Status of TMD extractions

Andrea Signori

Hadronic physics with
lepton and hadron beams

Sept. 5th 2017

Outline of the talk

1) Transverse-Momentum-Dependent distributions (**TMDs**)

2) **formalism**

2) **extractions** : unpolarized

3) **extractions** : polarized (Sivers)

4) **gluon** TMDs

5) **spin-1** TMDs

TMDs

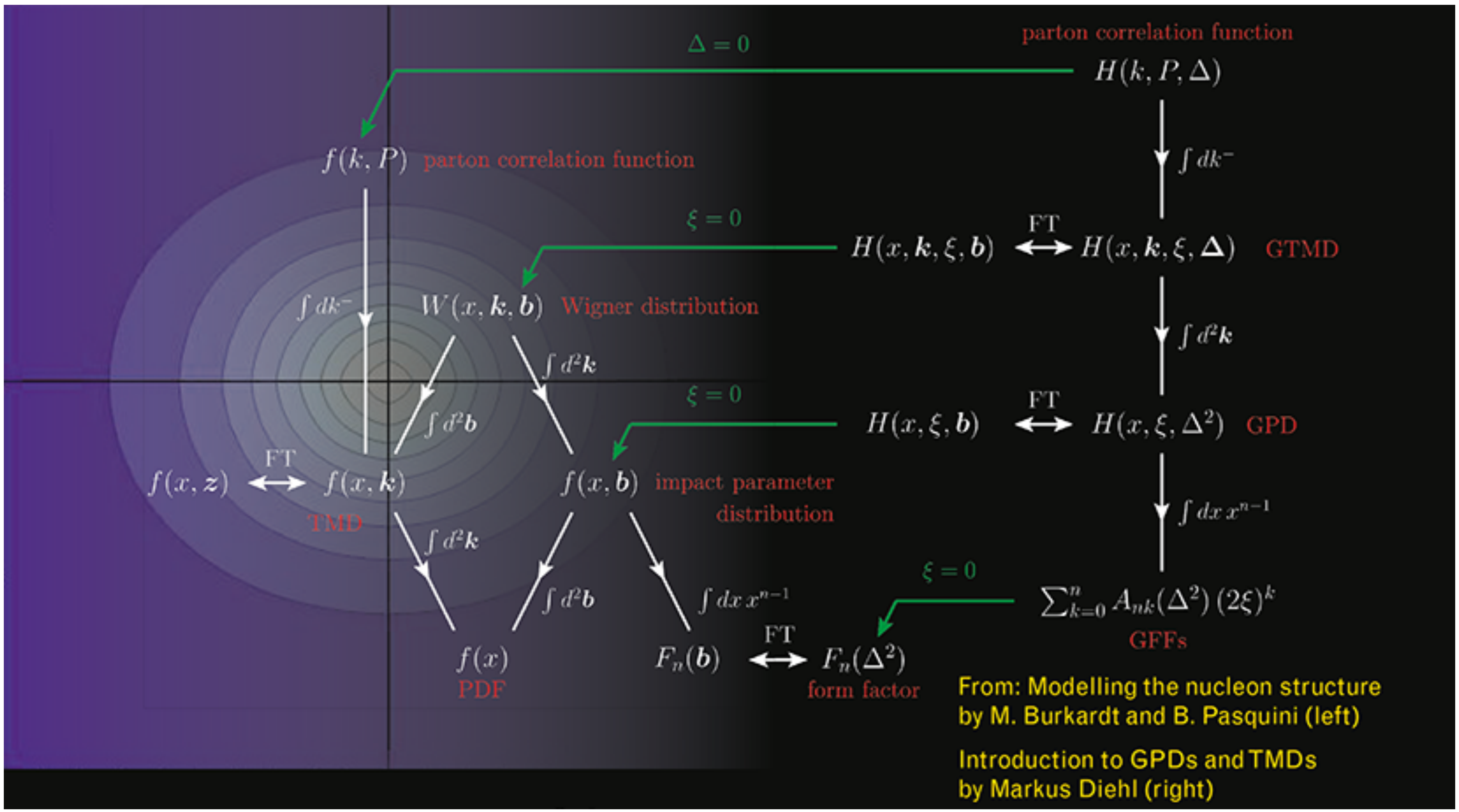
References (intro and reviews) :

- "The 3D structure of the nucleon" **EPJ A (2016) 52**
- J.C. Collins "**Foundations of perturbative QCD**"
- P.J. Mulders' **lecture notes**
- TMD collaboration **summer school**
- A. Bacchetta's **lecture notes**

Jefferson Lab

The hadronic landscape

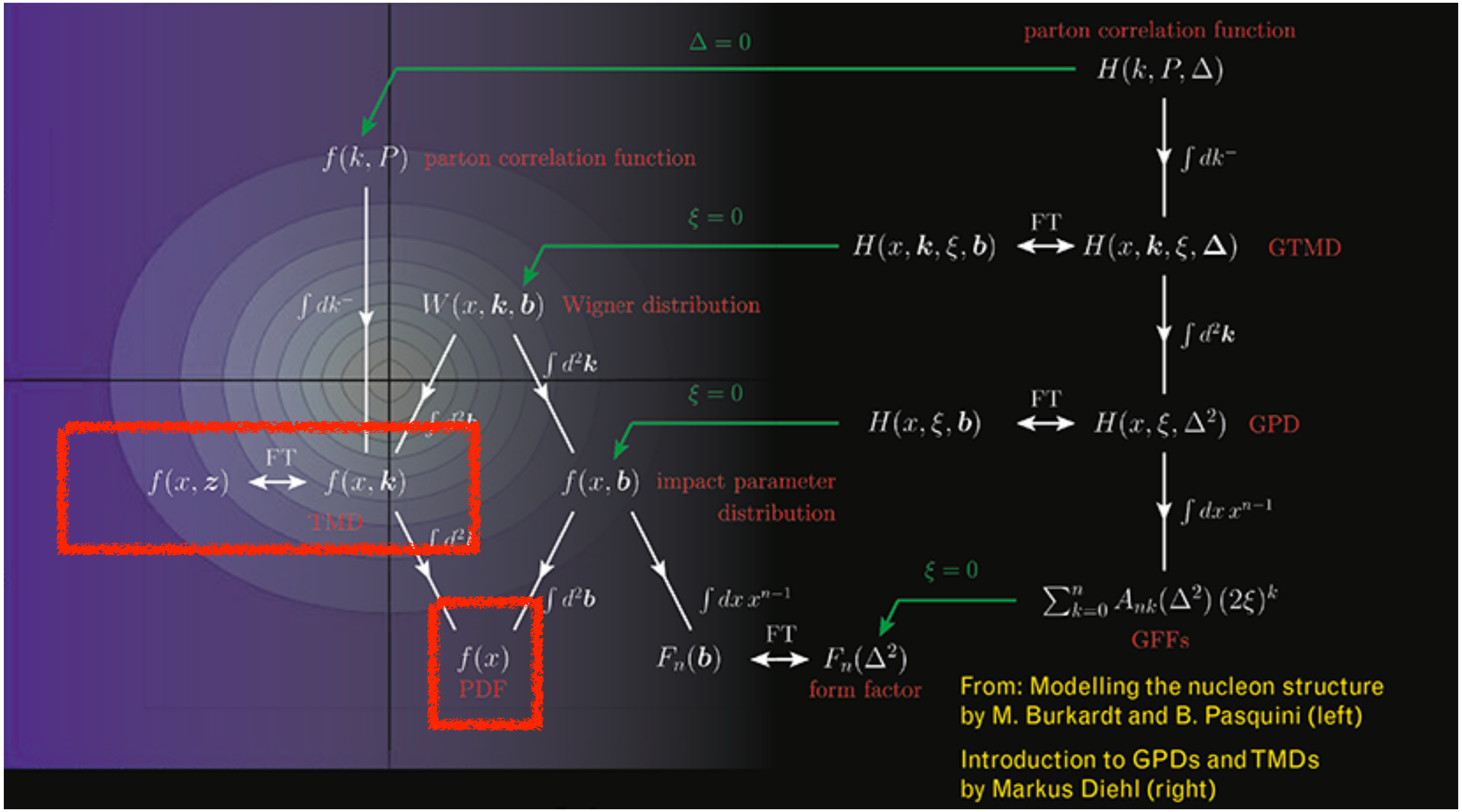
Manifestation of hadron structure in scattering processes



Jefferson Lab

The hadronic landscape

Manifestation of hadron structure in scattering processes

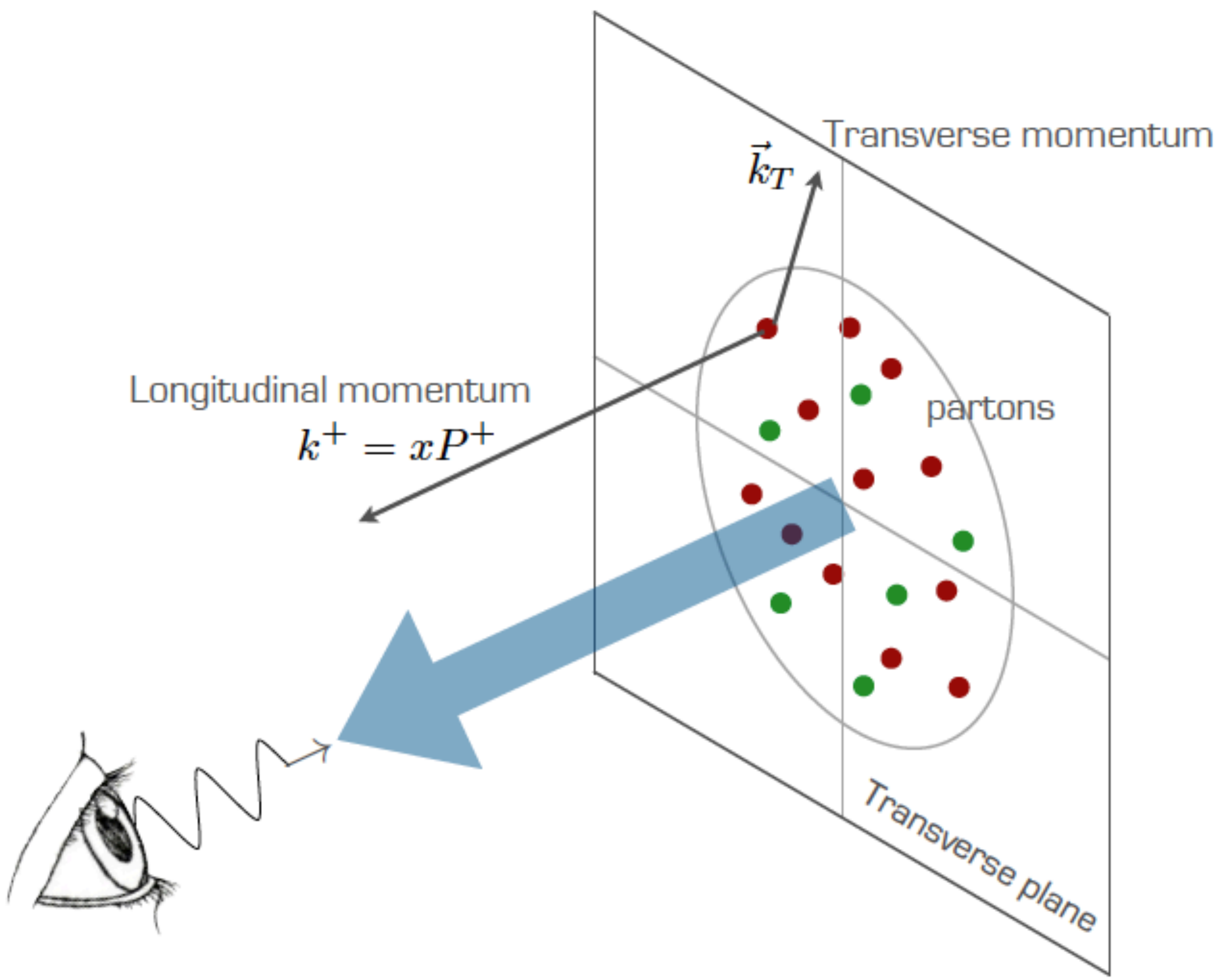


Nature is “**smooth**” : understand the link between TMDs & PDFs

Jefferson Lab

quark TMD PDFs

$$\Phi_{ij}(k,P;S\quad) \sim \text{F.T.}\ \langle PS\quad|\ \bar{\psi}_j(0)\ U_{[0,\xi]}\ \psi_i(\xi)\ |PS\quad\rangle|_{LF}$$



extraction of a **quark**
not collinear with the proton

Jefferson Lab

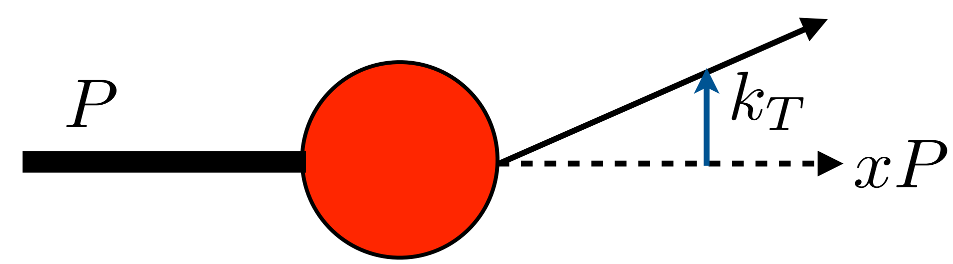
quark TMD PDFs

$$\Phi_{ij}(k,P;S\quad) \sim \mathrm{F.T.}\ \langle PS\quad|\ \bar{\psi}_j(0)\ U_{[0,\xi]}\ \psi_i(\xi)\ |PS\quad\rangle_{|LF}$$

Quarks	γ^+	$\gamma^+\gamma^5$	$i\sigma^{i+}\gamma^5$
U	$\boldsymbol{f_1}$		$h_1^\perp$
L		$\boldsymbol{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\boldsymbol{h_1}$, $h_{1T}^\perp$

Sivers TMD PDF

unpolarized TMD PDF



extraction of a **quark**
not collinear with the proton

encode all the possible
spin-spin and **spin-orbit**
correlation
between the proton
and its constituents

bold : also collinear
red : time-reversal odd (universality properties)

Jefferson Lab

Status of TMD phenomenology

Theory, data, fits : we are in a position to start validating the formalism

quark pol.

nucleon pol.	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Twist-2 TMDs

Only first attempts

Limited data, theory, fits

see, e.g, Bacchetta, Radici, arXiv:1107.5755
Anselmino, Boglione, Melis, PRD86 (12)
Echevarria, Idilbi, Kang, Vitev, PRD 89 (14)
Anselmino, Boglione, D'Alesio, Murgia, Prokudin, arXiv: 1612.06413
Anselmino et al., PRD87 (13)
Kang et al. arXiv:1505.05589

Lu, Ma, Schmidt, arXiv:0912.2031
Lefky, Prokudin arXiv:1411.0580
Barone, Boglione, Gonzalez, Melis, arXiv:1502.04214

Jefferson Lab

Status of TMD phenomenology

Theory, data, fits : we are in a position to start validating the formalism

quark pol.

nucleon pol.

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

Twist-2 TMDs

Only first attempts

Big effort at JLab to explore all of them

Limited data, theory, fits

see, e.g, Bacchetta, Radici, arXiv:1107.5755
Anselmino, Boglione, Melis, PRD86 (12)
Echevarria, Idilbi, Kang, Vitev, PRD 89 (14)
Anselmino, Boglione, D'Alesio, Murgia, Prokudin, arXiv:1612.06413
Anselmino et al., PRD87 (13)
Kang et al. arXiv:1505.05589

Lu, Ma, Schmidt, arXiv:0912.2031
Lefky, Prokudin arXiv:1411.0580
Barone, Boglione, Gonzalez, Melis, arXiv:1502.04214

Jefferson Lab

The frontier

Nucleon tomography in momentum space:
to understand how hadrons are built in terms of the elementary degrees of freedom of QCD

High-energy phenomenology:
to improve our understanding of high-energy scattering experiments and their potential to explore BSM physics

A selection of open questions (formalism) :

1) How well do we understand collinear and TMD **factorization** ?

2) How (well) can we **match** collinear and TMD factorization ?

3) can we quantify **factorization breaking** effects ?

4) how can we investigate gluon TMDs ?

...

The frontier

Nucleon tomography in momentum space:
to understand how hadrons are built in terms of the elementary degrees of freedom of QCD

High-energy phenomenology:
to improve our understanding of high-energy scattering experiments and their potential to explore BSM physics

More open questions (phenomenology) :

1) what is the **functional form** of TMDs at low transverse momentum ?

2) what is its **kinematic** and **flavor** dependence ?

3) can we attempt a global fit of TMDs ?

4) can we test the generalized **universality** of TMDs ?

5) what's the impact of hadron structure on the determination of Standard Model parameters ?

TMD & collinear factorization

References:

- J.C. Collins "Foundations of perturbative QCD"
- SCET literature

Collinear and TMD factorization

Let's consider a process with
three separate scales:

(SIDIS, Drell-Yan, e+e- to hadrons, pp to quarkonium, ...)

hadronic mass scale

$$\Lambda_{\rm QCD} \ll q_T \ll Q$$

hard scale

(related to the) transverse momentum of the observed particle

The ratios

$\Lambda_{\rm QCD}/Q$ $\Lambda_{\rm QCD}/q_T$ q_T/Q

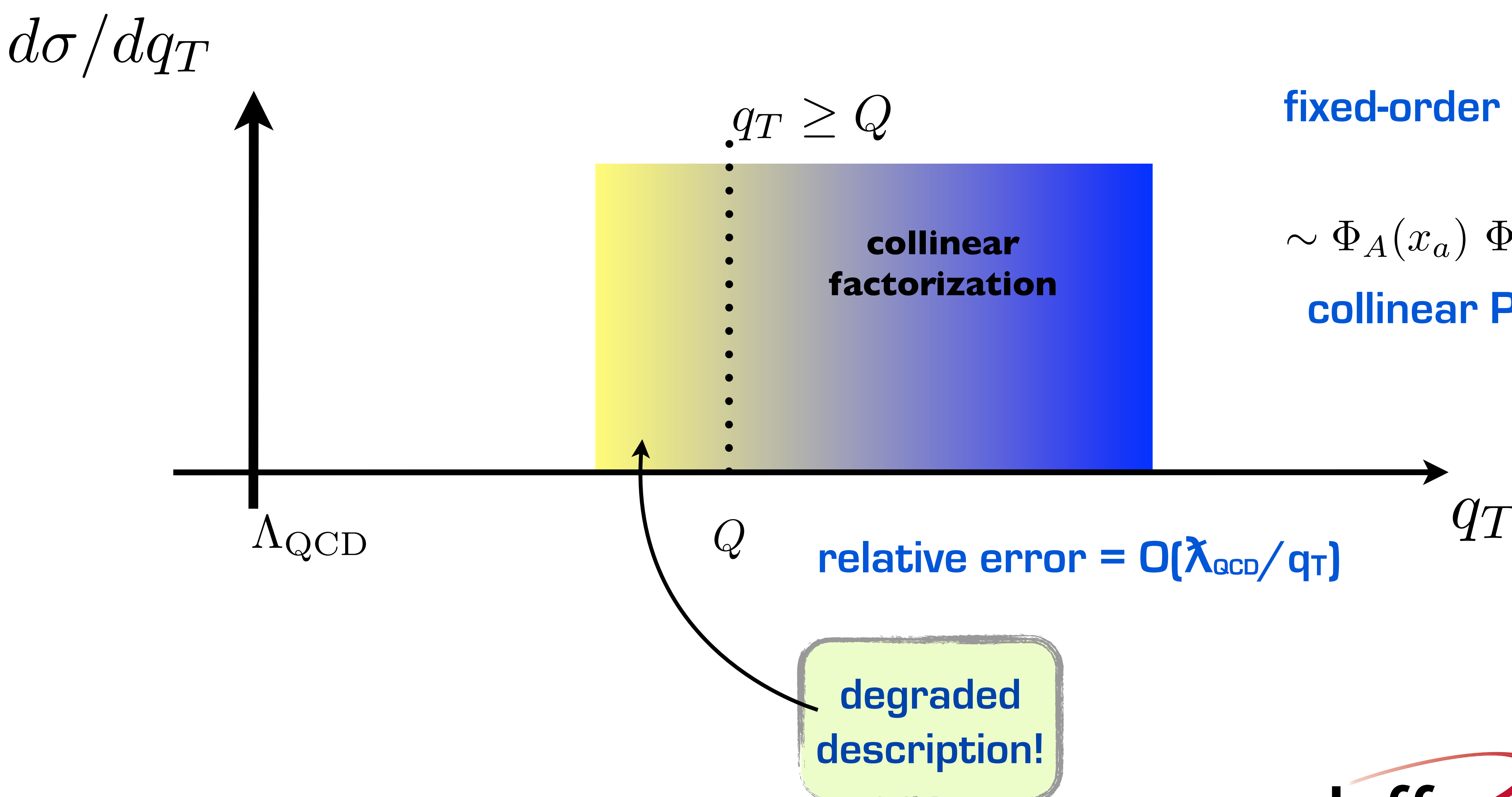
select the factorization theorem that we rely on.

According to their **values** we can access **different "projections"** of hadron structure

Collinear and TMD factorization

The key of phenomenology : emergence of TMD and collinear distributions from **factorization theorems**

fixed Q, variable q_T



fixed-order term

$\sim \Phi_A(x_a)\ \Phi_B(x_b)$

collinear PDFs

relative error = $O(\Lambda_{QCD}/q_T)$

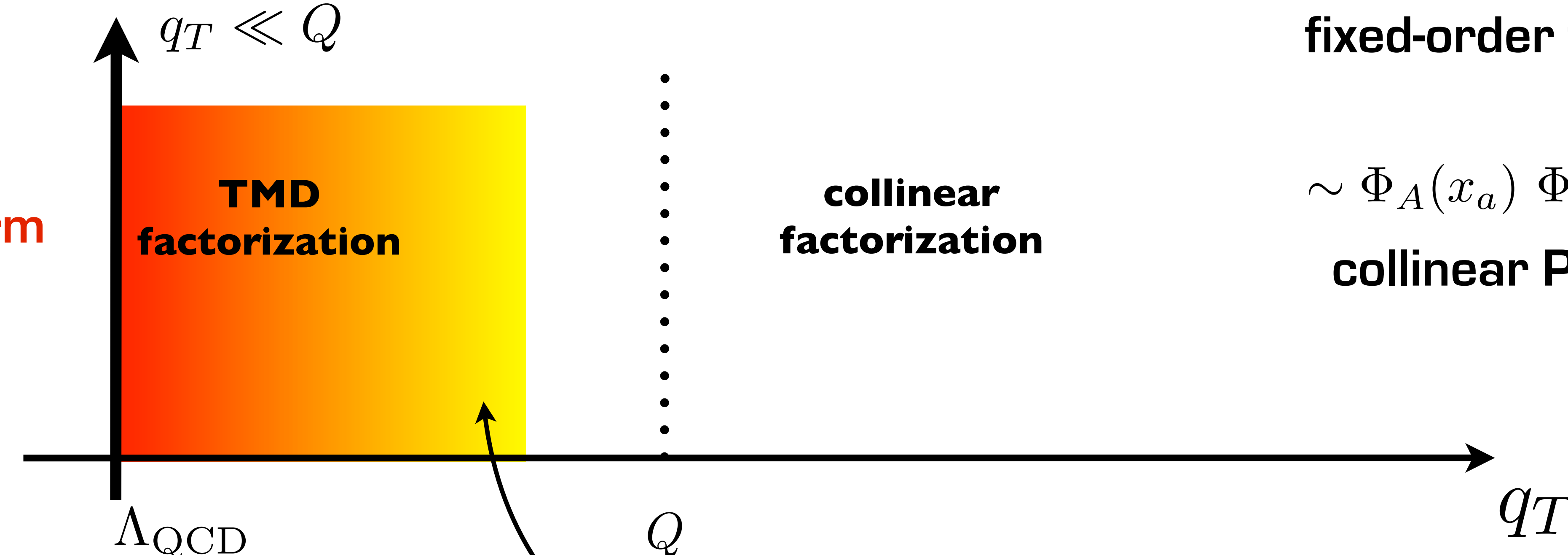
Jefferson Lab

Collinear and TMD factorization

The key of phenomenology : emergence of TMD and collinear distributions from **factorization theorems**

fixed Q, variable q_T

$d\sigma/dq_T$



resummed term (W)

fixed-order term

$\sim \Phi_A(x_a)\ \Phi_B(x_b)$

collinear PDFs

$\Phi_A(x_a, \mathbf{k}_{Ta})\ \Phi_B(x_b, \mathbf{k}_{Tb}) \ \sim$ **TMD PDFs**

relative error = O(q_T/Q)

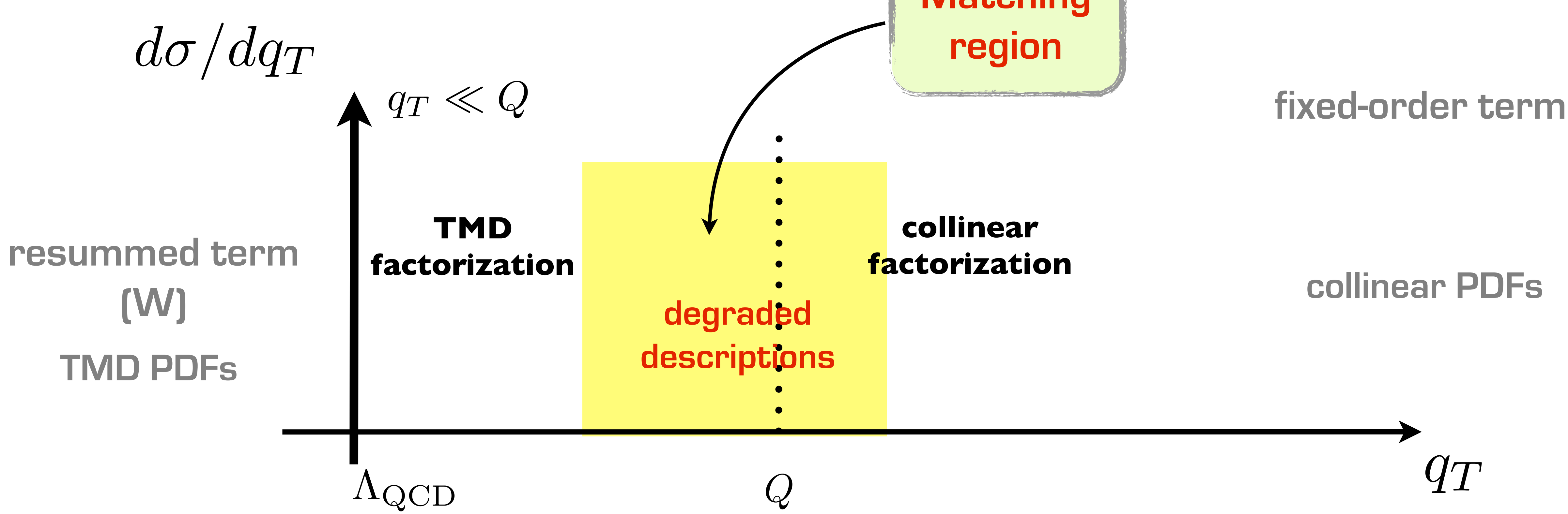
degraded description!

Jefferson Lab

Collinear and TMD factorization

The key of phenomenology : emergence of TMD and collinear distributions from **factorization theorems**

fixed Q, variable q_T



W, relative error = $O(q_T/Q)$

F.O., relative error = $O(\Lambda_{QCD}/q_T)$

We need a prescription to deal with the region where both descriptions are not good

Collinear and TMD factorization

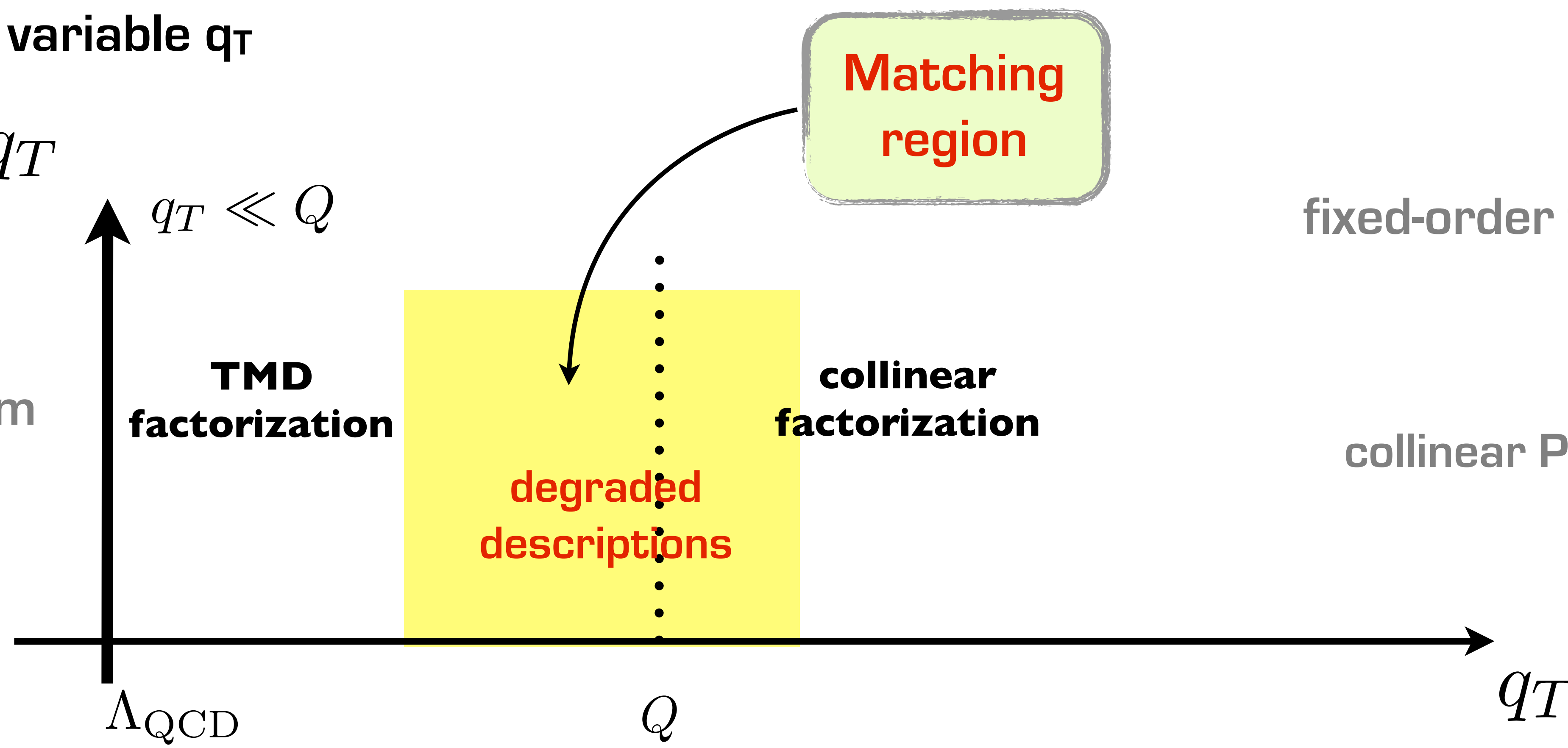
The key of phenomenology : emergence of TMD and collinear distributions from **factorization theorems**

fixed Q, variable q_T

$d\sigma/dq_T$

resummed term (W)

TMD PDFs



fixed-order term

collinear PDFs

The extraction of the nonperturbative part of TMDs is affected by the **description of the whole q_T range**

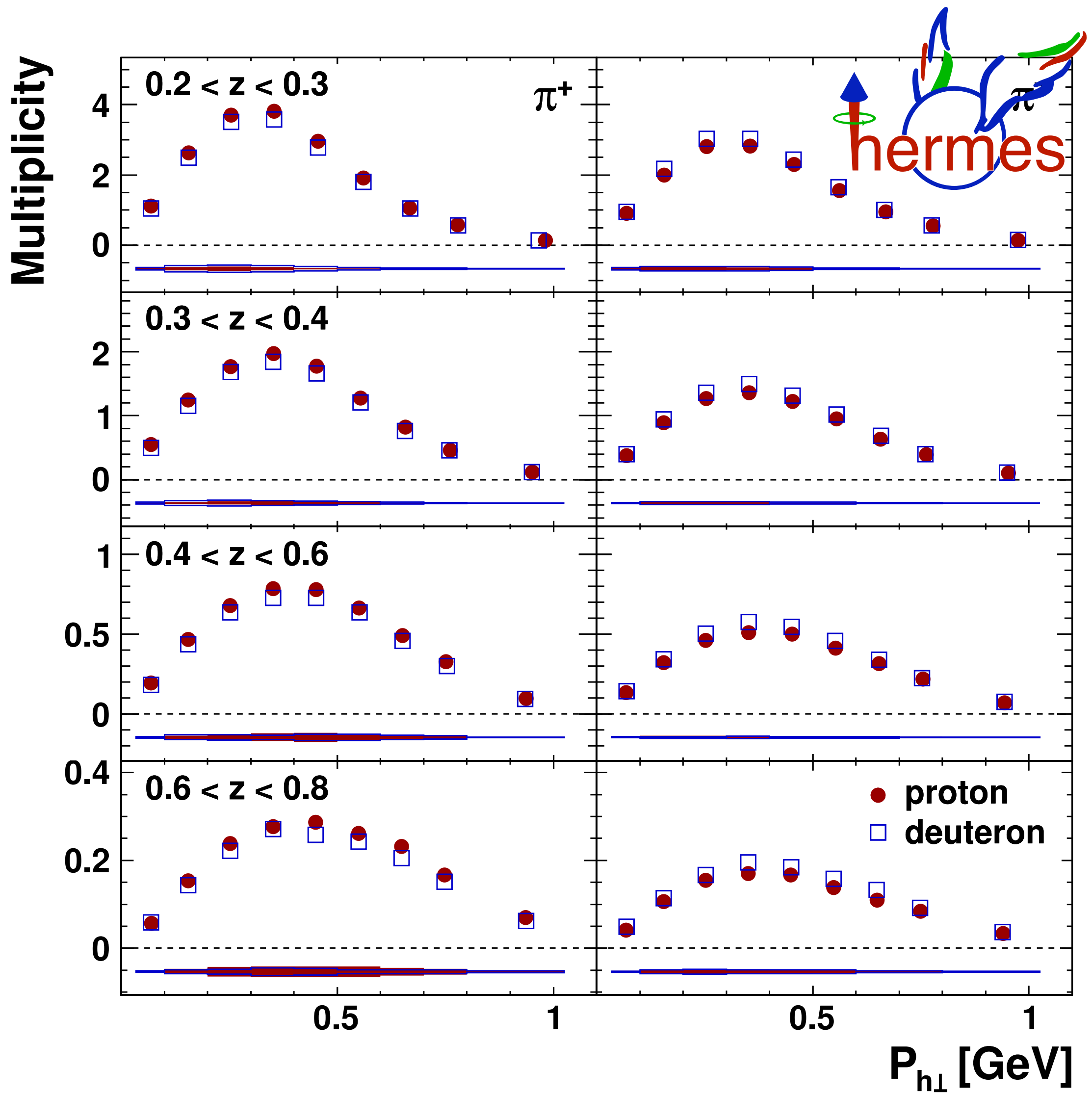
→ Crucial, especially at **low Q** (e.g. JLab kinematics), where the **regions shrink**

→ polarization ?

