3D structure: present and future

Alessandro Bacchetta

Funded by

3DSPIN
MAPPING THE PROTON IN 3D

erc
European Research Council

INFN
Istituto Nazionale di Fisica Nucleare

UNIVERSITÀ
DI PAVIA

Acknowledgements

Even if I will present an overview, I acknowledge the contribution of my research group in shaping and developing many of the ideas that I will mention

- Filippo Delcarro, Luca Mantovani, Fulvio Piacenza (PhD students)
- Giuseppe Bozzi, Cristian Pisano (post-docs)
- Barbara Pasquini, Marco Radici (staff)

Disclaimer

My task was to talk about the present and the future, but

It is difficult to predict, especially the future

N. Bohr

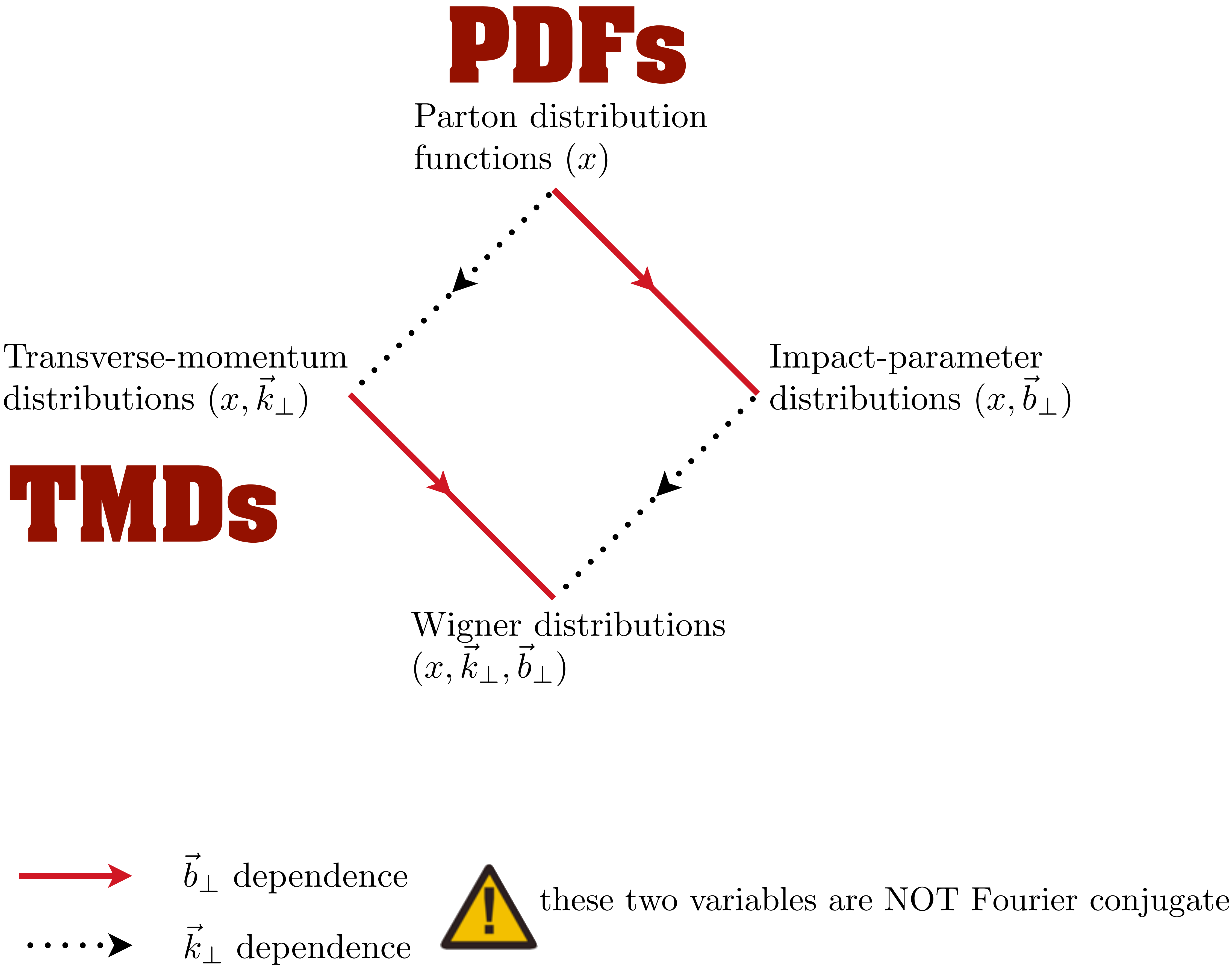
In the end, I will mainly focus on present and mainly about TMDs

Disclaimer

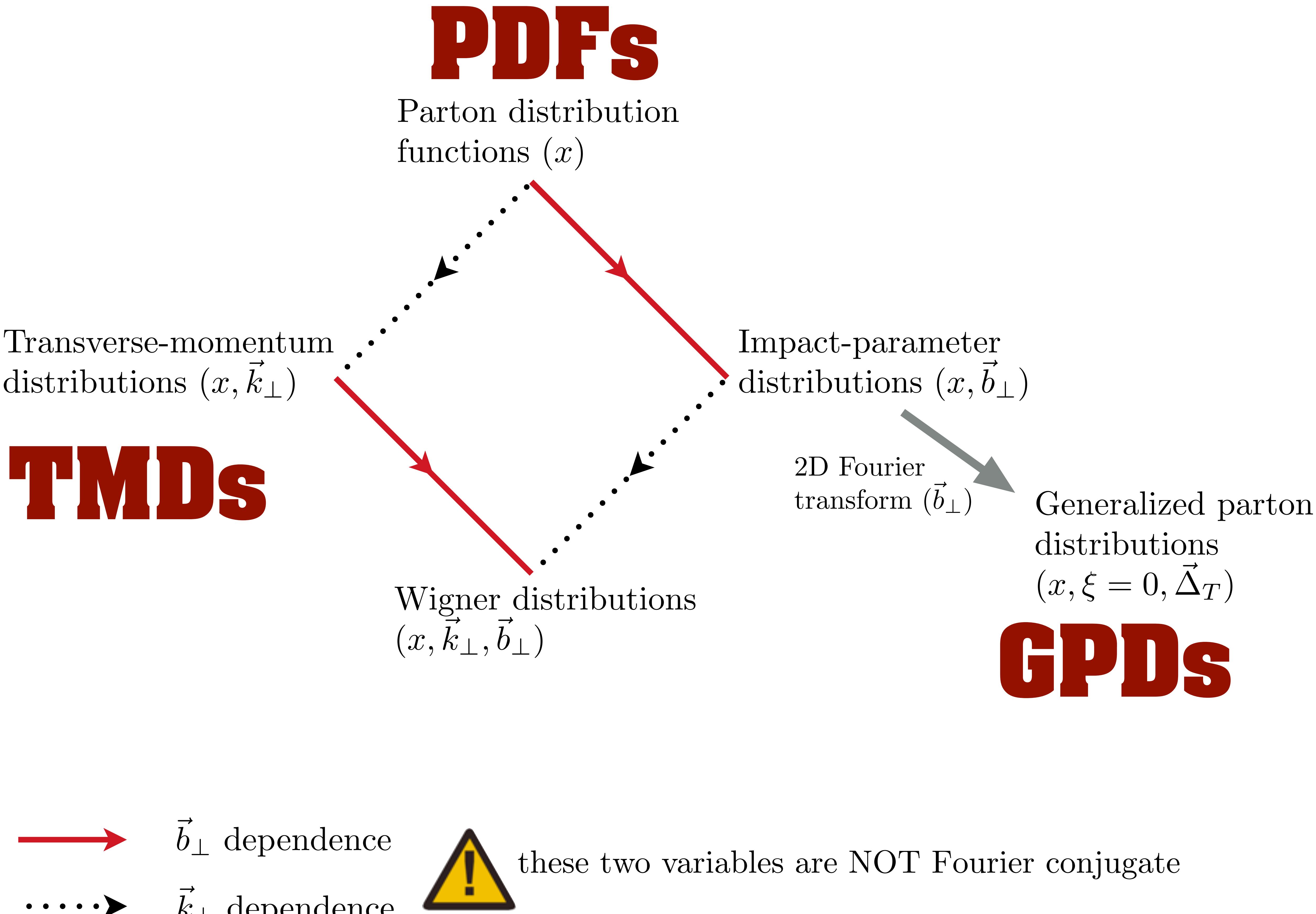
My task was to talk about the present and the future, but

> “It is difficult to predict, especially the future”
>
> N. Bohr

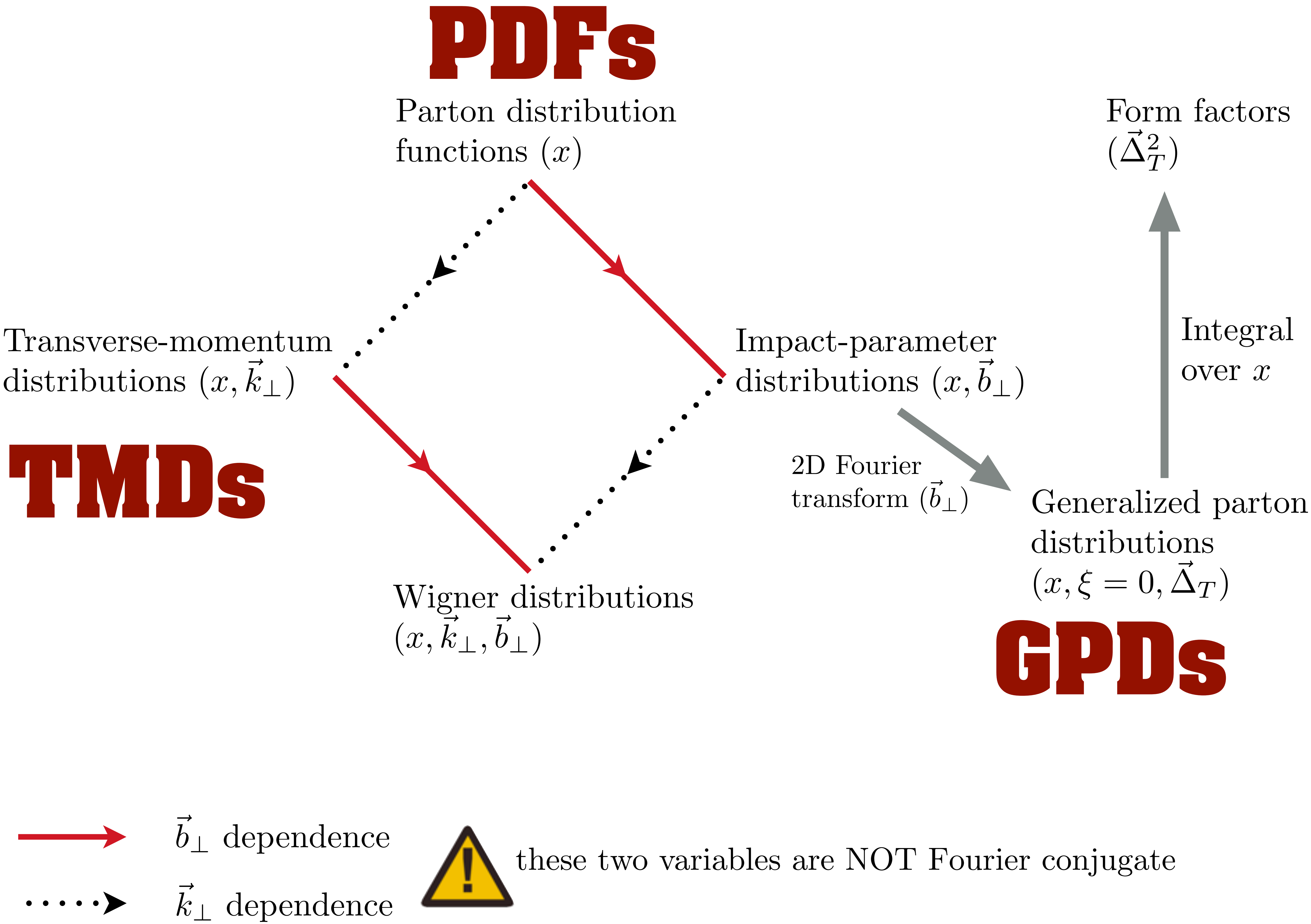
In the end, I will mainly focus on present and mainly about TMDs



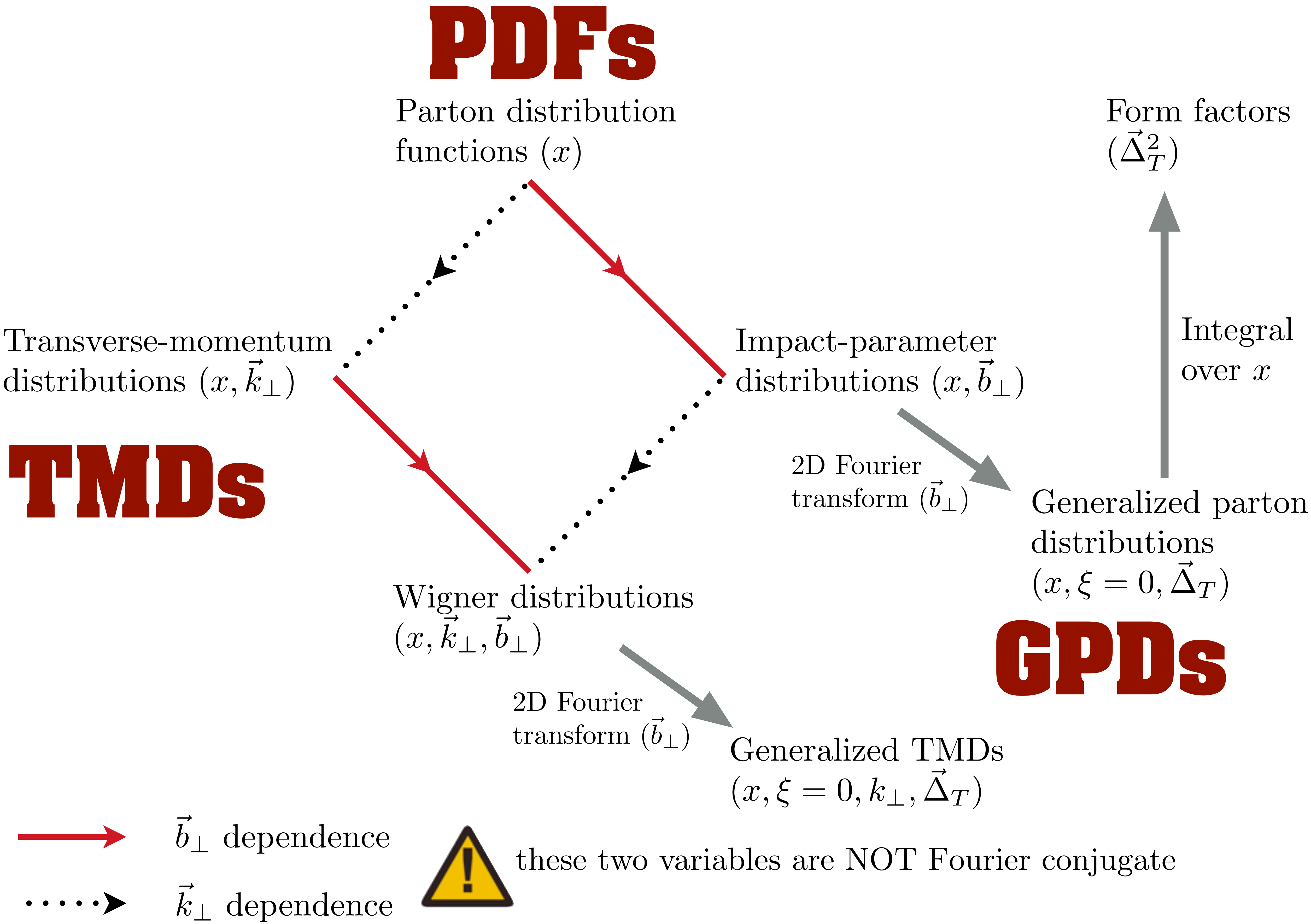
see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)



see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

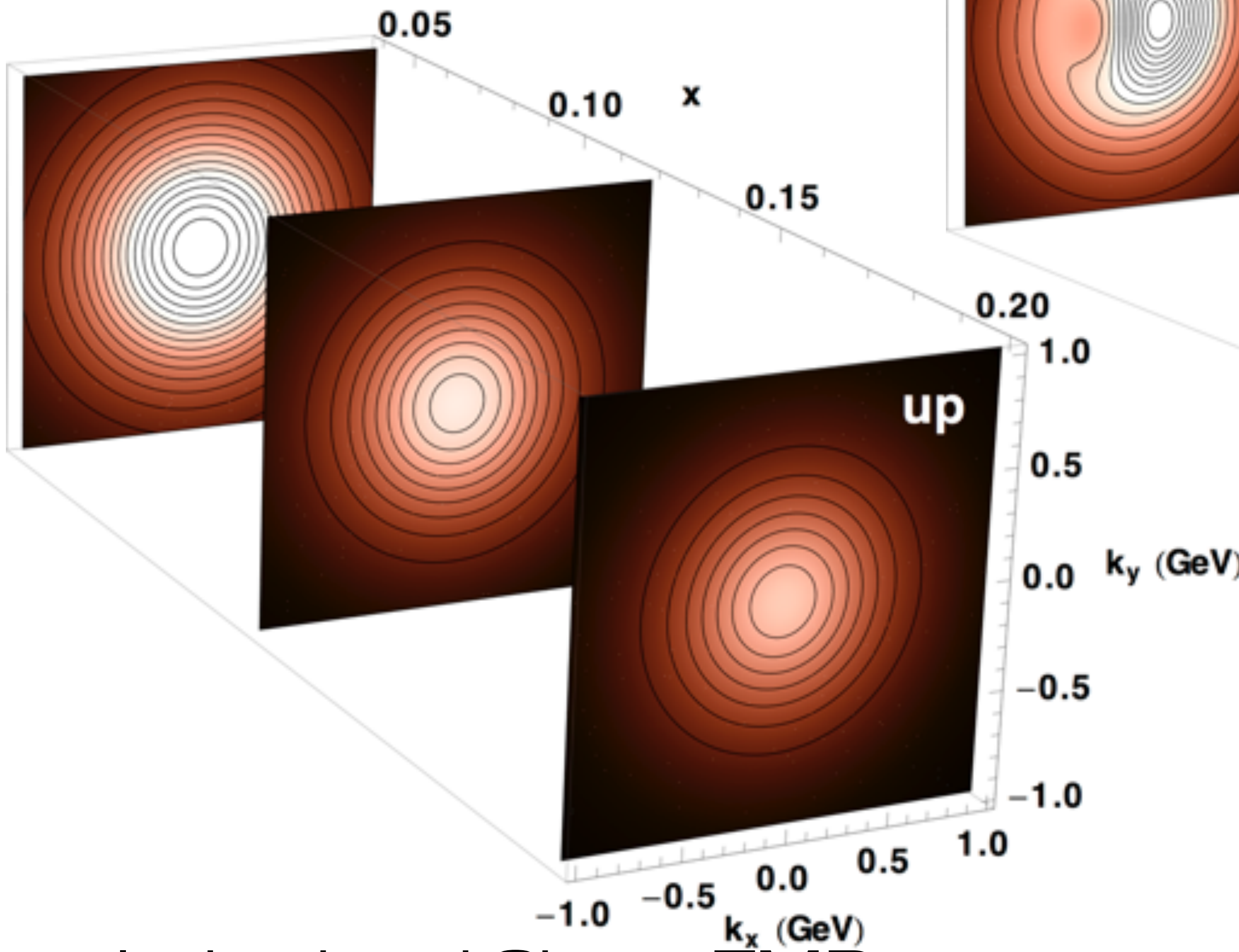


see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

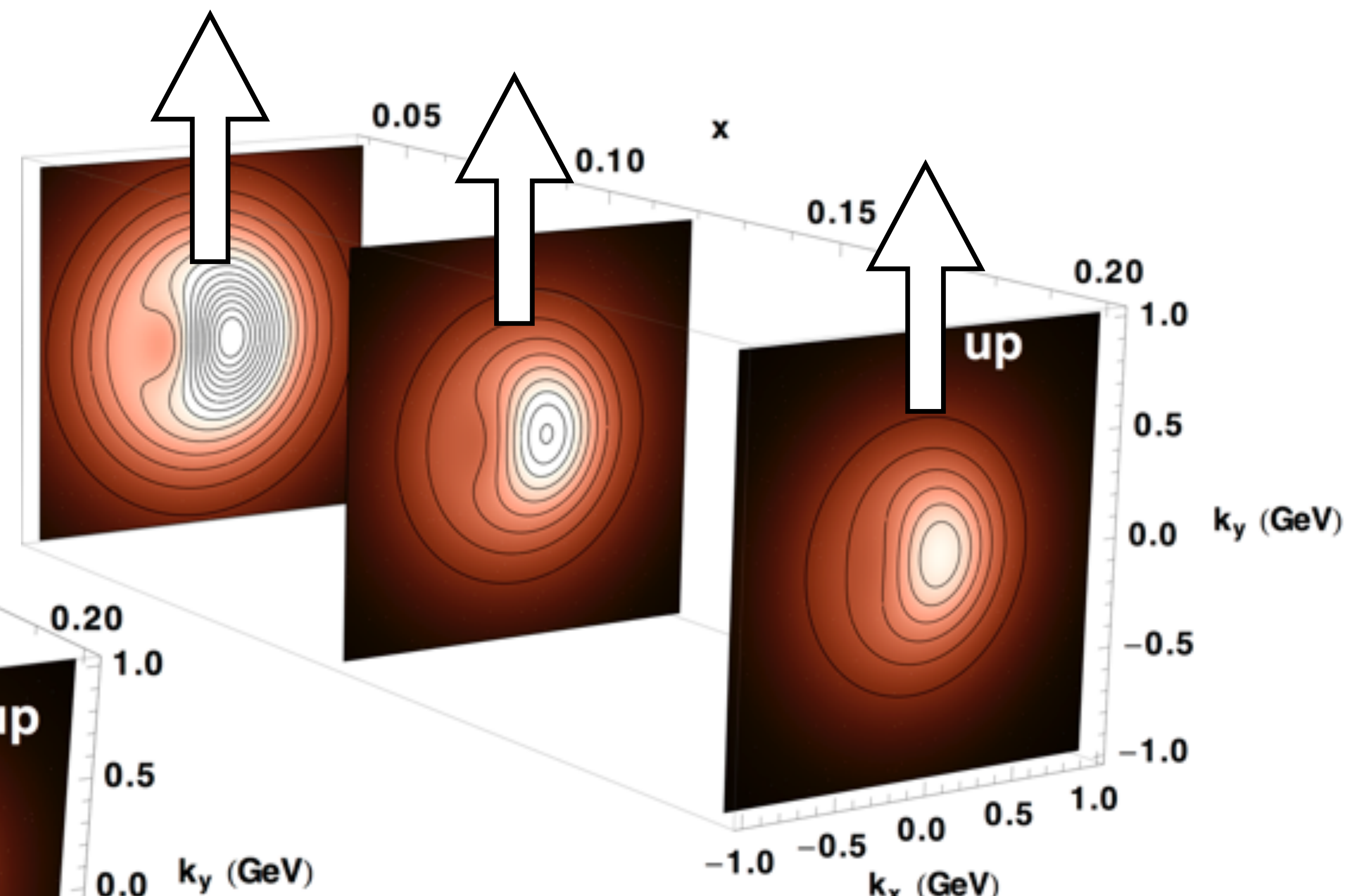


see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

3D structure in momentum space

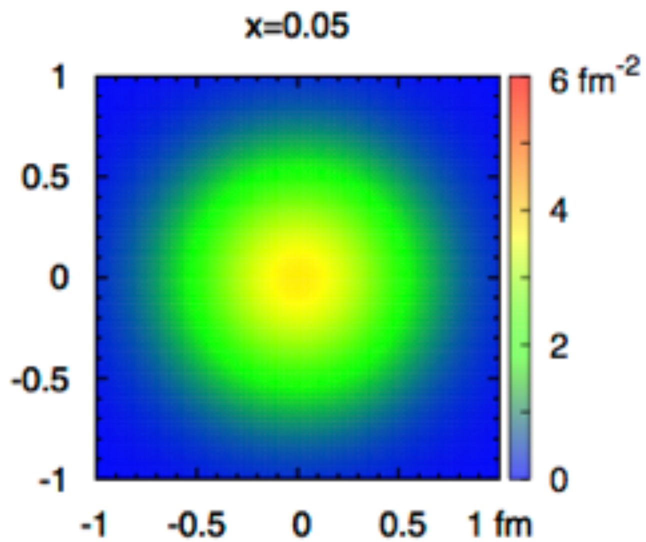


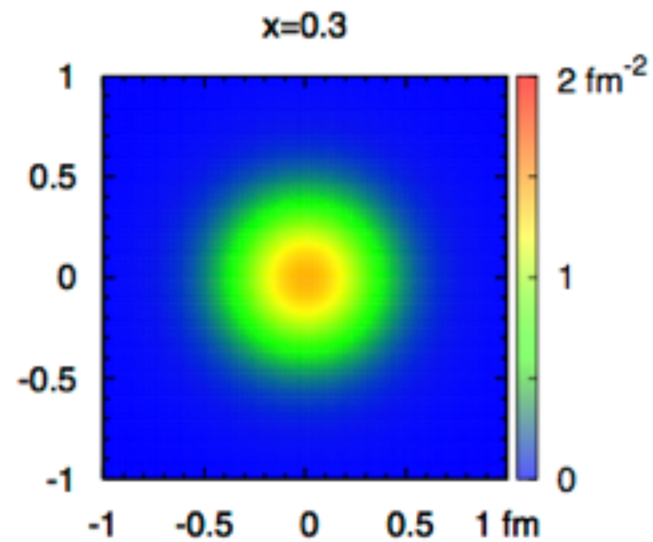
Unpolarized and Sivers TMDs



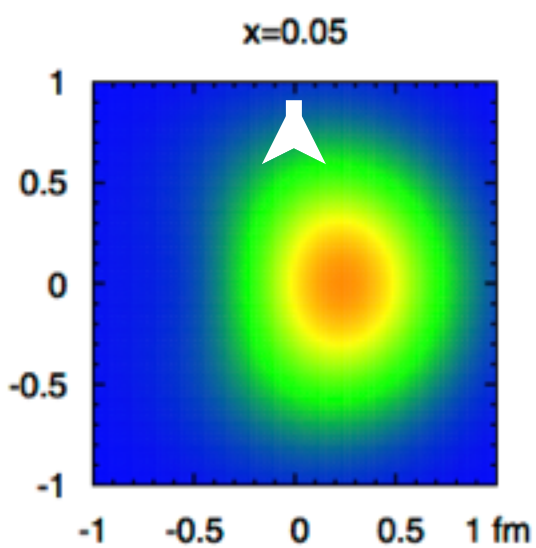
With spin

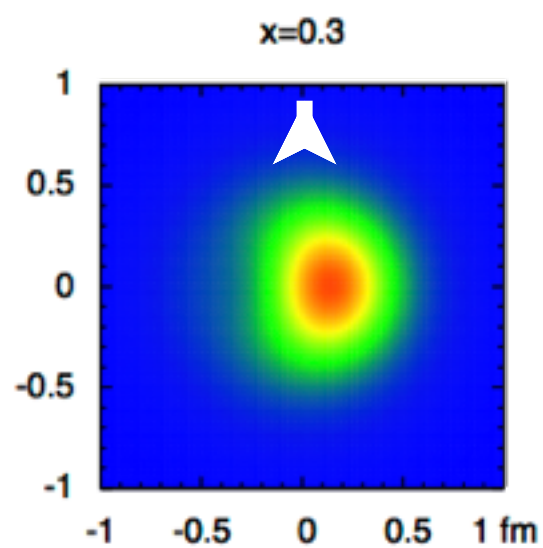
3D structure in impact parameter space





down valence





- Fourier t. of GPDs at (x,0,t)
- Model assumptions are critical
- up: smaller distorsion and opposite sign

Diehl, Kroll, arXiv:1302.4604, and talk by M. Diehl at DIS 2013

Recent review

The European Physical Journal A
All Volumes & Issues

The 3-D Structure of the Nucleon

ISSN: 1434-6001 (Print) 1434-601X (Online)

In this topical collection (17 articles)

EPJ A (2016) 52

The present situation

The present situation

- We have some indications about the qualitative behaviour of some of these densities (much better than just five years ago), but we are still far from precision

The present situation

- We have some indications about the qualitative behaviour of some of these densities (much better than just five years ago), but we are still far from precision

- “Model assumptions” (intended in a broad way) are critical

The present situation

- We have some indications about the qualitative behaviour of some of these densities (much better than just five years ago), but we are still far from precision
- “Model assumptions” (intended in a broad way) are critical
- A good amount of data is already available (but still insufficient)

The future priorities (in my humble opinion)

The future priorities (in my humble opinion)

- Obtain precise determinations of TMDs and GPDs (and direct or indirect determinations of Wigner distributions/generalized TMDs)

The future priorities (in my humble opinion)

- Obtain precise determinations of TMDs and GPDs (and direct or indirect determinations of Wigner distributions/generalized TMDs)

- Find applications of this knowledge outside the field of “proton structure” studies (and react accordingly)

The future priorities (in my humble opinion)

- Obtain precise determinations of TMDs and GPDs (and direct or indirect determinations of Wigner distributions/generalized TMDs)

- Find applications of this knowledge outside the field of “proton structure” studies (and react accordingly)

- Train young generations (and find jobs for them)

Some of the present-day challenges

Change of sign of Sivers function

Change of sign of Sivers function

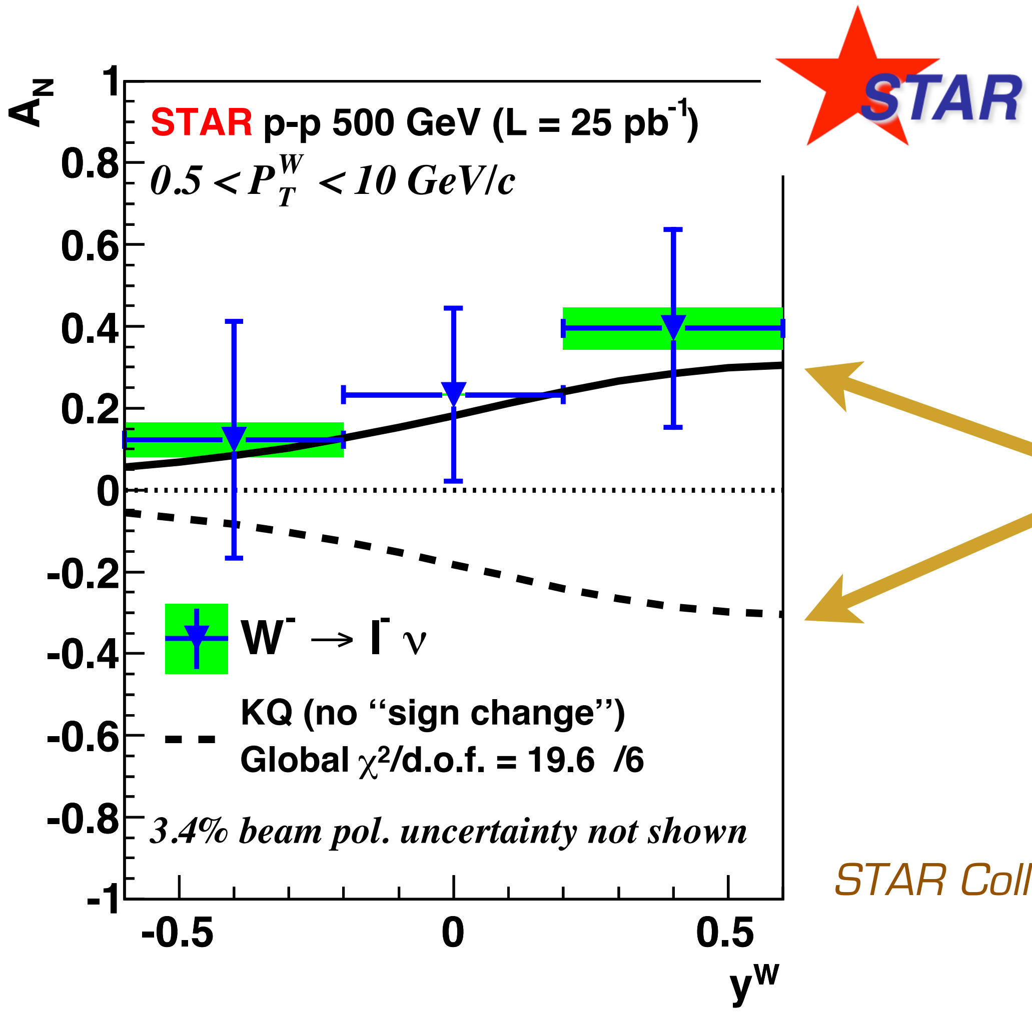
Sivers function $_{\text{SIDIS}}$ = − Sivers function $_{\text{Drell-Yan}}$

Collins, PLB 536 (02)

Change of sign of Sivers function

Sivers function $_{\text{SIDIS}}$ = − Sivers function $_{\text{Drell-Yan}}$

Collins, PLB 536 (02)



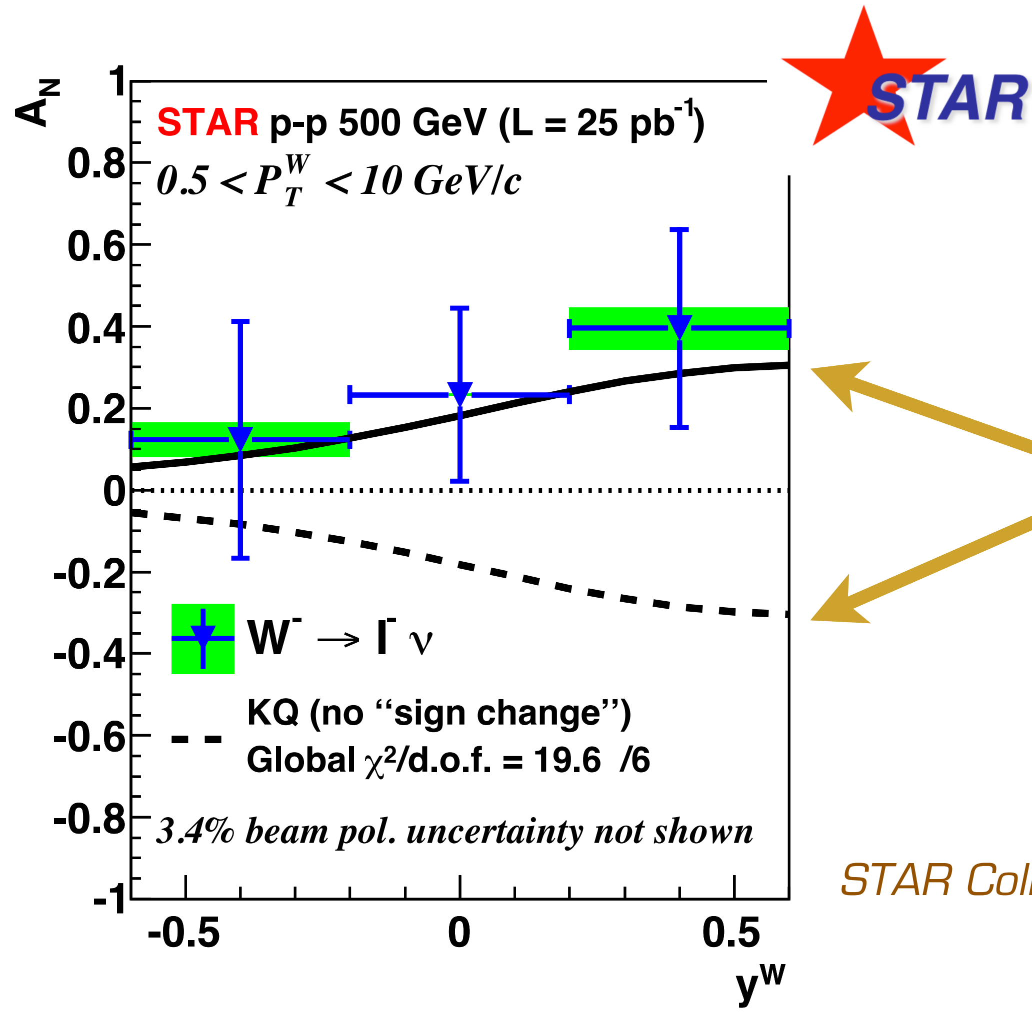
first evidence of sign change?

