PHENOMENOLOGY OF 3D NUCLEON STRUCTURE

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Jefferson Lab
23 March 2021

3DSPIN
MAPPING THE PROTON IN 3D

Previously: Andrea Signori talk

Introduction

Tomography in momentum space

TMDs: definition and process dependence

TMDs: factorization and evolution

TMDs: extractions from data

Outlook and references

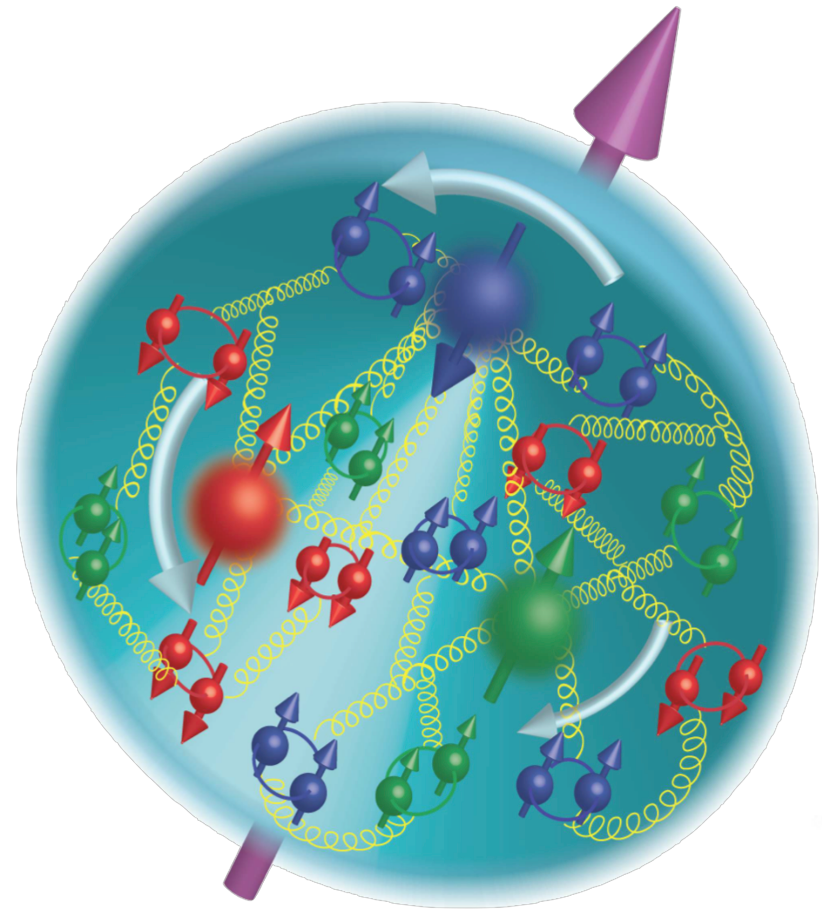
Outline

- Extraction of Sivers function and unpolarized TMDs
  - Overview of TMDs formalism
  - Relation between experimental observables and TMDs
  - Relation between unpolarized TMDs and Sivers distribution
  - Our choices for parametrization
  - Overview of experiments and data considered
  - Results and comparisons
  - Sign change in DY

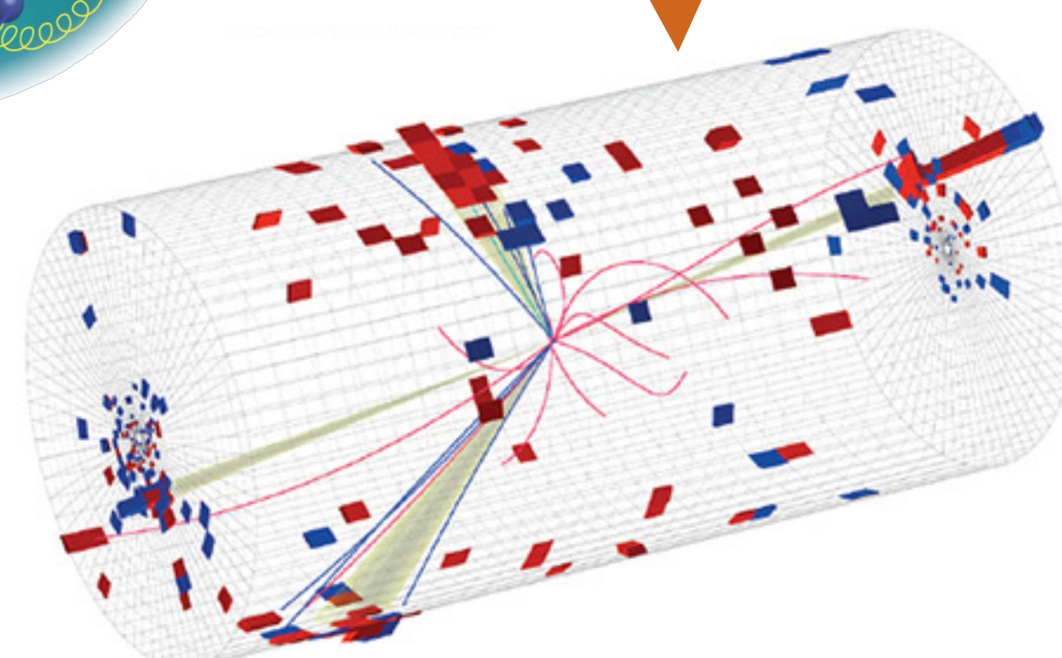
Why is it interesting to study the nucleon Structure?

$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \overline{\psi}_q (i \not\partial - g \not{A} + m)\psi_q - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

Check Theoretical predictions



Make predictions for future experiments (EIC)



Transverse Momentum Distributions: TMD PDF

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, $h_{1T}^{\perp}$

unpolarized

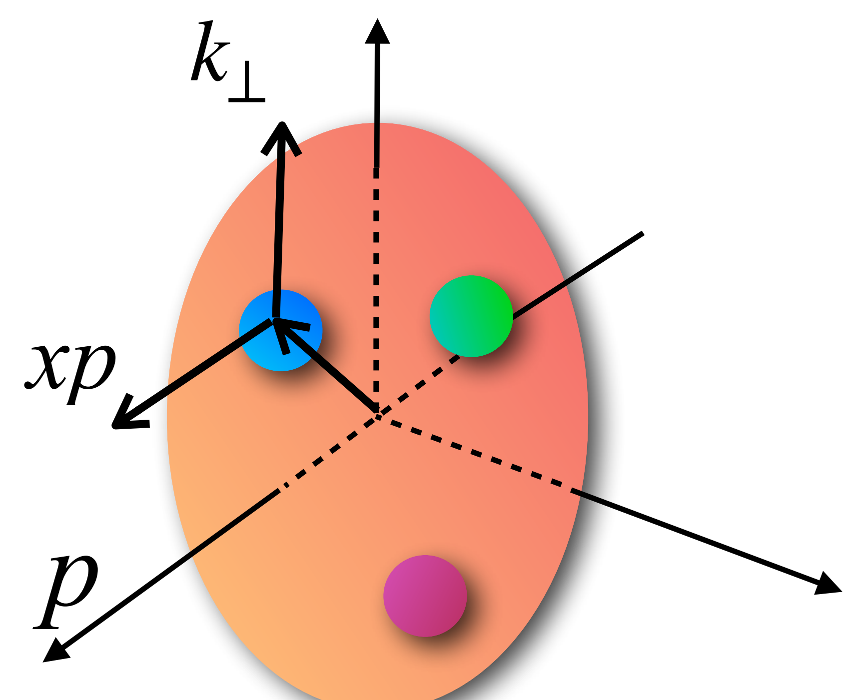
Sivers function

dependence on:

longitudinal momentum fraction x

transverse momentum $k_\perp$

energy scale



PDF and FF

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}	$h_1,\ h_{1T}^\perp$

TMD Parton Distribution Functions
(TMD PDFs)

quark pol. U	L	T
D_1		$H_1^\perp$

(Additional FFs if we consider hadron polarization

TMD Fragmentation Functions
(TMD FFs)

dependence on

longitudinal momentum fraction $x,\ z$

transverse momentum $\boldsymbol{k}_\perp, \boldsymbol{P}_\perp$

energy scale

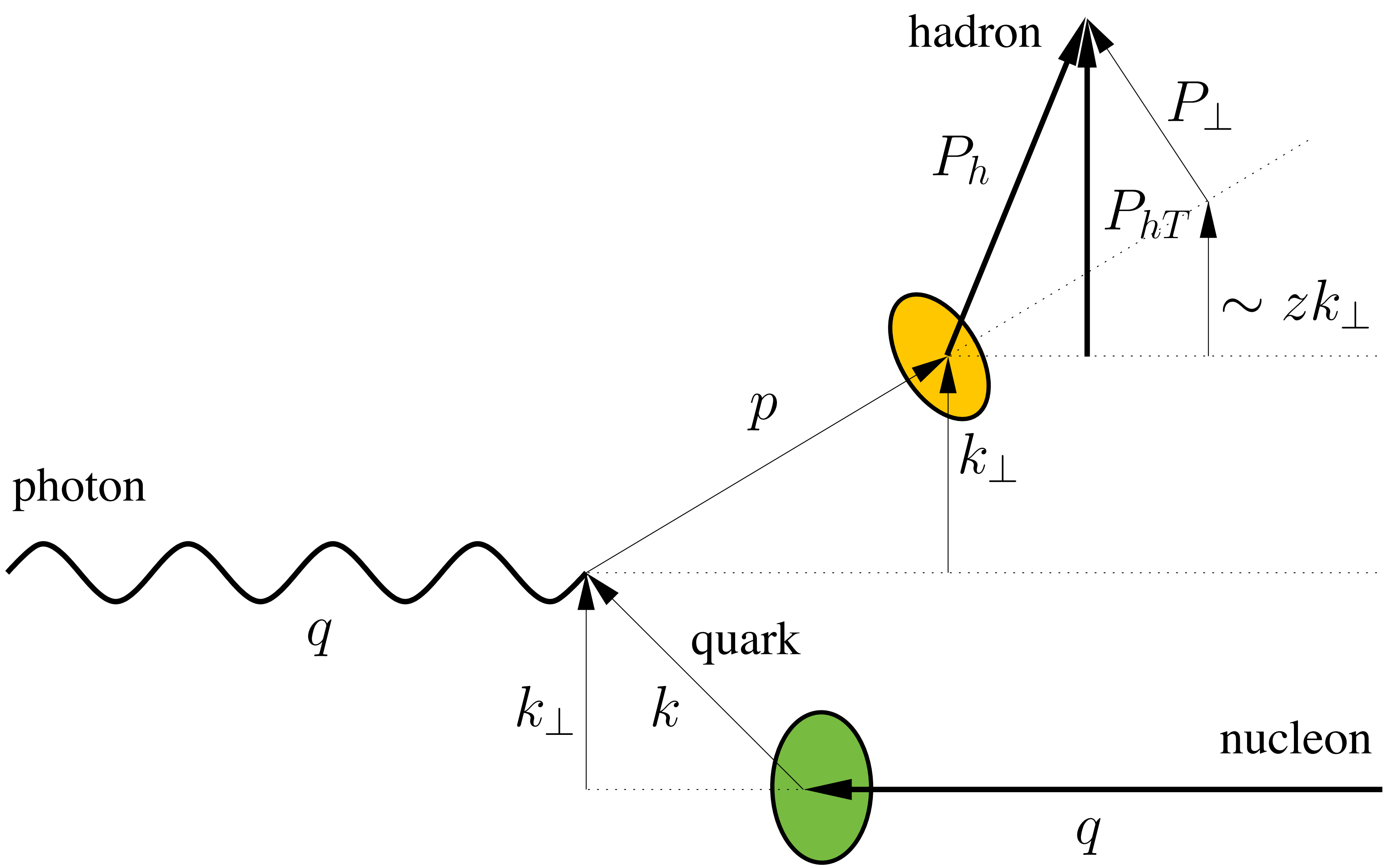
UNPOLARIZED TMD

PDF AND FF

Structure functions and TMDs: SIDIS

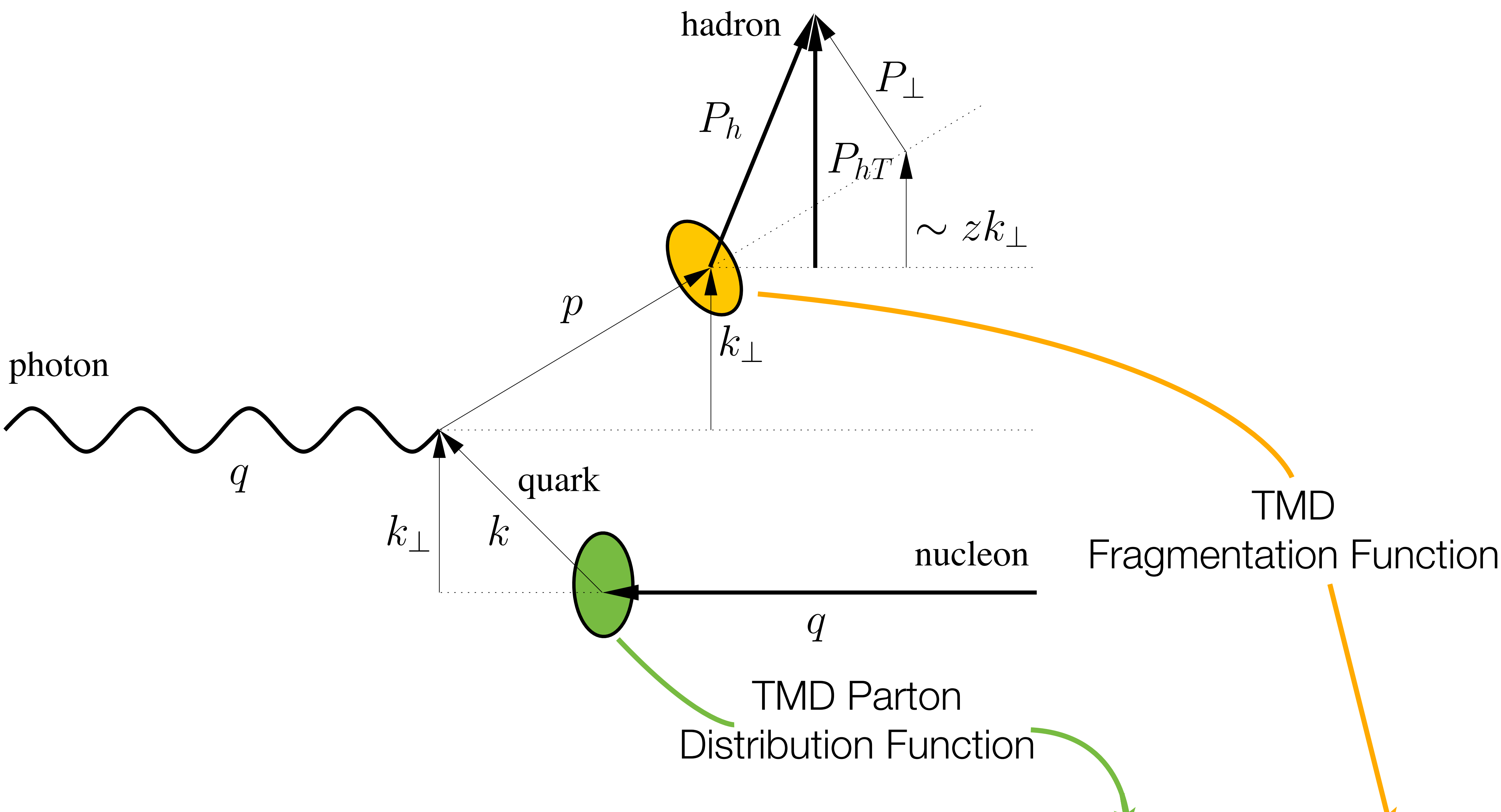
multiplicities

$$m_N^h\left(x,z,\boldsymbol{P}_{hT}^2,Q^2\right)=\frac{d\sigma_N^h/\left(dxdzd\boldsymbol{P}_{hT}^2dQ^2\right)}{d\sigma_{DIS}/\left(dxdQ^2\right)}\approx\frac{\pi F_{UU,T}\left(x,z,\boldsymbol{P}_{hT}^2,Q^2\right)}{F_T(x,Q^2)}$$



FACTORIZATION

Structure functions and TMDs

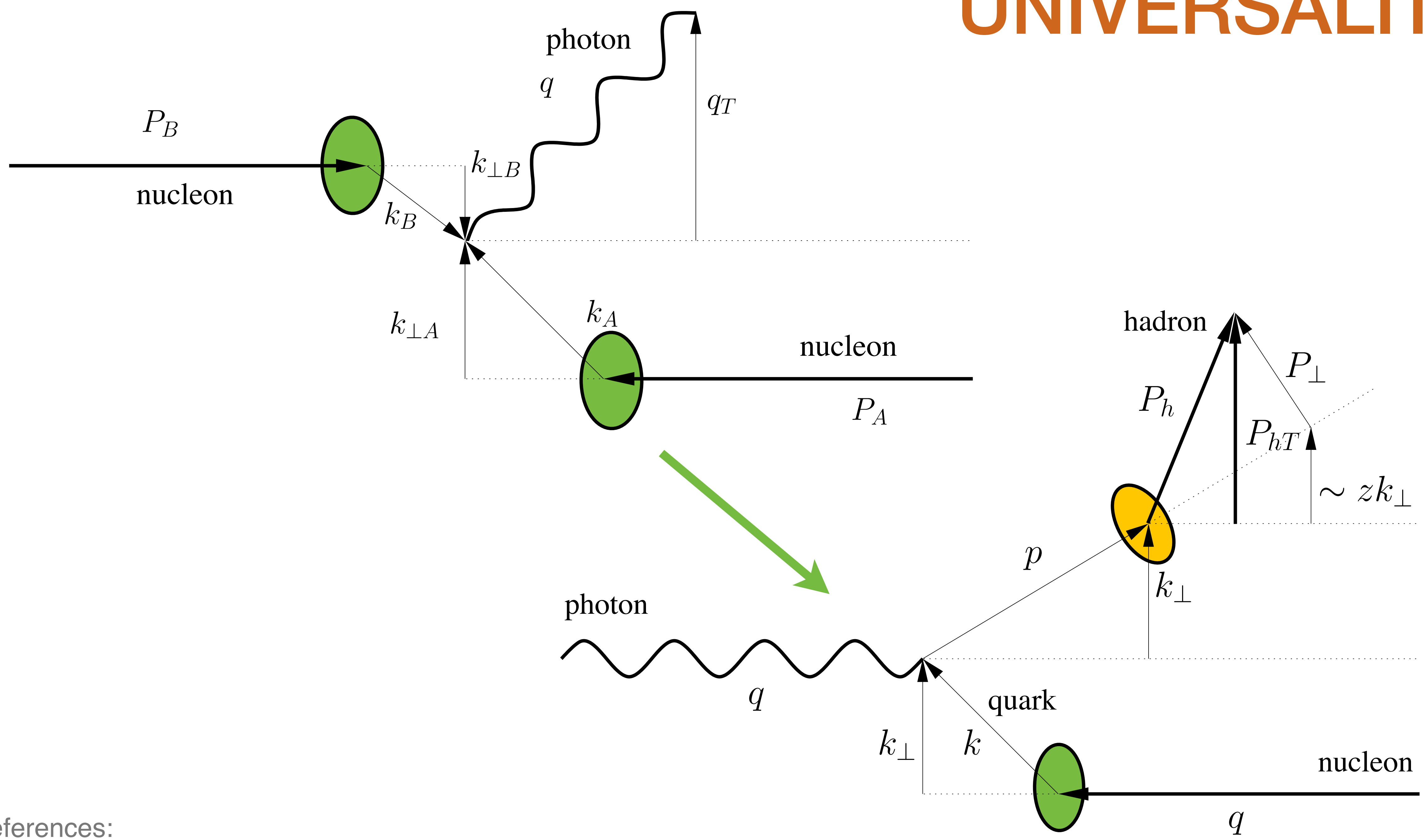


$$F_{UU,T}\left(x,z,\boldsymbol{P}_{hT}^2,Q^2\right) \simeq \sum_a \mathscr{H}_{UUT}^a \int d^2\boldsymbol{k}_\perp d^2\boldsymbol{P}_\perp\, f_1^a(x,\boldsymbol{k}_\perp^2;Q^2)\, D_1^{a\to h}(z,\boldsymbol{P}_\perp^2;Q^2)$$

$$\times\, \delta^2(z\boldsymbol{k}_\perp - \boldsymbol{P}_{hT} + \boldsymbol{P}_\perp) + Y_{UUT} + \mathcal{O}\left(M^2/Q^2\right)$$