Jefferson Lab

Need of TMD evolution

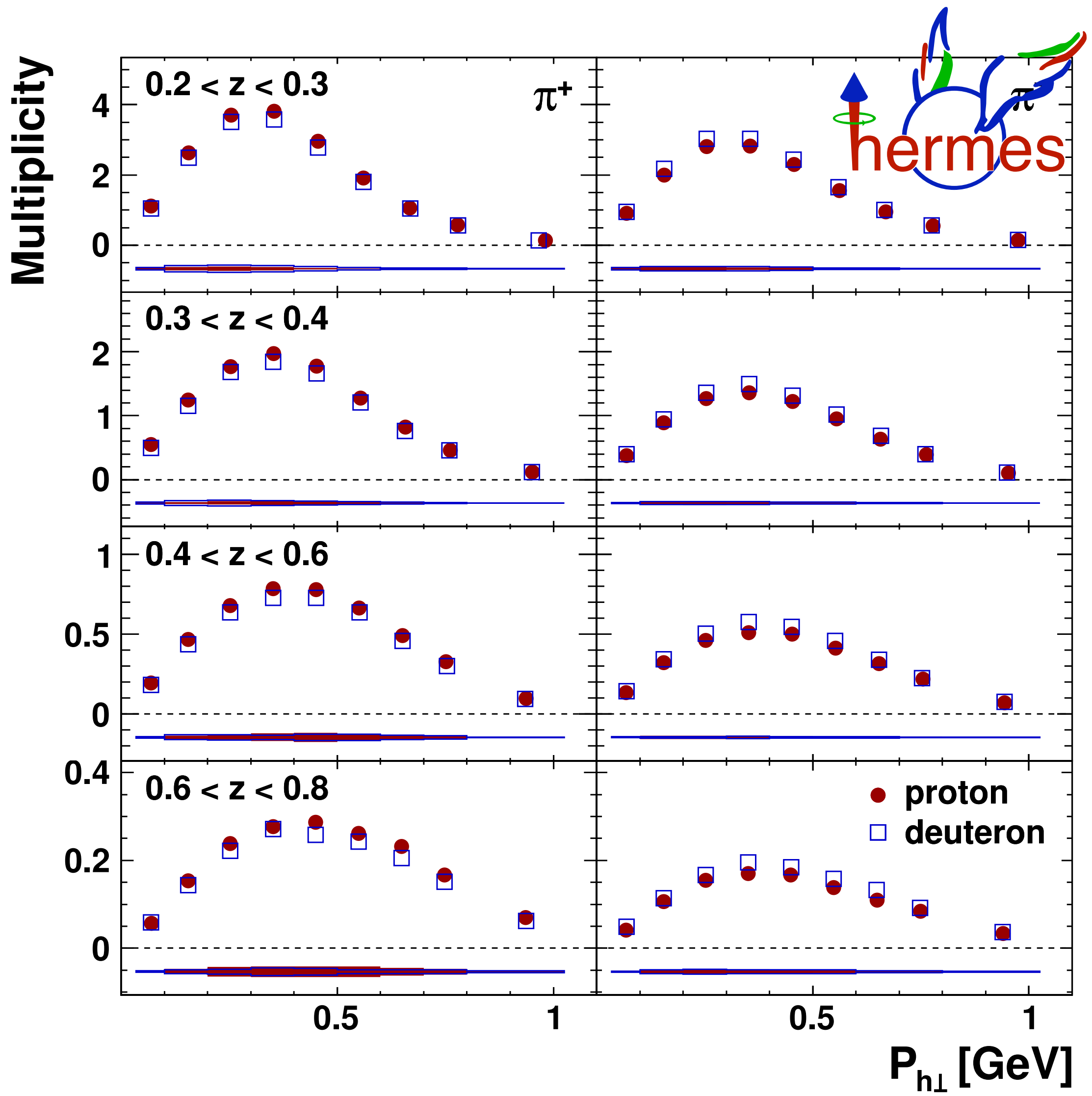
HERMES, Q ≈ 1.5 GeV



Airapetian et al., PRD87 (2013)

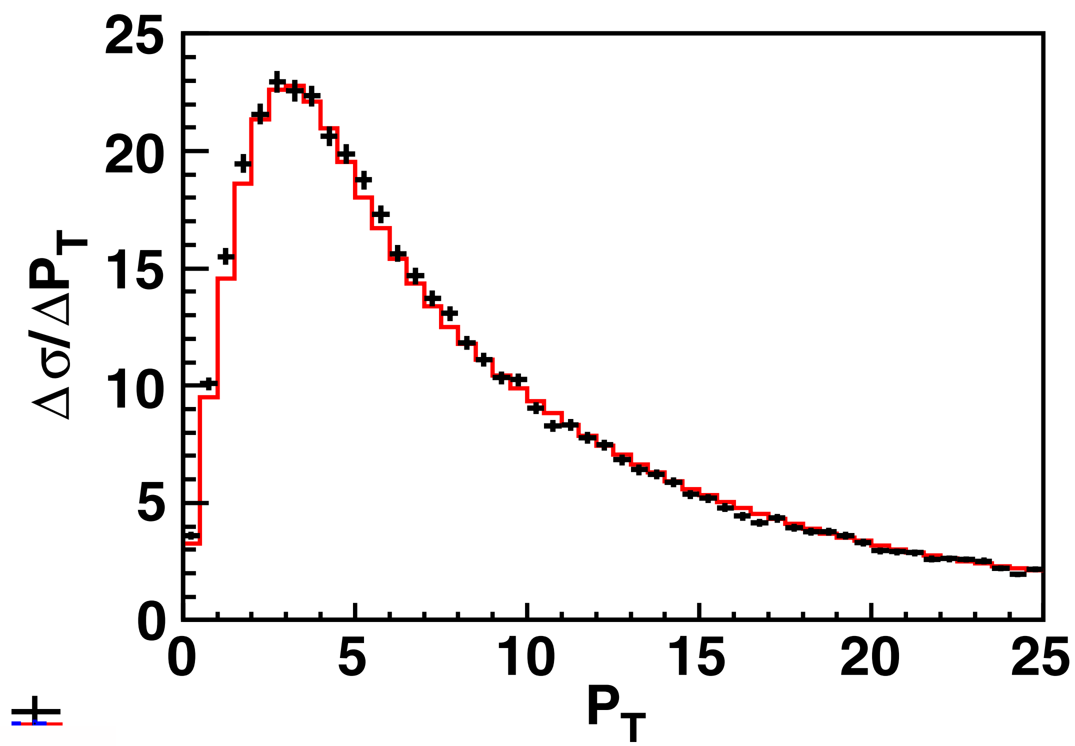
Need of TMD evolution

HERMES, Q ≈ 1.5 GeV



Airapetian et al., PRD87 (2013)

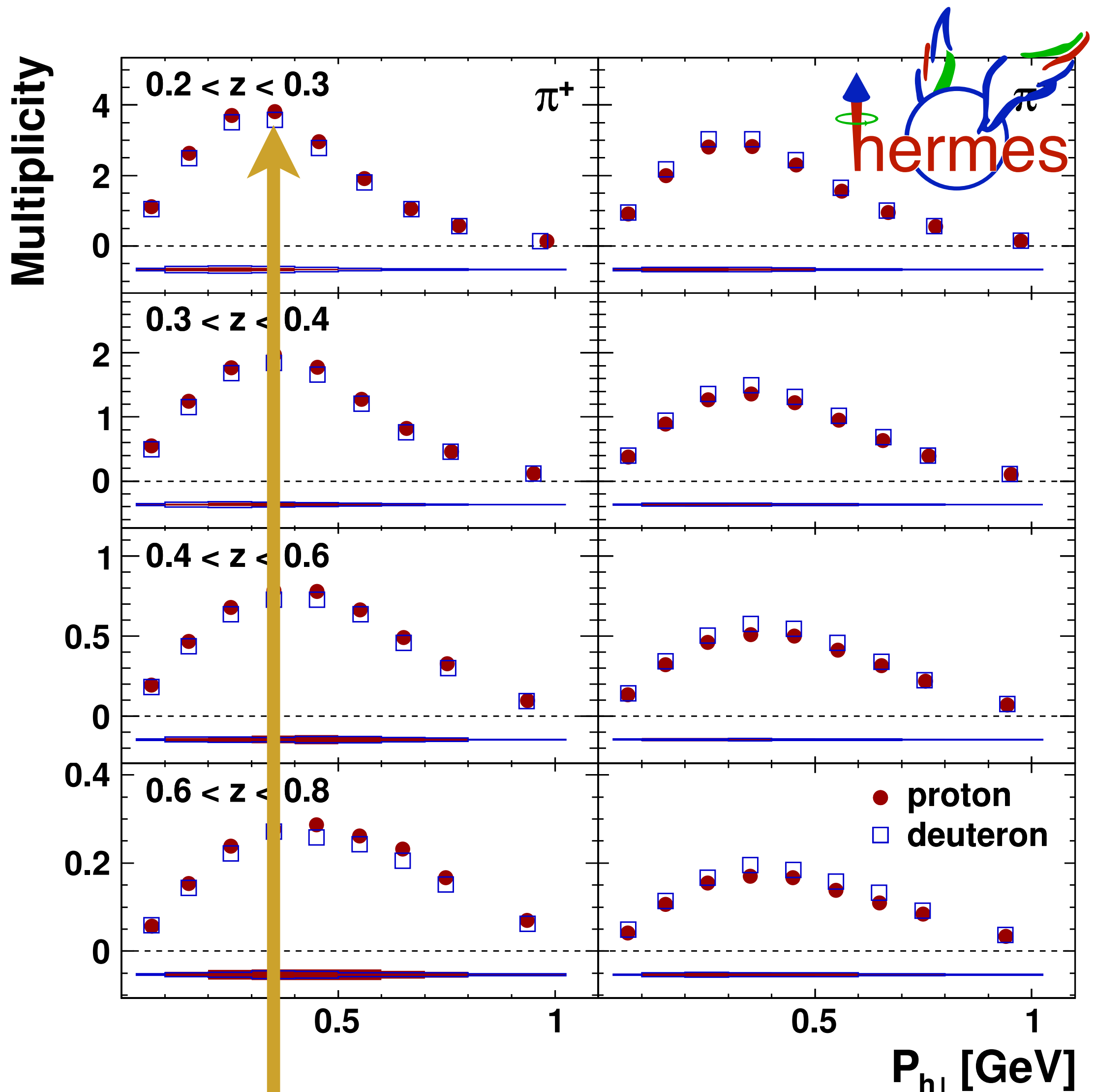
CDF, Q ≈ 91 GeV



Aaltonen et al., PRD86 (2012)

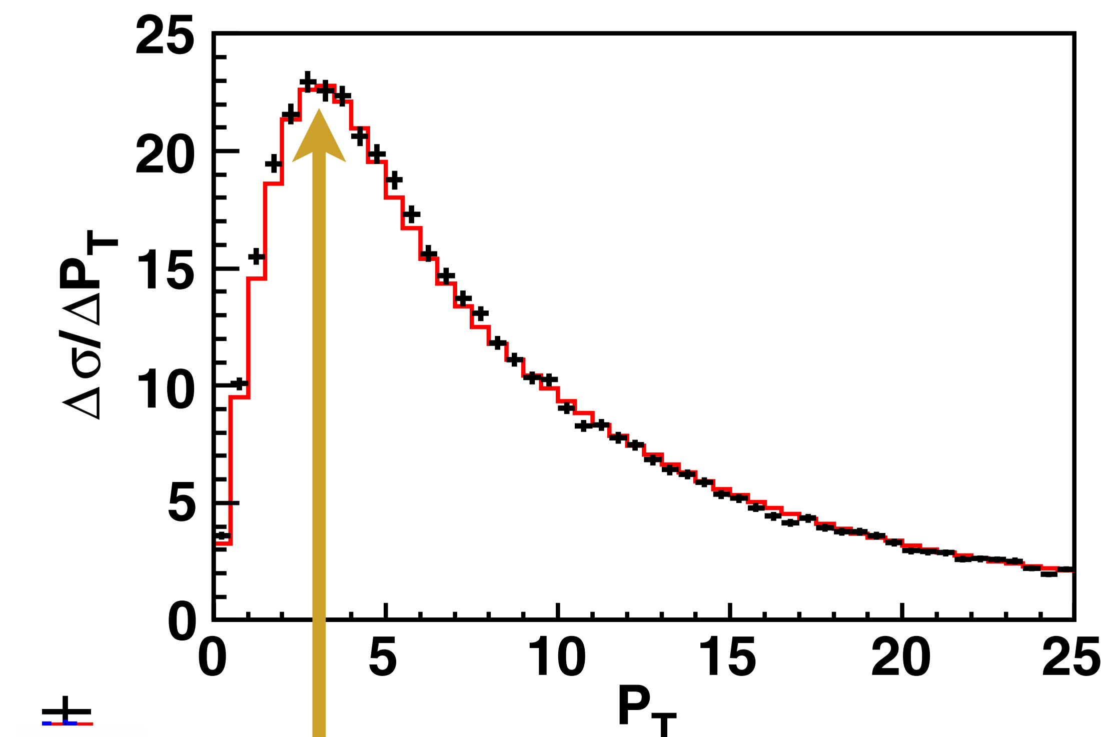
Need of TMD evolution

HERMES, Q ≈ 1.5 GeV



Airapetian et al., PRD87 (2013)

CDF, Q ≈ 91 GeV



Aaltonen et al., PRD86 (2012)

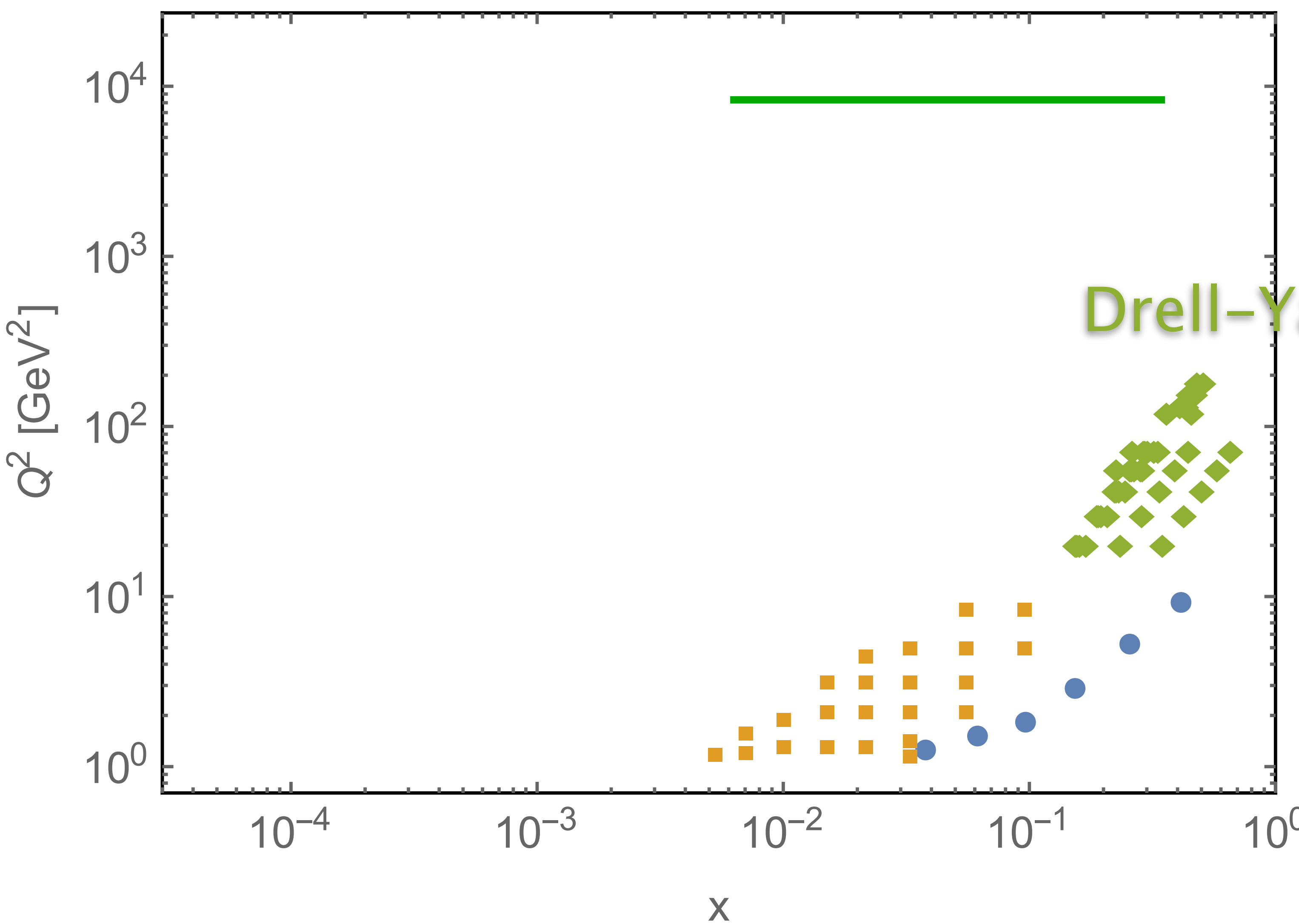
Width of TMDs changes of one order of magnitude:
we can we explain this with TMD evolution

Extraction of unpolarized TMDs

References :

- "The 3D structure of the nucleon" **EPJ A (2016) 52**
- Bacchetta et al. **JHEP 1706 (2017) 081**
- A. Signori , **PhD thesis**
- Angelez-Martinez et al. **arXiv:1507.05267**
- EIC white paper, JLab 12 GeV white paper, ...
- ...

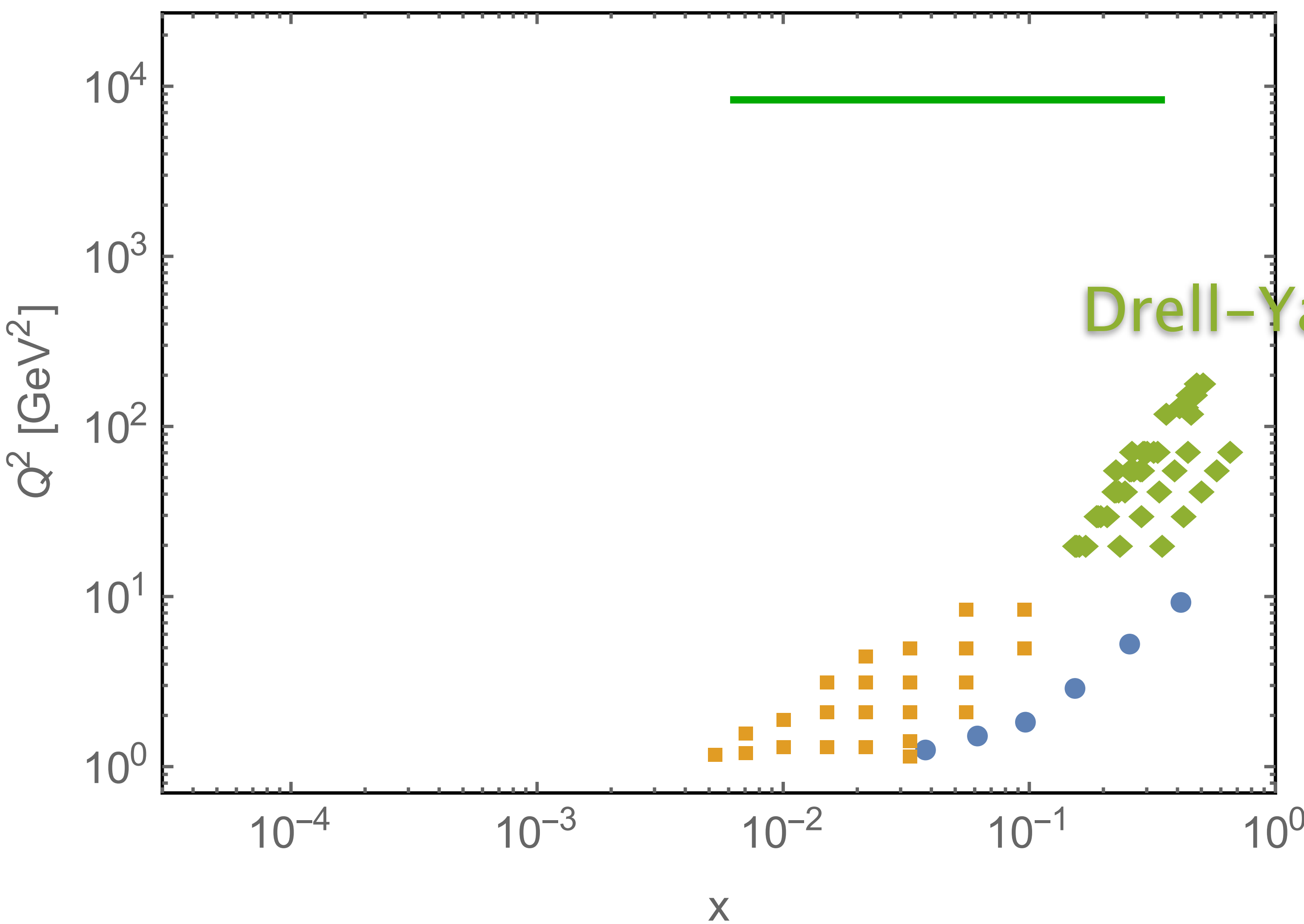
Experimental measurements



Drell-Yan@ Fermilab

Jefferson Lab

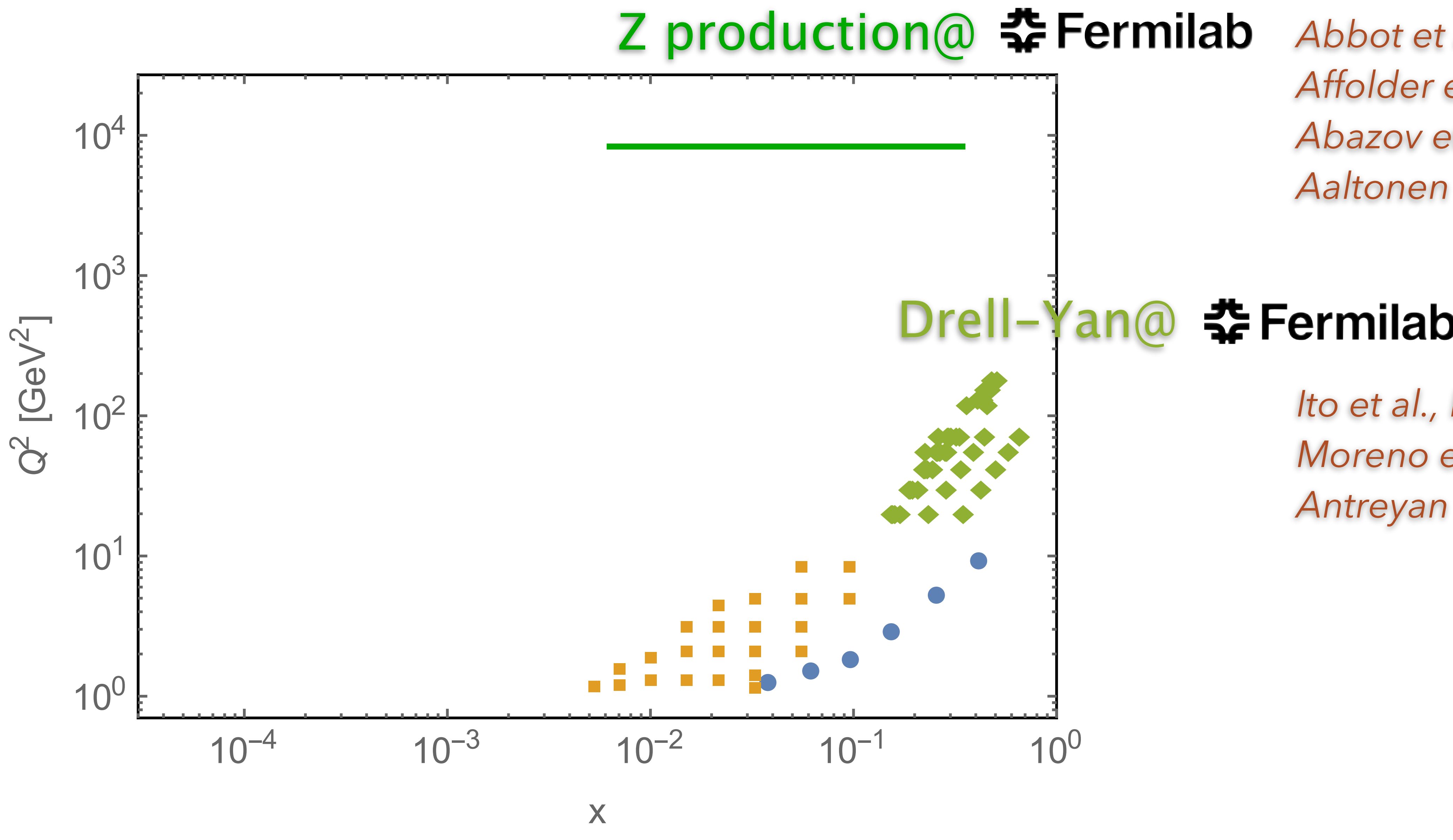
Experimental measurements



Drell–Yan@ Fermilab

Ito et al., PRD93 (81)
Moreno et al. PRD 43 (91)
Antreyan et al. PRL47 (81)

Experimental measurements

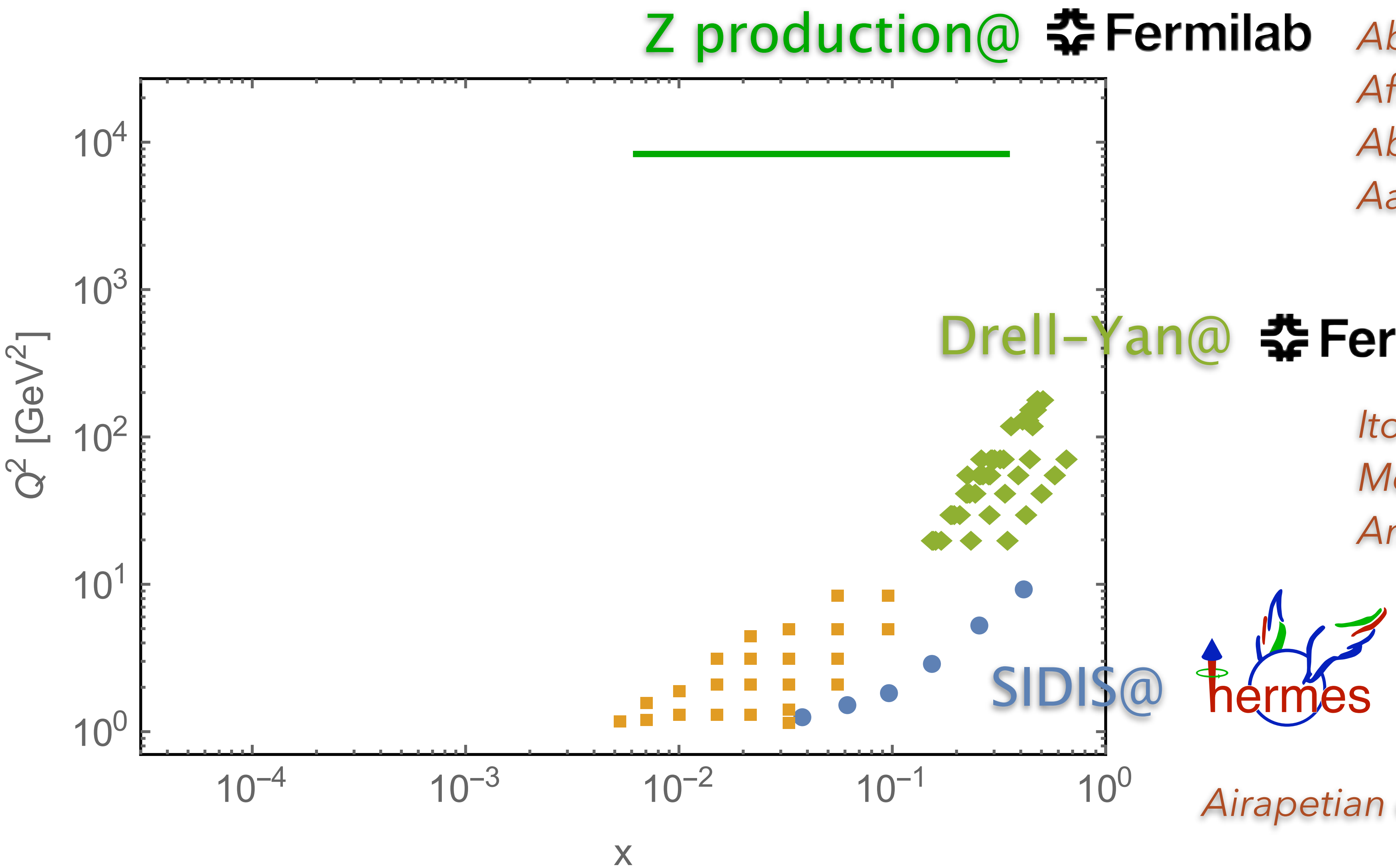


Abbot et al. hep-ex/9909020
Affolder et al. hep-ex/0001021
Abazov et al. arXiv:0712.0803
Aaltonen et al. arXiv:1207.7138

Ito et al., PRD93 (81)
Moreno et al. PRD 43 (91)
Antreyan et al. PRL47 (81)

Jefferson Lab

Experimental measurements



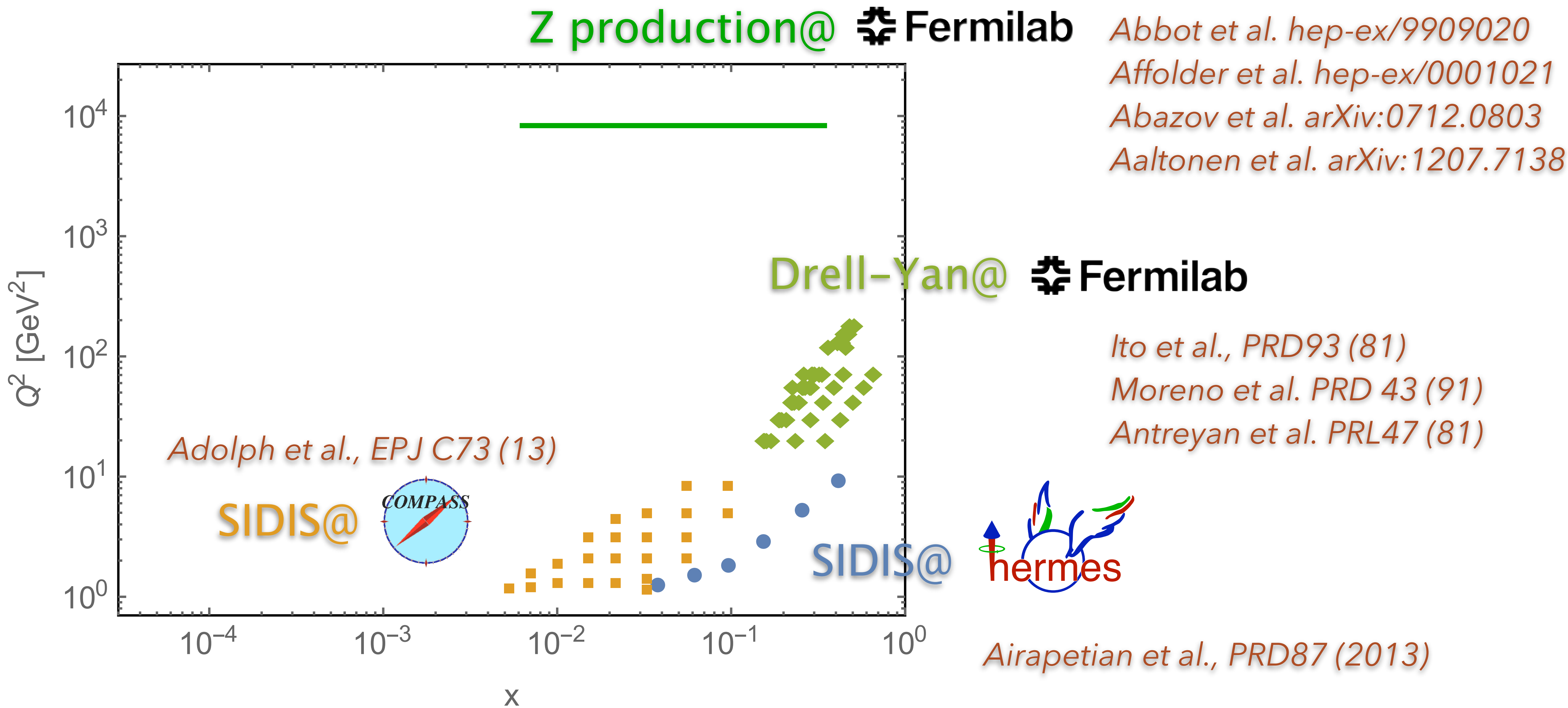
Abbot et al. hep-ex/9909020
Affolder et al. hep-ex/0001021
Abazov et al. arXiv:0712.0803
Aaltonen et al. arXiv:1207.7138

