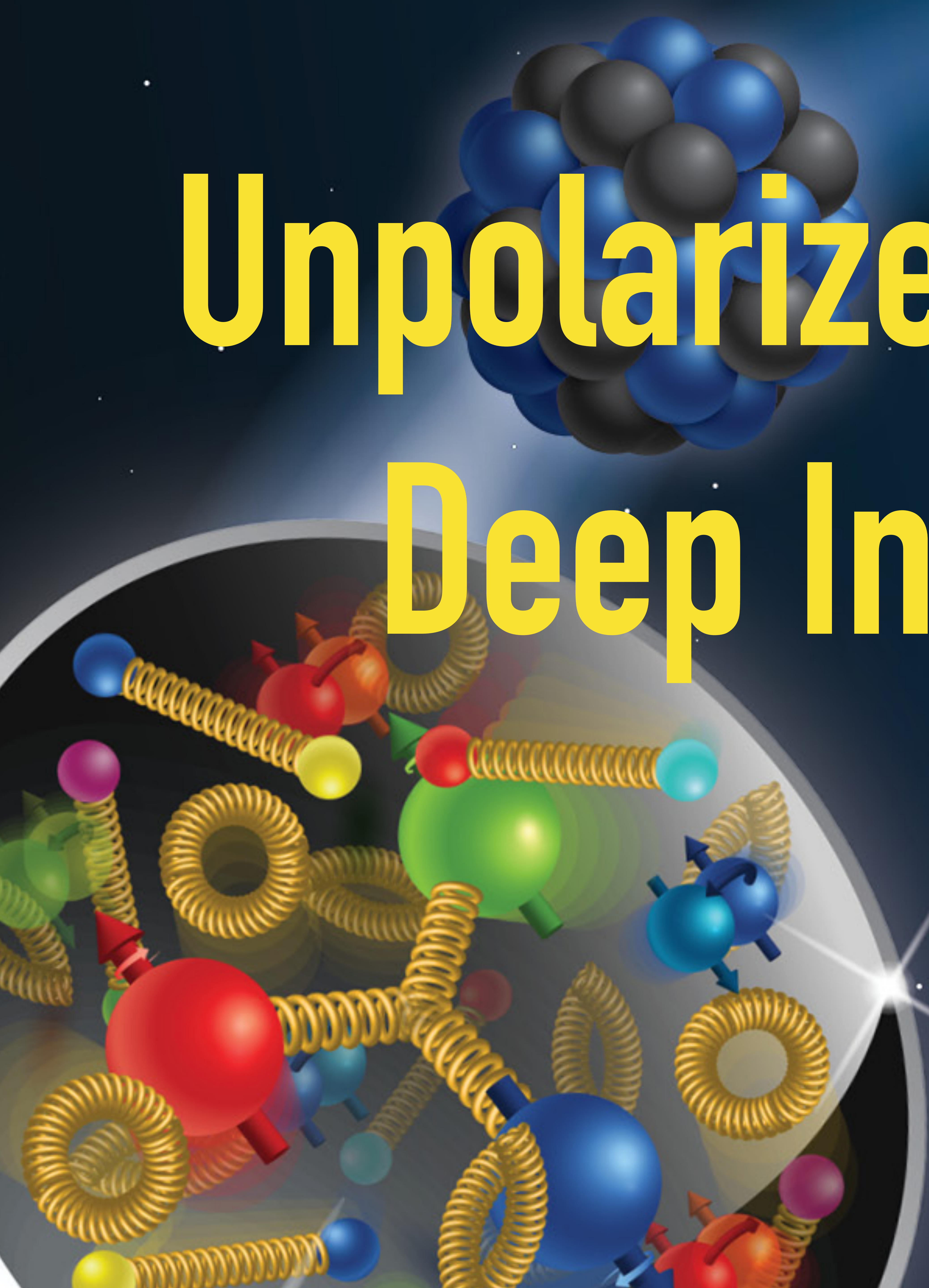
Unpolarized Semi-Inclusive Deep Inelastic Scattering with ^3He at SoLID



Alexei Prokudin

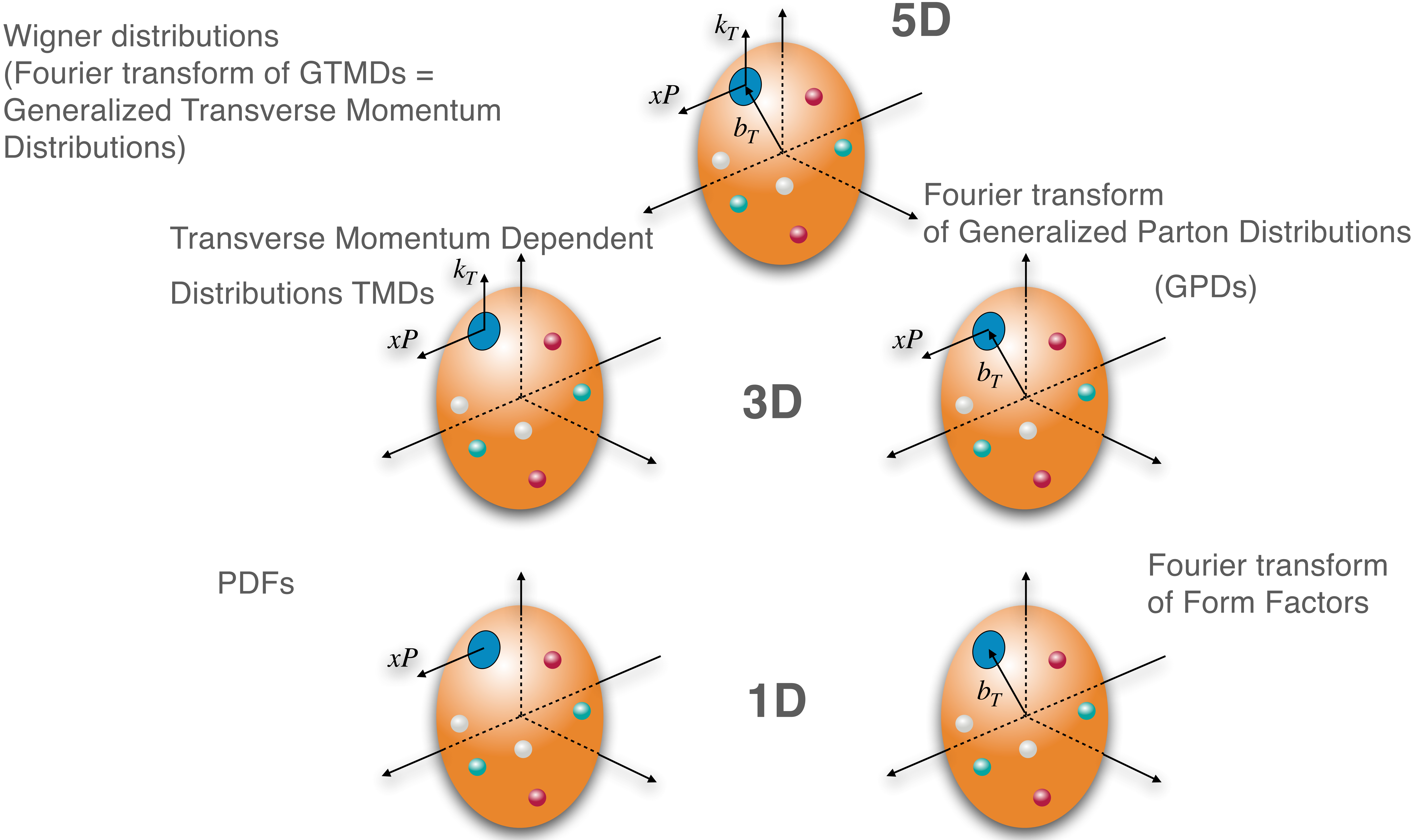
Pennsylvania State University Berks and Jefferson Lab

BASED ON

“SIDIS Unpolarized Cross Sections from a 3He Target with the Solenoidal Large Intensity Device at JLab”

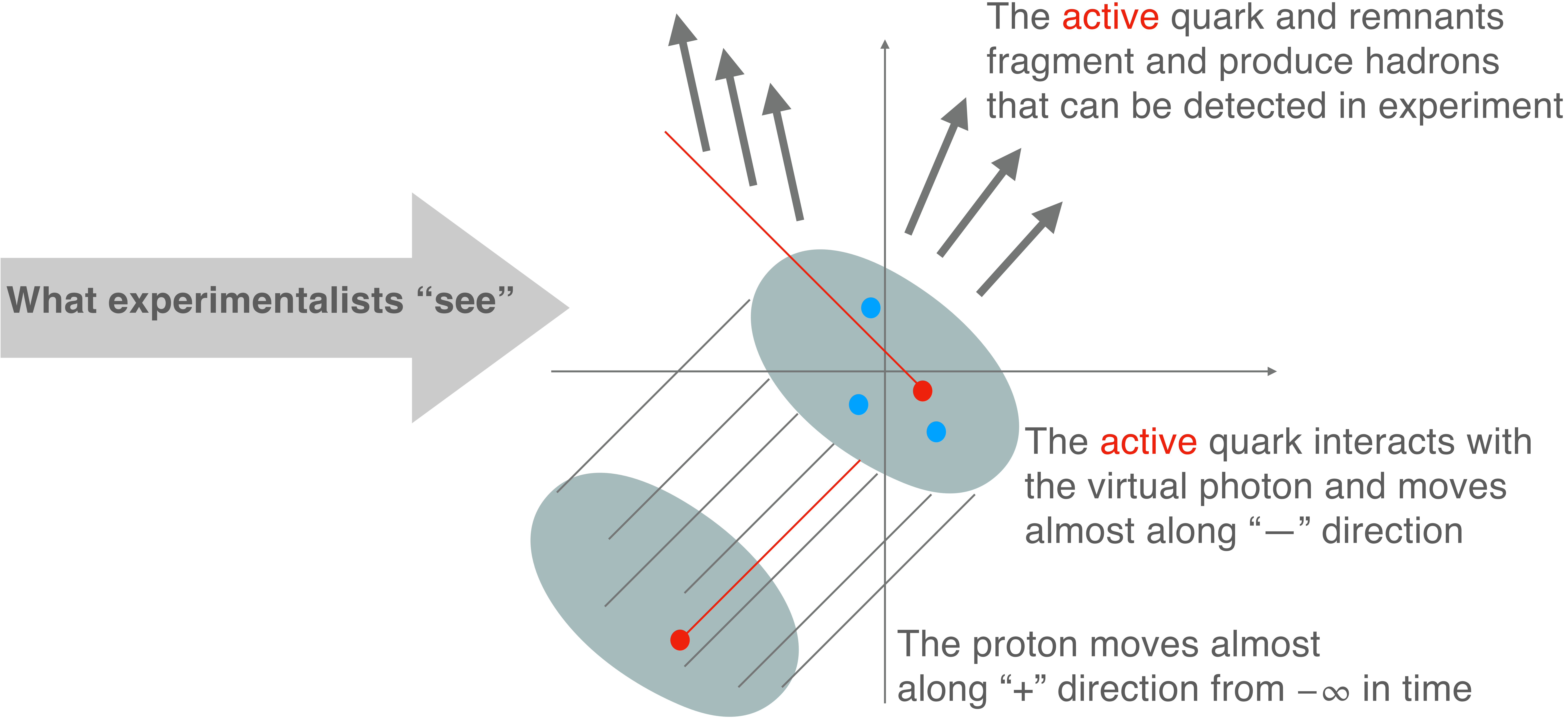
Matteo Cerutti, Jian-Ping Chen, Umberto D’Alesio, Haiyan Gao, Shuo Jia,
Vladimir Khachatryan, Alexei Prokudin, Lorenzo Rossi, Ye Tian, and Zhiwen Zhao
e-Print: 2512.20897 *to be published in PRC*

MOTIVATION



SEE, E.G., C. LORCÉ, B. PASQUINI, M. VANDERHAEGHEN, JHEP 1105 (11)

