

Università degli Studi di Cagliari

Dipartimento di Fisica



Azimuthal modulations in double quarkonium production in polarized hadronic collisions

Franco E. Barattini

In collaboration with

Carlo Flore and Cristian Pisano

Double Quarkonium Production: From LHCb to SMOG and LHCSpin

Polarized Hadronic Collisions

Provide access to their spin-dependent 3D structure.

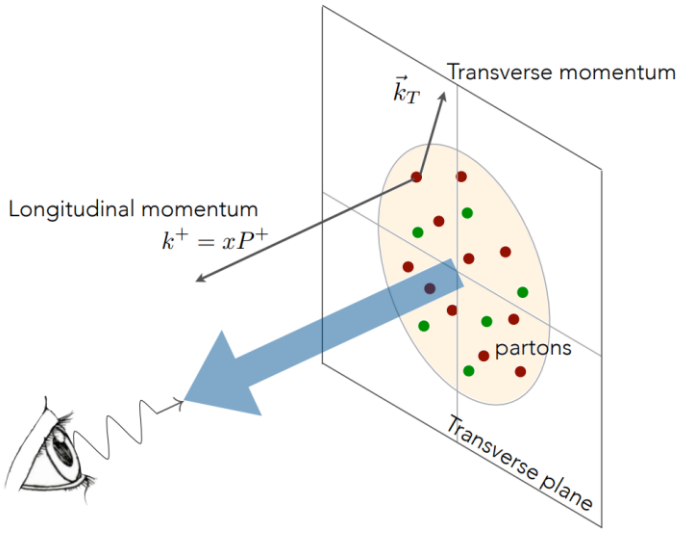
Azimuthal modulations as probes

The cross section encodes information on the underlying partonic dynamics within its angular structure.

Double-quarkonium production

Previously proposed as a promising tool for gluon and quark TMD studies.

TMDs

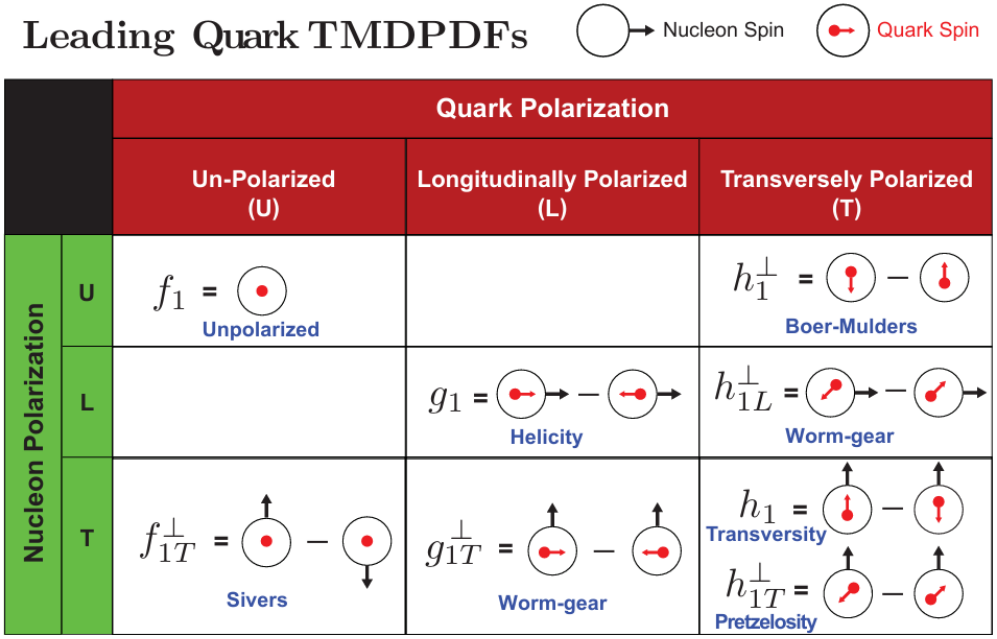


This work

Studying how the different kinematic regimes of SMOG and LHCSpin affect the relative contributions of gluon- and quark-initiated channels.

Status of Quark TMDs

Many spin-dependent distributions as a consequence of non-zero transverse momenta.



	Accuracy
PV 2017 arXiv:1703.10157	NLL
SV 2019 arXiv:1912.06532	N^{3}LL(-)
MAPTMD 2022 arXiv:2206.07598	N^{3}LL(-)
MAPTMD 2024 arXiv:2405.13833	N^{3}LL
ART25 arXiv:2503.11201	N^{4}LL(-)
MAPNN 2025 arXiv:2502.13833	N^{3}LL
JAM25$_{\text{PDF+TMD}}$ arXiv:2510.13771	NNLL

- Several fits already made for many quark TMDs.

