C-even quarkonium and di-J/ψ production

Nanako Kato ✉
University and INFN Cagliari

Quarkonia As Tools 2025
Centre Paul Langevin, Aussois, January 5-11th, 2025

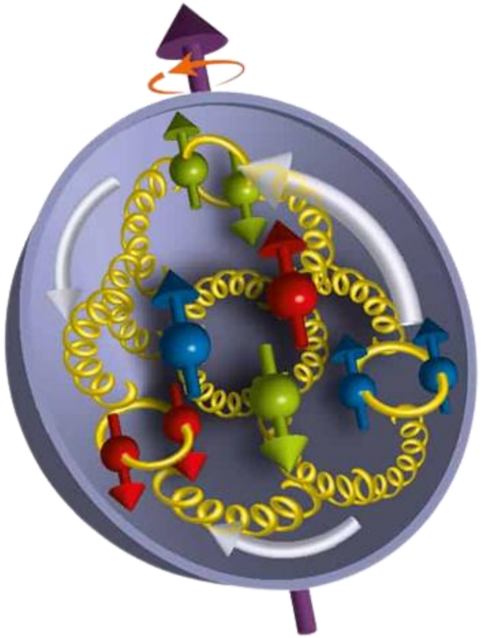
Outline

- Introduction
- Gluon TMDs
- C-even quarkonium production
- Di-J/ψ production
- Summary

Introduction

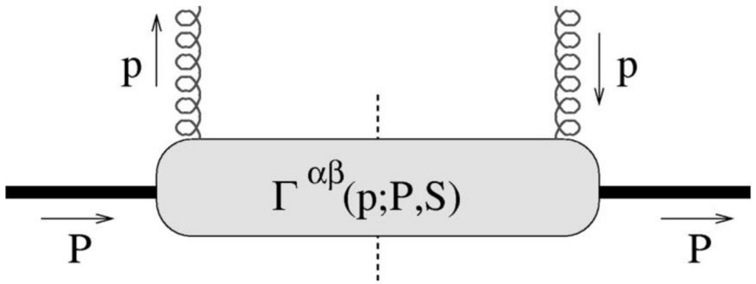
- Studying the production of quarkonia in *pp* collisions is a useful tool for probing gluon TMDs

- Gluon TMDs are still poorly known: since they encode the information on the intrinsic motion of the gluons inside hadrons, their knowledge is a key ingredient to understand polarization phenomena



Gluon TMDs

Gluon correlator



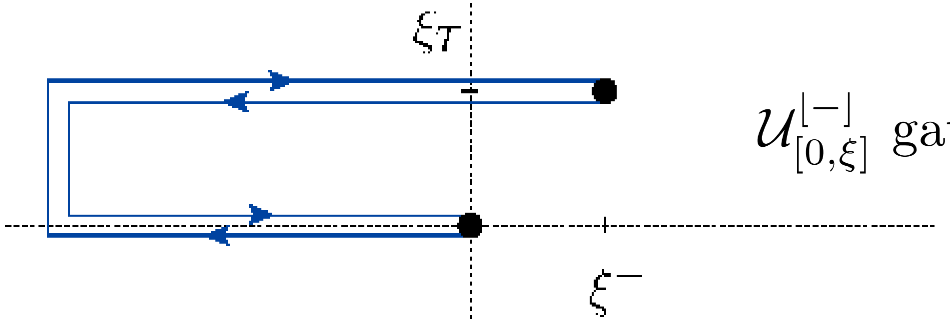
Mulders, Rodrigues, PRD 63 (2001)
Buffing, Mukherjee, Mulders, PRD 88 (2013)
Boer, Cotogno, Van Daal, Mulders, Signori, Zhou, JHEP 1610 (2016)

Gauge invariant definition of the gluon correlator

$$\Gamma_g^{[U,U']\alpha\beta}(x,\boldsymbol{p}_T) \propto \langle P,S|\ \mathrm{Tr}\left[\,F^{\alpha+}(0)\,U_{[0,\xi]}F^{\beta+}(\xi)\,U'_{[\xi,0]}\,\right]|P,S\rangle\,\Big|_{\mathrm{LF}}$$

Gauge link:

$$\mathcal{U}^{\mathcal{C}}_{[0,\xi]} = \mathcal{P}\exp\Big(-ig\int_{\mathcal{C}[0,\xi]} ds_\mu A^\mu(s)\Big)$$



$\mathcal{U}^{[-]}_{[0,\xi]}$ gauge link

Gluon TMDs

Gluon polar. / Proton polar.	Unpolarized	Circular	Linear
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_1^g, h_{1T}^{\perp g}$

T-even

T-odd

Angeles-Martinez et al., *Acta Phys., Pol B46 (2015)*

$h_1^{\perp g}$: linearly polarized gluon distribution in unpolarized hadron

$f_{1T}^{\perp g}$: gluon Sivers function in transversely polarized hadron

$h_{1T}^g,\ h_{1T}^{\perp g}$: helicity flip distributions

$h_1^g \equiv h_{1T}^g + \frac{\boldsymbol{p}_T^2}{2M_p^2} h_{1T}^{\perp g}$: vanishes under p_T integration

Gluon TMDs

The hadronic correlators are parametrized as follows

$$\Gamma_U^{\mu\nu}(x,\boldsymbol{p}_T) = \frac{1}{2x}\left\{ -\, g_T^{\mu\nu}\, f_1^g(x,\boldsymbol{p}_T^2) + \left(\frac{p_T^\mu p_T^\nu}{M_h^2} + g_T^{\mu\nu}\,\frac{\boldsymbol{p}_T^2}{2M_h^2}\right) h_1^{\perp\, g}(x,\boldsymbol{p}_T^2)\right\}$$

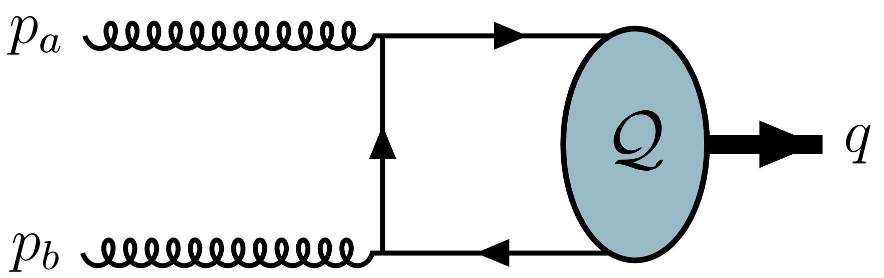
$$\Gamma_L^{\mu\nu}(x,\boldsymbol{p}_T) = \frac{1}{2x}\, S_L\, \left\{ i\epsilon_T^{\mu\nu}\, g_{1L}^g(x,\boldsymbol{p}_T^2) + \frac{\epsilon_T^{p_T\{\mu}p_T^{\nu\}}}{M_h^2}\, h_{1L}^{\perp\, g}(x,\boldsymbol{p}_T^2)\right\}$$

$$\Gamma_T^{\mu\nu}(x,\boldsymbol{p}_T) = \frac{1}{2x}\left\{ g_T^{\mu\nu}\,\frac{\epsilon_T^{p_T S_T}}{M_h}\, f_{1T}^{\perp\, g}(x,\boldsymbol{p}_T^2) + i\epsilon_T^{\mu\nu}\,\frac{p_T\cdot S_T}{M_h}\, g_{1T}^{\perp\, g}(x,\boldsymbol{p}_T^2) - \frac{\epsilon_T^{p_T\{\mu}S_T^{\nu\}} + \epsilon_T^{S_T\{\mu}p_T^{\nu\}}}{4M_h}\, h_1^g(x,\boldsymbol{p}_T^2) \right.$$
$$\left. + \frac{4\,(p_T\cdot S_T)\,\epsilon_T^{p_T\{\mu}p_T^{\nu\}} + \boldsymbol{p}_T^2\left[\epsilon_T^{p_T\{\mu}S_T^{\nu\}} + \epsilon_T^{S_T\{\mu}p_T^{\nu\}}\right]}{8M_h^3}\, h_{1T}^{\perp\, g}(x,\boldsymbol{p}_T^2)\right\}$$

C-even quarkonium production

NRQCD

The model used to describe quarkonium production is **Non-Relativistic QCD** (NRQCD)



- Double power series expansion → α_S, v
- Hard process calculated perturbatively
- Soft process given by LDMEs

$$v_c^2 \simeq 0.3$$
$$v_b^2 \simeq 0.1$$

G. T. Bodwin, E. Braaten, G. P. Lepage, PRD 51 (1995)

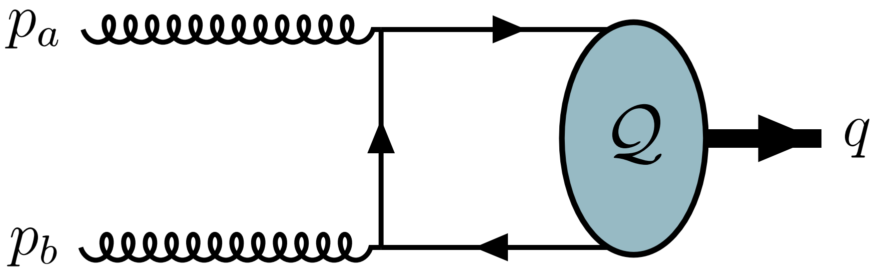
The hadronization of the pair is encoded in LDME (not calculable perturbatively)

C-even quarkonia

For this kind of quarkonium states Color-Singlet production mechanism dominates:

$$p(P_A, S_A) + p(P_B, S_B) \; \rightarrow \; Q\overline{Q}[^{2S+1}L_J^{(1)}](q) + X$$