INTERPRETATION OF DEEP INELASTIC SCATTERING



INTERPRETATION OF DEEP INELASTIC SCATTERING

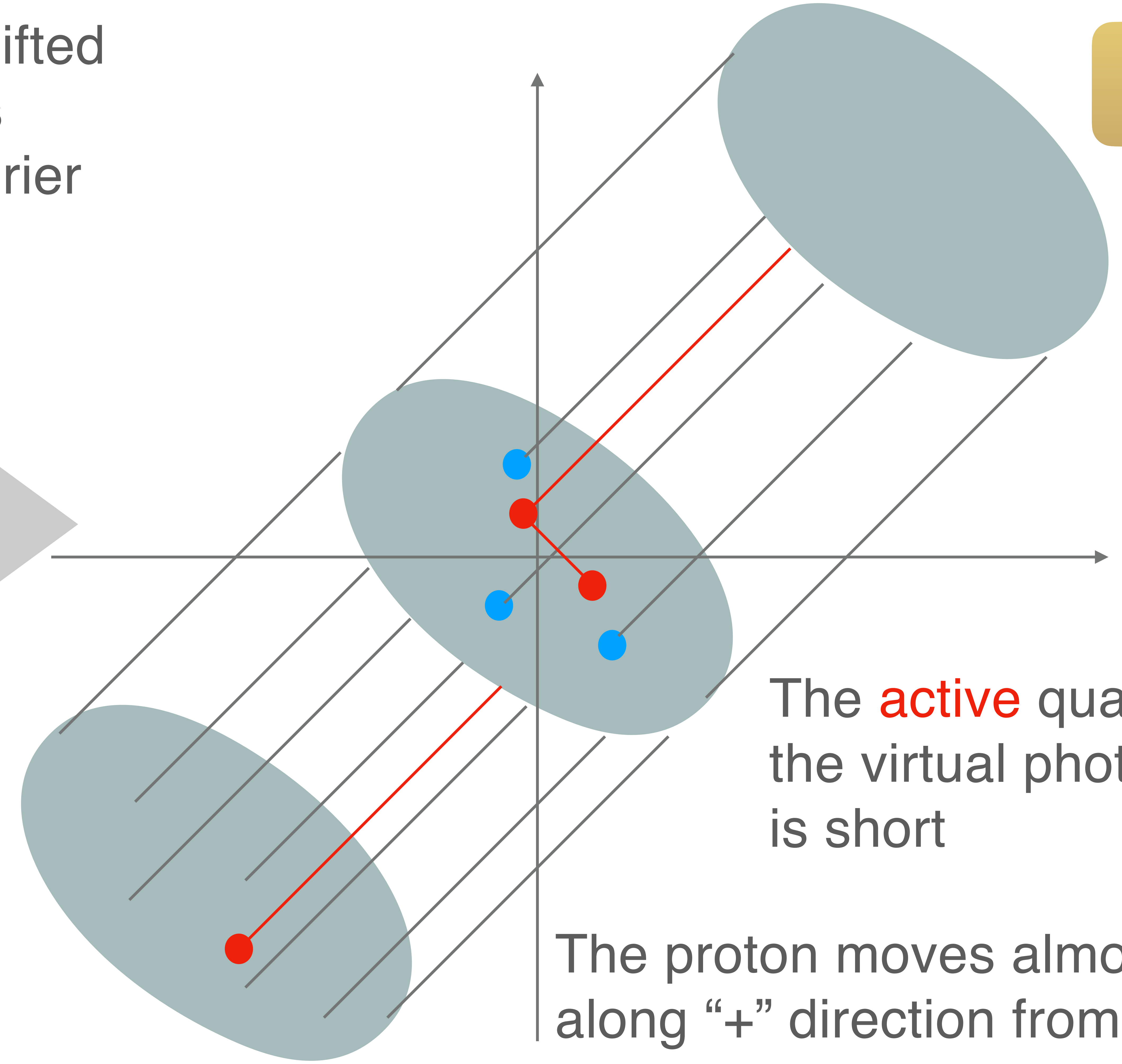
The proton recombines in a proton with the active quark shifted along "—" direction and moves to $+\infty$ in time, this shift is Fourier conjugate to x.

How theorists "interpret"

Interpretation of the bilocal matrix element

$$e^{ixP^+b^-}\langle P,S\,|\,\bar{\psi}(b^-)\psi(0)\,|\,P,S\rangle$$

Structure is encoded here in terms of collinear Parton Distribution Functions (PDFs)



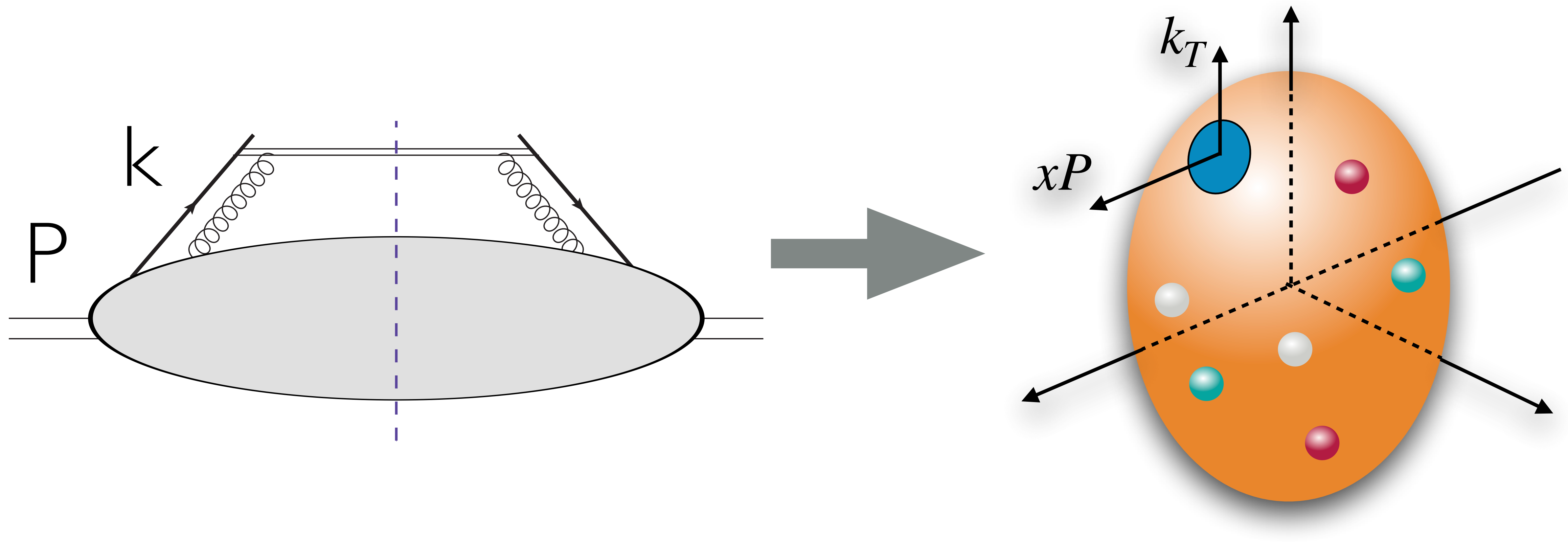
The active quark interacts with the virtual photon, the interaction is short

The proton moves almost along "+" direction from $-\infty$ in time

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 - 3D structure!



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

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.

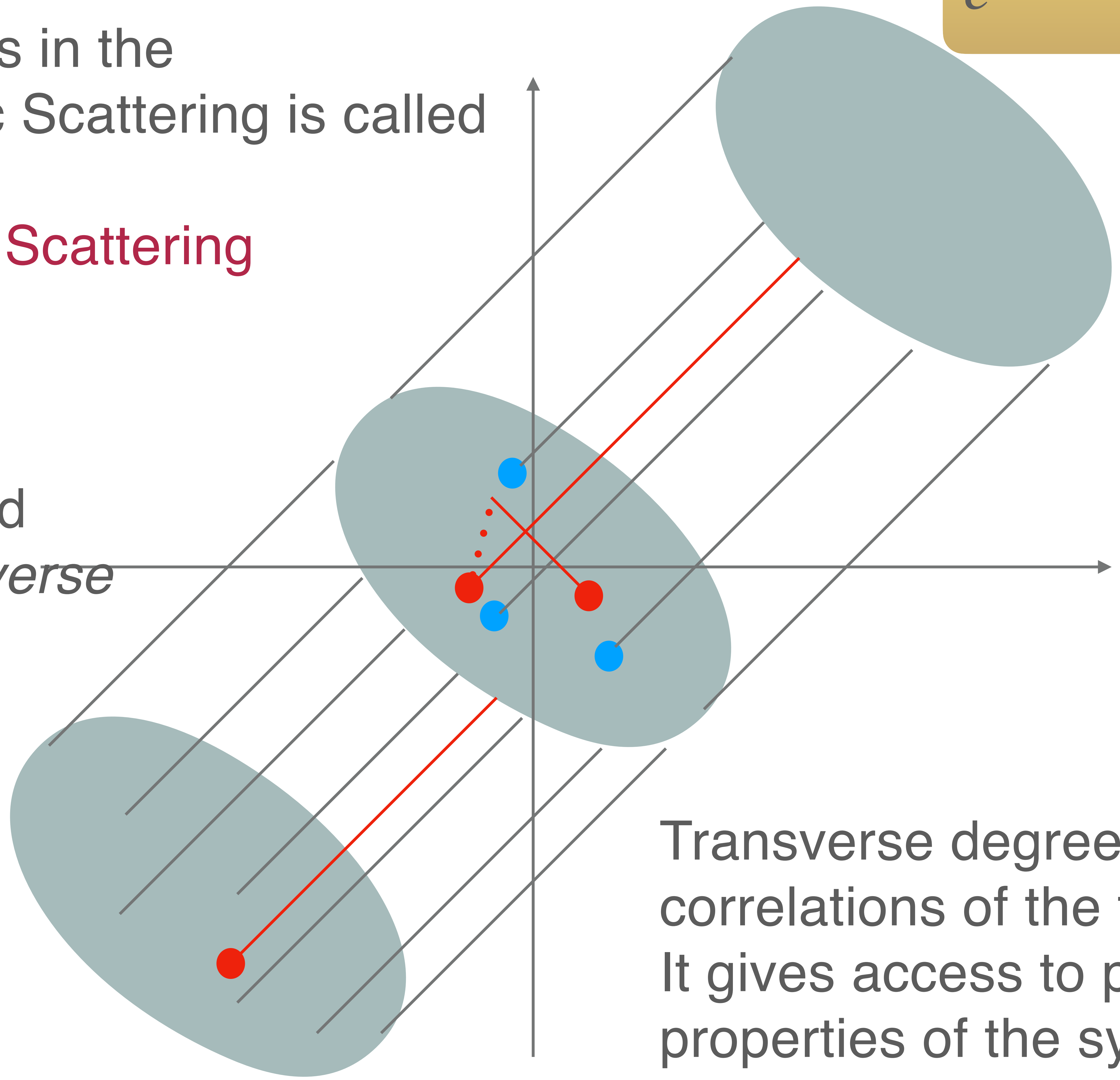
INTERPRETATION OF SEMI-INCLUSIVE DEEP INELASTIC SCATTERING

$$e^{ixP^+b^- - ik_T b_T}\langle P,S\,|\,\bar{\psi}(b^-,b_T)\psi(0)\,|\,P,S\rangle$$

If we detect one of the hadrons in the final state, then Deep Inelastic Scattering is called

Semi-Inclusive Deep Inelastic Scattering

The proton recombines in a proton with active quark shifted along "—" direction and *transverse direction* "T" and moves to $+\infty$ in time, these shifts are Fourier conjugate to x and k_T



This new transverse degree of freedom allows to resolve 3 dimensional structure encoded in Transverse Momentum Dependent distribution and fragmentation functions (TMDs)

Transverse degree of freedom allows to study correlations of the transverse motion and spin etc. It gives access to purely quantum mechanical properties of the system

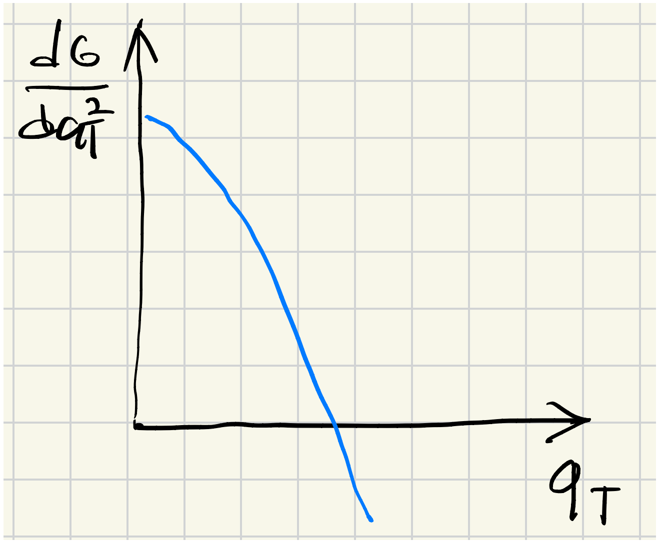
SEMI-INCLUSIVE DEEP INELASTIC SCATTERING

