Relating TMD phenomenology to QCD

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erc European Research Council

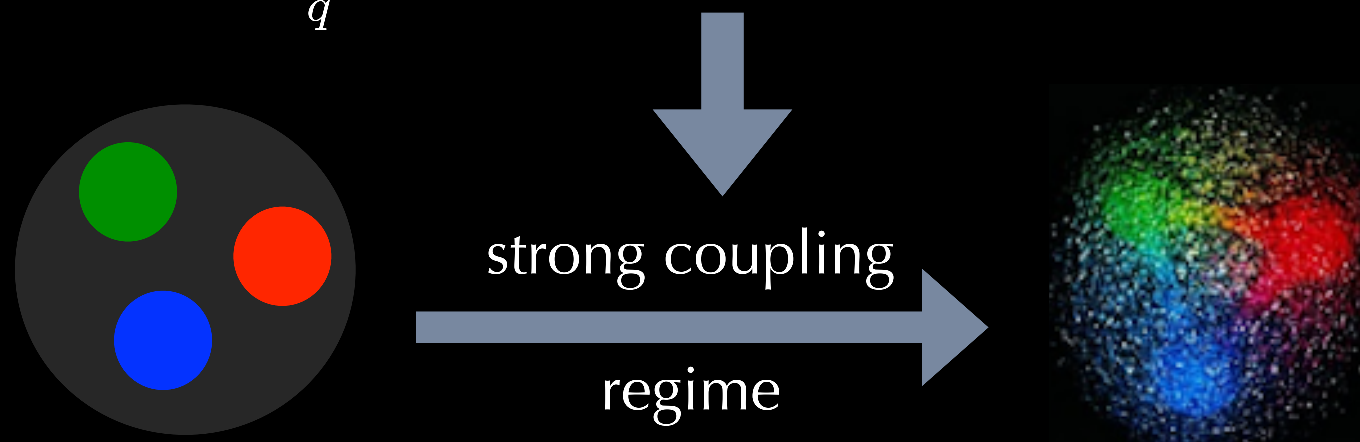
3DSPIN MAPPING THE PROTON IN 3D

HAS QCD HADRONIC STRUCTURE AND QUANTUM CHROMODYNAMICS

A "millennium problem" …

QCD is the most complex part of the Standard Model

$$\mathcal{L}_{\rm QCD} = \sum_q \bar{\psi}_q \left(i\partial\!\!\!/ - gA\!\!\!/ + m\right)\psi_q - \frac{1}{4} G_{\mu\nu} G^{\mu\nu}$$



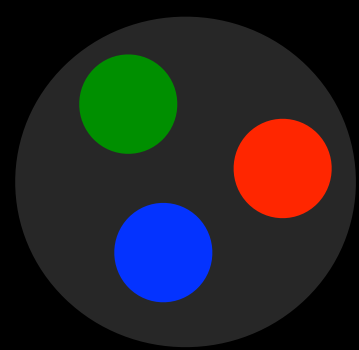
Nucleon: 3 valence quarks ? highly nonlinear dynamics of an infinite many-body system

how do macroscopic properties of Nucleons (mass, size, spin..), of its resonances, of atomic nuclei, emerge ?

A "millennium problem" …

QCD is the most complex part of the Standard Model

$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \bar{\psi}_q \left(i\partial\!\!\!/ - g A\!\!\!/ + m \right) \psi_q - \frac{1}{4} G_{\mu\nu} G^{\mu\nu}$$



strong coupling

regime

Nucleon: 3 valence quarks

?

highly nonlinear dynamics of an infinite many-body system

how do macroscopic properties of Nucleons (mass, size, spin..), of its resonances, of atomic nuclei, emerge ?

understanding **confinement** → understanding every-day world

If you don't understand it, firstly you map it…

Where are partons ?

How do they move ?

If you don’t understand it, firstly you map it…

Where are partons ?

Maps in
position space

GPDs

not connected by
Fourier Transform

How do they move ?

Maps in
momentum space

TMDs

Wigner Distributions

(full information)

If you don't understand it, firstly you map it…

Where are partons ?

How do they move ?

Maps in
position space

↓

GPDs

(see
next talk)

Maps in
momentum space

↓

TMDs

this talk

not connected by
Fourier Transform

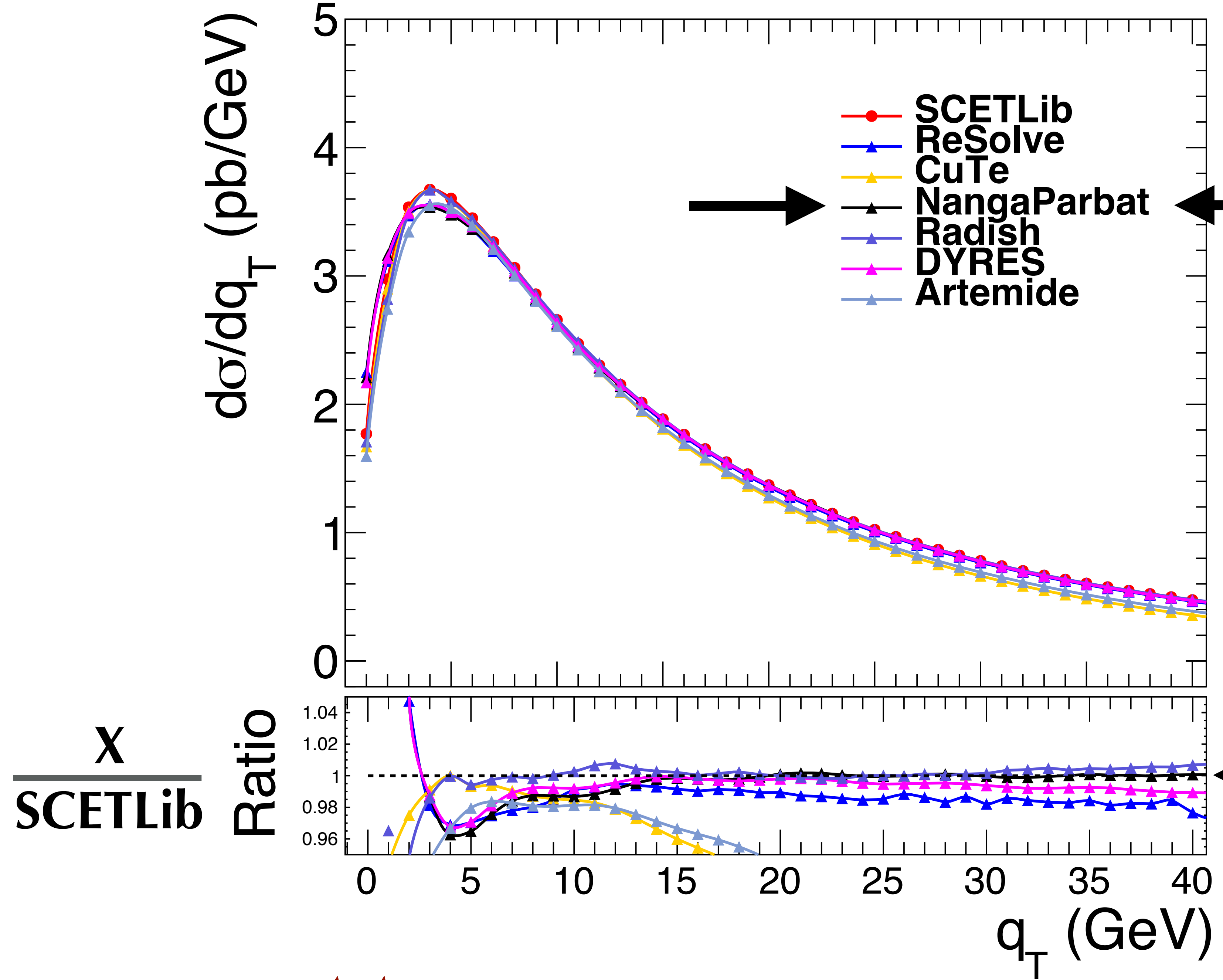
Wigner Distributions

(full information)

Entering the era of precision studies for TMDs

Z production at y=0

benchmarking W term resummed at N³LL



NangaParbat

or the new

Pavia 2019 TMD fit

Bacchetta, Bertone, Bissolotti, Bozzi, Delcarro, Piacenza, Radici, in preparation

agreement within ±(1-2)% for $5 < q_T < 80$ GeV

A. Apyan
CERN EW Working Group, 10-14-2019

From 1D map …

quark

nucleon

Nucleon Polarization		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
	U	$f_1 =$		
	L		$g_1 =$ -	
	T			$h_1 =$ -

at leading twist

unpolarized

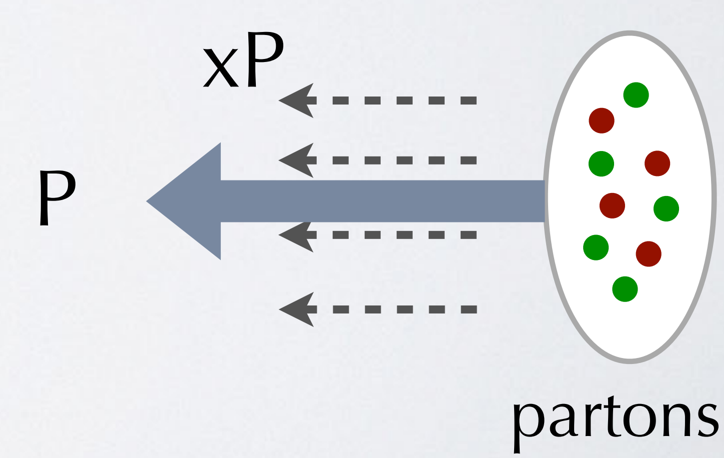
helicity

transversity

from PDF (x)

1D map

of internal motion



From 1D map … to 3D map

quark

nucleon

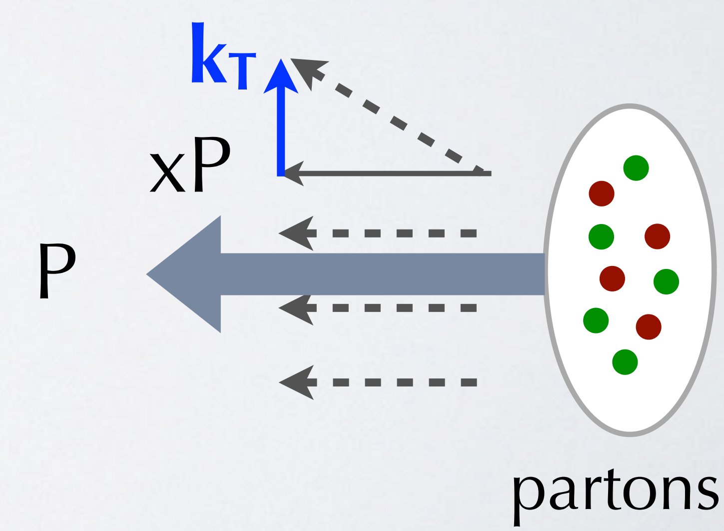
		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$	*	$h_1^{\perp} =$ -
	L	*	$g_1 =$ -	$h_{1L}^{\perp} =$ -
	T	$f_{1T}^{\perp} =$ -	$g_{1T} =$ -	$h_1 =$ - $h_{1T}^{\perp} =$ -

at leading twist

* forbidden by Parity invariance

Mulders & Tangerman, N.P. ***B461*** *(96)*
*Boer & Mulders, P.R. D**57*** *(98)*

to TMD (x,k_T)
3D map
of internal motion



A wealth of information !

quark

nucleon

at leading twist

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Nucleon Polarization	U	$f_1 =$	*	$h_1^\perp =$ -
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Boer-Mulders

L worm gear

transversity

pretzelosity

Sivers

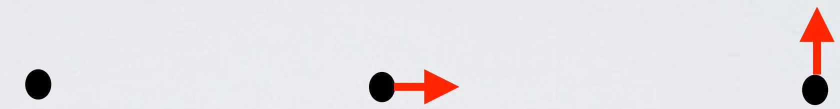
T worm gear

3D maps of

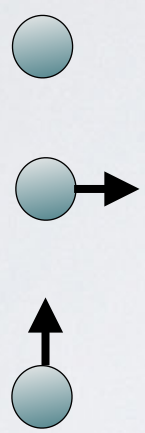
- partonic quantum correlations: spin-spin, spin-momentum (orbit)
- quantum correlations between partonic motion and macroscopic nucleon properties (spin)
- partonic orbital motion (most TMDs vanish with no L^q)
- color-gauge invariance and time-reversal symmetry of QCD

A wealth of information !

quark



nucleon



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at leading twist

* forbidden by Parity invariance

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f^\perp$	$g^\perp$	h , e
	L	$f_L^\perp$	$g_L^\perp$	h_L , e_L
	T	f_T , $f_T^\perp$	g_T , $g_T^\perp$	h_T , e_T $h_T^\perp$, $e_T^\perp$

at subleading twist

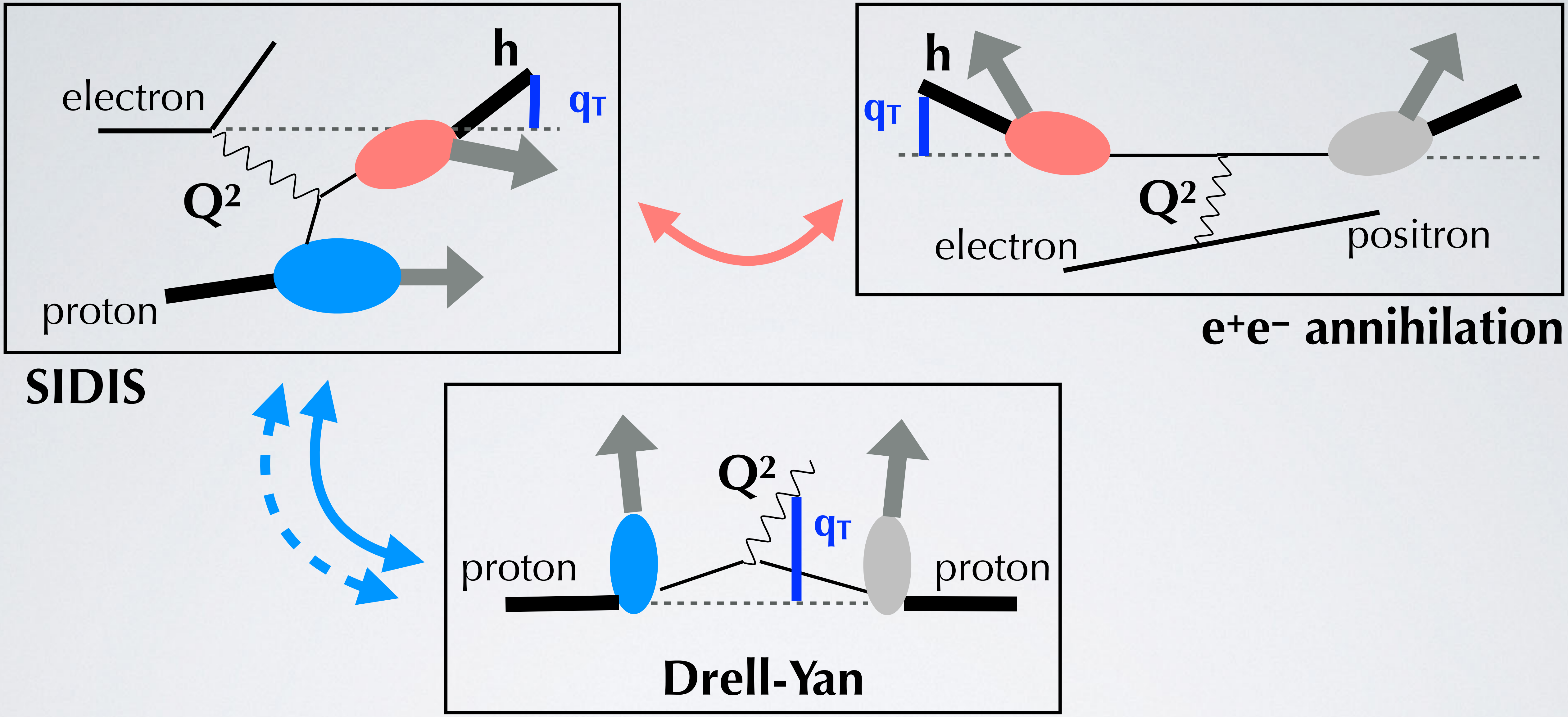
more quark-gluon correlations

but no factorization theorem (yet)

although conjecture for low-q_T factorized formula that recovers collinear known result at high-q_T

Bacchetta et al.,
*P.L. **B797** (19) 134850*
arXiv:1906.07037

TMD factorization and universality



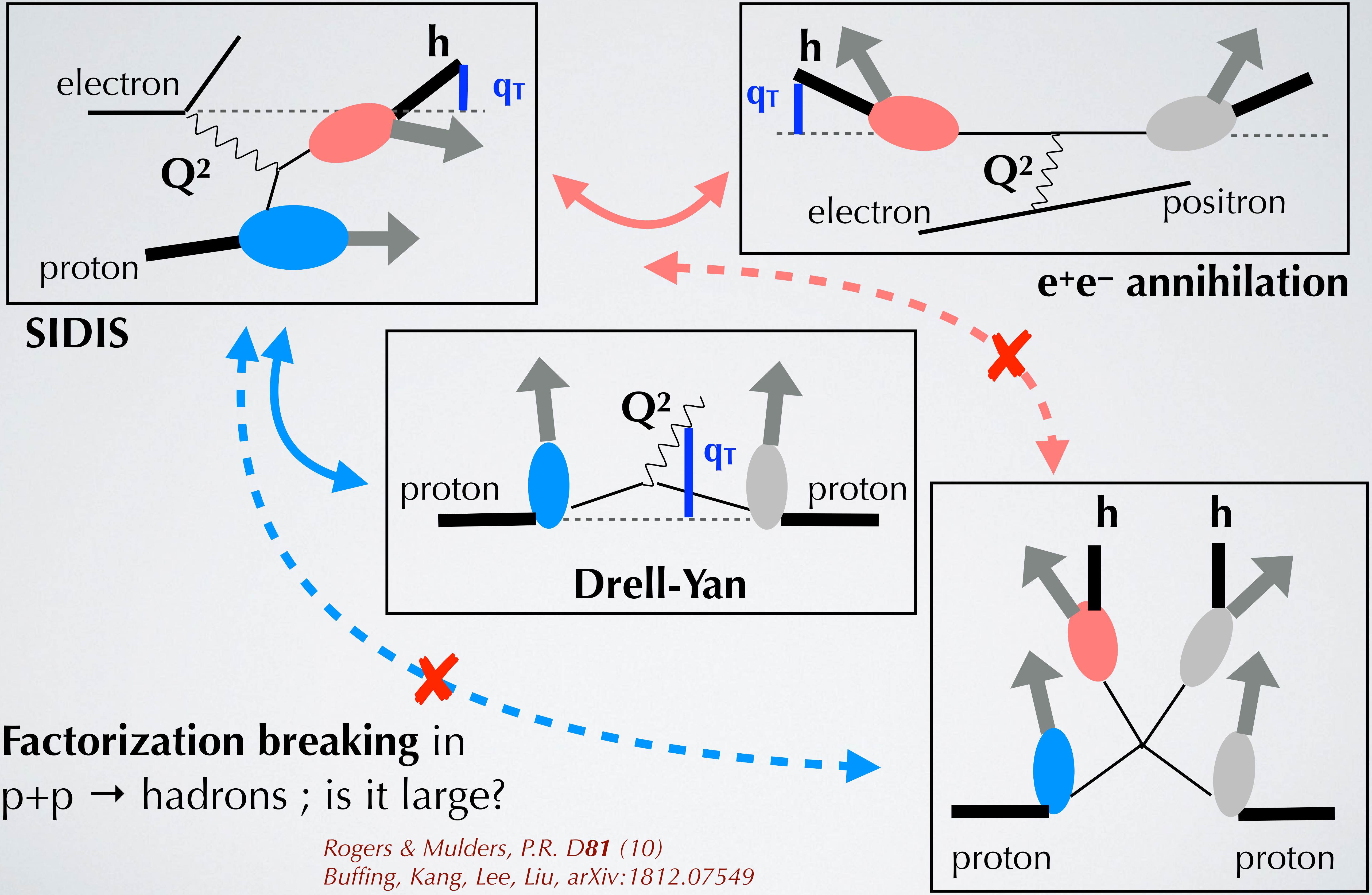
Factorization theorems well understood for $q_T \ll Q$
for TMD **distributions** and **fragmentations**

*Ji, Yuan, Ma, P.R. D**71** (05)*
*Rogers & Aybat, P.R. D**83** (11)*
Collins, "Foundations of Perturbative QCD" (11)
*Echevarria, Idilbi, Scimemi, JHEP **1207** (12)*

Universality not trivial for
naïve T-odd TMD **distributions**

*Collins, P.L. **B536** (02)*
*Collins & Metz, P.R.L. **93** (04)*
*Buffing, Mukherjee, Mulders, P.R. D**86** (12)*

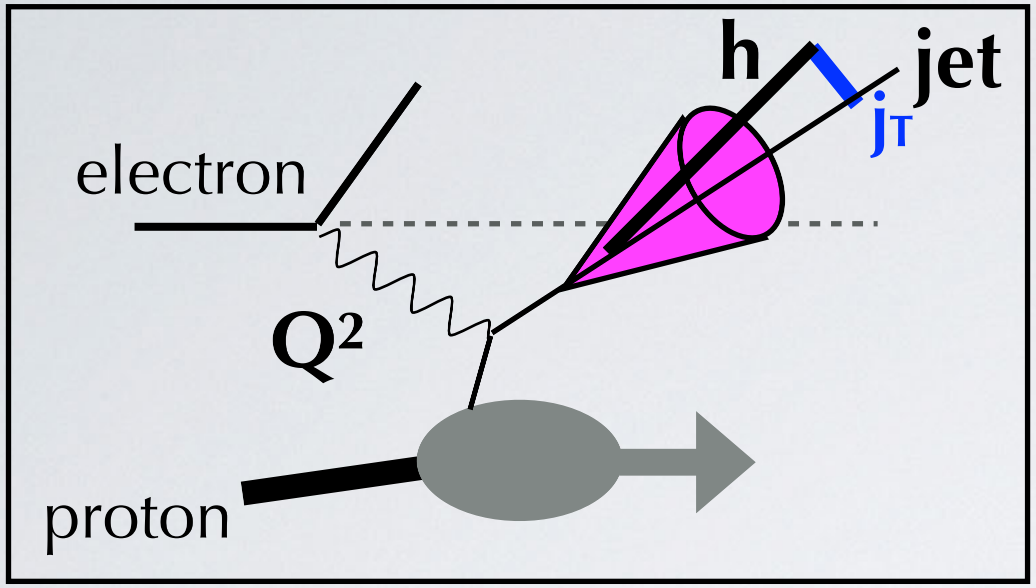
TMD factorization and universality



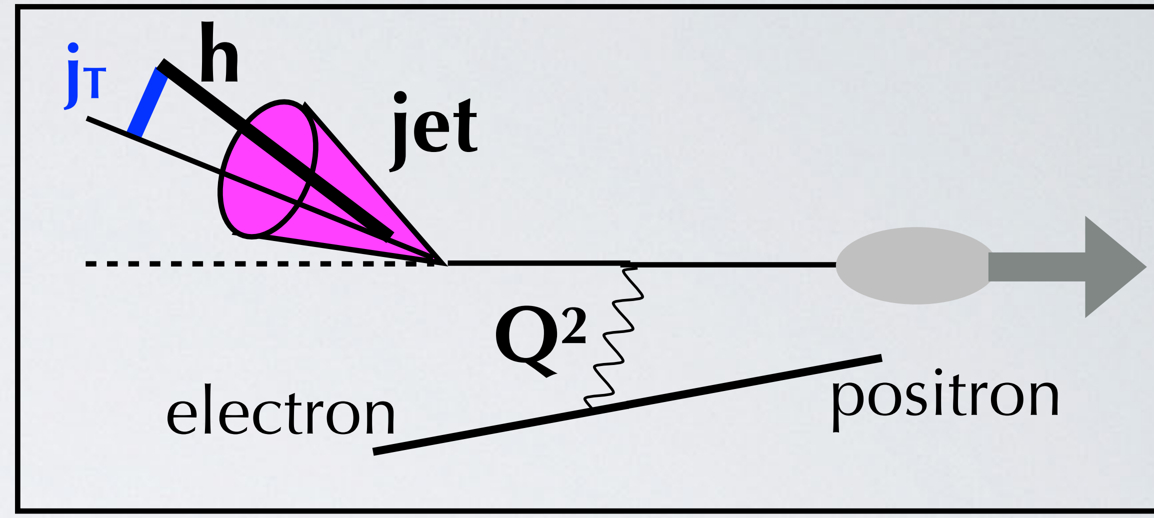
Factorization breaking in
p+p → hadrons ; is it large?