Ito et al., PRD93 (81)
Moreno et al. PRD 43 (91)
Antreyan et al. PRL47 (81)

Airapetian et al., PRD87 (2013)

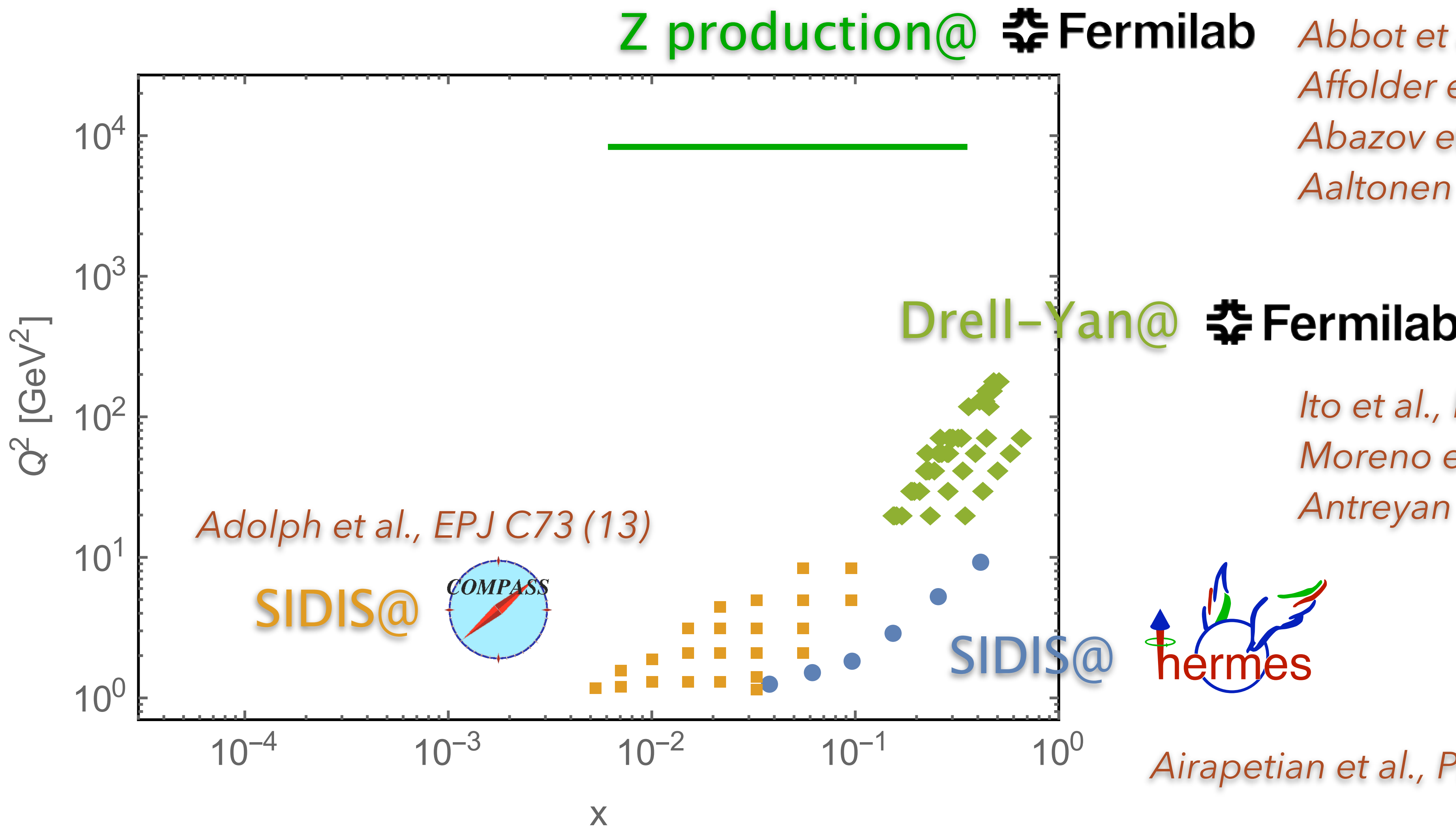
Jefferson Lab

Experimental measurements



Jefferson Lab

Experimental measurements



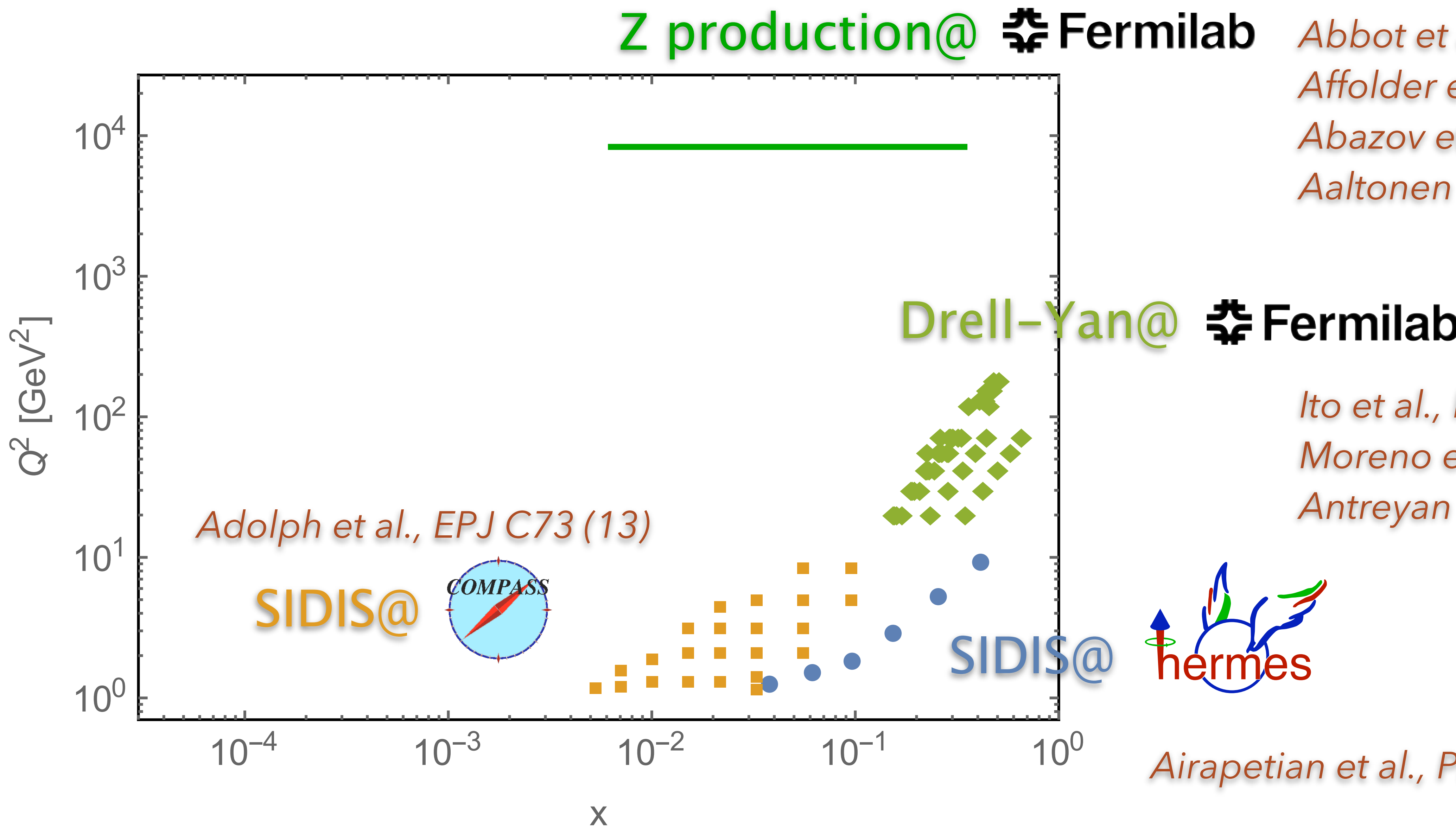
Abbot et al. hep-ex/9909020
Affolder et al. hep-ex/0001021
Abazov et al. arXiv:0712.0803
Aaltonen et al. arXiv:1207.7138

Ito et al., PRD93 (81)
Moreno et al. PRD 43 (91)
Antreyan et al. PRL47 (81)

Airapetian et al., PRD87 (2013)

Electron-positron annihilation data are still **missing**
(only some azimuthal asymmetries are available)

Experimental measurements



Abbot et al. hep-ex/9909020
Affolder et al. hep-ex/0001021
Abazov et al. arXiv:0712.0803
Aaltonen et al. arXiv:1207.7138

Ito et al., PRD93 (81)
Moreno et al. PRD 43 (91)
Antreyan et al. PRL47 (81)

Airapetian et al., PRD87 (2013)

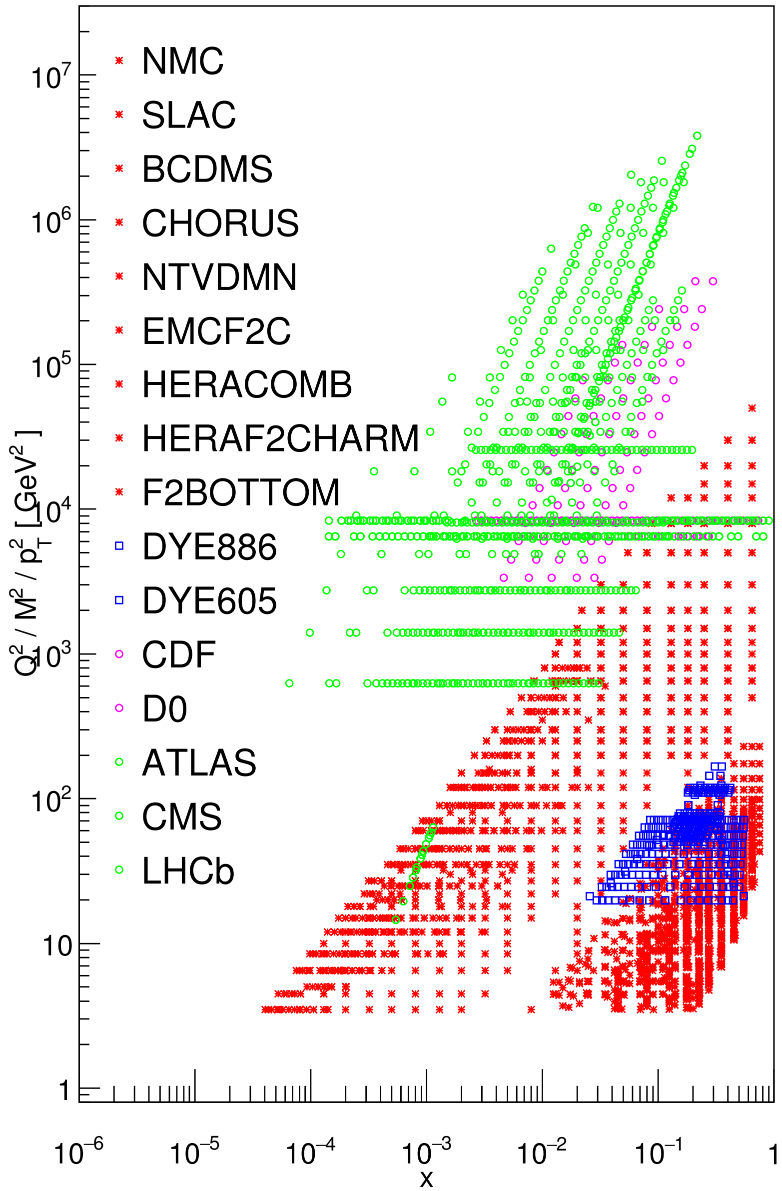
Electron-positron annihilation data are still **missing**
(only some azimuthal asymmetries are available)

crucial for analyses of TMD FFs !!

Jefferson Lab

Comparison with collinear PDF fits

see talk by E. Nocera at POETIC2016



data sets available:

collinear PDFs ←

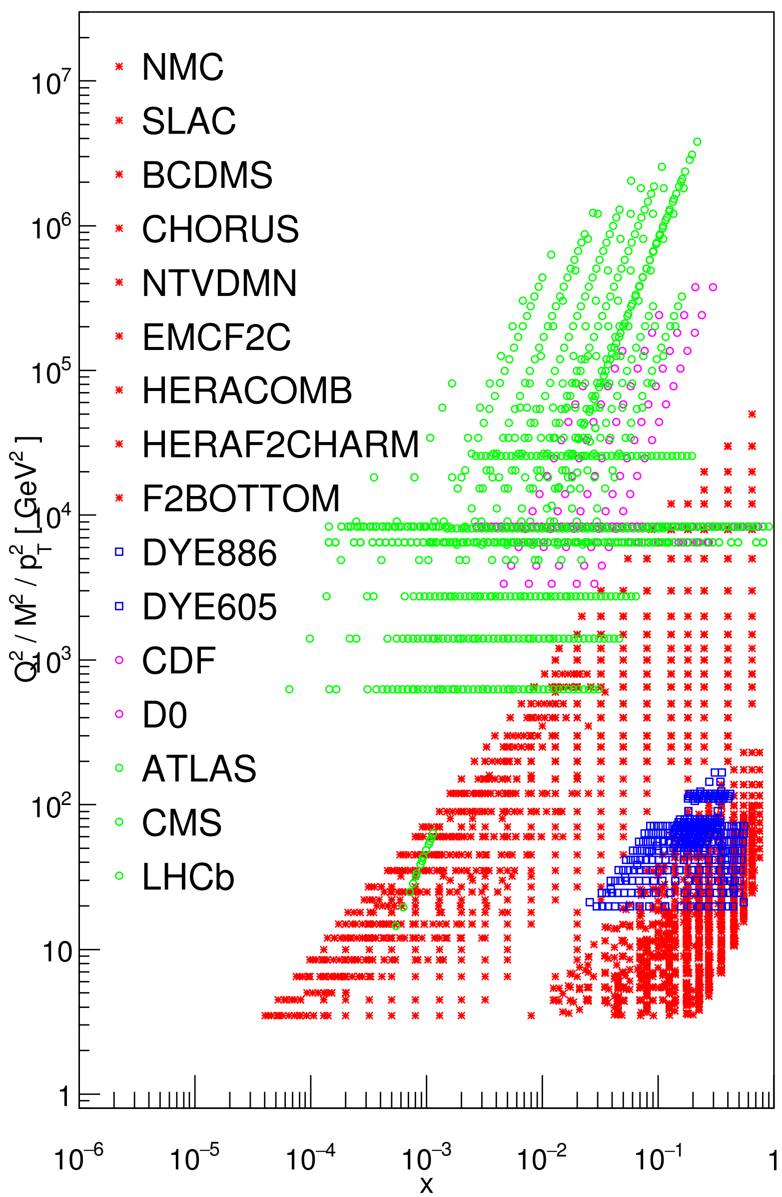
vs

TMD PDFs →

Jefferson Lab

Comparison with collinear PDF fits

see talk by E. Nocera at POETIC2016

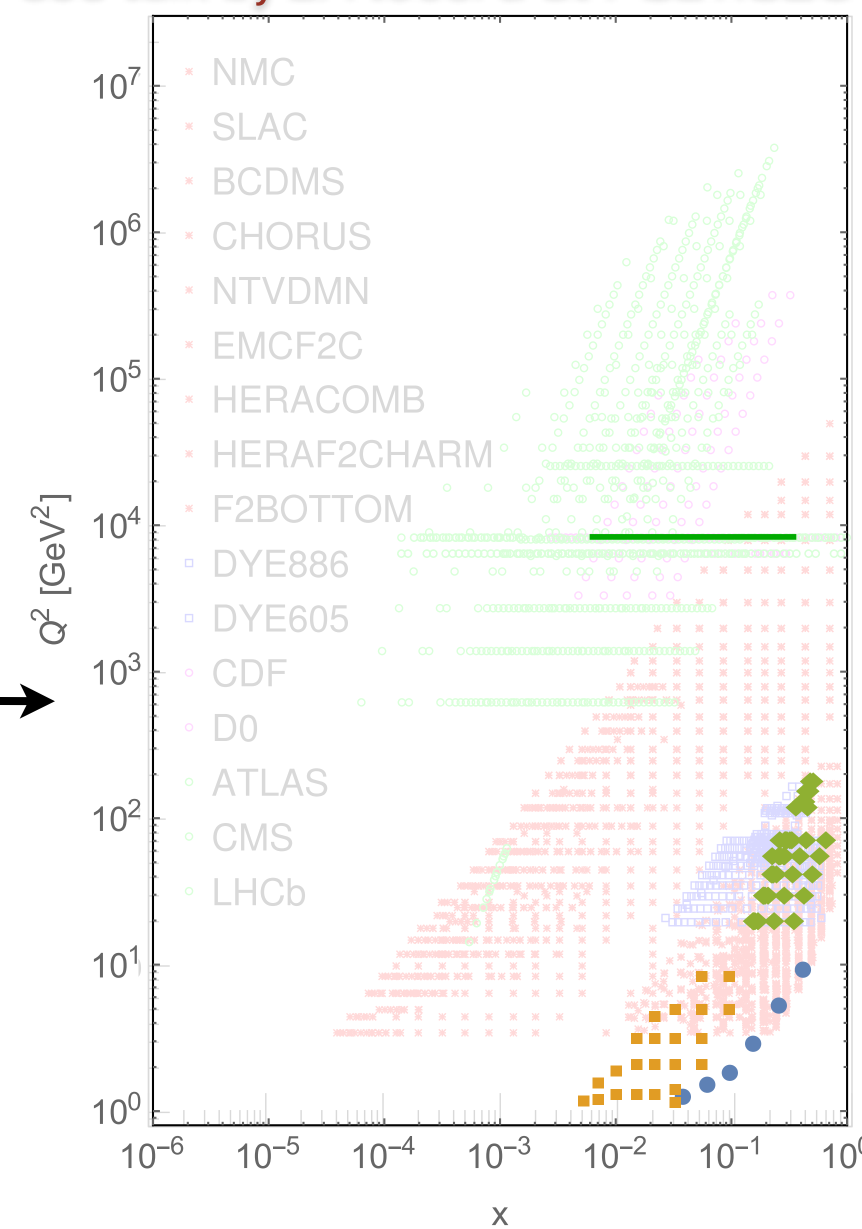


data sets available:

collinear PDFs

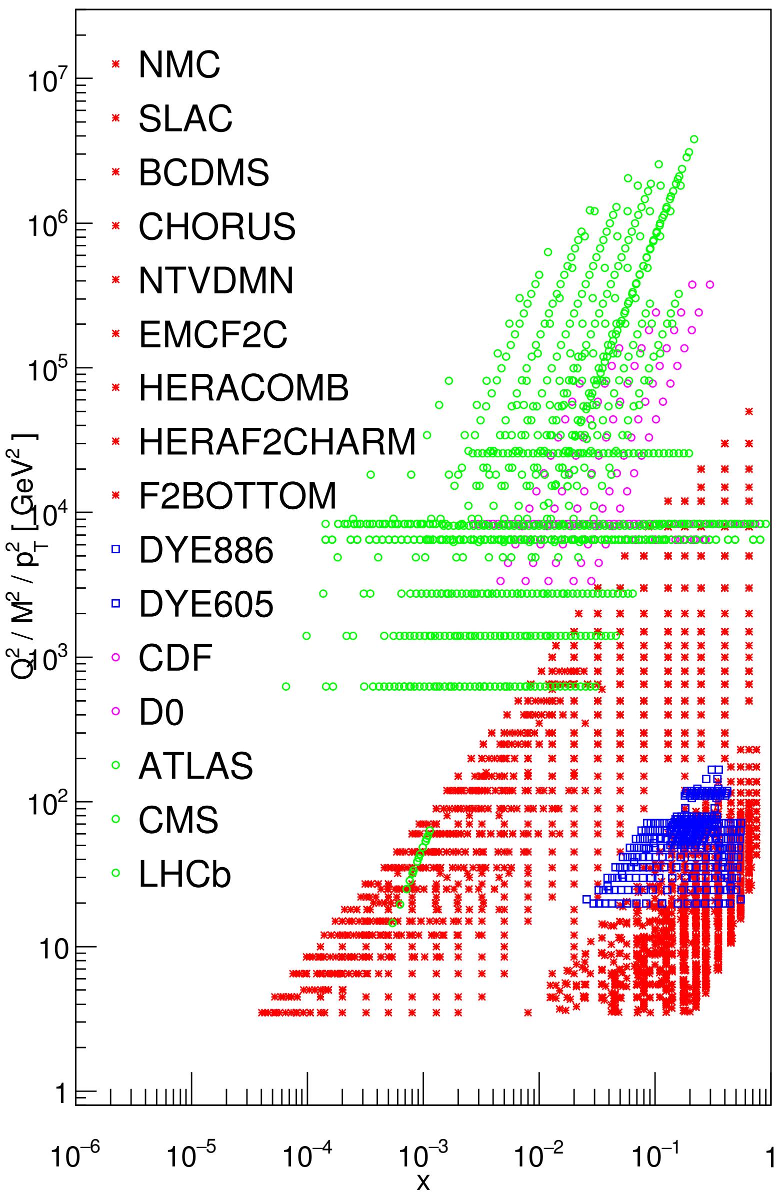
vs

TMD PDFs



Comparison with collinear PDF fits

see talk by E. Nocera at POETIC2016

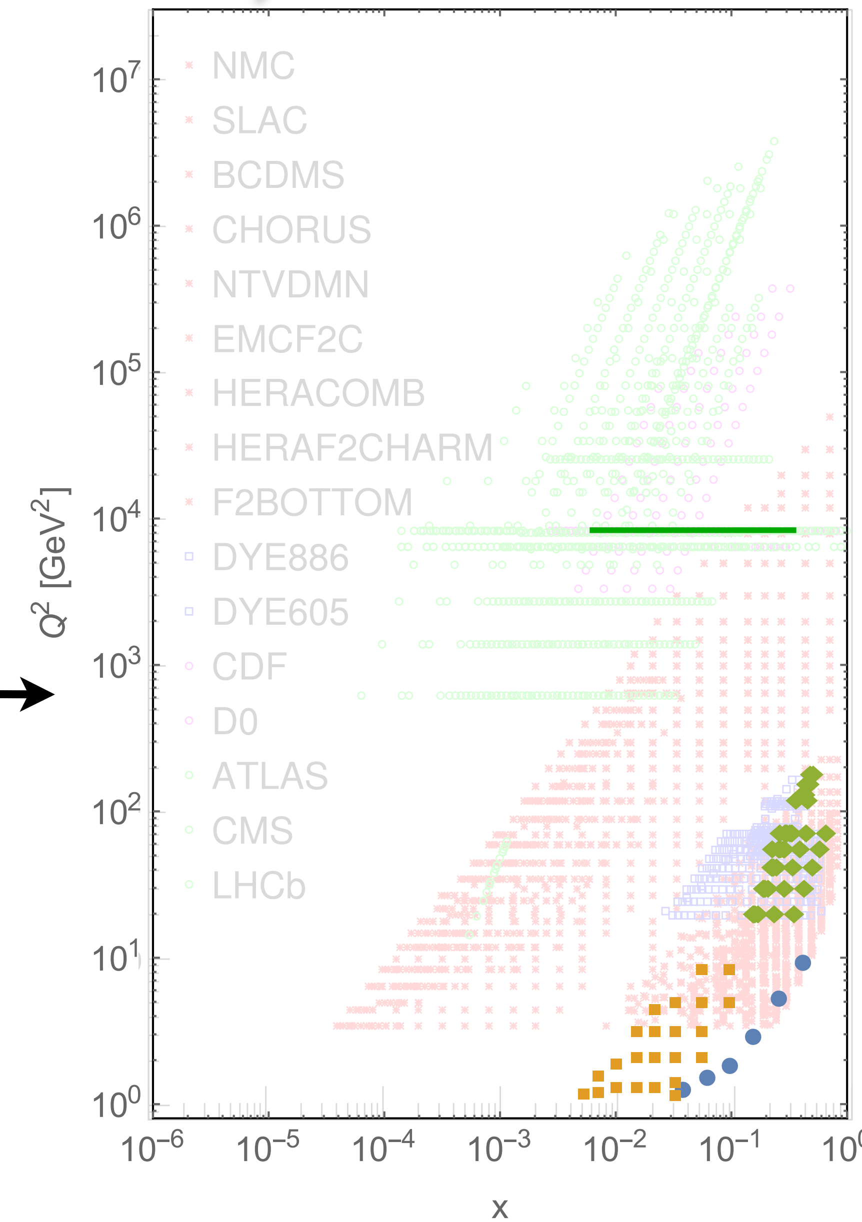


data sets available:

collinear PDFs

vs

TMD PDFs



On top of extending **data set**, many improvements are needed:
higher **perturbative** orders, **matching** with high transverse momentum, **flavor** dependence, flexible functional forms...

Jefferson Lab

What do we know ?

(only a selection of results!)

	Framework	HERMES	COMPASS	DY	Z production	N of points
KN 2006 hep-ph/0506225	LO-NLL	✘	✘	✔	✔	98
Pavia 2013 (+Amsterdam, Bilbao) arXiv:1309.3507	No evo (QPM)	✔	✘	✘	✘	1538
Torino 2014 (+JLab) arXiv:1312.6261	No evo (QPM)	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NLO-NNLL	✘	✘	✔	✔	223
EIKV 2014 arXiv:1401.5078	LO-NLL	1 (x,Q^2) bin	1 (x,Q^2) bin	✔	✔	500 (?)
Pavia/JLab 2017 arXiv:1703.10157	LO-NLL	✔	✔	✔	✔	8059
SV 2017 arXiv:1706.01473	NNLO-NNLL	✘	✘	✔	✔	309

(courtesy A. Bacchetta)

Jefferson Lab

What do we know ?

(only a selection of results!)

	Framework	HERMES	COMPASS	DY	Z production	N of points
KN 2006 hep-ph/0506225	LO-NLL	✘	✘	✔	✔	98
Pavia 2013 (+Amsterdam, Bilbao) arXiv:1309.3507	No evo (QPM)	✔	✘	✘	✘	1538
Torino 2014 (+JLab) arXiv:1312.6261	No evo (QPM)	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NLO-NNLL	✘	✘	✔	✔	223
EIKV 2014 arXiv:1401.5078	LO-NLL	1 (x,Q^2) bin	1 (x,Q^2) bin	✔	✔	500 (?)
Pavia/JLab 2017 arXiv:1703.10157	LO-NLL	✔	✔	✔	✔	8059
SV 2017 arXiv:1706.01473	NNLO-NNLL	✘	✘	✔	✔	309

(courtesy A. Bacchetta)

Jefferson Lab

Features

	Framework	HERMES	COMPASS	DY	Z production	N of points
Pavia/JLab 2017 arXiv:1703.10157	LO-NLL	✔	✔	✔	✔	8059

PROs

almost a **global fit** of quark unpolarized TMDs

includes **TMD evolution**

replica (bootstrap) fitting methodology

kinematic dependence in intrinsic part of TMDs

intrinsic momentum: **beyond the Gaussian** assumption

CONs

no "pure" info on TMD FFs

accuracy of TMD evolution : not the state of the art

only "low" transverse momentum (no fixed order and Y-term)

flavor separation in the transverse plane : problematic

Jefferson Lab

TMD PDFs at 1 GeV

$$\widetilde{f}^{a}_{1\mathrm{NP}}(x, b_T^2) = \frac{1}{2\pi} e^{-g_{1a}\frac{b_T^2}{4}} \left(1 - \frac{\lambda g_{1a}^2}{1 + \lambda g_{1a}} \frac{b_T^2}{4}\right)$$

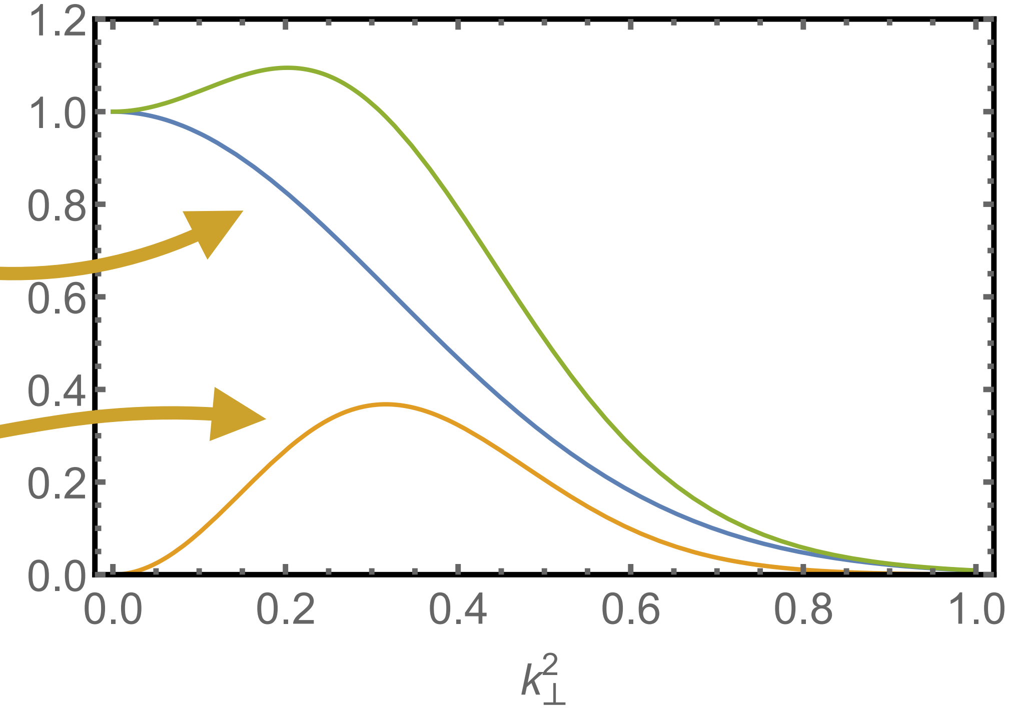
$$f^{a}_{1\mathrm{NP}}(x, \boldsymbol{k}_\perp^2) = \frac{1}{\pi} \, \frac{\left(e^{-\frac{\boldsymbol{k}_\perp^2}{g_{1a}}} + \lambda \boldsymbol{k}_\perp^2 \, e^{-\frac{\boldsymbol{k}_\perp^2}{g_{1a}}}\right)}{g_{1a} + \lambda \, g_{1a}^2}$$

Jefferson Lab

TMD PDFs at 1 GeV

$$\widetilde{f}^{a}_{1\mathrm{NP}}(x, b_T^2) = \frac{1}{2\pi} e^{-g_{1a}\frac{b_T^2}{4}} \left(1 - \frac{\lambda g_{1a}^2}{1 + \lambda g_{1a}} \frac{b_T^2}{4}\right)$$

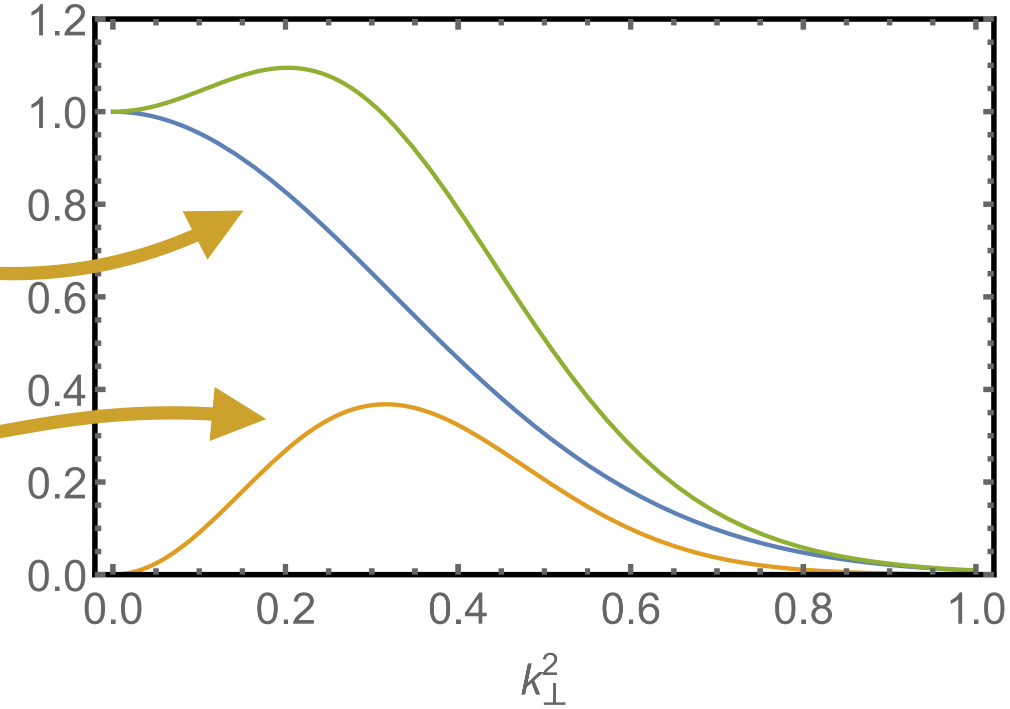
$$f^{a}_{1\mathrm{NP}}(x, \boldsymbol{k}_\perp^2) = \frac{1}{\pi} \frac{\left(e^{-\frac{\boldsymbol{k}_\perp^2}{g_{1a}}} + \lambda \boldsymbol{k}_\perp^2 e^{-\frac{\boldsymbol{k}_\perp^2}{g_{1a}}}\right)}{g_{1a} + \lambda\, g_{1a}^2}$$