Status of Gluon TMDs

Two recent independent extractions of f_1^g now exist

- From CMS/ATLAS Higgs data at N3L

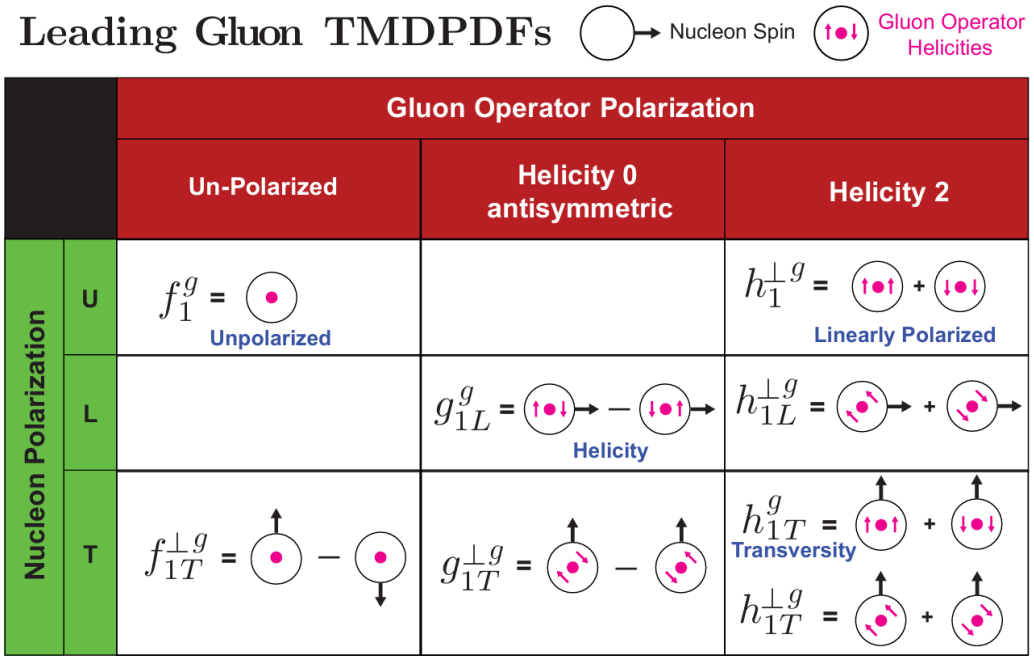
  [Anedda, Bertone, Bozzi, Cerutti, EPJC 86 (2026) 8, 1024]

- From LHCb di-J/ψ data at NNLL

  [Boer et al., arXiv:2609.01000 [hep-ph]]

Almost no experimental information for spin dependent distributions. Only positivity constrains or phenomenological models are present.

$$\left|f_{1T}^{\perp g}(x, \boldsymbol{p}_T^2)\right| \leq \frac{M_p}{|\boldsymbol{p}_T|} f_1^g(x, \boldsymbol{p}_T^2)$$

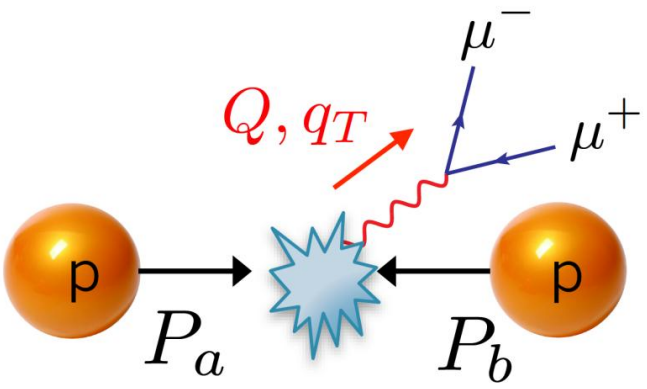




A proposal for a polarized fixed-target experiment at LHC

- **Fixed Target:** LHC proton beam interacting with a polarized gaseous target
- **SMOG2 Operational Predecessor:** An unpolarized gas-target system already operating at LHCb
- **Polarized Target:** Enables access to spin-dependent observables
- **Large-x reach:** access to a less explored region of TMDs.
- **Heavy quarkonium production:** a promising probe of gluon TMDs.

Hadroproduction of a Quakonium Pair in TMD Factorization

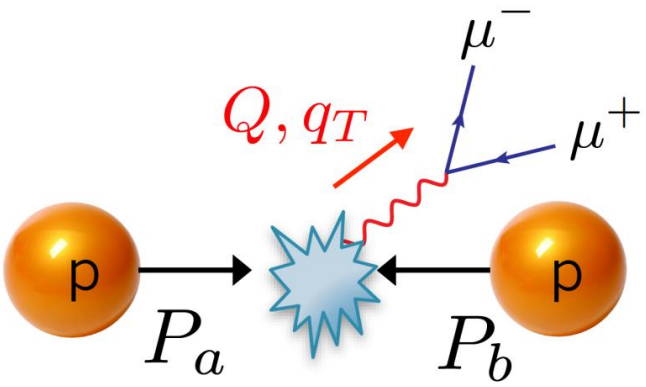


Similar to Drell-Yan process, the Quarkonium pair acquires a non-zero transverse momentum from the addition of the colliding parton's momenta.

Some differences:

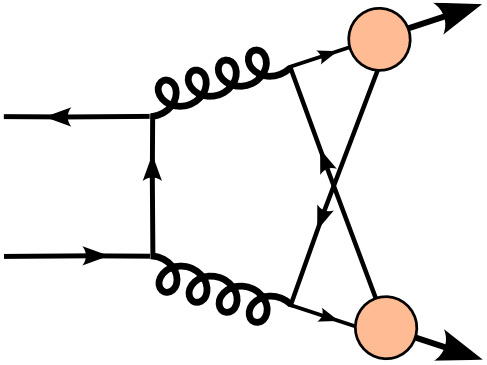
- Two heavy quark-antiquark pairs created perturbatively.
- Hadronization is described by NRQCD Long Distance Matrix Elements.
- Color Singlet production mechanism is dominant (Safe to use in TMD).

