INFN
Istituto Nazionale di Fisica Nucleare

HAS QCD
HADRONIC STRUCTURE AND
QUANTUM CHROMODYNAMICS

UNIVERSITÀ
DI PAVIA

MAPTMD22:

A new extraction of unpolarized TMDs through global fits

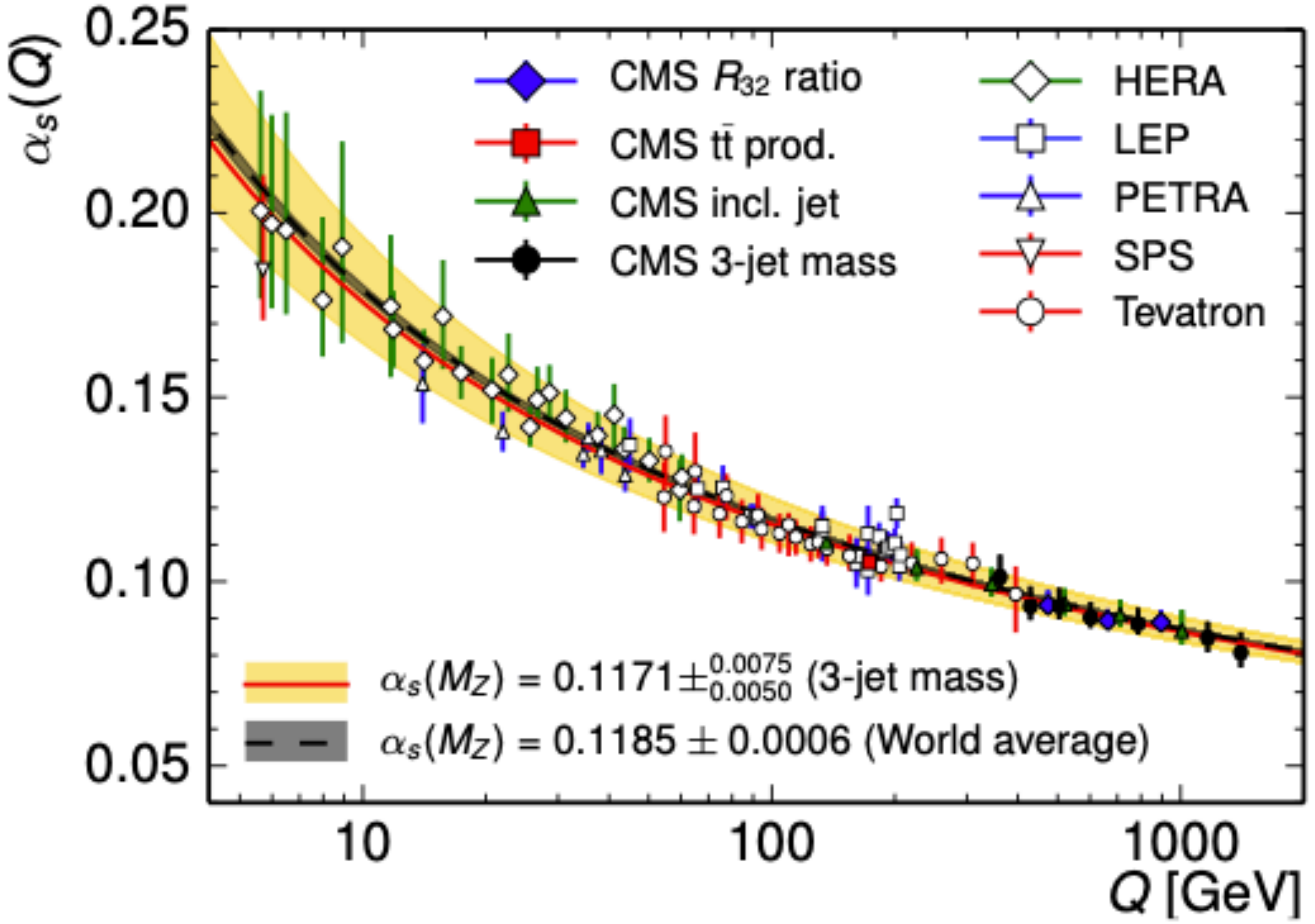
MAP Collaboration
Matteo Cerutti

EIC Users Group
Early Career Workshop

July 24th

Running coupling - QCD

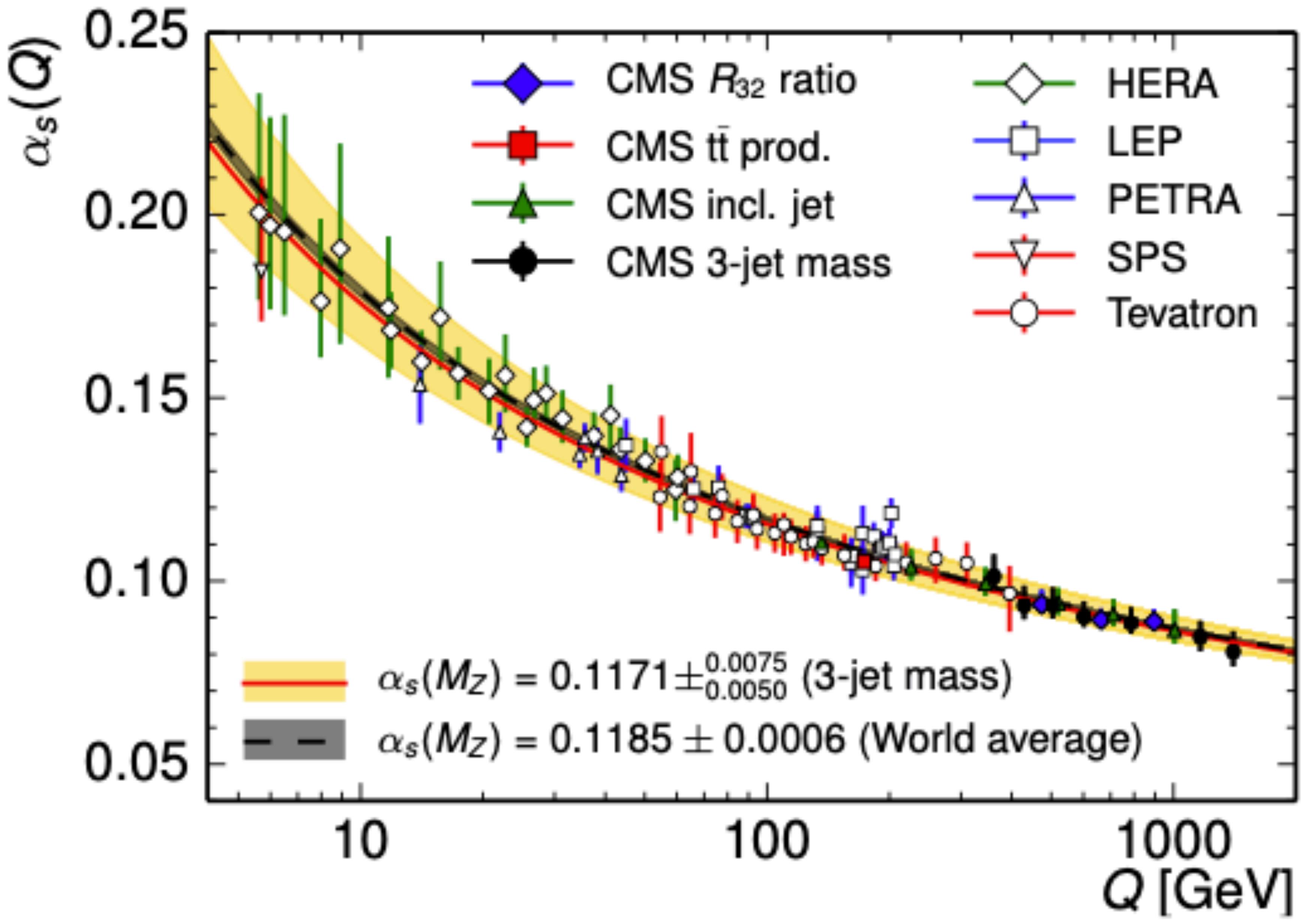
It depends on the energy
scale of the process



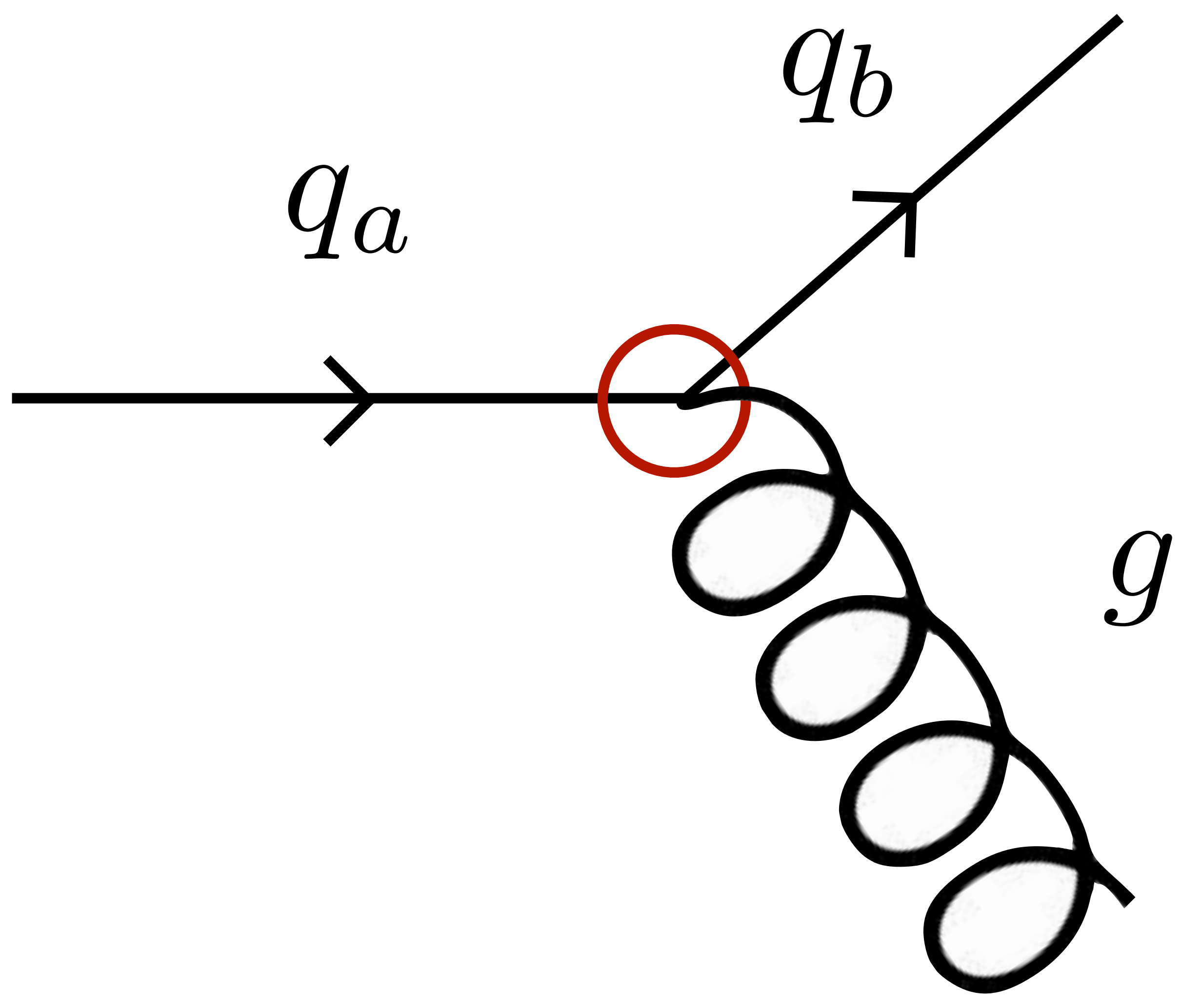
CMS Collaboration, Eur.Phys.J. C 75 (2015)

Running coupling - QCD

It depends on the energy
scale of the process



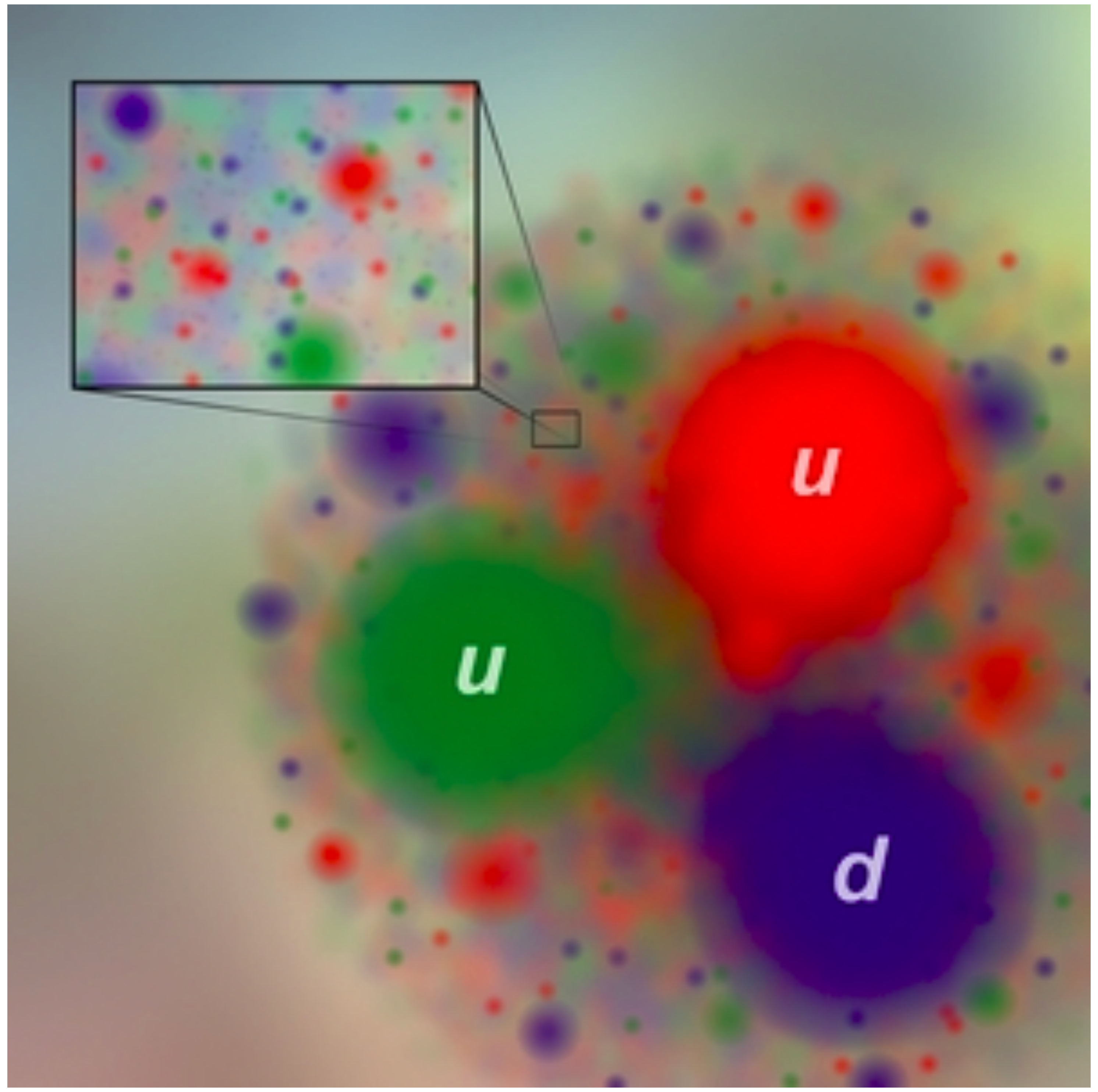
CMS Collaboration, Eur.Phys.J. C 75 (2015)



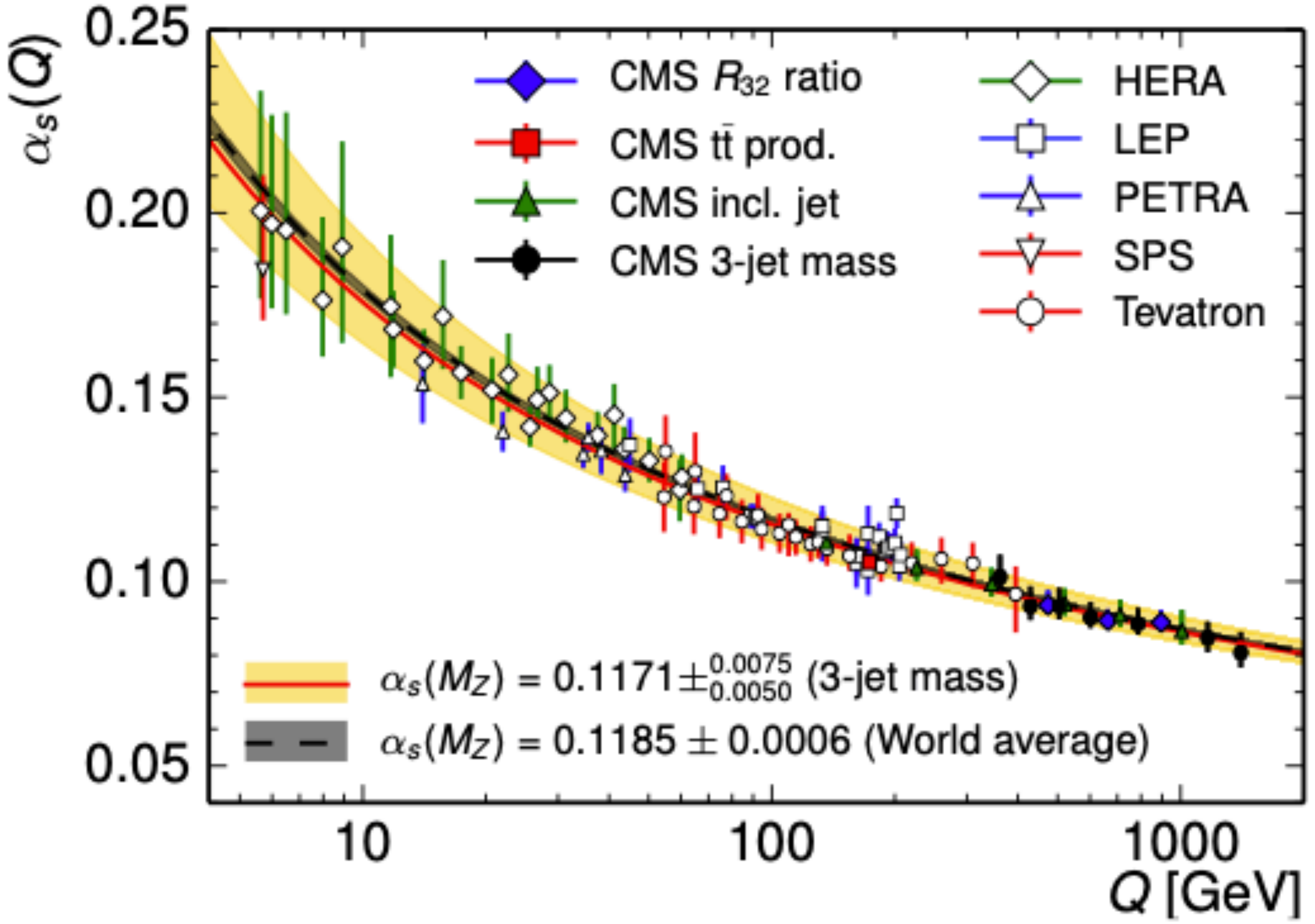
Perturbative Physics

$$d\sigma(Q) \sim d\sigma^{(0)} + \alpha_S^1(Q) d\sigma^{(1)} + \ldots$$

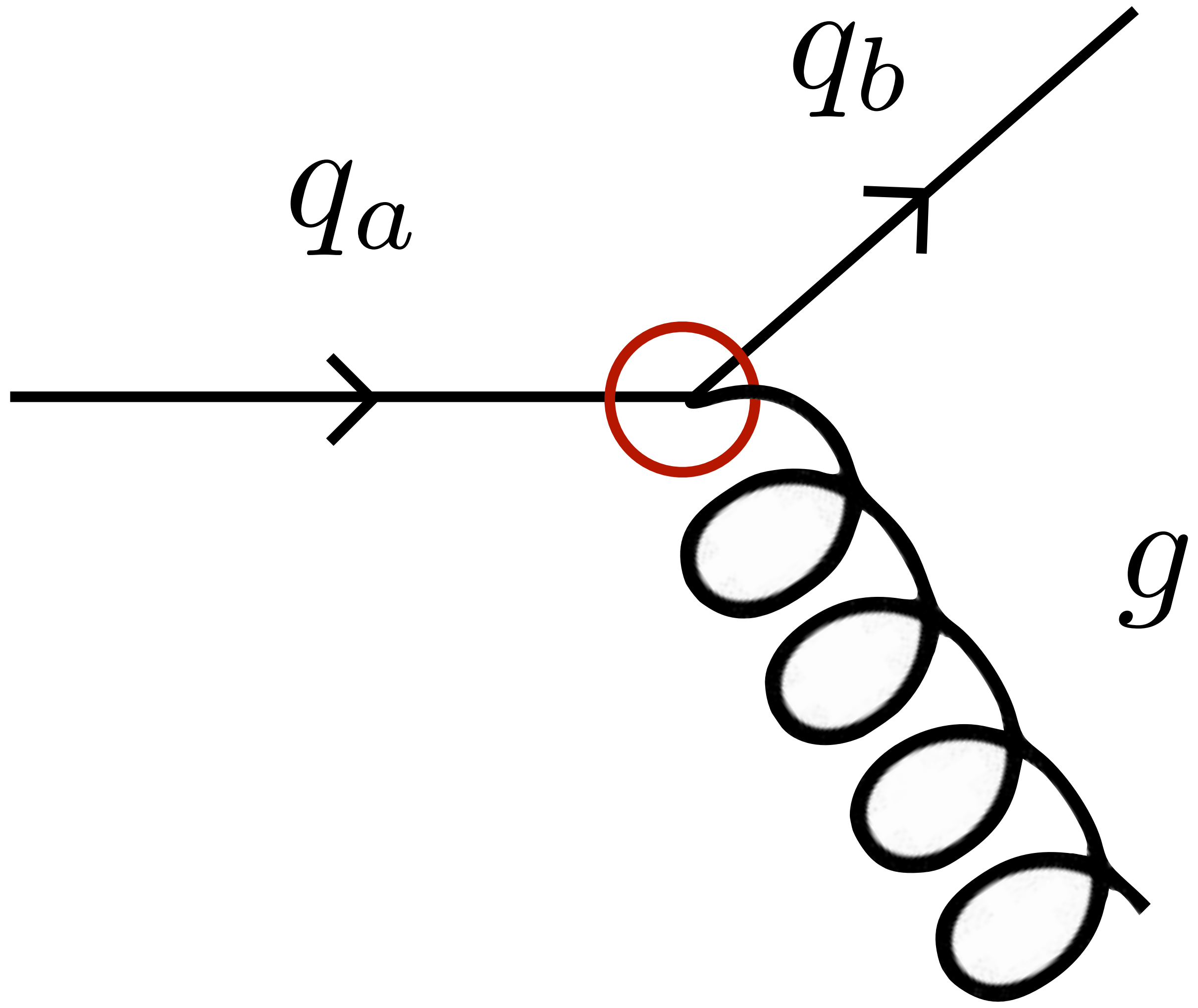
Running coupling - QCD



It depends on the energy scale of the process



CMS Collaboration, Eur.Phys.J. C 75 (2015)



Non-Perturbative Physics

Color confinement

Perturbative Physics

$$d\sigma(Q) \sim d\sigma^{(0)} + \alpha_S^1(Q) d\sigma^{(1)} + \dots$$

Understanding the color confinement

Understanding the color confinement

Map of the internal structure of hadrons

Understanding the color confinement

Map of the internal structure of hadrons

Parton Distribution Functions (PDFs)

Understanding the color confinement

Map of the internal structure of hadrons

Hadronization process

Parton Distribution Functions (PDFs)

Understanding the color confinement

Map of the internal structure of hadrons

Parton Distribution Functions (PDFs)

Hadronization process

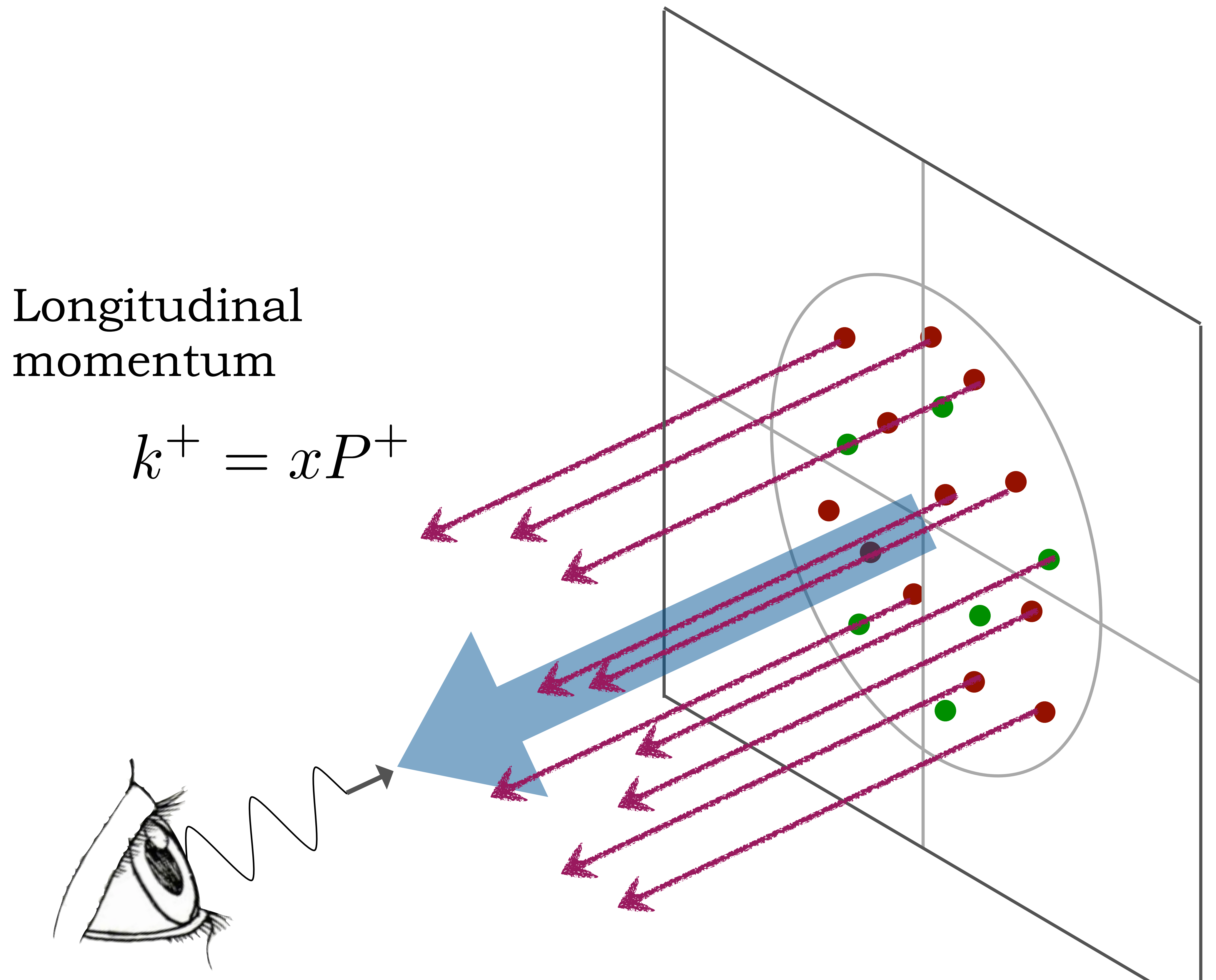
Fragmentation Functions (FFs)

Parton Distribution Functions (PDFs)

1D maps

Collinear framework

The only nonzero component of the quark momentum is the one in the same direction of the parent hadron



$$k^+ = xP^+$$

x : fraction of longitudinal momentum of the parent hadron carried by the internal quark

Parton Distribution Functions (PDFs)

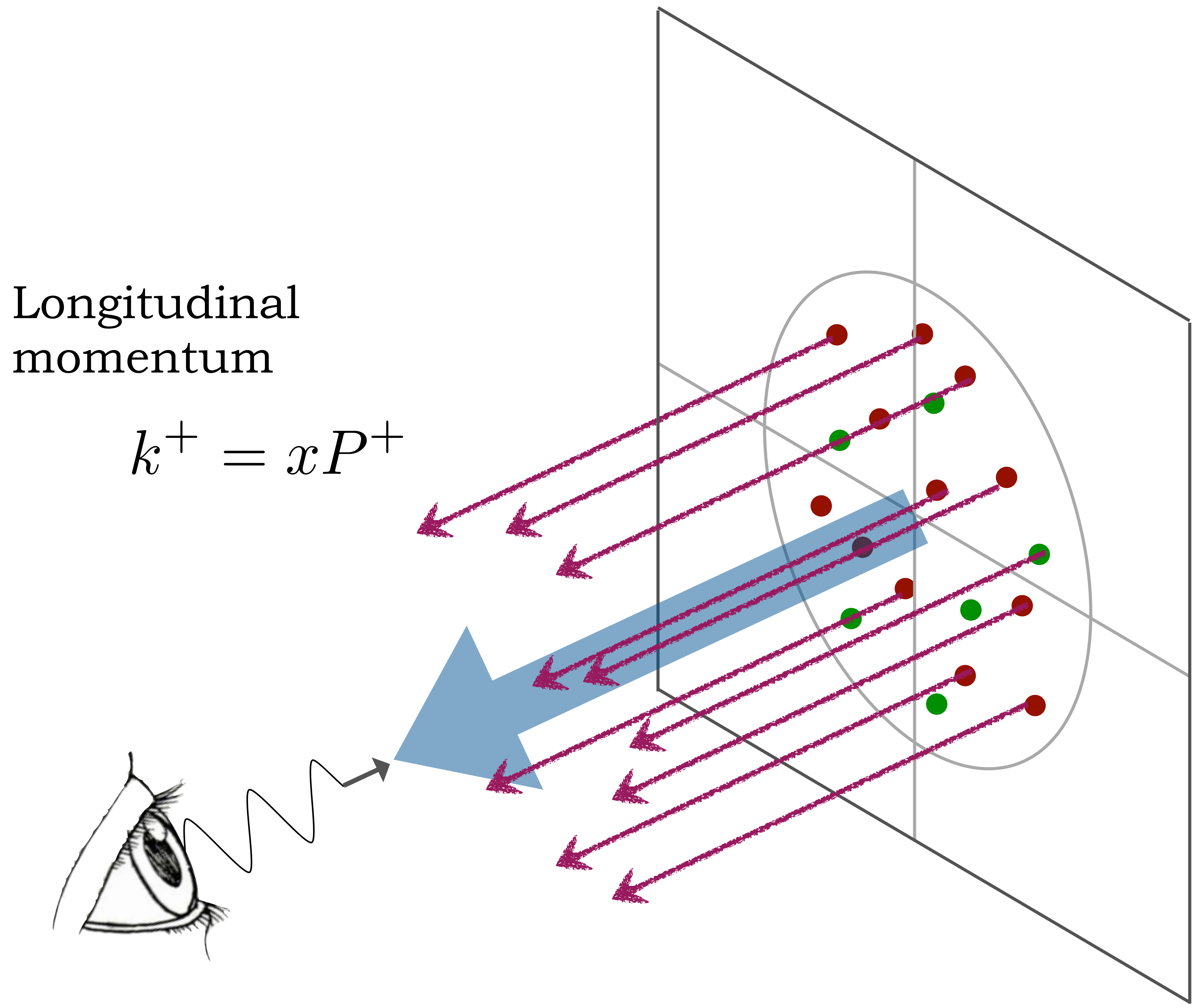
1D maps

Collinear framework

Quark Polarisation

Nucleon Pol.

