Gluon TMDs from quarkonium production

in collaboration with L. Maxia, C. Pisano

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Outline

- Introduction
- Gluon TMDs
- C-even quarkonium production
- Results
- Summary

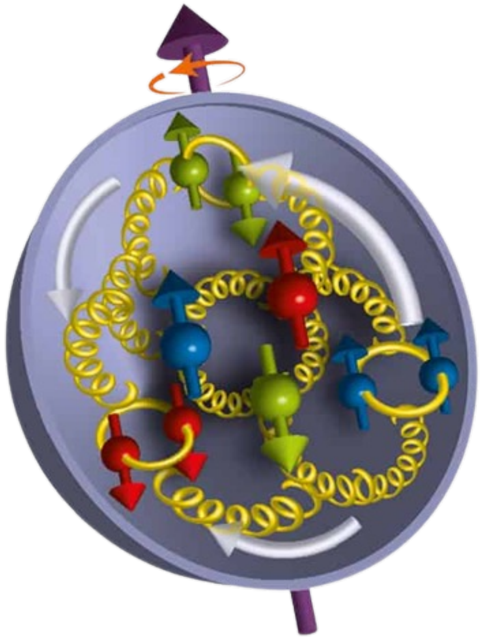
Introduction

- Studying the production of *C*-even **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

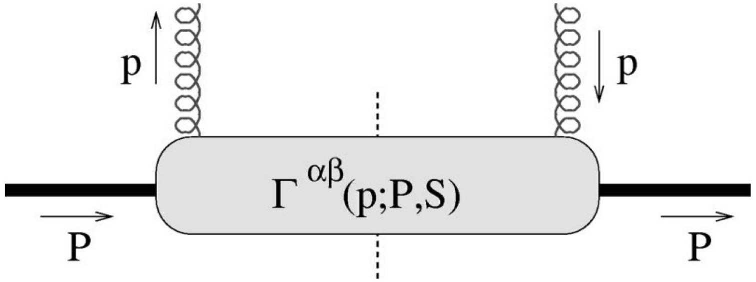
- TMD factorization + NRQCD

- Single spin asymmetries (SSAs)



Gluon TMDs

Gluon correlator



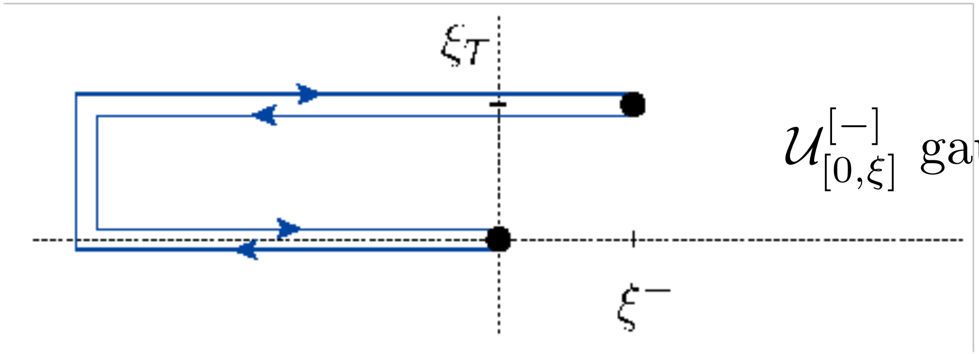
Mulders, Rodrigues, PRD 63 (2001)
Buffing, Mukherjee, Mulders, PRD 88 (2013)
Boer, Cotogno, Van Daal, Mulders, Signori, Zhou, JHEP 1610 (2016)

Gauge invariant definition of the gluon correlator

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

Gauge link:

