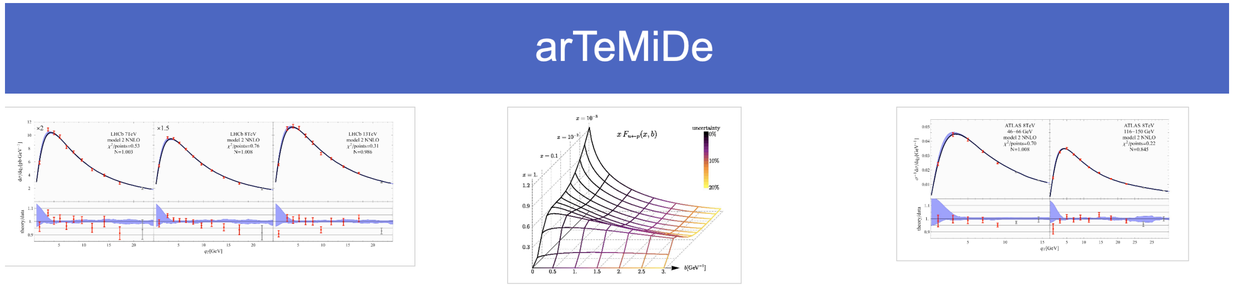
You can obtain NangaParbat directly from the github repository:

https://github.com/MapCollaboration/NangaParbat

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

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

https://teorica.fis.ucm.es/artemide/



Global Fits

	Accuracy	SIDIS	DY	Z production	N of points	χ^2/N_{data}
Pavia 2017 JHEP 06 (2017) 081	NLL	✔	✔	✔	8059	1.55
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A new extraction of proton quark unpolarized TMDs

MAP Collaboration, JHEP 10 (2022)

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MAP Collaboration, JHEP 10 (2022)

A new extraction of proton quark unpolarized TMDs

- Global analysis of Drell-Yan and Semi-Inclusive DIS data sets: ***2031*** data points
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- Extremely good description: $\chi^2/\mathrm{N_{data}} = 1.06$

MAP Collaboration, JHEP 10 (2022)

Main differences with SV19

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  Collins-Soper-Sterman vs ***zeta-prescription***

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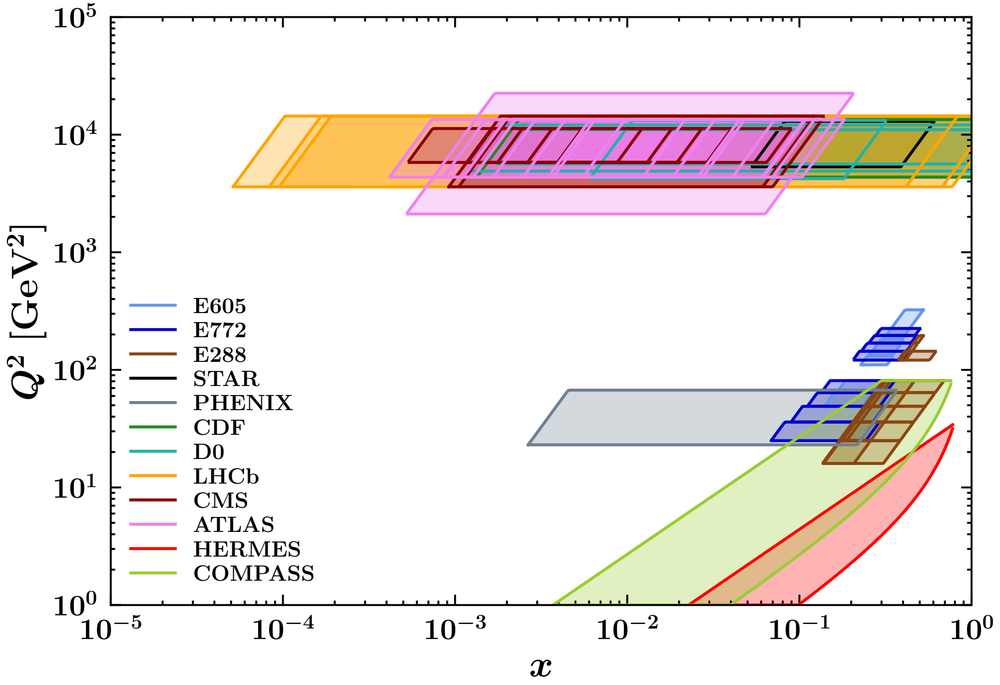
- Different criteria of data selection

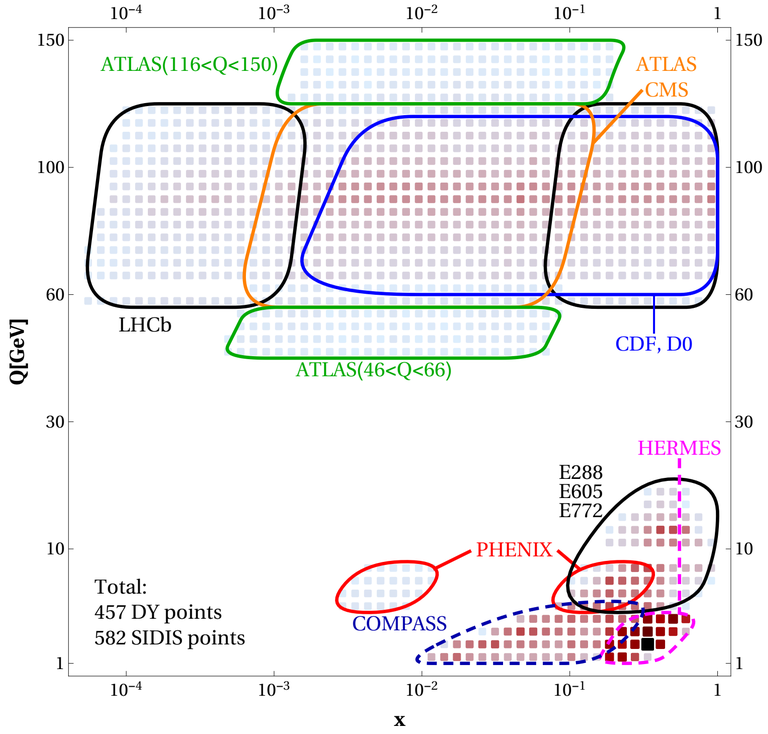
Comparison included datasets

MAPTMD22



484(DY) + 1547(SIDIS) = 2031 fitted data

SV19



457(DY) + 582(SIDIS) = 1039 fitted data

Visualization of TMD PDFs

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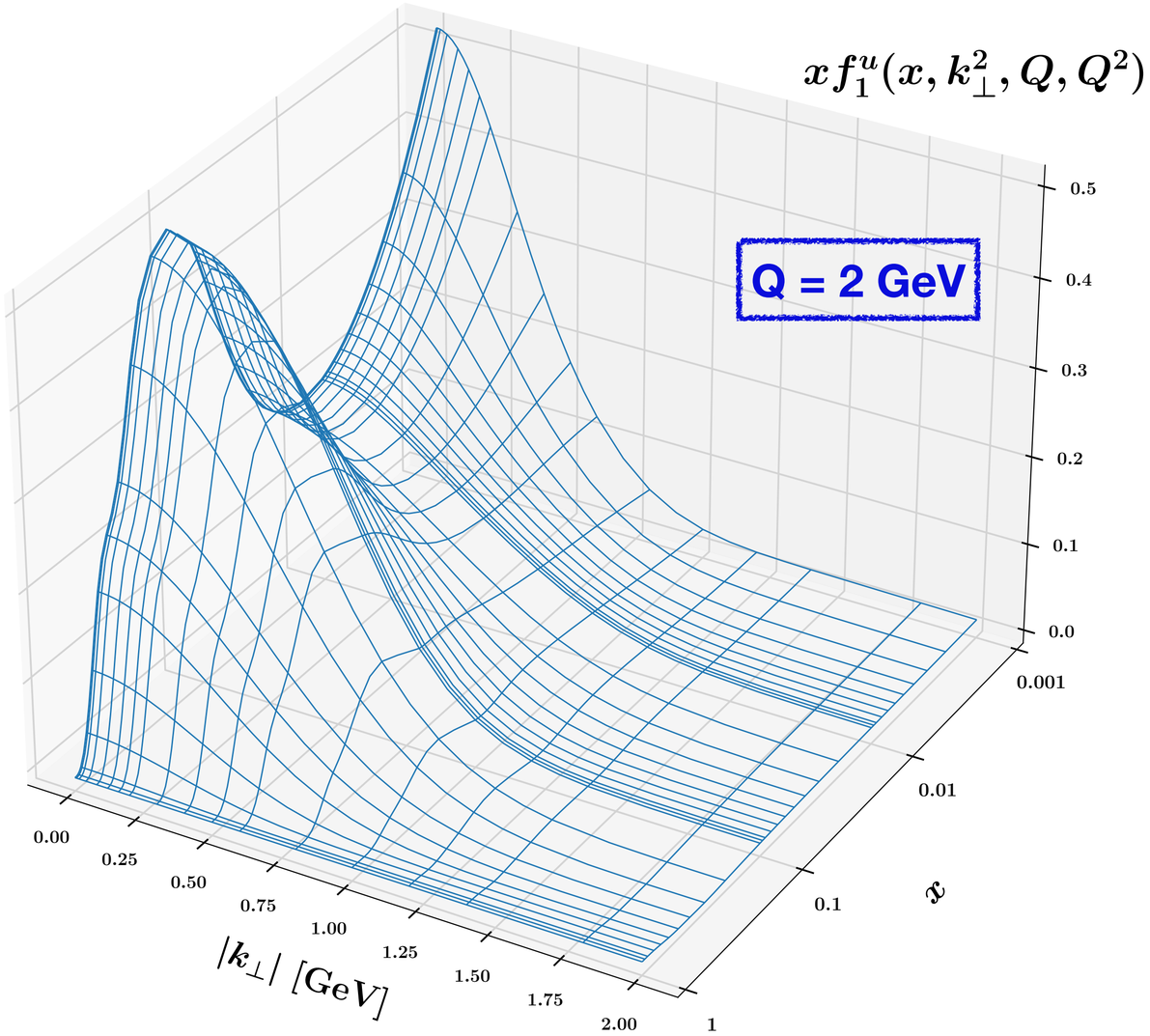

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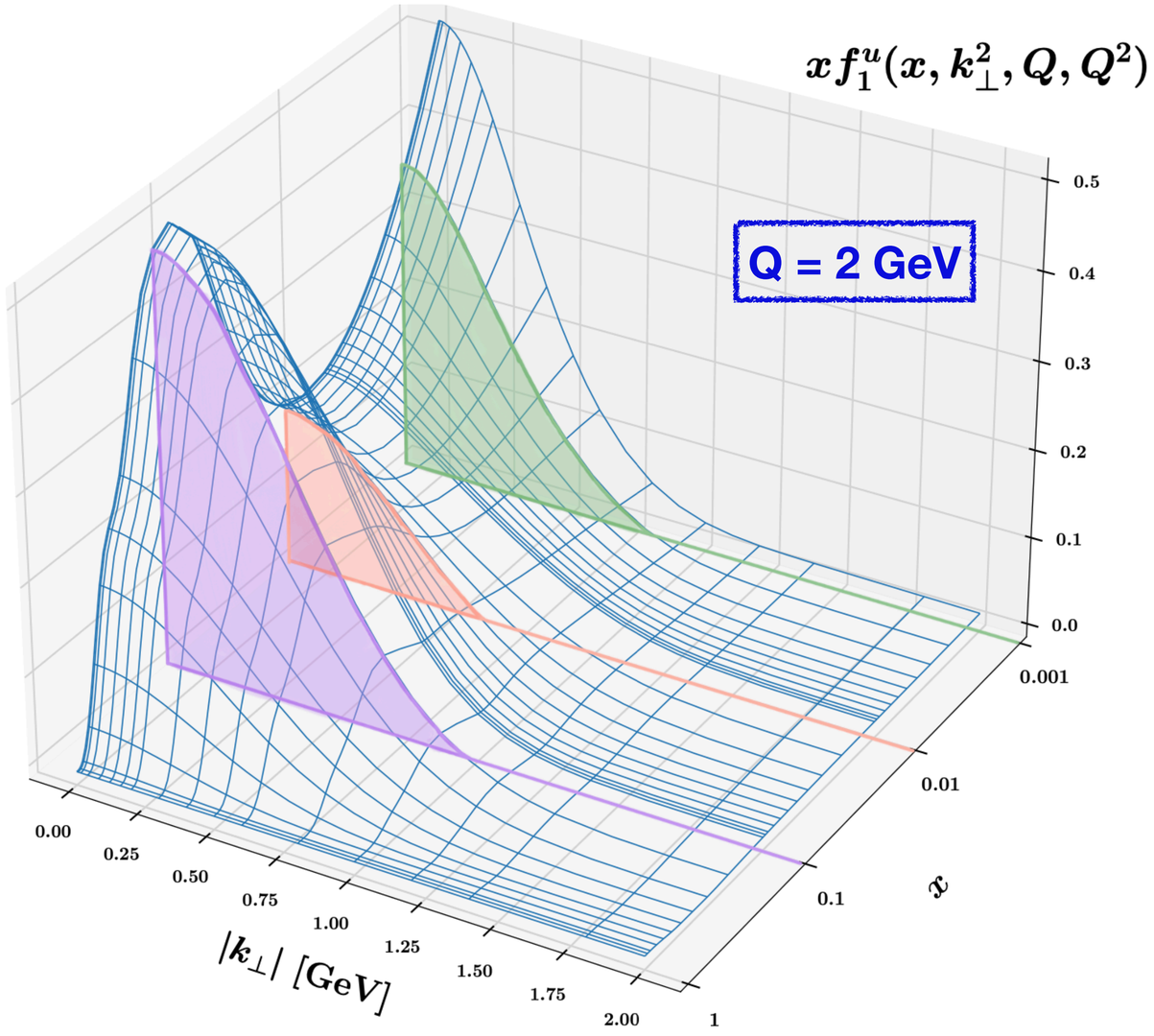