STAR Collab. arXiv:1511.06003

Change of sign of Sivers function

Sivers function $_{\text{SIDIS}}$ = – Sivers function $_{\text{Drell-Yan}}$

Collins, PLB 536 (02)



first evidence of sign change?

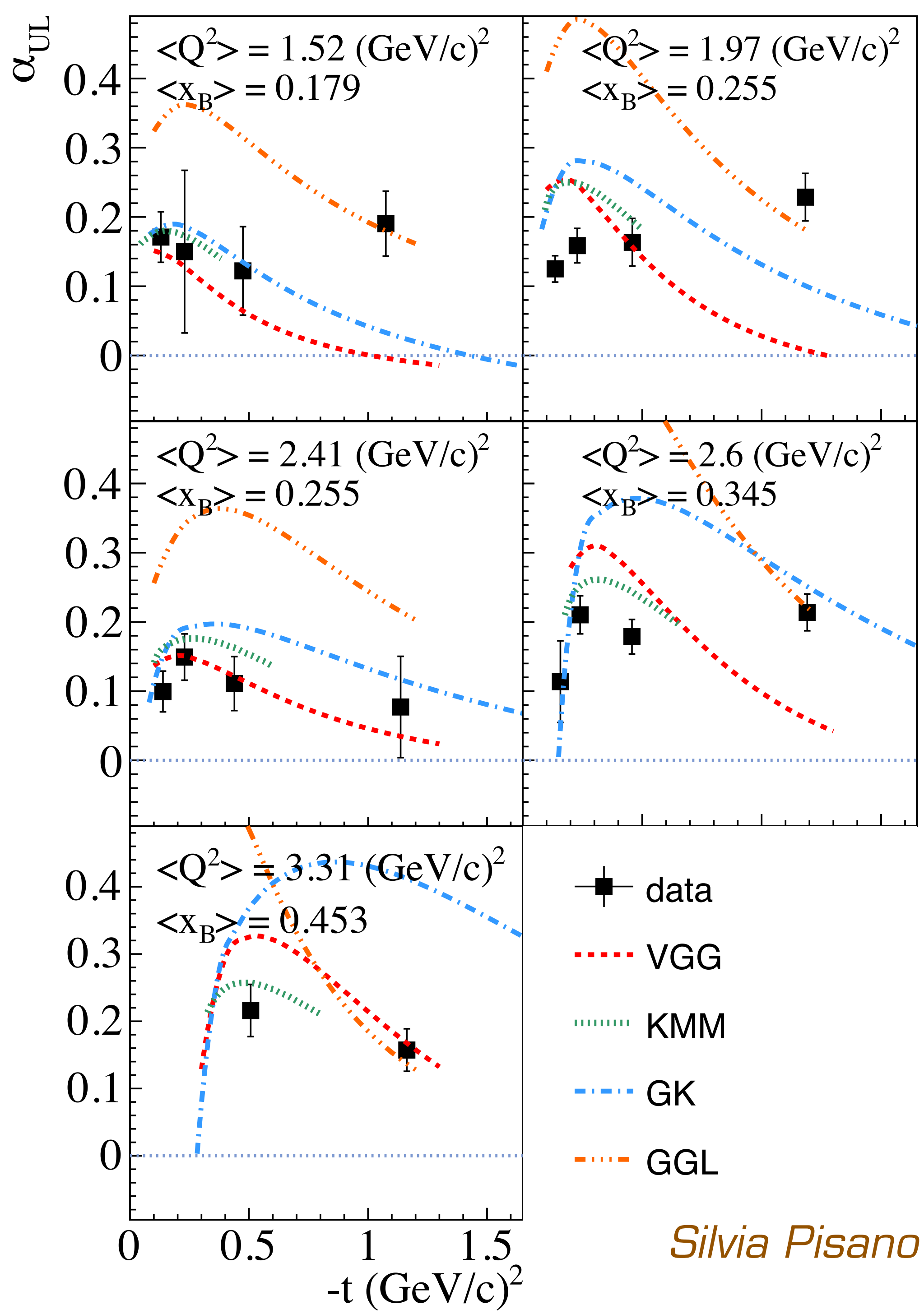
STAR Collab. arXiv:1511.06003

We hope to have a clear result from COMPASS

see talks by Catarina Quintans

GPD parametrizations

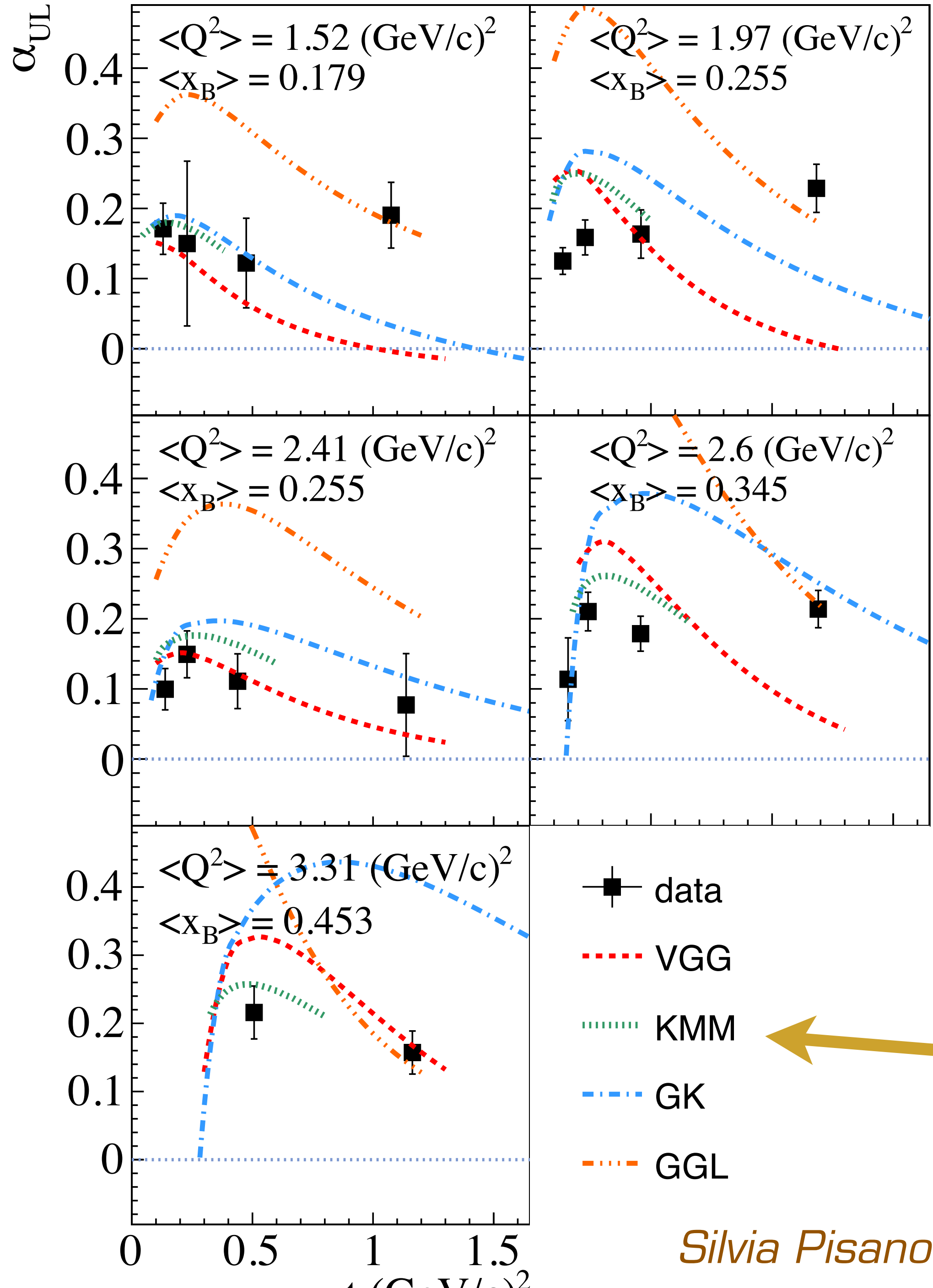
Example of data: target spin asymmetry at CLAS



Silvia Pisano et al., arXiv:1501.07052

GPD parametrizations

Example of data: target spin asymmetry at CLAS

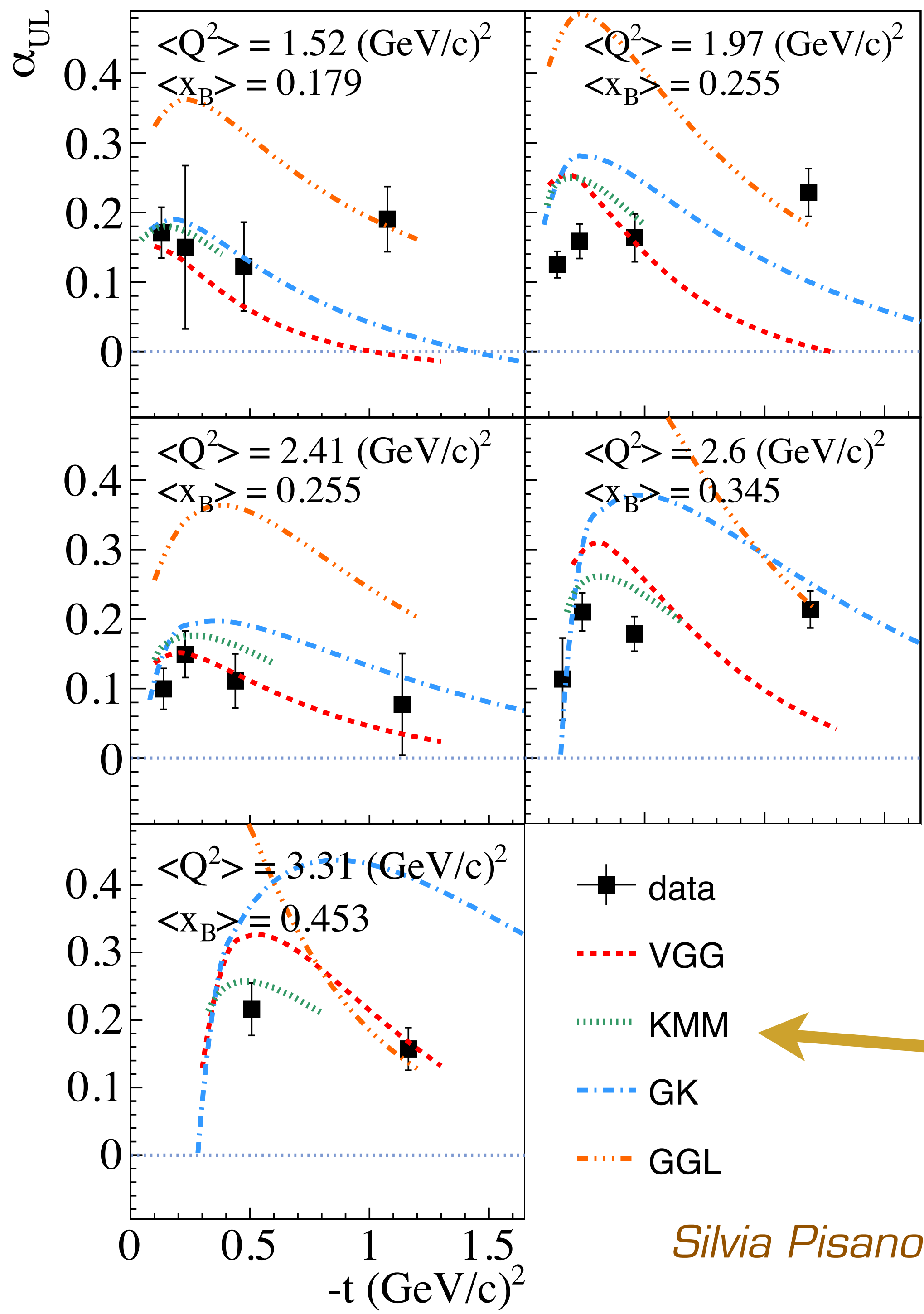


Parametrizations available on the market

Silvia Pisano et al., arXiv:1501.07052

GPD parametrizations

Example of data: target spin asymmetry at CLAS

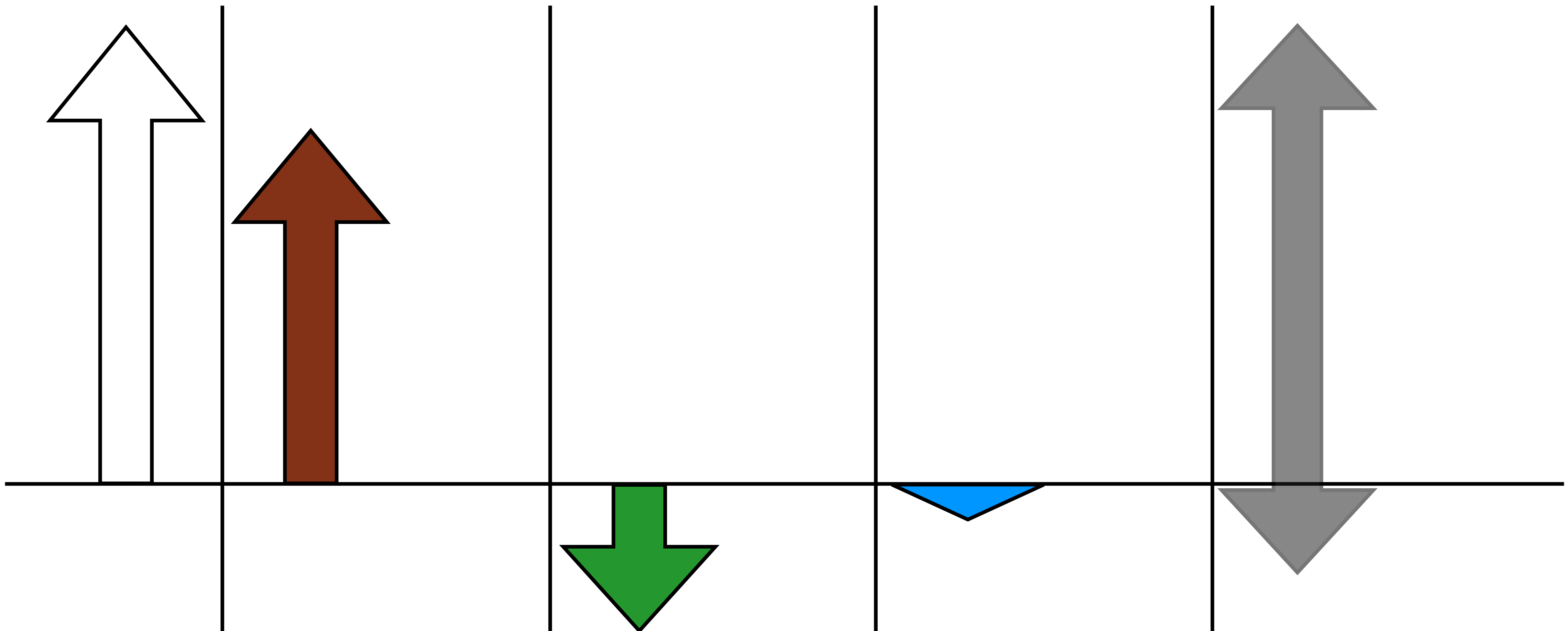


Most parametrizations are not describing ALL data in a satisfactory way.

Parametrizations available on the market

Silvia Pisano et al., arXiv:1501.07052

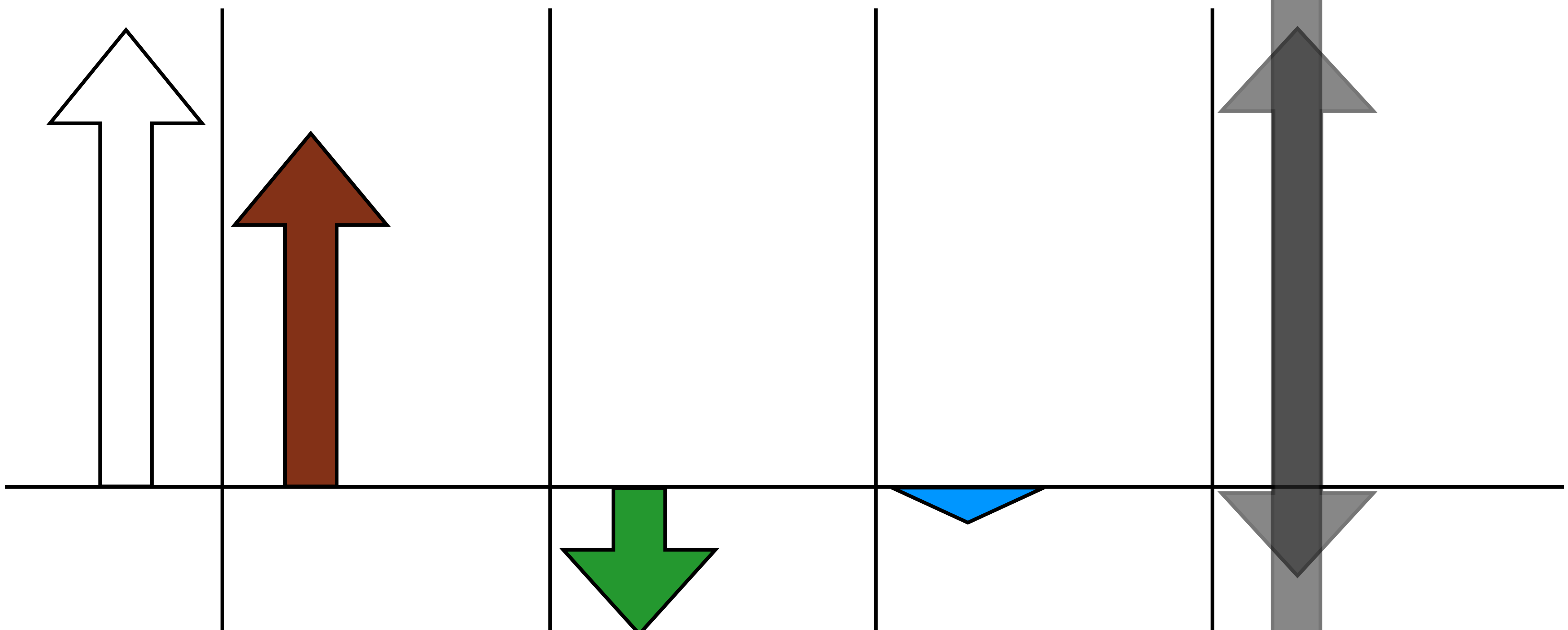
Status of spin sum rule



Proton spin	$u+\bar{u}$		$d+\bar{d}$		$s+\bar{s}$		g		
	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	
	82 ± 2		-45 ± 4		-11 ± 10		40 ± 60		DSSV

de Florian, Sassot, Stramann, Vogelsang, PRL 113 (14)
NNPDF, Ball et al. NPB 887 (14), Tab. 12, 13

Status of spin sum rule

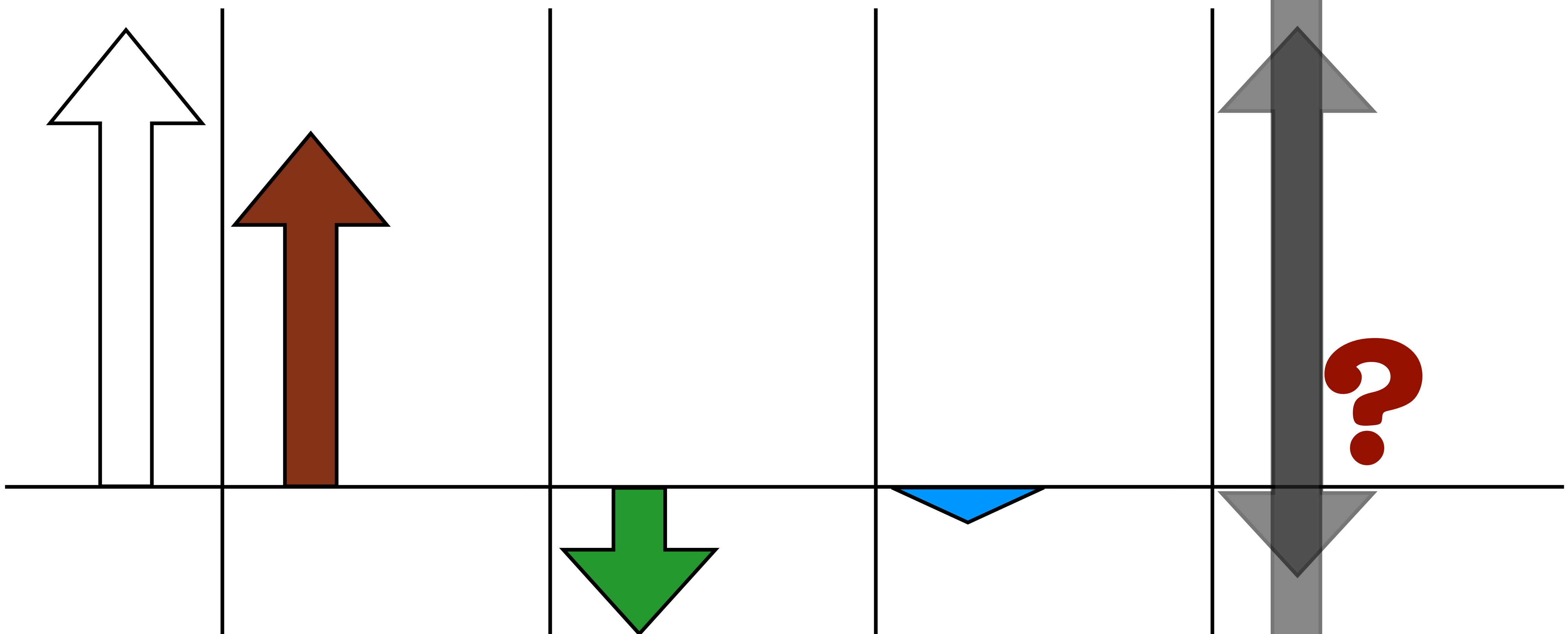


Proton spin

$u+\bar{u}$		$d+\bar{d}$		$s+\bar{s}$		g		
spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	
82 ± 2		-45 ± 4		-11 ± 10		40 ± 60		DSSV
79 ± 7		-47 ± 7		-12 ± 10		3 ± 324		NNPDF

de Florian, Sassot, Stramann, Vogelsang, PRL 113 (14)
NNPDF, Ball et al. NPB 887 (14), Tab. 12, 13

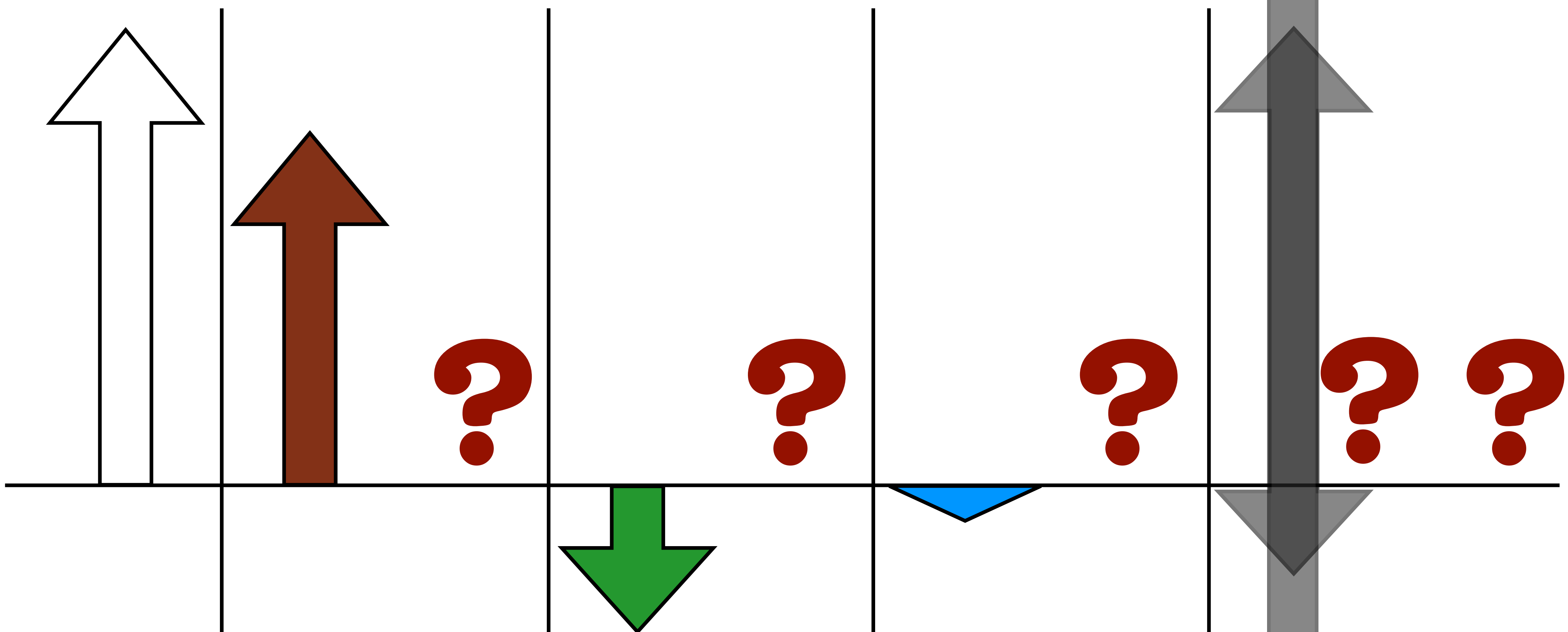
Status of spin sum rule



	$u+\bar{u}$		$d+\bar{d}$		$s+\bar{s}$		g		
Proton spin	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	
	82 ± 2		-45 ± 4		-11 ± 10		40 ± 60		DSSV
	79 ± 7		-47 ± 7		-12 ± 10		3 ± 324		NNPDF

de Florian, Sassot, Stramann, Vogelsang, PRL 113 (14)
NNPDF, Ball et al. NPB 887 (14), Tab. 12, 13

Status of spin sum rule



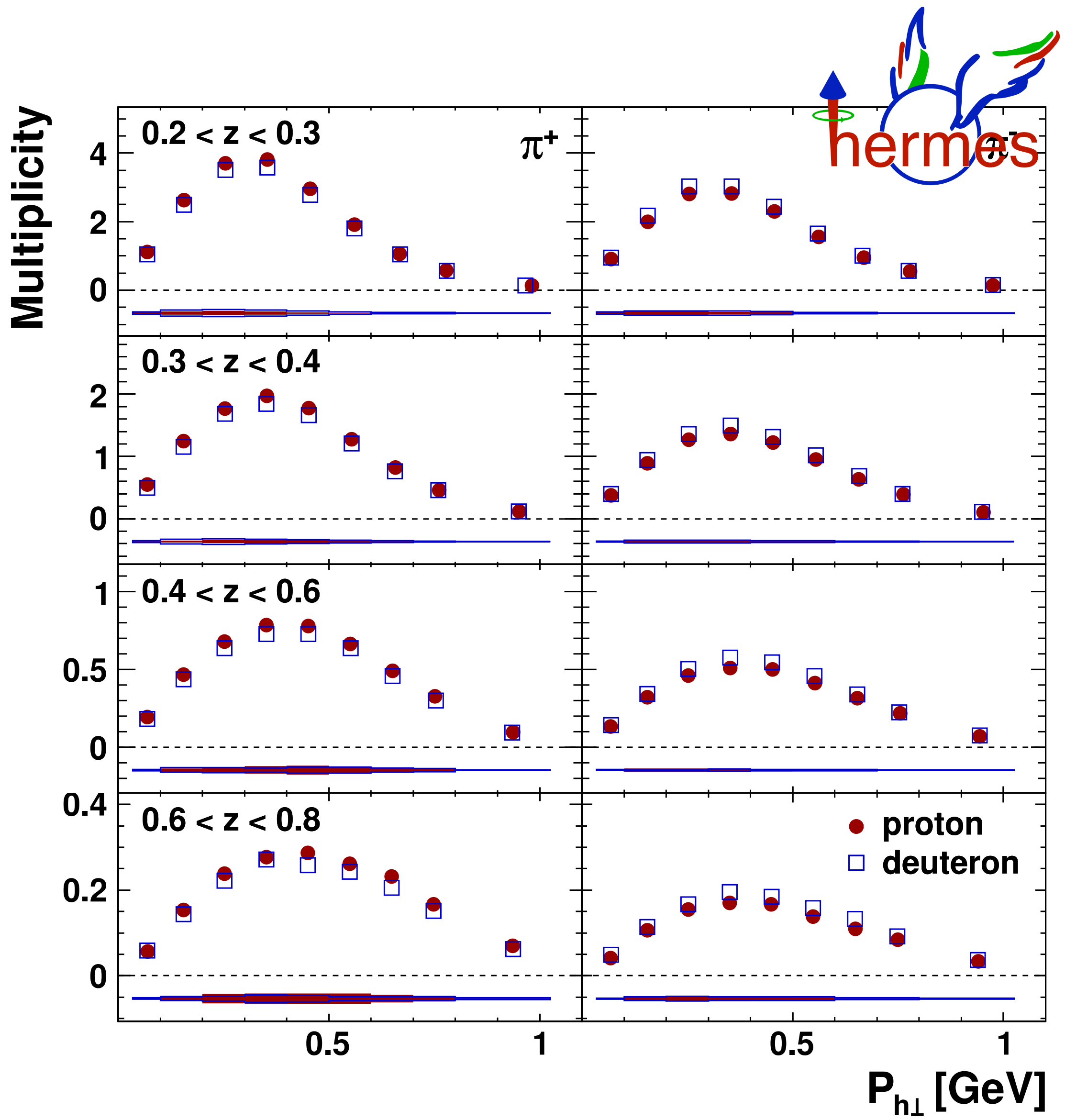
Proton spin	$u+\bar{u}$		$d+\bar{d}$		$s+\bar{s}$		g		
	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	spin (%)	OAM	
	82 ± 2		-45 ± 4		-11 ± 10		40 ± 60		DSSV
	79 ± 7		-47 ± 7		-12 ± 10		3 ± 324		NNPDF

de Florian, Sassot, Stramann, Vogelsang, PRL 113 (14)

NNPDF, Ball et al. NPB 887 (14), Tab. 12, 13

TMD evolution

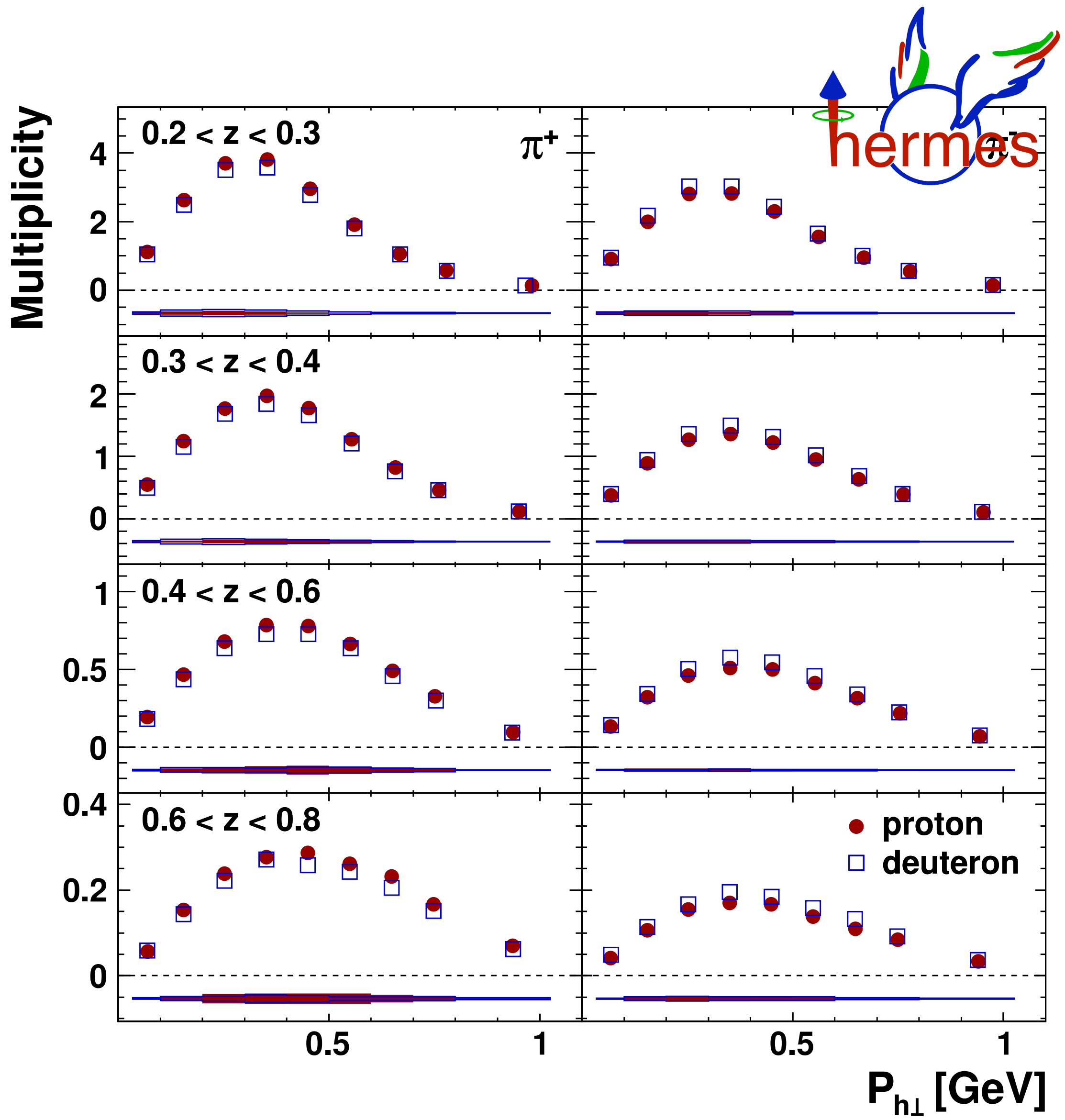
HERMES, Q ≈ 1.5 GeV



Airapetian et al., PRD87 (2013)