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



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

Twist-2 gluon TMDs

Parametrization of correlators

Twist-2 gluon TMDs

Parametrization of correlators

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

Twist-2 gluon TMDs

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

Twist-2 gluon TMDs

Parametrization of correlators

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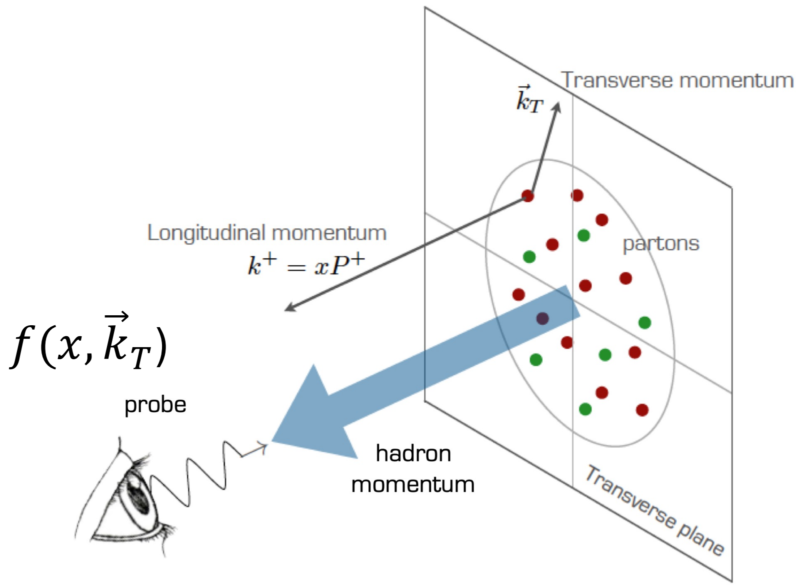
$$\Gamma_T^{\mu\nu}(x,\boldsymbol{p}_T) = \frac{1}{2x}\left\{ g_T^{\mu\nu}\,\frac{\epsilon_T^{p_T S_T}}{M_h}\, f_{1T}^{\perp\, g}(x,\boldsymbol{p}_T^2) \,+\, i\epsilon_T^{\mu\nu}\,\frac{p_T\cdot S_T}{M_h}\, g_{1T}^{\perp\, g}(x,\boldsymbol{p}_T^2) \,-\, \frac{\epsilon_T^{p_T\{\mu} S_T^{\nu\}} \,+\, \epsilon_T^{S_T\{\mu}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

Twist-2 gluon TMDs



A. Bacchetta

Nucleon Spin — Gluon Operator Helicities

Nucleon Polarization	Gluon Operator Polarization: Un-Polarized	Gluon Operator Polarization: Helicity 0 antisymmetric	Gluon Operator Polarization: Helicity 2
U	f_1^g = ; Unpolarized		$h_1^{\perp g}$ = + ; Linearly Polarized
L		g_{1L}^g = − ; Helicity	$h_{1L}^{\perp g}$ = + ; Worm-gear L
T	$f_{1T}^{\perp g}$ = − ; Sivers	$g_{1T}^{\perp g}$ = − ; Worm-gear T	h_{1T}^g = + ; Transversity; $h_{1T}^{\perp g}$ = +

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

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

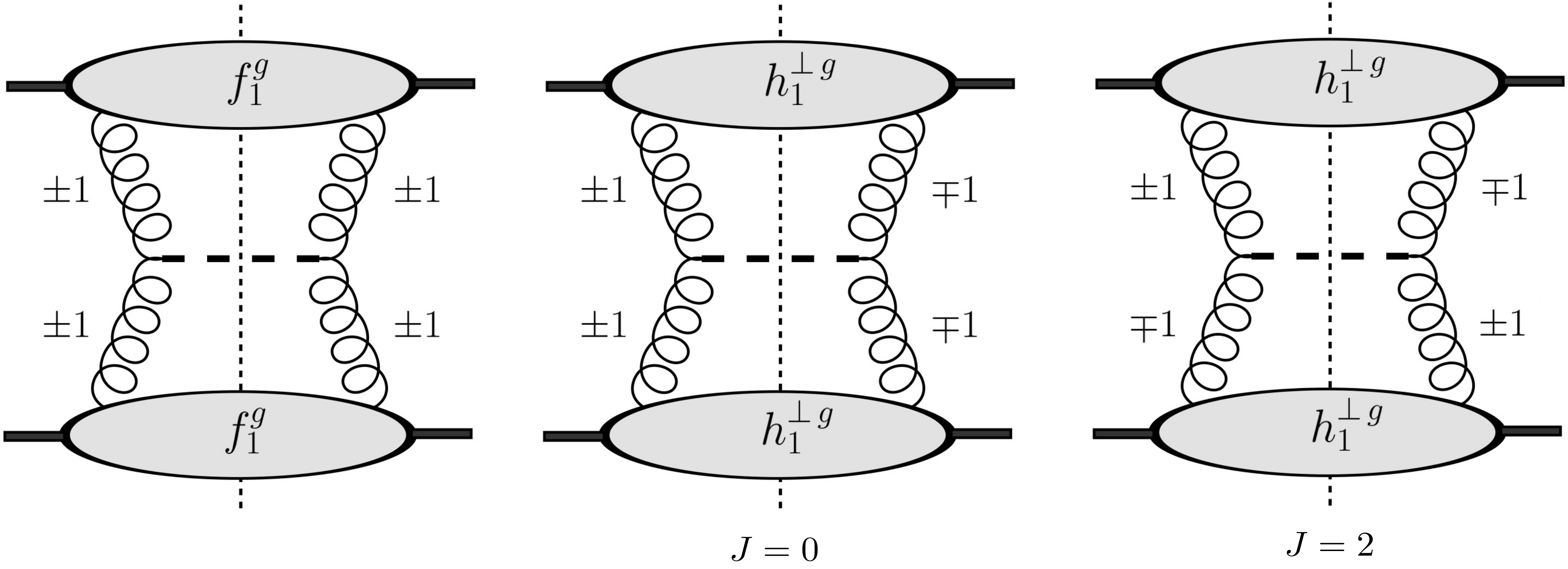
$h_{1T}^g, h_{1T}^{\perp g}$: helicity flip distributions

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

Angeles-Martinez et al., Acta Phys., Pol B46 (2015)
Boussarie, R, et al. "TMD handbook."