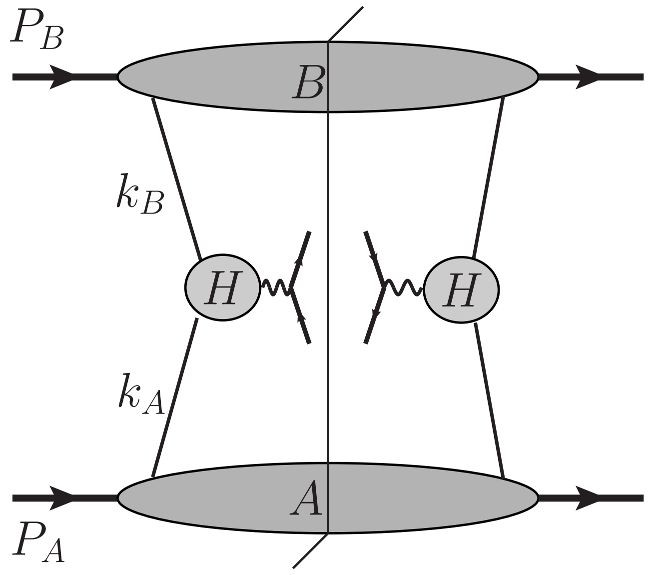
TMD FACTORIZATION

Cross-sections of Semi-Inclusive Deep Inelastic Scattering, Drell-Yan, e^+e^- annihilation into a pair of hadrons differential in transverse momentum can be written as

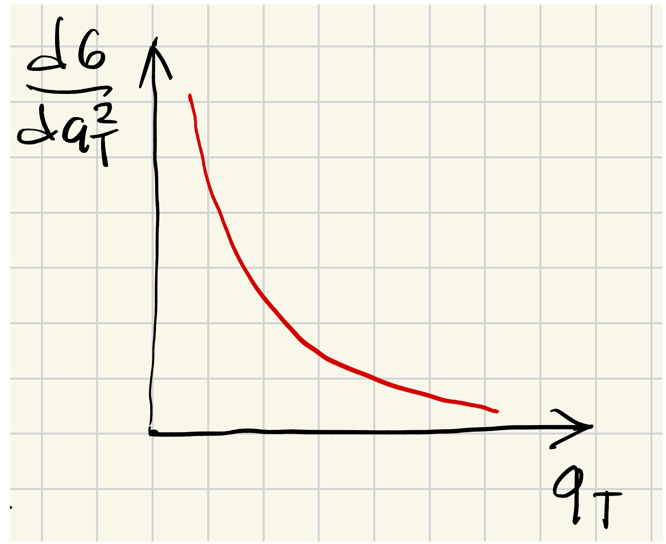
$$\frac{d\sigma}{dq_T} = \underbrace{W(q_T, Q)} + \underbrace{Y(q_T, Q)} + \underbrace{error}$$

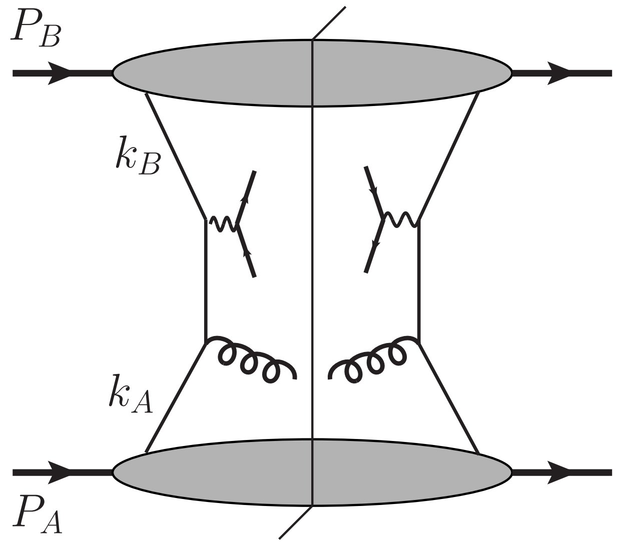
The term that is valid at $q_T \ll Q$ contains TMDs



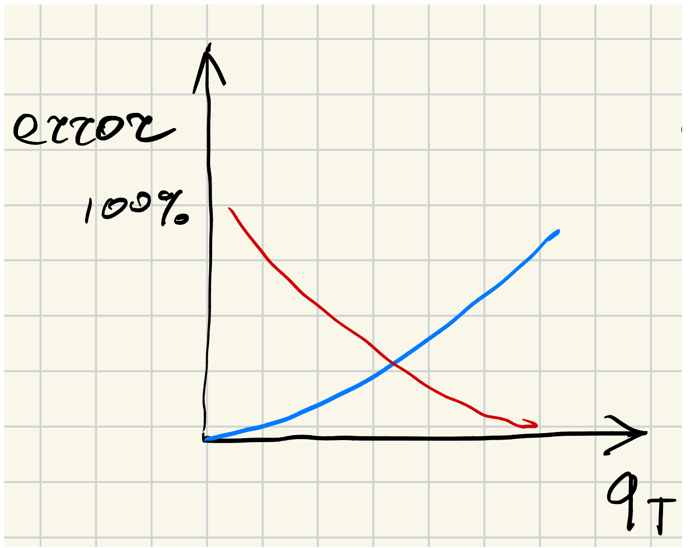


The term that is valid at $q_T \sim Q$ contains collinear PDFs





The error term



TRANSVERSE MOMENTUM DEPENDENT DISTRIBUTIONS

TMD Handbook, arxiv:2304.03302

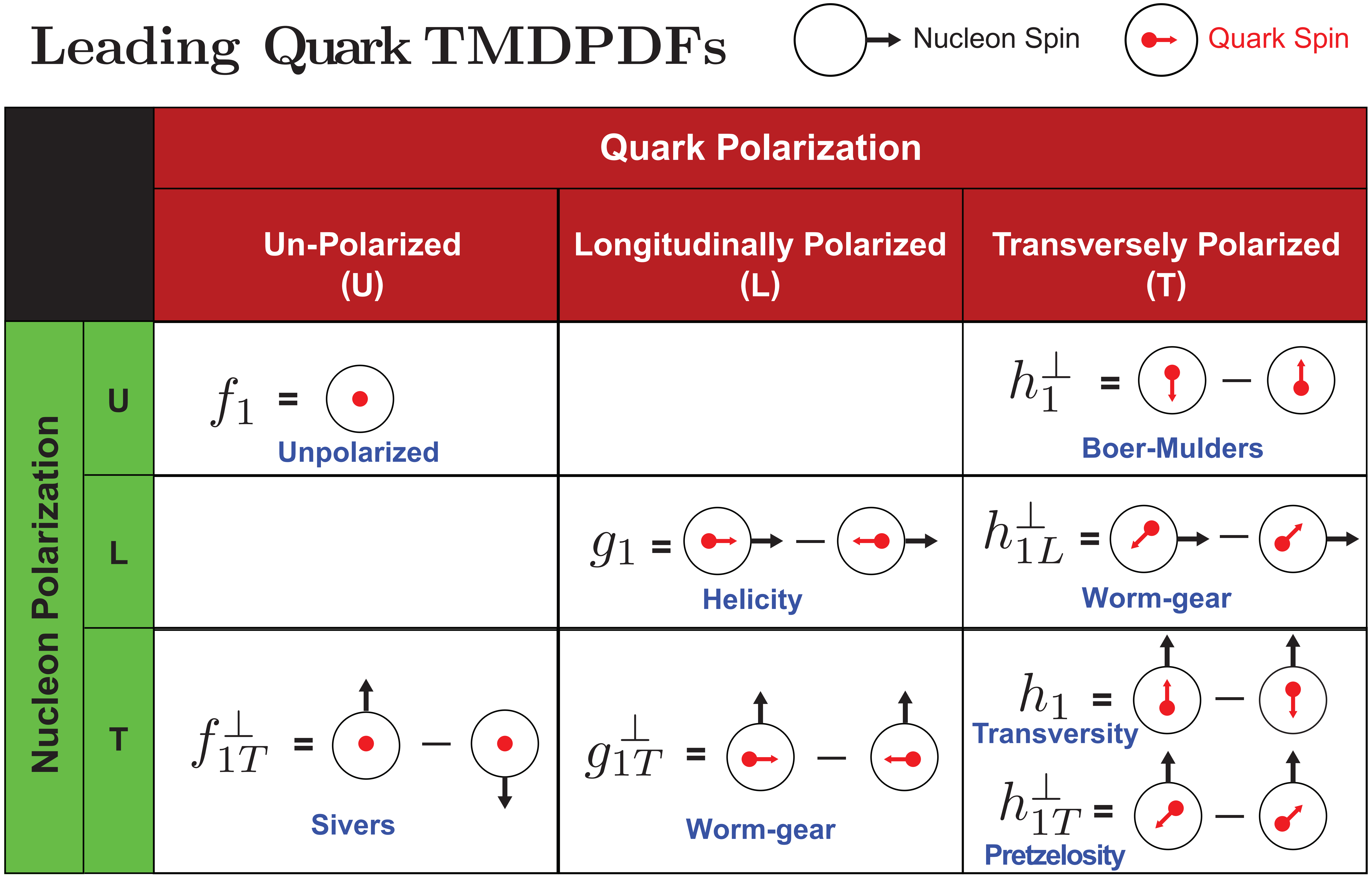


Figure 2.5: Leading power quark parton distribution functions for the proton or a spin-1/2 hadron.

TMD Handbook, arxiv:2304.03302

The quark TMDs are projections of a bilocal matrix element $\Phi^{[\Gamma]} \sim \langle PS \,|\, \bar{q}\Gamma q \,|\, PS \rangle$, where for twist-2 TMDs the basis is $\Gamma = \{\gamma^+, \gamma^+\gamma_5, i\sigma^{\alpha+}\gamma_5\}$

$$\tilde{f}_{i/p_S}^{[\gamma^+]}(x, \mathbf{b}_T, \mu, \zeta) = \tilde{f}_1(x, b_T) + i\epsilon_{\rho\sigma} b_T^{\rho} S_T^{\sigma} M \tilde{f}_{1T}^{\perp}(x, b_T)\,,$$

$$\tilde{f}_{i/p_S}^{[\gamma^+\gamma_5]}(x, \mathbf{b}_T, \mu, \zeta) = S_L \tilde{g}_1(x, b_T) + i b_T \cdot S_T M \tilde{g}_{1T}^{\perp}(x, b_T)\,,$$

$$\tilde{f}_{i/p_S}^{[i\sigma^{\alpha+}\gamma_5]}(x, \mathbf{b}_T, \mu, \zeta) = S_T^{\alpha} \tilde{h}_1(x, b_T) - i S_L b_T^{\alpha} M \tilde{h}_{1L}^{\perp}(x, b_T) + i\epsilon^{\alpha\rho} b_{\perp\rho} M \tilde{h}_1^{\perp}(x, b_T)$$

$$+ \frac{1}{2}\mathbf{b}_T^2 M^2 \left(\frac{1}{2} g_T^{\alpha\rho} + \frac{b_T^{\alpha} b_T^{\rho}}{\mathbf{b}_T^2} \right) S_{\perp\rho} \tilde{h}_{1T}^{\perp}(x, b_T)\,. \quad (2.126)$$