Extraction from SIDIS & Drell-Yan

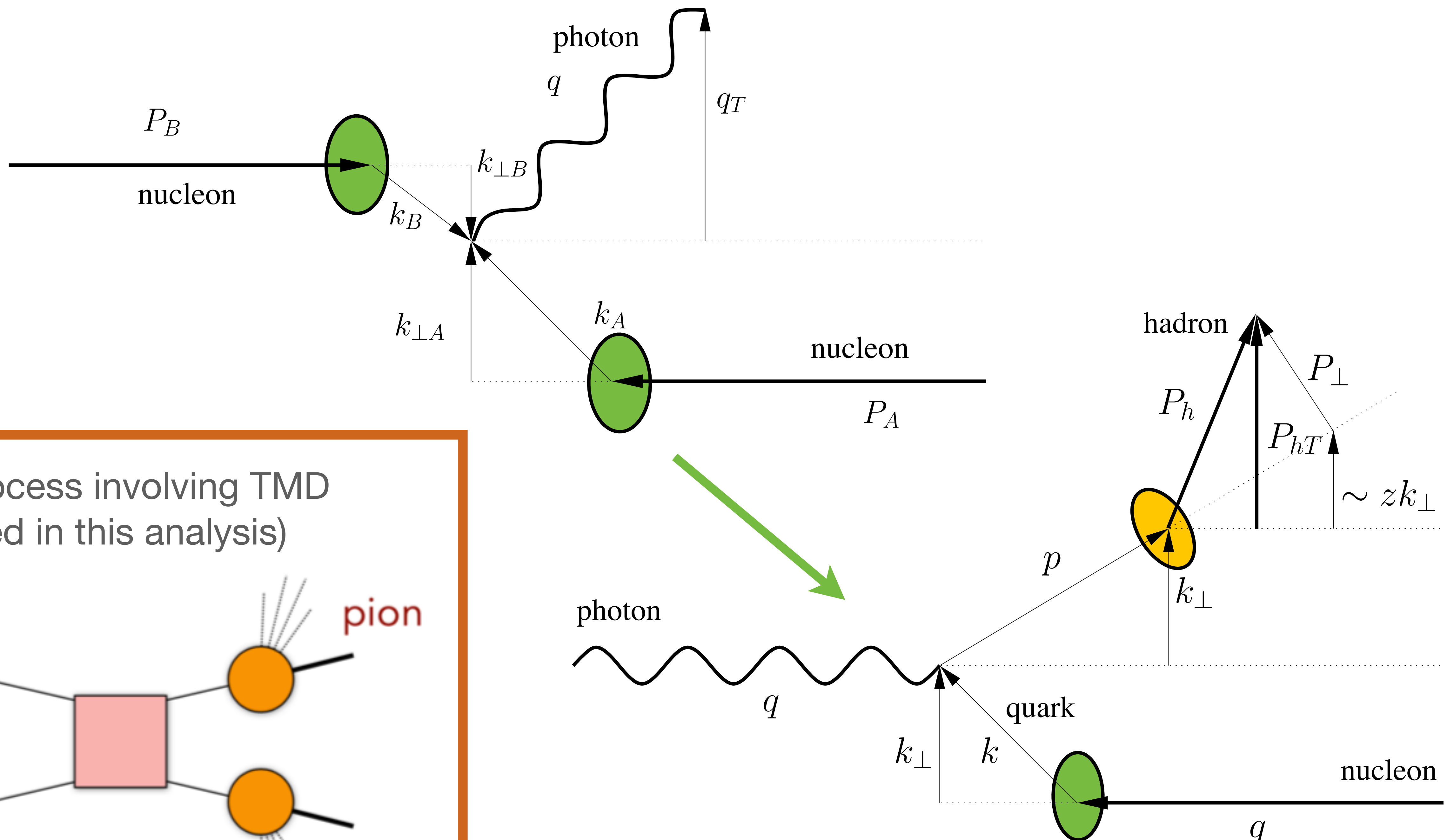
UNIVERSALITY



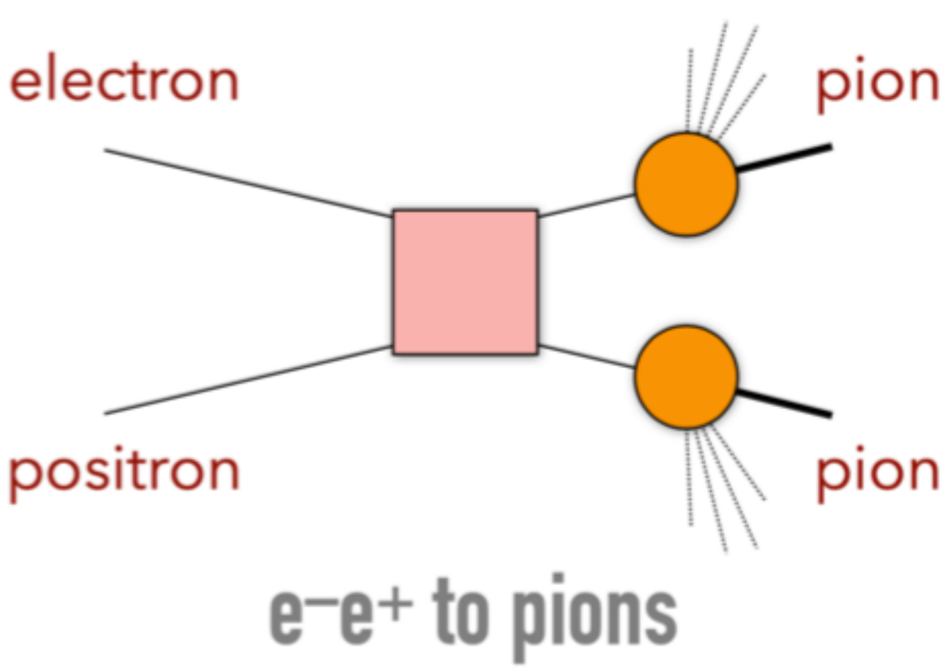
References:
Ji, Ma, Yuan, PRD 71
Collins “Founcation of perturbative QCD”
Rogers,Aybat, PRD 83
Echevarria, Idilbi, Scimemi JHEP 1207

Extraction from SIDIS & Drell-Yan

UNIVERSALITY



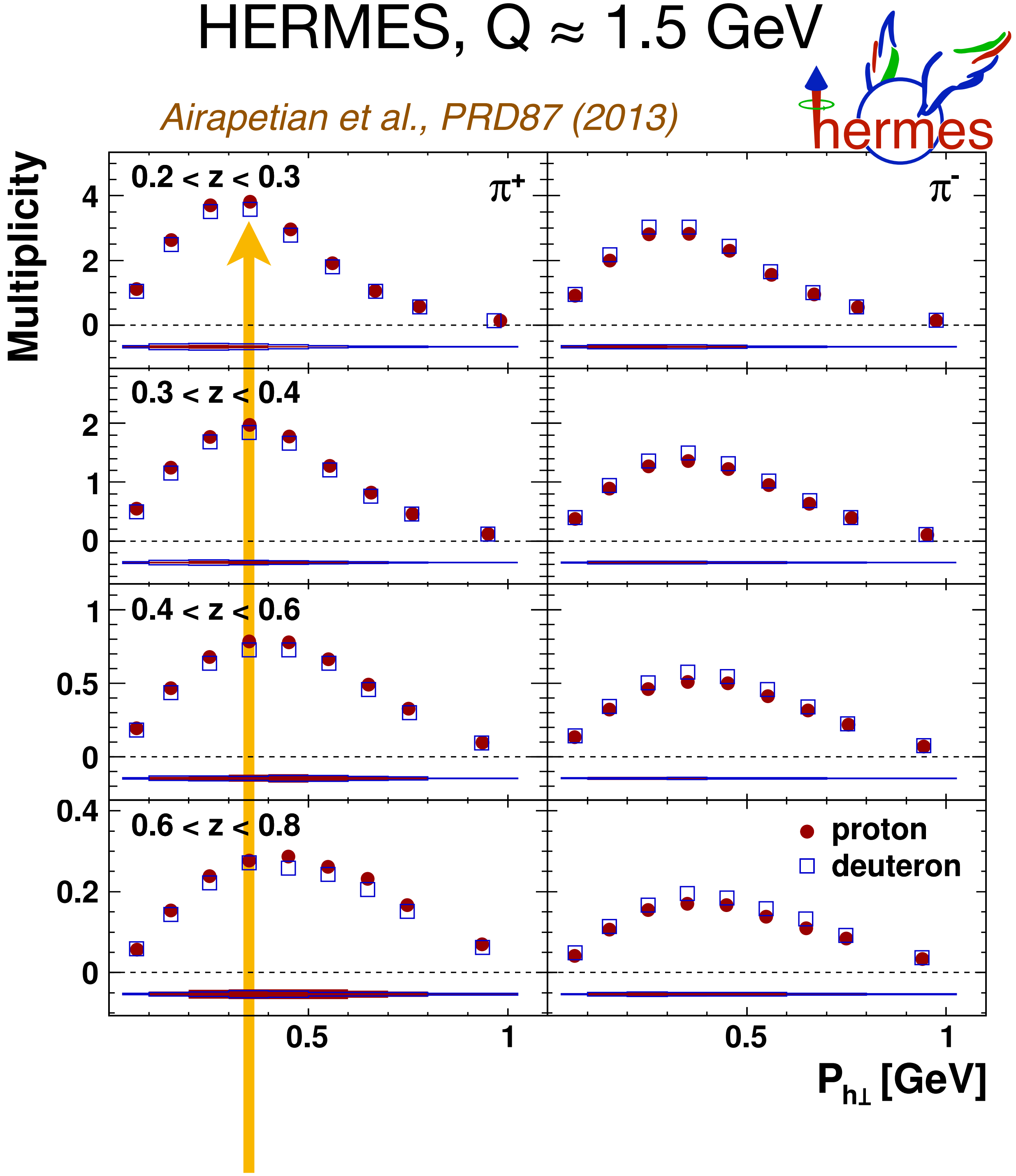
Another process involving TMD
(not included in this analysis)



TMD Evolution

HERMES, Q ≈ 1.5 GeV

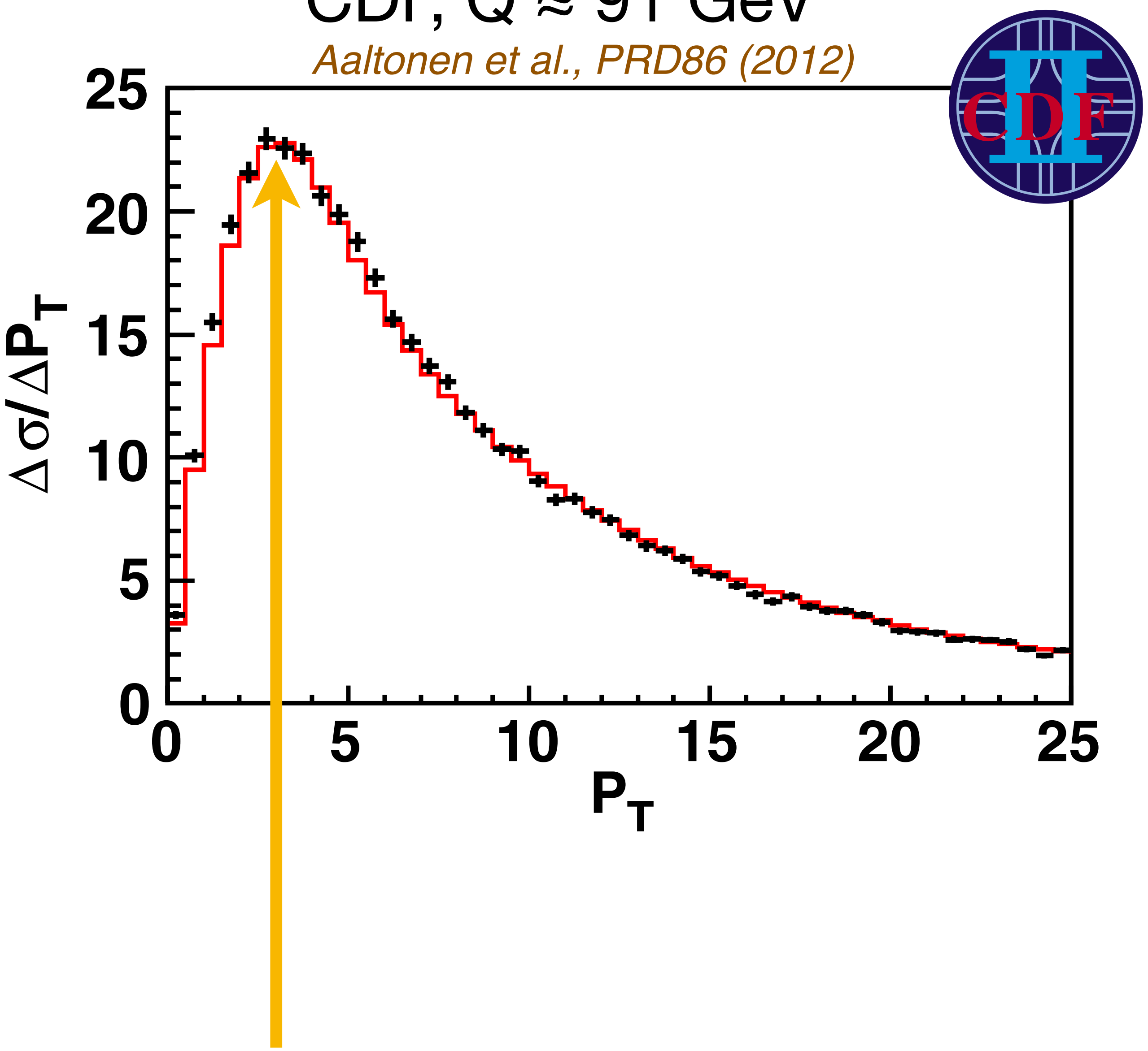
Airapetian et al., PRD87 (2013)



reproduce shift of
TMD peak with energy scale

CDF, Q ≈ 91 GeV

Aaltonen et al., PRD86 (2012)



Width of TMDs changes of one order of magnitude

→ **EVOLUTION**

Parametrization: perturbative and NP

Fourier transform: b_T space

Alternative notation: ξ_T

Wilson Coefficient (pQCD)

collinear PDF (NP but well known)

$$F_{f/P}\left(x,\mathbf{b}_T;\mu,\zeta\right)=\sum_j C_{f/j}\left(x,b_*;\mu_b,\zeta_F\right)\otimes f_{j/P}\left(x,\mu_b\right)$$

$$\times\exp\left\{K\left(b_*;\mu_b\right)\ln\frac{\sqrt{\zeta_F}}{\mu_b}+\int_{\mu_b}^{\mu}\frac{d\mu'}{\mu'}\left[\gamma_F-\gamma_K\ln\frac{\sqrt{\zeta_F}}{\mu'}\right]\right\}$$

$$\times\exp\left\{g_K\left(b_T\right)\ln\left(\sqrt{\zeta_F}/\sqrt{\zeta_{F,0}}\right)\right\}\hat{f}_{NP}(x,b_T)$$

Sudakov form factor (pQCD)

nonperturbative part of evolution

Intrinsic nonperturbative part of TMD

CSS formalism

Parametrization: Accuracy

$$F_{f/P}\left(x, \mathbf{b}_T; \mu, \zeta\right) = \sum_j C_{f/j}\left(x, b_*; \mu_b, \zeta_F\right) \otimes f_{j/P}\left(x, \mu_b\right)$$

$$\times \exp\left\{ K\left(b_*; \mu_b\right) \ln \frac{\sqrt{\zeta_F}}{\mu_b} + \int_{\mu_b}^{\mu} \frac{d\mu'}{\mu'} \left[\gamma_F - \gamma_K \ln \frac{\sqrt{\zeta_F}}{\mu'} \right] \right\}$$

$$\times \exp\left\{ g_K\left(b_T\right) \ln \left(\sqrt{\zeta_F} / \sqrt{\zeta_{F,0}} \right) \right\} \hat{f}_{NP}(x, b_T)$$

Accuracy	γ_K	γ_F	K	$C_{f/j}$	H
LL	α_s	-	-	1	1
NLL	α_s^2	α_s	α_s	1	1
NLL'	α_s^2	α_s	α_s	α_s	α_s
N²LL	α_s^3	α_s^2	α_s^2	α_s	α_s
N²LL'	α_s^3	α_s^2	α_s^2	α_s^2	α_s^2
N³LL	α_s^4	α_s^3	α_s^3	α_s^2	α_s^2
N³LL'	α_s^4	α_s^3	α_s^3	α_s^3	α_s^3

unpol. PV17 (NLL)

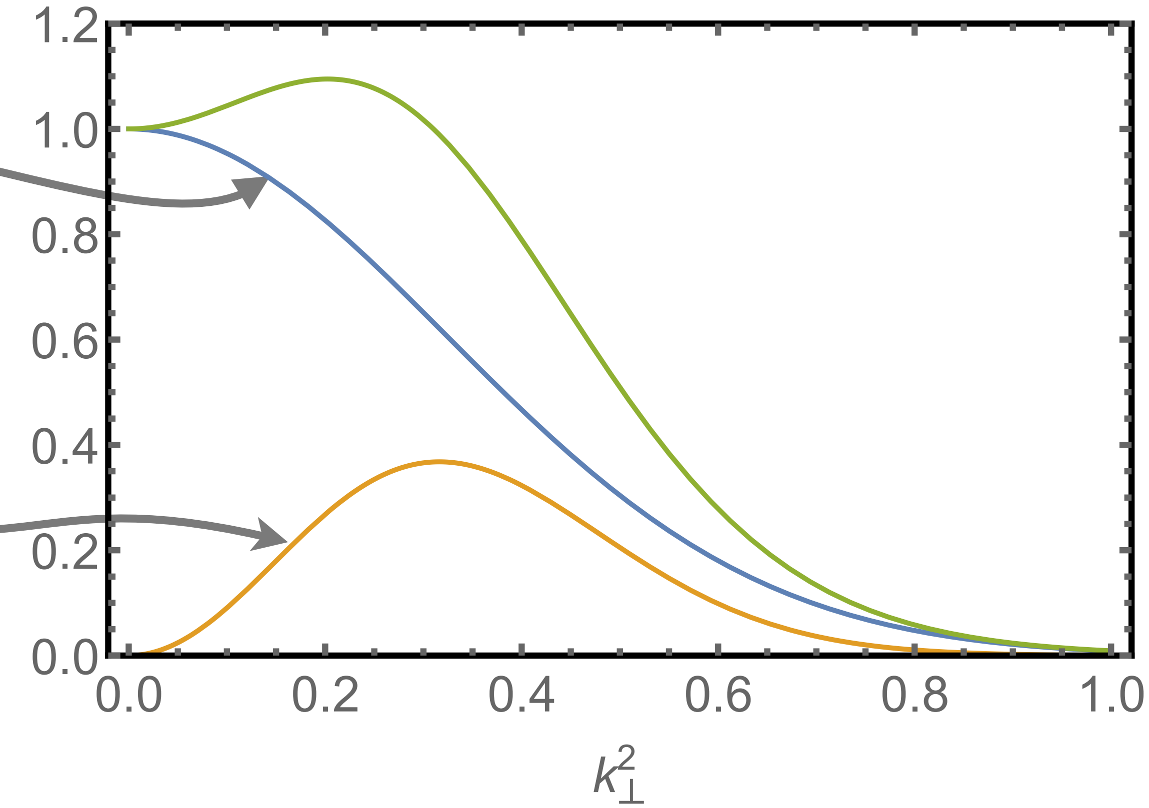
unpol. PV19 (N³LL)

Model: non perturbative elements

input TMD PDF @ Q^2=1GeV^2

$$\tilde{f}^a_{NP} = \mathcal{F}.\mathcal{T}.\ \text{of}$$

$$\left(\exp\left(\frac{-k_\perp^2}{g_1}\right) + \lambda k_\perp \exp\left(\frac{-k_\perp^2}{g_1}\right)\right)$$



for the FF we use two different variances

sum of two different gaussians
dependent on transverse momenta

- **11 free parameters** to fit to data.
- Perturbative accuracy: **LO+NLL**
- **Monte Carlo** bootstrap (replicas) for experimental error

b* prescription

$$\left(\frac{d\sigma}{dq_T}\right) \propto \int \frac{d^2\mathbf{b}}{4\pi} e^{i\mathbf{b}\cdot\mathbf{q}_T} F_q(x_1,\mathbf{b}) F_{\bar{q}}(x_2,\mathbf{b})$$

when b_T becomes large

$$\alpha_s(\mu_b) = \alpha\left(\frac{2e^{-\gamma_E}}{b}\right) \gg 1$$

invalidates perturbative calculations

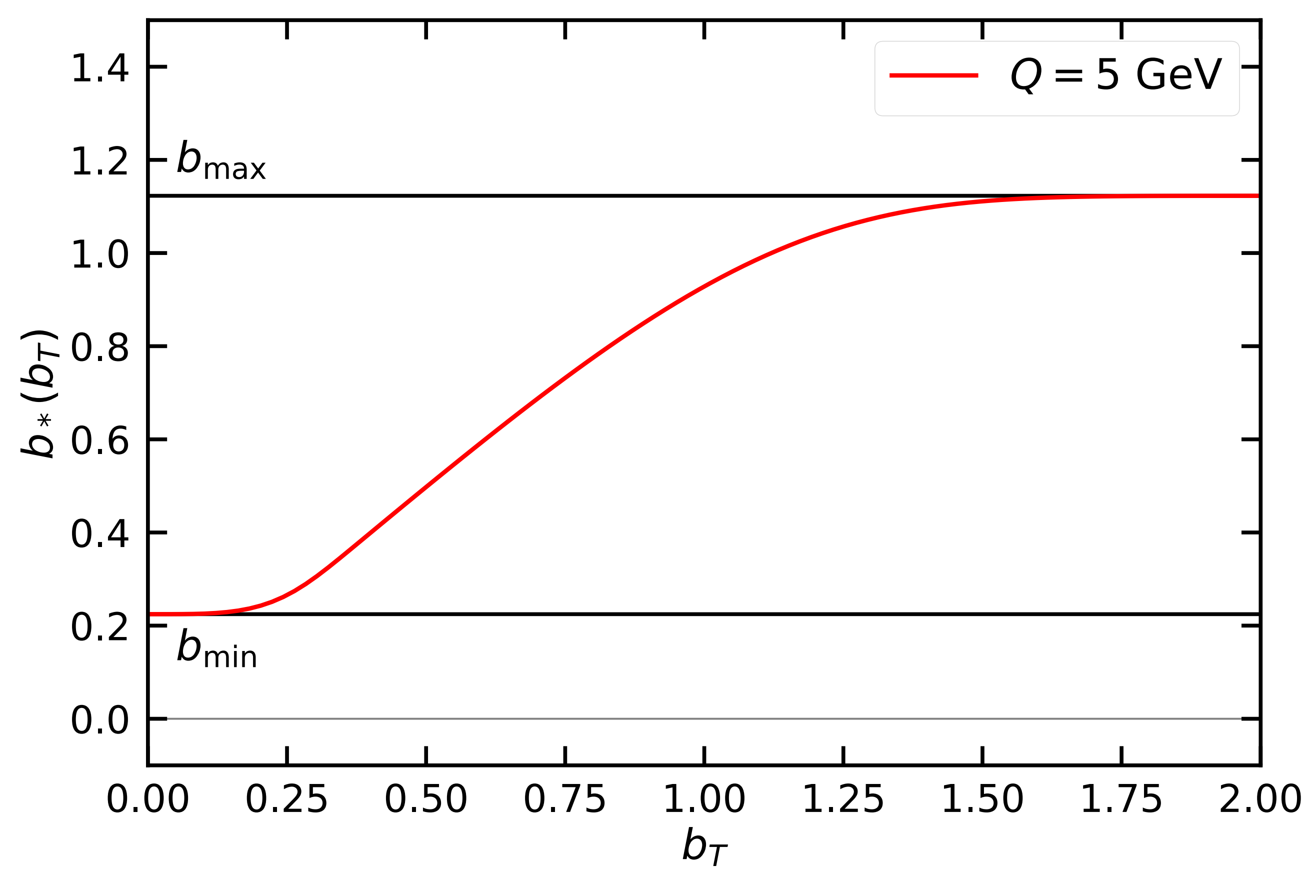
$\Rightarrow b_{\max}$

when b_T becomes small

Fixed order

$\Rightarrow b_{\min}$

$$b_*(b) = b_{\max}\left(\frac{1-\exp\left(-\frac{b^4}{b_{\max}^4}\right)}{1-\exp\left(-\frac{b^4}{b_{\min}^4}\right)}\right)^{\frac{1}{4}}$$



