Probing TMDs through double quarkonium production in hadronic collisions *

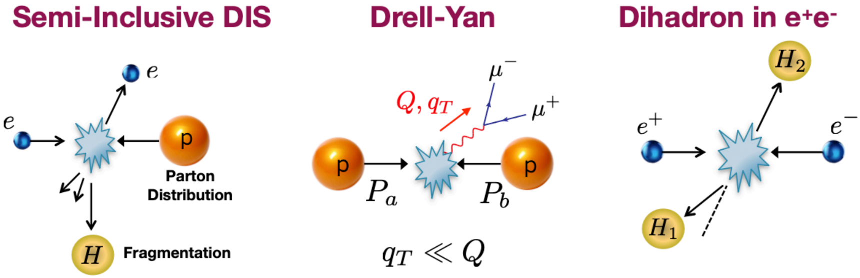
Cristian Pisano

University and INFN Cagliari

*Mainly based on arXiv:2508:15482 [hep-ph], in collaboration with Carlo Flore

Quark TMDs

Two scale processes $Q^2 \gg q_T^2$



Factorization proven

All orders in α_s
Leading order in powers of $1/Q$ (twist)

Collins, Cambridge University Press (2011)
Boussarie et al, TMD handbook 2304.03302

QUARKS	*unpolarized*	*chiral*	*transverse*
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_{1T}, $h_{1T}^\perp$

Angeles-Martinez *et al.*, Acta Phys, Pol. B46 (2015)
Mulders, Tangerman, NPB 461 (1996)
Boer, Mulders, PRD 57 (1998)

- $h_1^{\perp\, q}$: T-odd distribution of transversely polarized quarks inside an unp. hadron
- $f_{1T}^{\perp\, g}$: T-odd distributions of unp. gluons inside a transversely pol. hadron
- h_{1T}^q, $h_{1T}^{\perp\, q}$: helicity flip distributions: T-even and chiral odd
- Transversity $h_1^q \equiv h_{1T}^q + \frac{\boldsymbol{p}_T^2}{2M_p^2}\, h_{1T}^{\perp\, q}$ survives under p_T integration

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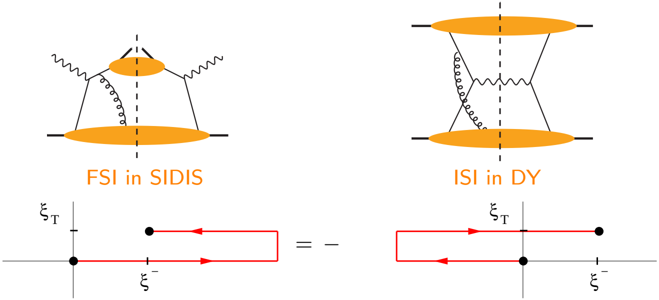
Gauge invariant definition of Φ (not unique)

$$\Phi^{[\mathcal{U}]} \propto \left\langle P, S \left| \overline{\psi}(0)\, \mathcal{U}^{\mathcal{C}}_{[0,\xi]}\, \psi(\xi) \right| P, S \right\rangle$$



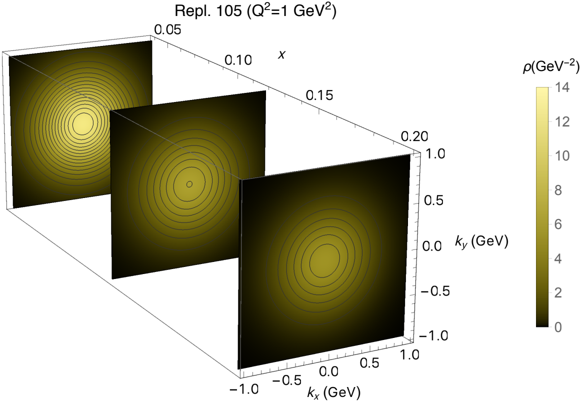
Sign change of T-odd distributions: fundamental test, still under experimental scrutiny

ISI/FSI lead to process dependence of TMDs, could even break factorization

Collins, Qiu, PRD 75 (2007)
Collins, PRD 77 (2007)
Rogers, Mulders, PRD 81 (2010)

