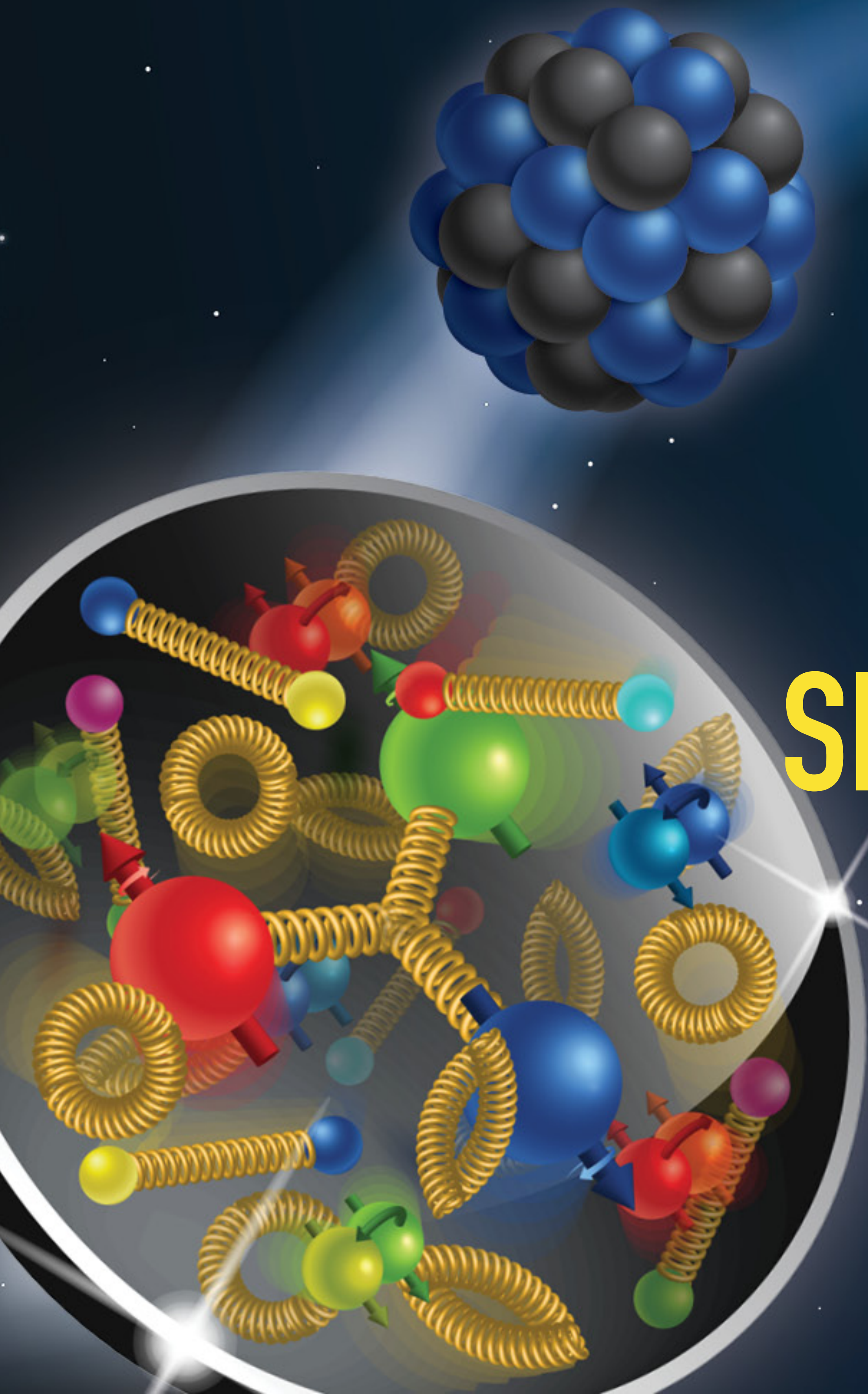


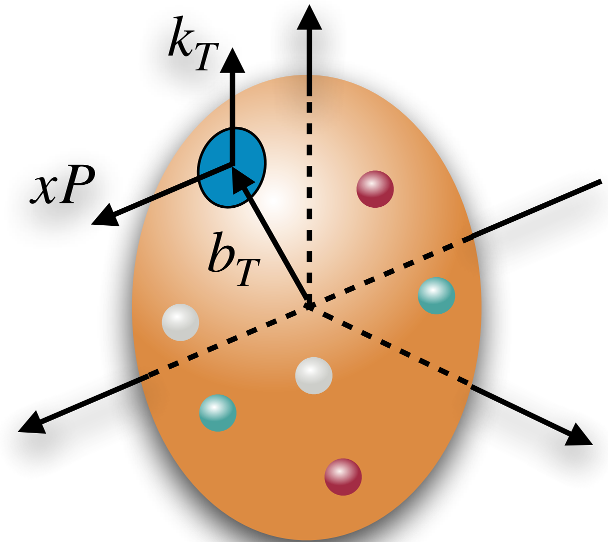
N^3LO extraction of the Sivers functions from SIDIS, DY and W±/Z data

Alexei Prokudin

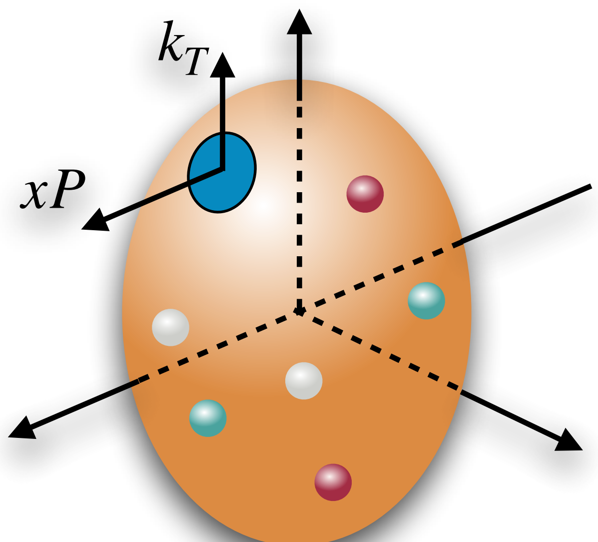
M. Bury, AP, A. Vladimirov, PRL 126, 112002 (2021)

M. Bury, AP, A. Vladimirov, JHEP 05 (2021) 151

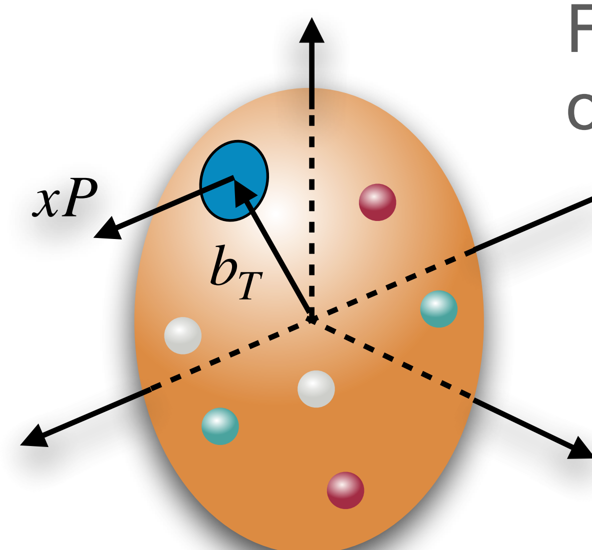
Wigner distributions
(Fourier transform of
GTMDs = Generalized
Transverse Momentum
Distributions)



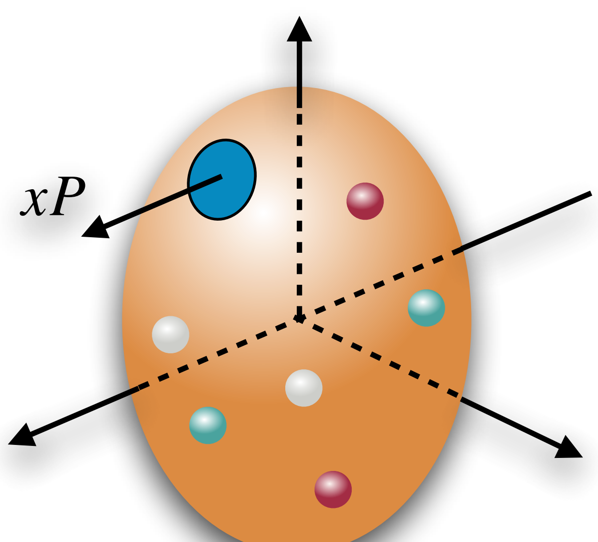
TMDs



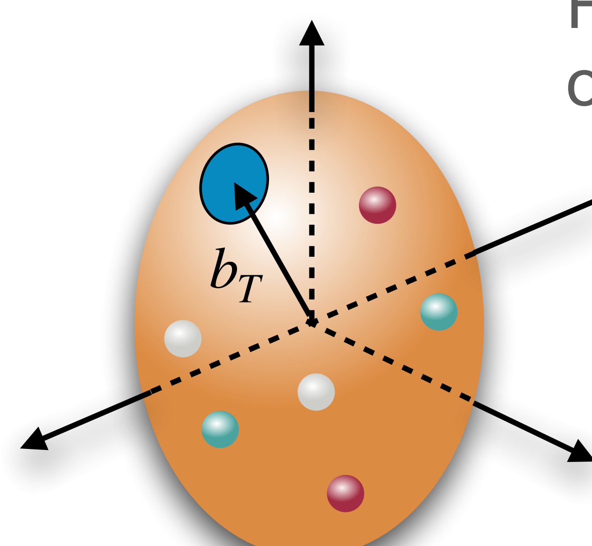
Fourier transform
of GPDs



PDFs



Fourier transform
of Form Factors

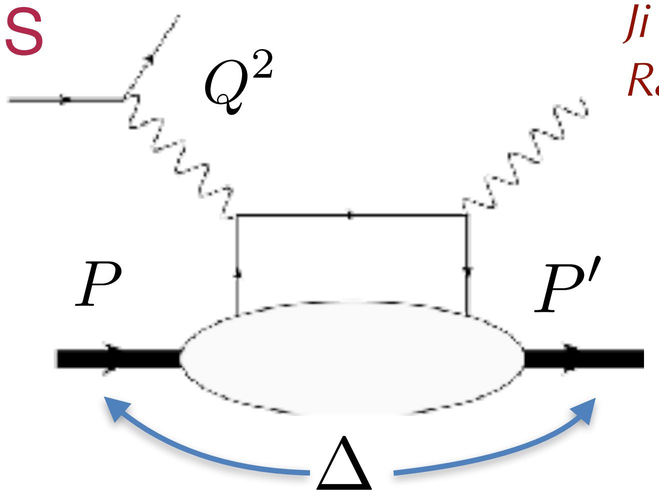


see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)

GPD

DVCS

Ji (1997)
Radyushkin (1997)



Q^2 ensures hard scale, pointlike interaction

$\Delta = P' - P$ momentum transfer can be varied independently

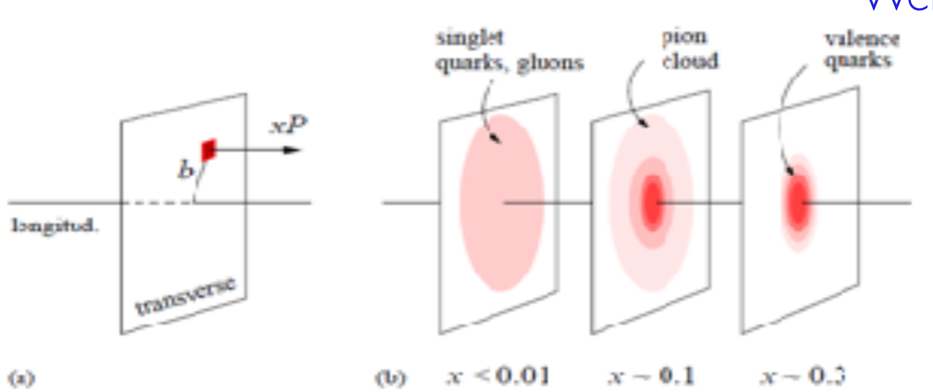
Connection to 3D structure

Burkardt (2000)
Burkardt (2003)

$$\rho(x,\vec{b}_\perp) = \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} e^{-i\vec{\Delta}_\perp\cdot\vec{b}_\perp} H_q(x,\xi=0,t=-\vec{\Delta}_\perp^2)$$

Drell-Yan frame $\Delta^+ = 0$ $\xi = -\frac{\Delta^+}{2\bar{p}^+}$

Weiss (2009)

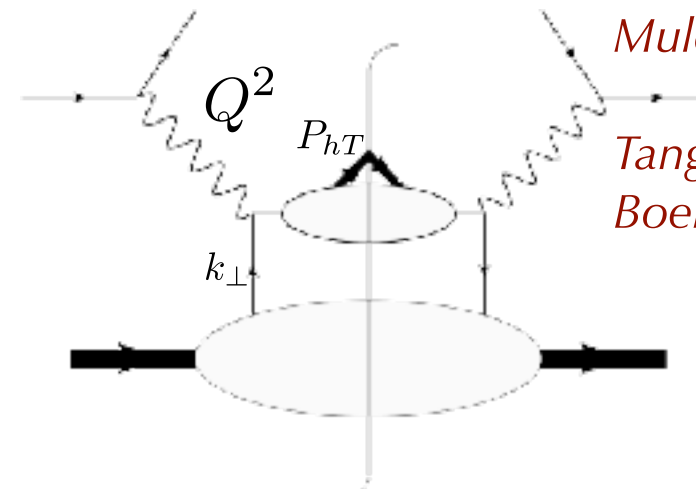


TMD

SIDIS

Kotzinian (1995), Mulders,

Tangerman (1995), Boer, Mulders (1998)



Q^2 ensures hard scale, pointlike interaction

P_{hT} final hadron transverse momentum can be varied independently

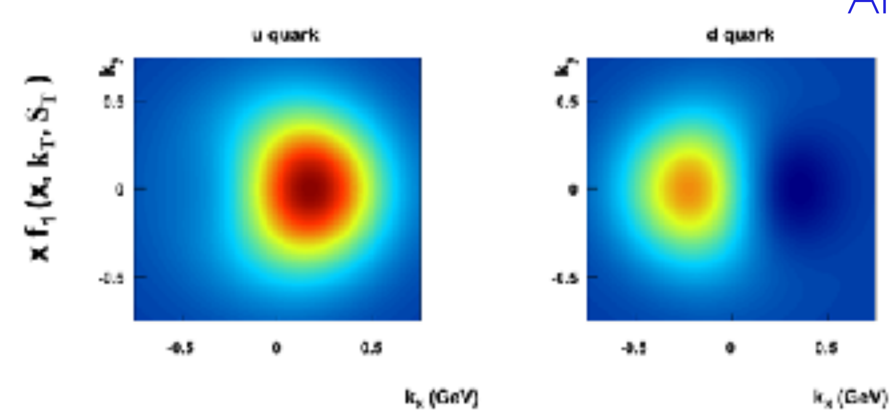
Connection to 3D structure

Ji, Ma, Yuan (2004)
Collins (2011)

$$\tilde{f}(x,\vec{b}_T) = \int d^2\vec{k}_\perp\, e^{i\vec{k}_\perp\cdot\vec{b}_T}\, f(x,\vec{k}_\perp)$$

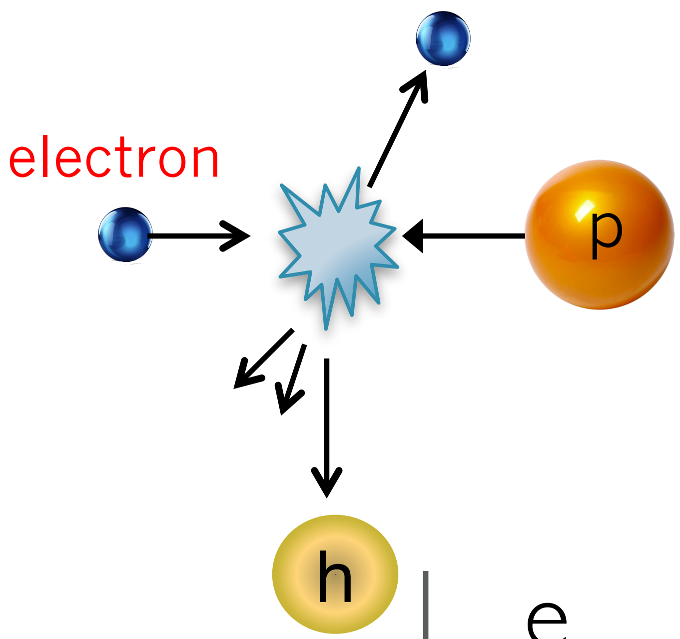
$\vec{b}$ is the transverse separation of parton fields in configuration space

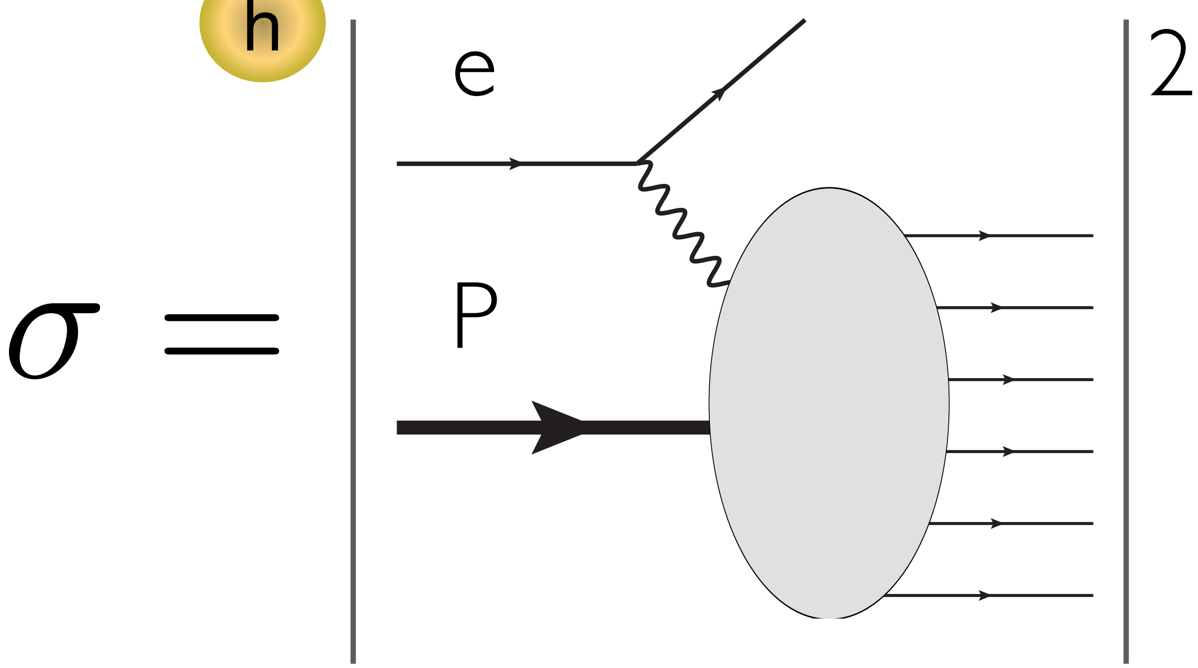
AP (2012)



QCD FACTORIZATION IS THE KEY!