Hadroproduction of a Quakonium Pair in TMD Factorization

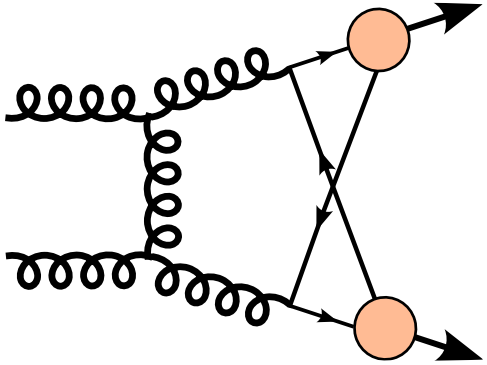


Similar to Drell-Yan process, the Quarkonium pair acquires a non-zero transverse momentum from the addition of the colliding parton's momenta.

Quark-Antiquark Channel



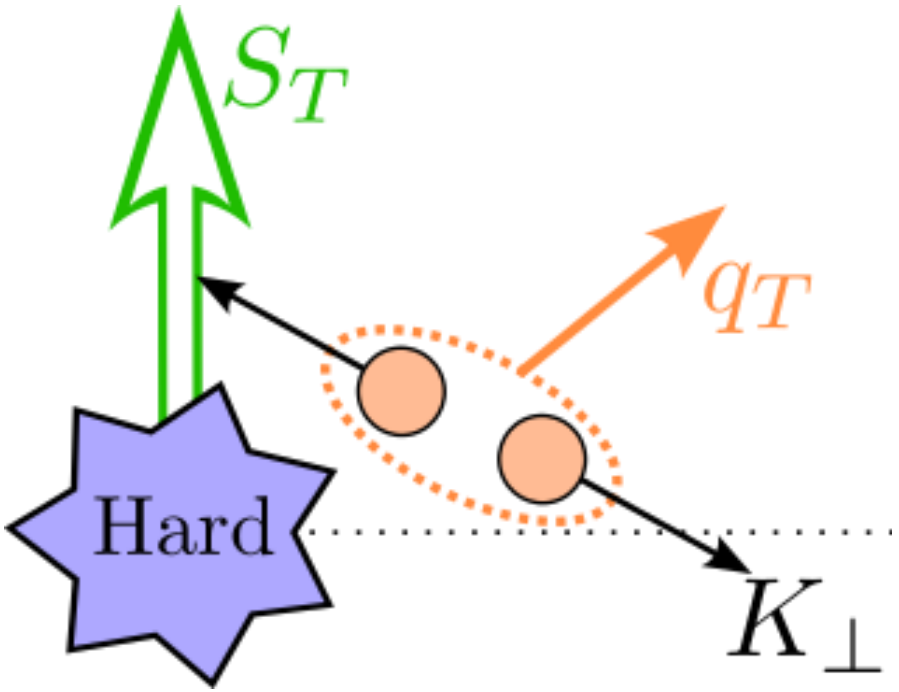
Gluon-Gluon Channel



Modulations and Structure Functions

The cross section can be expressed in terms of structure functions for each azimuthal modulations.

$$d\sigma = F_{UU} + F_{UU}^{\cos 2(\phi_T - \phi_\perp)} \cos 2(\phi_T - \phi_\perp) + \ldots$$



q_T Momenta of the Quarkonium pair.

$K_\perp$ Transverse momenta of each quarkonium.

S_T Spin of the transversely polarized proton.

Modulations and Structure Functions

The cross section can be expressed in terms of structure functions for each azimuthal modulations.

$$d\sigma = F_{UU} + F_{UU}^{\cos 2(\phi_T - \phi_\perp)} \cos 2(\phi_T - \phi_\perp) + \dots$$

The structure functions represent the magnitude of the azimuthal modulations in every point of the phase space.

$$F_j = H_j(Y_{QQ}, M_{QQ}, \Delta y, m_Q) \times \mathcal{C}[\omega_j f_1 f_2](Y_{QQ}, M_{QQ}, q_T)$$

Perturbative | Non-Perturbative

Studying different structure functions, we can access to different convolutions of TMDs.

$$\mathcal{C}[\omega f_1 f_2] \equiv \mathcal{C}[\omega(k_{1T}, k_{2T}) f_1(x_1, k_{1T}) f_2(x_2, k_{2T})]$$

Modulations and Structure Functions (Di-J/ψ)

Unpolarized

$$d\sigma = F_{UU} + F_{UU}^{\cos 2(\phi_T - \phi_\perp)} \cos 2(\phi_T - \phi_\perp) + F_{UU}^{\cos 4(\phi_T - \phi_\perp)} \cos 4(\phi_T - \phi_\perp)$$