	Accuracy	SIDIS HERMES	SIDIS COMPASS	DY fixed target	DY collider	N of points	χ^2/N_{points}
Pavia 2017 arXiv:1703.10157	NLL	✓	✓	✓	✓	8059	1.55
SV 2019 arXiv:1912.06532	$\mathrm{N^3LL^-}$	✓	✓	✓	✓	1039	1.06
MAP22 arXiv:2206.07598	$\mathrm{N^3LL^-}$	✓	✓	✓	✓	2031	1.06
MAP24 arXiv:2405.13833	$\mathrm{N^3LL}$	✓	✓	✓	✓	2031	1.08
ART25 arXiv:2503.11201	$\mathrm{N^3LL}$	✓	✓	✓	✓	1209	1.05

Distribution of unpolarized quarks



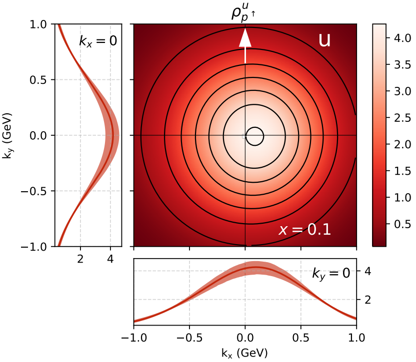
For unpolarized protons, the distribution of unp. quarks is cylindrically symmetric

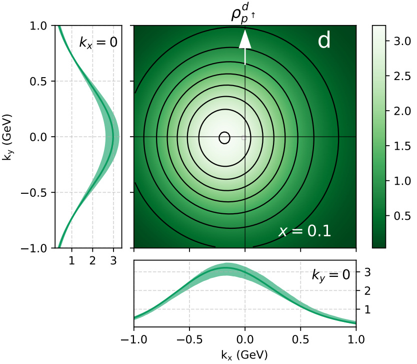
What happens if the proton is transversely polarized?

Same formalism can be used to have a consistent picture (125 data points)

Distortion in the transverse plane of the TMD quark distribution in a $p^{\uparrow}$

$$\Phi^{[\gamma^+]}_{q/p^{\uparrow}}(x, k_x, k_y) = f_1^q(x, k_T^2) - \frac{k_x}{M} f_{1T}^{\perp q}(x, k_T^2) \qquad [Q^2 = 4 \text{ GeV}^2]$$

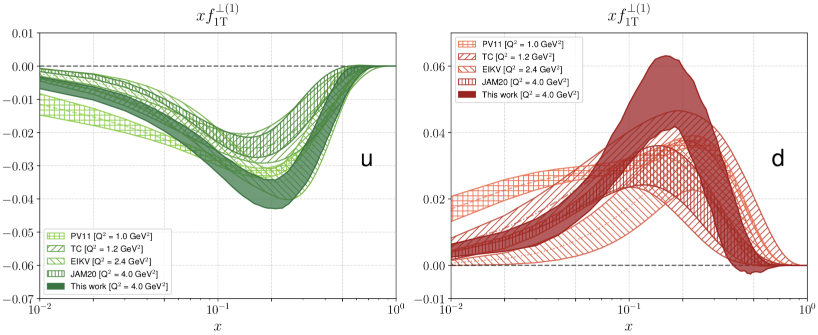




Bacchetta, Delcarro, Pisano, Radici, CP, PLB 827 (2022)

Non zero Sivers effect related to parton orbital angular momentum

$$f_{1T}^{\perp(1)\,q}(x) = \int \mathrm{d}^2\boldsymbol{k}_T\, \frac{k_T^2}{2M_p^2}\, f_{1T}^{\perp\,q}(x, \boldsymbol{k}_T^2)$$



Bacchetta, Delcarro, Pisano, Radici, CP, PLB 827 (2022)

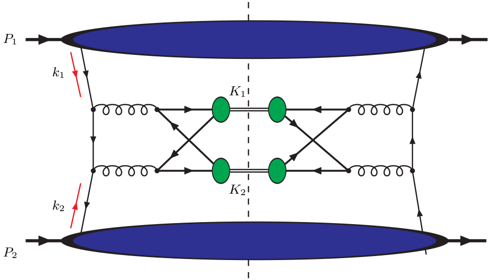
More data from CERN, JLab, EIC will help to reduce error bands and extend the ranges in x and Q^2

J/ψ-pair production at COMPASS

COMPASS Collaboration, PLB 838 (2023)

J/ψ's are relatively easy to detect. Studied at LHCb, CMS & ATLAS
gg fusion dominant at collider energies, negligible $q\bar{q}$ contributions