We need a probe to “see” quarks and gluons





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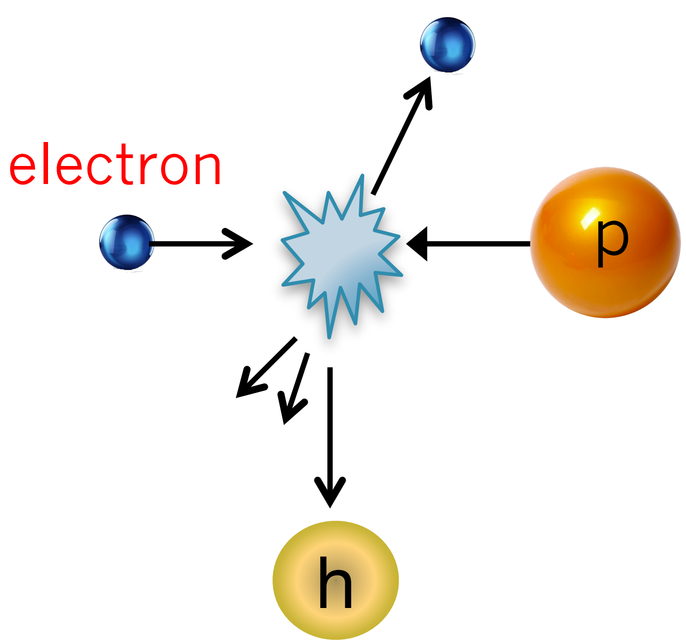
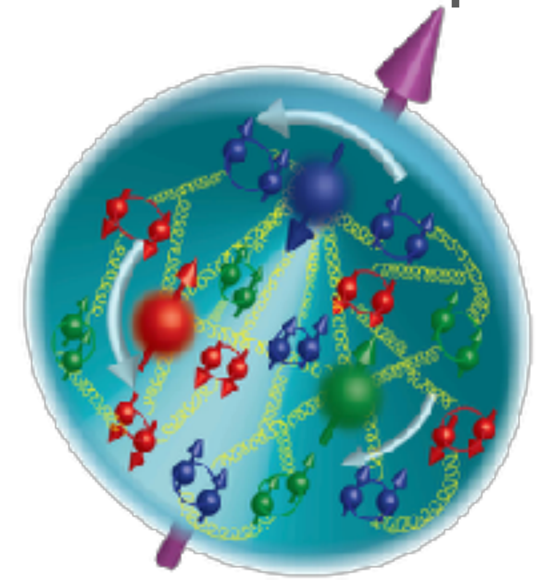
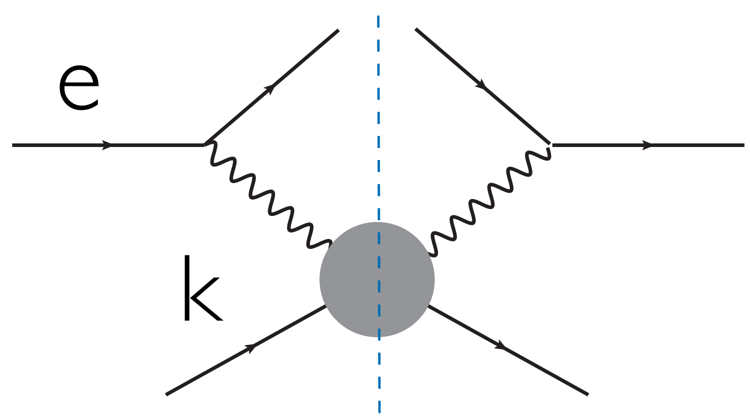
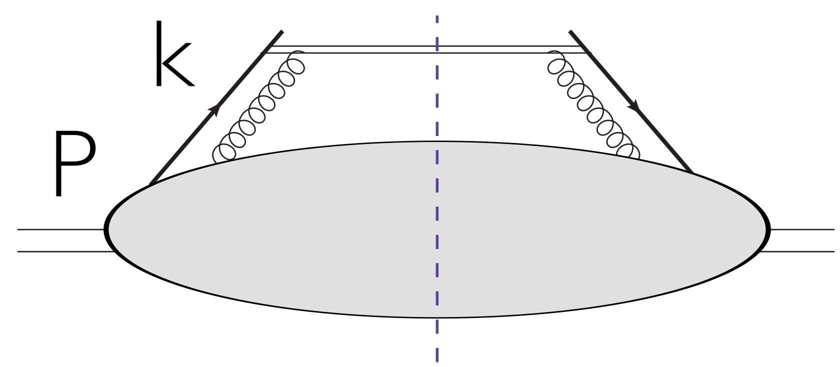




$\sigma \approx$



$\otimes$

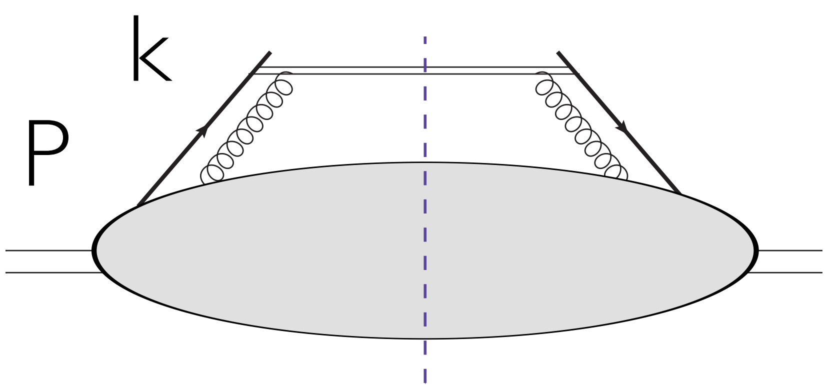


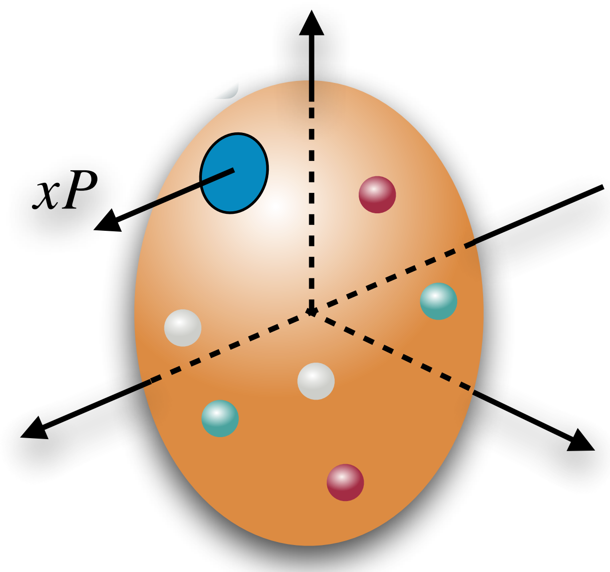
$+\mathcal{O}\left(\frac{M^2}{Q^2}\right)$

Factorization Probe Structure Power corrections

HADRON'S PARTONIC STRUCTURE

Collinear Parton Distribution Functions





$f_{q/P}(x)$

longitudinal

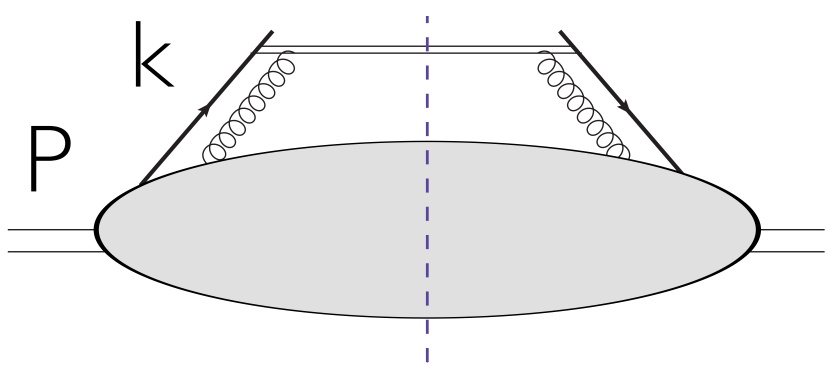
Probability density to find a quark with a momentum fraction x

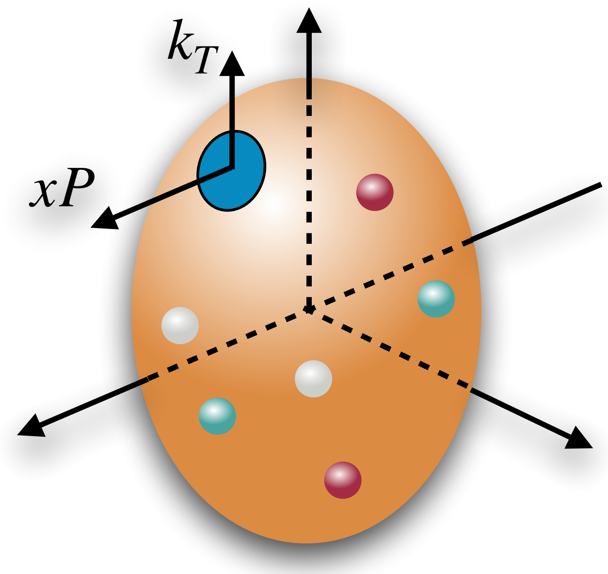
Hard probe resolves the particle nature of partons, but is not sensitive to hadron's structure at ~fm distances.

HADRON'S PARTONIC STRUCTURE

To study the physics of *confined motion of quarks and gluons* inside of the proton one needs a new type "hard probe" with two scales.

Transverse Momentum Dependent functions





$$f_{q/P}(x, k_T)$$

longitudinal & transverse

One large scale (Q) sensitive to particle nature of quark and gluons

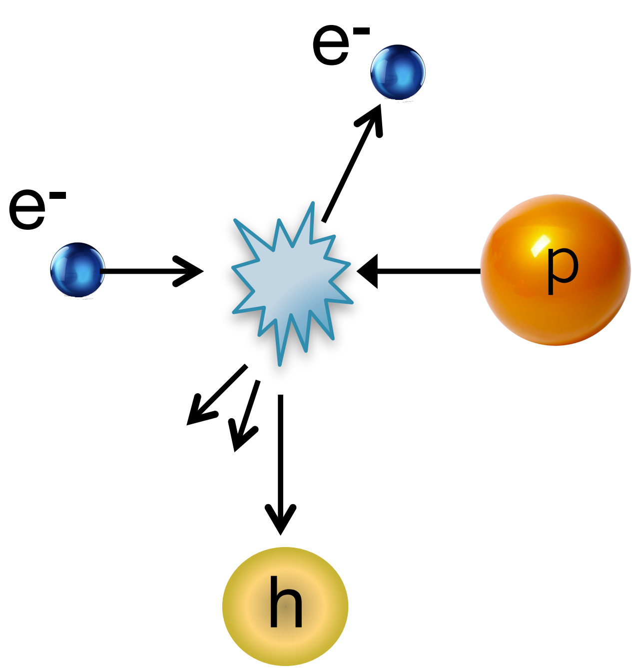
One small scale (k_T) *sensitive to how QCD bounds partons* and to the detailed structure at ~fm distances.

TRANSVERSE MOMENTUM DEPENDENT FACTORIZATION

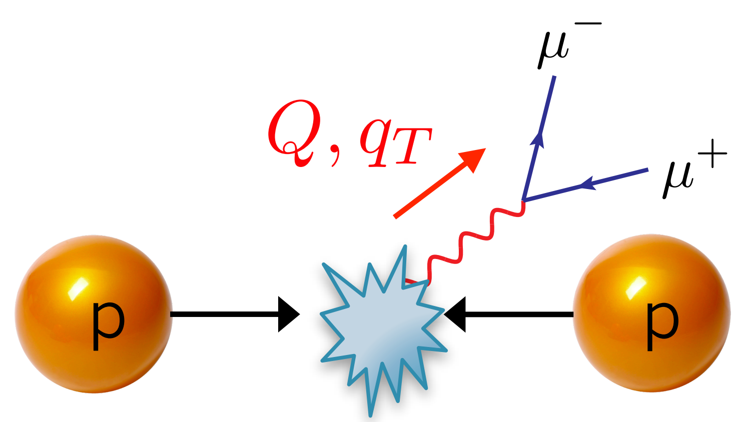
Small scale → $q_T \ll Q$ ← Large scale

The confined motion (k_T dependence) is encoded in TMDs

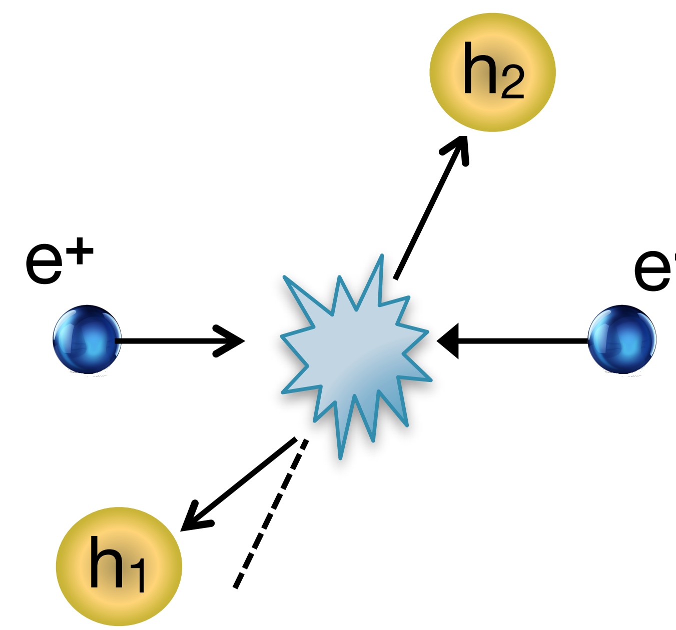
Semi-Inclusive DIS	**Drell-Yan**	**Dihadron in e^+e^-**
$\sigma \sim f_{q/P}(x, k_T) D_{h/q}(z, k_T)$	$\sigma \sim f_{q/P}(x_1, k_T) f_{\bar{q}/P}(x_2, k_T)$	$\sigma \sim D_{h_1/q}(z_1, k_T) D_{h_2/\bar{q}}(z_2, k_T)$



Meng, Olness, Soper (1992)
Ji, Ma, Yuan (2005)
Idilbi, Ji, Ma, Yuan (2004)
Collins (2011)

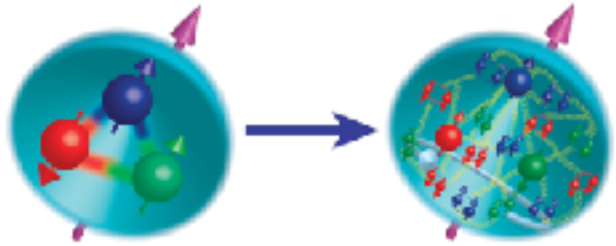


Collins, Soper, Sterman (1985)
Ji, Ma, Yuan (2004)
Collins (2011)

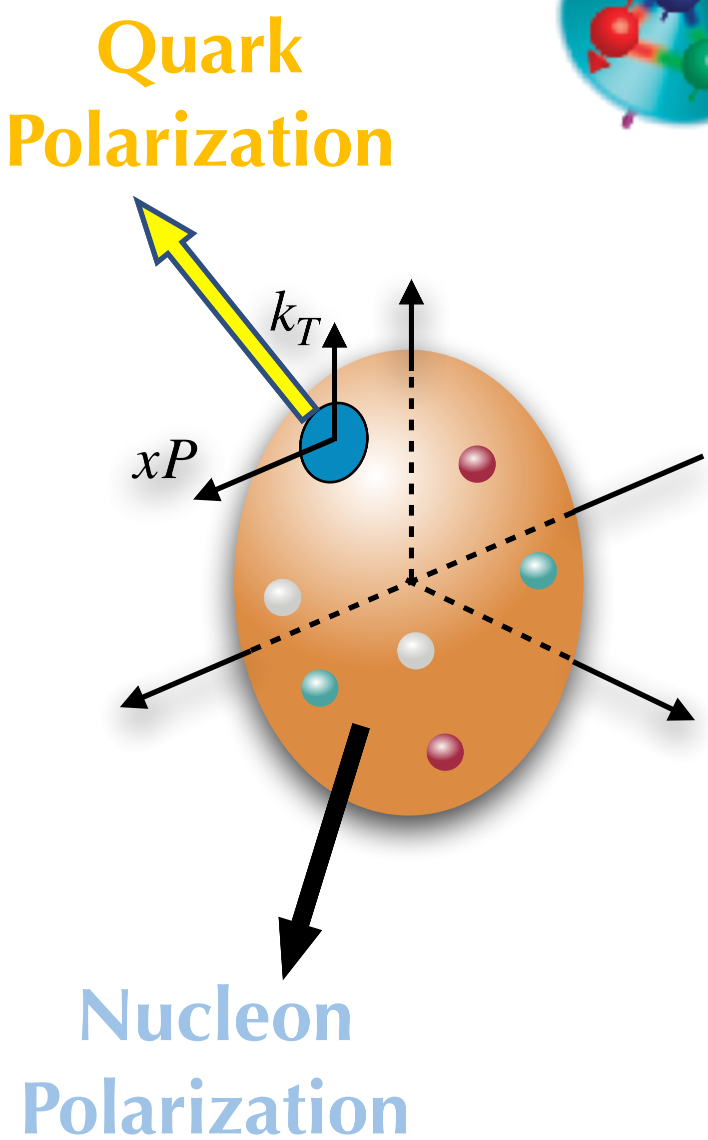


Collins, Soper (1983)
Collins (2011)