Single Longitudinaly Polarized

$$+ S_L \left[F_{UL}^{\sin 2(\phi_T - \phi_\perp)} \sin 2(\phi_T - \phi_\perp) + F_{UL}^{\sin 4(\phi_T - \phi_\perp)} \sin 4(\phi_T - \phi_\perp) \right]$$

Single Transversely Polarized

$$+ |S_T| \Bigg[F_{UT}^{\sin(\phi_T - \phi_S)} \sin(\phi_T - \phi_S)$$

$$+ F_{UT}^{\sin(\phi_T + \phi_S - 2\phi_\perp)} \sin(\phi_T + \phi_S - 2\phi_\perp) + F_{UT}^{\sin(3\phi_T - \phi_S - 2\phi_\perp)} \sin(3\phi_T - \phi_S - 2\phi_\perp)$$

$$+ F_{UT}^{\sin(3\phi_T + \phi_S - 4\phi_\perp)} \sin(3\phi_T + \phi_S - 4\phi_\perp) + F_{UT}^{\sin(5\phi_T - \phi_S - 4\phi_\perp)} \sin(5\phi_T - \phi_S - 4\phi_\perp) \Bigg]$$

Modulations and Structure Functions (Di-J/ψ)

Unpolarized

$$d\sigma = F_{UU} + F_{UU}^{\cos 2(\phi_T - \phi_\perp)} \cos 2(\phi_T - \phi_\perp) + F_{UU}^{\cos 4(\phi_T - \phi_\perp)} \cos 4(\phi_T - \phi_\perp)$$

Single Longitudinaly Polarized

$$+ S_L \left[F_{UL}^{\sin 2(\phi_T - \phi_\perp)} \sin 2(\phi_T - \phi_\perp) + F_{UL}^{\sin 4(\phi_T - \phi_\perp)} \sin 4(\phi_T - \phi_\perp) \right]$$

Single Transversely Polarized

$$+|S_T| \Bigg[F_{UT}^{\sin(\phi_T - \phi_S)} \sin(\phi_T - \phi_S)$$

$$+ F_{UT}^{\sin(\phi_T + \phi_S - 2\phi_\perp)} \sin(\phi_T + \phi_S - 2\phi_\perp) + F_{UT}^{\sin(3\phi_T - \phi_S - 2\phi_\perp)} \sin(3\phi_T - \phi_S - 2\phi_\perp)$$

$$+ F_{UT}^{\sin(3\phi_T + \phi_S - 4\phi_\perp)} \sin(3\phi_T + \phi_S - 4\phi_\perp) + F_{UT}^{\sin(5\phi_T - \phi_S - 4\phi_\perp)} \sin(5\phi_T - \phi_S - 4\phi_\perp) \Bigg]$$

Now we have computed the gluon-gluon channel contributions to single polarized proton collisions.

Modulations and Structure Functions (Di-J/ψ)

Unpolarized

$$d\sigma = F_{UU} + F_{UU}^{\cos 2(\phi_T - \phi_\perp)} \cos 2(\phi_T - \phi_\perp) + F_{UU}^{\cos 4(\phi_T - \phi_\perp)} \cos 4(\phi_T - \phi_\perp)$$

The gluon-gluon channel was computed previously only for unpolarized collisions.

J.P Lansberg et al. Phys.Lett.B 784 (2018), 217-222.

Single Longitudinaly Polarized

$$+ S_L \left[F_{UL}^{\sin 2(\phi_T - \phi_\perp)} \sin 2(\phi_T - \phi_\perp) + F_{UL}^{\sin 4(\phi_T - \phi_\perp)} \sin 4(\phi_T - \phi_\perp) \right]$$

Single Transversely Polarized

$$+ |S_T| \Bigg[F_{UT}^{\sin(\phi_T - \phi_S)} \sin(\phi_T - \phi_S)$$

$$+ F_{UT}^{\sin(\phi_T + \phi_S - 2\phi_\perp)} \sin(\phi_T + \phi_S - 2\phi_\perp) + F_{UT}^{\sin(3\phi_T - \phi_S - 2\phi_\perp)} \sin(3\phi_T - \phi_S - 2\phi_\perp)$$

$$+ F_{UT}^{\sin(3\phi_T + \phi_S - 4\phi_\perp)} \sin(3\phi_T + \phi_S - 4\phi_\perp) + F_{UT}^{\sin(5\phi_T - \phi_S - 4\phi_\perp)} \sin(5\phi_T - \phi_S - 4\phi_\perp) \Bigg]$$

Modulations and Structure Functions (Di-J/ψ)

Unpolarized

$$d\sigma = F_{UU} + F_{UU}^{\cos 2(\phi_T - \phi_\perp)} \cos 2(\phi_T - \phi_\perp) + F_{UU}^{\cos 4(\phi_T - \phi_\perp)} \cos 4(\phi_T - \phi_\perp)$$

Single Longitudinaly Polarized

$$+ S_L \left[F_{UL}^{\sin 2(\phi_T - \phi_\perp)} \sin 2(\phi_T - \phi_\perp) + F_{UL}^{\sin 4(\phi_T - \phi_\perp)} \sin 4(\phi_T - \phi_\perp) \right]$$