*Rogers & Mulders, P.R. D**81** (10)*
Buffing, Kang, Lee, Liu, arXiv:1812.07549

Hadron-in-jet hybrid framework



SIDIS

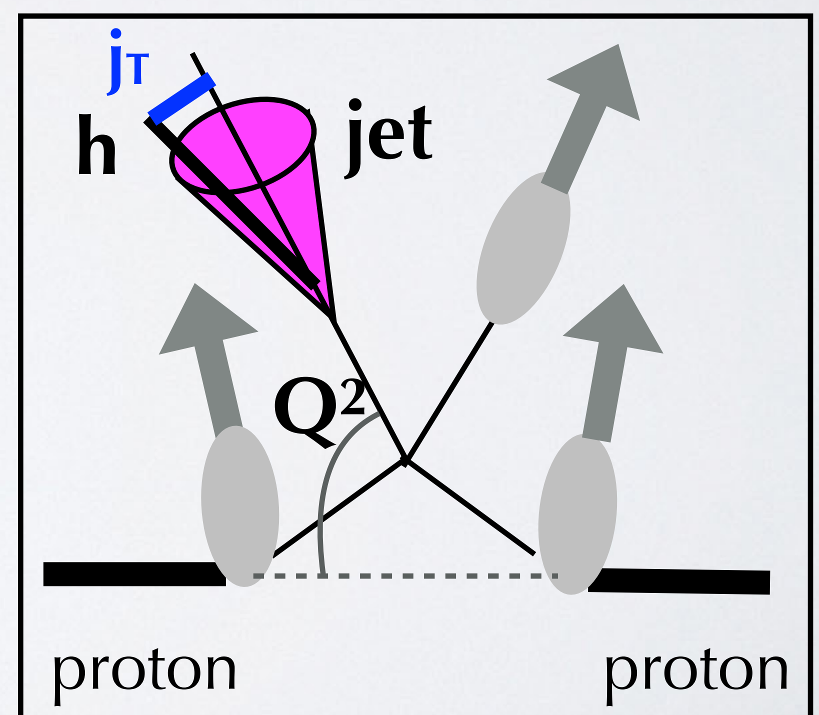


e^+e^- annihilation

hybrid scheme:

- TMD framework for TMD **fragmentation**
- collinear framework for PDF

Factorization theorem and **universality** for TMD **fragmentation**

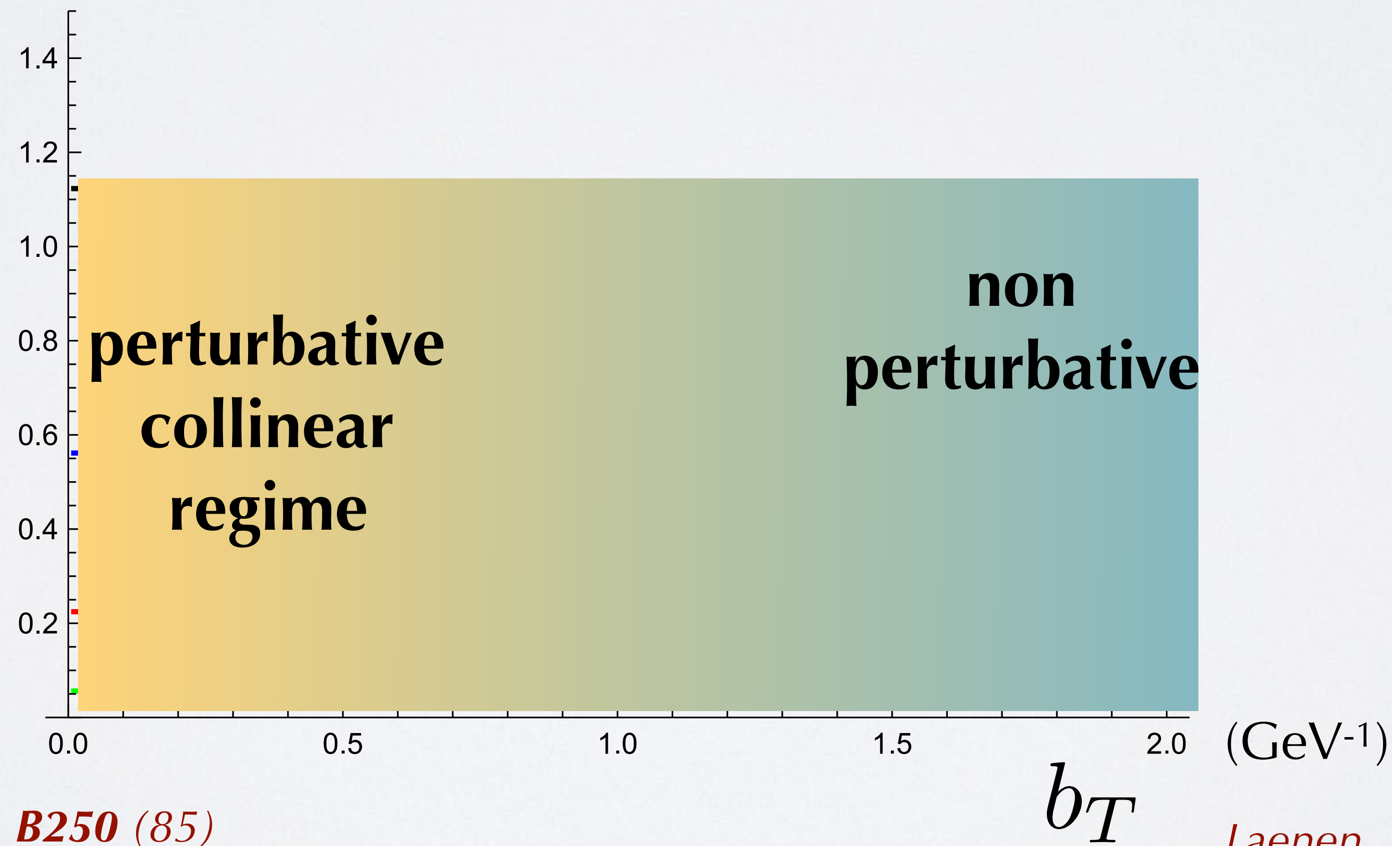


*Kang, Liu, Ringer, Xing, JHEP **1711** (17), arXiv:1705.08443*
*Kang, Prokudin, Ringer, Yuan, P.L. **B774** (17), arXiv:1707.00913*

TMD evolution

more easily studied in impact-parameter (b_T) space

$$f_1^q(x, \boldsymbol{b}_T; Q^2) = \sum_i \left(C_{q/i} \otimes f_1^i\right)(x, b_*; \mu_b)\, e^{S(b_*;\mu_b,Q)}\, e^{g_K(b_T)\,\log\frac{Q}{Q_0}}\, f_{\rm NP}^q(x, b_T; Q_0^2)$$



*Collins, Soper, Sterman, N.P. **B250** (85)*
Collins, "Foundations of Perturbative QCD" (2011)
*Rogers and Aybat, P.R. D**83** (11)*

others schemes possible: *Laenen, Sterman Vogelsang, P.R.L. **84** (00)*
*Bozzi et al., N.P. **B737** (06)*
*Echevarria et al., E.P.J. **C73** (13) …*

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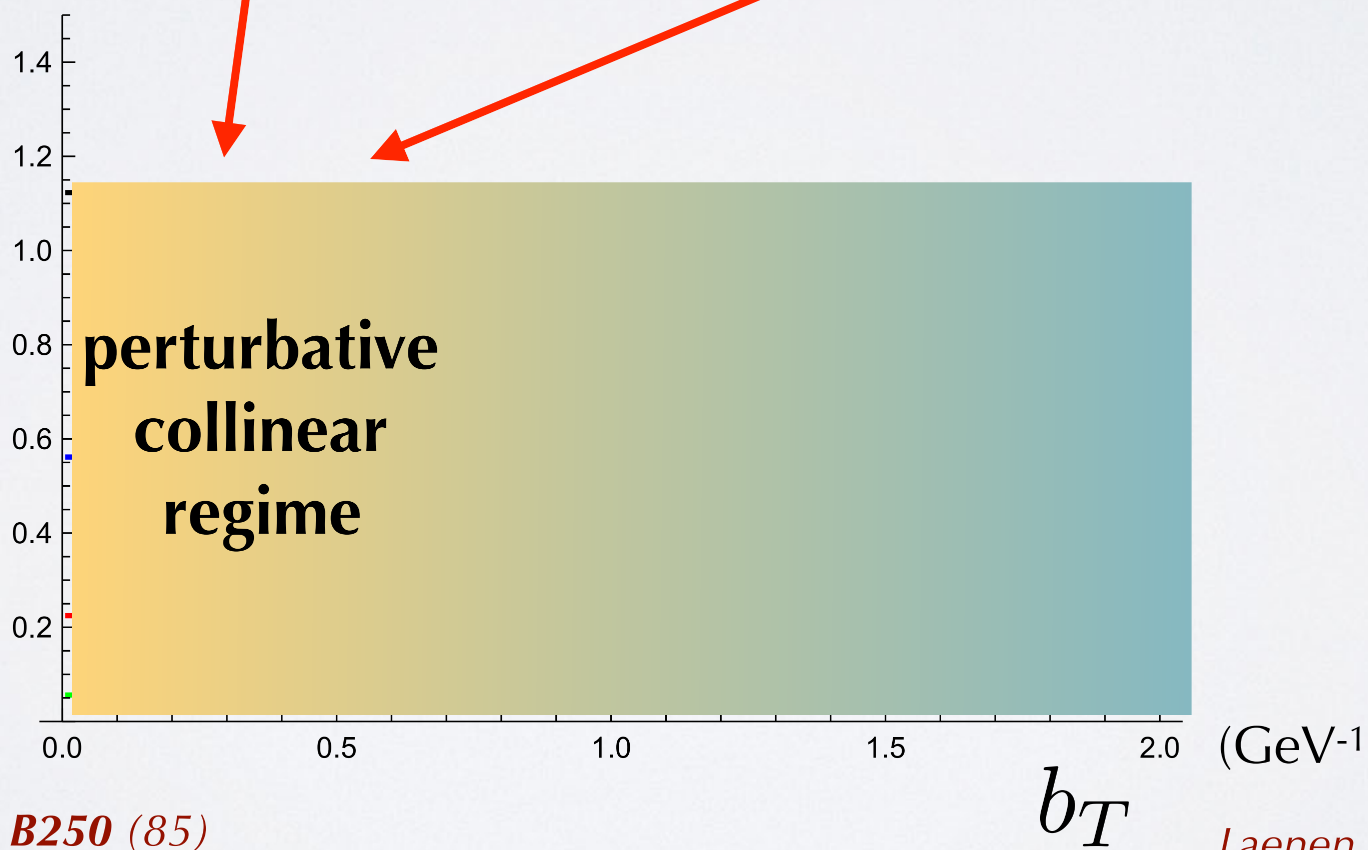
OPE matching to **collinear regime** $b_T \ll 1/\Lambda_{QCD}$
{**perturbative** $C(x,b_T)$} $\otimes$ PDF(x,μ_b)

CSS and RGE **perturbative** evolution to large b_T



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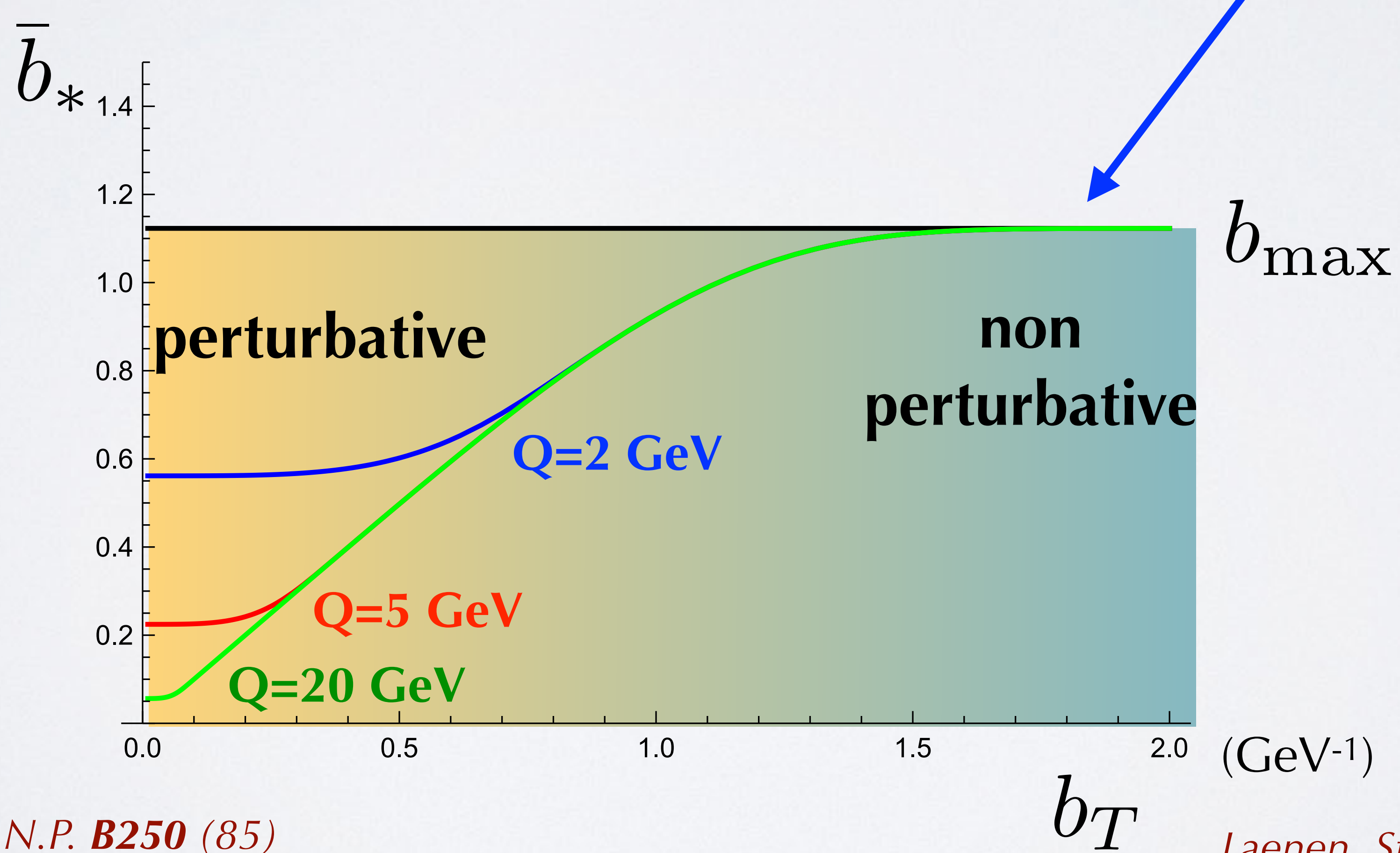
use b*(b_T) prescription
to avoid Landau pole

evolution and intrinsic b_T dep.
nonperturbative

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

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

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



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use $b^*(b_T)$ prescription
to avoid Landau p

o.

matching to nonperturbative part implies choice of functional forms with parameters to be fitted to data

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

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

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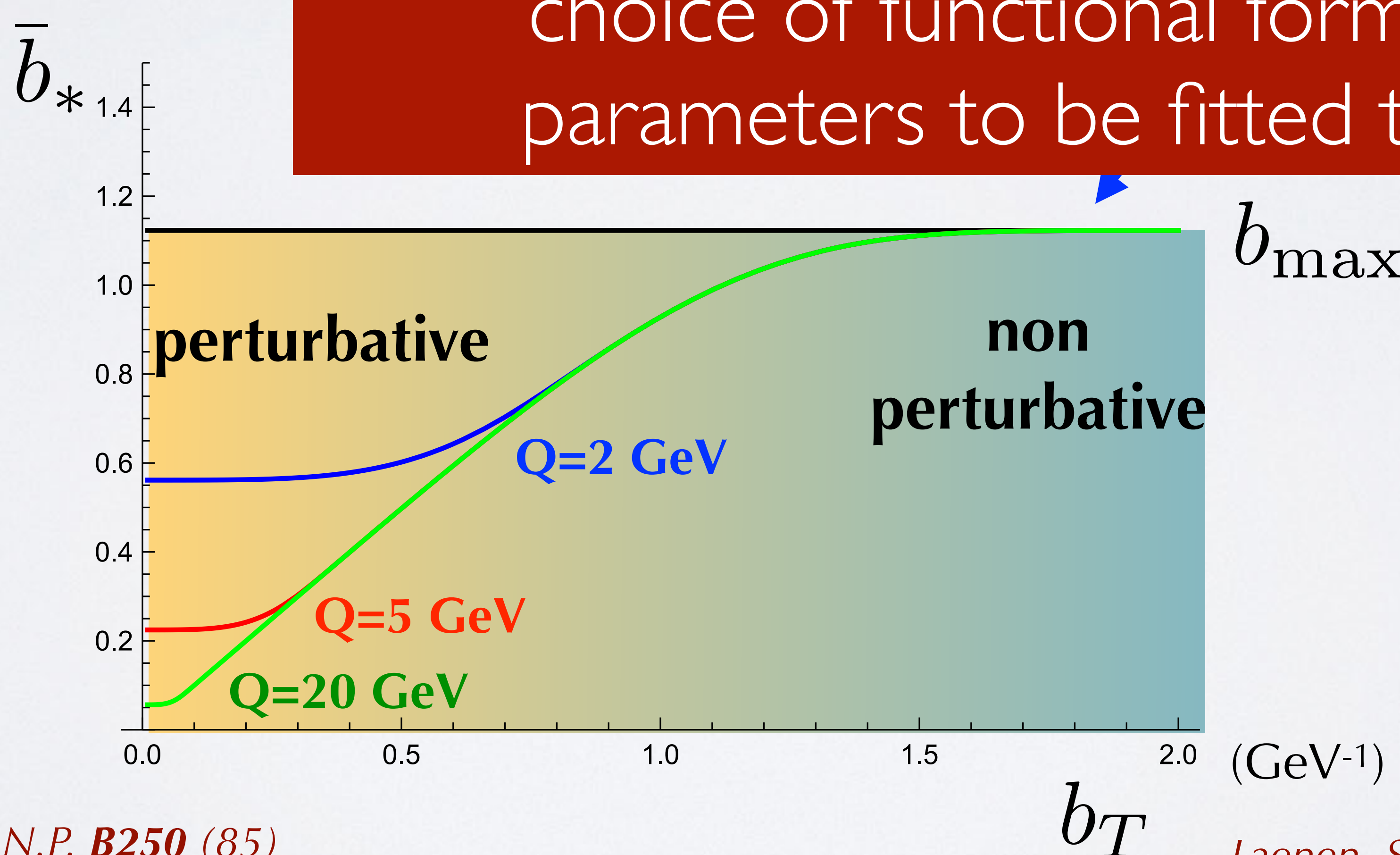

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Perturbative accuracy in resummation

$$f_1^q(x, \boldsymbol{b}_T; Q^2) = \sum_i \left(C_{q/i} \otimes f_1^i\right)(x, b_*; \mu_b)\, e^{S(b_*;\mu_b,Q)} \ \ldots.$$

order	Wilson coeffs.	Sudakov form factor
LL	$\tilde{C}^0$	$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right)$
NLL	$\tilde{C}^0$	$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right)$ $\alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$
NLL′	$\tilde{C}^0$ $\alpha_S \tilde{C}^1$	$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right)$ $\alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$
NNLL	$\tilde{C}^0$ $\alpha_S \tilde{C}^1$	$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right)$ $\alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$ $\alpha_S^n \ln^{2n-2}\left(\frac{Q^2}{\mu_b^2}\right)$
NNLL′	$\tilde{C}^0$ $\alpha_S \tilde{C}^1$ $\alpha_S^2 \tilde{C}^2$	$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right)$ $\alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$ $\alpha_S^n \ln^{2n-2}\left(\frac{Q^2}{\mu_b^2}\right)$
NNNLL	$\tilde{C}^0$ $\alpha_S \tilde{C}^1$ $\alpha_S^2 \tilde{C}^2$	$\alpha_S^n \ln^{2n}\left(\frac{Q^2}{\mu_b^2}\right)$ $\alpha_S^n \ln^{2n-1}\left(\frac{Q^2}{\mu_b^2}\right)$ $\alpha_S^n \ln^{2n-2}\left(\frac{Q^2}{\mu_b^2}\right)$ $\alpha_S^n \ln^{2n-3}\left(\frac{Q^2}{\mu_b^2}\right)$

The TMDs at leading twist

quark

nucleon

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$	*	$h_1^{\perp} =$ -
	L	*	$g_1 =$ -	$h_{1L}^{\perp} =$ -
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at leading twist

Boer-Mulders

L worm gear

transversity

pretzelosity

Sivers

T worm gear

each TMD enters the cross section with a specific dependence on (azimuthal) angles of kinematics → extract them with azimuthal (spin) asymmetries

All relevant azimuthal (spin) asymmetries have been measured by

hermes COMPASS Jefferson Lab

The TMDs at leading twist

quark

nucleon

Nucleon Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)	
U	$f_1 =$	*	$h_1^\perp = \quad - $	Boer-Mulders
L	*	$g_1 = \quad - $	$h_{1L}^\perp = \quad - $	L worm gear
T	$f_{1T}^\perp = \quad - $	$g_{1T} = \quad - $	$h_1 = \quad - $	transversity
	Sivers	T worm gear	talk H. Gao	pretzelosity

at leading twist

this talk

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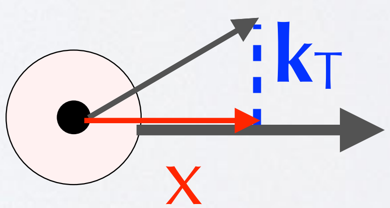
the unpolarized TMD (x, k_T)



how does $\langle k_T^2 \rangle$ depend on x ? on flavor ? on energy ?