Similarly for fragmentation functions

TRANSVERSE MOMENTUM DEPENDENT DISTRIBUTIONS

TMD Handbook, arxiv:2304.03302

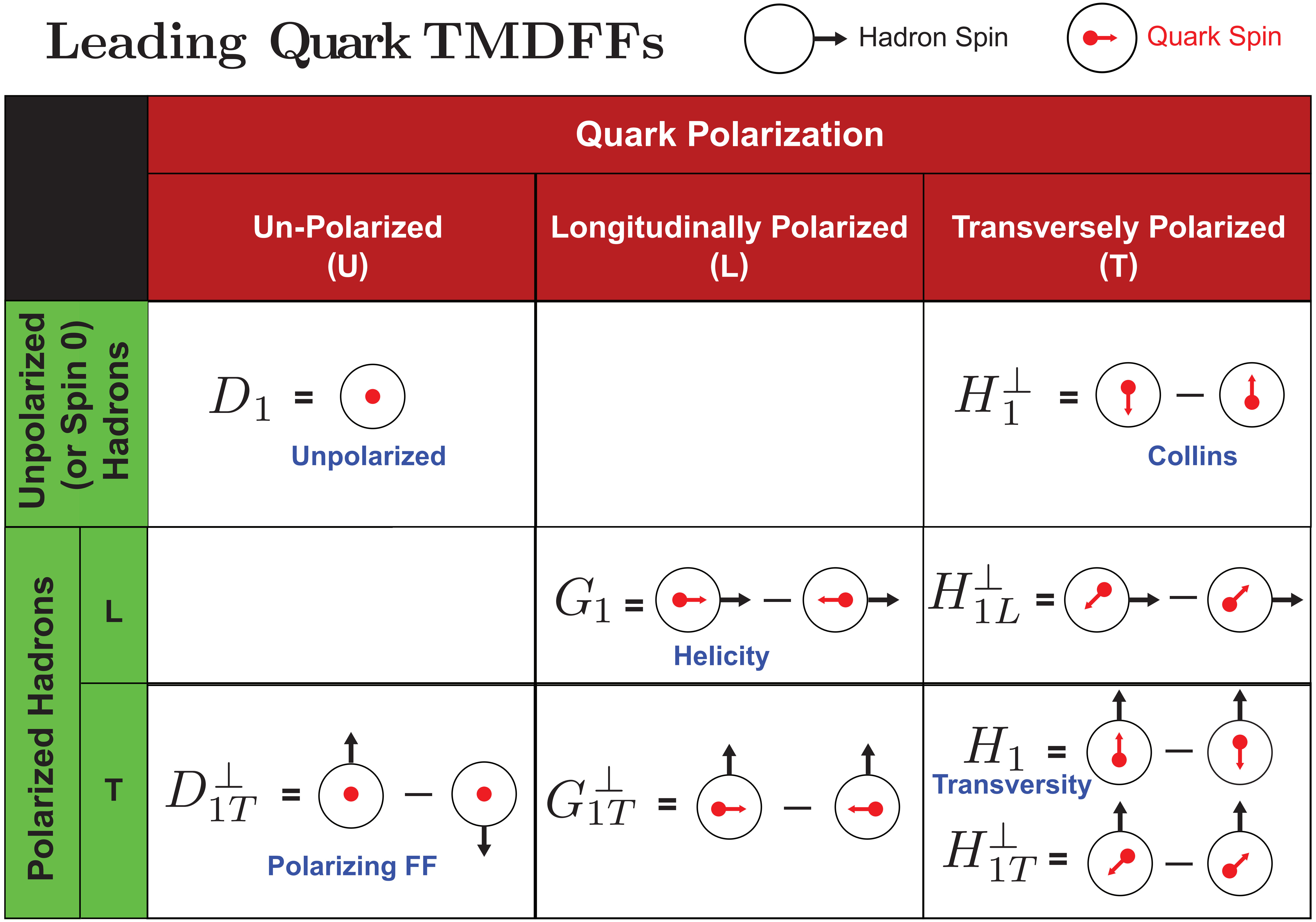


Figure 2.6: Leading power quark TMD fragmentation functions for a spin-1/2 (or for an unpolarized or spin 0) hadron.

The quark TMD FFs are projections of a bilocal matrix element, where for twist-2 TMDs the basis is $\Gamma = \{\gamma^+, \gamma^+\gamma_5, i\sigma^{\alpha+}\gamma_5\}$

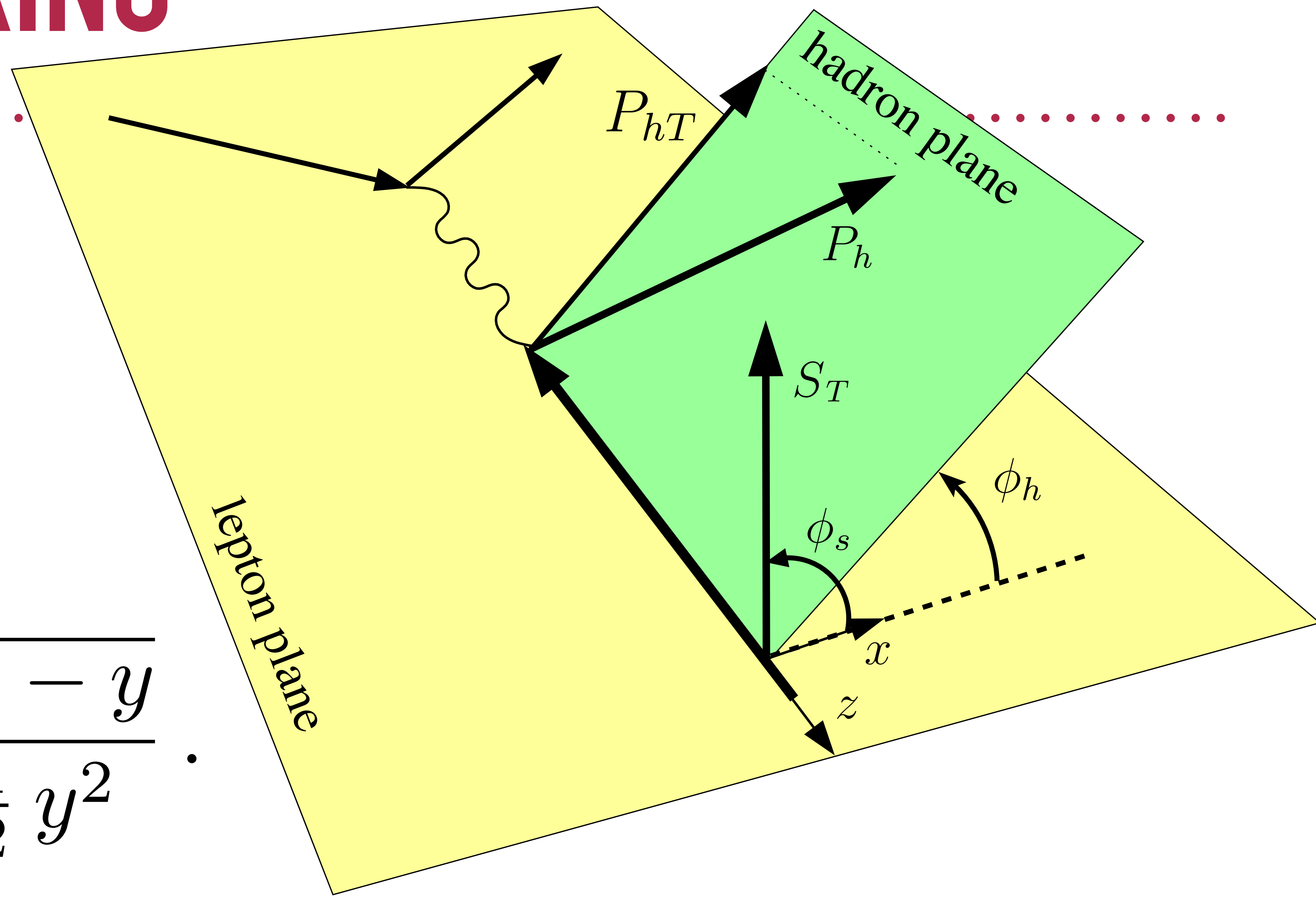
$$\tilde{\Delta}_{h/i}^{[\gamma^+]}(z, \mathbf{b}_T, \mu, \zeta) = \tilde{D}_1(z, b_T) - i\epsilon_{T\,\rho\sigma} b_T^\rho S_T^\sigma M_h \tilde{D}_{1T}^\perp(z, b_T)\,,$$

$$\tilde{\Delta}_{h/i}^{[\gamma^+\gamma_5]}(z, \mathbf{b}_T, \mu, \zeta) = S_L \tilde{G}_1(z, b_T) + i b_T \cdot S_T M_h \tilde{G}_{1T}^\perp(z, b_T)\,,$$

$$\tilde{\Delta}_{h/i}^{[i\sigma^{\alpha+}\gamma_5]}(z, \mathbf{b}_T, \mu, \zeta) = S_T^\alpha \tilde{H}_1(z, b_T) + i S_L b_T^\alpha M_h \tilde{H}_{1L}^\perp(z, b_T) - i\epsilon_T^{\alpha\rho} b_{\perp\rho} M_h \tilde{H}_1^\perp(z, b_T)$$

$$+ \frac{1}{2}\mathbf{b}_T^2 M_h^2 \left(\frac{1}{2} g_T^{\alpha\rho} + \frac{b_T^\alpha b_T^\rho}{\mathbf{b}_T^2}\right) S_{\perp\,\rho} \tilde{H}_{1T}^\perp(z, b_T)\,. \qquad (2.135)$$

UNPOLARIZED SEMI-INCLUSIVE DEEP INELASTIC SCATTERING



The relevant kinematic variables expressed via Lorentz invariants are:

$$x = \frac{Q^2}{2\,P\cdot q}, \quad y = \frac{P\cdot q}{P\cdot l}, \quad z_h = \frac{P\cdot P_h}{P\cdot q}.$$

We will explore unpolarized structure functions:

$$\sigma_0 = \frac{2\pi\alpha_{\rm em}^2}{x\,y\,Q^2}\left(1-y+\frac{1}{2}y^2\right) \quad p_1 = \frac{1-y}{1-y+\frac{1}{2}\,y^2}, \quad p_3 = \frac{(2-y)\sqrt{1-y}}{1-y+\frac{1}{2}\,y^2}.$$

$$\frac{d\sigma}{dx\,dy\,dz_h\,d\phi_h\,dP_{h\perp}^2} = \sigma_0\left[F_{UU,T} + p_1 F_{UU,L} + \cos(\phi_h)\,p_3\,F_{UU}^{\cos\phi_h} + \cos(2\phi_h)\,p_1\,F_{UU}^{\cos 2\phi_h}\right]$$

$F_{UU,T}$ and $F_{UU}^{\cos 2\phi_h}$ are leading power, $F_{UU}^{\cos\phi_h}$ is next-to-leading power $\sim \mathcal{O}(\Lambda/Q)$, and $F_{UU,L}$ is next-to-next-to-leading power $\sim \mathcal{O}(\Lambda^2/Q^2)$

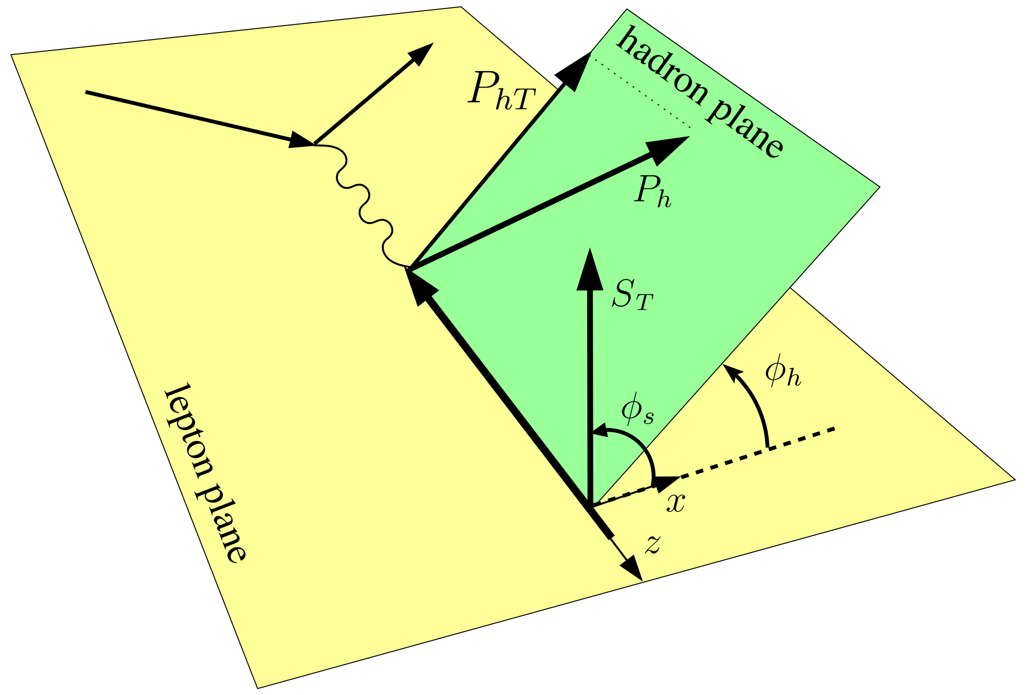
A. Bacchetta et al, JHEP 02 (2007) 093
TMD Handbook, arxiv:2304.03302
S. Piloneta, A. Vladimirov e-Print: 2510.14496
L. Gamberg, Z. Kang, D. Shao, J. Terry, F. Zhao arxiv:2211.13209
M.A. Ebert, A. Gao and I.W. Stewart, JHEP 06 (2022) 007
S. Piloneta, A. Vladimirov JHEP 03 (2026) 049 arxiv: 2510.14496
Ian Balitsky, Alexei Prokudin JHEP 05 (2026) 265 arxiv:2601.18882