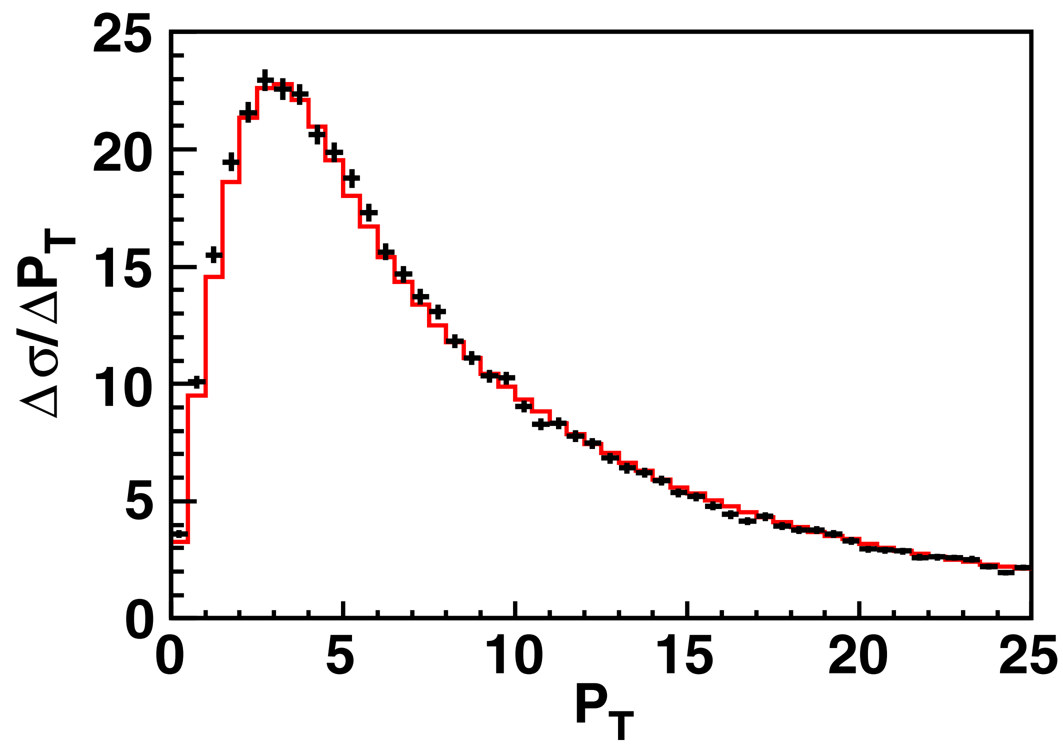
TMD evolution

HERMES, Q ≈ 1.5 GeV



Airapetian et al., PRD87 (2013)

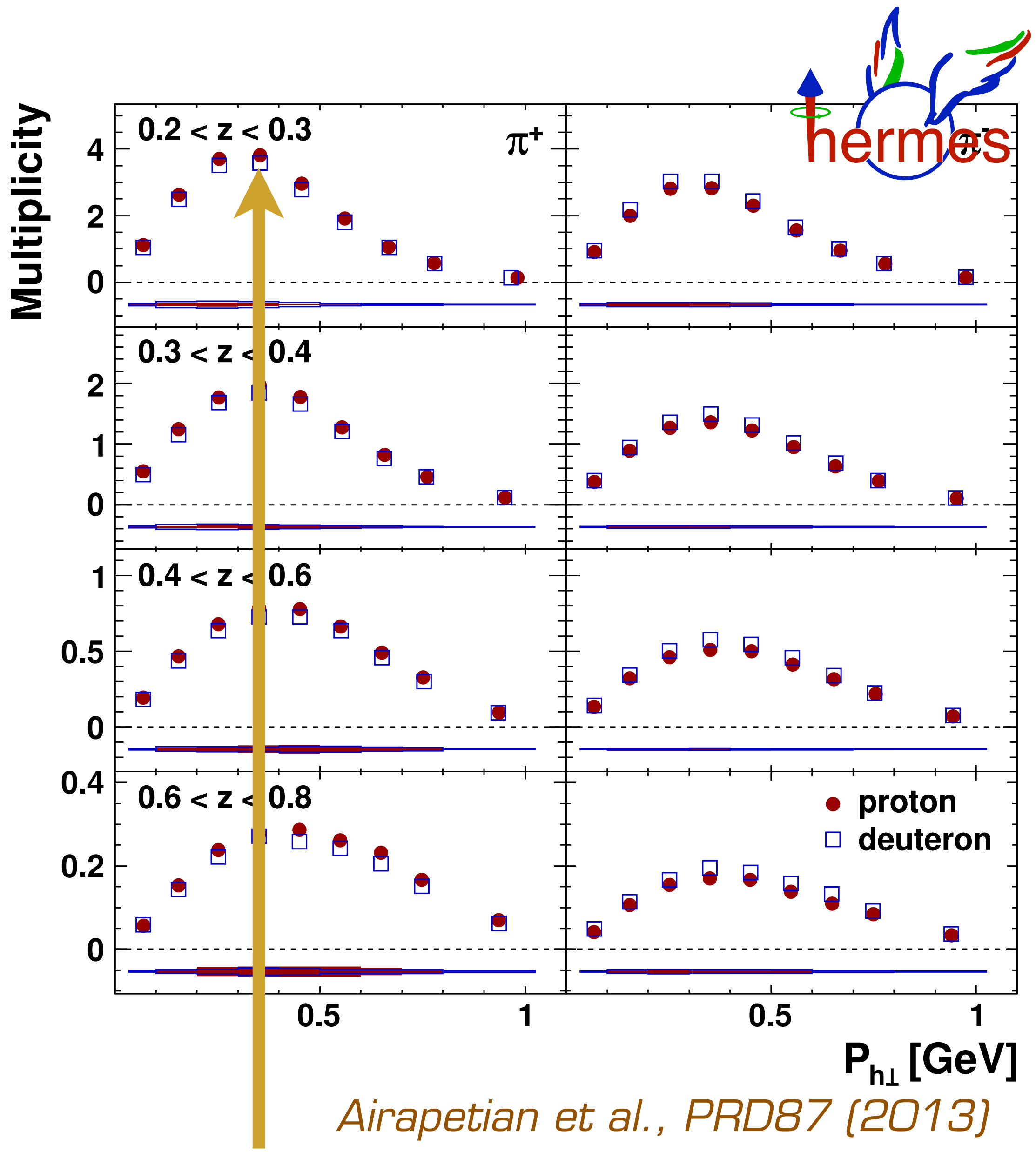
CDF, Q ≈ 91 GeV



Aaltonen et al., PRD86 (2012)

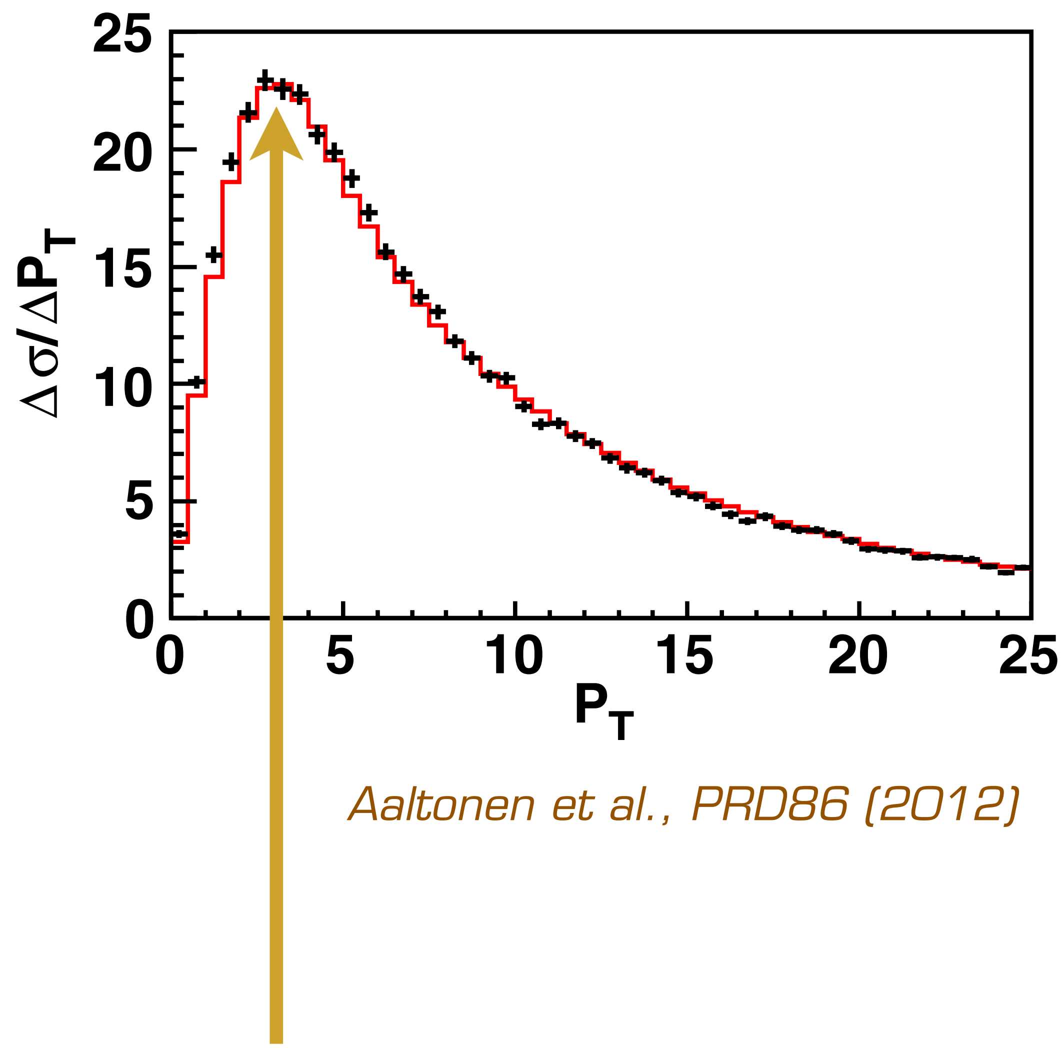
TMD evolution

HERMES, Q ≈ 1.5 GeV



Airapetian et al., PRD87 (2013)

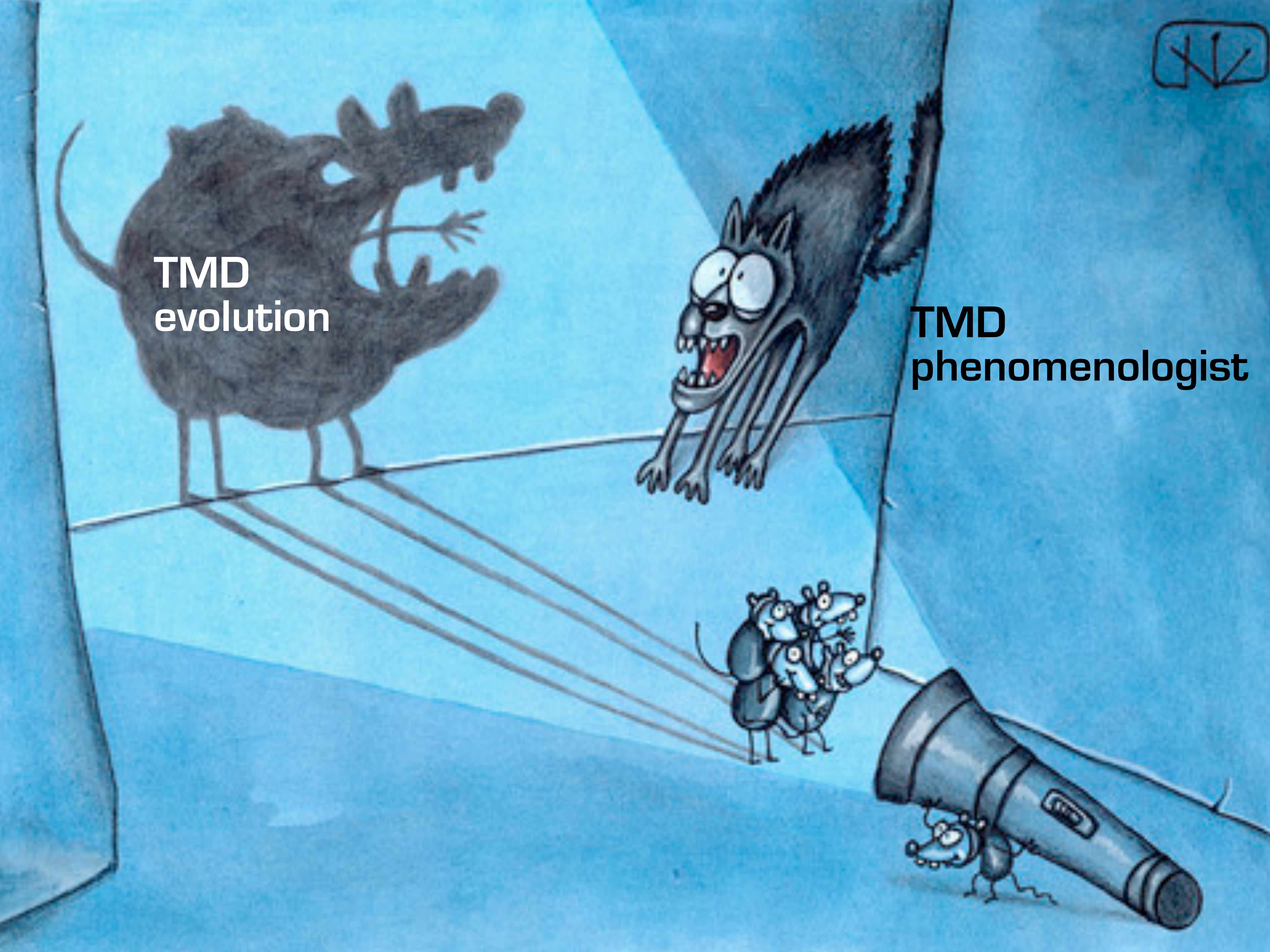
CDF, Q ≈ 91 GeV



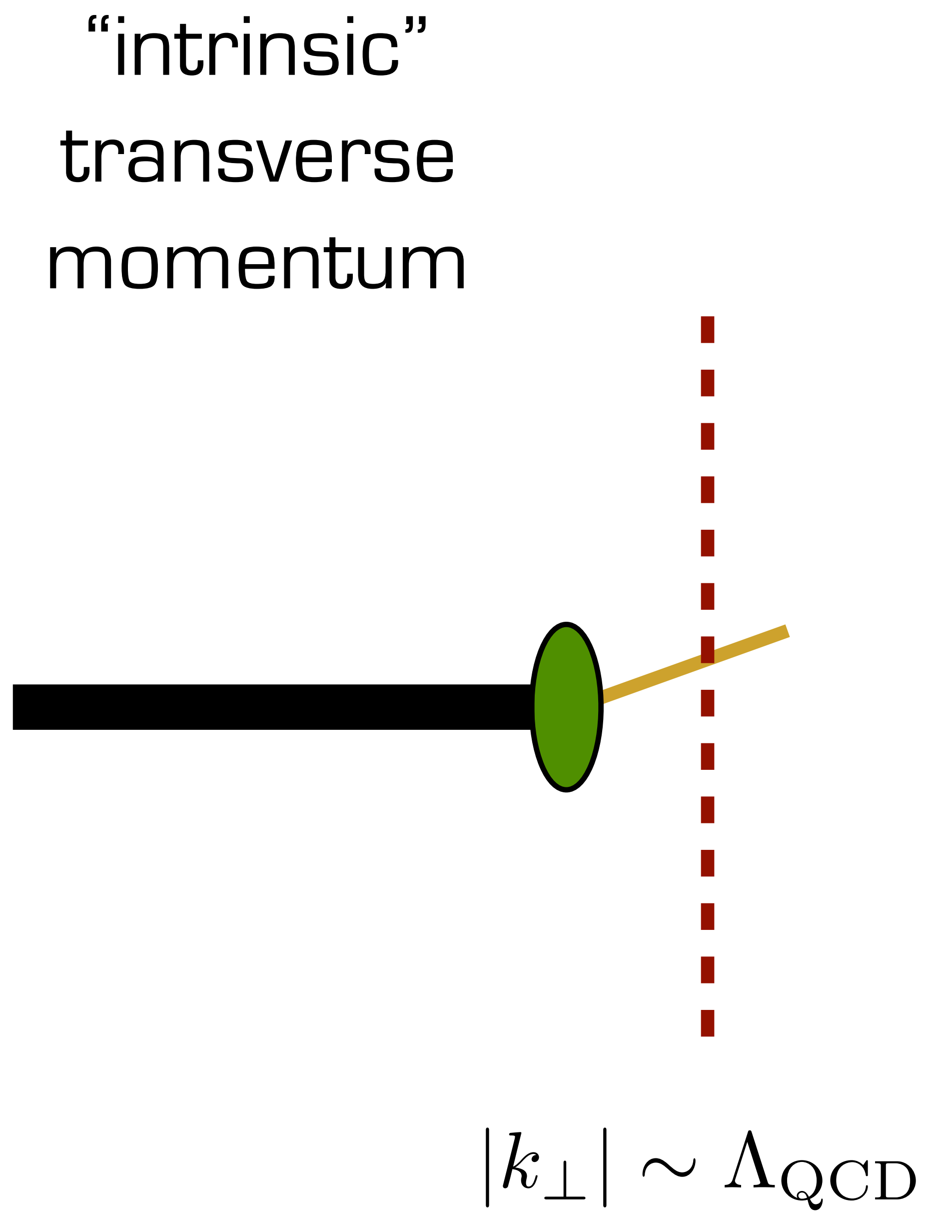
Aaltonen et al., PRD86 (2012)

Width of TMDs changes of one order of magnitude: can we explain this in detail? (TMD evolution)


TMD
evolution
TMD
phenomenologist


TMD
evolution
TMD
phenomenologist

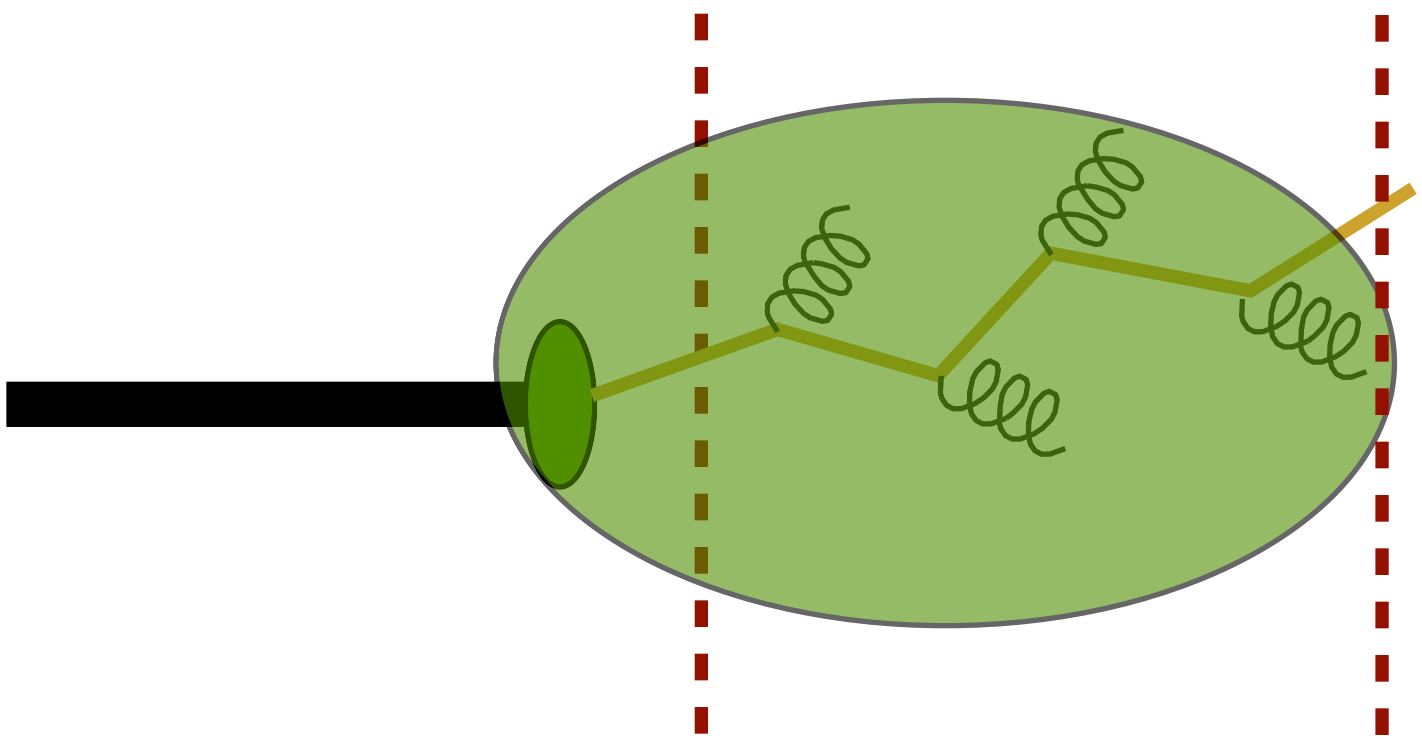
TMD and QCD corrections



TMD and QCD corrections

“intrinsic” transverse momentum

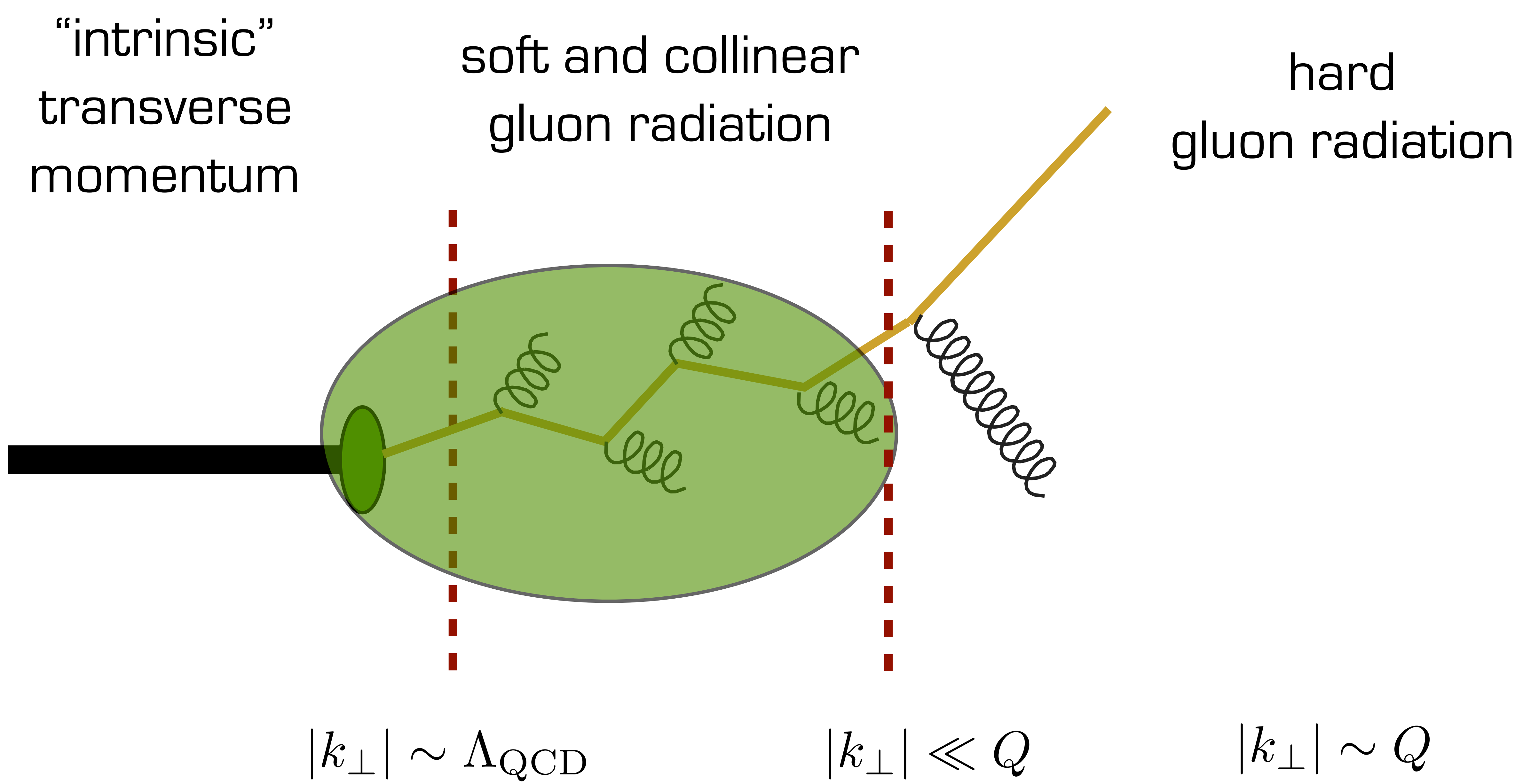
soft and collinear gluon radiation



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

$|k_\perp| \ll Q$

TMD and QCD corrections



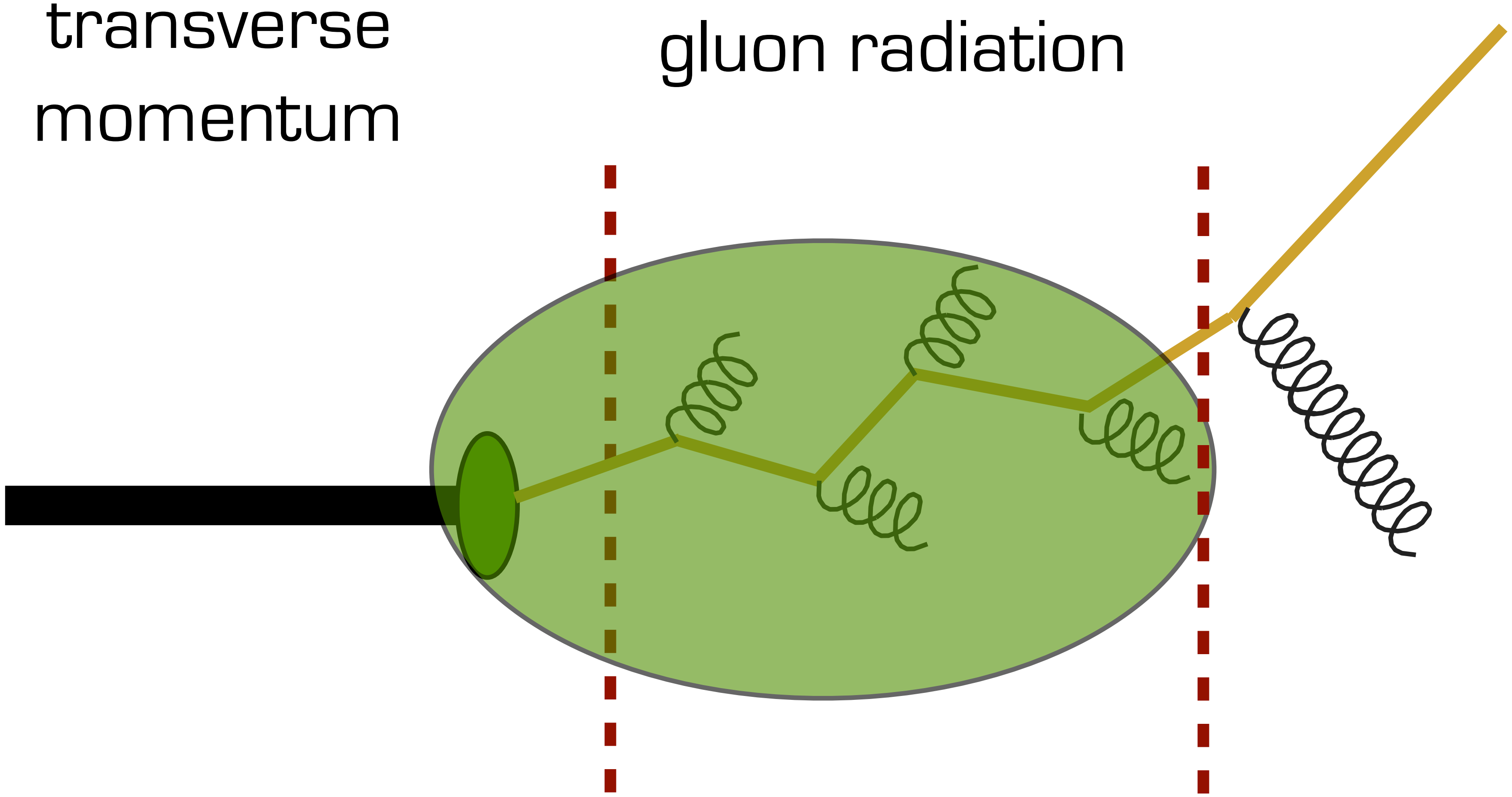
TMD and QCD corrections

TMD formalism

"intrinsic" transverse momentum

soft and collinear gluon radiation

hard gluon radiation



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

$|k_\perp| \ll Q$

$|k_\perp| \sim Q$

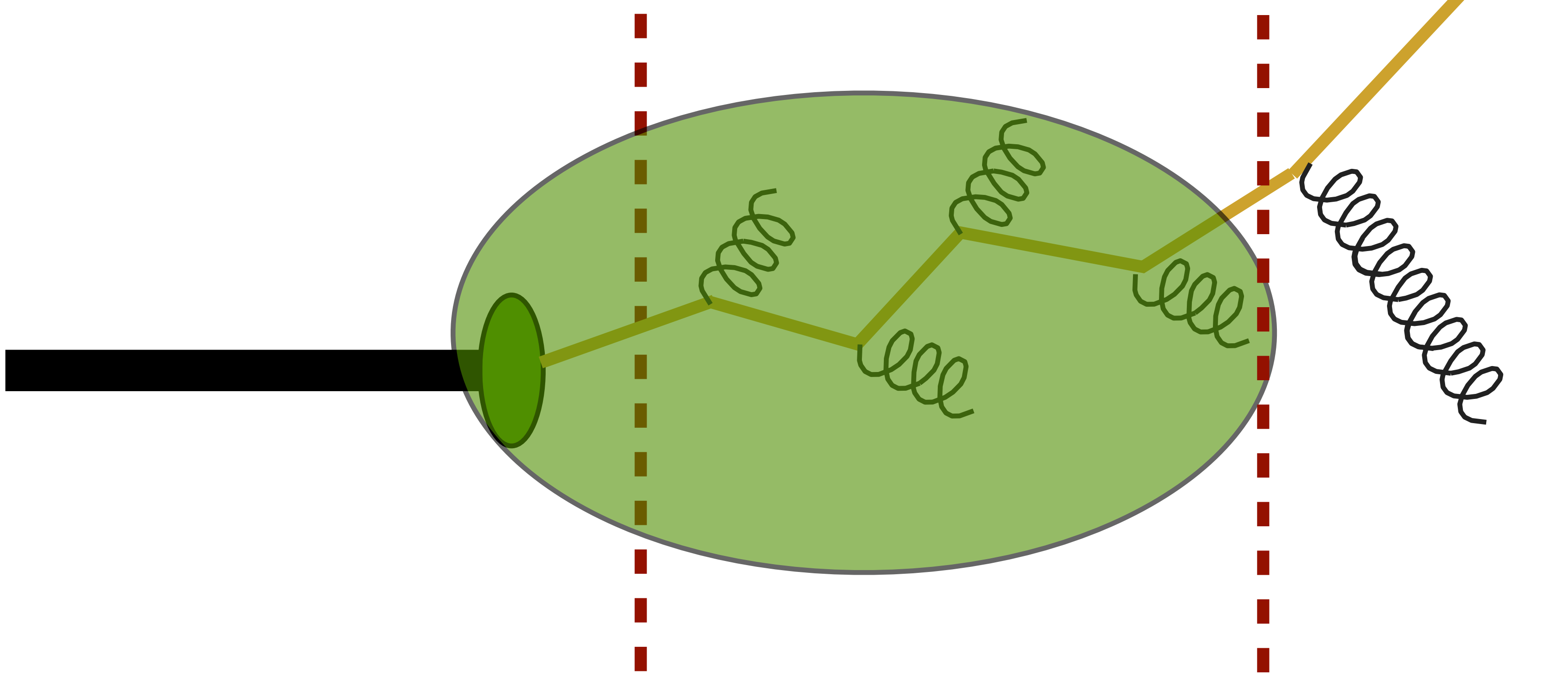
TMD and QCD corrections

TMD formalism	collinear formalism

"intrinsic" transverse momentum

soft and collinear gluon radiation

hard gluon radiation



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

$|k_\perp| \ll Q$

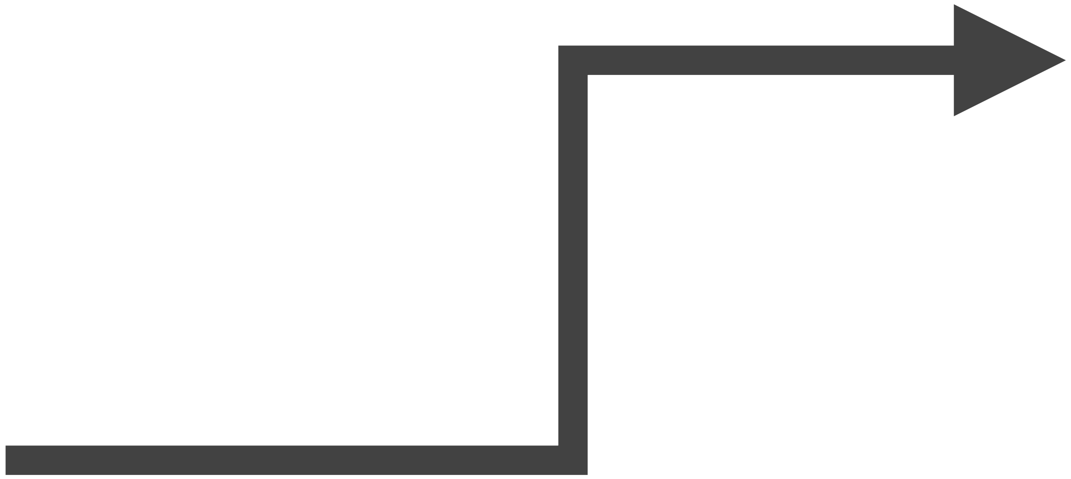
$|k_\perp| \sim Q$

A “phase transition” in TMD studies

A “phase transition” in TMD studies

1D

(standard parton distribution functions - PDFs)