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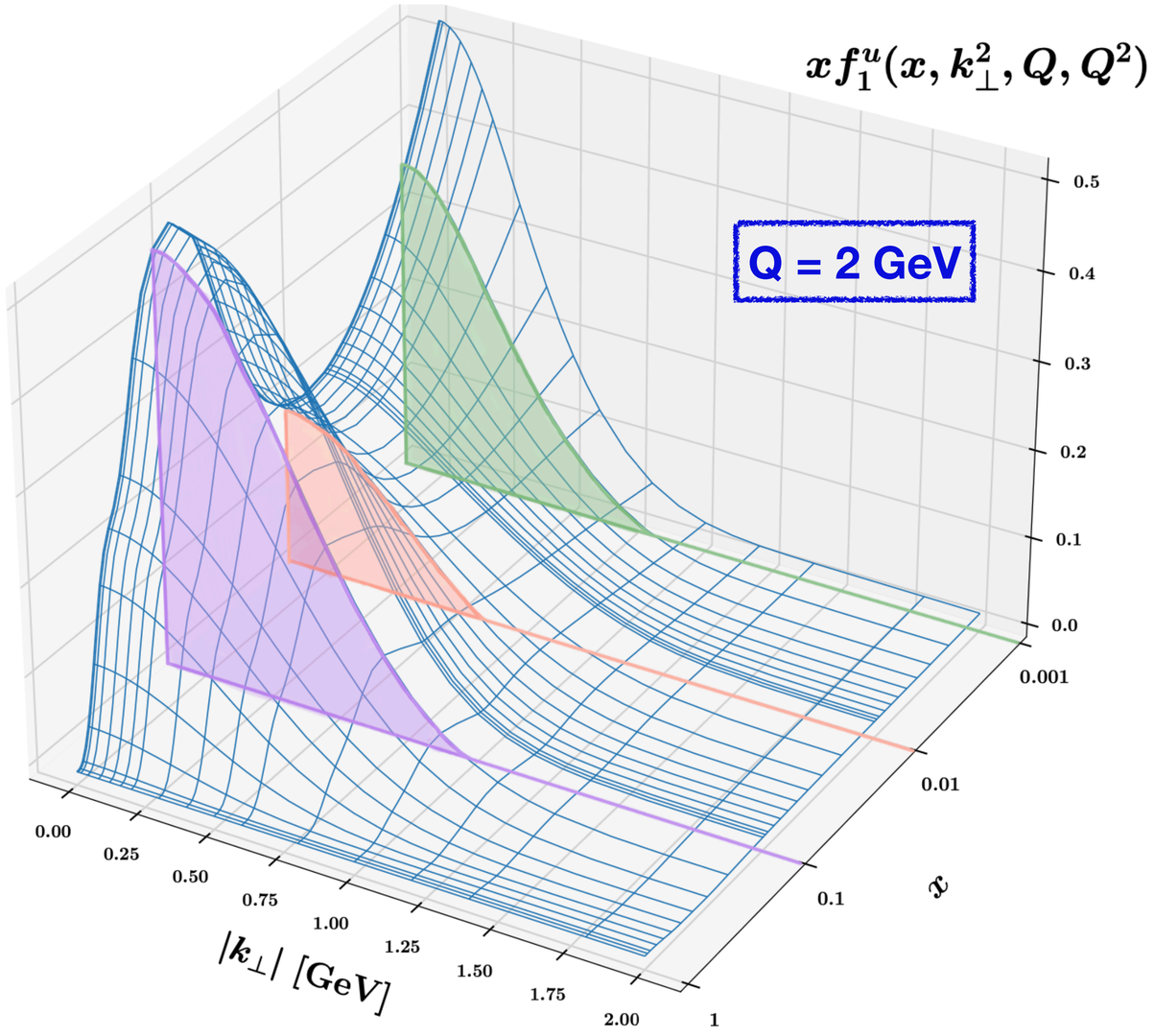

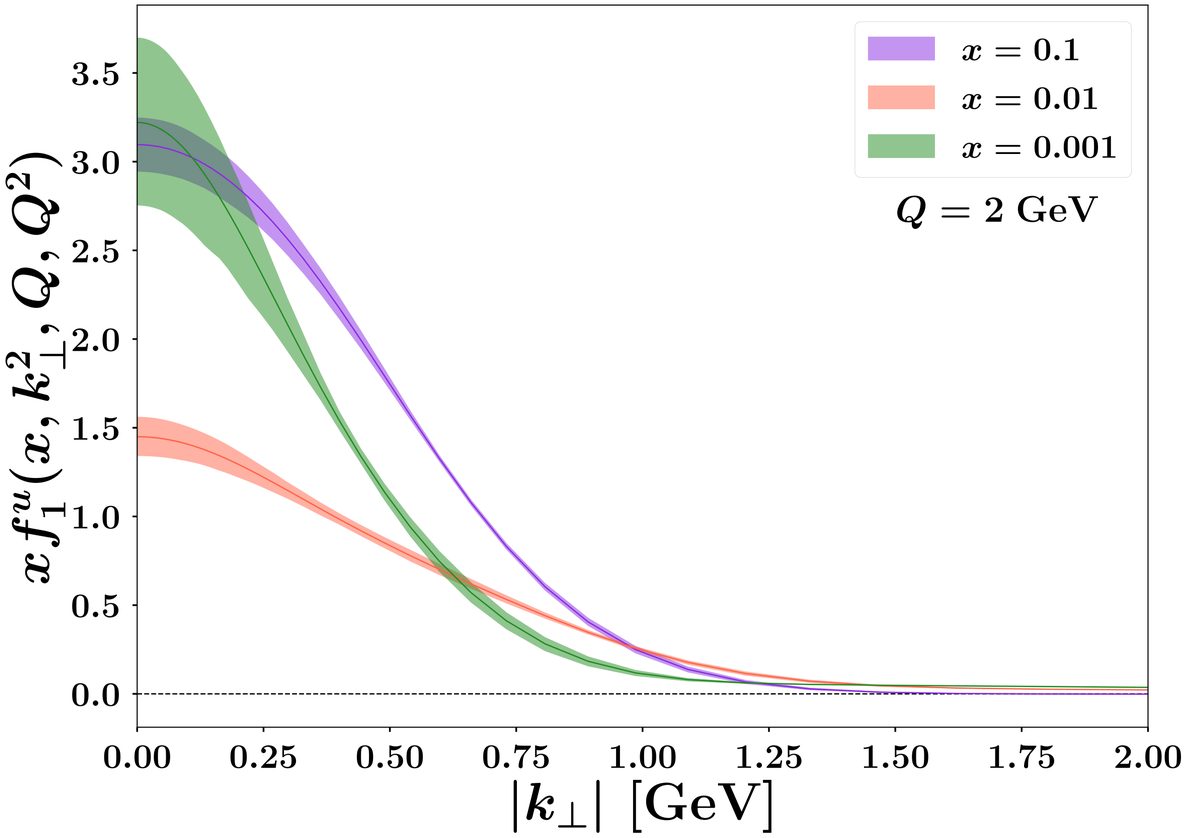

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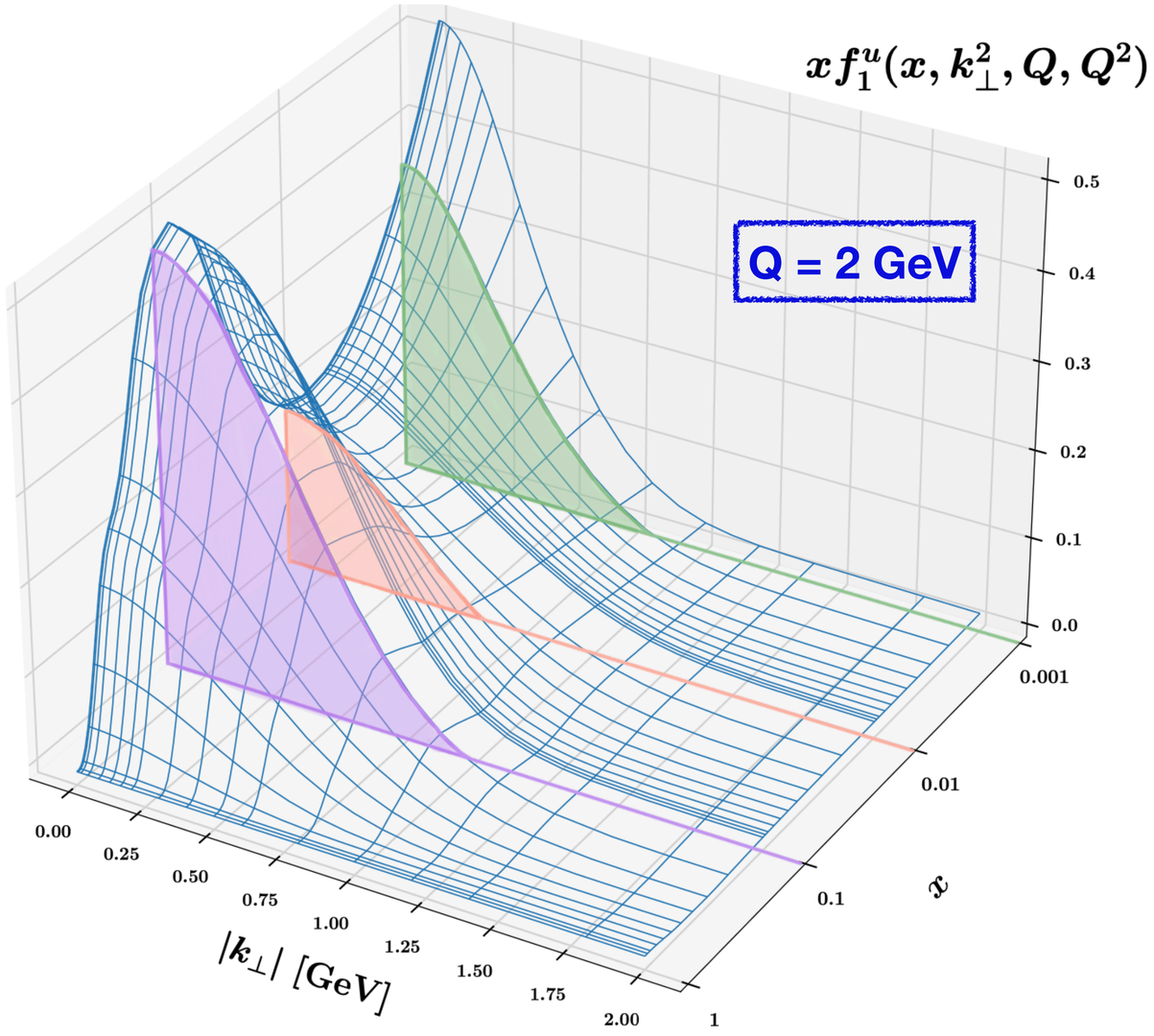

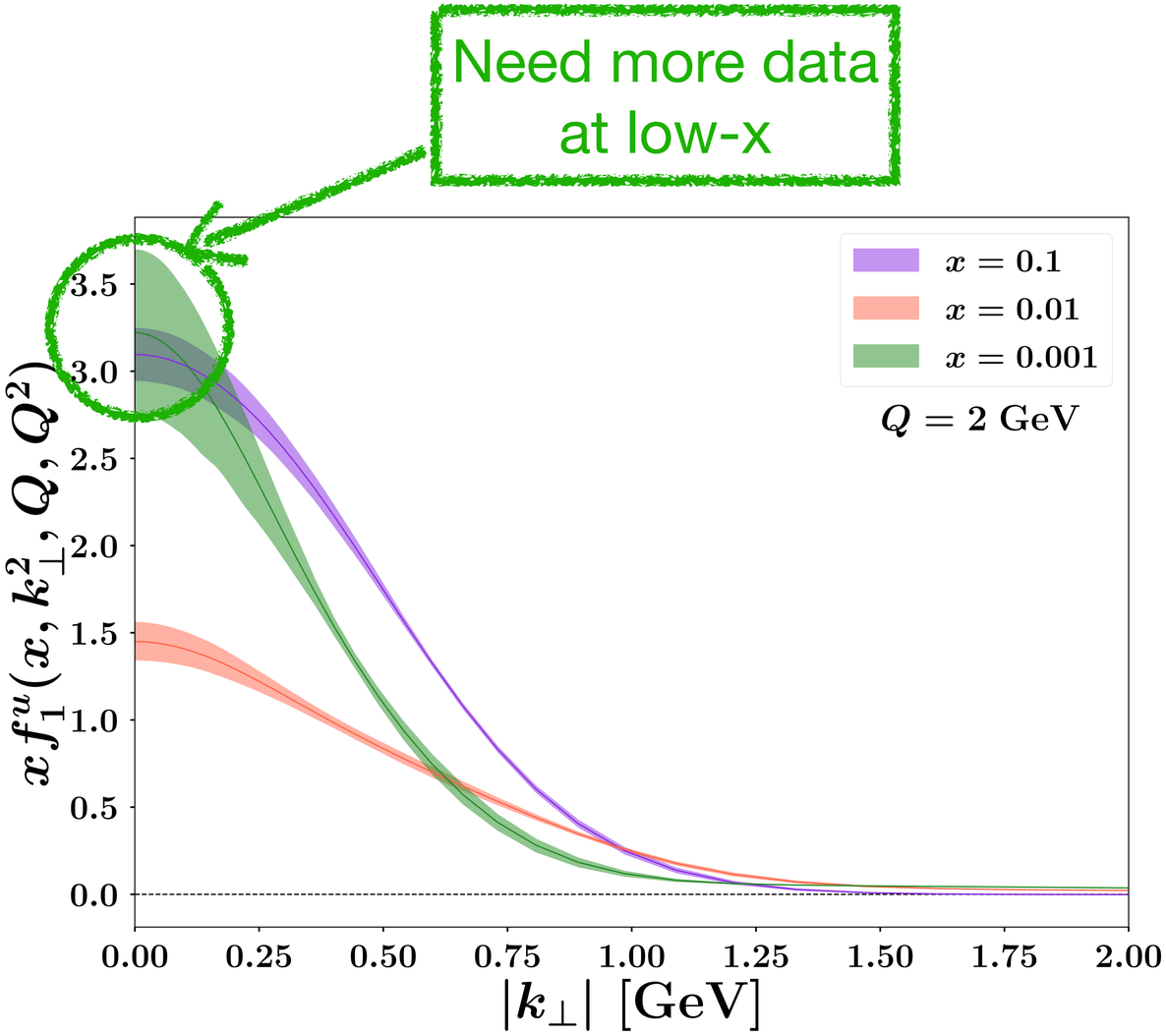

Comparison of TMD PDFs

Eur.Phys.J.C 81 (2021) 8, 752

Comparison of TMD PDFs

- Home
- TMDplotter
- Source Code Download
- PDF sets (names)
- PDF sets Download (New)
- Updates/News
- Source Code Download (Old)
- TMD-Project
- CCFM uPDF evolution code
- Contact

TMDlib is hosted by Hepforge, IPPP Durham

TMDlib

TMDlib2 and TMDplotter: a platform for 3D hadron structure studies

NEW manual released 2103.09741

- TMDplotter
- Download source from TMDlib 2.X
- Download source from TMDlib 1.X
- Any questions or comments should be directed to tmdlib@projects.hepforge.org.
- TMDlib1 Doxygen Documentation

