

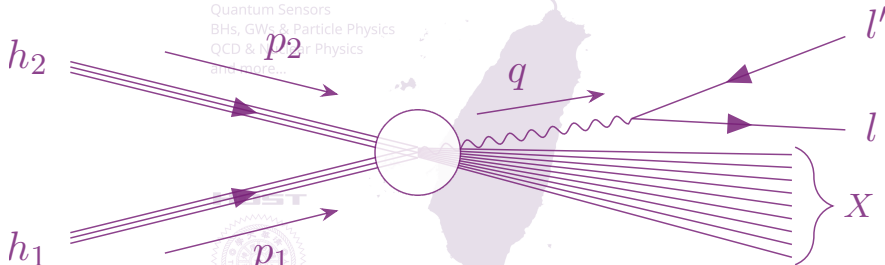
Phenomenology of transverse momentum dependent parton distribution functions in baryons and mesons

June 15-18, 2026, NTHU, Hsinchu, Taiwan



國立陽明交通大學
NATIONAL YANG MING CHIAO TUNG UNIVERSITY

High Energy Astroparticle Physics
Neutrino Physics
Quantum Sensors
BHs, GWs & Particle Physics
QCD & Nuclear Physics
and more...



Valentin Moos

The 16th Particle Physics Phenomenology Workshop, NTHU, Hsinchu, June 2026



SPONSORS
NCTS
TG2.1 & TG2.4

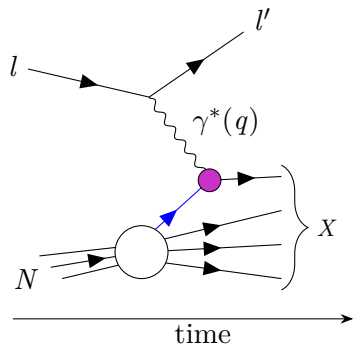


國立陽明交通大學
Office of Research and Development, NTHU

Process I: DIS (Deeply inelastic scattering)

DIS: Probe nucleon initial state

$$l(k) + N(P) \longrightarrow l'(k') + X$$



Kinematics in DIS

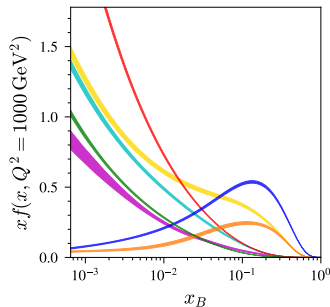
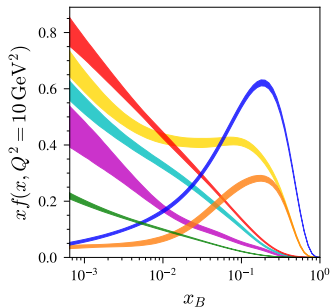
$$Q^2 = -q^2$$
$$x_B = \frac{Q^2}{2P \cdot q}$$

$$\frac{d\sigma^{\text{DIS}}}{dQ} = \int_0^1 dx f_f(x, \mu) \sigma^{\text{part}}(x, Q, \mu)$$

Process I: DIS (Deeply inelastic scattering)

DIS: Probe nucleon initial state

The picture we get:



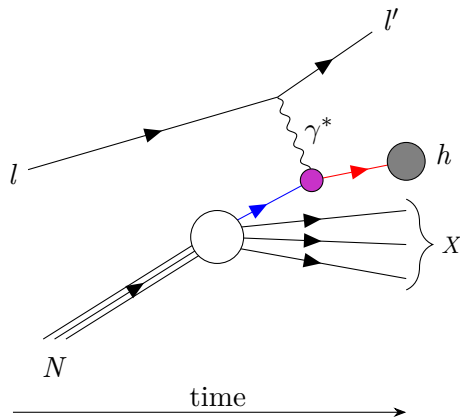
$g/10$
 $u_V \bar{u}$
 $d_V d$
 $s/2 c$

MSHT20
[2012.04684]