TMD PDFs at 1 GeV

$$\tilde{f}^a_{1\mathrm{NP}}(x, b_T^2) = \frac{1}{2\pi} e^{-g_{1a}\frac{b_T^2}{4}} \left(1 - \frac{\lambda g_{1a}^2}{1 + \lambda g_{1a}} \frac{b_T^2}{4}\right)$$

$$f^a_{1\mathrm{NP}}(x, \boldsymbol{k}_\perp^2) = \frac{1}{\pi} \frac{\left(e^{-\frac{\boldsymbol{k}_\perp^2}{g_{1a}}} + \lambda \boldsymbol{k}_\perp^2 e^{-\frac{\boldsymbol{k}_\perp^2}{g_{1a}}}\right)}{g_{1a} + \lambda\, g_{1a}^2}$$



x-dependent width

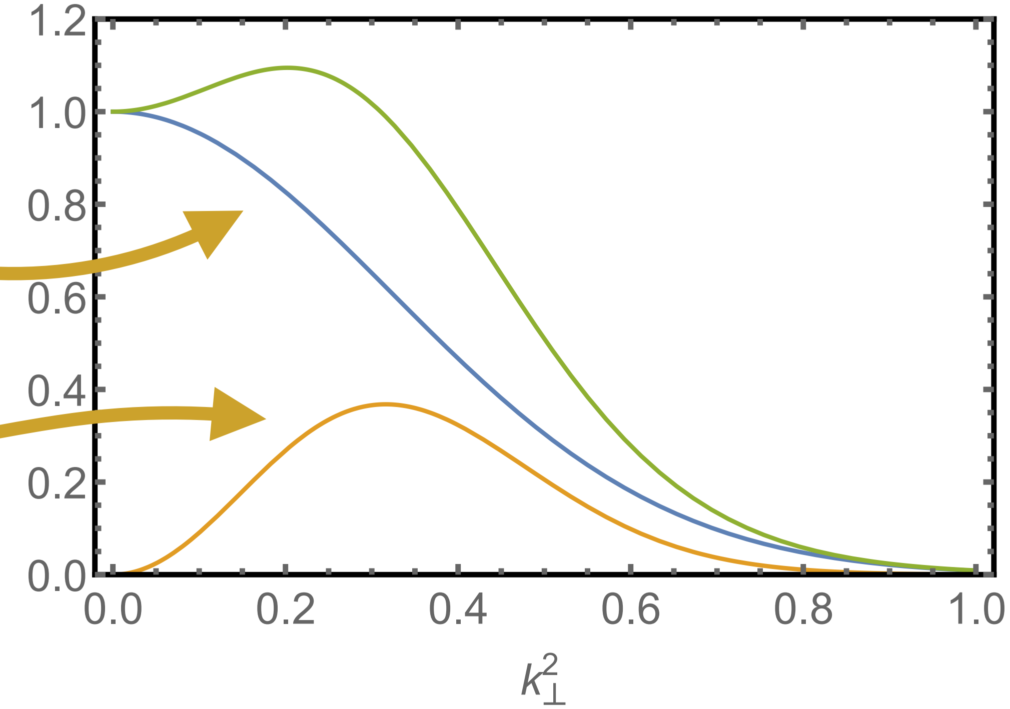
$$g_1(x) = N_1 \frac{(1-x)^\alpha\ x^\sigma}{(1-\hat{x})^\alpha\ \hat{x}^\sigma}$$

Jefferson Lab

TMD PDFs at 1 GeV

$$\widetilde{f}^{a}_{1\mathrm{NP}}(x, b_T^2) = \frac{1}{2\pi} e^{-g_{1a}\frac{b_T^2}{4}} \left(1 - \frac{\lambda g_{1a}^2}{1+\lambda g_{1a}} \frac{b_T^2}{4}\right)$$

$$f^{a}_{1\mathrm{NP}}(x, \boldsymbol{k}_\perp^2) = \frac{1}{\pi} \frac{\left(e^{-\frac{\boldsymbol{k}_\perp^2}{g_{1a}}} + \lambda \boldsymbol{k}_\perp^2 e^{-\frac{\boldsymbol{k}_\perp^2}{g_{1a}}}\right)}{g_{1a} + \lambda\, g_{1a}^2}$$



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

Fragmentation function is similar
Including TMD PDFs and FFs, in total: 11 free parameters
(4 for TMD PDFs, 6 for TMD FFs, 1 for TMD evolution)

Jefferson Lab

Agreement data-theory

Flavor independent scenario

Flavor independent configuration | 11 parameters

Points	Parameters	χ^2	χ^2/d.o.f.
8059	11	12629 ± 363	1.55 ± 0.05

	HERMES $p \to \pi^+$	HERMES $p \to \pi^-$	HERMES $p \to K^+$	HERMES $p \to K^-$
Points	190	190	189	187
χ^2/points	4.83	2.47	0.91	0.82

Hermes P/D into π+:
problems at low z

	HERMES $D \to \pi^+$	HERMES $D \to \pi^-$	HERMES $D \to K^+$	HERMES $D \to K^-$	COMPASS $D \to h^+$	COMPASS $D \to h^-$
Points	190	190	189	189	3125	3127
χ^2/points	3.46	2.00	1.31	2.54	1.11	1.61

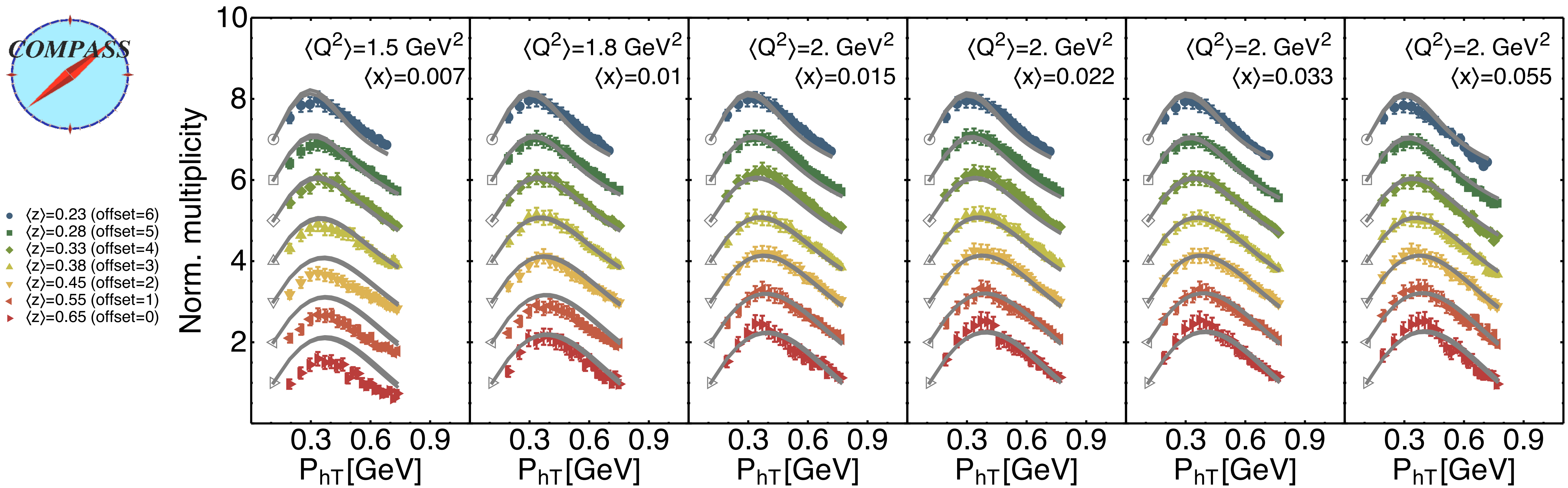
	E288 [200]	E288 [300]	E288 [400]	E605
Points	45	45	78	35
χ^2/points	0.99	0.84	0.32	1.12

Hermes kaons better than pions:
larger uncertainties from FFs

Compass : better agreement due to
#points and normalization

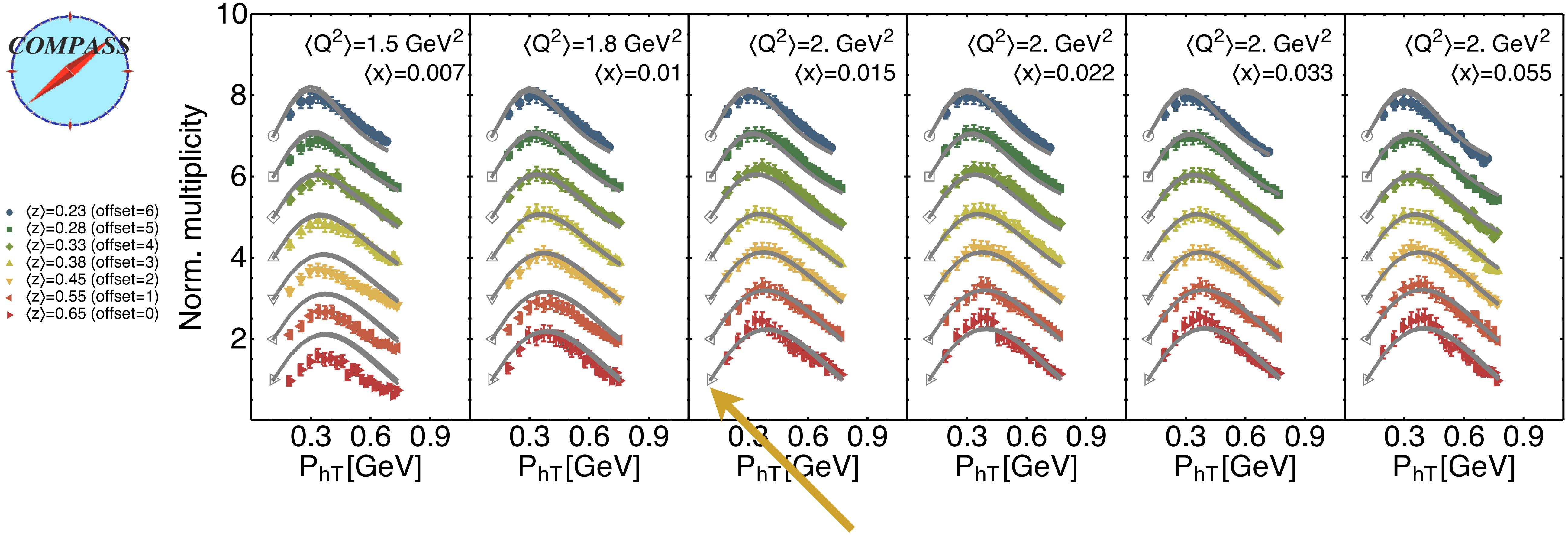
	CDF Run I	D0 Run I	CDF Run II	D0 Run II
Points	31	14	37	8
χ^2/points	1.36	1.11	2.00	1.73

COMPASS, selected bins



Deuteron h^- $\chi^2/\text{dof} = 1.58$

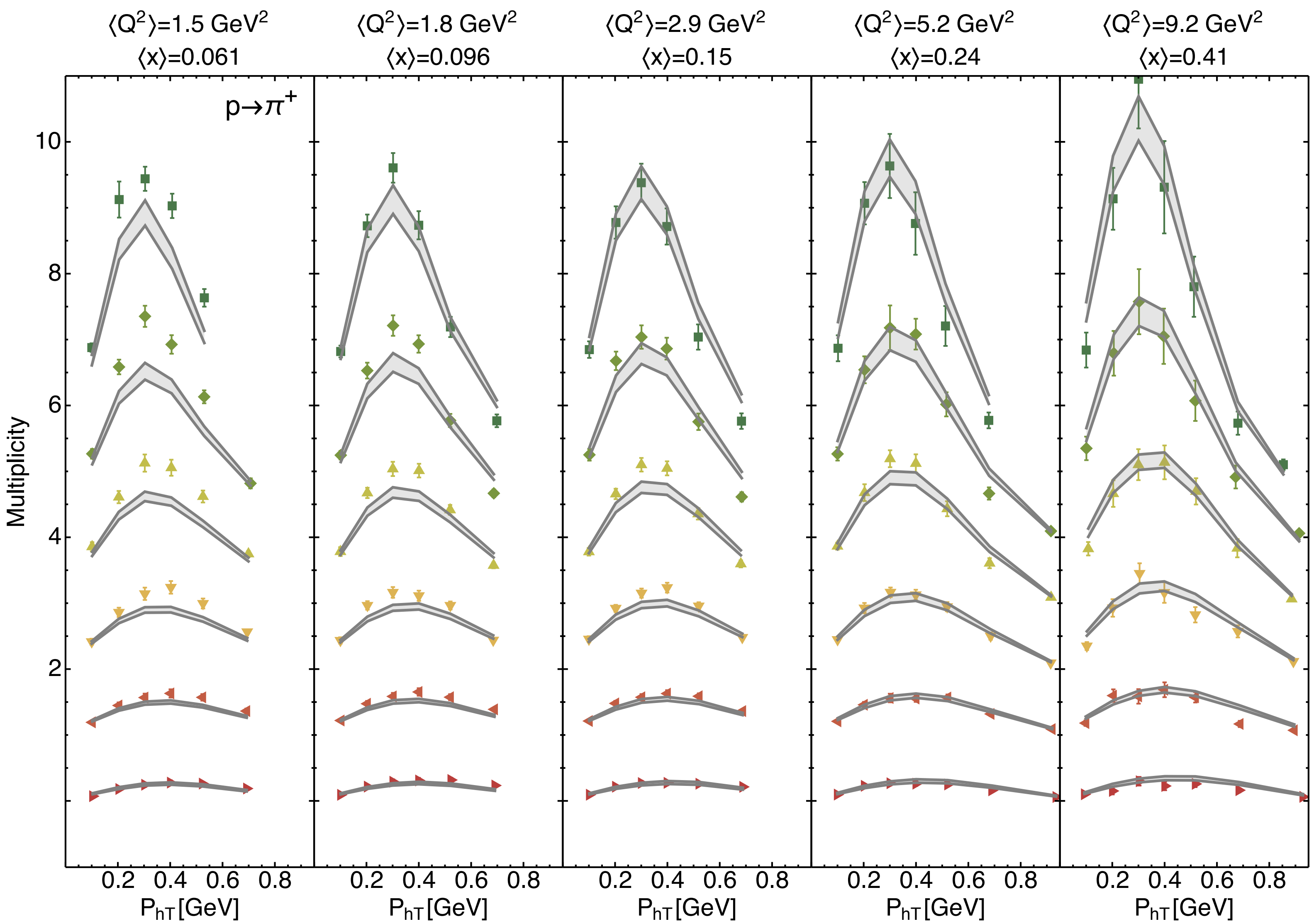
COMPASS, selected bins



First points are not fitted, but used as normalization

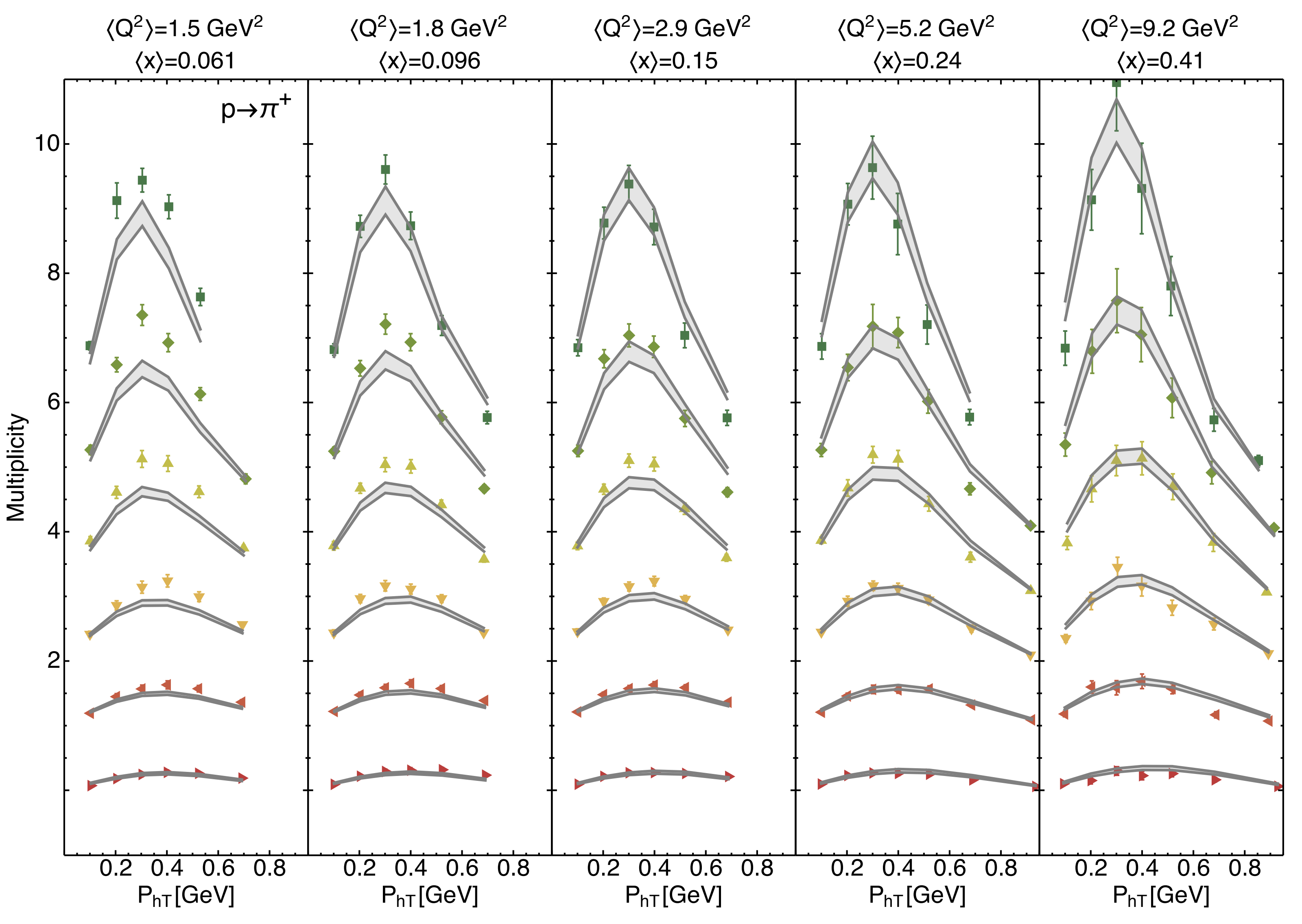
Deuteron h^- $\chi^2/\text{dof} = 1.58$

HERMES, selected bins



Contributions to chi2 mainly from **normalization**, not shape
(also in Z-boson production)

HERMES, selected bins



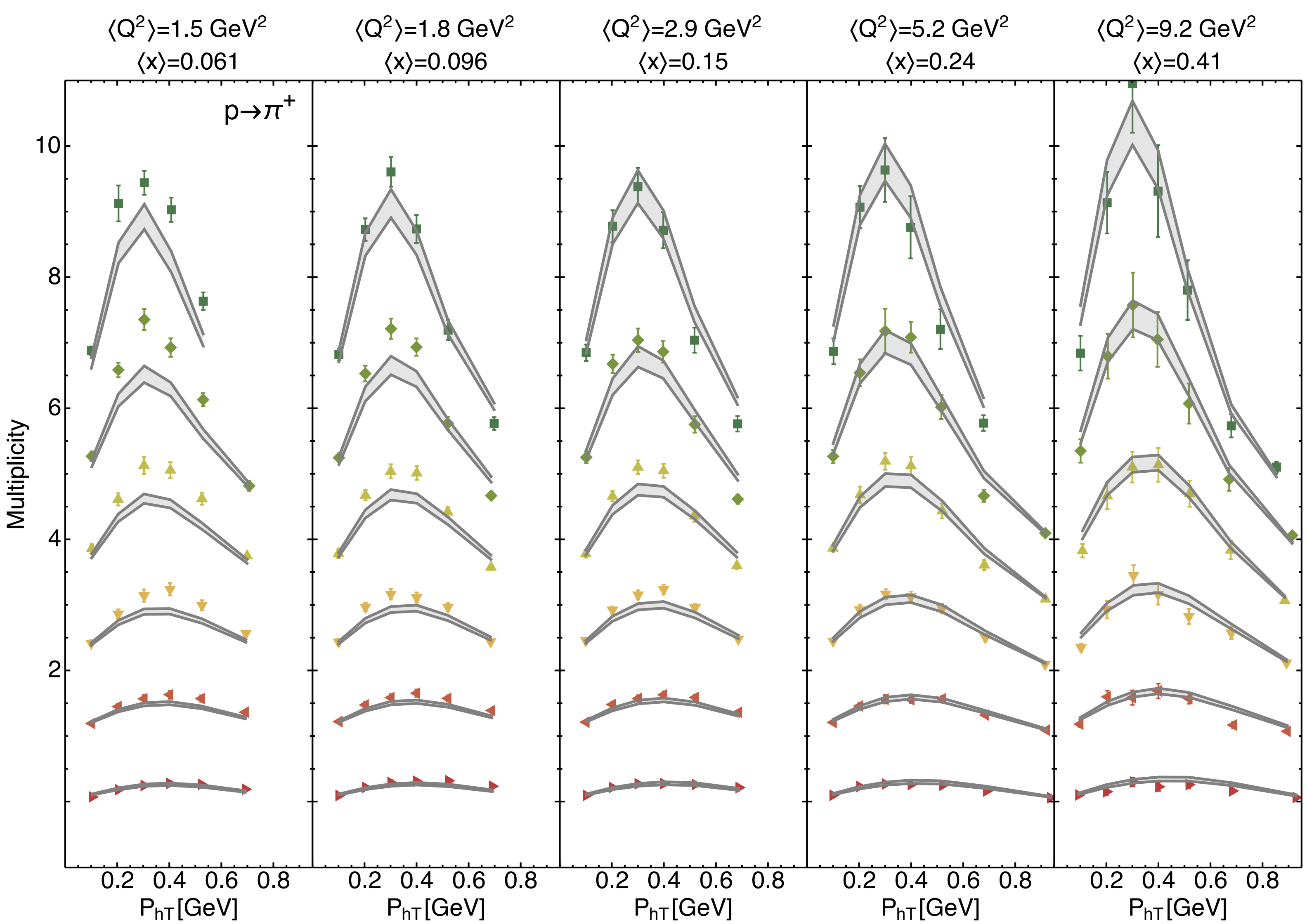
$\chi^2/\mathrm{dof} = 4.80$

The worst of all channels...

Contributions to chi2 mainly from **normalization**, not shape (also in Z-boson production)

Jefferson Lab

HERMES, selected bins



$\chi^2/\mathrm{dof} = 4.80$

The worst of all channels...

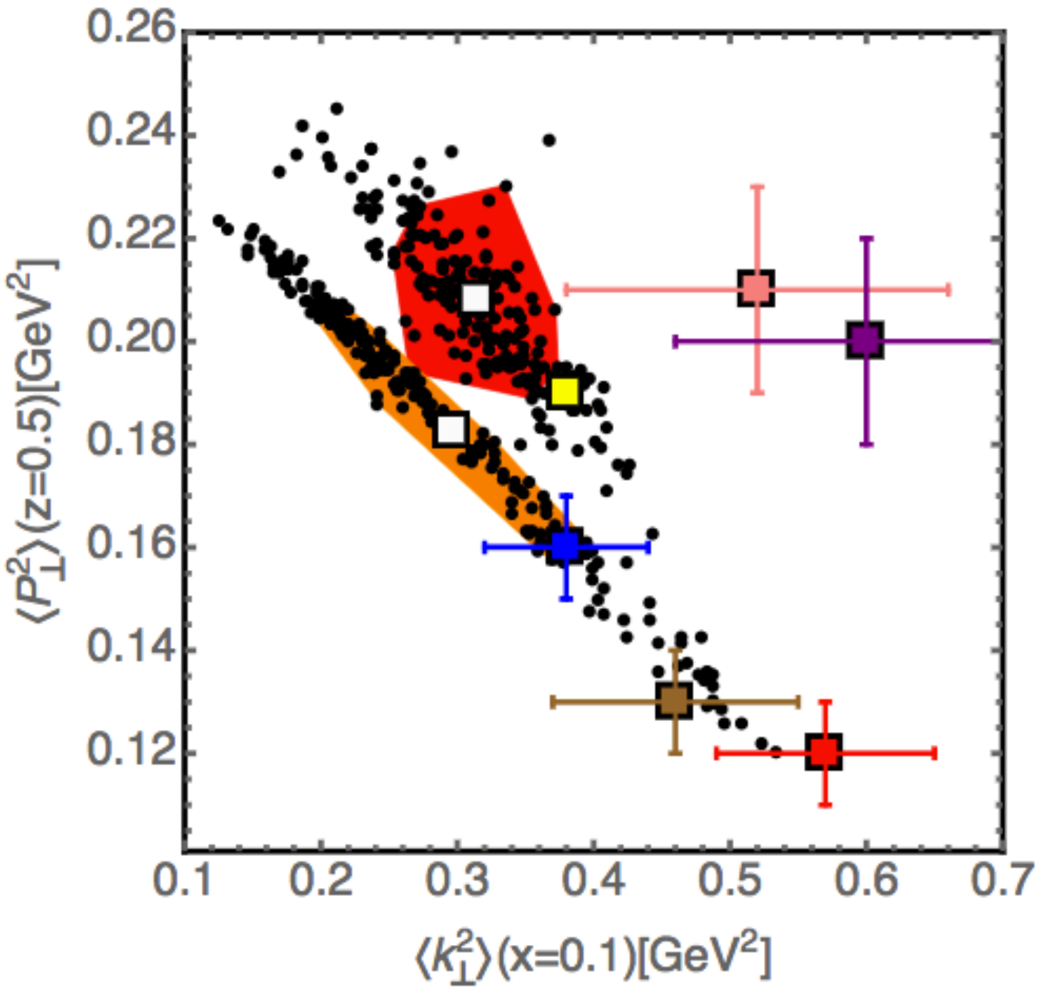
However **normalizing** the theory curves to the first bin, without changing the parameters of the fit, χ^2/dof becomes good

Contributions to chi2 mainly from **normalization**, not shape (also in Z-boson production)

Jefferson Lab

Best-fit values

Flavor independent scenario



- Bacchetta, Delcarro, Pisano, Radici, Signori,
- Signori, Bacchetta, Radici, Schnell arXiv:1309.3507
- Schweitzer, Teckentrup, Metz, arXiv:1003.2190
- Anselmino et al. arXiv:1312.6261 [HERMES]
- Anselmino et al. arXiv:1312.6261 [HERMES, high z]
- Anselmino et al. arXiv:1312.6261 [COMPASS, norm.]
- Anselmino et al. arXiv:1312.6261 [COMPASS, high z, norm.]
- Echevarria, Idilbi, Kang, Vitev arXiv:1401.5078 (Q = 1.5 GeV)

Red/orange regions : **68% CL** from replica method

Inclusion of **DY/Z diminishes the correlation**

Inclusion of **Compass** increases the $\langle P_\perp^2 \rangle$ and reduces its spread

e+e- would further reduce the correlation

Caveat for comparisons :
NP effects (as the intrinsic momentum) always depend on the accuracy of the perturbative part ;

determined as observed - calculable

Jefferson Lab

Polarized TMDs (Sivers)

References :

- "The 3D structure of the nucleon" **EPJ A (2016) 52**
- STAR **arXiv:1511.06003**
- Compass: **arxiv:1704.00488**
- ...

Process dependence

Gauge invariance and T-reversal invariance generate a **sign change** between the **Sivers** TMD PDF in **Drell-Yan** and **Semi-Inclusive DIS**

Process dependence

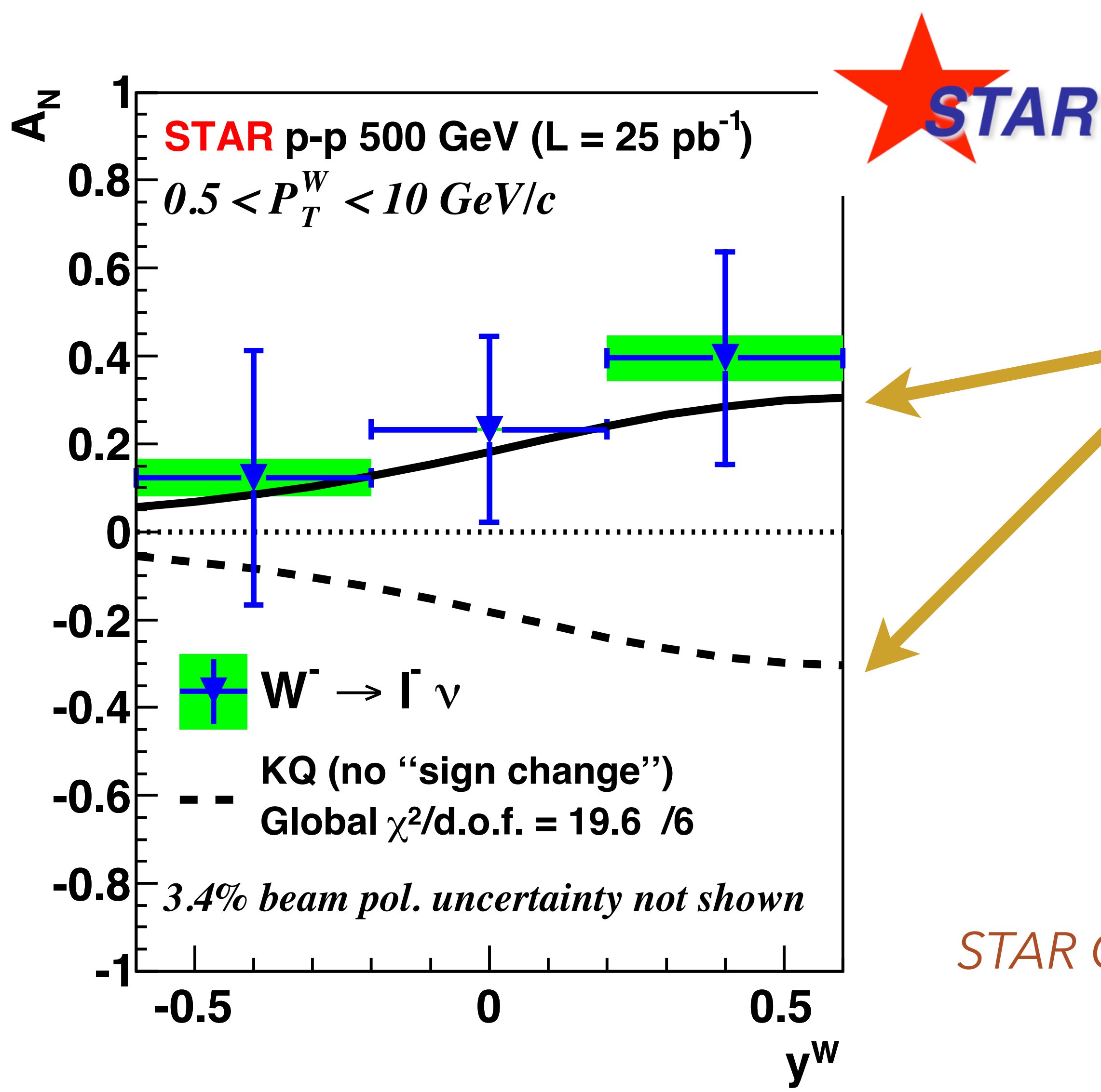
Gauge invariance and T-reversal invariance generate a **sign change** between the **Sivers** TMD PDF in **Drell-Yan** and **Semi-Inclusive DIS**

Collins, PLB 536 (02)

Process dependence

Gauge invariance and T-reversal invariance generate a **sign change** between the **Sivers** TMD PDF in **Drell-Yan** and **Semi-Inclusive DIS**

Collins, PLB 536 (02)



first evidence of sign change?