✓Leading structures are relatively well understood

✓Subleading structures are not easy to separate experimentally from leading ones

✓Leading power structure functions may receive power suppressed contributions

SEMI-INCLUSIVE DEEP INELASTIC SCATTERING AT LEADING POWER



$\ell(l) + p(P) \to \ell(l') + h(P_h) + X$

Each structure function is a convolution

$$\mathcal{C}\left[\omega\, f\, D\right] = x \sum_a H_{aa}(Q^2, \mu^2) \int \mathrm{d}^2\boldsymbol{k}_\perp\, \mathrm{d}^2\boldsymbol{p}_\perp\, \delta^{(2)}(z_h \boldsymbol{k}_\perp + \boldsymbol{p}_\perp - \boldsymbol{P}_{h\perp})\omega\, f^a(x, \boldsymbol{k}_\perp^2)\, D^a(z_h, \boldsymbol{p}_\perp^2)$$

The unpolarized structure function at leading power is:

$$F_{UU,T}^{\mathrm{LP}} = \mathcal{C}\left[f_1 D_1\right]$$

✓Information on unpolarized TMD PDF and FF

✓Their widths, flavor dependence, etc

The $\cos 2\phi_h$ modulation at leading power is:

$$F_{UU}^{\cos 2\phi_h} = \mathcal{C}\left[\frac{2(\hat{\boldsymbol{h}} \cdot \boldsymbol{k}_\perp)(\hat{\boldsymbol{h}} \cdot \boldsymbol{p}_\perp) - (\boldsymbol{k}_\perp \cdot \boldsymbol{p}_\perp)}{z_h M m_h} \kappa h_1^\perp H_1^\perp\right]$$

✓Boer-Mulders TMD, Collins FF

✓How transversely polarized quarks fragment

✓Info on transversely polarized quarks

The $\cos \phi_h$ modulation at NLP is:

$$F_{UU}^{\cos \phi_h} = \mathcal{C}\left[-\frac{2(\hat{\boldsymbol{h}} \cdot \boldsymbol{k}_\perp)}{Q} f_1 D_1\right] + \mathcal{C}\left[-\frac{2\boldsymbol{k}_\perp^2}{z_h M m_h Q}(\hat{\boldsymbol{h}} \cdot \boldsymbol{p}_\perp)\kappa h_1^\perp H_1^\perp\right]$$