Our understanding of hadron evolves: TMDs with Polarization



Nucleon emerges as a strongly interacting, relativistic bound state of quarks and gluons



		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1(x,k_T^2)$ *Unpolarized*		$h_1^{\perp}(x,k_T^2)$ - *Boer-Mulders*
	L		$g_1(x,k_T^2)$ - *Helicity*	$h_{1L}^{\perp}(x,k_T^2)$ - *Kozinian-Mulders,"worm" gear*
	T	$f_{1T}^{\perp}(x,k_T^2)$ - *Sivers*	$g_{1T}(x,k_T^2)$ - *Kozinian-Mulders, "worm" gear*	$h_1(x,k_T^2)$ - *Transversity* $h_{1T}^{\perp}(x,k_T^2)$ - *Pretzelosity*

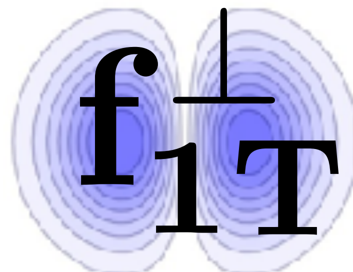
Analogous tables for:

- Gluons $f_1 \to f_1^g$ etc
- Fragmentation functions
- Nuclear targets $S \neq \frac{1}{2}$

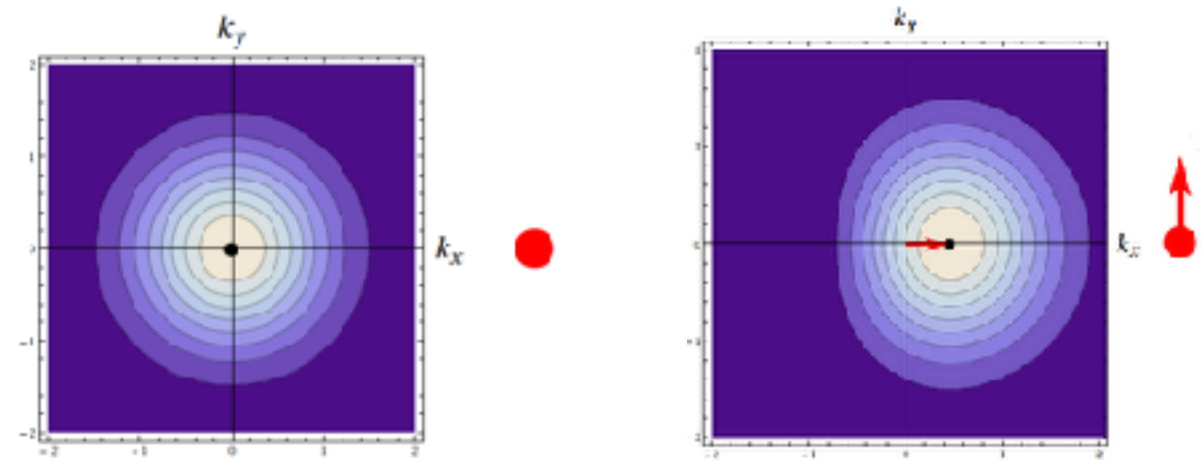
THE SIVERS FUNCTION

THE SIVERS FUNCTION

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



Sivers 1989



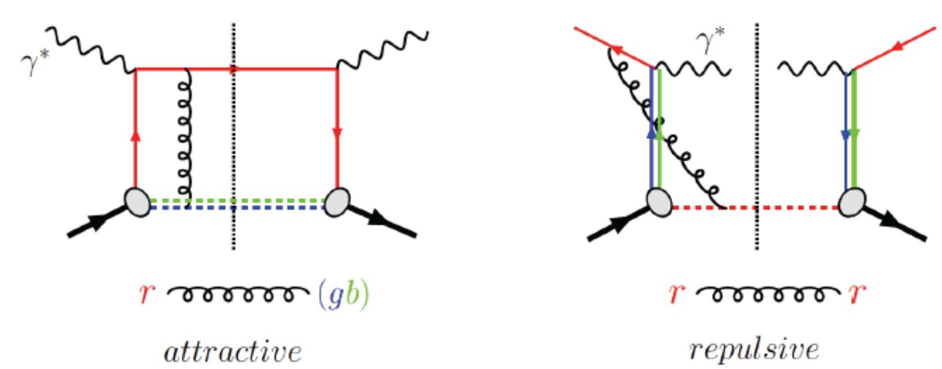
- Describes unpolarized quarks inside of transversely polarized nucleon

- Generates asymmetries in SIDIS and DY

Kotzinian (1995)
Mulders, Tangerman (1995)
Boer, Mulders (1998)

- Changes sign in DY w.r.t. SIDIS

Brodsky, Hwang, Schmidt (2002)
Collins (2002)

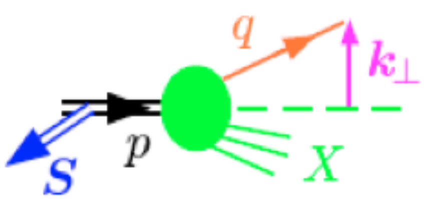


$$f_{1T}^{\perp SIDIS} = -f_{1T}^{\perp DY}$$

THE SIVERS FUNCTION

The Sivers function: unpolarized quark distribution inside a transversely polarized nucleon

Sivers 1989



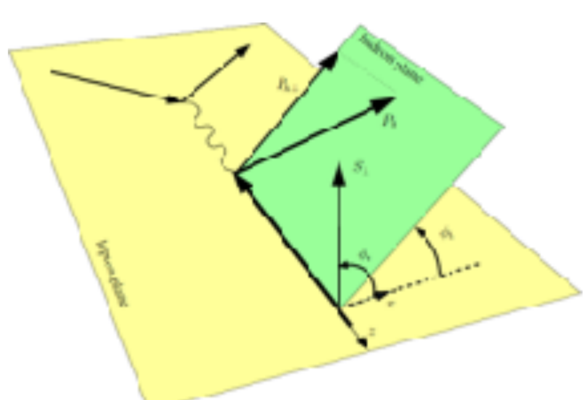
Spin independent

Spin dependent

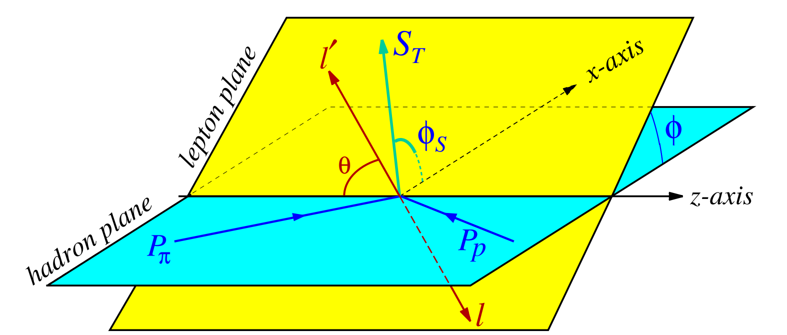
$$f_{q/h^\uparrow}(x, \vec{k}_\perp, \vec{S}) = f_{q/h}(x, k_\perp^2) - \frac{1}{M} f_{1T}^{\perp q}(x, k_\perp^2) \vec{S} \cdot (\hat{P} \times \vec{k}_\perp)$$

$$\ell P \to \ell' \pi X$$

$$\pi^-(P_\pi) + N(P_p, S) \to \ell^+ \ell^- + X$$



Kotzinian (1995), Mulders, Tangerman (1995), Boer, Mulders (1998)



Collins-Soper frame

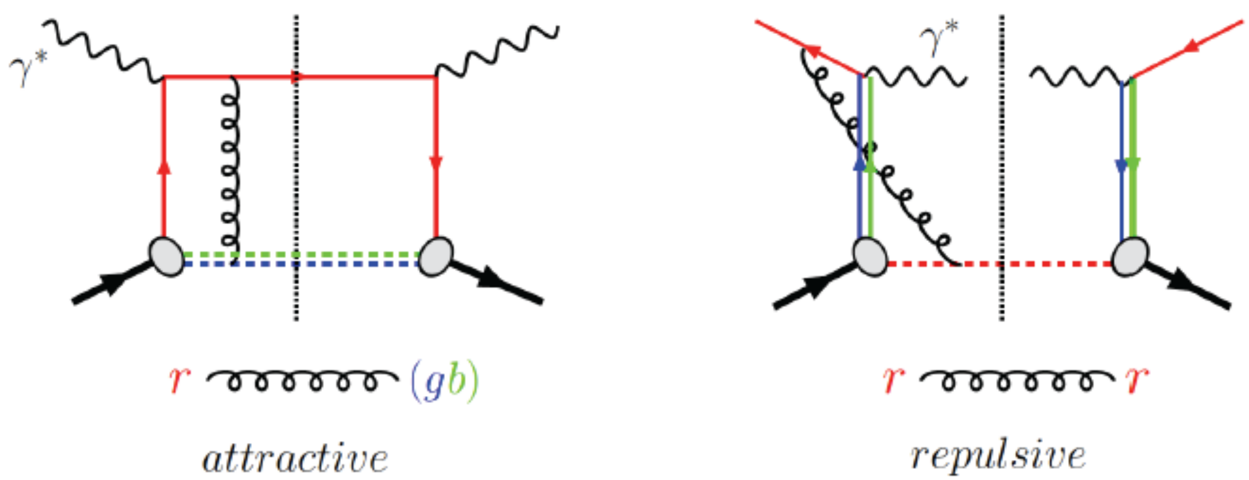
$$\sigma(S_T) \sim \sin(\phi_h - \phi_S) f_{1T}^\perp \otimes D_1$$

$$\sigma(S_T) \sim \sin(\phi_S) f_{1T}^\perp \otimes f_1$$

SIGN CHANGE OF THE SIVERS FUNCTION

Colored objects are surrounded by gluons, profound consequence of gauge invariance:

The Sivers function has opposite sign when gluon couple after quark scatters (SIDIS) or before quark annihilates (Drell-Yan)



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

Brodsky, Hwang, Schmidt `02
Belitsky, Ji,Yuan `04
Collins `02
Boer,Mulders,Pijlman `04
Kang, Qiu `08
Kovchegov, Sievert `18
etc

Crucial test of TMD factorization and collinear twist-3 factorization
Several labs worldwide measure Sivers effect in SIDIS and Drell-Yan
BNL, CERN, FERMILAB etc

The verification of the sign change is an NSAC (DOE and NSF) milestone

THE SIVERS FUNCTION

Large – N_c result $f_{1T}^{\perp u} = - f_{1T}^{\perp d}$ Pobylitsa 2003

→ Confirmed by phenomenological extractions

→ Confirmed by experimental measurements

Relation to GPDs (*E*) and anomalous magnetic moment Burkardt 2002

$$f_{1T}^{\perp q} \sim \kappa^q$$

→ Predicted correct sign of Sivers asymmetry in SIDIS

→ Shown to be model-dependent Meissner, Metz, Goeke 2007

→ Used in phenomenological extractions Bacchetta, Radici 2011

THE SIVERS FUNCTION

Sum rule

Burkardt 2004

- Conservation of transverse momentum
- Average transverse momentum shift of a quark inside a transversely polarized nucleon

$$\langle k_T^{i,q} \rangle = \varepsilon_T^{ij} S_T^j f_{1T}^{\perp(1)q}(x)$$

$$f_{1T}^{\perp(1)q}(x) = \int d^2 k_\perp \frac{k_\perp^2}{2M^2} f_{1T}^{\perp q}(x, k_\perp^2)$$

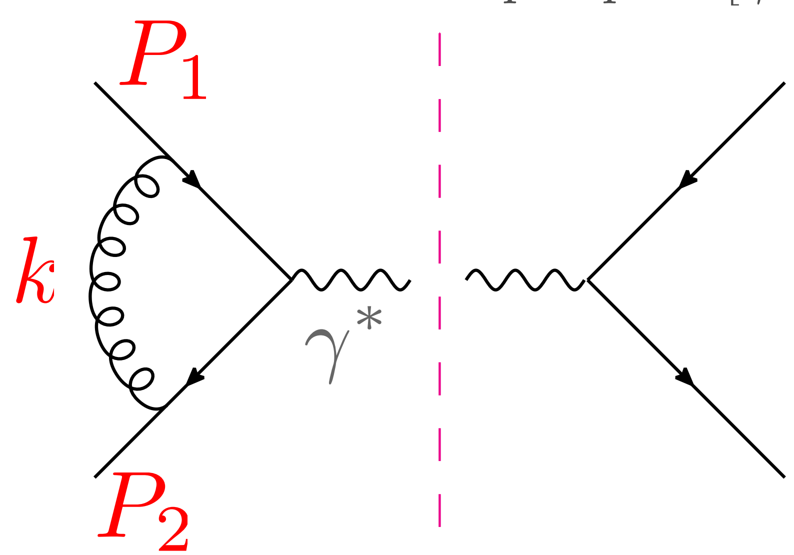
- Sum rule

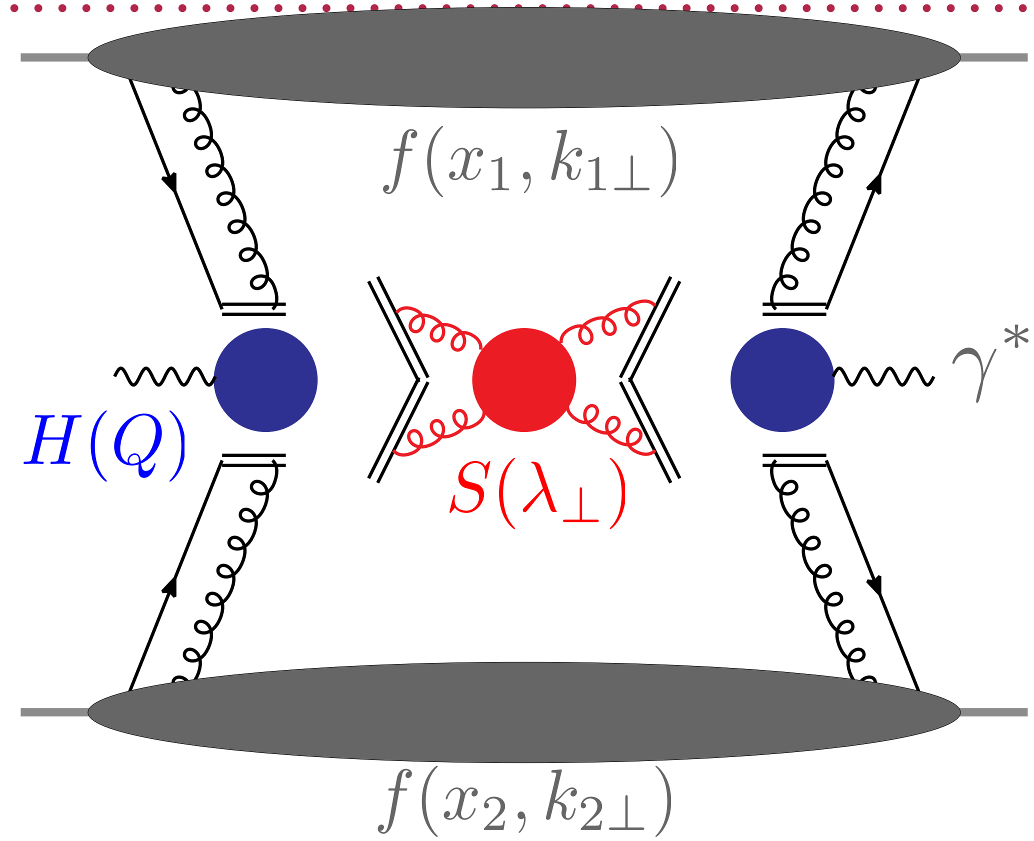
$$\sum_{a=q,g} \int_0^1 dx \langle k_T^{i,a} \rangle = 0 \qquad \sum_{a=q,g} \int_0^1 dx\, f_{1T}^{\perp(1)a}(x) = 0$$

THE SCALE DEPENDENCE

TMD FACTORIZATION IN A NUT-SHELL

$$p + p \to [\gamma^* \to \ell^+ \ell^-] + X$$





Factorization of regions:
(1) k//P_1, (2) k//P_2, (3) k soft, (4) k hard

$$F(x,b) = f(x,b)\sqrt{S(b)}$$

$$\frac{d\sigma}{dQ^2 dy d^2 q_\perp} = \int \frac{d^2 b}{(2\pi)^2} e^{i q_\perp \cdot b} H(Q) F(x_1, b) F(x_2, b)$$

$$\mu^2 \frac{dF(x,b;\mu,\zeta)}{d\mu^2} = \frac{\gamma_F(\mu,\zeta)}{2} F(x,b;\mu,\zeta),$$

$$\zeta \frac{dF(x,b;\mu,\zeta)}{d\zeta} = -\mathcal{D}(b,\mu) F(x,b;\mu,\zeta),$$

Collins-Soper Equations

μ = renormalization scale

ζ = Collins-Soper parameter

TMD FACTORIZATION

Collins, Soper, Sterman (85), Collins (11), Rogers, Collins (15)

$$F(x, k_\perp; Q) = \frac{1}{(2\pi)^2} \int d^2 b e^{ik_\perp \cdot b} F(x, b; Q) = \frac{1}{2\pi} \int_0^\infty db\, b J_0(k_\perp b) F(x, b; Q)$$

$$F(x, b; Q) \approx C \otimes F(x, c/b^*) \times \exp\left\{ -\int_{c/b^*}^{Q} \frac{d\mu}{\mu} \left(A \ln \frac{Q^2}{\mu^2} + B \right) \right\} \times \exp\left(-S_{\text{non-pert}}(b, Q) \right)$$

OPE/collinear part

transverse part, Sudakov FF

- The evolution is complicated as one evolves in 2 dimensions
- The presence of a non-perturbative evolution kernel makes calculations more involved
- Theoretical constraints exist on both non-perturbative shape of TMD and the non-perturbative kernel of evolution