Process II (Ib): SIDIS

SIDIS: Probe nucleon **initial state** AND **hadronisation** of struck quark

$$l(k) + N(P) \longrightarrow l'(k') + h(p_h) + X$$



$$Q^2 = -q^2$$

$$x_B = \frac{Q^2}{2P \cdot q}$$

$$z = \frac{P \cdot p_h}{P \cdot q}$$

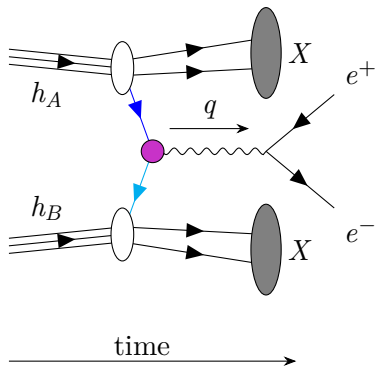
$$q_T = p_h \perp \langle P, q \rangle$$

$$\sigma^{\text{SIDIS}} \sim f_f \otimes D_f \otimes \sigma^{\text{part.}}$$

Process III: Drell-Yan

DY: Probe double nucleon initial state

$$h_1(p_1) + h_2(p_2) \longrightarrow l(k) + \bar{l}(k') + X$$



$$Q^2 = q^2$$

$$x_{1,2} = \frac{q^\pm}{p_{1,2}^\pm}$$

$$y = \frac{1}{2} \ln \left(\frac{x_1}{x_2} \right)$$

$$q_T = q \perp \langle p_1, p_2 \rangle$$

$$\sigma^{\text{DY}} \sim f_f \otimes f_f \otimes \sigma^{\text{part.}}$$

DY cross section in LP TMD factorisation

Explicit

(neglecting Z boson contributions)

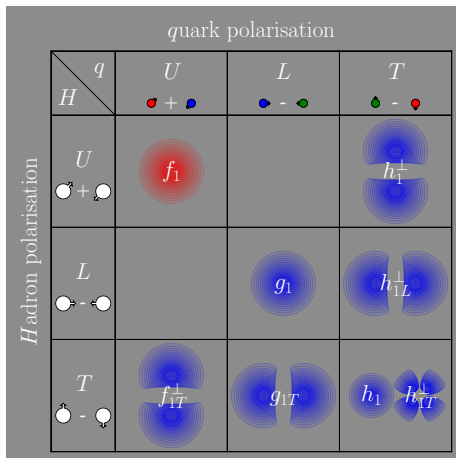
$$\frac{d\sigma}{dQ^2 dy d^2\mathbf{q}_T} = \frac{2\pi\alpha_{\text{em}}^2(Q)}{3N_c s Q^2} \left(1 + \frac{q_T^2}{2Q^2}\right) \sum_f C_{\text{DY}}(Q) \\ \times \int_0^\infty db b J_0(\mathbf{b}\mathbf{q}_T) \left(\frac{Q^2}{\zeta_Q(b)}\right)^{-2\mathcal{D}(b,Q)} f_{1,f}(x_1, b) f_{1,\bar{f}}(x_2, b)$$

Schematic:

$$\sigma(\mathbf{q}_T) = H_{\text{pert.}} \otimes \left(F_1^{\text{NP}} \cdot F_2^{\text{NP}}\right)(b)$$

Scale dependence of TMDs via the **CS kernel**.

8 TMD distributions



Parameterised forms of TMDs include 8 functions.

Polarisation of quark
 \sim **internal** spinor operator (Γ)

Polarisation of hadron
 \sim **external** state of nucleon

The same panel exists for the final state distributions (FFs)

How we "construct" the TMDPDFs:

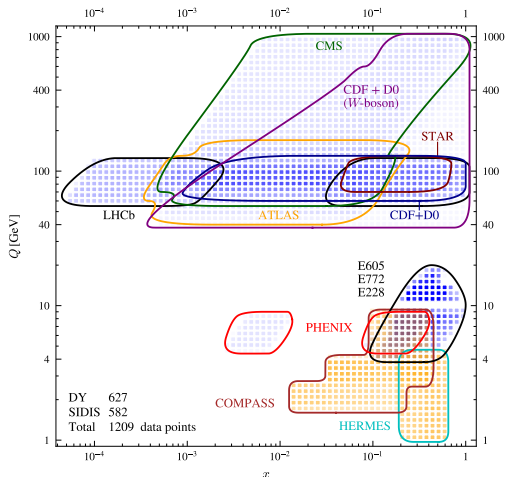
$$f_{1,f}(x, b) = \left(\sum_{f'} C_{f \rightarrow f'} \otimes q_{f'} \right) (x, b) \cdot f_{\text{NP}}^f(x, b)$$