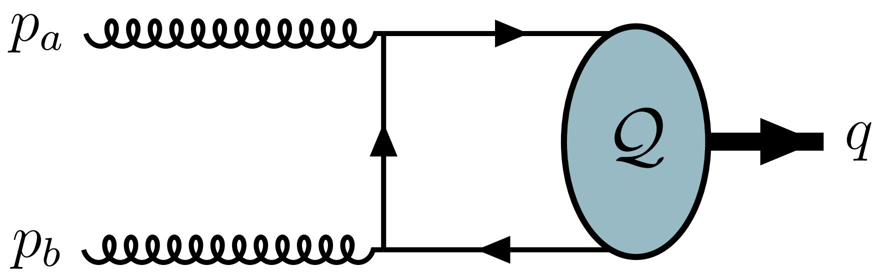
Twist-2 gluon TMDs

Gluon helicities in the squared amplitude for J=0 and J=2 quarkonium production



Boer, Pisano, PRD 86 (2012)

Non-Relativistic QCD



[Bodwin, Braaten, Lepage, PRD 51 (1995)](#)

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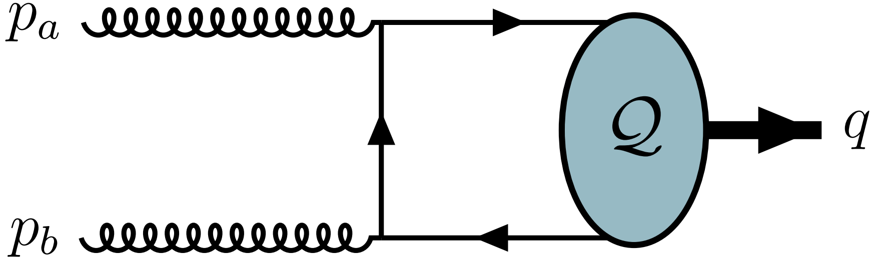
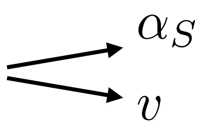


Non-Relativistic QCD (NRQCD)

- Double power series expansion



Bodwin, Braaten, Lepage, PRD 51 (1995)

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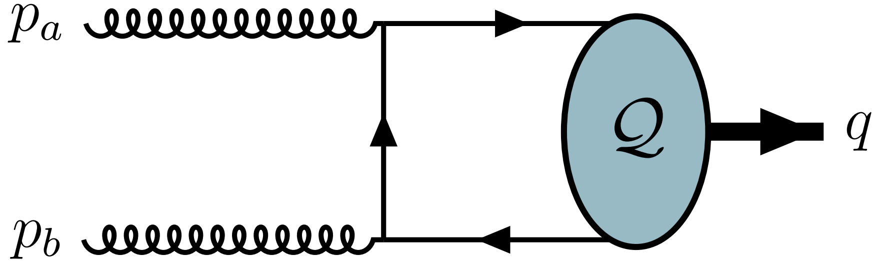

Non-Relativistic QCD (NRQCD)

- Double power series expansion → α_S, v
- Hard process calculated perturbatively

Bodwin, Braaten, Lepage, PRD 51 (1995)

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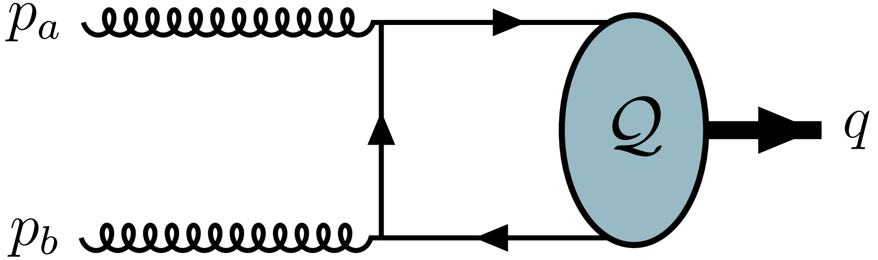

Non-Relativistic QCD (NRQCD)

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

In the kinematic region where the transverse momentum q_T of the produced quarkonium state is much smaller than its invariant mass, namely $q_T \ll M$, TMD factorization is expected to be applicable

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

Bodwin, Braaten, Lepage, PRD 51 (1995)

C-even quarkonia

C-even quarkonia

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

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

C-even quarkonia

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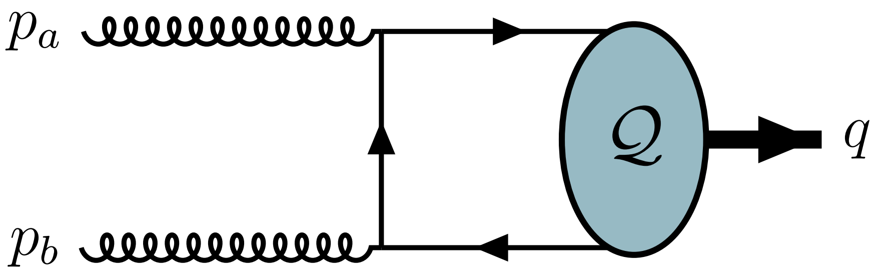
The leading order diagram is the **gluon-gluon fusion**:



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

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

Amplitude using NRQCD

General expression for the amplitudes:

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

Calculable in pQCD
Contains the LDME

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

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

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

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

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

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

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

Perturbative short-distance coefficients

Long distance matrix elements (LDME)

Cross sections: UU

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$$\frac{d\sigma(\eta_{\mathcal{Q}})}{dyd^2\boldsymbol{q}_T} \propto \mathcal{C}[f_1^g f_1^g][1 - R(\boldsymbol{q}_T^2)]$$

$$\frac{d\sigma(\chi_{\mathcal{Q}0})}{dyd^2\boldsymbol{q}_T} \propto \mathcal{C}[f_1^g f_1^g][1 + R(\boldsymbol{q}_T^2)]$$

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

$$R(\boldsymbol{q}_T^2) \equiv \frac{\mathcal{C}[w h_1^{\perp g} h_1^{\perp g}]}{\mathcal{C}[f_1^g f_1^g]}$$

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

Boer, Pisano, PRD 86 (2012)

Cross sections: UU

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

Boer, Pisano, PRD 86 (2012)

The **convolution** is defined as:

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

Results: cross sections

Cross section computed for all combinations of initial proton polarizations:
UU, UT, TU, UL, LU, LT, TL, TT, LL

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

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

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Cross section computed for all combinations of initial proton polarizations:

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Structure functions

Structure functions

Unpolarized and single-transversely polarized structure functions

Structure functions

Unpolarized and single-transversely polarized structure functions

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

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

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

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

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

Structure functions

Unpolarized and single-transversely polarized structure functions

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

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

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

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

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

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

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

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

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

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

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Unpolarized and single-transversely polarized structure functions

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

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

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

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

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

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

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

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

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

Observable measurable at **LHCSpin project**, a fixed target experiment planned at LHCb

The LHCSpin project

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:

- Multi-dimensional nucleon structure in a previously unexplored kinematic region at LHC energies
- Measure experimental observables sensitive to both **polarized quarks and gluons TMDs, PDFs,** and **GPDs**
- Heavy-ion physics: probe collective phenomena in heavy-light systems through **ultra-relativistic collisions** of heavy nuclei with transv. pol. deuterons

Evolution of fixed target systems at LHCb:

L. Pappalardo et al., Nuovo Cim.C 47 (2024) 4, 235
P. Di Nezza et al., PoS (PSTP2022)001
A. Accardi et al. arXiv:2504.16034 (2025)

Luciano's talk

Single-Spin Asymmetries (SSAs)

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

Single-Spin Asymmetries (SSAs)

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

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

Independent from LDMEs

Single-Spin Asymmetries (SSAs)