A “phase transition” in TMD studies

1D

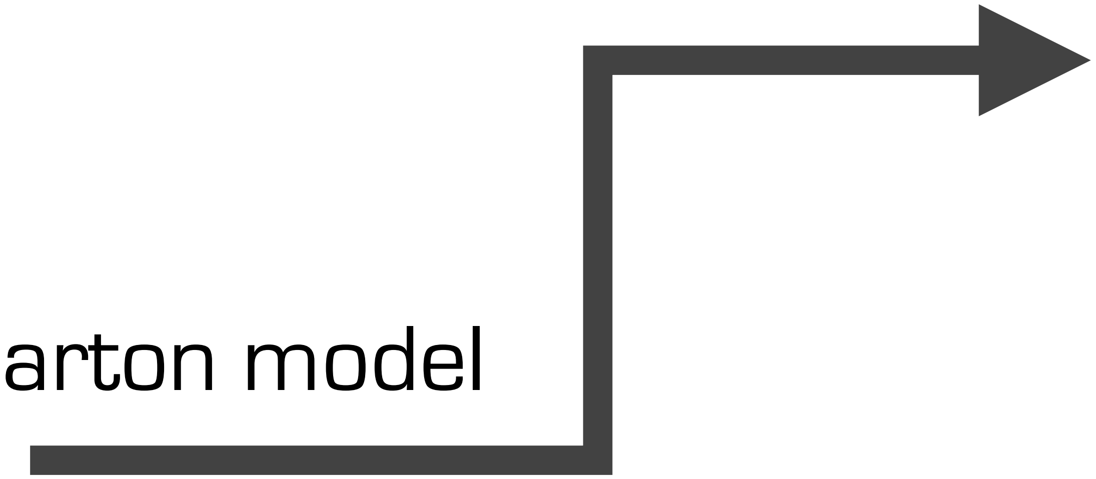
(standard parton distribution functions - PDFs)

Parton model

A “phase transition” in TMD studies

1D

(standard parton distribution functions - PDFs)



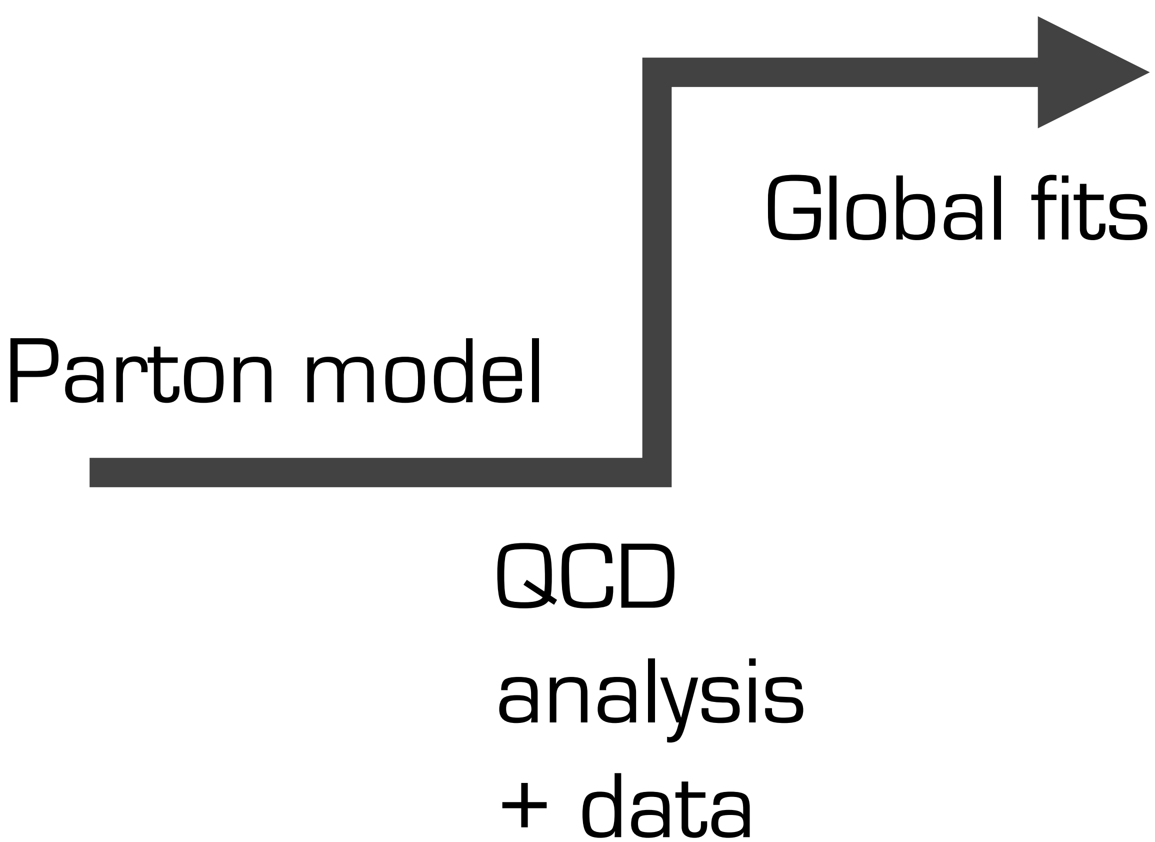
Parton model

QCD analysis + data

A “phase transition” in TMD studies

1D

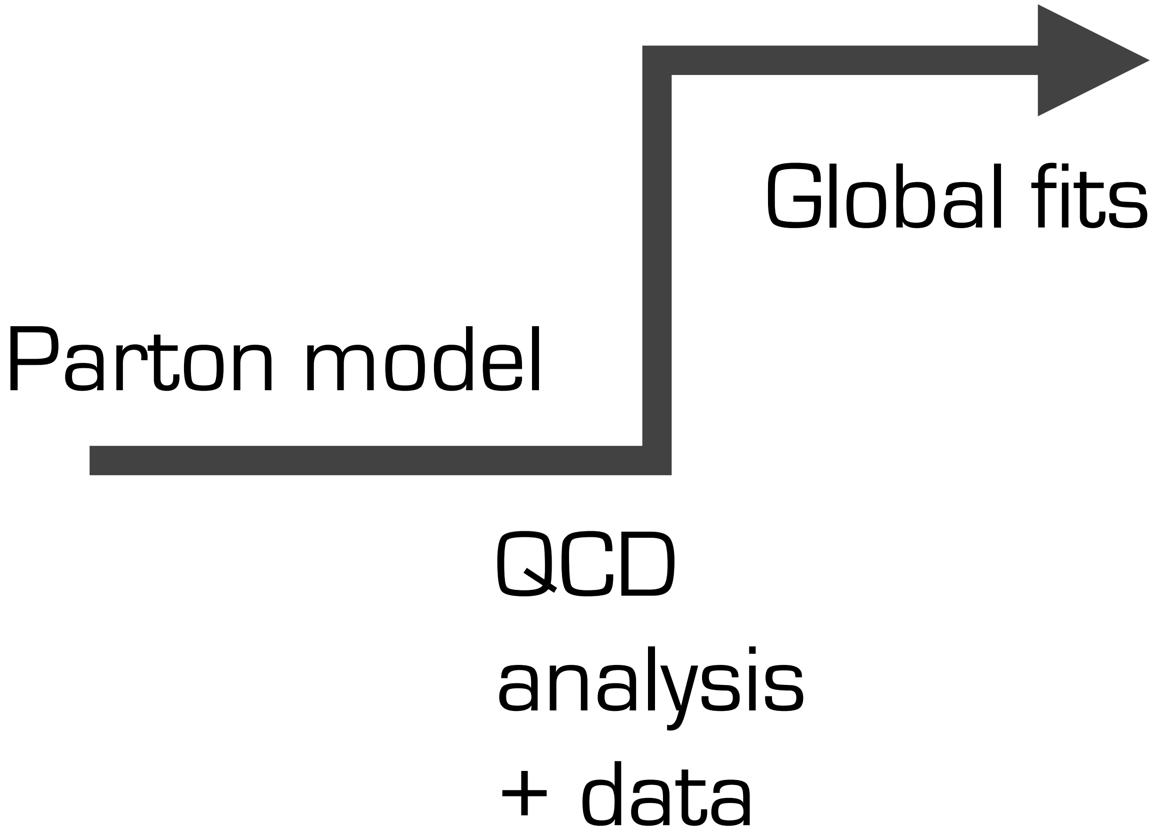
(standard parton distribution functions - PDFs)



A “phase transition” in TMD studies

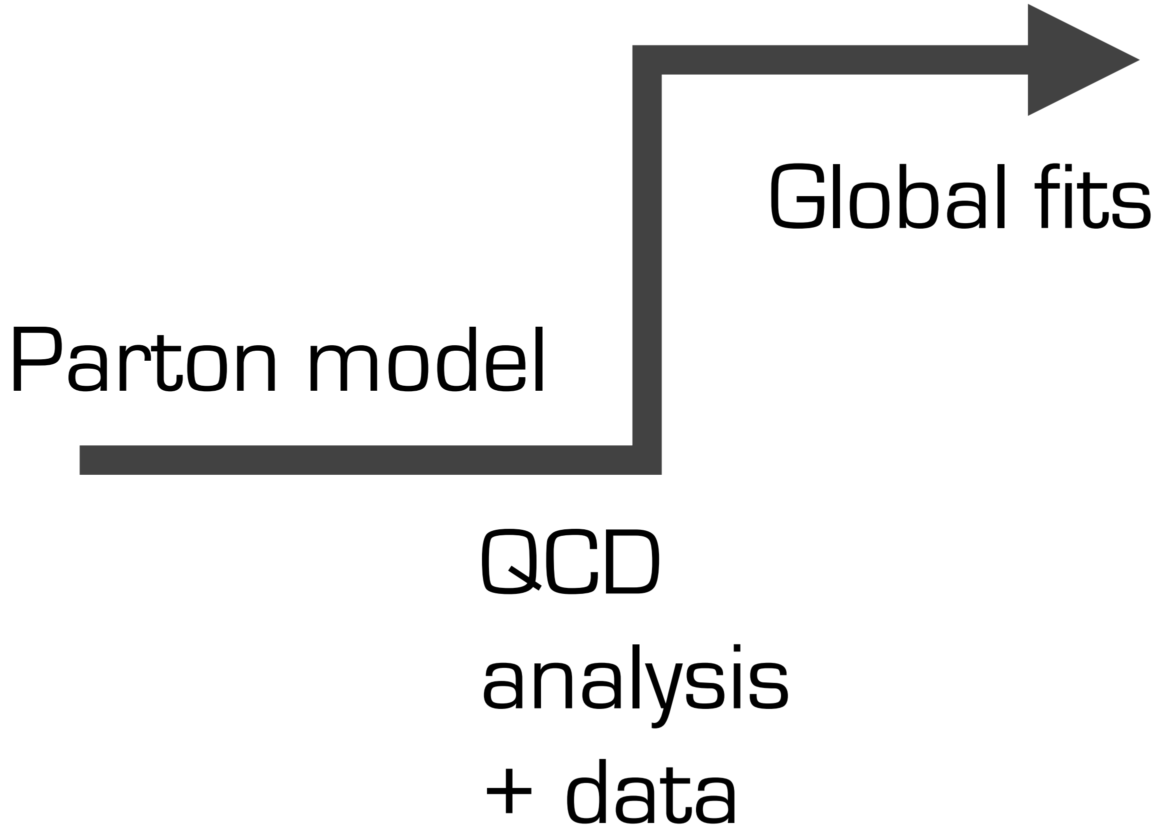
1D

(standard parton distribution functions - PDFs)



3D

(transverse momentum distributions - TMDs)



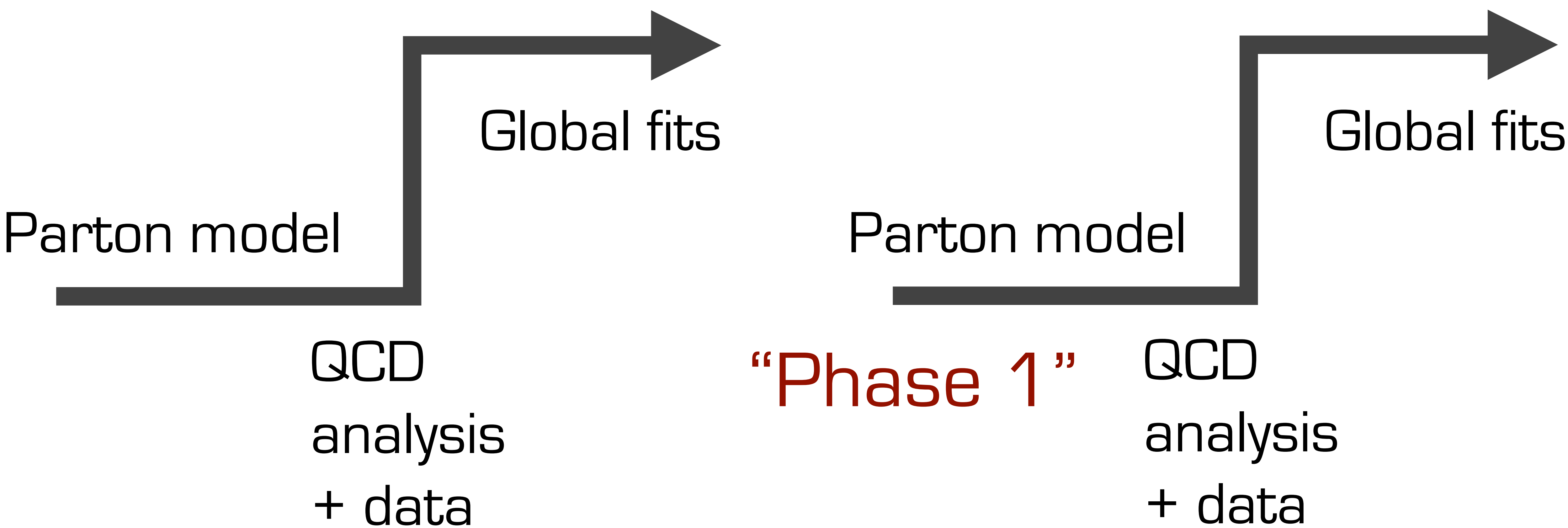
A “phase transition” in TMD studies

1D

(standard parton distribution functions - PDFs)

3D

(transverse momentum distributions - TMDs)



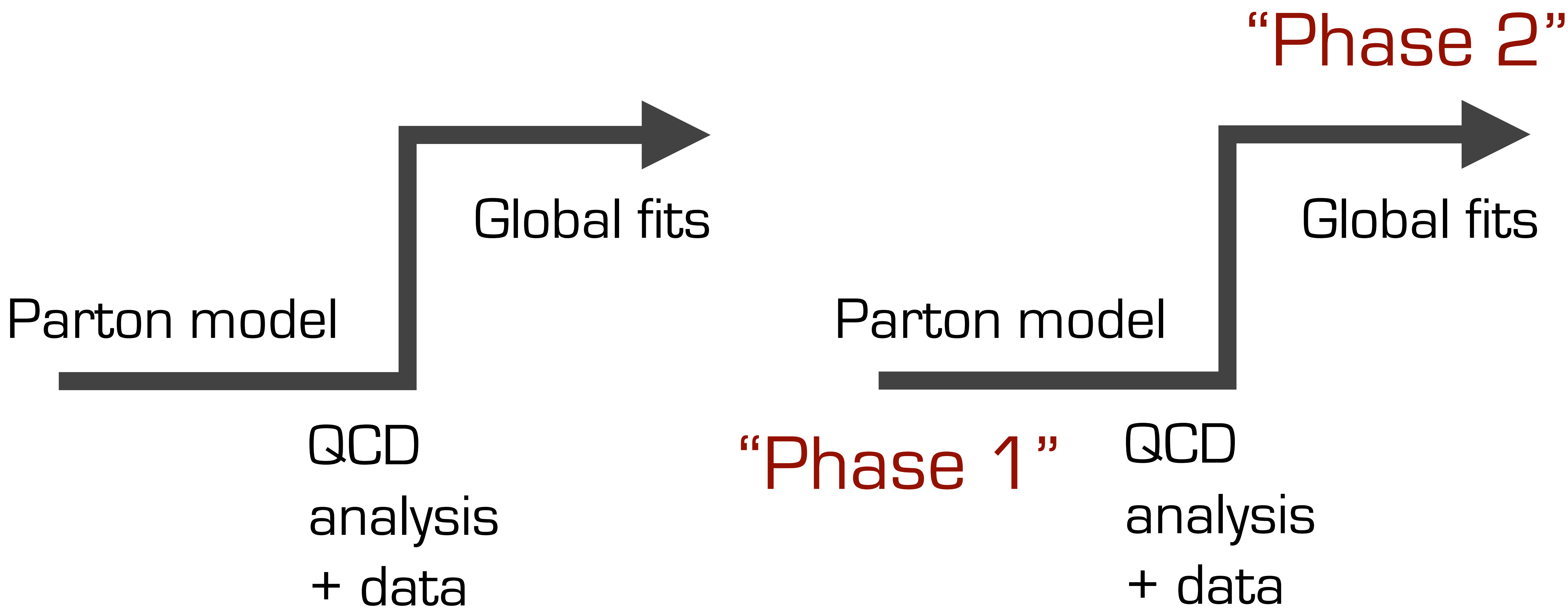
A “phase transition” in TMD studies

1D

(standard parton distribution functions - PDFs)

3D

(transverse momentum distributions - TMDs)



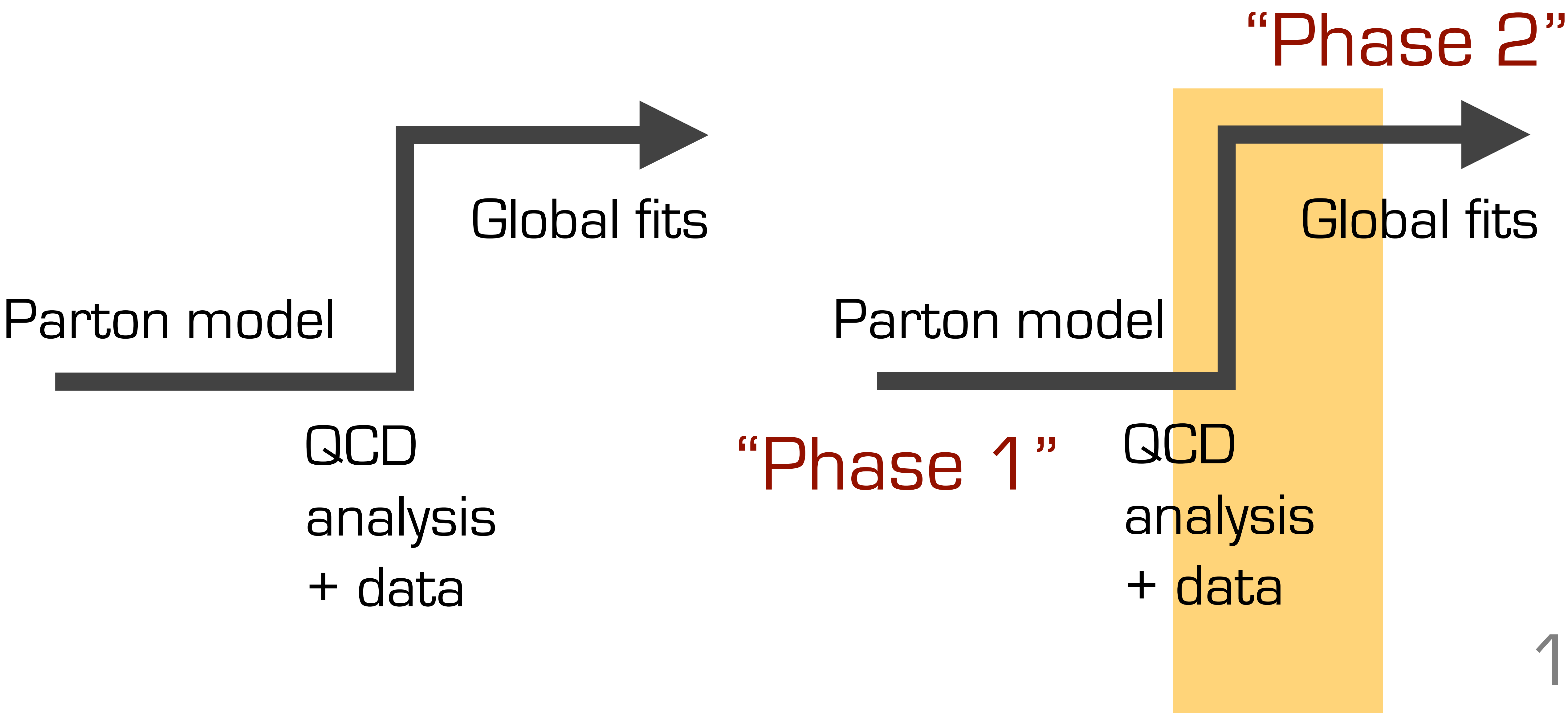
A “phase transition” in TMD studies

1D

(standard parton distribution functions - PDFs)

3D

(transverse momentum distributions - TMDs)




Phase
1
“parton
model”
Phase
2
“global
fits”

TMD evolution: Fourier transform

$$f_1^a(x, k_\perp; \mu^2) = \frac{1}{2\pi} \int d^2 b_T e^{-ib_T \cdot k_\perp} \widetilde{f}_1^a(x, b_T; \mu^2)$$

Rogers, Aybat, PRD 83 (11)
Collins, "Foundations of Perturbative QCD" (11)

possible schemes, e.g.,
Collins, Soper, Sterman, NPB250 (85)
Laenen, Sterman, Vogelsang, PRL 84 (00)
Echevarria, Idilbi, Schaefer, Scimemi, EPJ C73 (13)

TMD evolution: Fourier transform

$$f_1^a(x, k_\perp; \mu^2) = \frac{1}{2\pi} \int d^2 b_T e^{-i b_T \cdot k_\perp} \widetilde{f}_1^a(x, b_T; \mu^2)$$

$$\widetilde{f}_1^a(x, b_T; \mu^2) = \sum_i \left(\tilde{C}_{a/i} \otimes f_1^i\right)(x, b_*; \mu_b) e^{\tilde{S}(b_*;\mu_b,\mu)} e^{g_K(b_T) \ln \frac{\mu}{\mu_0}} \hat{f}_{\mathrm{NP}}^a(x, b_T)$$

Rogers, Aybat, PRD 83 (11)
Collins, "Foundations of Perturbative QCD" (11)

possible schemes, e.g.,
Collins, Soper, Sterman, NPB250 (85)
Laenen, Sterman, Vogelsang, PRL 84 (00)
Echevarria, Idilbi, Schaefer, Scimemi, EPJ C73 (13)

TMD evolution: Fourier transform

$$f_1^a(x,k_\perp;\mu^2) = \frac{1}{2\pi}\int d^2b_T e^{-ib_T\cdot k_\perp}\widetilde{f}_1^a(x,b_T;\mu^2)$$

$$\widetilde{f}_1^a(x,b_T;\mu^2) = \sum_i \big(\tilde{C}_{a/i}\otimes f_1^i\big)(x,b_*;\mu_b)\, e^{\tilde{S}(b_*;\mu_b,\mu)}\, e^{g_K(b_T)\ln\frac{\mu}{\mu_0}}\, \hat{f}^a_{\mathrm{NP}}(x,b_T)$$

collinear PDF

pQCD

nonperturbative part of evolution

nonperturbative part of TMD

Rogers, Aybat, PRD 83 (11)
Collins, "Foundations of Perturbative QCD" (11)

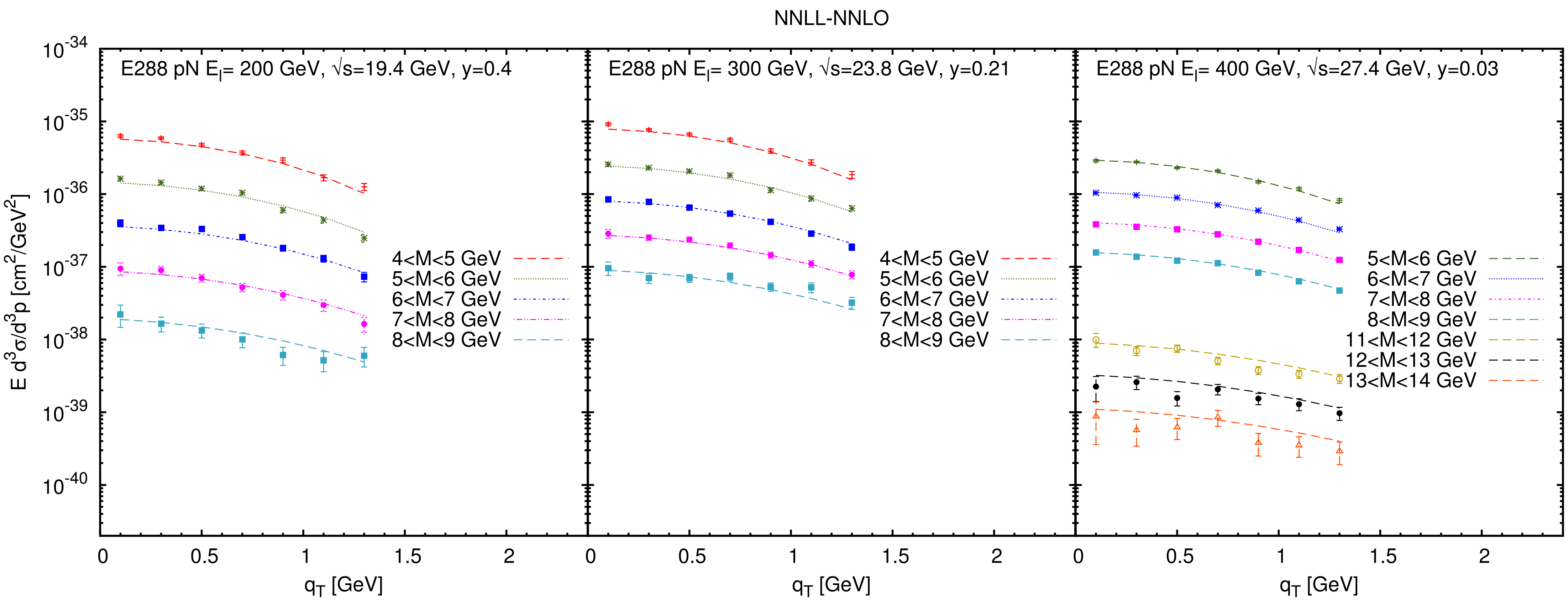
possible schemes, e.g.,
Collins, Soper, Sterman, NPB250 (85)
Laenen, Sterman, Vogelsang, PRL 84 (00)
Echevarria, Idilbi, Schaefer, Scimemi, EPJ C73 (13)

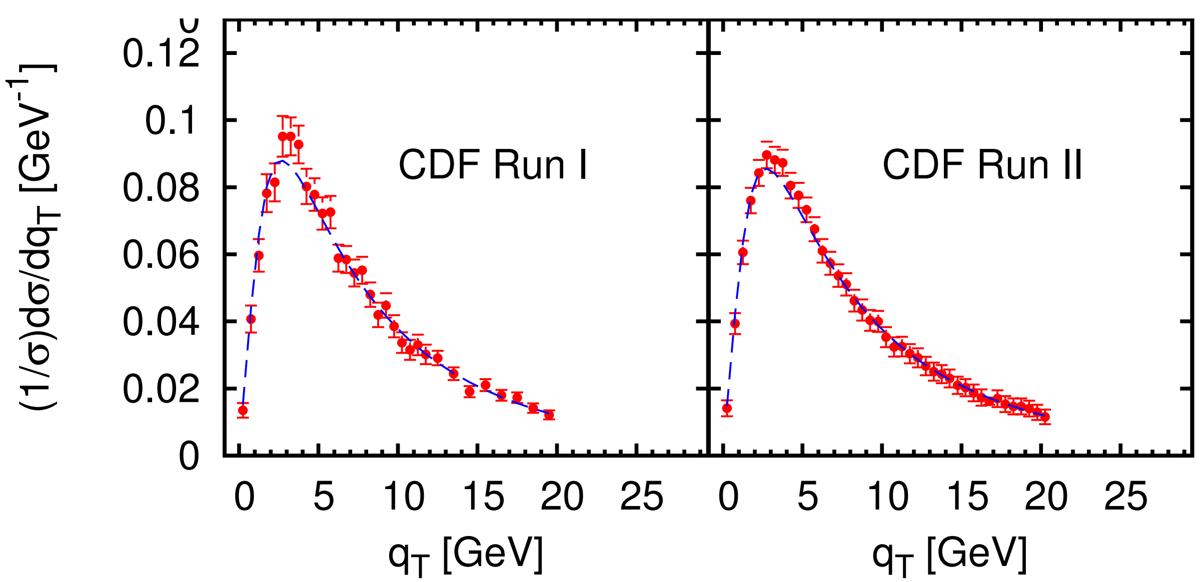
Presently *or soon* available fits

	Framework	HERMES	COMPASS	DY	Z production	N of points
KN 2006 hep-ph/0506225	NLL	✘	✘	✔	✔	98
Pavia 2013 (+Amsterdam,Bilbao) arXiv:1309.3507	No evo	✔	✘	✘	✘	1538
Torino 2014 (+JLab) arXiv:1312.6261	No evo	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NNLL	✘	✘	✔	✔	223
EIKV 2014 arXiv:1401.5078	NLL	1 (x,Q^2) bin	1 (x,Q^2) bin	✔	✔	500 (?)
Pavia 2016	NLL	✔	✔	✔	✔	8156