Experimental data

SIDIS μN

6252
data points

SIDIS eN

1514
data points

Total: 8059 data

E288

E605

Drell-Yan

203
data points

Z Production

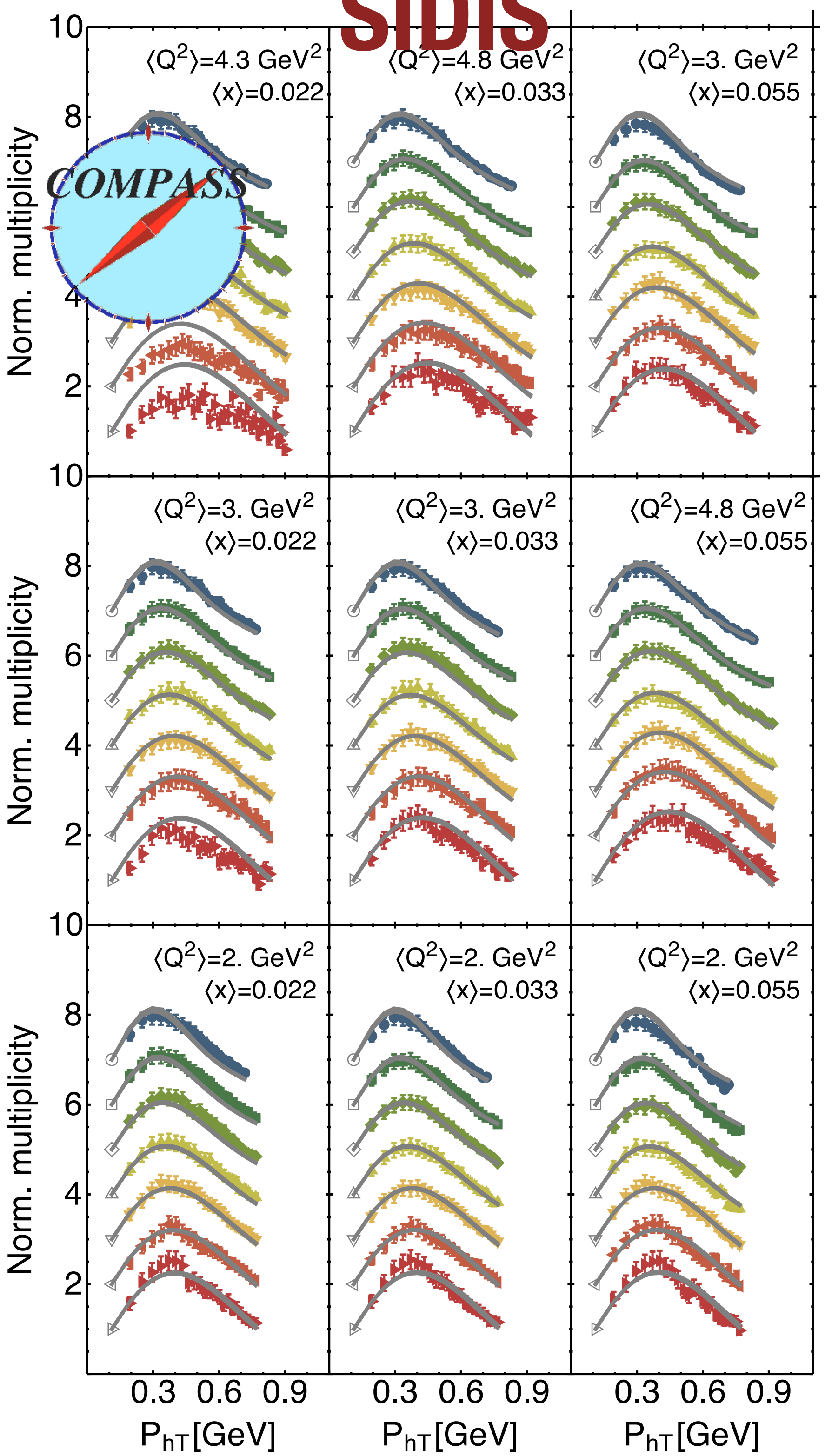
90
data points

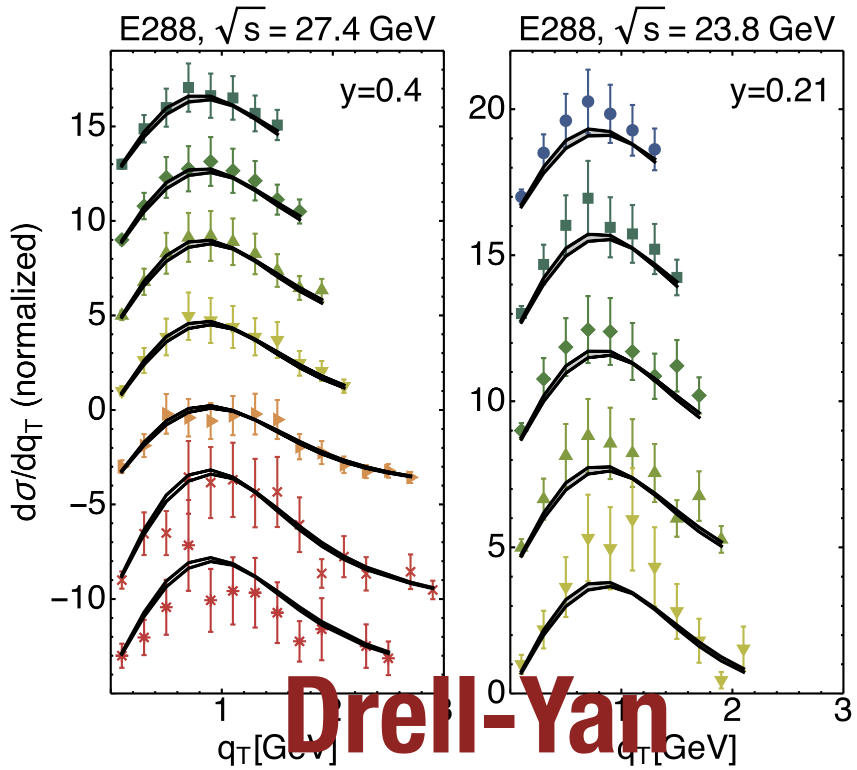
PV17 RESULTS

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

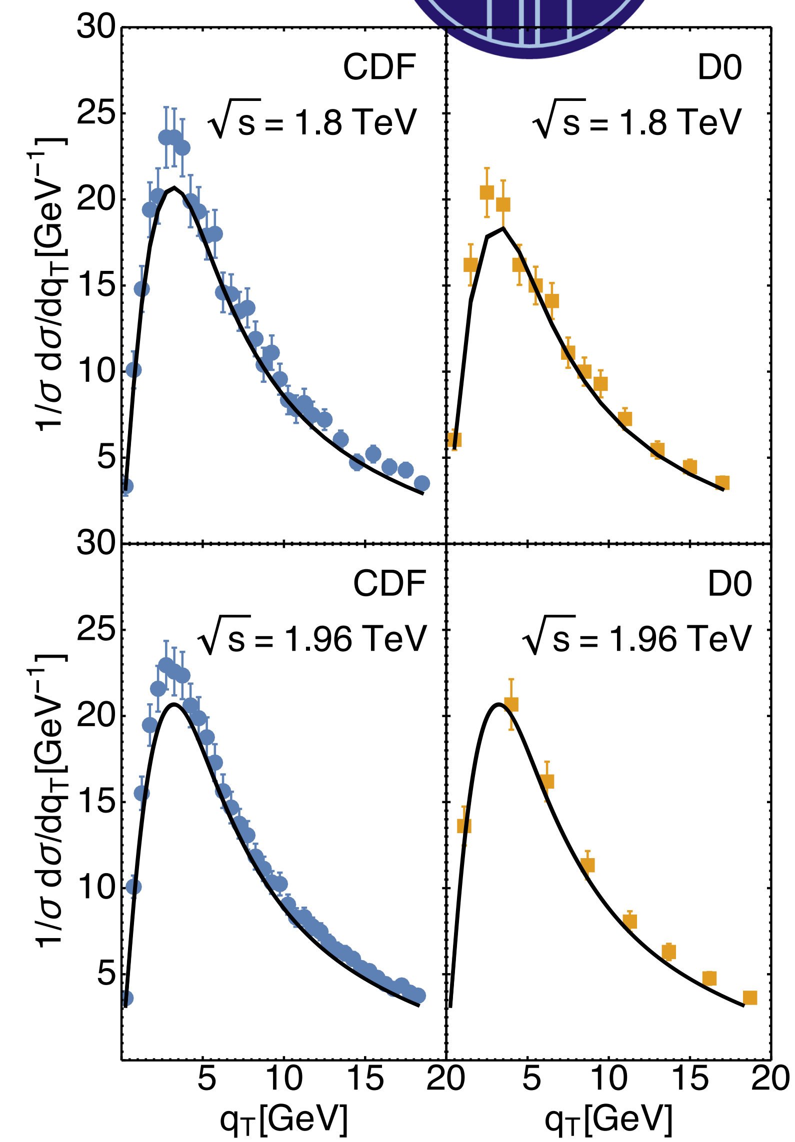
Fermilab

SIDIS





Drell-Yan



LO - NLL

$$\chi^2 = 1.55$$

Z production

Pavia 2017 assessment

- **PROs:**
  - almost a **global fit** of quark unpolarised TMDs,
  - includes TMD **evolution**
  - Monte Carlo (replica) method,
  - **kinematic dependence** of the intrinsic q_T,
  - **beyond Gaussian** assumption for intrinsic q_T.

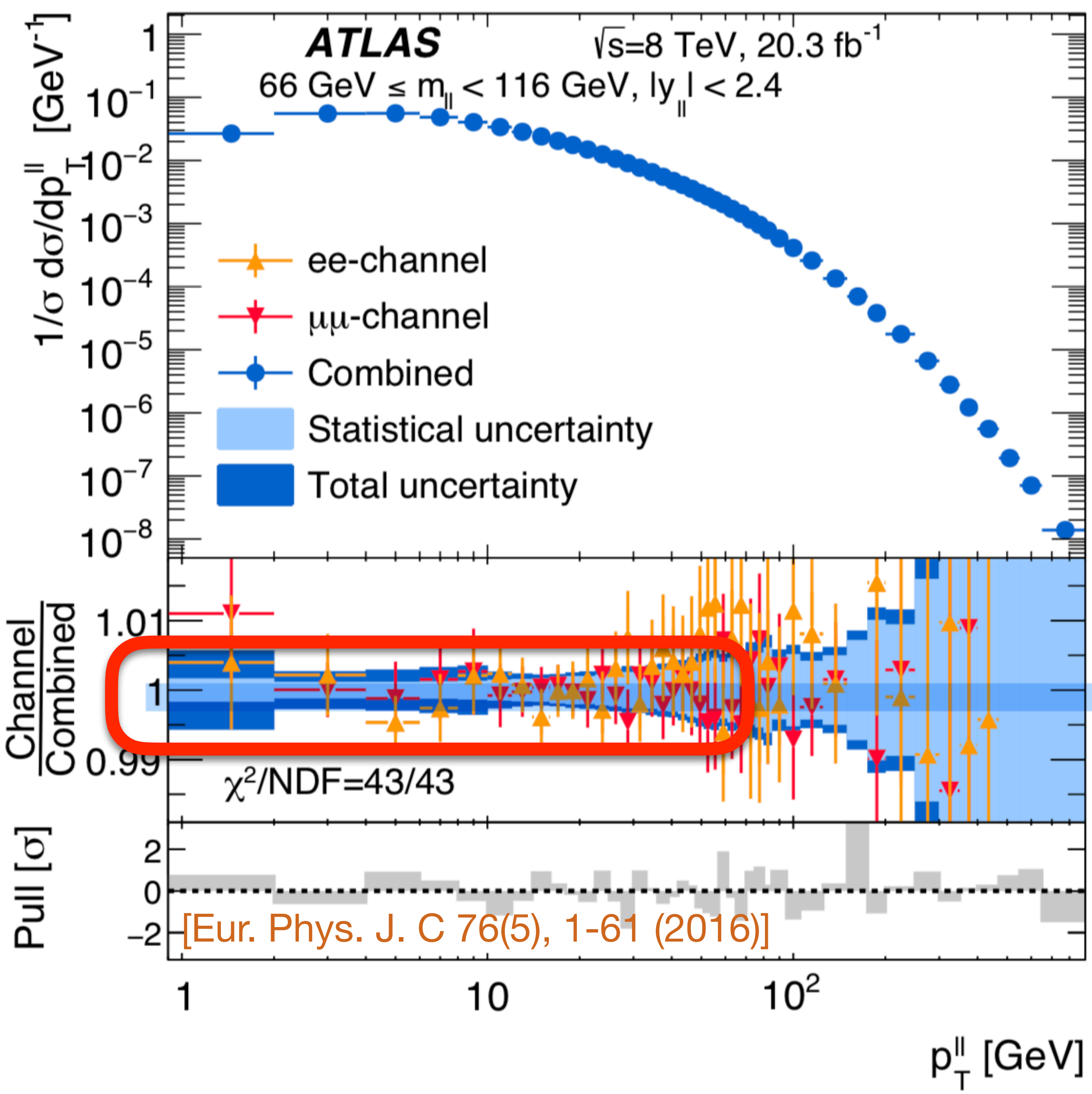
- **CONs:**
  - **theoretical accuracy** not the state of the art,
  - no **LHC** data,
  - no **flavour dependence**,
  - only "low" q_T (no matching to **fixed order**),
  - no "pure" info on TMD **FFs** (would need e^+e^- data).

▷ Actively working to improve on the downsides.

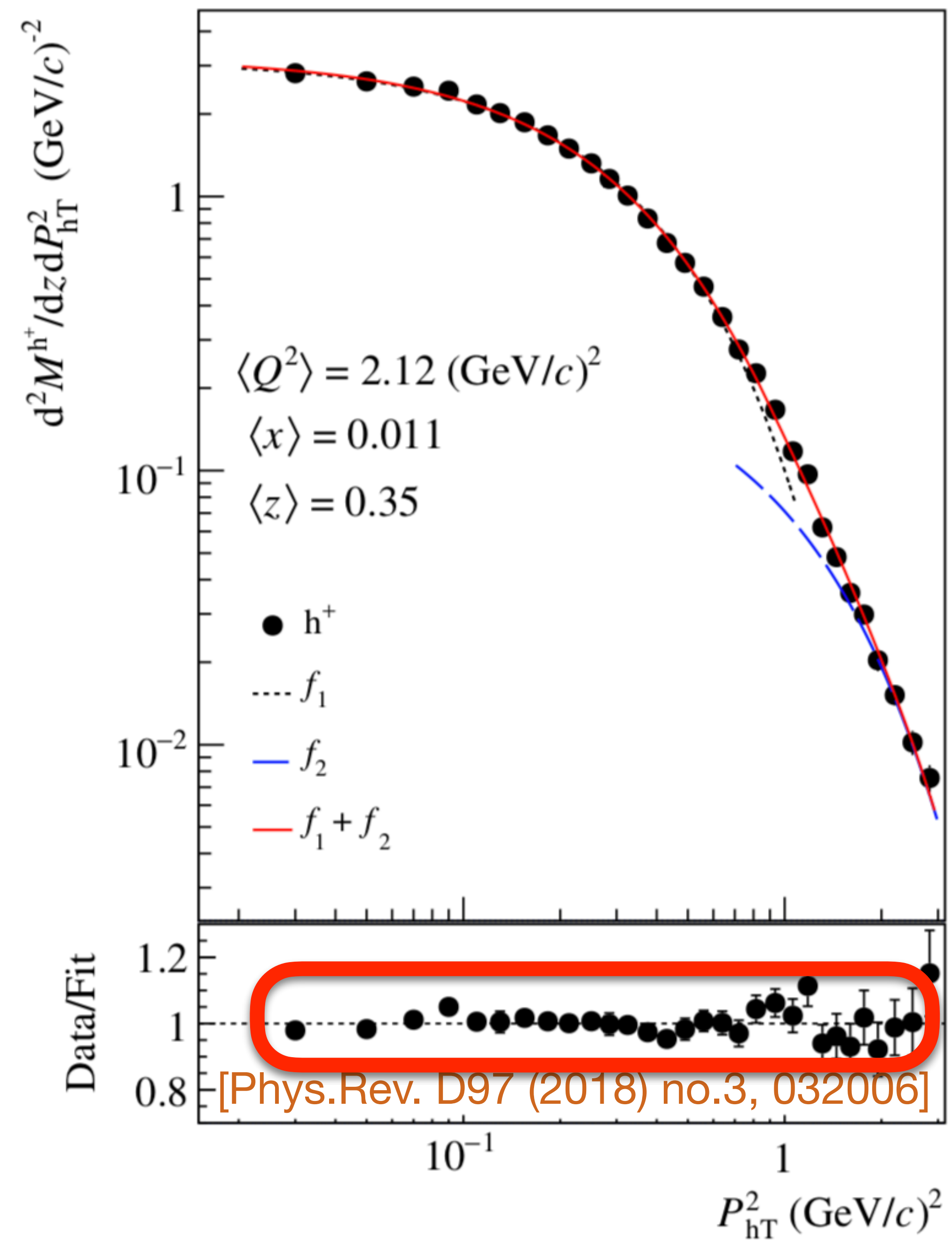
Pavia+JLab 2019 unpolarized TMD fit

Higher order corrections

Measurements of qT distributions have reached the sub-percent level uncertainties



[Eur. Phys. J. C 76(5), 1-61 (2016)]



[Phys.Rev. D97 (2018) no.3, 032006]

State-of-the-art calculations are thus necessary to hope to describe this data

higher-order corrections and possibly **matching** between **TMD** and **collinear**.

Pavia + JLab 2019 TMD fit

perturbative accuracy up to

N3LL

Drell-Yan

LHC data

NO normalisation

coefficients

$\chi^2 = 1.07$

Monte Carlo approach

200 replicas

Non perturbative function

QGaussian **Gaussian**

$$f_{\rm NP}(x,b,\zeta) = \left[\frac{1-\lambda}{1+g_1(x)\frac{b^2}{4}} + \lambda \exp\left(-g_{1,B}(x)\frac{b^2}{4}\right)\right]$$

$$\times \quad \exp\left[-\left(g_2 + g_{2B} b^2\right)\log\left(\frac{\zeta}{Q_0^2}\right)\frac{b^2}{4}\right]$$

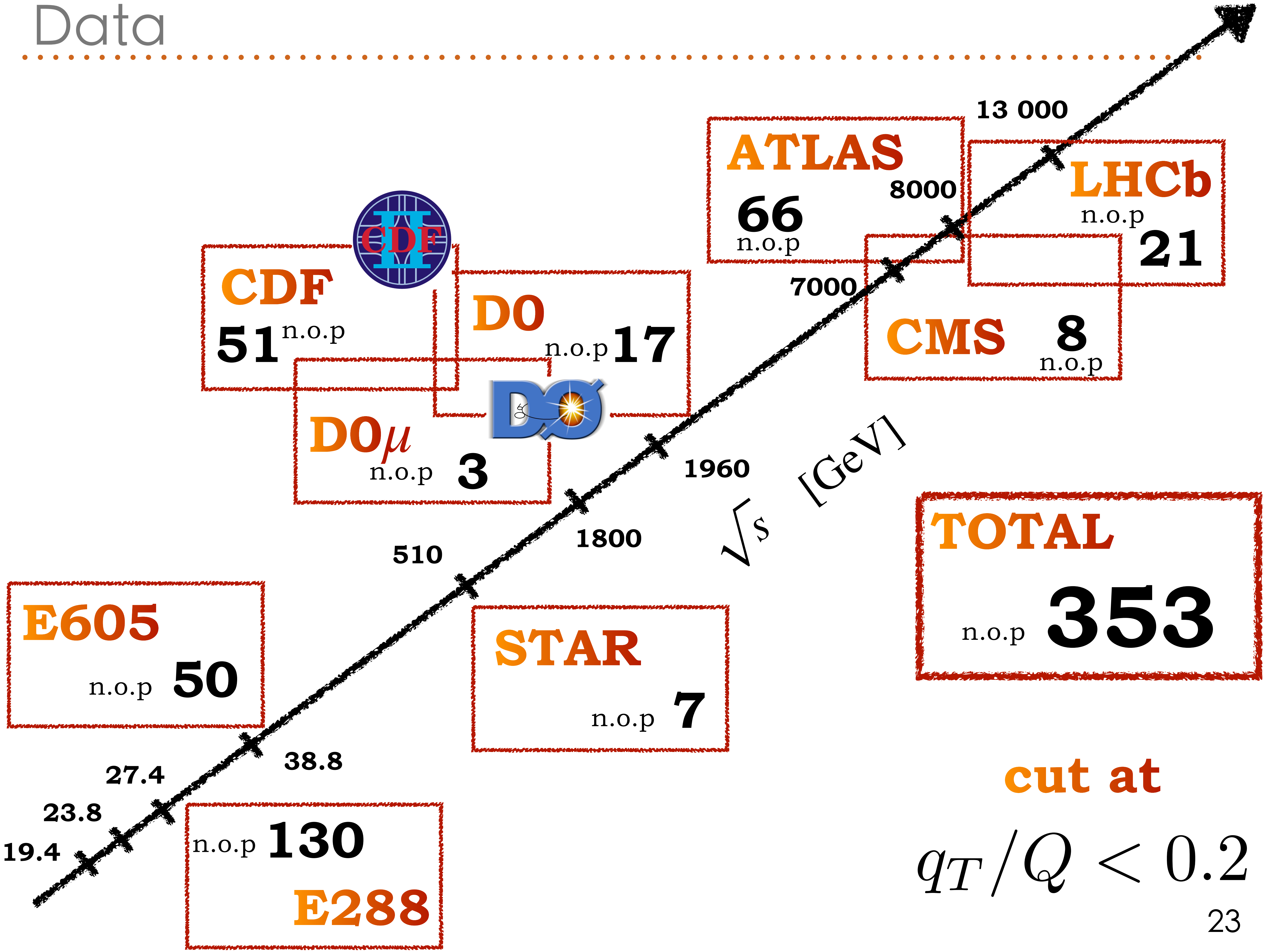
x-dependence

$$g_1(x) = \frac{N_1}{x\sigma}\exp\left[-\frac{1}{2\sigma^2}\ln^2\left(\frac{x}{\alpha}\right)\right]$$

$$g_{1,B}(x) = \frac{N_{1B}}{x\sigma_B}\exp\left[-\frac{1}{2\sigma_B^2}\ln^2\left(\frac{x}{\alpha_B}\right)\right]$$