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Independent from LDMEs

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

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

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

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

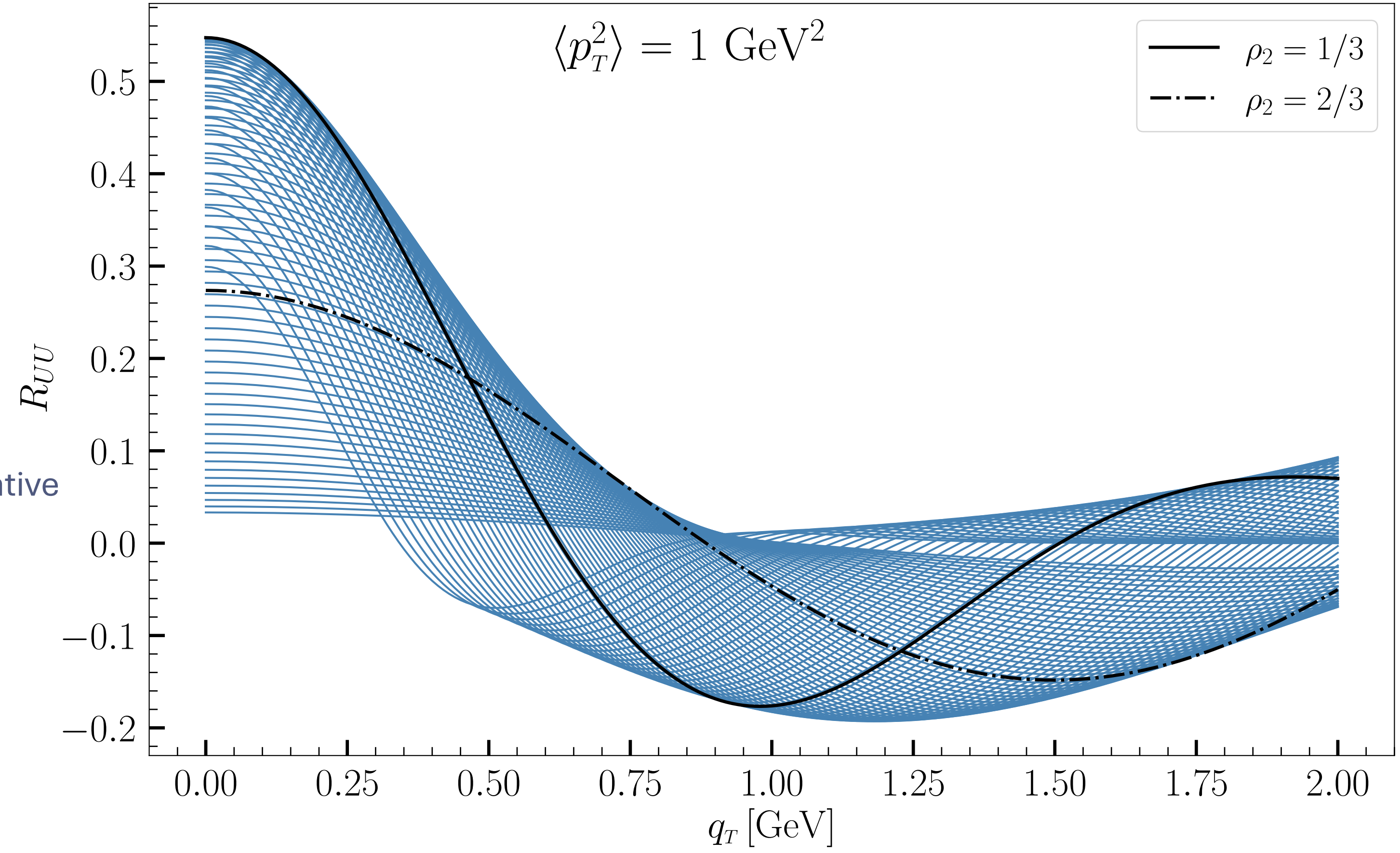
Numerical results

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

$$0.1 < \rho_2 < 0.9$$

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

Numerical results



R_{UU}: measures the relative value of the linearly polarized distribution over the unpolarized distribution

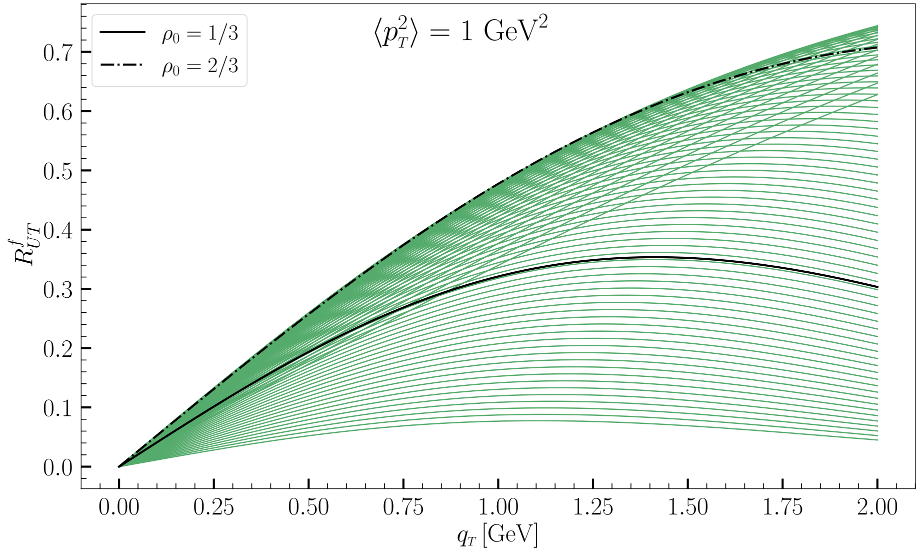
$$R_{UU} = \frac{\mathcal{C}\left[w_{UU}^{h}\, h_1^{\perp\, g}\, h_1^{\perp\, g}\right]}{\mathcal{C}\left[f_1^g\, f_1^g\right]}$$

$$0.1 < \rho_2 < 0.9$$

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

Numerical results

Relative value of the linearly polarized distribution and the Sivers function with respect to the unpolarized distribution