Leading order diagram:



$$g(p_a) + g(p_b) \; \rightarrow \; Q\overline{Q}[^{2S+1}L_J^{(1)}](q)$$

In the kinematic region where $\boldsymbol{q_T} \ll \boldsymbol{M}$, **TMD factorization** is expected to be applicable

$$d\sigma \propto \Gamma_g^{\mu\nu}(x_a, \boldsymbol{p}_{aT}) \, \Gamma_g^{\rho\sigma}(x_b, \boldsymbol{p}_{bT}) \, \mathcal{A}_{\mu\rho} \, (\mathcal{A}_{\nu\sigma})^*$$

Amplitude using NRQCD

General expression for the amplitudes:

contains the LDME

$$\mathcal{A}(gg \to Q\bar{Q}[^{2S+1}L_J^{(1)}])(p_a, p_b, q) = \int \frac{d^4k}{(2\pi)^4} Tr[O(q,k)\, \phi(q,k)]$$

calculable perturbatively

R. Baier, R. Ruckl, Z. Phys. C 19 (1983)
D. Boer, C. Pisano, PRD 86 (2012)

$\eta_Q(^1S_0)$ $\quad \mathcal{A}[^1S_0^{(1)}] \propto R_0(0)\epsilon^{\mu\nu\rho\sigma} p_{a\rho} p_{b\sigma}$

$\chi_{Q0}(^3P_0)$ $\quad \mathcal{A}[^3P_0^{(1)}] \propto R_1'(0)\Big[-3g^{\mu\nu} + \frac{2}{M^2} q^\mu p_a^\nu\Big]$

$\chi_{Q2}(^3P_2)$ $\quad \mathcal{A}[^3P_2^{(1)}] \propto_s R_1'(0)\varepsilon_{J_z}^{\rho\sigma}(q)\Big[\frac{4}{M^2} g^{\mu\nu} p_{a\rho} p_{a\sigma} - g_\rho^\mu g_\sigma^\nu - g_\rho^\nu g_\sigma^\mu\Big]$

$$\langle 0|\, \mathcal{O}_1^{\eta_Q}(^1S_0)\, |0\rangle = \frac{N_c}{2\pi}|R_0(0)|^2[1+\mathcal{O}(v^4)]$$

$$\langle 0|\, \mathcal{O}_1^{\chi_{QJ}}(^3P_J)\, |0\rangle = \frac{3N_c}{2\pi}(2J+1)|R_1'(0)|^2[1+\mathcal{O}(v^2)]$$

$$d\sigma^{pp\to Q\bar{Q}} = \sum_n d\hat{\sigma}[gg \to Q\bar{Q}]\, \langle 0|\, \mathcal{O}_n(^{2S+1}L_J^{(1)})\, |0\rangle$$

Perturbative short-distance coefficients

Long distance matrix elements (LDME)

Cross sections

$$\frac{d\sigma(\eta_{\mathcal{Q}})}{dy d^2\boldsymbol{q}_T} \propto \mathcal{C}[f_1^g f_1^g] - \mathcal{C}[w h_1^{\perp g} h_1^{\perp g}]$$

$$\frac{d\sigma(\chi_{\mathcal{Q}0})}{dy d^2\boldsymbol{q}_T} \propto \mathcal{C}[f_1^g f_1^g] + \mathcal{C}[w h_1^{\perp g} h_1^{\perp g}]$$

$$\frac{d\sigma(\chi_{\mathcal{Q}2})}{dy d^2\boldsymbol{q}_T} \propto \mathcal{C}[f_1^g f_1^g]$$

Proton A **unpolarized**
Proton B **unpolarized**

D. Boer, C. Pisano, PRD 86 (2012)

The **convolution** is defined as:

$$\mathcal{C}[w\, F_1^g\, F_2^g] = \int d^2\boldsymbol{p}_{aT}\, d^2\boldsymbol{p}_{bT}\, w(\boldsymbol{p}_{aT}, \boldsymbol{p}_{bT})\, F_1^g(x_a, \boldsymbol{p}_{aT})\, F_2^g(x_b, \boldsymbol{p}_{bT})\, \delta^2(\boldsymbol{p}_{aT} + \boldsymbol{p}_{bT} - \boldsymbol{q}_T)$$

Cross sections

Calculated new contributions from **polarized protons**:

$$\frac{\mathrm{d}\sigma[\mathcal{Q}]}{\mathrm{d}y\,\mathrm{d}^2\boldsymbol{q}_T} = F_{UU}^{\mathcal{Q}} + F_{UL}^{\mathcal{Q}}\,S_{BL} + F_{LU}^{\mathcal{Q}}\,S_{AL} + F_{UT}^{\mathcal{Q},\sin\phi_{S_B}}\,|\boldsymbol{S}_{BT}|\sin\phi_{S_B} + F_{TU}^{\mathcal{Q},\sin\phi_{S_A}}\,|\boldsymbol{S}_{AT}|\sin\phi_{S_A}$$
$$+ F_{LL}^{\mathcal{Q}}\,S_{AL}\,S_{BL} + F_{LT}^{\mathcal{Q},\cos\phi_{S_B}}\,S_{AL}\,|\boldsymbol{S}_{BT}|\cos\phi_{S_B} + F_{TL}^{\mathcal{Q},\cos\phi_{S_A}}\,|\boldsymbol{S}_{AT}|\,S_{BL}\cos\phi_{S_A}$$
$$+ |\boldsymbol{S}_{AT}|\,|\boldsymbol{S}_{BT}|\left(F_{TT}^{\mathcal{Q},\cos(\phi_{S_A}-\phi_{S_B})}\cos(\phi_{S_A}-\phi_{S_B}) + F_{TT}^{\mathcal{Q},\cos(\phi_{S_A}+\phi_{S_B})}\cos(\phi_{S_A}+\phi_{S_B})\right)$$

NK, L. Maxia, C. Pisano, PRD 110 0234028 (2024)

Each structure function can be factorized:

$F^{\mathcal{Q}}$

$H^{\mathcal{Q}} = \sum_{n=0}^{\infty}\left(\frac{\alpha_s}{\pi}\right)^n H_n^{\mathcal{Q}}$ — perturbative part

$\mathcal{C}[w\,F_1^g\,F_2^g]$

LDME — non-perturbative part

$\phi_{S_{A(B)}}$ = azimuthal angle of spin vector $S_{A(B)}$

Structure functions

Unpolarized and single-transversely polarized structure functions

$$F_{UU}^{\eta_Q} \propto \left(\mathcal{C}\left[f_1^g f_1^g\right] - \mathcal{C}\left[w_{UU}\, h_1^{\perp\, g} h_1^{\perp\, g}\right]\right)$$

$$F_{UU}^{\chi_{Q0}} \propto \left(\mathcal{C}\left[f_1^g f_1^g\right] + \mathcal{C}\left[w_{UU}\, h_1^{\perp\, g} h_1^{\perp\, g}\right]\right)$$

$$F_{UU}^{\chi_{Q2}} \propto \mathcal{C}\left[f_1^g f_1^g\right]$$

$$F_{UT}^{\eta_Q,\sin\phi_{S_B}} \propto \left(-\mathcal{C}\left[w_{UT}^f\, f_1^g f_{1T}^{\perp\, g}\right] + \mathcal{C}\left[w_{UT}^h\, h_1^{\perp\, g} h_1^g\right] - \mathcal{C}\left[w_{UT}^{h^\perp}\, h_1^{\perp\, g} h_{1T}^{\perp\, g}\right]\right)$$

$$F_{UT}^{\chi_{Q0},\sin\phi_{S_B}} \propto \left(-\mathcal{C}\left[w_{UT}^f\, f_1^g f_{1T}^{\perp\, g}\right] - \mathcal{C}\left[w_{UT}^h\, h_1^{\perp\, g} h_1^g\right] + \mathcal{C}\left[w_{UT}^{h^\perp}\, h_1^{\perp\, g} h_{1T}^{\perp\, g}\right]\right)$$

$$F_{UT}^{\chi_{Q2},\sin\phi_{S_B}} \propto -\mathcal{C}\left[w_{UT}^f\, f_1^g f_{1T}^{\perp\, g}\right]$$

$$w_{UU} = \frac{\boldsymbol{p}_{aT}^2 \boldsymbol{p}_{bT}^2}{4M_p^4} \cos\left[2(\phi_a - \phi_b)\right]$$

$$w_{UT}^f = \frac{|\boldsymbol{p}_{bT}|}{M_p} \cos\phi_b$$

$$w_{UT}^h = \frac{\boldsymbol{p}_{aT}^2\, |\boldsymbol{p}_{bT}|}{4M_p^3} \cos(\phi_b - 2\phi_a)$$

$$w_{UT}^{h^\perp} = \frac{\boldsymbol{p}_{aT}^2\, |\boldsymbol{p}_{bT}|^3}{8M_p^5} \cos(3\phi_b - 2\phi_a)$$

ϕ_a = azimuthal angle of p_{aT}
ϕ_b = azimuthal angle of p_{bT}

Observables (in principle) measurable with the **LHCSpin project**, a future fixed-target experiment at LHC

Single Spin Asymmetries (SSAs)

Proton A **unpolarized**
Proton B **transversely polarized**

$$A_N^{\mathcal{Q},\sin\phi_S} = 2\frac{\int d\phi_S \sin\phi_S [d\sigma(\phi_S) - d\sigma(\phi_S+\pi)]}{\int d\phi_S [d\sigma(\phi_S) + d\sigma(\phi_S+\pi)]} = \frac{F_{UT}^{\mathcal{Q},\sin\phi_S}}{F_{UU}^{\mathcal{Q}}}$$