Extractions of unpolarized TMD

	Framework	HERMES	COMPASS	DY	Z production	N of points
Pavia 2013 arXiv:1309.3507	parton model	✔	✘	✘	✘	1538
Torino 2014 arXiv:1312.6261	parton model	✔ (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 (?)
SIYY 2014 arXiv:1406.3073	NLL′	✘	✔	✔	✔	200 (?)
Pavia 2017 arXiv:1703.10157	NLL	✔	✔	✔	✔	8059
SV 2017 arXiv:1706.01473	NNLL′	✘	✘	✔	✔ (LHC)	309
BSV 2019 arXiv:1902.08474	NNLL′	✘	✘	✔	✔ (LHC)	457
Pavia 2019 in preparation	up to N^3LL	✘	✘	✔	✔ (LHC)	319

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SIYY 2014 arXiv:1406.3073	NLL′	✘	✔	✔	✔	200 (?)
Pavia 2017 arXiv:1703.10157	NLL	✔	✔	✔	✔	8059
SV 2017 arXiv:1706.01473	NNLL′	✘	✘	✔	✔ (LHC)	309
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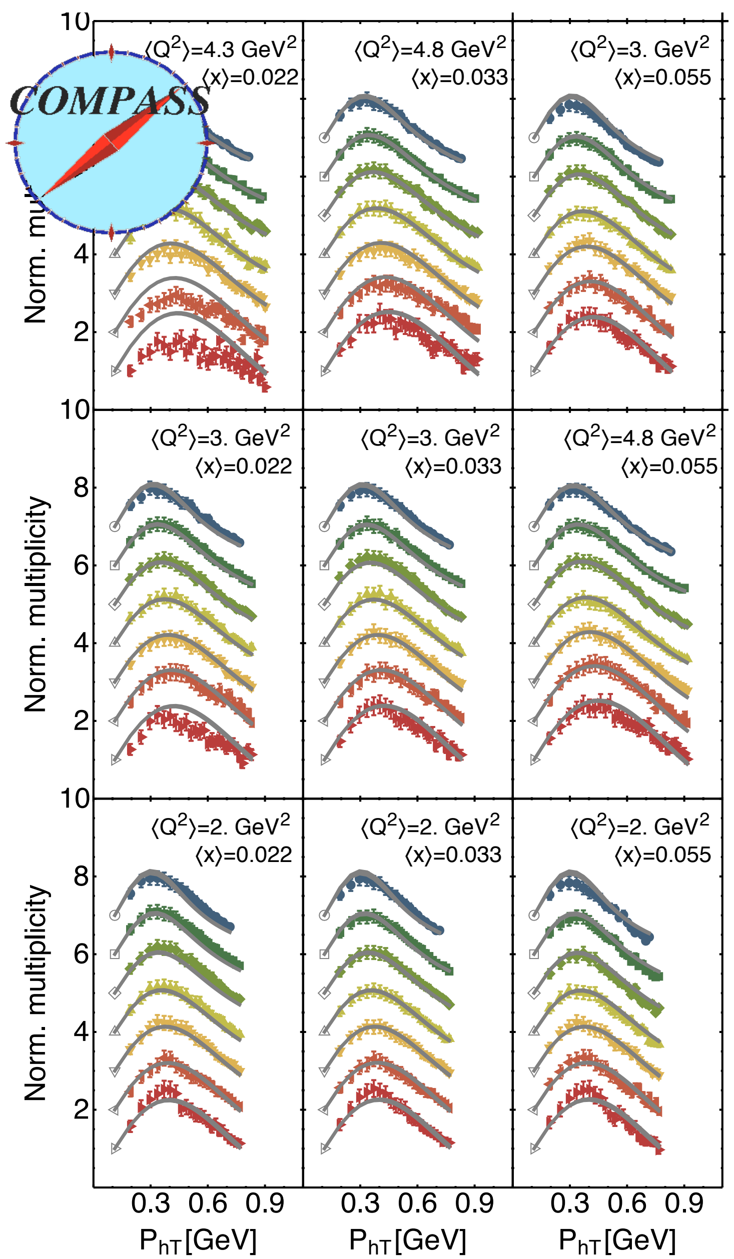
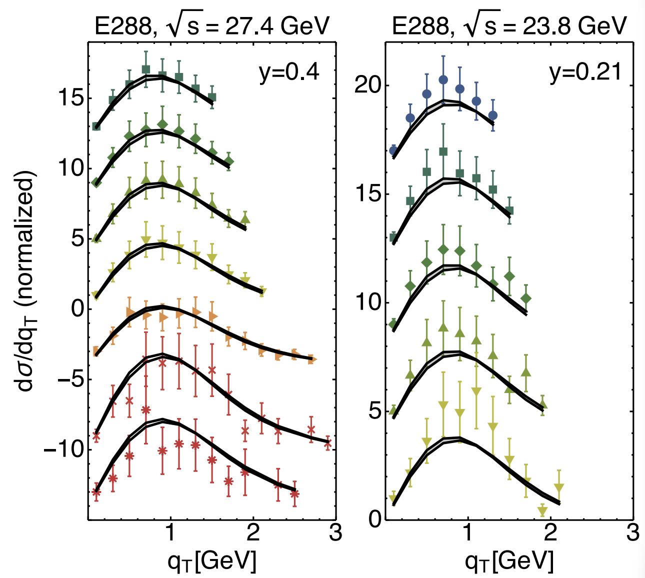
The Pavia 2017 fit

first fit putting together SIDIS, Drell-Yan, and Z production

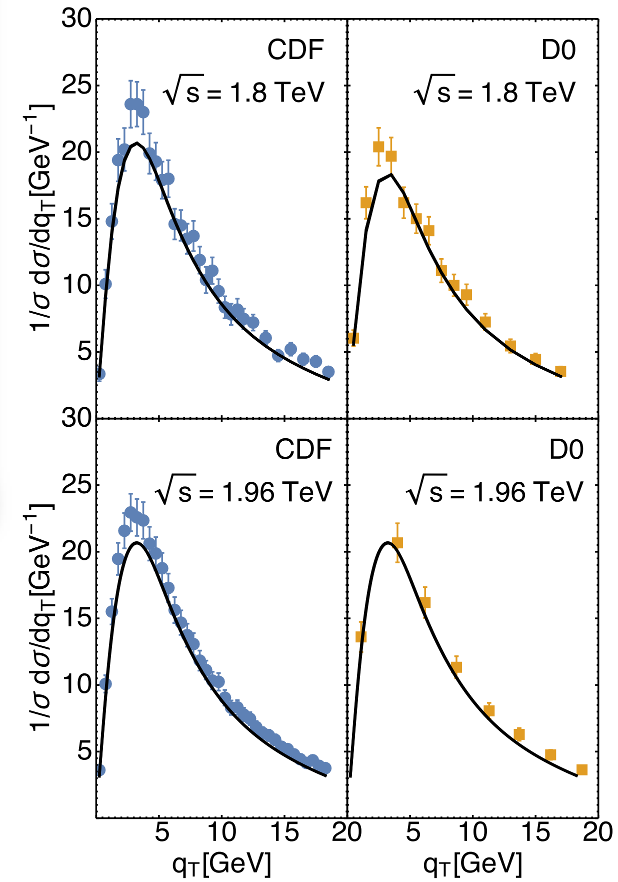




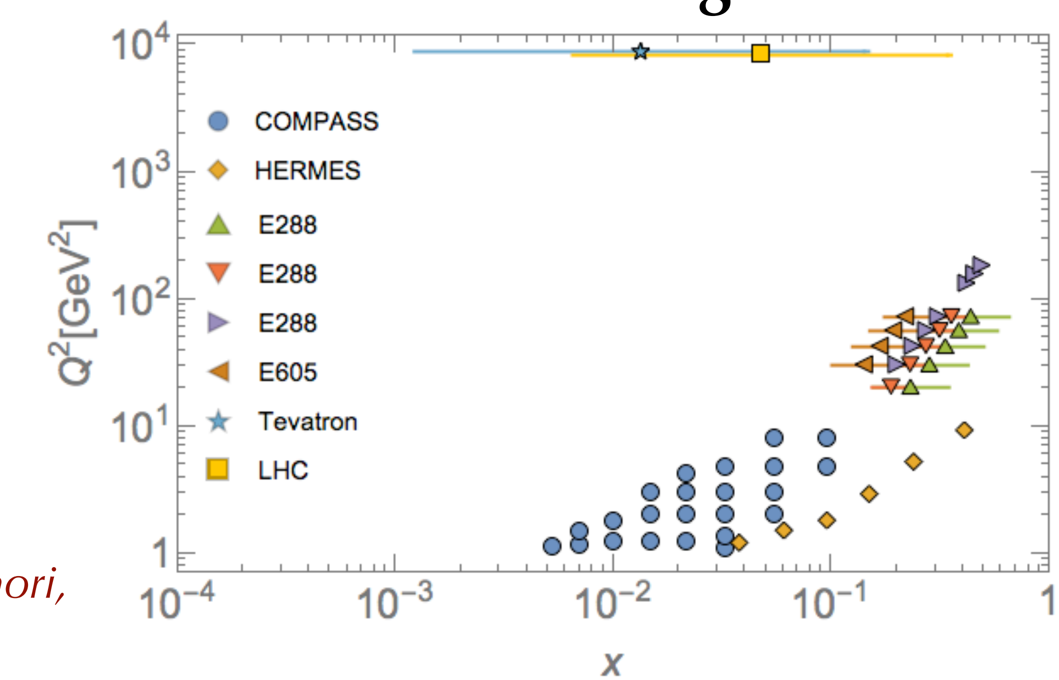
data points
8059

 # fit parameters
11

global χ²/d.o.f.
1.55 ± 0.05



data coverage



*Bacchetta, Delcarro, Pisano, Radici, Signori, JHEP **1706** (17) 081, arXiv:1703.10157*

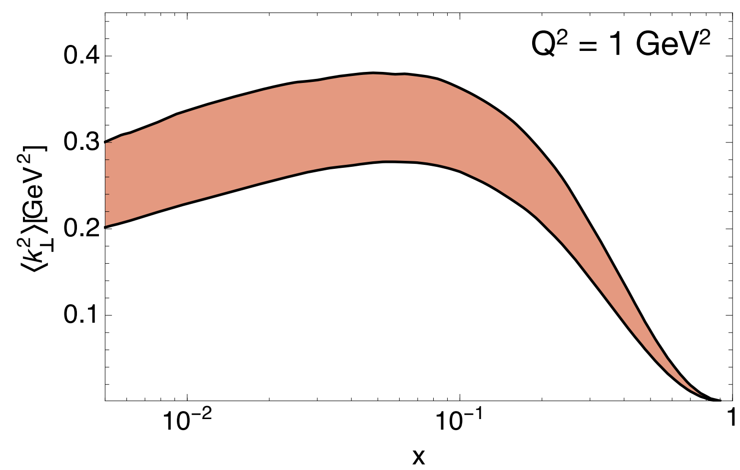
The Pavia 2017 fit

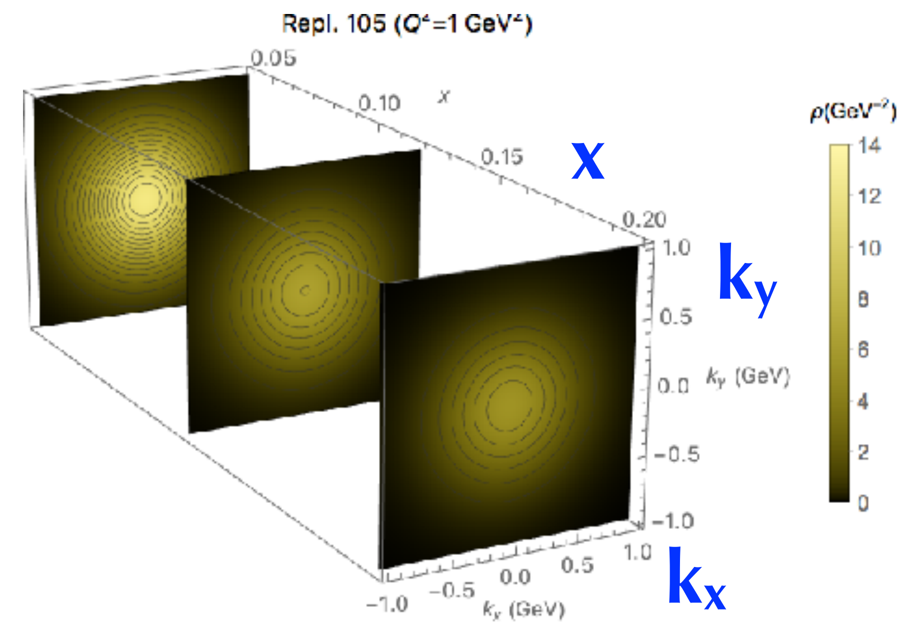
first fit putting together SIDIS, Drell-Yan, and Z production

Bacchetta, Delcarro, Pisano, Radici, Sigı
arXiv:1703.10157

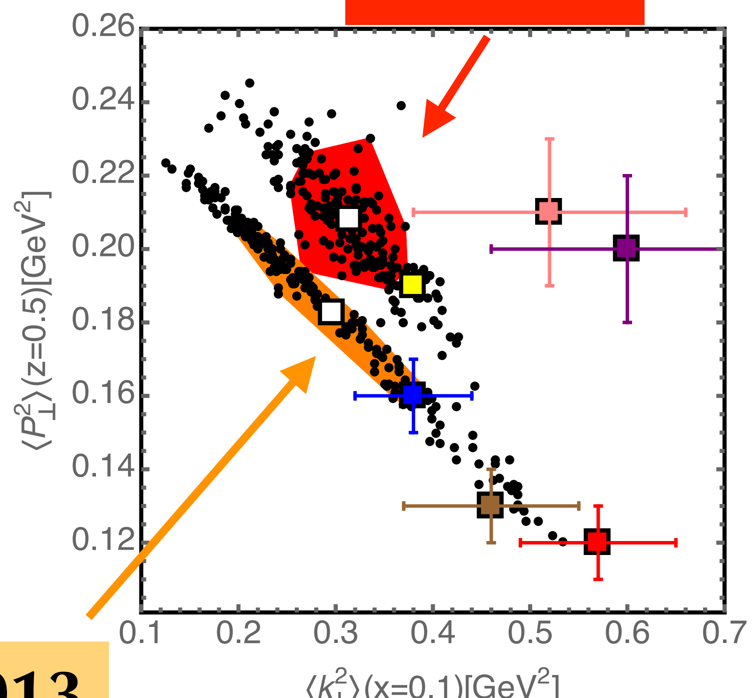
TMD(x,$\mathbf{k}_T$;Q_0) = sum of two Gaussians with width(x)

PDF=NLO GJR 2008





PV 2017



Transverse momentum in FFs

Transverse momentum in PDFs

PV 2013
only Hermes data

anticorrelation (driven by SIDIS) despite Drell-Yan data (but no LHC data)

- Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157
- 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)

Impact of TMD on W mass extraction

PV 2017 global fit: no room for flavor dependence of intrinsic k_T

PV 2013 only Hermes data: slightly better χ^2 with flavor dependence of k_T

Using TMD with intrinsic nonperturbative part $f_{\rm NP}^{q}(x, b_T; Q_0^2)$

- generate pseudo-data for q_T-spectrum of $W^\pm$ with sets of flavor-dep. parameters that give the same q_T-spectrum of Z^0, from p_T-lepton data and uncertainties of ATLAS and CDF
- make a template fit of these pseudo-data by varying M_W on a set of flavor-indep. parameters

*Bacchetta, Bozzi, Radici, Ritzmann, Signori, P.L. **B788** (19) 542, arXiv:1807.02101*

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*Bacchetta, Bozzi, Radici, Ritzmann, Signori, P.L. **B788** (19) 542, arXiv:1807.02101*

⇒ shifts comparable to world-average uncertainty

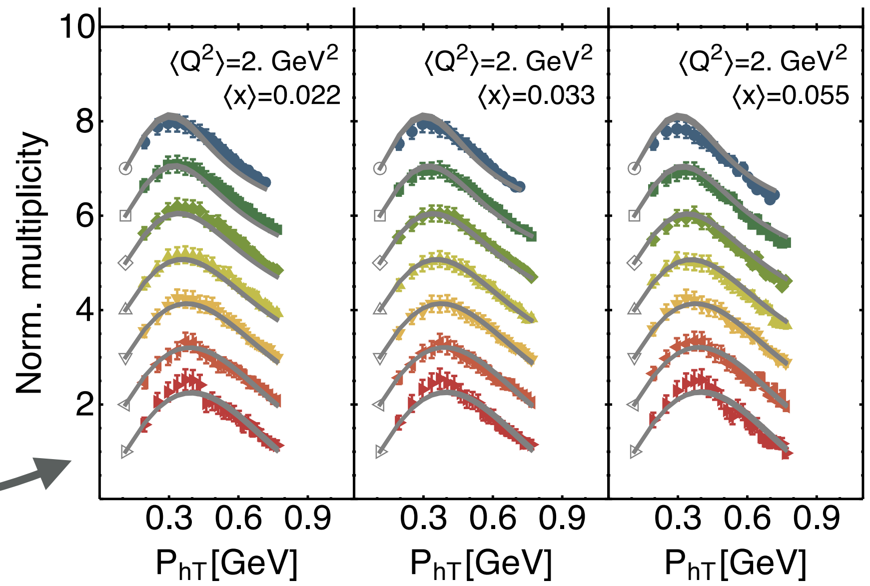
$-6 \leq \Delta M_{W^\pm} \leq +9$ MeV

$-4 \leq \Delta M_{W^-} \leq +4$ MeV

current extractions of M_W do not include flavor sensitivity; we might need it for a better ΔM_W

Problems with normalization of (SIDIS) data

Pavia 2017 global fit: for each {x,z,Q^2} bin fit normalization in first bin in P_{hT}



Problems with normalization of (SIDIS) data

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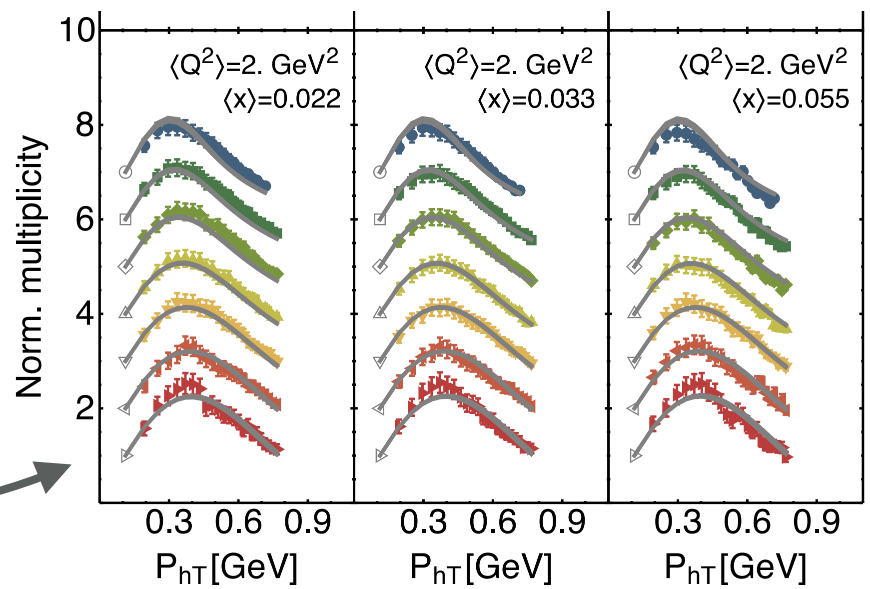
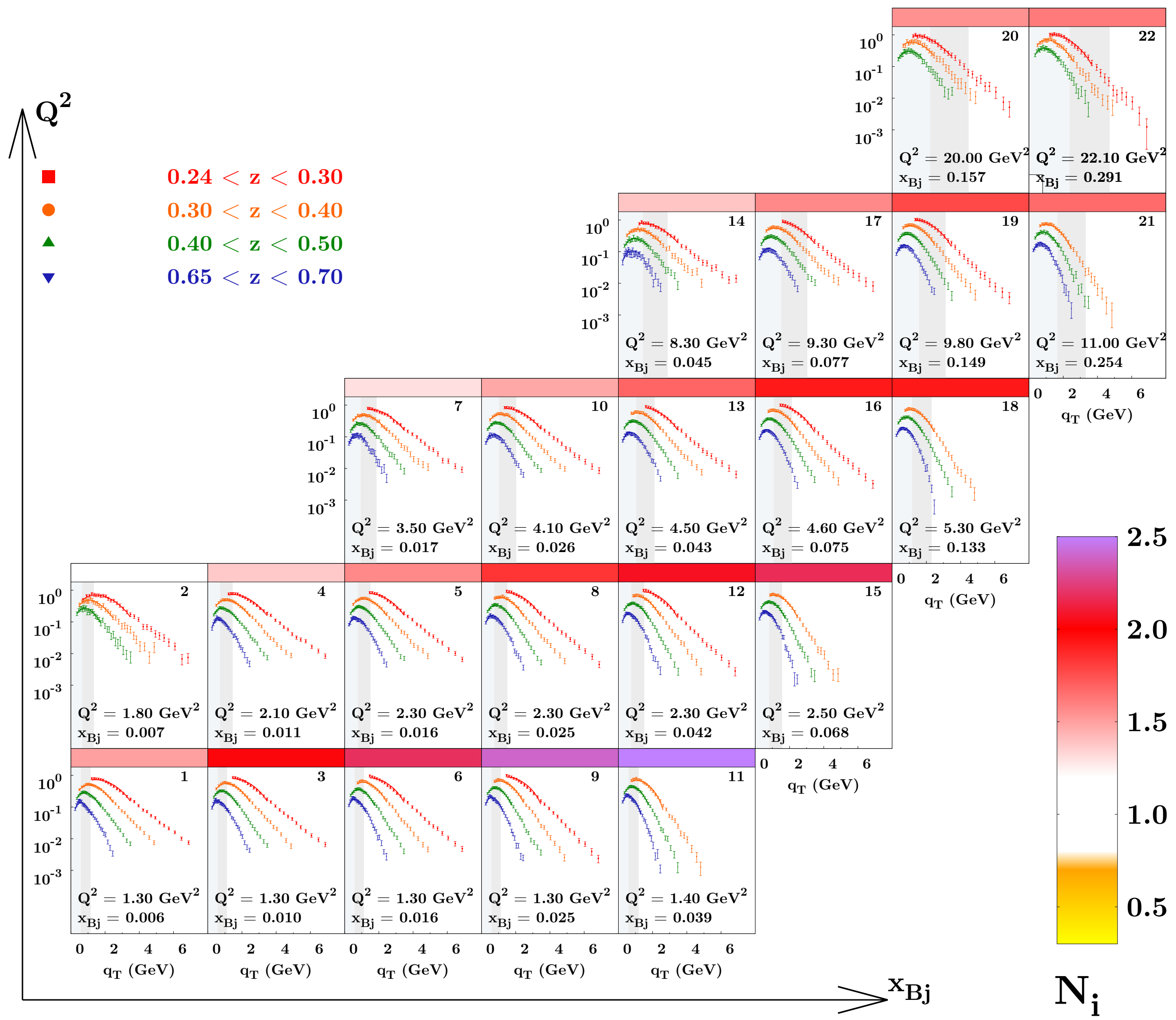
first bin in P_{hT}





the Torino group also confirms that large normalization factors have to be introduced to describe the new COMPASS data