9 parameters

Data



cut at

$$q_T/Q < 0.2$$

Fit quality

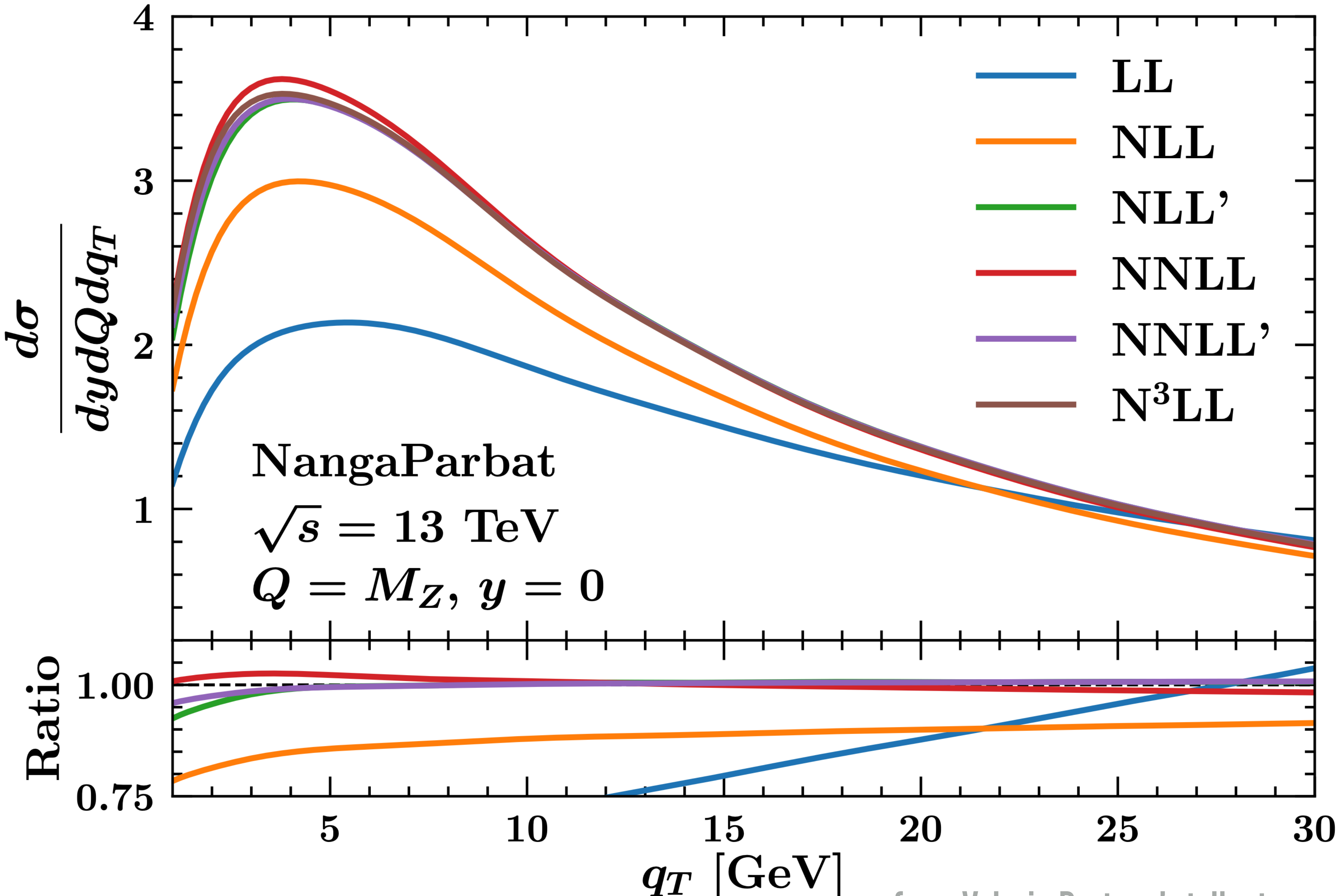
perturbative convergence

also observed by Bertone, Scimemi, Vladimirov
arXiv:1902.08474

Order	NLL’	NNLL	NNLL’	N3LL
χ_0^2 / n.d.p.	3.2628	1.6686	1.1465	**1.0705**

Global χ^2 as a function of the perturbative accuracy

Perturbative convergence



from Valerio Bertone's talk at
https://indico.cern.ch/event/849342/

NangaParbat

Nanga Parbat: a TMD fitting framework

Nanga Parbat is a fitting framework aimed at the determination of the non-perturbative component of TMD distributions.

Download

will be **publicly available**

You can obtain NangaParbat directly from the github repository:

based on APFEL++ to extract **TMD PDFs** and **FFs**

Pavia 2019 assessment

- Current precision of data requires the most accurate calculations

  └── perturbative convergence

N3LL

- A sound treatment of **uncertainties** is also required

  └── correlated systematics,
  PDFs uncertainties

- **Simultaneous** description of low- and high-energy data with

NO normalisation coefficients

POLARIZED TMD

QUARK SIVERS

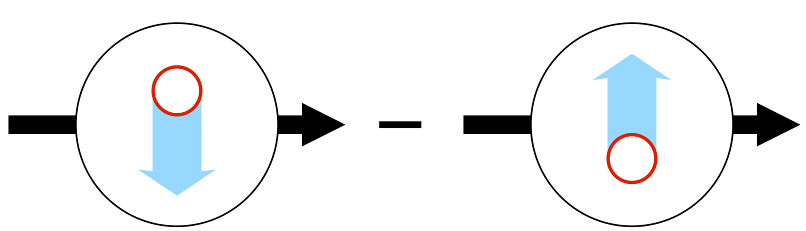
Transverse Momentum Distributions

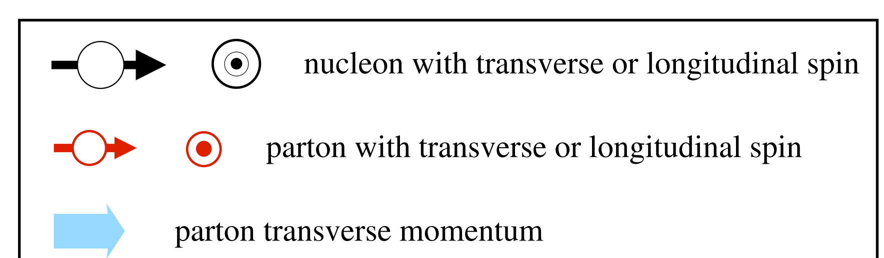
quark pol. / nucleon pol.

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

$f_{1T}^\perp$ → Sivers function

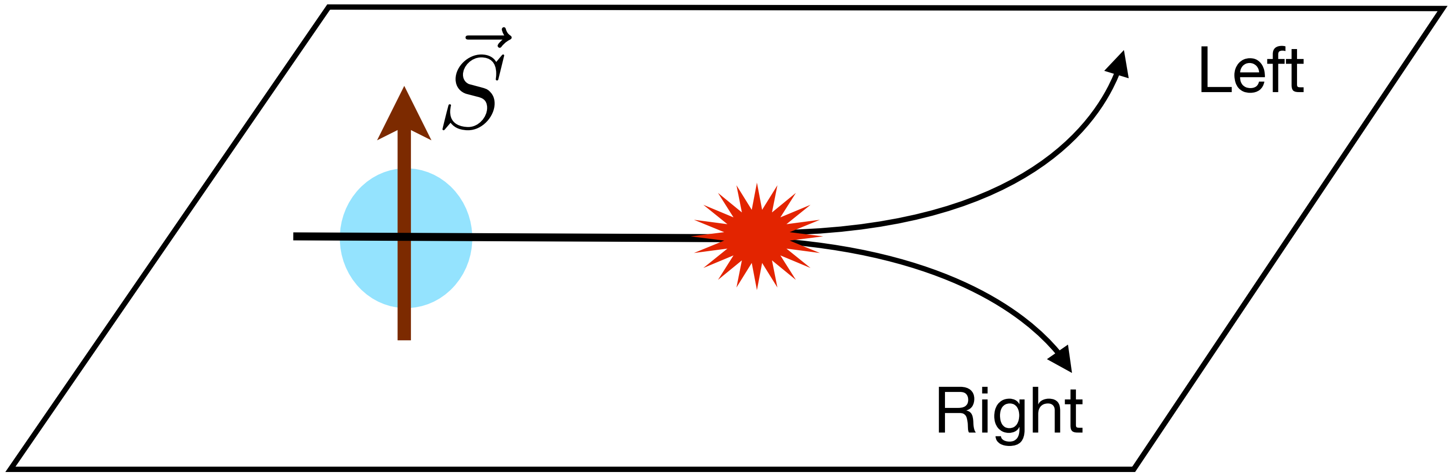
→number density of unpolarized partons inside a transversely polarized nucleon

$f_{1T}^\perp =$ 



Single-spin asymmetry (SSAs)

Consider scattering of transversely polarized proton off an unpolarized proton or electron



The asymmetry is defined as

$$A_N(x_F, p_\perp) \equiv \frac{L - R}{L + R} = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$$

Spin and quark motion correlation

spin budget of hadrons

missing contributions from elementary constituents not yet quantified

SSAs in hadron reactions

not vanishing as expected with increasing energy

correlation with parton dynamics

Effect of polarization on nucleon internal structure density

polarized TMDs and anomalous magnetic moment

SSA: early theory prediction

QCD theory predicts that if partons have only longitudinal momentum, SSA should vanish [Kane, Pumplin and Repko (1978)]

observation of significant polarization in those reactions would contradict either QCD or its applicability

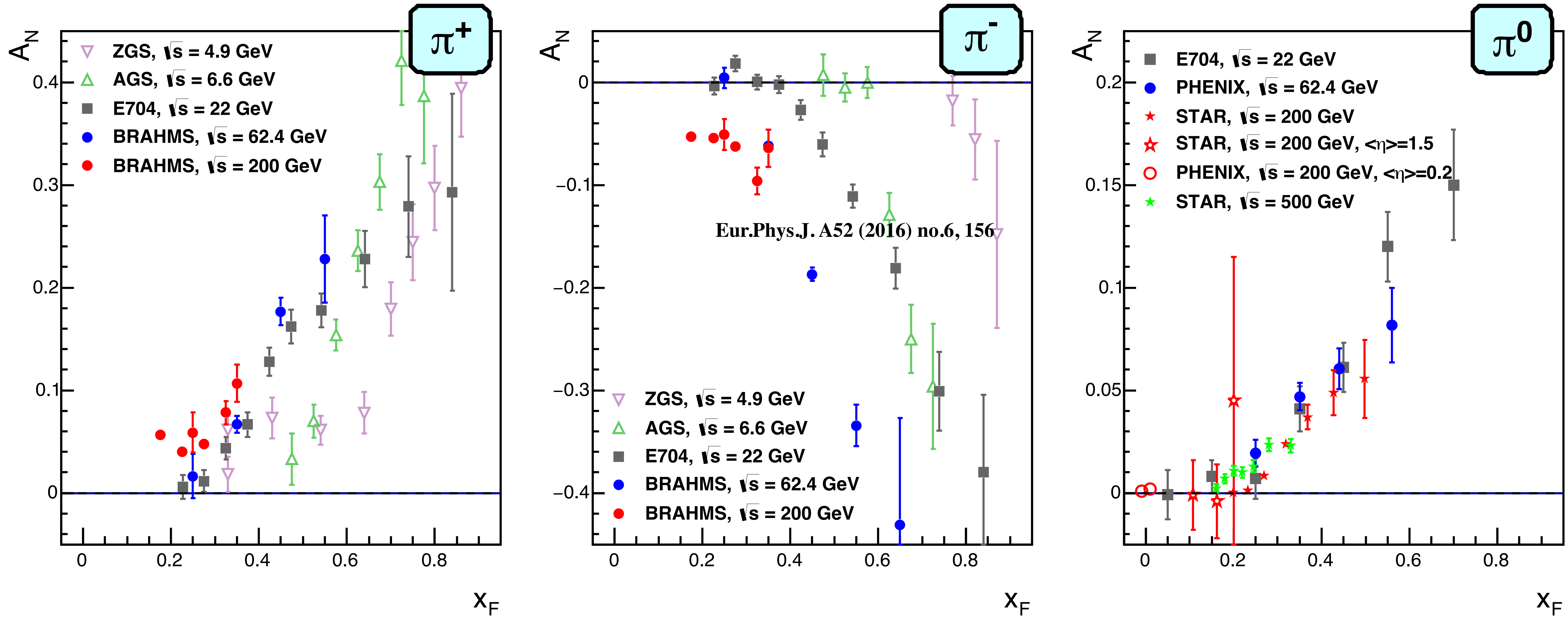


Fig. 1. Transverse single spin asymmetry measurements for charged and neutral pions at different center-of-mass energies as a function of Feynman-x, x_F.

[Aschenauer et al. - Eur.Phys.J. A52 (2016) no.6, 156]

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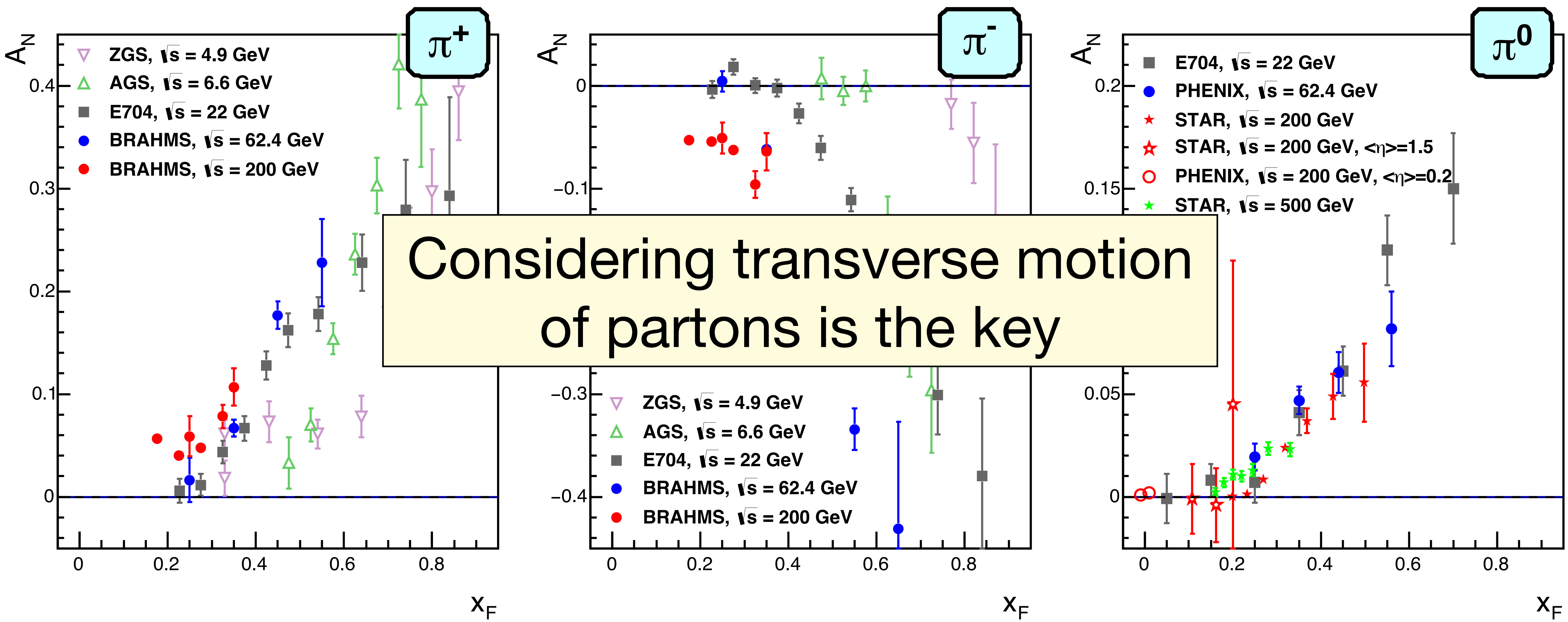


Considering transverse motion of partons is the key

SSAs and parton transverse momentum

Correlation between transverse motion of partons and corresponding azimuthal effects
first pointed out in ’77 by Feynman, Fox and Field

→origin of transverse momentum in DY processes:
-non-zero intrinsic momentum of partons in the nucleon (NP)
-recoil of gluons radiated off active quarks (pert. effect).

→ precursors of the Generalized Parton Model (GPM)

The related QCD evolution of TMDs was studied in the ‘80s by Collins-Soper-Sterman (CSS).
→perturbative + NP

SSAs and TMDs: Sivers function

In the '90s Sivers and Collins proposed two important correlations between transverse motion and spin

TMD "Sivers function" $f_{1T}^{\perp}$

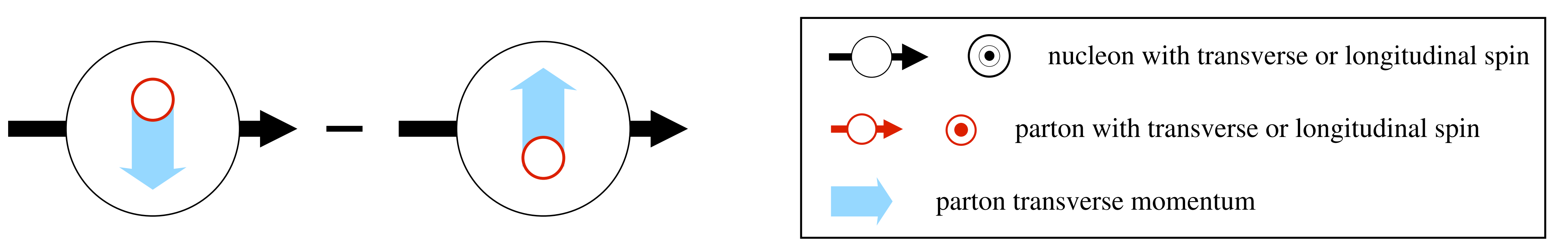
to describe the large SSAs in π-production off hadron-hadron scattering

→ could originate from intrinsic motion of quarks
→**inner asymmetry of unpolarized quarks inside a transversely polarized nucleon**

In the '90s Sivers and Collins proposed two important correlations between transverse motion and spin

TMD "Sivers function" $f_{1T}^{\perp}$

→number density of unpolarized partons inside a transversely polarized nucleon

$f_{1T}^{\perp} =$ 

Sivers function

Single-spin production asymmetries from the hard scattering of pointlike constituents

Dennis Sivers
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439
(Received 28 April 1989)

When one takes into account the transverse momenta of the constituents in a polarized proton, there exists a kinematic, "trigger-bias," effect in the formulation of the QCD-based hard-scattering model which can lead to single-spin production asymmetries. It seems convenient to represent the coherent spin-orbit forces in a polarized proton by defining an asymmetry in the transverse-momentum distribution of the fundamental constituents. It may then be possible to organize the hard-scattering model so that the kinematic constraints of hard 2→2 scattering provide the leading contribution at large transverse momentum to asymmetries of the type $A_N d\sigma(hp_\uparrow \rightarrow \text{jet}+x)$, $A_N d\sigma(hp_\uparrow \rightarrow \text{“}\pi\text{”}x)$, where $p_\uparrow$ denotes a transversely polarized proton and "π" represents any spinless meson composed of light quarks. This approach provides testable relationships between different asymmetries.

Sivers, Phys. Rev. D41 (1990)

Vanishing Sivers function

[J.Collins - Nucl. Phys. B396 (1993)]

"Fragmentation of Transversely Polarized Quark Probes in Transverse Momentum Distributions"

> Sivers [21] suggested that the $k_\perp$ distribution of the quark could have an azimuthal asymmetry when the initial hadron has transverse polarization. However, such an asymmetry is prohibited because QCD is time-reversal invariant. This is shown in the appendix.

apply space and time-reversal symmetry to the quark fields in the operator definition of the parton densities.

⬇

Sivers function has to be zero

Sivers function reappearing

Final-state interactions and single-spin asymmetries in semi-inclusive deep inelastic scattering ☆

Stanley J. Brodsky [a], Dae Sung Hwang [a,b], Ivan Schmidt [c]

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[b] *Department of Physics, Sejong University, Seoul 143-747, South Korea*
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Received 2 February 2002; accepted 2 February 2002

Editor: H. Georgi

Abstract

Recent measurements from the HERMES and SMC Collaborations show a remarkably large azimuthal single-spin asymmetries A_{UL} and A_{UT} of the proton in semi-inclusive pion leptoproduction $\gamma^*(q)p \to \pi X$. We show that final-state interactions from gluon exchange between the outgoing quark and the target spectator system lead to single-spin asymmetries in deep inelastic lepton–proton scattering at leading twist in perturbative QCD; i.e., the rescattering corrections are not power-law suppressed at large photon virtuality Q^2 at fixed x_{bj}. The existence of such single-spin asymmetries requires a phase difference between two amplitudes coupling the proton target with $J_p^z = \pm 1/2$ to the same final-state, the same amplitudes which are necessary to produce a nonzero proton anomalous magnetic moment. We show that the exchange of gauge particles between the outgoing quark and the proton spectators produces a Coulomb-like complex phase which depends on the angular momentum L^z of the proton's constituents and is thus distinct for different proton spin amplitudes. The single-spin asymmetry which arises from such final-state interactions does not factorize into a product of distribution function and fragmentation function, and it is not related to the transversity distribution $\delta q(x, Q)$ which correlates transversely polarized quarks with the spin of the transversely polarized target nucleon.

[Brodsky, Hwang, Schmidt - Physics Letters B 530 (2002) 99–107]

Sivers function reappearing

Final-state interactions and single-spin asymmetries in semi-inclusive deep inelastic scattering ☆

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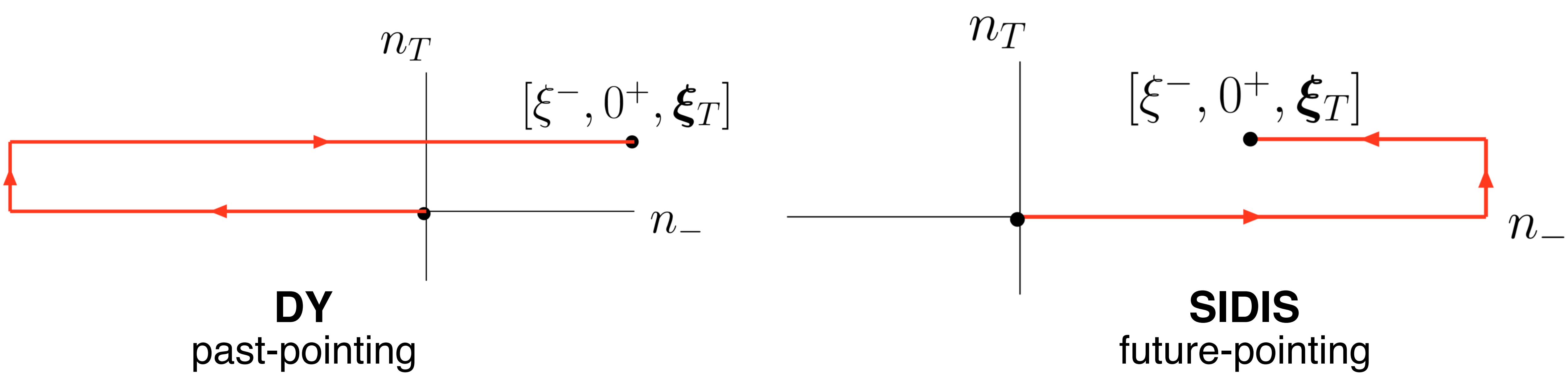
We show that final state interactions from gluon exchange between the outgoing and the target spectator lead to single spin asymmetries in deep inelastic lepton-proton at leading twist in perturbative QCD

between the outgoing quark and the proton spectators produces a Coulomb-like complex phase which depends on the angular momentum L^z of the proton's constituents and is thus distinct for different proton spin amplitudes. The single-spin asymmetry which arises from such final-state interactions does not factorize into a product of distribution function and fragmentation function, and it is not related to the transversity distribution $\delta q(x, Q)$ which correlates transversely polarized quarks with the spin of the transversely polarized target nucleon.