- ▶ TMDPDF \sim *perturbative* if the transverse distance b is small
- ▶ *perturbative* part is expansion and convolution with PDFs
- ▶ Fit easier AND relation TMDs \leftrightarrow PDFs satisfied by construction
- ▶

$$\int dk_T \text{TMD}(x, k_T) \neq \text{PDF}(x) \quad !$$

- ▶ total TMDPDF is product of *perturbative* expression
and NP parametrisation

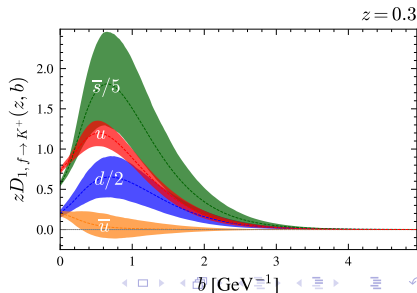
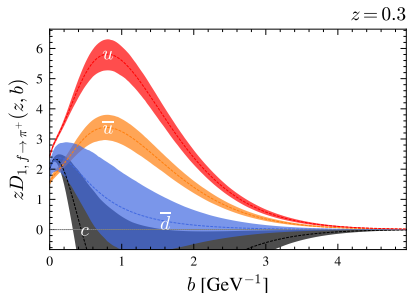
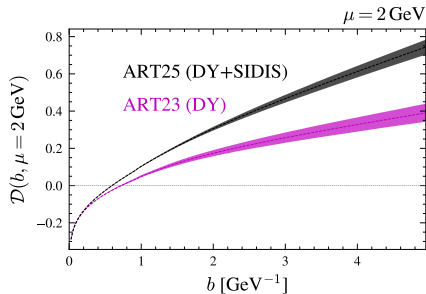
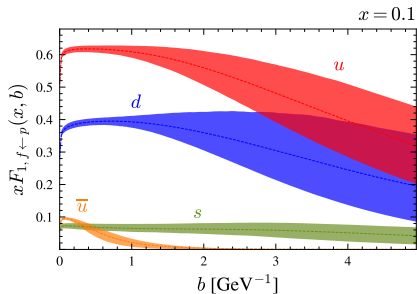
Kinematic range of included data, datasets



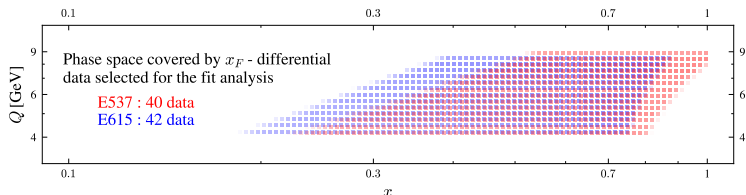
Features:

- ▶ large range of resolution scale: 1 GeV \rightarrow 1 TeV
- ▶ W production in DY
- ▶ SIDIS (flavour sensitive!) and DY data
- ▶ $\frac{q_T}{Q} < 0.25$ (TMD region!)

Extracted functions: CS-kernel and TMDPDFs & -FFs



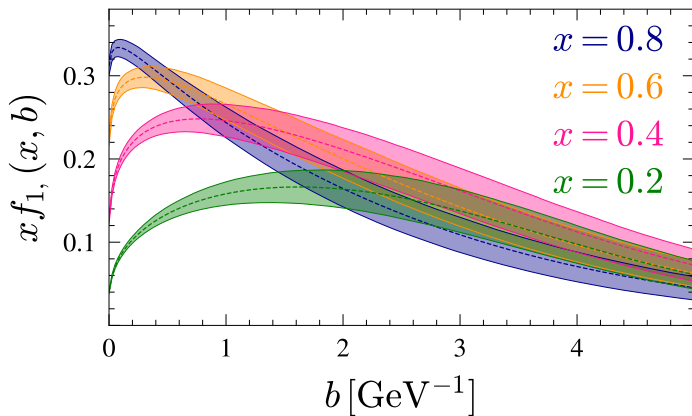
Pion DY data :



In comparison to the nucleon data:

- ▶ small range of resolution scale: 4 GeV \rightarrow 8 GeV
- ▶ small range of momentum fraction $0.18 < x_\pi < 1.0$
- ▶ $\pi^- + p/n$ dominated by **valence quark** channel $\bar{u} + u$
- ▶ **LARGE** normalisation uncertainty

Extracted function: pion TMDPDFs



Recent TMDPDF analysis can rely on

- ▶ global analyses from Drell-Yan and SIDIS data
- ▶ N⁴LO perturbative accuracy hard scattering / evolution
- ▶ flavour dependence in ansatzes
- ▶ explore the full panel of the leading twist distributions (Sivers, helicity, transversity)
- ▶ simultaneous analysis of PDFs and TMDs (reduce correlation bias)

Extracted function: going to k_T space

We want to understand the transverse momentum distribution ...