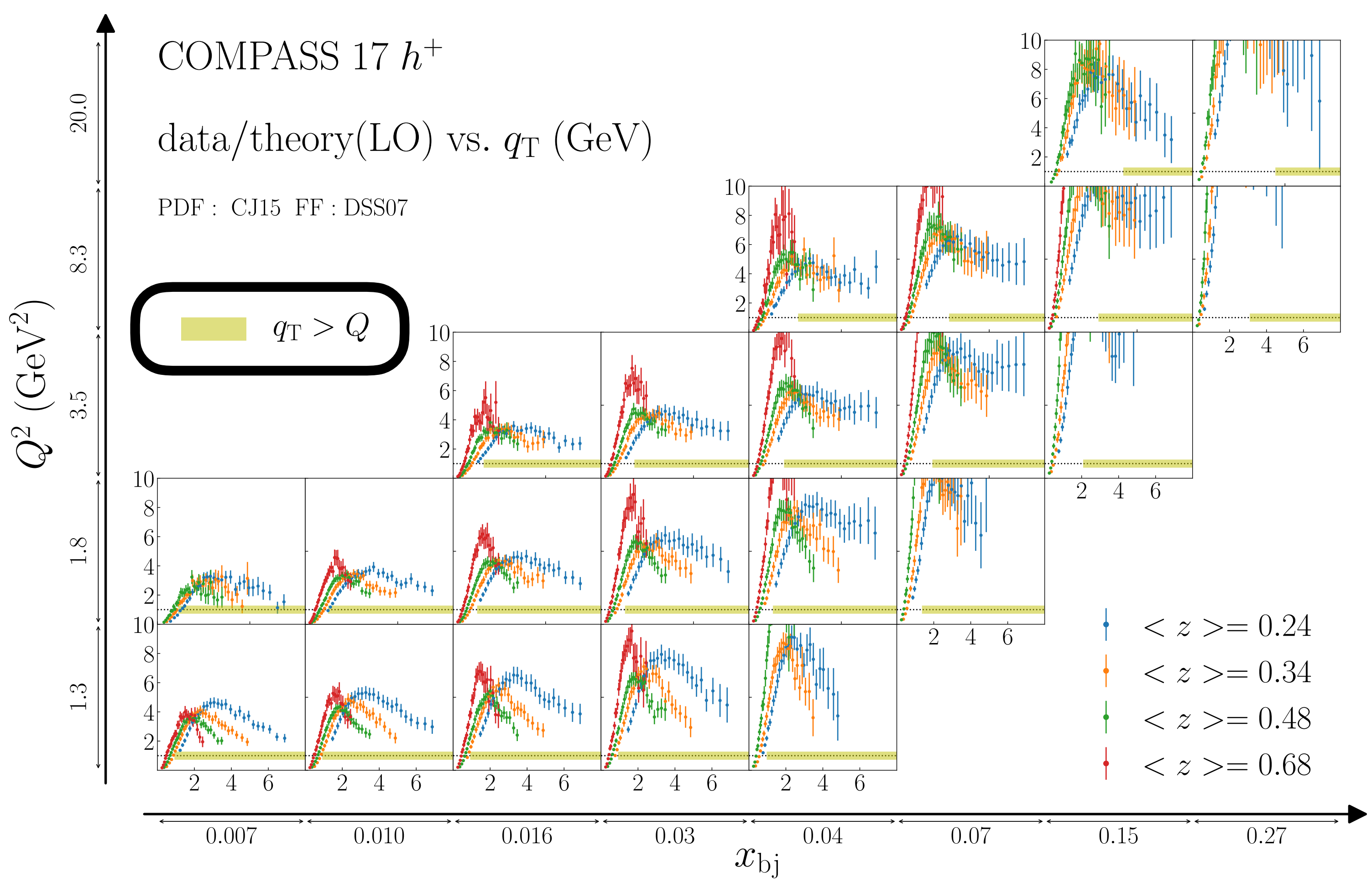
COMPASS Collaboration,
*P.R. D**97** (18) 032006, arXiv:1709.07374*

talk Gonzalez at DIS2019

Problems with normalization of (SIDIS) data

Study of "safe" TMD region

*Boglione et al., JHEP **1910** (19) 122, arXiv:1904.12882*

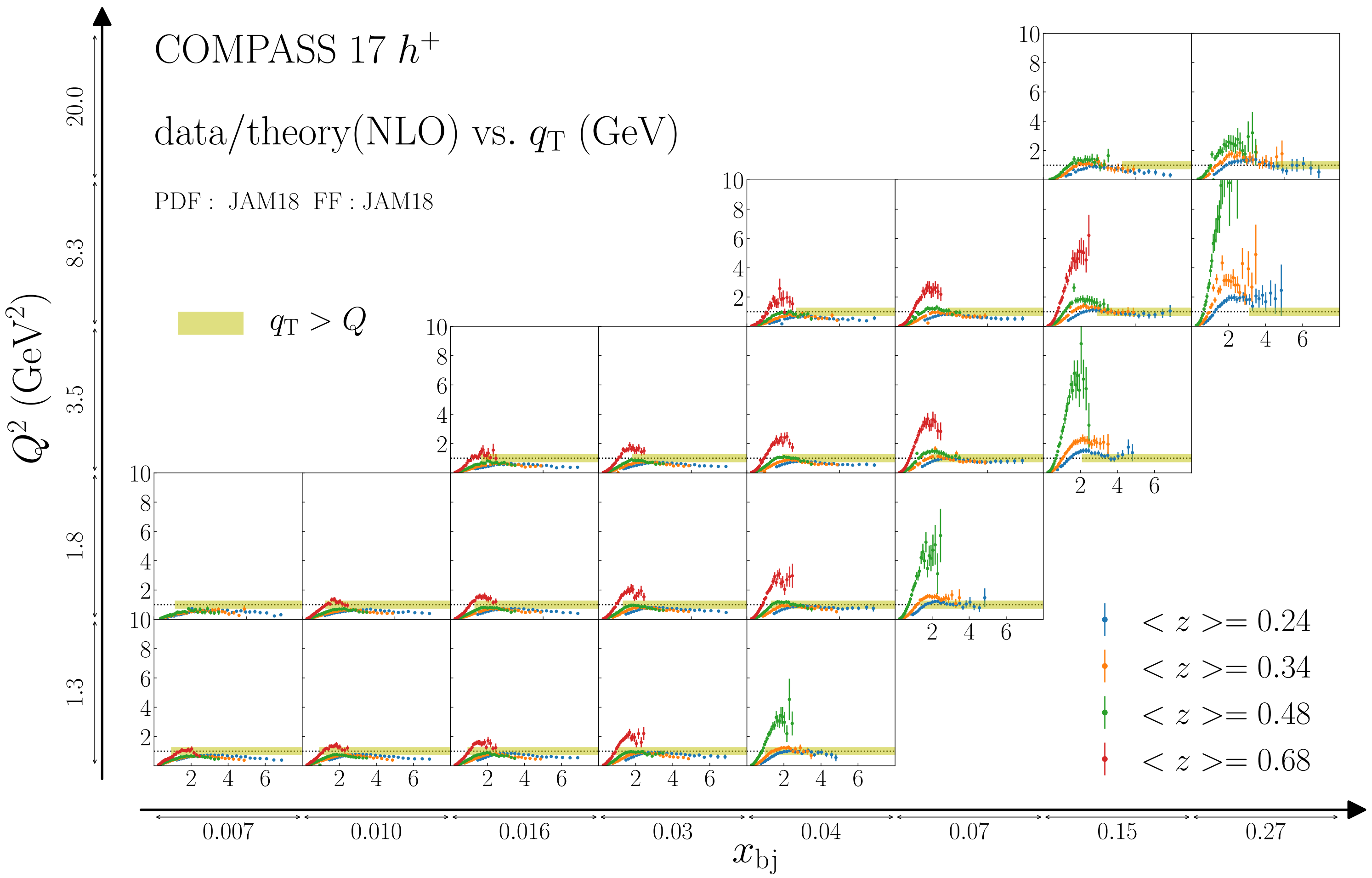


*Gonzalez, Rogers, Sato, Wang, P.R. D**98** (18) 114005, arXiv:1808.04396*

At high q_T, collinear formula should be valid, but large discrepancies are observed

Problems with normalization of (SIDIS) data

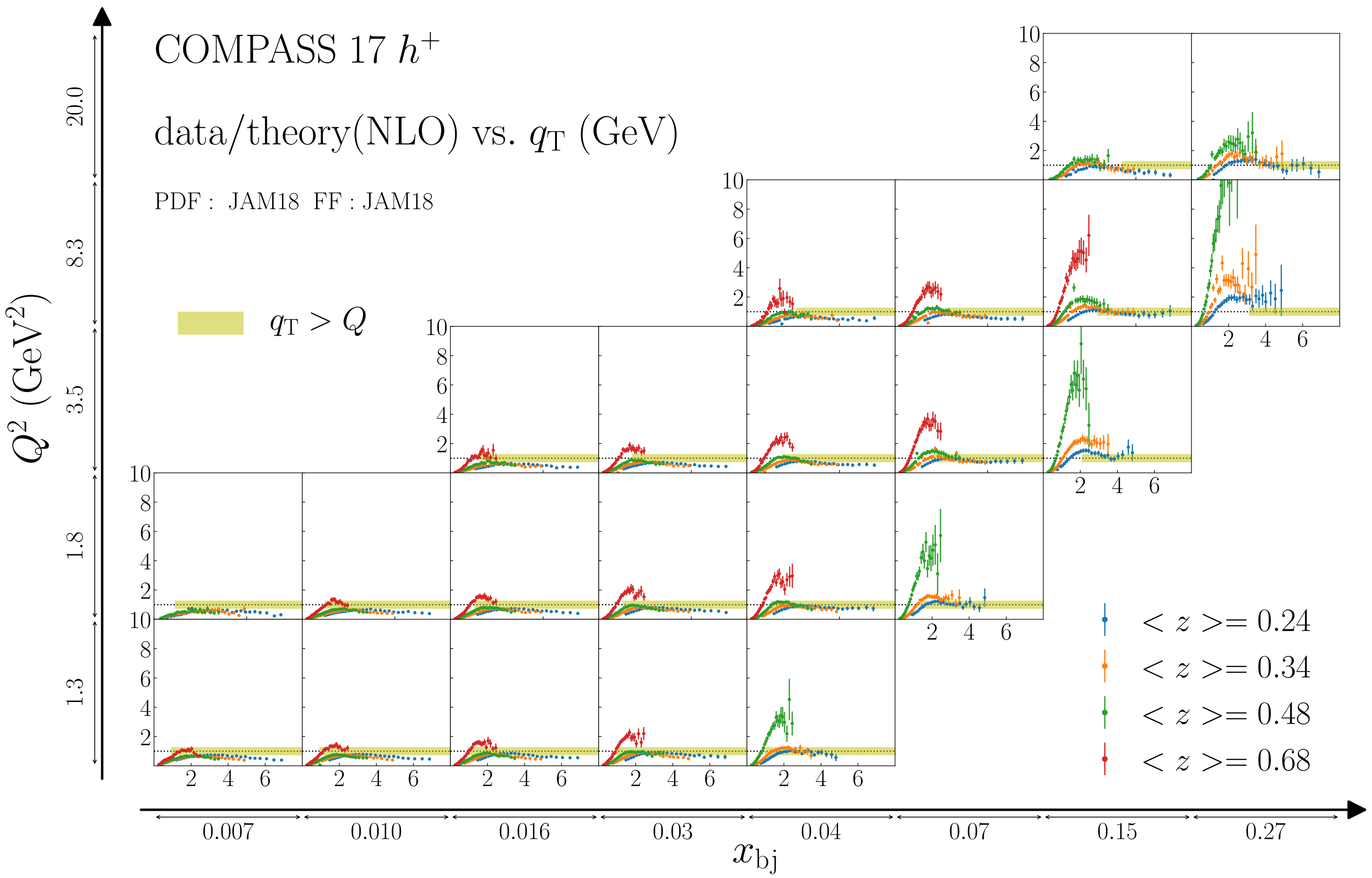
Gonzalez, Rogers, Sato, Wang,
*P.R. D**98** (18) 114005, arXiv:1808.04396*



Discrepancies largely resolved by improving perturb. accuracy (NLO) and modifying the gluon collinear fragmentation function

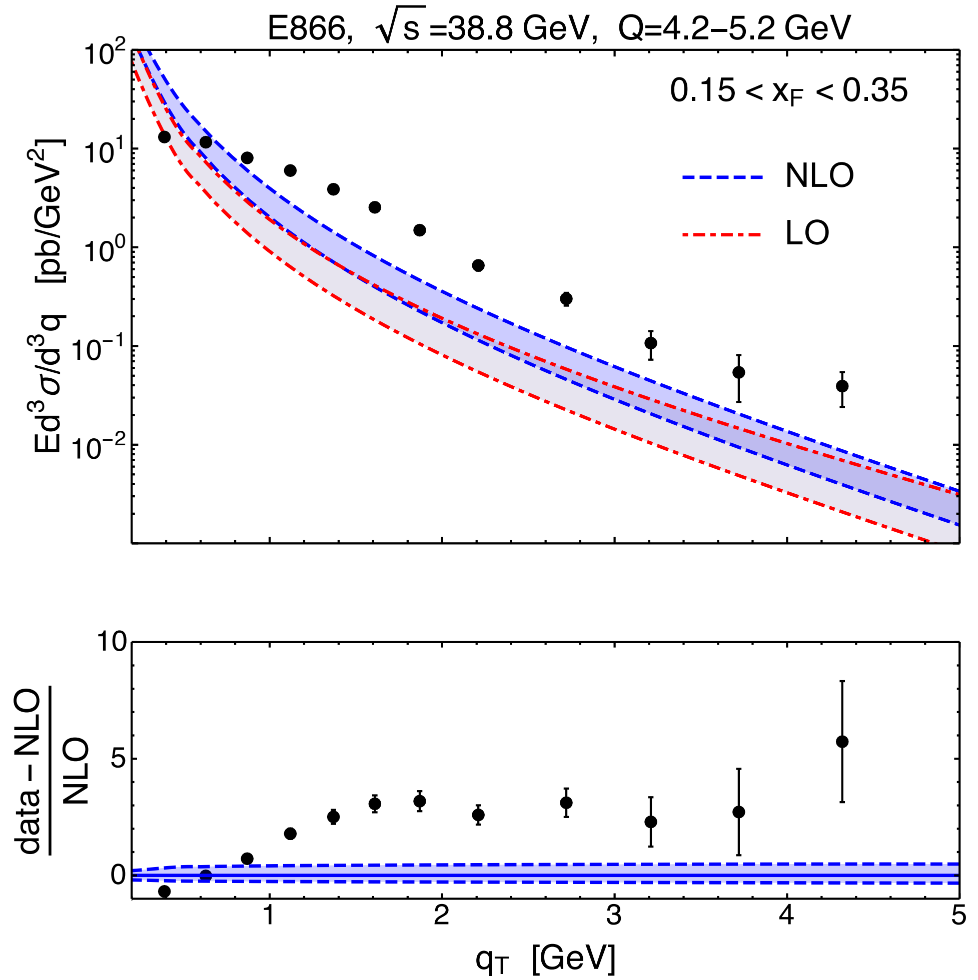
Problems with normalization of (SIDIS) data

Gonzalez, Rogers, Sato, Wang,
*P.R. D**98** (18) 114005, arXiv:1808.04396*



Discrepancies largely resolved by improving perturb. accuracy (NLO) and modifying the gluon collinear fragmentation function

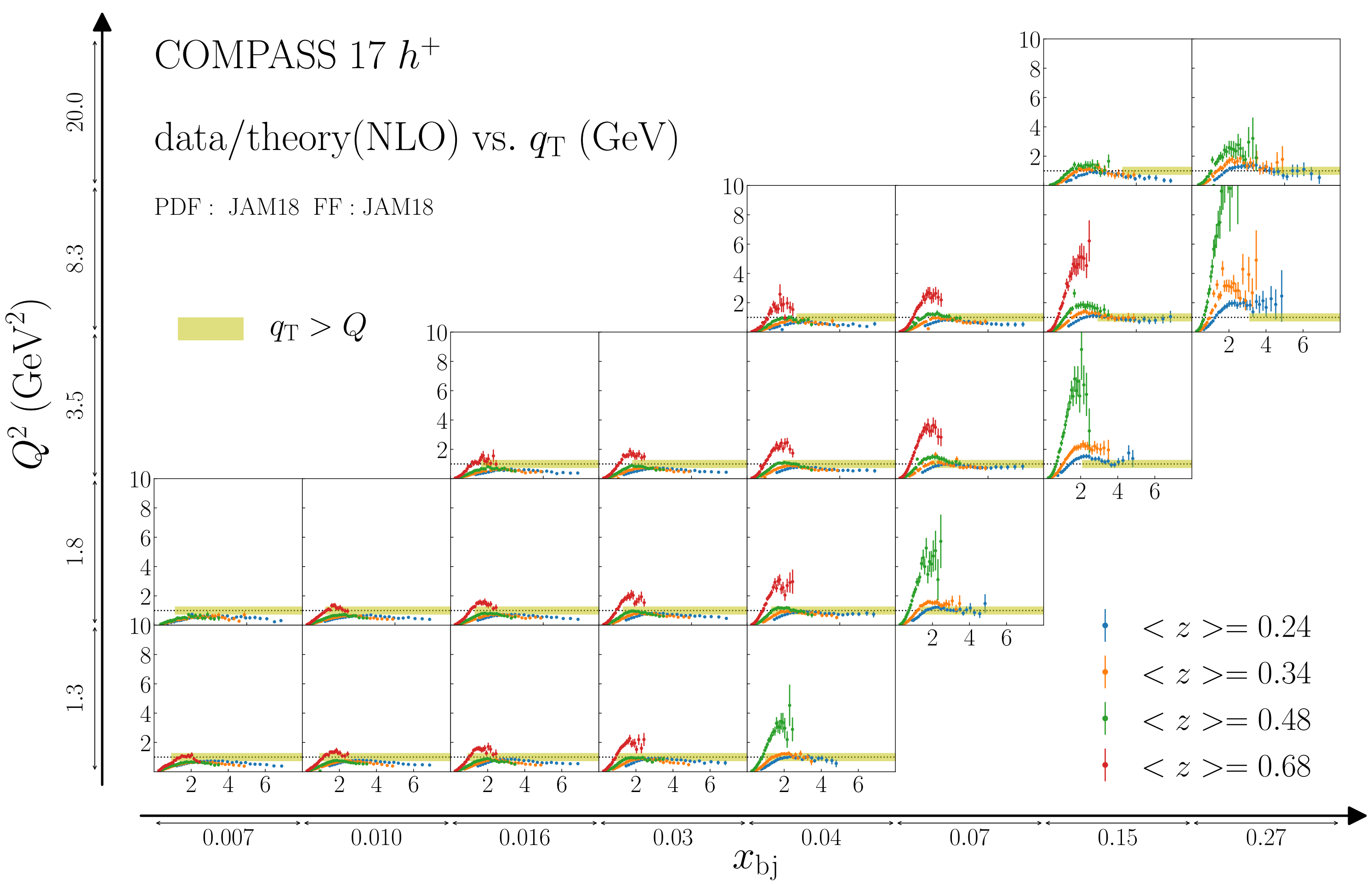
Bacchetta et al.,
*P.R. D**100** (19) 014018, arXiv:1901.06916*



However, problems found also at low-energy Drell-Yan

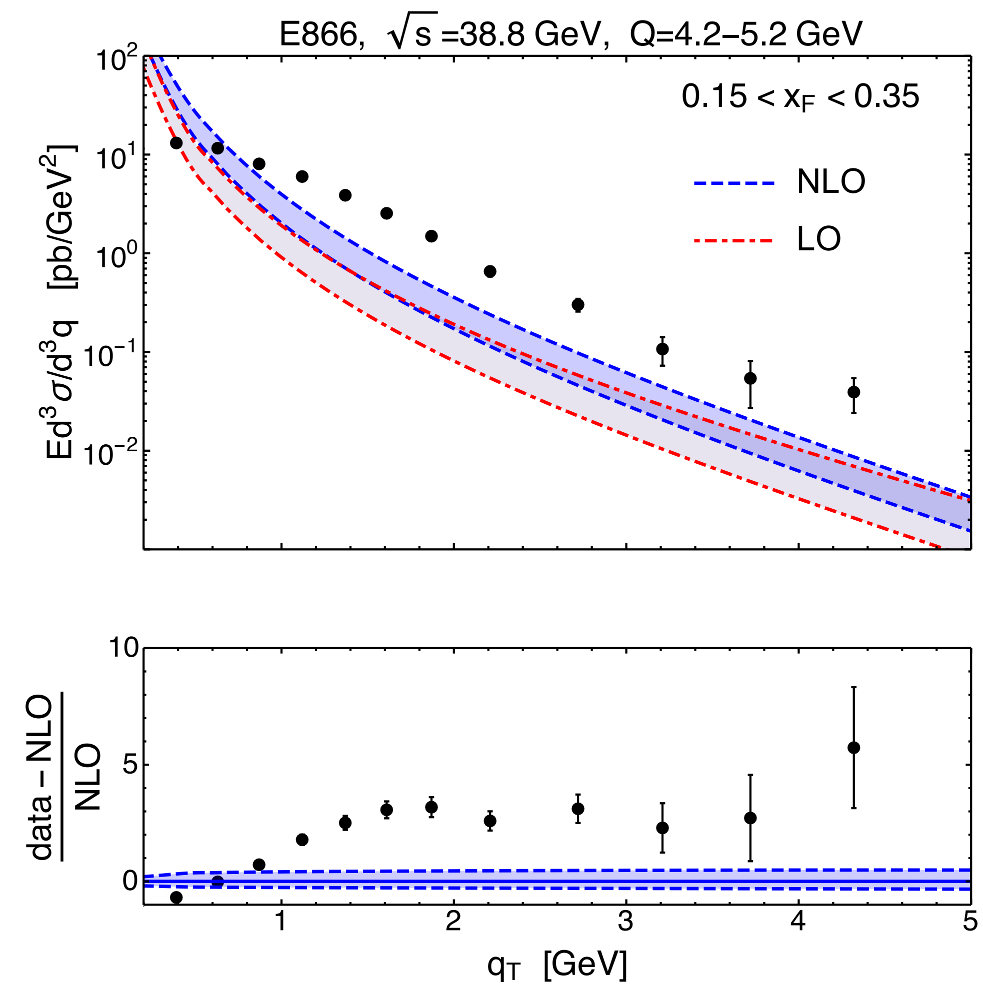
Problems with normalization of (SIDIS) data