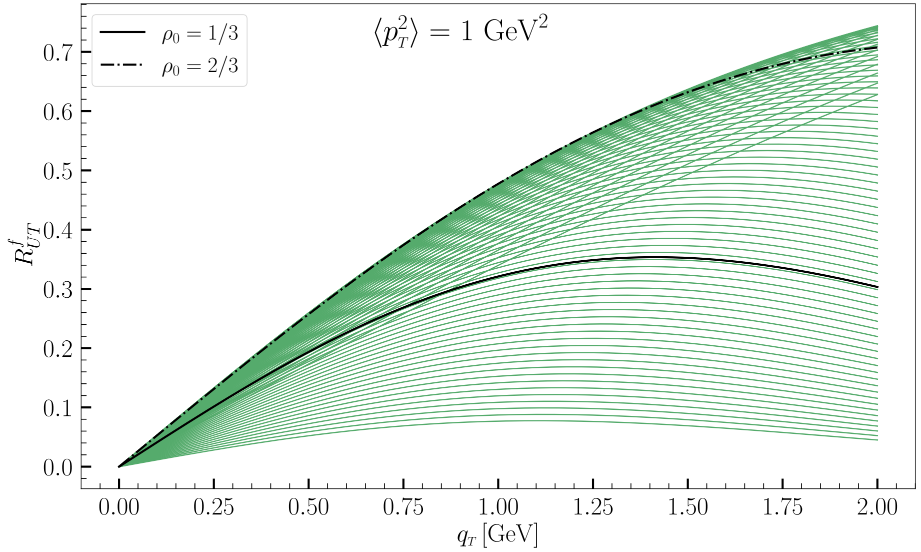
$$R_{UT}^f = \frac{\mathcal{C}\left[w_{UT}^f\, f_1^g\, f_{1T}^{\perp g}\right]}{\mathcal{C}\left[f_1^g\, f_1^g\right]}$$

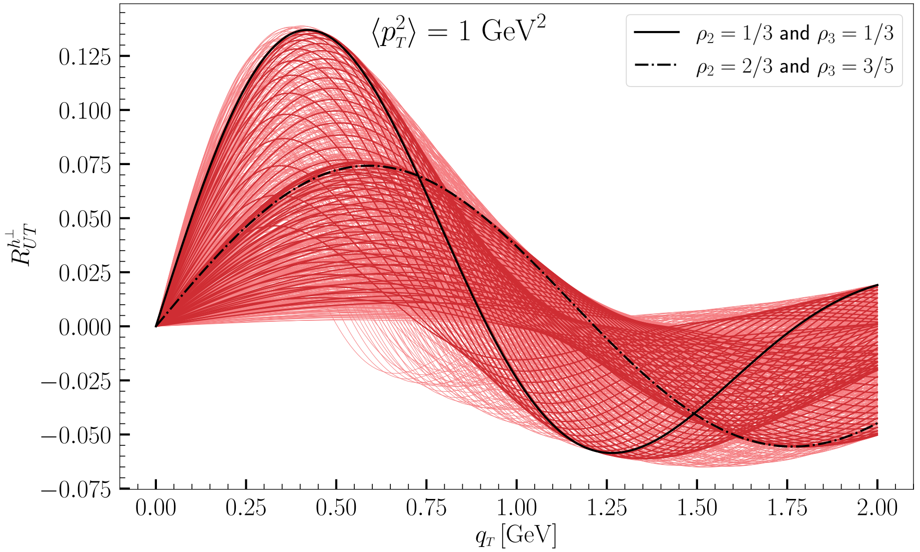
$$0.1 < \rho_0 < 0.9$$

$\rho_0 \rightarrow f_{1T}^{\perp g}$ Sivers
$\rho_1 \rightarrow h_1^g$
$\rho_2 \rightarrow h_1^{\perp g}$ lin. pol.
$\rho_3 \rightarrow h_{1T}^{\perp g}$

Numerical results

Relative value of the linearly polarized distribution and the Sivers function with respect to the unpolarized distribution