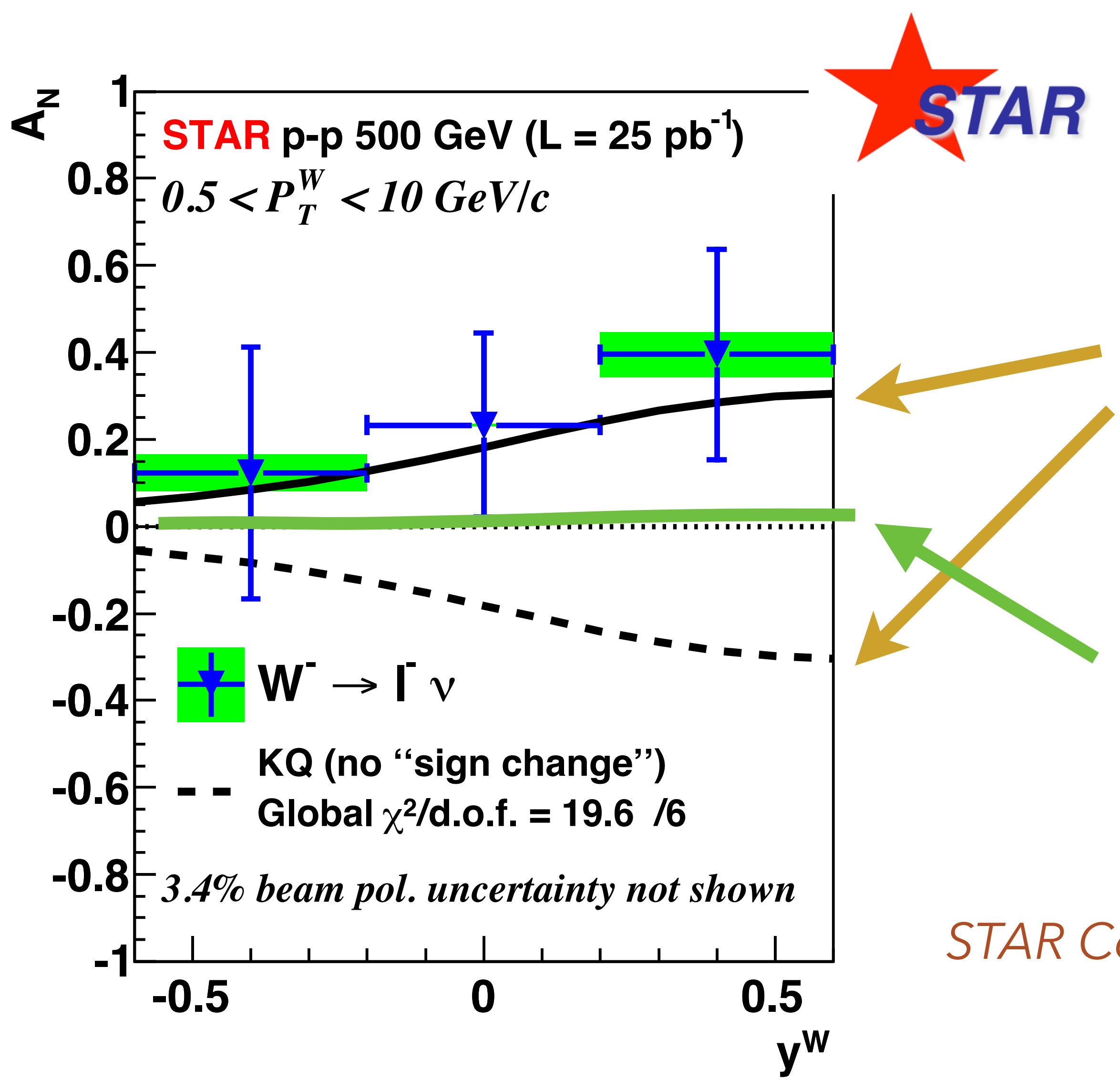
STAR Collab. arXiv:1511.06003

Jefferson Lab

Process dependence

Gauge invariance and T-reversal invariance generate a **sign change** between the **Sivers** TMD PDF in **Drell-Yan** and **Semi-Inclusive DIS**

Collins, PLB 536 (02)



first evidence of sign change?

prediction with TMD evolution equations

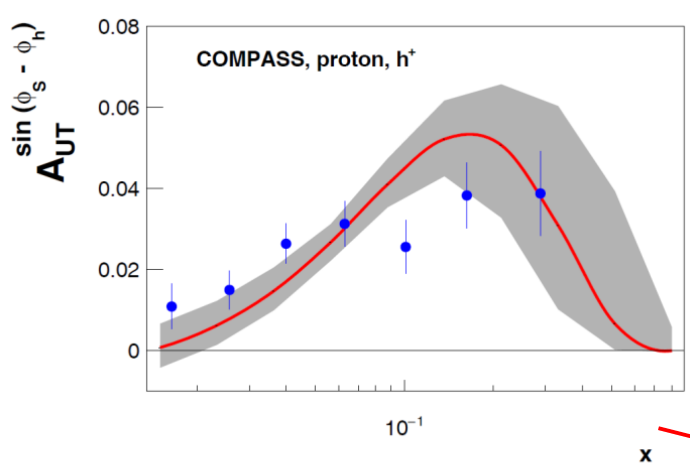
STAR Collab. arXiv:1511.06003

Jefferson Lab

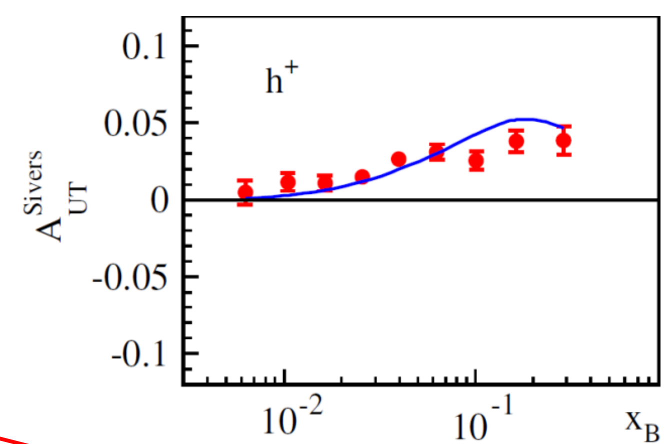
Process dependence

Sivers asymmetry in Semi-Inclusive DIS

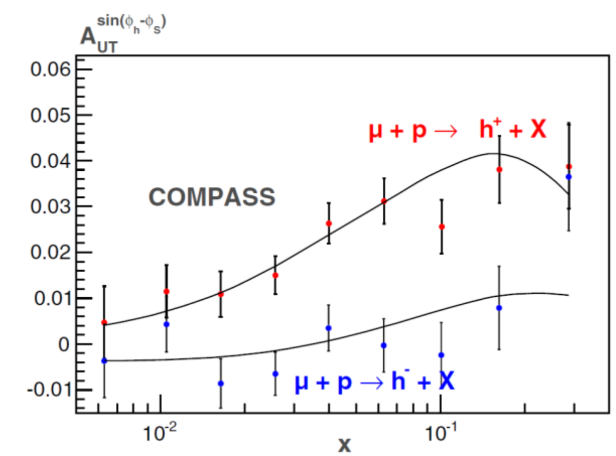
DGLAP (2016)
M. Anselmino et al., **arXiv:1612.06413**



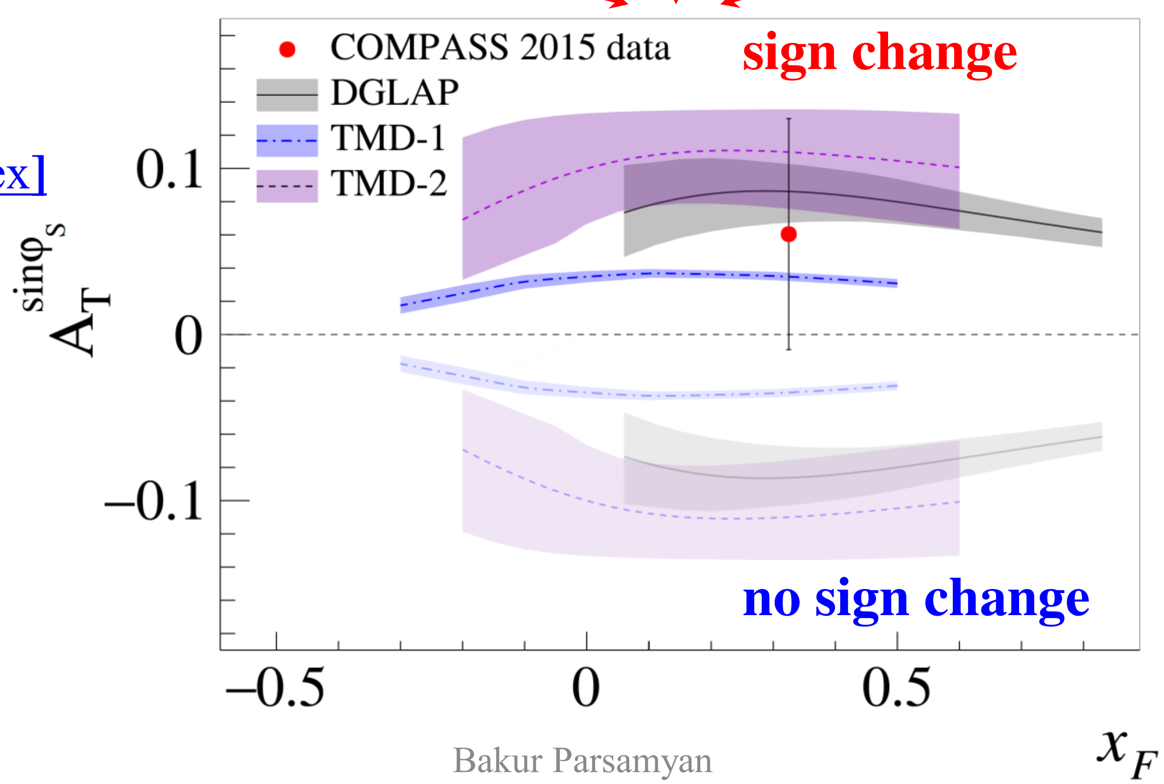
TMD-1 (2014)
M. G. Echevarria et al. **PRD89,074013**



TMD-2 (2013)
P. Sun, F. Yuan, **PRD88, 114012**



New! **03 April 2017**
COMPASS
CERN-EP-2017-059
[arXiv:1704.00488[hep-ex]](arXiv:1704.00488[hep-ex])



Sivers asymmetry in Drell-Yan

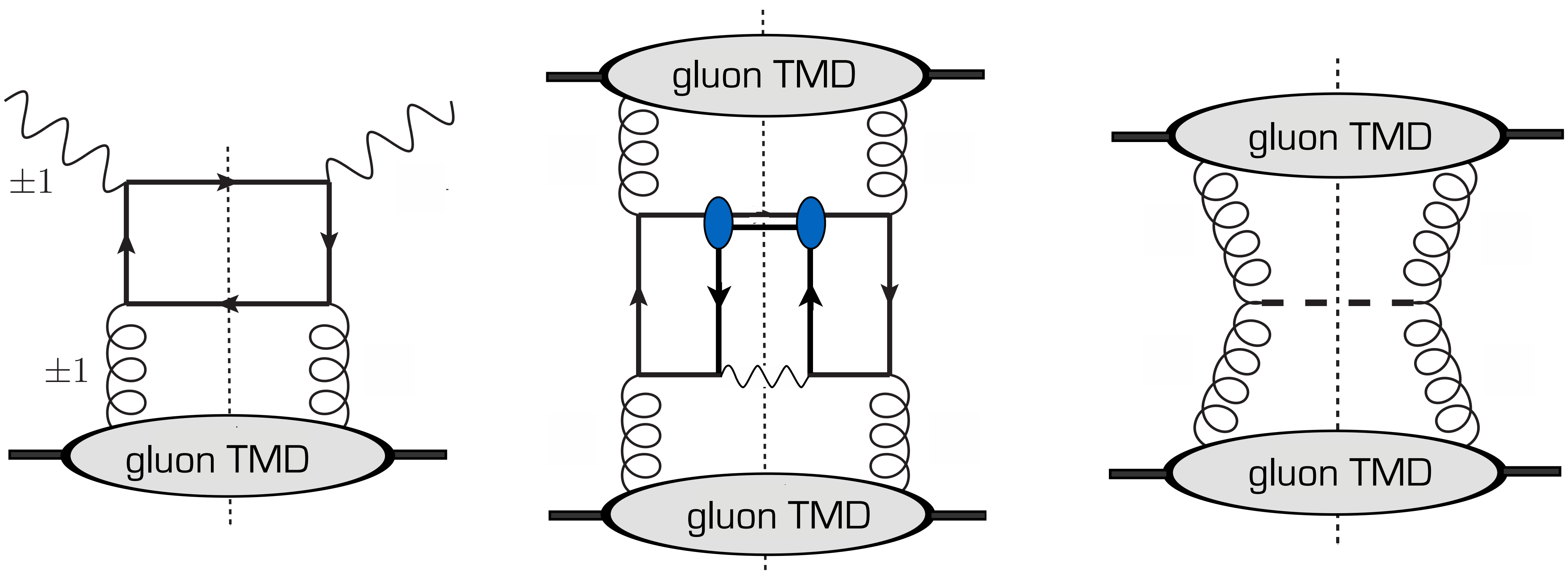
courtesy B. Parsamyan

n Lab

Gluon TMDs

Gluon TMDs

$e\,p \to e$ jet jet X $\qquad$ $p\,p \to J/\psi\,\gamma\,X$ $\qquad$ $p\,p \to \eta_c\,X$

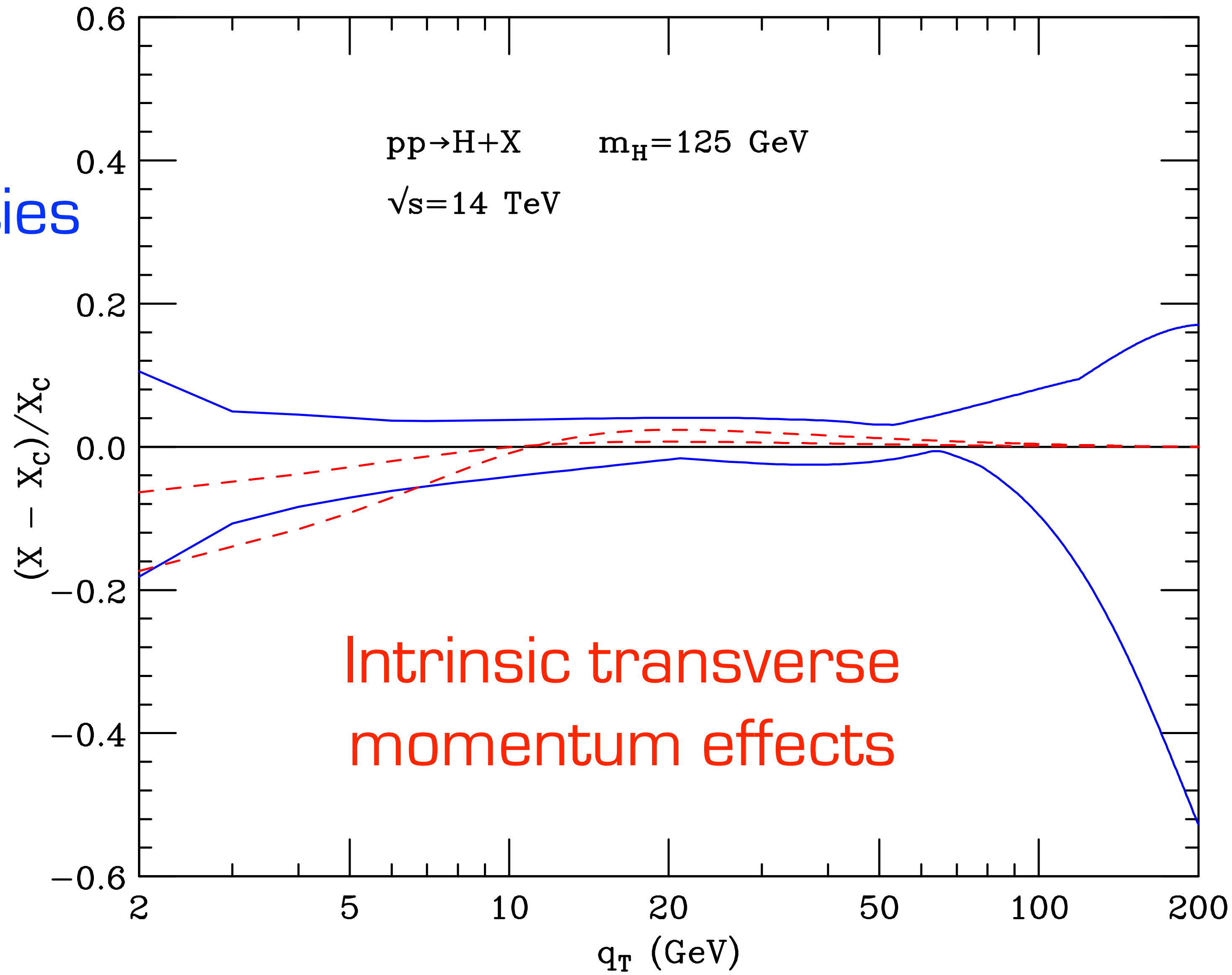


see, e.g.,
- Boer, den Dunnen, Pisano, Schlegel, Vogelsang, PRL108 (12)
- den Dunnen, Lansberg, Pisano, Schlegel, PRL 112 (14)
- AS: PhD thesis , arXiv:1602.03405
- AFTER@LHC working group: arXiv:1702.01546 , arXiv:1610.05228 , ...
- Echevarria et al. arXiv:1502.05354
- ...

Higgs transverse momentum

G. Ferrera, talk at REF 2014, Antwerp, https://indico.cern.ch/event/330428/

PDF uncertainties

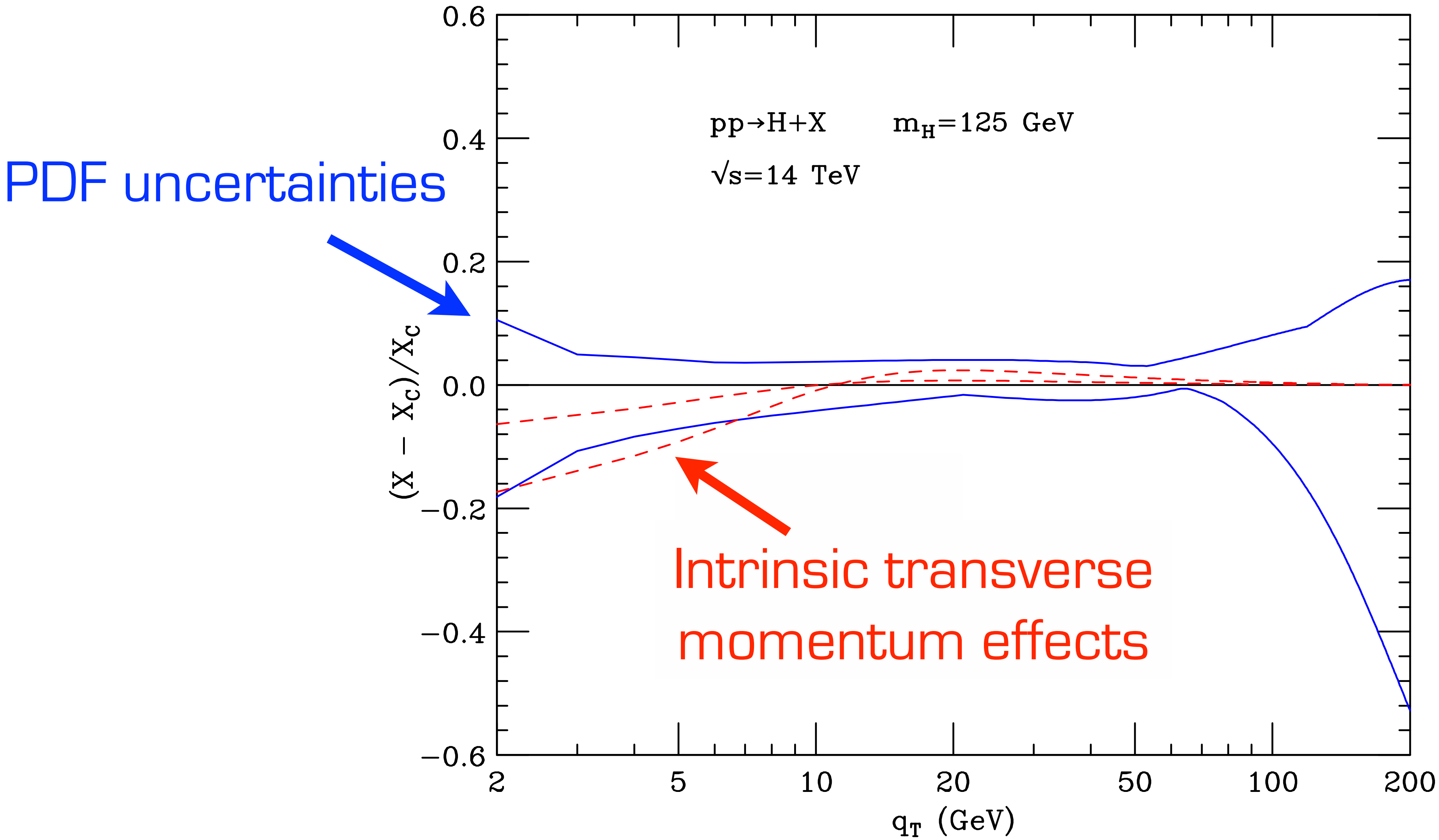


Intrinsic transverse momentum effects

Jefferson Lab

Higgs transverse momentum

G. Ferrera, talk at REF 2014, Antwerp, https://indico.cern.ch/event/330428/



Jefferson Lab

Spin 1 TMDs

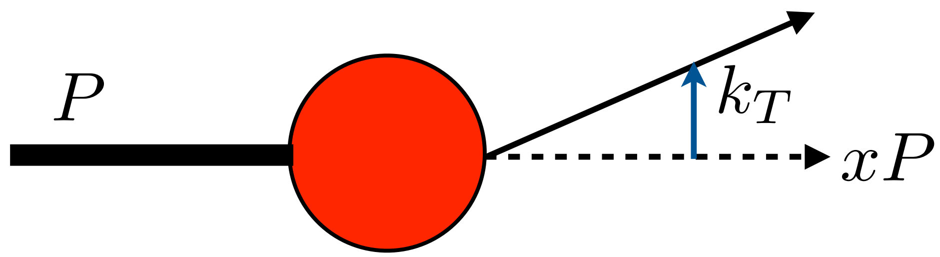
References :

- quark TMDs : Phys.Rev. D62 (2000) 114004
- gluon TMDs : JHEP 1610 (2016) 013
- ...

quark TMD PDFs

$$\Phi_{ij}(k,P;S,T) \sim \text{F.T.}\ \langle PST|\ \bar{\psi}_j(0)\ U_{[0,\xi]}\ \psi_i(\xi)\ |PST\rangle_{|LF}$$

Quarks	γ^+	$\gamma^+\gamma^5$	$i\sigma^{i+}\gamma^5$
U	$\boldsymbol{f_1}$		$h_1^\perp$
L		$\boldsymbol{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\boldsymbol{h_1},\ h_{1T}^\perp$
LL	$\boldsymbol{f_{1LL}}$		$h_{1LL}^\perp$
LT	f_{1LT}	g_{1LT}	$h_{1LT},\ h_{1LT}^\perp$
TT	f_{1TT}	g_{1TT}	$h_{1TT},\ h_{1TT}^\perp$



extraction of a **quark**
not collinear with the proton

a similar scheme holds for
TMD FFs and gluons

bold : also collinear
red : time-reversal odd (universality properties)

Jefferson Lab

quark TMD PDFs

recent investigations of the T-even TMDs in the context of DSE
arXiv:1707.03787

Quarks	γ^+	$\gamma^+\gamma^5$	$i\sigma^{i+}\gamma^5$
U	$\boldsymbol{f_1}$		$h_1^\perp$
L		$\boldsymbol{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\boldsymbol{h_1}$, $h_{1T}^\perp$
LL	$\boldsymbol{f_{1LL}}$		$h_{1LL}^\perp$
LT	f_{1LT}	g_{1LT}	h_{1LT}, $h_{1LT}^\perp$
TT	f_{1TT}	g_{1TT}	h_{1TT}, $h_{1TT}^\perp$

Collinear, related to b1(x) (under scrutiny at JLab)

Collinear & T-odd : should be zero! (to be investigated)

bold : also collinear
red : time-reversal odd (universality properties)

Conclusions : a path to move forward

1) Phenomenology of TMDs is well underway ...

2) ... but there are a lot of theoretical challenges to be addressed: definition of kinematic regions in SIDIS, matching, perturbative accuracy, a better understanding of hadronization, context for gluon TMDs , ...

3) we definitely need more data, at the moment especially for e+e-

4) Working with some approximations, we are getting closer to a global fit analysis of TMDs

5) polarized structure functions unexplored from the point of view of QCD, but we have guidance from parton model studies (see JLab activities)

Backup

Beware of different notations...

Amsterdam	Seattle (arXiv:1108.1713)	
p	k	momentum of parton in distribution function
$\boldsymbol{p}_T$	$\boldsymbol{k}_\perp$	parton transverse momentum in distribution function
k	p	momentum of fragmenting parton
$\boldsymbol{k}_T$	$\boldsymbol{p}_\perp$	trans. momentum of fragmenting parton w.r.t. final hadron
$\boldsymbol{K}_T$	$\boldsymbol{P}_\perp$	trans. momentum of final hadron w.r.t. fragmenting parton
$\boldsymbol{P}_{h\perp}$	$\boldsymbol{P}_{hT}$	transverse momentum of final hadron w.r.t. virtual photon

TMDs and their evolution

FT of TMDs :

$$\tilde{F}_i(x, b_T; Q, Q^2) = \tilde{F}_i(x, b_T, \mu_{\hat{b}}, \mu_{\hat{b}}^2) \times$$

$$\exp\left\{ \int_{\mu_{\hat{b}}}^{Q} \frac{d\mu}{\mu} \gamma_F[\alpha_s(\mu), Q^2/\mu^2] \right\} \left(\frac{Q^2}{\mu_{\hat{b}}^2} \right)^{-K(\hat{b}_T;\mu_{\hat{b}}) - g_K(\overline{b_T};\{\lambda\})}$$

Sudakov form factor : perturbative and **nonperturbative** contributions

---

(input) TMD distribution : Wilson coefficients and **intrinsic part**

Collinear distribution!

$$\tilde{F}_i(x, b_T; \mu_{\hat{b}}, \mu_{\hat{b}}^2) = \sum_{j=q,\bar{q},g} C_{i/j}(x, \hat{b}_T; \mu_{\hat{b}}, \mu_{\hat{b}}^2) \otimes f_j(x; \mu_{\hat{b}}) \tilde{F}_{i,NP}(x, \overline{b_T}; \{\lambda\})$$

Nonperturbative parts defined in a “negative” way : **observed-calculable**

Jefferson Lab

TMDs and their evolution

Distribution for intrinsic transverse momentum (and its FT):

$$\tilde{F}_{i,NP}(x, \bar{b}_T; \{\lambda\})$$

a Gaussian ?

Soft gluon emission

$$g_K(\bar{b}_T; \{\lambda\})$$

TMDs and their evolution

Distribution for intrinsic transverse momentum (and its FT):

$$\tilde{F}_{i,NP}(x, \bar{b}_T; \{\lambda\})$$

a Gaussian ?

Soft gluon emission

$$g_K(\bar{b}_T; \{\lambda\})$$

Separation of **b_T regions**

$$\hat{b}_T(b_T; b_{\min}, b_{\max}) \;\begin{cases} \nearrow\; b_{\max}\ , & b_T \to +\infty \\ \sim\; b_T\ , & b_{\min} \ll b_T \ll b_{\max} \\ \searrow\; b_{\min}\ , & b_T \to 0 \end{cases}$$

High b_T limit : avoid Landau pole

Low b_T limit : recover fixed order expression

Jefferson Lab

Models - evolution and b_T regions

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

$$\hat{b}(b_T; b_{\min}, b_{\max}) = b_{\max} \left(\frac{1 - e^{-b_T^4 / b_{\max}^4}}{1 - e^{-b_T^4 / b_{\min}^4}} \right)$$

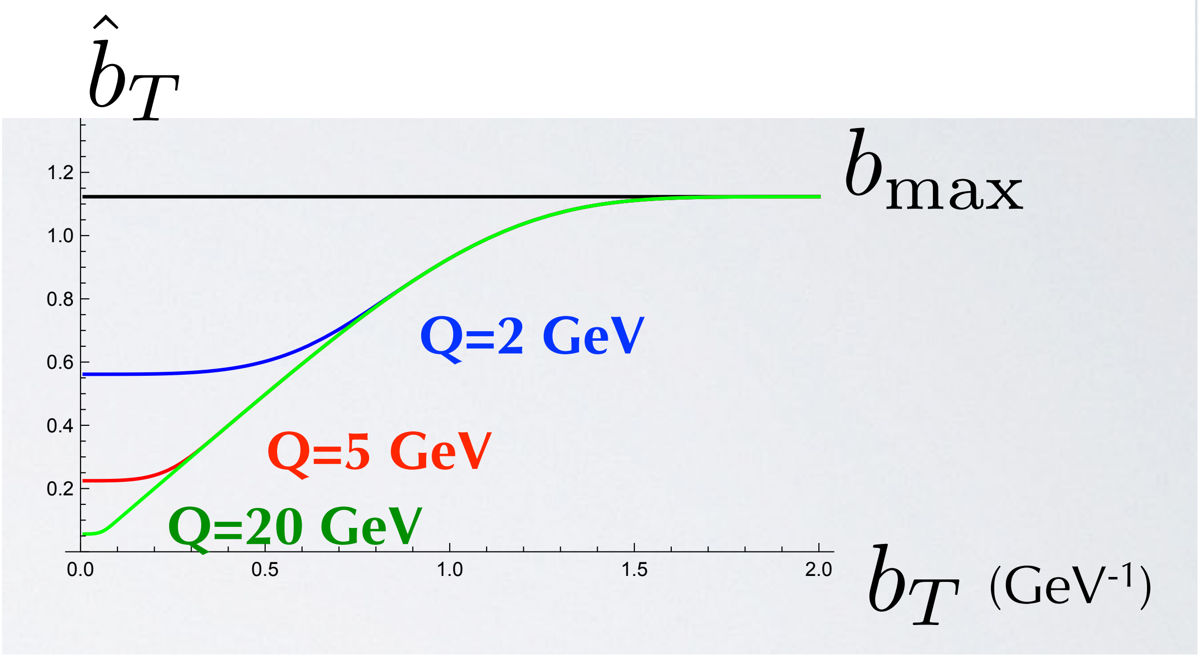
$\nearrow$ $b_{\max}$, $\quad b_T \to +\infty$

$\searrow$ $b_{\min}$, $\quad b_T \to 0$

$$b_{\max} = 2e^{-\gamma_E}$$

$$b_{\min} = 2e^{-\gamma_E}/Q$$

These choices guarantee that for Q=1 GeV the TMD coincides with the NP model



Models - evolution and b_T regions

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

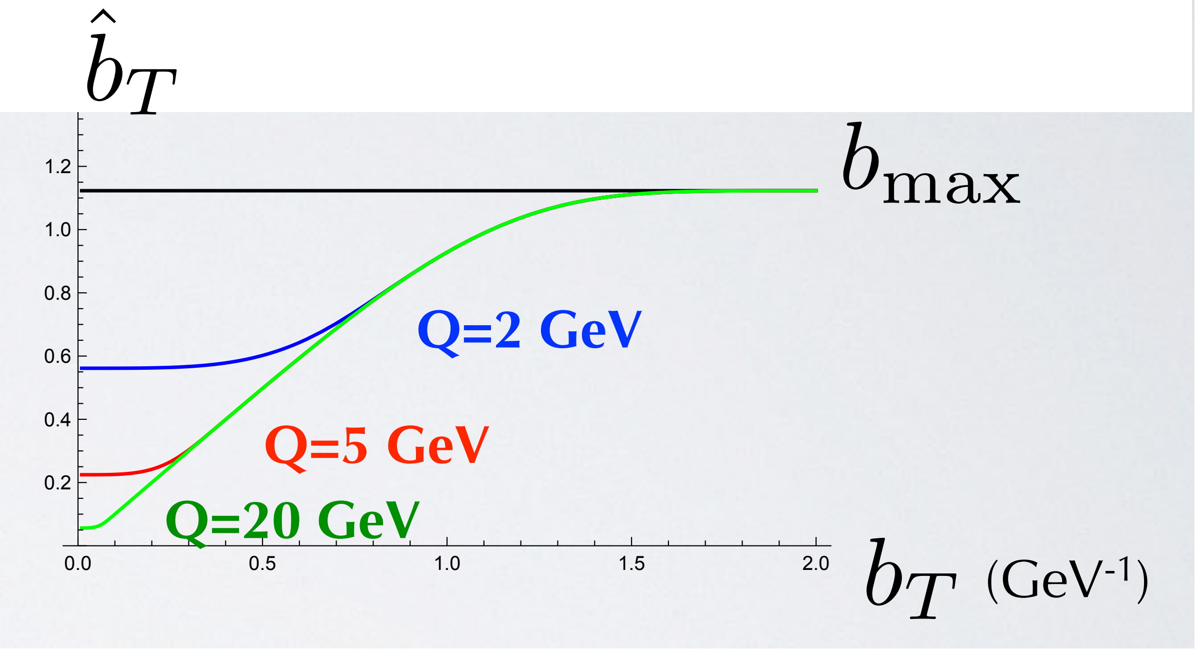
$$\hat{b}(b_T; b_{\min}, b_{\max}) = b_{\max} \left(\frac{1 - e^{-b_T^4/b_{\max}^4}}{1 - e^{-b_T^4/b_{\min}^4}} \right)$$

$\nearrow$ $b_{\max}\ , \quad b_T \to +\infty$

$\searrow$ $b_{\min}\ , \quad b_T \to 0$

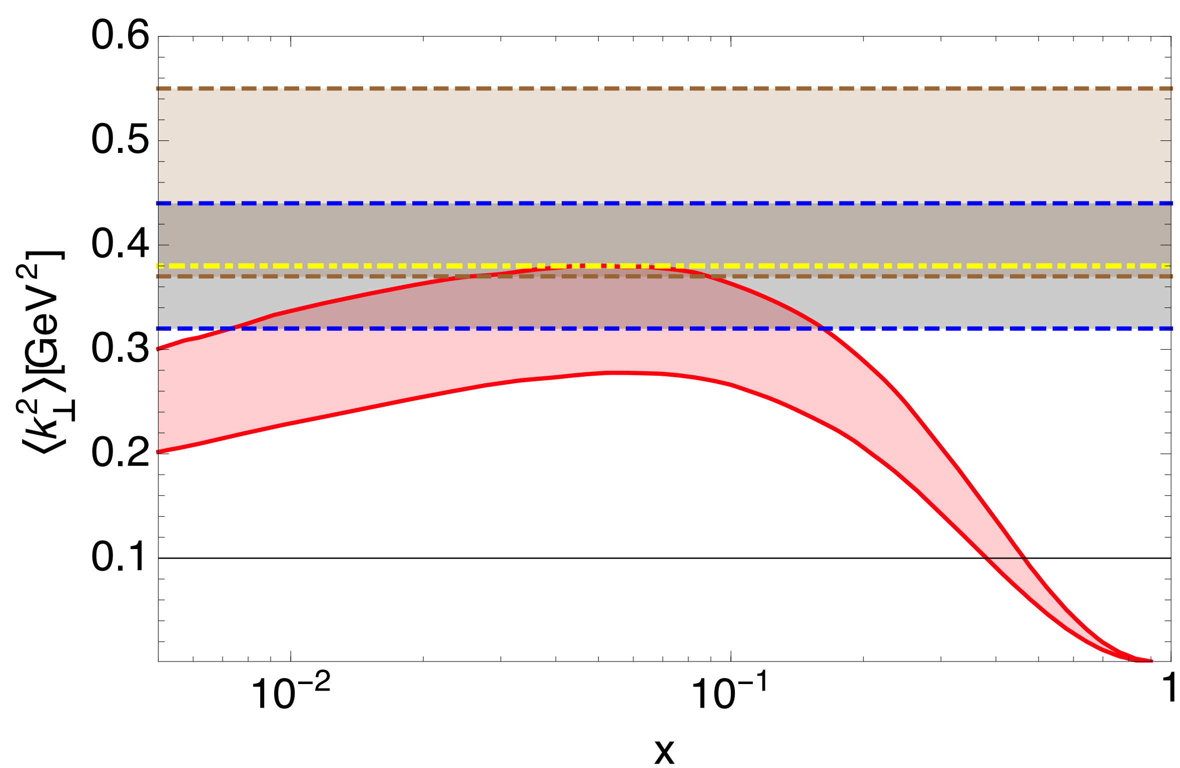
$b_{\min} \sim 1/Q\ , \quad \mu_{\hat{b}} < Q$