Upper bounds for SSAs using **gaussian parameterization**

$$f_1^g(x,\boldsymbol{p}_T^2) = \frac{f_1^g(x)}{\pi\langle p_T^2\rangle}\exp\left[-\frac{\boldsymbol{p}_T^2}{\langle p_T^2\rangle}\right]$$

unpolarized TMD

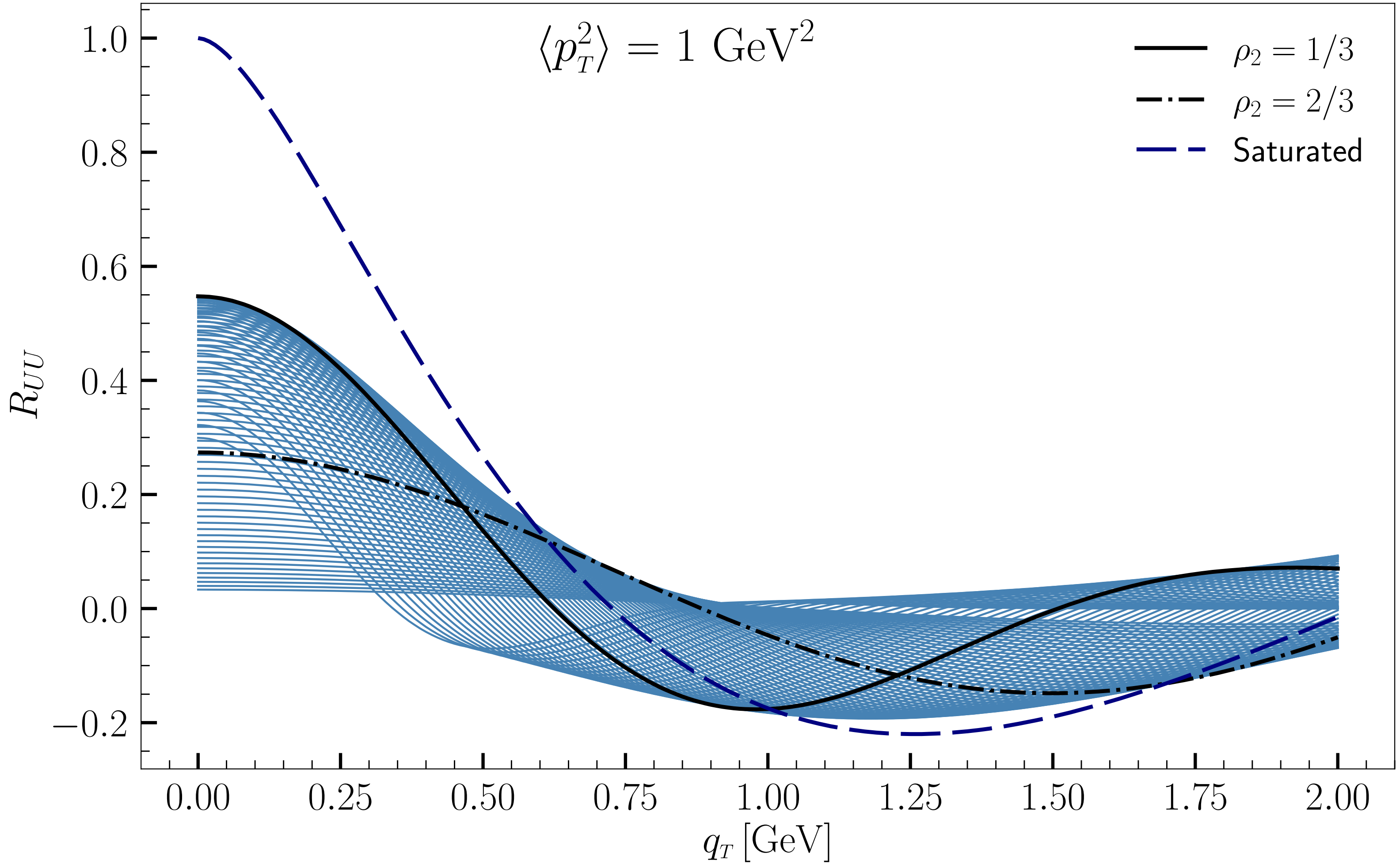
Positivity bounds

$$\left|f_{1T}^{\perp g}(x,\boldsymbol{p}_T^2)\right|,\ \left|h_1^g(x,\boldsymbol{p}_T^2)\right| \le \frac{M_p}{|\boldsymbol{p}_T|} f_1^g(x,\boldsymbol{p}_T^2)\,,$$

$$\frac{1}{2}\left|h_1^{\perp g}(x,\boldsymbol{p}_T^2)\right| \le \frac{M_p^2}{\boldsymbol{p}_T^2} f_1^g(x,\boldsymbol{p}_T^2)\,,$$

$$\frac{1}{2}\left|h_{1T}^{\perp g}(x,\boldsymbol{p}_T^2)\right| \le \frac{M_p^3}{|\boldsymbol{p}_T|^3} f_1^g(x,\boldsymbol{p}_T^2)\,.$$

Numerical results



Relative magnitude of the linearly polarized distribution to the unpolarized TMD

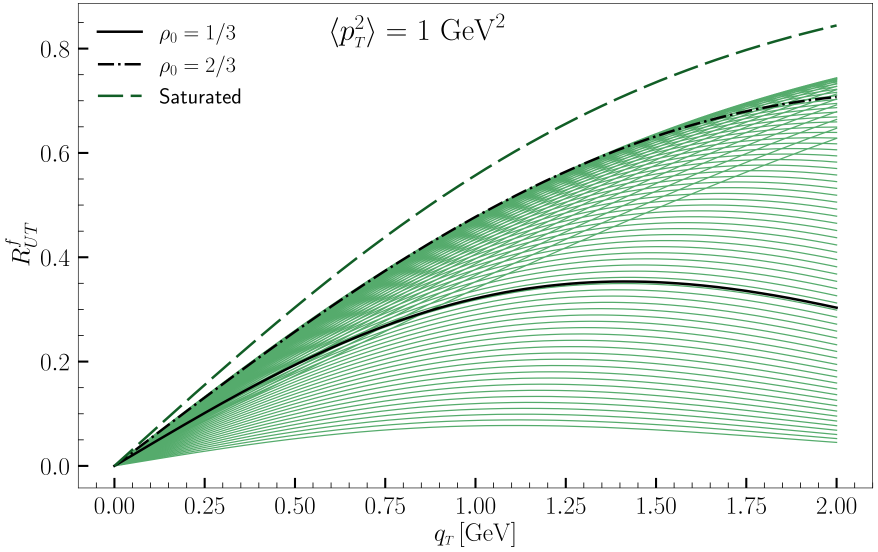
$$R_{UU} = \frac{\mathcal{C}\left[w_{UU}^{h}\, h_1^{\perp\, g}\, h_1^{\perp\, g}\right]}{\mathcal{C}\left[f_1^g\, f_1^g\right]}$$

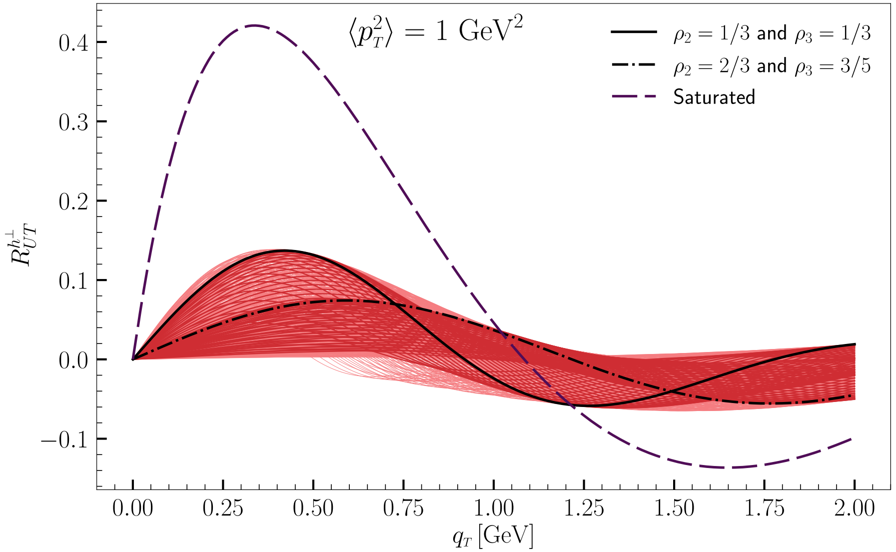
$0.1 < \rho_2 < 0.9$

$\rho_2 \rightarrow h_1^{\perp g}$

Numerical results

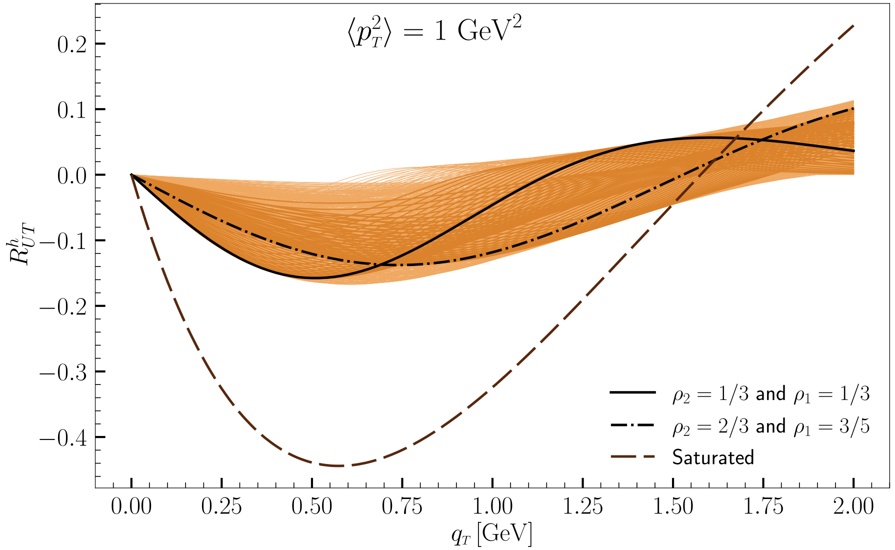
Relative magnitude of the linearly polarized distributions and the Sivers function to the unpolarized TMD