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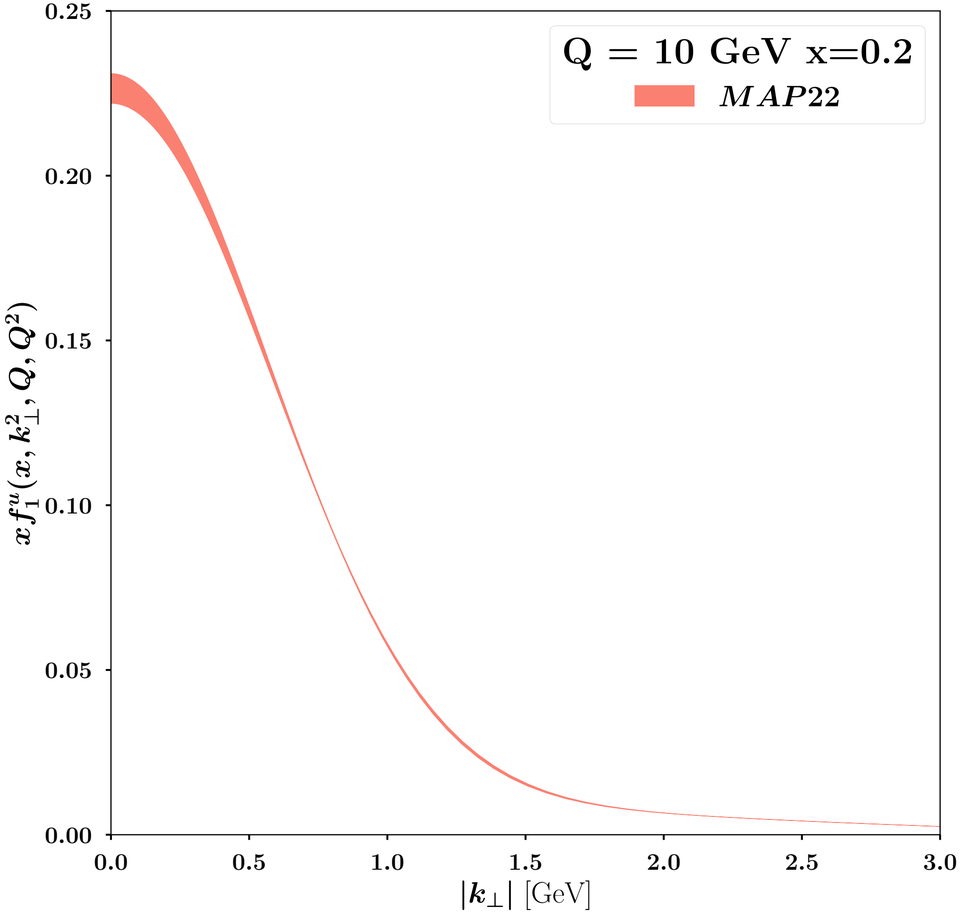

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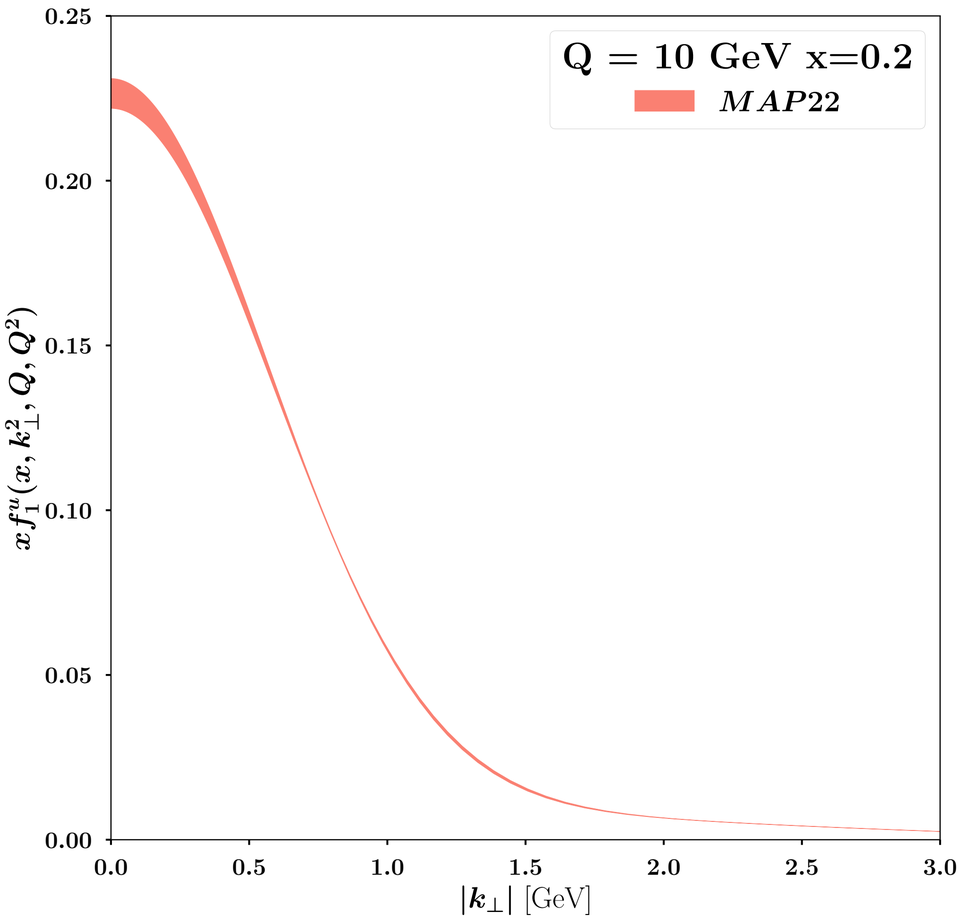

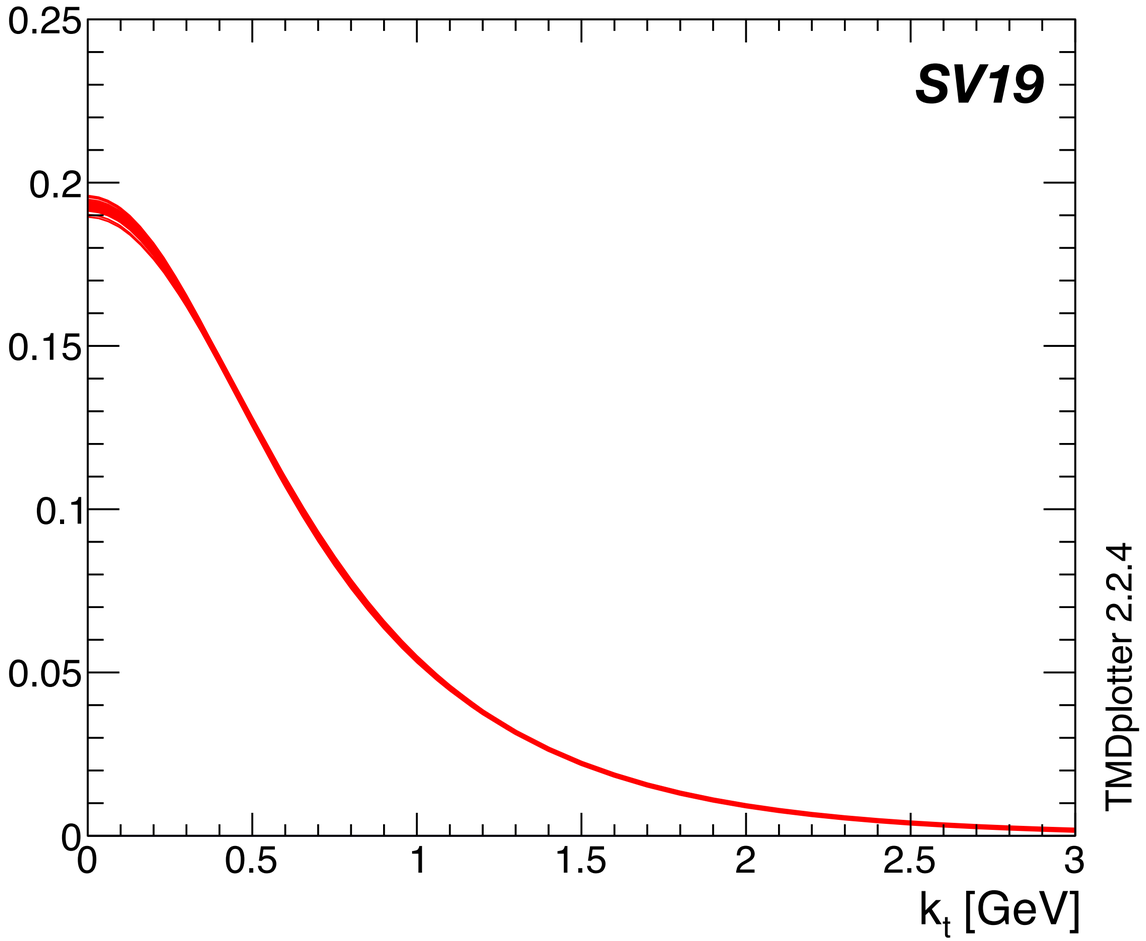

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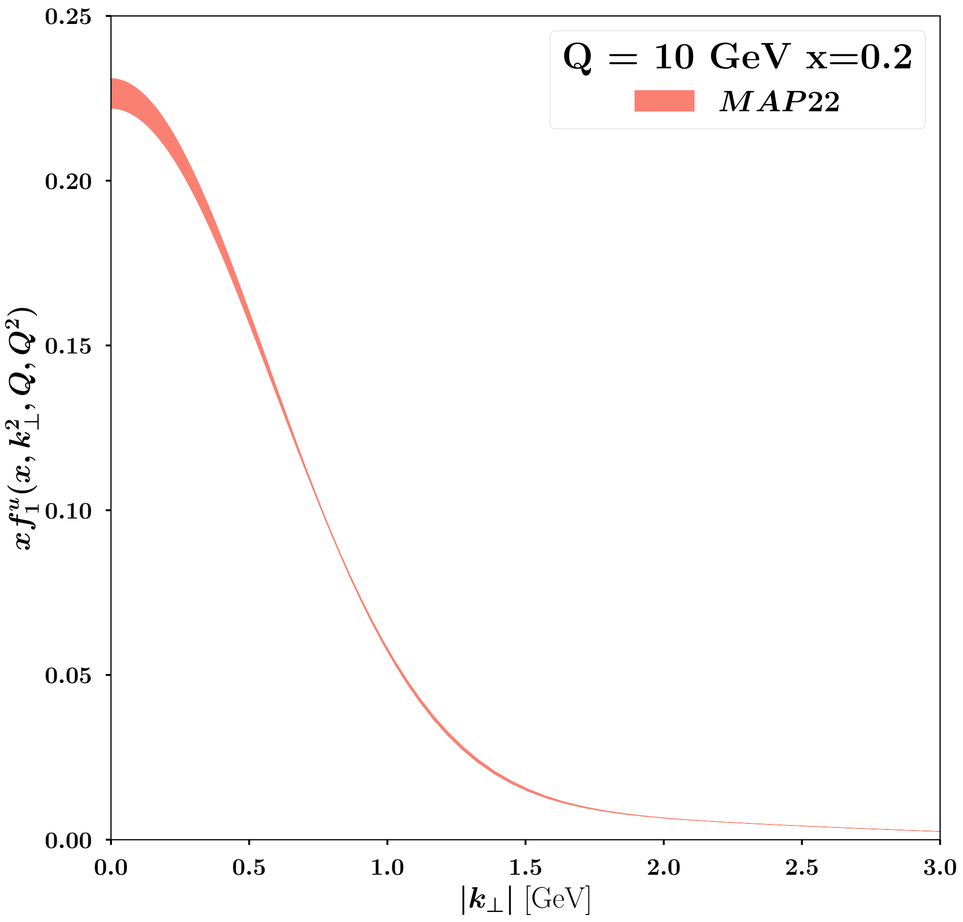

