Studying gluon TMDs via J/ψ-pair production at the LHC in the fixed-target mode

Fixed target experiments at LHC - strong2020 workshop

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1. Introduction
2. Gluon TMDs
3. Azimuthal modulations
4. Experimental applications
5. Conclusions

General introduction

Azimuthal modulations of the cross section for inclusive production of quarkonium pairs in hadronic collisions

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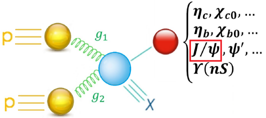
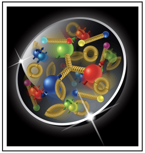
Inclusive production of J/ψ pairs in *pp* collisions (gluon fusion)



$\hookrightarrow$ **understanding the internal structure of nucleons**

$\hookrightarrow$ gluon dynamics poorly known



Results $\rightarrow$ future measurements at LHC fixed-target experiments

$\hookrightarrow$ unexplored Transverse Momentum Dependent PDFs (TMDs)

Our knowledge of the internal structure of the proton

PDFs → great precision
Collinear QCD phenomenology

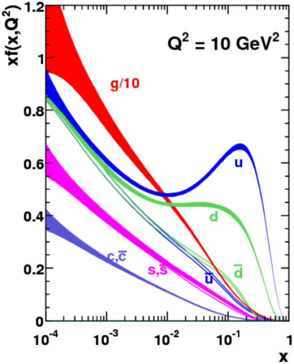
↪ only 1D information
↪ x dependence

⇓

3D structure of the nucleon
Beyond collinear factorisation

⇓

Transverse dynamics!



▷ Nucleon structure in terms of **TMDs** → quark TMDs
→ gluon TMDs

TMDs → quark and gluon ones

TMDs → 3D structure of the nucleon

Correlations between k_T and the polarisation of the nucleon/parton

2 components ▷ collinear (x)

▷ transversal ($\vec{k}_\perp$) → generate q_T (final-state)

Quark TMDs extracted from data

↪ SIDIS, DY processes

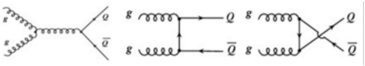
↪ Precision era!

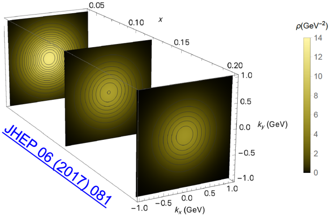
Gluon TMDs → lack of data

↪ Extremely poorly know!

↪ How to measure them?

Inclusive **quarkonium** production





JHEP 06 (2017) 081

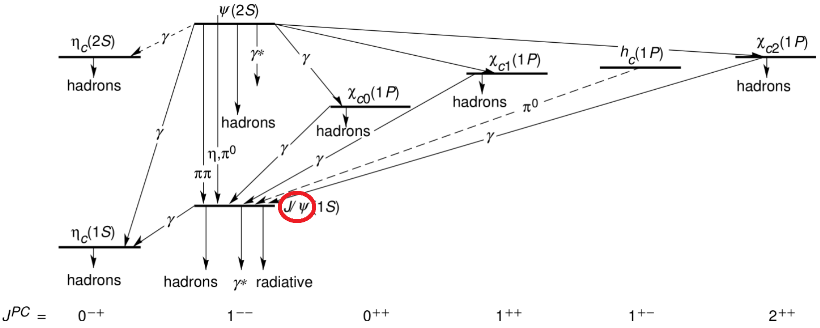
		Quark			
		U	**L**	**T**	
Nucleon	**U**	f_1		$h_1^\perp$	
	L		g_{1L}	$h_{1L}^\perp$	
	T	$f_{1T}^\perp$	g_{1T}	h_1	$h_{1T}^\perp$

Quarkonium production processes

Quarkonium = meson made of a Q and its $\bar{Q}$

$\hookrightarrow$ *charmonium* ($c\bar{c}$): J/ψ, Ψ', η_c, χ_c...

$\hookrightarrow$ *bottomonium* ($b\bar{b}$): Υ, η_b, χ_b...