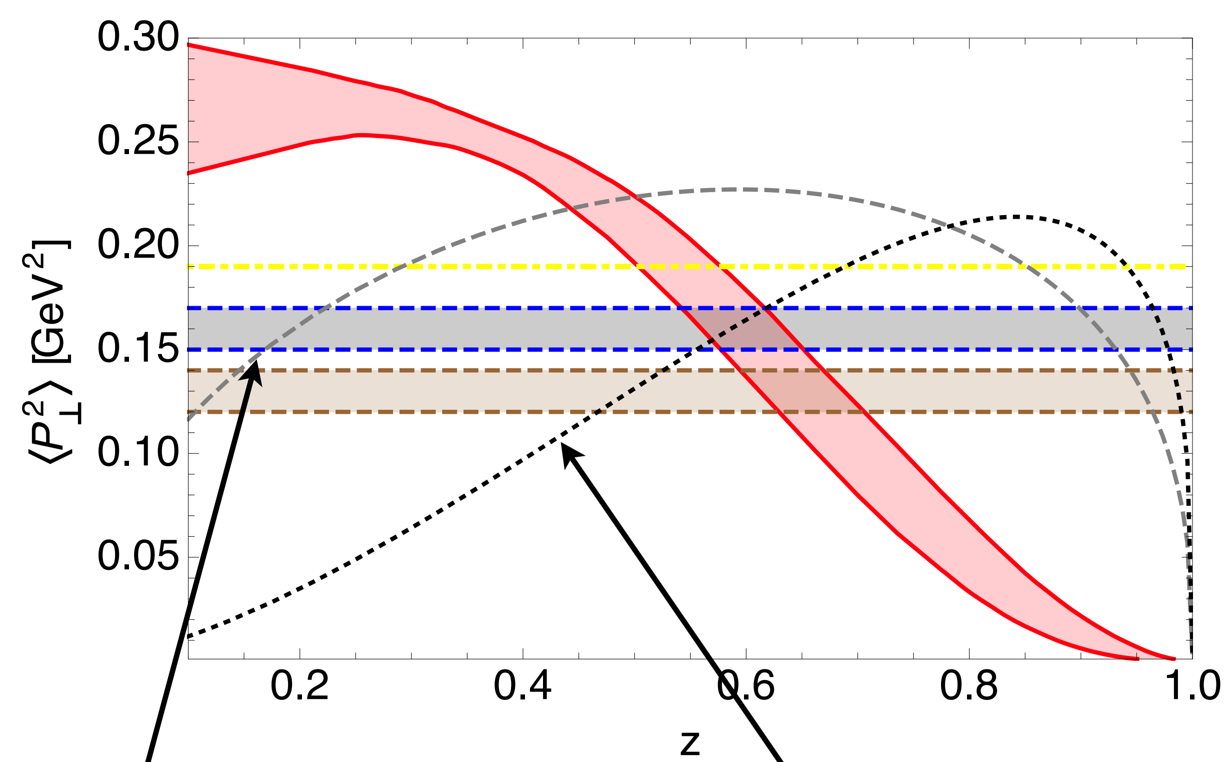
The phenomenological importance of b_{min} is a signal that -especially in SIDIS data at **low Q**- we are exiting the proper TMD region and approaching the region of collinear factorization



Kinematic dependence

Comparison with other extractions :





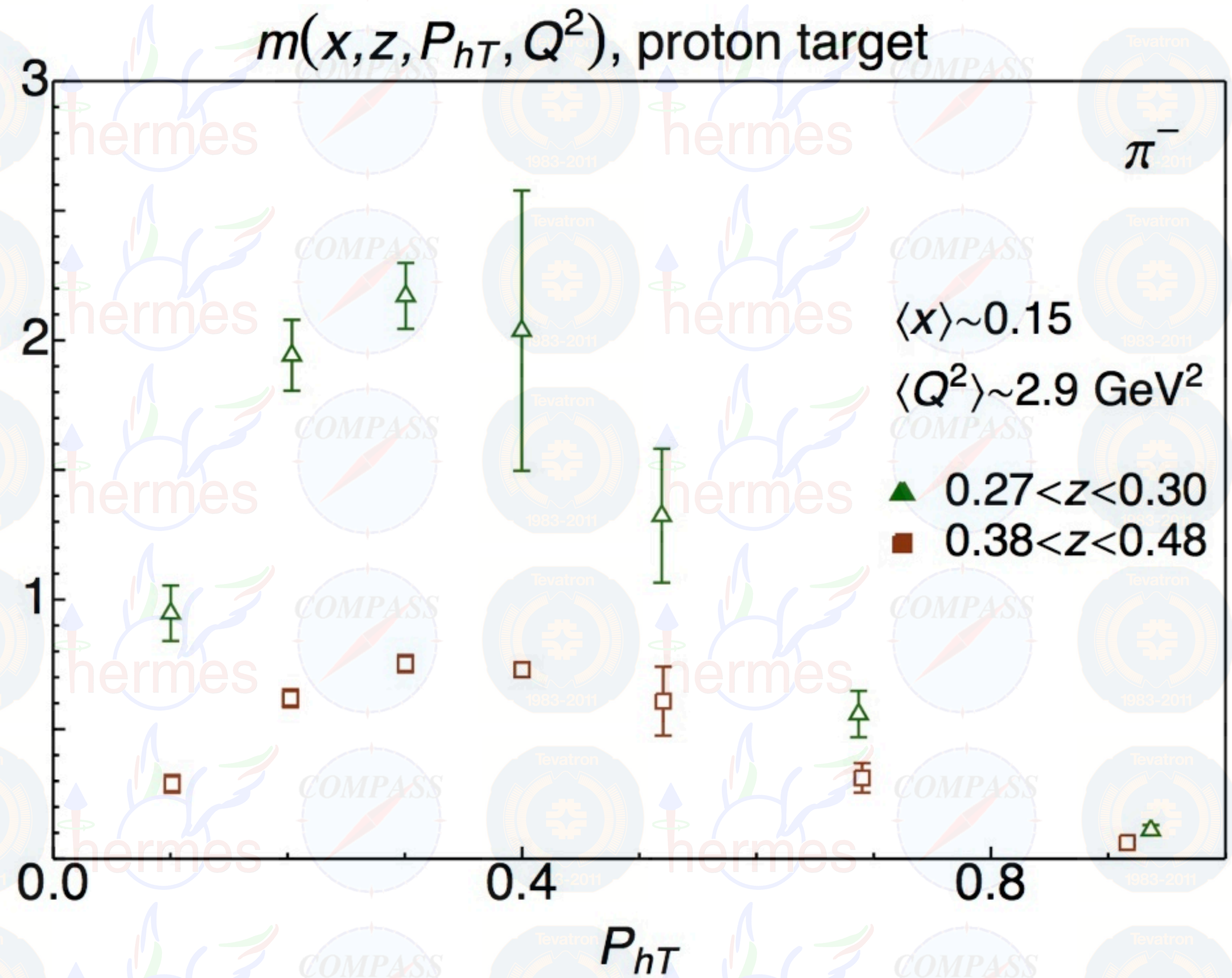
Color code : same as previous slide

GMC trans

Anselmino et al.
hep-ph/9901442

Jefferson Lab

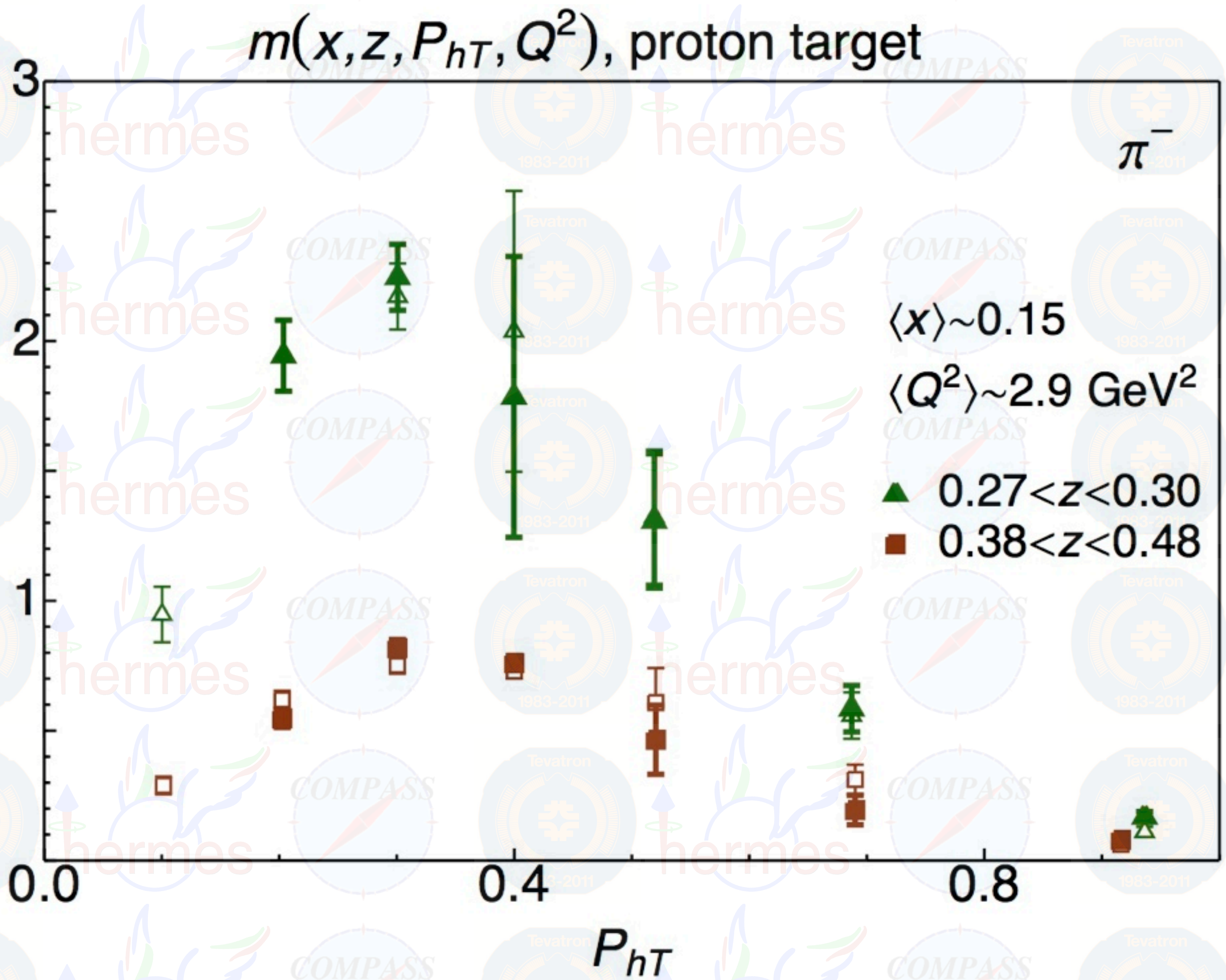
The replica method



Sample of original data

Jefferson Lab

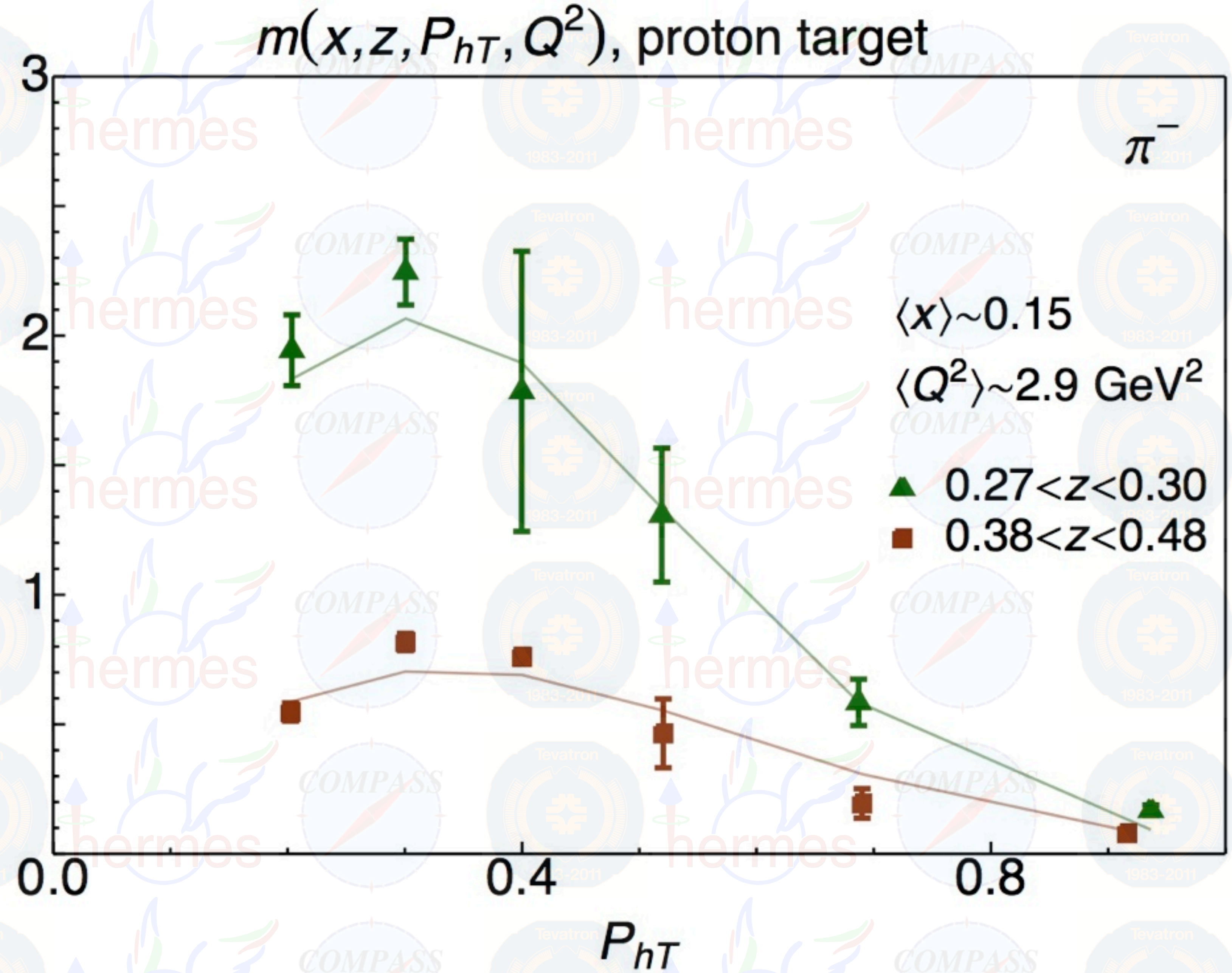
The replica method



Replica of the original data with Gaussian noise

Jefferson Lab

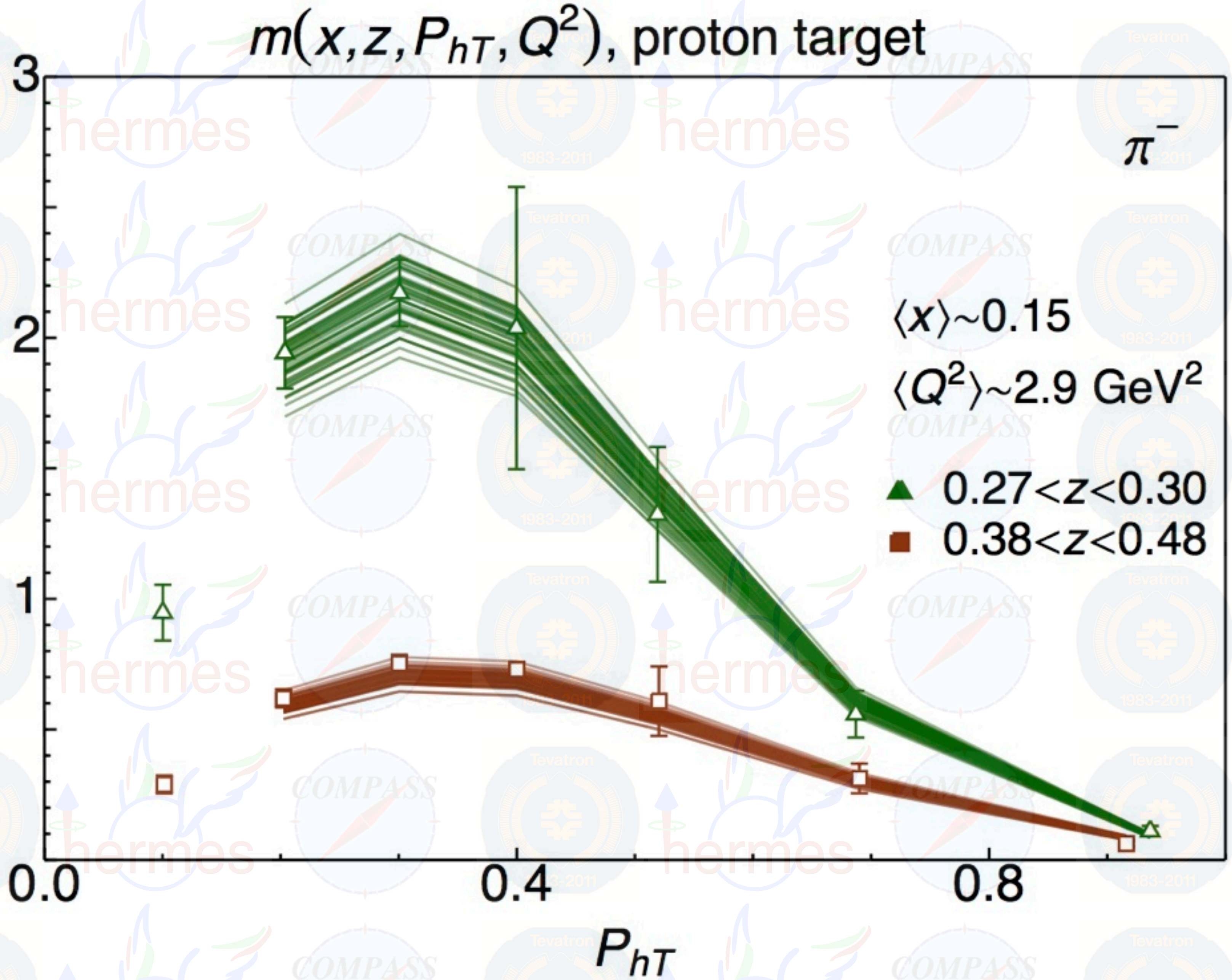
The replica method



Fit of the replicated data

Jefferson Lab

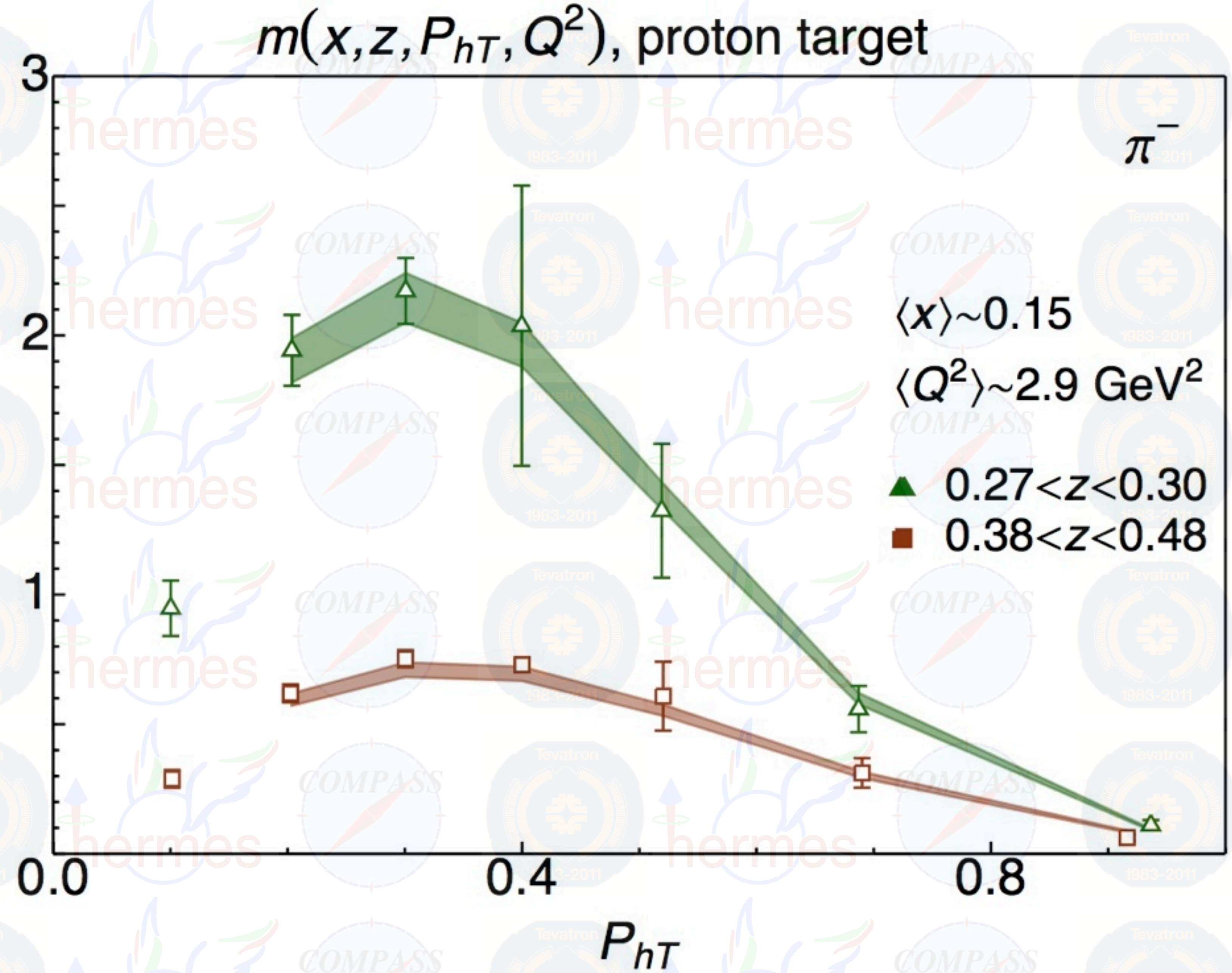
The replica method



Repeat the generation and the fit N times

Jefferson Lab

The replica method



Obtain **distributions of best values** - calculate **68% CL bands**

Data sets and selections

SIDIS

	HERMES $p \to \pi^+$	HERMES $p \to \pi^-$	HERMES $p \to K^+$	HERMES $p \to K^-$
Reference	[61]			
Cuts	$Q^2 > 1.4$ GeV^2 $0.2 < z < 0.7$ $P_{hT} < \text{Min}[0.2\ Q, 0.7\ Qz] + 0.5$ GeV			
Points	190	190	189	187
Max. Q^2	9.2 GeV^2			
x range	$0.06 < x < 0.4$			

TMD factorization ($P_{hT}/z \ll Q^2$)

avoid target fragmentation (low z) and exclusive contributions (high z)

In order to avoid the problems with the normalization in COMPASS data (see Compass coll., Erratum)

	HERMES $D \to \pi^+$	HERMES $D \to \pi^-$	HERMES $D \to K^+$	HERMES $D \to K^-$	COMPASS $D \to h^+$	COMPASS $D \to h^-$
Reference	[61]				[62]	
Cuts	$Q^2 > 1.4$ GeV^2 $0.2 < z < 0.7$ $P_{hT} < \text{Min}[0.2\ Q, 0.7\ Qz] + 0.5$ GeV					
Points	190	190	189	189	3125	3127
Max. Q^2	9.2 GeV^2				10 GeV^2	
x range	$0.06 < x < 0.4$				$0.006 < x < 0.12$	
Notes					Observable: $m_{\text{norm}}(x, z, \boldsymbol{P}_{hT}^2, Q^2)$, eq. (38)	

Jefferson Lab

Data sets and selections

	E288 200	E288 300	E288 400	E605
Reference	[65]	[65]	[65]	[66]
Cuts	$q_T < 0.2\ Q + 0.5$ GeV			
Points	45	45	78	35
$\sqrt{s}$	19.4 GeV	23.8 GeV	27.4 GeV	38.8 GeV
Q range	4-9 GeV	4-9 GeV	5-9, 11-14 GeV	7-9, 10.5-18 GeV
Kin. var.	y=0.4	y=0.21	y=0.03	$-0.1 < x_F < 0.2$

TMD factorization ($q_T \ll Q^2$)

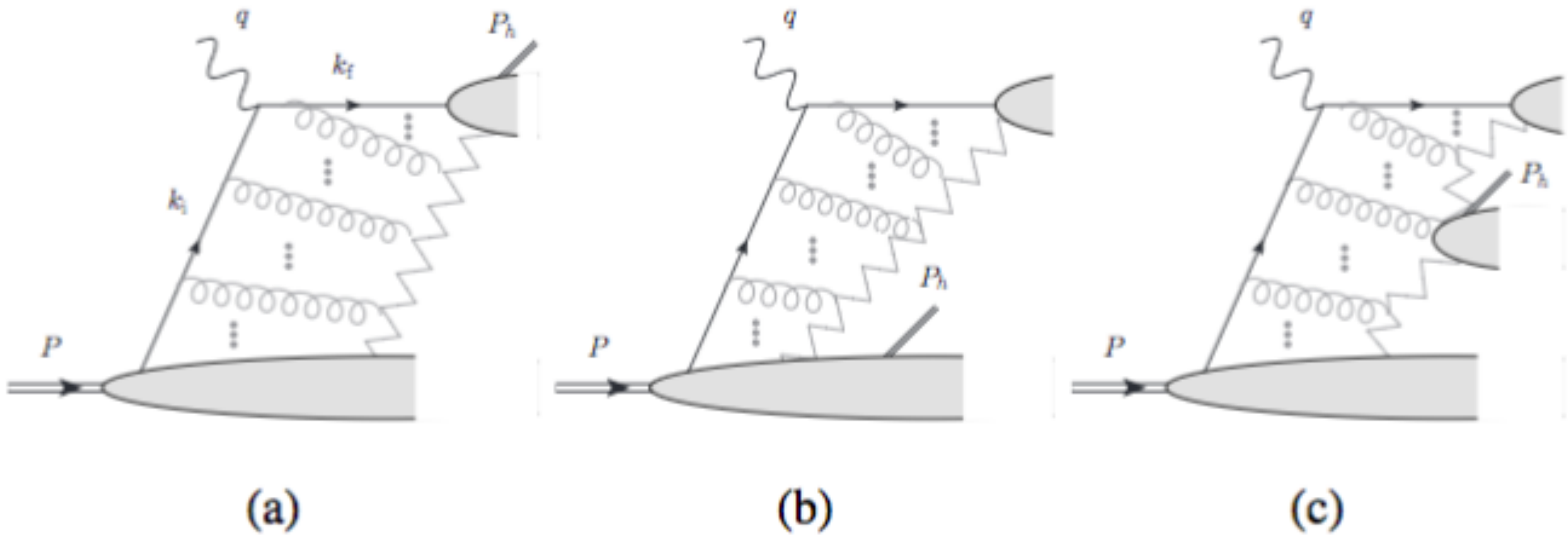
Drell-Yan

	CDF Run I	D0 Run I	CDF Run II	D0 Run II
Reference	[67]	[68]	[69]	[70]
Cuts	$q_T < 0.2\ Q + 0.5$ GeV $= 18.7$ GeV			
Points	31	14	37	8
$\sqrt{s}$	1.8 TeV	1.8 TeV	1.96 TeV	1.96 TeV
Normalization	1.114	0.992	1.049	1.048

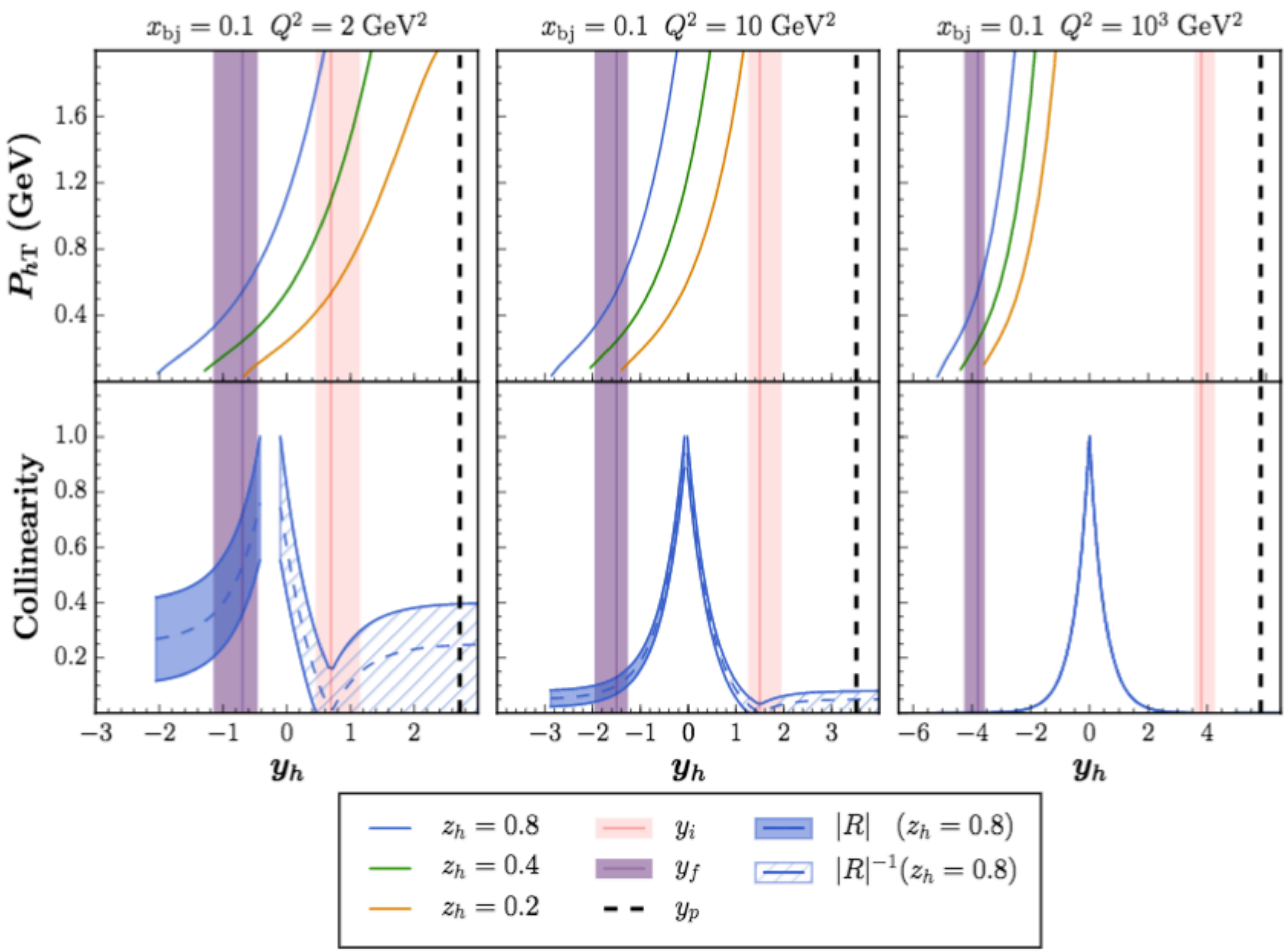
Z

normalization :
fixed from DEMS fit,
different from exp.
(not really relevant for TMD parametrizations)

Target vs current vs central regions



Target vs current vs central regions



Jefferson Lab

Evolution at work

SIDIS @ Compass

$Q \in [1, 3.2]$ GeV

electron-positron

(Bes-III - Belle)

$Q = 3.82$ GeV $Q = 10$ GeV

p-Cu Drell-Yan

(E288, E605 @ Tevatron)

$Q \in [4, 18]$ GeV

W production

(LHC, Tevatron)

$Q = 80.385$ GeV

Data sets and QCD evolution

$Q = 1.55$ GeV

SIDIS @ Hermes

η_b $Q = 9.39$ GeV

quarkonium production

(LHC, AFTER@LHC)

$Q = 91.187$ GeV

Z production

(LHC, Tevatron)

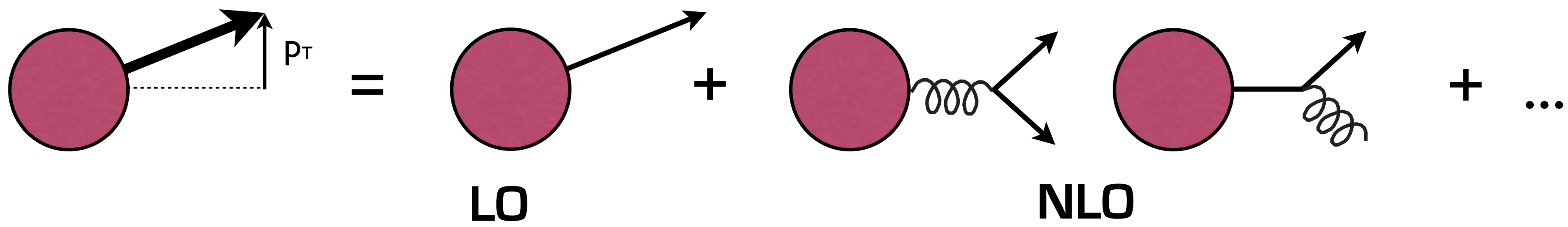
Medium energy:
the best Q-range
to constrain NP TMDs