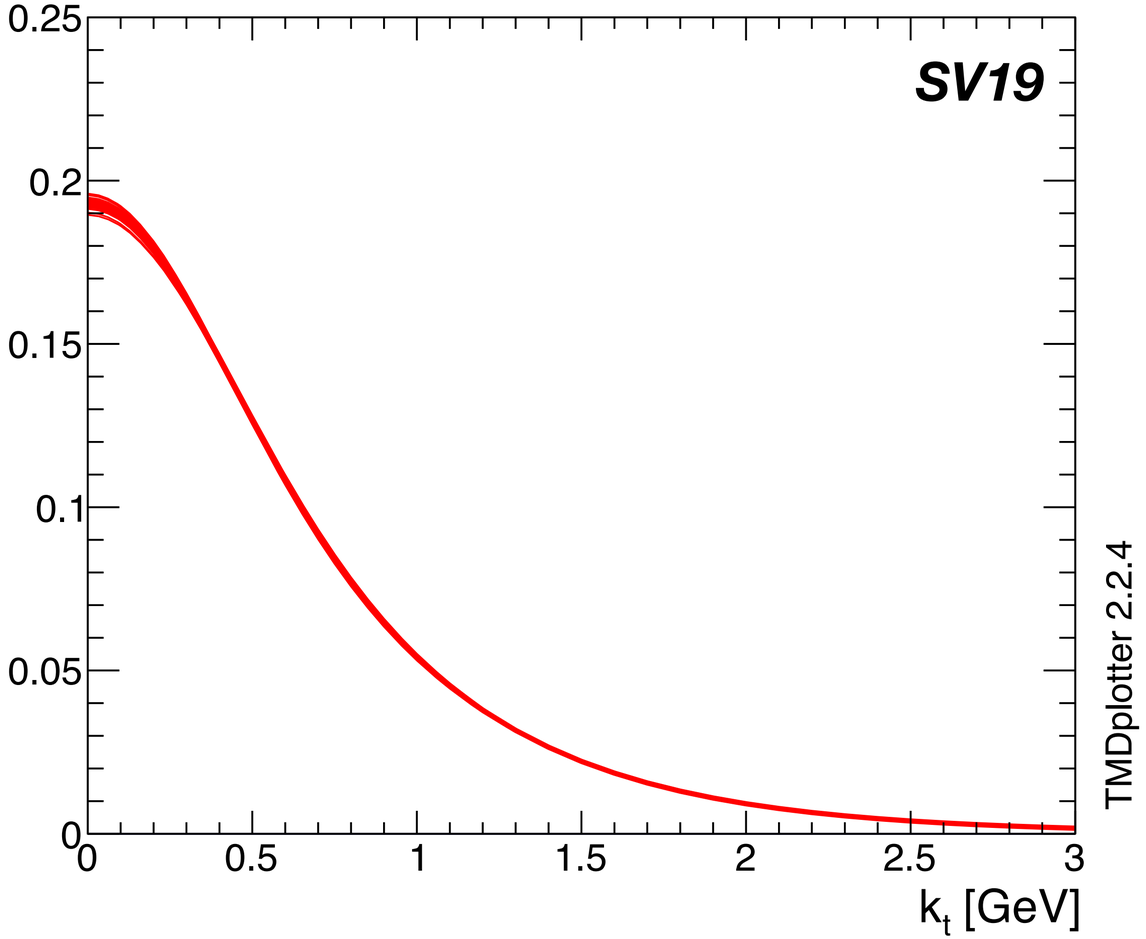

Good agreement in shape and quite good in normalization

Comparison of TMD PDFs

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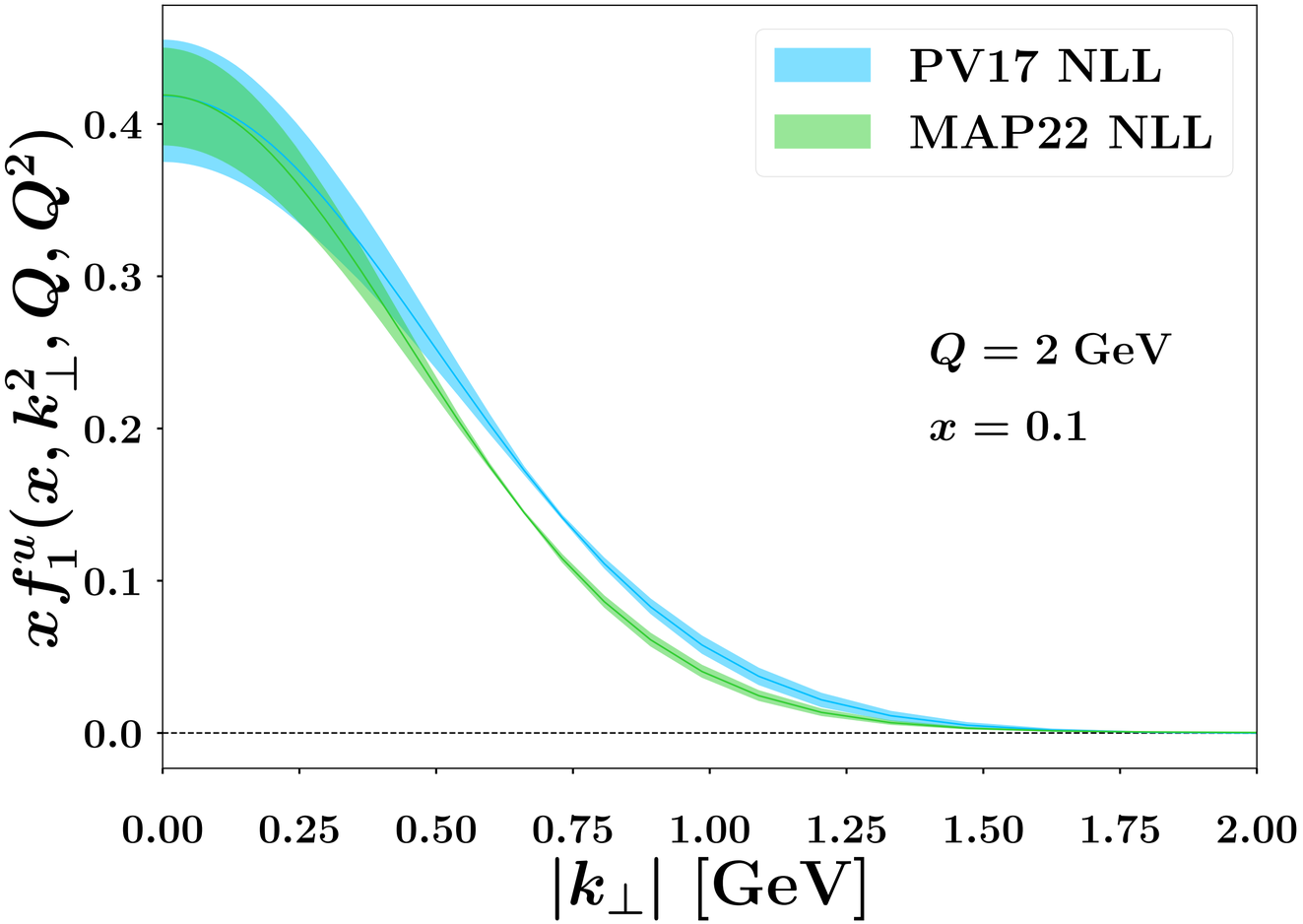

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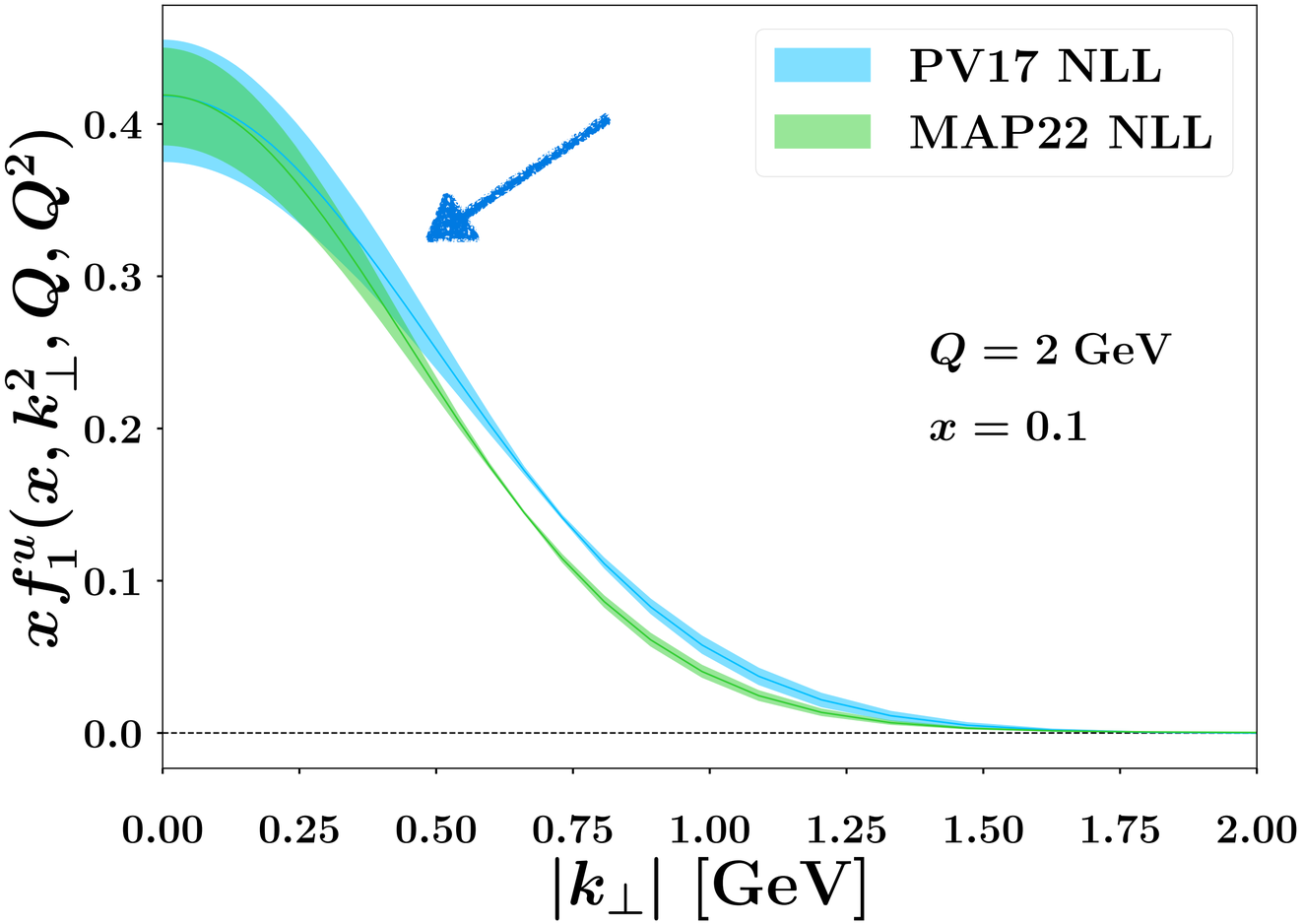

Very good agreement!

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Pion-induced Drell-Yan process

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Experiment	$\sqrt{s}$ [GeV]	Q [GeV]	N_{bins}	x_F	
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$f_{1\pi}^{NP}(x, \zeta, \mathbf{b}_T)$ → ***3 fitting parameters***

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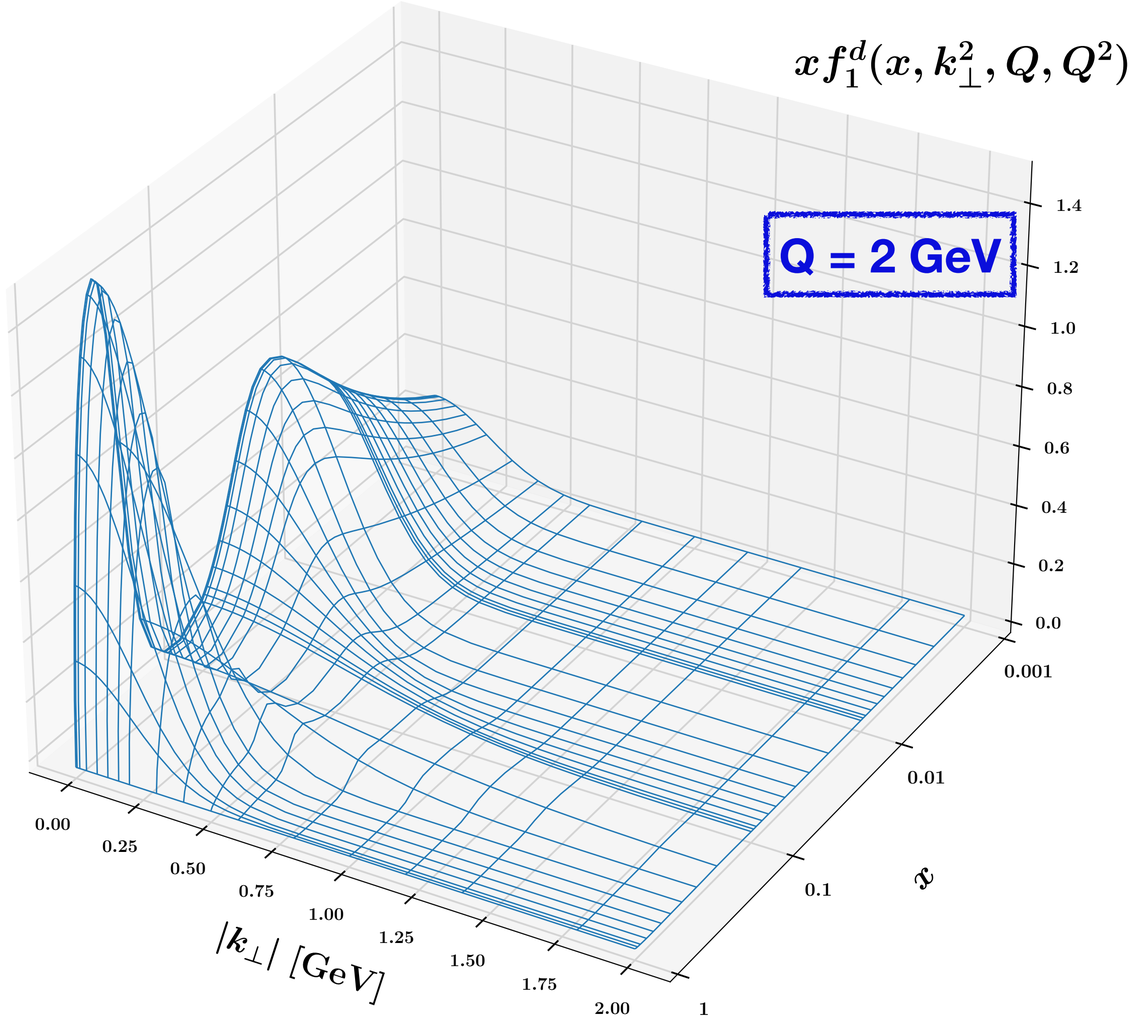