$$R_{UT}^{f} = \frac{\mathcal{C}\left[w_{UT}^{f}\, f_1^{g}\, f_{1T}^{\perp\, g}\right]}{\mathcal{C}\left[f_1^{g}\, f_1^{g}\right]}$$

$$R_{UT}^{h} = \frac{\mathcal{C}\left[w_{UT}^{h}\, h_1^{\perp\, g}\, h_1^{g}\right]}{\mathcal{C}\left[f_1^{g}\, f_1^{g}\right]}$$



$\rho_0 \to f_{1T}^{\perp g}$ Sivers

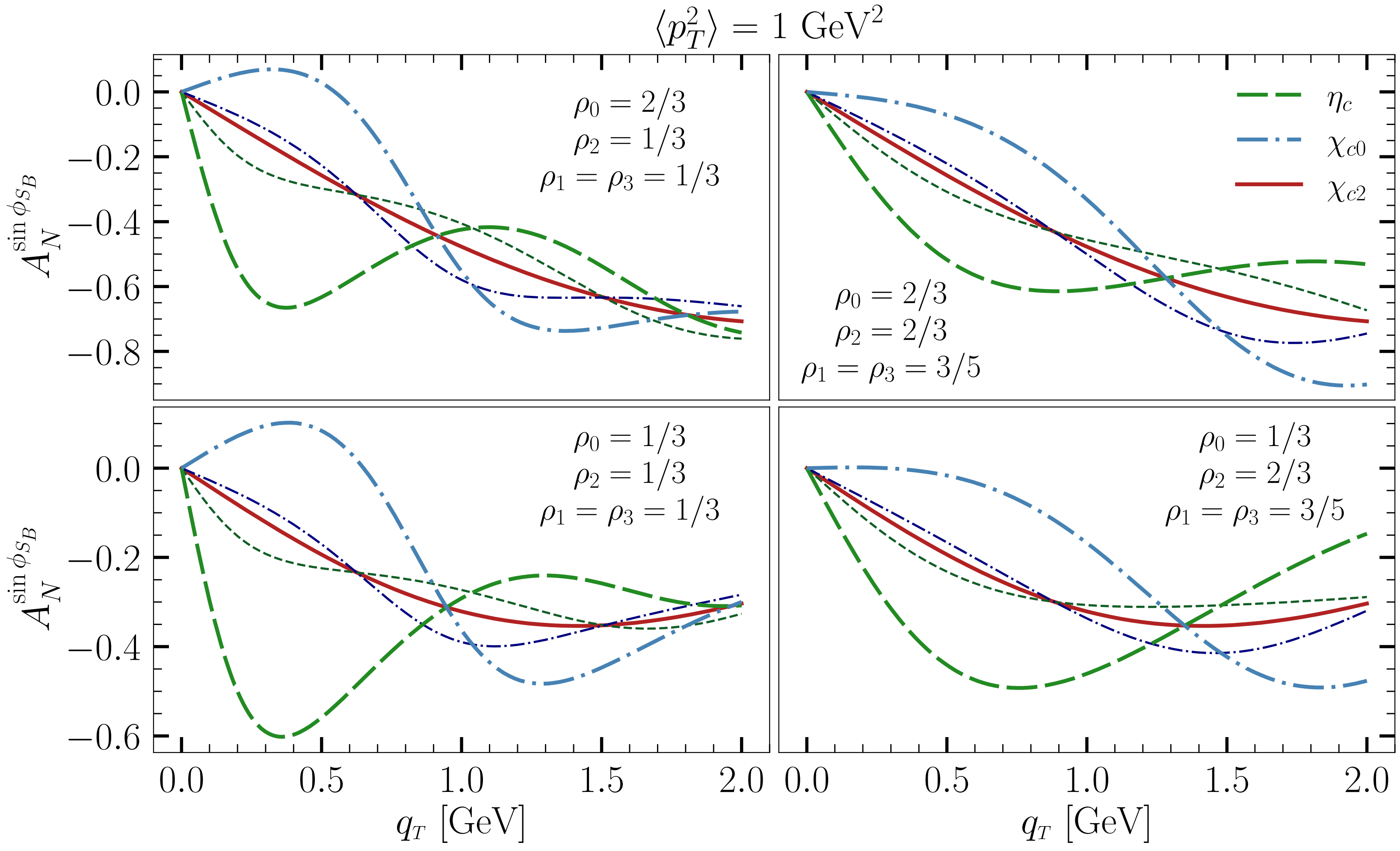
$\rho_1 \to h_1^{g}$

$\rho_2 \to h_1^{\perp g}$ lin. pol.

$\rho_3 \to h_{1T}^{\perp g}$

$$R_{UT}^{h\perp} = \frac{\mathcal{C}\left[w_{UT}^{h\,\perp}\, h_1^{\perp g}\, h_{1T}^{\perp g}\right]}{\mathcal{C}\left[f_1^{g}\, f_1^{g}\right]}$$

Numerical results: upper bounds of SSAs



$$A_N^{\eta_Q, \sin\phi_{S_B}} = \frac{-R_{UT}^f + R_{UT}^h - R_{UT}^{h^\perp}}{1 - R_{UU}}$$

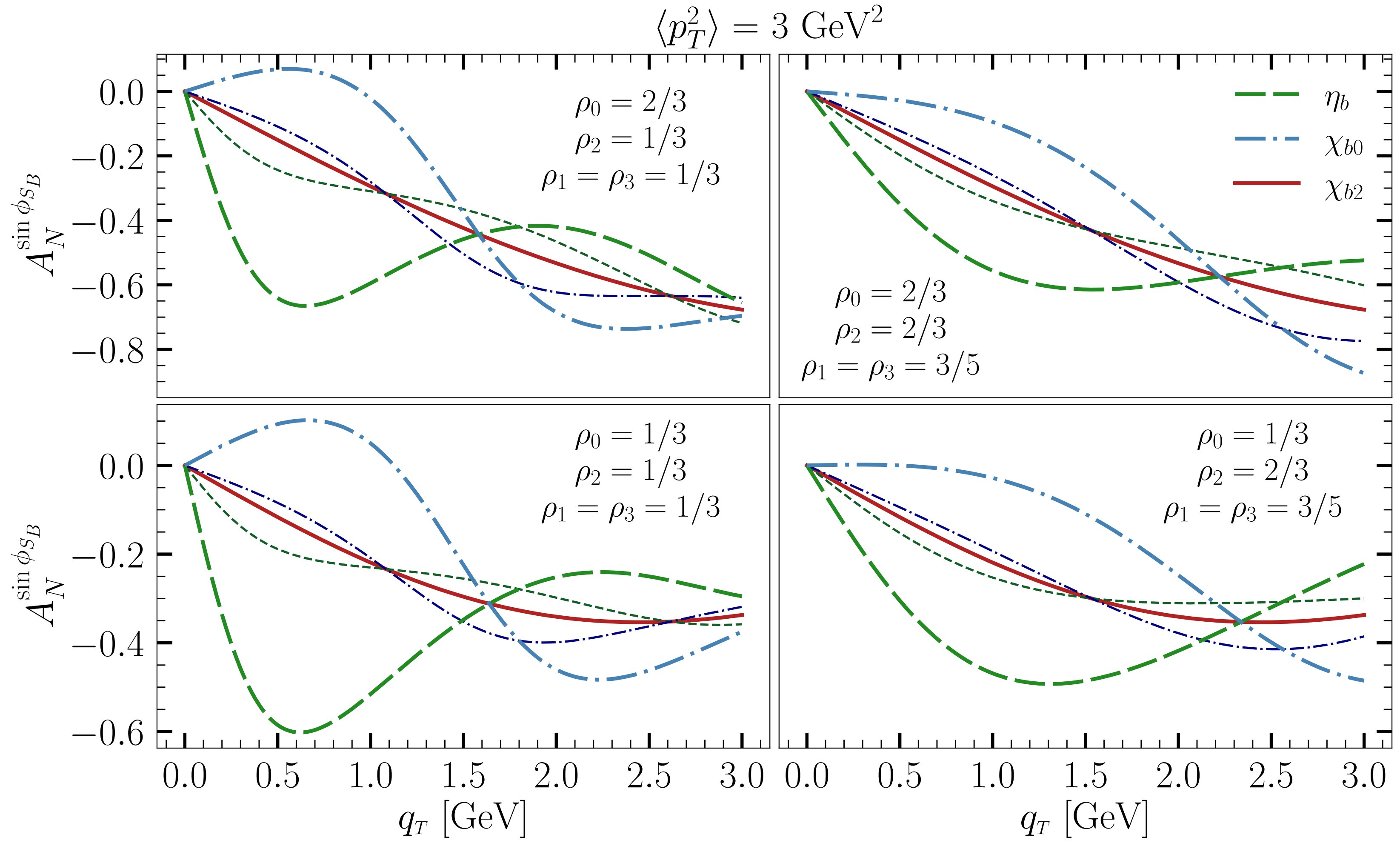
$$A_N^{\chi_{Q0}, \sin\phi_{S_B}} = \frac{-R_{UT}^f - R_{UT}^h + R_{UT}^{h^\perp}}{1 + R_{UU}}$$

$$A_N^{\chi_{Q2}, \sin\phi_{S_B}} = -R_{UT}^f$$

SSAs for χ_{Q2} production entirely driven by the **Sivers function**

By comparing the SSAs for η_Q and χ_{Q0} states with those for χ_{Q2} we can reveal the impact of the combined effects of the linearly polarized gluon TMDs