Jefferson Lab

Perturbative accuracy

Overview of the terminology

$C_{i/j}$ **Wilson coefficients** : expansion of the TMD distribution on a basis of collinear PDFs

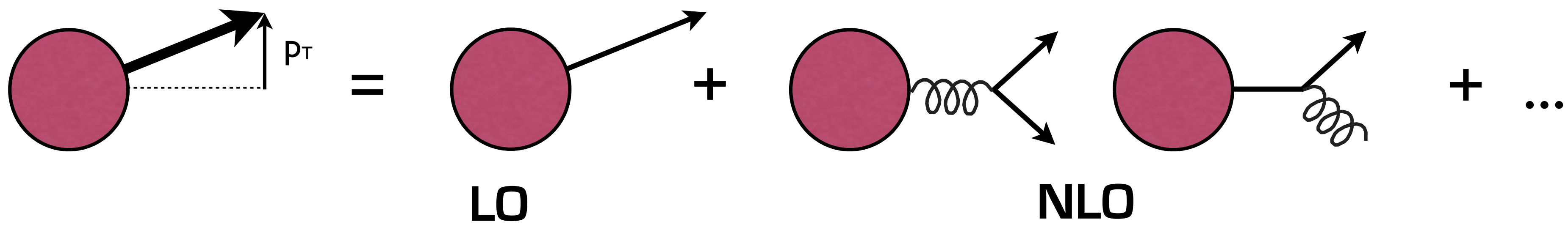


Jefferson Lab

Perturbative accuracy

Overview of the terminology

$C_{i/j}$ **Wilson coefficients** : expansion of the TMD distribution on a basis of collinear PDFs



Anomalous dimension of the TMD and **logarithmic expansion**

$$\gamma_F[\alpha_s(\mu), \zeta/\mu^2] \sim \underbrace{\alpha_s L}_{\text{LL}} + \underbrace{(\alpha_s + \alpha_s^2 L)}_{\text{NLL}} + \underbrace{(\alpha_s^2 + \alpha_s^3 L)}_{\text{NNLL}} + \cdots$$

$$\sim \; 1 + \alpha_s + \alpha_s^2 + \cdots$$

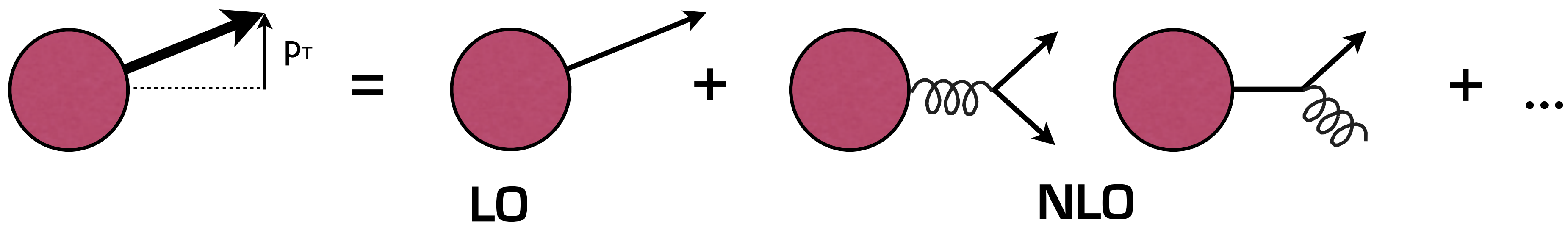
$$L = \ln \frac{Q^2}{\mu} \; , \quad \alpha_s L \sim 1$$

Jefferson Lab

Perturbative accuracy

Overview of the terminology

$C_{i/j}$ **Wilson coefficients** : expansion of the TMD distribution on a basis of collinear PDFs



Anomalous dimension of the TMD and **logarithmic expansion**

$$\gamma_F[\alpha_s(\mu), \zeta/\mu^2] \sim \underbrace{\alpha_s L}_{\text{LL}} + \underbrace{(\alpha_s + \alpha_s^2 L)}_{\text{NLL}} + \underbrace{(\alpha_s^2 + \alpha_s^3 L)}_{\text{NNLL}} + \cdots$$

$$\sim \; 1 + \alpha_s + \alpha_s^2 + \cdots$$

$$L = \ln \frac{Q^2}{\mu} \; , \quad \alpha_s L \sim 1$$

Collins-Soper kernel : a power series in the coupling

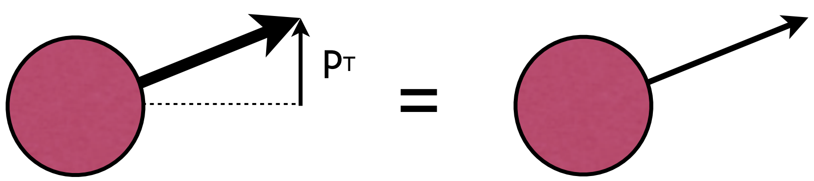
$$K(b_T; \mu_b) \sim 1 + \alpha_s + \alpha_s^2 \cdots$$

accuracy chosen consistently
with Wilson coefficients
and anomalous dimension

Jefferson Lab

Perturbative accuracy

$C_{i/j}$ **Wilson coefficients** : expansion of the TMD distribution on a basis of collinear PDFs



LO

Anomalous dimension of the TMD and **logarithmic expansion**

$$\mu_{\hat{b}} = 2e^{-\gamma_E}/\bar{b}_\star$$

$$\gamma_F[\alpha_s(\mu), \zeta/\mu^2] \sim \underbrace{\alpha_s L}_{\text{LL}} + \underbrace{(\alpha_s + \alpha_s^2 L)}_{\text{NLL}} + \cdots$$

$$\sim 1 + \alpha_s + \cdots$$

$C_{i/j}$	γ_{nc}	Γ_{cusp}	K	*accuracy*
0	0	0	0	QPM
0	0	1	0	LO-LL
0	1	2	1	LO-NLL
0	2	3	2	LO-NNLL
1	1	2	1	NLO-NLL
1	2	3	2	NLO-NNLL
2	2	3	2	NNLO-NNLL

Collins-Soper kernel : a power series in the coupling

$$K(b_T; \mu_b) \sim 1 + \alpha_s + \cdots$$

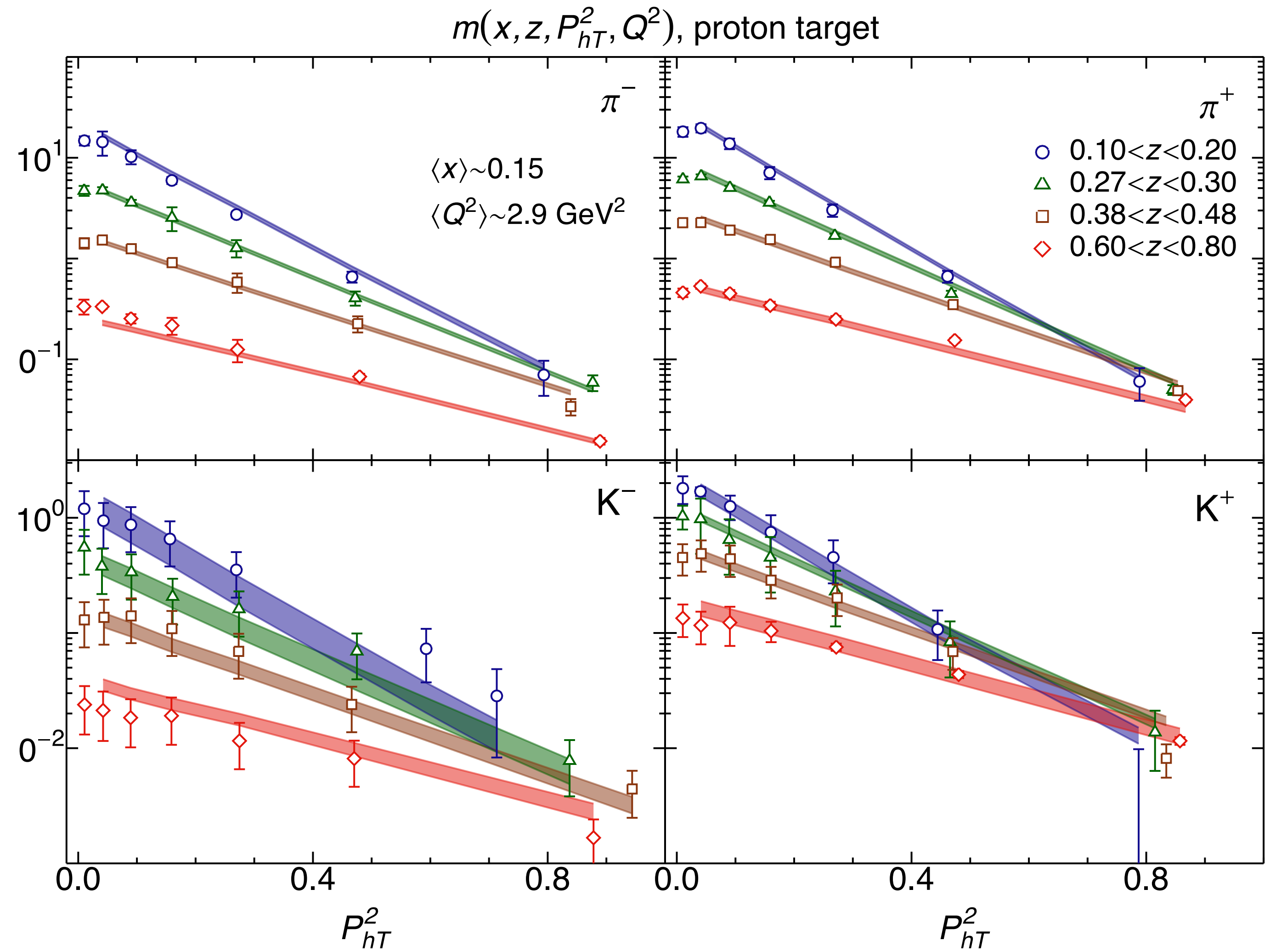
Jefferson Lab

Pavia / Amsterdam / Bilbao 2013

proton target global χ^2 / d.o.f. = 1.63 ± 0.12
no flavor dep. 1.72 ± 0.11

π^-
1.80 ± 0.27
1.83 ± 0.25

K^-
0.78 ± 0.15
0.87 ± 0.16



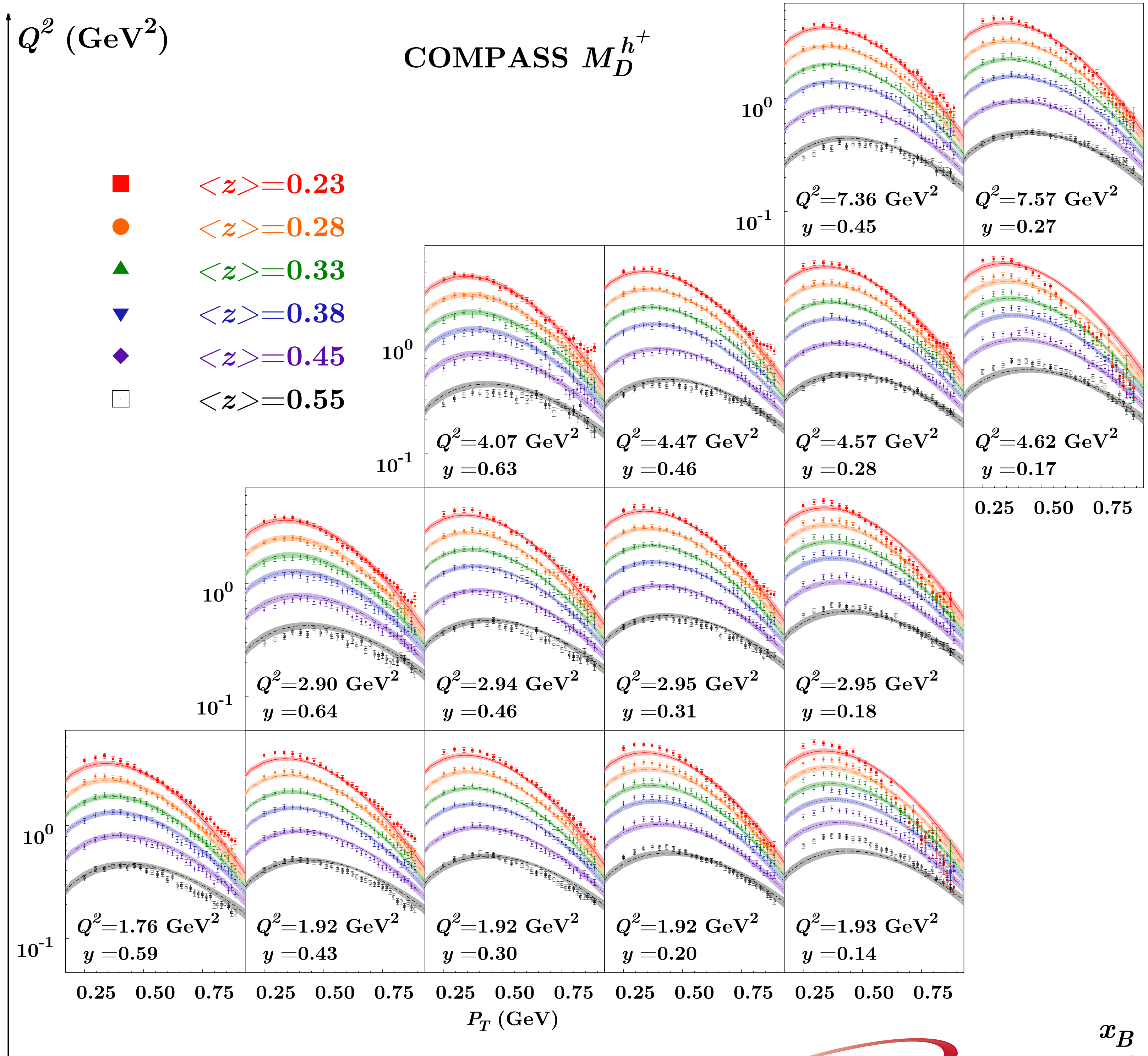
π^+
2.64 ± 0.21
2.89 ± 0.23

K^+
0.46 ± 0.07
0.43 ± 0.07

Jefferson Lab

Torino / JLab 2014

COMPASS $M_D^{h^+}$

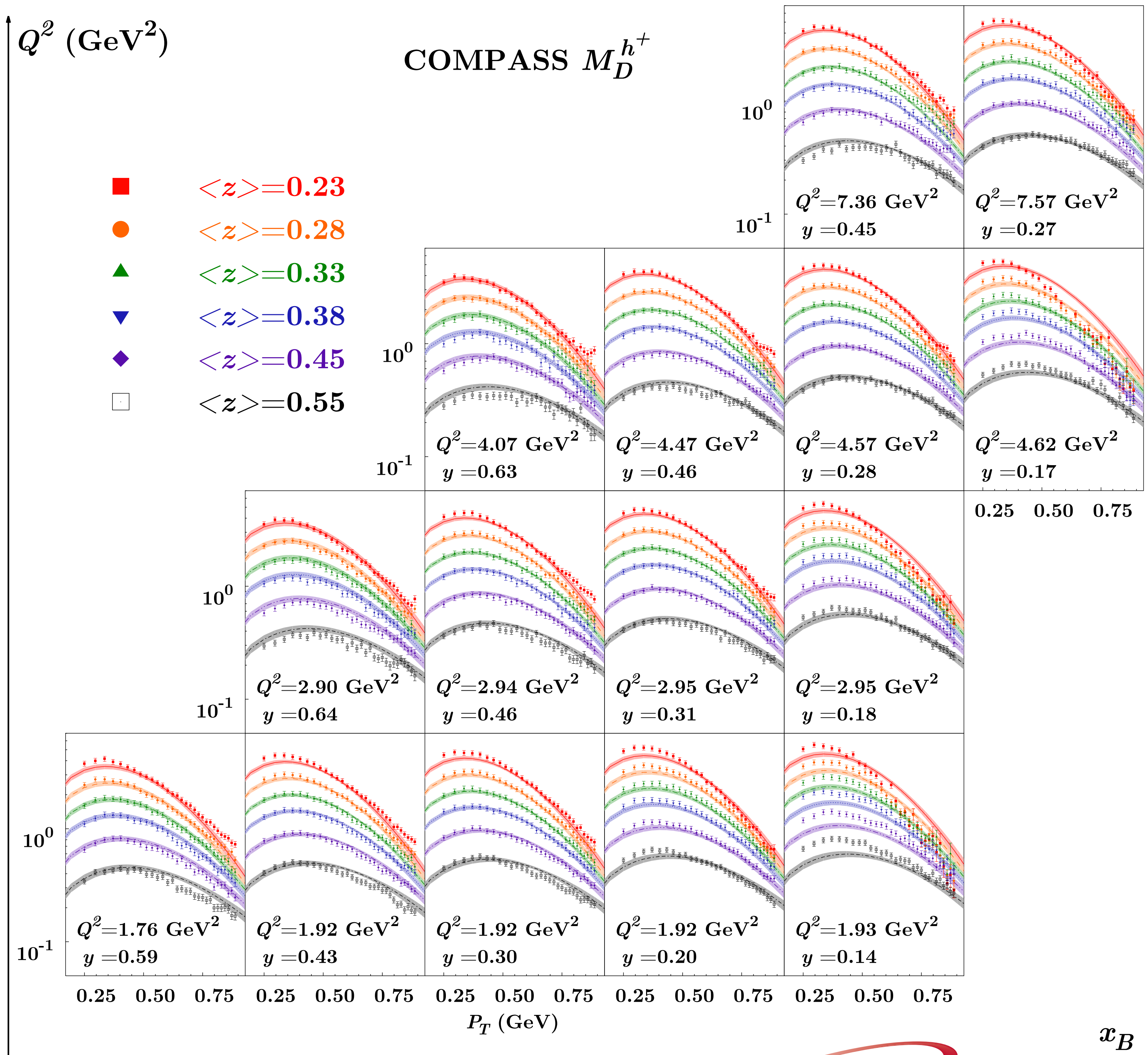


Anselmino, Boglione, Gonzalez, Melis, Prokudin, JHEP 1404 (14)

Jefferson Lab

Torino / JLab 2014

COMPASS $M_D^{h^+}$



χ^2/dof = 3.79

with ad-hoc normalization

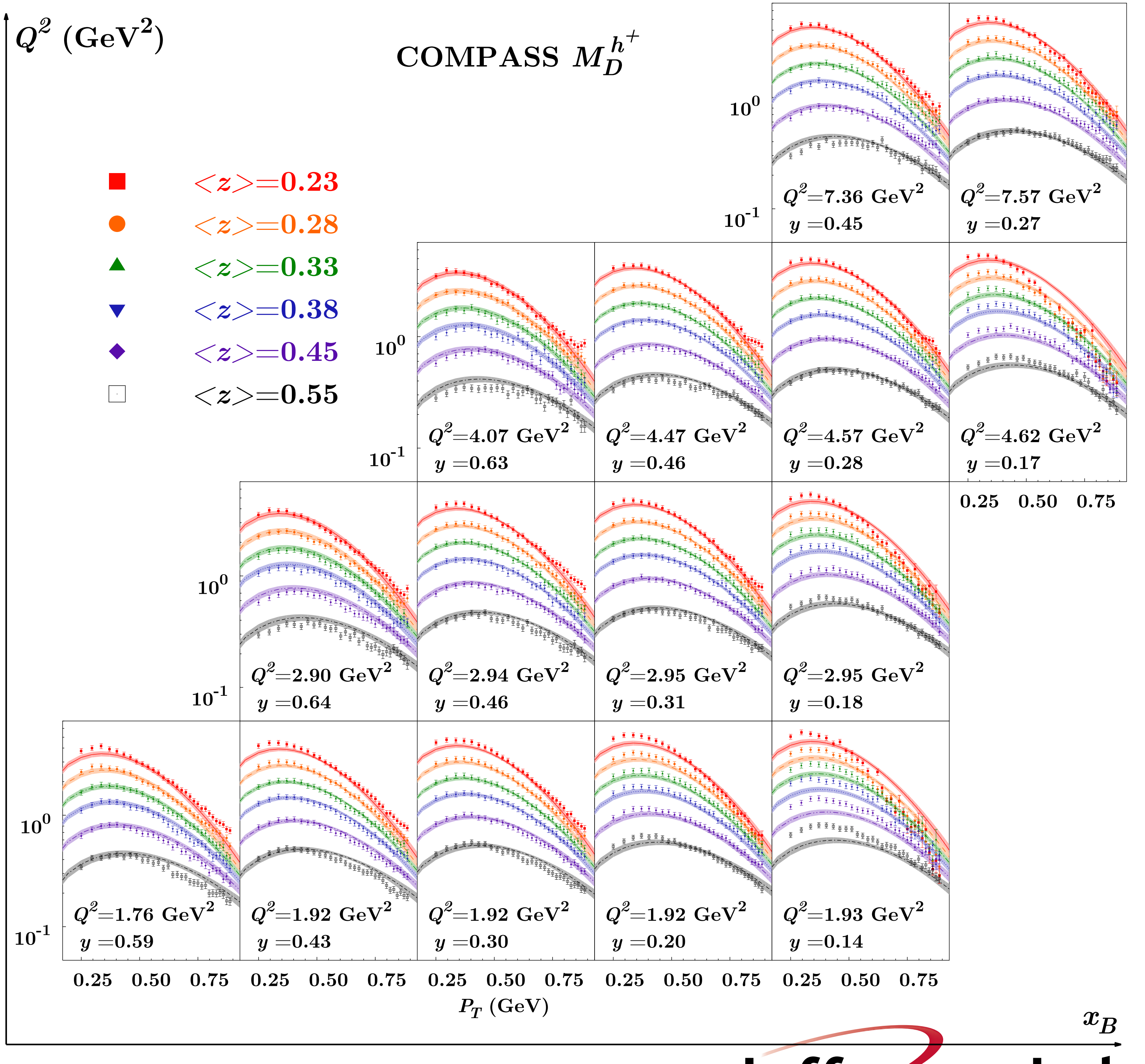
Anselmino, Boglione, Gonzalez, Melis, Prokudin, JHEP 1404 (14)

Torino / JLab 2014

COMPASS $M_D^{h^+}$

$\chi^2/\mathrm{dof} = 3.79$
with ad-hoc normalization

see Compass coll. Erratum



Anselmino, Boglione, Gonzalez, Melis, Prokudin, JHEP 1404 (14)

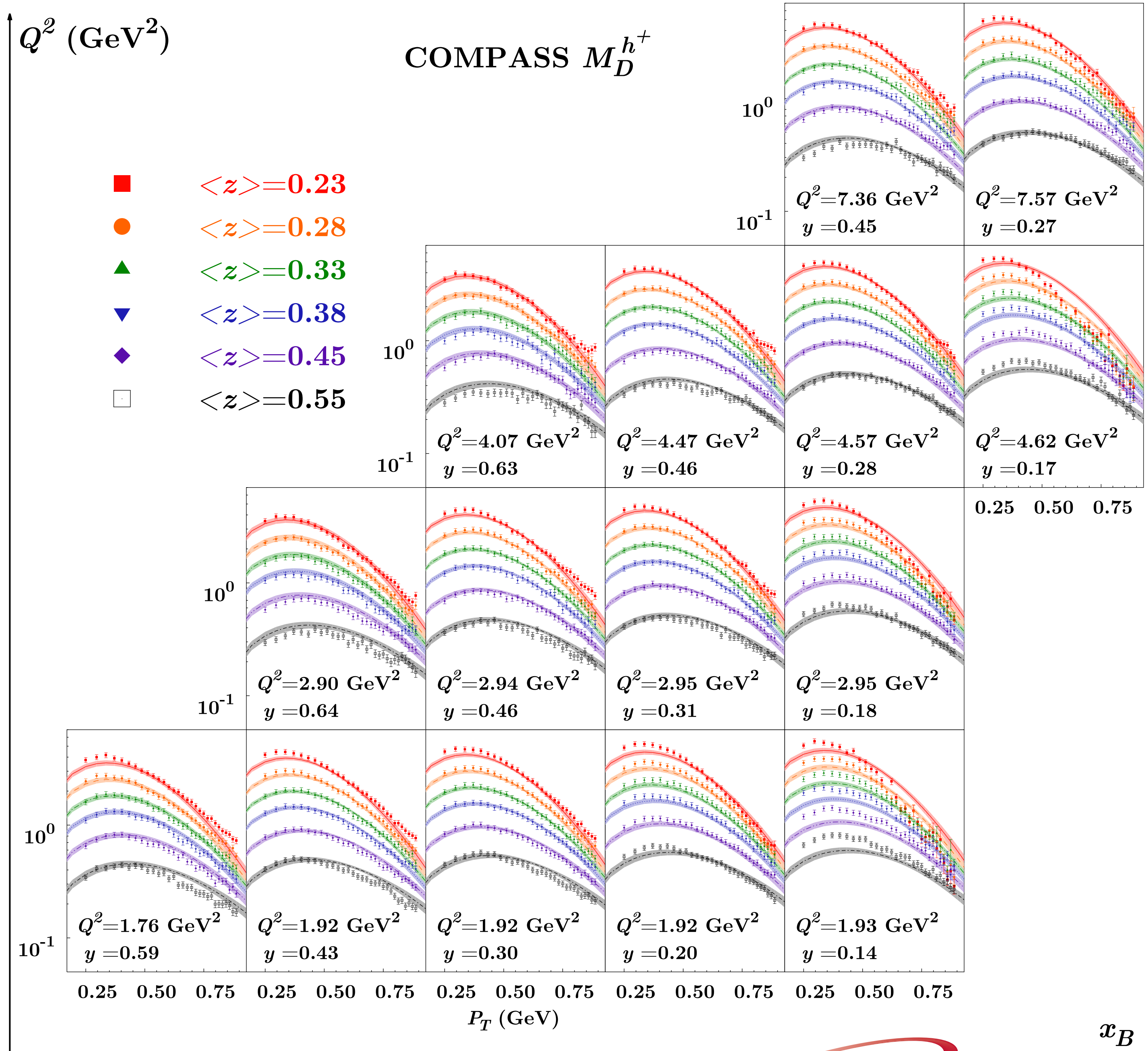
Torino / JLab 2014

COMPASS $M_D^{h^+}$

simple Gaussian ansatz

$\chi^2/\text{dof} = 3.79$
with ad-hoc normalization

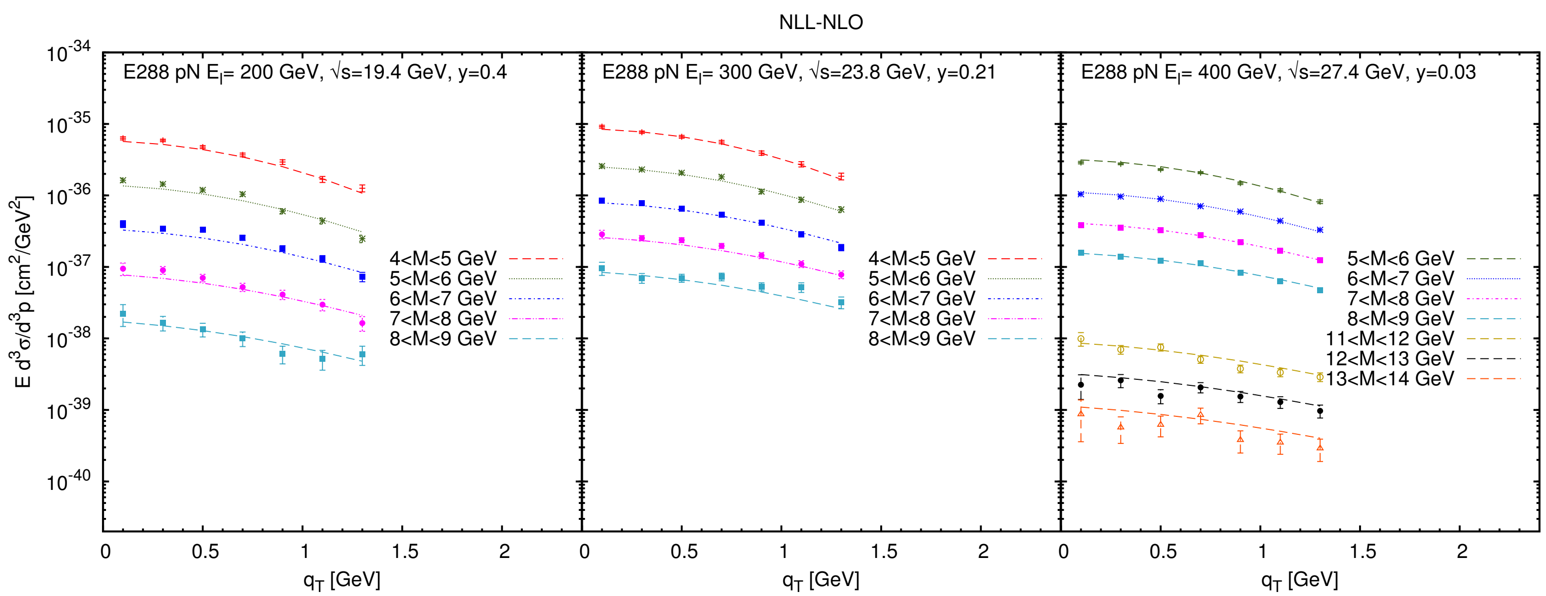
see Compass coll. Erratum

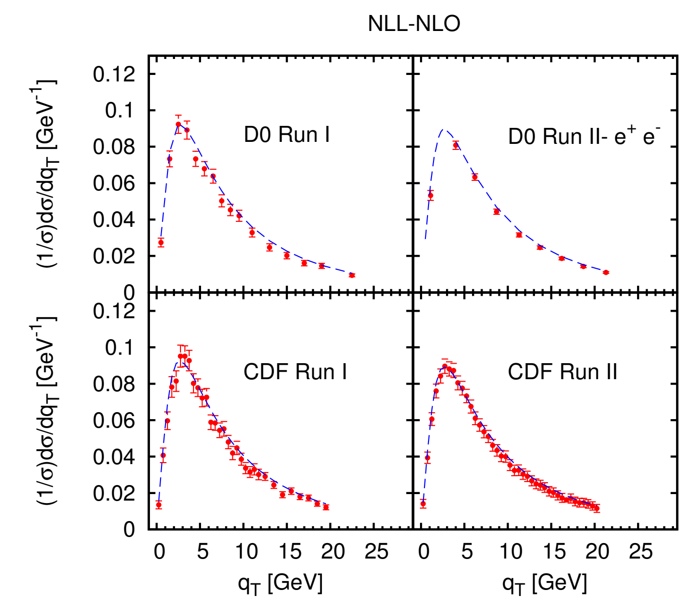


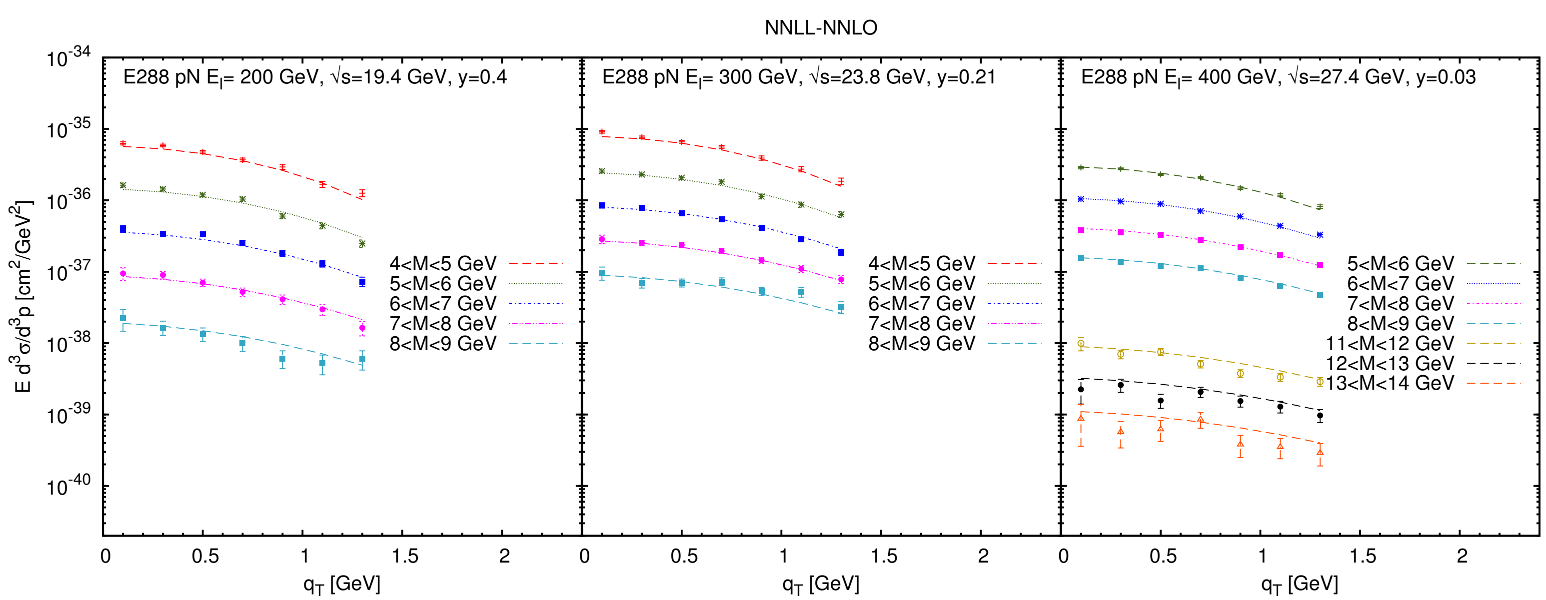
Anselmino, Boglione, Gonzalez, Melis, Prokudin, JHEP 1404 (14)