DEMS 2014

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



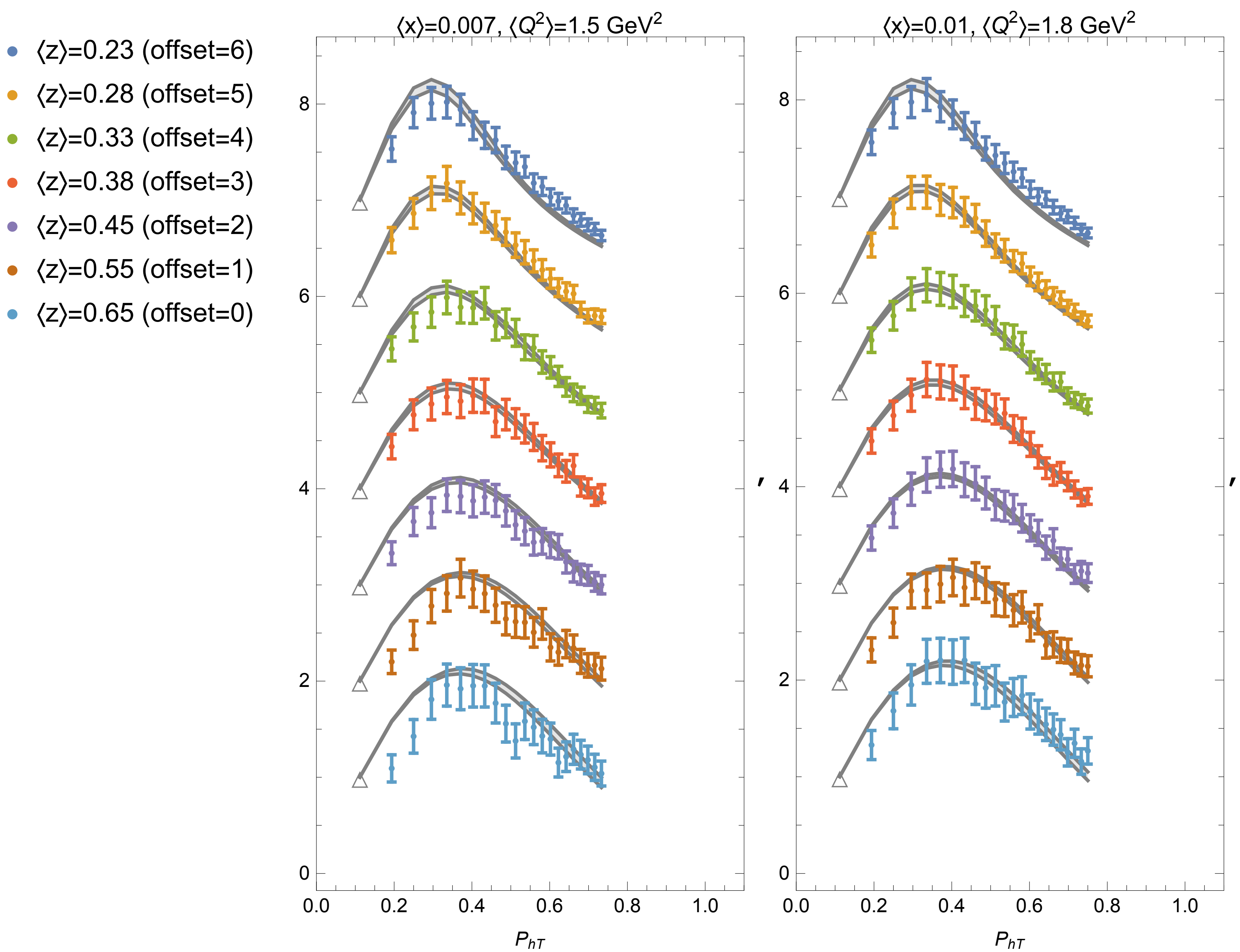


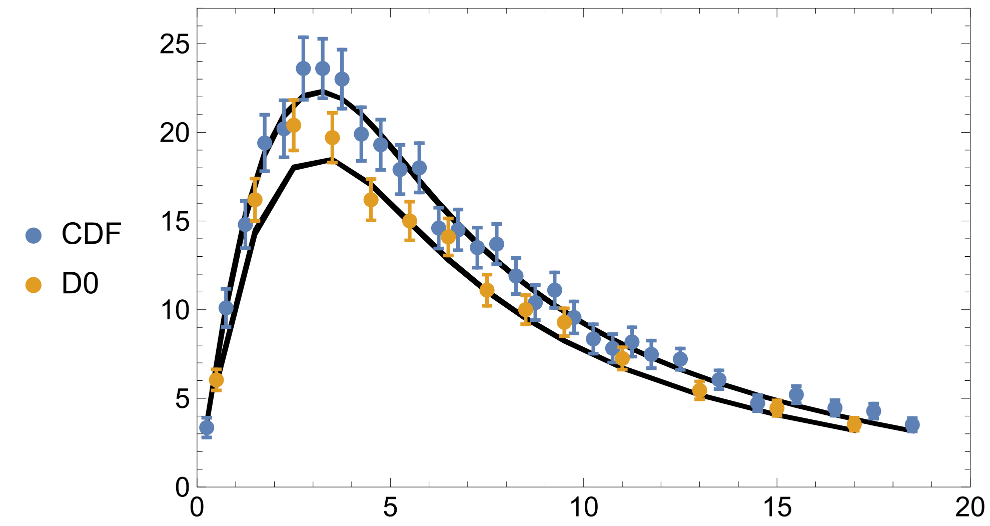
NNLL

$\chi^2/dof = 1.10$

see talk by U. D'Alesio

Glimpses of Pavia's results



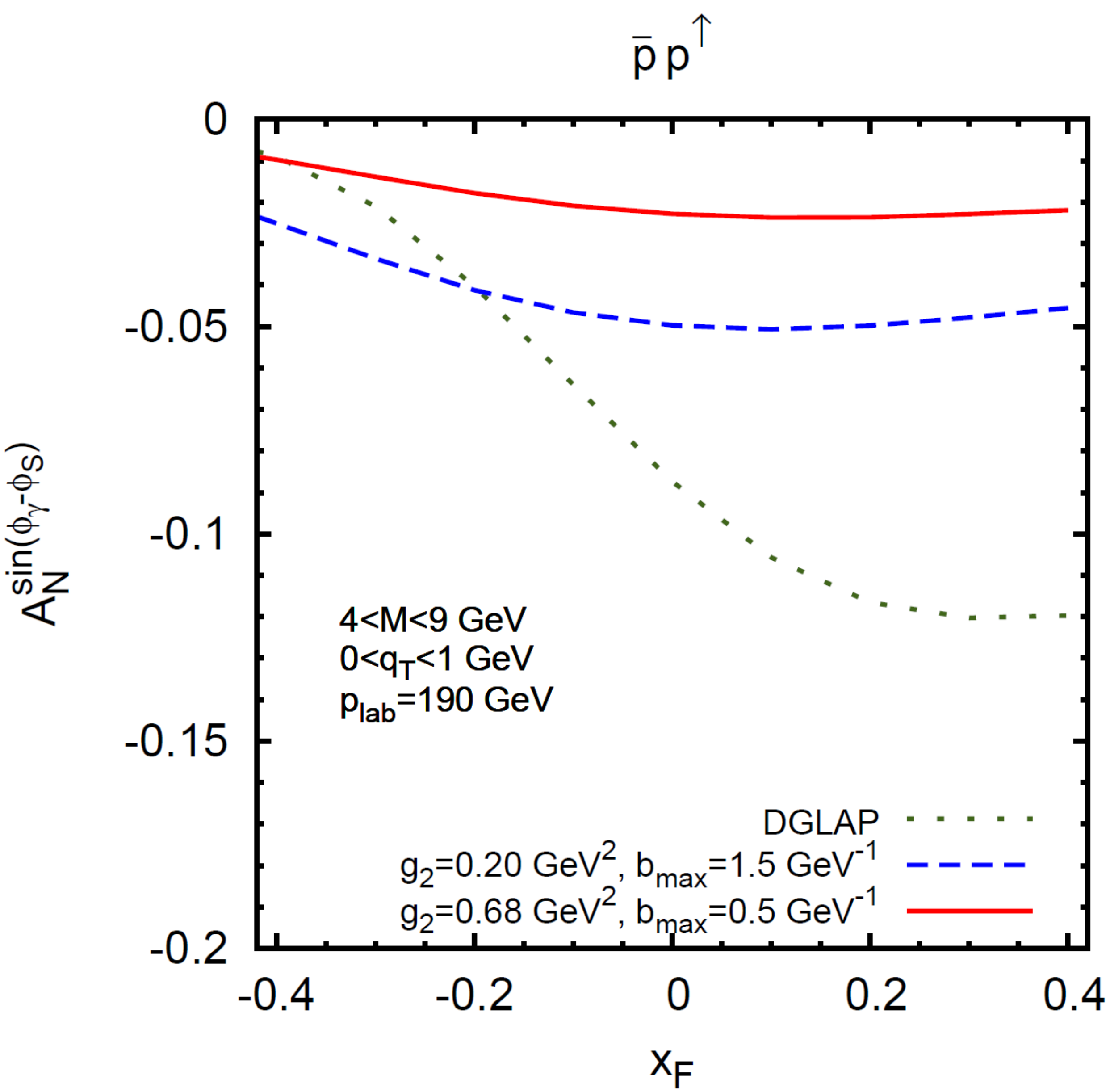


This is the first fit putting together data from SIDIS to Z production

$\chi^2/\text{dof} = 1.55 \pm 0.05$

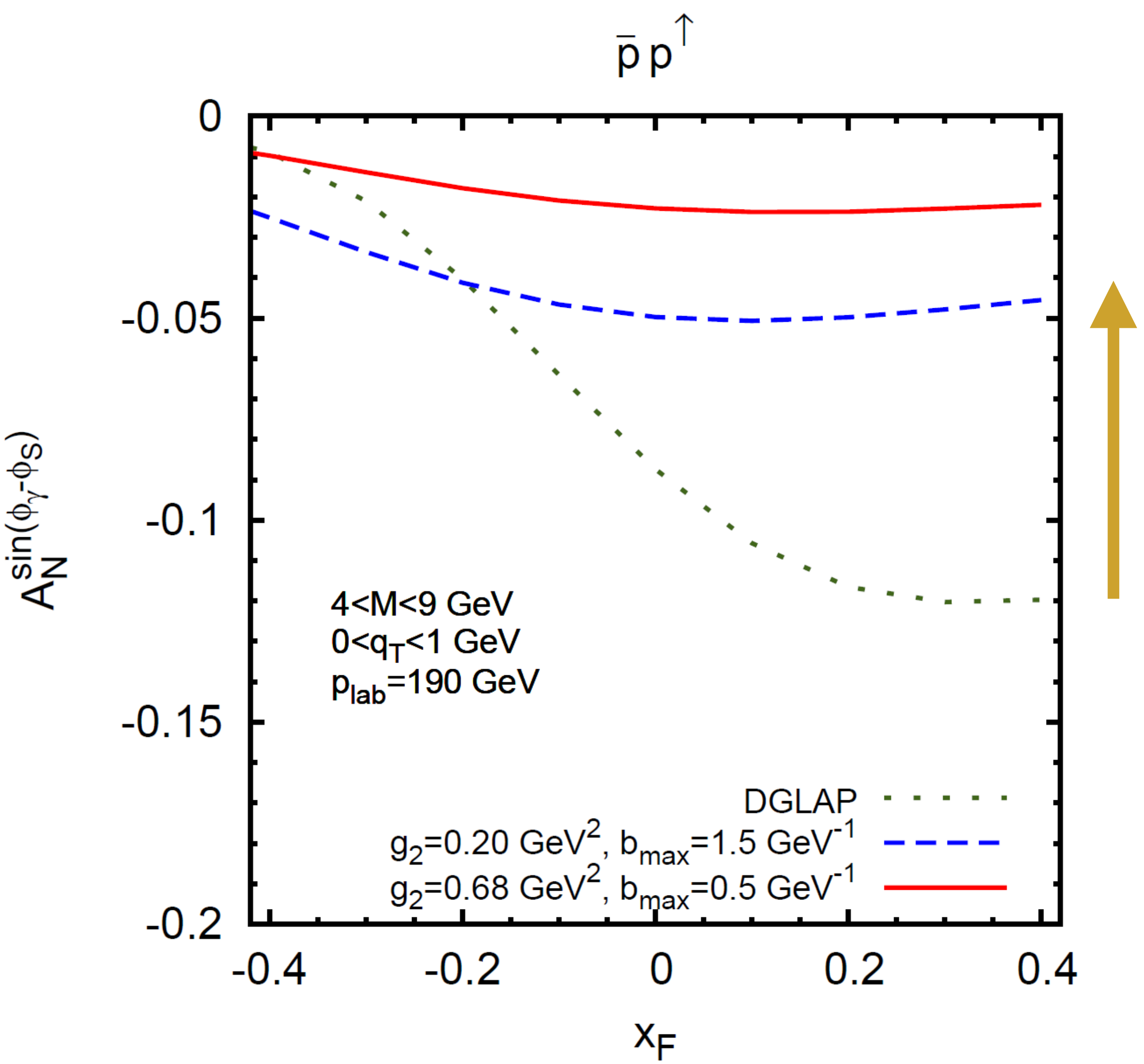
Bacchetta, Delcarro, Pisano, Radici, Signori, in preparation

Evolution and Sivers sign change



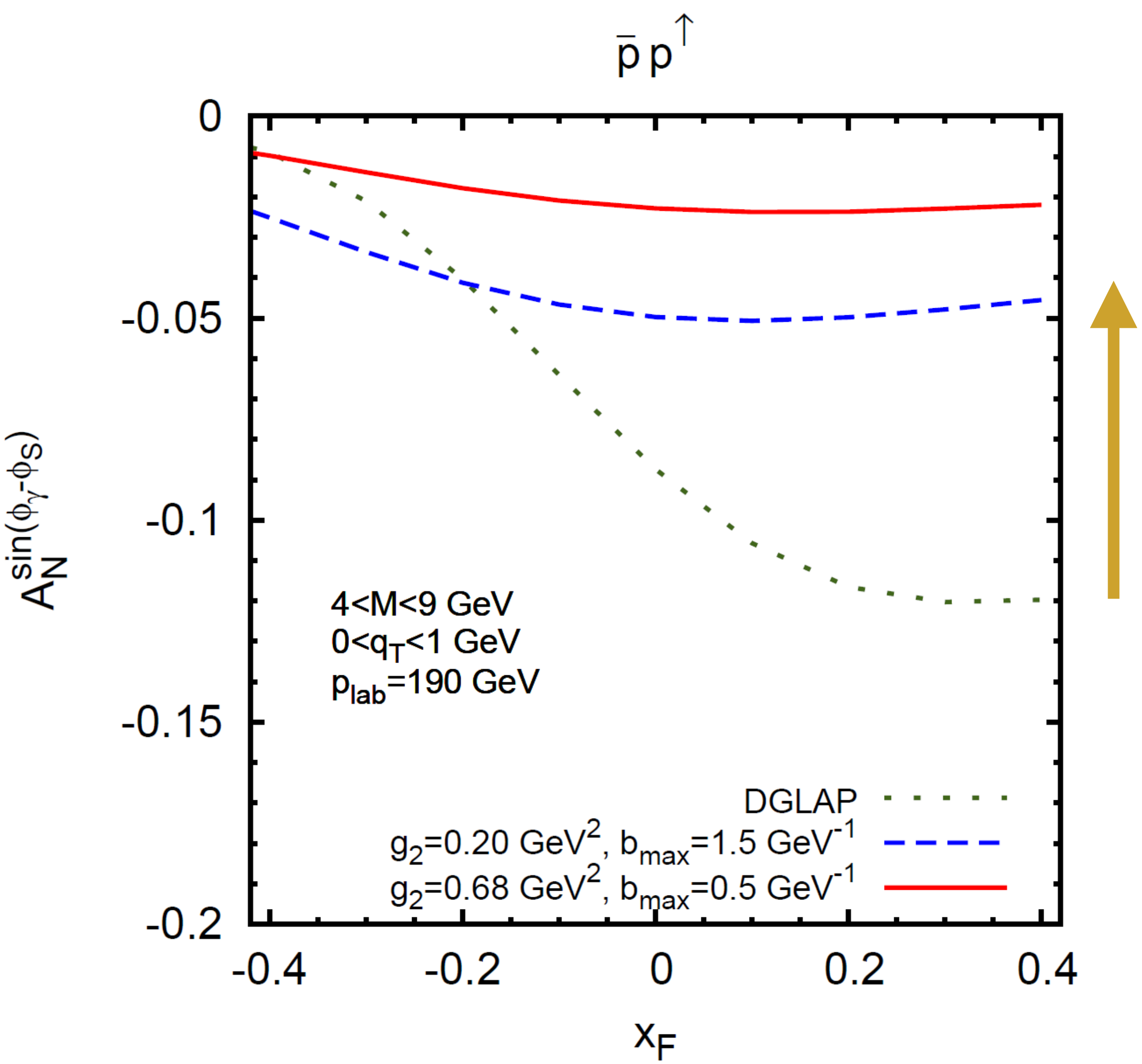
S. Melis, Nuovo Cim. C036 (13)

Evolution and Sivers sign change



S. Melis, Nuovo Cim. C036 (13)

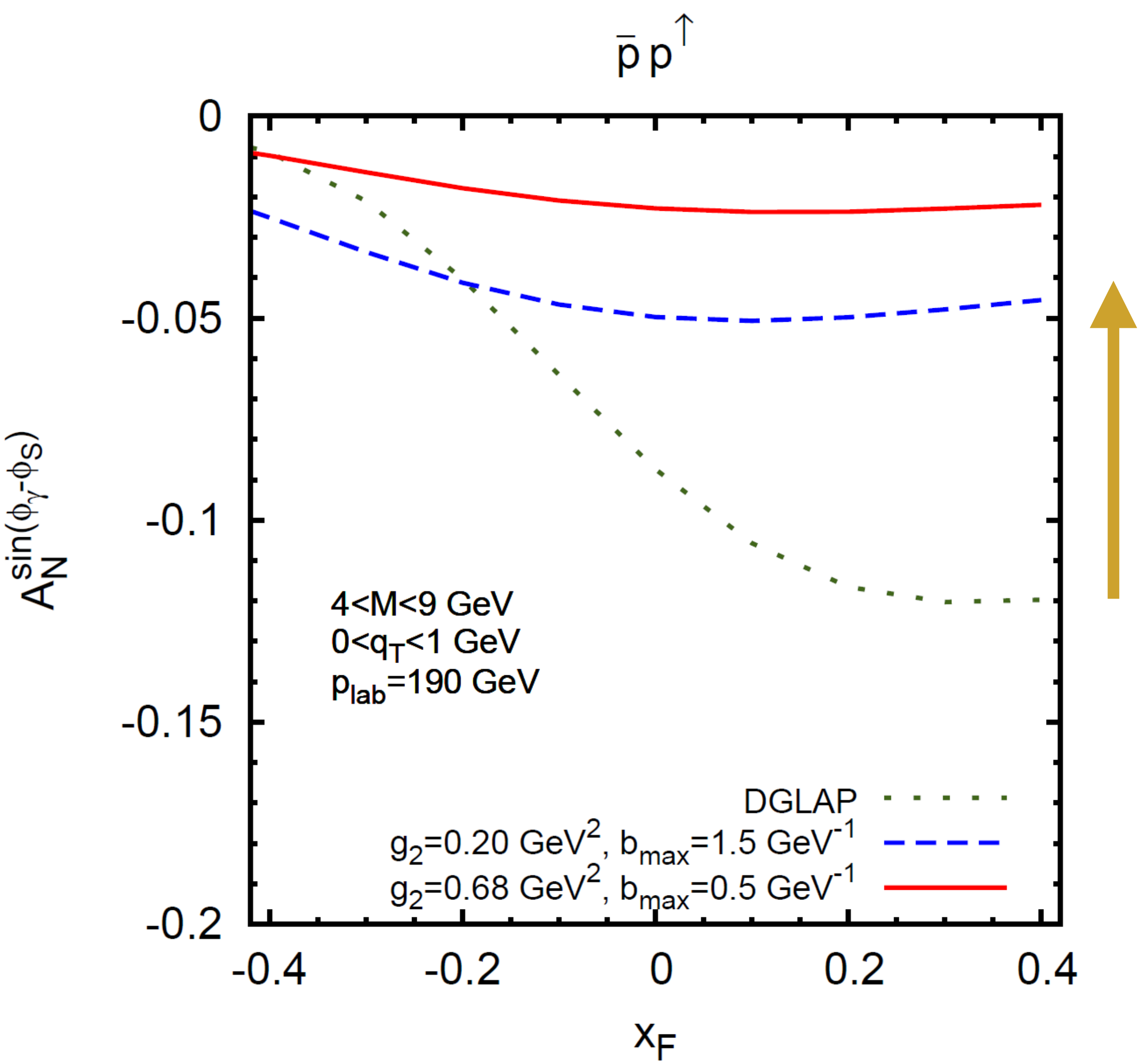
Evolution and Sivers sign change



S. Melis, Nuovo Cim. C036 (13)

Different implementations of TMD evolution affect the asymmetry in a different way (Pavia 2016: g_2 = 0.12)

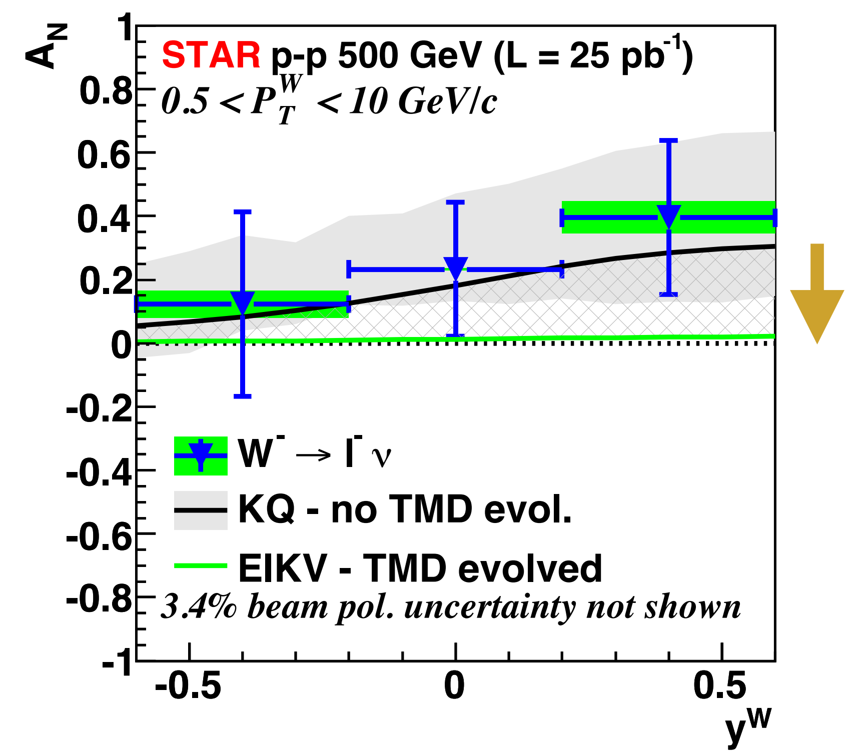
Evolution and Sivers sign change



S. Melis, Nuovo Cim. C036 (13)

Different implementations of TMD evolution affect the asymmetry in a different way (Pavia 2016: g_2 = 0.12)

STAR Collab. arXiv:1511.06003
EIKV, arXiv:1401.5078



The Y term

Collins et al., arXiv: 1605.00671
and T. Rogers's talk at Trento 2016

The Y term

Collins et al., arXiv: 1605.00671
and T. Rogers's talk at Trento 2016

$$F_{UU,T}(x,z,\boldsymbol{P}_{hT}^2,Q^2) = x\sum_a \mathcal{H}^a_{UU,T}(Q^2;\mu^2)\int \frac{d\boldsymbol{b}_\perp^2}{4\pi} J_0(|\boldsymbol{b}_T||\boldsymbol{P}_{h\perp}|)\tilde{f}_1^a\big(x,z^2\boldsymbol{b}_\perp^2;\mu^2\big)\,\tilde{D}_1^{a\to h}\big(z,\boldsymbol{b}_\perp^2;\mu^2\big)$$
$$+\, Y_{UU,T}\big(Q^2,\boldsymbol{P}_{hT}^2\big) + \mathcal{O}\big(M^2/Q^2\big)$$

The Y term

Collins et al., arXiv: 1605.00671
and T. Rogers's talk at Trento 2016

The W term

Good approximation

If

$q_{\mathrm{T}} \ll Q$

$$F_{UU,T}(x,z,\boldsymbol{P}_{hT}^2,Q^2) = x\sum_a \mathcal{H}^a_{UU,T}(Q^2;\mu^2)\int \frac{d\boldsymbol{b}_\perp^2}{4\pi} J_0(|\boldsymbol{b}_T||\boldsymbol{P}_{h\perp}|)\tilde{f}_1^a\big(x,z^2\boldsymbol{b}_\perp^2;\mu^2\big)\,\tilde{D}_1^{a\to h}\big(z,\boldsymbol{b}_\perp^2;\mu^2\big)$$
$$+\,Y_{UU,T}\big(Q^2,\boldsymbol{P}_{hT}^2\big)+\mathcal{O}\big(M^2/Q^2\big)$$

The Y term

Collins et al., arXiv: 1605.00671
and T. Rogers's talk at Trento 2016

<u>The W term</u>

Good approximation

If

$q_{\mathrm{T}} \ll Q$

$$F_{UU,T}(x,z,\boldsymbol{P}_{hT}^2,Q^2) = x\sum_a \mathcal{H}^a_{UU,T}(Q^2;\mu^2)\int \frac{d\boldsymbol{b}_\perp^2}{4\pi} J_0(|\boldsymbol{b}_T||\boldsymbol{P}_{h\perp}|)\tilde{f}_1^a\big(x,z^2\boldsymbol{b}_\perp^2;\mu^2\big)\,\tilde{D}_1^{a\to h}\big(z,\boldsymbol{b}_\perp^2;\mu^2\big)$$
$$+ Y_{UU,T}\big(Q^2,\boldsymbol{P}_{hT}^2\big) + \mathcal{O}\big(M^2/Q^2\big)$$

<u>The Y term</u>

Good approximation

If

$q_{\mathrm{T}} \gg m$

The Y term

Collins et al., arXiv: 1605.00671
and T. Rogers's talk at Trento 2016

<u>The W term</u>

Good approximation

If

$q_{\mathrm{T}} \ll Q$

$$F_{UU,T}(x,z,\boldsymbol{P}_{hT}^2,Q^2) = x\sum_a \mathcal{H}_{UU,T}^a(Q^2;\mu^2) \int \frac{d\boldsymbol{b}_\perp^2}{4\pi} J_0(|\boldsymbol{b}_T||\boldsymbol{P}_{h\perp}|)\tilde{f}_1^a\big(x,z^2\boldsymbol{b}_\perp^2;\mu^2\big)\,\tilde{D}_1^{a\to h}\big(z,\boldsymbol{b}_\perp^2;\mu^2\big)$$
$$+\,Y_{UU,T}\big(Q^2,\boldsymbol{P}_{hT}^2\big) + \mathcal{O}\big(M^2/Q^2\big)$$

<u>The Y term</u>

Good approximation

If

$q_{\mathrm{T}} \gg m$

The Y term guarantees that the calculation at high P_{hT} agrees with perturbative calculation done with collinear factorization

The Y term

Collins et al., arXiv: 1605.00671
and T. Rogers's talk at Trento 2016

<u>The W term</u>

Good approximation

If

$q_{\mathrm{T}} \ll Q$

$$F_{UU,T}(x,z,\boldsymbol{P}_{hT}^2,Q^2) = x\sum_a \mathcal{H}^a_{UU,T}(Q^2;\mu^2)\int \frac{d\boldsymbol{b}_\perp^2}{4\pi} J_0(|\boldsymbol{b}_T||\boldsymbol{P}_{h\perp}|)\tilde{f}_1^a\big(x,z^2\boldsymbol{b}_\perp^2;\mu^2\big)\,\tilde{D}_1^{a\to h}\big(z,\boldsymbol{b}_\perp^2;\mu^2\big)$$
$$+ Y_{UU,T}\big(Q^2,\boldsymbol{P}_{hT}^2\big) + \mathcal{O}\big(M^2/Q^2\big)$$

<u>The Y term</u>

Good approximation

If

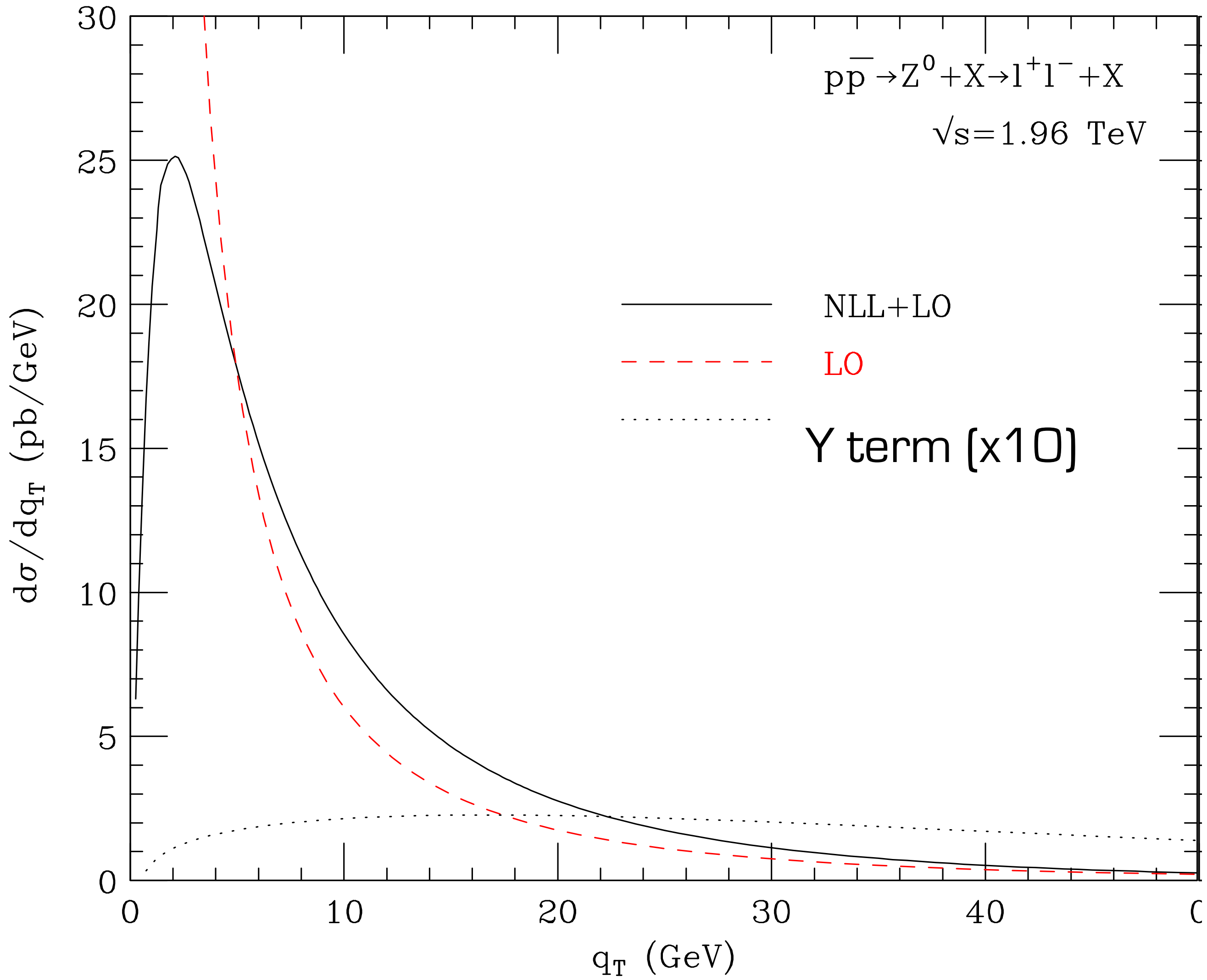
$q_{\mathrm{T}} \gg m$

The Y term guarantees that the calculation at high P_{hT} agrees with perturbative calculation done with collinear factorization

see talk by Gamberg

Y term in Z boson production

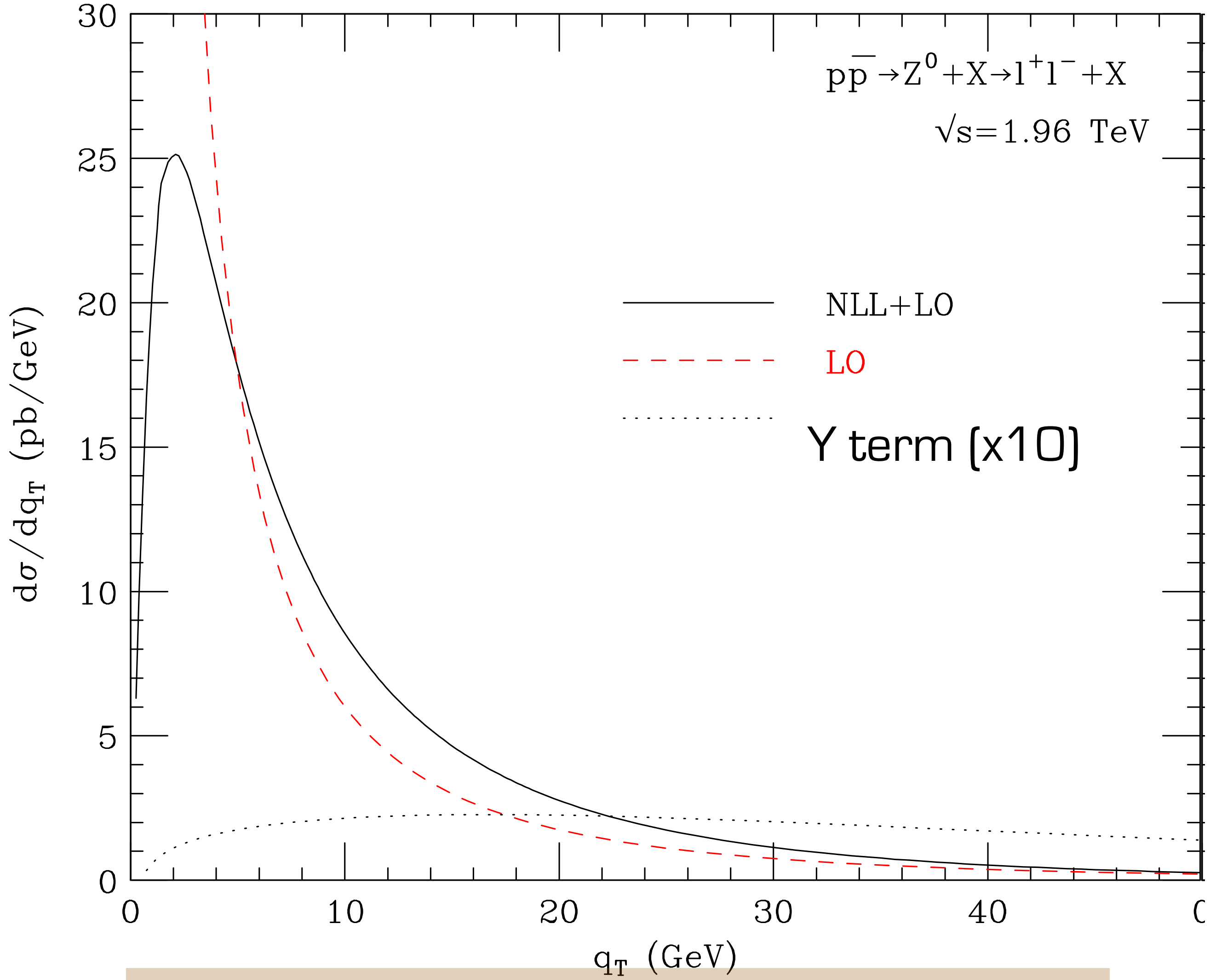
Bozzi et al. [*arXiv:0812.2862*]



In these conditions, the matching works.
Almost the full range is dominated by resummation

Y term in Z boson production

Bozzi et al. arXiv:0812.2862



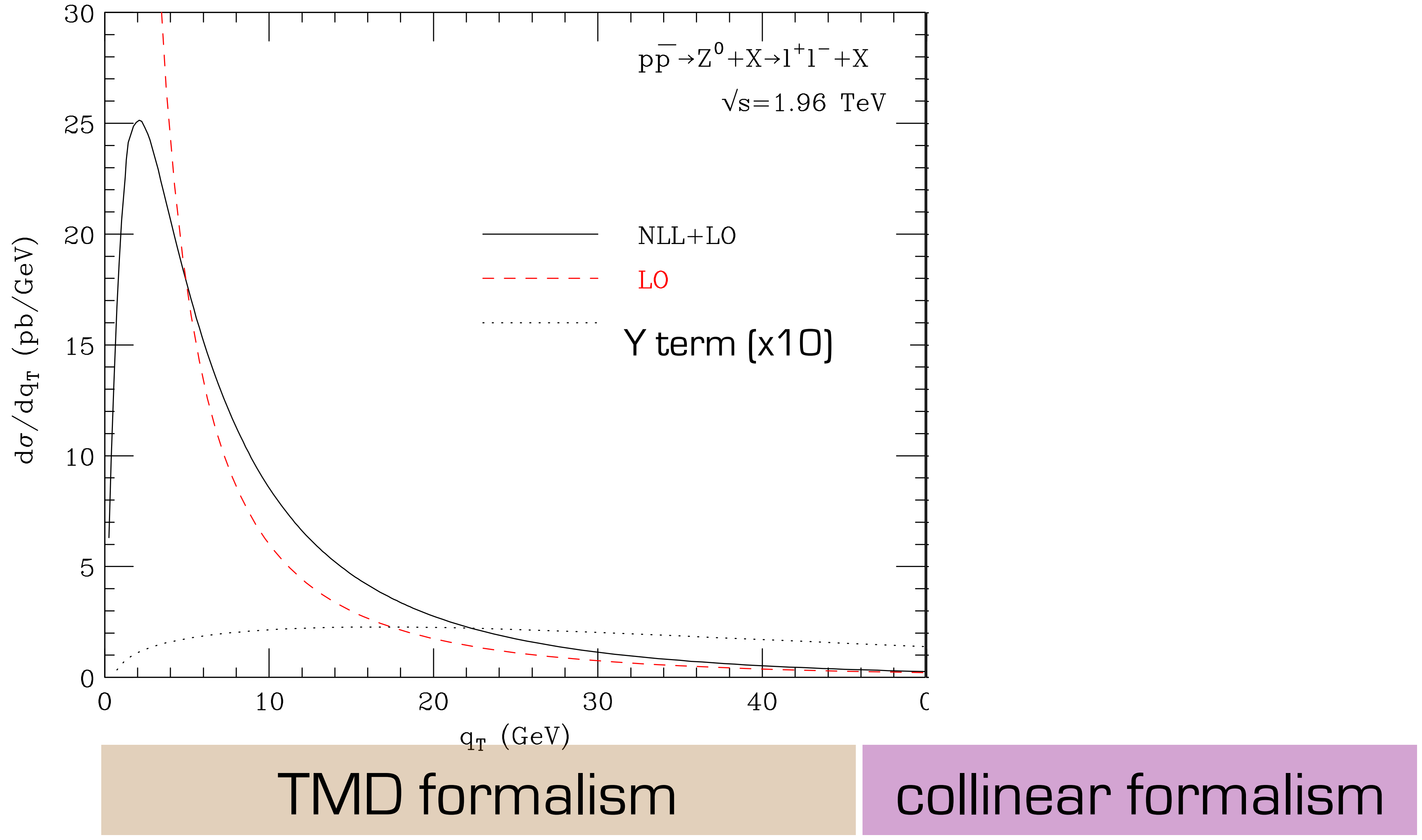
TMD formalism

In these conditions, the matching works.