	U	L	T
U	$f_1(x)$		
L			
T			



$f_1(x)$ probability density of finding an unpolarised quark (gluon) carrying a fraction x of the unpolarised hadron momentum

Mulders-Tangerman, NPB 461 (1996)
Boer-Mulders, PRD 57 (1998)

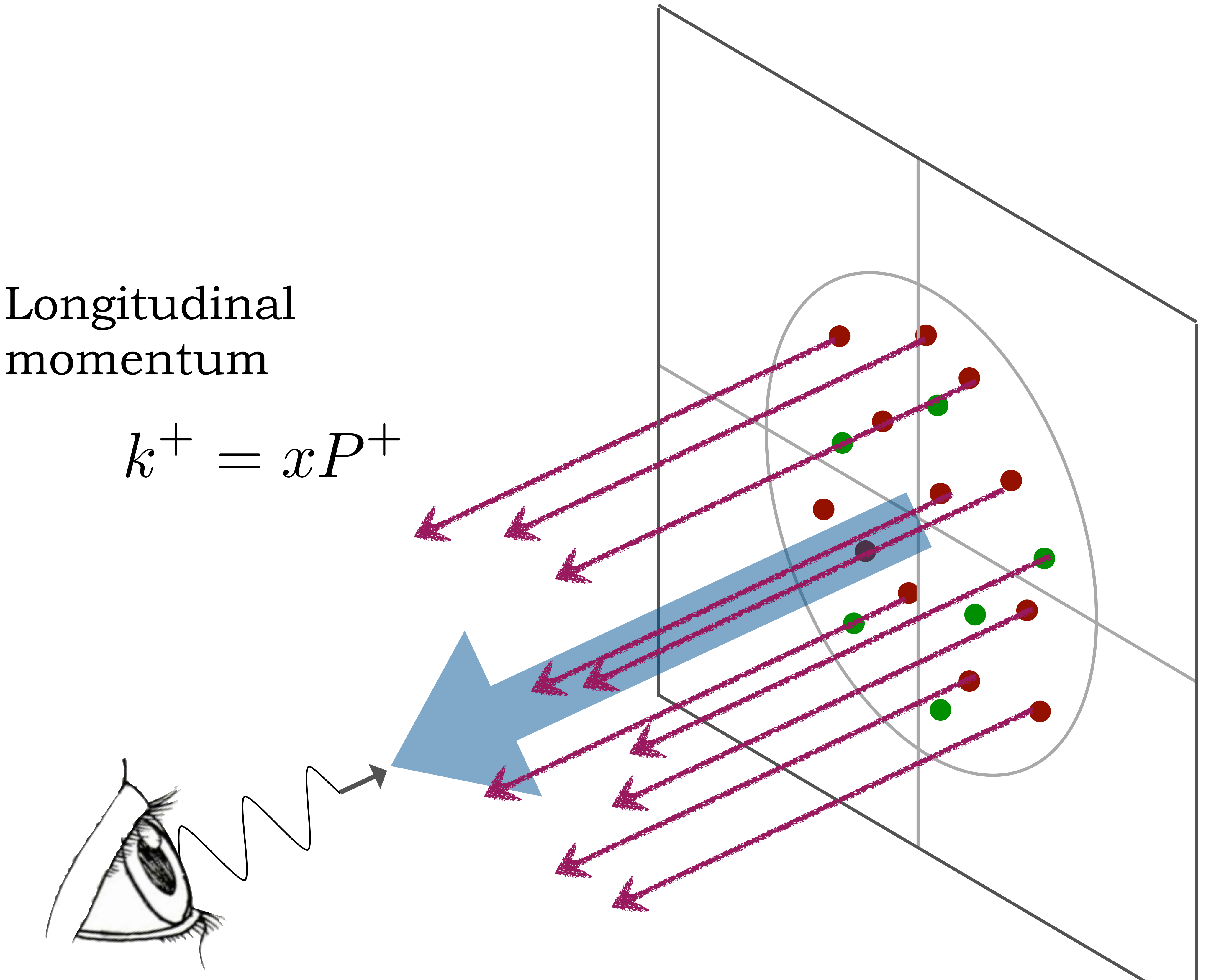
Parton Distribution Functions (PDFs)

1D maps

Collinear framework

Quark Polarisation

Nucleon Pol.	U	L	T
U	$f_1(x)$		
L		$g_1(x)$	
T			$h_1(x)$



Longitudinal momentum

$$k^+ = xP^+$$

$f_1(x)$ probability density of finding an unpolarised quark (gluon) carrying a fraction x of the unpolarised hadron momentum

Mulders-Tangerman, NPB 461 (1996)
Boer-Mulders, PRD 57 (1998)

Unexplained observations

1D maps

We cannot explain, for e.g. :

Unexplained observations

1D maps

We cannot explain, for e.g. :

- Single Spin Asymmetries (SSA)
  J. Adams et al., P.R.L. 92 (2004) 171801
- Violation of the Lam-Tung sum rule
  J. S. Conway et al., P.R. D39 (1989)
- Results of EMC experiment (“spin crisis”)
  J. Ashman et al., P.L. B206 (1988)

Unexplained observations

1D maps

We <u>cannot</u> explain, for e.g. :

- Single Spin Asymmetries (SSA)
  J. Adams et al., P.R.L. 92 (2004) 171801
- Violation of the Lam-Tung sum rule
  J. S. Conway et al., P.R. D39 (1989)
- Results of EMC experiment ("spin crisis")
  J. Ashman et al., P.L. B206 (1988)

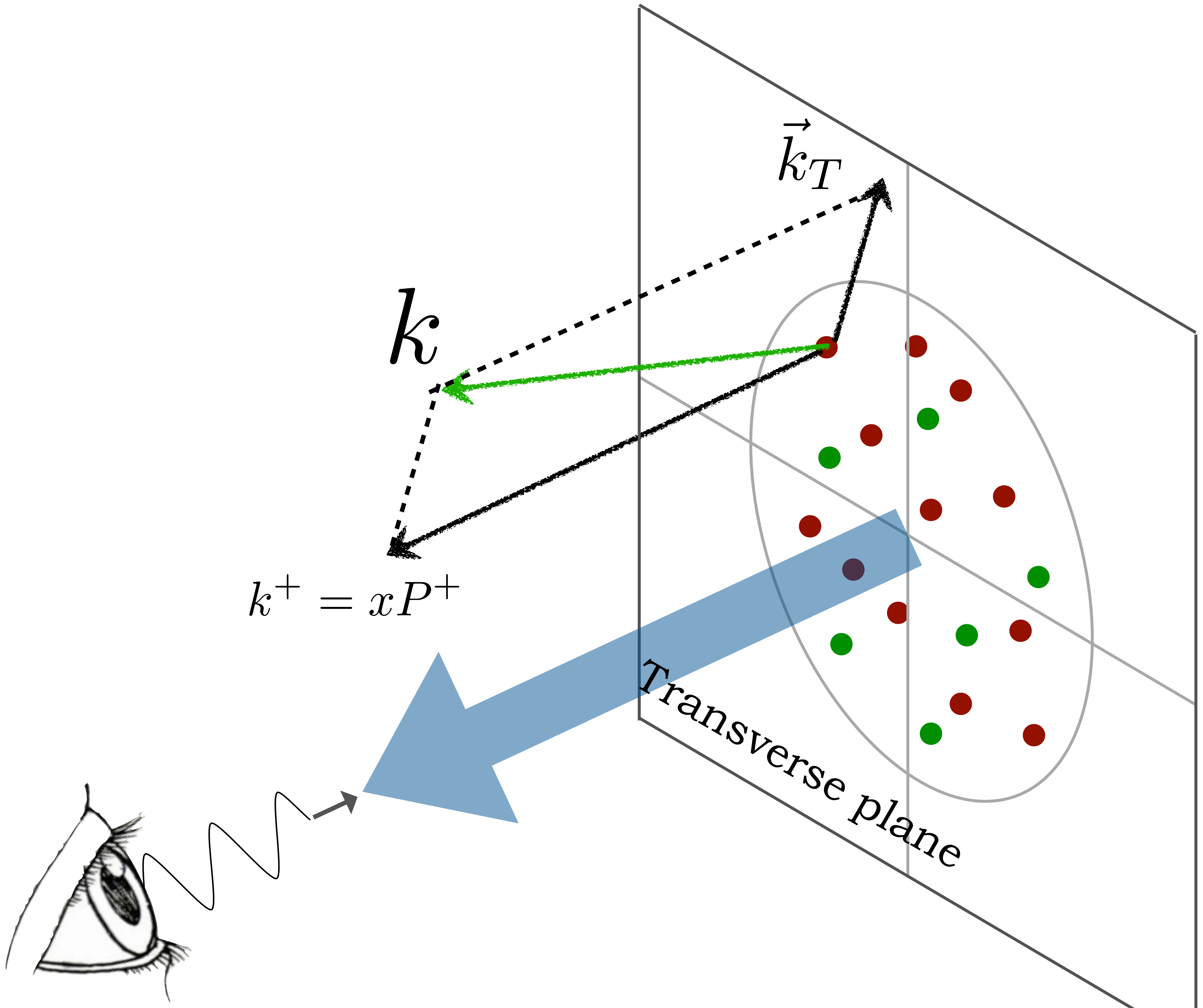
FAILED

Transverse-Momentum-Dependent PDFs (TMDs)

3D maps

Non-collinear framework

The quark momentum is characterised by an intrinsic component transverse to the parent hadron momentum



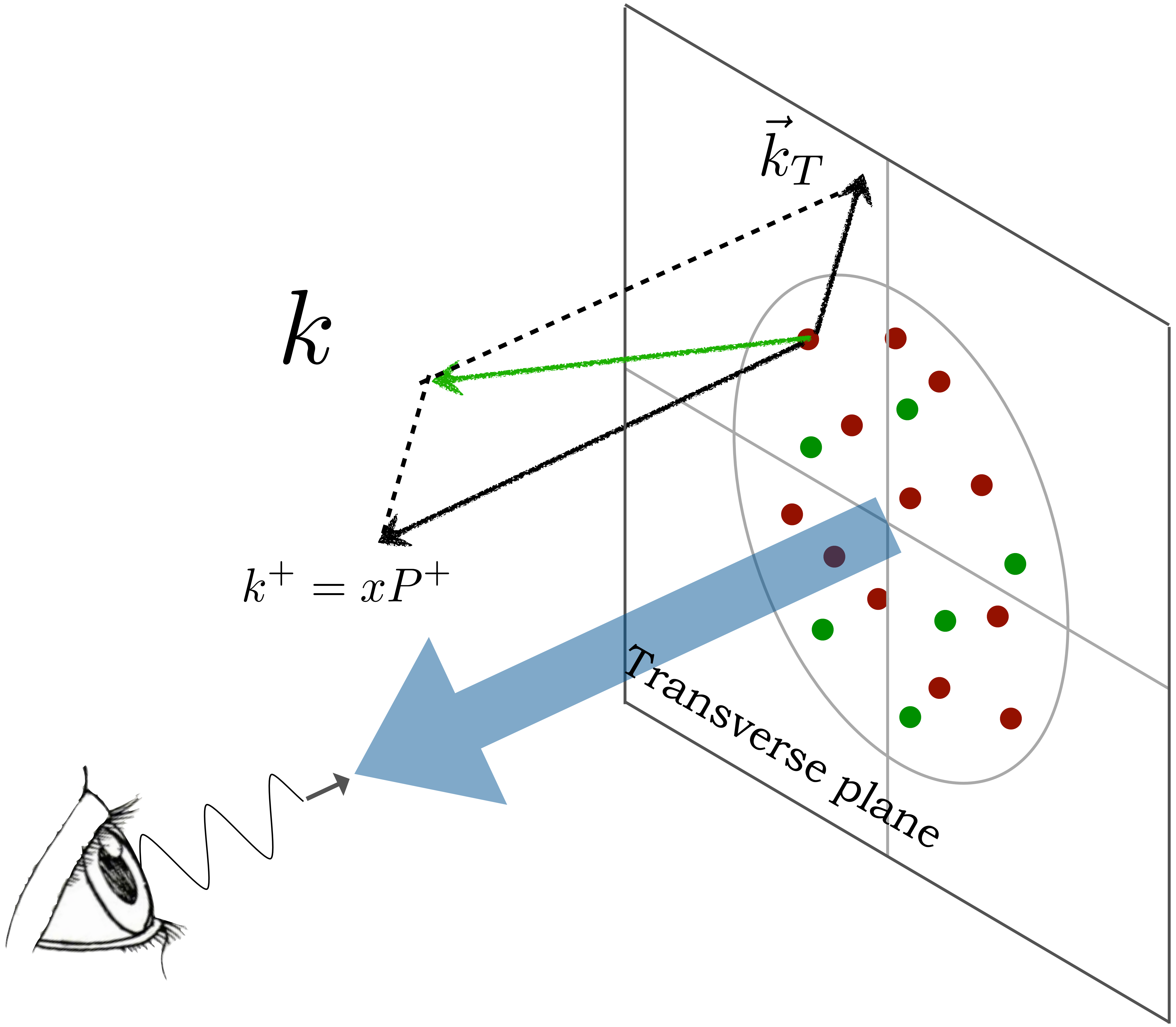
$\vec{k}_T =$ intrinsic (non-perturbative) transverse momentum of the quark

3D Maps

Quark Polarization

Nucleon Pol.

	U	L	T
U			
L			
T			



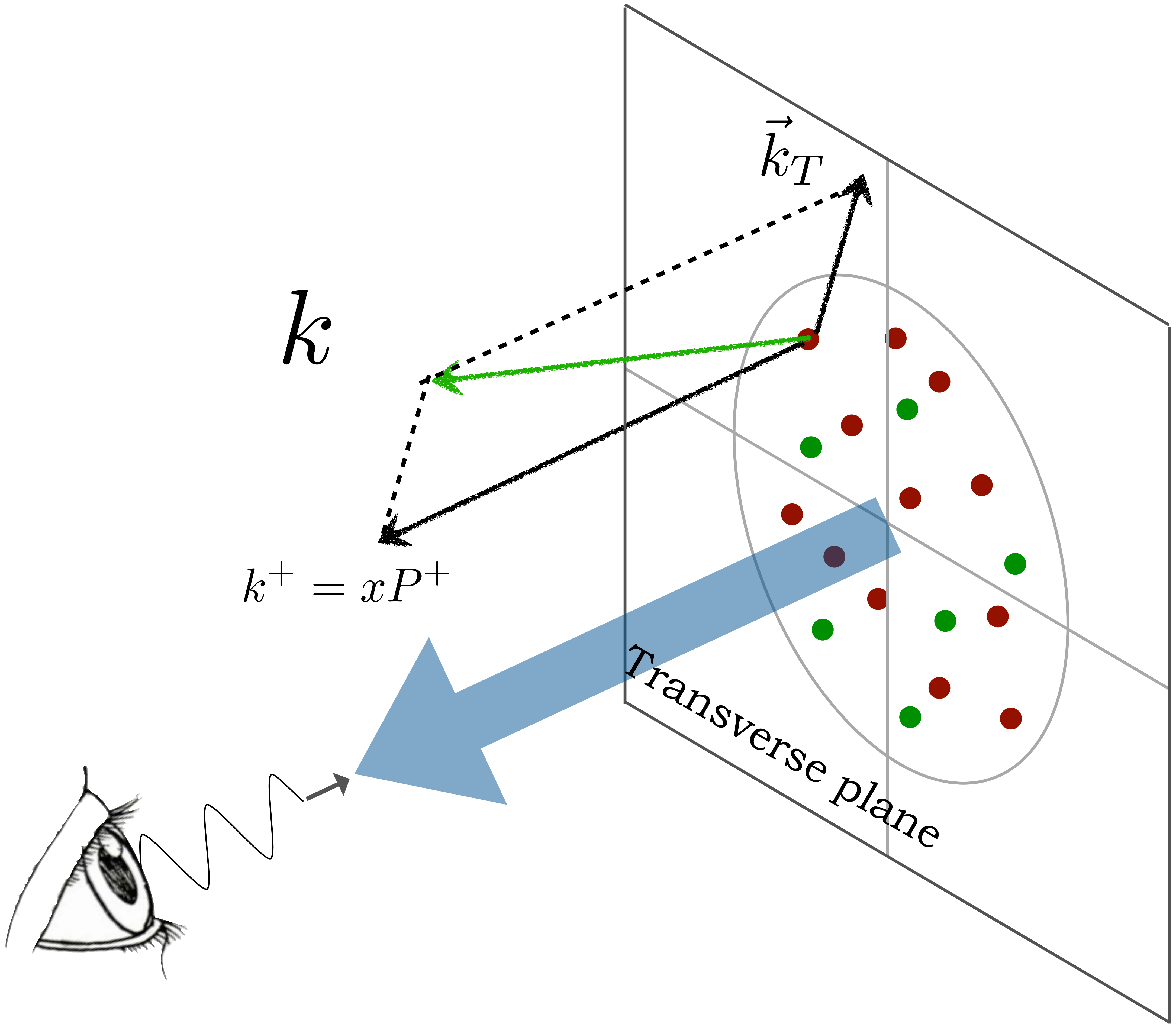
Mulders-Tangerman, NPB 461 (1996)
Boer-Mulders, PRD 57 (1998)

3D Maps

Quark Polarization

Nucleon Pol.

	U	L	T
U	f_1		
L		g_1	
T			h_1



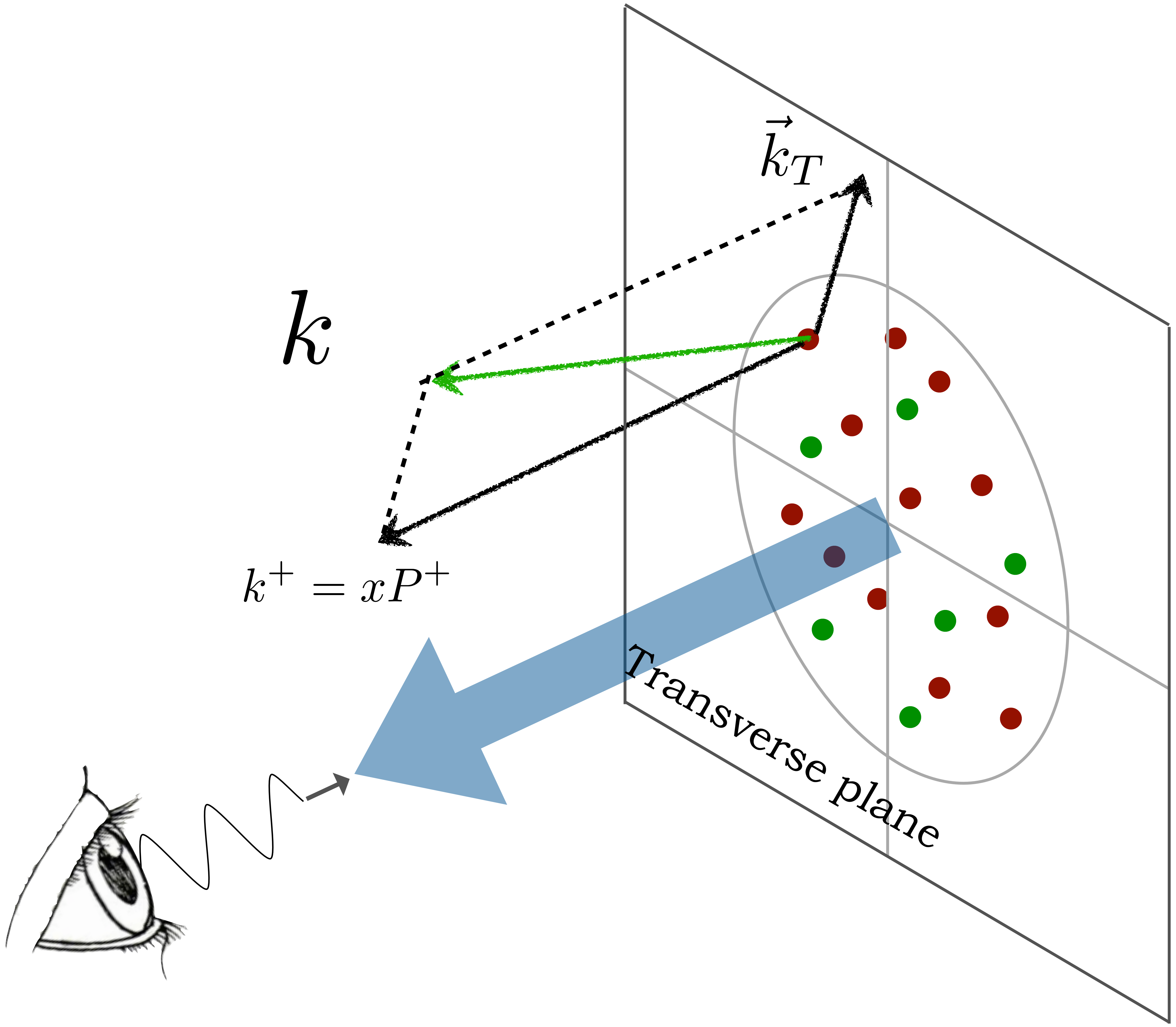
Mulders-Tangerman, NPB 461 (1996)
Boer-Mulders, PRD 57 (1998)

3D Maps

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 $h_{1T}^\perp$



Mulders-Tangerman, NPB 461 (1996)
Boer-Mulders, PRD 57 (1998)

3D Maps

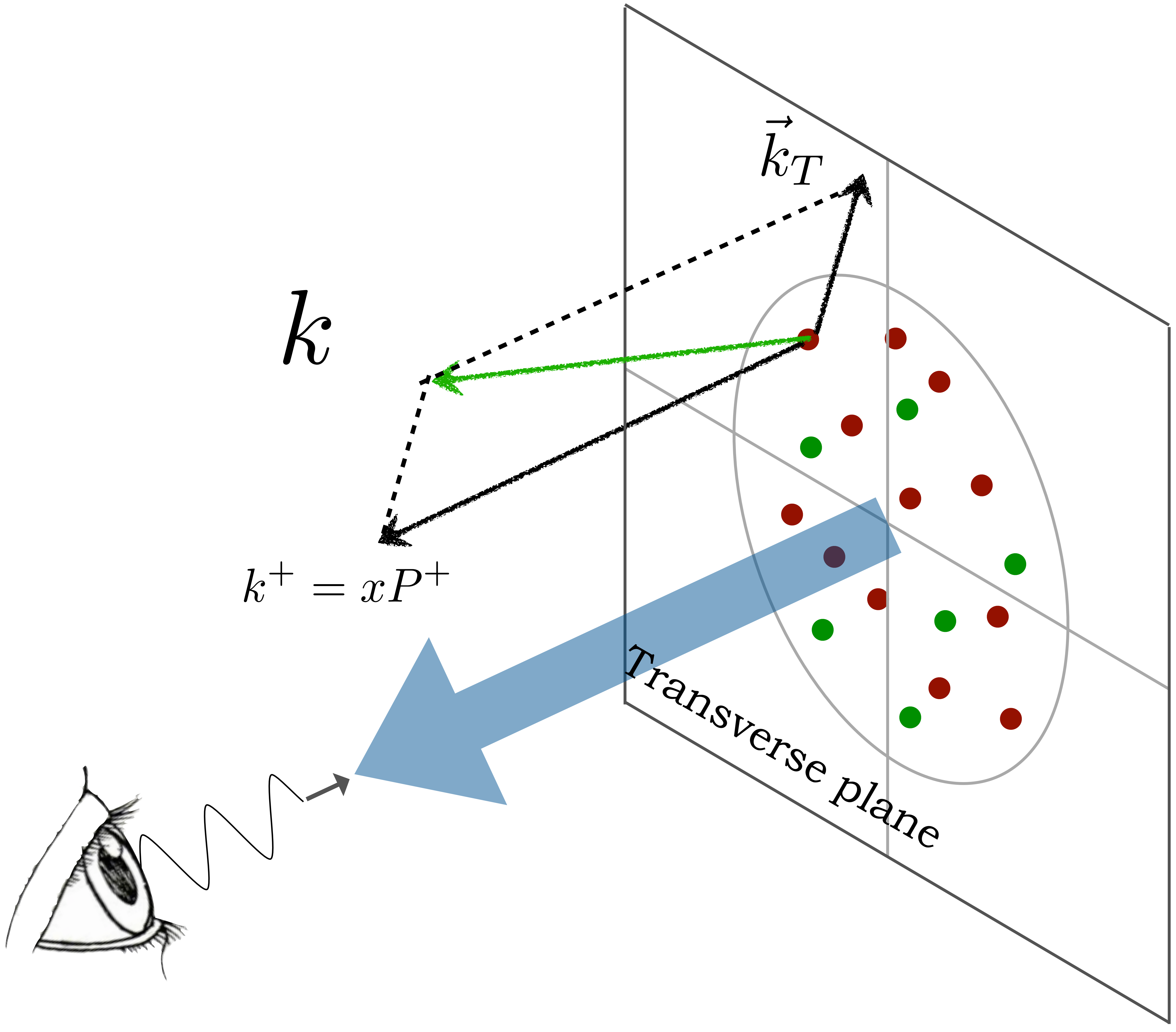
Quark Polarization

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



Mulders-Tangerman, NPB 461 (1996)
Boer-Mulders, PRD 57 (1998)

3D Maps

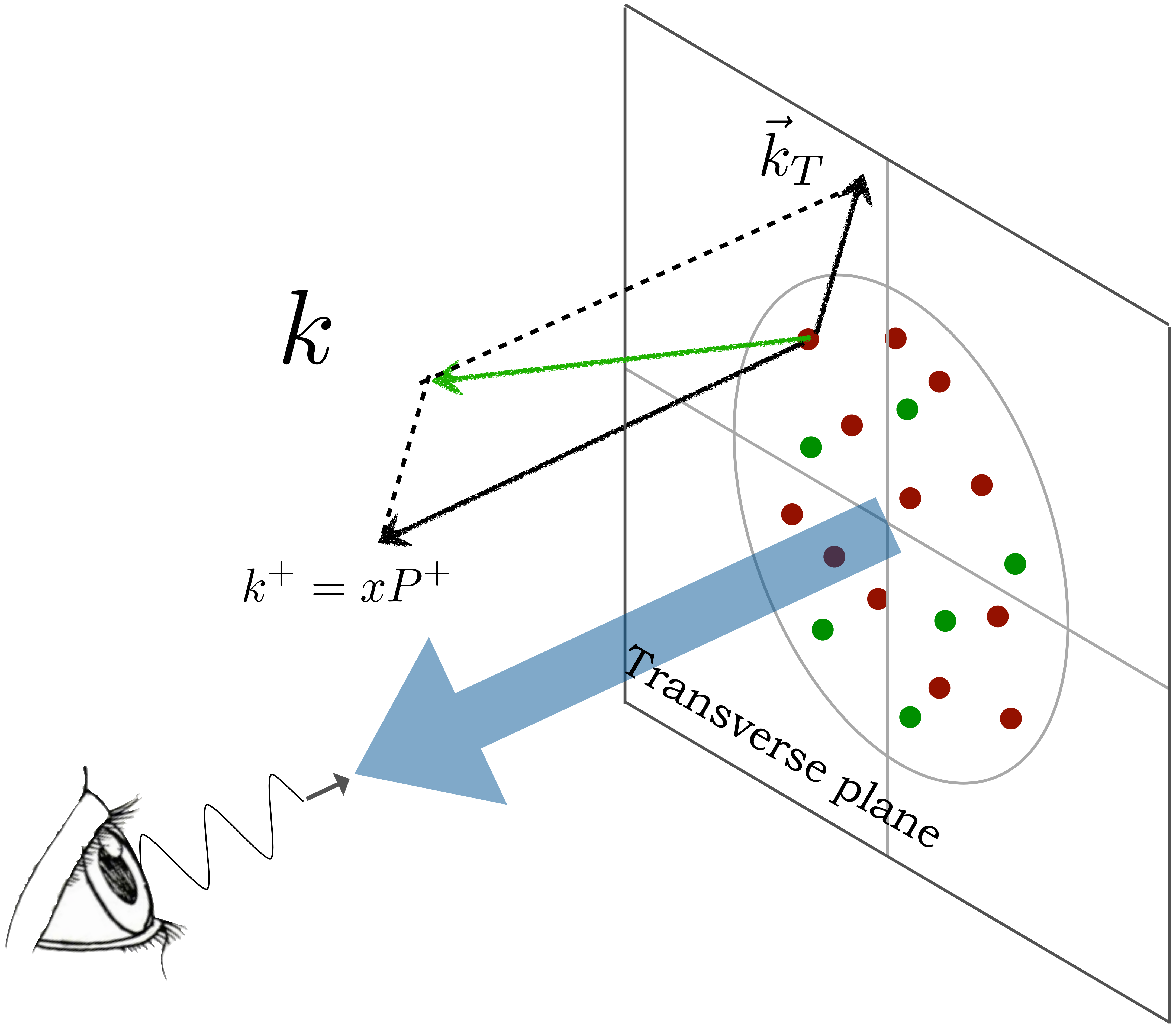
Quark Polarization

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



Mulders-Tangerman, NPB 461 (1996)
Boer-Mulders, PRD 57 (1998)