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

$0.1 < \rho_0 < 0.9$

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

$0.1 < \rho_3 < 0.9$ for thicker lines

$\rho_0 \rightarrow f_{1T}^{\perp g}$ Sivers
$\rho_1 \rightarrow h_1^{g}$
$\rho_2 \rightarrow h_1^{\perp g}$ lin. pol.
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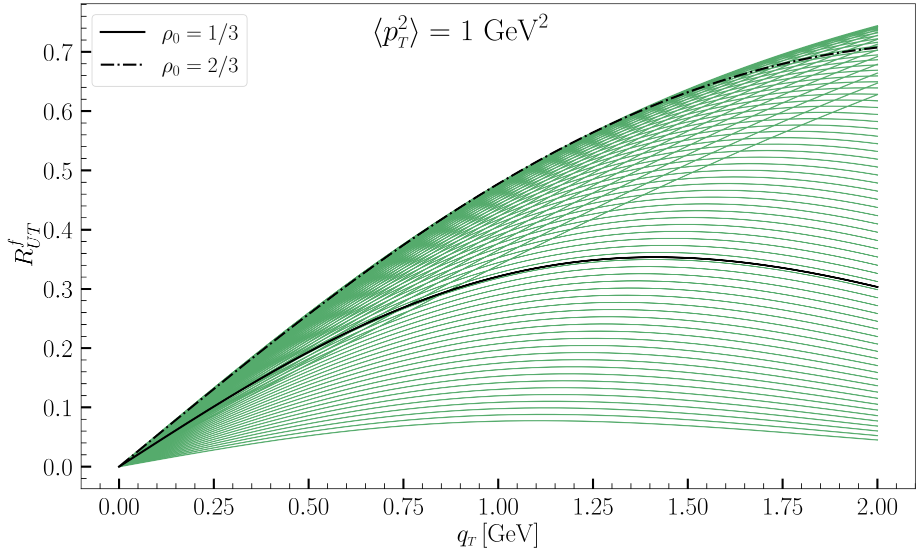
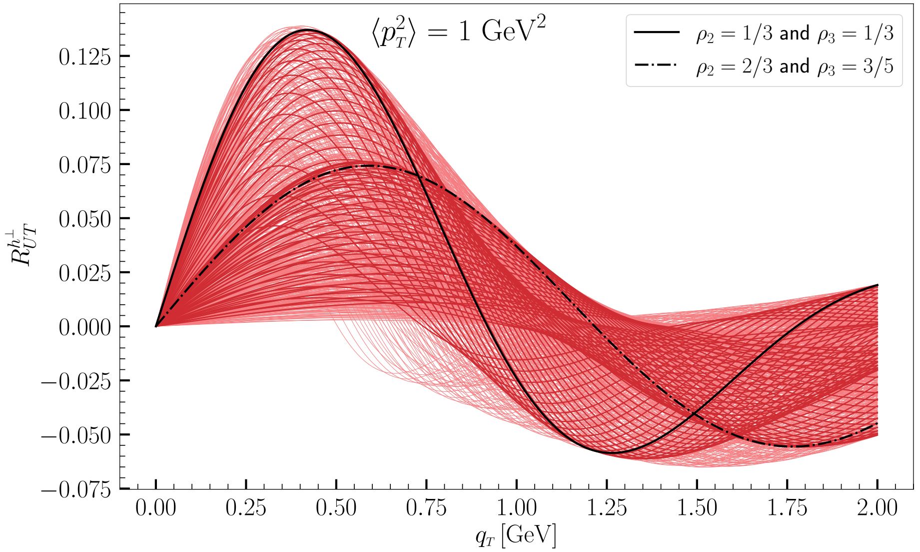
Numerical results

Relative value of the linearly polarized distribution and the Sivers function with respect to the unpolarized distribution