✓Large “Cahn” modulation

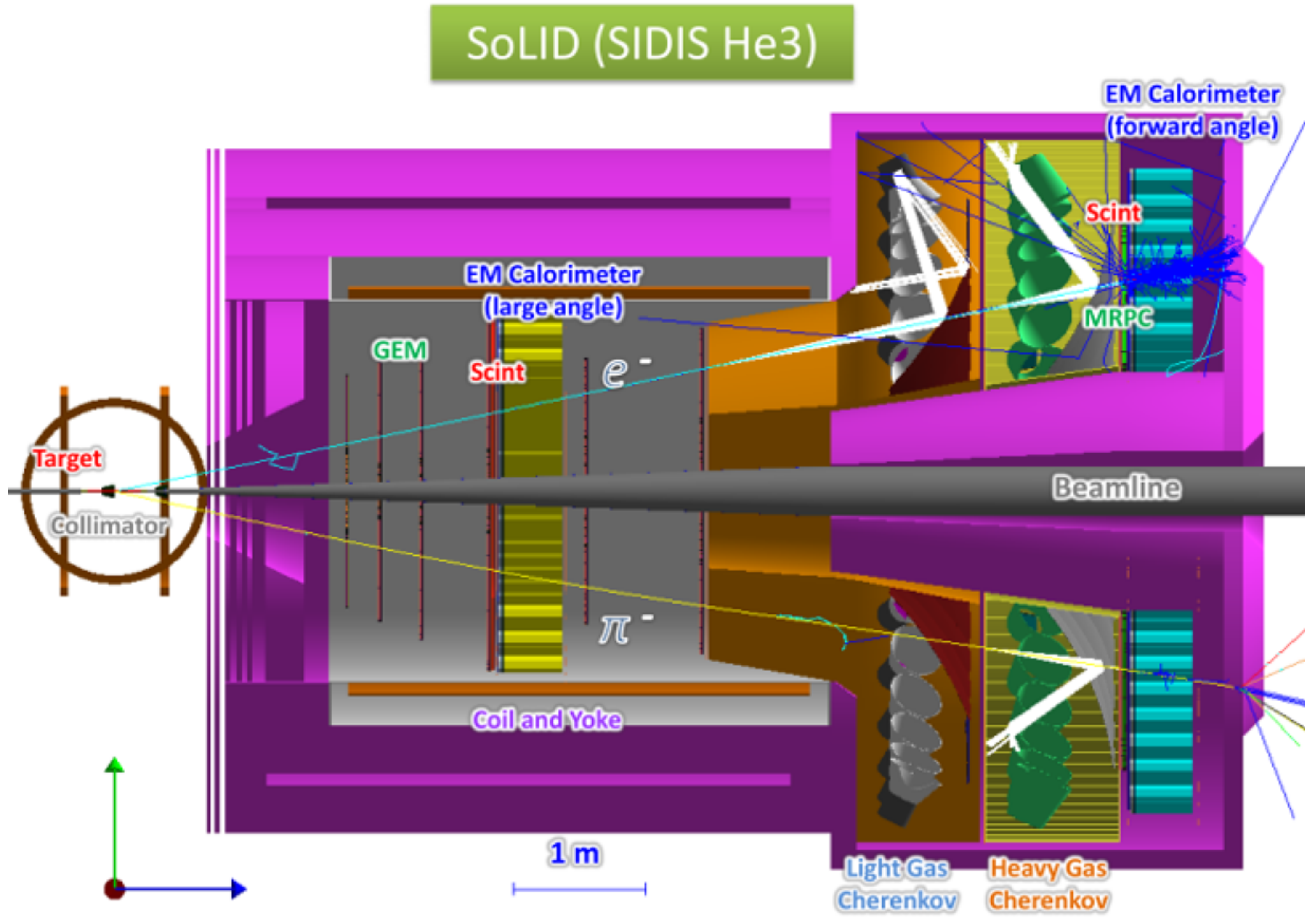
✓Intrinsic motion effect

✓Access to subleading TMDs

SoLID IMPACT STUDY

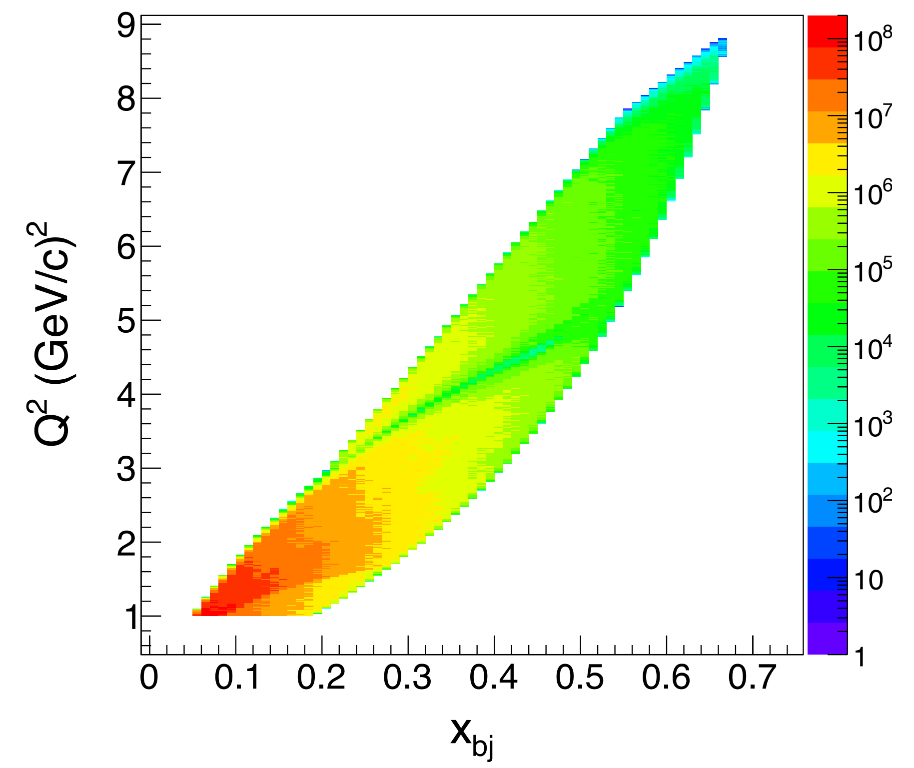
SoLID

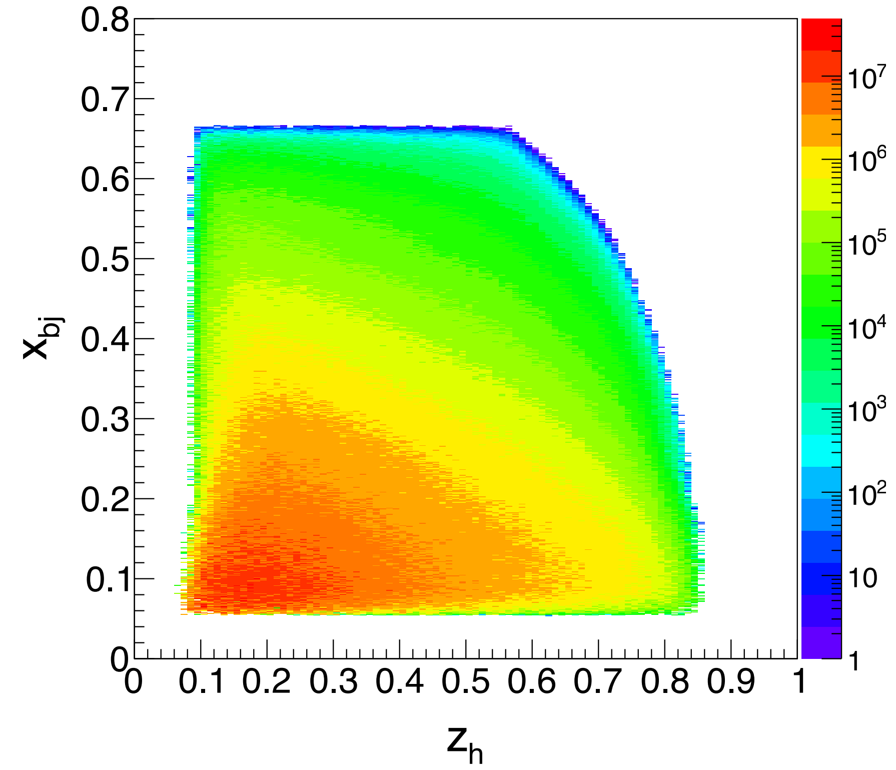
SOLENOIDAL LARGE INTENSITY DEVICE



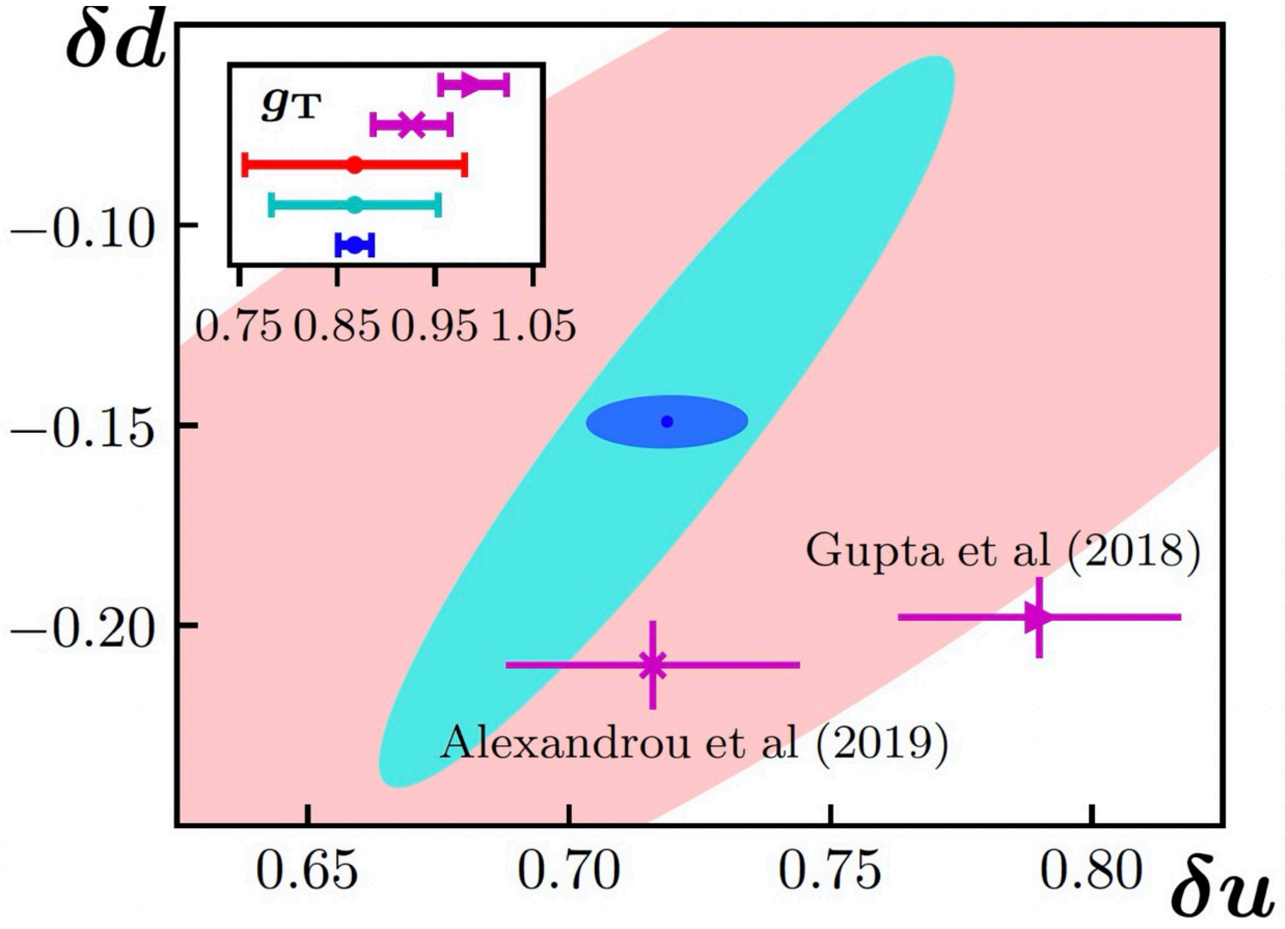
The Solenoidal Large Intensity Device (SoLID) is a new experimental apparatus planned for Hall A. Approved SIDIS experiments

- ☑ E12-11-007: Single and Double Spin Asymmetries on Longitudinally Polarized ^{3}He (neutron)
- ☑ E12-10-006: Single Spin Asymmetries on Transversely Polarized ^{3}He (neutron)
- ☑ E12-11-108: Single Spin Asymmetries on Transversely Polarized NH3 (proton)





Importance of ^{3}He target was demonstrated in many impact studies:



JAM20
JAM20 + EIC(ep)
JAM20 + EIC($ep+e^3He$)

"The ^{3}He data is especially crucial for a precise determination of the down quark transversity TMD PDF and for up and down flavor separation"

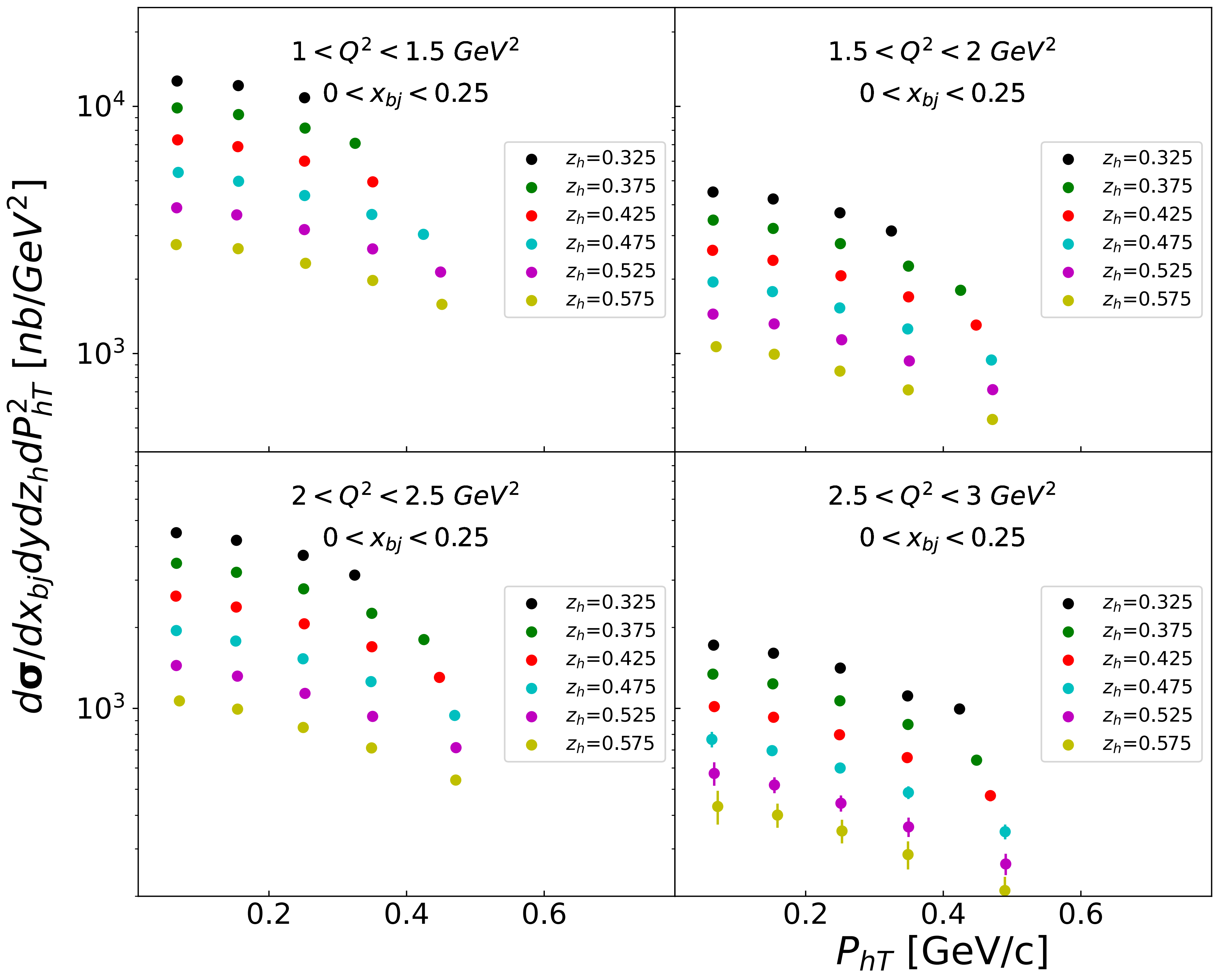
L. Gamberg et al Phys.Lett.B 816 (2021) 136255

Abdul Khalek etl al Nucl.Phys.A 1026 (2022) 122447

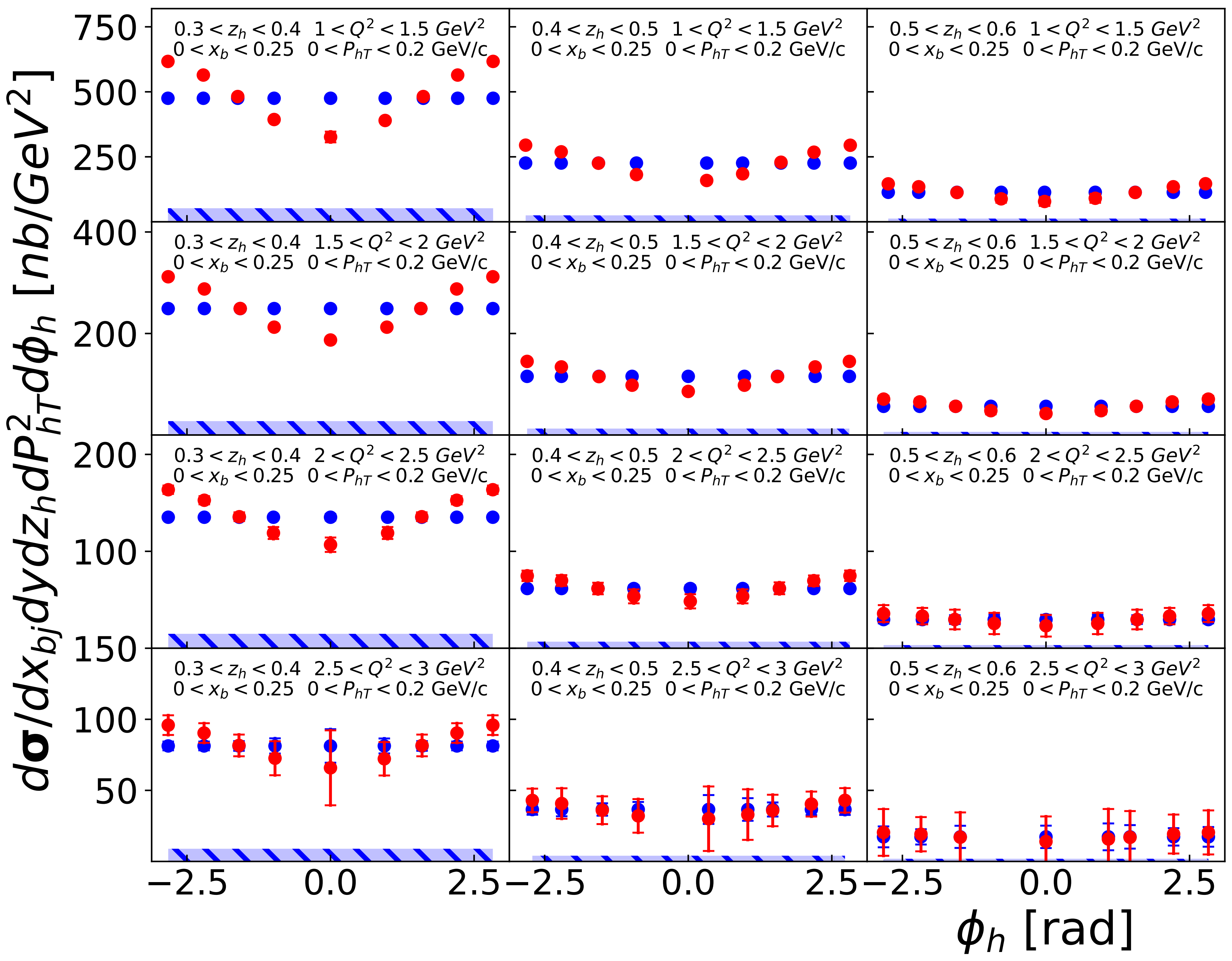
IMPACT STUDY

M.Cerutti et al, arXiv: 2512.20897

The pseudo-data was generated using MAP24TMD framework for unpolarized cross-sections and by a parton model framework that contains azimuthal modulations. The systematic errors were taken from the SoLID proposal, $\lesssim 11\ \%$, for pions



Unpolarized cross section for π^+ production at beam energy 11 GeV as a function of P_{hT} in a specific x_{bj} and Q^2 kinematic bins, and at $z_h \in [0.3,0.7]$.



Unpolarized cross section for π^+ production at beam energy of 11 GeV as a function of ϕ_h in a specific x_{bj}, Q^2, z_h bin with (red points) and without (red points) azimuthal modulation.