Single Transversely Polarized

$$+ |S_T| \Bigg[F_{UT}^{\sin(\phi_T - \phi_S)} \sin(\phi_T - \phi_S)$$

$$+ F_{UT}^{\sin(\phi_T + \phi_S - 2\phi_\perp)} \sin(\phi_T + \phi_S - 2\phi_\perp) + F_{UT}^{\sin(3\phi_T - \phi_S - 2\phi_\perp)} \sin(3\phi_T - \phi_S - 2\phi_\perp)$$

$$+ F_{UT}^{\sin(3\phi_T + \phi_S - 4\phi_\perp)} \sin(3\phi_T + \phi_S - 4\phi_\perp) + F_{UT}^{\sin(5\phi_T - \phi_S - 4\phi_\perp)} \sin(5\phi_T - \phi_S - 4\phi_\perp) \Bigg]$$

The quark-antiquark channel was computed previously by my collaborators for any polarization state.

C. Flore and C. Pisano , JHEP 02 (2026), 085

Unpolarized Proton Collisions

Two hard coefficients for the quark-antiquark channel (blue), and four within the gluon-gluon channel (red).

$$F_{UU} = H_1^{q\bar{q}}\, C[f_1^q f_1^{\bar{q}}] + H_1^{gg}\, C[f_1^g f_1^g] + H_2^{gg}\, C[\omega_{UU}^1 h_1^{\perp g} h_1^{\perp g}]$$

$$F_{UU}^{\cos 2(\phi_T - \phi_\perp)} = H_2^{q\bar{q}}\, C[\omega_{UU}^2 h_1^{\perp q} h_1^{\perp \bar{q}}] + H_3^{gg}\, (C[\omega_{UU}^3 f_1^g h_1^{\perp g}] + C[\tilde{\omega}_{UU}^3 h_1^{\perp g} f_1^g])$$

$$F_{UU}^{\cos 4(\phi_T - \phi_\perp)} = H_4^{gg}\, C[\omega_{UU}^4 h_1^{\perp g} h_1^{\perp g}]$$

We can approximate magnitude of these hard coefficients if we consider a reasonable kinematic regime for the study:

$$M_{QQ} \gg 2m_Q$$

(Invariant mass larger than the sum of both J/ψ Masses)

$$\Delta y \sim 0$$

(Avoids the region where DPS could be dominant)

Unpolarized Proton Collisions

In these exact limits, we can extract some ideas about the complicated structure of the cross section.

$$M_{QQ} \gg 2m_Q$$

$$\Delta y \sim 0$$

For gluons, we can observe a clear hierarchy, allowing us to ignore some contributions to the modulations.

$$H_1^{gg} \approx H_4^{gg} \qquad H_2^{gg} \approx H_3^{gg} \approx 0 + \mathcal{O}\left(\frac{2m_Q}{M_{QQ}}\right)$$

$$F_{UU} = H_1^{q\bar{q}}\, C[f_1^q f_1^{\bar{q}}] + H_1^{gg}\, C[f_1^g f_1^g] + H_2^{gg}\, C[\omega_{UU}^1 h_1^{\perp g} h_1^{\perp g}]$$

0

For quarks instead, we can observe that their contributions is around 40 times larger than the largest gluonic hard coefficient.

$$H_1^{q\bar{q}} \approx H_2^{q\bar{q}} \qquad H_1^{q\bar{q}} \approx 40 H_1^{gg}$$

Therefore, quark-antiquark channel can provide a contribution as big as the gluon-gluon depending on the kinematic region we address.

Single Transversely Polarized Proton Collisions

Our results for the gluon-gluon channel Structure Functions to single polarized proton collisions.

$$F_{UT}^{\sin(\phi_T-\phi_{S2})} = H_1^{q\bar{q}}\, C[\omega_{UT}^1 f_1^q f_{1T}^{\perp\bar{q}}] + H_1^{gg}\, C[\omega_{UT}^1 f_1^g f_{1T}^{\perp g}]$$
$$+ H_2^{gg}\,(C[\omega_{UT}^2 h_1^{\perp g} h_1^g] - C[\omega_{UT}^3 h_1^{\perp g} h_{1T}^{\perp g}])$$

$$F_{UT}^{\sin(\phi_T+\phi_{S2}-2\phi_\perp)} = H_2^{q\bar{q}}\, C[\tilde{\omega}_{UT}^1 h_1^{\perp q} h_1^{\bar{q}}] - H_3^{gg}\left(C[\omega_{UT}^2 h_1^{\perp g} f_{1T}^{\perp g}] + \frac{1}{2} C[\omega_{UT}^1 f_1^g h_1^g]\right)$$

$$F_{UT}^{\sin(3\phi_T-\phi_{S2}-2\phi_\perp)} = 2H_2^{q\bar{q}}\, C[\tilde{\omega}_{UT}^4 h_1^{\perp q} h_{1T}^{\perp\bar{q}}] + H_3^{gg}\,(C[\omega_{UT}^4 h_1^{\perp g} f_{1T}^{\perp g}] - C[\omega_{UT}^5 f_1^g h_{1T}^{\perp g}])$$

$$F_{UT}^{\sin(3\phi_T+\phi_{S2}-4\phi_\perp)} = -H_4^{gg}\, C[\omega_{UT}^4 h_1^{\perp g} h_1^g]$$

$$F_{UT}^{\sin(5\phi_T-\phi_{S2}-4\phi_\perp)} = -H_4^{gg}\, C[\omega_{UT}^3 h_1^{\perp g} h_{1T}^{\perp g}]$$

The hard coefficients are the same as those for the unpolarized case.