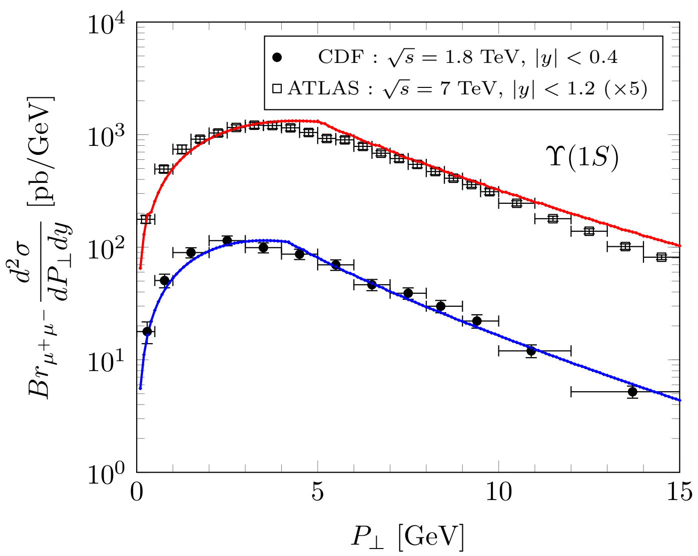
✓ **Non-perturbative: fitted from data**

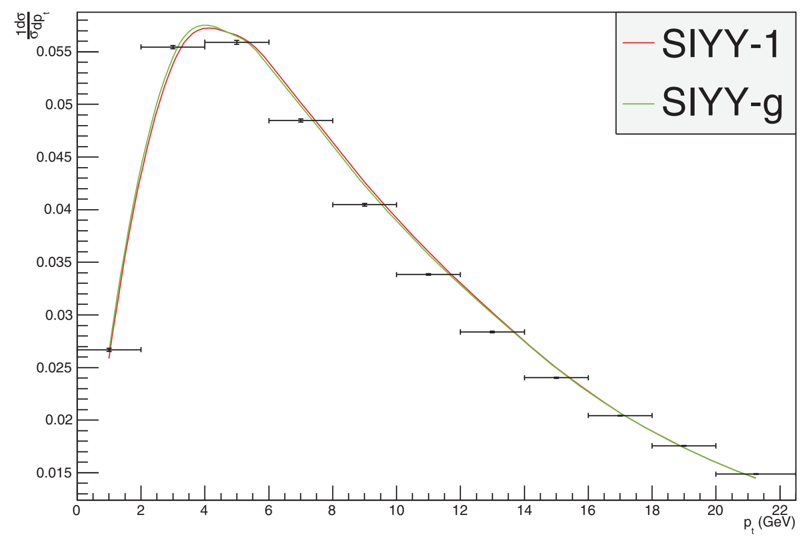
✓ The key ingredient – ln(Q) piece is spin-independent

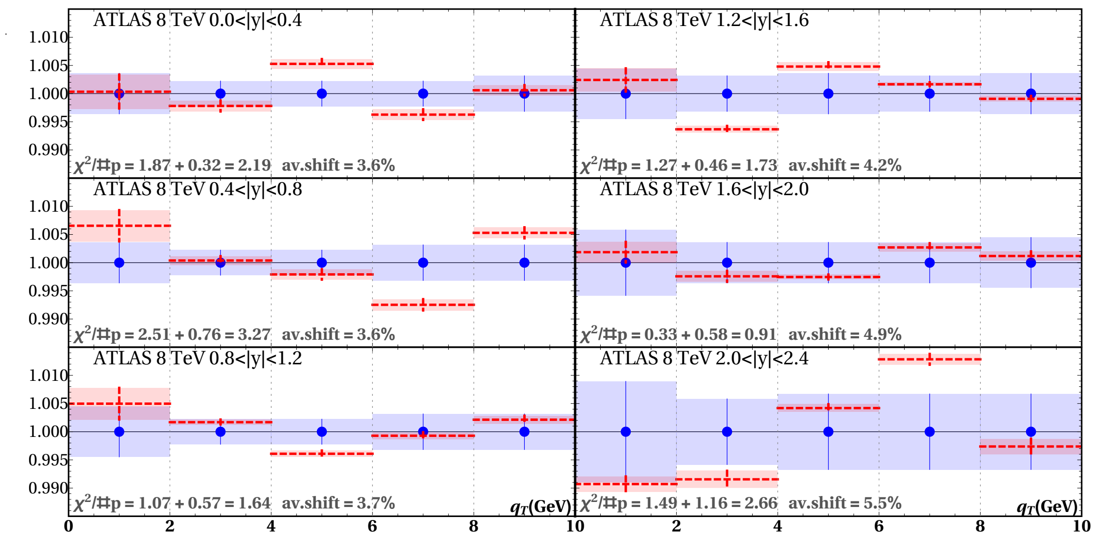
✓ Non-perturbative shape of TMDs is to be extracted from data

✓ One can use information from models or ab-initio calculations, such as lattice QCD: shape of TMDs, non-perturbative kernel.

SUCCESS OF TMD FACTORIZATION PREDICTIVE POWER







Qiu, Watanabe arXiv:1710.06928 *Sun, Isaacson, Yuan, Yuan arXiv:1406.3073* *Bertone, Scimemi, Vladimirov arXiv:1902.08474*

Upsilon production

Z boson production at the LHC

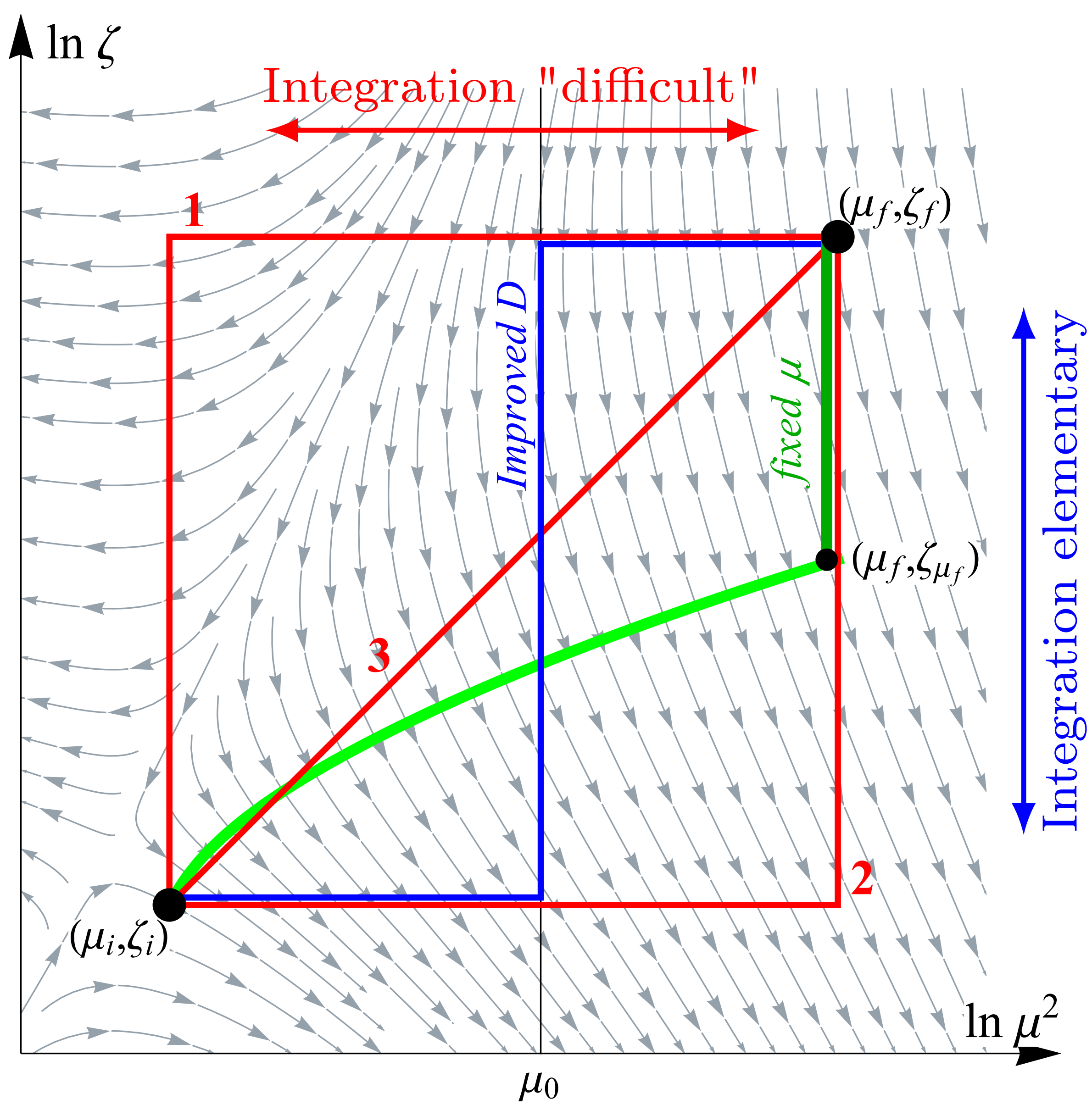
- TMD factorization (with an appropriate matching to collinear results) aims at an accurate description (and prediction) of a differential in q_T cross section in a wide range of q_T
- LHC results at 7 and 13 TeV are accurately predicted from fits of lower energies

TMD EVOLUTION CONTAINS NON-PERTURBATIVE COMPONENT

- TMD evolution is a two scale evolution
- Remarkably simple in the zeta-prescription

Scimemi, Vladimirov (18), (20)

Vladimirov (20)



$$F(x,b;\mu,\zeta) = \left(\frac{\zeta}{\zeta_\mu(b)}\right)^{-\mathcal{D}(b,\mu)} F(x,b)$$

$F(x,b)$ is the "optimal" TMD

$\zeta_\mu(b)$ calculable function

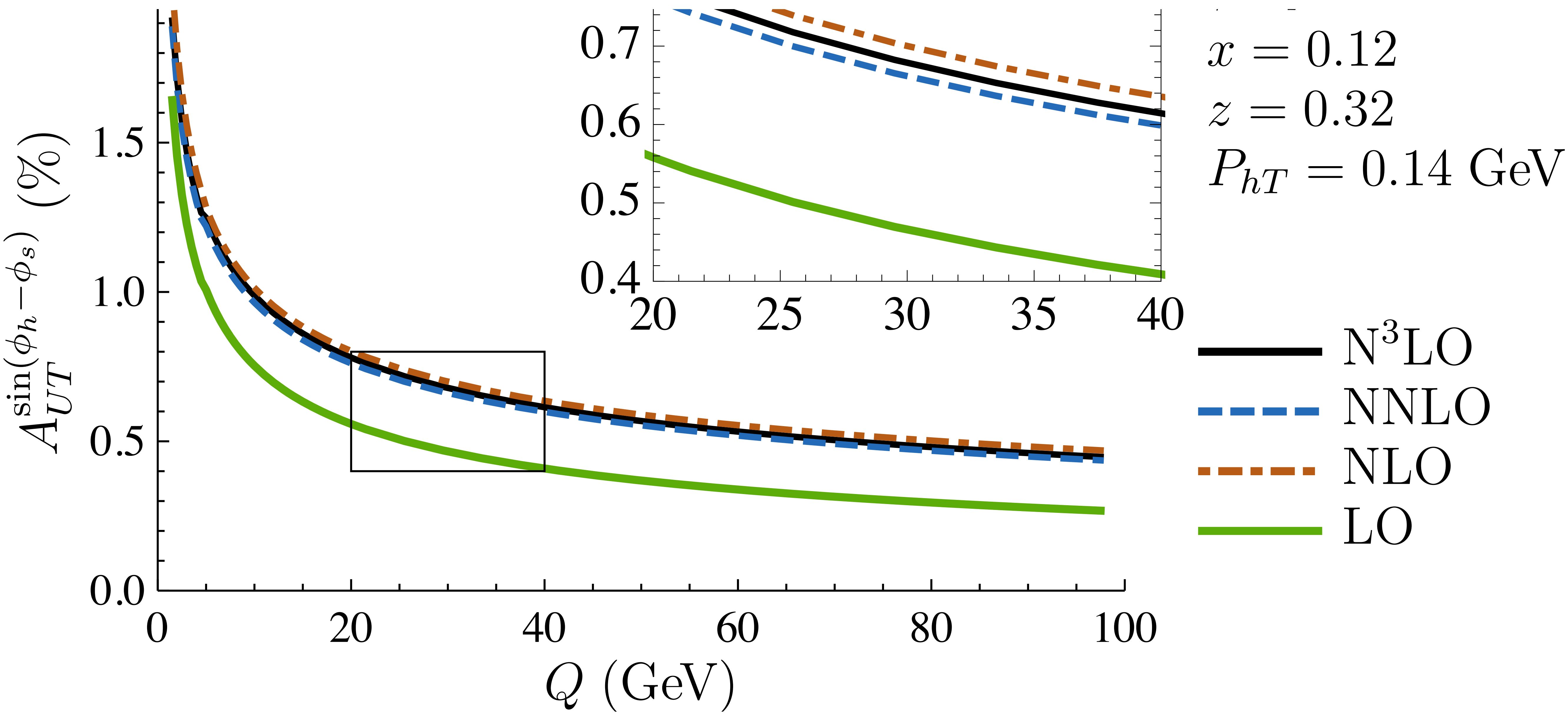
$\mathcal{D}(b,\mu)$ Colins-Soper kernel or rapidity anomalous dimension. Fundamental universal function related to the properties of QCD vacuum

THE ANALYSIS

THE SIVERS ASYMMETRY

$$f_{1T;q\leftarrow h}^{\perp}(x,b) = N_q \frac{(1-x)x^{\beta_q}(1+\epsilon_q x)}{\dots} \exp\left(-\frac{r_0 + x r_1}{\dots} b^2\right)$$

$\mathbf{N^3LO}$ =	C_V (cancel)	γ_V	Γ_{cusp}	CS-kernel at small-b	unpol.TMD at small-b
	α_s^3	α_s^3	α_s^4	α_s^3	α_s^2



THE PARAMETRIZATION

Large-x not constrained

$\sim (1-x)$

Possibility of a node

ϵ_u, ϵ_d

$$f_{1T;q\leftarrow h}^{\perp}(x,b) = N_q \frac{(1-x)x^{\beta_q}(1+\epsilon_q x)}{n(\beta_q,\epsilon_q)} \exp\left(-\frac{r_0 + x r_1}{\sqrt{1+r_2 x^2 b^2}} b^2\right)$$

u, d, s, sea = ubar, dbar, bar

Common for all flavors
Similar to unpolarized SV19

Sea is not constrained

$\beta_s = \beta_{sea} \qquad \epsilon_s = \epsilon_{sea} = 0$

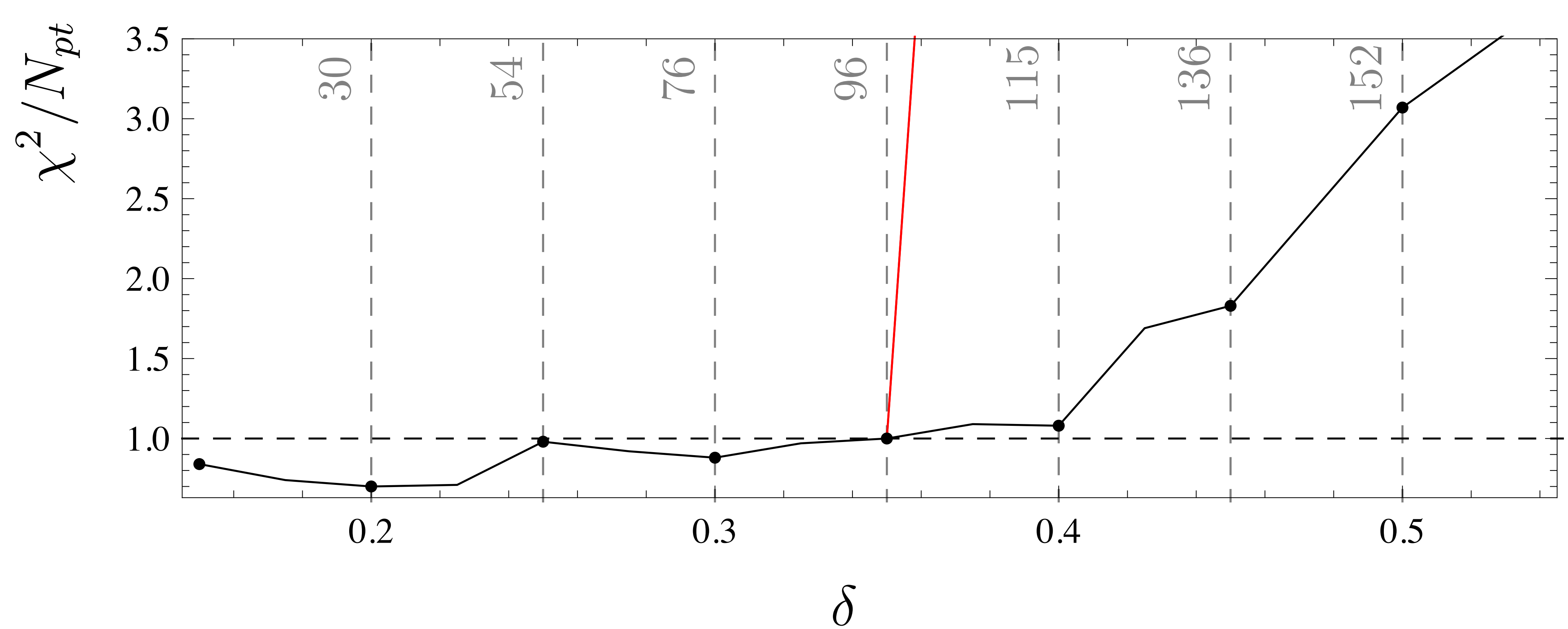
- 12 free parameters, flavor independent r_0, r_1, r_2
- Valence quarks: $N_{u,d}, \beta_{u,d}, \epsilon_{u,d}$
- Sea quarks: $N_{s,sea}, \beta_s = \beta_{sea}$
- Data driven fit, no constraints
- Positivity is satisfied in the region covered by the data