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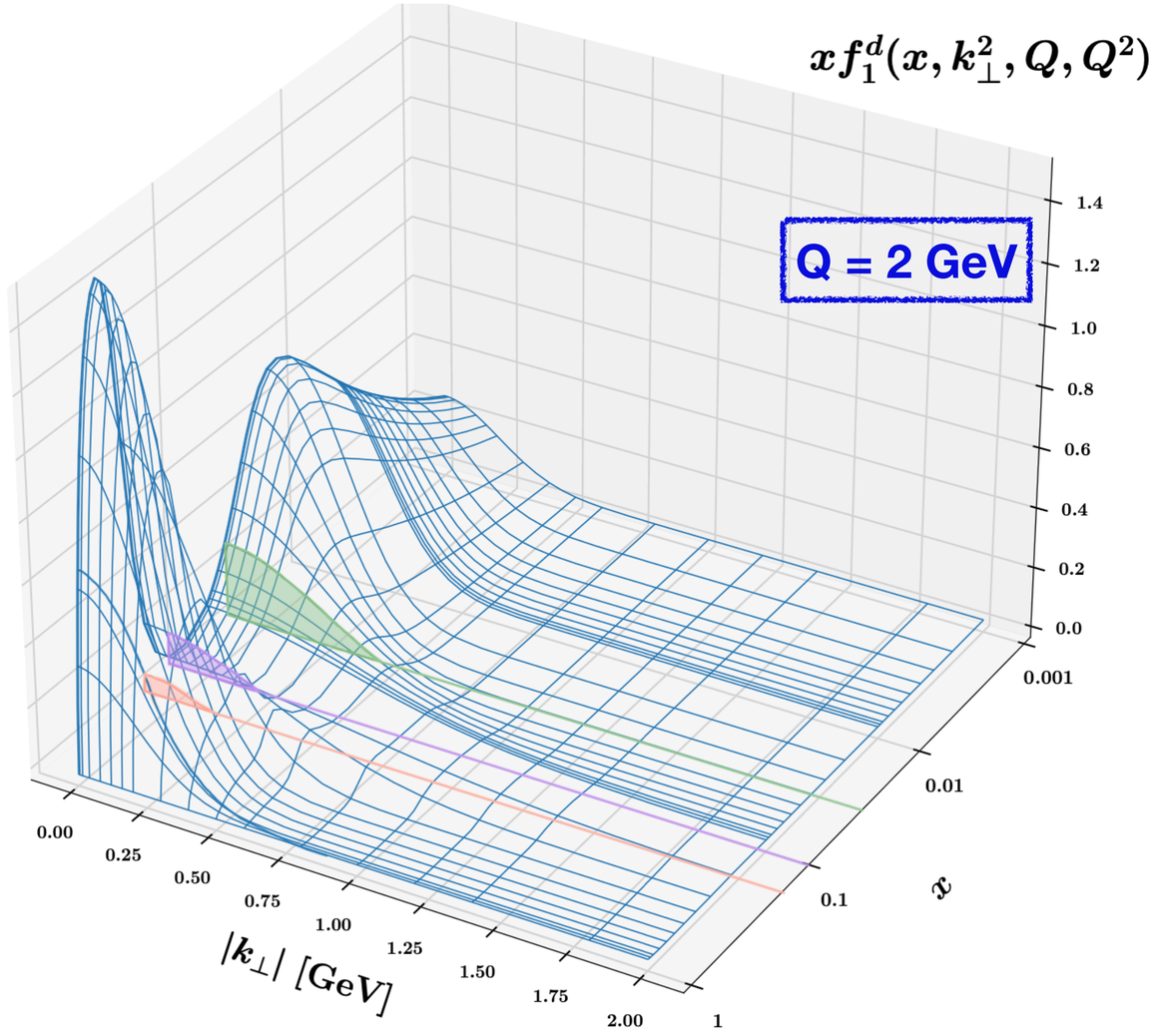
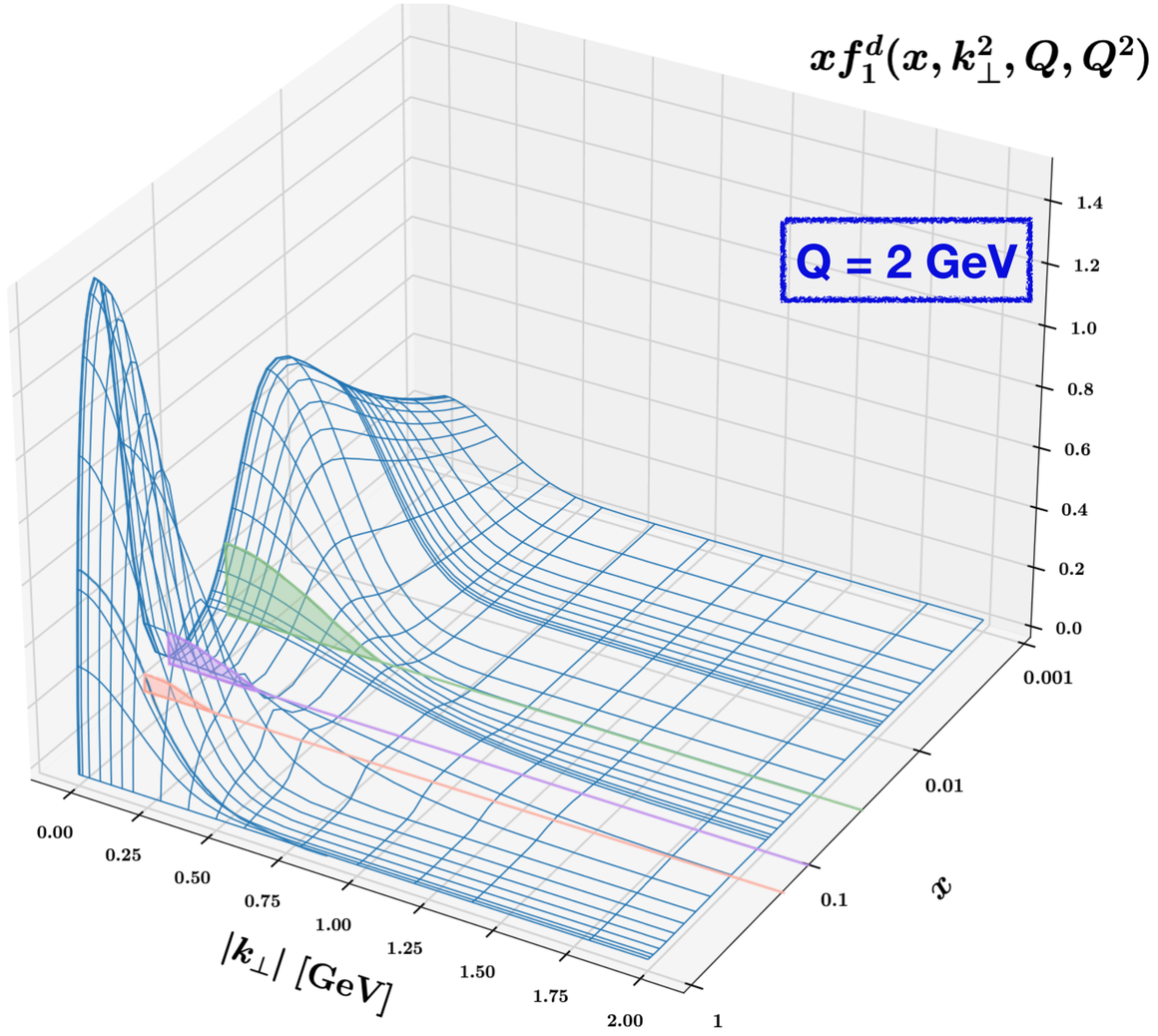
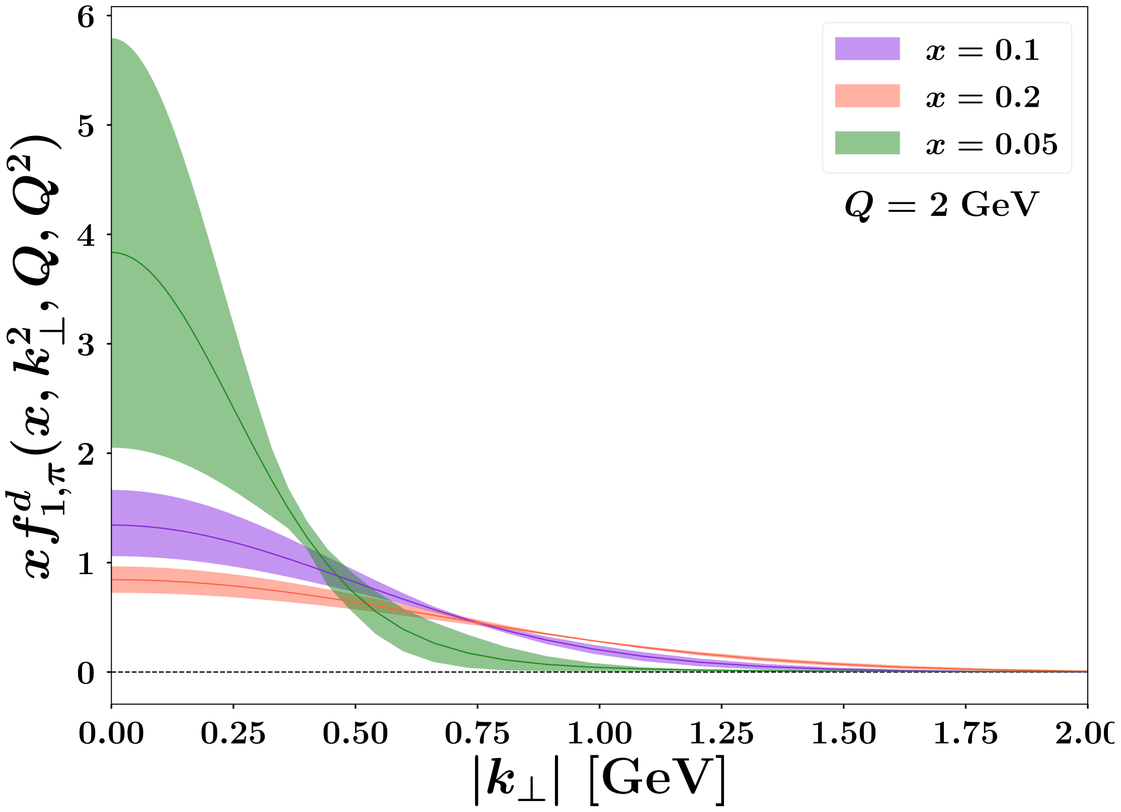


Visualization of pion TMD PDFs





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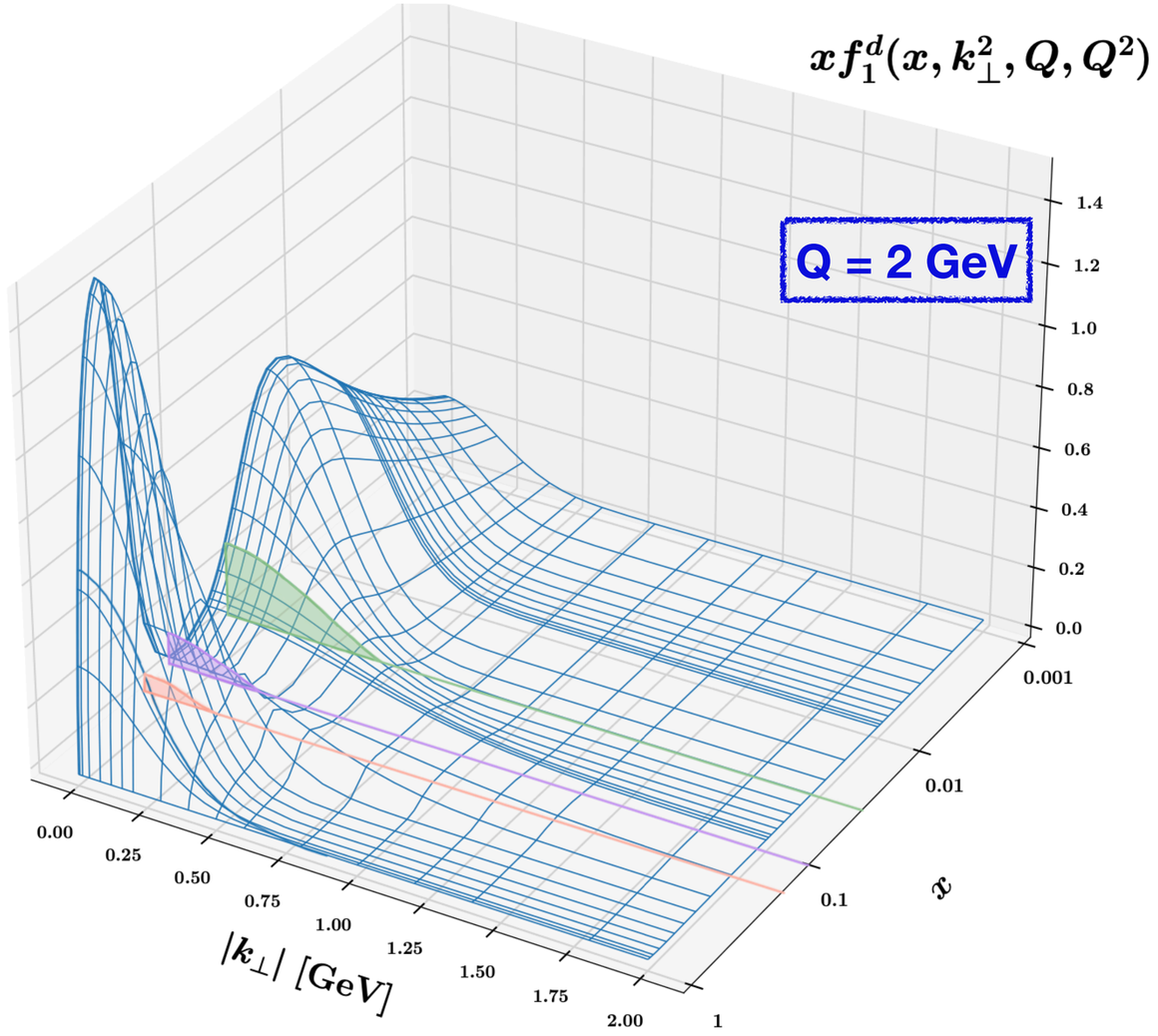

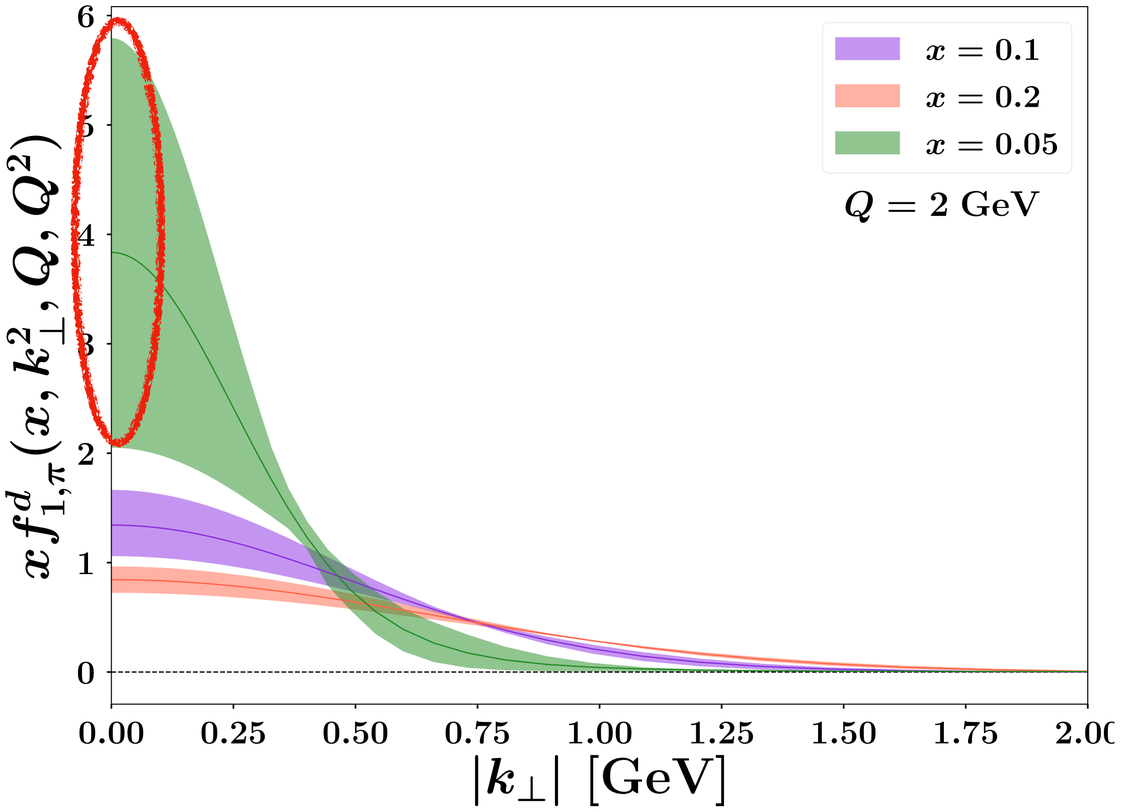

Data not very sensitive

Comparison of pion TMD PDFs

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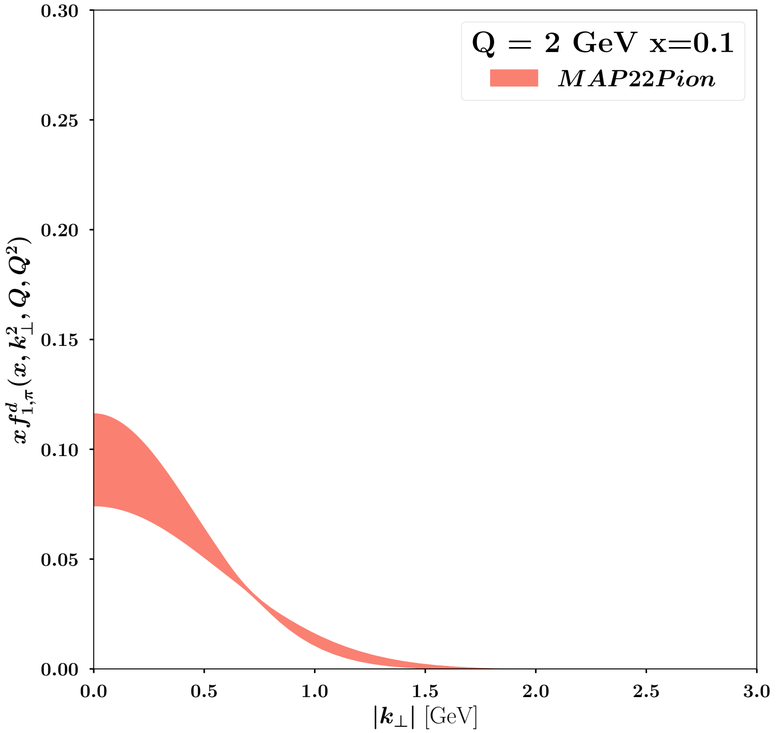