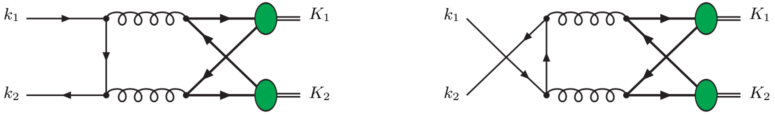
According to NRQCD, Color Octet contribution $\mathcal{O}(v^6)$ w.r.t. Color Singlet one



Color Singlet Model: colorless final state similar to DY (only ISI)

At COMPASS $\bar{u}u$ channel dominant, allowing for flavor separation

At LO pQCD in the Color Singlet Model, relevant diagrams for the $q\bar{q}$ channel:



C. Flore, CP, arXiv:2508.15482

$\phi_T, \phi_\perp, \phi_S$: azimuthal angles of $\boldsymbol{q}_T \equiv \boldsymbol{K}_{1\perp} + \boldsymbol{K}_{2\perp}$, $\boldsymbol{K}_\perp \equiv (\boldsymbol{K}_{1\perp} - \boldsymbol{K}_{2\perp})/2$ and S_T

Angular modulations for the process $\pi^- p \to J/\psi\, J/\psi\, X$ ($q\bar{q}$ channel)

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y_1\,\mathrm{d}y_2\,\mathrm{d}^2\boldsymbol{K}_\perp\,\mathrm{d}^2\boldsymbol{q}_T} \propto \frac{\alpha_s^4}{M_\psi^2\, M_\perp^6\, s}\,|R_\psi(0)|^4 \Big\{ F_{UU} + F_{UU}^{\cos 2(\phi_T-\phi_\perp)} \cos 2(\phi_T - \phi_\perp)$$
$$+ F_{UL}^{\sin 2(\phi_T-\phi_\perp)} \sin 2(\phi_T-\phi_\perp) + |\boldsymbol{S}_T| F_{UT}^{\sin(\phi_T-\phi_S)} \sin(\phi_T - \phi_S)$$
$$+ |\boldsymbol{S}_T| F_{UT}^{\sin(\phi_T+\phi_S-2\phi_\perp)} \sin(\phi_T+\phi_S-2\phi_\perp)$$
$$+ |\boldsymbol{S}_T| F_{UT}^{\sin(3\phi_T-\phi_S-2\phi_\perp)} \sin(3\phi_T-\phi_S-2\phi_\perp) + \ldots \Big\}$$

Exactly as for the DY process (double spin asymmetries not shown here)
S. Arnold, A. Metz, M. Schlegel, PRD 79 (2009)

The structure functions are given by products of a hard part and a convolution of TMDs

$$F_{UU} = H_U(z, M_\psi, K_\perp)\, f_1^q \otimes f_1^{\bar q}$$
$$F_{UU}^{\sin 2(\phi_T - \phi_\perp)} = H_P(z, M_\psi, K_\perp)\, h_1^{\perp\, q} \otimes h_{1L}^{\bar q}$$
$$F_{UU}^{\cos 2(\phi_T - \phi_\perp)} = H_P(z, M_\psi, K_\perp)\, h_1^{\perp\, q} \otimes h_1^{\perp\, \bar q}$$
$$F_{UT}^{\sin(\phi_T - \phi_S)} = H_U(z, M_\psi, K_\perp)\, f_1^q \otimes f_{1T}^{\perp\, \bar q}$$
$$F_{UT}^{\sin(\phi_T + \phi_S - 2\phi_\perp)} = H_P(z, M_\psi, K_\perp)\, h_1^{\perp\, q} \otimes h_1^{\bar q}\,,$$
$$F_{UT}^{\sin(3\phi_T - \phi_S - 2\phi_\perp)} = H_P(z, M_\psi, K_\perp)\, h_1^{\perp\, q} \otimes h_{1T}^{\perp\, \bar q}$$

Hard functions:

$$H_U = \left[5 - 12\, z(1-z)\left(1 - \frac{M_\psi^2}{M_\perp^2}\right) - \frac{M_\psi^2}{M_\perp^2}\right] \qquad H_P = -\left(1 - \frac{M_\psi^2}{M_\perp^2}\right)[1 - 12\, z(1-z)]$$