[Brodsky, Hwang, Schmidt - Physics Letters B 530 (2002) 99–107]

Sivers function sign change

vanishing Sivers function? ⟶ Final state interactions and Wilson lines to consider

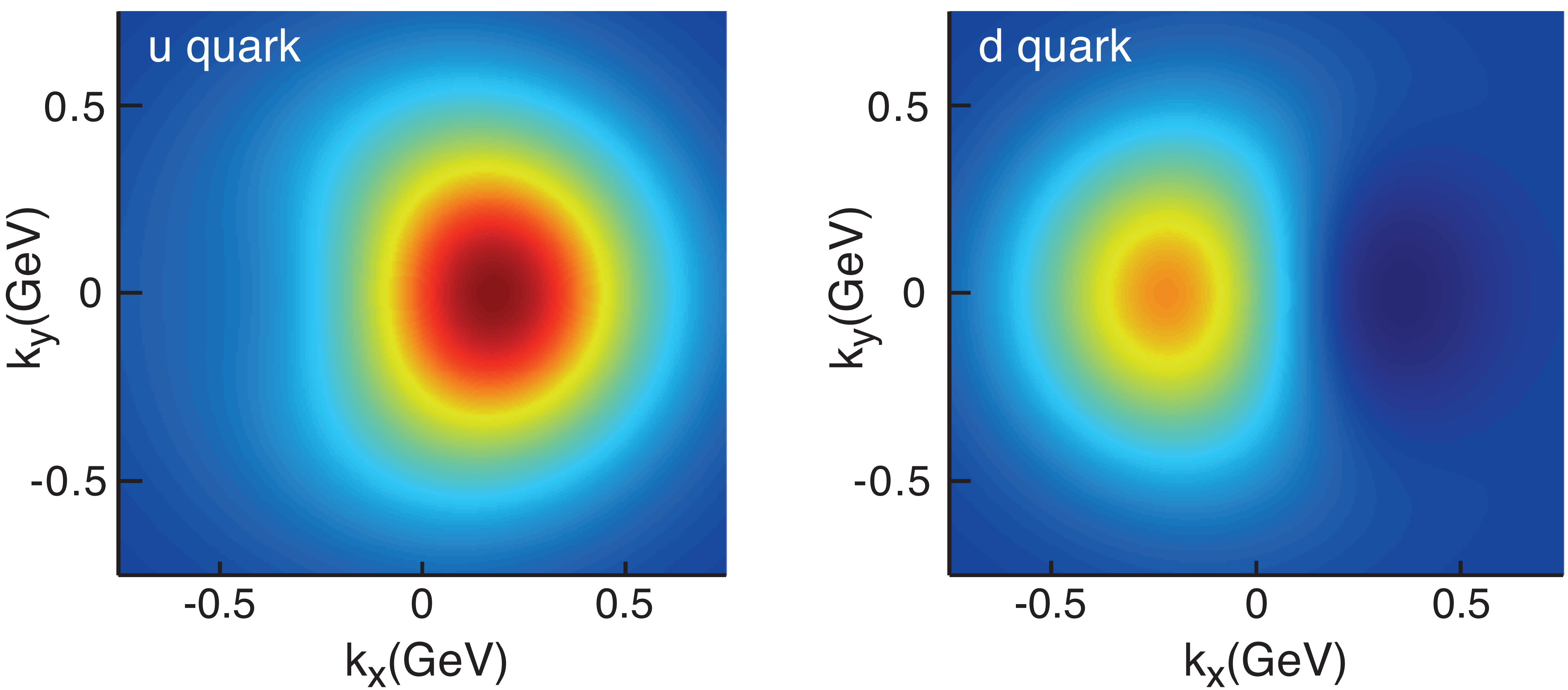


Sign change in Sivers function

$$f_{1T,DIS}^{\perp} = -f_{1T,DY}^{\perp}$$

⇒ presence of a non-zero Sivers function $f_{1T}^{\perp}$ will induce a dipole deformation of f_1

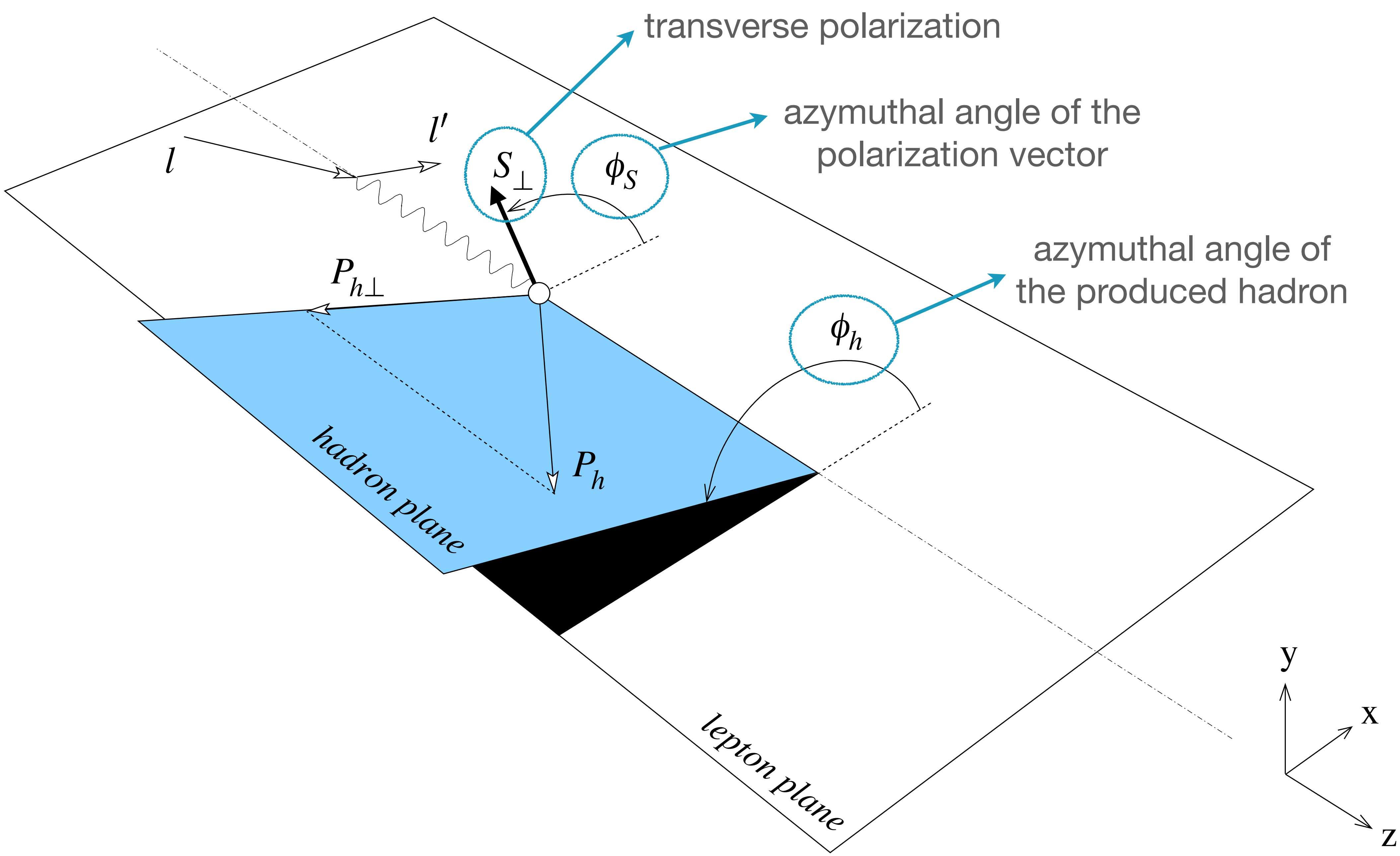
$x\, f_1(x, k_T, S_T)$



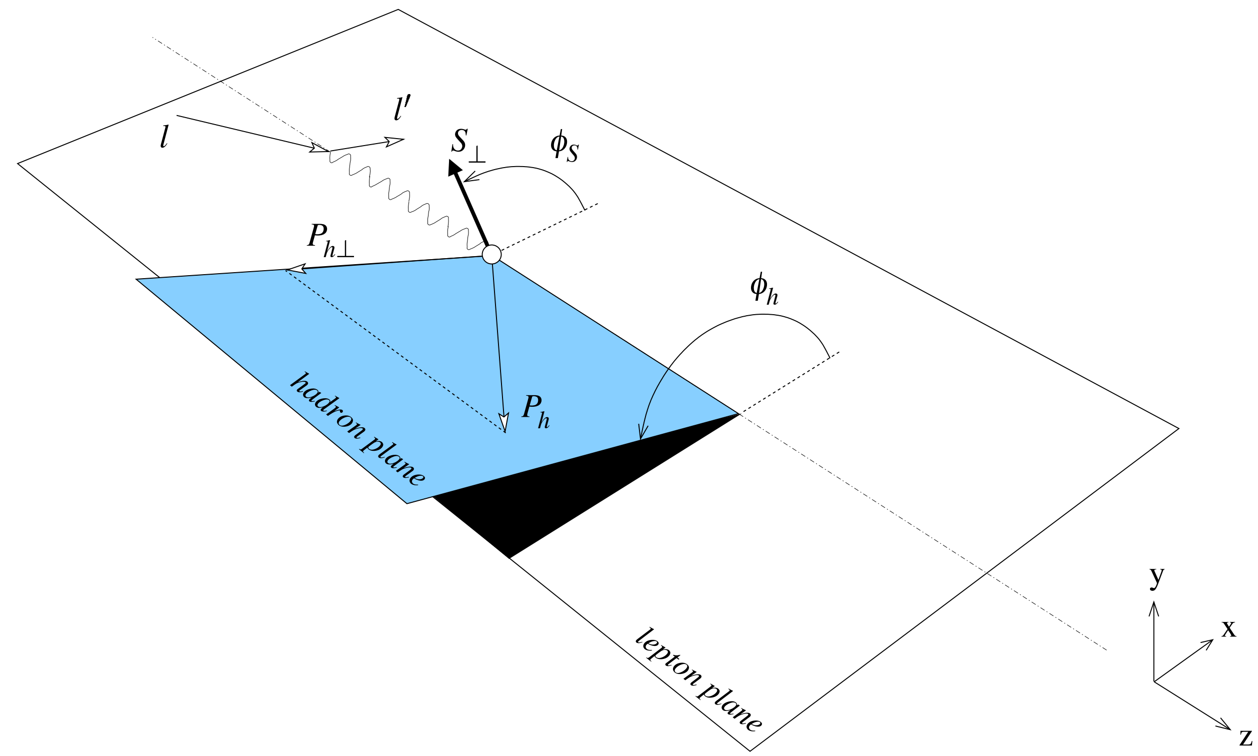
[from EIC White Paper]

Extraction of Sivers Function

Determined through its contributions to the cross section of polarized SIDIS



Extraction of Sivers Function



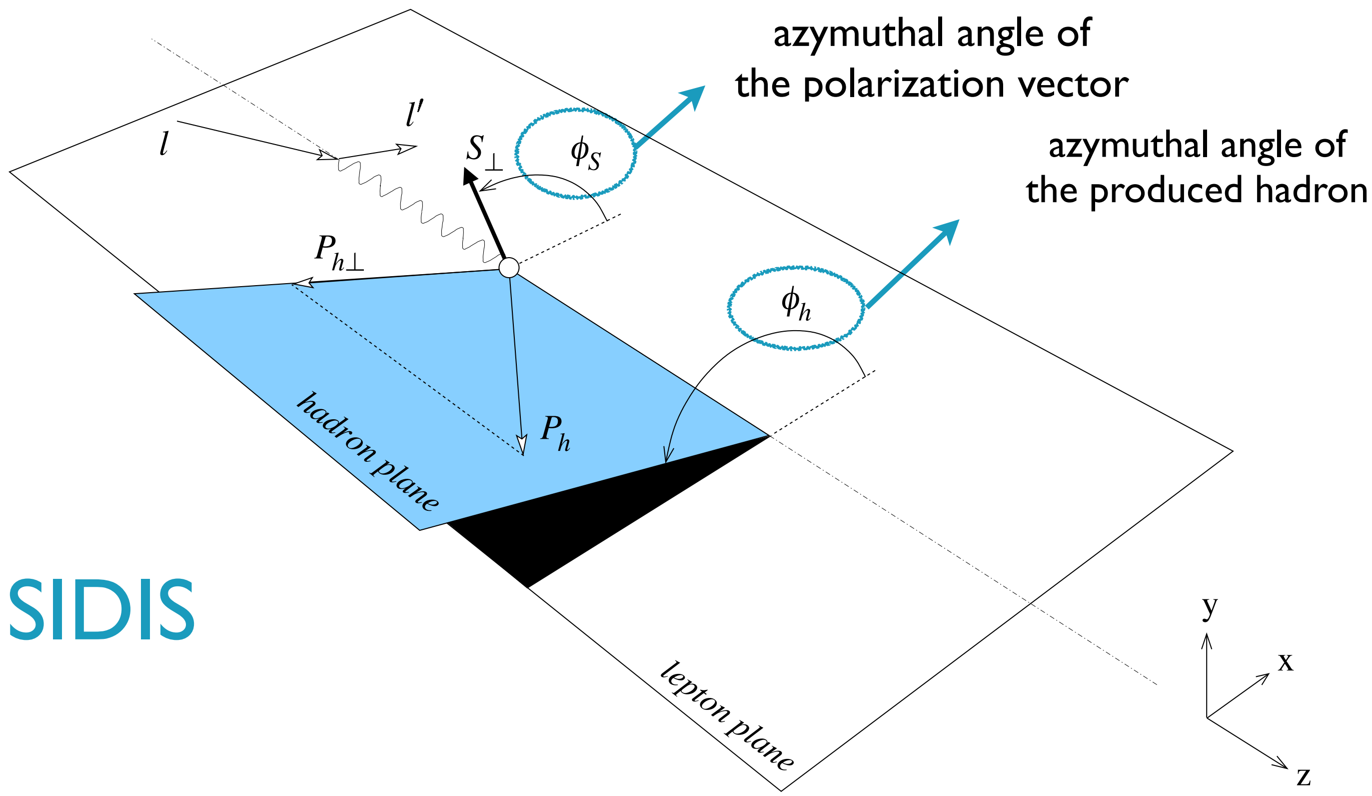
Isolating the terms relevant to the $\sin(\phi_h - \phi_S)$ modulation

$$A_{UT}^{\sin(\phi_h-\phi_S)} = \frac{\int d\phi_S \, d\phi_h \, [d\sigma^\uparrow - d\sigma^\downarrow] \, \sin(\phi_h - \phi_S)}{\int d\phi_S \, d\phi_h \, [d\sigma^\uparrow + d\sigma^\downarrow]}$$

↓ in terms of structure functions

$$A_{UT}^{\sin(\phi_h-\phi_S)} = \frac{F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}}{F_{UU,T} + \varepsilon F_{UU,L}}$$

Extraction of Sivers Function



SIDIS

LO - NLL

$$A_{UT}^{\sin(\phi_h - \phi_S)} \equiv \langle \sin(\phi_h - \phi_S) \rangle \sim \frac{f_{1T}^{\perp} \otimes D_1^{a\to h}}{f_1^a \otimes D_1^{a \to h}}$$

universality

first Sivers extraction with unpolarised TMDs extracted from data

Parametrization of Sivers function

Sivers function can be parametrized in terms of its **first moment**

$$f_{1T}^{\perp}(x, k_{\perp}^2) = f_{1T}^{\perp(1)}(x)\, f_{1TNP}^{\perp}(x, k_{\perp}^2)$$

nonperturbative part arbitrary, but constrained by the **positivity bound.**

$$f_{1TNP}^{\perp}(x, k_{\perp}^2) = \frac{1}{\pi K_f} \frac{1}{F_{max}} \frac{(1 + \lambda_S k_{\perp}^2)}{(M_1^2 + \lambda_S M_1^4)} e^{-k_{\perp}^2/M_1^2} f_{1NP}(x, k_{\perp}^2)$$

following the NP part of the unpolarized TMD

$$f_{1NP}(x, k_{\perp}^2) = \frac{1}{\pi} \frac{(1 + \lambda k_{\perp}^2)}{(g_{1a} + \lambda g_{1a}^2)} e^{-k_{\perp}^2/g_{1a}}$$

Free parameters $\lambda_S\,, M_1$

Parametrization of Sivers function

normalization
(abs.value <1)

$T_n(x)$ Chebyshev polynomials

$$f_{1T}^{\perp(1)}(x) = \frac{N_{Siv}^{a}}{G_{max}^{a}} x^{\alpha_a}(1-x)^{\beta_a}\Big(1 + A_a T_1(x) + B_a T_2(x)\Big)\, f_1(x, Q^2)$$

maximum value
of the function

Radici [Phys. Rev. Lett., 120(19):192001, 2018]

Free parameters $N_{Siv}^{a}\,, \alpha_a\,, \beta_a\,, A_a\,, B_a$

Flavor dependent: distinct for up, down, sea

Evolution of Sivers

We simply assume that $f_{1T}^{\perp(1)}$ evolves in the same way as unpolarized f_1

Difference in the Wilson coefficients: $C^i \to C^{Siv}$

At our accuracy level (LO): $C^{Siv(0)} = \delta(1-x)\delta^{ai}$

The evolved Sivers function first moment becomes

$$\tilde{f}_{1T}^{\perp(1)a}(x, \xi_T^2; Q^2) =$$

nonperturbative part of TMD

$$= \sum_i \left(\tilde{C}_{a/i} \otimes f_1^i\right)\left(x, \bar{\xi}_*; \mu_b\right) e^{\tilde{S}\left(\bar{\xi}_*; \mu_b, \mu\right)} e^{g_K(\xi_T)\ln(\mu/\mu_0)} \hat{f}_{1TNP}^{\perp(1)a}\left(x, \xi_T\right)$$

collinear PDF

(Wilson Coefficient)

(Sudakov form factor)

pQCD

nonperturbative part of evolution

Fourier transform: ξ_T space

Experimental data

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

Experimental data

proton [H]

95
data points

neutron [^{3}He]

6
data points

Using only one projection
to avoid fully correlated data

deuteron [^{6}LiD]

88
data points

Proton [NH_3]