The Sivers Asymmetry

A particularly interesting observable from the previous results is the Sivers Asymmetry

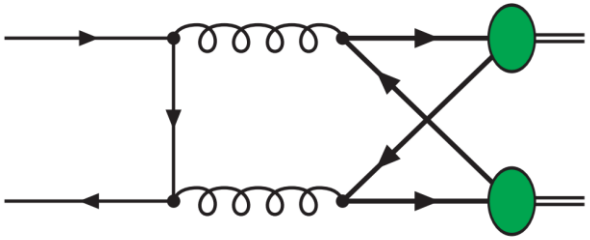
$$A_{UT}^{\sin(\phi_T-\phi_S)} = \langle \sin(\phi_T-\phi_S) \rangle = \frac{F_{UT}^{\sin(\phi_T-\phi_S)}}{F_{UU}}$$

In terms of TMD convolutions and Hard Factors, the approximate expression of the Sivers Asymmetry is

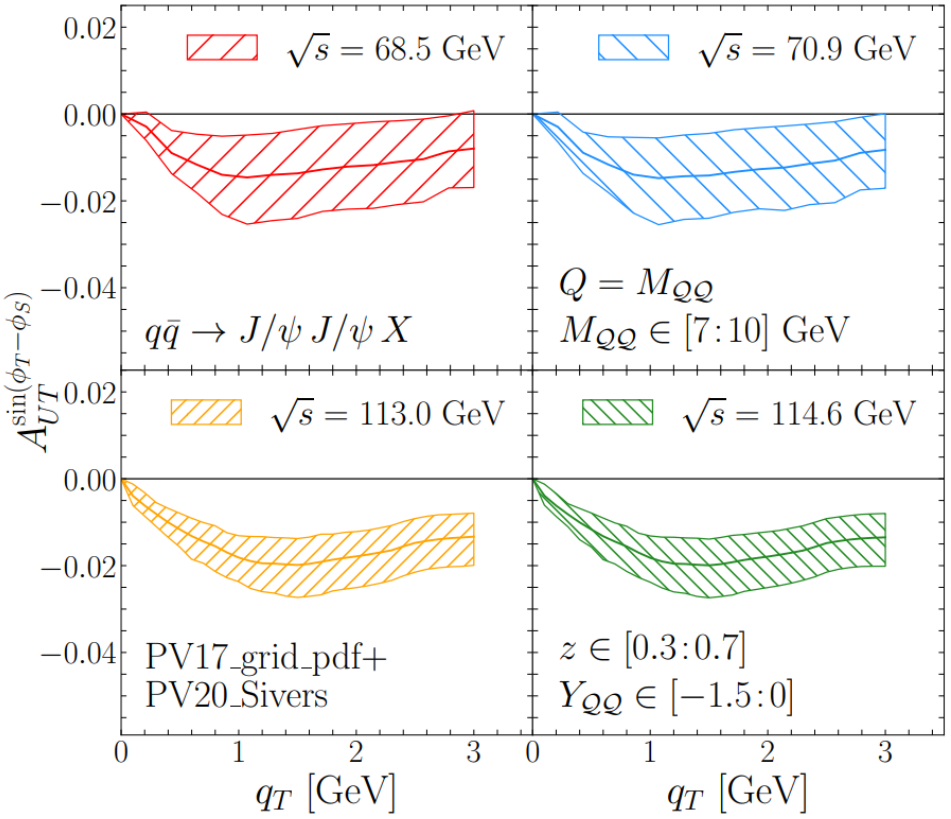
$$A_{UT}^{\sin(\phi_T-\phi_S)} = \frac{H_1^{q\bar{q}}\, C[\omega_{UT}^1 f_1^q f_{1T}^{\perp \bar{q}}] + H_1^{gg}\, C[\omega_{UT}^1 f_1^g f_{1T}^{\perp g}]}{H_1^{q\bar{q}}\, C[f_1^q f_1^{\bar{q}}] + H_1^{gg}\, C[f_1^g f_1^g]}$$

This asymmetry could provide a useful constraint on the gluon Sivers function.

Quark-AntiQuark Channel



- The Sivers Asymmetry in the production of a J/Psi pair was recently studied.
- The results obtained show relatively small values for the Sivers Asymmetry.
- Gluon Channel was not included.
- A non-zero gluon Sivers function could significantly modify this results.