TMD Factorization

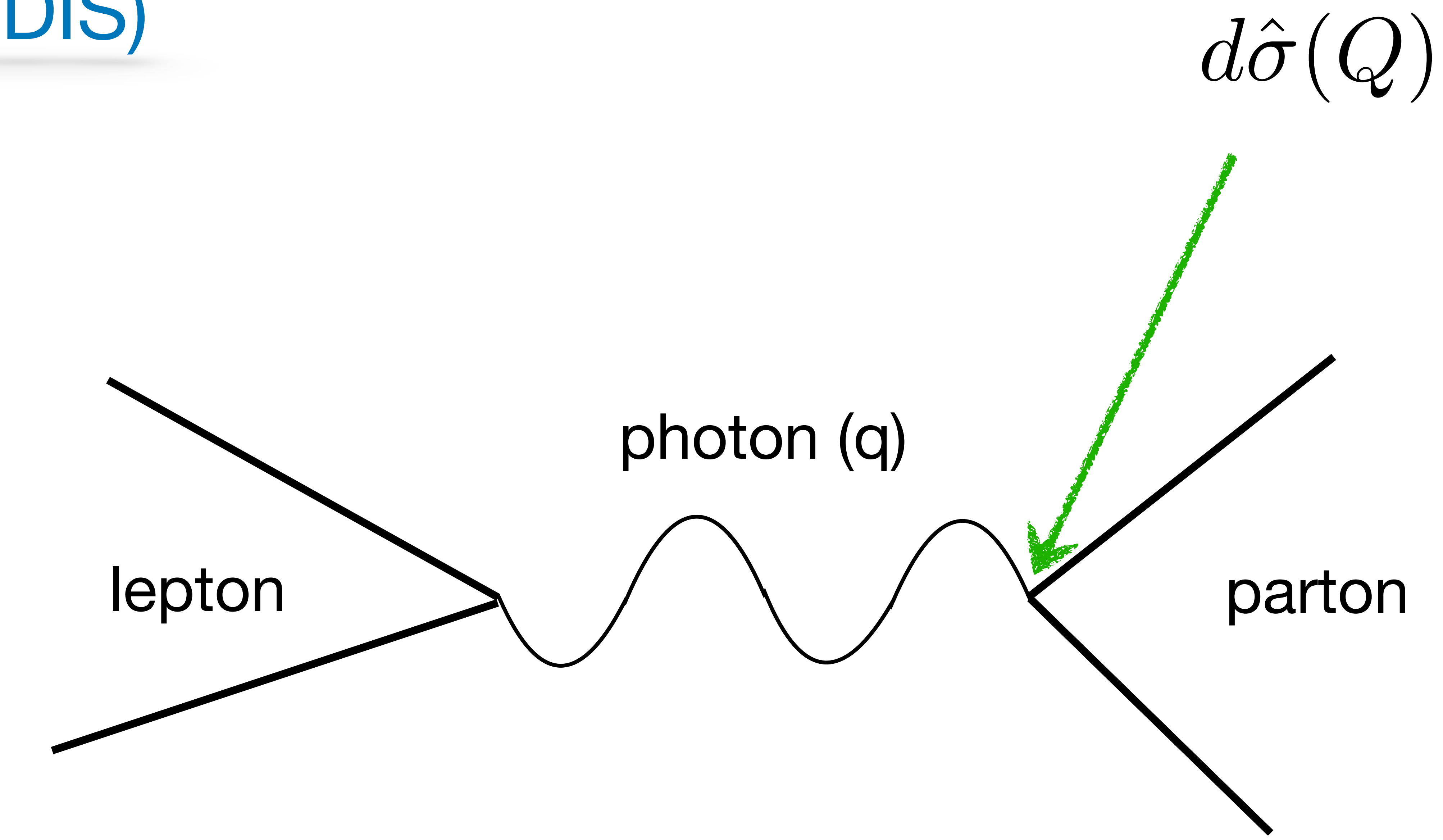
Semi-Inclusive Deep Inelastic Scattering (SIDIS)

If $Q^2 \gg M^2$

$$d\sigma \sim \text{perturbative} \otimes \text{nonperturbative}$$

↓

Elementary cross section



TMD Factorization

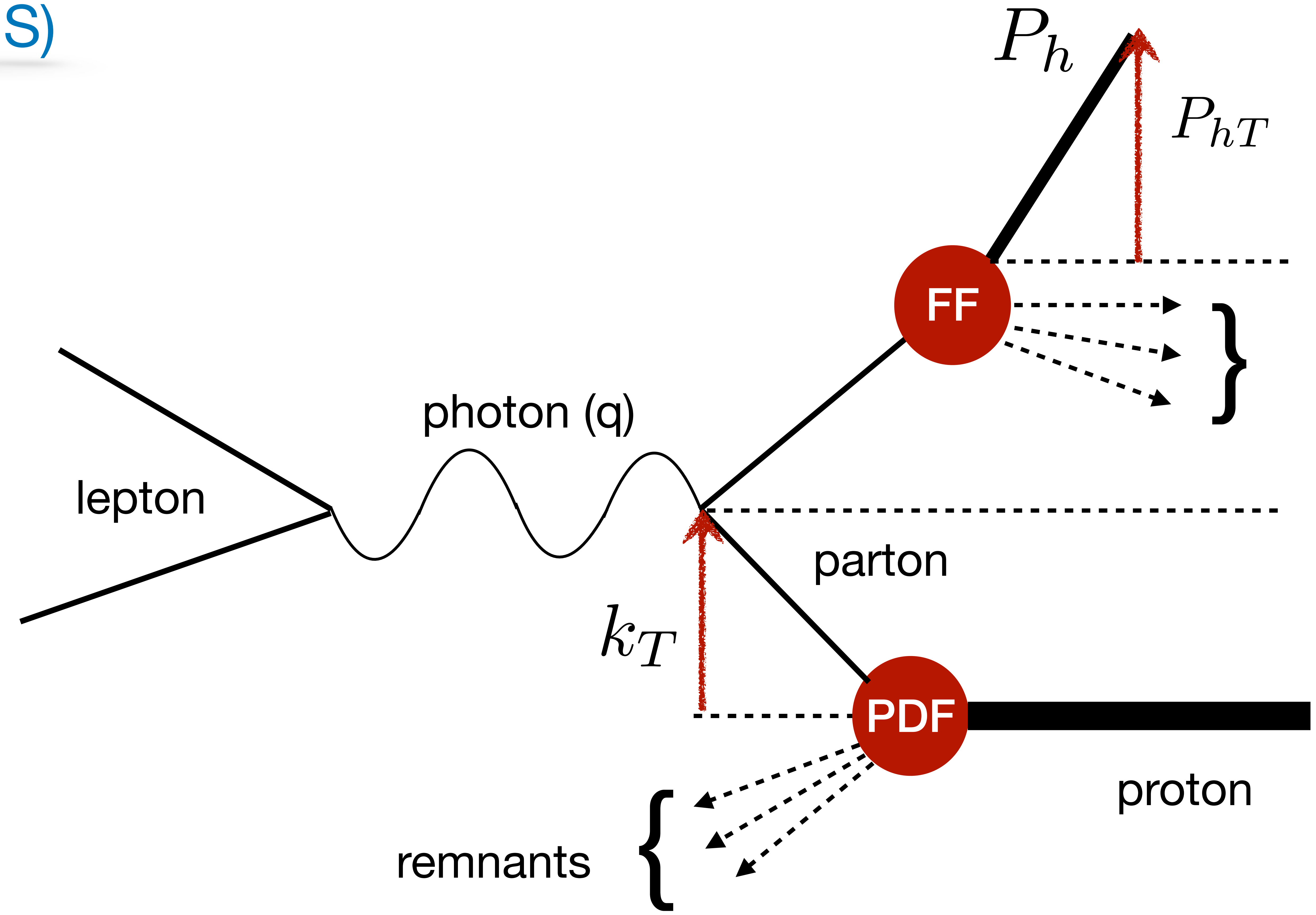
Semi-Inclusive Deep Inelastic Scattering (SIDIS)

If $Q^2 \gg M^2$ and $Q^2 \gg P_{hT}^2$

$$d\sigma \sim \text{perturbative} \otimes \text{nonperturbative}$$

Elementary cross section

TMD partonic densities



TMD Factorization

Factorization theorems for several processes:

- $l + N \to l' + h + X$ SIDIS
- $e^+ + e^- \to h_1 + h_2 + X$ DIA
- $H_1 + H_2 \to l^- + l^+ + X$ Drell Yan
- $H_1 + H_2 \to W/Z + X$ Drell Yan
- ~~$H_1 + H_2 \to \text{jet} + X$~~
- ~~$H_1 + H_2 \to \text{heavy quark} + X$~~

J. Collins, “Foundation of Perturbative QCD”
Collins, Metz, PRL 93 (2004)
Rogers, Mulders, PRD81 (2010)

TMD Factorization

Factorization theorems for several processes:

- $l + N \to l' + h + X$ SIDIS → TMD PDF and FF
- $e^+ + e^- \to h_1 + h_2 + X$ DIA → TMD FFs
- $H_1 + H_2 \to l^- + l^+ + X$ Drell Yan → TMD PDFs
- $H_1 + H_2 \to W/Z + X$ Drell Yan → TMD PDFs
- ~~$H_1 + H_2 \to \text{jet} + X$~~
- ~~$H_1 + H_2 \to \text{heavy quark} + X$~~

J. Collins, “Foundation of Perturbative QCD”
Collins, Metz, PRL 93 (2004)
Rogers, Mulders, PRD81 (2010)

TMD Factorization

Factorization theorems for several processes:

$l + N \to l' + h + X$	SIDIS	$\longrightarrow$	TMD PDF and FF
$e^+ + e^- \to h_1 + h_2 + X$	DIA	$\longrightarrow$	TMD FFs
$H_1 + H_2 \to l^- + l^+ + X$	Drell Yan	$\longrightarrow$	TMD PDFs
$H_1 + H_2 \to W/Z + X$	Drell Yan		

- ~~$H_1 + H_2 \to \text{jet} + X$~~
- ~~$H_1 + H_2 \to \text{heavy quark} + X$~~

GLOBAL ANALYSES

J. Collins, “Foundation of Perturbative QCD”

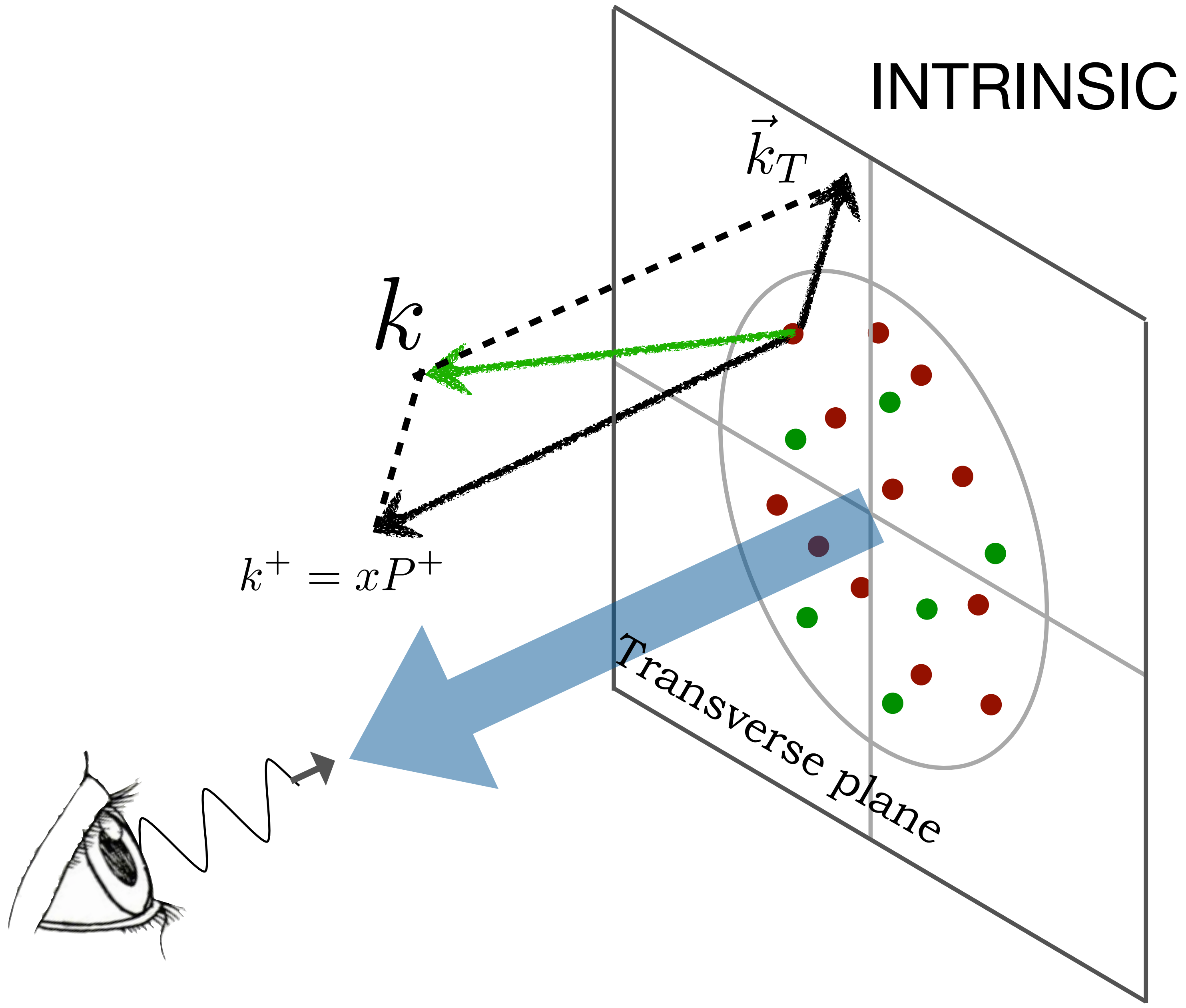
Collins, Metz, PRL 93 (2004)

Rogers, Mulders, PRD81 (2010)

Structure of a TMD distribution

Fourier transform in b_T-space

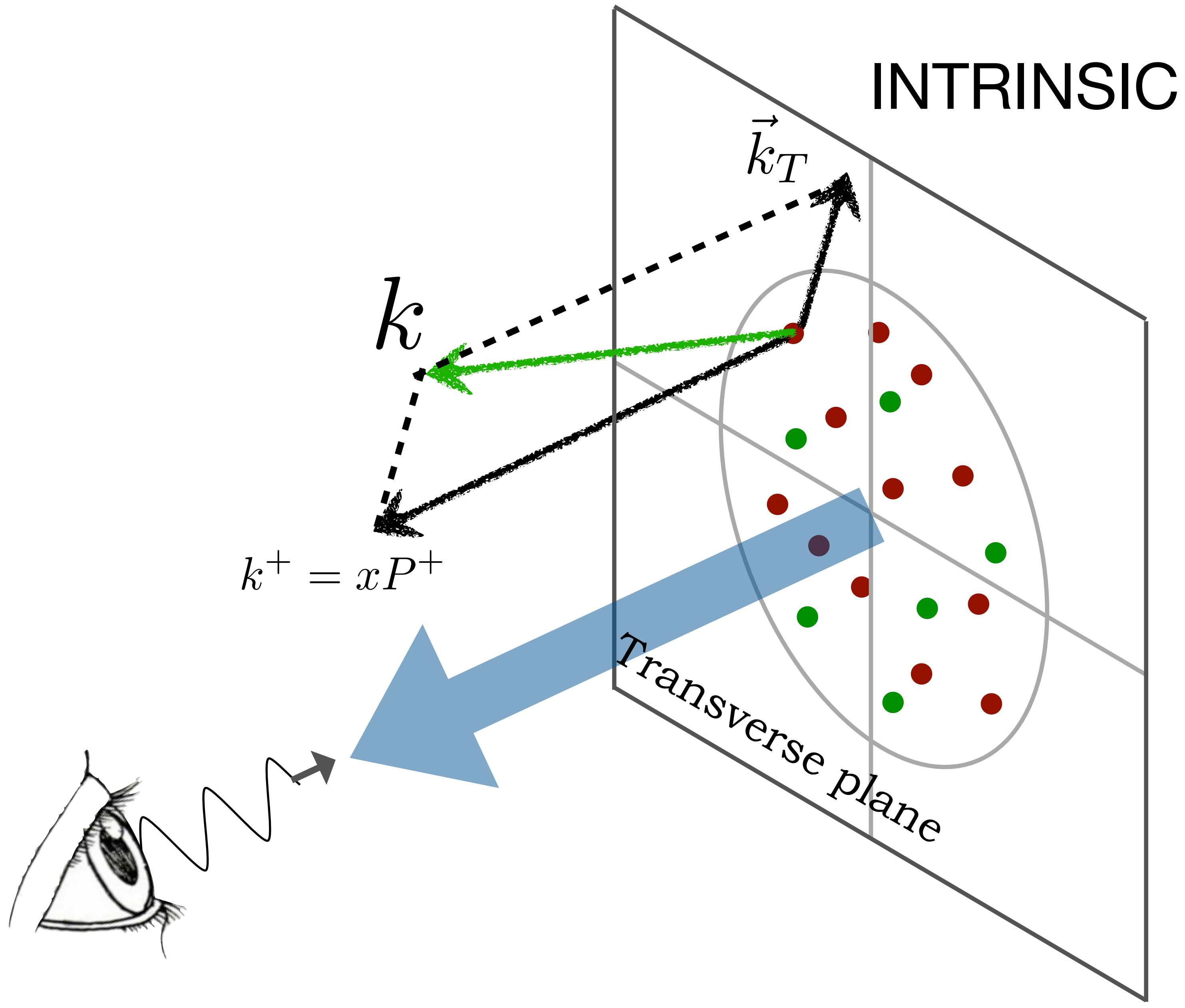
$$\tilde{F}_a(x, b_T^2; \mu, \zeta) = \int \frac{d^2 k_T}{(2\pi)^2} e^{i b_T \cdot k_T} F_a(x, k_T^2; \mu, \zeta)$$



Structure of a TMD distribution

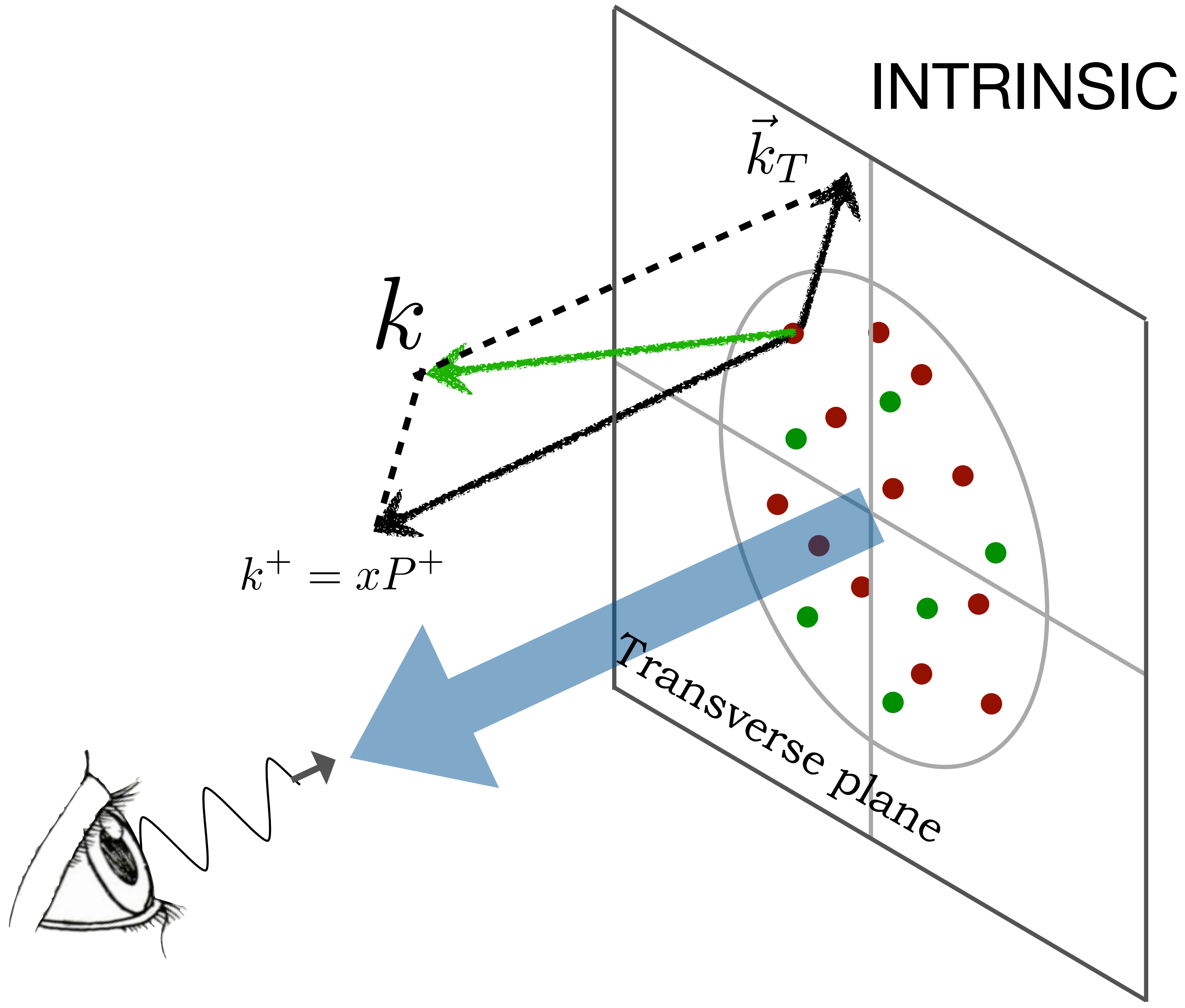
Fourier transform in b$_T$-space

$$\tilde{F}_a(x, b_T^2; \mu, \zeta) = \int \frac{d^2 k_T}{(2\pi)^2} e^{i b_T \cdot k_T} F_a(x, k_T^2; \mu, \zeta)$$



How to express a TMD distribution?

Structure of a TMD distribution



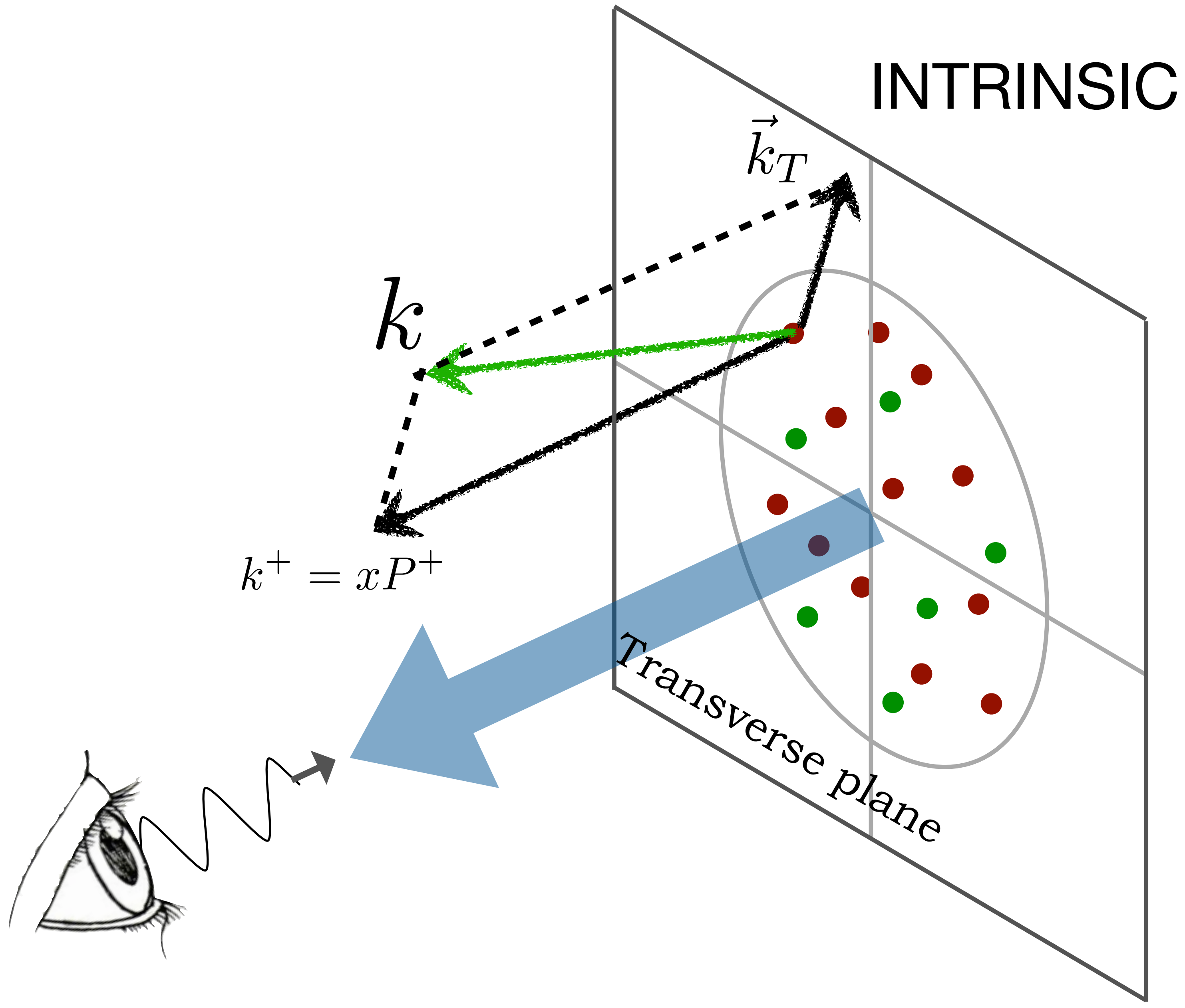
Fourier transform in b_T-space

$$\tilde{F}_a(x, b_T^2; \mu, \zeta) = \int \frac{d^2 k_T}{(2\pi)^2} e^{i b_T \cdot k_T} F_a(x, k_T^2; \mu, \zeta)$$

How to express a TMD distribution?

$$\tilde{F}_a(x, b_T^2; Q, Q^2) = [C_{a/b}(x, b_T^2, \mu_b) \otimes F_a(x; \mu_b)] e^{S_{\text{pert}}(\mu_b^2, Q^2)} e^{S_{\text{NP}}(b_T, Q^2; \lambda)} \tilde{F}_{a,NP}(x, b_T^2; \lambda')$$

Structure of a TMD distribution



Fourier transform in b_T-space

$$\tilde{F}_a(x, b_T^2; \mu, \zeta) = \int \frac{d^2 k_T}{(2\pi)^2} e^{i b_T \cdot k_T} F_a(x, k_T^2; \mu, \zeta)$$

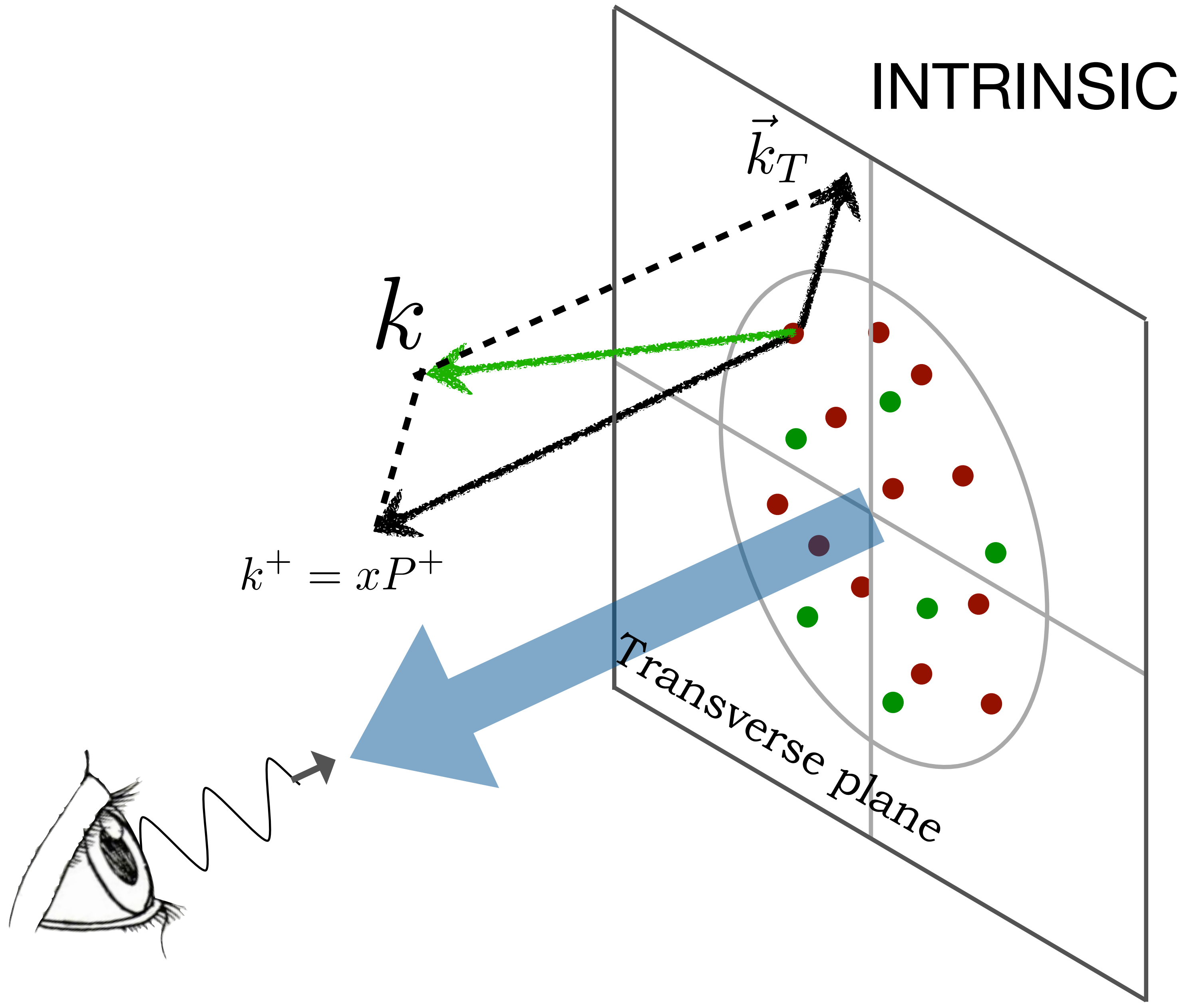
How to express a TMD distribution?

$$\tilde{F}_a(x, b_T^2; Q, Q^2) = [C_{a/b}(x, b_T^2, \mu_b) \otimes F_a(x; \mu_b)] e^{S_{\text{pert}}(\mu_b^2, Q^2)} e^{S_{\text{NP}}(b_T, Q^2; \lambda)} \tilde{F}_{a,NP}(x, b_T^2; \lambda')$$

Matching coefficient
(Pertubative calc.)