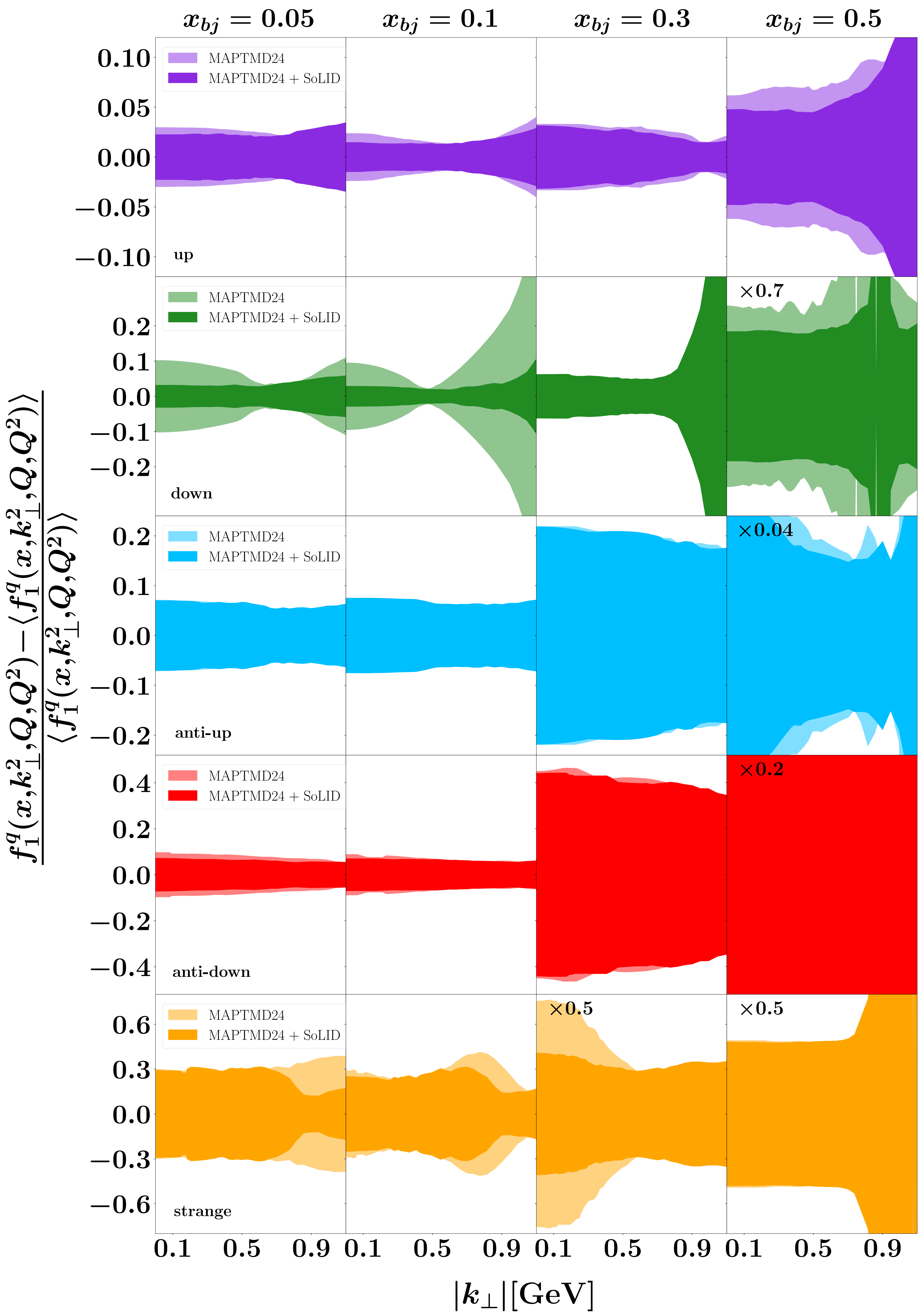
MAP24: A. Bacchetta et al., JHEP 08, 232 (2024)

S. Bastami et al JHEP 06 (2019) 007
https://github.com/TianboLiu/LiuSIDIS

IMPACT STUDY

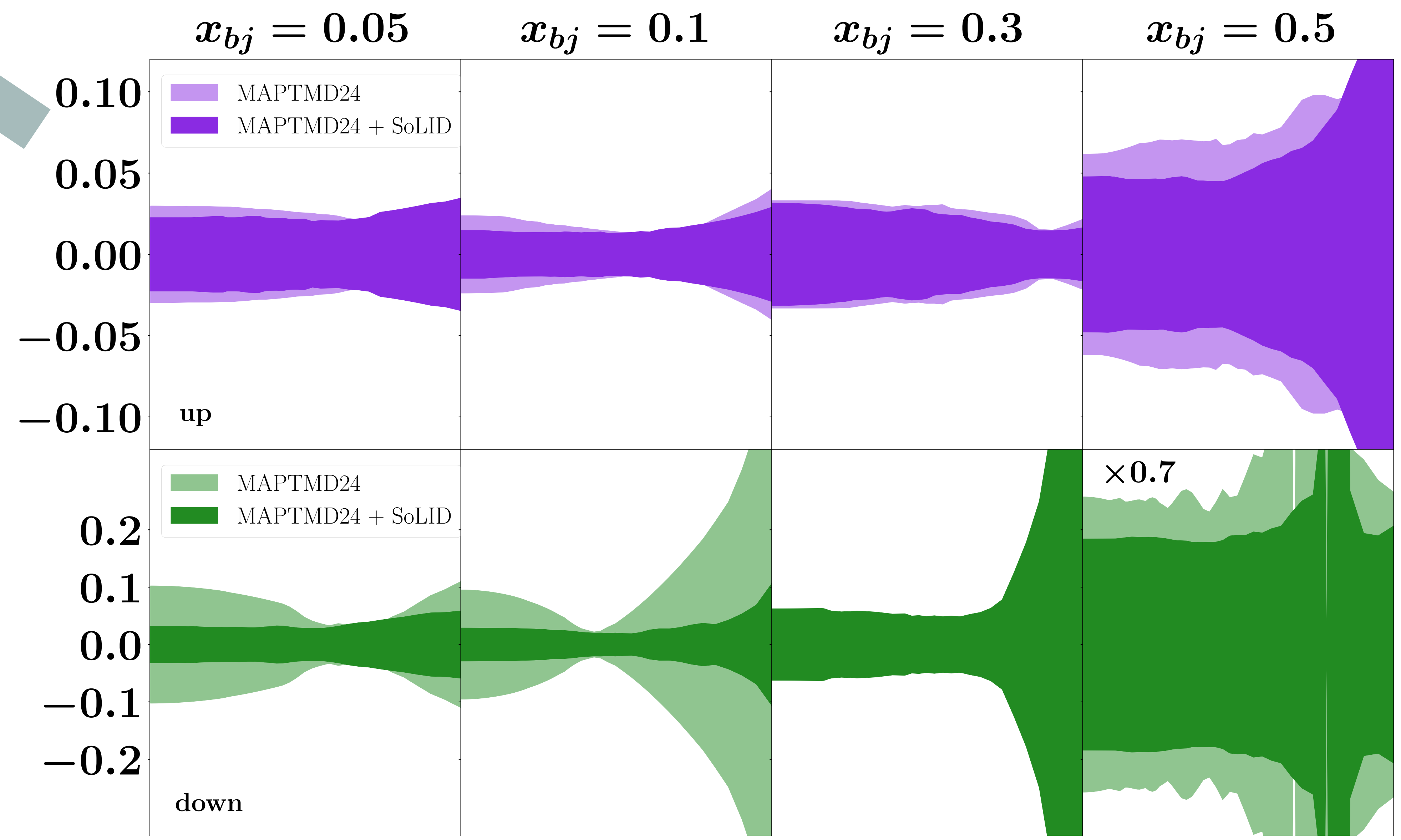
M.Cerutti et al, arXiv: 2512.20897

A new analysis MAP24+SoLID was performed to estimate the impact of the pseudo data.



Results for the TMD PDFs as function of $k_\perp$ at $Q^2 = 2\ \mathrm{GeV}^2$ for various values of x. Lighter shade color is for previous knowledge, solid bands indicate the impact of SoLID.

As expected the major impact is for down and up quarks across all values of x.



IMPACT STUDY

M.Cerutti et al, arXiv: 2512.20897

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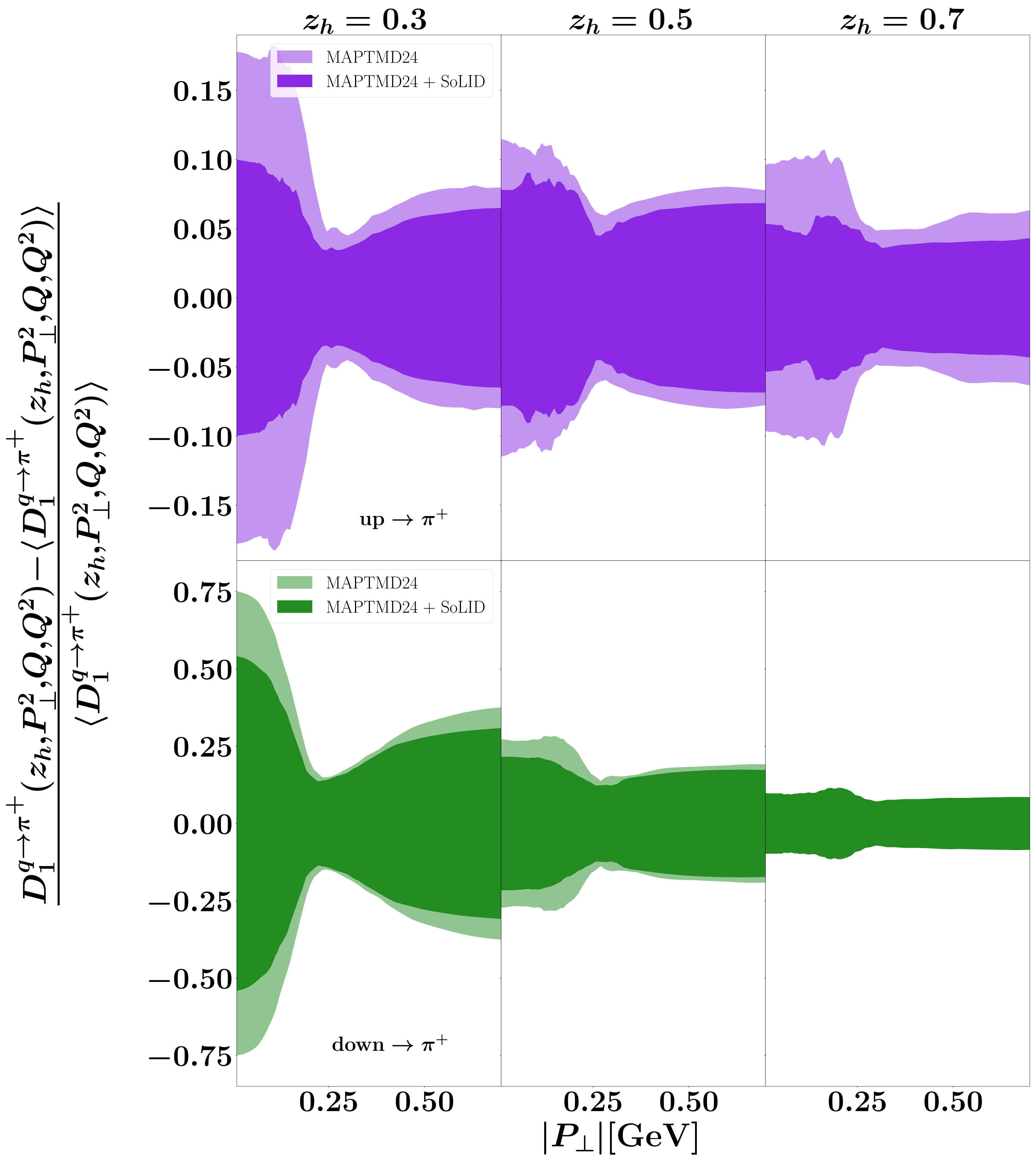
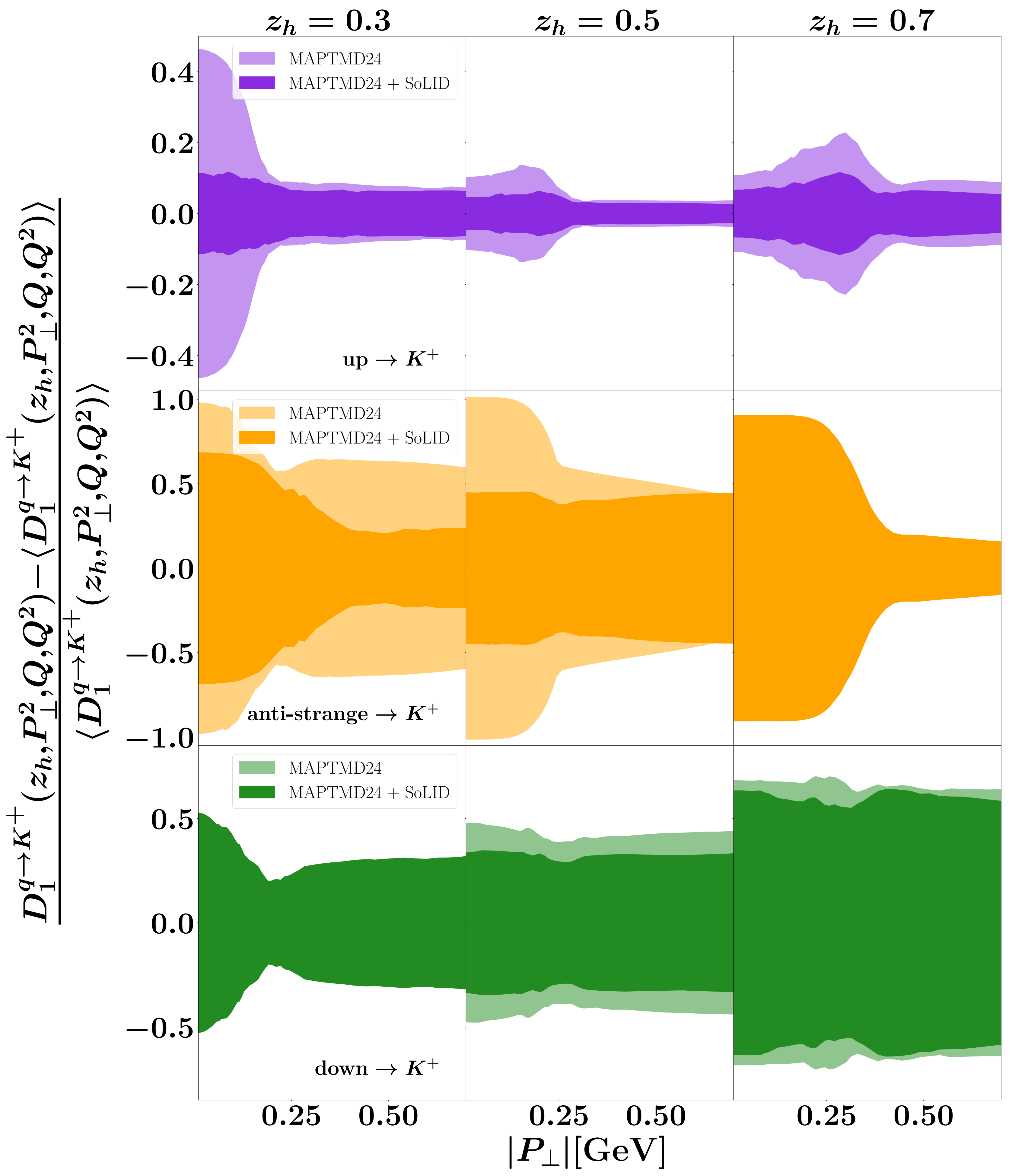