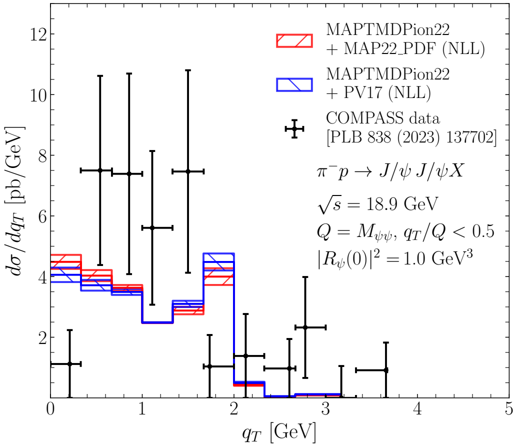
Kinematic variables:

$$M_\perp^2 = M_\psi^2 + K_\perp^2\,, \qquad z = \frac{K_1 \cdot k_1}{k_1 \cdot k_2} = \frac{1}{1 + e^{y_1 - y_2}}$$

In the collinear limit: agreement with existing results

V.G Kartvelishvilil, S.M. Ésakiya, SJP 3 (1983)

J/ψ-pair production at COMPASS
Unpolarized cross section

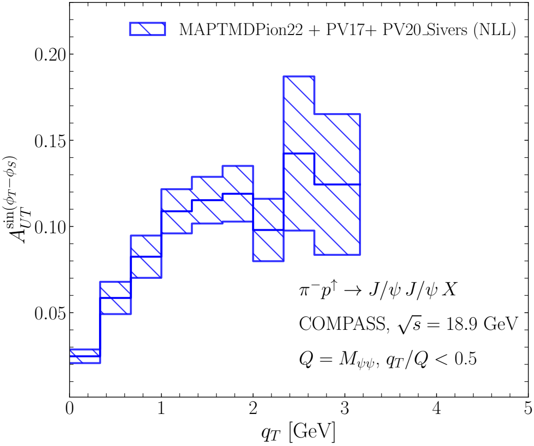


Only about 25 events recorded (AMBER can improve the statistics)

Double parton scattering and intrinsic effects charm negligible; gg channel $\mathcal{O}(10^{-3})$ pb

Feed-down and NLO corrections to be included

$$A_{UT}^{\sin(\phi_T-\phi_S)} = \frac{f_1^q \otimes f_{1T}^{\perp\,\bar{q}}}{f_1^q \otimes f_1^{\bar{q}}}$$



Same kinematics and q_T-binning of the unpolarized cross section

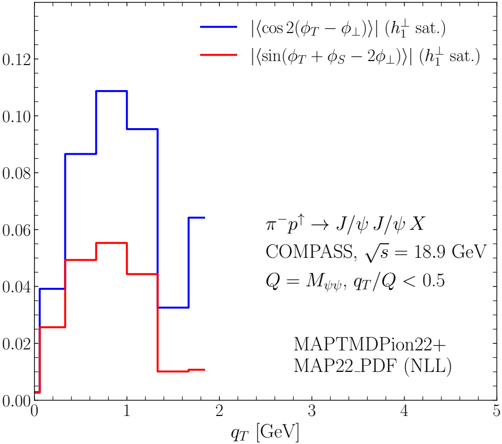
Sign change of $f_{1T}^{\perp\,q}$ w.r.t. SIDIS is assumed

Asymmetry driven by the dominant $\bar{u}_\pi u_p$ channel

J/ψ-pair production at COMPASS

Sivers asymmetry

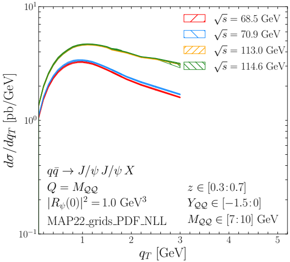
$$\langle \cos 2(\phi_T - \phi_\perp)\rangle = \frac{H_P}{H_U}\,\frac{h_1^{\perp\,q} \otimes h_1^{\perp\,\bar{q}}}{f_1^q \otimes f_1^{\bar{q}}} \qquad \langle \sin(\phi_T + \phi_S - 2\phi_\perp)\rangle = \frac{H_P}{H_U}\,\frac{h_1^{\perp\,q}\, h_1^{\bar{q}}}{f_1^q \otimes f_1^{\bar{q}}}$$

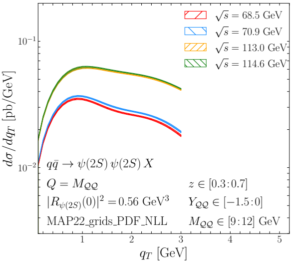


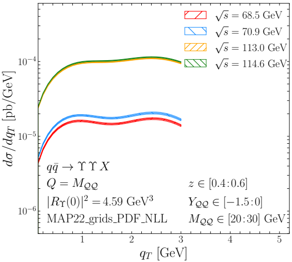
Predictions involving $h_1^{\perp\,q}$ are obtained by saturating its positivity bound:

$$|h_1^{\perp q}(x, \boldsymbol{k}_T)| \leq \frac{M_h}{|\boldsymbol{k}_T|} f_1^q(x, \boldsymbol{k}_T)$$