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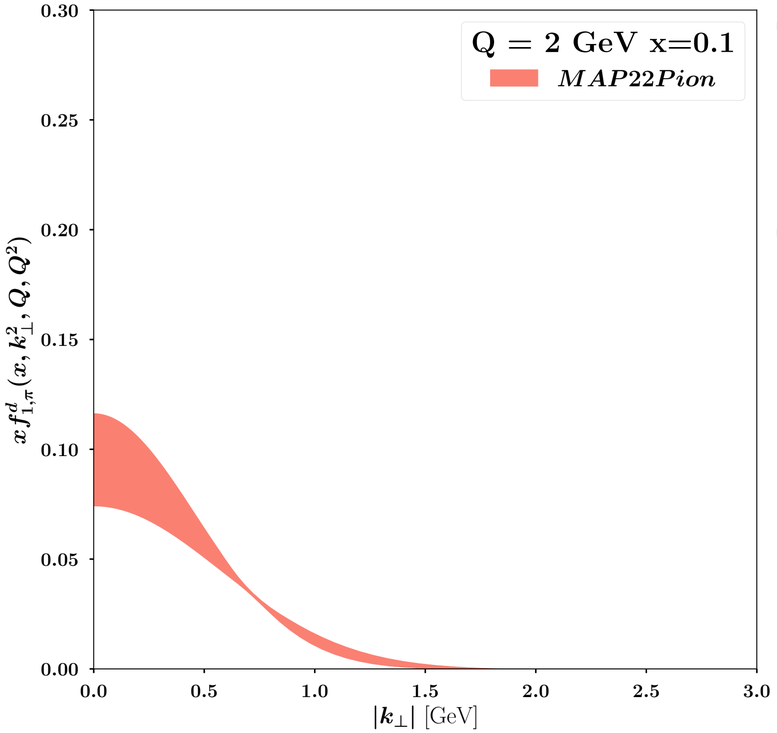

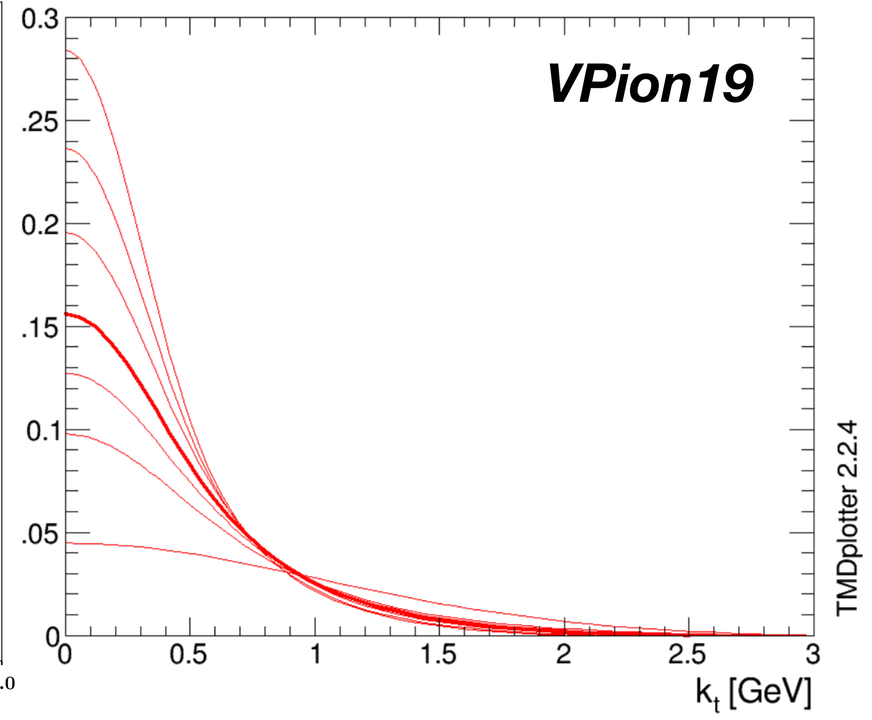

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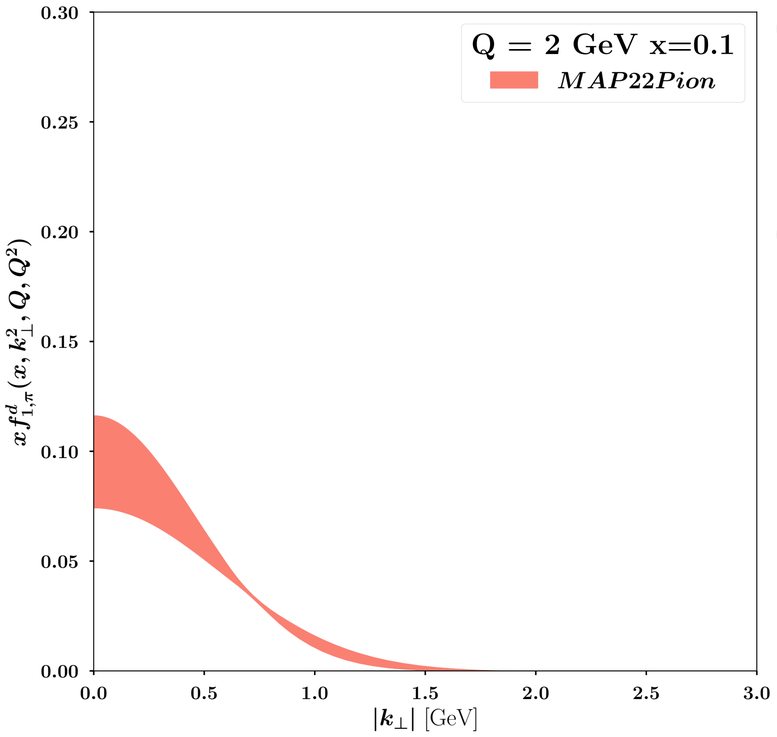

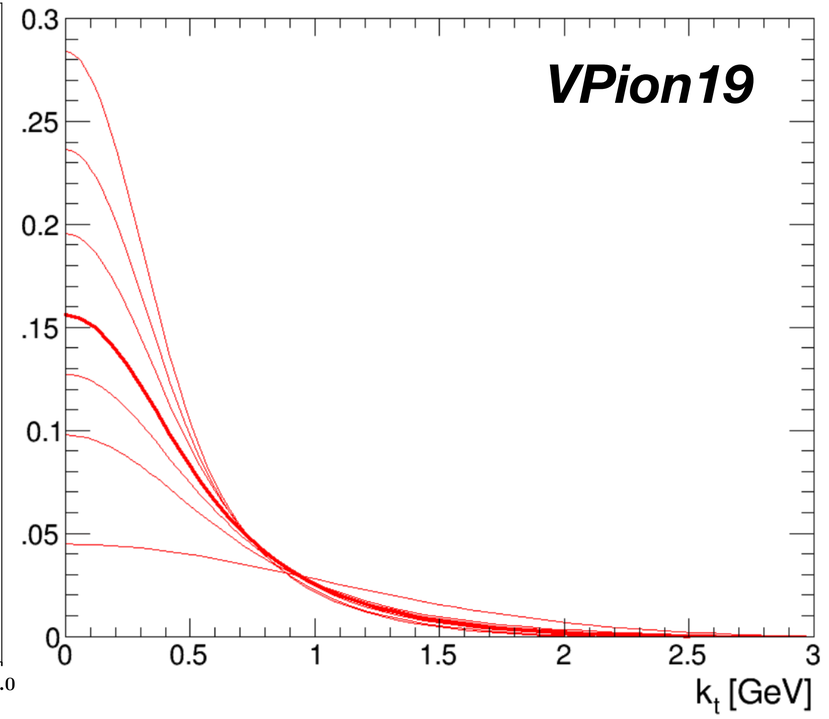

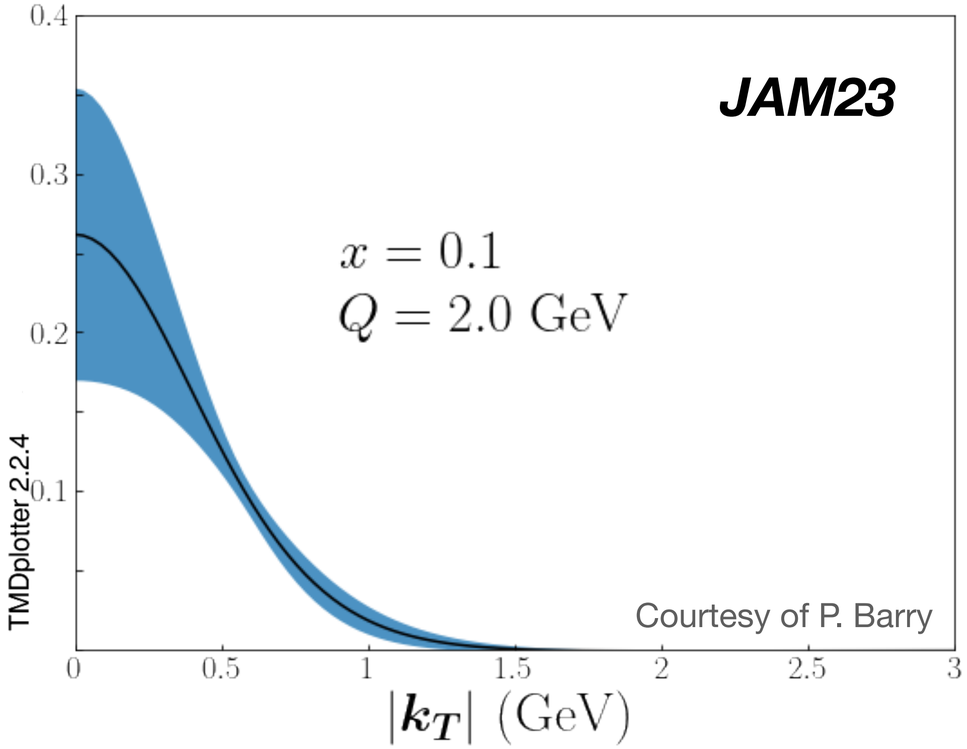

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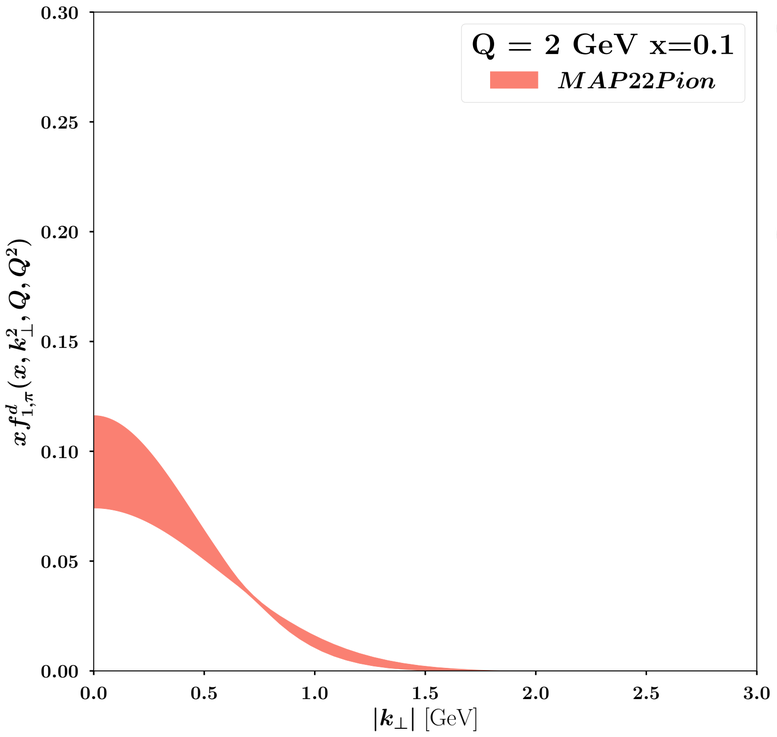