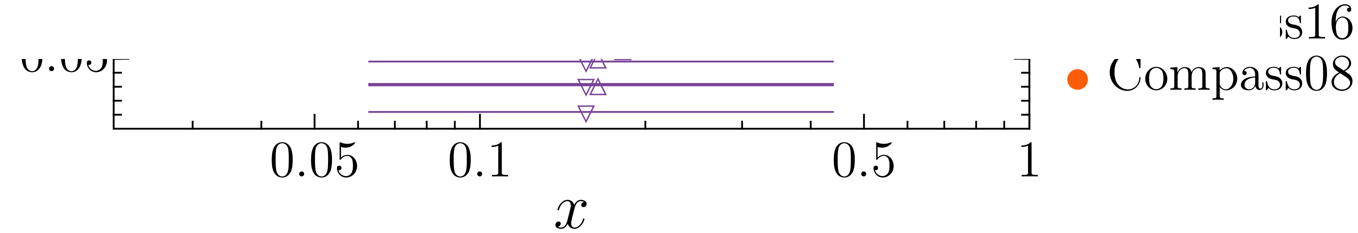
DATA SELECTION

Bury, Prokudin, Vladimirov (2021)

Dataset name	Ref.	Reaction	# Points
Compass08	[36]	$d^{\uparrow} + \gamma^* \to \pi^+$	1 / 9
		$d^{\uparrow} + \gamma^* \to \pi^-$	1 / 9
		$d^{\uparrow} + \gamma^* \to K^+$	1 / 9
Com			
Herr			
JLal			
SIDI			
Com			
Star			
Star			
Star			
DY			
Total			76

- Only P_T dependence used to avoid double counting
- Data selection compatible with





FIT RESULTS

Bury, Prokudin, Vladimirov (2021)

- Replica method using Artemide framework
- Errors both from the data and the uncertainty due to unpolarized TMD

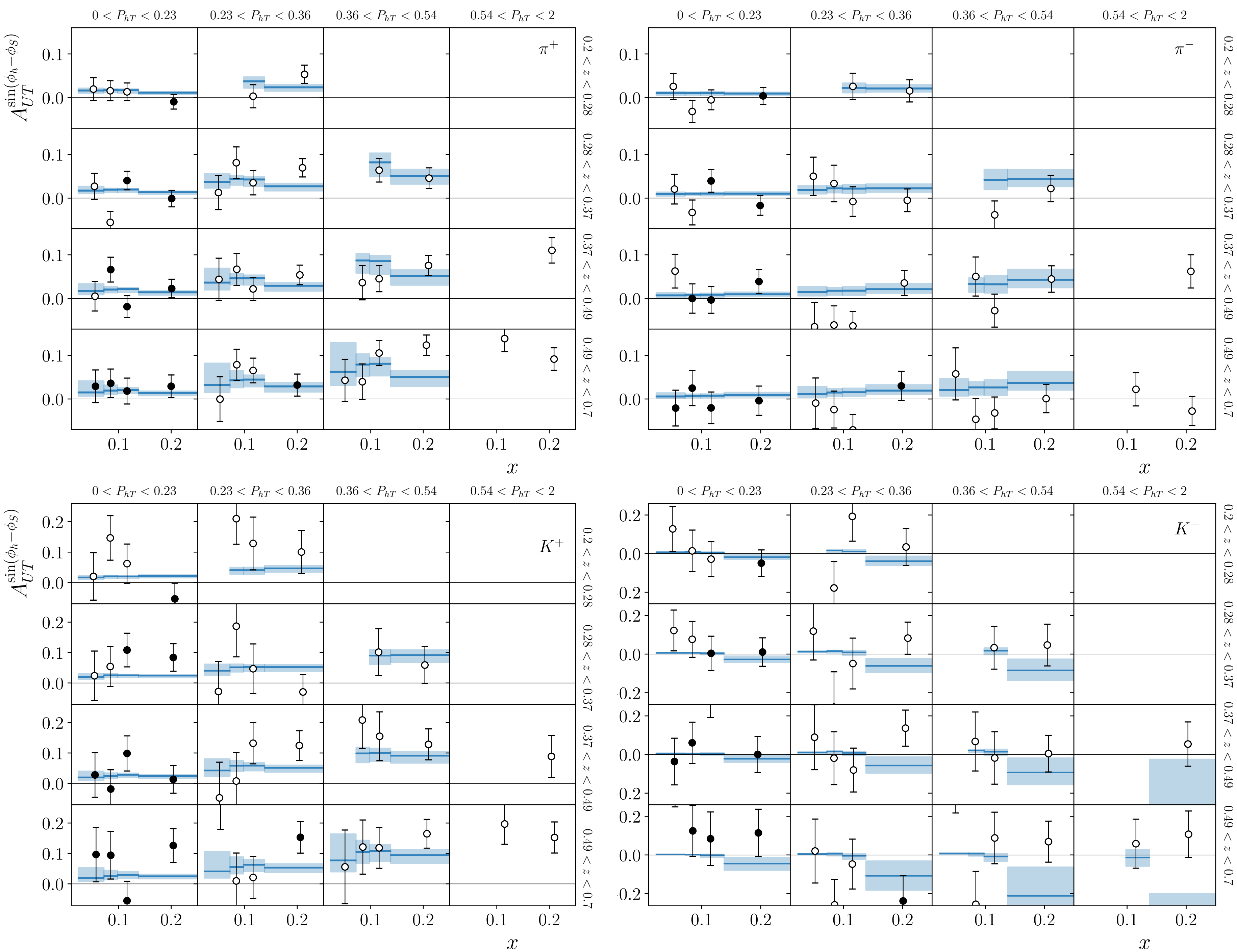
Name	χ^2/N_{pt}[SIDIS]	χ^2/N_{pt}[DY]	χ^2/N_{pt}[total]
SIDIS at N^{3}LO	$0.87^{+0.13}_{+0.03}$	$1.23^{+0.50}_{-0.24}$ no fit	$0.93^{+0.16}_{+0.01}$
SIDIS+DY at N^{3}LO	$0.88^{+0.15}_{+0.04}$	$0.90^{+0.31}_{+0.00}$	$0.88^{+0.15}_{+0.05}$

- Unbiased parametrization
- No tension between SIDIS and DY data — universality
- Good convergence of the fit for all data sets

N3LO EXTRACTION OF THE SIVERS FUNCTION

Bury, Prokudin, Vladimirov (2021)

HERMES 2020 3D binning description



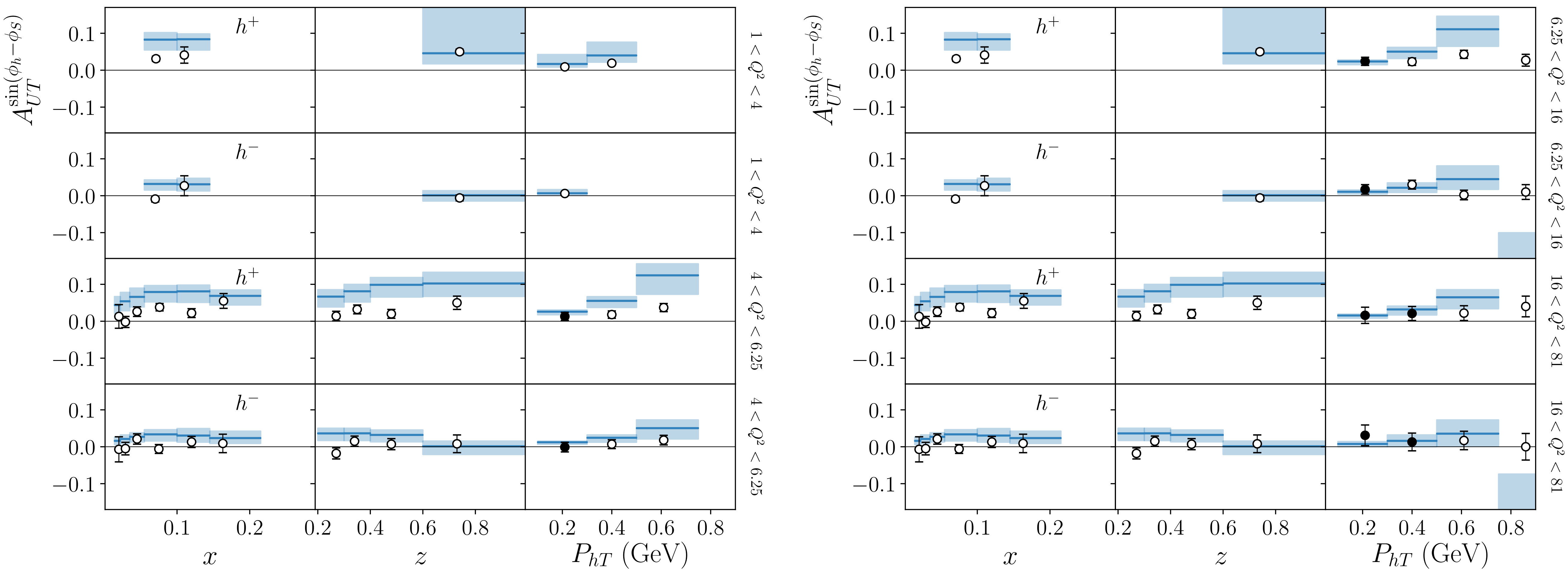
Filled in points used in the fit

Open points are predictions

N3LO EXTRACTION OF THE SIVERS FUNCTION

Bury, Prokudin, Vladimirov (2021)

COMPASS SIDIS data

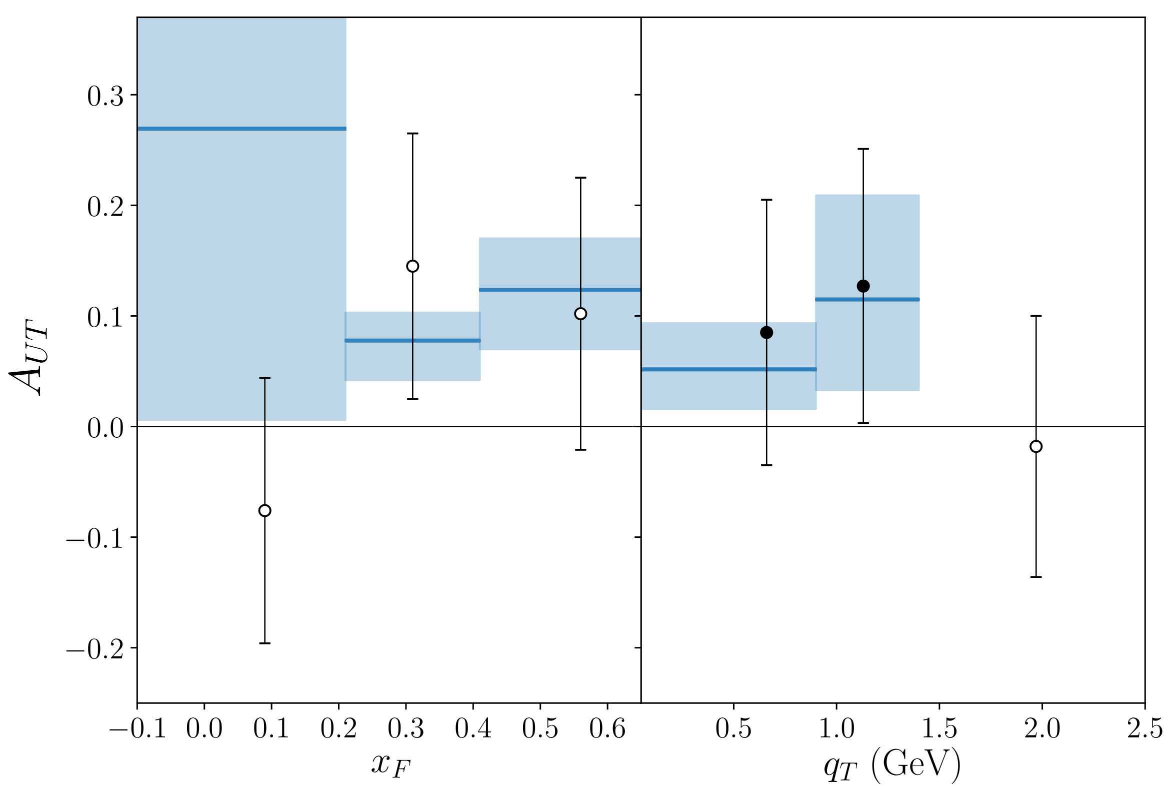


N3LO EXTRACTION OF THE SIVERS FUNCTION

Bury, Prokudin, Vladimirov (2021)

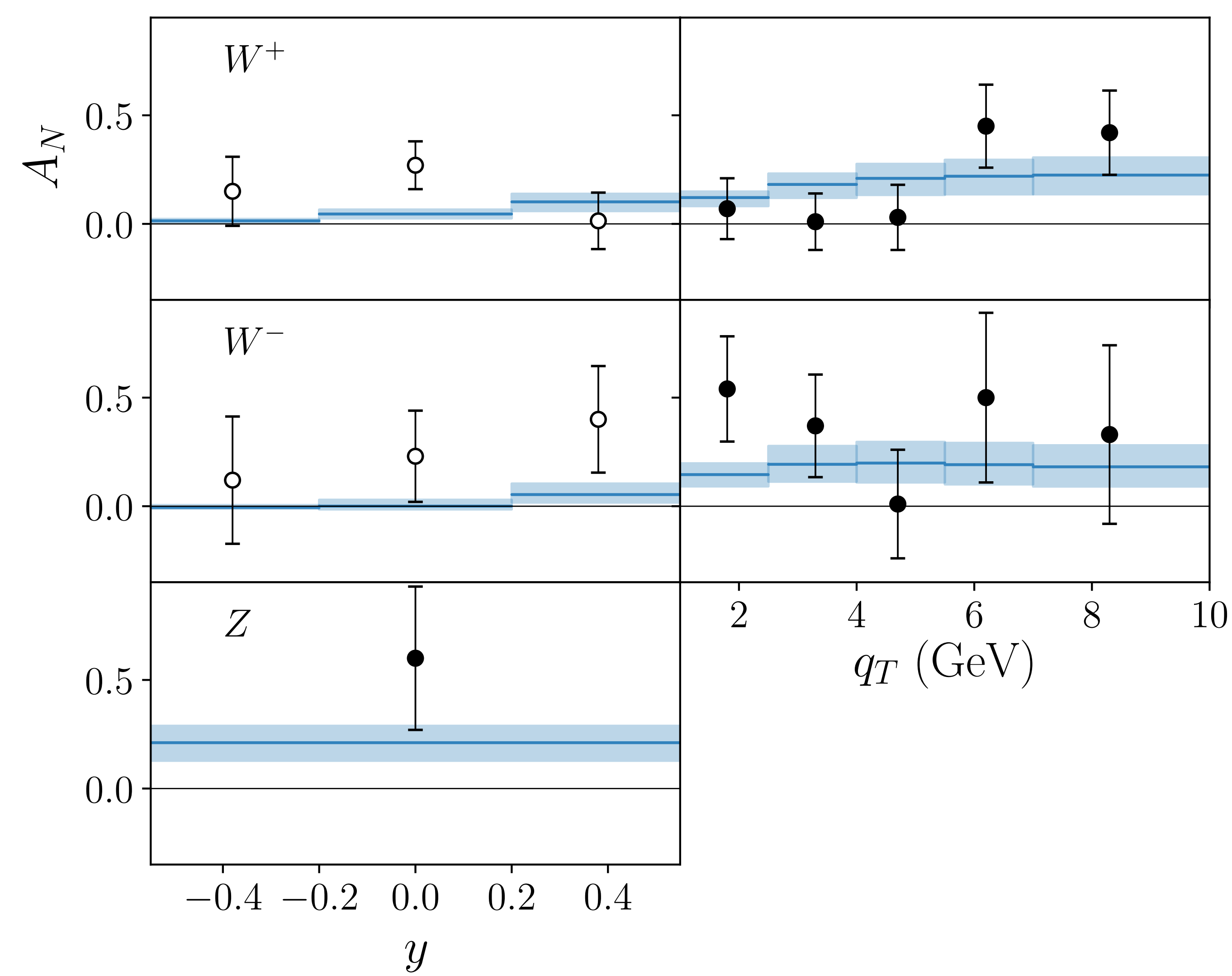
Pion induced Drell-Yan, COMPASS

COMPASS Collab. Phys. Rev. Lett. 119, 112002 (2017)



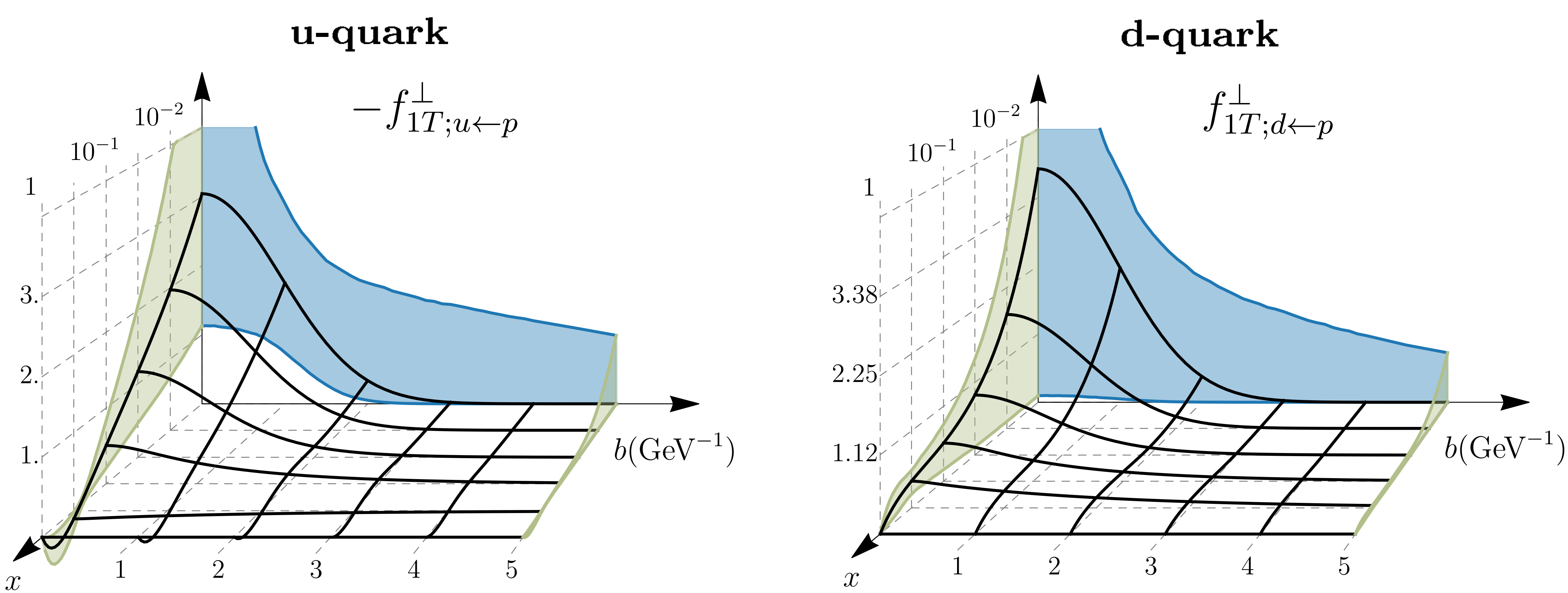
W/Z production, STAR

STAR Collab. Phys. Rev. Lett. 116, 132301 (2016)