Almost the full range is dominated by resummation

Y term in Z boson production

Bozzi et al. arXiv:0812.2862

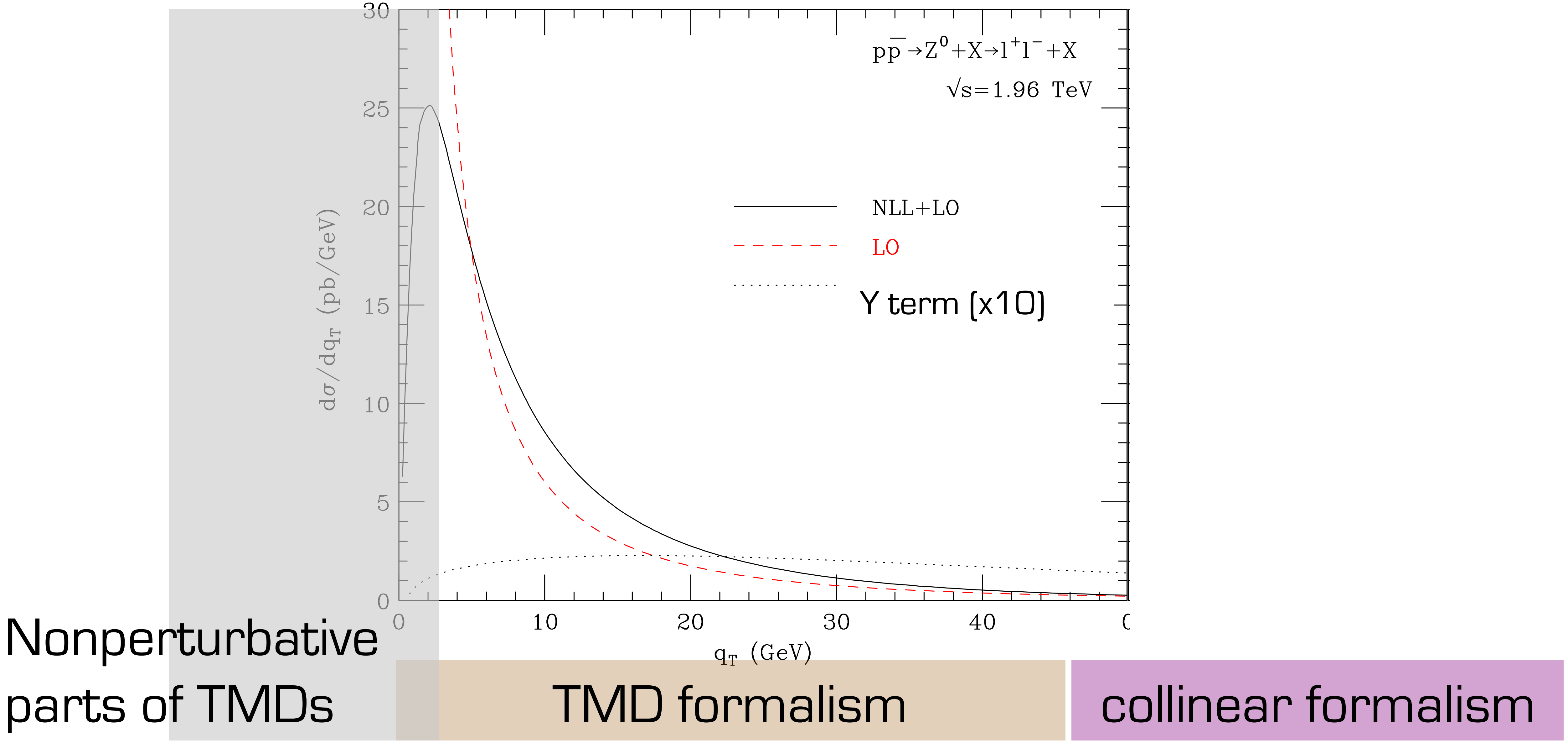


In these conditions, the matching works.

Almost the full range is dominated by resummation

Y term in Z boson production

Bozzi et al. arXiv:0812.2862

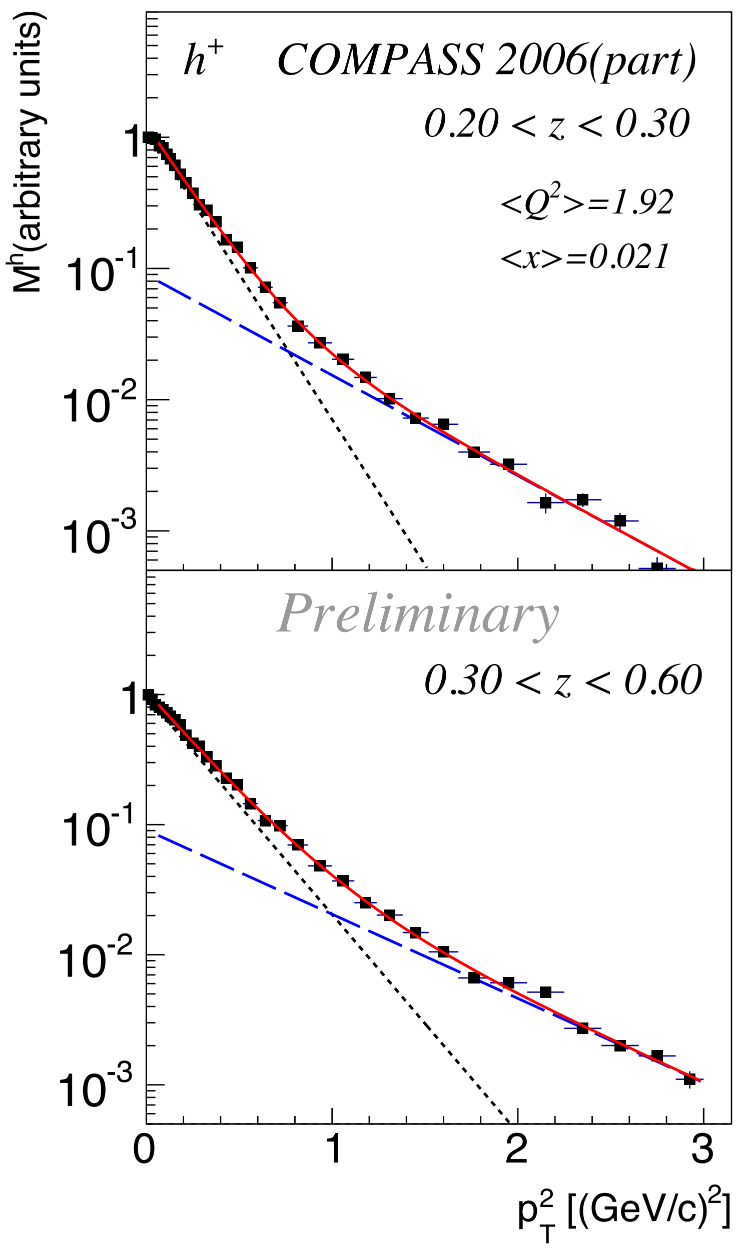


In these conditions, the matching works.

Almost the full range is dominated by resummation

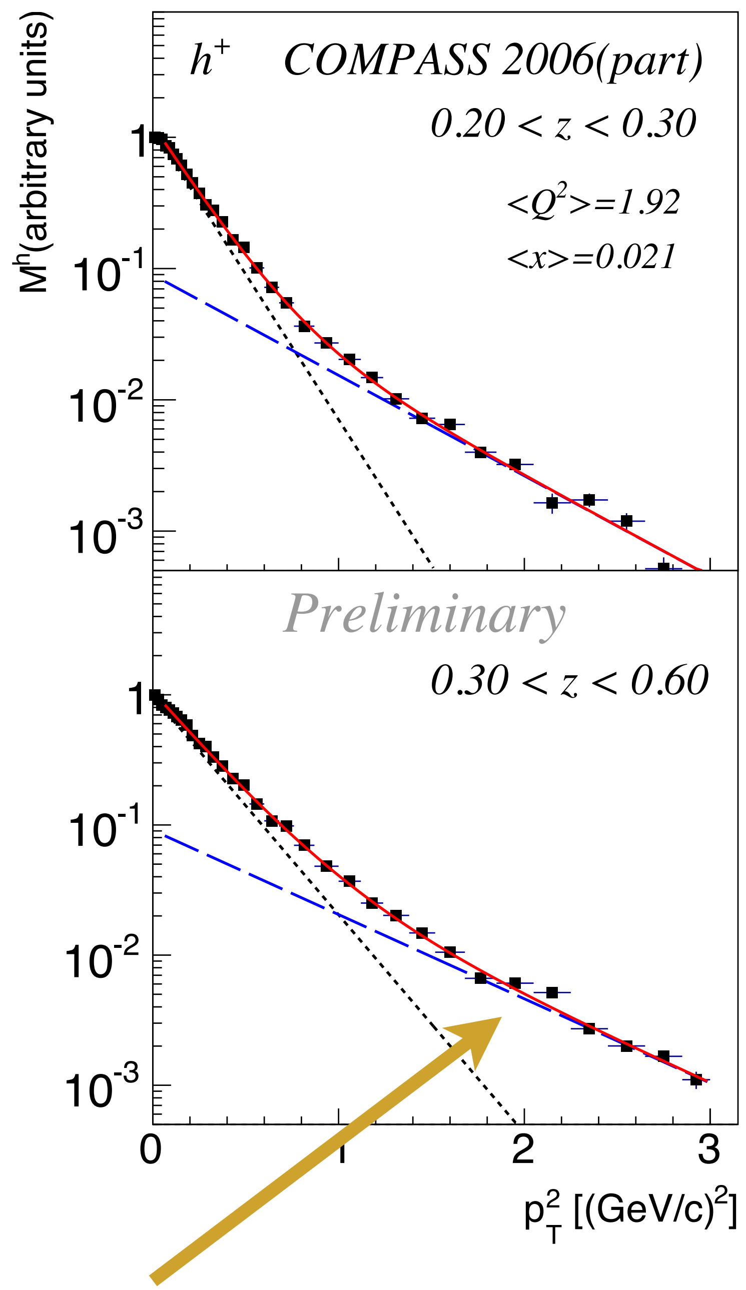
New COMPASS data and Y term

M. Stolarsky, SPIN 2014



New COMPASS data and Y term

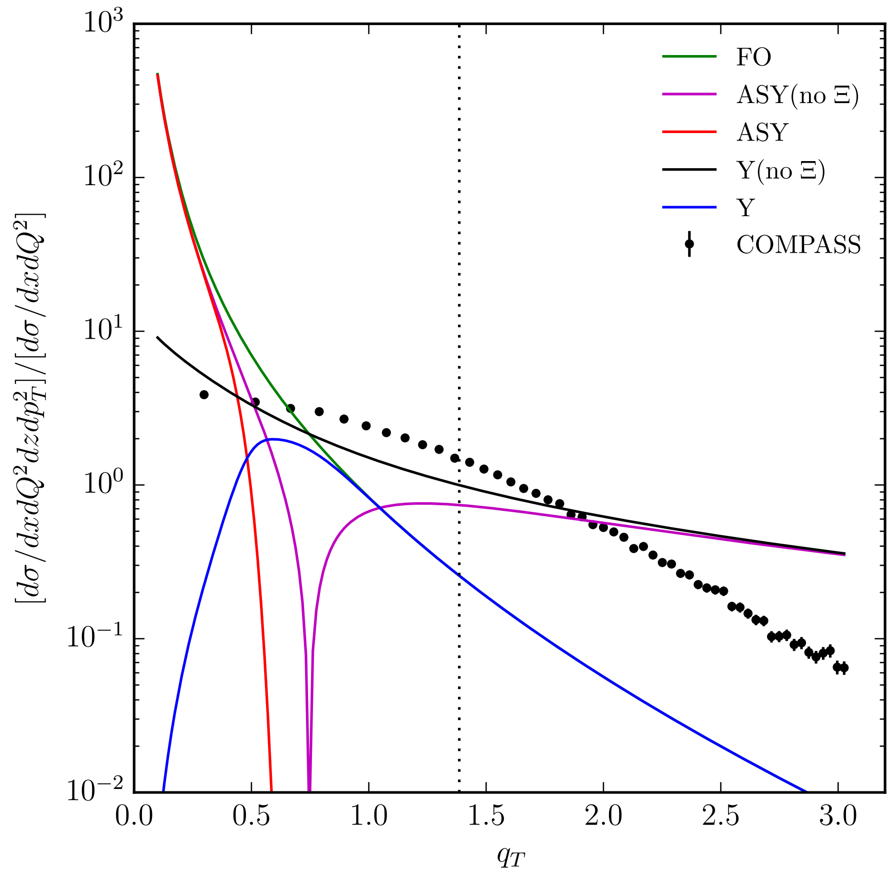
M. Stolarsky, SPIN 2014



Is this the onset of high-transverse-momentum perturbative contributions?

Matching with fixed-order calculations

Collins et al., arXiv: 1605.00671

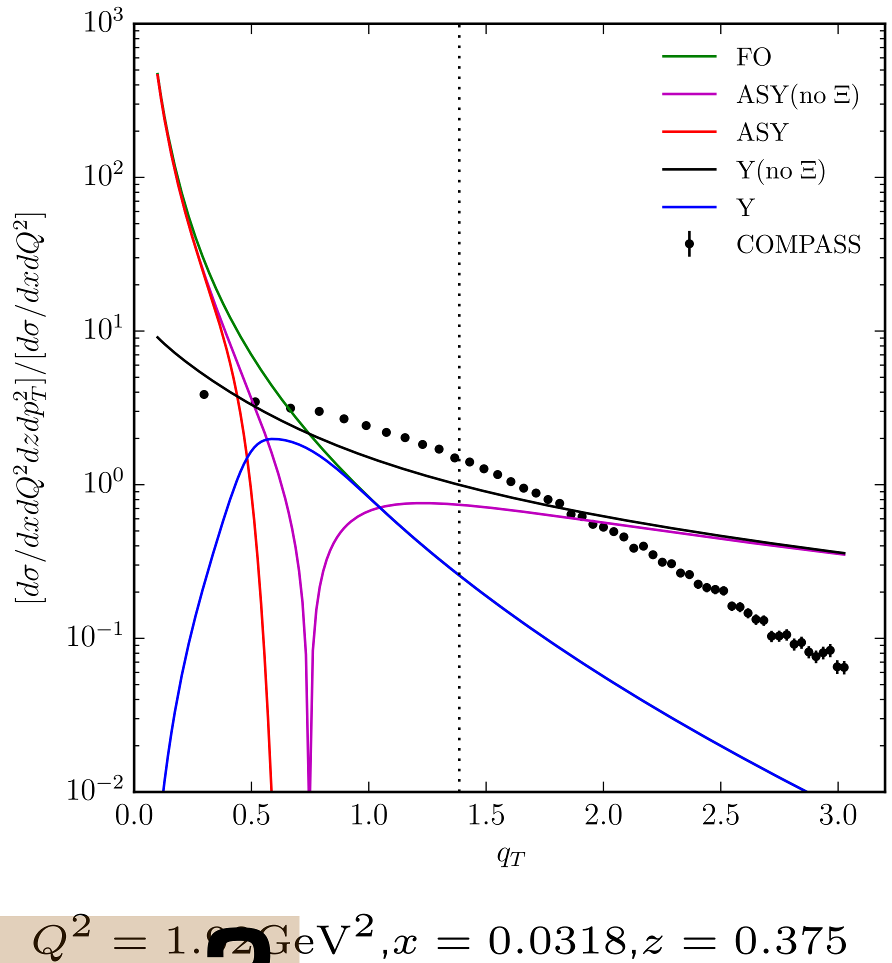


$Q^2 = 1.92\text{GeV}^2, x = 0.0318, z = 0.375$

The collinear calculation (green line) is much smaller than data
Standard Y term is bigger than data (black line) ➞ modifications needed (blue line)

Matching with fixed-order calculations

Collins et al., arXiv: 1605.00671

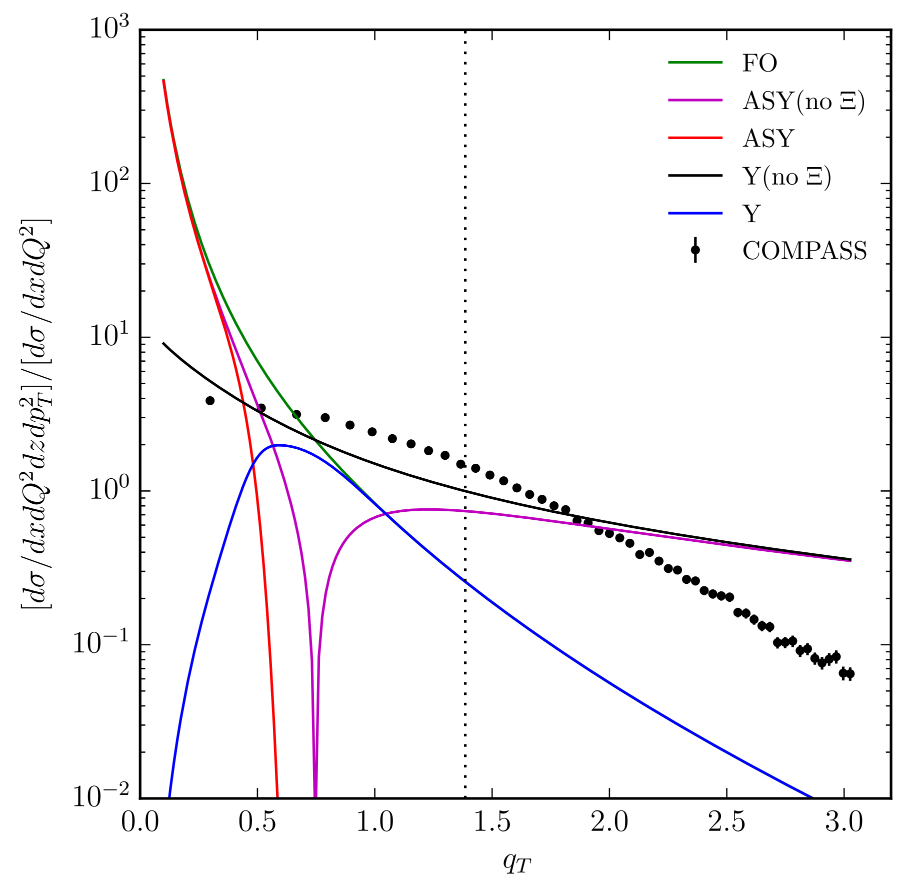


TMD formalism**?**

The collinear calculation (green line) is much smaller than data
Standard Y term is bigger than data (black line) → modifications needed (blue line)

Matching with fixed-order calculations

Collins et al., arXiv: 1605.00671



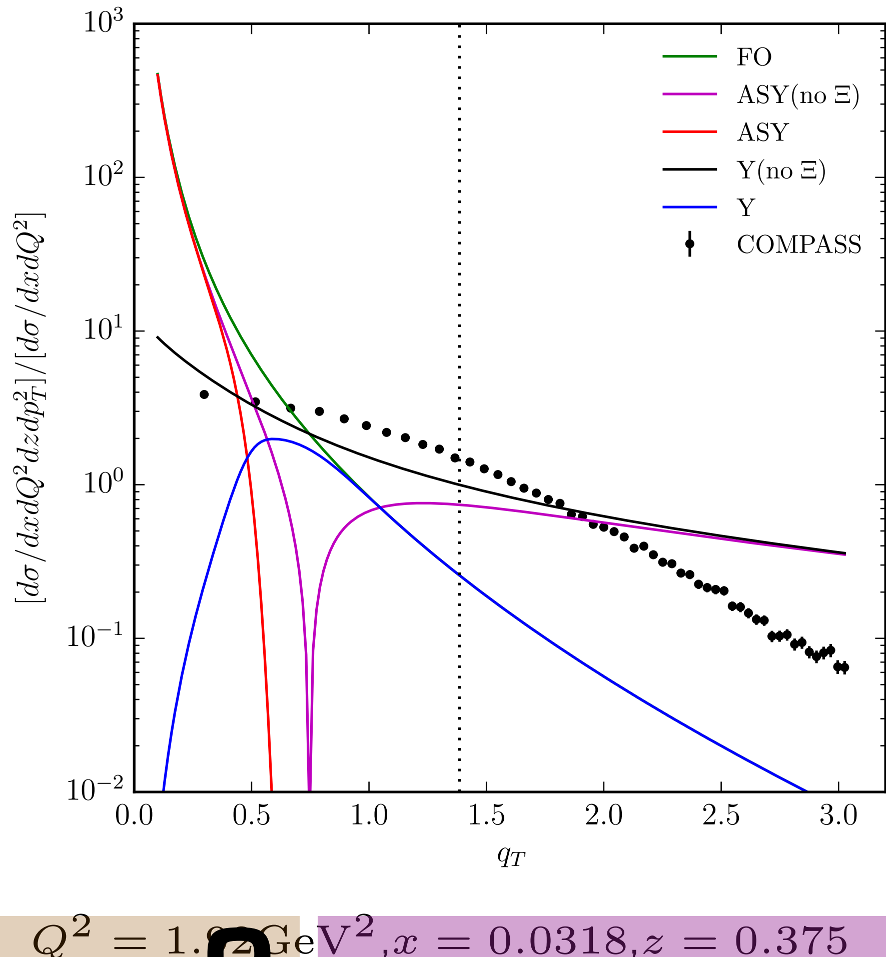
$Q^2 = 1.82\,\mathrm{GeV}^2, x = 0.0318, z = 0.375$

TMD formalism **?** collinear formalism **?**

The collinear calculation (green line) is much smaller than data
Standard Y term is bigger than data (black line) ➞ modifications needed (blue line)

Matching with fixed-order calculations

Collins et al., arXiv: 1605.00671



TMD formalism **?** collinear formalism **?**

The collinear calculation (green line) is much smaller than data
Standard Y term is bigger than data (black line) → modifications needed (blue line)

see talk by Gamberg

TMD present stage

TMD present stage

- Fit start working well with data from very different experiments

TMD present stage

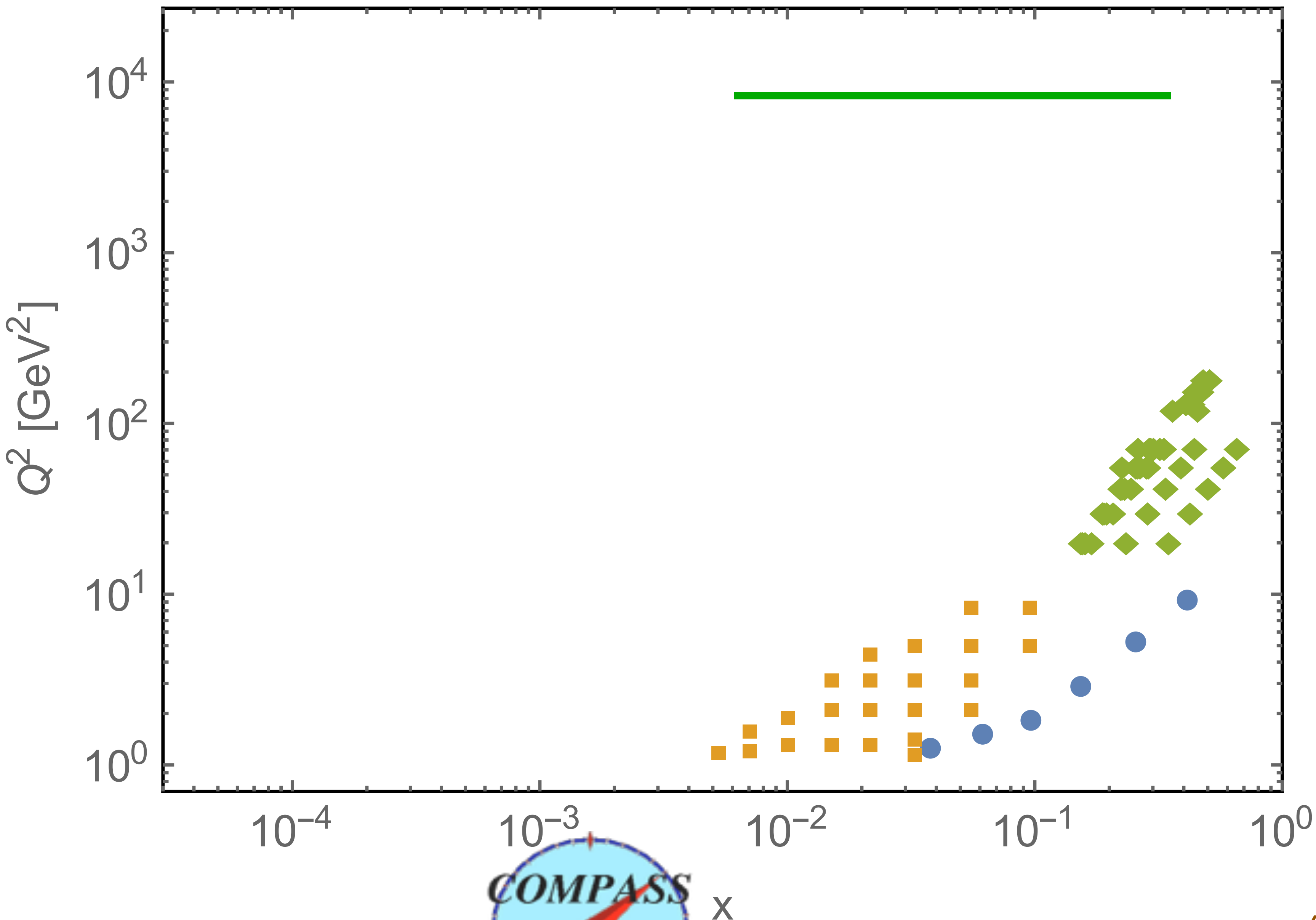
- Fit start working well with data from very different experiments
- There is still strong dependence on the assumptions made in the fits and on the implementation of TMD evolution

TMD present stage

- Fit start working well with data from very different experiments
- There is still strong dependence on the assumptions made in the fits and on the implementation of TMD evolution
- The theory is still not completely under control in the low energy region

Extensions of data sets

Available data

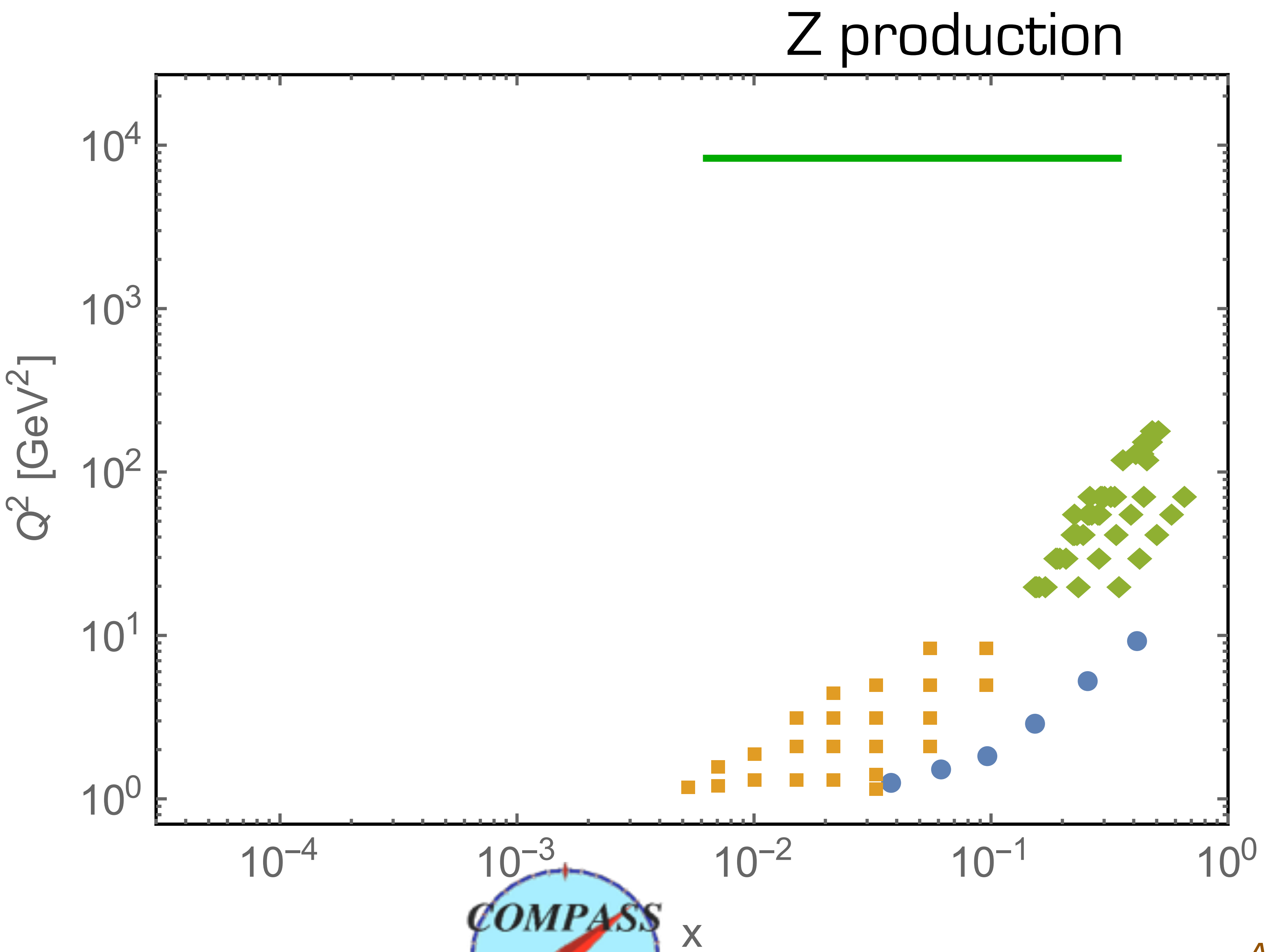


Adolph et al., EPJ C73 (13)

Airapetian et al., PRD87 (2013)

Available data

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



Drell-Yan@
Fermilab

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

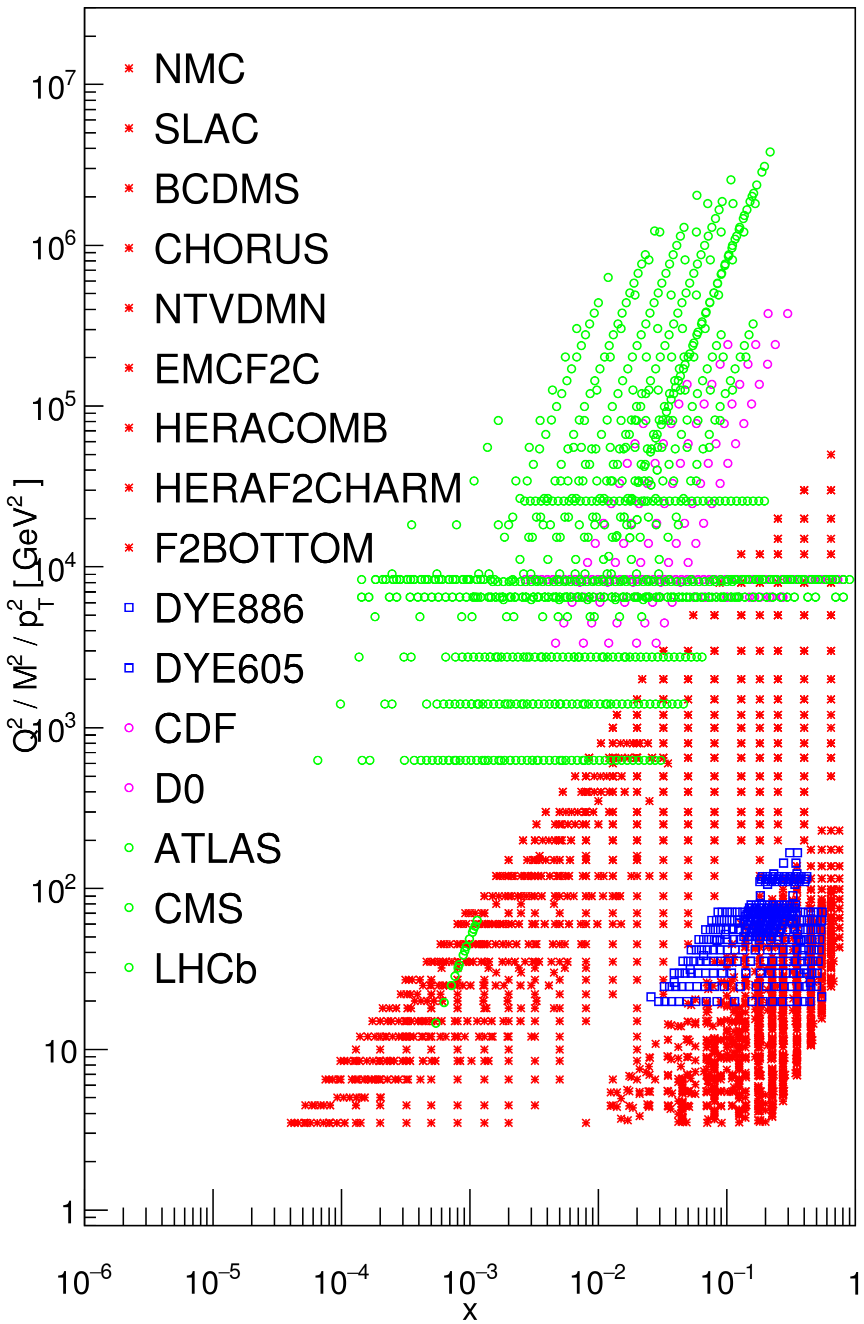
hermes

Airapetian et al., PRD87 (2013)