C. Flore and C. Pisano , JHEP 02 (2026), 085

Preliminary Results for SMOG2

We first compute the contributions from each channel to the total cross section of di-J/ψ production within the SMOG2 (LHCSpin) kinematic range.

$$d\sigma = H_1^{q\bar{q}} \mathcal{C}[f_1^q f_1^{\bar{q}}] + H_1^{gg} \mathcal{C}[f_1^g f_1^g]$$

For the unpolarized gluon TMD we use the recent extraction published in **[Boer et al., arXiv:2609.01000 [hep-ph]]** See Samuel's Talk

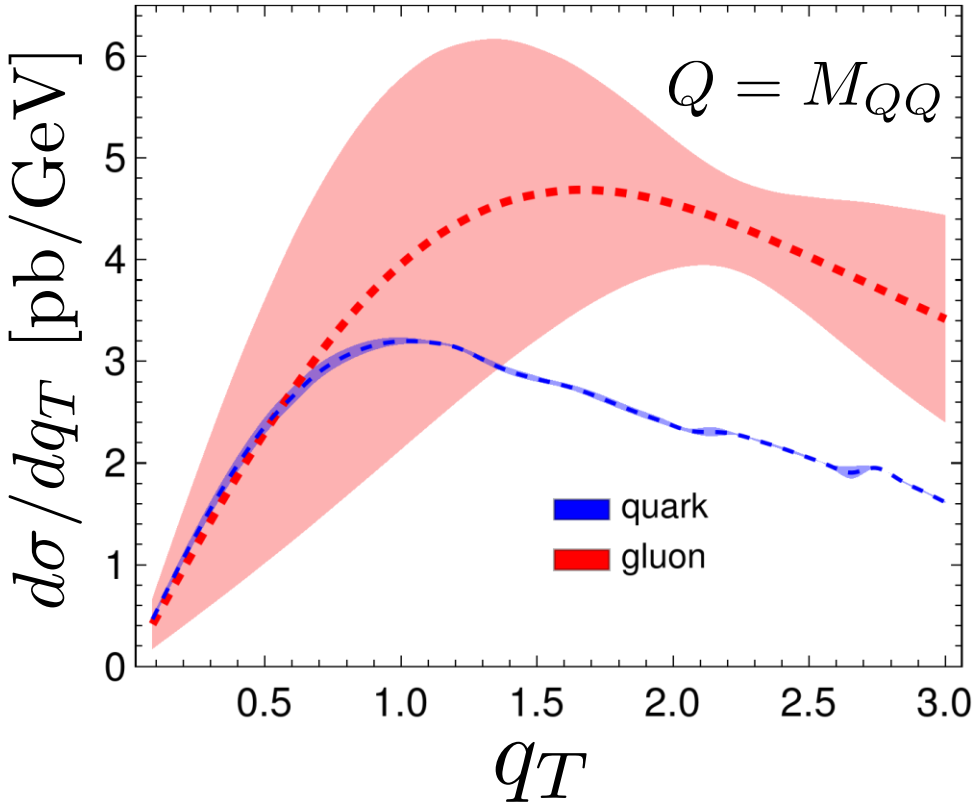
They implement TMD evolution, modeling the nonperturbative Sudakov factor to fit LHCb di-J/ψ data.

- The x range for LHCb di-J/ψ is kept well under 0.1 while SMOG2 and LHCSpin reach large values of x (~0.5)
- Thet don't fit the normalization of the unpolarized gluon TMD.

Preliminary Results for SMOG2

We first compute the contributions from each channel to the total cross section within the SMOG2 (LHCSpin) kinematic range.

$$\sqrt{S} = 113 \text{ GeV}$$
$$M_{QQ} = [7 : 10] \text{ GeV}$$
$$Y_{QQ} = [-1.5 : 0]$$
$$|\Delta y| = [0 : 0.8]$$



From these results we find a gluonic contribution that becomes dominant at the largest values of qT.

Preliminary Results for LHCSpin

Considering the same kinematics, we can now try to compute the values of the Sivers Asymmetry.

$$A_{UT}^{\sin(\phi_T-\phi_S)} = \frac{H_1^{q\bar{q}}\, C[\omega_{UT}^1 f_1^q f_{1T}^{\perp\bar{q}}] + H_1^{gg}\, C[\omega_{UT}^1 f_1^g f_{1T}^{\perp g}]}{H_1^{q\bar{q}}\, C[f_1^q f_1^{\bar{q}}] + H_1^{gg}\, C[f_1^g f_1^g]}$$

$f_{1T}^{\perp g}$ Will provide a large model dependence on the total asymmetry

To distinguish the effect of the Gluon Sivers function, let us again separate both contributions in the numerator.