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

$0.1 < \rho_0 < 0.9$

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

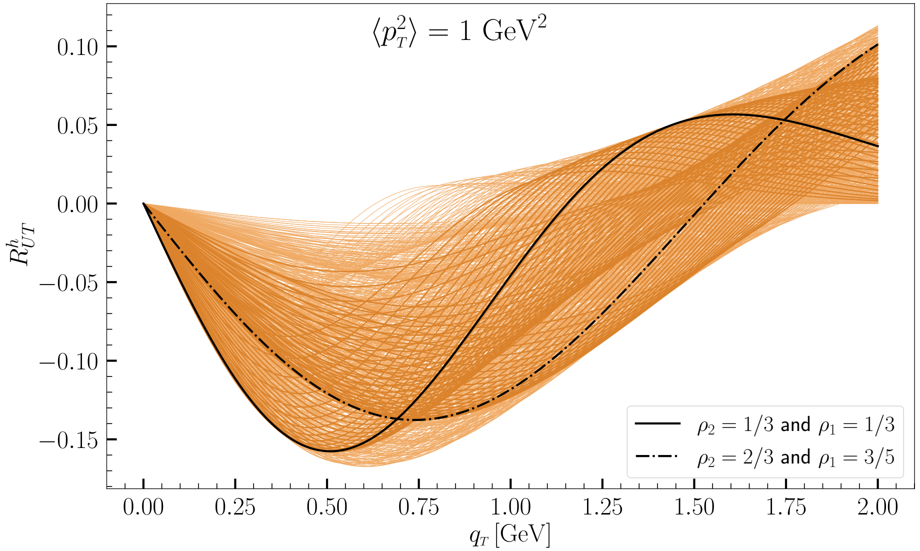
$0.1 < \rho_3 < 0.9$ for thicker lines

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

$\rho_1 \to h_1^g$

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

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



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

$0.1 < \rho_1 < 0.9$ for thicker lines

Upper bounds for SSAs

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

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

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

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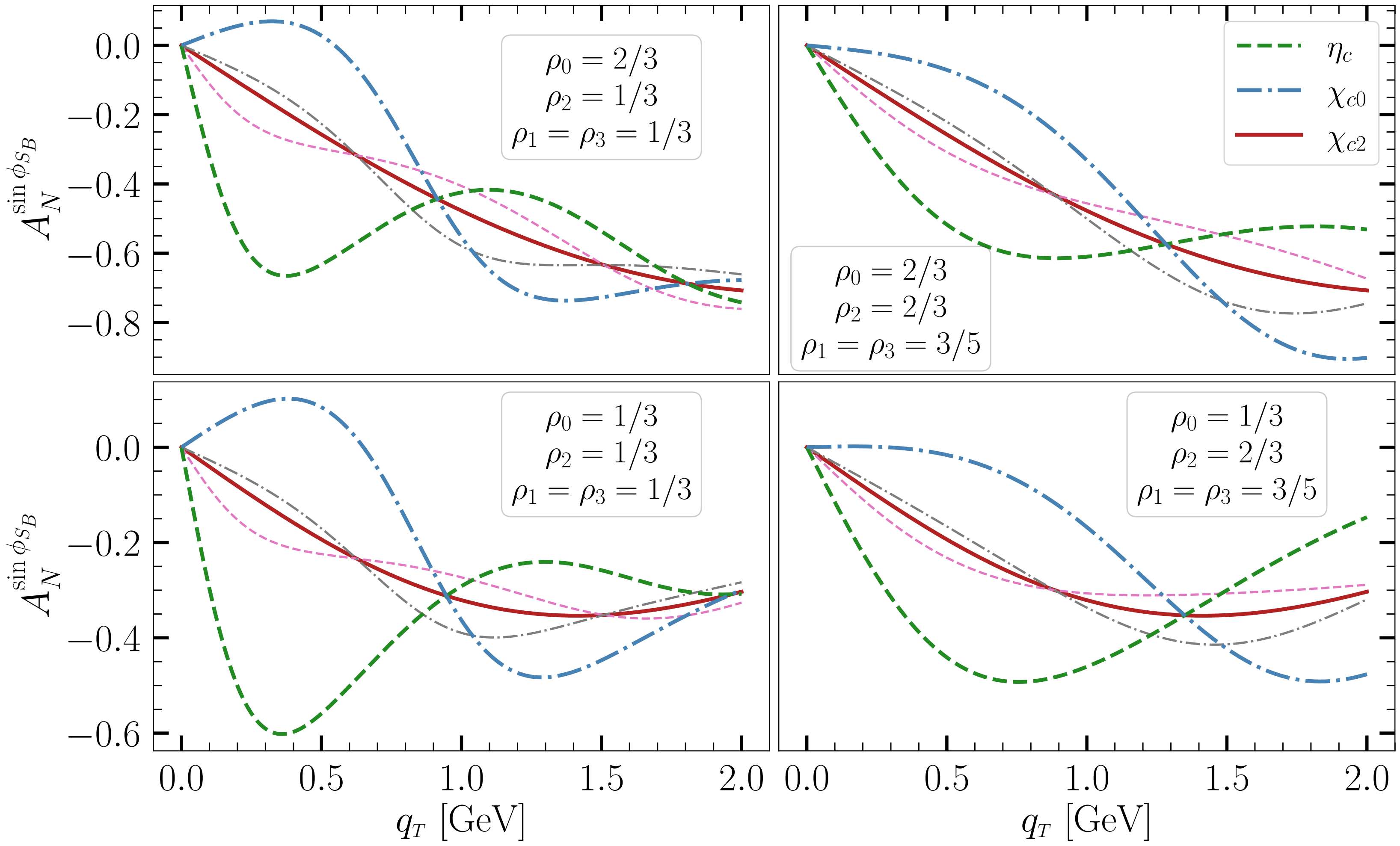
$$A_N^{\chi_{Q2},\sin\phi_{S_B}} = -R_{UT}^f$$

SSA for χ_{Q2} production depends **only** on the Sivers function!

By comparing the SSAs for η_Q and χ_{Q0} with those for χ_{Q2} we can comprehend the relevance of the combined effects of the linearly polarized gluon TMDs.

Upper bounds for SSAs



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

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

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

SSA for χ_{Q2} production depends **only** on the Sivers function!

By comparing the SSAs for η_Q and χ_{Q0} with those for χ_{Q2} we can comprehend the relevance of the combined effects of the linearly polarized gluon TMDs.

Summary of the talk

- *C*-even **quarkonium production in *p-p* collisions**
- Used NRQCD and CS mechanism
- 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**

SAR WORS

THANK YOU!

IV SARDINIAN WORKSHOP ON SPIN

SAR WORS

BACKUP SLIDES

IV SARDINIAN WORKSHOP ON SPIN

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

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

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

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

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

$0 < \rho_i < 1$

LHCSpin timeline

SMOG2

2024 - 2026

2026 - 2029

LHC LS3
Installation of the apparatus at the IR4

2030 - 2033

LHC Run4
Data taking at the IR4

2034 - 2035

LHC LS4
Installing the target at LHCb

2036 -

LHC Run5+6
Data taking at the LHCb

The LHCspin apparatus consists of a new-generation HERMES-like polarized gaseous fixed target to be installed usptream of the VELO.
With its installation, LHCb will be the first experiment to simultaneously collect data from unpolarized beam-beam collisions at $\sqrt{s} = 14$ TeV and polarized and unpolarized beam-target collisions at $\sqrt{s} = 100$ GeV.