Quarkonium production processes

Experimental point of view:

- quarkonium production observed in different experiments
- J/ψ: easy to produce and detect
  $\hookrightarrow$ plenty of experimental data

Theoretical point of view:

- Not clear how to treat quarkonium production
- 3 common models → Colour Singlet Model (CSM)
  → Colour Octet Mechanism (COM)
  → Colour Evaporation Model (CEM)
- not complete agreement with experimental data
- for J/ψ-pair production: **CSM** best description

1. Introduction
2. **Gluon TMDs**
3. Azimuthal modulations
4. Experimental applications
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TMD factorisation

Study of gluon TMDs → TMD factorisation ($q_T \ll Q$)

General factorised cross section
↪ collinear partonic scattering amplitude (*perturbative*)
↪ k_T-dependent correlators (*non-perturbative*)

$$d\sigma = \int dx_1 dx_2 d^2\vec{k}_{T1} d^2\vec{k}_{T2} \delta^{(2)}(\vec{k}_{T1} + \vec{k}_{T2} - \vec{q}_T)$$
$$\times \Phi_g^{\mu\nu}(x_1, \vec{k}_{T1}) \Phi_g^{\rho\sigma}(x_2, \vec{k}_{T2}) \left[\hat{\mathcal{M}}_{\mu\rho} \hat{\mathcal{M}}^*_{\nu\sigma} \right]\Big|_{\substack{k_1 = x_1 P_1 \\ k_2 = x_2 P_2}}$$
$$+ \mathcal{O}\left(\frac{q_T^2}{Q^2}\right)$$

Gluon TMDs

2 independent collinear partonic distributions:

- $f_1^g(x)$ *"unpolarised"*
- $g_1^g(x)$ *"circular"*

Unpolarised protons → 2 TMDs:

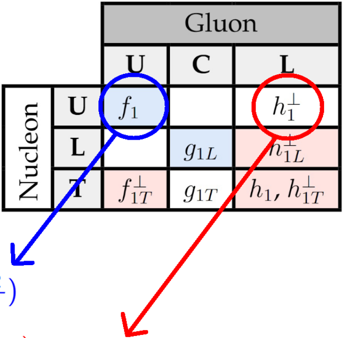
- f_1^g: unpolarised gluon TMD
- $h_1^{\perp g}$: linearly polarised gluon TMD

		Gluon		
		U	**C**	**L**
Nucleon	**U**	f_1		$h_1^\perp$
	L		g_{1L}	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

Gluon TMDs and correlators

TMD correlator parametrisation for an unpolarised proton

- ▷ unpolarised: $f_1^g \longrightarrow$
- ▷ linearly polarised: $h_1^{\perp g} \longrightarrow$



		Gluon		
		U	**C**	**L**
Nucleon	**U**	f_1		$h_1^\perp$
	L		g_{1L}	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

$$\Phi_g^{\mu\nu}(x,\vec{k}_T) = -\frac{1}{2x}\left[g_T^{\mu\nu} f_1^g(x,\vec{k}_T^2) - \left(\frac{k_T^\mu k_T^\nu}{M_H^2} + g_T^{\mu\nu}\frac{\vec{k}_T^2}{2M_H^2} \right) h_1^{\perp g}(x,\vec{k}_T^2) \right]$$

↪ Second term goes to 0 if $k_T = 0$

Why di-J/ψ production?

- Single J/ψ production: a lot of data at low p_T ✓
  $\hookrightarrow$ but gluon in the final state → presence of soft gluons (non-perturbative) between Initial State Interactions (ISIs) and Final State Interactions (FSIs) can be problematic
  $\hookrightarrow$ **no** TMD factorisation
- Single η_c production: no gluon in the final state ✓
  $\hookrightarrow$ but no data at low p_T: **no** TMD factorisation
- Double J/ψ production:
  ▷ data at low p_T ✓
  ▷ no gluon in the final state ✓
  $\hookrightarrow$ gluon fusion: ISI can be encapsulated in the TMDs
  $\hookrightarrow$ consider CSM: no FSIs