Evolution
(perturbative calc.)

Structure of a TMD distribution



Fourier transform in b$_T$-space

$$\tilde{F}_a(x, b_T^2; \mu, \zeta) = \int \frac{d^2 k_T}{(2\pi)^2} e^{i b_T \cdot k_T} F_a(x, k_T^2; \mu, \zeta)$$

How to express a TMD distribution?

$$\tilde{F}_a(x, b_T^2; Q, Q^2) = [C_{a/b}(x, b_T^2, \mu_b) \otimes F_a(x; \mu_b)] e^{S_{\text{pert}}(\mu_b^2, Q^2)} e^{S_{\text{NP}}(b_T, Q^2; \lambda)} \tilde{F}_{a,NP}(x, b_T^2; \lambda')$$

Matching coefficient
(Pertubative calc.)

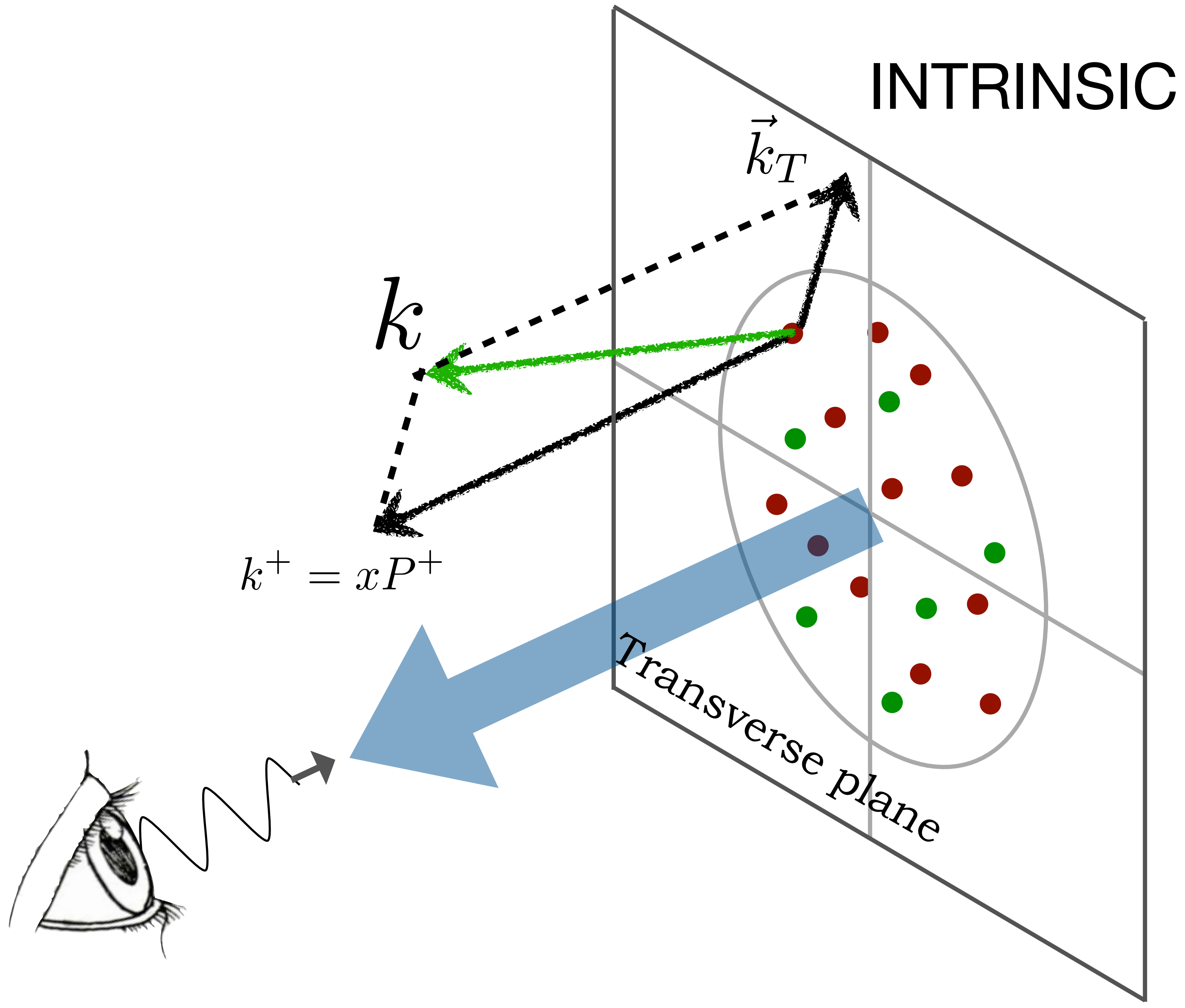
Collinear PDF
(previous fit)

Evolution
(perturbative calc.)

Structure of a TMD distribution

Fourier transform in b_T-space

$$\tilde{F}_a(x, b_T^2; \mu, \zeta) = \int \frac{d^2 k_T}{(2\pi)^2} e^{i b_T \cdot k_T} F_a(x, k_T^2; \mu, \zeta)$$



How to express a TMD distribution?

$$\tilde{F}_a(x, b_T^2; Q, Q^2) = [C_{a/b}(x, b_T^2, \mu_b) \otimes F_a(x; \mu_b)] e^{S_{\text{pert}}(\mu_b^2, Q^2)} e^{S_{\text{NP}}(b_T, Q^2; \lambda)} \tilde{F}_{a,NP}(x, b_T^2; \lambda')$$

Matching coefficient
(Pertubative calc.)

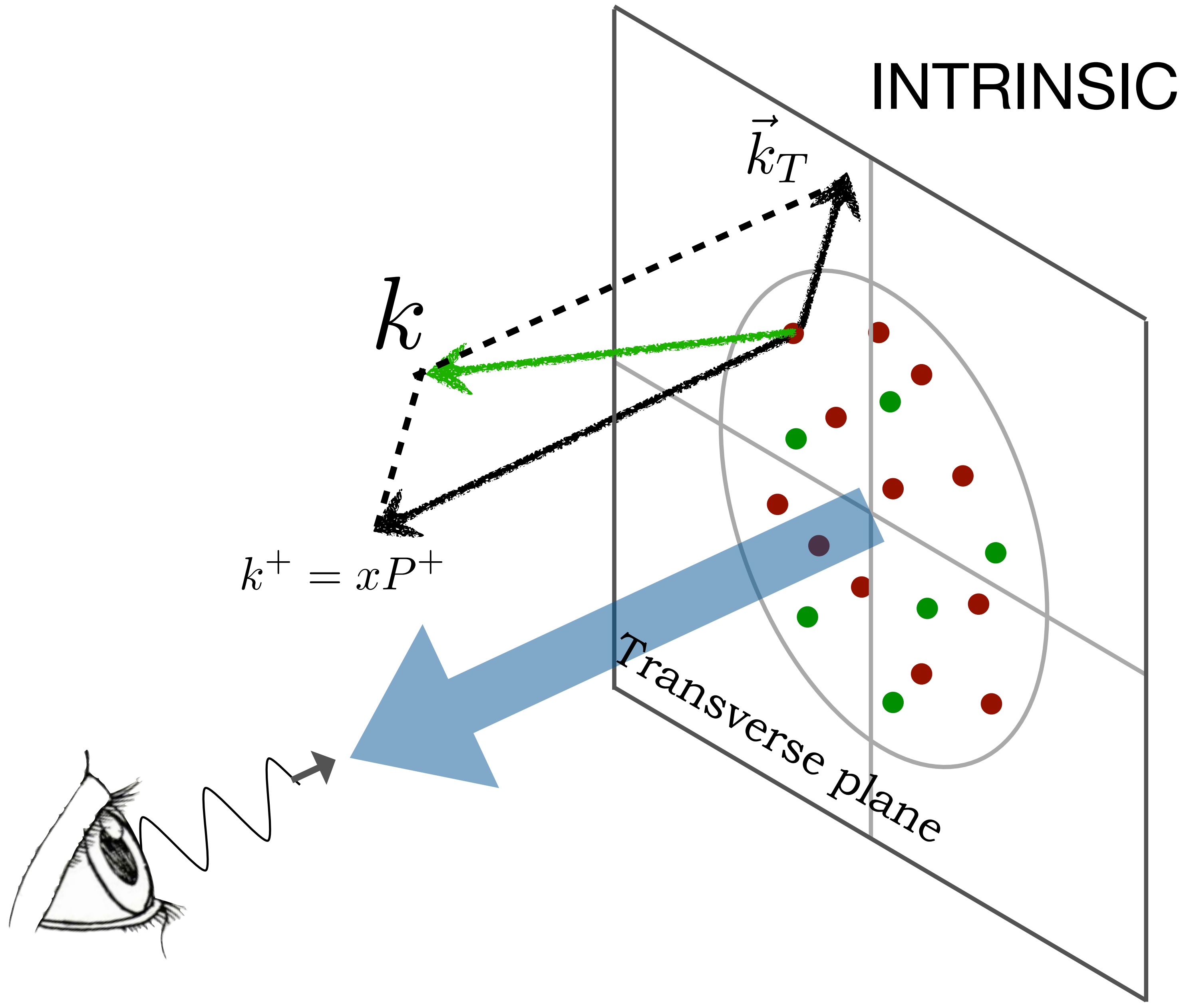
Collinear PDF
(previous fit)

Evolution
(perturbative calc.)

Evolution
(model-dependent)

TMD part of the parton density
(model-dependent)

Structure of a TMD distribution



Fourier transform in b$_T$-space

$$\tilde{F}_a(x, b_T^2; \mu, \zeta) = \int \frac{d^2 k_T}{(2\pi)^2} e^{i b_T \cdot k_T} F_a(x, k_T^2; \mu, \zeta)$$

How to express a TMD distribution?

$$\tilde{F}_a(x, b_T^2; Q, Q^2) = [C_{a/b}(x, b_T^2, \mu_b) \otimes F_a(x; \mu_b)] e^{S_{\text{pert}}(\mu_b^2, Q^2)} \boxed{e^{S_{\text{NP}}(b_T, Q^2; \lambda)} \tilde{F}_{a,NP}(x, b_T^2; \lambda')}$$

Matching coefficient
(Pertubative calc.)

Collinear PDF
(previous fit)

Evolution
(perturbative calc.)

Evolution
(model-dependent)

TMD part of the parton density
(model-dependent)

Accuracy of calculation

$$\tilde{F}_a(x,b_T^2;Q,Q^2) = [C_{a/b}(x,b_T^2,\mu_b) \otimes F_a(x;\mu_b)] e^{S_{\rm pert}(\mu_b^2,Q^2)} e^{S_{\rm NP}(b_T,Q^2;\lambda)} \tilde{F}_{a,NP}(x,b_T^2;\lambda')$$

Accuracy of calculation

$$\tilde{F}_a(x,b_T^2;Q,Q^2) = [C_{a/b}(x,b_T^2,\mu_b)\otimes F_a(x;\mu_b)]\boxed{e^{S_{\rm pert}(\mu_b^2,Q^2)}}e^{S_{\rm NP}(b_T,Q^2;\lambda)}\tilde{F}_{a,NP}(x,b_T^2;\lambda')$$

Accuracy of calculation

$$\tilde{F}_a(x, b_T^2; Q, Q^2) = [C_{a/b}(x, b_T^2, \mu_b) \otimes F_a(x; \mu_b)] \boxed{e^{S_{\text{pert}}(\mu_b^2, Q^2)}} e^{S_{\text{NP}}(b_T, Q^2; \lambda)} \tilde{F}_{a,NP}(x, b_T^2; \lambda')$$

- $S_{\text{pert}}(\mu_b, Q) = 1 + \sum_{k=0}^{\infty} \sum_{n=1+[k/2]}^{\infty} \left(\frac{\alpha_S(Q)}{4\pi} \right)^n \sum_{k=1}^{2n} L^{2n-k} R^{(n,2n-k)} \qquad L = \ln\left(\frac{Q^2}{\mu_b^2} \right)$

Accuracy of calculation

$$\tilde{F}_a(x, b_T^2; Q, Q^2) = [C_{a/b}(x, b_T^2, \mu_b) \otimes F_a(x; \mu_b)] \boxed{e^{S_{\text{pert}}(\mu_b^2, Q^2)}} e^{S_{\text{NP}}(b_T, Q^2; \lambda)} \tilde{F}_{a,NP}(x, b_T^2; \lambda')$$

- $S_{\text{pert}}(\mu_b, Q) = 1 + \sum_{k=0}^{\infty} \sum_{n=1+[k/2]}^{\infty} \left(\frac{\alpha_S(Q)}{4\pi} \right)^n \sum_{k=1}^{2n} L^{2n-k} R^{(n,2n-k)}$ $\qquad L = \ln \left(\frac{Q^2}{\mu_b^2} \right)$

Accuracy

Sudakov form factor

Matching coefficient

Accuracy of calculation

$$\tilde{F}_a(x, b_T^2; Q, Q^2) = [C_{a/b}(x, b_T^2, \mu_b) \otimes F_a(x; \mu_b)] e^{S_{\rm pert}(\mu_b^2, Q^2)} e^{S_{\rm NP}(b_T, Q^2; \lambda)} \tilde{F}_{a,NP}(x, b_T^2; \lambda')$$

- $S_{\rm pert}(\mu_b, Q) = 1 + \sum_{k=0}^{\infty} \sum_{n=1+[k/2]}^{\infty} \left(\frac{\alpha_S(Q)}{4\pi} \right)^n \sum_{k=1}^{2n} L^{2n-k} R^{(n,2n-k)}$ $\qquad L = \ln \left(\frac{Q^2}{\mu_b^2} \right)$

Accuracy	Sudakov form factor	Matching coefficient
LL	$\alpha_S^n \ln^{2n} \left(\frac{Q^2}{\mu_b^2} \right)$	$O(\alpha_S^0)$

Accuracy of calculation

$$\tilde{F}_a(x, b_T^2; Q, Q^2) = [C_{a/b}(x, b_T^2, \mu_b) \otimes F_a(x; \mu_b)] \boxed{e^{S_{\text{pert}}(\mu_b^2, Q^2)}} e^{S_{\text{NP}}(b_T, Q^2; \lambda)} \tilde{F}_{a,NP}(x, b_T^2; \lambda')$$

- $S_{\text{pert}}(\mu_b, Q) = 1 + \sum_{k=0}^{\infty} \sum_{n=1+[k/2]}^{\infty} \left(\frac{\alpha_S(Q)}{4\pi}\right)^n \sum_{k=1}^{2n} L^{2n-k} R^{(n,2n-k)}$ $\qquad L = \ln\left(\frac{Q^2}{\mu_b^2}\right)$

Accuracy	Sudakov form factor	Matching coefficient
LL	$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right)$	$O(\alpha_S^0)$
NLL	$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right), \quad \alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$	$O(\alpha_S^0)$

Recent Global Analyses

	Accuracy	SIDIS	DY	Z production	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
Pavia 2019 arXiv:1912.07550	N^3LL	✘	✔	✔	353	1.02

Our work in the last two years

New Global Fit

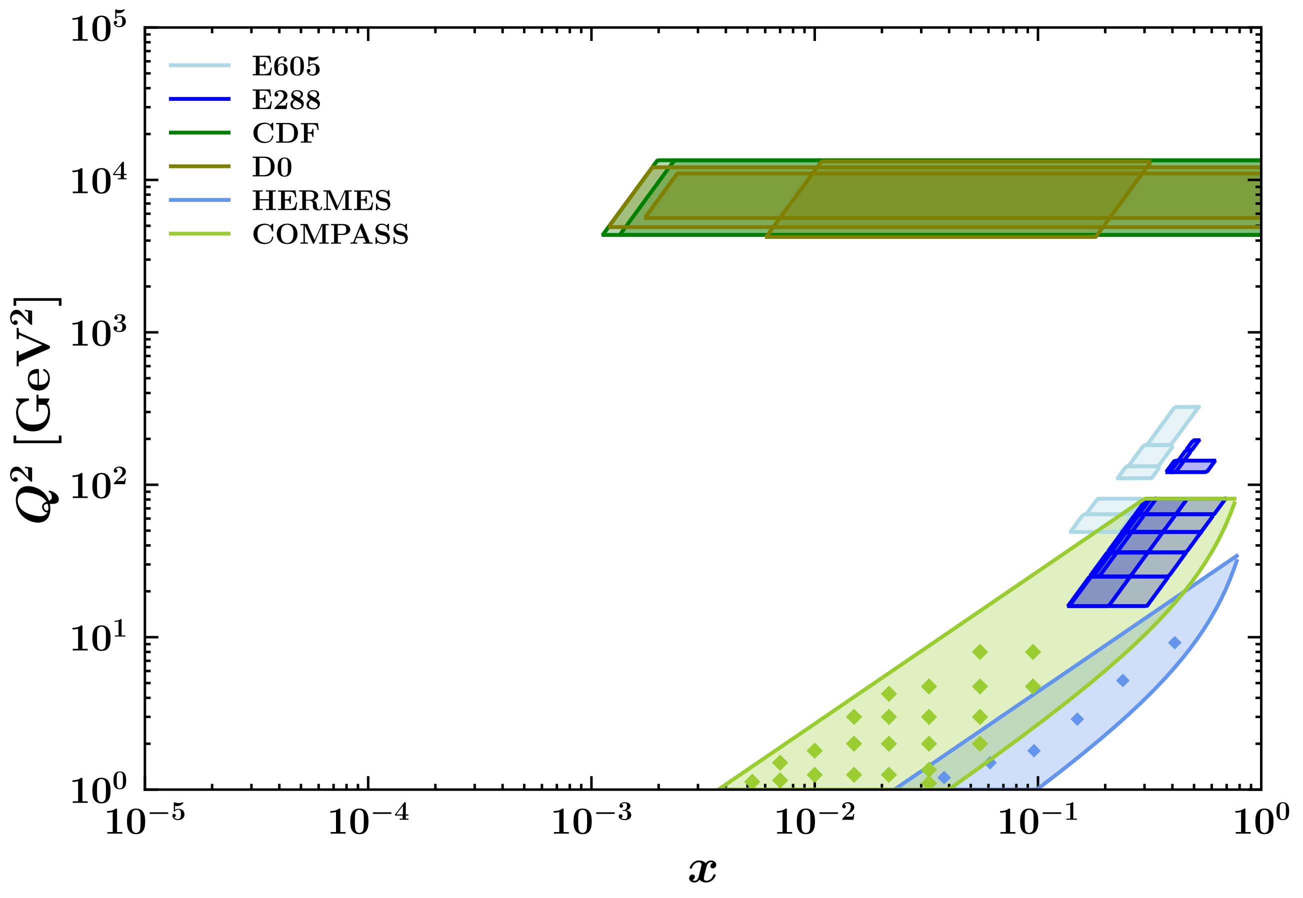
Simultaneously extraction of unpolarized TMD PDFs and FFs

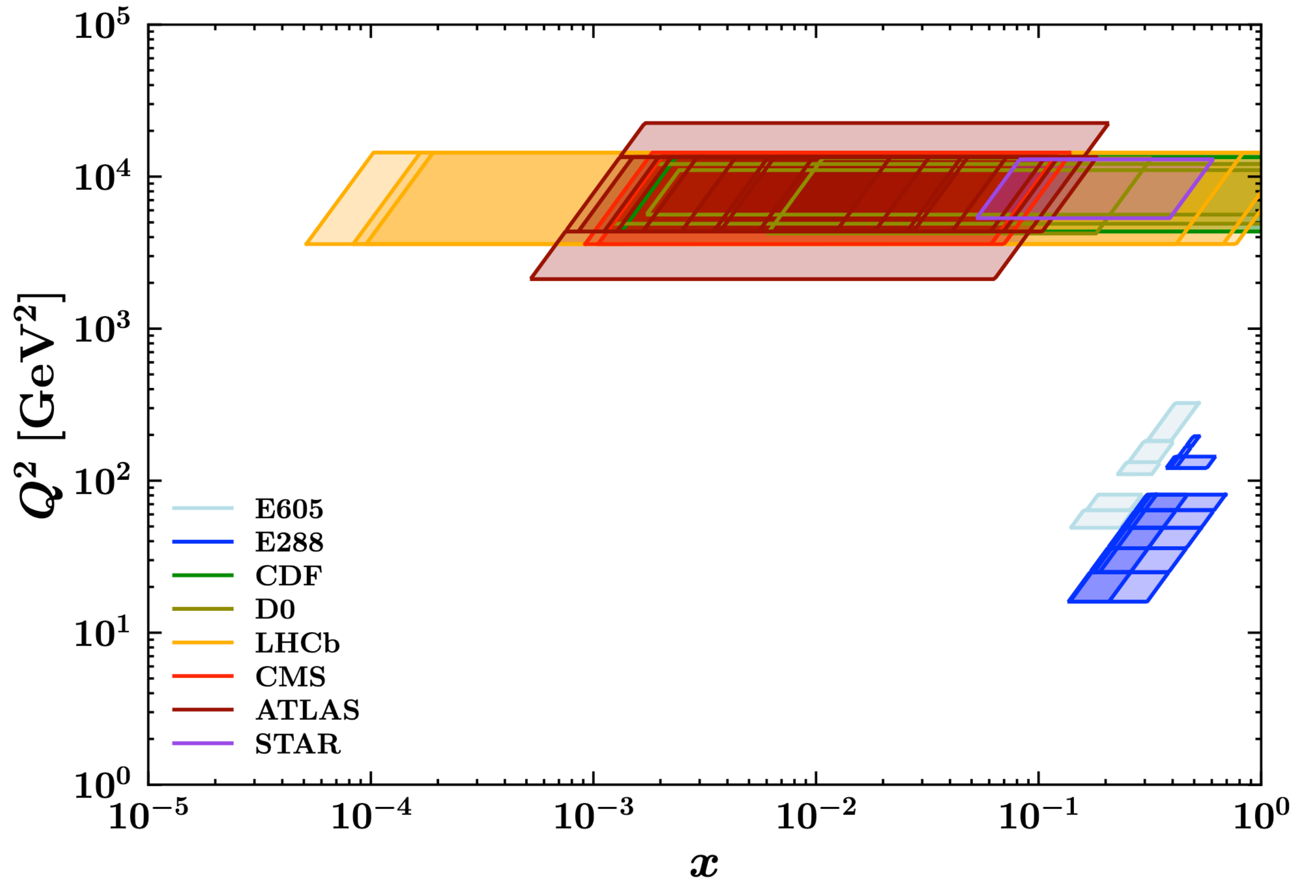
Our work in the last two years

New Global Fit

Simultaneously extraction of unpolarized TMD PDFs and FFs

- ✓ SIDIS + Drell Yan



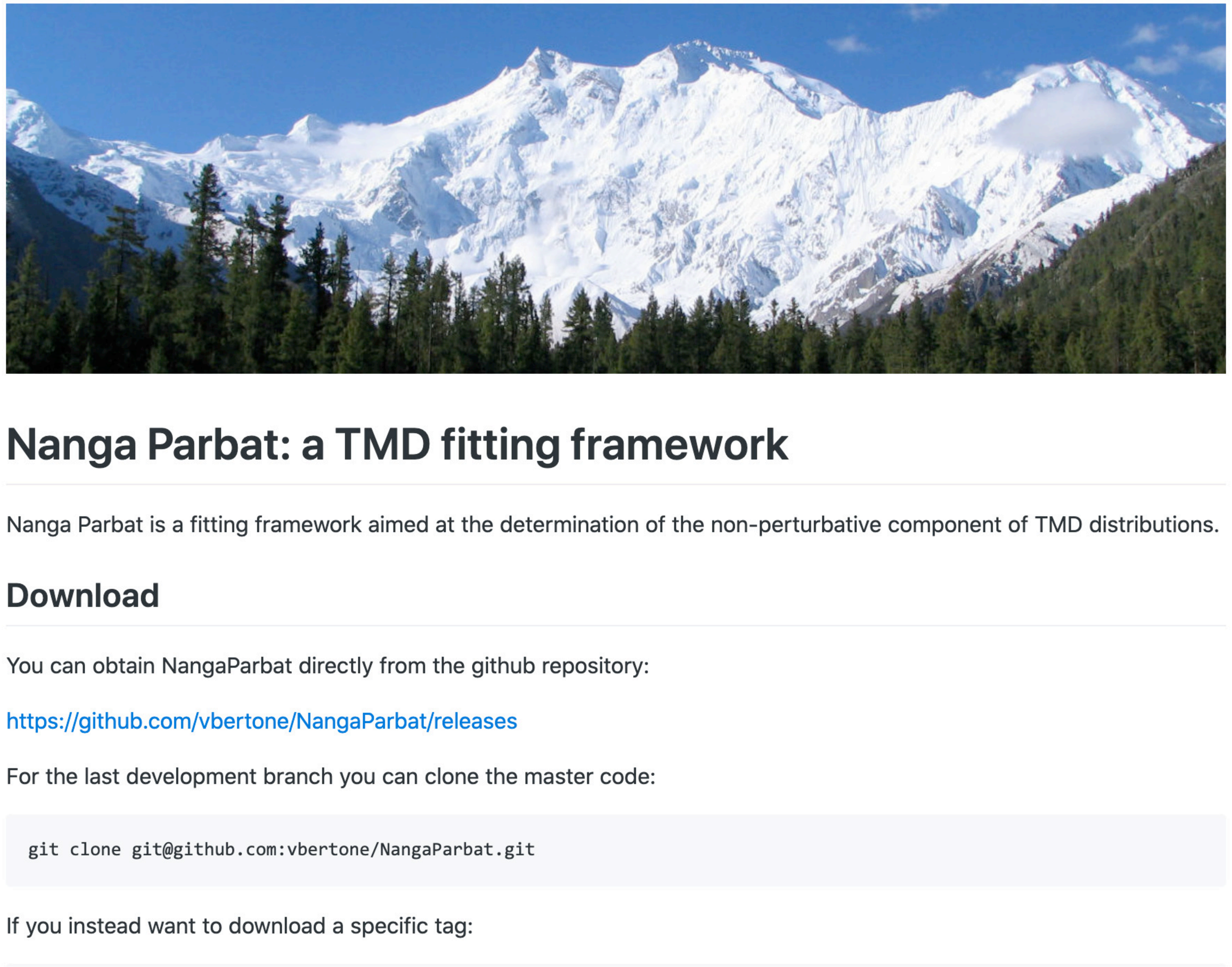


Our work in the last two years

New Global Fit

Simultaneously extraction of unpolarized TMD PDFs and FFs

- ✓ SIDIS + Drell Yan
- ✓ Integrated variables



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/vbertone/NangaParbat/releases

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

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

If you instead want to download a specific tag:

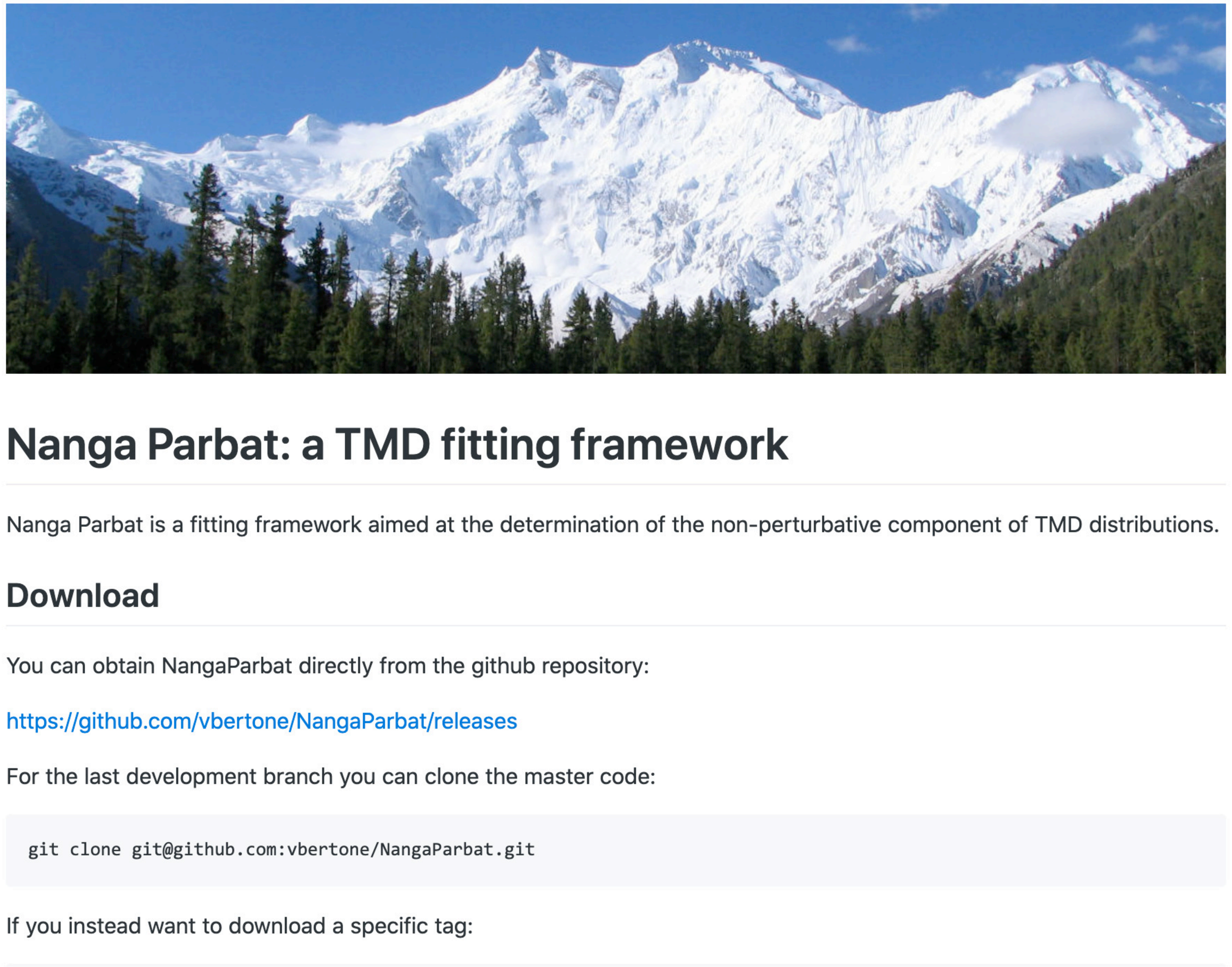
https://github.com/MapCollaboration

Our work in the last two years

New Global Fit

Simultaneously extraction of unpolarized TMD PDFs and FFs

- ✓ SIDIS + Drell Yan
- ✓ Integrated variables
- ○ Up to N^2LL/N^3LL



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/vbertone/NangaParbat/releases