Gonzalez, Rogers, Sato, Wang,
*P.R. D**98** (18) 114005, arXiv:1808.04396*



Discrepancies largely resolved by improving perturb. accuracy (NLO) and modifying the gluon collinear fragmentation function

Bacchetta et al.,
*P.R. D**100** (19) 014018, arXiv:1901.06916*

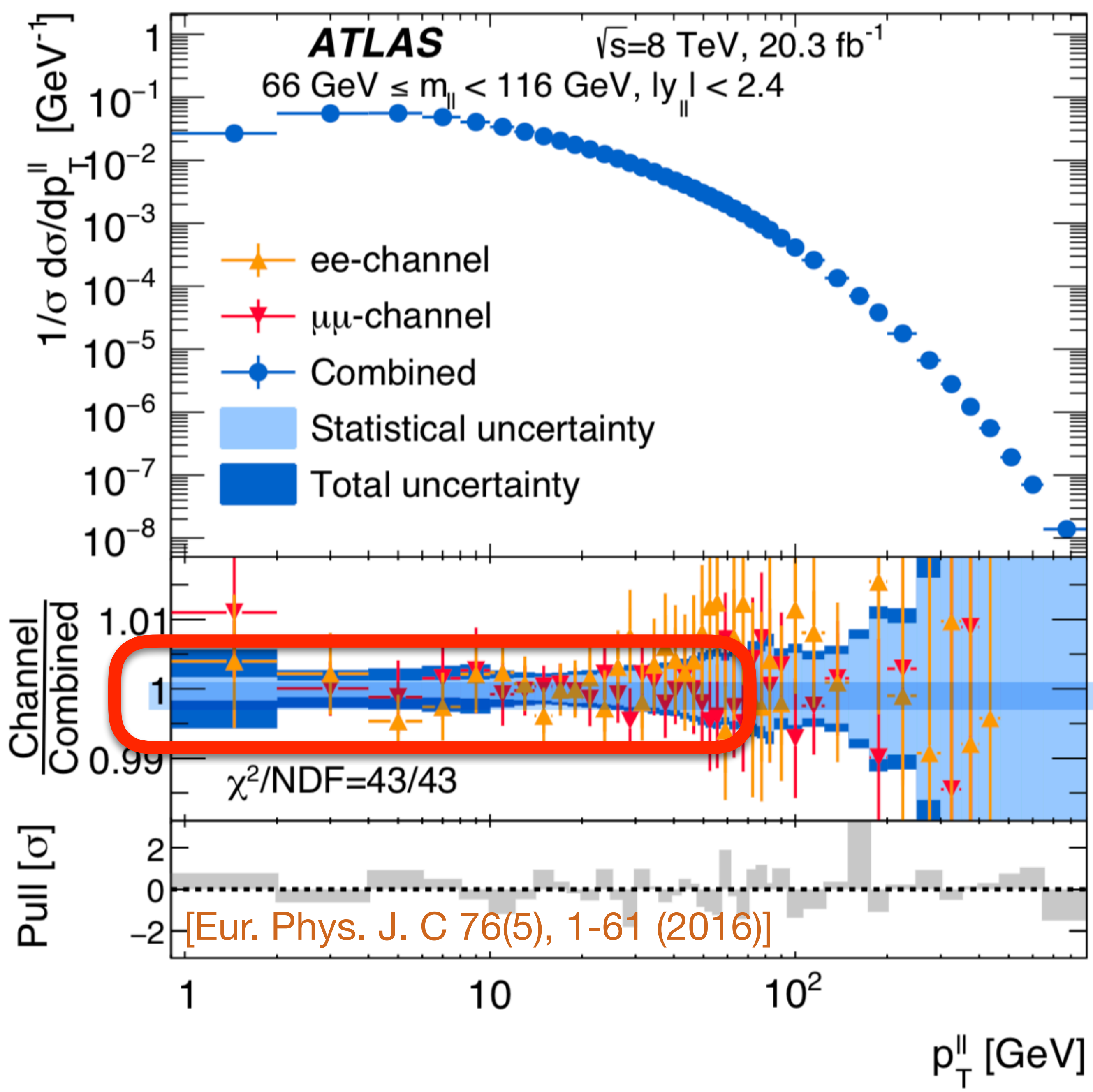


However, problems found also at low-energy Drell-Yan

while trying to solve the (SIDIS) normalization problem, focus on improving the accuracy of TMD description of low-q_T Drell-Yan dσ data

State-of-the-art precision at LHC

Measurements of q_T distributions of Z have reached the sub% precision
Calculations have reached the NNLO-N^{3}LL level *Bizon et al., E.P.J. **C79** (19) 868, arXiv:1905.05171*



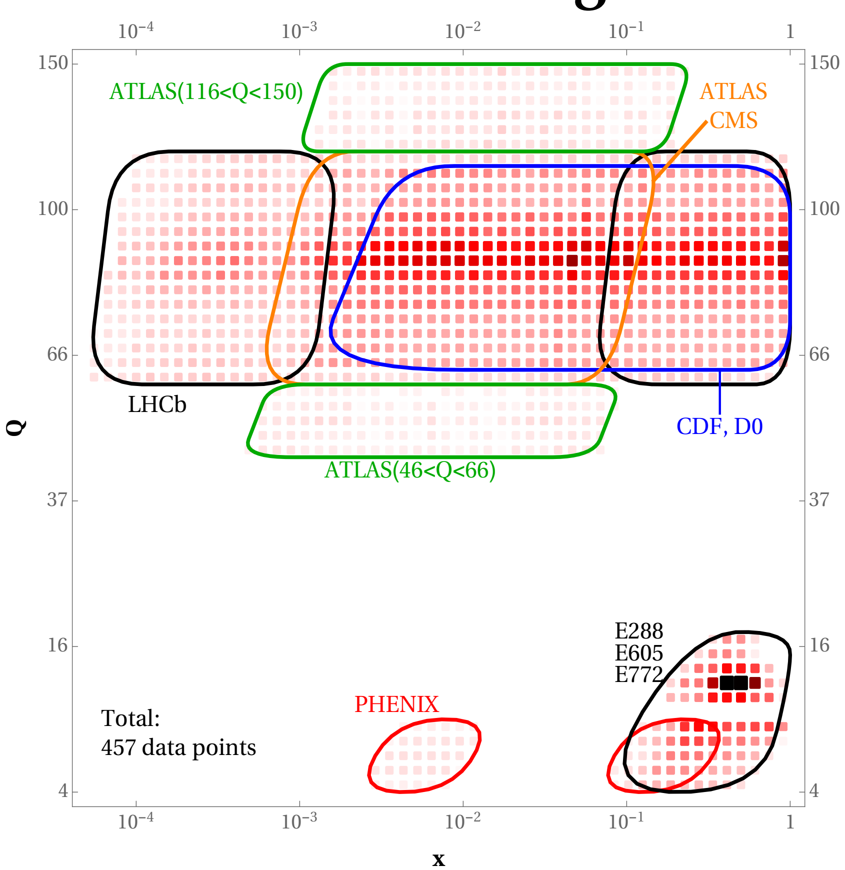
Extractions of unpolarized TMD

	Framework	HERMES	COMPASS	DY	Z production	N of points
Pavia 2013 arXiv:1309.3507	parton model	✔	✘	✘	✘	1538
Torino 2014 arXiv:1312.6261	parton model	✔ (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 (?)
SIYY 2014 arXiv:1406.3073	NLL′	✘	✔	✔	✔	200 (?)
Pavia 2017 arXiv:1703.10157	NLL	✔	✔	✔	✔	8059
SV 2017 arXiv:1706.01473	NNLL′	✘	✘	✔	✔ (LHC)	309
BSV 2019 arXiv:1902.08474	NNLL′	✘	✘	✔	✔ (LHC)	457
Pavia 2019 in preparation	up to N^3LL	✘	✘	✔	✔ (LHC)	319

The BSV 2019 fit

first fit to fully include LHC data at high accuracy NNLO+NNLL

data coverage

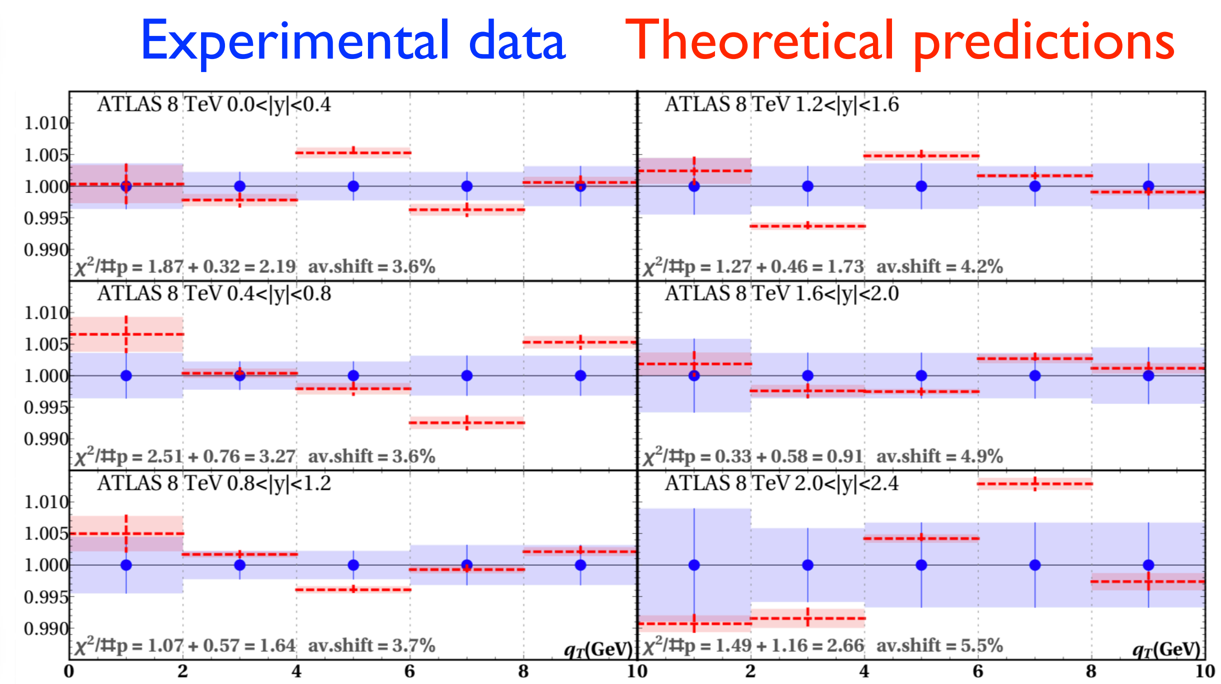


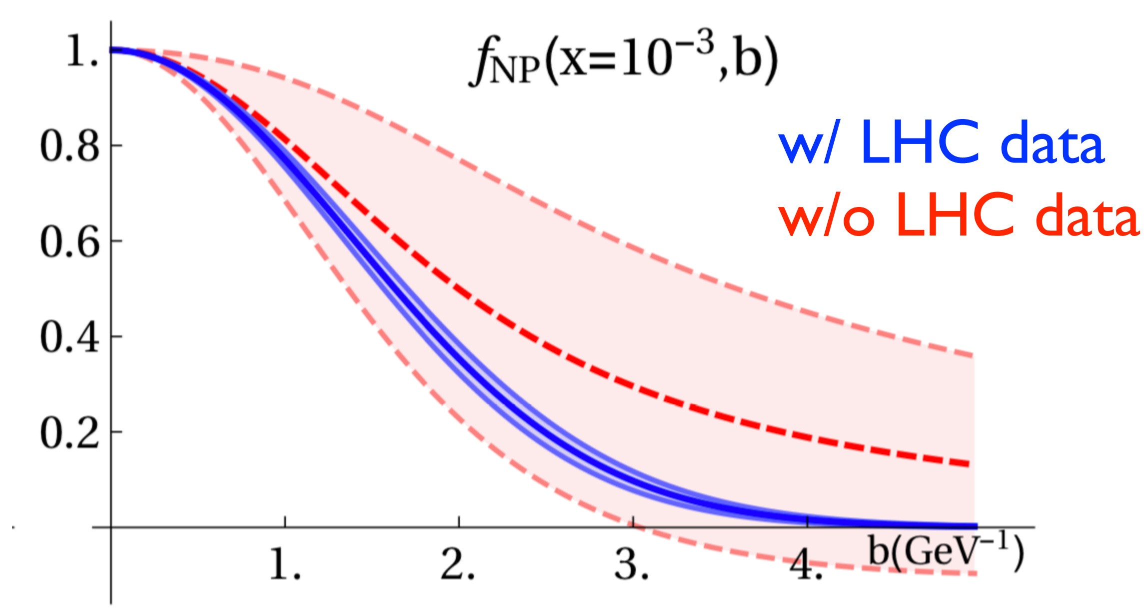
Bertone, Scimemi, Vladimirov,
*JHEP **1906** (19) 028, arXiv:1902.08474*

data points
457

 # fit parameters
7

global χ^2/d.o.f.
1.17





large impact of LHC data !

The Pavia 2019 fit (preliminary)

current top accuracy NNLO+N^{3}LL , matching LHC state-of-art

data coverage similar to BSV19 + STAR data

data points
319

 # fit parameters
9

global χ^2/d.o.f.
1.12 ± 0.01

- correlation of syst. errors (including collinear PDFs)
- Montecarlo method for stat. errors
- including kin. cuts on final leptons
- full integration in bins when required (no "narrow-width",.. approx.)
- no ad-hoc normalization

functional form (nonperturbative part)

$$e^{-g_2 \log\left(\frac{Q^2}{Q_0^2}\right)\frac{b_T^2}{4} - g_{2B}\log\left(\frac{Q^2}{Q_0^2}\right)\frac{b_T^4}{4}} \quad f_{\rm NP}(x, b_T)$$

evolution **intrinsic**

Bacchetta, Bertone, Bissolotti, Bozzi, Delcarro, Piacenza, Radici, in preparation

$$f_{\rm NP}(x, b_T) = (1-\lambda)\frac{1}{1+g_1(x) b_T^2/4} + \lambda\, e^{-g_{1B}(x)\, b_T^2/4}$$

"Q - Gaussian"

$$g_1(x) = N_1 \frac{(1-x)^\alpha x^\sigma}{(1-\hat{x})^\alpha \hat{x}^\sigma} \qquad g_{1B}(x) = N_2 \frac{x^{\alpha'}(1-x)^{\beta'}}{\hat{x}^{\alpha'}(1-\hat{x})^{\beta'}}$$

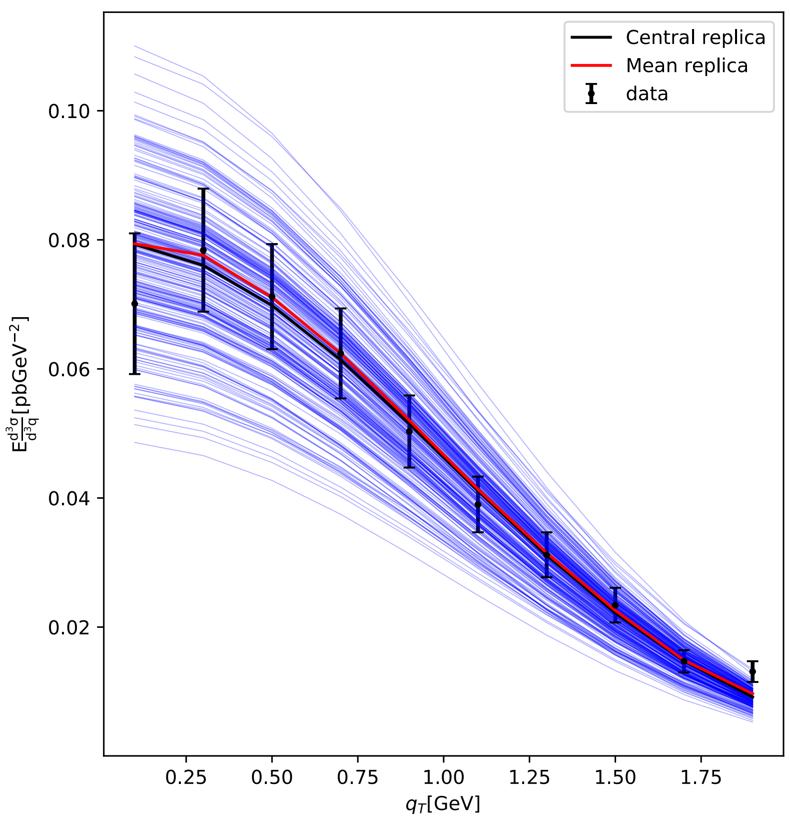
width(x)
(similar to PV2017)

PDF = MMHT2014nnlo68cl

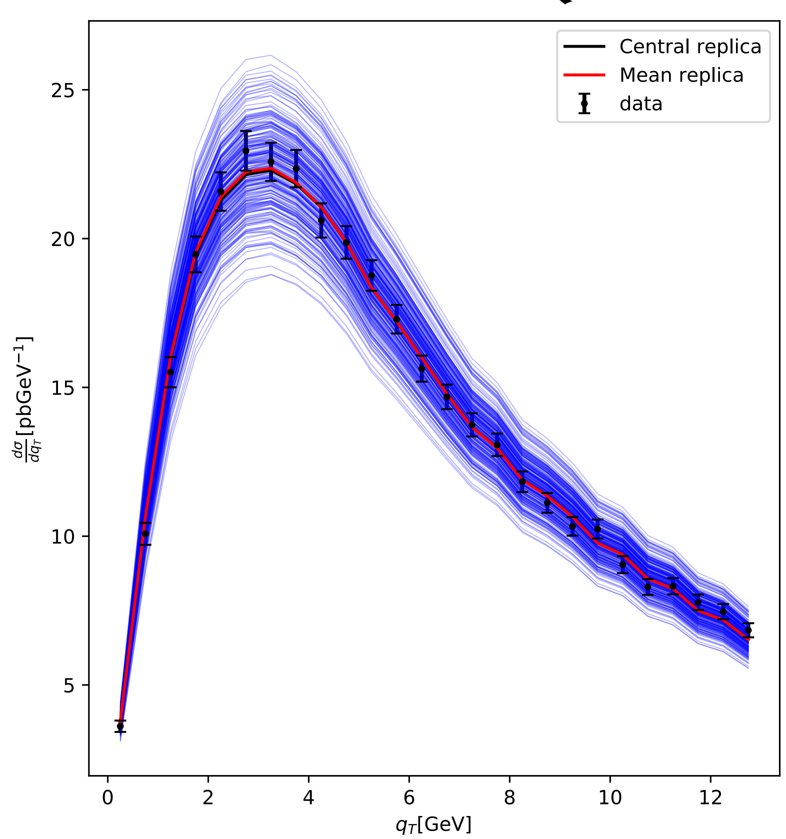
The Pavia 2019 fit (preliminary)

Very good reproduction of low- and high-energy data

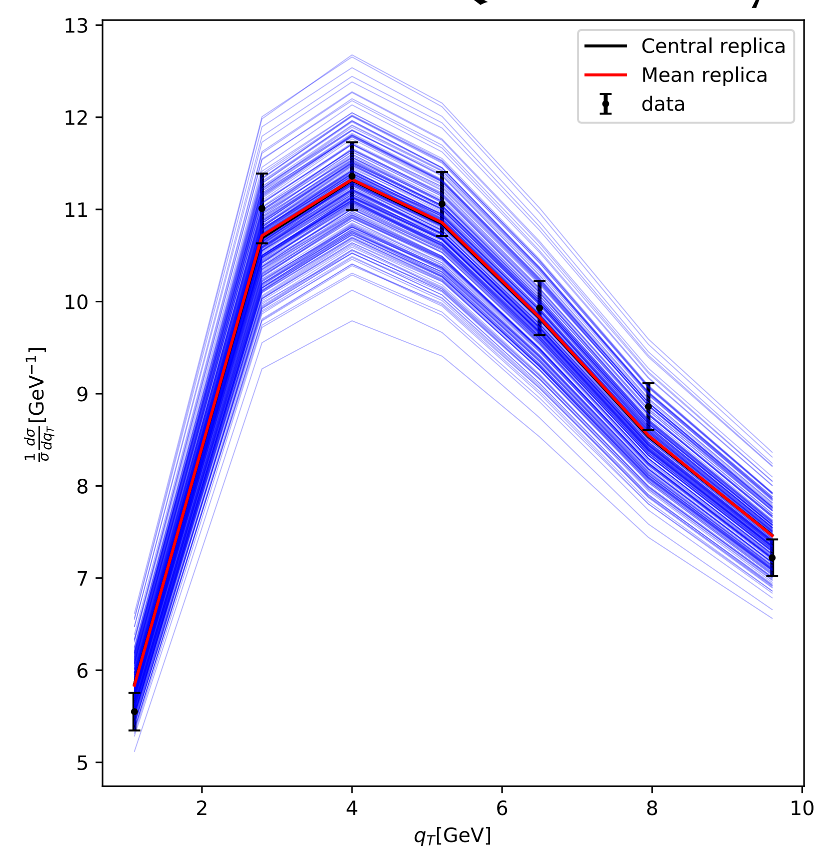
E605 10.5< Q< 11.5 x_F=0.1



CDF RunII 66< Q< 116



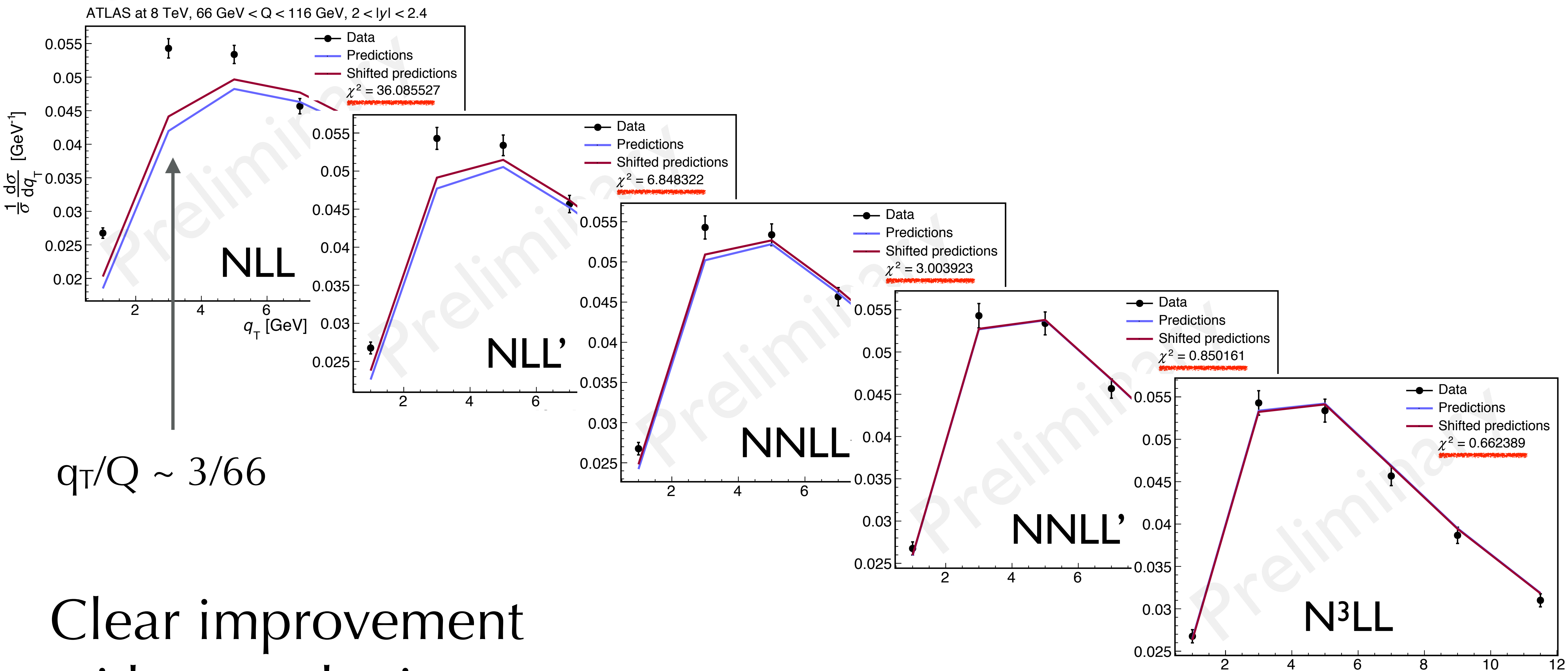
LHCb 13 TeV 60< Q< 120 2< y< 4.5



300 replicas

Bacchetta, Bertone, Bissolotti, Bozzi, Delcarro, Piacenza, Radici, in preparation