J/ψ-pair production at SMOG and LHCspin



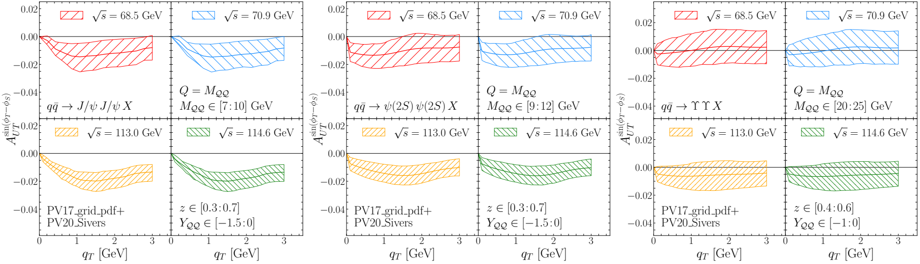




gg channel no longer negligible: 30-40% of the $q\bar{q}$ one at low $\sqrt{s}$
$2\times$ $q\bar{q}$ channel at higher energies

Further studies on gluon TMDs are needed to confirm our estimates

Υ-pair production can be used as a tool for constraining unpolarized TMDs at large x



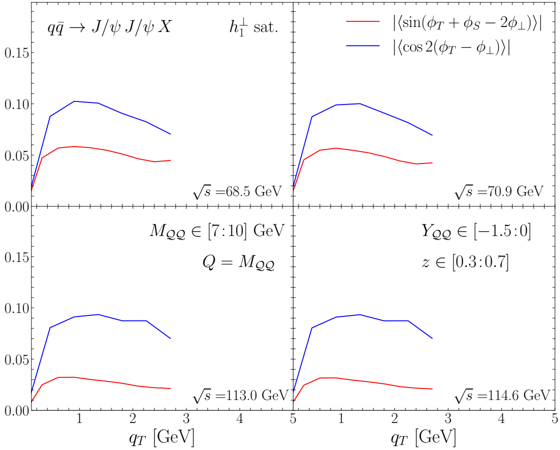
Magnitude of 1-2% expected for di-J/ψ and di-$\psi(2S)$; even smaller for di-Υ

Larger asymmetry would signal nonzero gluon Sivers function

Negative sign of $A_{UT}^{\sin(\phi_T-\phi_S)}$ w.r.t. COMPASS due to different flavor combinations in pp and $\pi^- p$

J/ψ-pair production at SMOG and LHCspin
Other single spin asymmetries

$$\langle \cos 2(\phi_T - \phi_\perp) \rangle = \frac{H_P}{H_U} \frac{h_1^{\perp\, q} \otimes h_1^{\perp\, \bar{q}}}{f_1^q \otimes f_1^{\bar{q}}} \qquad \langle \sin(\phi_T + \phi_S - 2\phi_\perp) \rangle = \frac{H_P}{H_U} \frac{h_1^{\perp\, q}\, h_1^{\bar{q}}}{f_1^q \otimes f_1^{\bar{q}}}$$



Maximized $|\langle \cos 2(\phi_T - \phi_\perp)\rangle|$ $\mathcal{O}(10\%)$, larger than $|\langle \sin(\phi_T + \phi_S - 2\phi_\perp)\rangle|$ ($\sim 5\%$)

- We studied double quarkonium production in hadronic scattering at fixed target experiments within the TMD framework

- The $q\bar{q}$ channel presents the same azimuthal modulations and color-flow structure as the DY process

- COMPASS (AMBER): ideal to probe quark TMDs as gluon contributions are suppressed, sizable azimuthal asymmetries, especially the Sivers one ($\sim 10-15\%$)

- LHC fixed-target experiments: $q\bar{q}$ channel dominant only up to $\sqrt{s}\sim 70$ GeV, small Sivers asymmetries for di-J/ψ, di-$\psi(2S)$ (1–2%), even smaller for di-Υ; important for gluon TMDs

- A consistent description of di-quarkonium production, SIDIS and DY is crucial to study TMDs, their universality and QCD evolution properties