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

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

If you instead want to download a specific tag:

https://github.com/MapCollaboration

A new Global Fit: MAPTMD22

	Accuracy	SIDIS	DY	Z production	N of points	χ^2/N_{data}
Pavia 2017 arXiv:1703.10157	NLL	✓	✓	✓	8059	1.55
SV 2019 arXiv:1912.06532	N^{3}LL$^-$	✓	✓	✓	1039	1.06
Pavia 2019 arXiv:1912.07550	N^{3}LL	✗	✓	✓	353	1.02
MAPTMD22	***N^{3}LL$^-$***	✓	✓	✓	***2031***	***1.06***

Bacchetta, Bertone, Bissolotti, Bozzi, MC, Piacenza, Radici, Signori arXiv: 2206.07598

MAPTMD22 — Included Dataset

Drell-Yan

Fixed-target low-energy DY

RHIC data

LHC and Tevatron data

$9 \lesssim Q \lesssim 11$ GeV excluded (Υ resonance)

$$q_T|_{\max} = 0.2Q$$

484 experimental points

MAPTMD22 — Included Dataset

Drell-Yan

Fixed-target low-energy DY

RHIC data

LHC and Tevatron data

$9 \lesssim Q \lesssim 11$ GeV excluded (Υ resonance)

$q_T|_{\max} = 0.2Q$

484 experimental points

SIDIS

HERMES data

COMPASS data

$Q > 1.3$ GeV

$0.2 < z < 0.7$

$P_{hT}|_{\max} = \min[\min[0.2Q, 0.5zQ] + 0.3 \text{ GeV}, zQ]$

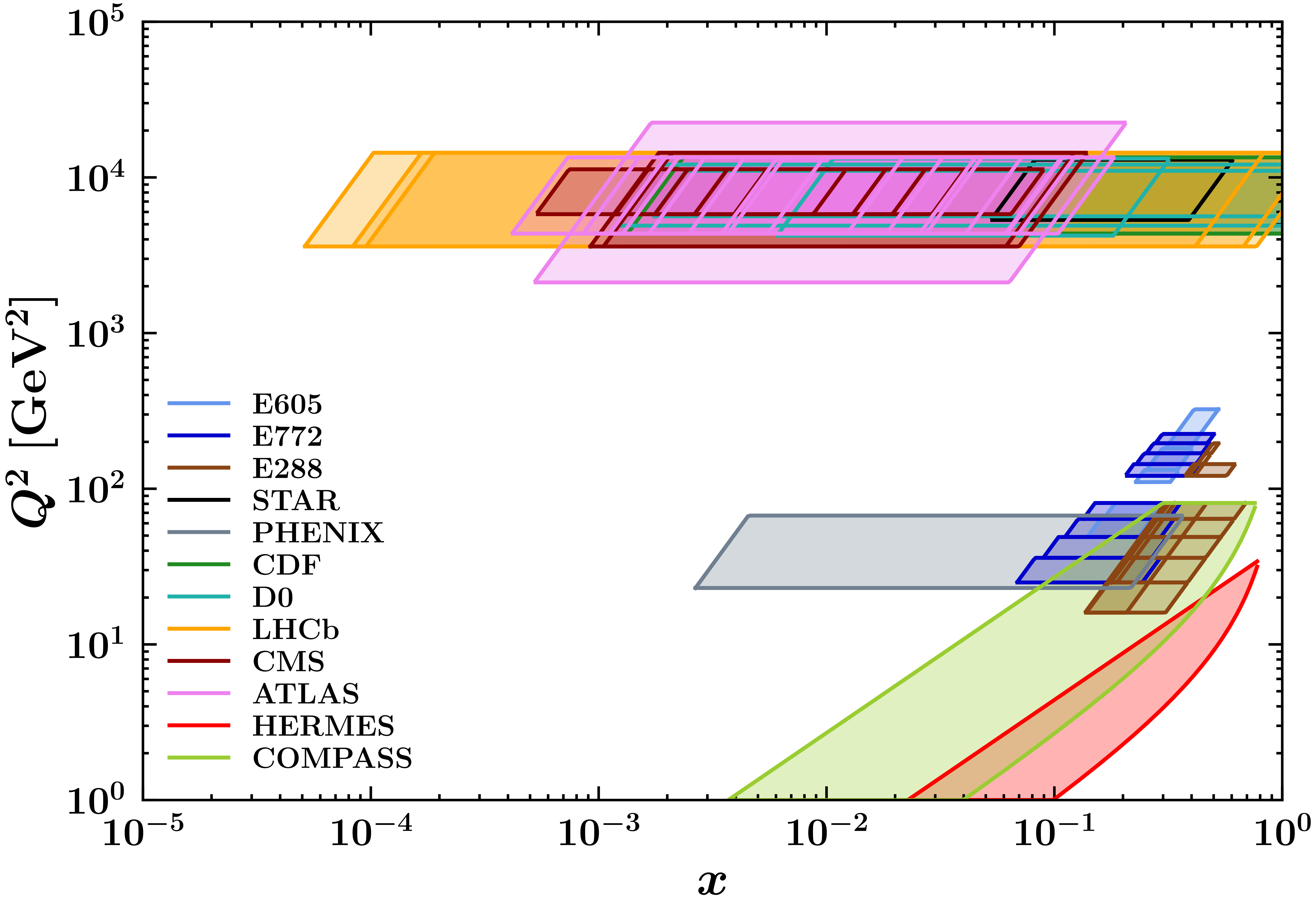
1547 experimental points

MAPTMD22 — Included Dataset

484 experimental points

1547 experimental points

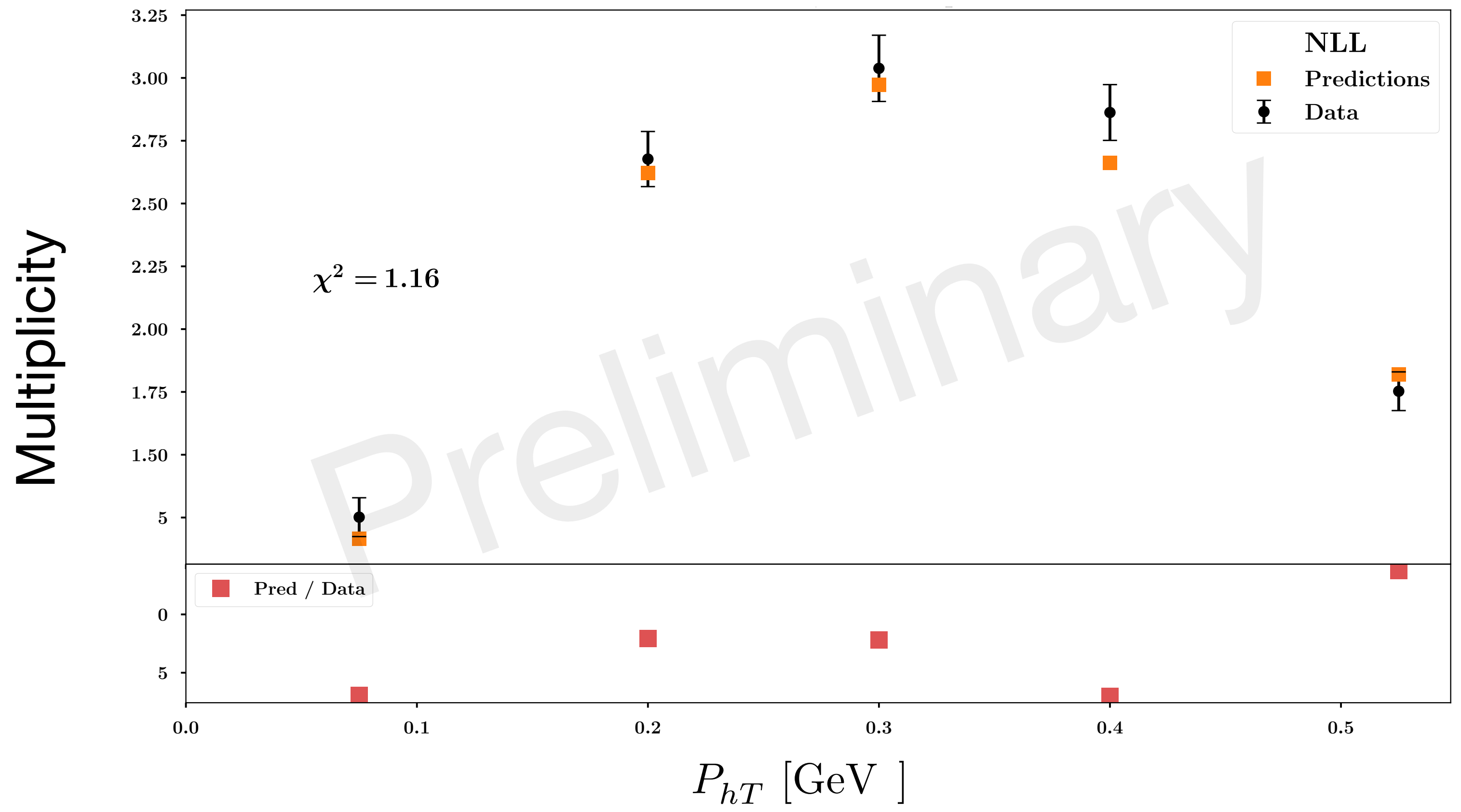
Total: 2031 fitted experimental points



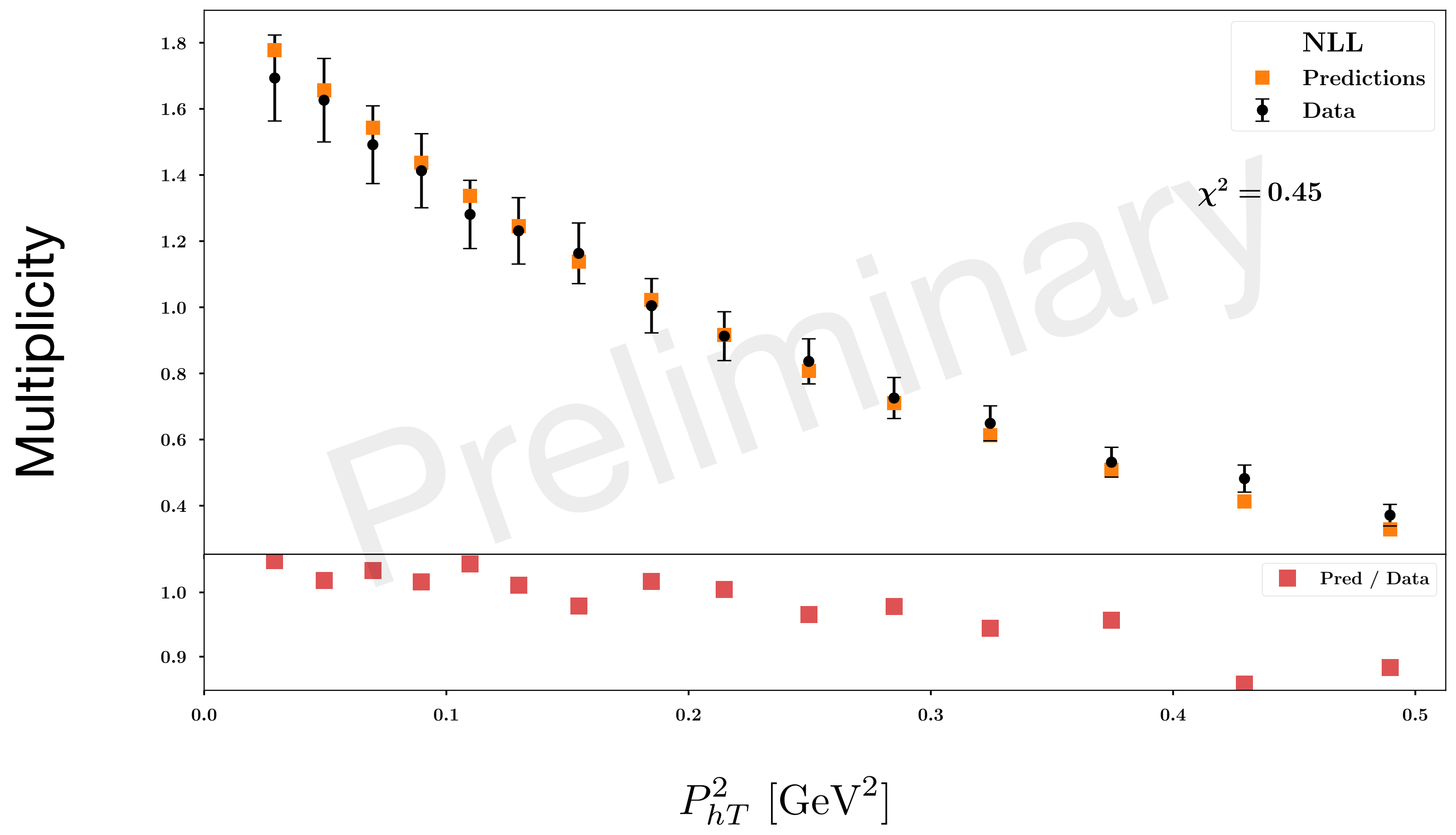
MAPTMD22 —Normalization of SIDIS

SIDIS multiplicities at NLL

HERMES



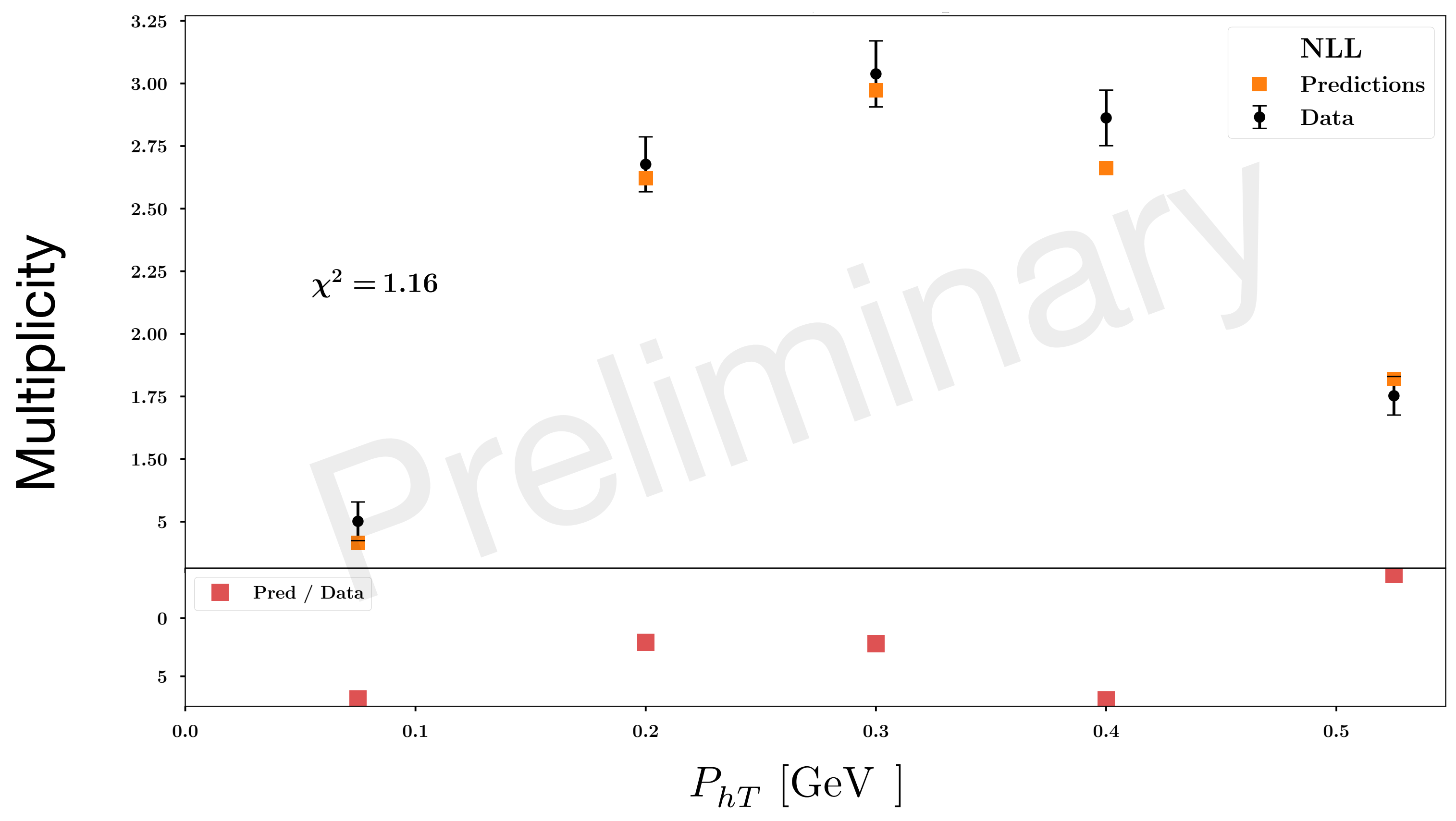
COMPASS



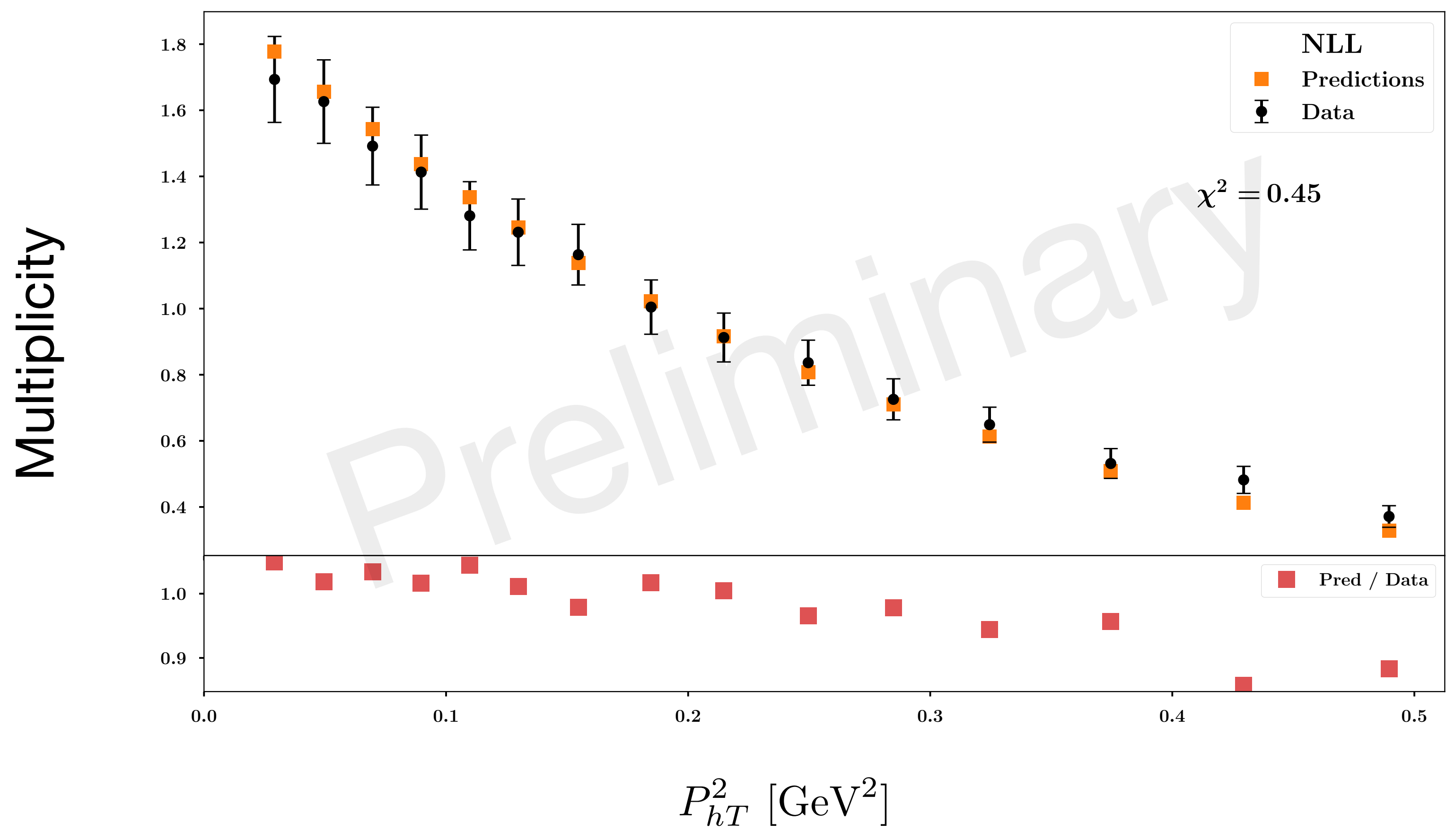
MAPTMD22 —Normalization of SIDIS

SIDIS multiplicities at NLL

HERMES

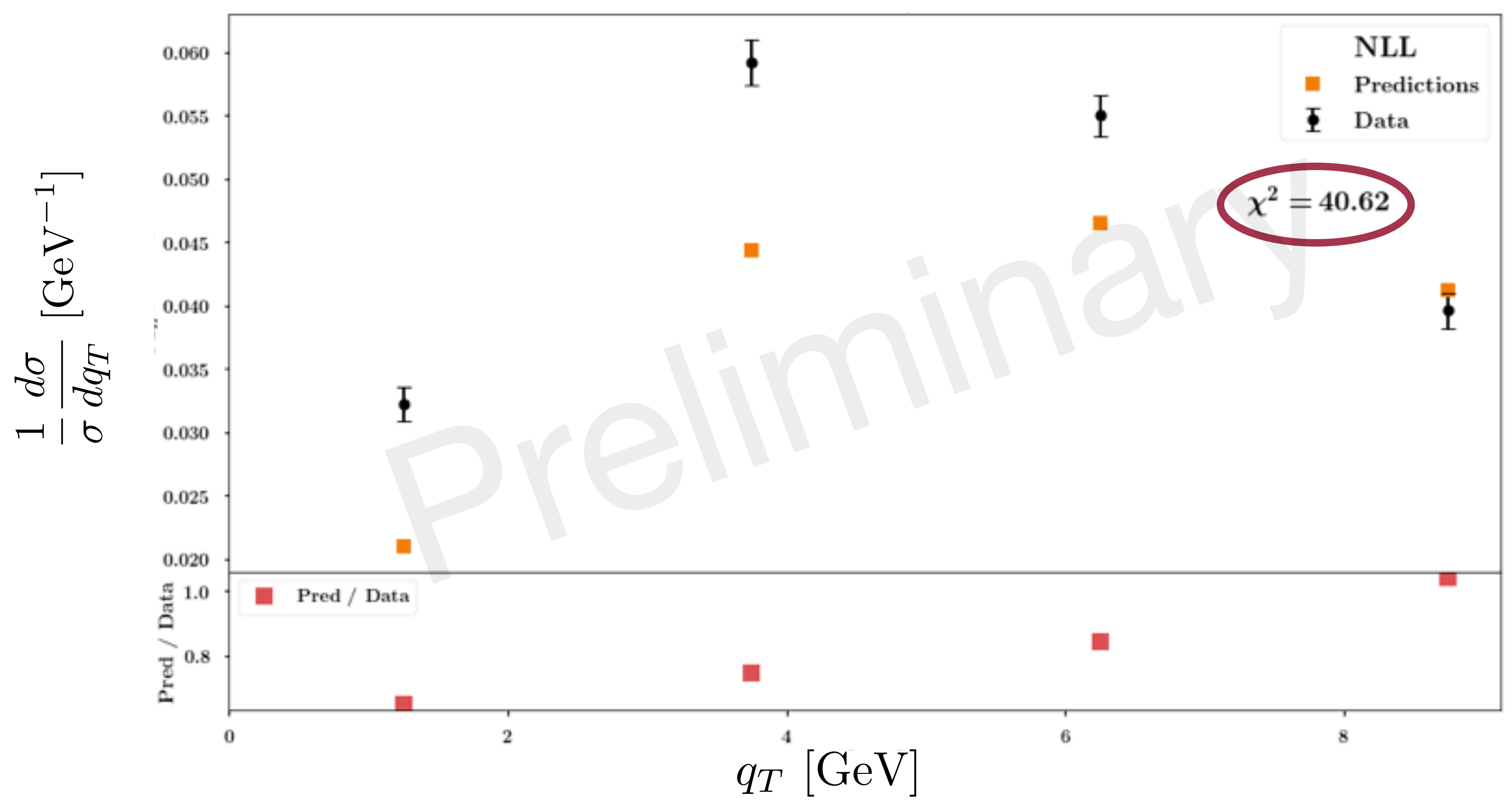


COMPASS

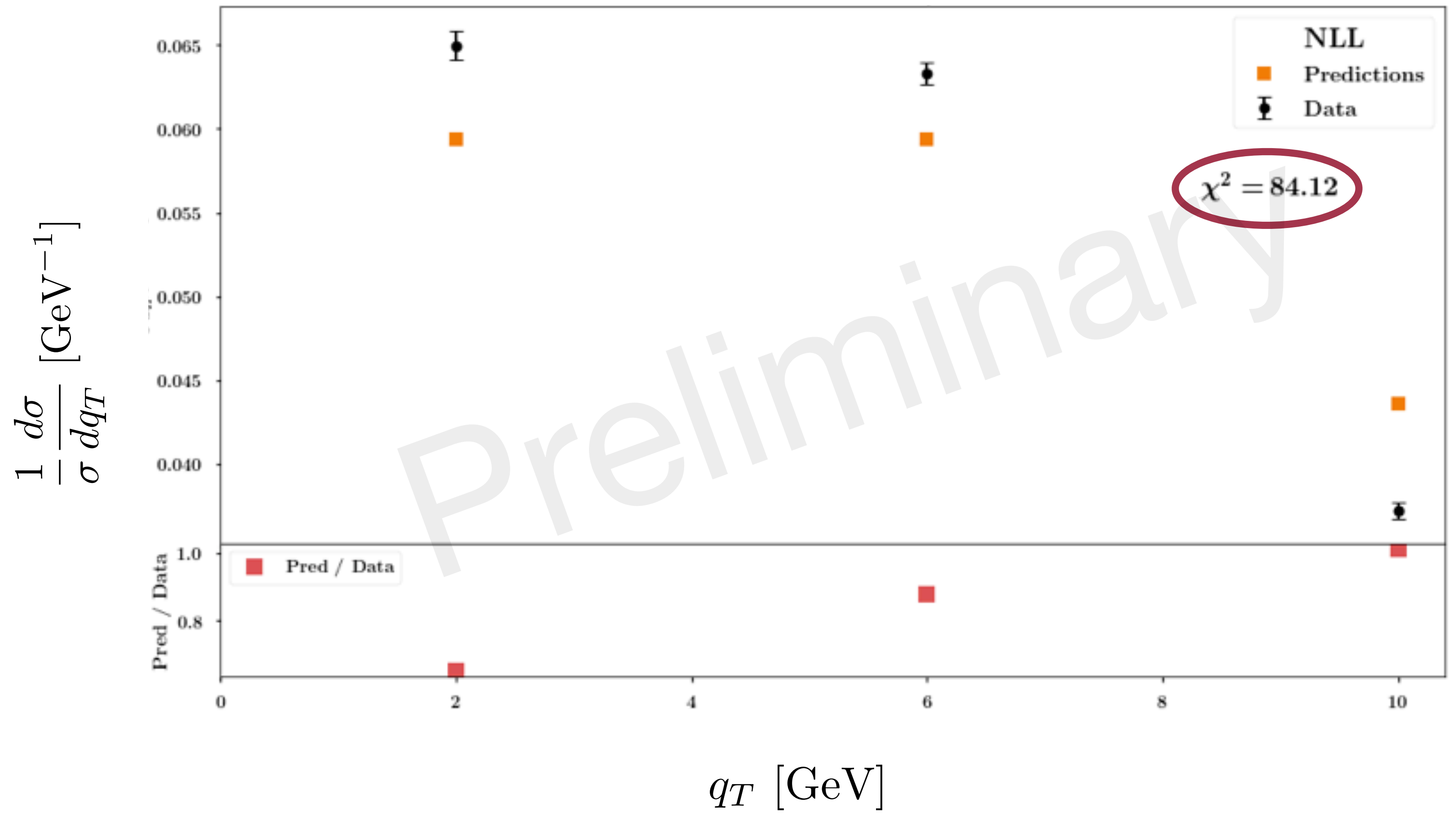


High-Energy Drell-Yan at NLL

CMS 7 TeV



D0 Run II muons

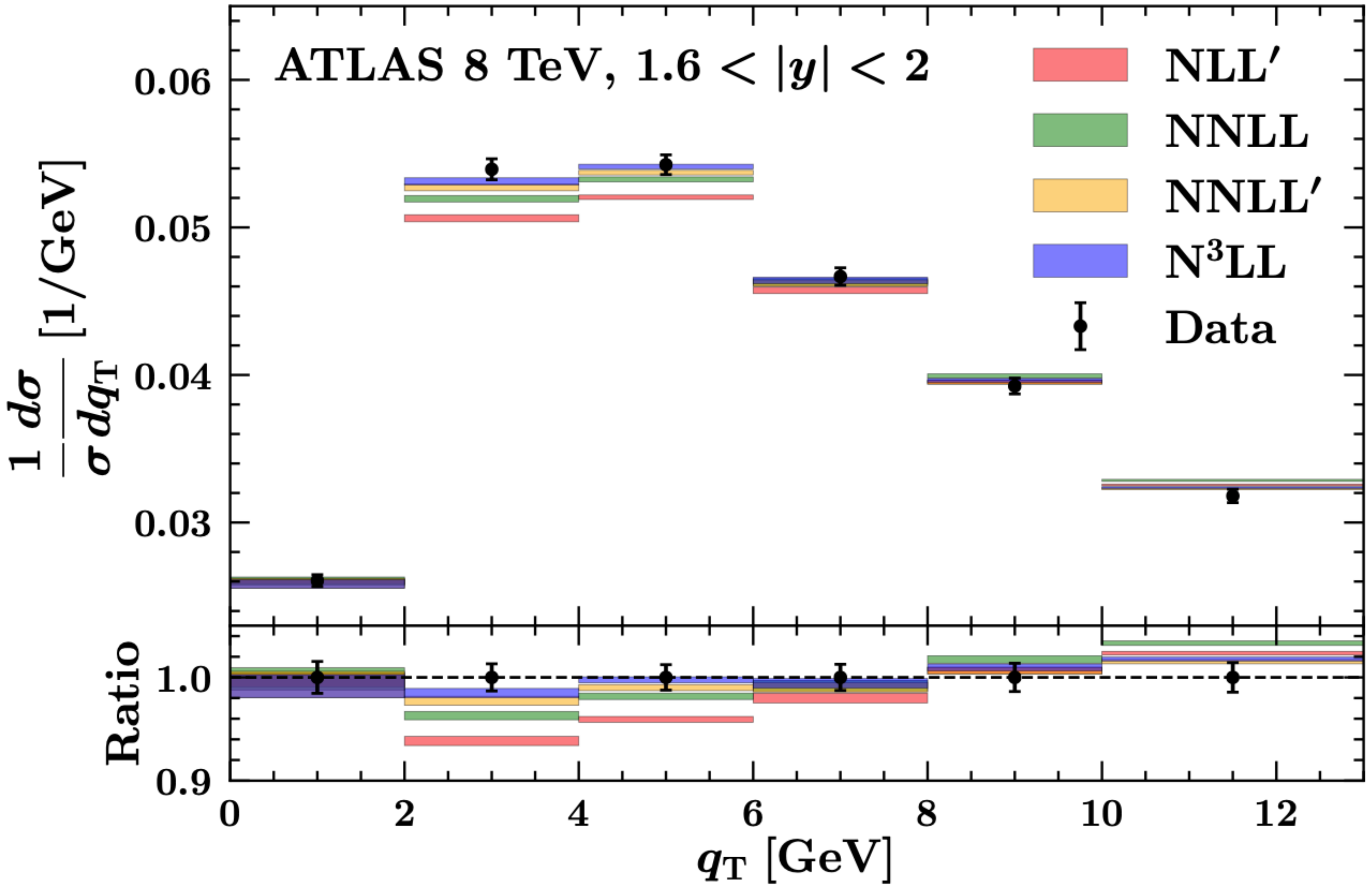