The Pavia 2019 fit (preliminary)



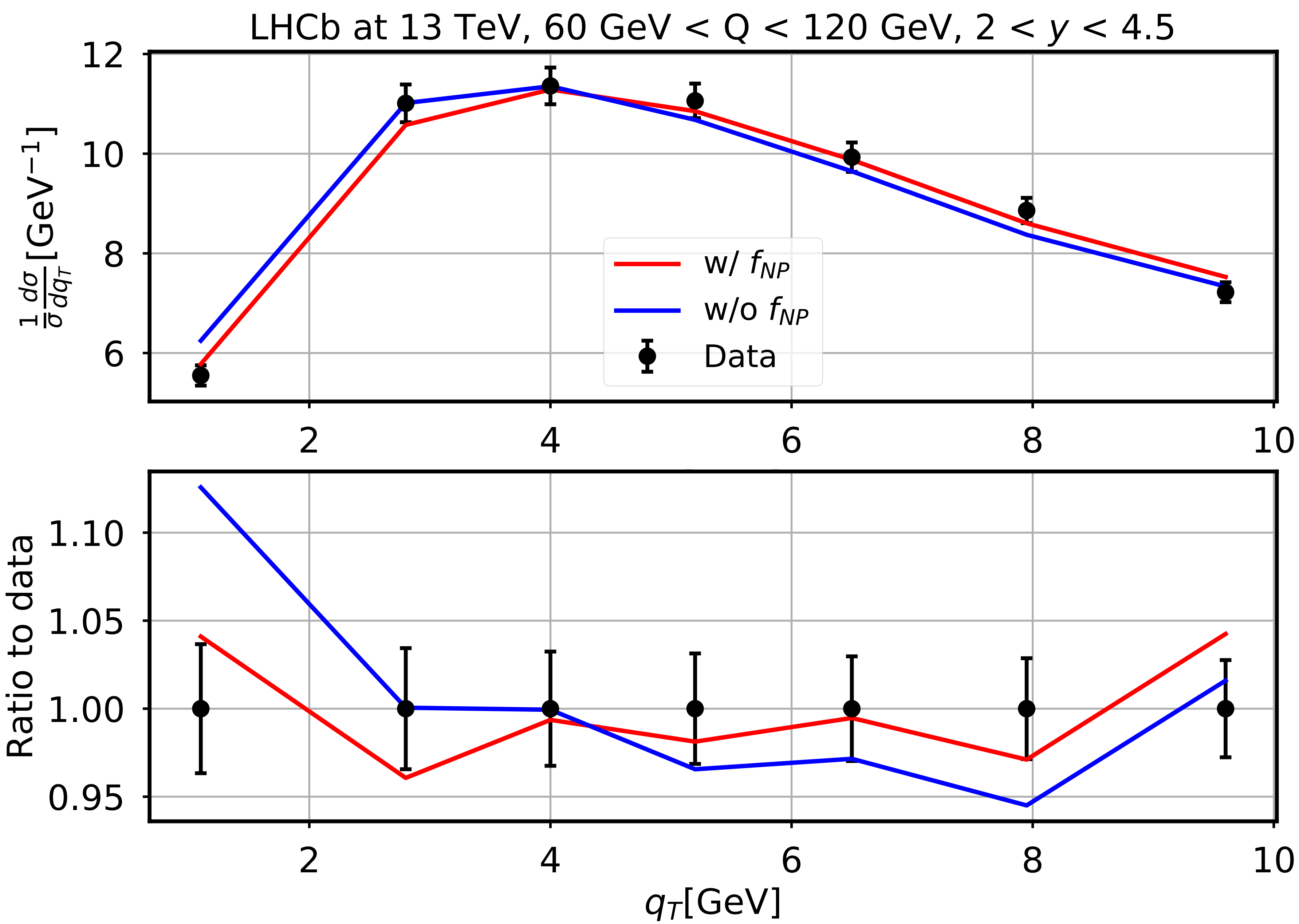
$q_T/Q \sim 3/66$

Clear improvement
with perturbative accuracy;
helps particularly at low q_T/Q (“TMD regime”)

Bacchetta, Bertone, Bissolotti, Bozzi, Delcarro, Piacenza, Radici, in preparation

The Pavia 2019 fit (preliminary)

Effect of nonperturbative intrinsic part $f_{NP}(x,b_T)$
(not included in other benchmark codes)

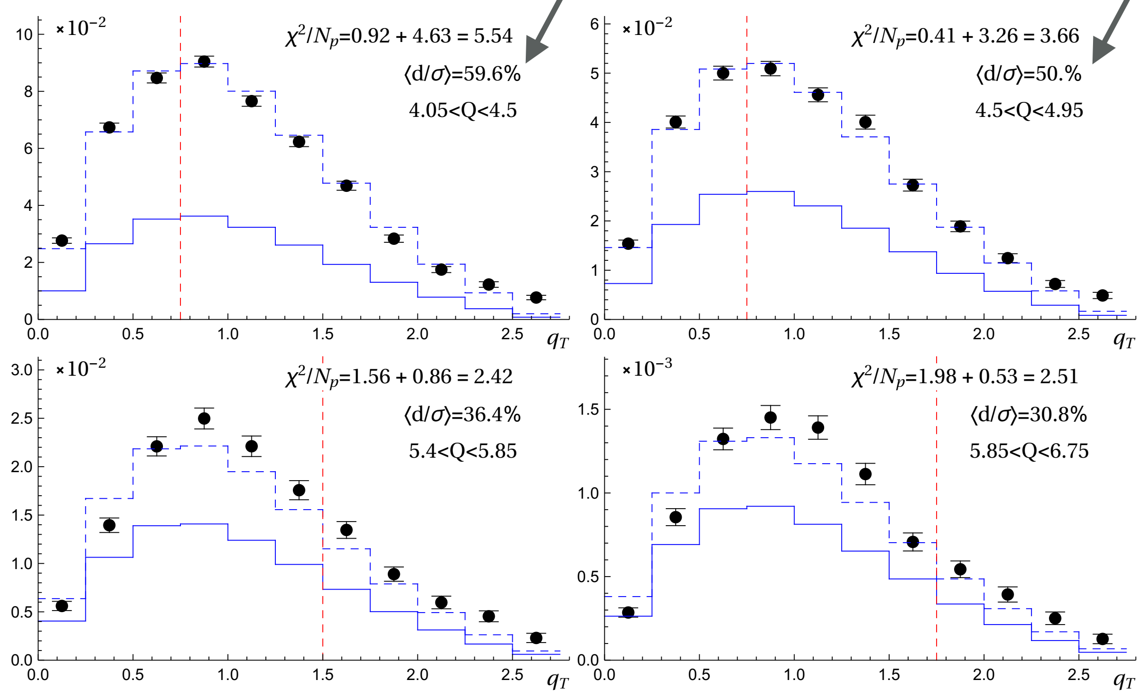


G. Bozzi
CERN EW Working Group, 10-14-2019

Pion unpolarized TMD

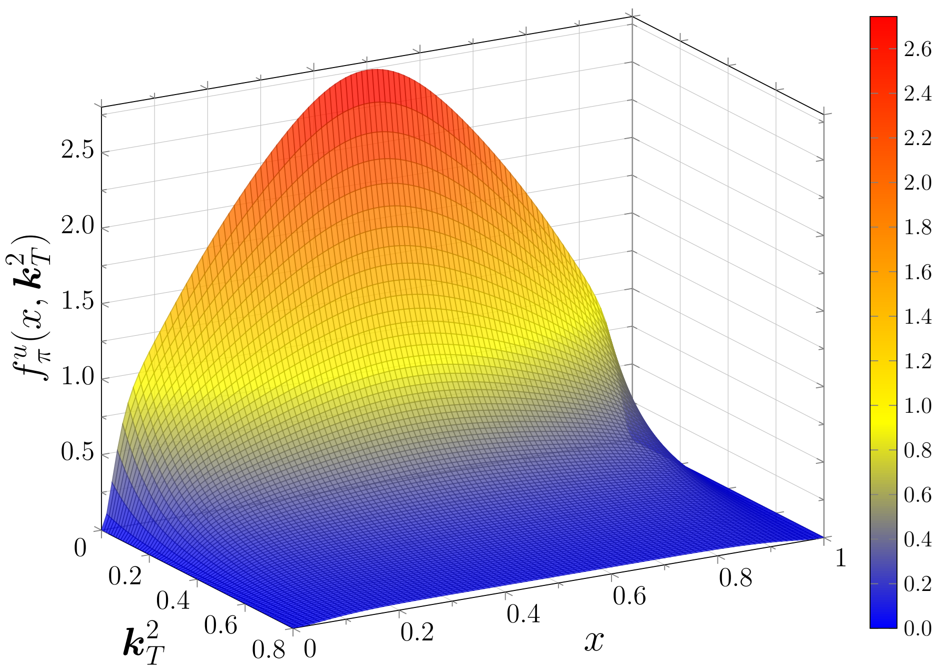
also affected by large ad-hoc normalization

Vladimirov,
*JHEP **1910** (19) 090, arXiv:1907.10356*



fit to E615 data

$Q^2 = 0.52$ GeV^2



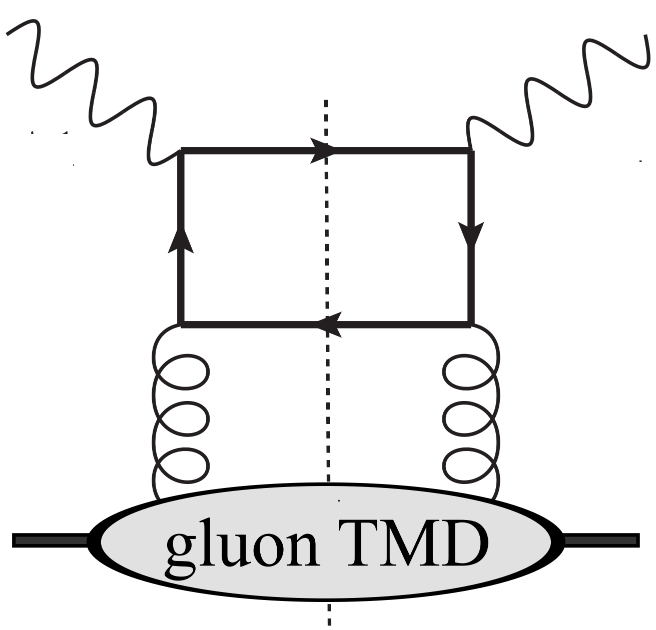
calculation of pion TMD based on
Dyson-Schwinger equations

Shi & Cloet,
*P.R.L. **122** (19) 082301, arXiv:1806.04799*

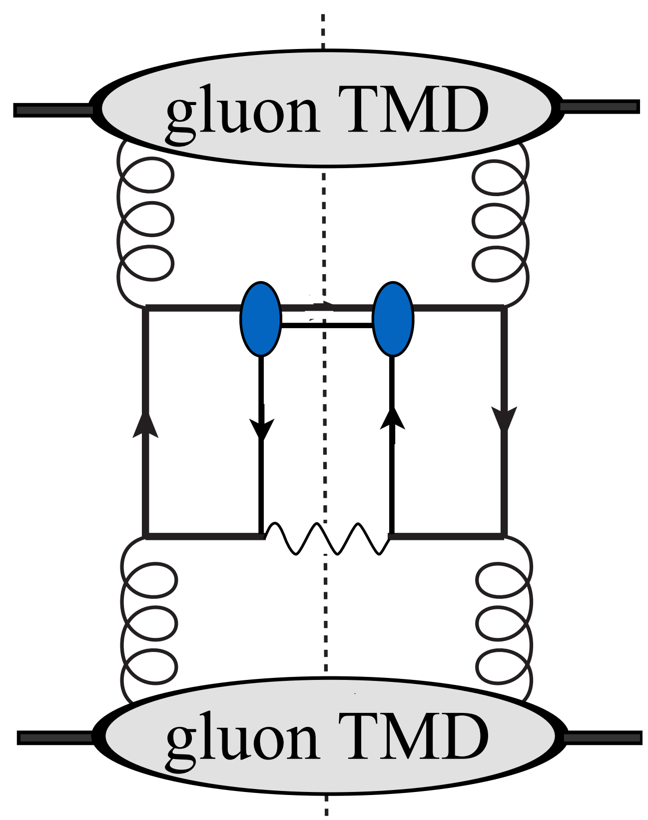
Gluon TMDs

basically unknown; so far, only explorations

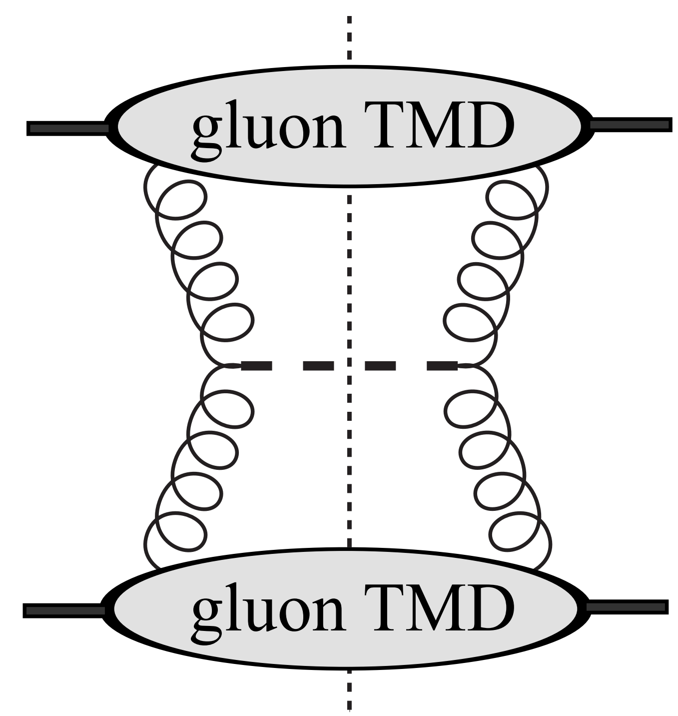
$e\ p \to e$ jet jet X



$p\ p \to J/\psi\ \gamma\ X$



$p\ p \to \eta_c\ X$



see, e.g.,

Boer, den Dunnen, Pisano, Schlegel, Vogelsang, P.R.L. ***108*** *(12) 032002*
den Dunnen, Lansberg, Pisano, Schlegel, P.R.L. ***112*** *(14) 212001*
*Mukherjee & Rajesh, P.R. D**93** (16)*
.....

The TMDs at leading twist

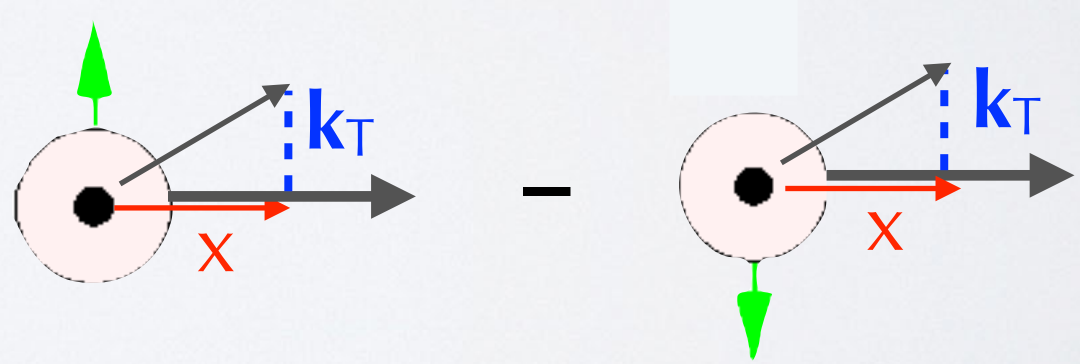
quark

nucleon

at leading twist

Nucleon Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	$f_1 =$	*	$h_1^\perp =$ -
L	*	$g_1 =$ -	$h_{1L}^\perp =$ -
T	$f_{1T}^\perp =$ -	$g_{1T} =$ -	$h_1 =$ - $h_{1T}^\perp =$ -

the Sivers function



(spin-orbit) correlation between k_T of parton and spin of Nucleon

the Sivers effect

Bacchetta & Contalbrigo,
*Il Nuovo Saggiatore **28** (12) n. 1,2*

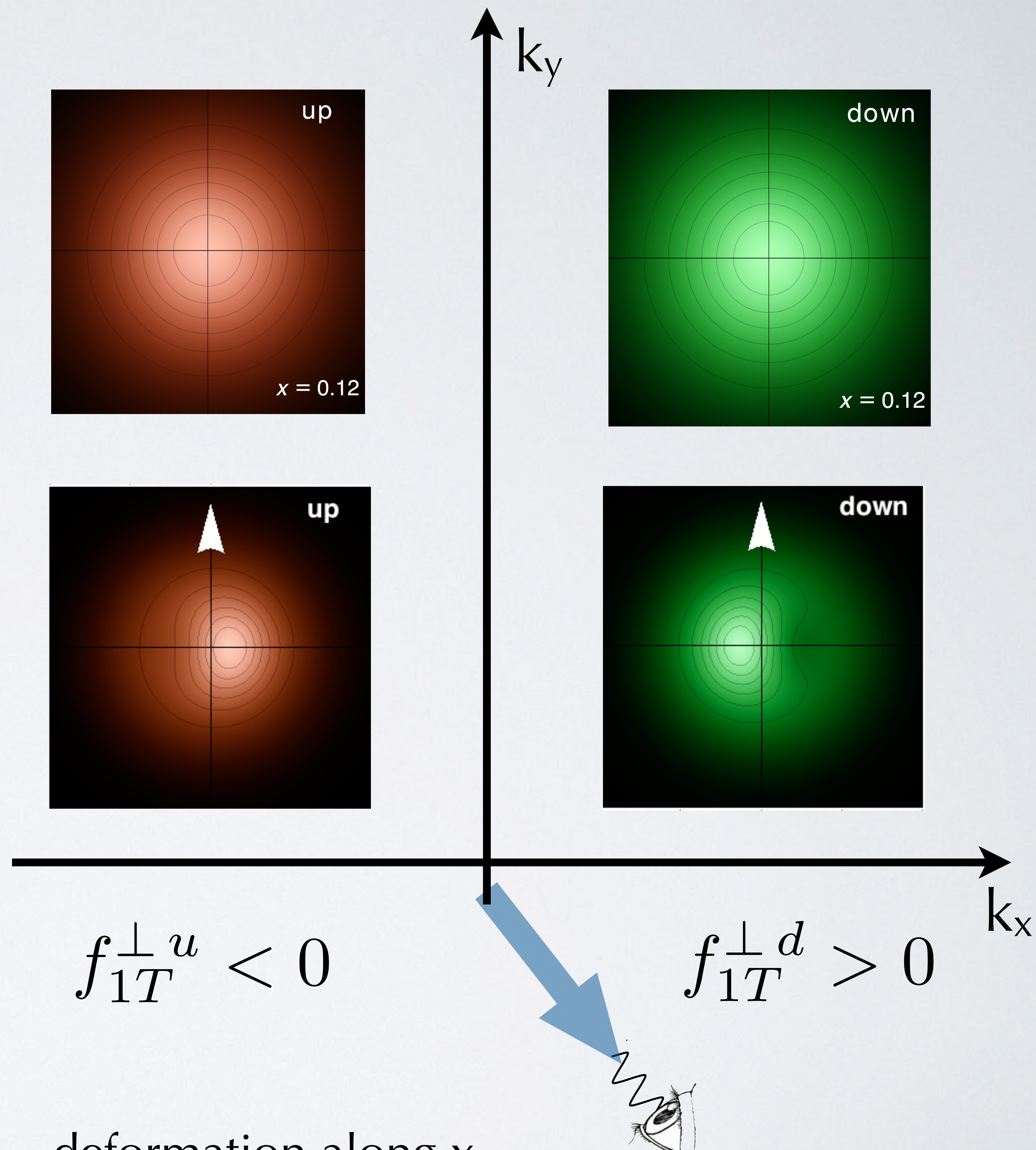
no polarization

polarization S_y ↑

distortion of quark distribution
in transversely polarized proton $P^\uparrow$

$$f_{q/p^\uparrow}(x,\boldsymbol{k}_T) = f_1^q(x,\boldsymbol{k}_T) - f_{1T}^{\perp q}(x,\boldsymbol{k}_T)\,\boldsymbol{S}\cdot\left(\frac{\hat{\boldsymbol{P}}}{M}\times\boldsymbol{k}_T\right)$$