Numerical results: upper bounds of SSAs



$$A_N^{\eta_Q,\sin\phi_{S_B}} = \frac{-R_{UT}^f + R_{UT}^h - R_{UT}^{h^\perp}}{1 - R_{UU}}$$

$$A_N^{\chi_{Q0},\sin\phi_{S_B}} = \frac{-R_{UT}^f - R_{UT}^h + R_{UT}^{h^\perp}}{1 + R_{UU}}$$

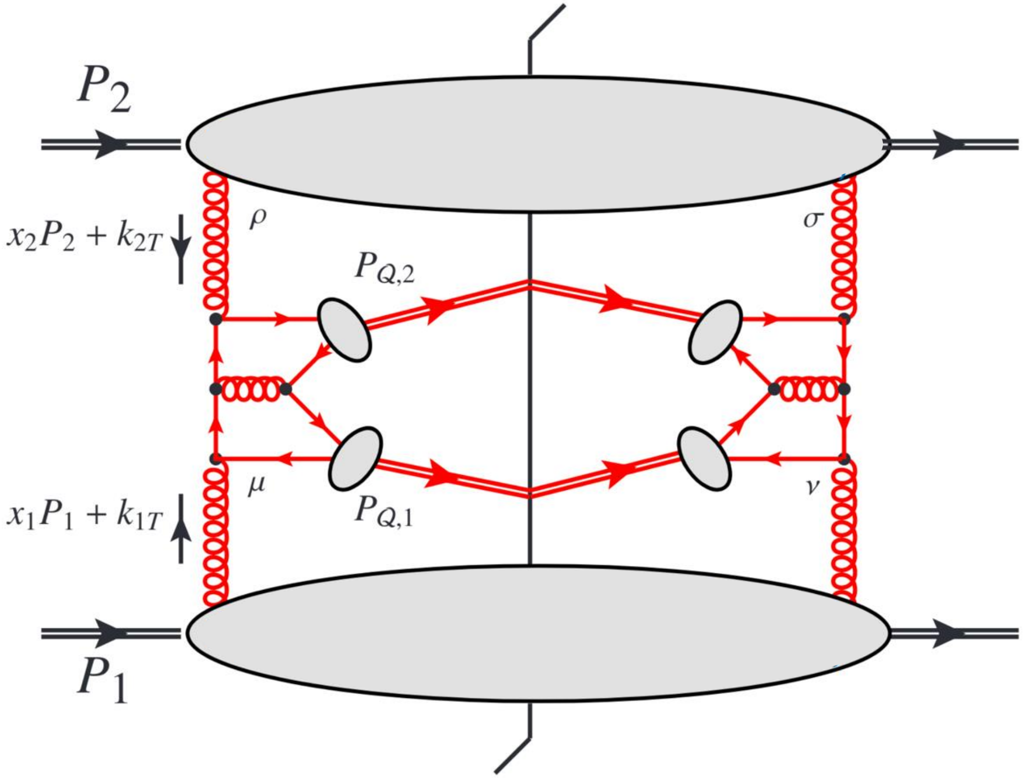
$$A_N^{\chi_{Q2},\sin\phi_{S_B}} = -R_{UT}^f$$

Broader in q_T compared to $\langle p_T^2 \rangle = 1 GeV^2$ SSAs

Di-J/ψ production

Di-J/ψ production

$$p(P_1) + p(P_2) \to \mathcal{Q}(P_{\mathcal{Q},1}) + \mathcal{Q}(P_{\mathcal{Q},2}) + X$$



Advantages:

- **Easily detected**: accessible at LHC
- Already measured by LHCb, CMS, ATLAS
- **2 particles** in the final state
- **Azimuthal asymmetries**: the relative azimuthal angle between two particles provides additional observables

J/ψ pair production in SPS from unpolarized *p*-*p* collision

$$g(k_1) + g(k_2) \to \mathcal{Q}(P_{\mathcal{Q},1}) + \mathcal{Q}(P_{\mathcal{Q},2})$$

Model: NRQCD at LO in v → **C**olor **S**inglet **M**odel (CSM)
J/ψ pair production dominated by the CS mechanism

F. Scarpa, D. Boer, M.G. Echevarria, J.-P. Lansberg, C. Pisano, M Schlegel, EPJC (2020) 80:87

Cross section

Scarpa et al., EPJC (2020) 80:87

Differential cross section: $d\sigma \propto \Gamma_g^{\mu\nu}(x_a, \boldsymbol{p}_{aT})\, \Gamma_g^{\rho\sigma}(x_b, \boldsymbol{p}_{bT})\, \mathcal{A}_{\mu\rho}\, (\mathcal{A}_{\nu\sigma})^*$

Unpolarized gluon correlator: $\Gamma_U^{\mu\nu}(x, \boldsymbol{p}_T) = \frac{1}{2x}\left\{ -g_T^{\mu\nu}\, f_1^g(x, \boldsymbol{p}_T^2) + \left(\frac{p_T^\mu p_T^\nu}{M_h^2} + g_T^{\mu\nu} \frac{\boldsymbol{p}_T^2}{2M_h^2} \right) h_1^{\perp\, g}(x, \boldsymbol{p}_T^2) \right\}$

$$\frac{d\sigma}{dM_{QQ}\, dy_{QQ}\, d^2\boldsymbol{q}_T\, d\Omega} \propto a + b \times \cos(2\phi_{CS}) + c \times \cos(4\phi_{CS})$$

$$a = F_1\, \mathcal{C}[f_1^g f_1^g] + F_2\, \mathcal{C}\,[w_2 h_1^{\perp g} h_1^{\perp g}]$$

$$b = F_3\, \mathcal{C}[w_3 f_1^g h_1^{\perp g}] + F_3'\, \mathcal{C}[w_3' h_1^{\perp g} f_1^g]$$

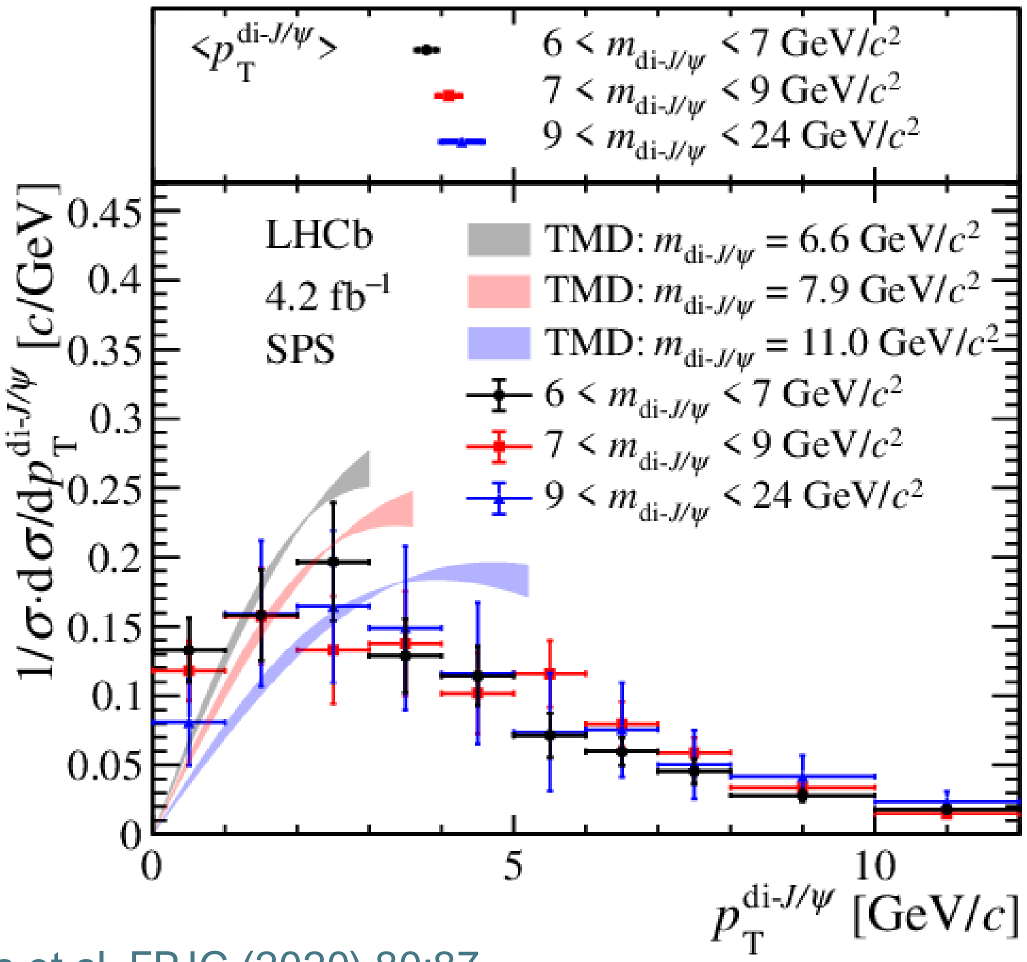
$$c = F_4\, \mathcal{C}[w_4 h_1^{\perp g} h_1^{\perp g}]$$