111
data points

Same kinematic cuts applied to unpolarized

x, z, P_{hT} data projections

Results

LO - NLL

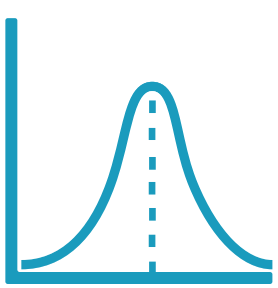
Replica method

Summary of results

Total number of data points: 117

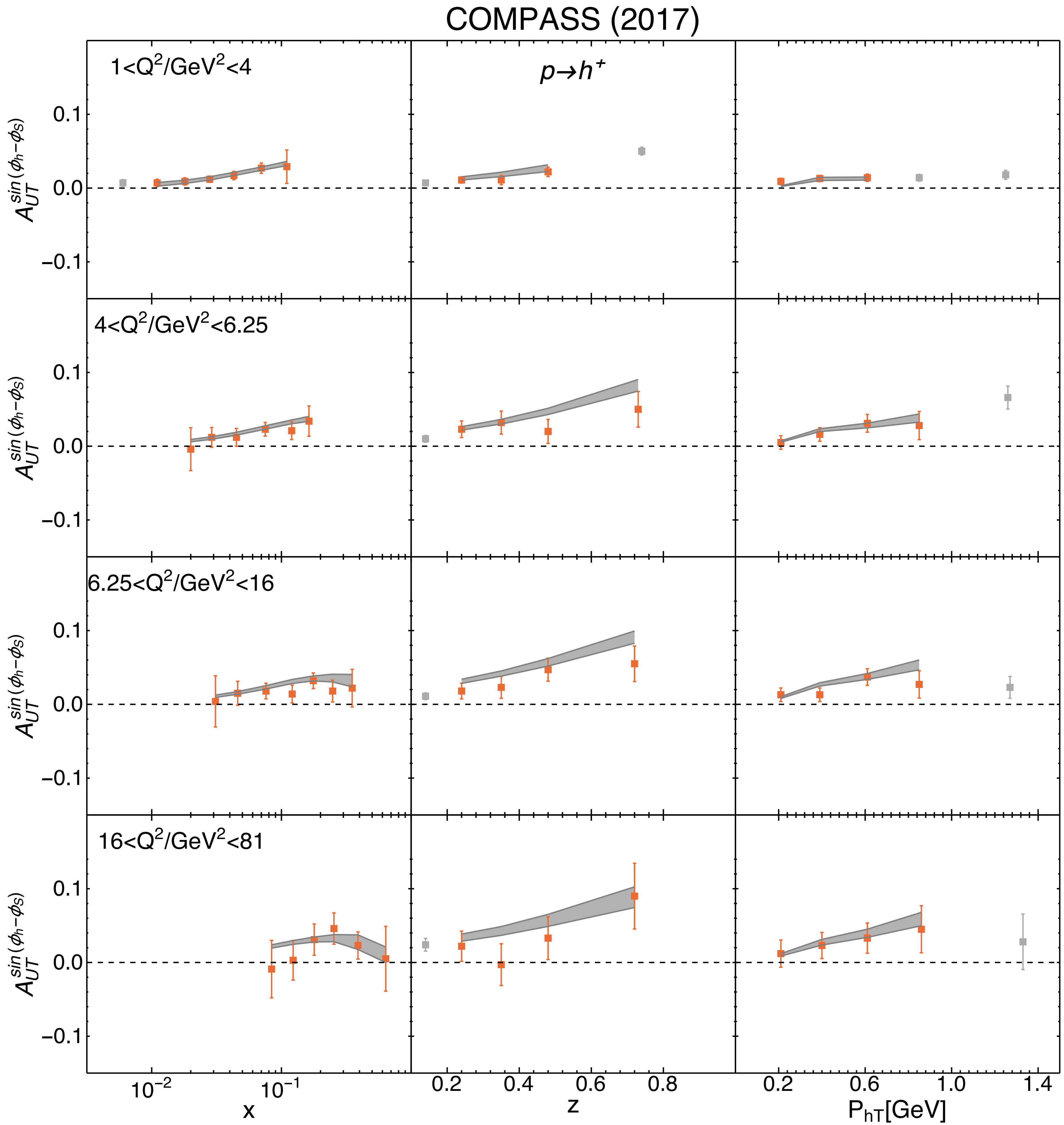
Total number of free parameters: 17

➛ for 3 different flavors



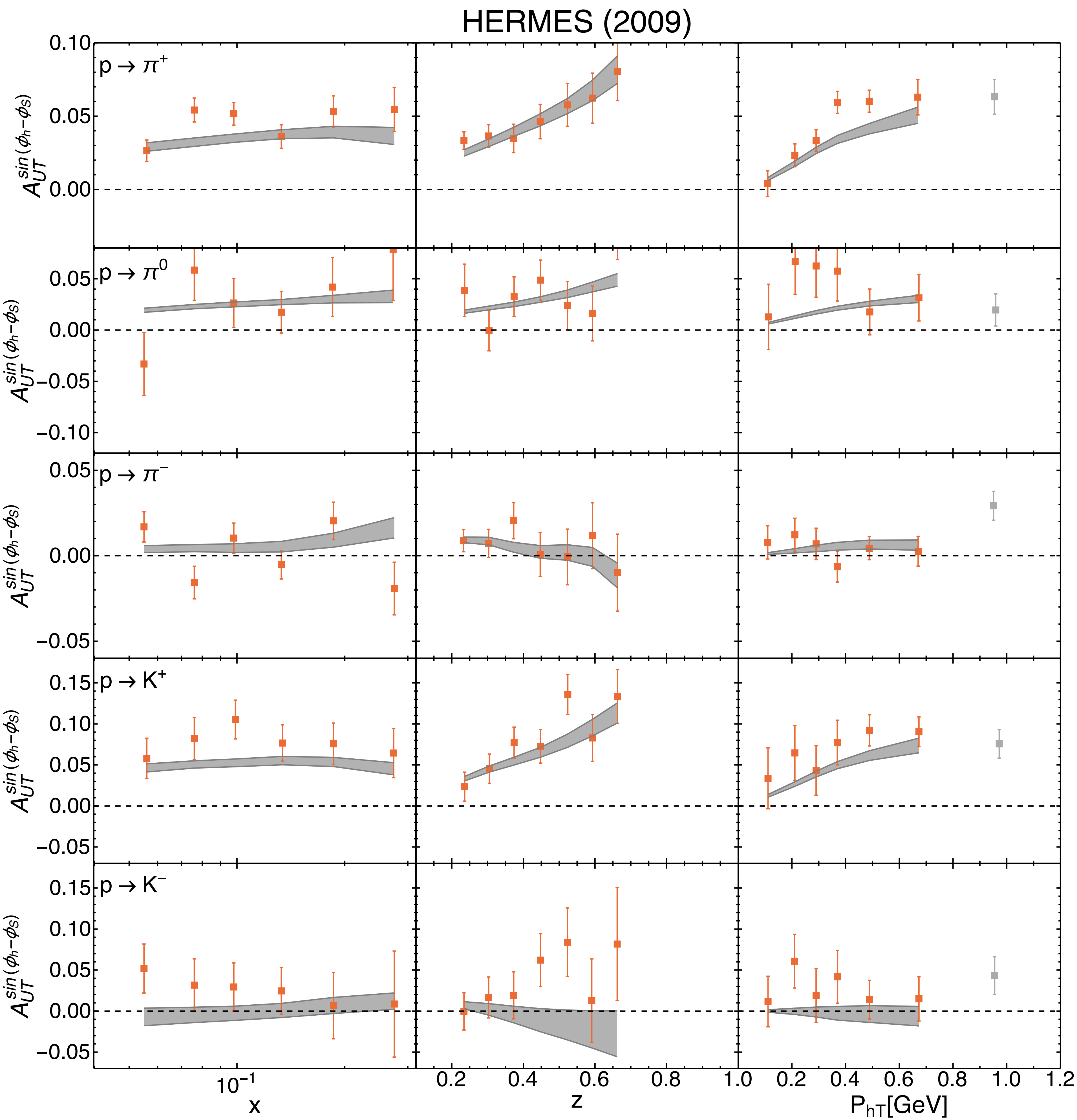
$$\chi^2/d.o.f = 1.12 \pm 0.06$$

[arXiv 2004.14278]



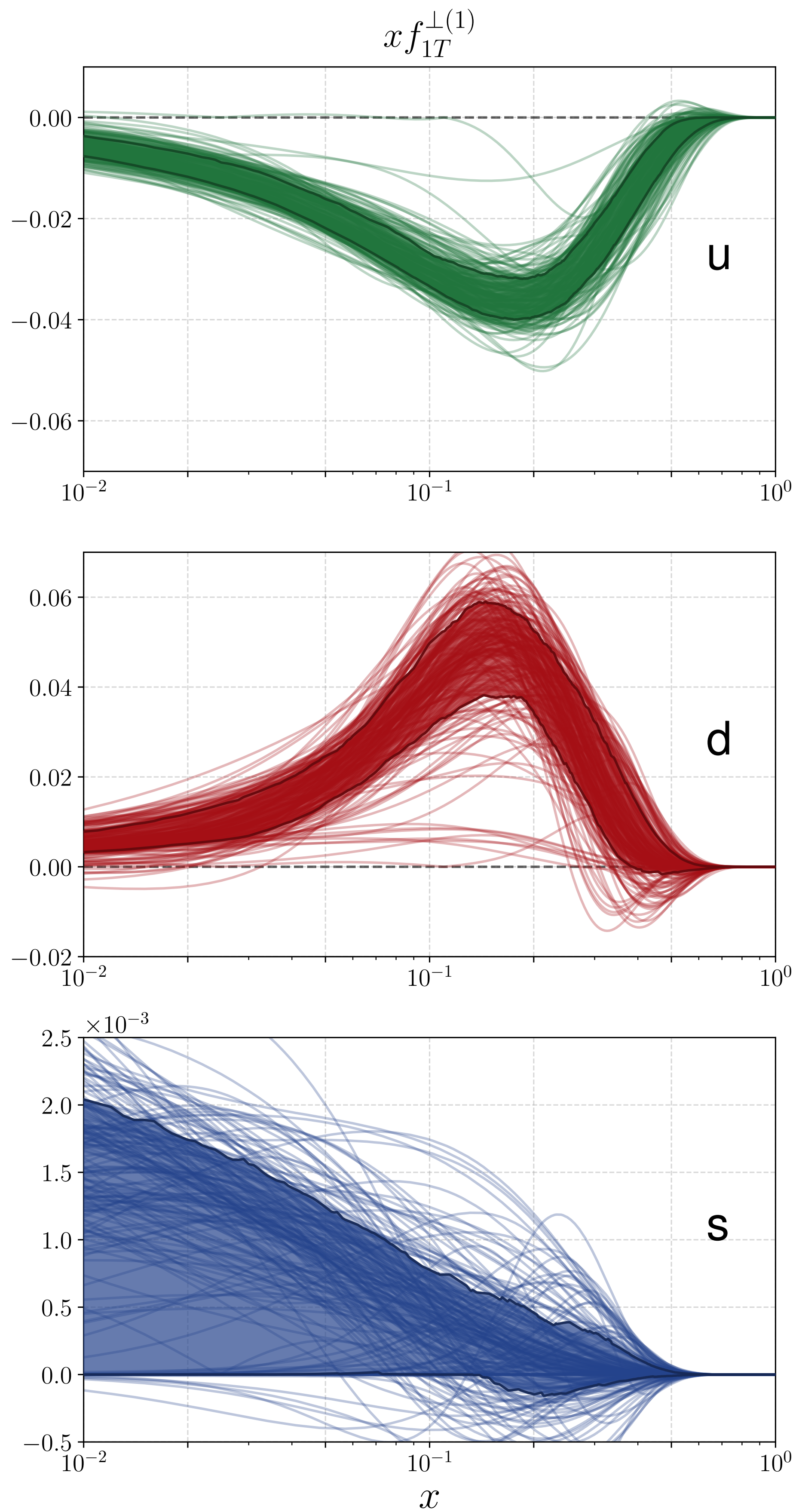
proton

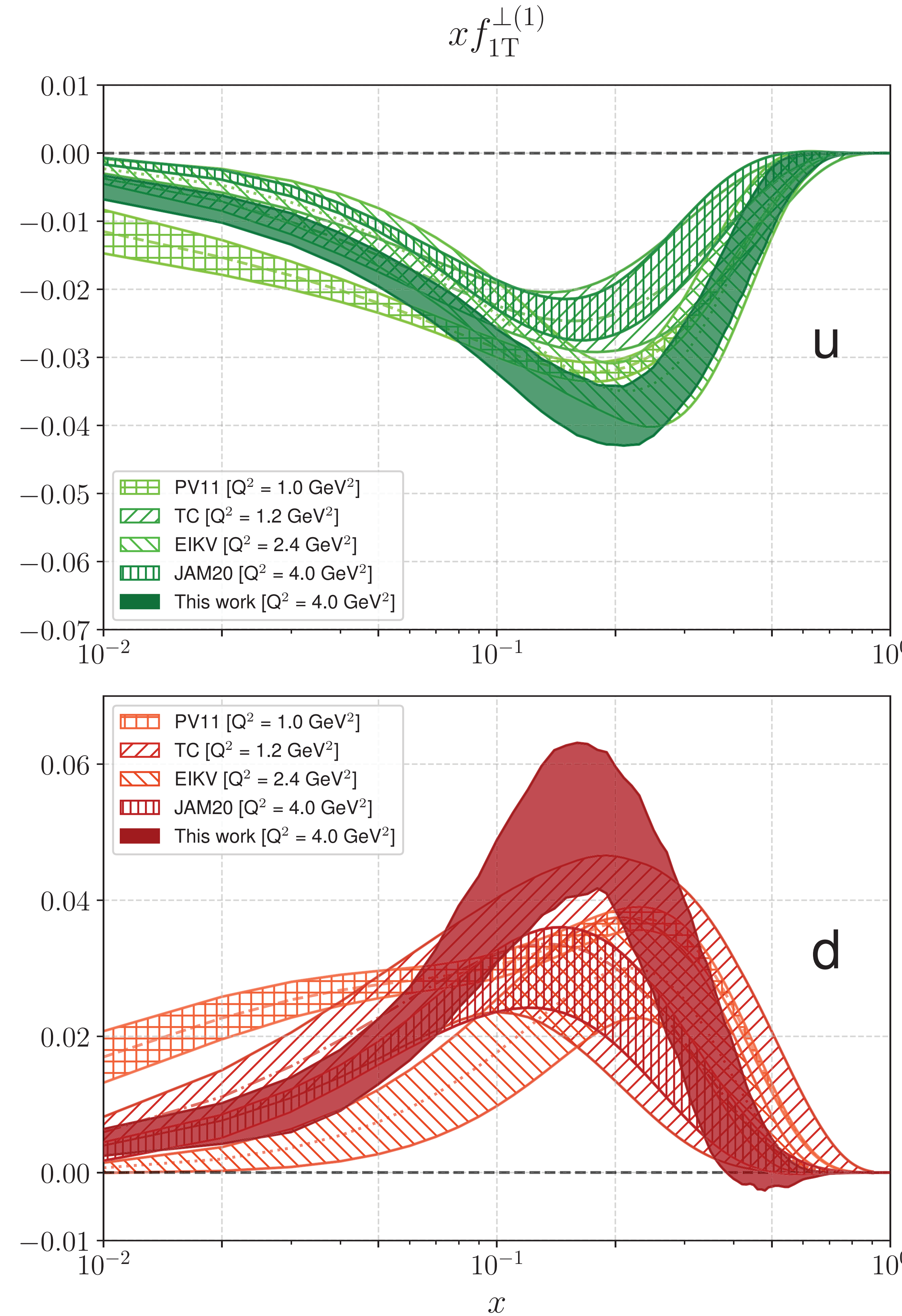
positive hadron



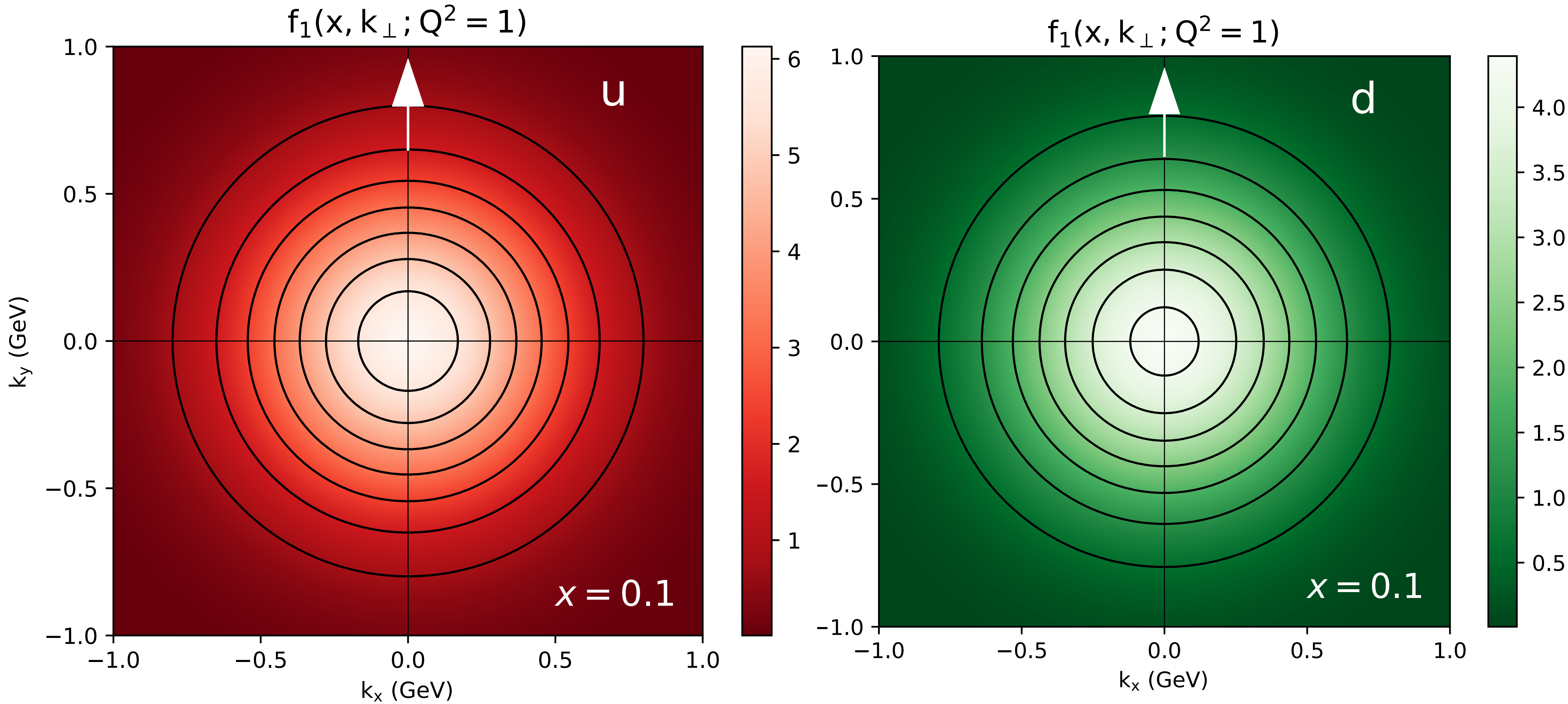
proton

Sivers function first moment comparison



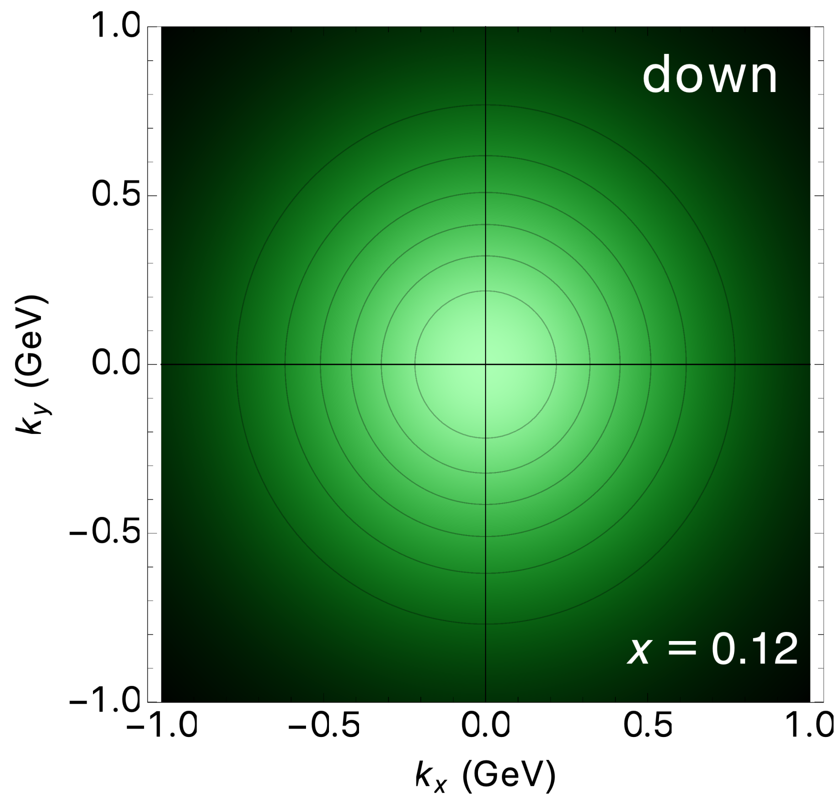


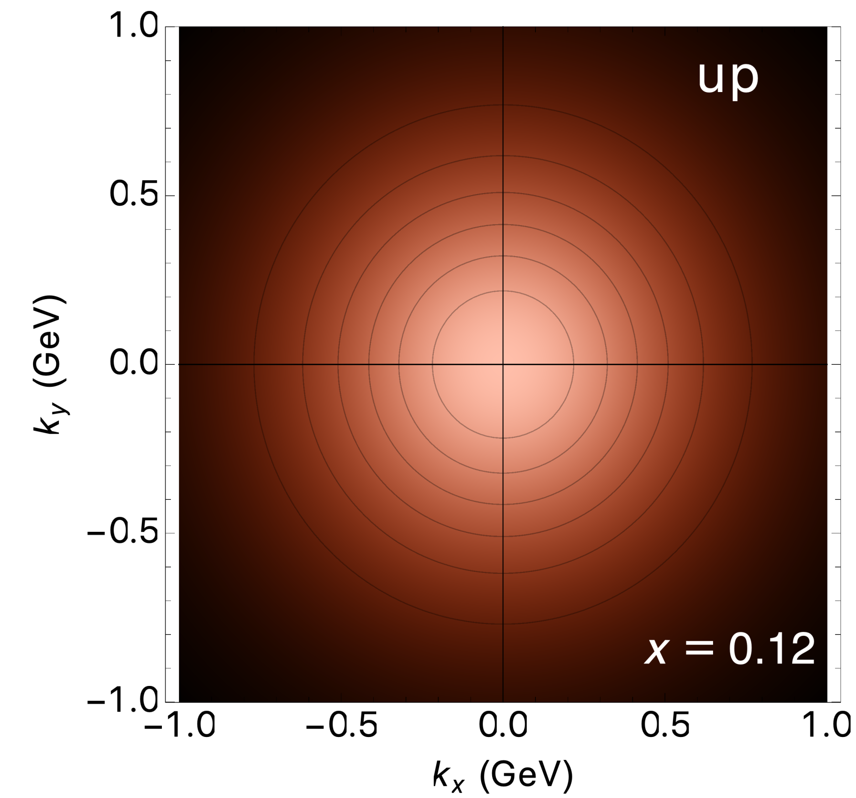
Visualization of TMDs: structure deformation



$$f_1(x, k_\perp; Q^2)$$

The proton in 3d (in momentum space)