COMPASS

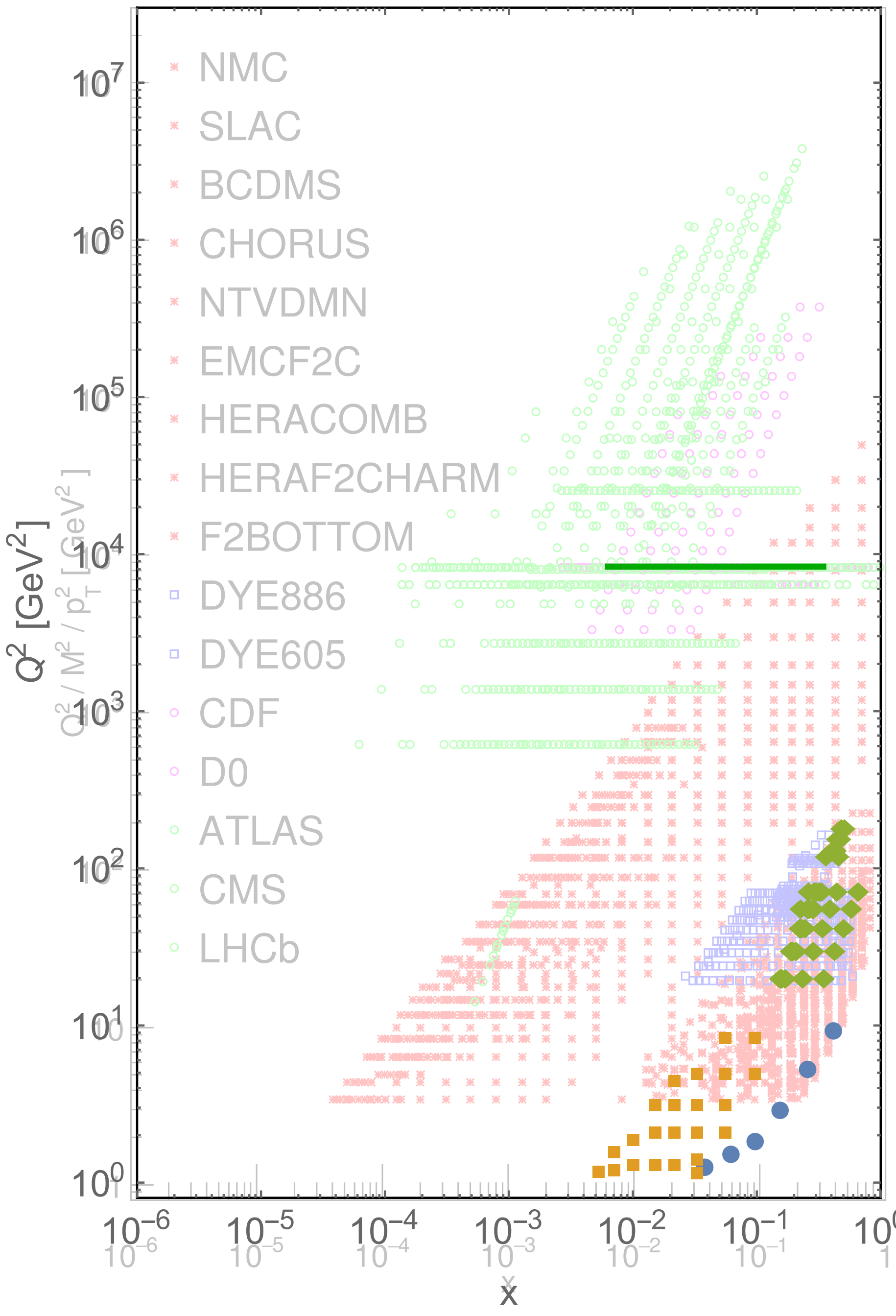
Adolph et al., EPJ C73 (13)

Comparison with collinear PDFs



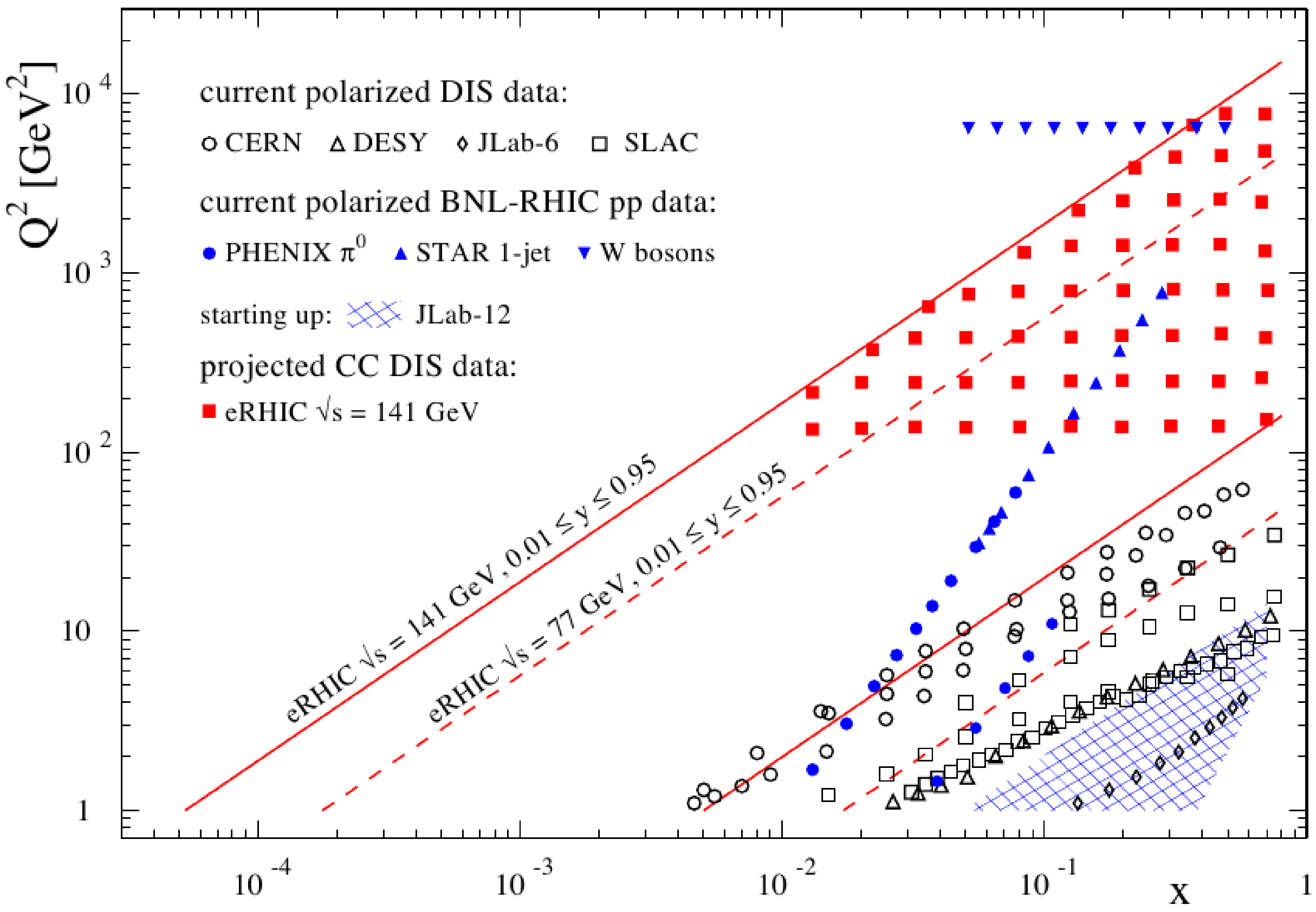
talk by E. Nocera at POETIC2016

Comparison with collinear PDFs



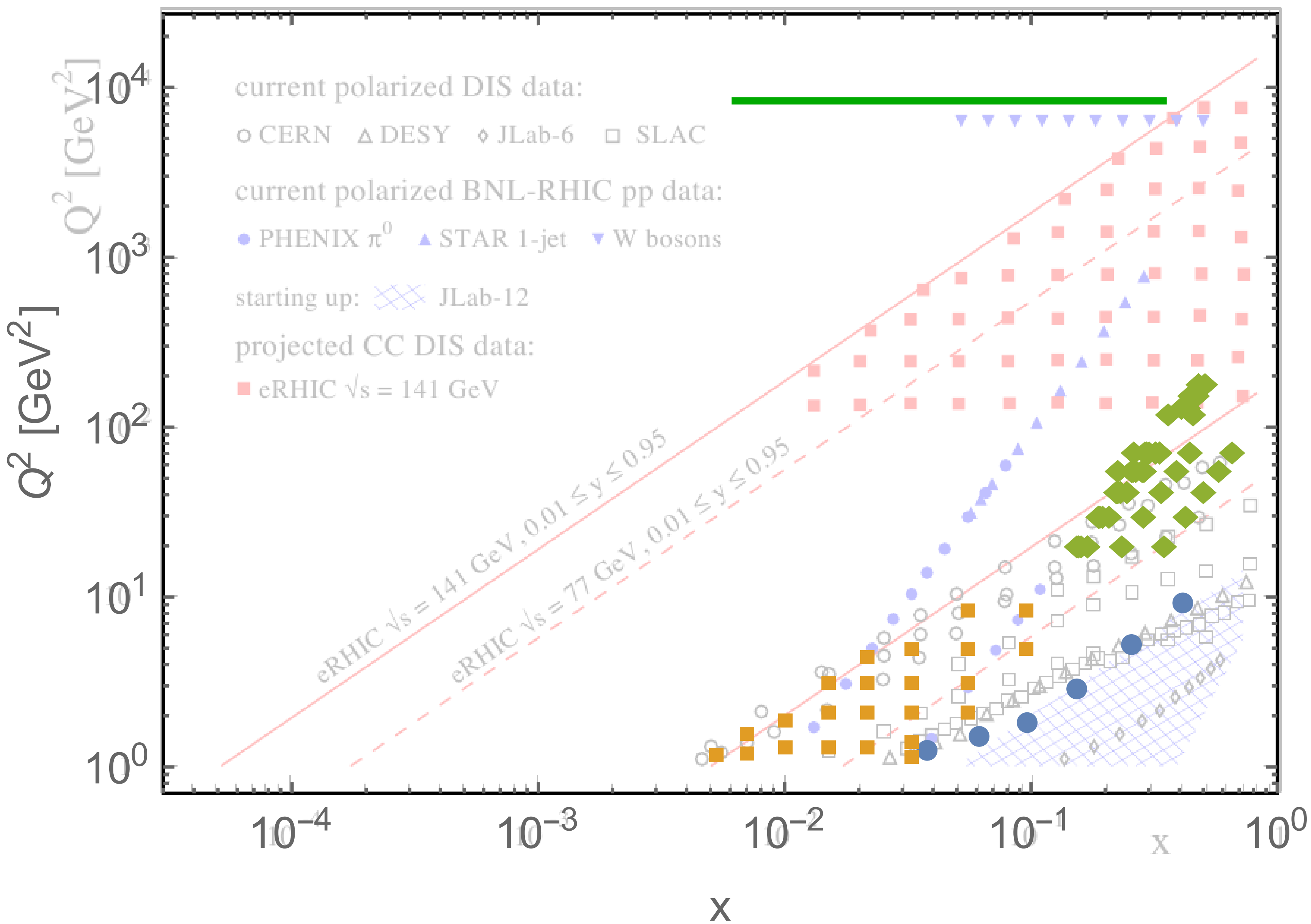
talk by E. Nocera at POETIC2016

Comparison with future perspectives

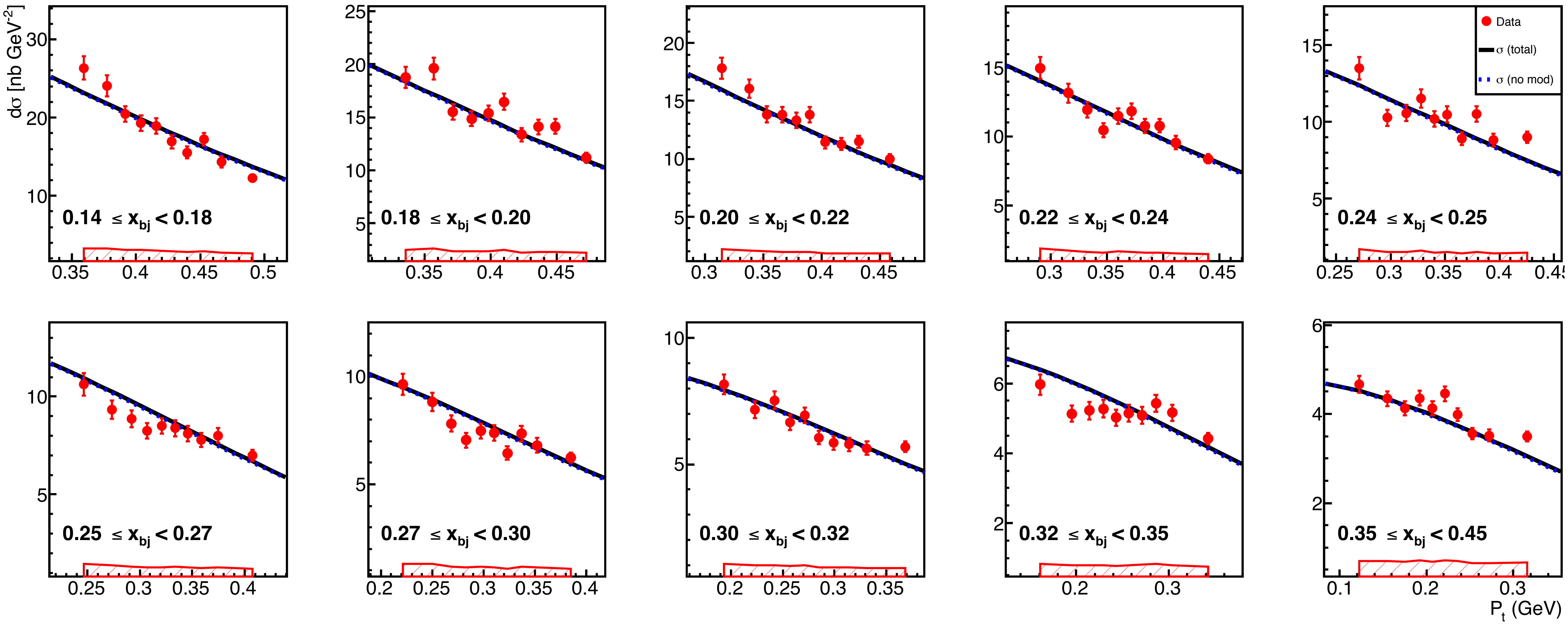


from EIC white paper EPJA 52 (2016), see talks by A. Deshpande, M. Contalbrigo

Comparison with future perspectives



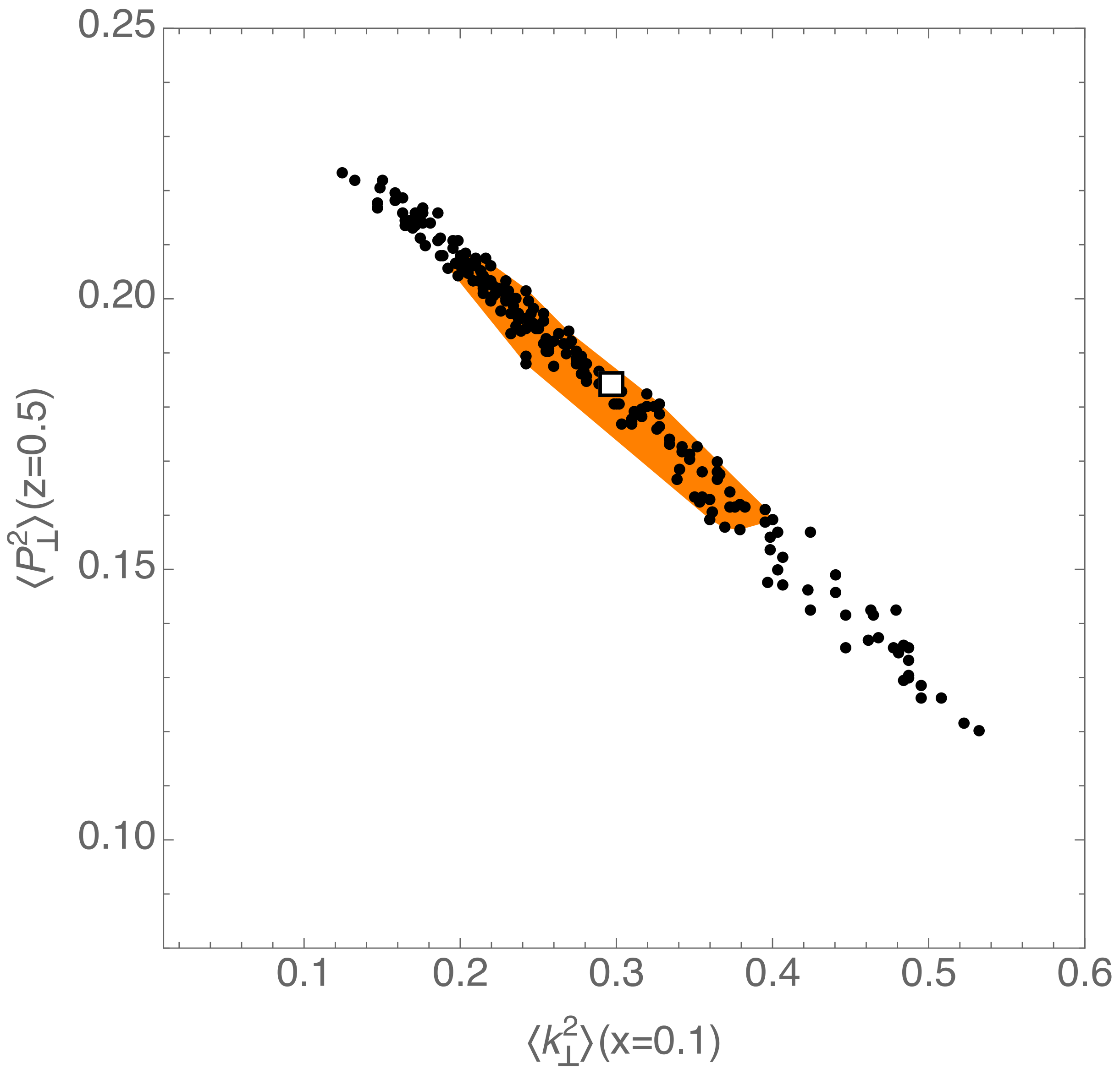
Recent ^{3}He data from JLab Hall A



Jefferson Lab

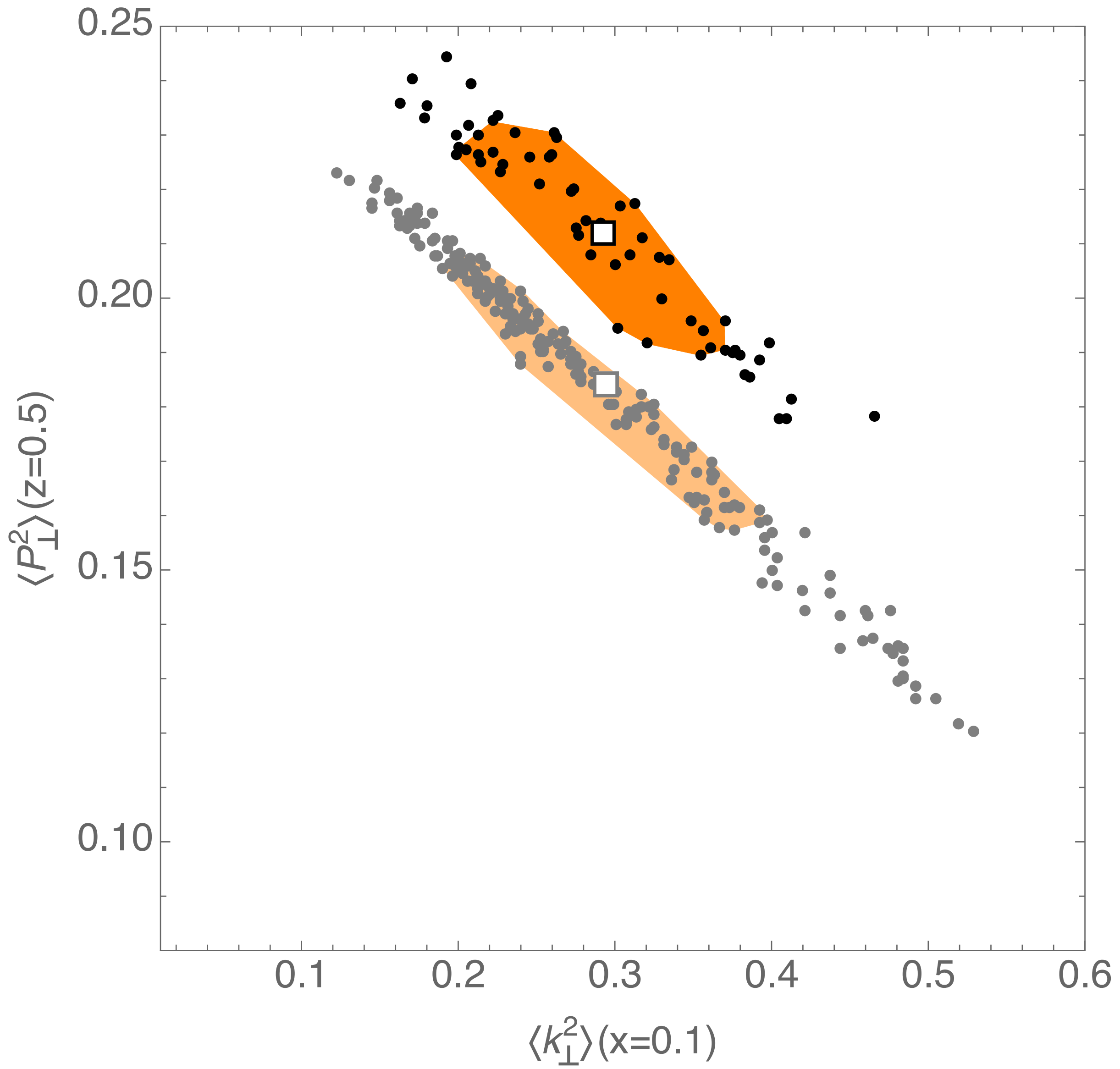
Yan et al., arXiv:1610.02350

Distribution-fragmentation k_T



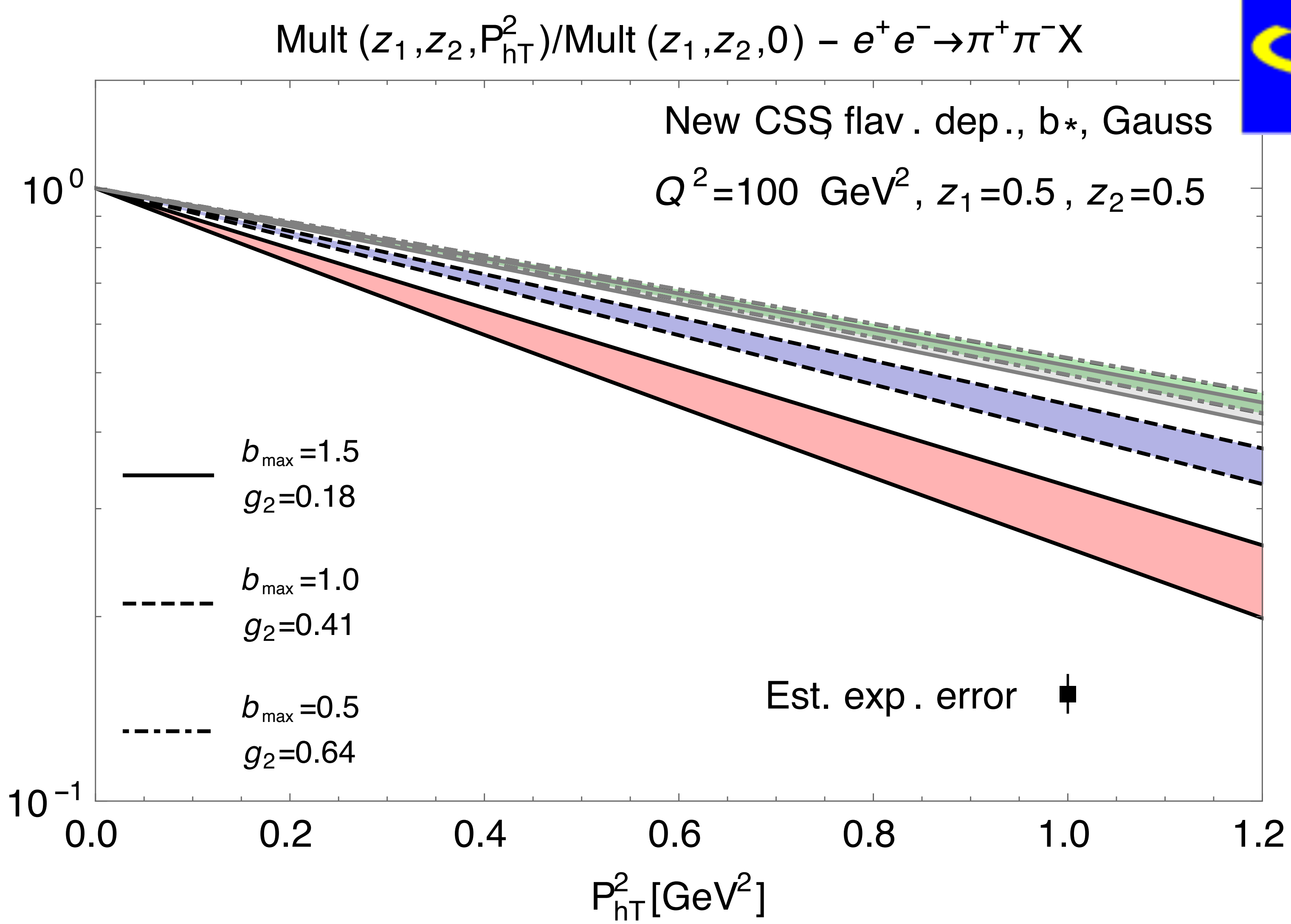
Pavia 2013 fit based only on SIDIS data showed a strong anticorrelation that could not be resolved without further data

Distribution-fragmentation k_T



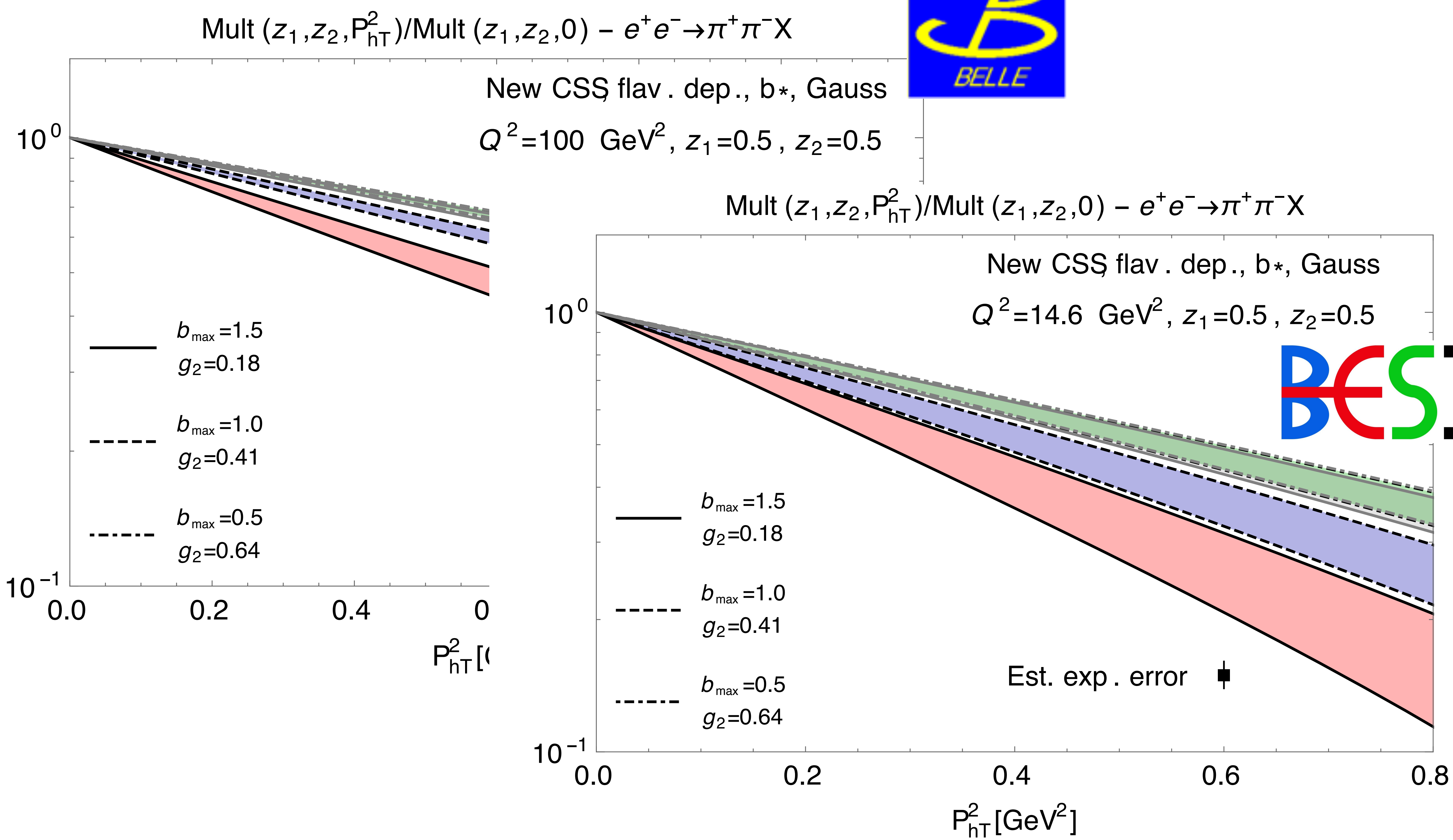
Pavia 2016 fit uses also DY data.
The anticorrelation is weaker than before but still strong.
Independent information about fragmentation kT is necessary.