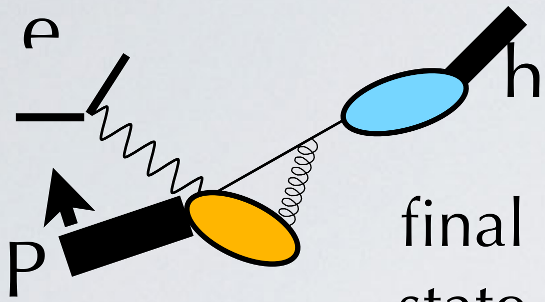
*Sivers, P.R. D**41** (90) 83*



$f_{1T}^{\perp u} < 0$ $f_{1T}^{\perp d} > 0$

deformation along x
depends on flavor

non-universality of Sivers function



final state

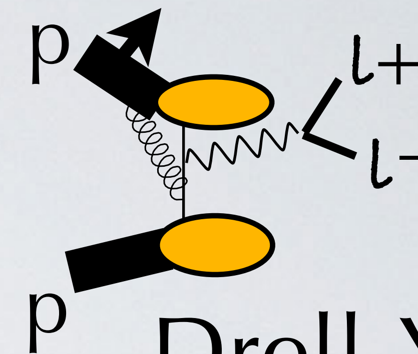
SIDIS

Collins, P.L. ***B536*** (02)

$$\text{Sivers}\Big|_{\text{SIDIS}} = -\text{Sivers}\Big|_{\text{D-Y}}$$

prediction based on fundamental properties of QCD

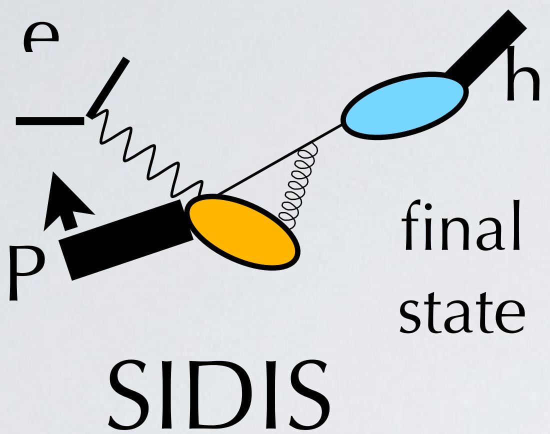
initial state



Drell-Yan

x_F

non-universality of Sivers function



Collins, P.L. ***B536*** *(02)*

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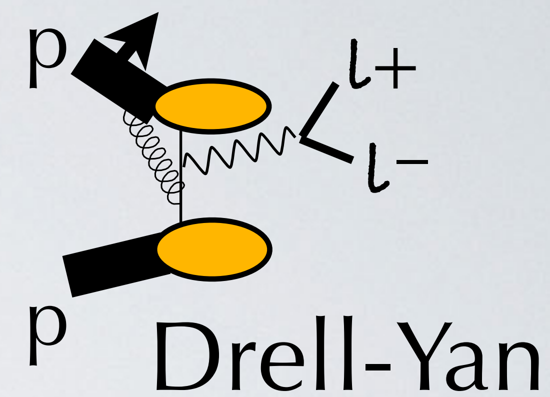
prediction based on fundamental properties of QCD

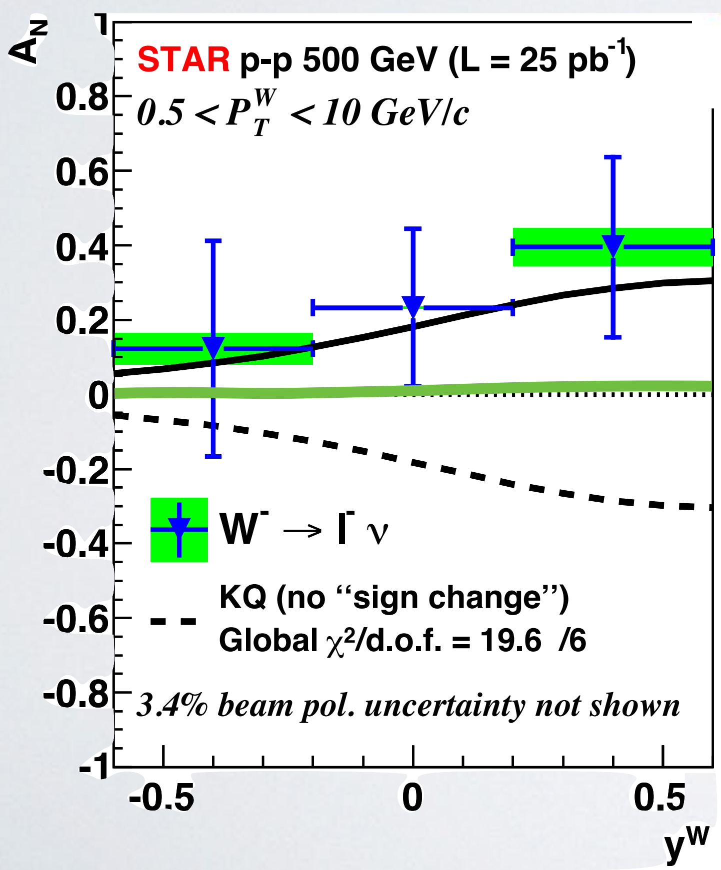
initial state



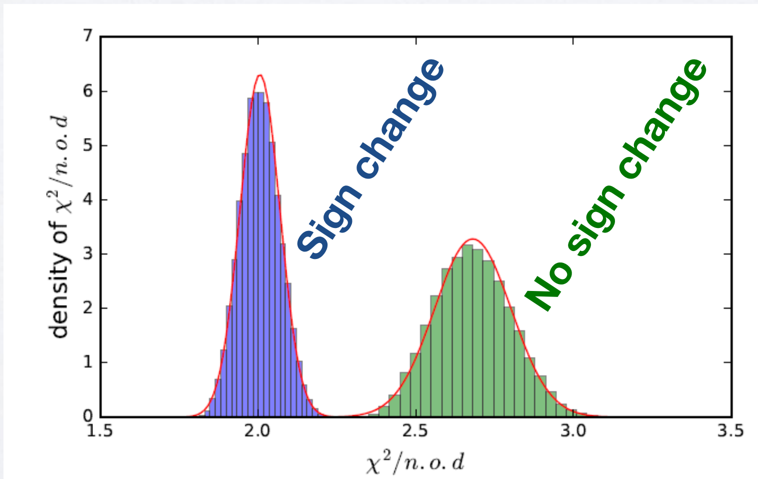
STAR, arXiv:1511.06003

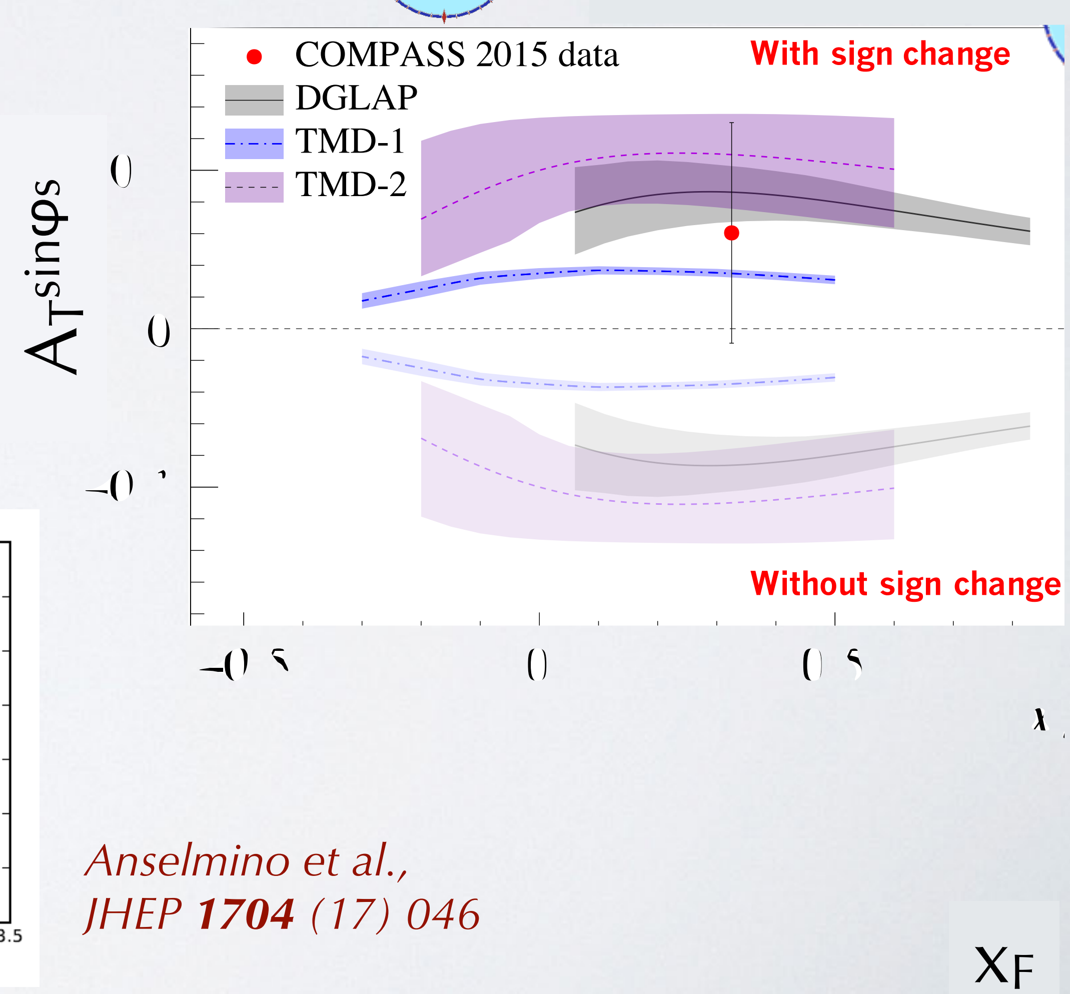
COMPASS, arXiv:1704.00488

$\pi^- P^\uparrow \rightarrow \ell^+ \ell^- X$



prediction with TMD evolution (??)





Anselmino et al., JHEP ***1704*** *(17) 046*

the Sivers Single-Spin Asymmetry in SIDIS

$$f_{1T}^{\perp} \otimes D_1$$

⬆

$$A_{UT}^{\sin(\phi_h - \phi_S)} = \frac{A(x,y)\, F_{UT,T}^{\sin(\phi_h - \phi_S)}(x, z, \boldsymbol{P}_{hT}^2, Q^2)}{A(x,y)\, F_{UU,T}(x, z, \boldsymbol{P}_{hT}^2, Q^2)}$$

⬇

$$f_1 \otimes D_1$$

First extraction of Sivers function using unpolarized TMDs f_1 and D_1 extracted from global fit of (SIDIS + Drell-Yan + Z-boson) data
[the Pavia 2017 fit]

Bacchetta, Delcarro, Pisano, Radici, in preparation

The Pavia 2019 fit of Sivers $f_{1T}^{\perp}$ (preliminary)

Bacchetta, Delcarro, Pisano, Radici, in preparation

data points
117

 # fit parameters
14

global χ^2/d.o.f.
1.12 ± 0.06

data coverage

hermes — proton [H]
95 data points

Jefferson Lab — neutron [^{3}He]
6 data points

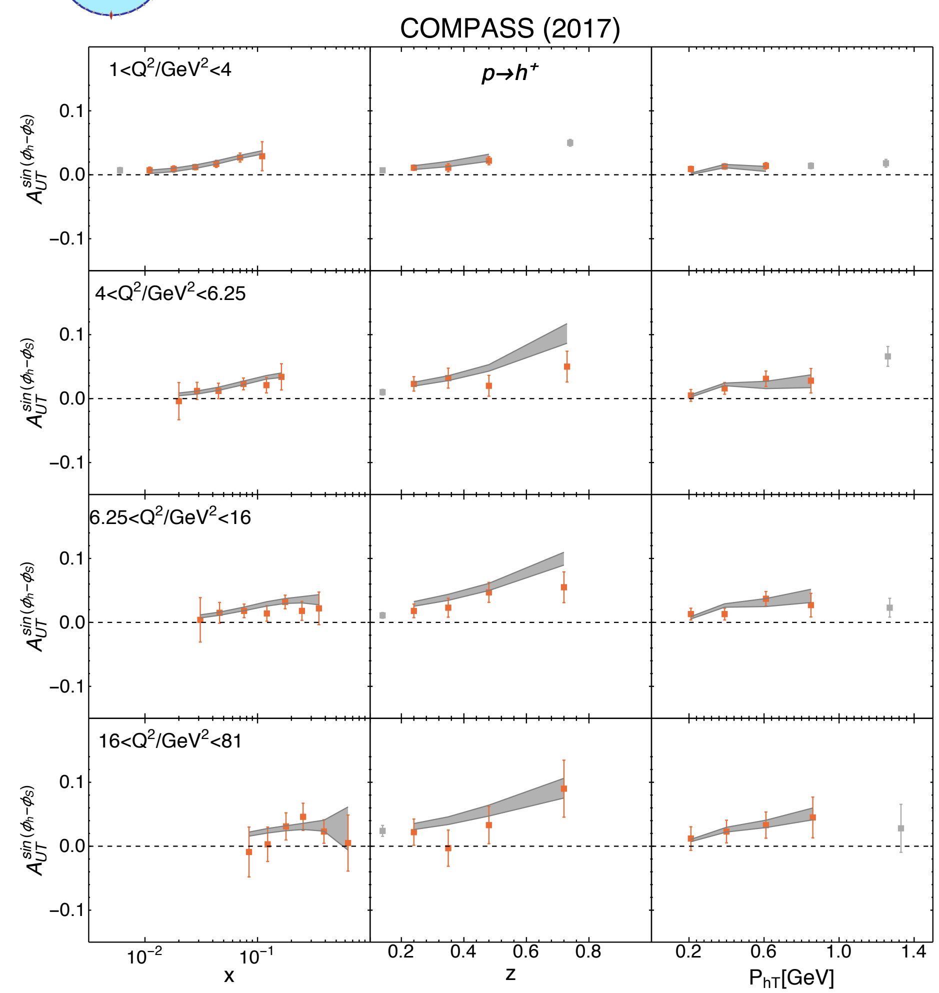
COMPASS 2009 — deuteron [^{6}LiD]
88 data points

COMPASS 2017 — Proton [NH_3]
111 data points

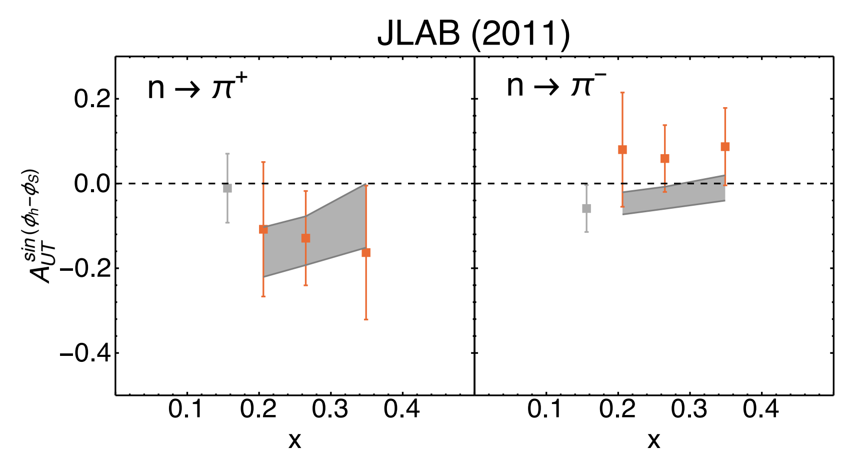
Same kinematic cuts applied to unpolarized

x, z, P_{hT} data projections

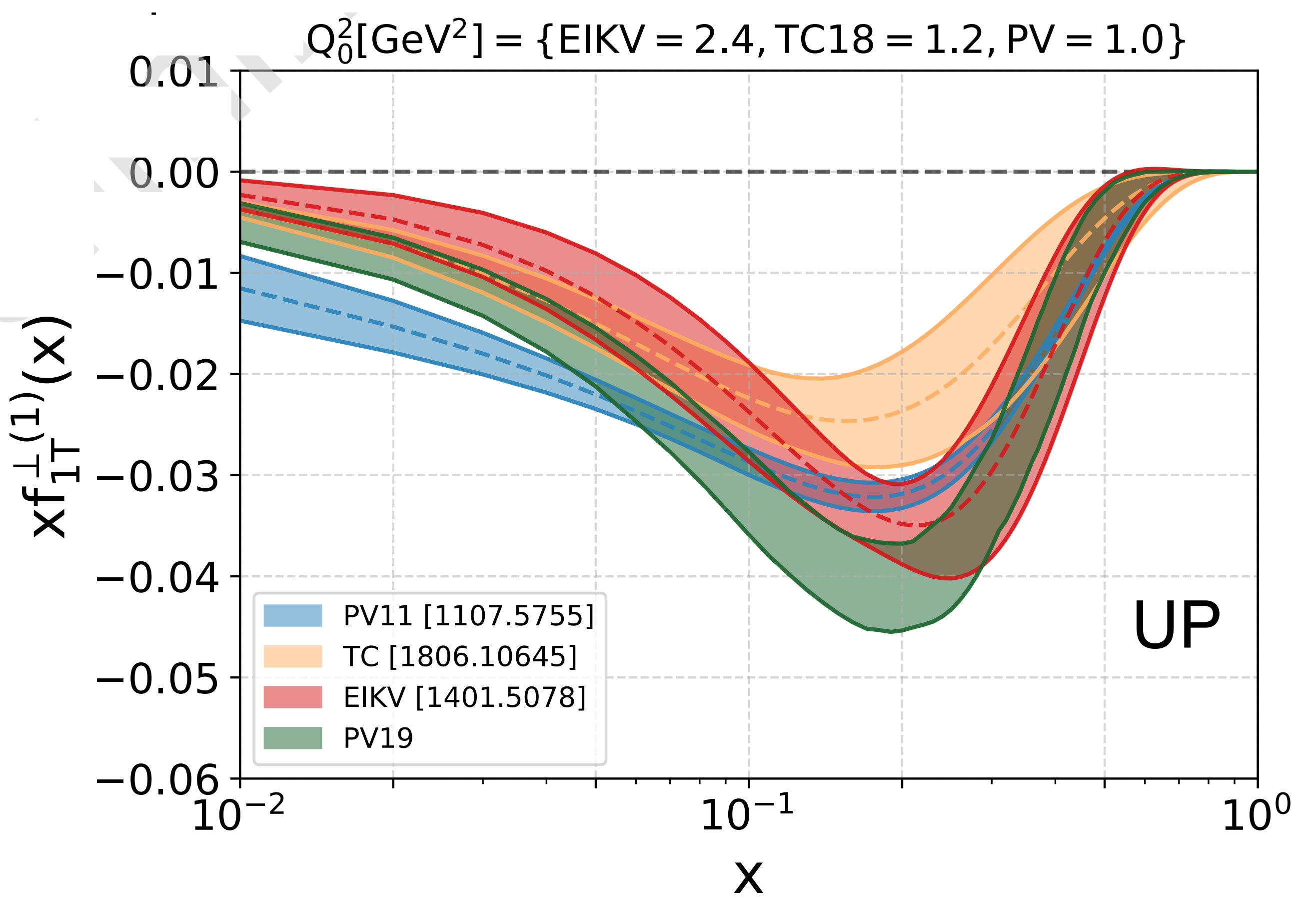
Adolph et al., P.L. ***B770*** *(17) 138*



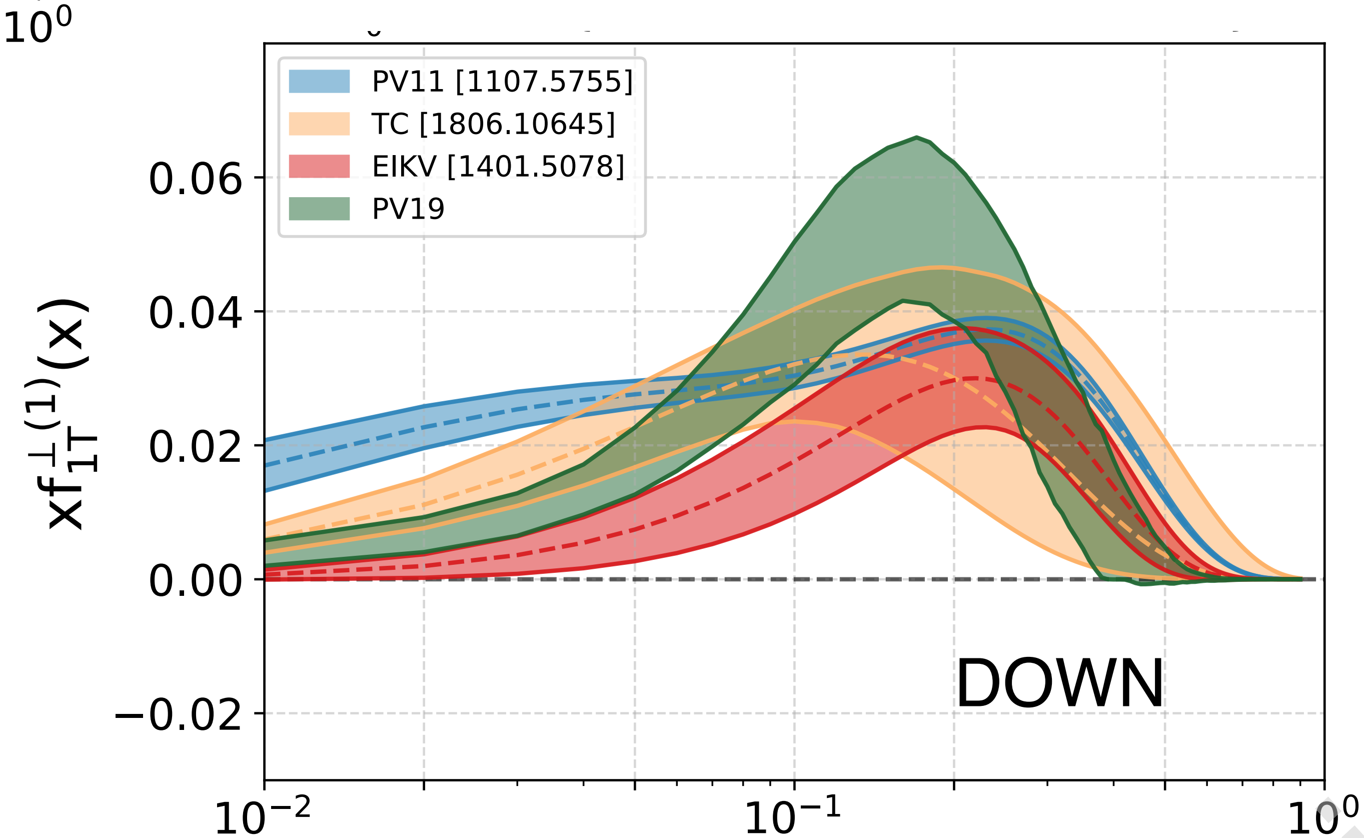
Qian et al., P.R.L. ***107*** *(11) 072003*