SIVERS FUNCTION IN THE POSITION SPACE

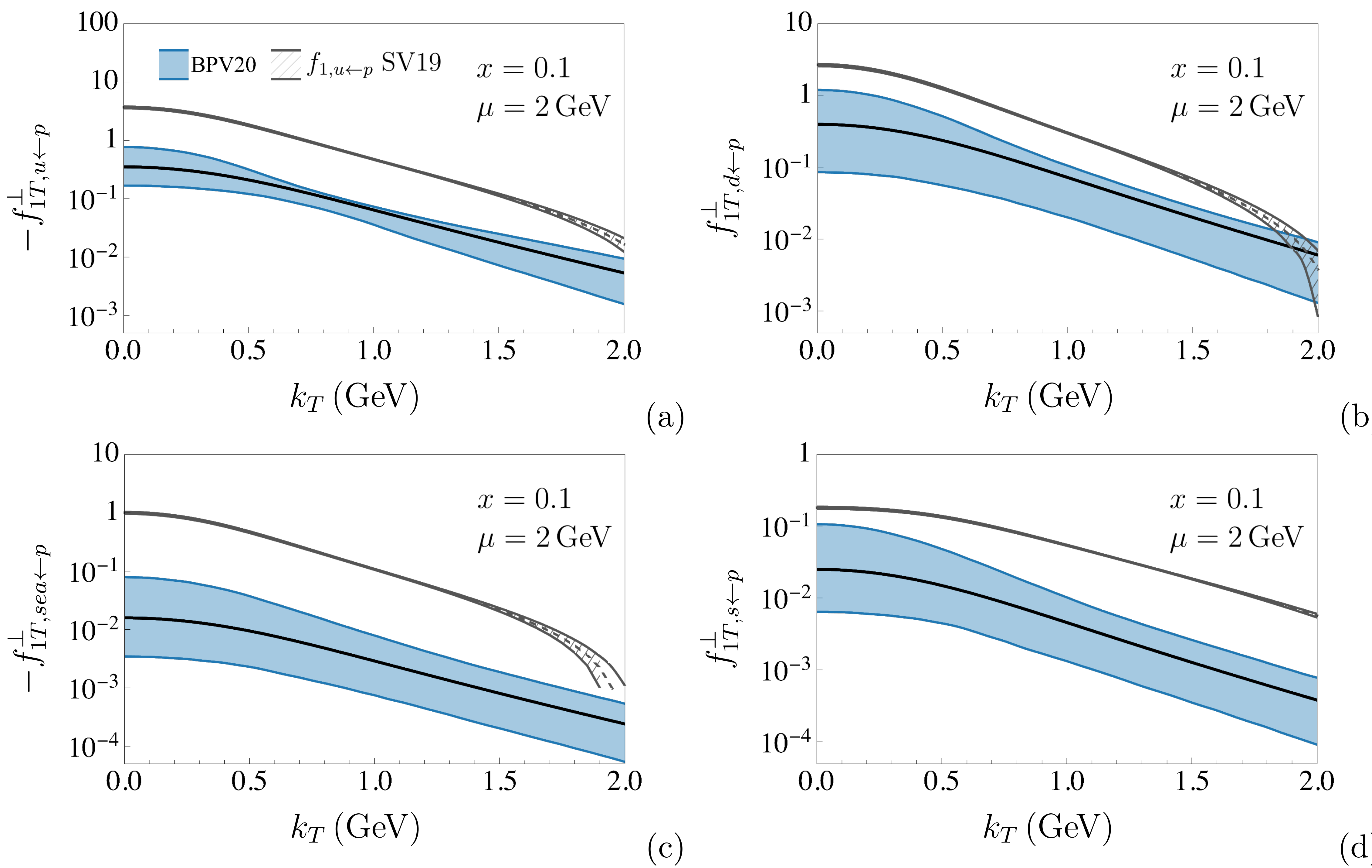
Bury, Prokudin, Vladimirov (2021)



- Large uncertainties
- Node for u quark
- More data needed: EIC, JLab 12, etc

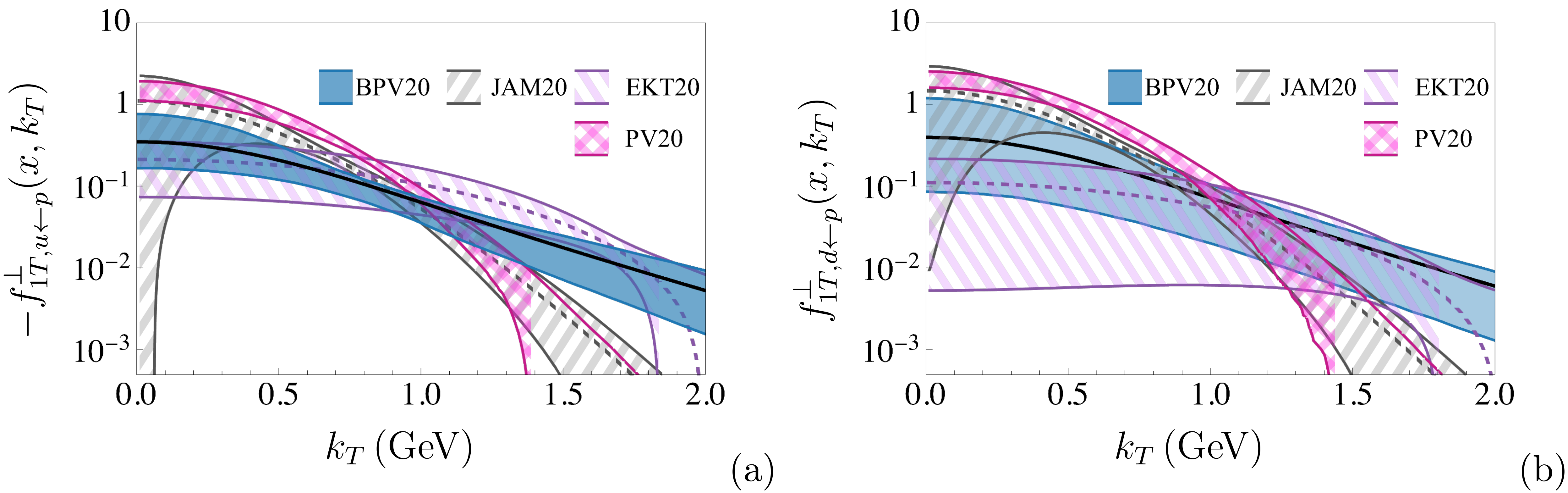
SIVERS FUNCTION IN THE MOMENTUM SPACE

Bury, Prokudin, Vladimirov (2021)



SIVERS FUNCTION IN THE MOMENTUM SPACE

Bury, Prokudin, Vladimirov (2021)



- Comparison to JAM20 (LO) analysis

  Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

- PV20, NLL analysis

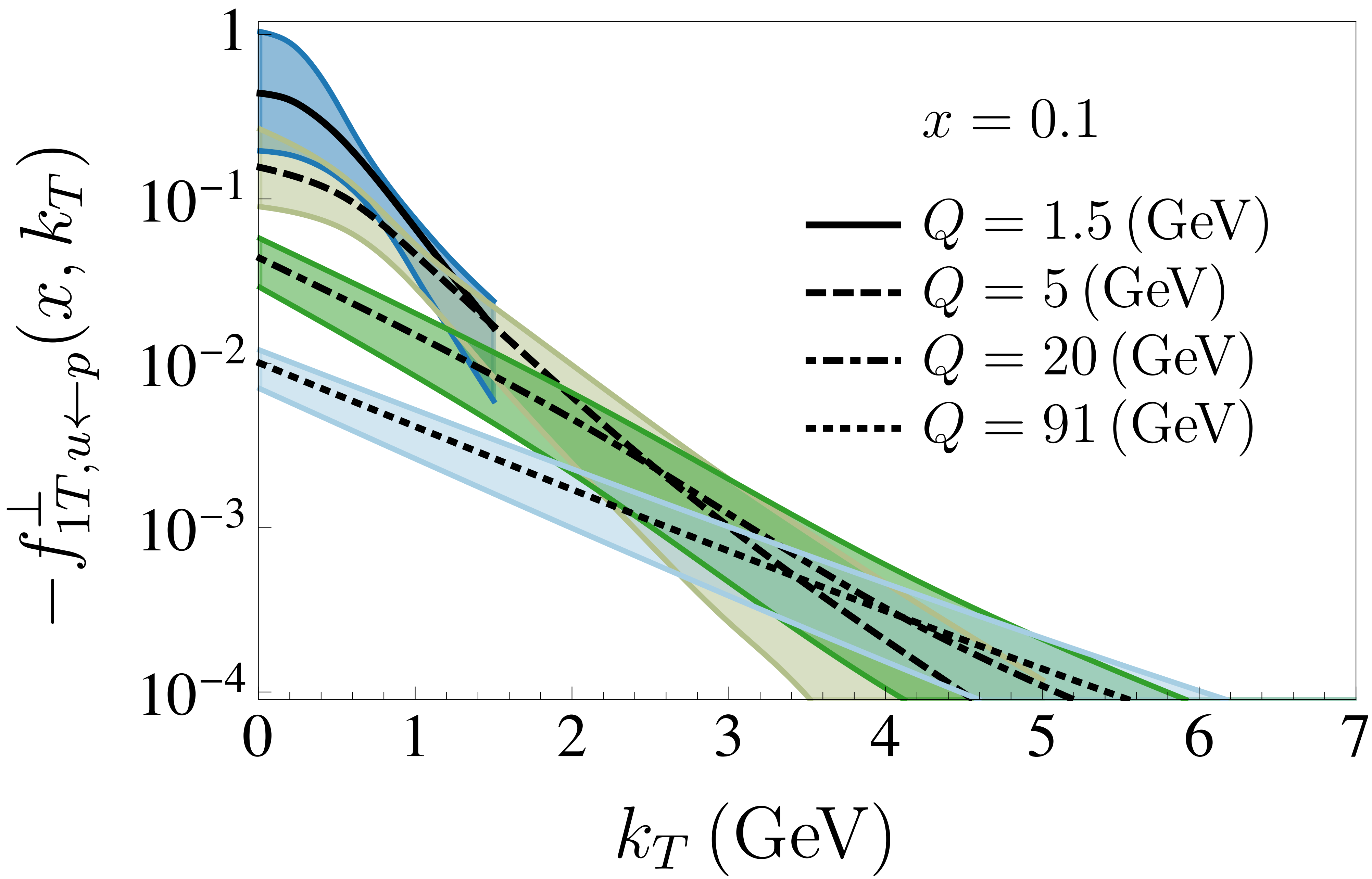
  Bacchetta, Delcarro, Pisano, Radici (2020)

- EKT20, NNLL analysis

  Echevarria, Terry, Kang (2020)

THE SIVERS FUNCTION

Bury, Prokudin, Vladimirov (2021)

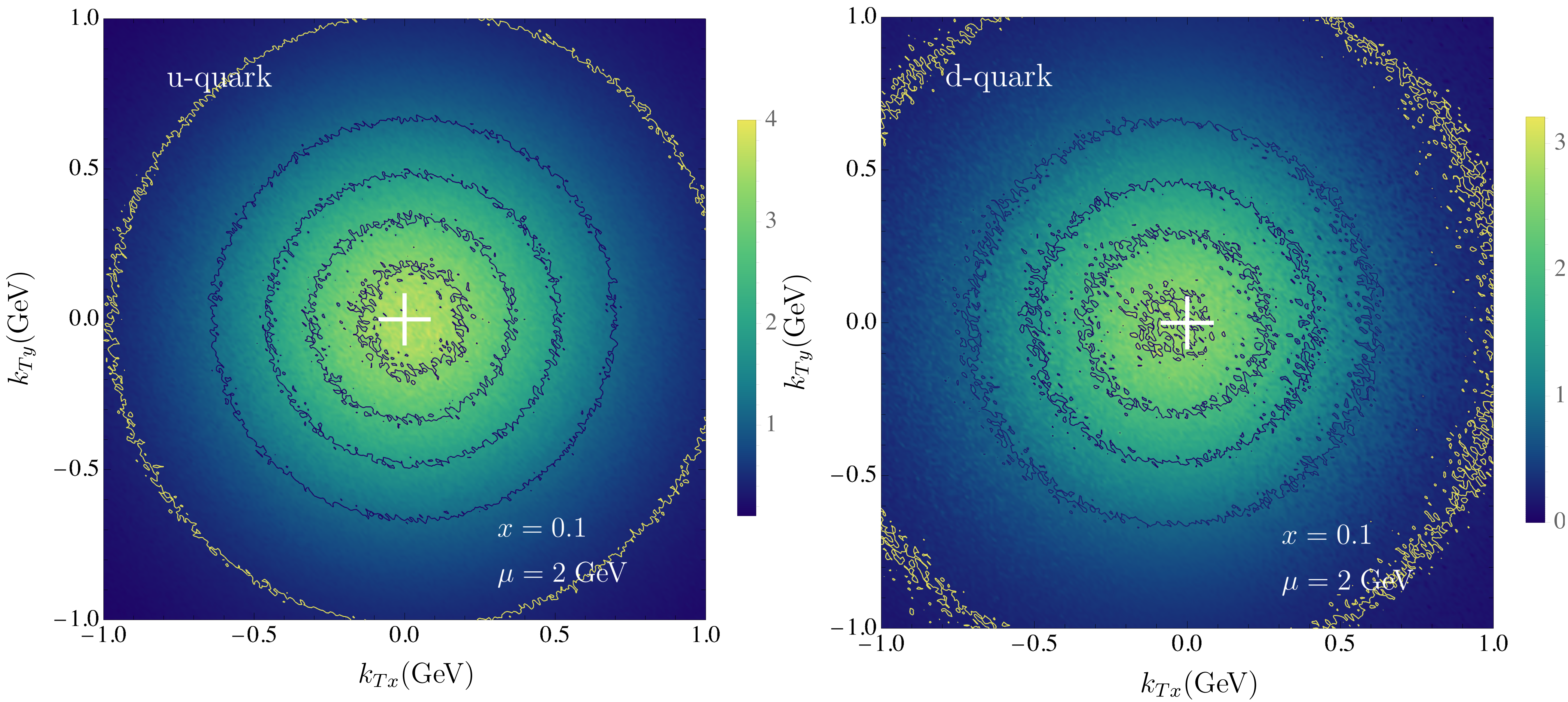


TOMOGRAPHY

NUCLEON TOMOGRAPHY

Bury, Prokudin, Vladimirov (2021)

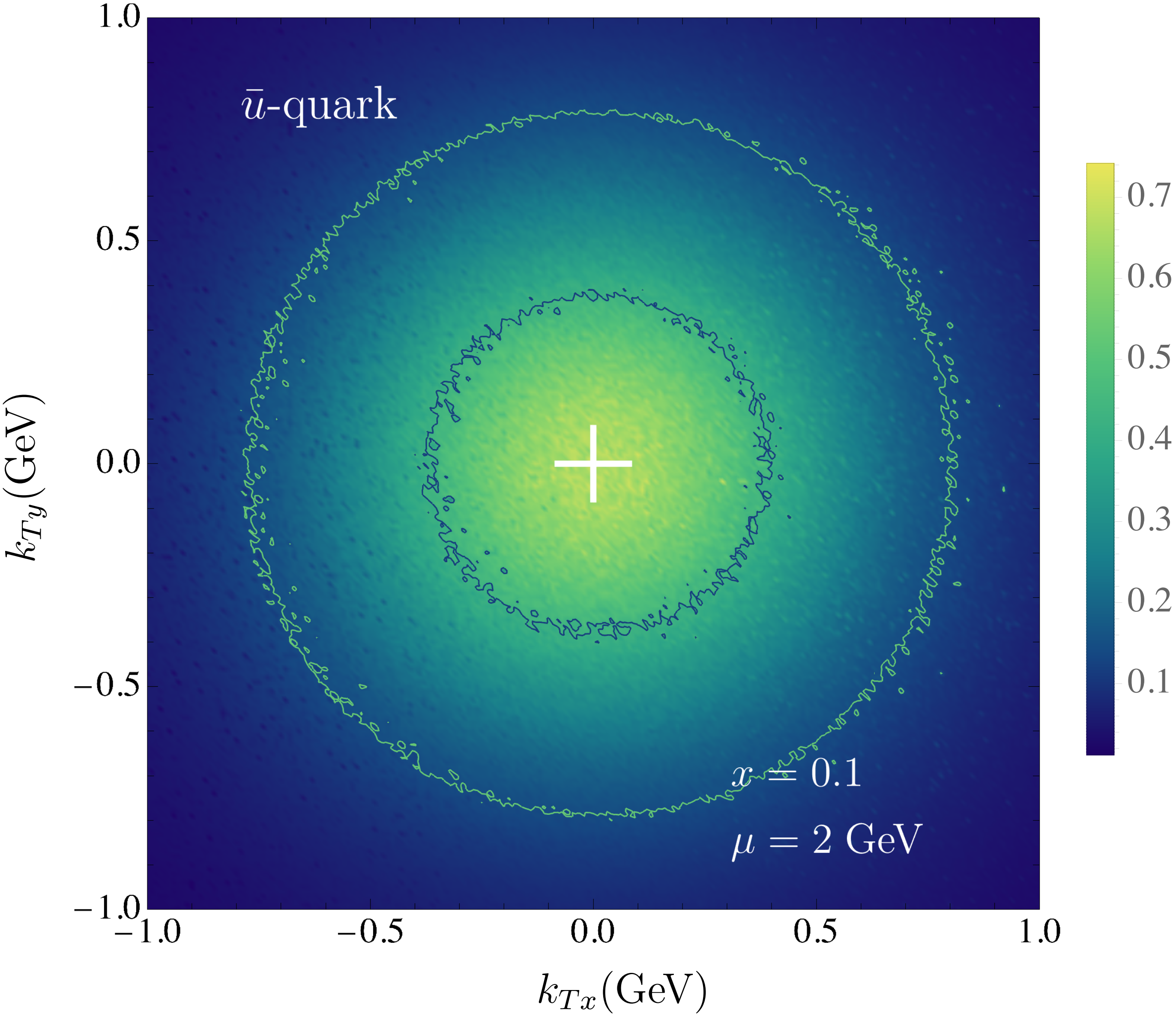
$$\rho_{1;q\leftarrow h^{\uparrow}}(x,\boldsymbol{k}_T,\boldsymbol{S}_T,\mu) = f_{1;q\leftarrow h}(x,k_T;\mu,\mu^2) - \frac{k_{Tx}}{M} f_{1T;q\leftarrow h}^{\perp}(x,k_T;\mu,\mu^2)$$