Cross section calculated in **Collins-Soper** frame:

$d\Omega = d\cos\theta_{CS}\, d\phi_{CS}$

$F_i(\theta_{CS}, M_{QQ})$: hard-scattering coefficients

Di-J/ψ production: normalized p_T spectrum



Average values of the p_T spectrum slightly increase with mass

Prediction: p_T distribution should broaden as M_{QQ} increases

LHCb data: no obvious broadening due to large uncertainties

Scarpa et al, EPJC (2020) 80:87

LHCb collab. JHEP03(2024)088

Azimuthal modulations

If we integrate the CS over ϕ_{CS} we have access to azimuthally independent CS

$$\frac{1}{2\pi}\int d\phi_{CS}\frac{d\sigma}{dM_{QQ}dy_{QQ}d^2\boldsymbol{P}_{QQT}d\Omega} = F_1\mathcal{C}[f_1^g f_1^g] + F_2\mathcal{C}[w_2 h_1^{\perp g} h_1^{\perp g}]$$

Normalized azimuthal modulation

$$\langle\cos(2,4\phi_{CS})\rangle = \frac{\int d\phi_{CS}\cos(2,4\phi_{CS})\frac{d\sigma}{dM_{QQ}dy_{QQ}d^2\boldsymbol{q}_T d\Omega}}{\int d\phi_{CS}\frac{d\sigma}{dM_{QQ}dy_{QQ}d^2\boldsymbol{q}_T d\Omega}}$$

Azimuthally-independent component

$$\langle\cos(2\phi_{CS})\rangle = \frac{1}{2}\frac{F_3(\mathcal{C}[w_3 f_1^g h_1^{\perp g}] + \mathcal{C}[w_3' h_1^{\perp g} f_1^g])}{F_1\mathcal{C}[f_1^g f_1^g] + F_2\mathcal{C}[w_2 h_1^{\perp g} h_1^{\perp g}]} \Longrightarrow f_1^g \otimes h_1^{\perp g}$$

$$\langle\cos(4\phi_{CS})\rangle = \frac{1}{2}\frac{F_4\mathcal{C}[w_4 h_1^{\perp g} h_1^{\perp g}]}{F_1\mathcal{C}[f_1^g f_1^g] + F_2\mathcal{C}[w_2 h_1^{\perp g} h_1^{\perp g}]} \Longrightarrow h_1^{\perp g} \otimes h_1^{\perp g}$$

Azimuthal modulations

Predictions based on

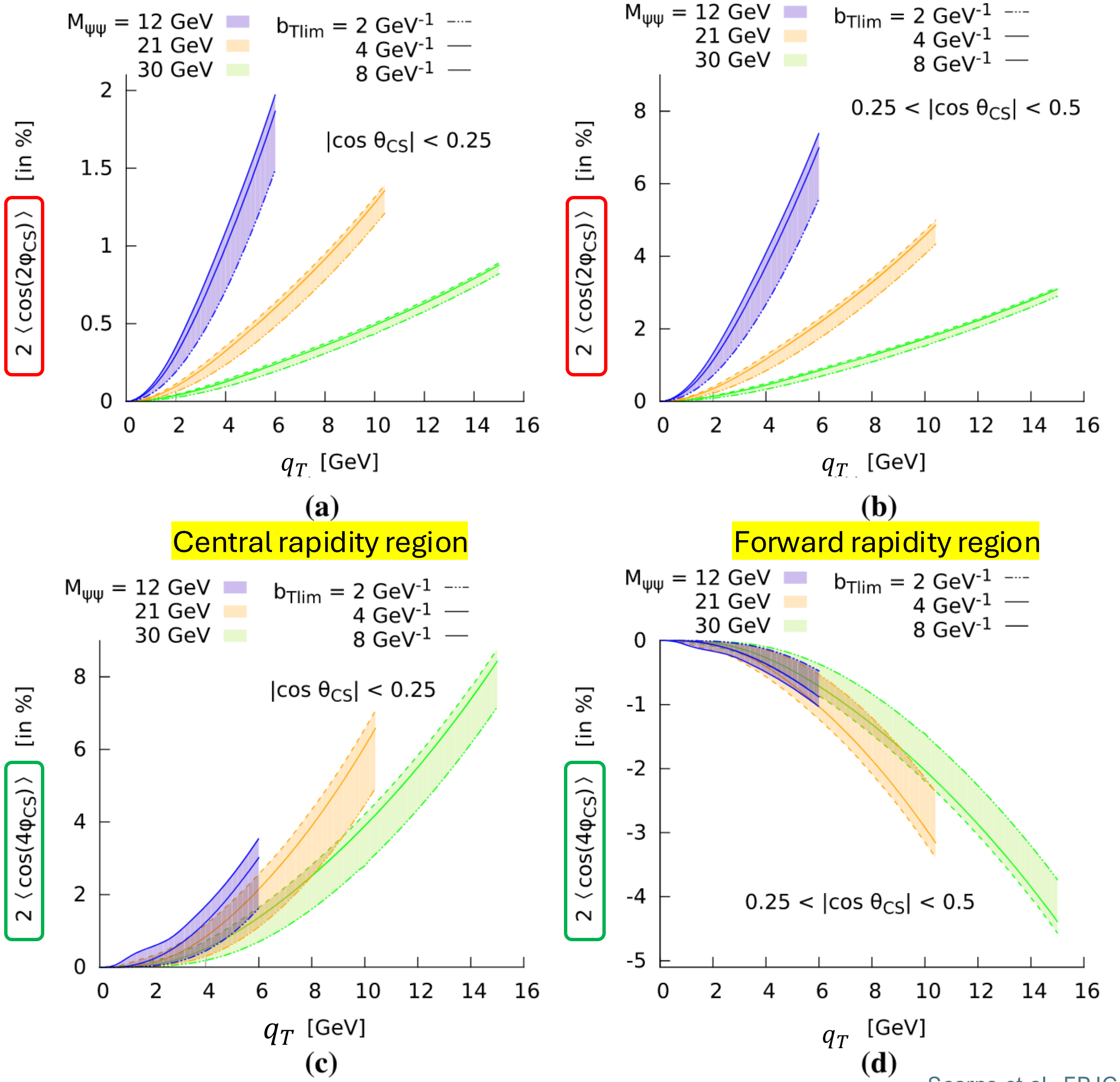
- Color Singlet Model (CSM)
- TMD evolution
- $x_1 \sim x_2 \sim 10^{-3}$

Azimuthal amplitudes ~5%!, increase with q_T

$$\langle\cos(2\phi_{CS})\rangle \simeq \frac{F_3}{F_1}\frac{\mathcal{C}[w_3 f_1^g h_1^{\perp g}]}{\mathcal{C}[f_1^g f_1^g]}$$

$$\langle\cos(4\phi_{CS})\rangle \simeq \frac{1}{2}\frac{F_4}{F_2}\frac{\mathcal{C}[w_4 h_1^{\perp g} h_1^{\perp g}]}{\mathcal{C}[f_1^g f_1^g]}$$

Max value of $\langle\cos 2\phi_{CS}\rangle$ due to F_3/F_1 peak at M_{QQ} = 12 GeV



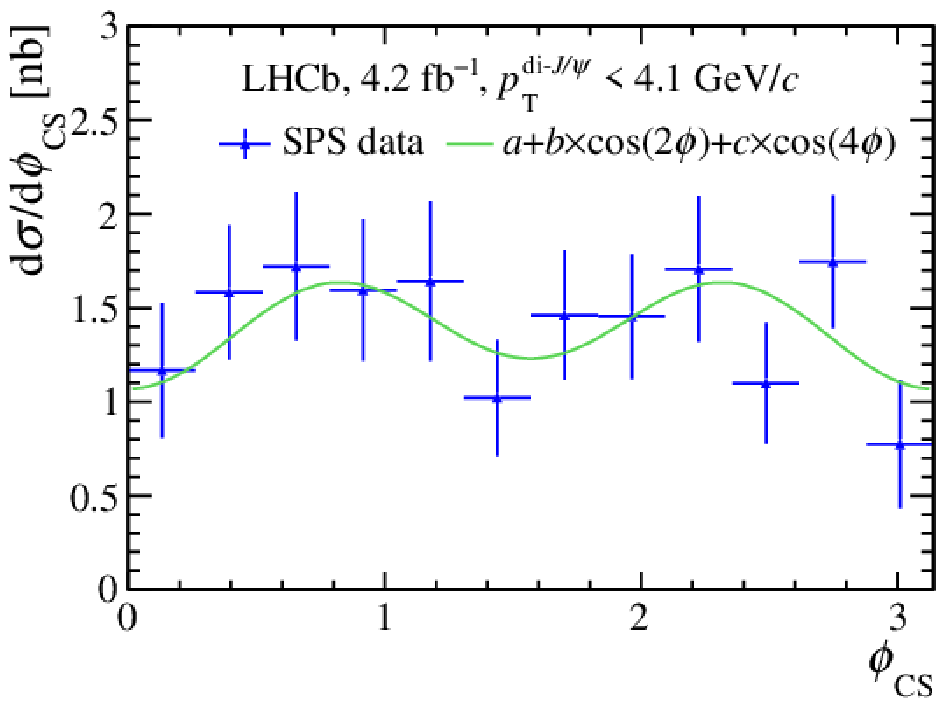
Scarpa et al., EPJC (2020) 80:87

Di-J/ψ production: data from LHCb

LHCb collab. JHEP03(2024)088

Measurement of J/ψ-pair production in pp collisions at $\sqrt{s} = 13$ TeV and study of gluon transverse-momentum dependent PDFs