Results for the TMD FFs for π^+. Lighter shade color is for previous knowledge, solid bands indicate the impact of SoLID

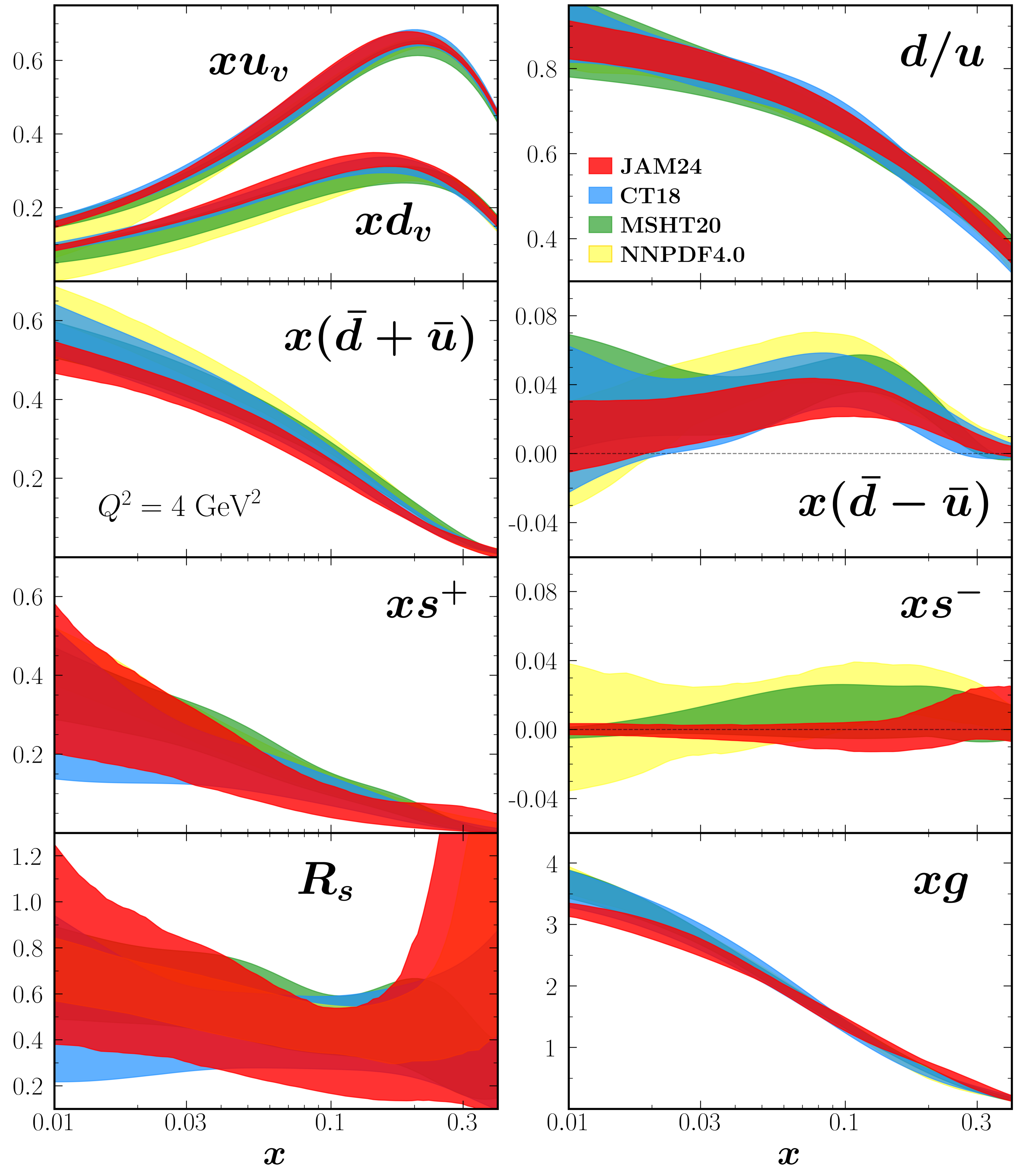


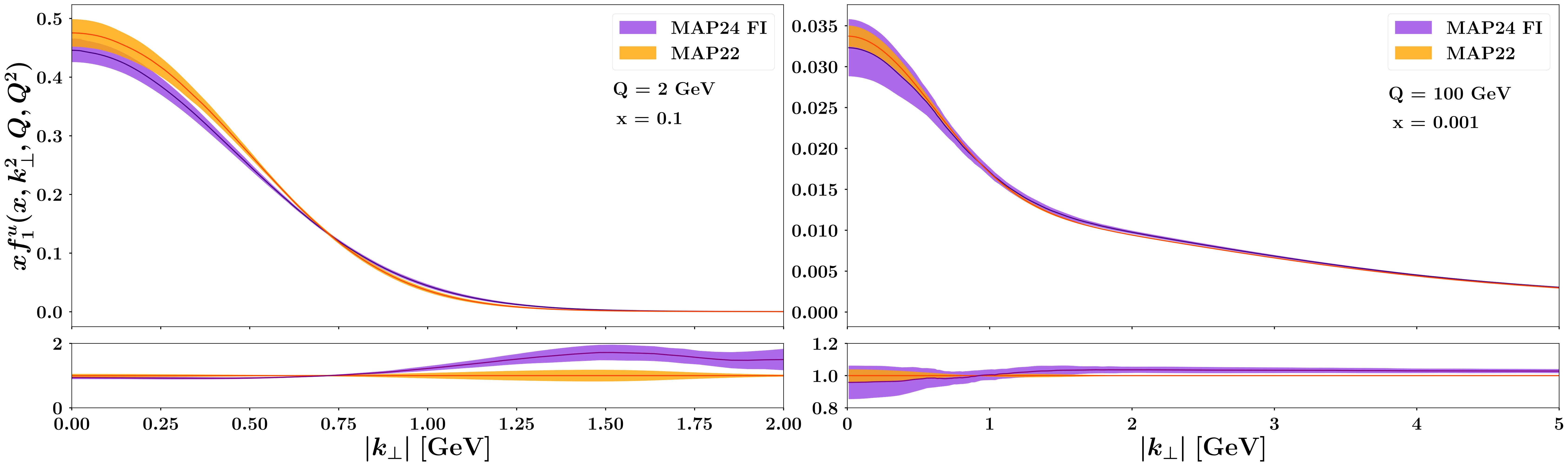
Results for the TMD FFs for K^+. Lighter shade color is for previous knowledge, solid bands indicate the impact of SoLID

IMPACT STUDY

Collinear distributions have flavor dependence. What about flavor dependence of TMDs?

MAP24: A. Bacchetta et al., JHEP 08, 232 (2024)





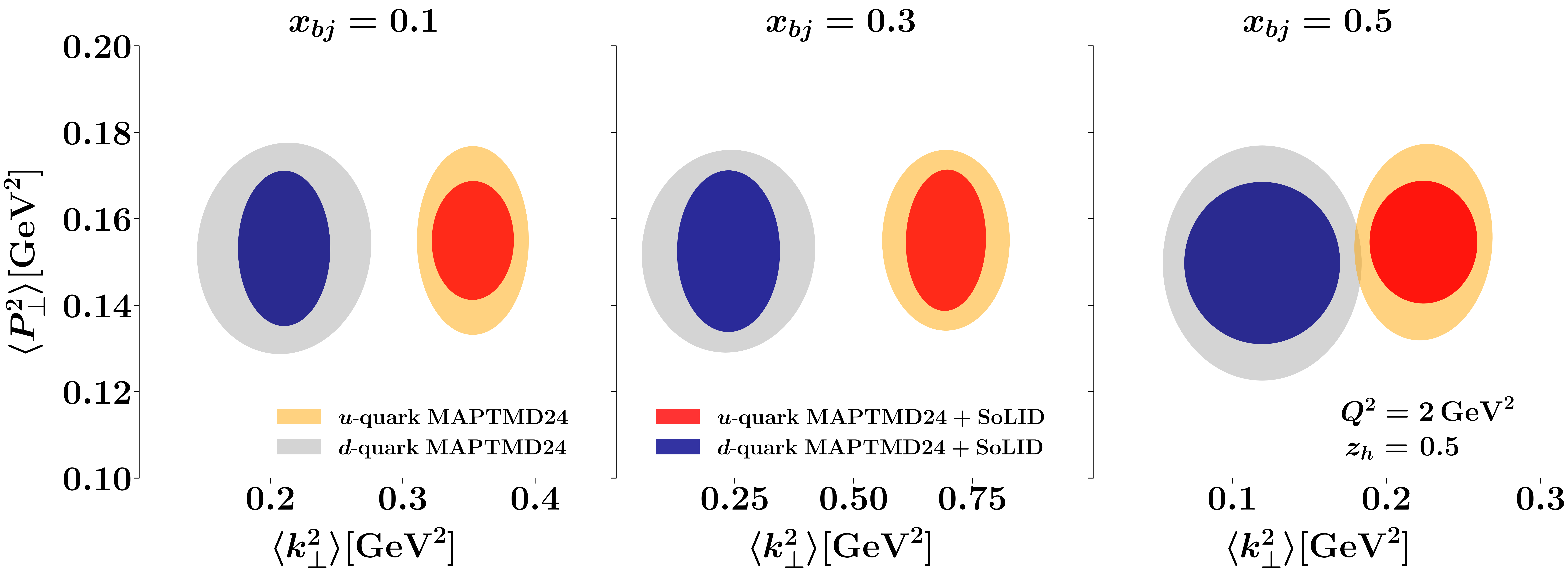
There are some hints on flavor dependence of TMDs. Purple is flavor independent analysis and orange is flavor dependent analysis MAP24.

Can SoLID data tell us more about it?

JAM Collaboration, T. Anderson Phys.Rev.D 112 (2025) 9, 094011

IMPACT STUDY

M.Cerutti et al, arXiv: 2512.20897



Impact of SoLID data on flavor separation of TMD PDFs (horizontal axis) and TMD FFs (vertical axis).

CONCLUSIONS

- SIDIS measurements at Jefferson Lab are promising to be impactful for the studies of the three-dimensional structure of the nucleon
- Combination of various polarizations and targets together with good PID is essential for such a program
- ^{3}He target SIDIS measurements at SoLID are going to be important for valence quark distribution and fragmentation functions studies, in particular for down quarks