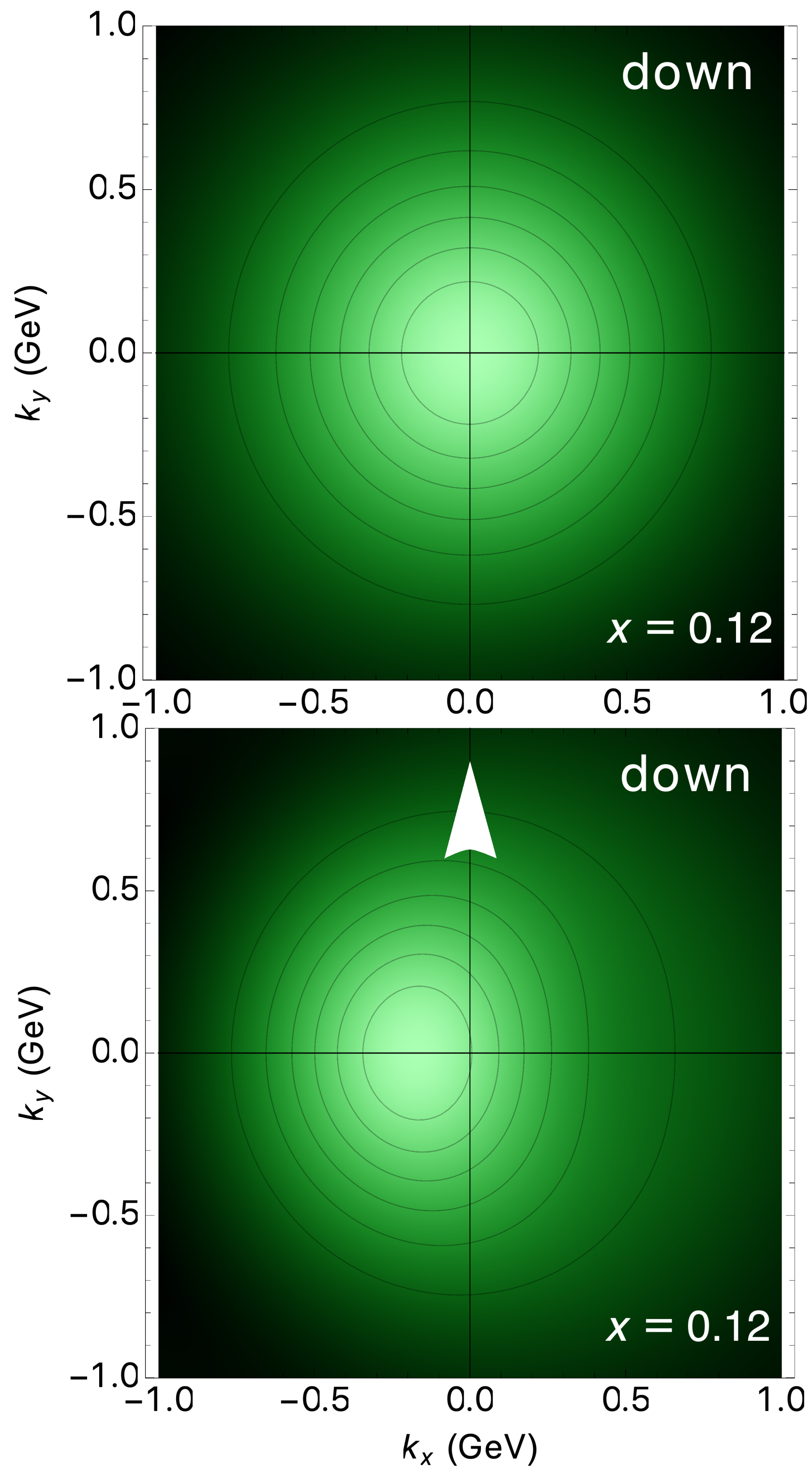




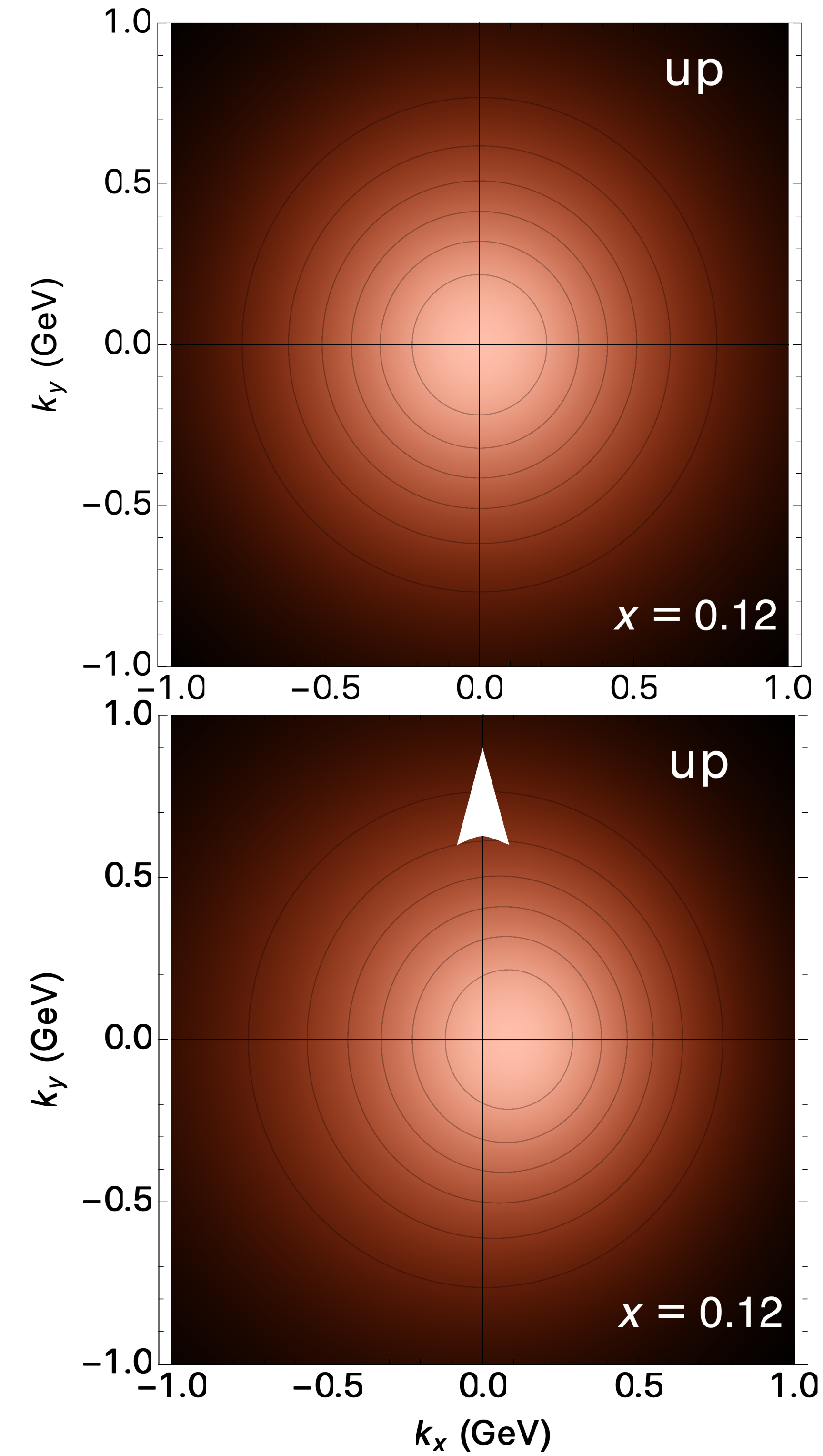
This is an image of the quark structure averaged over spin.

What happens if we include spin?

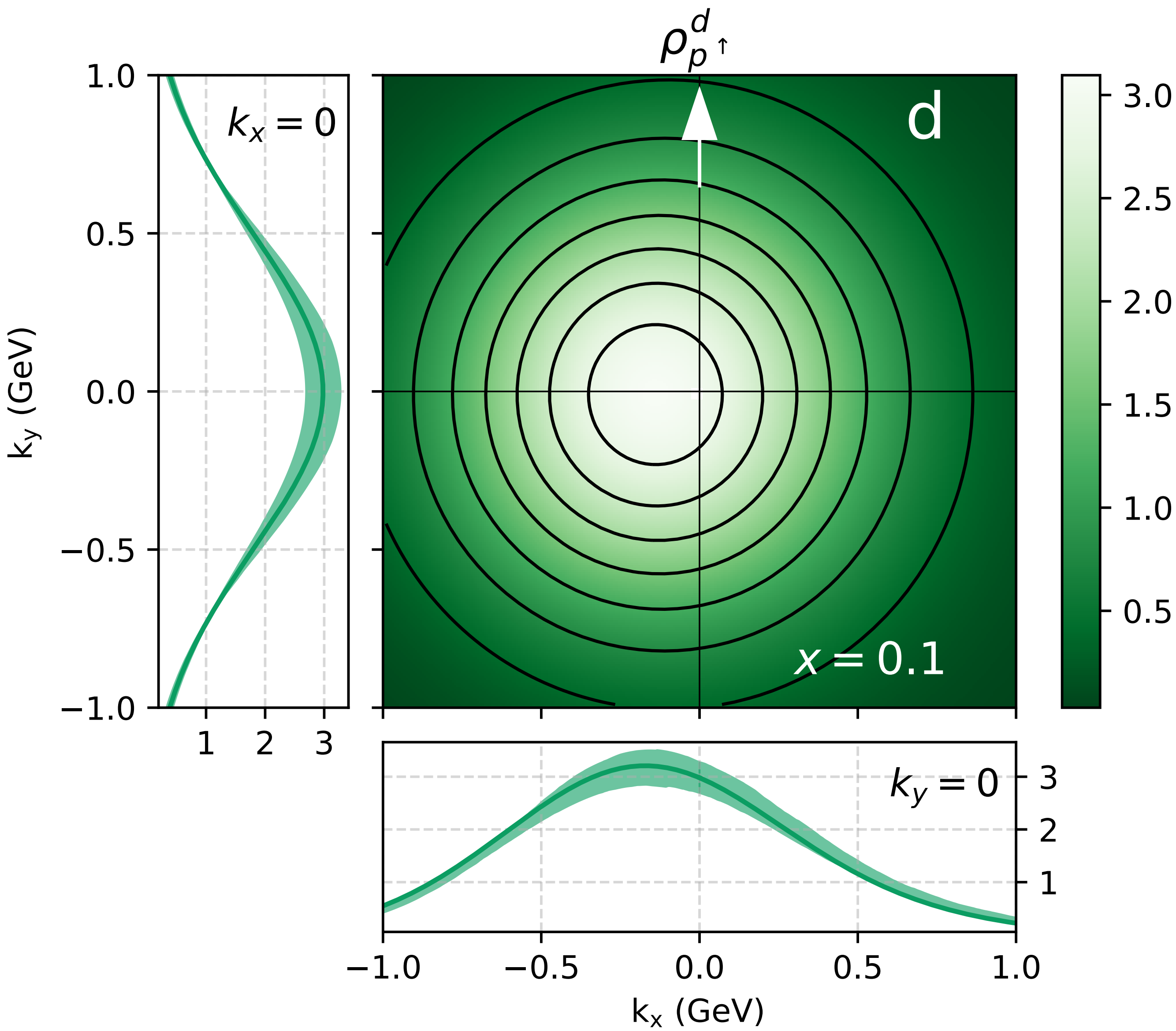
The proton in 3d (in momentum space)

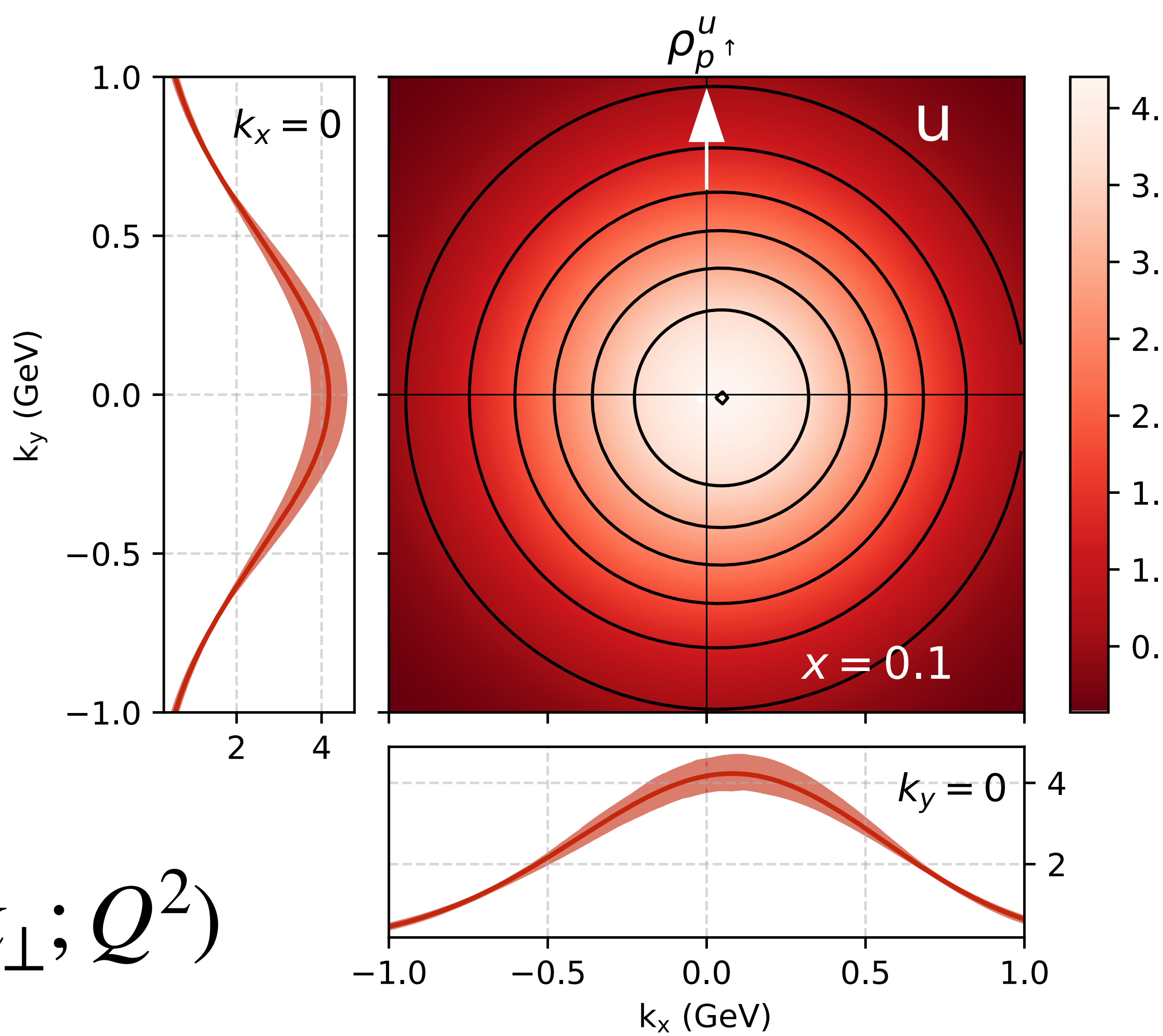


with
orbital angular
momentum
“Sivers effect”



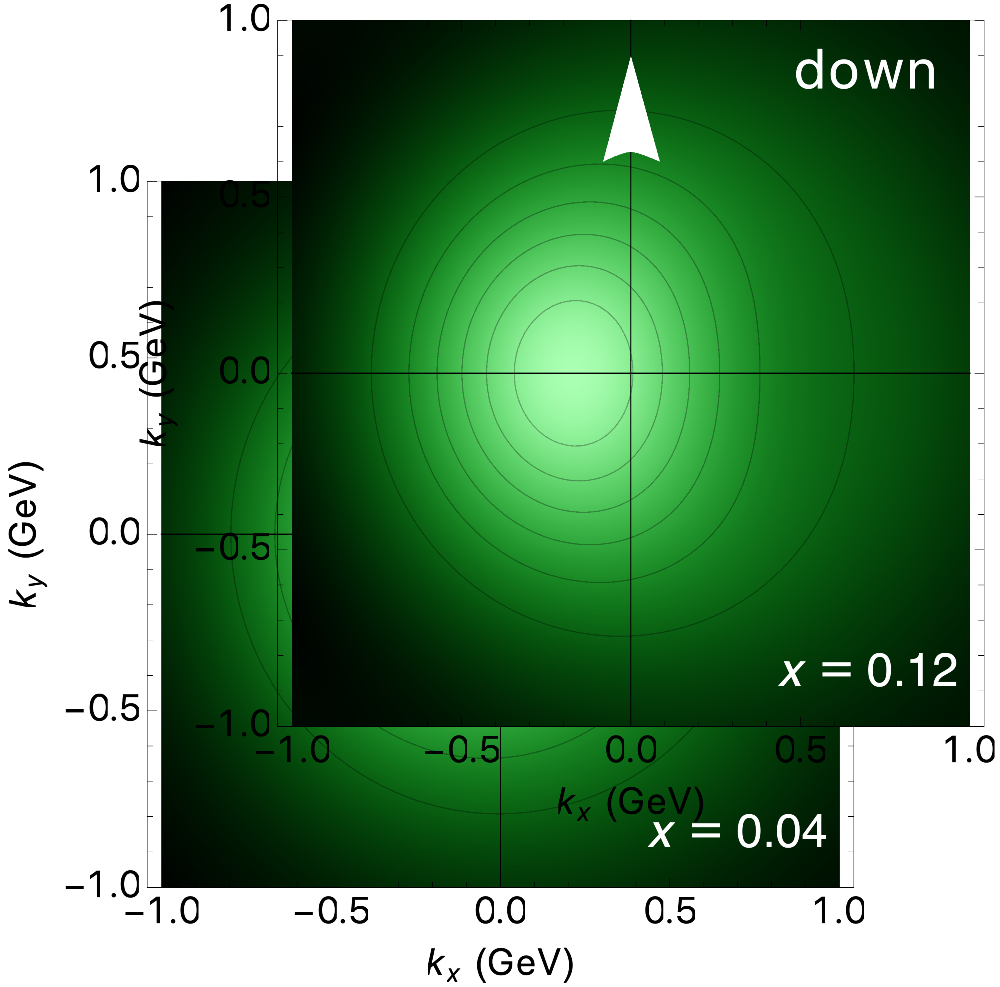
Visualization of TMDs: structure deformation

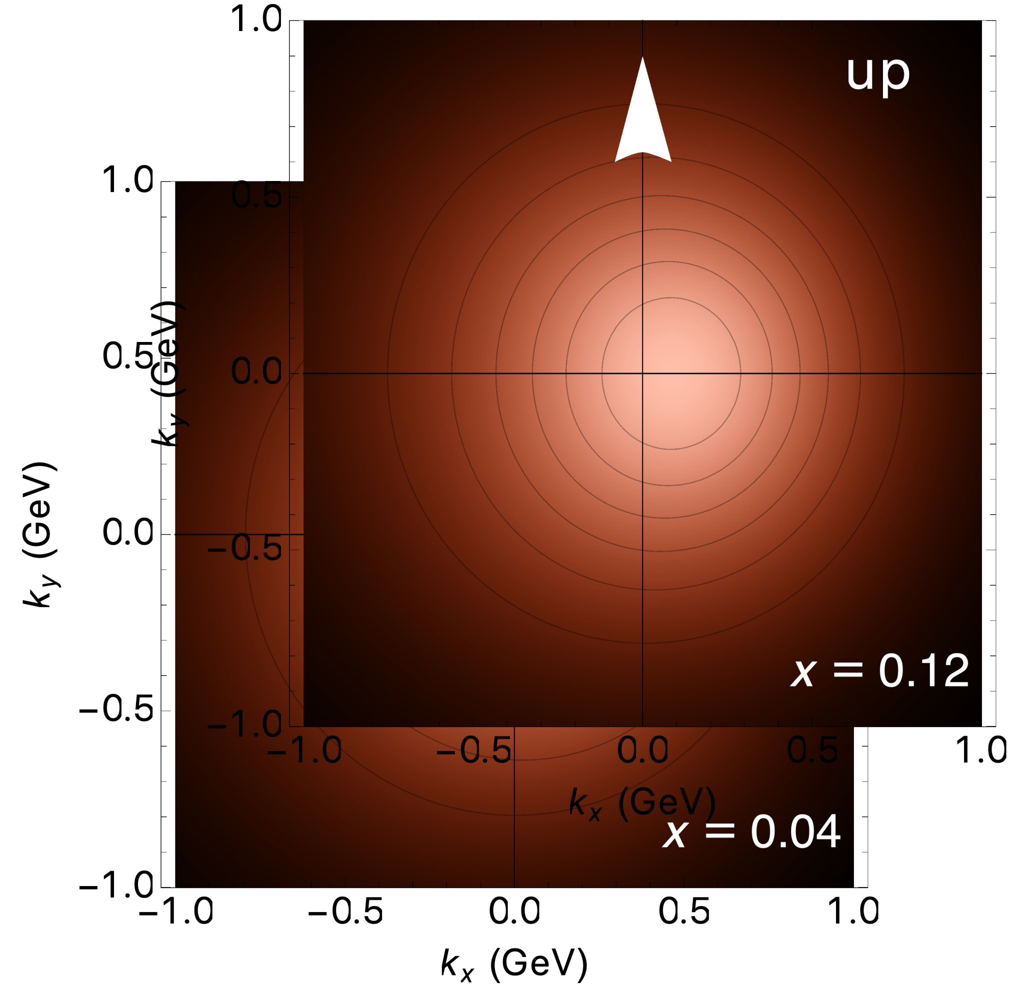




$$\rho = f_1(x, k_\perp; Q^2) - (k_\perp/M) f_{1T}^\perp(x, k_\perp; Q^2)$$

“REAL” 3D images in momentum space

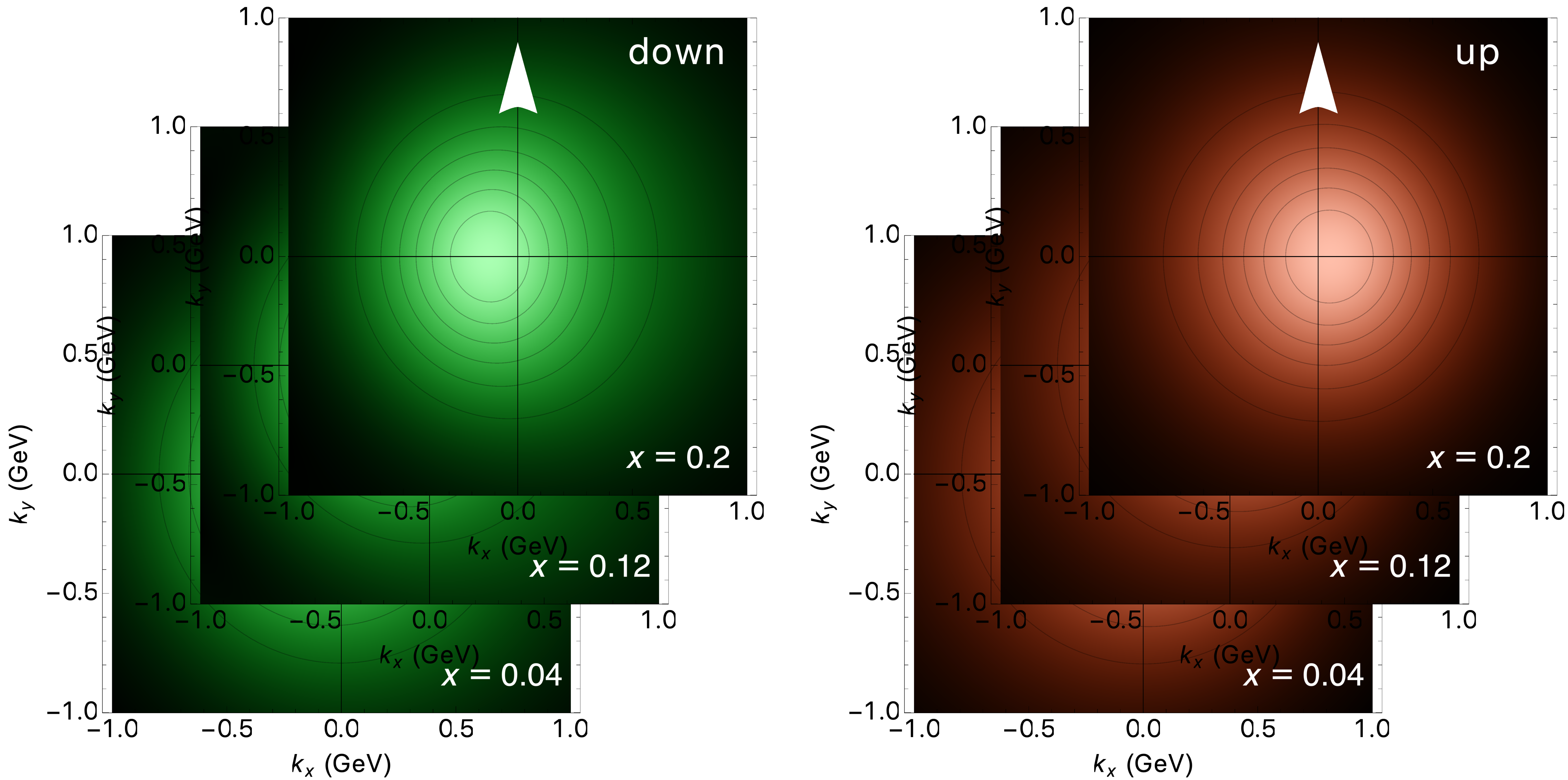




Images entirely based on data (polarized and unpolarized)