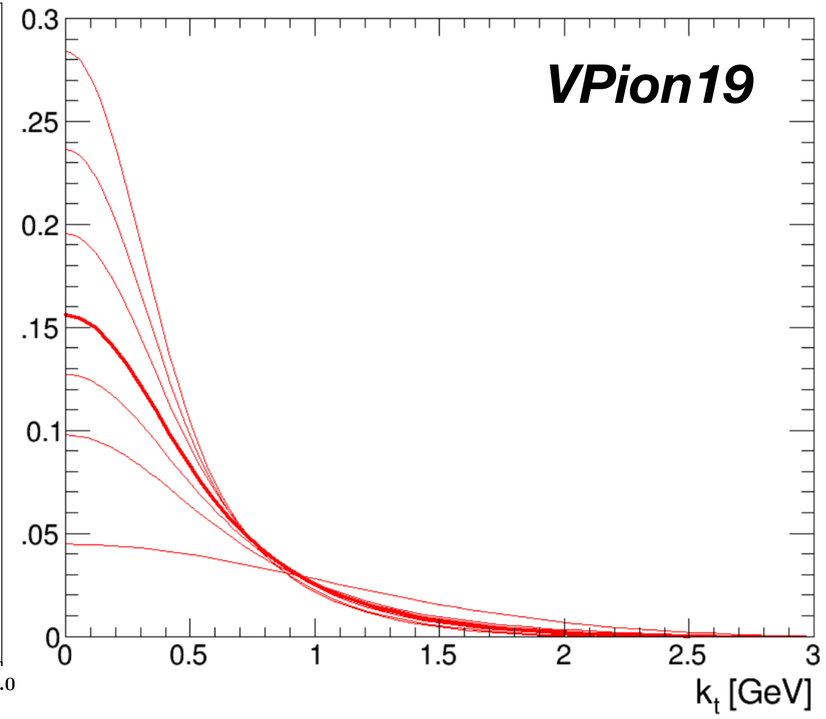

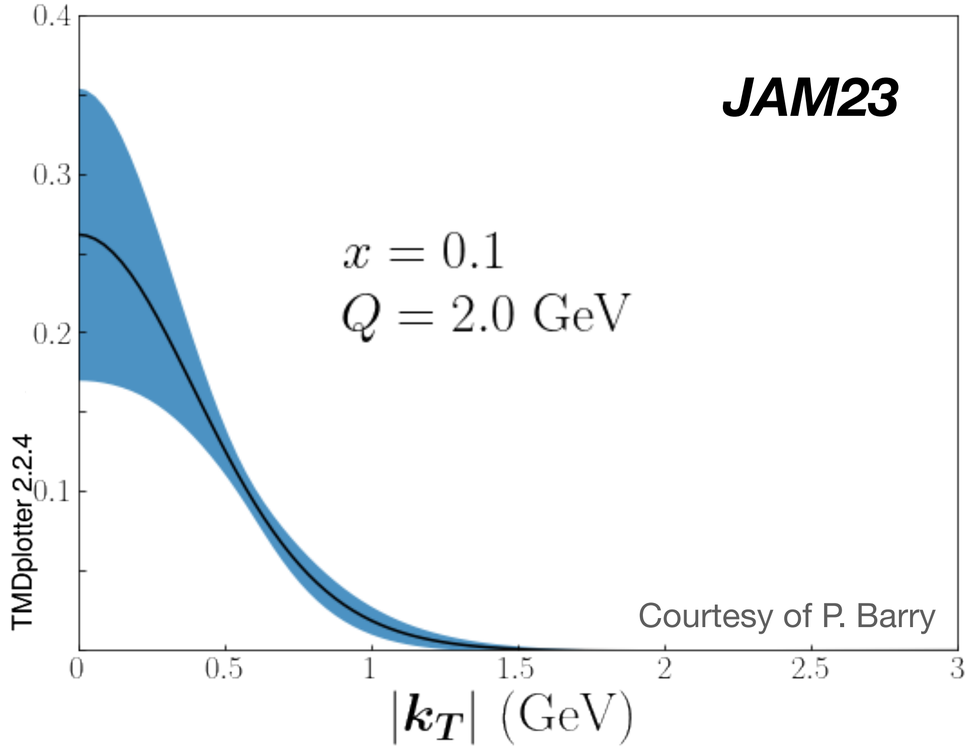

Compatible

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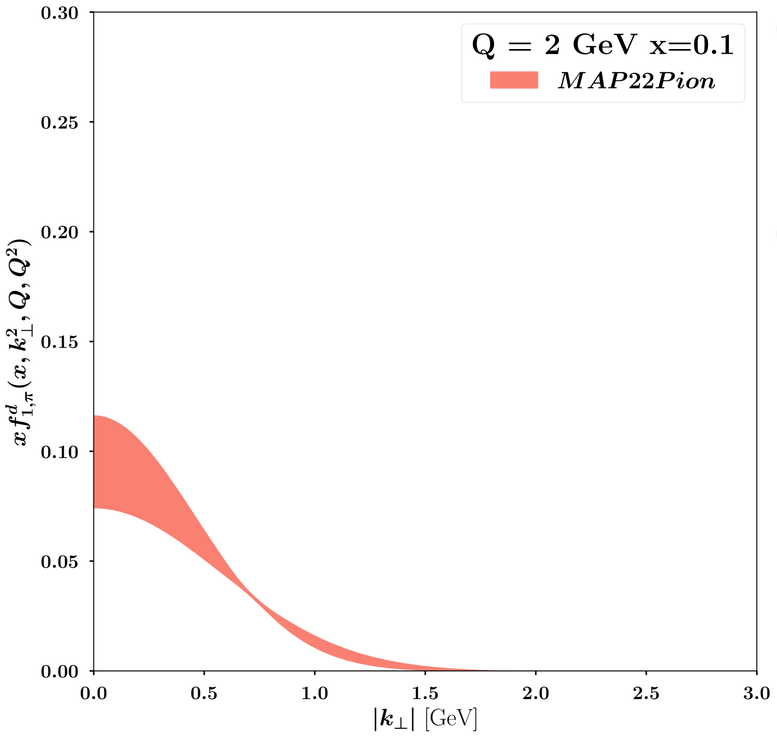

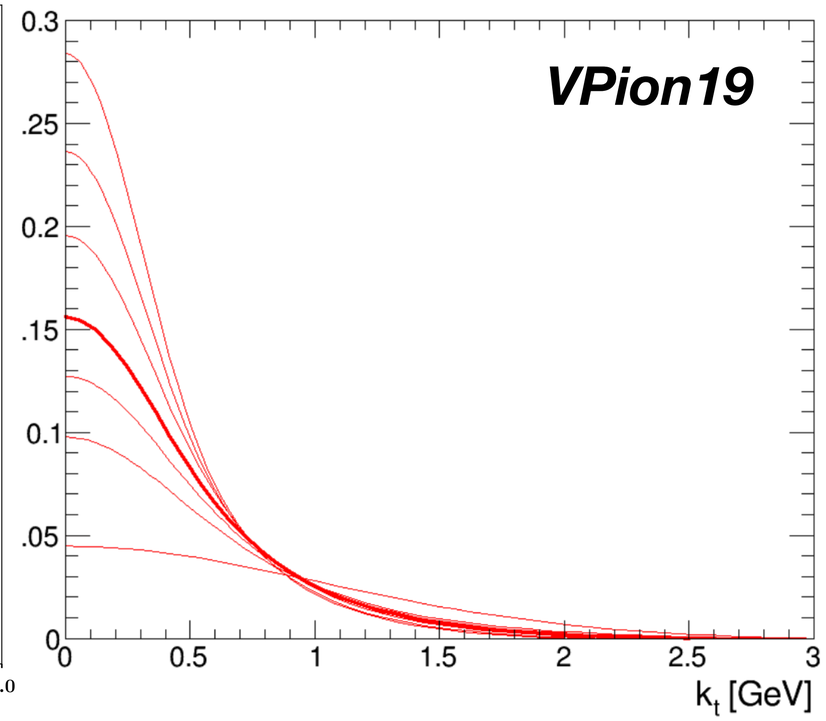

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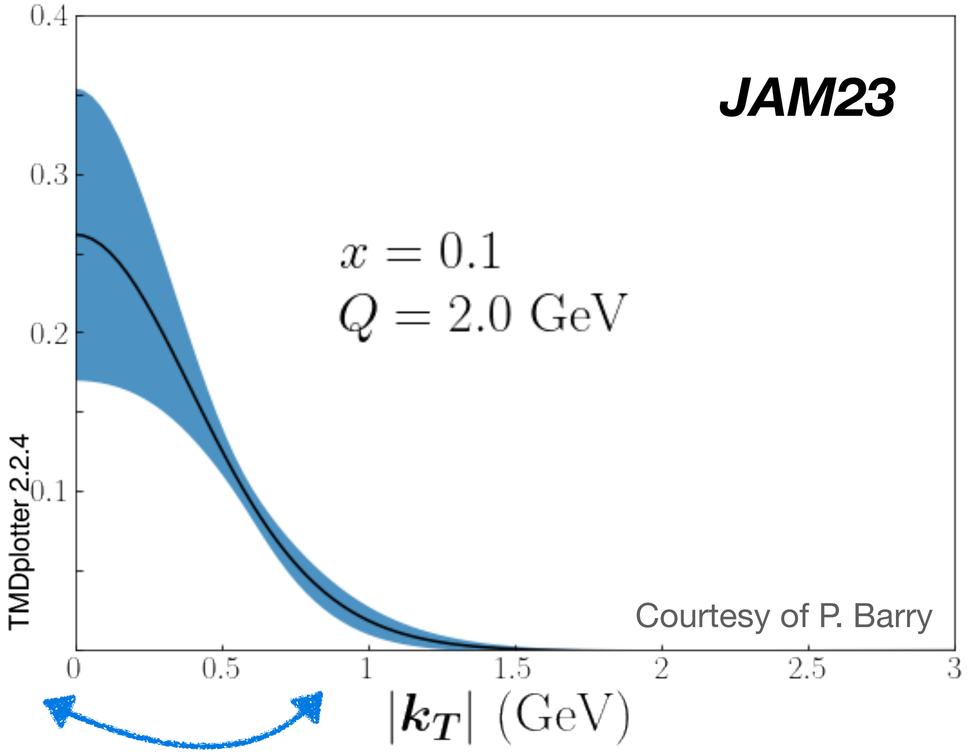

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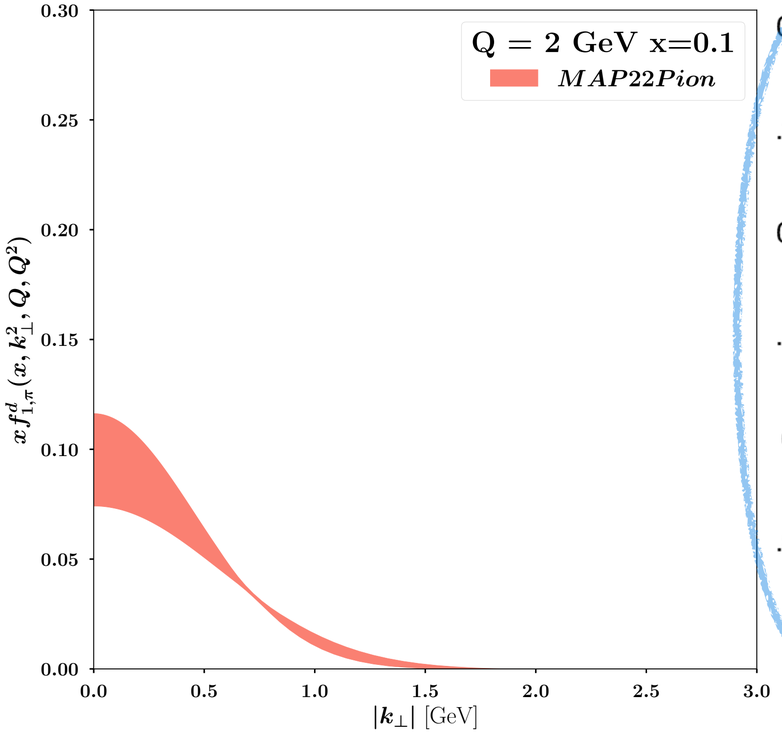

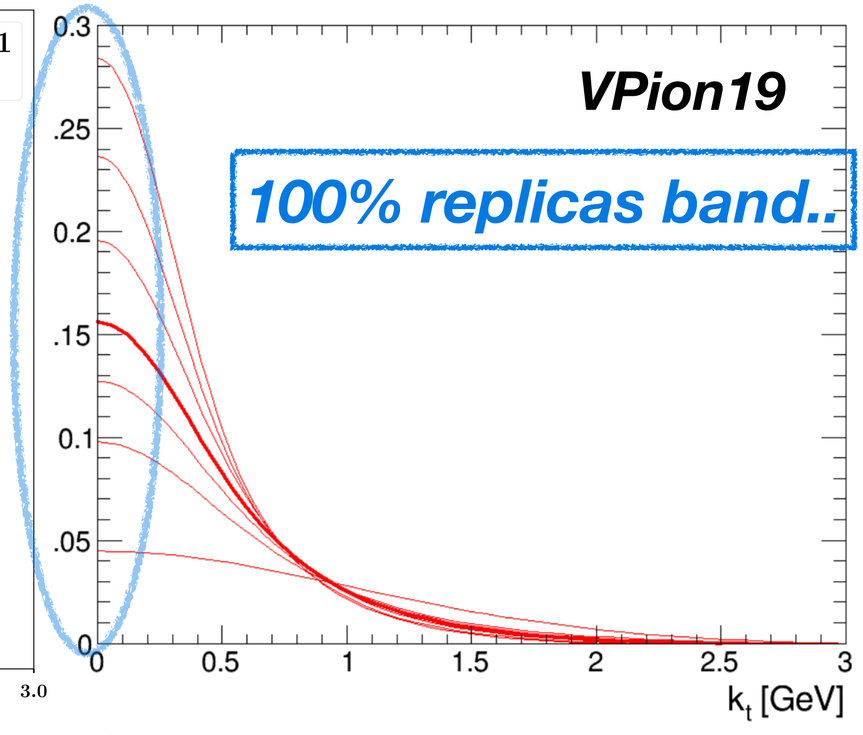

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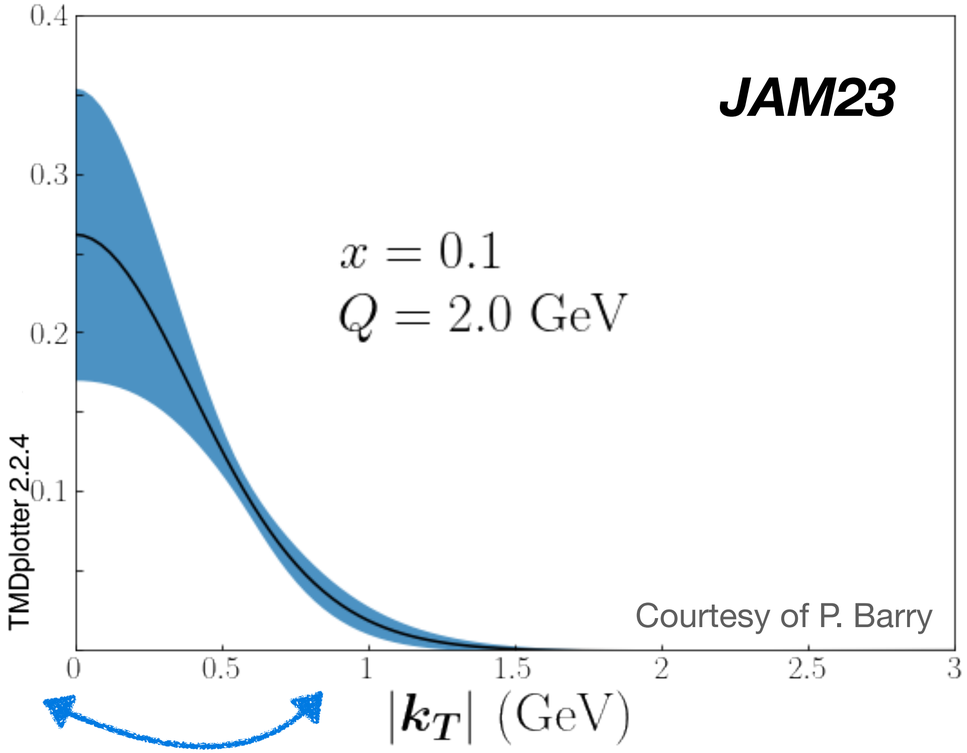