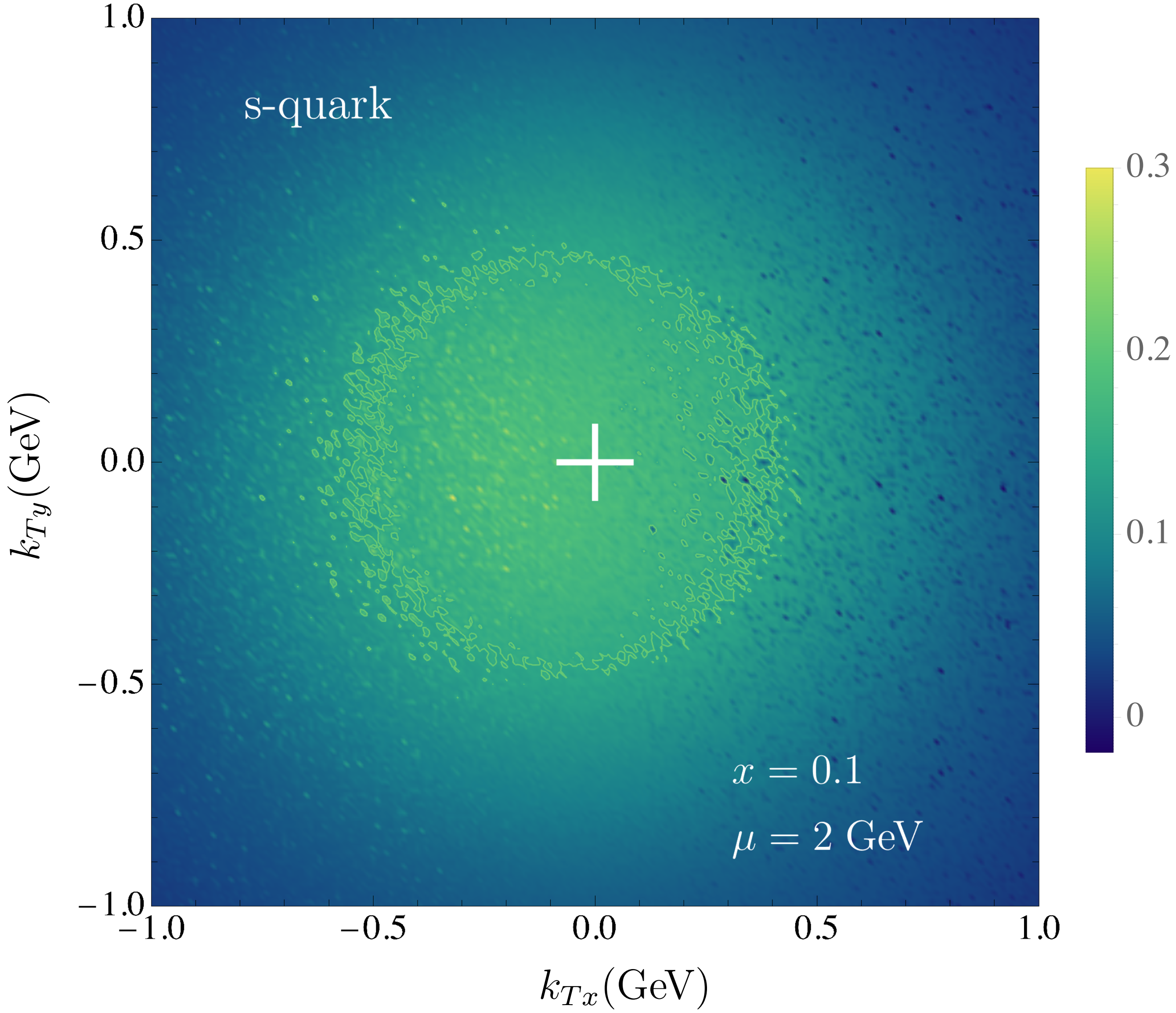


NUCLEON TOMOGRAPHY

Bury, Prokudin, Vladimirov (2021)

$$\rho_{1;q\leftarrow h^{\uparrow}}(x, \boldsymbol{k}_T, \boldsymbol{S}_T, \mu) = f_{1;q\leftarrow h}(x, k_T; \mu, \mu^2) - \frac{k_{Tx}}{M} f_{1T;q\leftarrow h}^{\perp}(x, k_T; \mu, \mu^2)$$





QS FUNCTIONS

THE QIU–STERMAN MATRIX ELEMENT

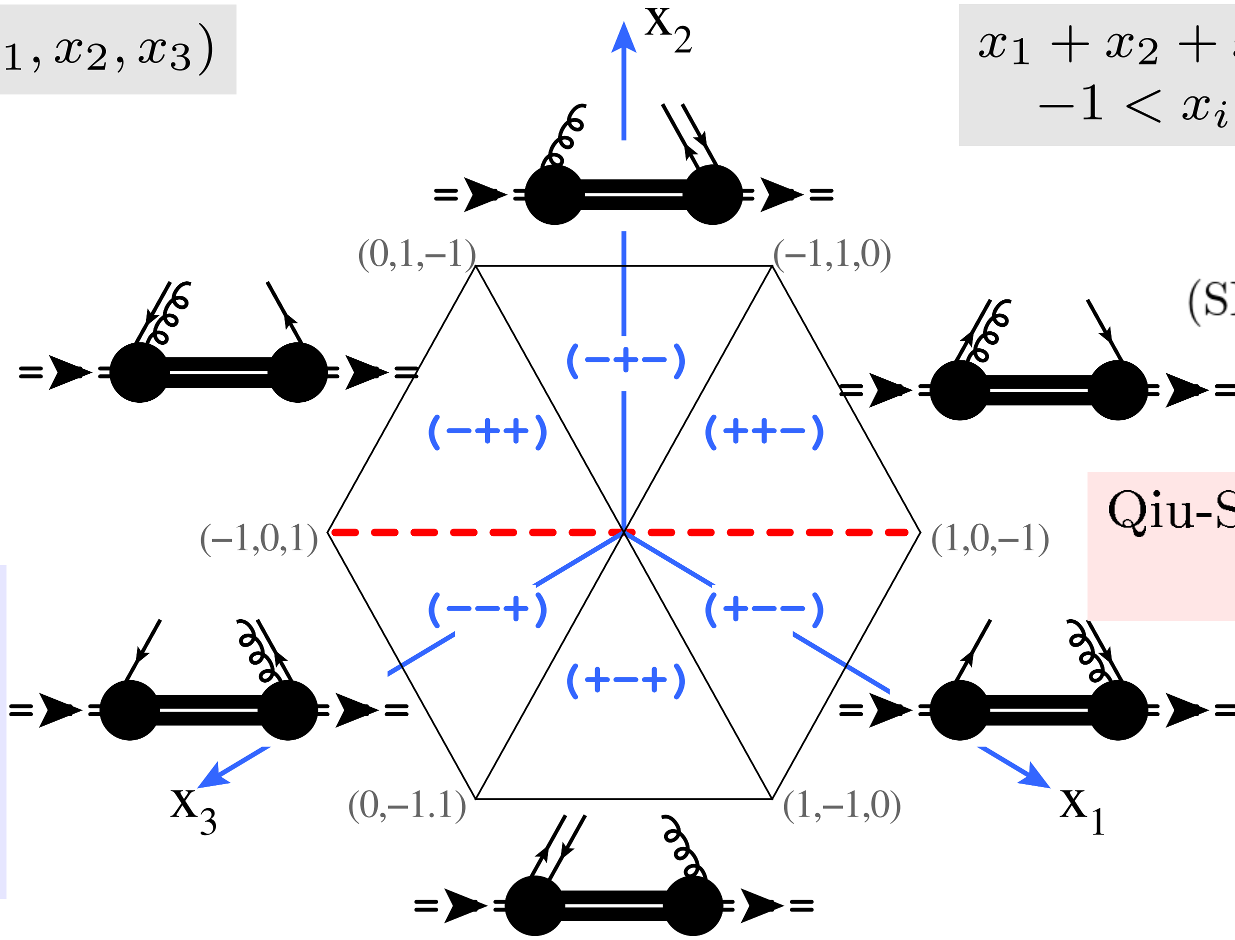
- At small b_T the Sivers function is related to the twist-3 function

Scimemi, Tarasov, Vladimirov (19)

$$\langle p,s|g\bar{q}(z_1 n)[z_1 n, z_2 n]\, \not{n}\, F_{\mu+}(z_2 n)[z_2 n, z_3 n] q(z_3 n)|p,s\rangle \tag{4.9}$$
$$= 2\epsilon_T^{\mu\nu} s_\nu (np)^2 M \int_{-1}^{1} dx_1 dx_2 dx_3 \delta(x_1+x_2+x_3) e^{-i(np)(x_1 z_1 + x_2 z_2 + x_3 z_3)} T_q(x_1,x_2,x_3),$$

$T(x_1,x_2,x_3)$

$x_1+x_2+x_3=0$
$-1<x_i<1$



Each region $x_i \lessgtr 0$ has its own partonic interpretation

$$\text{(DY)} \quad f_{1T}^{\perp}(x,\boldsymbol{b}) = \pi T(-x,0,x) + O(\boldsymbol{b}^2),$$
$$\text{(SIDIS)} \quad f_{1T}^{\perp}(x,\boldsymbol{b}) = -\pi T(-x,0,x) + O(\boldsymbol{b}^2).$$

Qiu-Sterman function
$T(-x,0,x)$

Important for description of asymmetries in PP, etc

THE QIU-STERMAN MATRIX ELEMENT

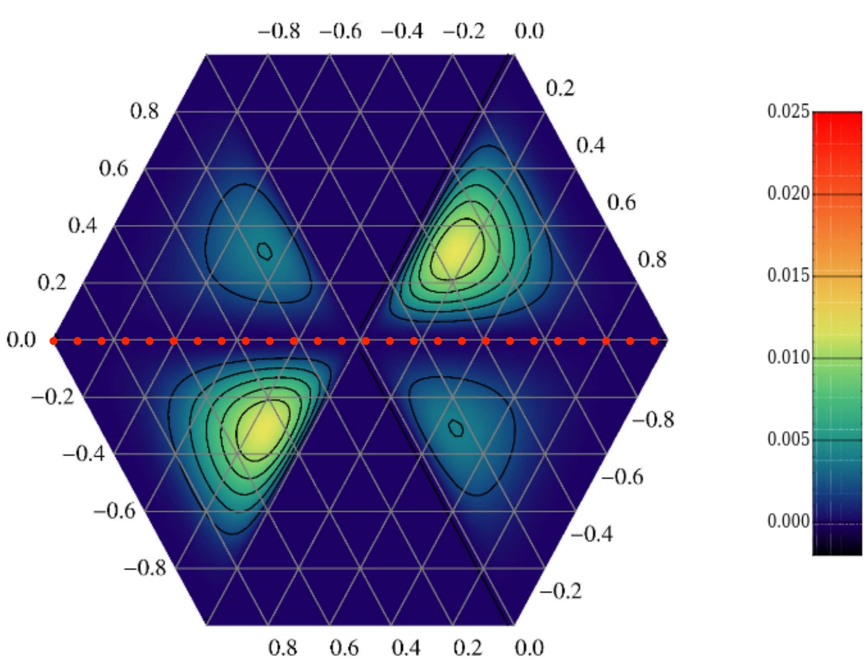
- Beyond LO it is complicated

Scimemi, Tarasov, Vladimirov (19)

$$f_{1T;q\leftarrow h;\text{DY}}^{\perp}(x,\boldsymbol{b};\mu,\zeta)=\pi T(-x,0,x)+\pi a_s(\mu)\Big\{$$
$$-2\mathbf{L}_\mu P\otimes T+C_F\left(-\mathbf{L}_\mu^2+2\mathbf{l}_\zeta\mathbf{L}_\mu+3\mathbf{L}_\mu-\frac{\pi^2}{6}\right)T(-x,0,x)$$
$$+\int d\xi\int_0^1 dy\delta(x-y\xi)\Big[\left(C_F-\frac{C_A}{2}\right)2\bar{y}T(-\xi,0,\xi)+\frac{3y\bar{y}}{2}\frac{G_+(-\xi,0,\xi)+G_-(-\xi,0,\xi)}{\xi}\Big]\Big\}$$
$$+O(a_s^2)+O(\boldsymbol{b}^2),$$

- Evolution of T is complicated and non closed

Braun et al (11), Kang, Qiu (09), Vogelsang



$1/N_c$-suppressed — The only QS-term

$$\mu^2\frac{d}{d\mu^2}T(-x,0,x)=2a_s(\mu)P\otimes T=2a_s\int d\xi\int_0^1 dy\delta(x-y\xi)\Big\{$$
$$\left(C_F-\frac{C_A}{2}\right)\Big[\left(\frac{1+y^2}{1-y}\right)_+T(-\xi,0,\xi)+(2y-1)_+T(-x,\xi,x-\xi)-\Delta T(-x,\xi,x-\xi)\Big]$$
$$+\frac{C_A}{2}\Big[\left(\frac{1+y}{1-y}\right)_+T(-x,x-\xi,\xi)+\Delta T(-x,x-\xi,\xi)\Big]$$
$$+\frac{1-2y\bar{y}}{4}\frac{G_+(-\xi,0,\xi)+Y_+(-\xi,0,\xi)+G_-(-\xi,0,\xi)+Y_-(-\xi,0,\xi)}{\xi}\Big\},$$

THE QIU–STERMAN MATRIX ELEMENT

- Invert the formula for Operator Product Expansion of Sivers via the QS functions

Bury, Prokudin, Vladimirov (2020)

$$T_q(-x,0,x;\mu_b) = -\frac{1}{\pi}\left(1 + C_F\frac{\alpha_s(\mu_b)}{4\pi}\frac{\pi^2}{6}\right) f_{1T;q\leftarrow h}^{\perp}(x,b)$$
$$-\frac{\alpha_s(\mu_b)}{4\pi^2}\int_x^1 \frac{dy}{y}\left[\frac{\bar{y}}{N_c} f_{1T;q\leftarrow h}^{\perp}\left(\frac{x}{y},b\right) + \frac{3y^2\bar{y}}{2x}G^{(+)}\left(-\frac{x}{y},0,\frac{x}{y};\mu_b\right)\right] + \mathcal{O}(a_s^2,b^2)$$

Choose the scale to eliminate logs $\mu_b = \dfrac{2e^{-\gamma_E}}{b}$

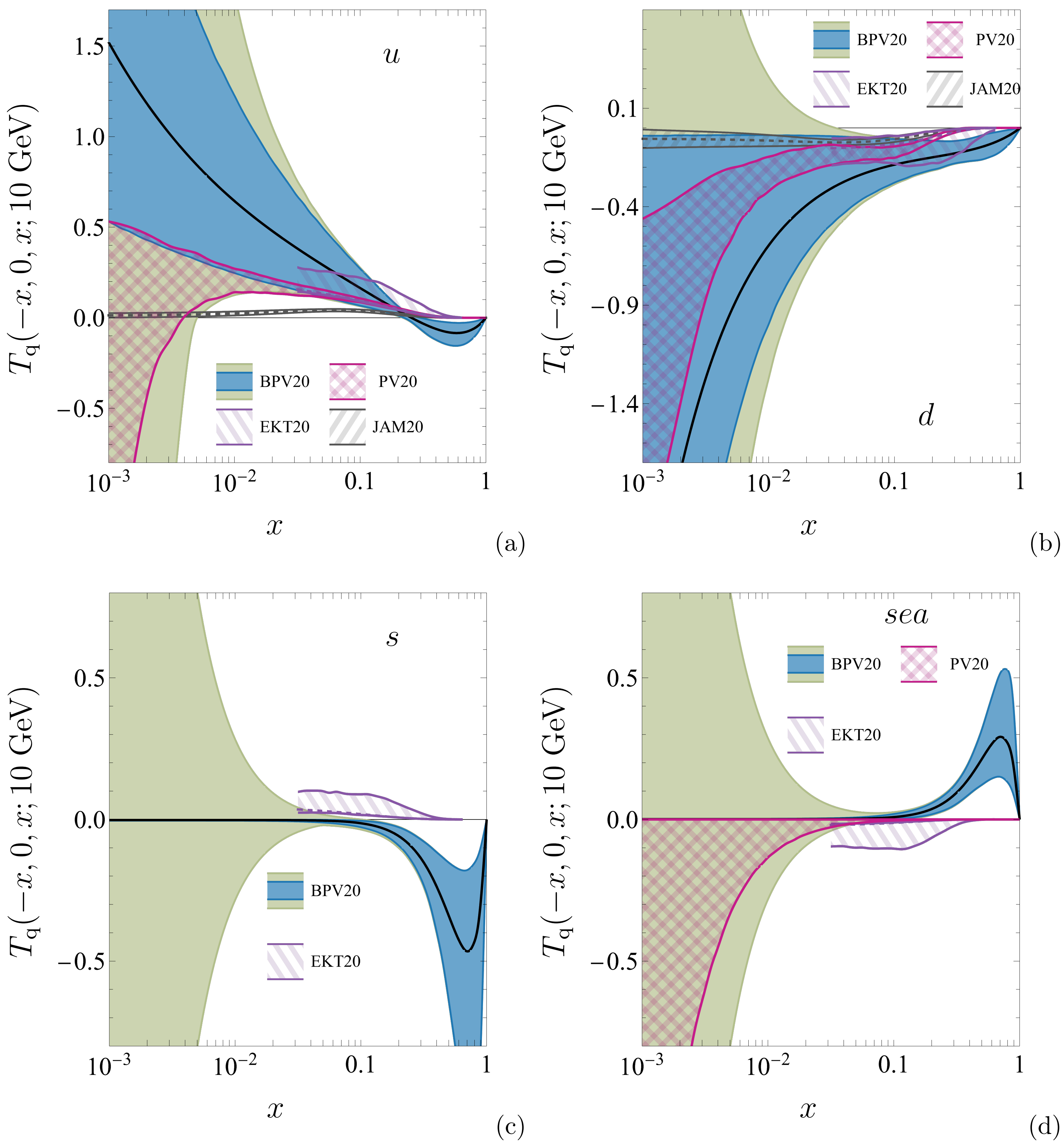
We choose $b = 0.11\ (\mathrm{GeV}^{-1}),\ \ \mu_\mathrm{b} = 10\ (\mathrm{GeV})$

and estimate gluon contribution $G^{(+)} = \pm(|T_u| + |T_d|)$

- Exact model independent relation!