DEMS 2014

D'Alesio, Echevarria, Melis, Scimemi, JHEP 1411 (14)







NLO-NNLL analysis
with evaluation of
theoretical uncertainties

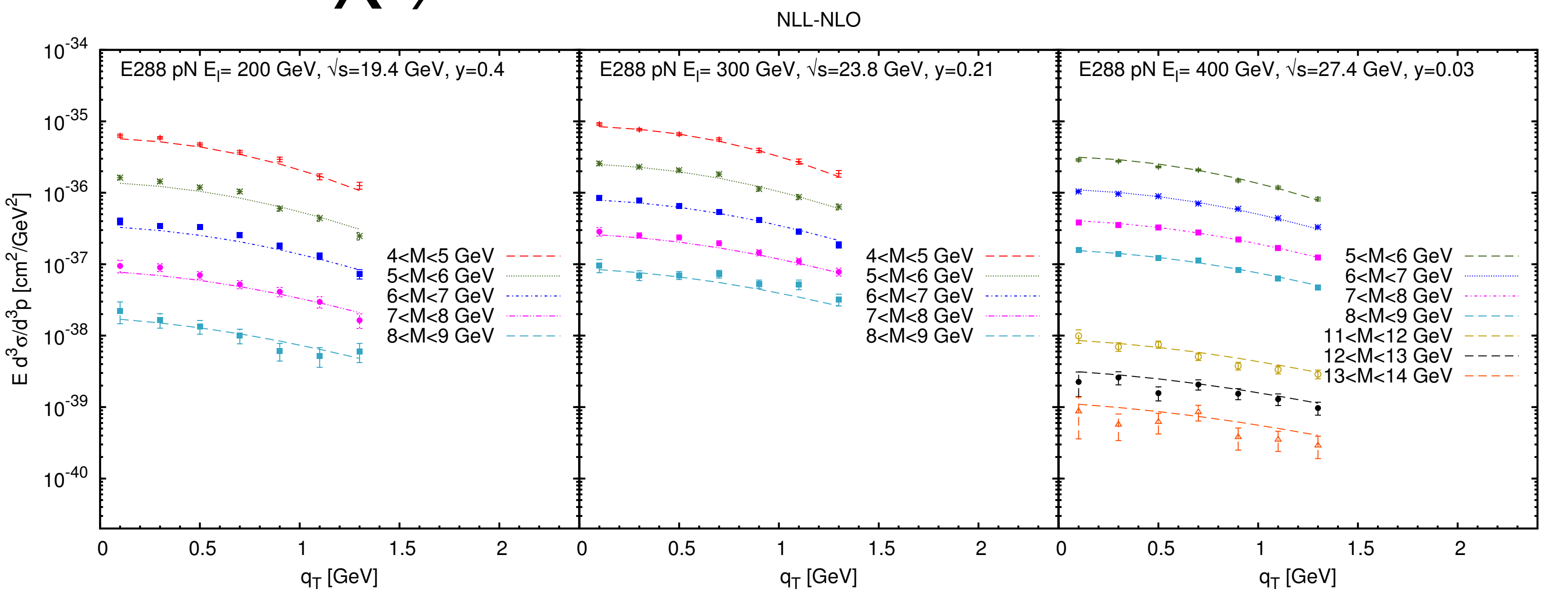
very good

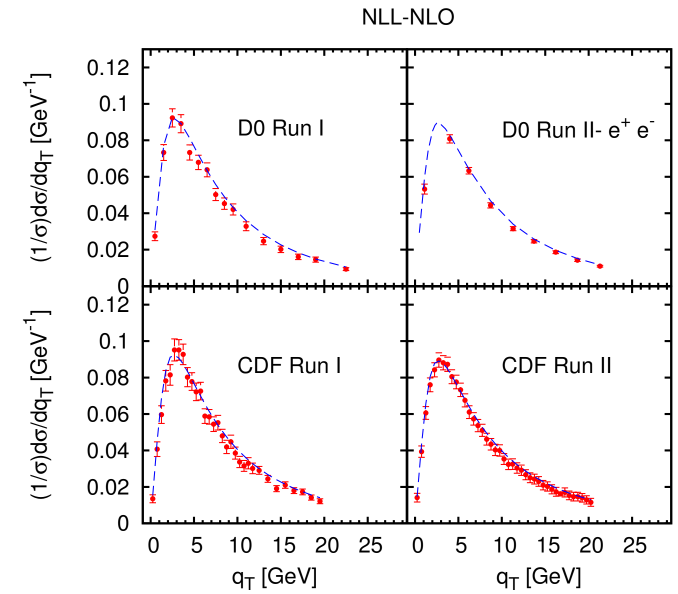
Jefferson Lab

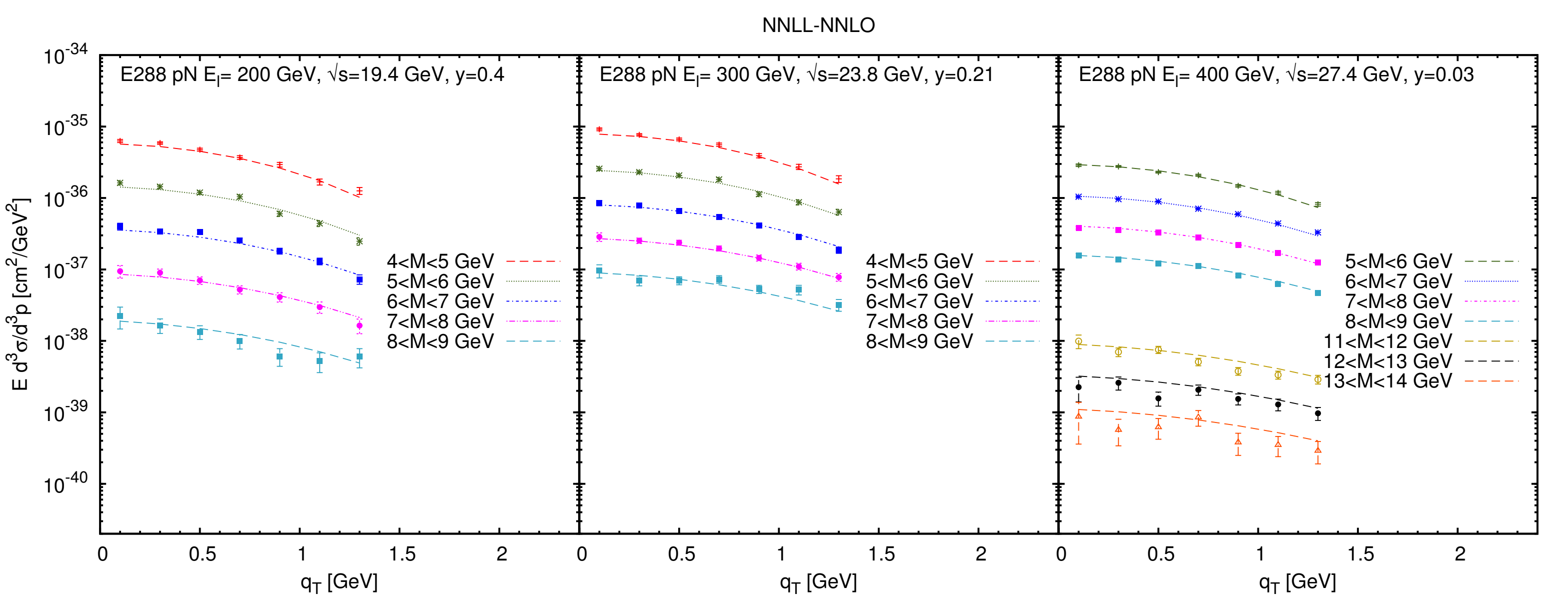
DEMS 2014

$\chi^2/\text{dof} = 0.81$

D'Alesio, Echevarria, Melis, Scimemi, JHEP 1411 (14)





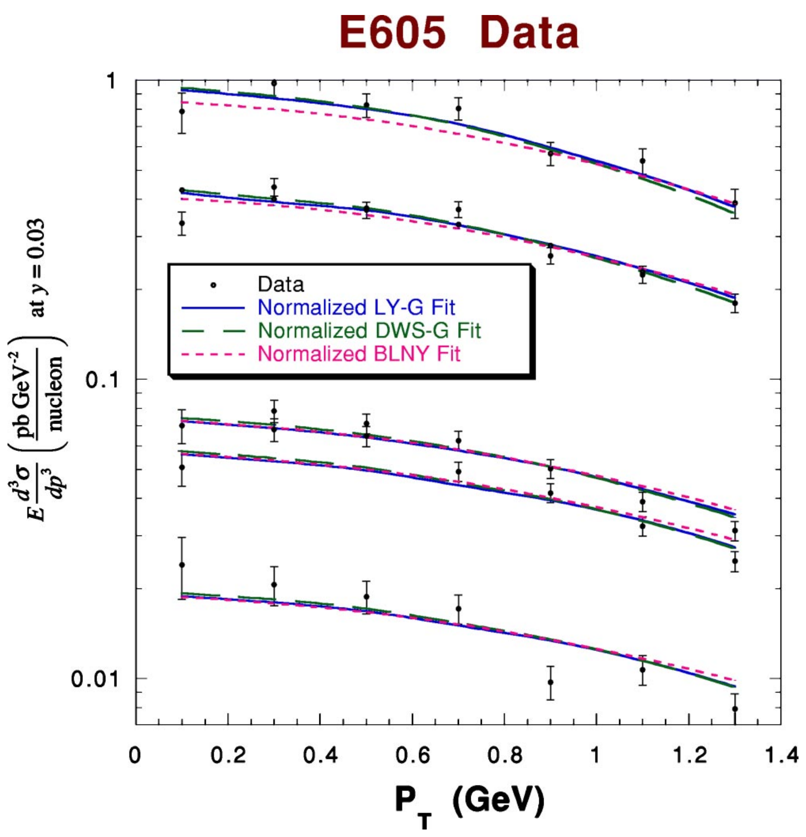


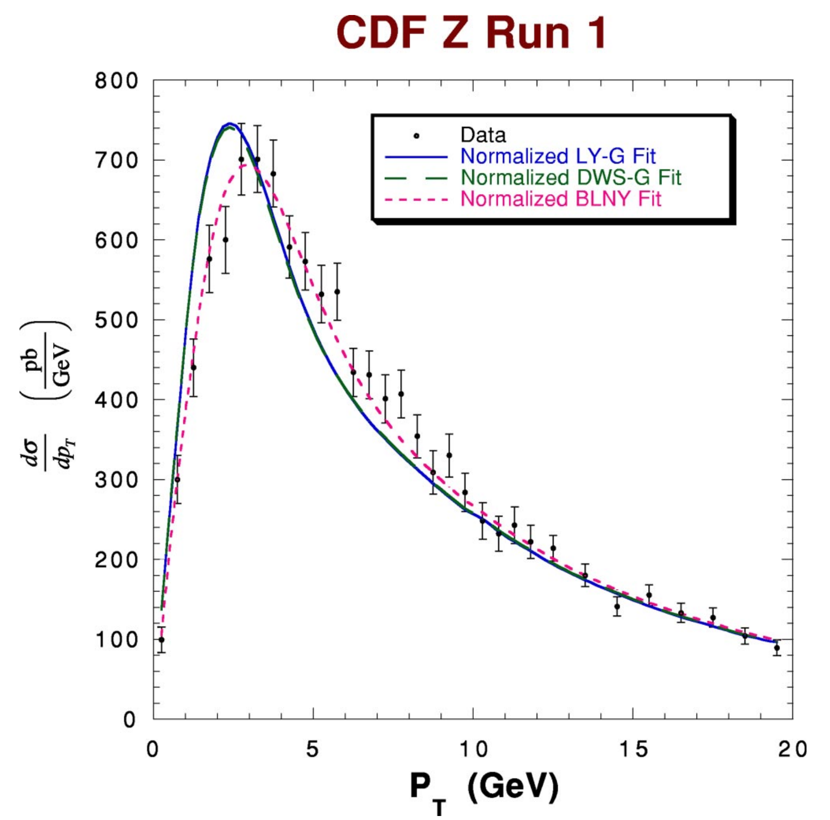
NLO-NNLL analysis with evaluation of theoretical uncertainties

very good

Jefferson Lab

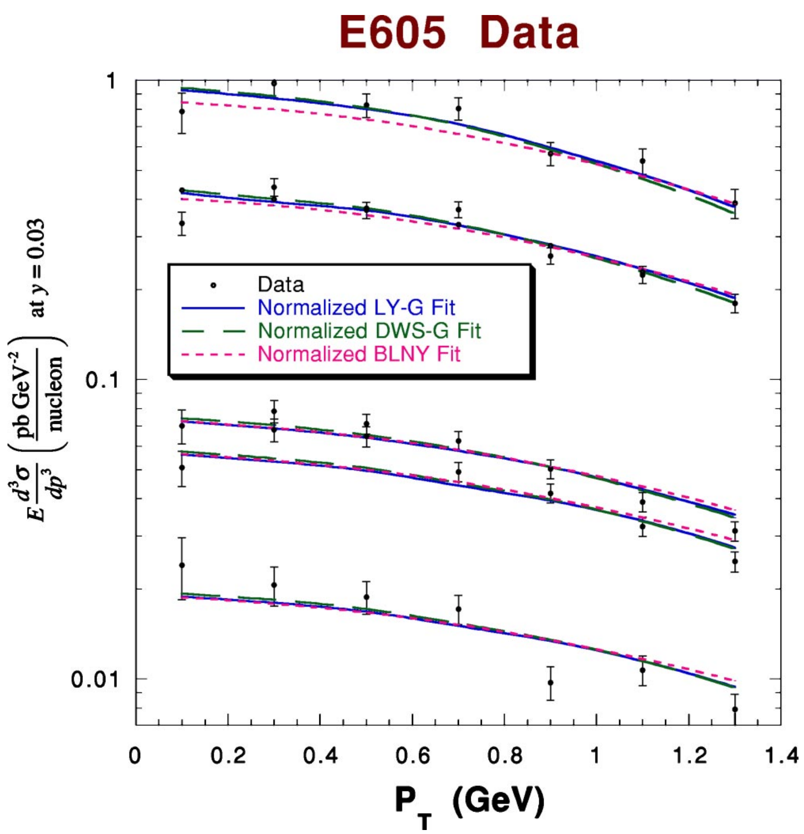
KN 2006

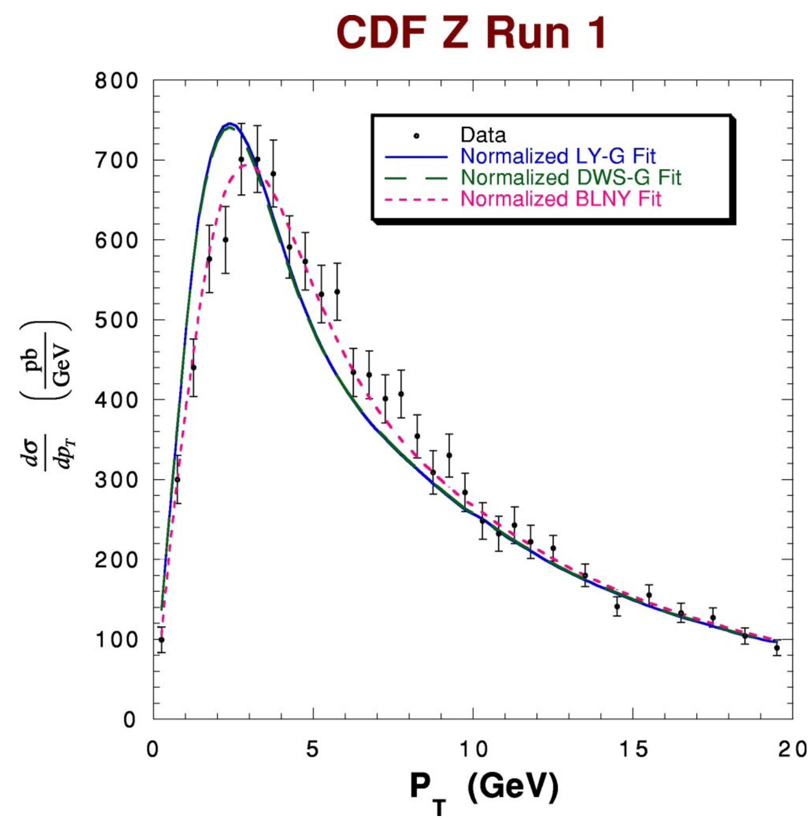




≈100 data points
$Q^2 > 4$ GeV

KN 2006





≈100 data points
Q^2>4 GeV

$$Q_0 = 3.2 \text{ GeV}$$

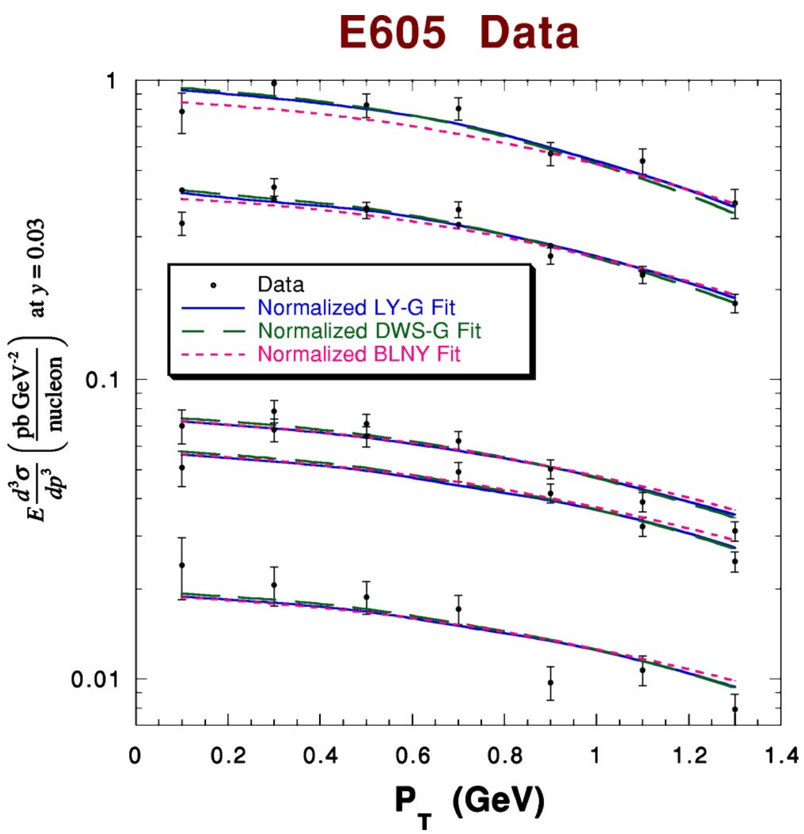
$$b_{\max} = 0.5 \text{ GeV}^{-1}$$

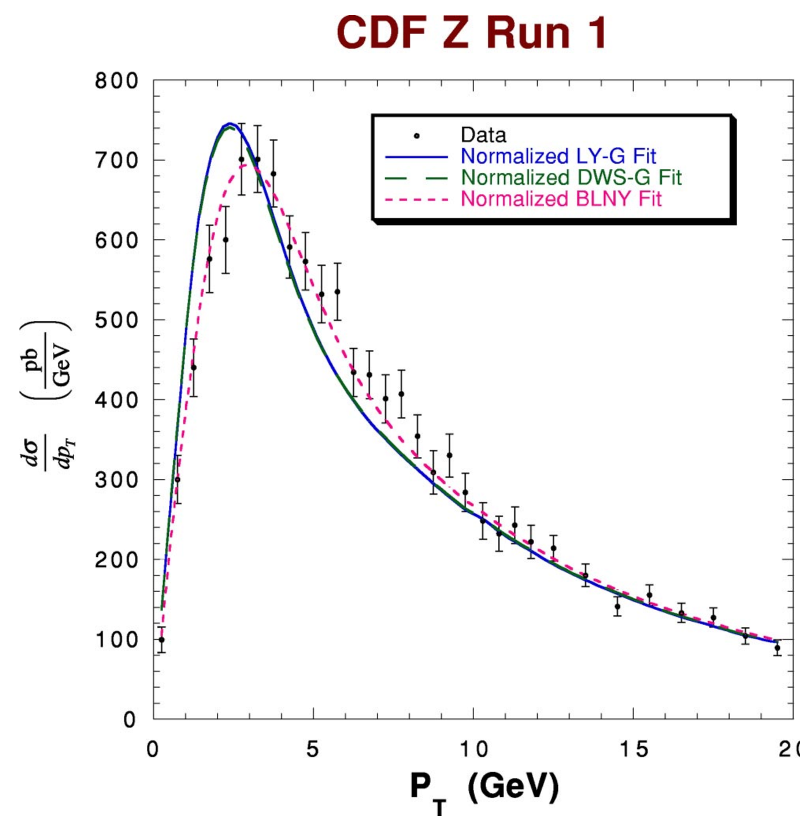
$$\frac{1}{\langle b_T^2 \rangle} = \frac{1}{2}\left(0.21 + 0.68 \log\left(\frac{Q}{2Q_0}\right) - 0.25 \log(10x)\right)$$

Brock, Landry, Nadolsky, Yuan, PRD67 (03)

Jefferson Lab

KN 2006





≈100 data points
Q^2>4 GeV

$$Q_0 = 3.2 \text{ GeV}$$

$$\frac{1}{\langle b_T^2 \rangle} = \frac{1}{2}\left(0.21 + 0.68 \log\left(\frac{Q}{2Q_0}\right) - 0.25 \log(10x)\right)$$

$$b_{\max} = 0.5 \text{ GeV}^{-1}$$

Brock, Landry, Nadolsky, Yuan, PRD67 (03)

$$\frac{1}{\langle b_T^2 \rangle} = \frac{1}{2}\left(0.20 + 0.184 \log\left(\frac{Q}{2Q_0}\right) - 0.026 \log(10x)\right)$$

$$b_{\max} = 1.5 \text{ GeV}^{-1}$$

Jefferson Lab

EIKV 2014

Parametrizations for intrinsic momenta
and soft gluon emission :

$$F_{NP}(b_T,Q)^{\rm pdf} = \exp\left[-b_T^2\left(g_1^{\rm pdf} + \frac{g_2}{2}\ln(Q/Q_0)\right)\right]$$

$$F_{NP}(b_T,Q)^{\rm ff} = \exp\left[-b_T^2\left(g_1^{\rm ff} + \frac{g_2}{2}\ln(Q/Q_0)\right)\right]$$

Pros and Cons :

1) a global analysis of SIDIS and DY/Z/W data

2) TMD evolution at LO-NLL

3) multidimensionality not exploited

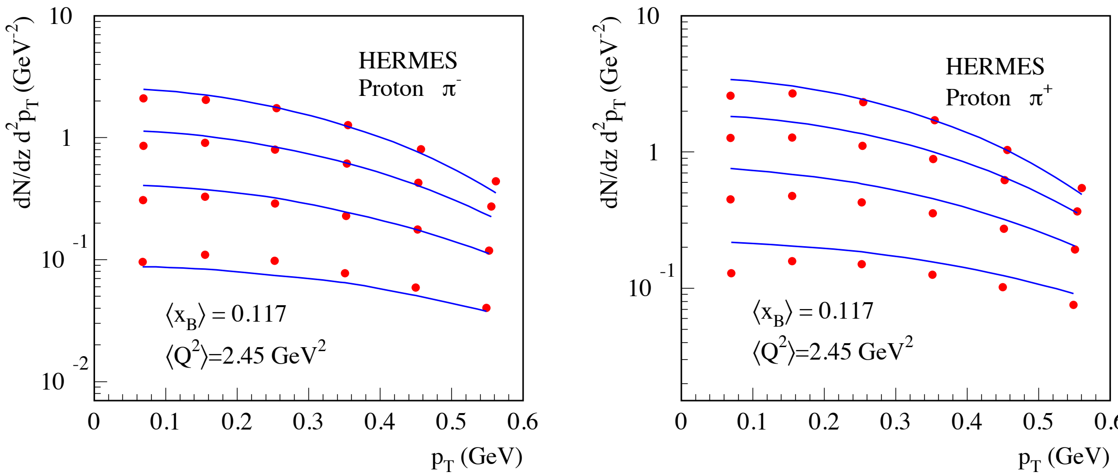
4) chi-square not provided

5) can't be considered as a "complete" fit

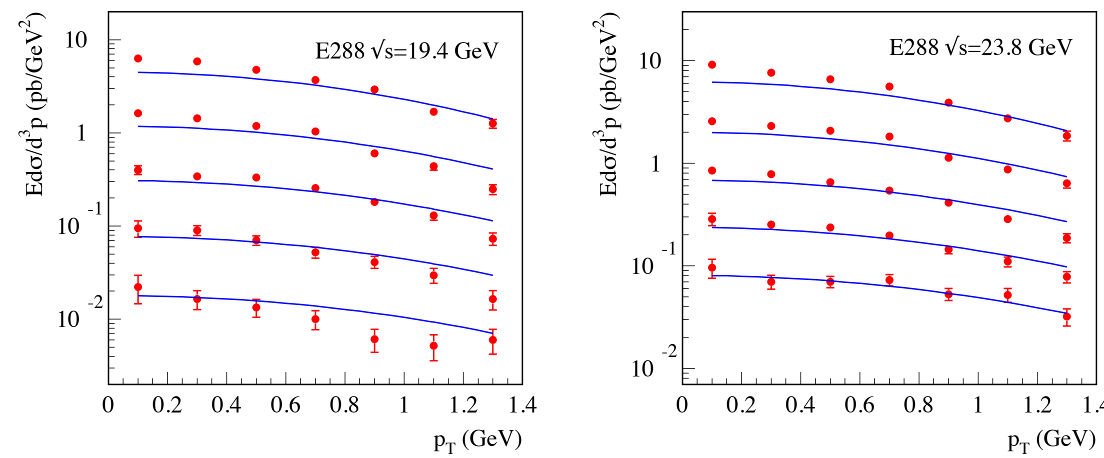
Jefferson Lab

EIKV 2014

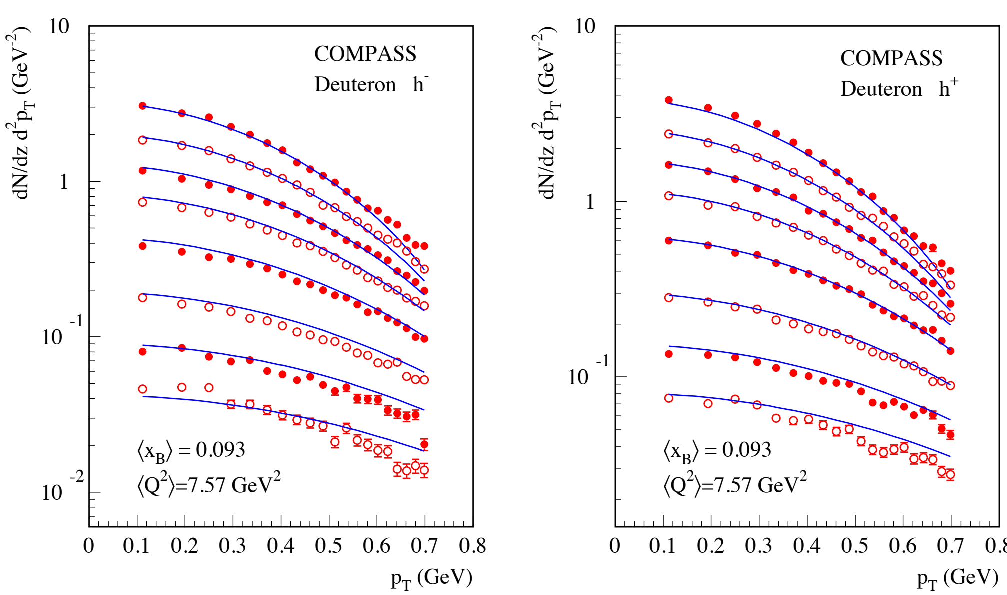
SIDIS



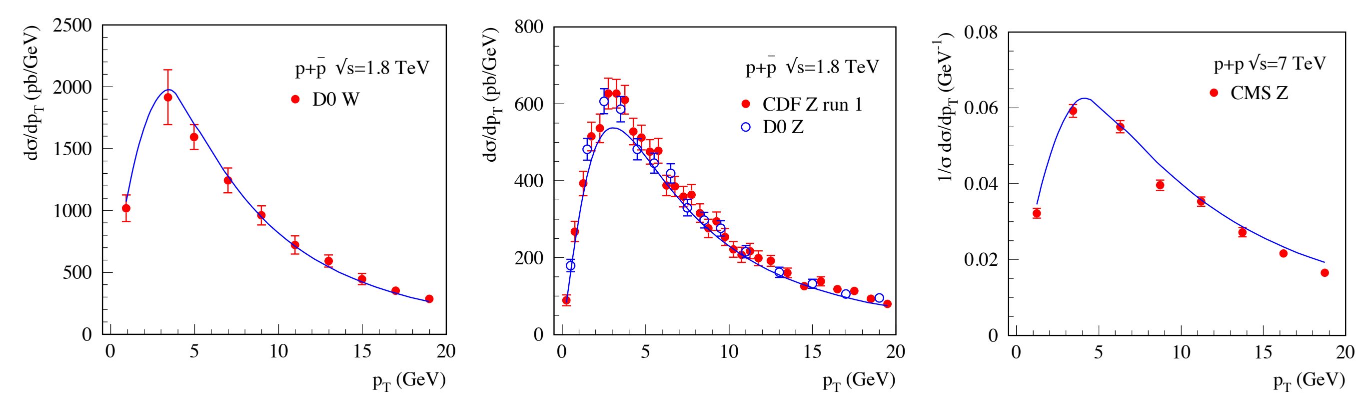
DRELL-YAN



SIDIS



W AND Z PRODUCTION



$$b_{\max} = 1.5\ \mathrm{GeV}^{-1}$$

$$g_2 = 0.16$$

Echevarria et al. arXiv:1401.5078

Jefferson Lab

Other studies

CSS formalism on DY/Z/W data:

1) Davies-Webber-Stirling (DOI: 10.1016/0550-3213(85)90402-X)

2) Ladinsky-Yuan (DOI: 10.1103/PhysRevD.50.R4239)

3) BLNY (DOI: 10.1103/PhysRevD.63.013004)

4) Hirai, Kawamura, Tanaka (DOI: 10.3204/DESY-PROC-2012-02/136) - complex-b prescription

...

combined SIDIS/DY/W/Z :

5) Sun, Yuan (arXiv:1308.5003)

6) Isaacson, Sun, Yuan, Yuan (arXiv:1406.3073)

...

... and the next challenges

The goal is not only to fit data,
but to answer fundamental questions in QCD in the best possible way

11) identification of the current fragmentation region in SIDIS ?

12) rise the accuracy of transverse momentum resummation

13) match TMD and collinear factorization : fixed-order description of the high transverse momentum region and its matching to the low transverse momentum one

14) order the hadronic tensor in terms of definite rank

---

15) include electron-positron annihilation, LHC and JLab data
16) address the flavor decomposition in transverse momentum
17) address the polarized structure functions
18) Monte Carlo generators and TMDs
19) what about spin 1 targets ?

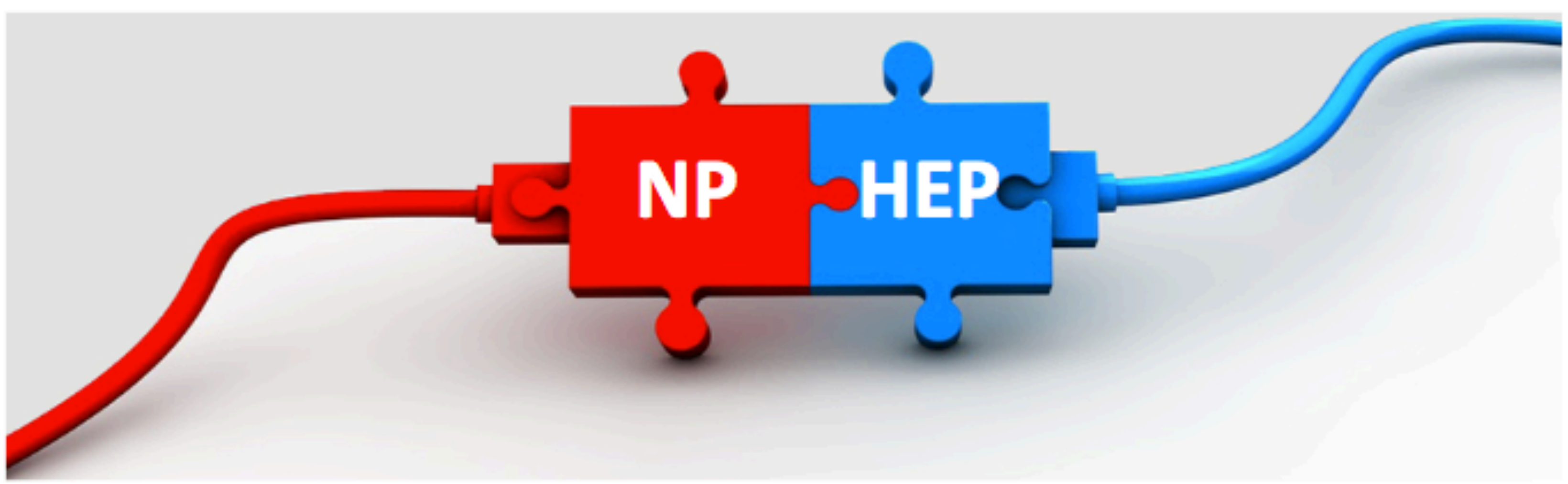
20) ...

Nikhef
VU
UNIVERSITÀ DI PAVIA
Jefferson Lab

Monte Carlo generators

LDRD

Mapping the hadronization description in the Pythia MCEG to the correlation functions of TMD factorization



see the talk by M. Diefenthaler

Jefferson Lab