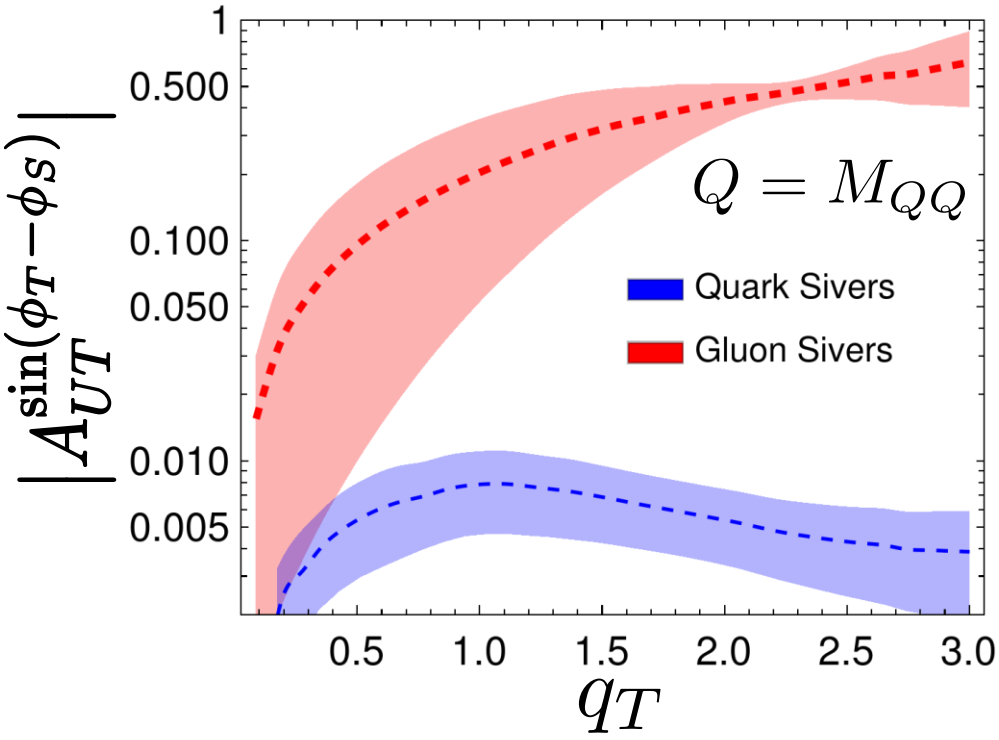
$$\frac{H_1^{q\bar{q}}\, C[\omega_{UT}^1 f_1^q f_{1T}^{\perp\bar{q}}]}{H_1^{q\bar{q}}\, C[f_1^q f_1^{\bar{q}}] + H_1^{gg}\, C[f_1^g f_1^g]} \qquad \frac{H_1^{gg}\, C[\omega_{UT}^1 f_1^g f_{1T}^{\perp g}]}{H_1^{q\bar{q}}\, C[f_1^q f_1^{\bar{q}}] + H_1^{gg}\, C[f_1^g f_1^g]}$$

Preliminary Results for LHCSpin

We saturate the positivity bound of the gluon Sivers function .

$$\left|f_{1T}^{\perp g}(x, \boldsymbol{p}_T^2)\right| \leq \frac{M_p}{|\boldsymbol{p}_T|} f_1^g(x, \boldsymbol{p}_T^2)$$

The gluon-gluon contribution to the magnitude of the Sivers asymmetry can be up to two orders of magnitude larger than the quark-antiquark contribution.



This highlights the potential to constrain the gluon Sivers function through esperimental deviations from the quark-antiquark contribution at LHCSpin.

Conclusions

- We applied TMD factorization in the hadro-production of double quarkonia (di-J/ψ), finding that in the kinematic regime of LHCSpin the quark-antiquark and the gluon-gluon channels contribute comparably to the unpolarized cross section.

- However, due to the limited knowledge of polarized gluon TMDs, we cannot provide good predictions for single-spin asymmetries (SSAs) as they would be strongly model-dependent.

- However, our results indicate that the gluon Sivers function can significantly modify the predictions at LHCSpin based on the quark–antiquark channel, highlighting the potential of double quarkonium production to provide complementary constraints on the gluon Sivers function.

Thanks for your attention

How con we observe modulations?

Azimuthal Moments:

$$R^W = \langle W(\phi_T, \phi_\perp) \rangle \equiv 2 \frac{\int d\Omega \, W(\phi_T, \phi_\perp) \, d\sigma(\phi_T, \phi_\perp, \phi_S)}{\int d\Omega \, d\sigma(\phi_T, \phi_\perp, \phi_S)} \qquad d\Omega = d\phi_S d\phi_T d\phi_\perp$$

Azimuthal Asymmetries:

$$A^W = \langle W(\phi_S, \phi_T, \phi_\perp) \rangle \equiv 2 \frac{\int d\phi_T d\phi_\perp W(\phi_S, \phi_T, \phi_\perp) \left(d\sigma(\phi_S, \phi_T, \phi_\perp) - d\sigma(\phi_S + \pi, \phi_T, \phi_\perp) \right)}{\int d\phi_T d\phi_\perp \left(d\sigma(\phi_S, \phi_T, \phi_\perp) + d\sigma(\phi_S + \pi, \phi_T, \phi_\perp) \right)}$$

One particularly importan example:

- Sivers Asymmetry $A_{UT}^{\sin(\phi_T - \phi_S)} = \langle \sin(\phi_T - \phi_S) \rangle = \frac{F_{UT}^{\sin(\phi_T - \phi_S)}}{F_{UU}}$

$$\frac{\langle \mathcal{O}^{J/\psi}({}^1S_0^{[8]})\rangle}{\langle \mathcal{O}^{J/\psi}({}^3S_1^{[1]})\rangle} \lesssim 2\cdot 10^{-2} \qquad \frac{\langle \mathcal{O}^{J/\psi}({}^3S_1^{[8]})\rangle}{\langle \mathcal{O}^{J/\psi}({}^3S_1^{[1]})\rangle} \lesssim 6\cdot 10^{-4} \qquad \frac{\langle \mathcal{O}^{J/\psi}({}^3P_0^{[8]})\rangle}{\langle \mathcal{O}^{J/\psi}({}^3S_1^{[1]})\rangle} \approx 0$$