MAPTMD22 — Normalization of SIDIS

MAPTMD22 — Normalization of SIDIS

High-Energy Drell-Yan beyond NLL

$Q \sim 100$ GeV



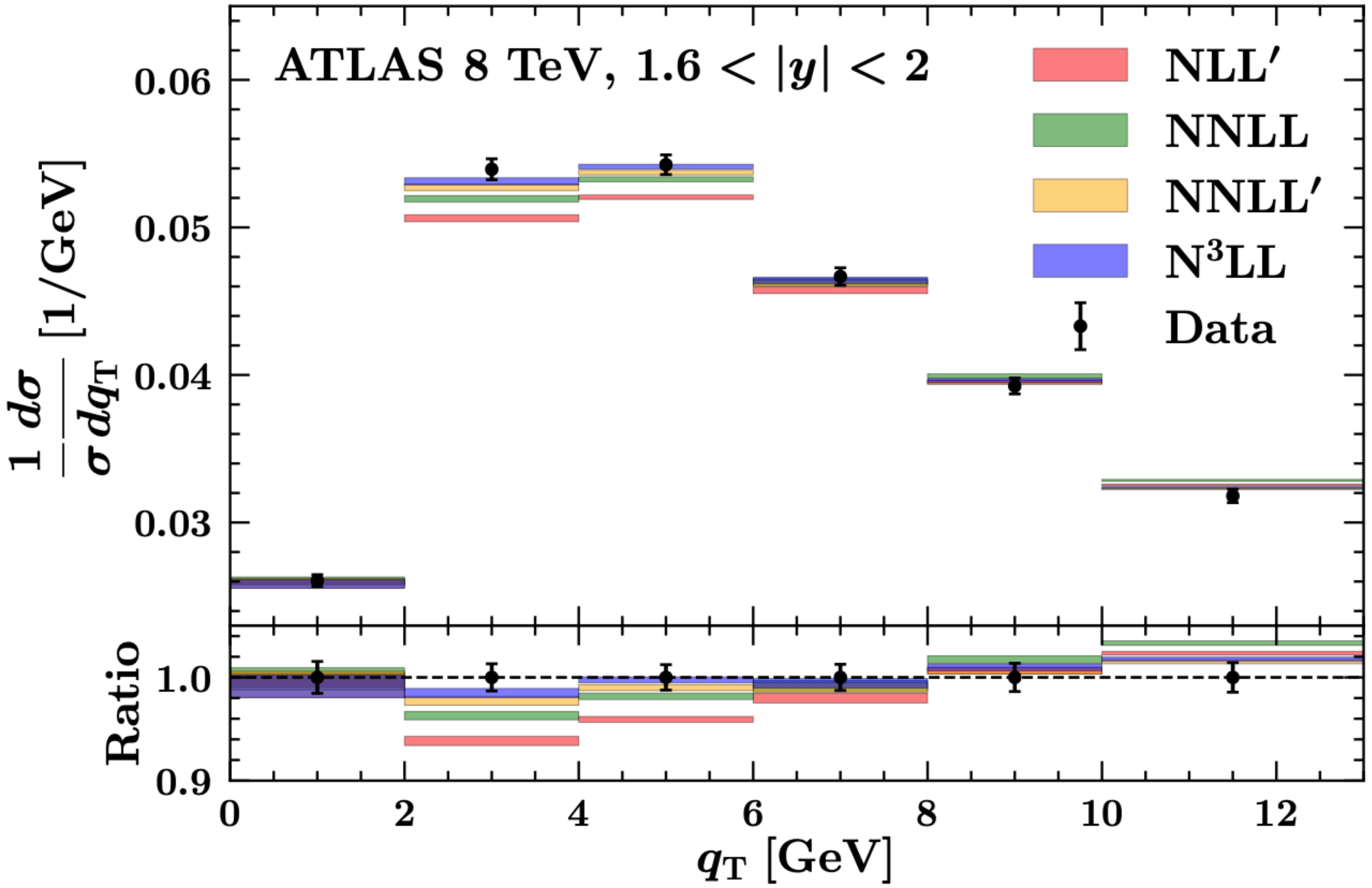
Bacchetta, Bertone, Bissolotti, Bozzi, Delcarro, Piacenza, Radici, arXiv:1912.07550

MAPTMD22 — Normalization of SIDIS

<u>SIDIS multiplicities beyond NLL</u>

<u>High-Energy Drell-Yan beyond NLL</u>

$Q \sim 100$ GeV



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

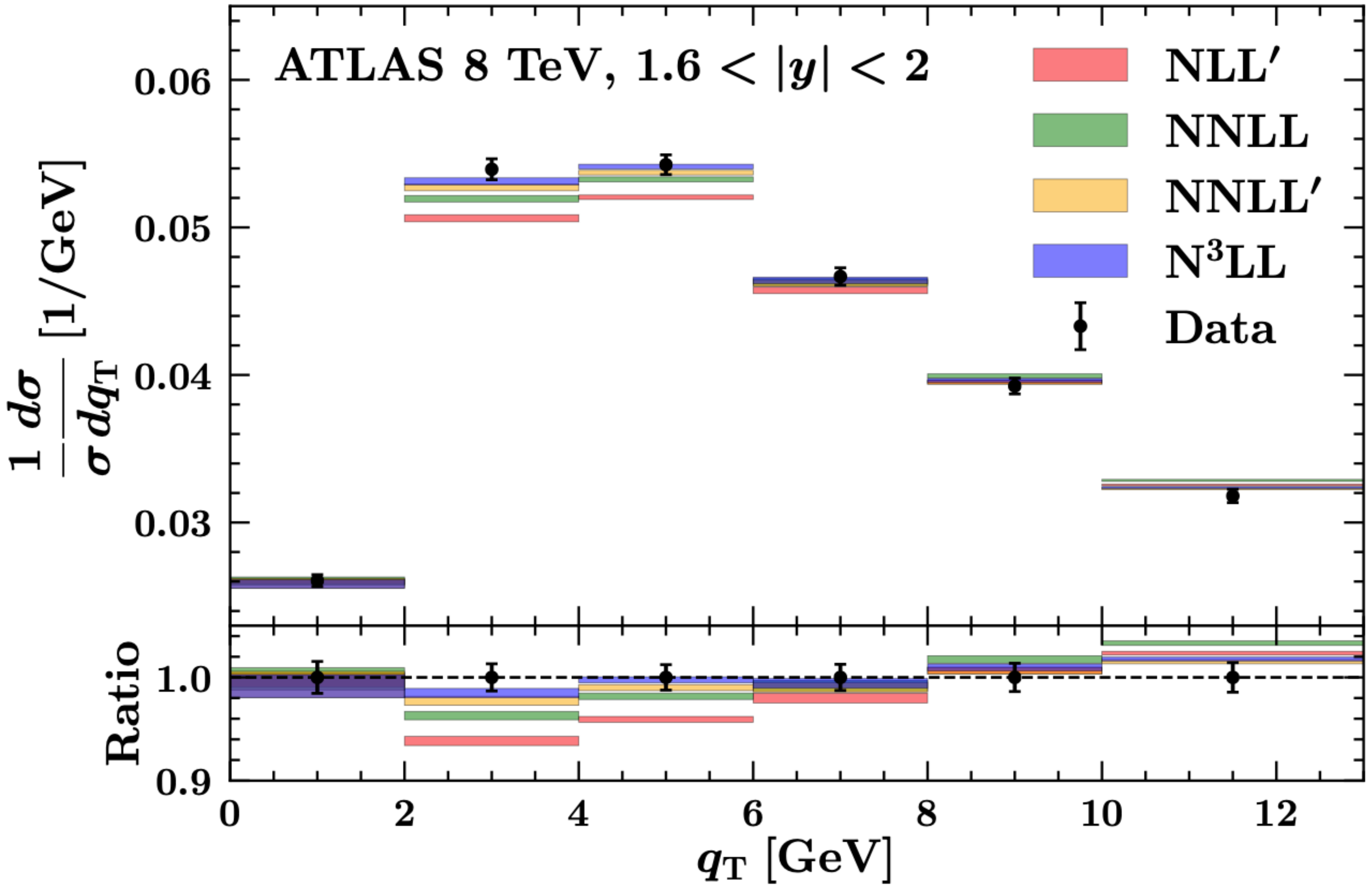
MAPTMD22 — Normalization of SIDIS

SIDIS multiplicities beyond NLL

$\boxed{Q \sim 2 \text{ GeV}}$

High-Energy Drell-Yan beyond NLL

$\boxed{Q \sim 100 \text{ GeV}}$

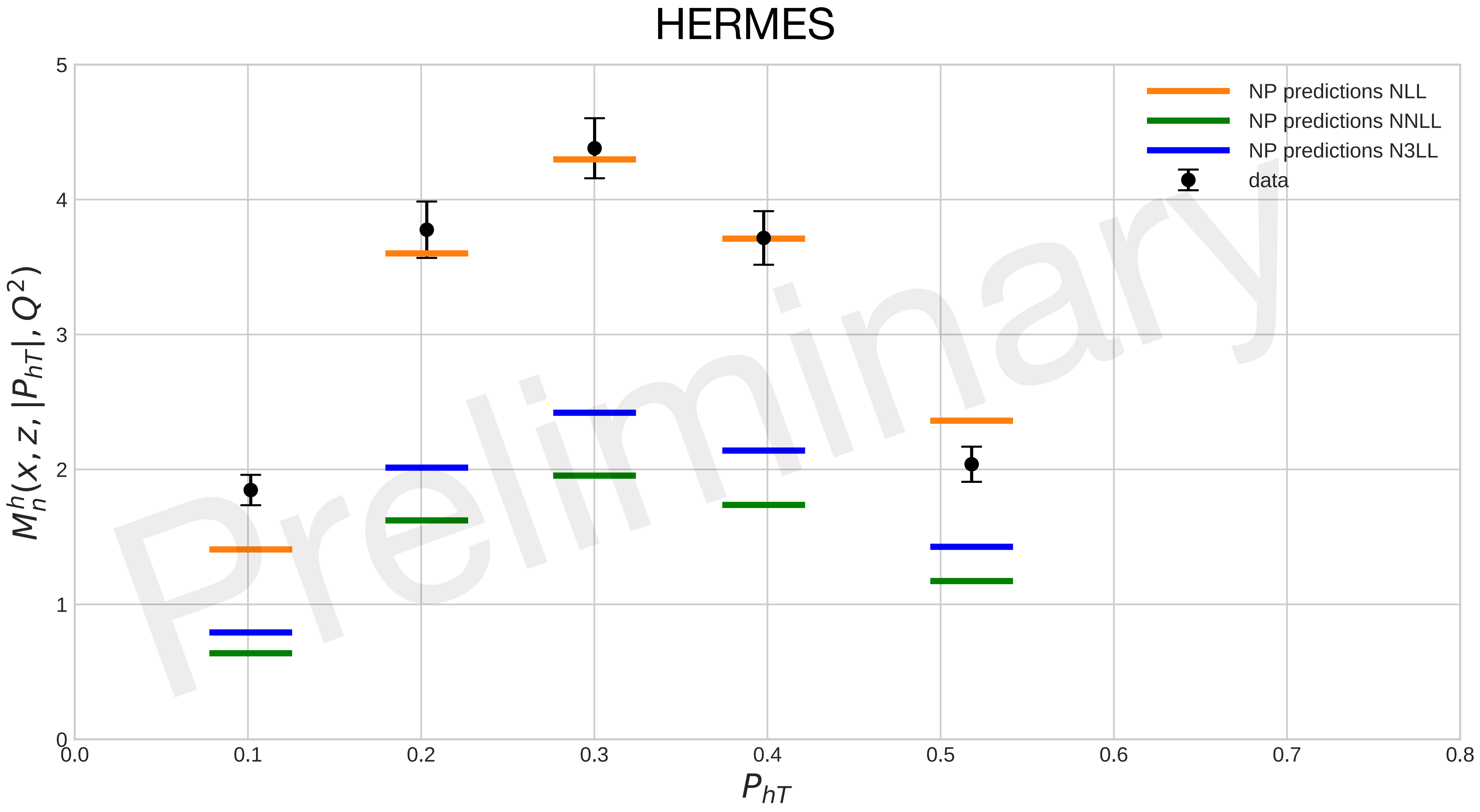


Bacchetta, Bertone, Bissolotti, Bozzi, Delcarro, Piacenza, Radici, arXiv:1912.07550

MAPTMD22 — Normalization of SIDIS

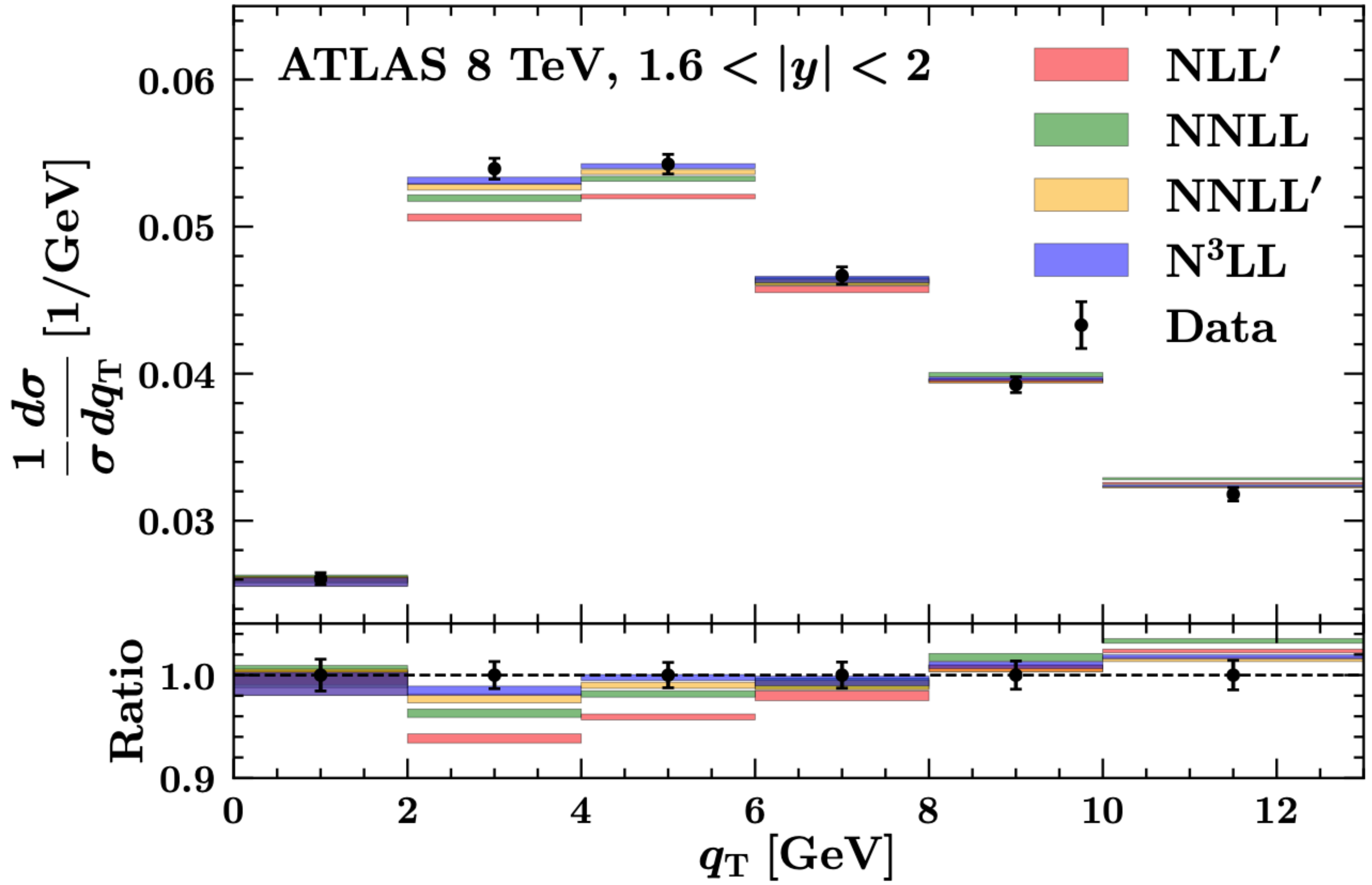
SIDIS multiplicities beyond NLL

$Q \sim 2$ GeV



High-Energy Drell-Yan beyond NLL

$Q \sim 100$ GeV

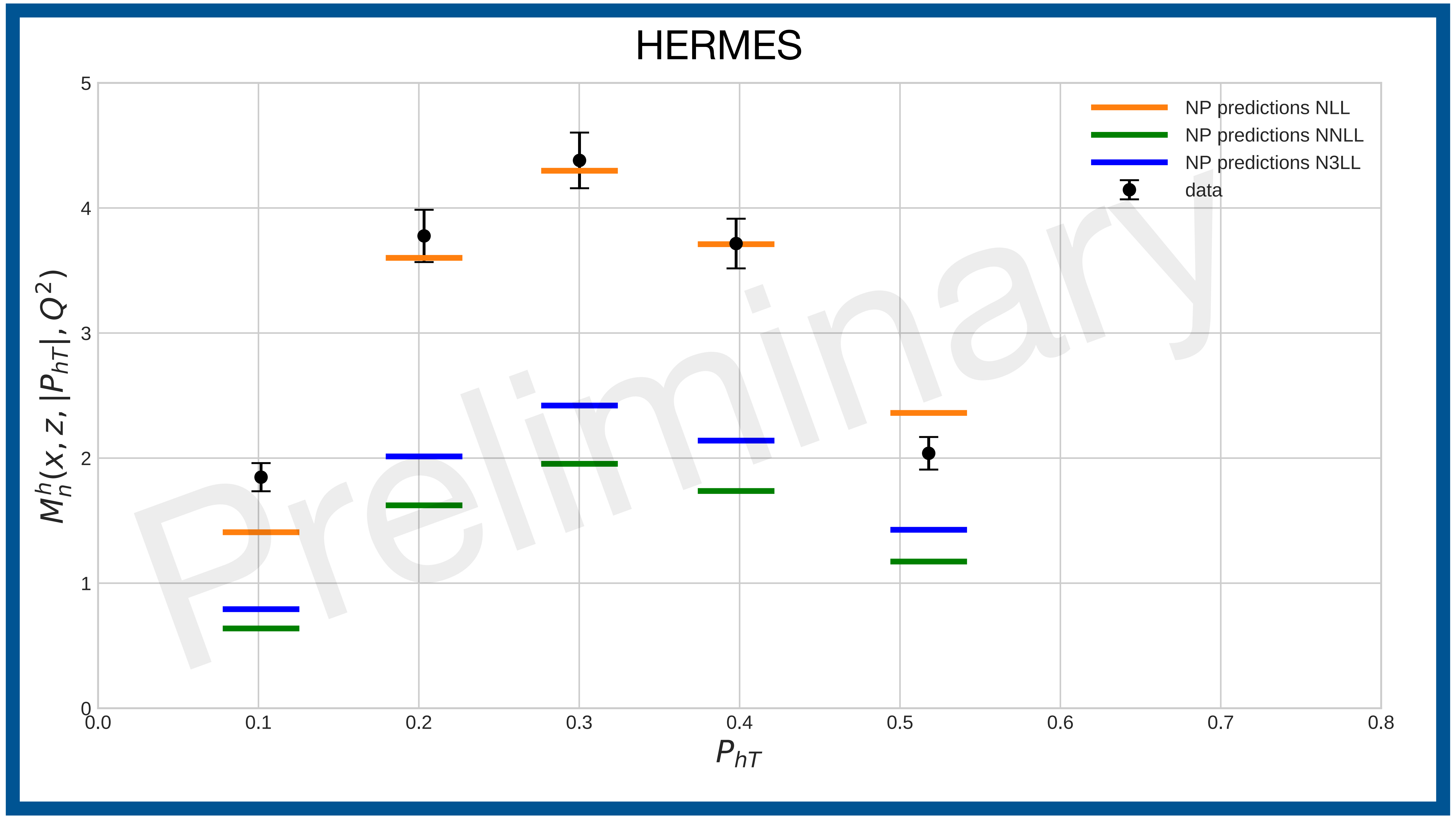


Bacchetta, Bertone, Bissolotti, Bozzi, Delcarro, Piacenza, Radici, arXiv:1912.07550

MAPTMD22 — Normalization of SIDIS

SIDIS multiplicities beyond NLL

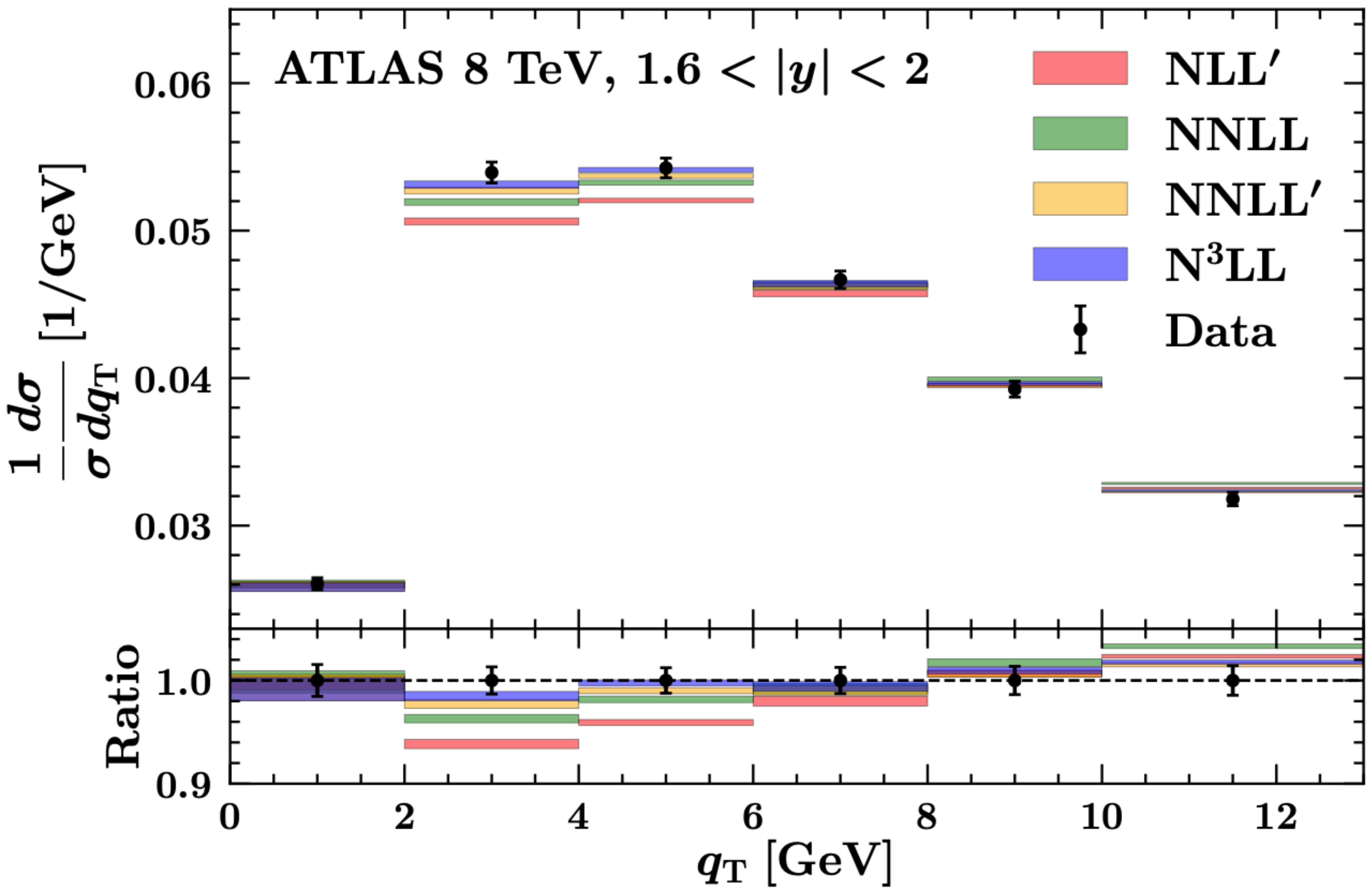
$Q \sim 2$ GeV



The description considerably worsens at higher orders!!

High-Energy Drell-Yan beyond NLL

$Q \sim 100$ GeV

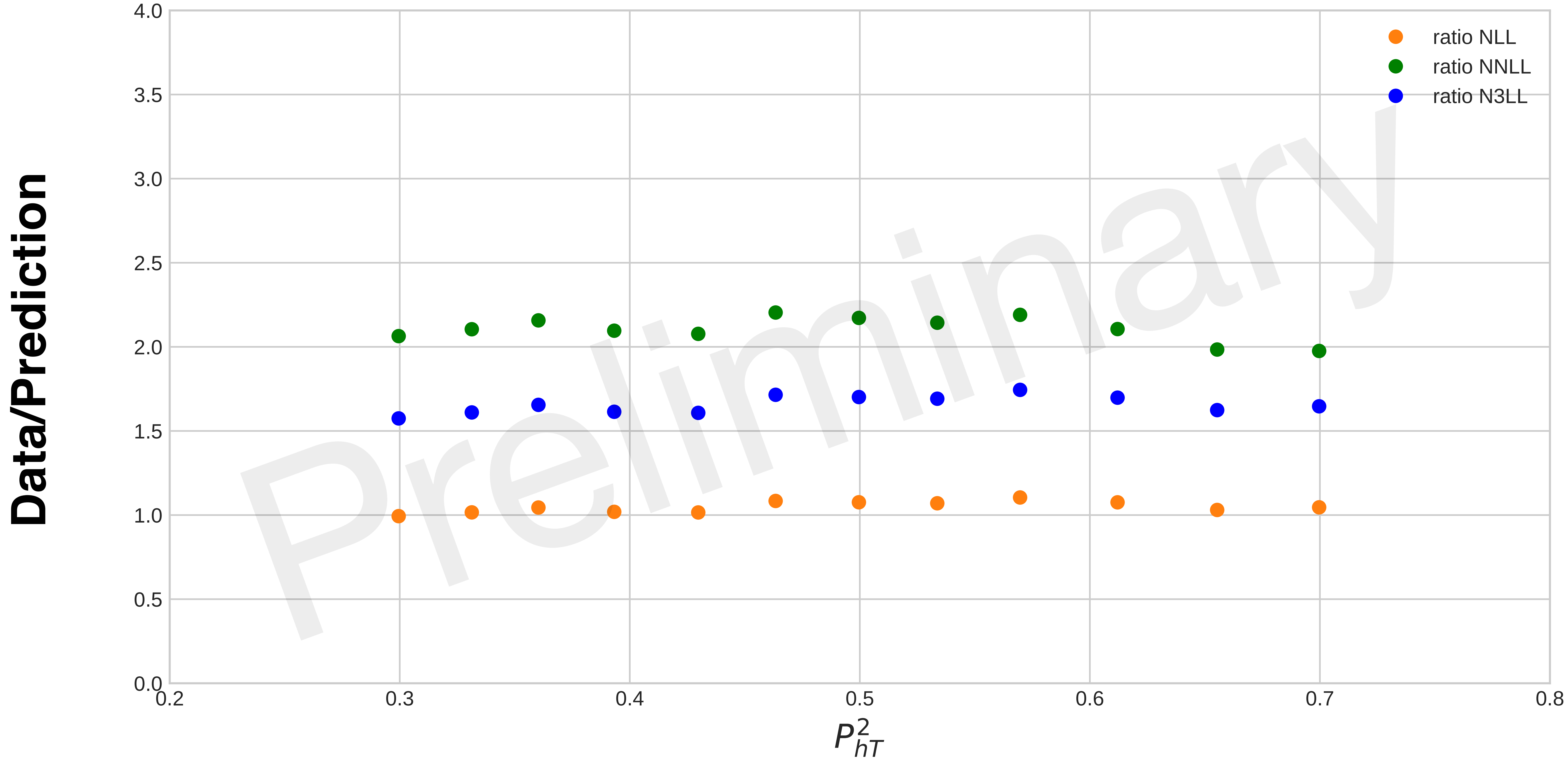


Bacchetta, Bertone, Bissolotti, Bozzi, Delcarro, Piacenza, Radici, arXiv:1912.07550

MAPTMD22 —Normalization of SIDIS

COMPASS multiplicities (one of many bins)

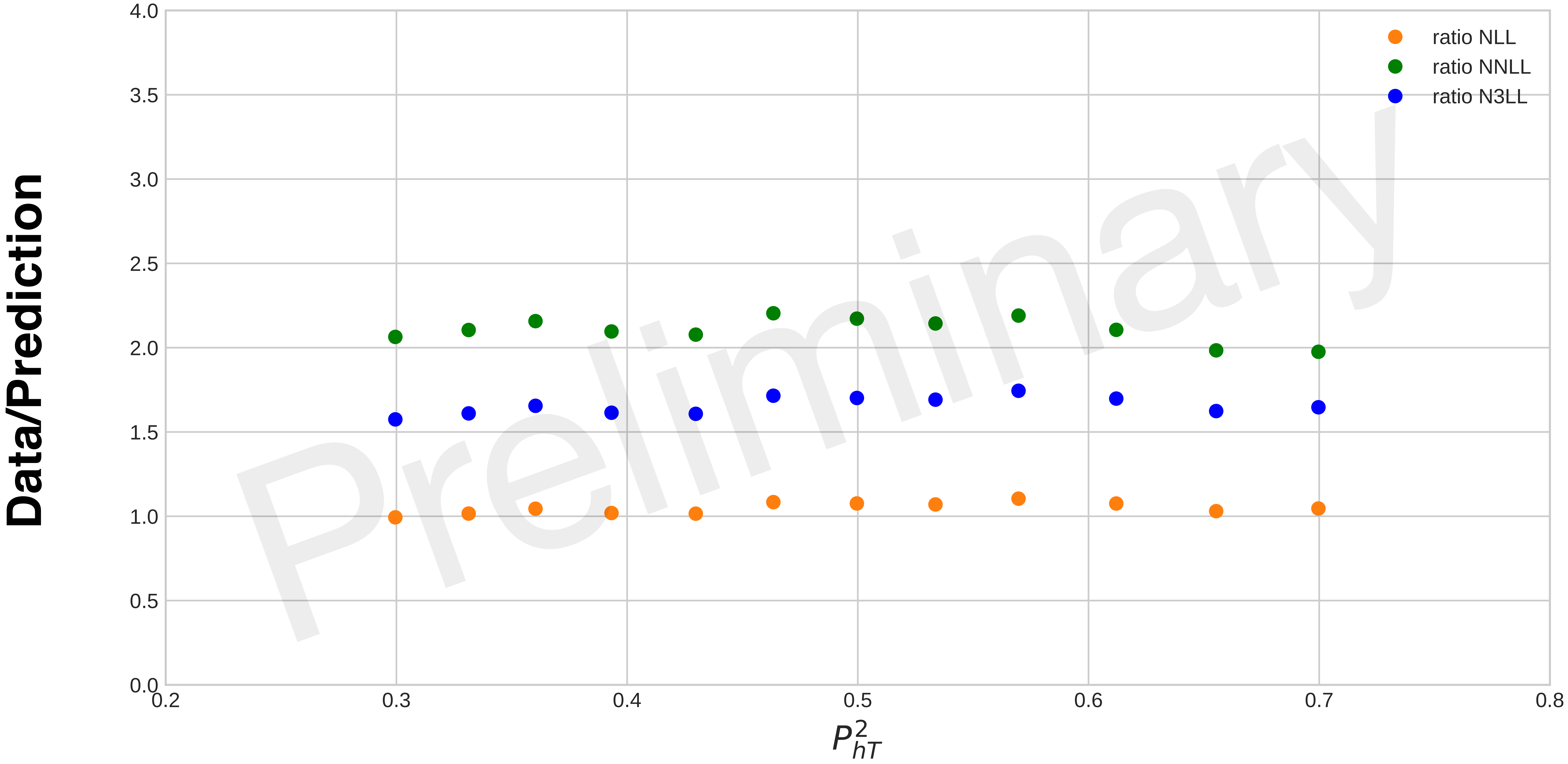
J.O. Gonzalez-Hernandez, PoS DIS2019 (2019) 176



MAPTMD22 —Normalization of SIDIS

COMPASS multiplicities (one of many bins)

J.O. Gonzalez-Hernandez, PoS DIS2019 (2019) 176



The discrepancy amounts to an almost <u>constant factor</u>!!