TMD fragmentation functions



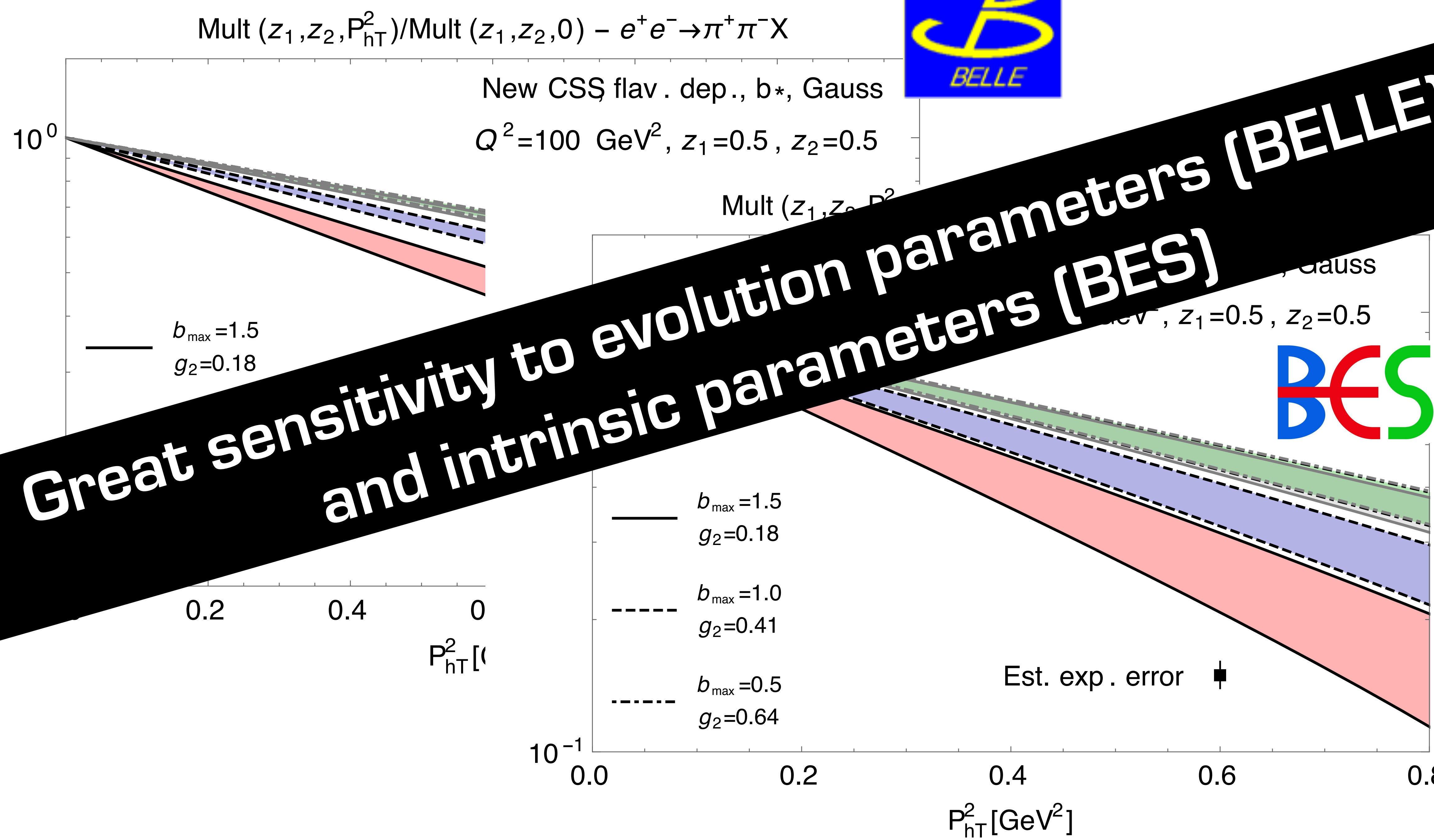
Bacchetta, Echevarria, Mulders, Radici, Signori, arXiv:1508.00402

TMD fragmentation functions



Bacchetta, Echevarria, Mulders, Radici, Signori, arXiv:1508.00402

TMD fragmentation functions



Great sensitivity to evolution parameters (BELLE) and intrinsic parameters (BES)

Bacchetta, Echevarria, Mulders, Radici, Signori, arXiv:1508.00402

Bruno Touschek, pioneer of e^+e^- colliders

You need also e^+e^- data
to study
TMD fragmentation functions

see talks by Artru, Matevosyan, Radici, Liang

Status of other extractions

Data, theory, fits

Only first attempts

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

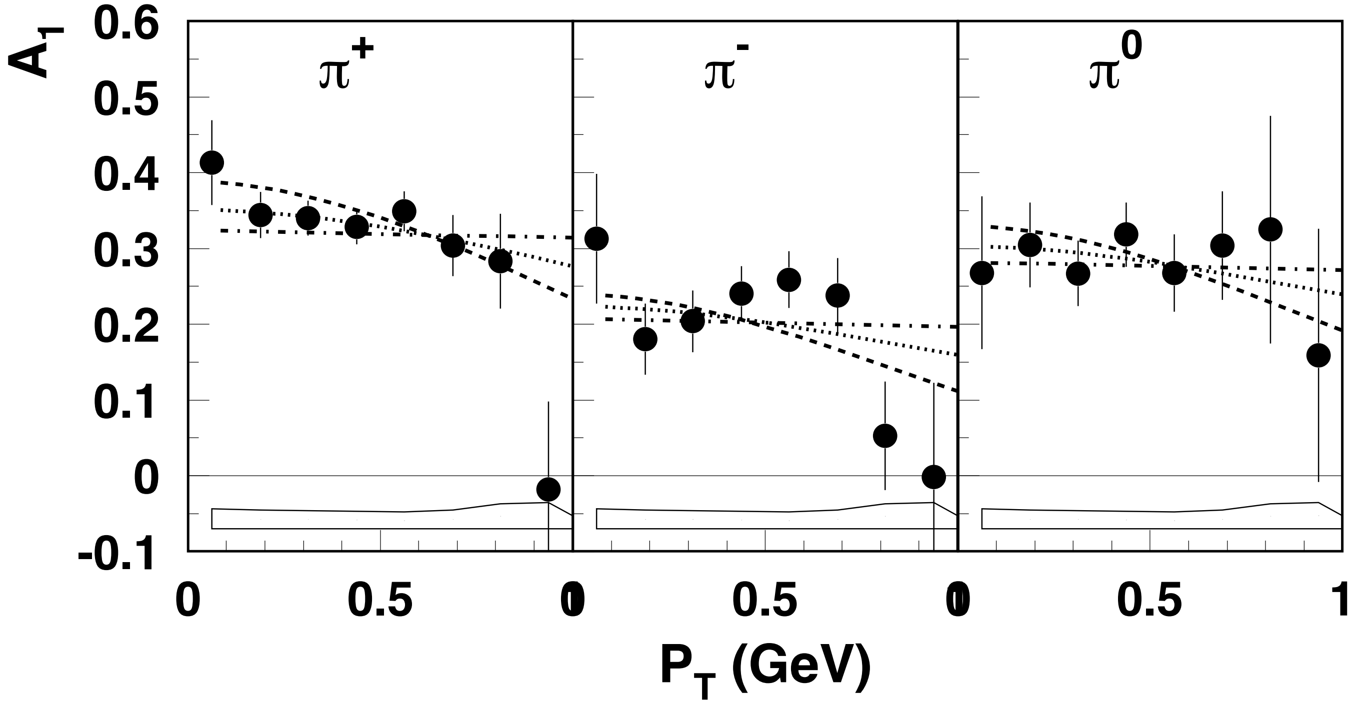
Twist-2 TMDs

Limited data, theory, fits

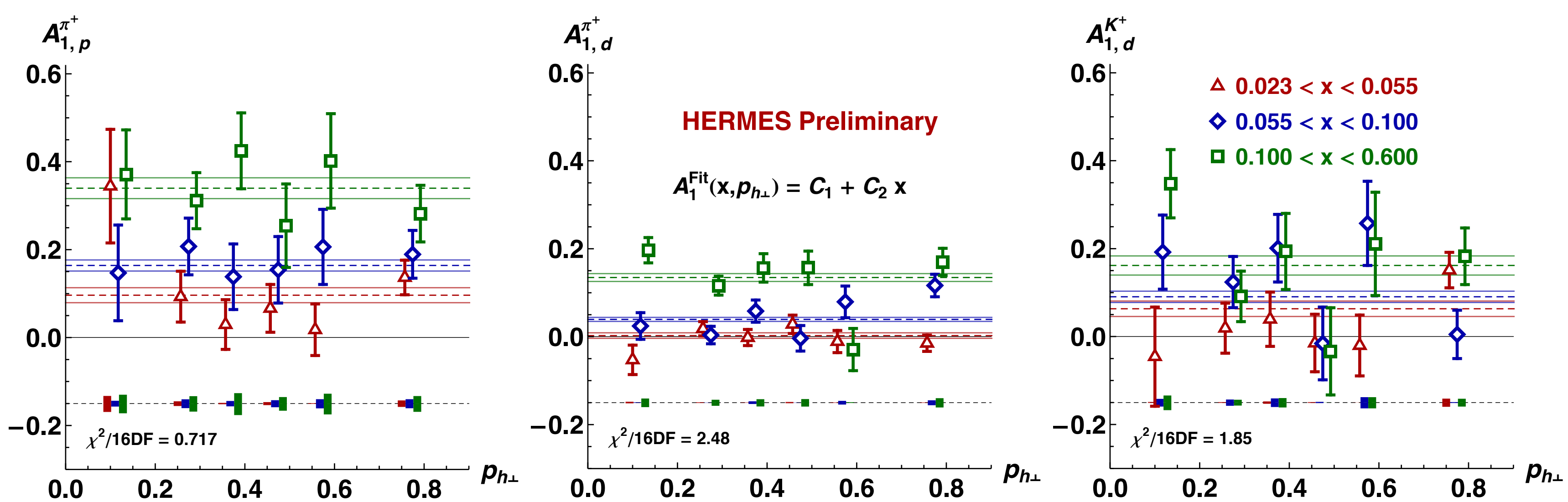
see talks by Courtoy, D'Alesio

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

Helicity TMD (F_{LL} structure function)

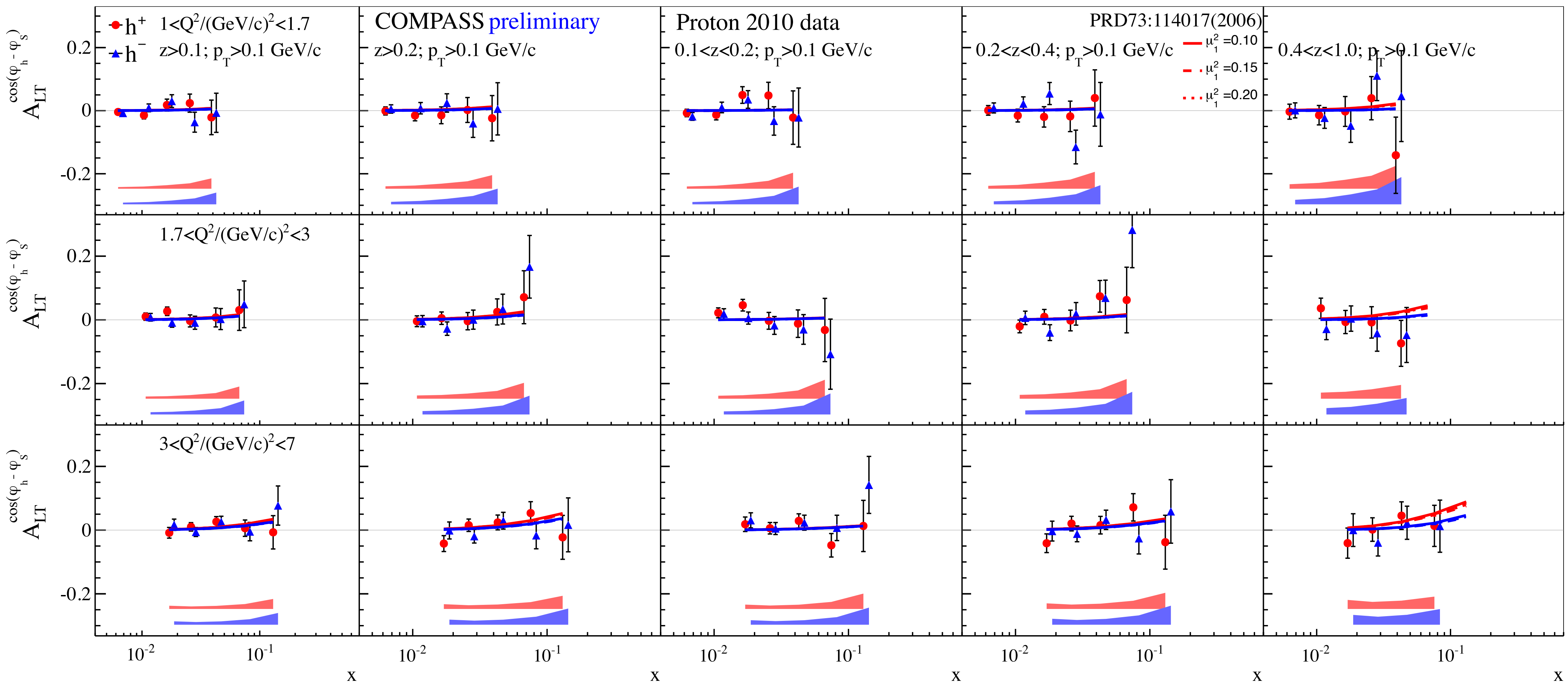


arXiv:1003.4549



http://dx.doi.org/10.3204/DESY-THESIS-2010-043

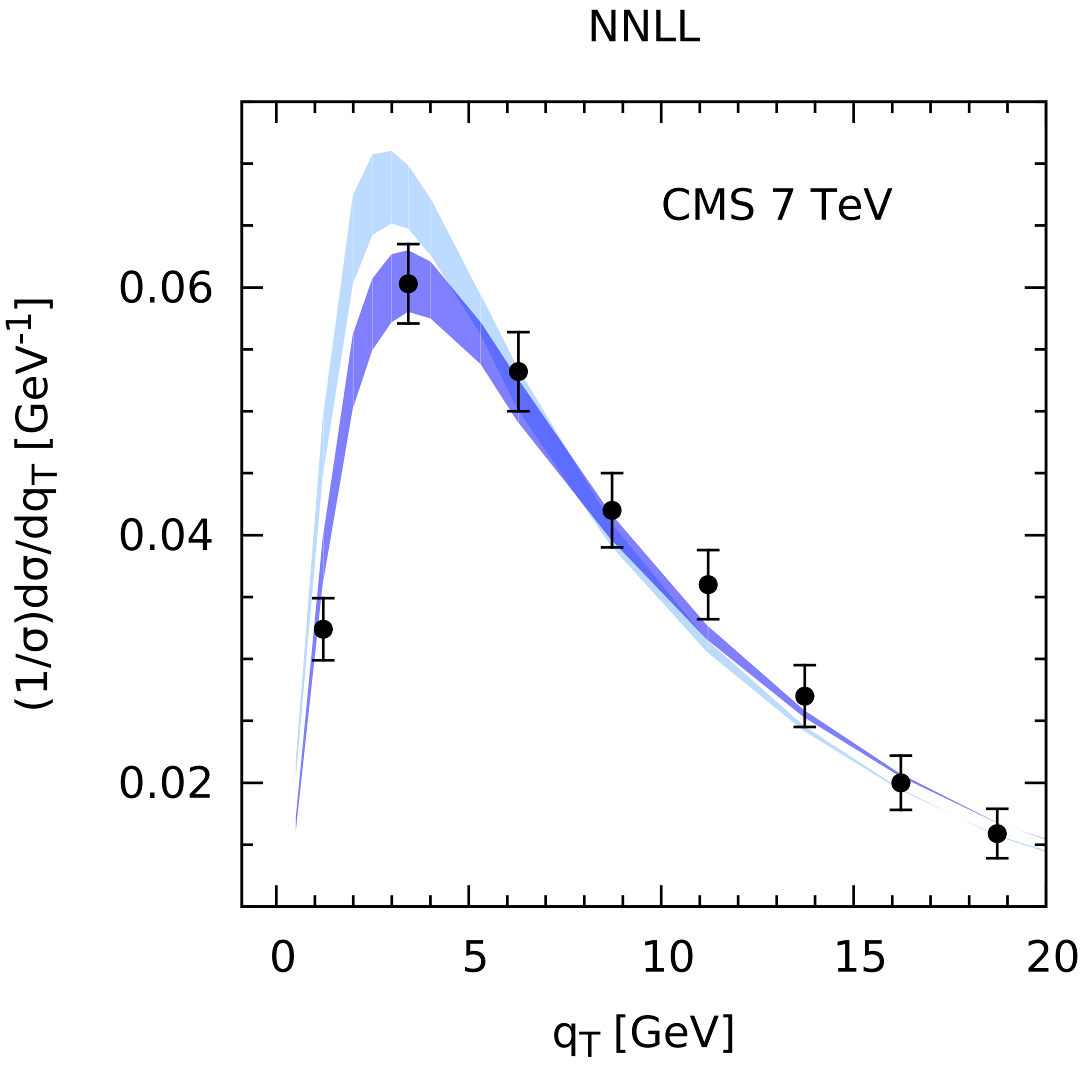
Worm-gear TMDs



see talk by B. Parsamyan
see also HERMES, [arXiv:1107.4227]

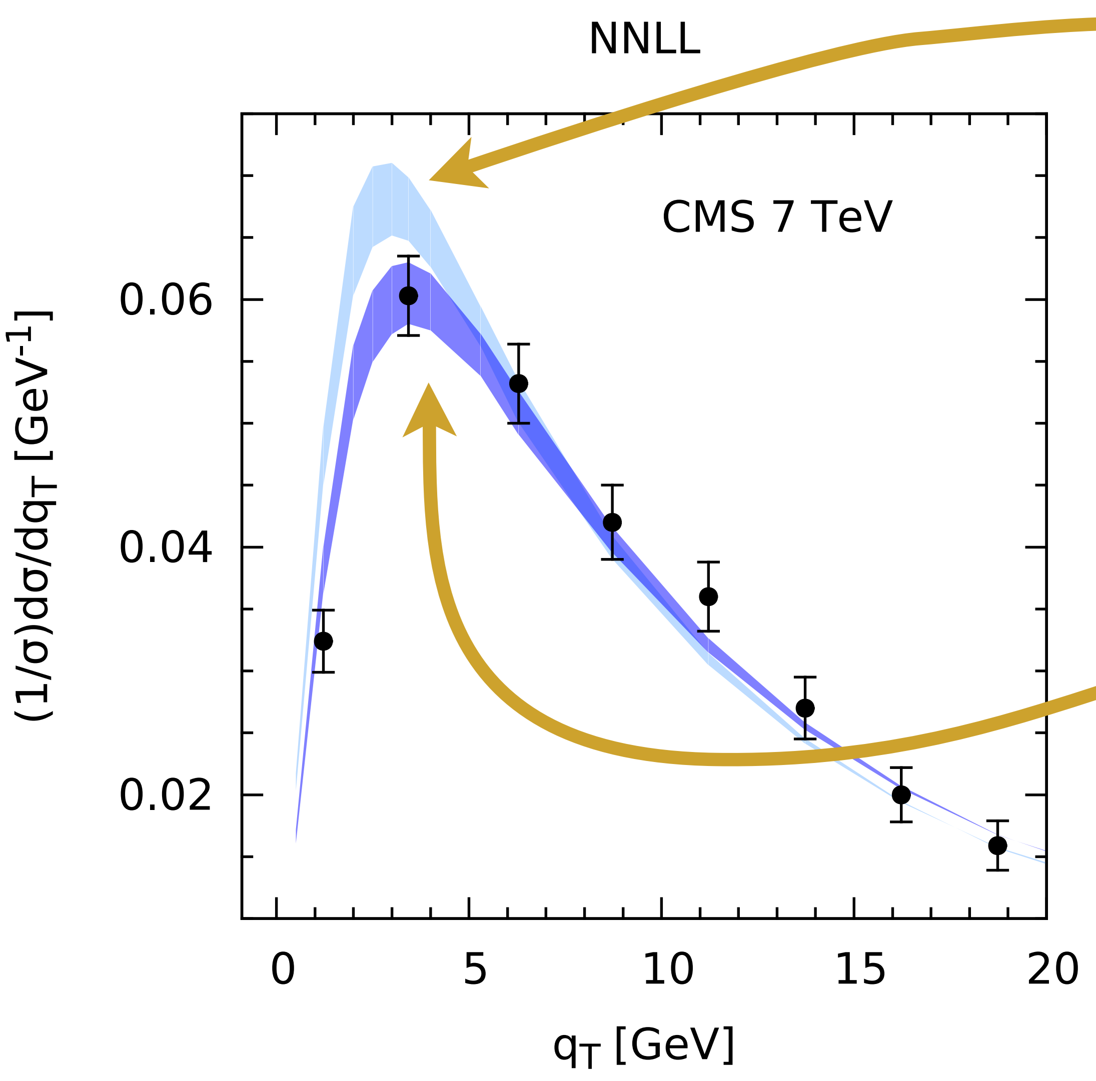
TMDs at LHC

Z boson transverse momentum



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

Z boson transverse momentum



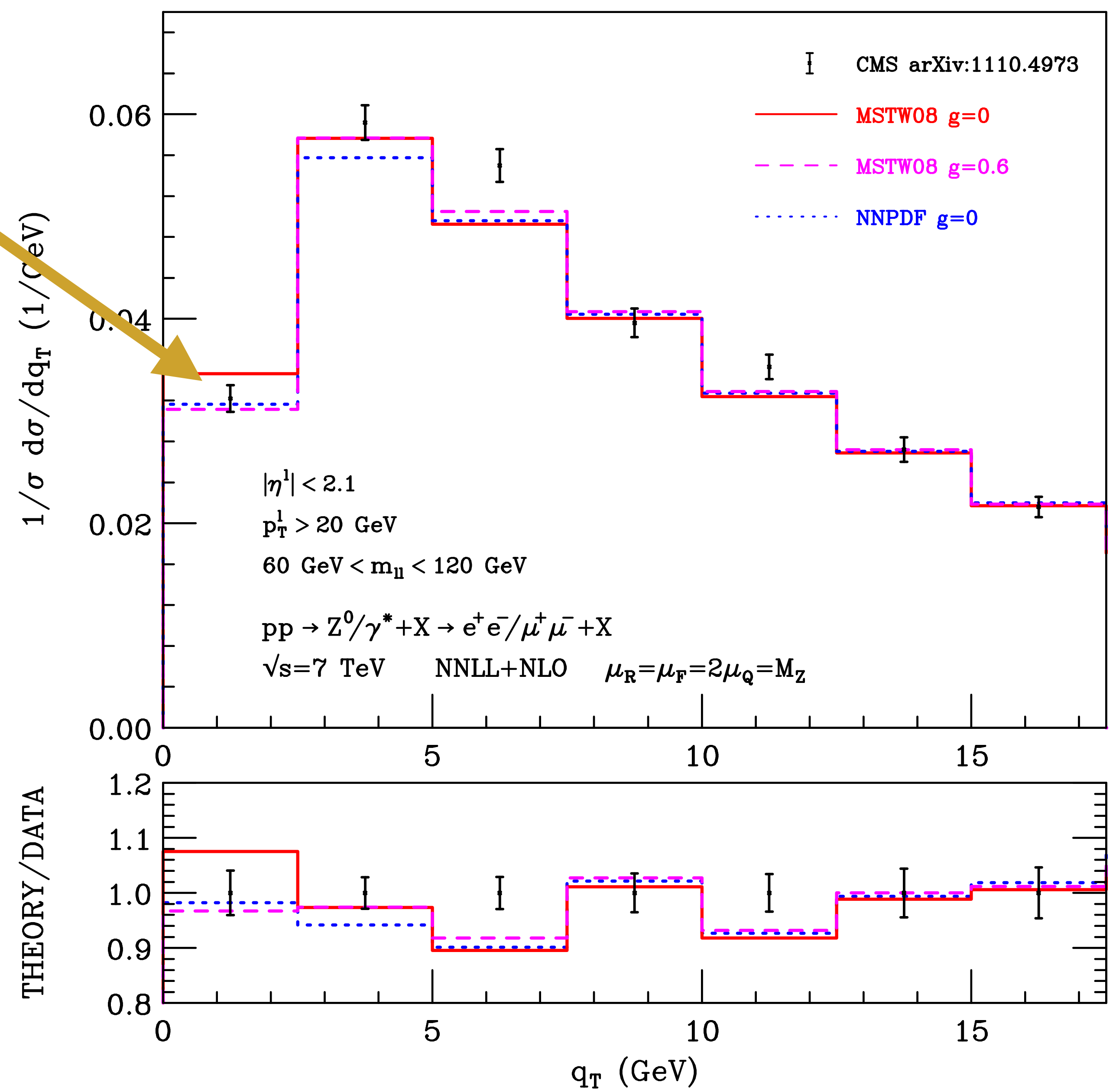
Perturbative transverse momentum only

With intrinsic transverse momentum

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

Z boson transverse momentum

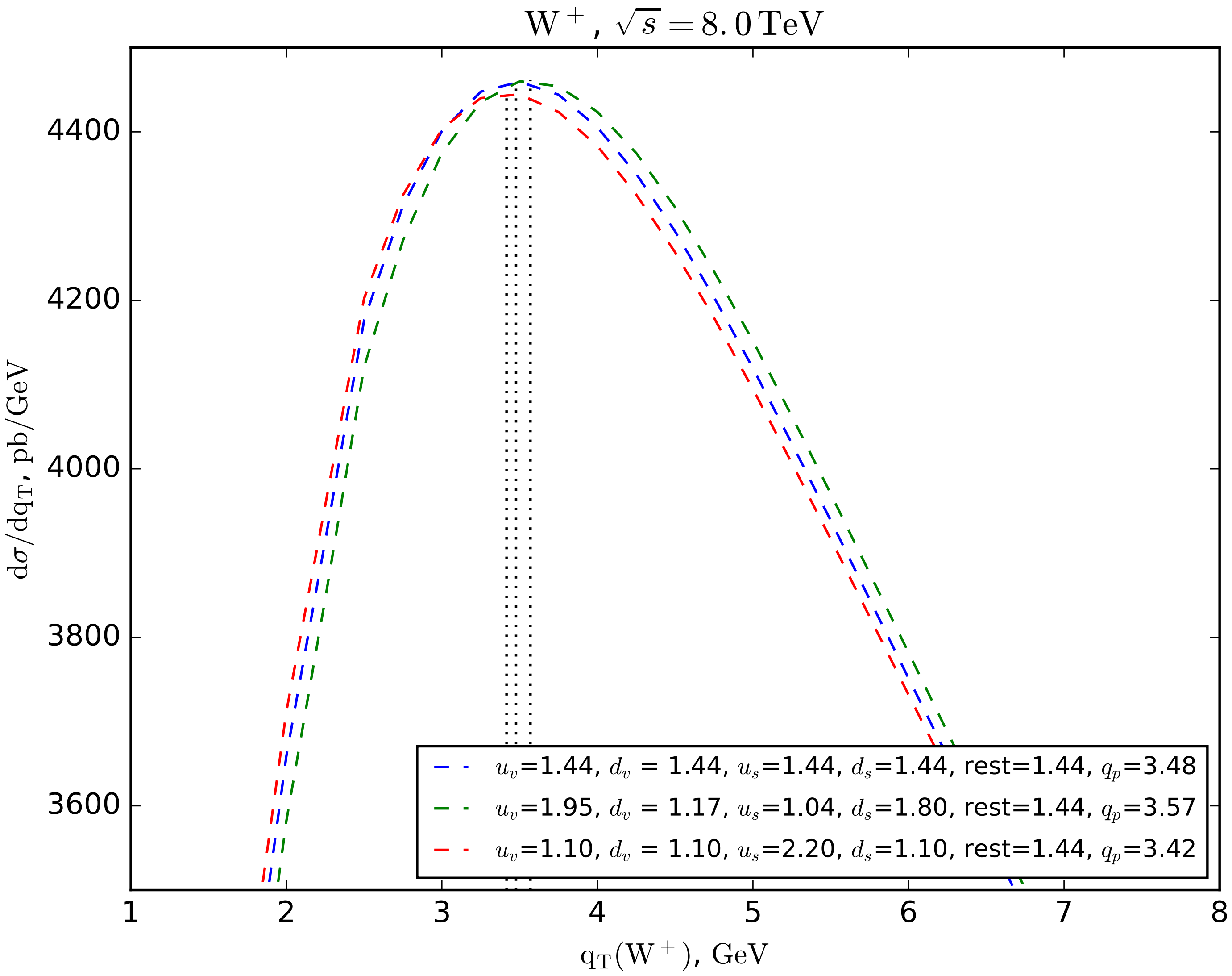
difference between red and magenta lines due to nonperturbative contributions



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

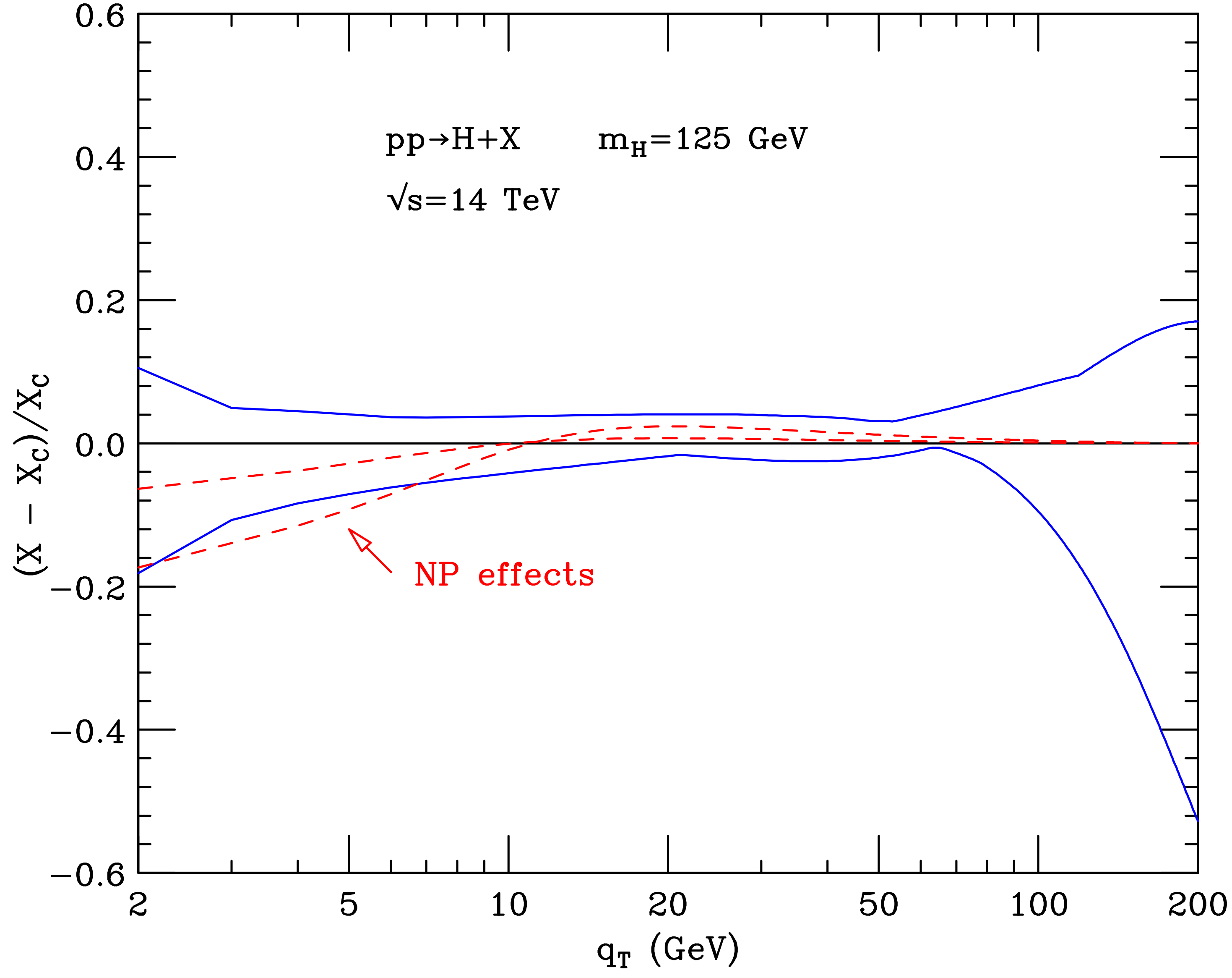
W transverse momentum

PhD thesis Andrea Signori



Flavor dependence of TMDs can affect the shape of the transverse-momentum spectrum of W bosons. In turn, this might be relevant for precise determinations of M_W

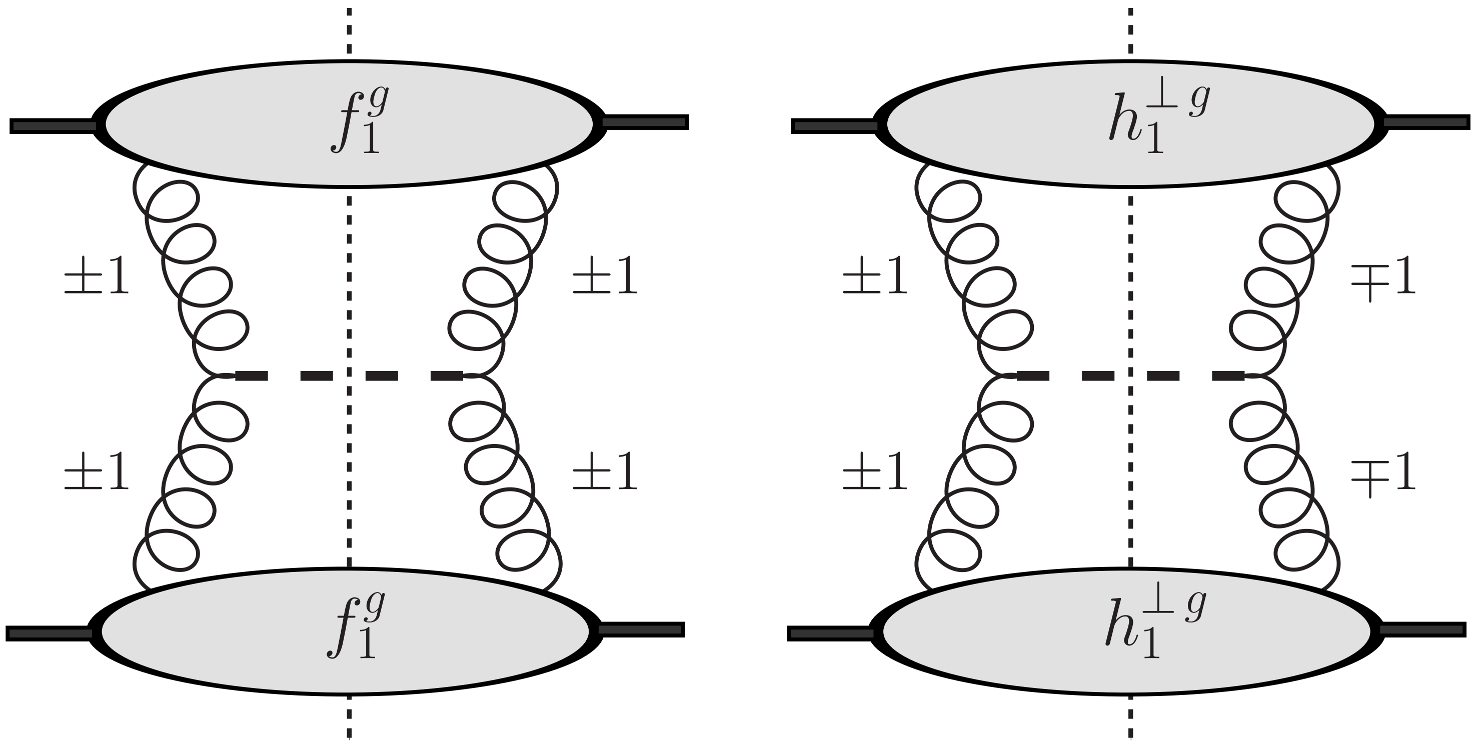
Higgs transverse momentum



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

Gluon TMDs (and linear polarisation)

Boer, den Dunnen, Pisano, Schlegel, Vogelsang, PRL108 (2012)



Not only we could be potentially sensitive to unpolarized gluon TMDs, but also to linearly polarized gluon TMDs

see talks by Boer, Schlegel, Pisano
and also low-x talks by Kovchecov, Cherednikov

TMDs at LHC

TMDs at LHC

- The description based on TMD formalism works well

TMDs at LHC

- The description based on TMD formalism works well
- Nonperturbative parts of TMDs affect the transverse-momentum distribution even up to 5 GeV

TMDs at LHC

- The description based on TMD formalism works well
- Nonperturbative parts of TMDs affect the transverse-momentum distribution even up to 5 GeV
- Data can be useful for TMD extraction, but finer binning at low transverse momentum is required

TMDs at LHC

- The description based on TMD formalism works well
- Nonperturbative parts of TMDs affect the transverse-momentum distribution even up to 5 GeV
- Data can be useful for TMD extraction, but finer binning at low transverse momentum is required
- Potential for gluon TMD studies

Other important issues related to LHC

Other important issues related to LHC

- Role of parton distribution functions (including 3D ones) in searches for physics beyond the standard model

see talks by Courtoy, Pitschmann

Other important issues related to LHC

- Role of parton distribution functions (including 3D ones) in searches for physics beyond the standard model

see talks by Courtoy, Pitschmann

- 3D distributions are just single-parton density distributions. For LHC, multiparton distributions turn out to be extremely relevant. They are also related to twist-3 parton distribution functions.

see talk by S. Scopetta

Conclusions

Conclusions

- Steady progress in the field of 3D nucleon structure, both experimental and theoretical

Conclusions

- Steady progress in the field of 3D nucleon structure, both experimental and theoretical
- Accurate extractions of parton distributions (quark and gluons) require more data

Conclusions

- Steady progress in the field of 3D nucleon structure, both experimental and theoretical

- Accurate extractions of parton distributions (quark and gluons) require more data

- I did not manage to predict much about the future, but I can say for sure that it will be bright!