→ **Safe TMD factorisation**

Hadronic cross section

The general formula for the cross section of gluon fusion is:

$$\begin{aligned} d\sigma^{gg} \propto\; & F_1 \times \mathcal{C}[f_1^g f_1^g] \\ & +F_2 \times \mathcal{C}[w_2 h_1^{\perp g} h_1^{\perp g}] \\ & +(F_3 \times \mathcal{C}[w_3 f_1^g h_1^{\perp g}] + F_3' \times \mathcal{C}[w_3' h_1^{\perp g} f_1^g])\cos(2\Phi_{CS}) \\ & +(F_4 \times \mathcal{C}[w_4 h_1^{\perp g} h_1^{\perp g}])\cos(4\Phi_{CS}) \end{aligned}$$

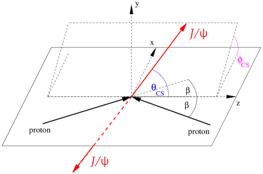
- first two members: azimuthally independent
- third member: $\cos(2\Phi_{CS})$-modulation
- fourth member: $\cos(4\Phi_{CS})$-modulation

Computation of azimuthal modulations

The correspondent expressions for $\cos(2\Phi_{CS})$ and $\cos(4\Phi_{CS})$:

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

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

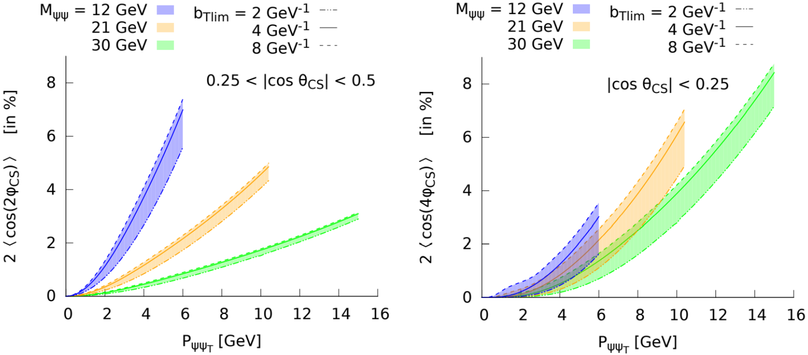


- The hard-scattering coefficients $(F_1,\ F_2,\ F_3,\ F_3',\ F_4)$ give the explicit dependence on $M_{\psi\psi}$ and θ_{CS}
- Set scale $Q^2 = M_{\psi\psi}^2$ and consider $M_{\psi\psi} = 8, 16$ GeV
  $\hookrightarrow$ TMD evolution applied in the computation

Results in collider mode: $\cos(2\Phi_{CS})$, $\cos(4\Phi_{CS})$

Plots considering:

- two ranges of $\cos(\theta_{CS})$: [0; 0.25] and [0.25; 0.50]
- three values for the invariant mass: 12, 21, 30 GeV; **x1=x2**



Eur.Phys.J.C 80 no.2,(2020) 87, arXiv:1909.05769 [hep-ph]

Fixed-target case

Goal: phenomenological study of the azimuthal modulations for J/ψ pair production in *pp* fixed-target collisions $\rightarrow x_1 \neq x_2$

Implementation: **ex-novo code** in Python
TMD factorisation
TMD convolutions
TMD evolution
(use of LHAPDF package for PDF parametrisation)

$\Downarrow$

Code validation: reproduced published results (collider mode)

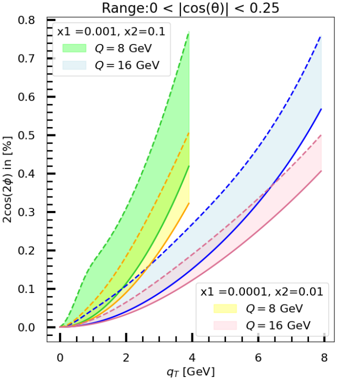
$\Downarrow$

NEW: **first studies** with $x_1 \neq x_2$ (fixed-target kinematics)
(two sets of x_1, x_2 but same rapidity $y = \frac{1}{2} \ln \frac{x_1}{x_2}$)

Preliminary: predictions for $\cos(2\Phi_{CS})$

Plots considering:

- range of $\cos(\theta_{CS})$: $[0; 0.25]$, $Q = M_{\psi\psi}$
- two different sets $(x_1; x_2)$: $(10^{-3}; 10^{-1})$ and $(10^{-4}; 10^{-2})$