MAPTMD22 —Normalization of SIDIS

MAPTMD22 —Normalization of SIDIS

SIDIS multiplicity

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

MAPTMD22 —Normalization of SIDIS

SIDIS multiplicity $$M(x, z, P_{hT}, Q) = \frac{d\sigma}{dx dQ dz dP_{hT}} \Bigg/ \frac{d\sigma}{dx dQ}$$

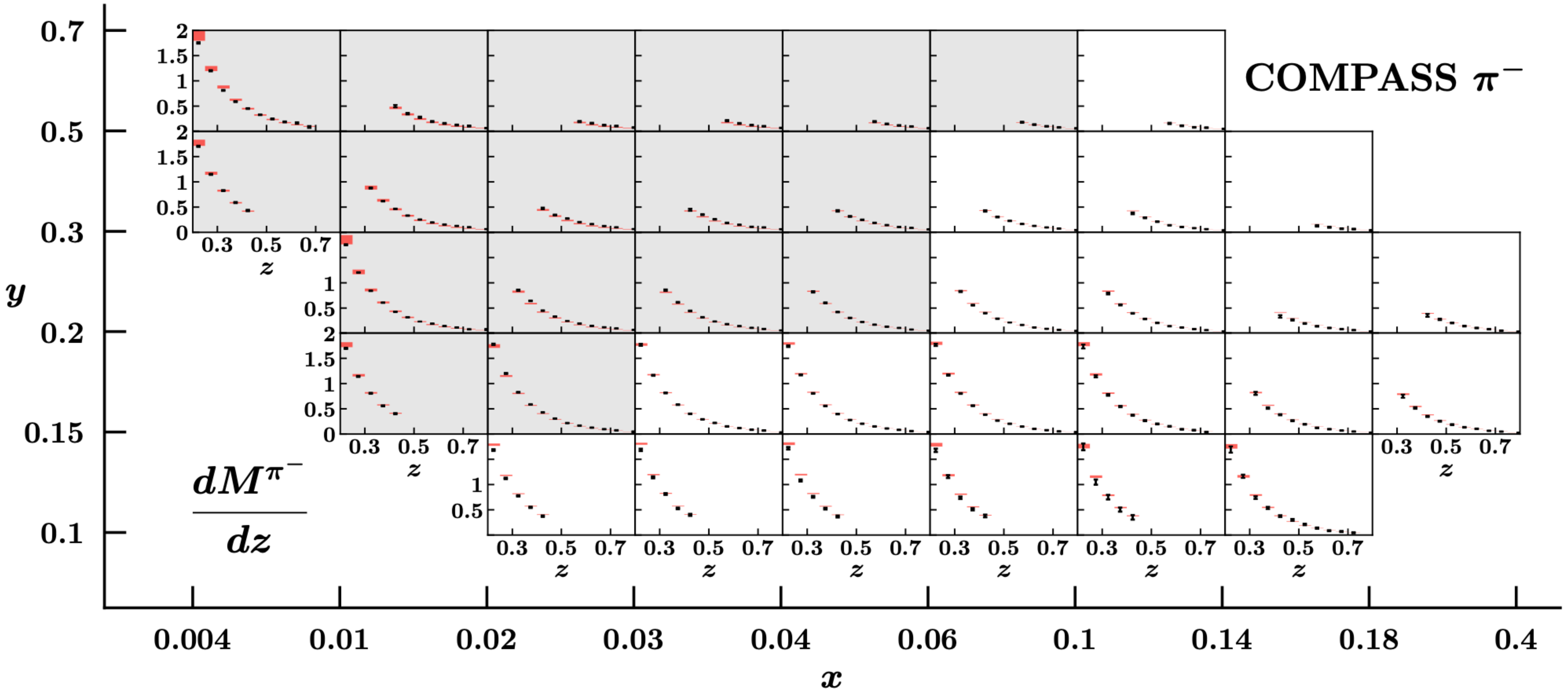
Collinear SIDIS cross section $$\frac{d\sigma}{dx dQ dz}$$

MAPTMD22 —Normalization of SIDIS

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

Collinear SIDIS cross section
$$\frac{d\sigma}{dxdQ\color{red}{dz}}$$

No problems of normalization!!



Khalek, Bertone, Nocera, arXiv: 2105.08725

MAPTMD22 —Normalization of SIDIS

SIDIS multiplicity

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

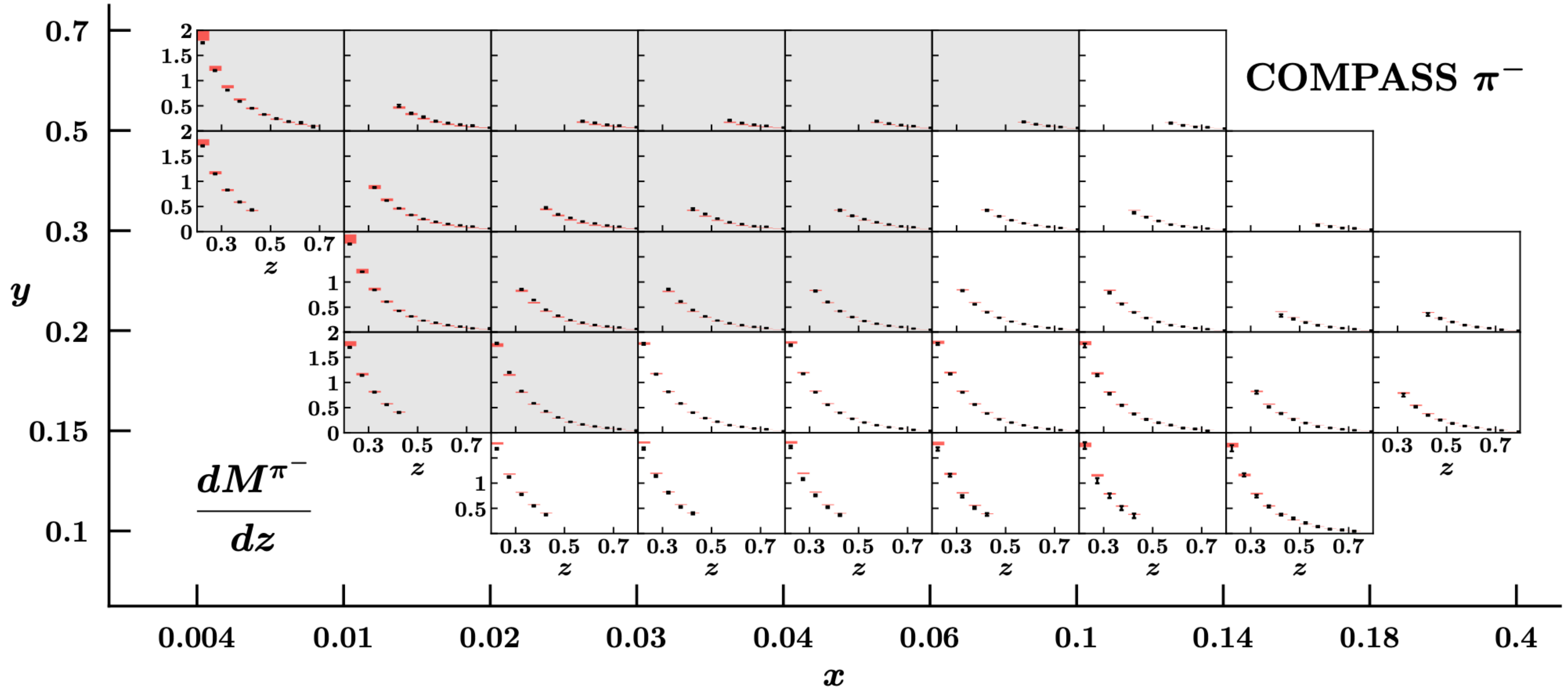
Collinear SIDIS cross section

$$\frac{d\sigma}{dx dQ dz}$$

No problems of normalization!!

Normalization of prediction such that

$$\int dP_{hT} \frac{d\sigma}{dx dQ dz dP_{hT}} = \frac{d\sigma}{dx dQ dz}$$



Khalek, Bertone, Nocera, arXiv: 2105.08725

MAPTMD22 —Normalization of SIDIS

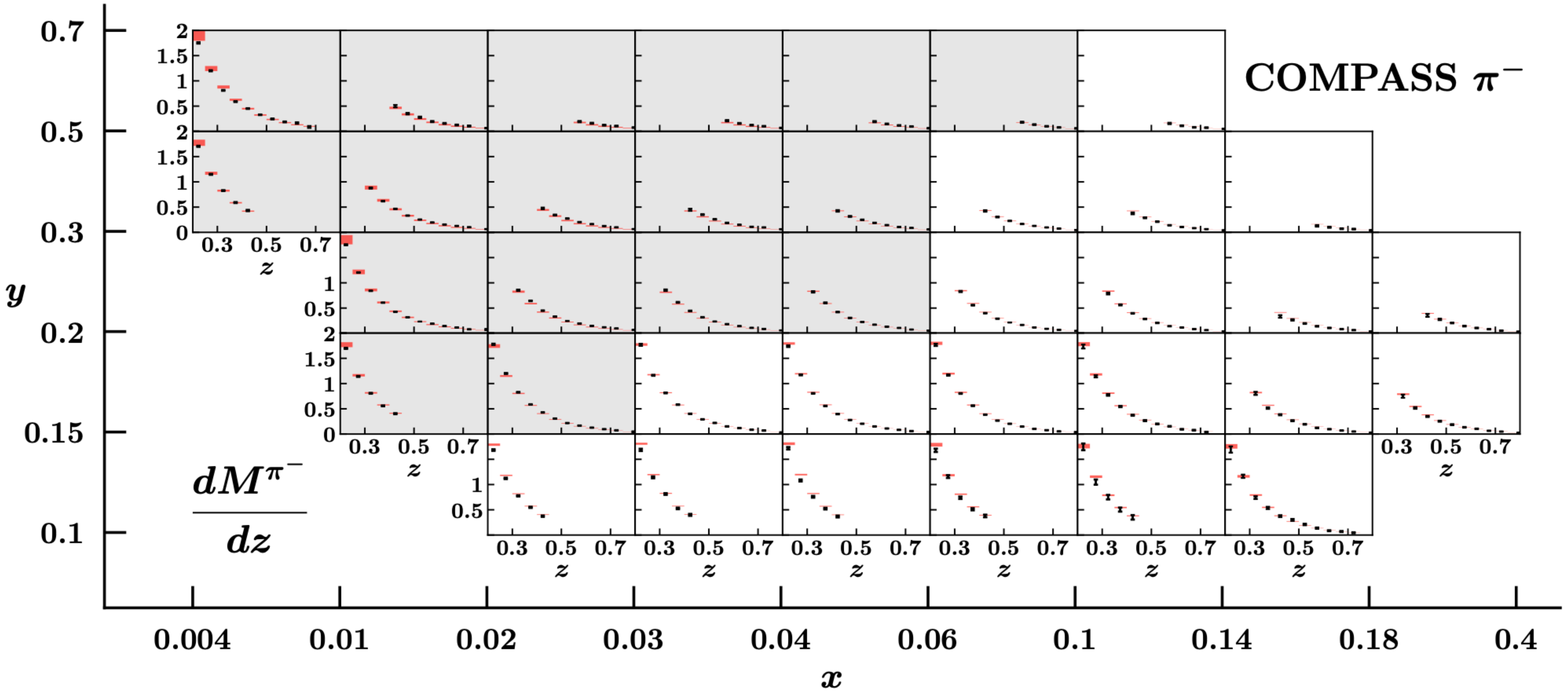
SIDIS multiplicity $$M(x,z,P_{hT},Q) = \frac{d\sigma}{dxdQdzdP_{hT}} \Big/ \frac{d\sigma}{dxdQ}$$

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

No problems of normalization!!

Normalization of prediction such that

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



Khalek, Bertone, Nocera, arXiv: 2105.08725

MAPTMD22 —Normalization of SIDIS

SIDIS multiplicity $M(x,z,P_{hT},Q) = \dfrac{d\sigma}{dx\,dQ\,dz\,dP_{hT}} \Big/ \dfrac{d\sigma}{dx\,dQ}$

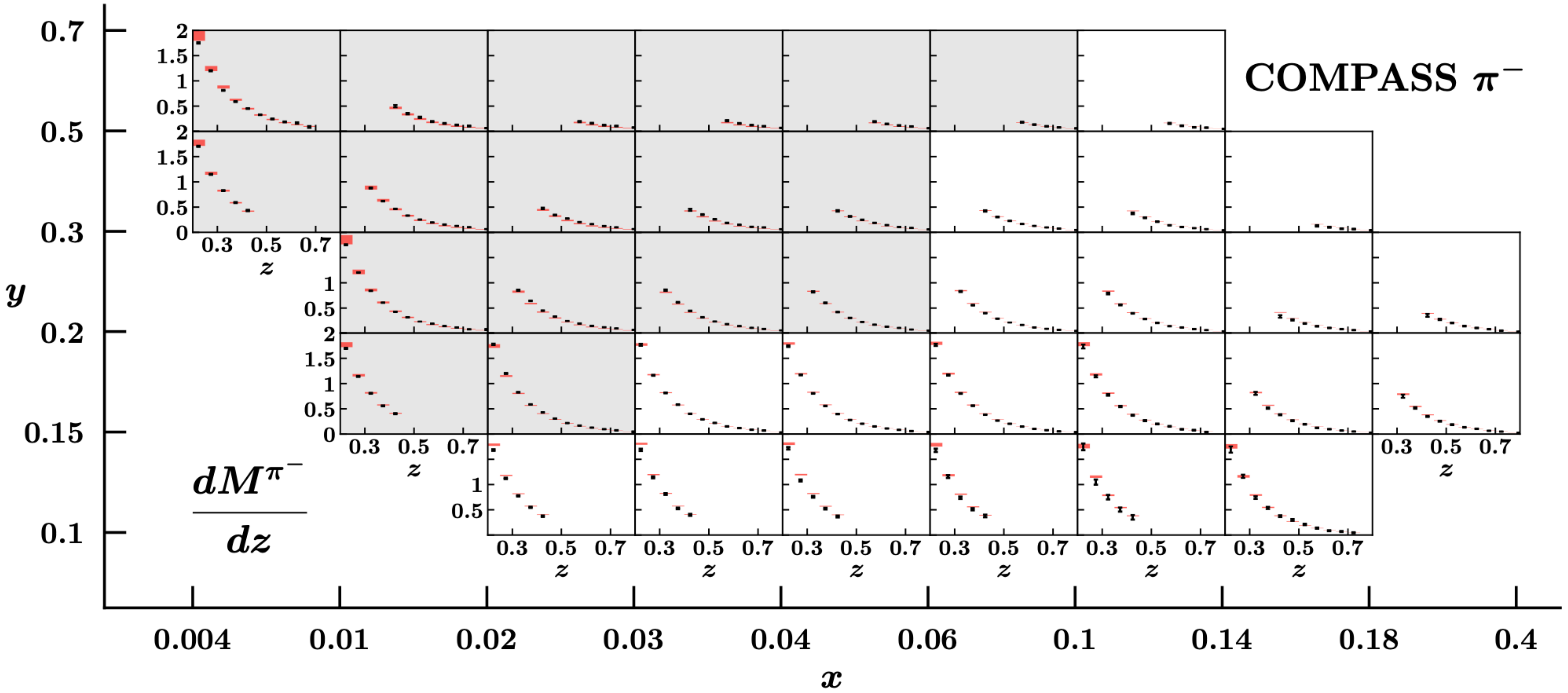
Collinear SIDIS cross section $\dfrac{d\sigma}{dx\,dQ\,dz}$

No problems of normalization!!

Normalization of prediction such that

$$\boxed{w(x,z,Q) = \frac{d\sigma}{dx\,dQ\,dz} \Big/ \int dP_{hT} \frac{d\sigma}{dx\,dQ\,dz\,dP_{hT}}}$$

$$M(x,z,P_{hT},Q) = \boxed{w(x,z,Q)} \frac{d\sigma}{dx\,dQ\,dz\,dP_{hT}} \Big/ \frac{d\sigma}{dx\,dQ}$$



Khalek, Bertone, Nocera, arXiv: 2105.08725

MAPTMD22 —Normalization of SIDIS

SIDIS multiplicity $$M(x, z, P_{hT}, Q) = \frac{d\sigma}{dx dQ dz dP_{hT}} \Big/ \frac{d\sigma}{dx dQ}$$

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

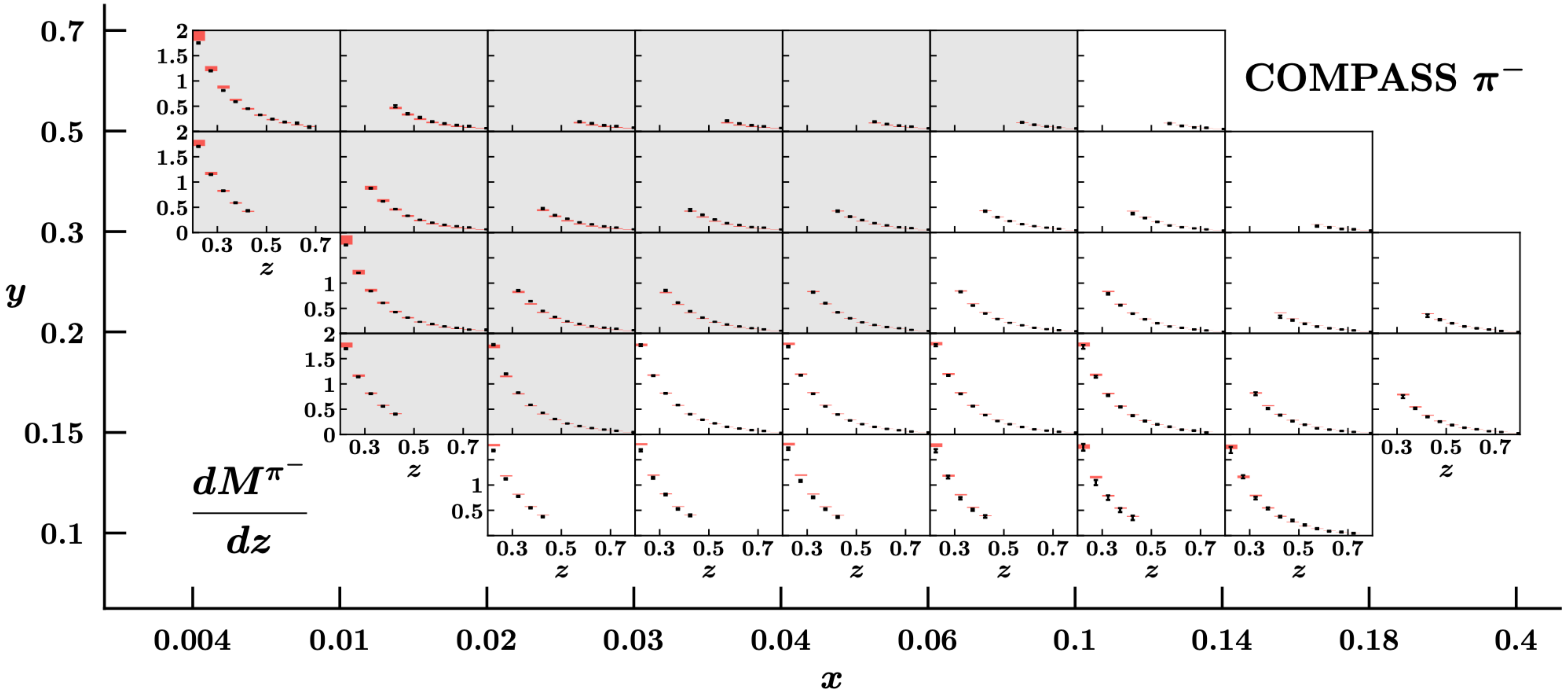
No problems of normalization!!

Normalization of prediction such that

$$\boxed{w(x, z, Q) = \frac{d\sigma}{dx dQ dz} \Big/ \int dP_{hT} \frac{d\sigma}{dx dQ dz dP_{hT}}}$$

$$M(x, z, P_{hT}, Q) = \boxed{w(x, z, Q)} \frac{d\sigma}{dx dQ dz dP_{hT}} \Big/ \frac{d\sigma}{dx dQ}$$

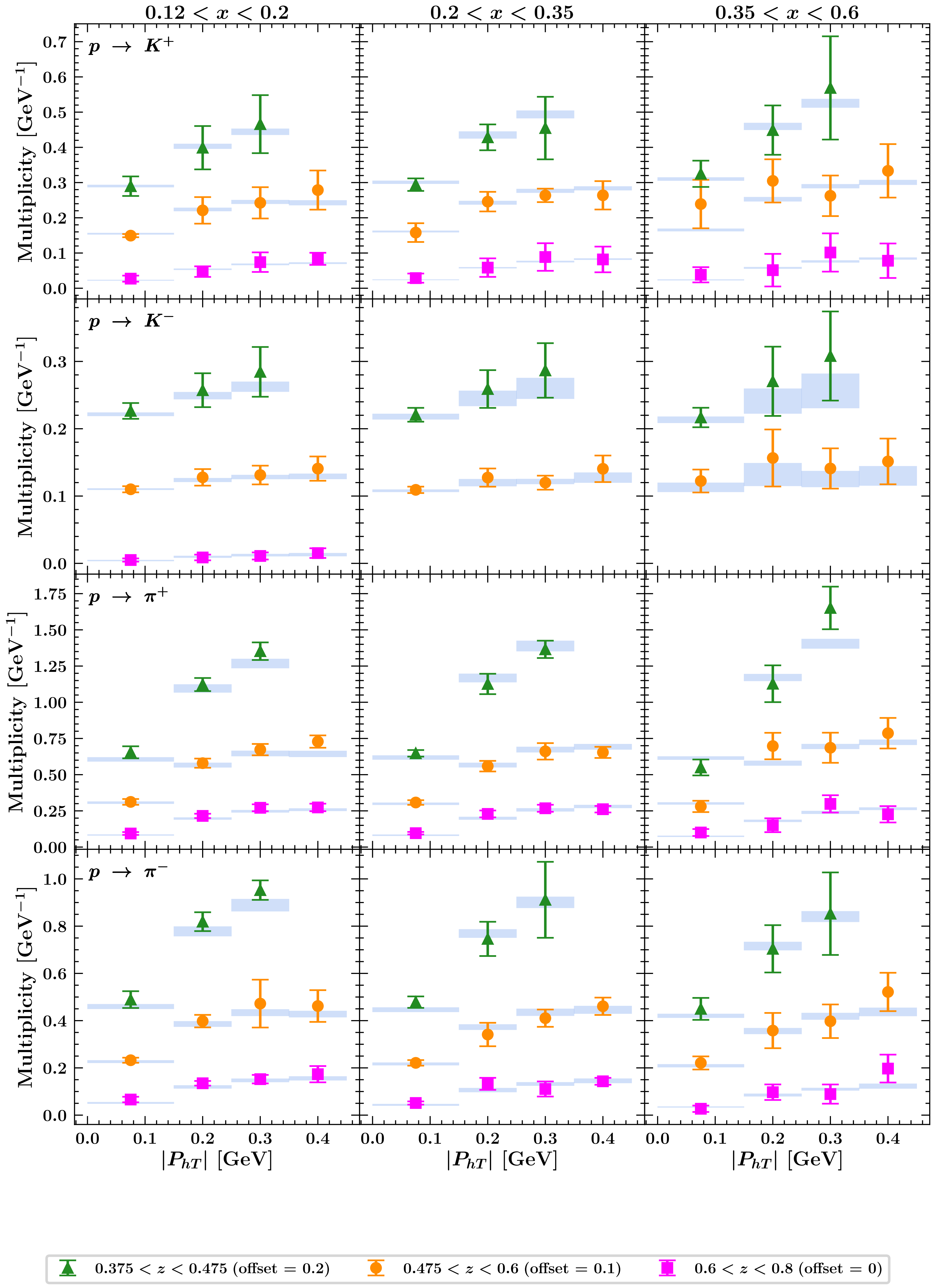
Independent of the fitting parameters!!