Bacchetta, Delcarro, Pisano, Radici, arXiv:2004.14278

“REAL” 3D images in momentum space



Images entirely based on data (polarized and unpolarized)

Bacchetta, Delcarro, Pisano, Radici, arXiv:2004.14278

Sivers function in DY

Drell-Yan process:

a polarized proton scatters off an unpolarized one → $W^{\pm}, Z_0$ in final state

transverse SSA for W

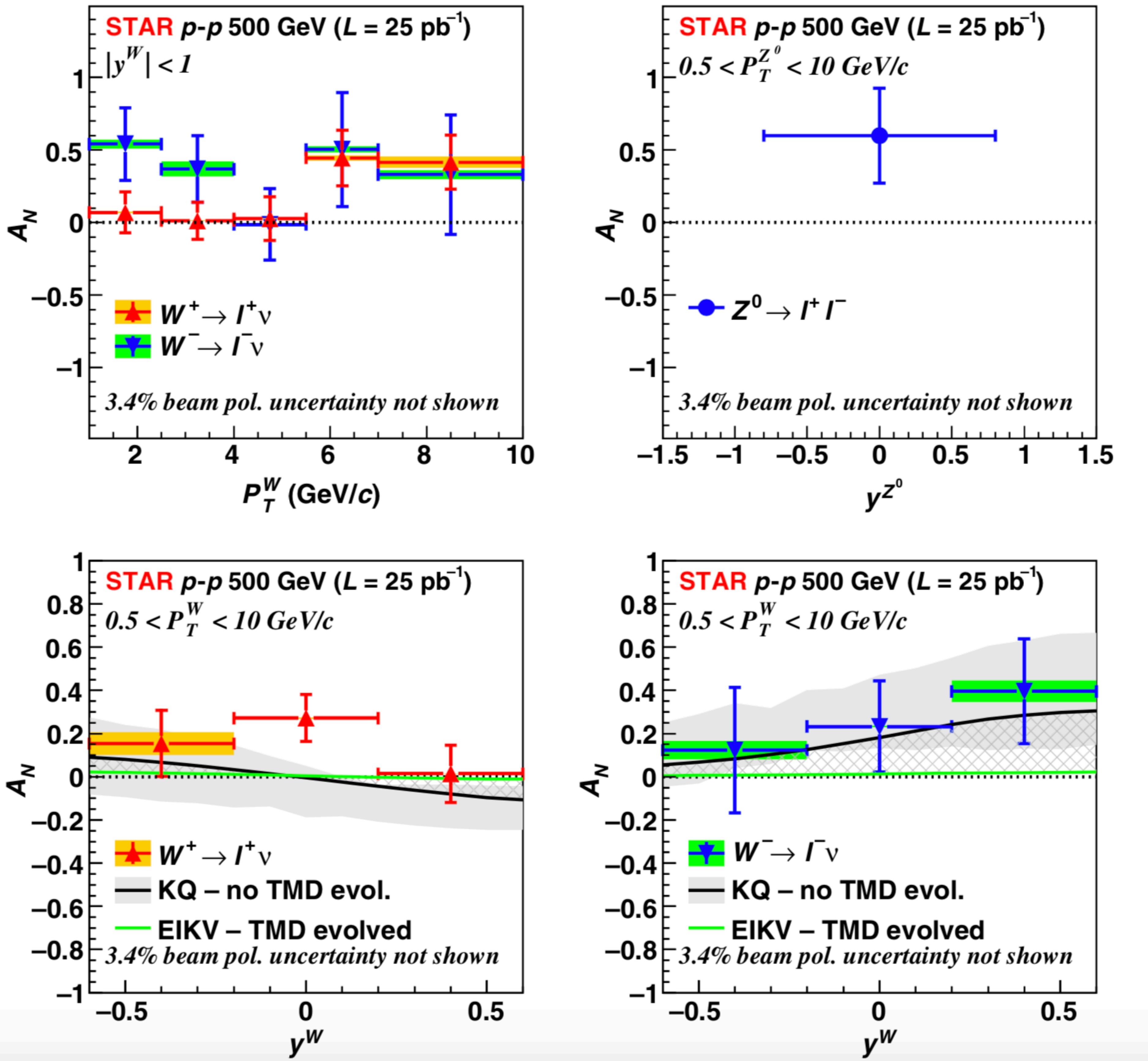
$$A_N^W = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

in terms of TMDs:

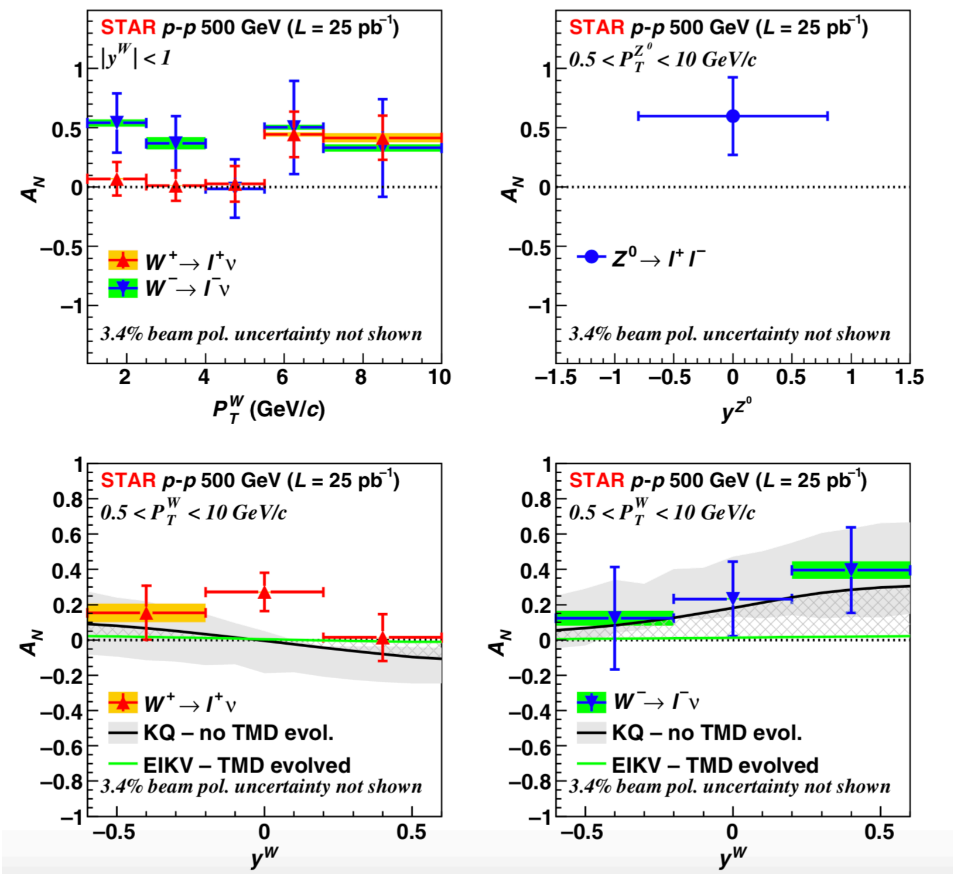
$$d\sigma^{\uparrow} - d\sigma^{\downarrow} = -M\sigma_0 \sum_{q1,q2} \left| V_{q1,q2} \right|^2 \int dk_{\perp 1} dk_{\perp 2} \delta^{(2)}(k_{\perp 1} + k_{\perp 2} - q_T) f_{1T}^{\perp(1)}(x_1, k_{\perp 1}) f_1(x_2, k_{\perp 2})$$

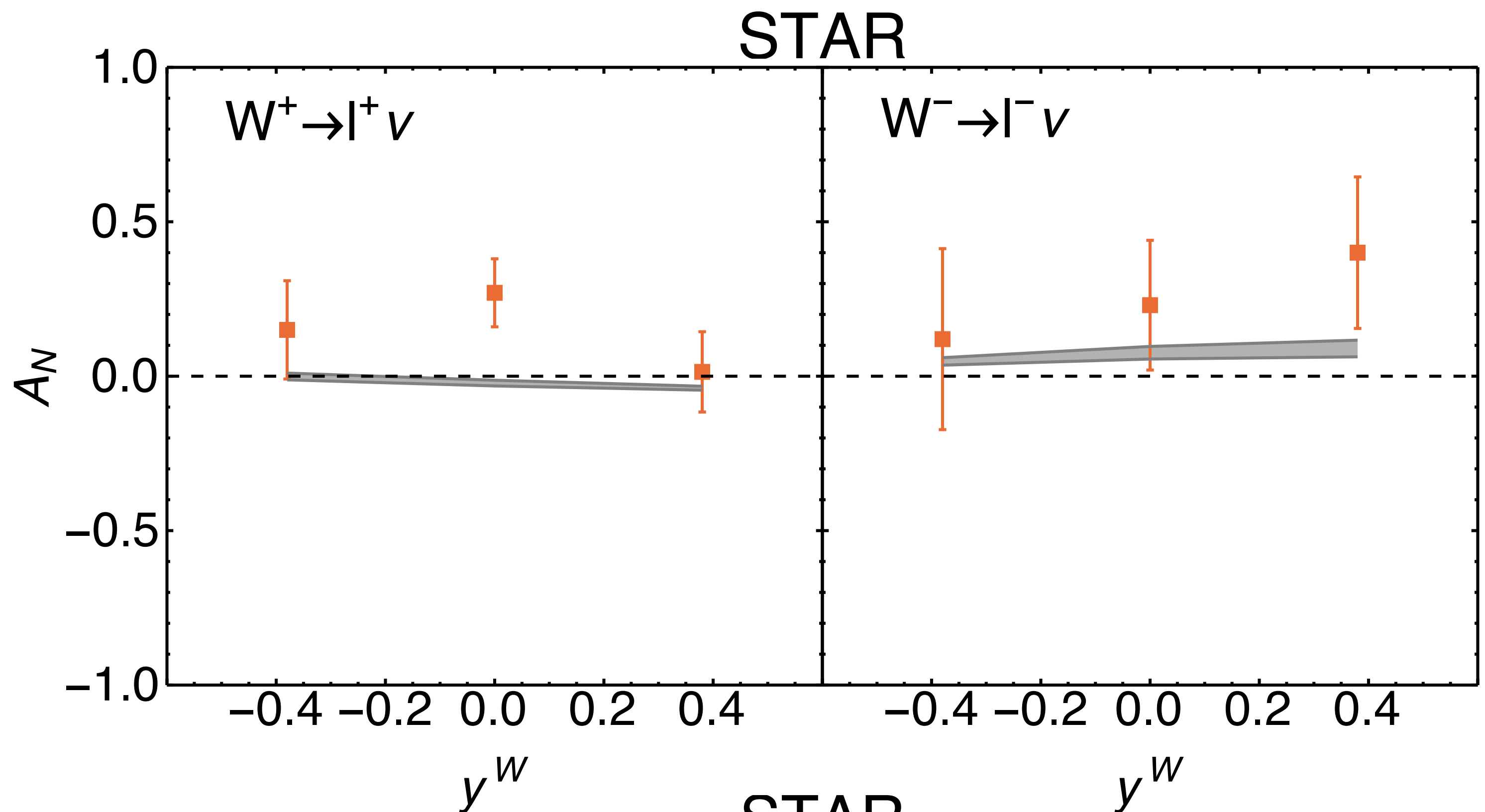
$$d\sigma^{\uparrow} + d\sigma^{\downarrow} = \sigma_0 \sum_{q1,q2} \left| V_{q1,q2} \right|^2 \int dk_{\perp 1} dk_{\perp 2} \delta^{(2)}(k_{\perp 1} + k_{\perp 2} - q_T) f_1(x_1, k_{\perp 1}) f_1(x_2, k_{\perp 2})$$

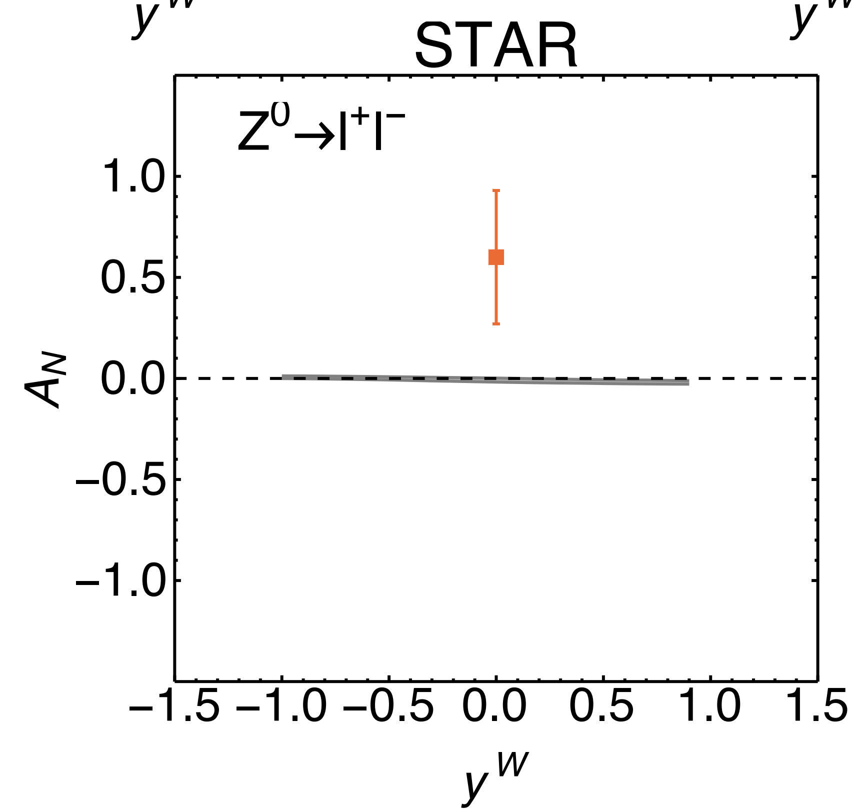
Sivers function sign change



Sivers function sign change

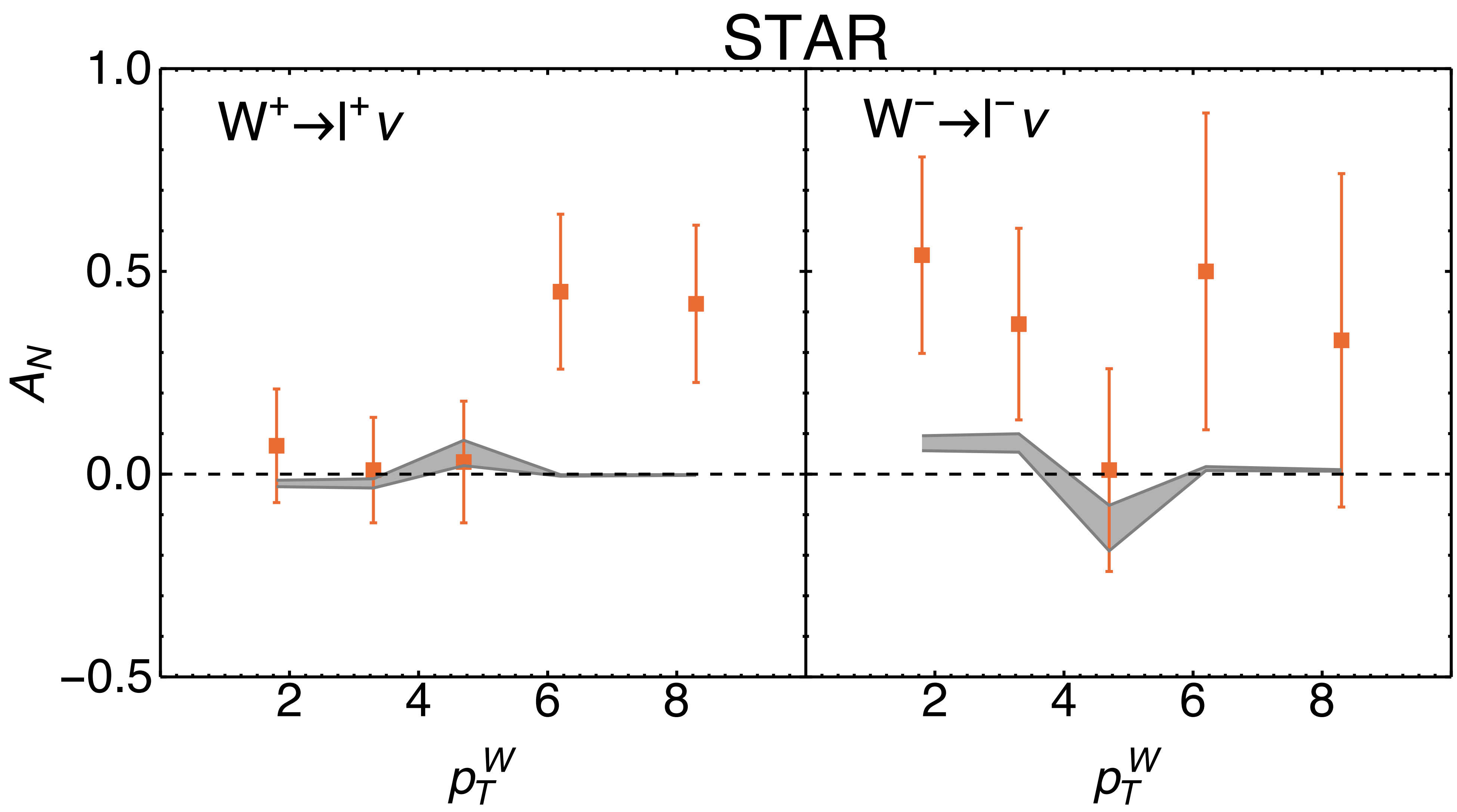






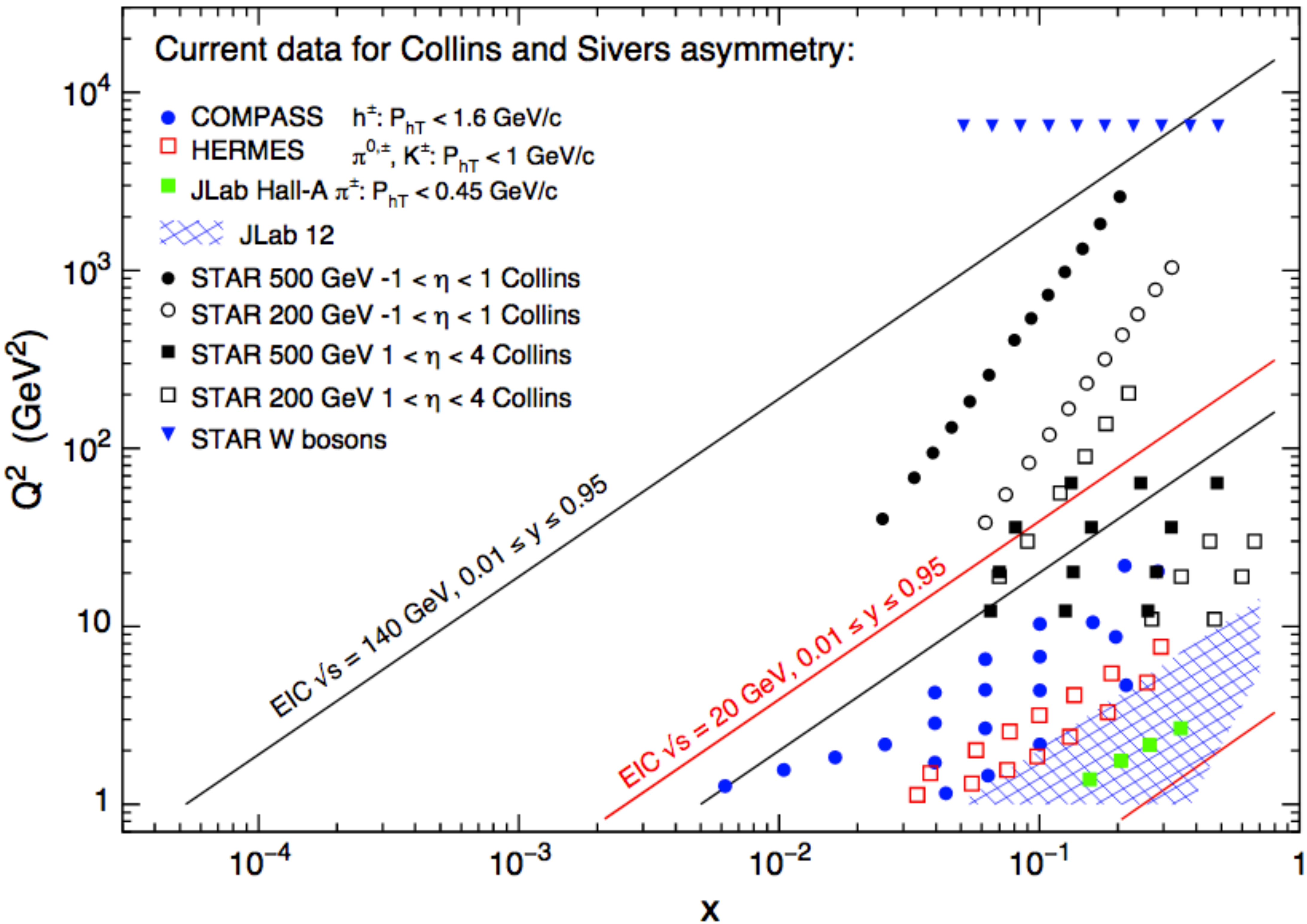
Evidence of sign change for Drell-Yan $f_{1T,DIS}^{\perp} = -f_{1T,DY}^{\perp}$

Sivers function sign change



Prediction using SIDIS extraction

TMDs at EIC



[EIC Yellow Report 2103.05419]

Conclusions

We reached an accuracy level of N3LL on unpolarized TMDs, covering a large set of data.

We extracted a functional form for Sivers distribution function, able to describe SIDIS data, with hints of sign change in DY

For the first time the determination of A_{UT} included unpolarized TMDs extracted directly from data with full formalism for QCD evolution

We are able to observe a deformation of the internal nucleon structure using our parametrization.