THE QIU-STERMAN MATRIX ELEMENT

Bury, Prokudin, Vladimirov (2020)



Compares well with Jam 20 (LO)

Jam20: Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

PV20 (NLL)

Bacchetta, Delcarro, Pisano, Radici (2020)

EKT20 (NNLL)

Echevarria, Kang, Terry (2020)

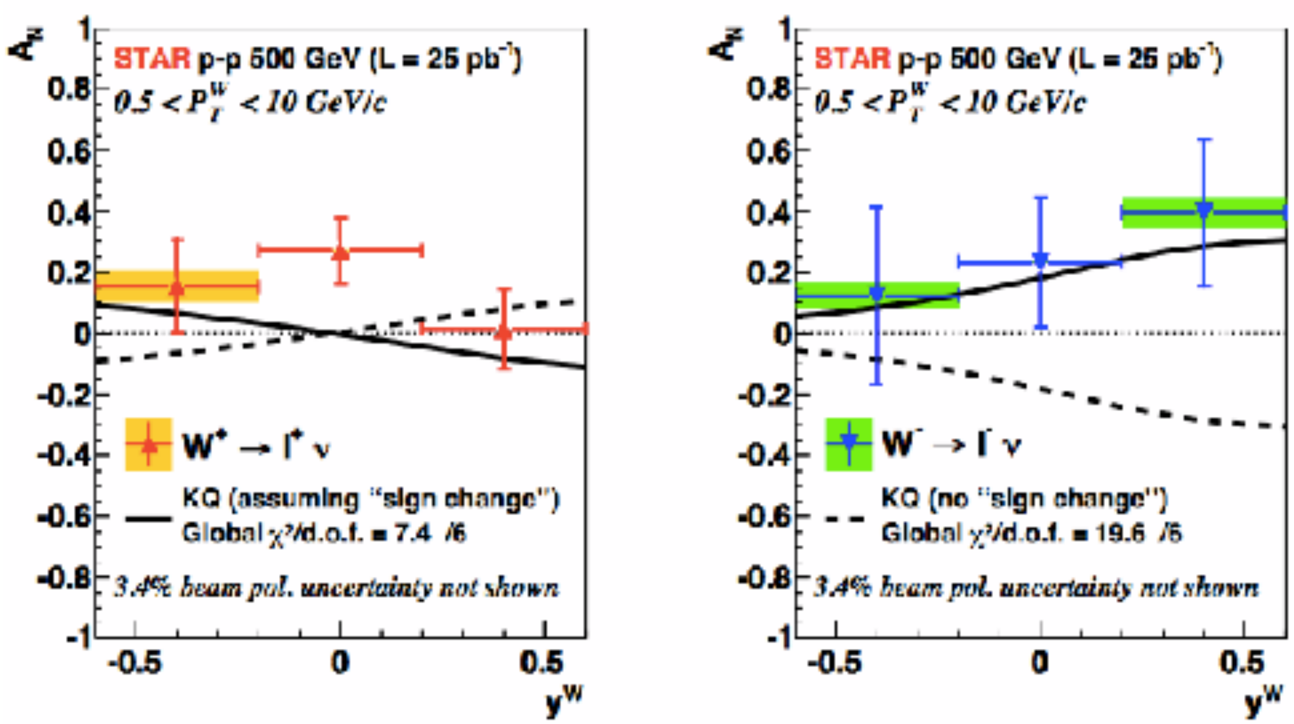
Sea quark functions is still a mystery to explore

PROCESS DEPENDENCE

PROCESS DEPENDENCE OF THE SIVERS FUNCTION

- First experimental hints on the sign change, W/Z production

STAR Collab. Phys. Rev. Lett. 116, 132301 (2016)



$$p^\uparrow p \to W^\pm X$$

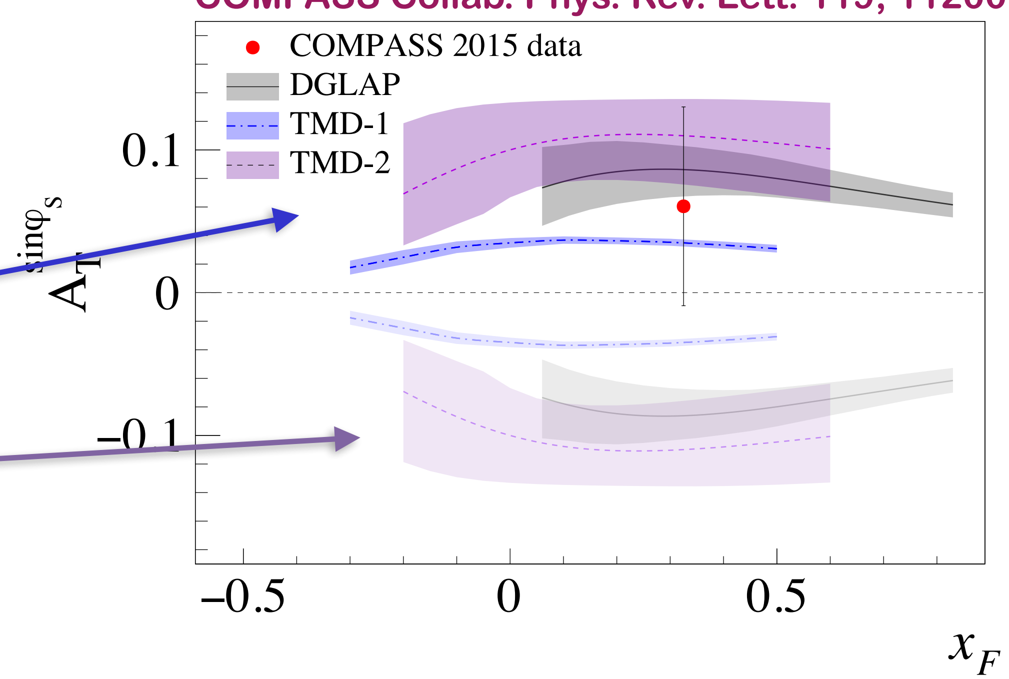
KQ → Kang, Qiu `09

- Pion induced Drell-Yan

COMPASS Collab. Phys. Rev. Lett. 119, 112002 (2017)

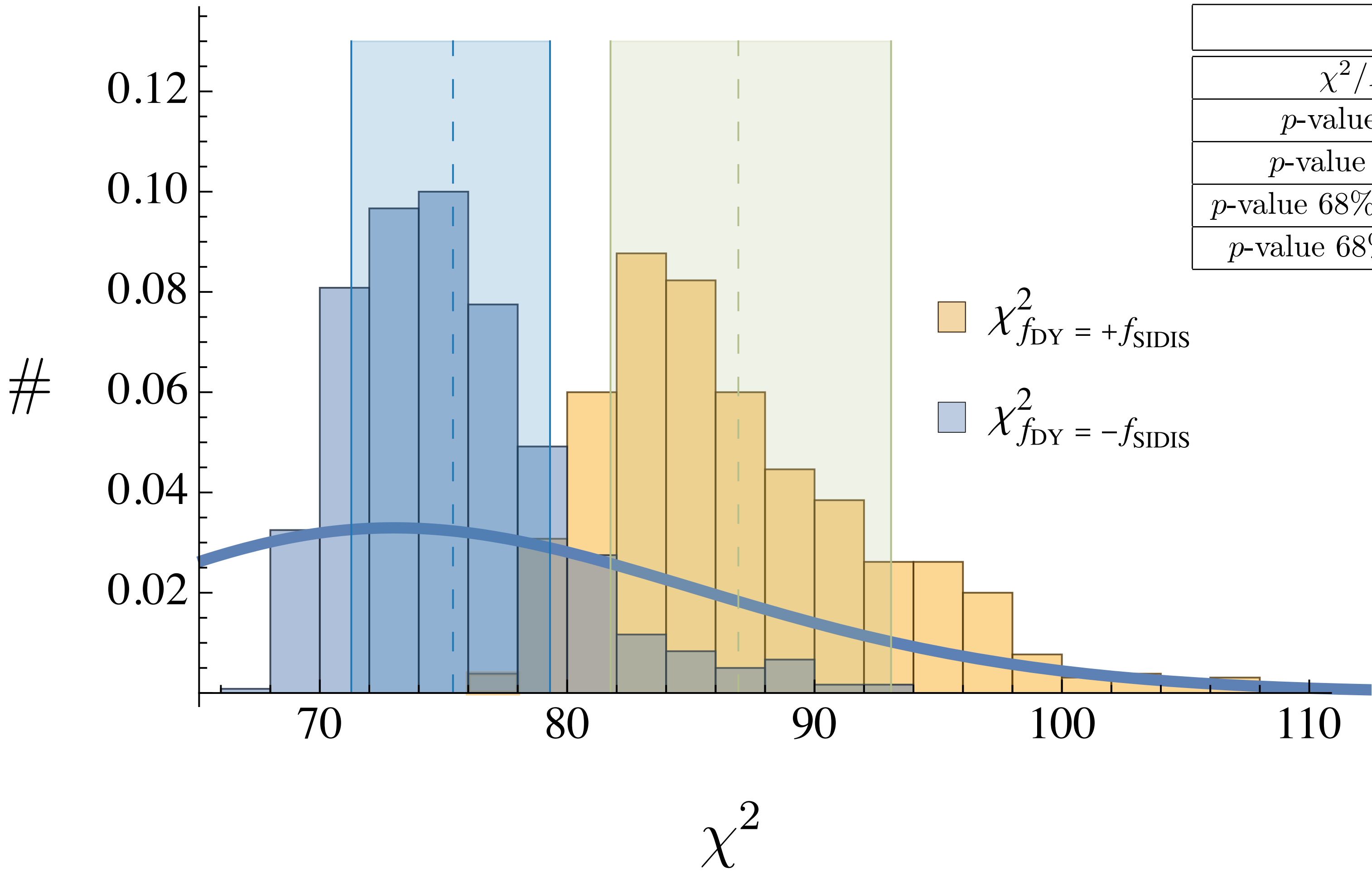
Sign change

No sign change



SIGN CHANGE

Bury, AP, Vladimirov (2021)



	$f^{\perp}_{1T\,[DY]} = -f^{\perp}_{1T\,[SIDIS]}$	$f^{\perp}_{1T\,[DY]} = +f^{\perp}_{1T\,[SIDIS]}$
χ^2/N_{pt}	$0.88^{+0.16}_{+0.06}$	$1.00^{+0.22}_{+0.08}$
p-value (CF)	0.74	0.44
p-value 68%CI	[0.60, 0.34]	[0.28, 0.08]
p-value 68%CI (SIDIS)	[0.67, 0.42]	[0.53, 0.11]
p-value 68%CI (DY)	[0.56, 0.17]	[0.68, 0.02]

Large contribution from antiquark Sivers functions to DY makes it possible to describe data without the sign change

$$f_{1T}^{\perp sea} \to -f_{1T}^{\perp sea}$$

SpinQuest data may prove important to constraint sea-quark functions

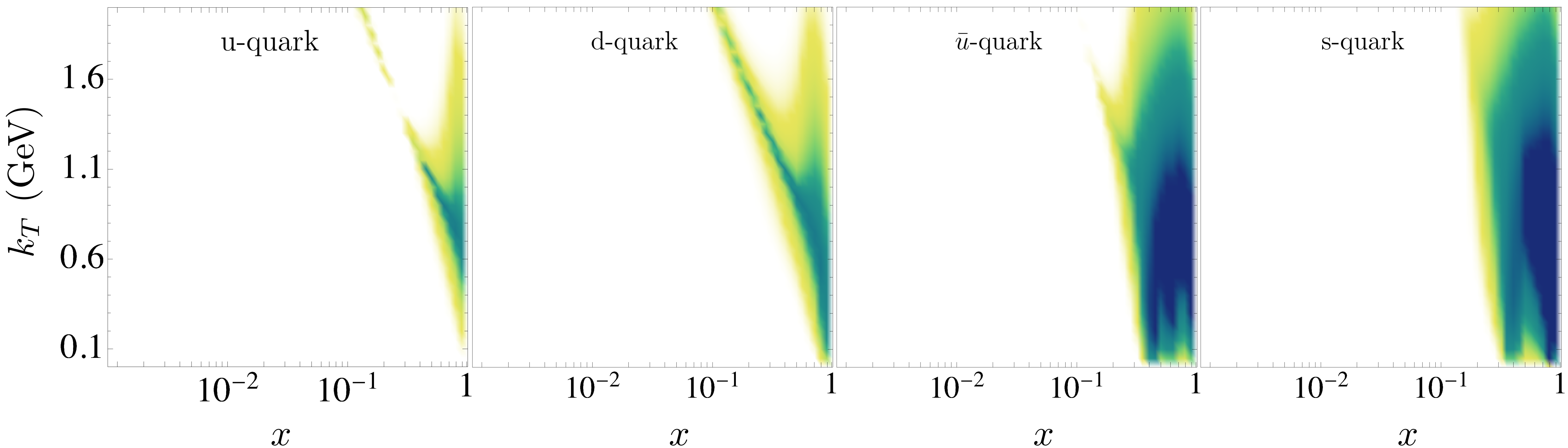
CONCLUSIONS

- We have extracted Sivers function from the first global fit of SIDIS, pion-induced Drell-Yan and W±/Z production experimental data at N3LO precision
- Conservative data cuts are used to ensure validity of factorization and unbiased parametrization
- Good agreement between SIDIS and DY data in an analysis with TMD evolution is achieved for the first time
- The Qiu-Sterman functions are extracted in a model independent way
- Our results set a new benchmark and the standard of precision for studies of TMD polarized functions

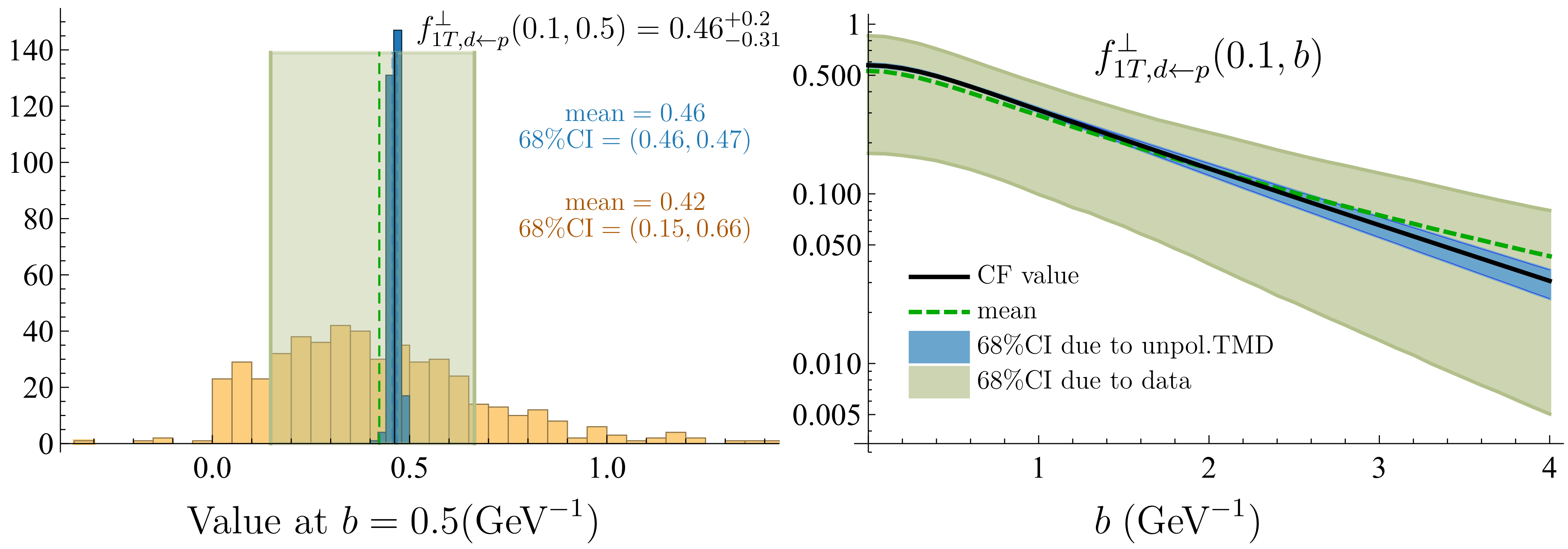
BACKUP

POSITIVITY

$$\frac{k_T^2}{M^2}\left(g_{1T}(x,k_T)^2 + f_{1T}^{\perp}(x,k_T)^2\right) \leqslant f_1(x,k_T)^2,$$



ERROR PROPAGATION



- Uncertainties estimated by replica method
  - Fitting 300 replicas of pseudo data
- Large and (often) asymmetric uncertainties
- Uncertainty due to unpol.TMD are non-negligible but much smaller then due to data