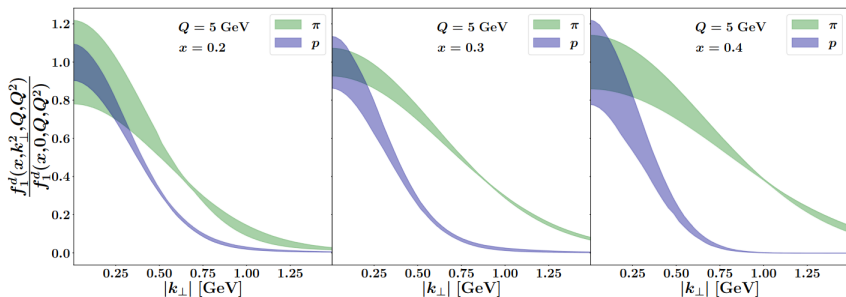
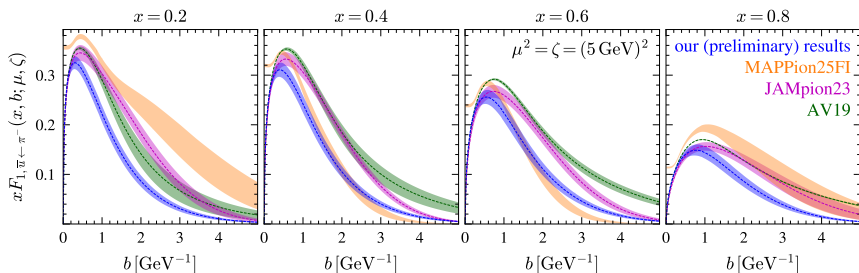


figure from [\[2509.25098\]](#)

... but its a long way to go, because data are only sensitive to the small components of the Fourier conjugate (b)

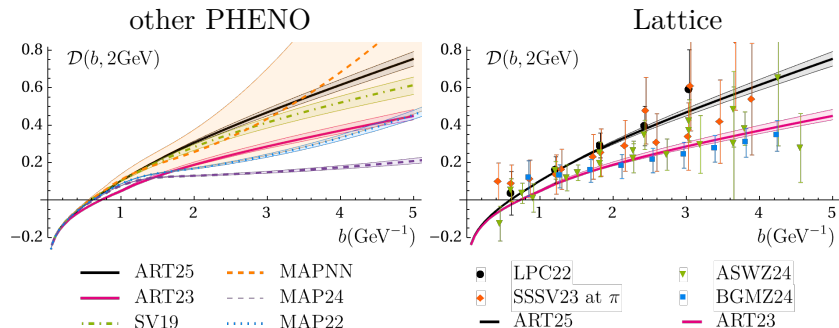
Extracted function: pion TMDPDFs compared with other studies



In the case of pion distributions, precise data are difficult to measure as the pion is not stable like the proton is.

$$d\sigma \sim \int_0^\infty db b J_0(\mathbf{bq}_T) \left(\frac{Q^2}{\zeta_Q(b)} \right)^{-2\mathcal{D}(b,Q)} f_{1,f}(x_1, b) f_{1,\bar{f}}(x_2, b)$$

Hankel transformation sensitive mostly to the small- b domain
 → uncontrolled extrapolation (model) into the large b regime.



We...

- ▶ can access hadronic structure through factorisation of high-energy processes
- ▶ already know a lot about collinear (1d) distributions
- ▶ can determine the distributions at small and intermediate transverse distance from data and perturbation theory
- ▶ know something, but much less about nucleon TMDPDFs at large transverse distance (non-perturbative regime) for the nucleon
- ▶ very little about meson distributions - simply because there is hardly any data

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- ▶ very little about meson distributions - simply because there is hardly any data
- ▶ explore this sector.