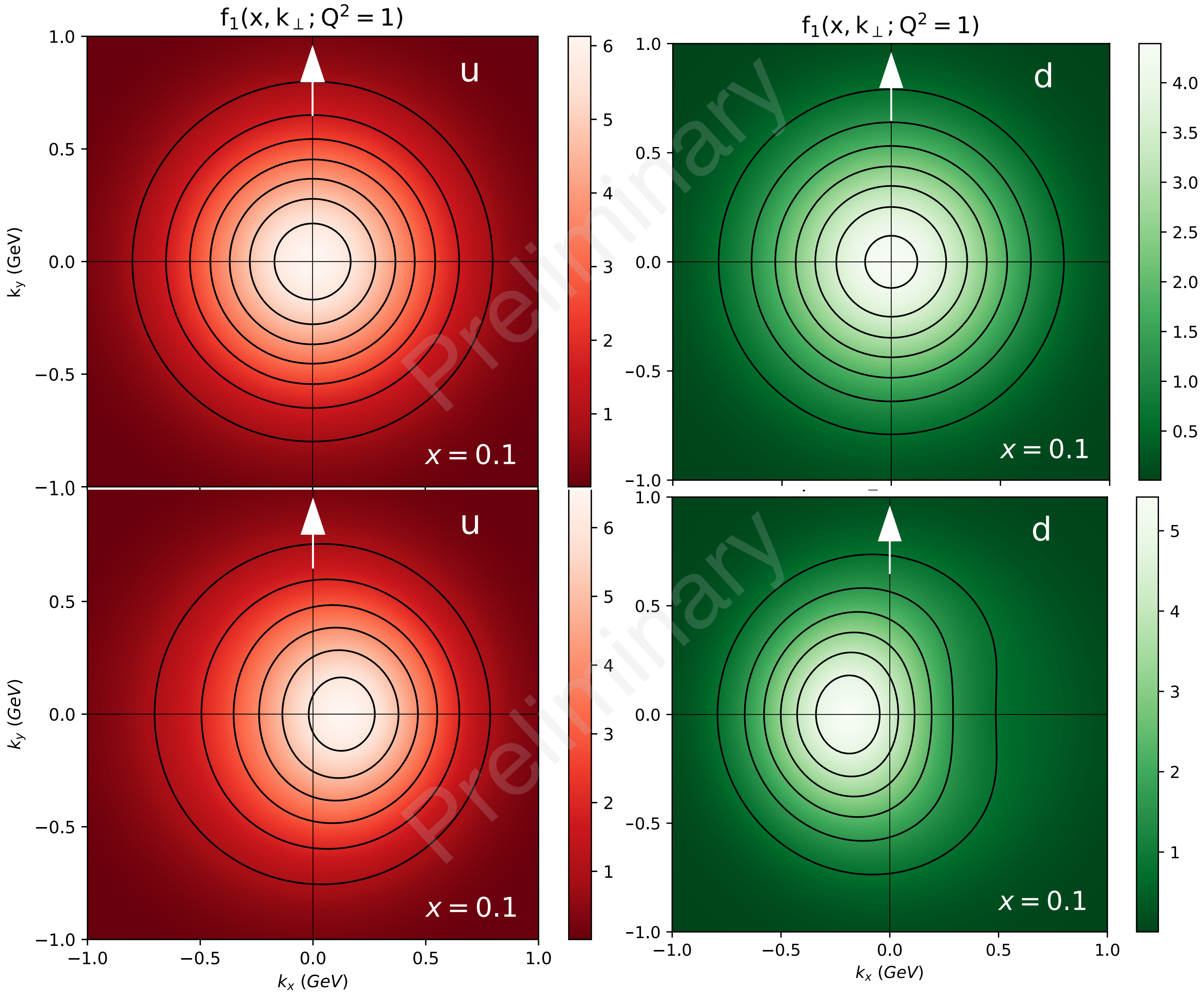
The Pavia 2019 fit of Sivers $f_{1T}^{\perp}$ (preliminary)



PV11	*Bacchetta & Radici, P.R.L.* ***107*** *(11)*
EIKV	*Echevarria et al., P.R. D**89** (14)*
TC	*Boglione et al., JHEP* ***1807*** *(18)*
PV19	*Bacchetta, Delcarro, Pisano, Radici, in preparation*



The Pavia 2019 fit of Sivers $f_{1T}^{\perp}$ (preliminary)



Bacchetta, Delcarro, Pisano, Radici, in preparation

$$f_{q/p^\uparrow}(x, \boldsymbol{k}_T) = f_1^q(x, \boldsymbol{k}_T)$$

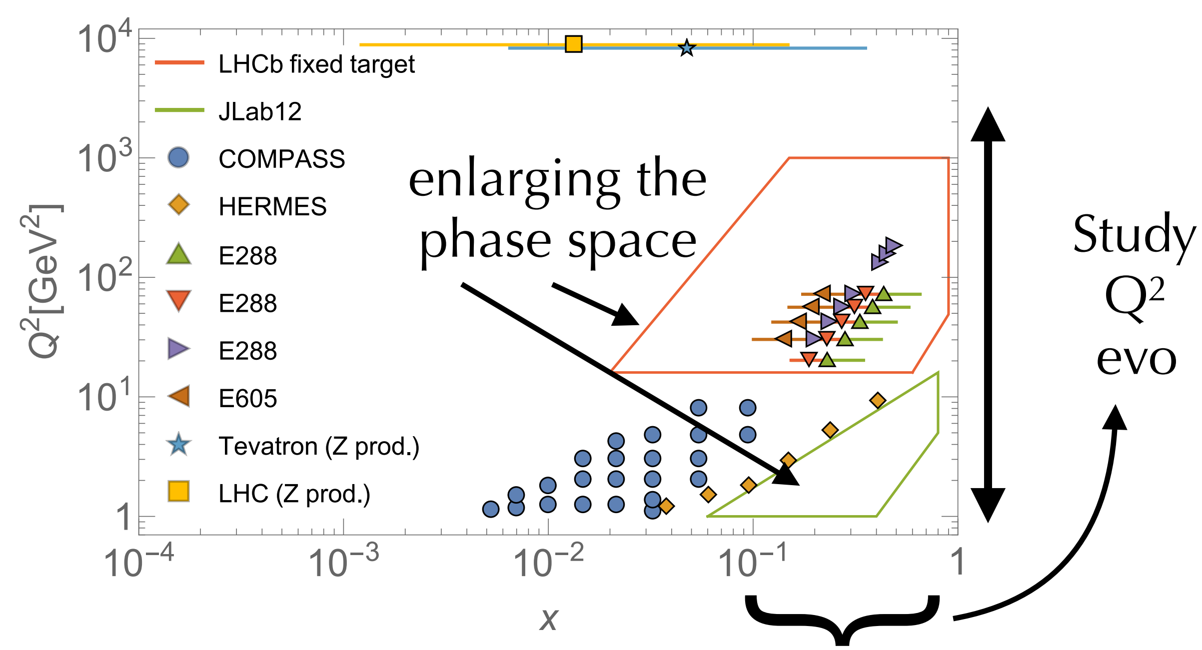
$$f_{q/p^\uparrow}(x, \boldsymbol{k}_T) = f_1^q(x, \boldsymbol{k}_T) - f_{1T}^{\perp q}(x, \boldsymbol{k}_T)\, \boldsymbol{S} \cdot \left(\frac{\hat{\boldsymbol{P}}}{M} \times \boldsymbol{k}_T \right)$$

(distorted) plots entirely based on data

Conclusions

- We are entering the era of precise 3D maps of the proton in momentum space
- Goal: link them to high-energy phenomenology, providing input (precision PDF→TMD, W mass → BSM physics…)
- Upcoming/future data will give further opportunities

JLab12 LHCb spin ALICE



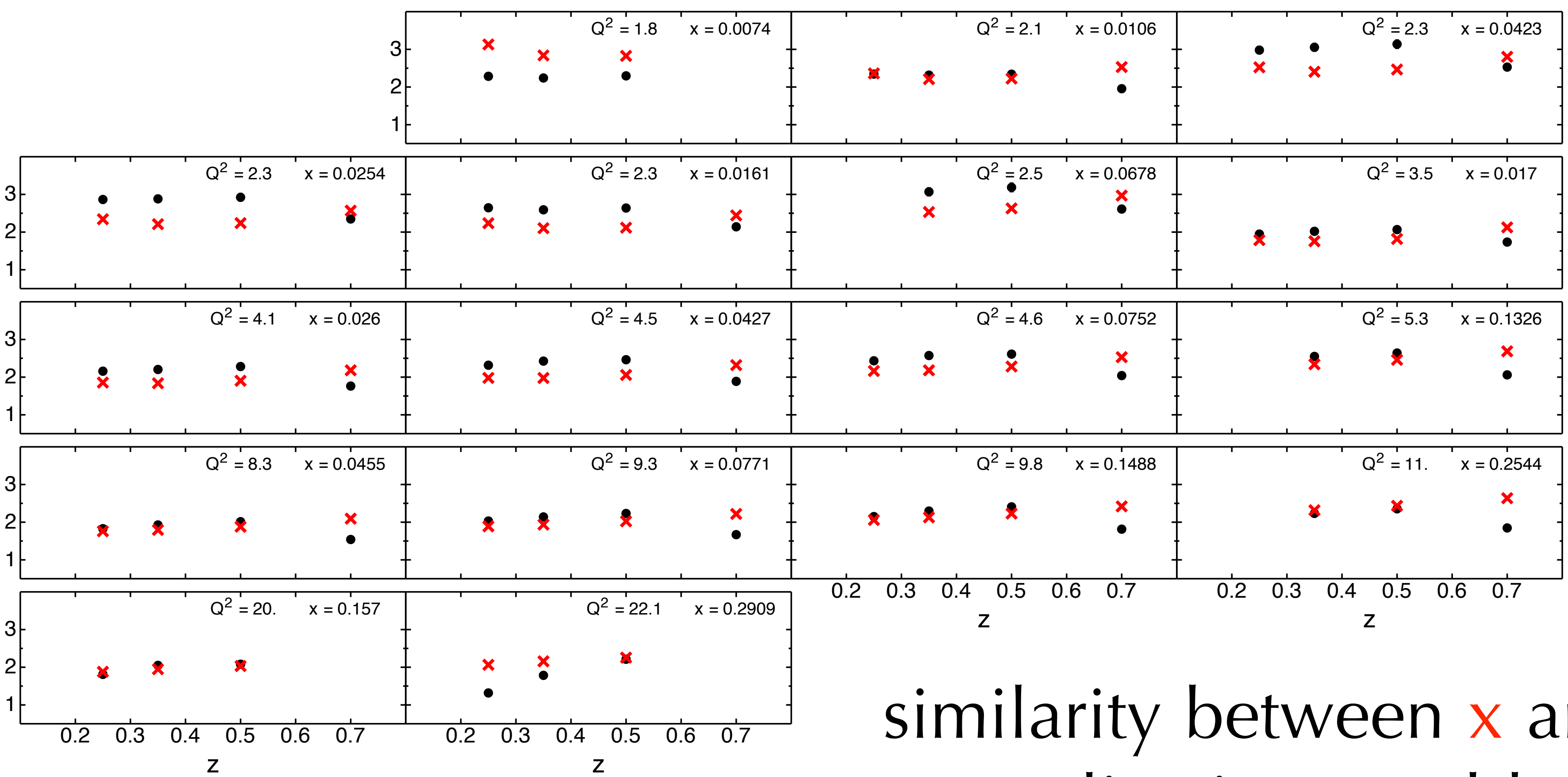
- The EIC will open a new era

Backup

Problems with normalization of (SIDIS) data

SIDIS data as multiplicities $M_N^h = \dfrac{d\sigma_N^h / dx\, dz\, d\boldsymbol{P}_{hT}^2\, dQ^2}{d\sigma_{\text{DIS}} / dx\, dQ^2}$

it should be $\text{N} = \int dz d\mathbf{P}_{hT}^2\, M_N^h = 1$ collinear formula



x 1/N at $O(\alpha_S)$

● normalization factors required to fit COMPASS data (at NLL′)

F. Piacenza, Ph.D. Thesis

similarity between x and ● might suggest that normalization problems are related to the fixed-order collinear formula (and to the matching between TMD and collinear regimes)

parametrization of Sivers $f_{1T}^{\perp}$

Pavia 2017 fit
unpol. TMD at scale Q_0

$$f_1^q(x, b_T; Q_0^2) = f_1^q(x; Q_0^2)\, f_{\rm NP}(x, b_T)$$

Bacchetta, Delcarro, Pisano, Radici, in preparation

Sivers TMD at scale Q_0

$$f_{1T}^{\perp q}(x, b_T; Q_0^2) = f_{1T}^{\perp(1)q}(x; Q_0^2)\, f_{1T\,{\rm NP}}^{\perp}(x, b_T)$$

parametric expression based on PDF f_1^q

normalized flavor-independent double Gaussian on top of $f_{\rm NP}$

PDF=NLO GJR 2008

$q = u_v, d_v, s$ (= sea)

normalized to grant **positivity** $\left(f_{1T}^{\perp(1)}(x, \boldsymbol{k}_T^2)\right)^2 \leq \frac{\boldsymbol{k}_T^2}{4M^2} \left(f_1(x, \boldsymbol{k}_T^2)\right)^2$

$$f_{1T}^{\perp q}(x, b_T; Q_0^2) \xrightarrow{\text{TMD evolution at NLL}} f_{1T}^{\perp q}(x, b_T; Q^2)$$

$$f_{1T}^{\perp(1)q}(x, \mu^2) = -\frac{1}{2M}\, T_F^q(x, x, \mu^2)$$ Qiu-Sterman

Ji, Qiu, Vogelsang, Yuan, hep-ph/0602239

approximate evolution of T_F as DGLAP evolution of f_1

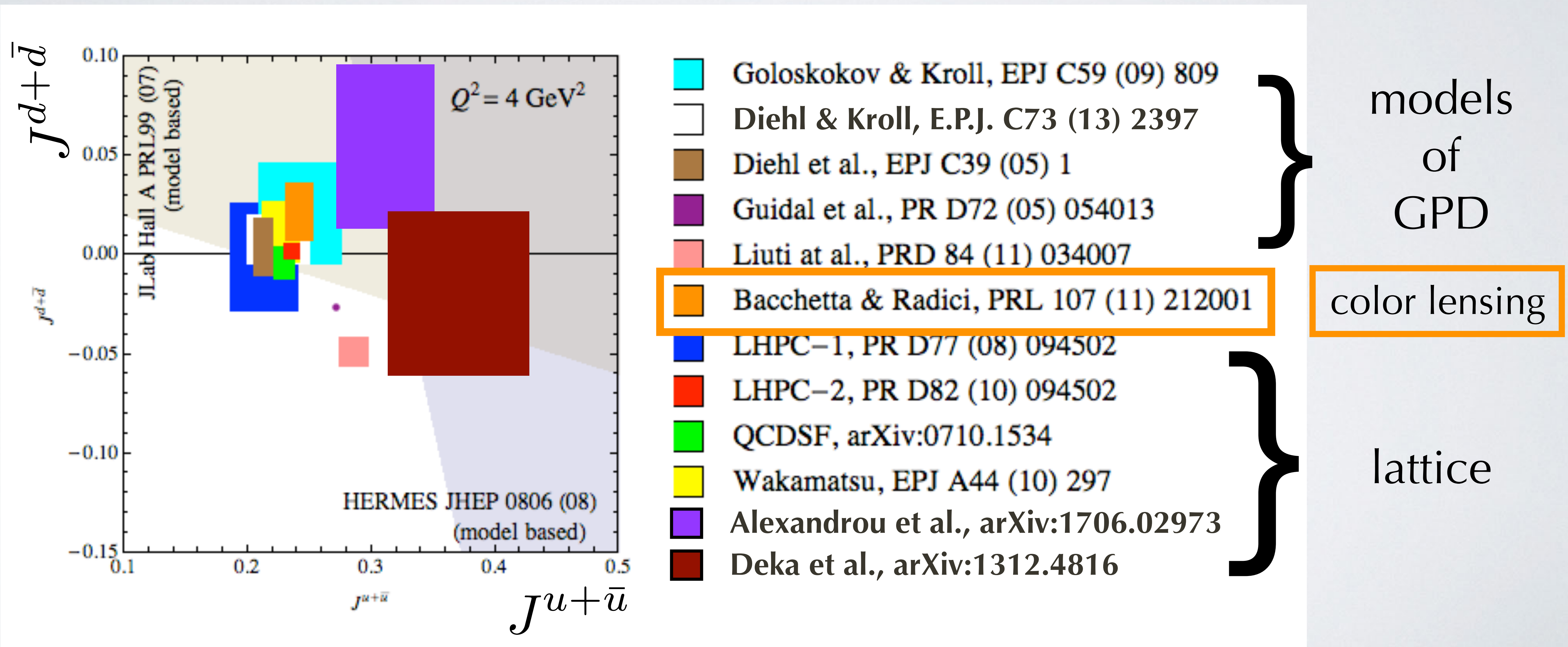
Sivers function ↔ quark total J

Ji's sum rule $J_z^q(Q^2) = \frac{1}{2}\int_0^1 dx\, x\, [H^q(x,0,0;Q^2) + E^q(x,0,0;Q^2)]$

model lensing funct. L(x) + fit $f_{1T}^{\perp}$ $\int d\boldsymbol{k}_T\, f_{1T}^{\perp q}(x,\boldsymbol{k}_T;Q_L^2) = -L(x)\, E^q(x,0,0;Q_L^2)$

(applicable only to 2-body systems)

Pasquini, Rodini, Bacchetta, arXiv:1907.06960



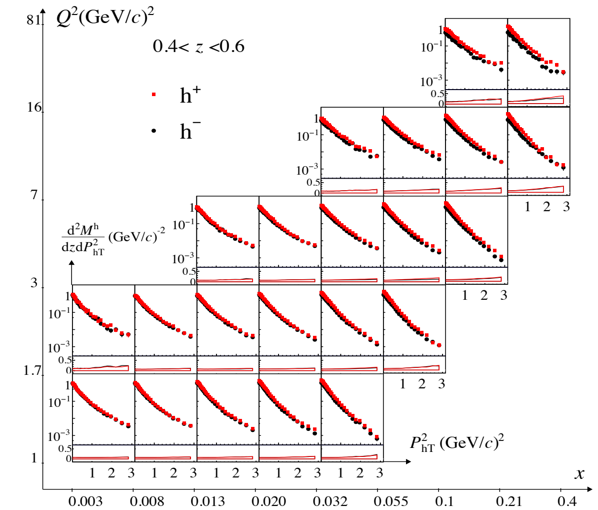
The Future

What's next ?

What's next ?

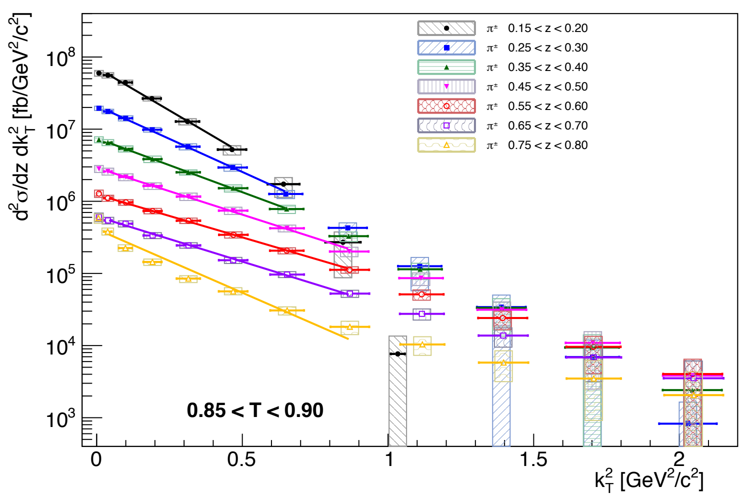
- Understand new Compass data

*Compass Collab., P.R. D**97** (18) 032006, arXiv:1709.07374*



- Also new multiplicity data from Hermes

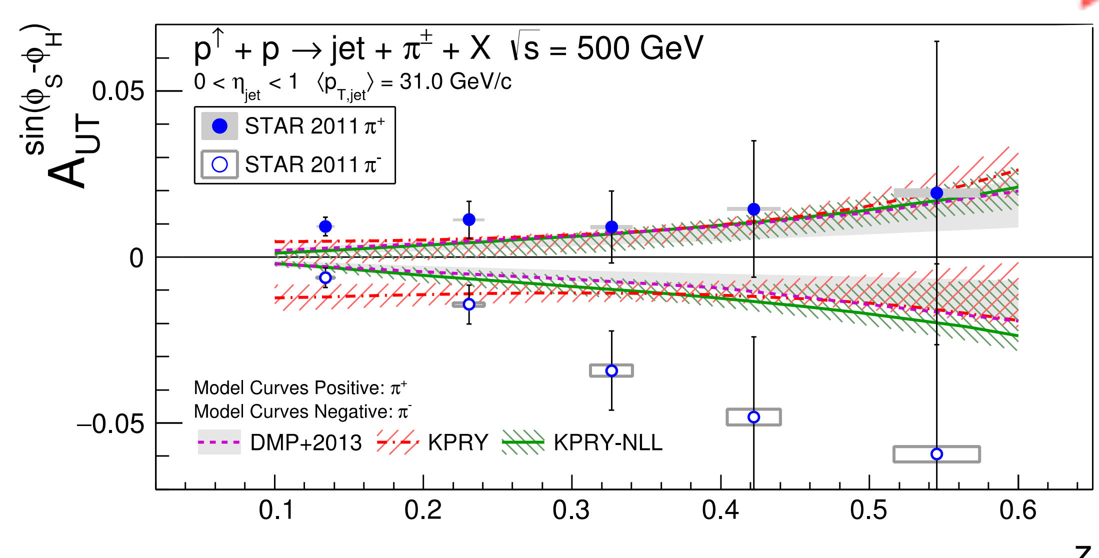
Hermes Collab., arXiv:1903.08544



- Include new Belle data on TMD fragm. (thrust axis…)

Belle Collab., arXiv:1807.02101

*Adamczyk et al. (STAR), P.R. D**97** (18)*



- systematic study of hadron-in-jet data: test universality of Collins funct.,…

KPRY *Kang et al., P.L. **B774** (17) 635*

DMP *D'Alesio et al., P.L. **B773** (17) 300*

What's next ?

- upcoming new data from **JLab12**
- future data from LHCb in fixed target mode (including polarization)
- future data from ALICE in fixed target mode
- long future from EIC