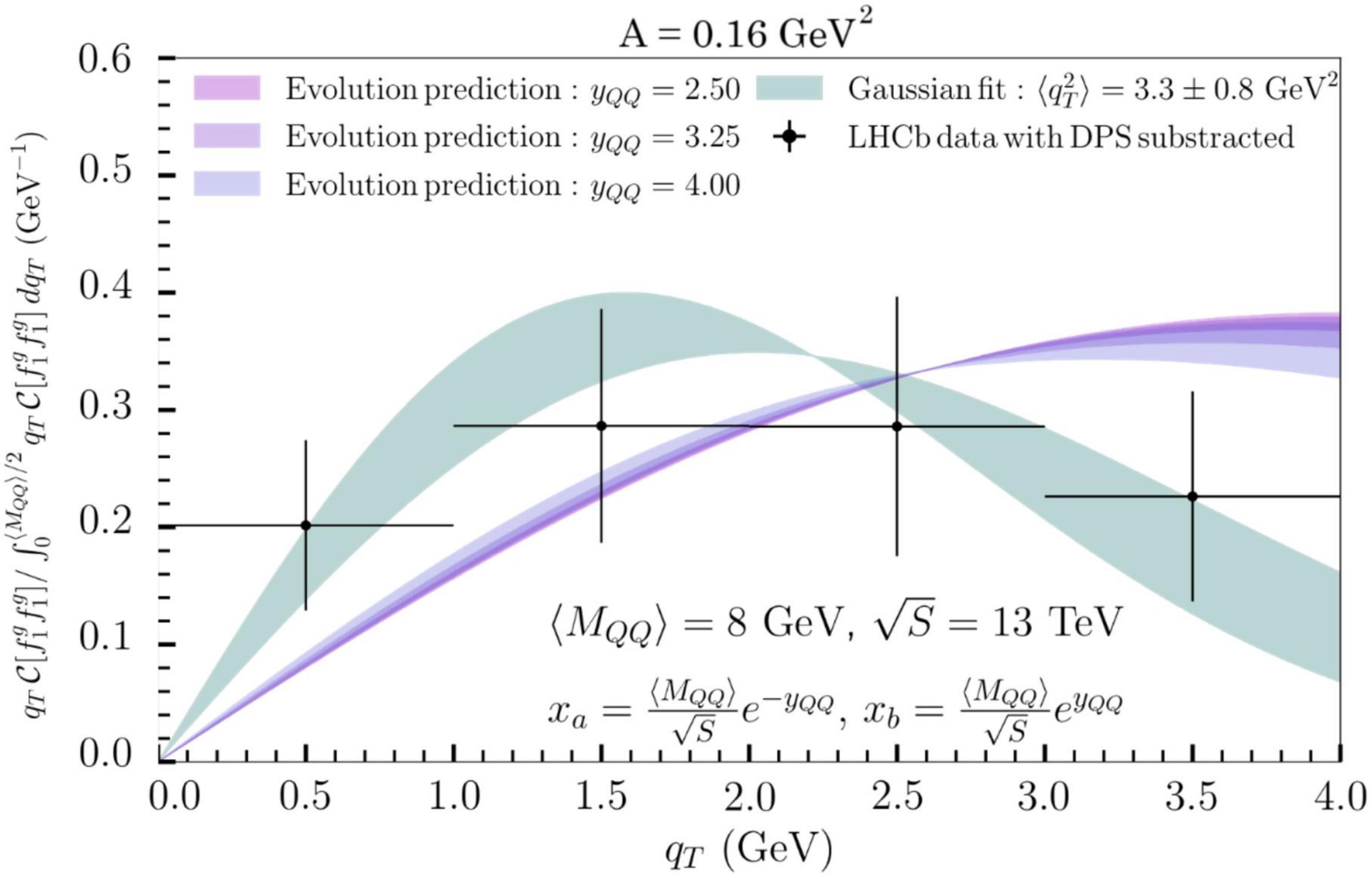
The LHCb collaboration



$$\langle \cos 2\phi_{CS} \rangle = -0.029 \pm 0.050 \text{ (stat)} \pm 0.009 \text{ (syst)}$$
$$\langle \cos 4\phi_{CS} \rangle = -0.087 \pm 0.052 \text{ (stat)} \pm 0.013 \text{ (syst)}$$

The results are consistent with zero, but the presence of an azimuthal asymmetry at a few percent level is allowed.

Di-J/ψ production



Normalized q_T spectrum
for 3 values of rapidity

Fixed invariant mass: $M_{QQ} = 8$ GeV

❗ need to improve prediction
by refining the non-perturbative Sudakov factor

↓

work in progress

A. Colpani Serri, J. Bor, D. Boer, J.-P. Lansberg, PoS(EPS-HEP2023)272

Summary of the talk

- ***C*-even quarkonium production in *p*-*p* collisions**
  - Max values of transverse SSAs for different quarkonium states
  - Asymmetries depend on the parametrization of the gluon TMDs but are independent of the LDMEs
  - Observables measurable at LHCSpin
  - For the future: transverse and longitudinal double-spin asymmetries
- **J/ψ pair production in *p*-*p* collisions**
  - A promising process to investigate gluon TMDs and measure azimuthal asymmetries
  - Further implementation needed refining TMD evolution: work in progress

Thanks for your attention!

Backup slides

Gaussian parametrization of the gluon TMDs

$$f_{1T}^{\perp\,g}(x,\boldsymbol{p}_T^2) = \mathcal{N}_0(x)\,\frac{f_1^g(x)}{\pi\langle p_T^2\rangle^{3/2}}\,M_p\,\sqrt{\frac{2(1-\rho_0)}{\rho_0}}\,\exp\left[\frac{1}{2}-\frac{1}{\rho_0}\,\frac{\boldsymbol{p}_T^2}{\langle p_T^2\rangle}\right]$$

$$h_1^g(x,\boldsymbol{p}_T^2) = \mathcal{N}_1(x)\,\frac{f_1^g(x)}{\pi\langle p_T^2\rangle^{3/2}}\,M_p\,\sqrt{\frac{2(1-\rho_1)}{\rho_1}}\,\exp\left[\frac{1}{2}-\frac{1}{\rho_1}\,\frac{\boldsymbol{p}_T^2}{\langle p_T^2\rangle}\right]$$

$$h_1^{\perp\,g}(x,\boldsymbol{p}_T^2) = 2\,\mathcal{N}_2(x)\,\frac{f_1^g(x)}{\pi\langle p_T^2\rangle^{2}}\,M_p^2\,\frac{(1-\rho_2)}{\rho_2}\,\exp\left[1-\frac{1}{\rho_2}\,\frac{\boldsymbol{p}_T^2}{\langle p_T^2\rangle}\right]$$

$$h_{1T}^{\perp\,g}(x,\boldsymbol{p}_T^2) = 2\,\mathcal{N}_3(x)\,\frac{f_1^g(x)}{\pi\langle p_T^2\rangle^{5/2}}\,M_p^3\,\left[\frac{2(1-\rho_3)}{3\rho_3}\right]^{3/2}\,\exp\left[\frac{3}{2}-\frac{1}{\rho_3}\,\frac{\boldsymbol{p}_T^2}{\langle p_T^2\rangle}\right]$$

$$0<\rho_i<1$$

Gaussian parametrization of the gluon TMDs

$$R_{UU} = \mathcal{C}[w^h_{UU} h_1^{\perp g} h_1^{\perp g}]/\mathcal{C}[f_1^g f_1^g]$$
$$= \frac{1}{16\langle p_T^2\rangle^2} \frac{(1-\rho_2)^2}{\rho_2} (\boldsymbol{q}_T^4 - 8\rho_2 \langle p_T^2\rangle \boldsymbol{q}_T^2 + 8\rho_2^2 \langle p_T^2\rangle^2) \exp\left[2 - \frac{1-\rho_2}{\rho_2} \frac{\boldsymbol{q}_T^2}{2\langle p_T^2\rangle}\right],$$

$$R^f_{UT} = \mathcal{C}[w^f_{UT} f_1^g f_{1T}^{\perp g}]/\mathcal{C}[f_1^g f_1^g]$$
$$= \frac{2}{\langle p_T^2\rangle^{1/2}} \sqrt{\frac{2(1-\rho_0)}{\rho_0}} \left(\frac{\rho_0}{1+\rho_0}\right)^2 |\boldsymbol{q}_T| \exp\left[\frac{1}{2} - \frac{1-\rho_0}{1+\rho_0} \frac{\boldsymbol{q}_T^2}{2\langle p_T^2\rangle}\right],$$

$$R^h_{UT} = \mathcal{C}[w^h_{UT} h_1^{\perp g} h_1^g]/\mathcal{C}[f_1^g f_1^g]$$
$$= \frac{1}{\langle p_T^2\rangle^{3/2}} \sqrt{\frac{2(1-\rho_1)}{\rho_1}} (1-\rho_2) \frac{{\rho_1}^2 \rho_2^2}{(\rho_1+\rho_2)^4} |\boldsymbol{q}_T| (\boldsymbol{q}_T^2 - 2(\rho_1+\rho_2)\langle p_T^2\rangle) \exp\left[\frac{3}{2} - \frac{2-\rho_1-\rho_2}{\rho_1+\rho_2} \frac{\boldsymbol{q}_T^2}{2\langle p_T^2\rangle}\right],$$

$$R^{h\perp}_{UT} = \mathcal{C}[w^{h\perp}_{UT} h_1^{\perp g} h_{1T}^{\perp g}]/\mathcal{C}[f_1^g f_1^g]$$
$$= \frac{1}{\langle p_T^2\rangle^{5/2}} \left[\frac{2(1-\rho_3)}{3\rho_3}\right]^{3/2} (1-\rho_2) \frac{\rho_2^2 \rho_3^4}{(\rho_2+\rho_3)^6} |\boldsymbol{q}_T| (\boldsymbol{q}_T^4 - 6(\rho_2+\rho_3)\langle p_T^2\rangle \boldsymbol{q}_T^2 + 6(\rho_2+\rho_3)^2 \langle p_T^2\rangle^2)$$
$$\times \exp\left[\frac{5}{2} - \frac{2-\rho_2-\rho_3}{\rho_2+\rho_3} \frac{\boldsymbol{q}_T^2}{2\langle p_T^2\rangle}\right],$$