▷ contribution below 1%

▷ $q_T < Q/2$ considered

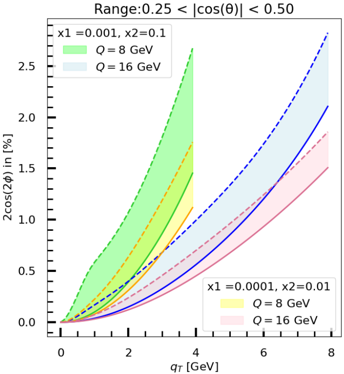
▷ big overlap in the low q_T region, not for large q_T

▷ ∼ same magnitude for low and high Q (lower for lower $x_{1,2}$)

Preliminary: predictions for $\cos(2\Phi_{CS})$

Plots considering:

- range of $\cos(\theta_{CS})$: [0.25; 0.50], $Q = M_{\psi\psi}$
- two different sets $(x_1; x_2)$: $(10^{-3}; 10^{-1})$ and $(10^{-4}; 10^{-2})$



▷ contribution up to 3% (measurable)

▷ $q_T < Q/2$ considered

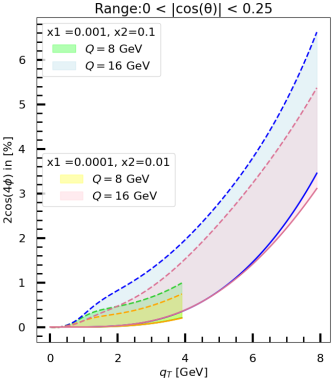
▷ big overlap in the low q_T region, not for large q_T

▷ $\sim$ same magnitude for low and high Q (lower for lower $x_{1,2}$)

Preliminary: predictions for $\cos(4\Phi_{CS})$

Plots considering:

- range of $\cos(\theta_{CS})$: [0; 0.25], $Q = M_{\psi\psi}$
- two different sets $(x_1; x_2)$: $(10^{-3}; 10^{-1})$ and $(10^{-4}; 10^{-2})$



▷ max contribution 5 − 6% (measurable)

▷ $q_T < Q/2$ considered

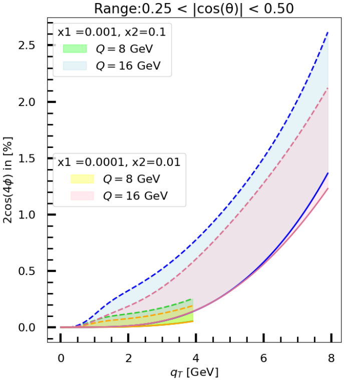
▷ overlap $\forall q_T$

▷ much higher amplitude for high Q (at high q_T)

Preliminary: predictions for $\cos(4\Phi_{CS})$

Plots considering:

- range of $\cos(\theta_{CS})$: $[0.25; 0.50]$, $Q = M_{\psi\psi}$
- two different sets $(x_1; x_2)$: $(10^{-3}; 10^{-1})$ and $(10^{-4}; 10^{-2})$



▷ contribution up to 3% (measurable)

▷ $q_T < Q/2$ considered

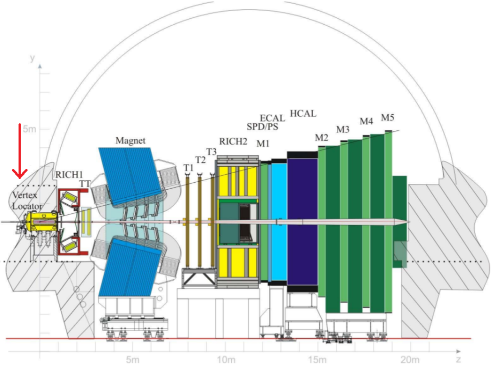
▷ overlap $\forall q_T$

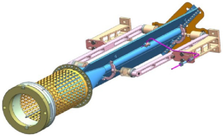
▷ higher amplitude for high Q (low Q negligible)

LHCb in the fixed-target mode: SMOG2

System for Measuring Overlap with Gas (SMOG): LHCb implementation for fixed-target data-taking

Upgrade: SMOG2 → openable storage cell in front of the VELO





(https://arxiv.org/abs/2111.09611)