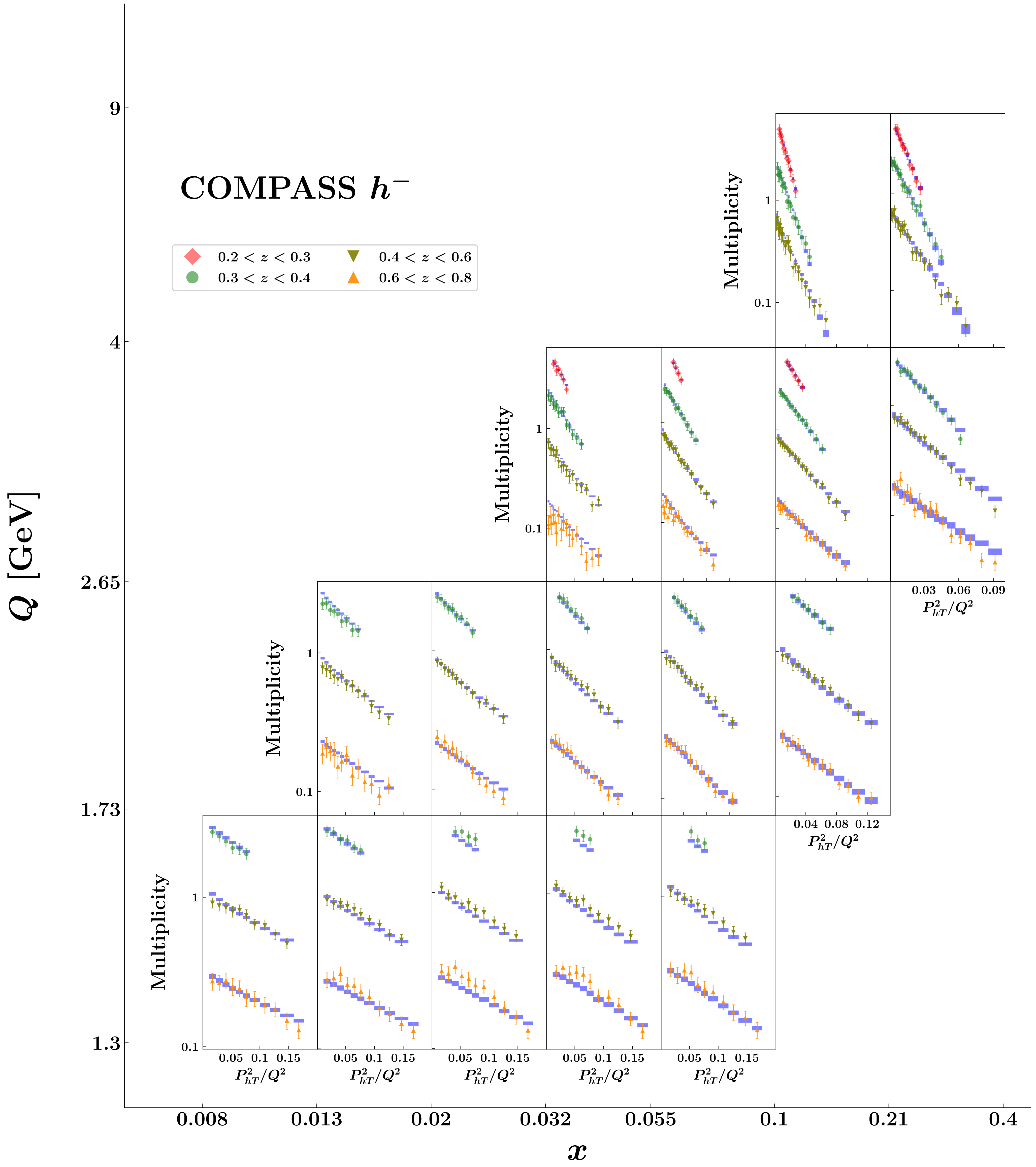


Khalek, Bertone, Nocera, arXiv: 2105.08725

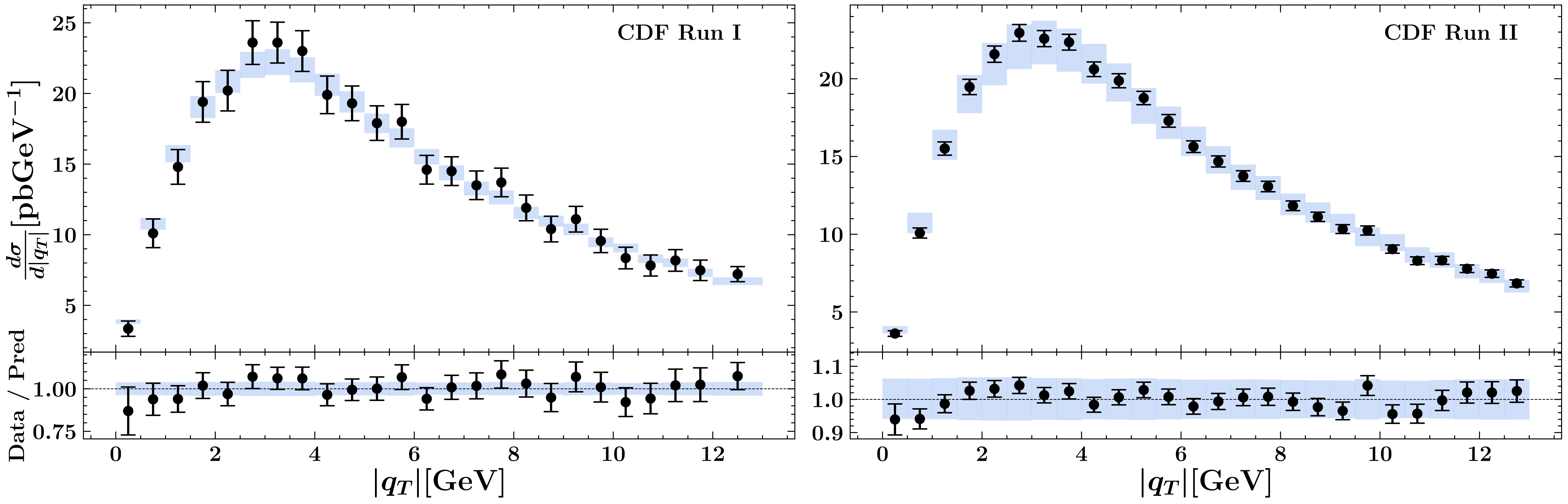
MAPTMD22 — Results of the fit $\chi^2/N_{data} = 1.06$

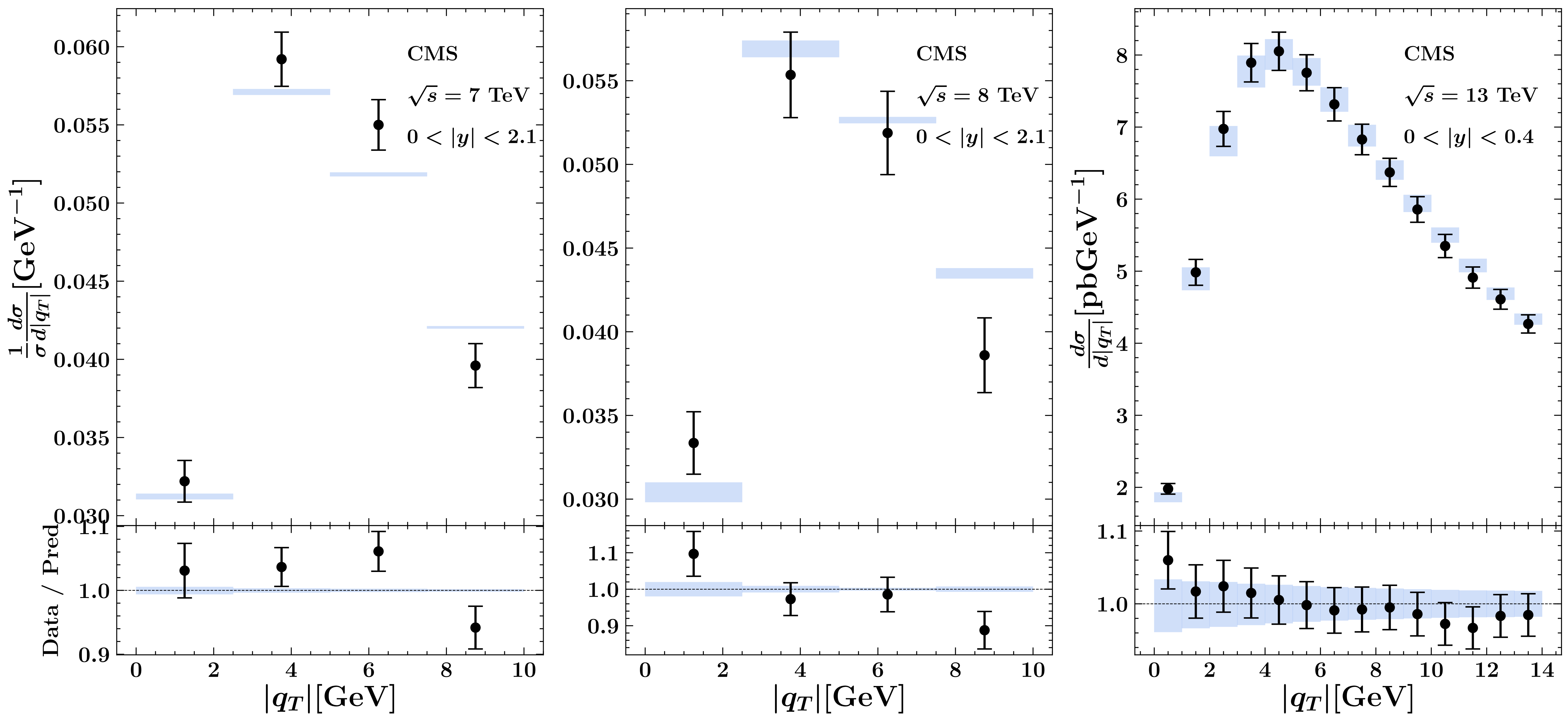
HERMES

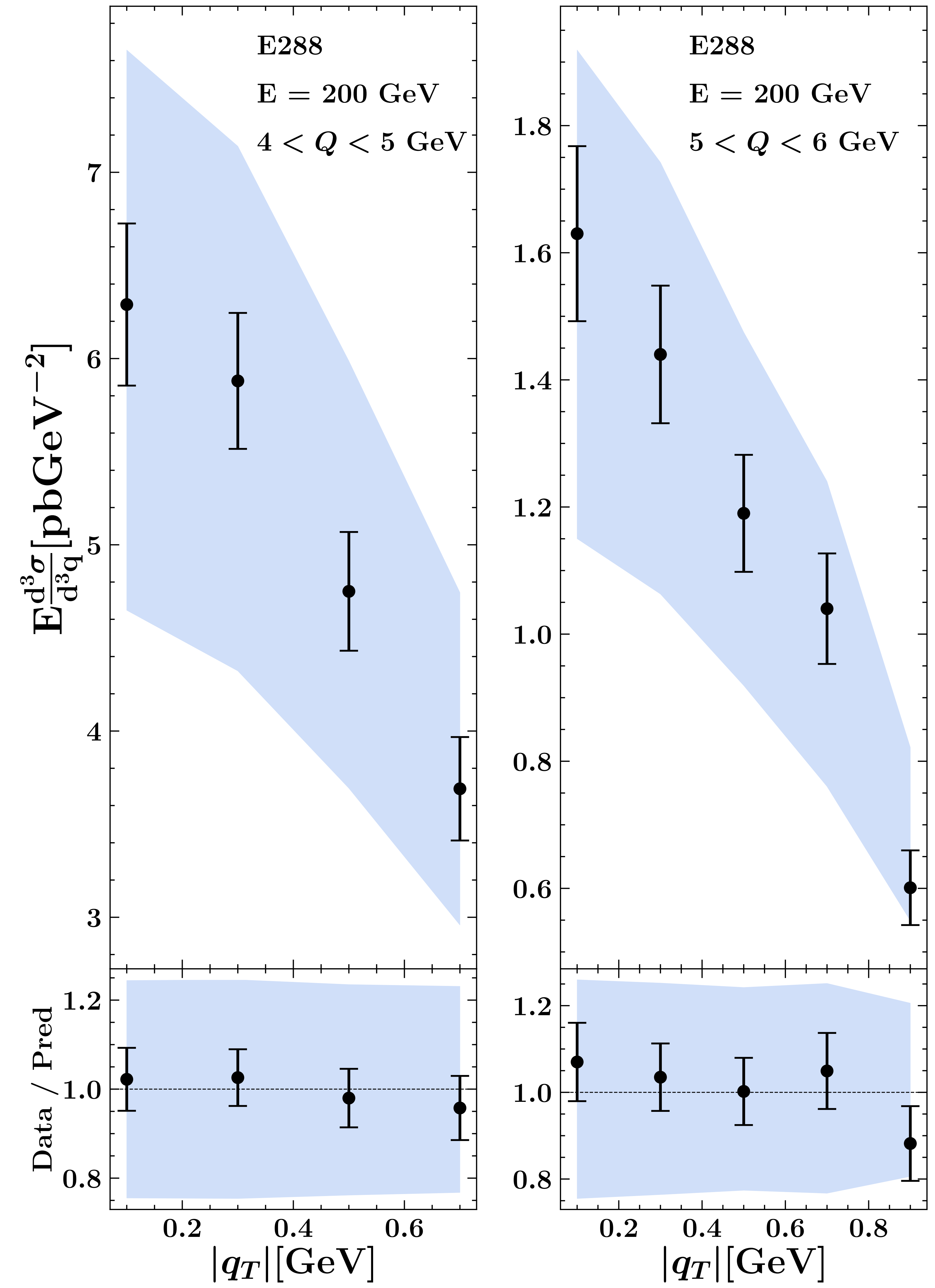




MAPTMD22 — Results of the fit $\chi^2/N_{data} = 1.06$

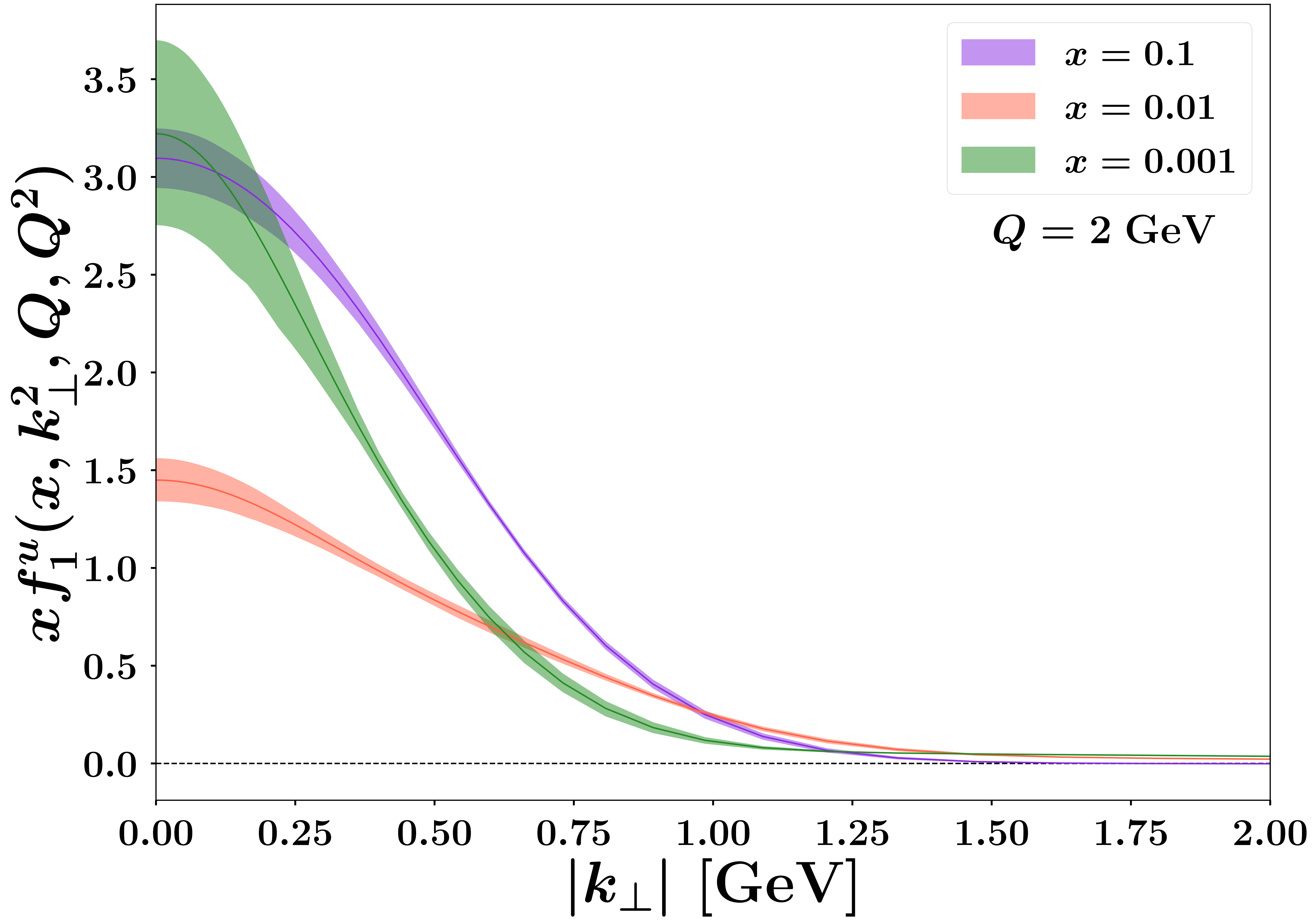


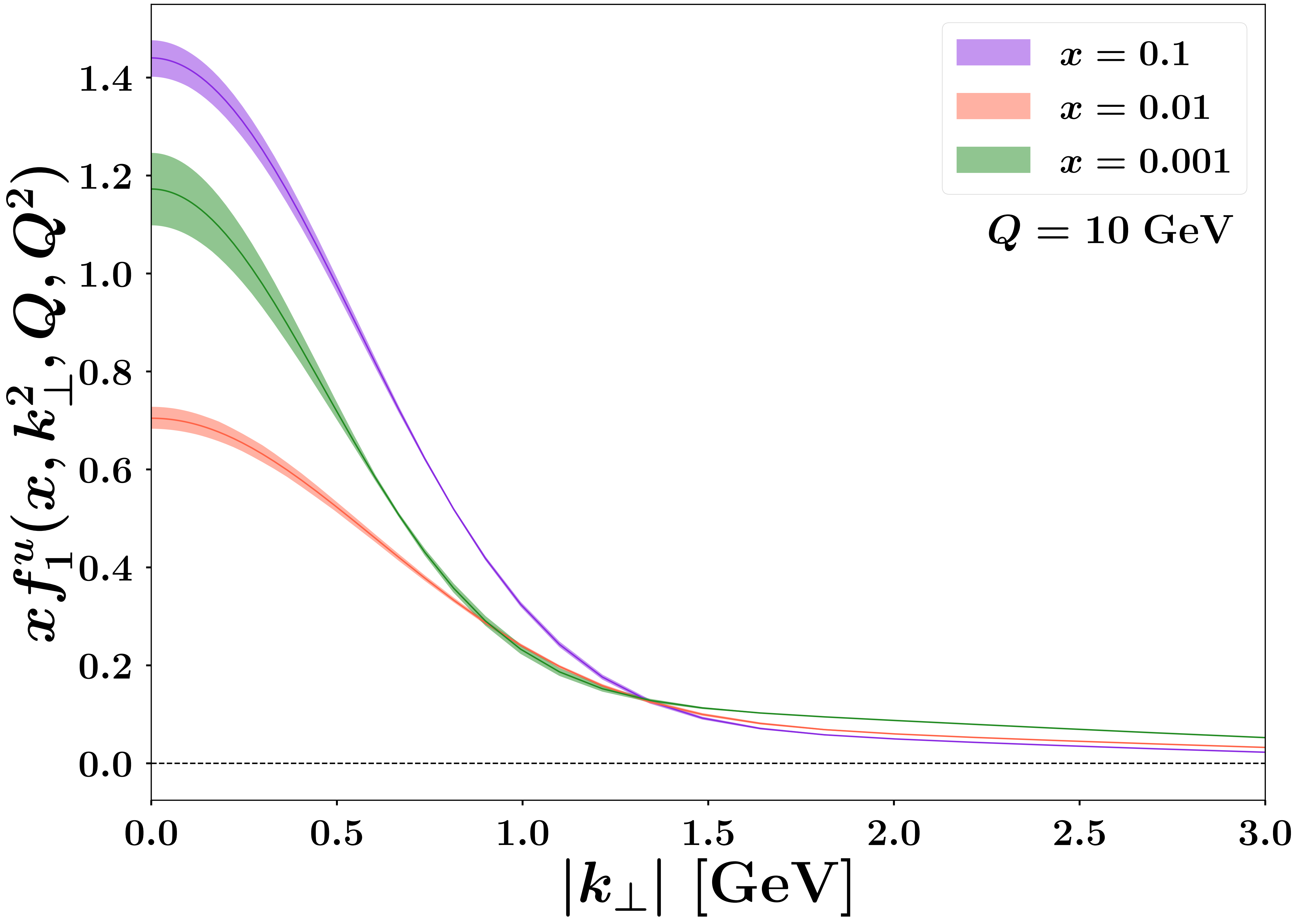




MAPTMD22 — Output of the fit

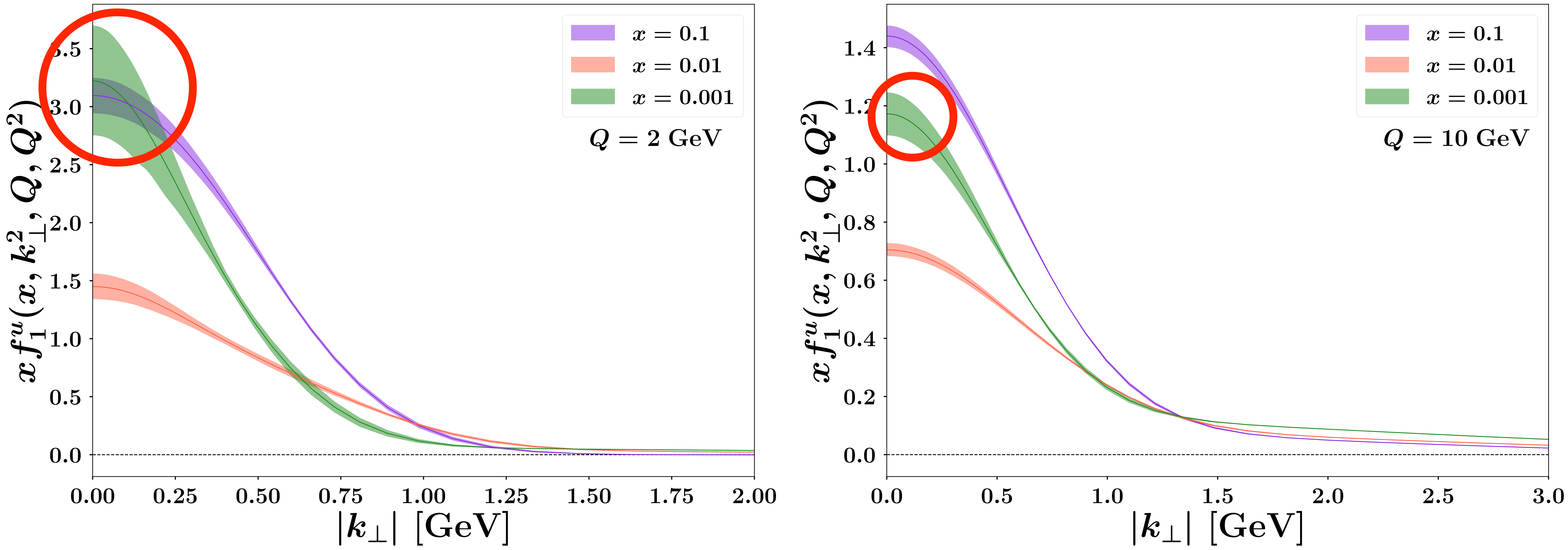
Visualisation of TMD PDFs





MAPTMD22 — Output of the fit

Visualisation of TMD PDFs



MAPTMD22 — Output of the fit

Collins-Soper kernel

MAPTMD22 — Output of the fit

Collins-Soper kernel

Kernel of the rapidity evolution equation

$$\frac{\partial \ln \hat{f}_1(x, b_T; \mu, \zeta)}{\partial \ln \sqrt{\zeta}} = K(b_T, \mu)$$

$$K(b_T, \mu_b) = K_{\text{pert}} + g_K(b_T)$$

MAPTMD22 — Output of the fit

Collins-Soper kernel

Kernel of the rapidity evolution equation

$$\frac{\partial \ln \hat{f}_1(x, b_T; \mu, \zeta)}{\partial \ln \sqrt{\zeta}} = K(b_T, \mu)$$

$$K(b_T, \mu_b) = K_{\text{pert}} + g_K(b_T)$$

perturbatively calculable

MAPTMD22 — Output of the fit

Collins-Soper kernel

Kernel of the rapidity evolution equation

$$\frac{\partial \ln \hat{f}_1(x, b_T; \mu, \zeta)}{\partial \ln \sqrt{\zeta}} = K(b_T, \mu)$$

$$K(b_T, \mu_b) = K_{\text{pert}} + g_K(b_T)$$

to be fitted

perturbatively calculable

MAPTMD22 — Output of the fit

Collins-Soper kernel

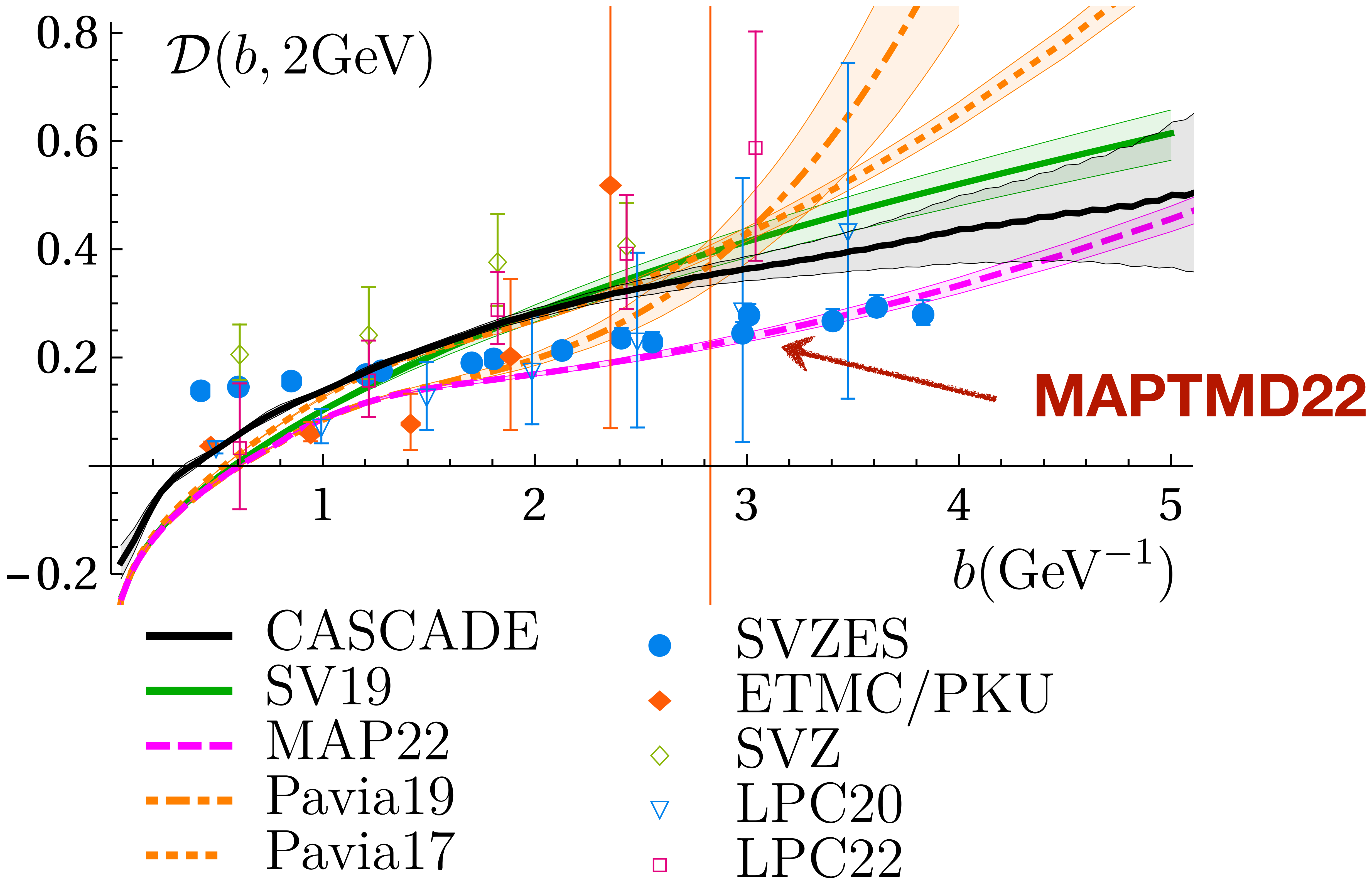
Kernel of the rapidity evolution equation

$$\frac{\partial \ln \hat{f}_1(x, b_T; \mu, \zeta)}{\partial \ln \sqrt{\zeta}} = K(b_T, \mu)$$

$$K(b_T, \mu_b) = K_{\text{pert}} + g_K(b_T)$$

to be fitted

perturbatively calculable



Martinez, Vladimirov, arXiv:2206.01105

Outlook and Conclusions

Outlook and Conclusions

- To build a map of the internal structure of hadrons we need to study TMDs

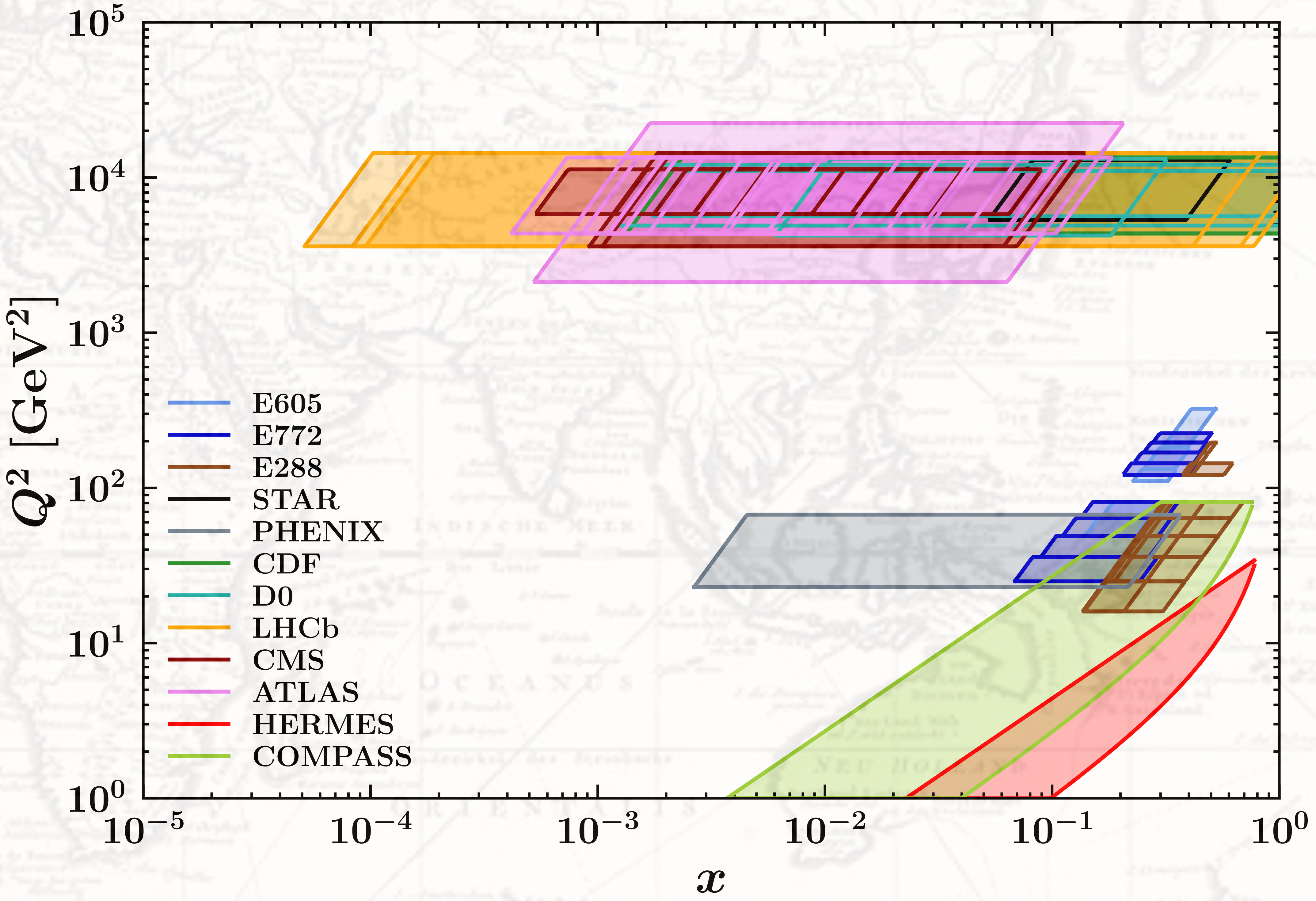
Outlook and Conclusions

- To build a map of the internal structure of hadrons we need to study TMDs

Present…

- MAPTMD22 is the most recent extraction of TMDs through global fits

MAPTMD22



Outlook and Conclusions

- To build a map of the internal structure of hadrons we need to study TMDs

Present…

- MAPTMD22 is the most recent extraction of TMDs through global fits

Future…

- The EIC machine will provide us a large amount of experimental data which will allow us to better constrain TMDs

MAPTMD22 + EIC