$0 < \rho_i < 1$

The LHCSpin project

Run 2	Run 3	Run 4
(2017-19)	(2022-24)	(2028-)

The project: implementation of a new-generation **fixed target polarized gas** in the LHCb spectrometer allowing spin physics at LHC for the first time

Goals:

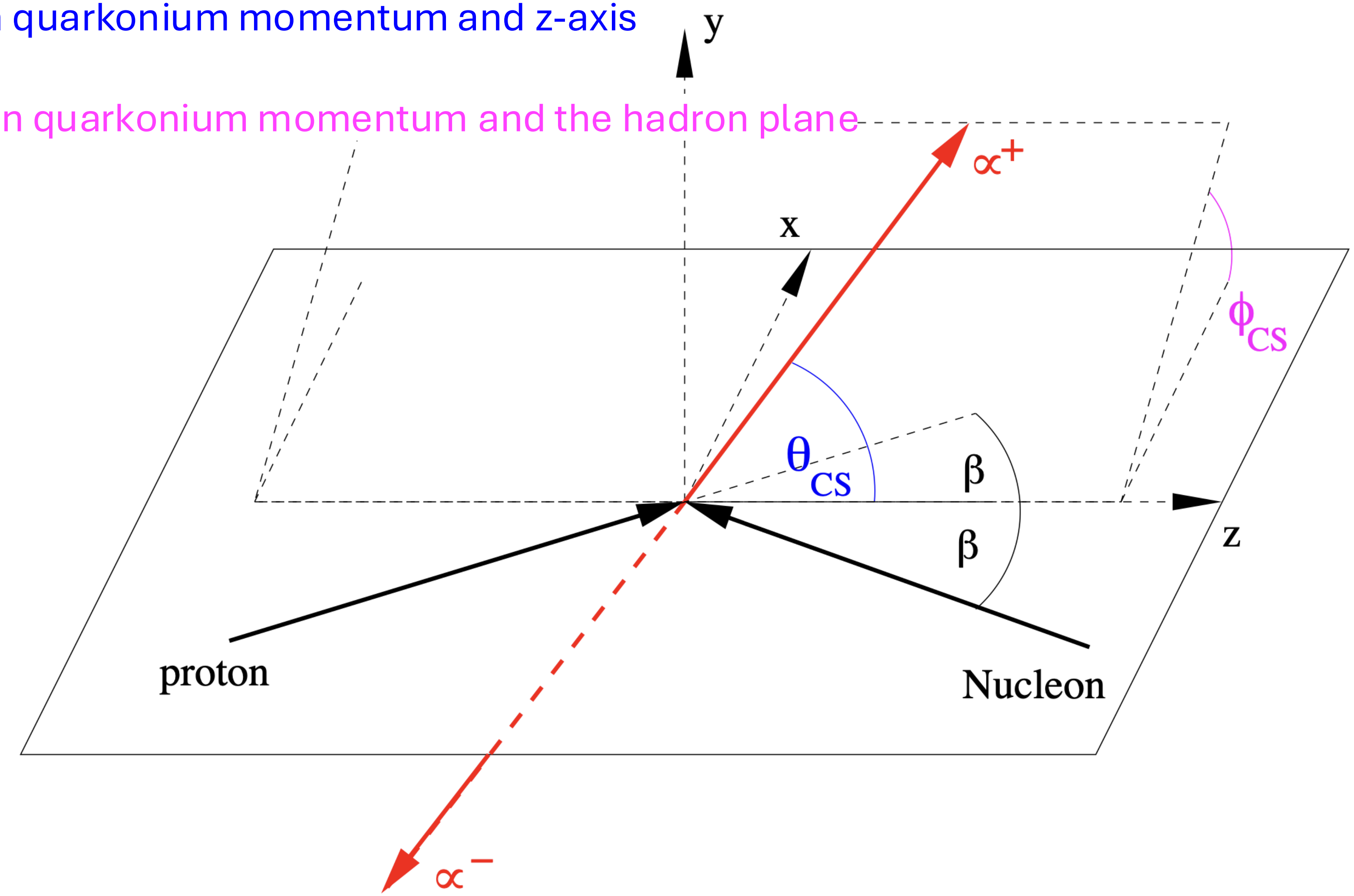
- Use of various unpolarized gases: investigate **PDFs** in both nucleons and nuclei
- Measure experimental observables sensitive to both **polarized quarks and gluons TMDs**
- Heavy-ion collisions: probe **Quark-Gluon Plasma** (QGP) properties

L. Pappalardo et al., *Nuovo Cim.C* 47 (2024) 4, 235
P. Di Nezza et al., PoS (PSTP2022)001

Collins-Soper frame

θ_{CS} = angle between quarkonium momentum and z-axis

ϕ_{CS} = angle between quarkonium momentum and the hadron plane



J. Kessler, PhD thesis (2007)

TMD evolution formalism

☞ Implemented in the **impact parameter space** (b_T)
Expression of the convolution:

$$\mathcal{C}[w\, f\, g](x_1, x_2, \boldsymbol{q}_T, Q) = \int_0^\infty \frac{db_T}{2\pi} b_T^n J_m(b_T\, q_T) e^{-S_A(b_T^*, Q^2, Q)} e^{-S_{NP}(bT, Q)} \hat{f}(x_1, b_T^*, \mu_b^2, \mu_b) \hat{g}(x_2, b_T^*, \mu_b^2, \mu_b)$$

Perturbative Sudakov factor

Bessel function of order m

Non-perturbative Sudakov factor

Typical choice for S_{NP} parametrization → **Gaussian**

$$S_{NP} = A \ln\left(\frac{Q}{Q_{NP}}\right) b_T^2 \qquad \text{with } Q_{NP} = 1 \text{ GeV}$$

EPJC (2020) 80:87

TMD evolution formalism

TMD convolutions in b_T-space

$$\mathcal{C}\left[f_1^g f_1^g\right] = \int_0^\infty \frac{db_T}{2\pi}\, b_T J_0(b_T q_T)\, e^{-S_A(b_T^*; M_{\mathcal{Q}\mathcal{Q}}^2, M_{\mathcal{Q}\mathcal{Q}})}\, e^{-S_{\rm NP}(b_c)}\, \tilde{f}_1^g(x_1, b_T^{*\,2}; \mu_b^2, \mu_b)\, \tilde{f}_1^g(x_2, b_T^{*\,2}; \mu_b^2, \mu_b)$$

$$\mathcal{C}\left[w_2\, h_1^{\perp\, g} h_1^{\perp\, g}\right] = \int_0^\infty \frac{db_T}{2\pi}\, b_T J_0(b_T q_T)\, e^{-S_A(b_T^*; M_{\mathcal{Q}\mathcal{Q}}^2, M_{\mathcal{Q}\mathcal{Q}})}\, e^{-S_{\rm NP}(b_c)}\, \tilde{h}_1^{\perp\, g}(x_1, b_T^{*\,2}; \mu_b^2, \mu_b)\, \tilde{h}_1^{\perp\, g}(x_2, b_T^{*\,2}; \mu_b^2, \mu_b)$$

$$\mathcal{C}\left[w_3\, f_1^g h_1^{\perp\, g}\right] = \int_0^\infty \frac{db_T}{2\pi}\, b_T J_2(b_T q_T)\, e^{-S_A(b_T^*; M_{\mathcal{Q}\mathcal{Q}}^2, M_{\mathcal{Q}\mathcal{Q}})}\, e^{-S_{\rm NP}(b_c)}\, \tilde{f}_1^g(x_1, b_T^{*\,2}; \mu_b^2, \mu_b)\, \tilde{h}_1^{\perp\, g}(x_2, b_T^{*\,2}; \mu_b^2, \mu_b)$$

$$\mathcal{C}\left[w_4\, h_1^{\perp\, g} h_1^{\perp\, g}\right] = \int_0^\infty \frac{db_T}{2\pi}\, b_T J_4(b_T q_T)\, e^{-S_A(b_T^*; M_{\mathcal{Q}\mathcal{Q}}^2, M_{\mathcal{Q}\mathcal{Q}})}\, e^{-S_{\rm NP}(b_c)}\, \tilde{h}_1^{\perp\, g}(x_1, b_T^{*\,2}; \mu_b^2, \mu_b)\, \tilde{h}_1^{\perp\, g}(x_2, b_T^{*\,2}; \mu_b^2, \mu_b)$$

EPJC (2020) 80:87