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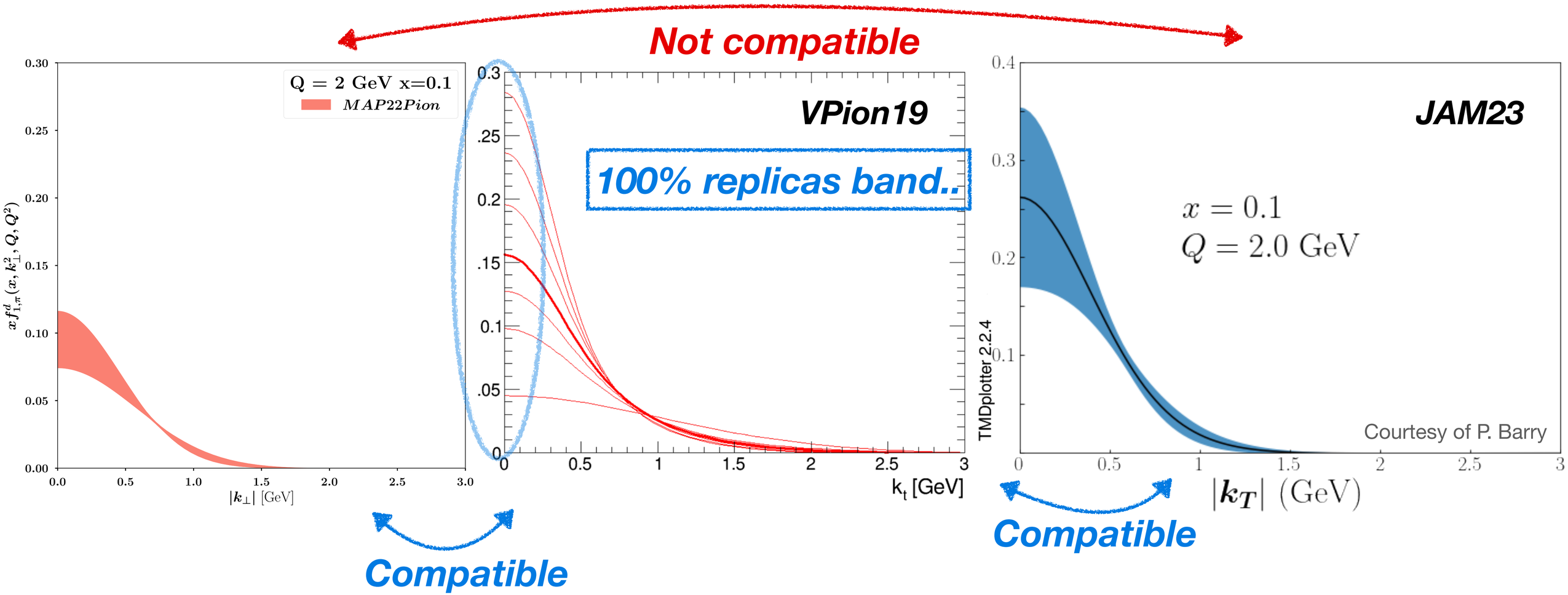

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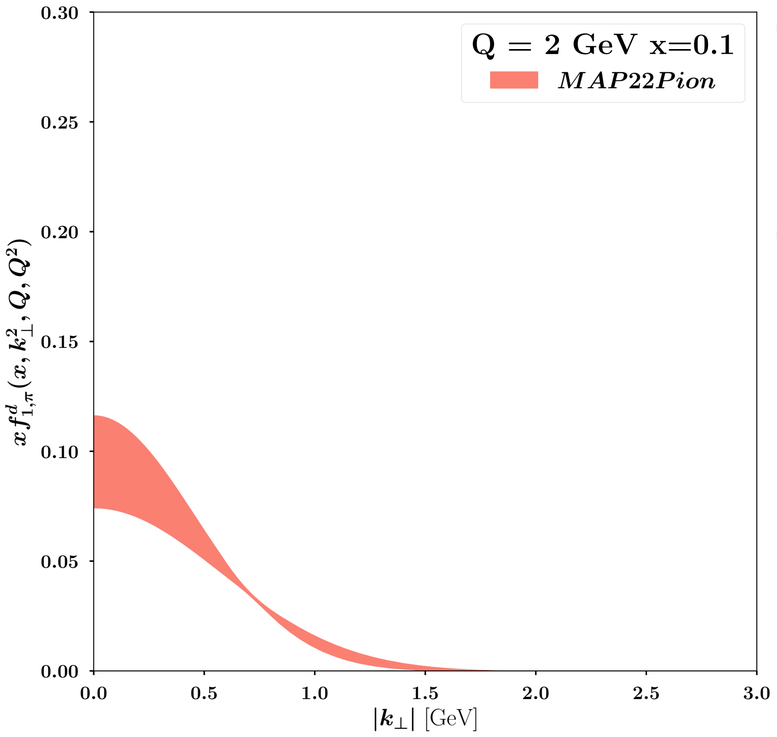

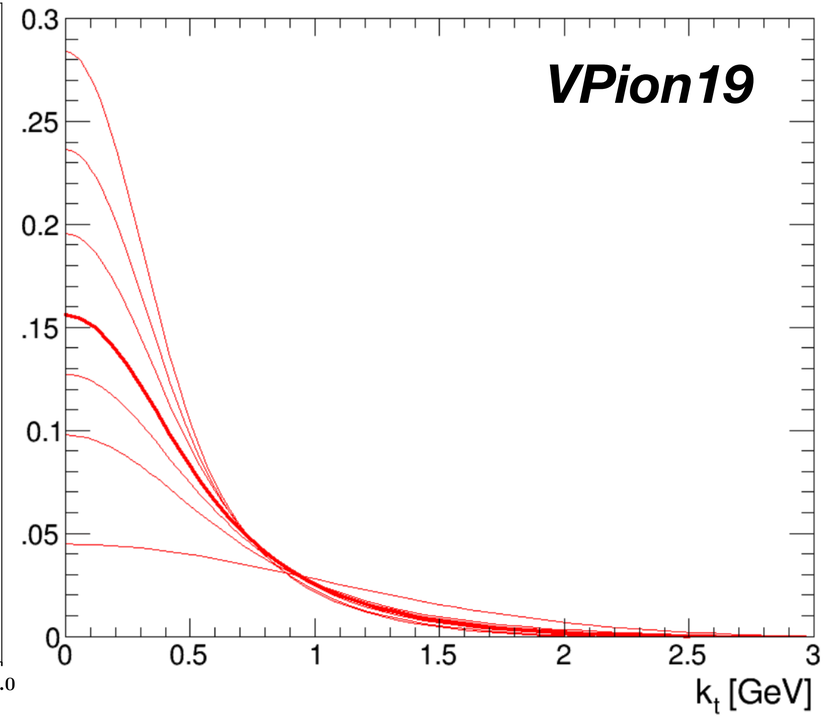

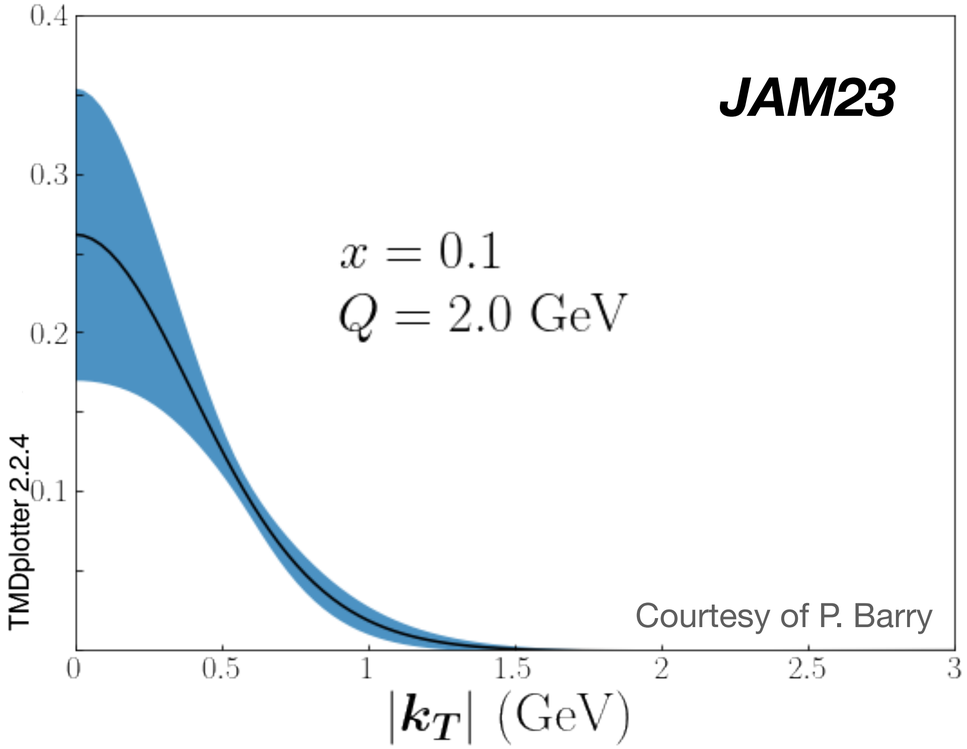

Starting point for Pion TMDs

Conclusions and outlooks

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- Flavour Dependence
- Refinement of Pion TMDs

Backup slides

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

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

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

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

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

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

Backup slides

Proton → ***MAPTMD22***

Pion → ***xFitter20***

$$f_{1\pi}^{NP}(x,\zeta,\mathbf{b}_T) = e^{-g_{1\pi}(x)\frac{\mathbf{b}_T^2}{4}}$$

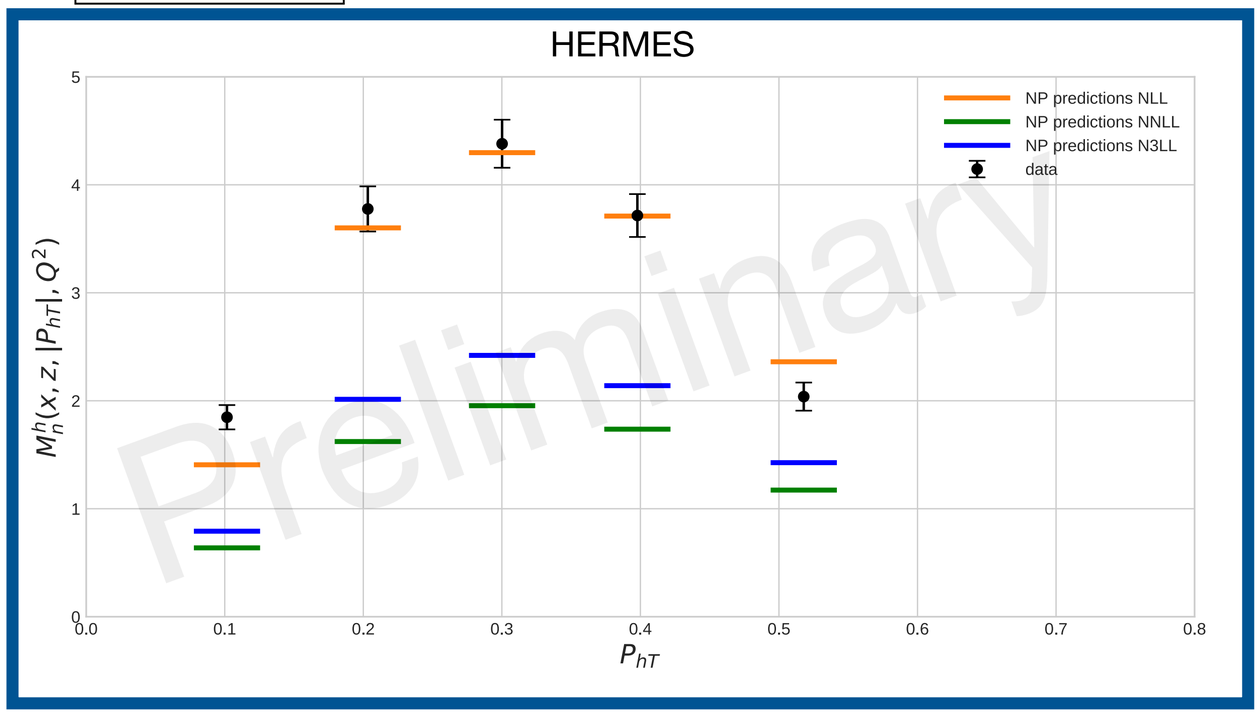
$$g_{1\pi}(x) = N_{1\pi}\frac{x^{\sigma_\pi}(1-x)^{\alpha_\pi^2}}{\hat{x}^{\sigma_\pi}(1-\hat{x})^{\alpha_\pi^2}}$$

3 fitting parameters

Backup slides

SIDIS multiplicities beyond NLL

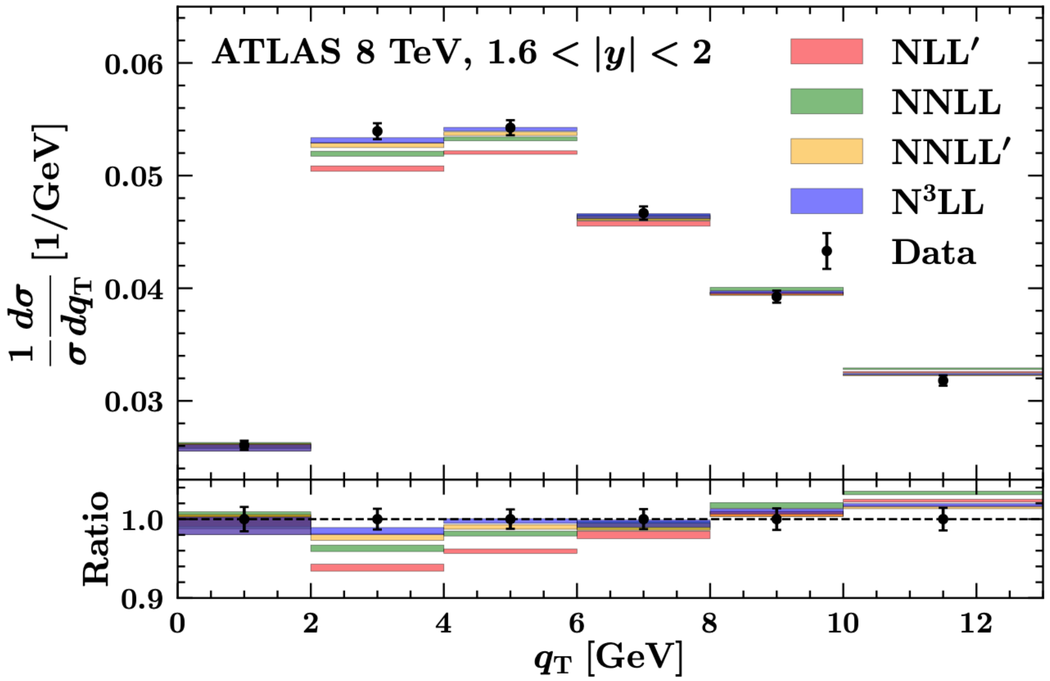
$Q \sim 2$ GeV



The description considerably worsens at higher orders!!

High-Energy Drell-Yan beyond NLL

$Q \sim 100$ GeV



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