LHCb in the fixed-target mode: SMOG2

- ▷ LHCb can run simultaneously in collider and fixed-target mode
- ▷ Beam-gas interaction region well defined
- ▷ Large target areal density ($\mathcal{L} \sim 10^{32}\text{cm}^{-2}\text{s}^{-1}$)
- ▷ Possibility to inject a wide range of gases through a gas injection system (not only noble gases!)
- ▷ Large statistics expected for $J/\psi \to \mu^+\mu^-$
  $\hookrightarrow$ (15M expected in LHC Run3)

Summary

- Quarkonium production is a great tool for many purposes
  $\hookrightarrow$ exploration of nucleon structure through gluon TMDs
- Double J/ψ production gives the possibility to investigate gluon TMD induced effects
  $\hookrightarrow$ azimuthal modulations already studied in the collider mode
- **NEW** Fixed-target mode: lower azimuthal modulations for $\frac{x1}{x2} \neq 1$ ($x1 \simeq x2$, collider mode, seems to be favoured)
- SMOG2: great opportunity to explore quarkonia production processes, in particular $J/\psi \to \mu^+\mu^-$: will be extensively produced at LHCb with SMOG2
- **FUTURE** Further studies can be made in the (near) future considering polarised protons → access to more gluon TMDs

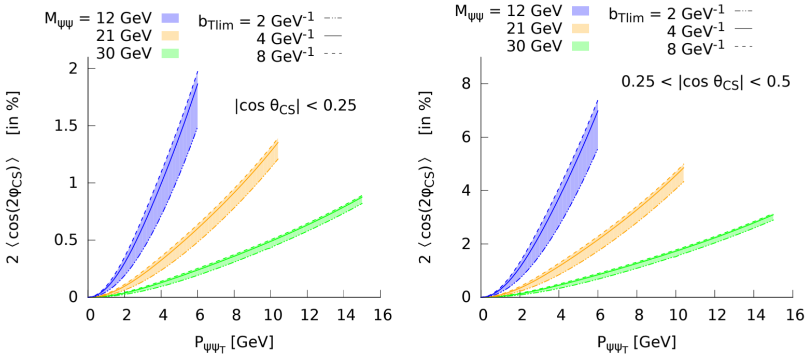
Thank you for your attention!

Backup slides

Results in collider mode: $\cos(2\Phi_{CS})$

Plots considering:

- two ranges of $\cos(\theta_{CS})$: [0; 0.25] and [0.25; 0.50]
- three values for the invariant mass: 12, 21, 30 GeV; **x1=x2**



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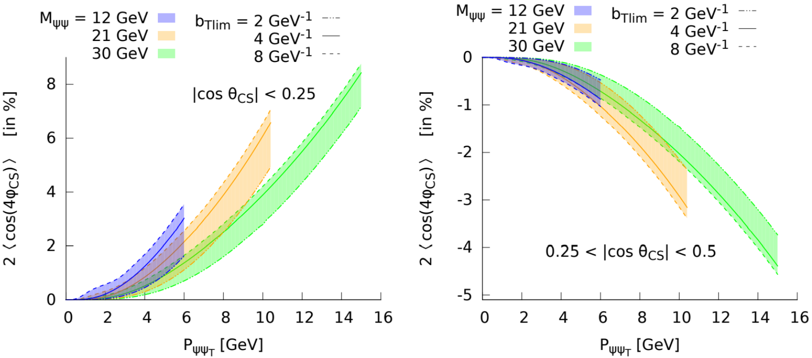
Results in collider mode: $\cos(4\Phi_{CS})$

Plots considering:

- two ranges of $\cos(\theta_{CS})$: [0; 0.25] and [0.25; 0.50]
- three values for the invariant mass: 12, 21, 30 GeV; **x1=x2**



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Hard scattering coefficients

$$F_1 = \frac{\mathcal{N}}{\mathcal{D} M_\Psi^2} \sum_{n=0}^{6} f_{1,n} (\cos\theta_{CS})^{2n} \qquad F_2 = \frac{2^4 3 M_\Psi^2 \mathcal{N}}{\mathcal{D} M_{\Psi\Psi}^4} \sum_{n=0}^{4} f_{2,n} (\cos\theta_{CS})^{2n}$$

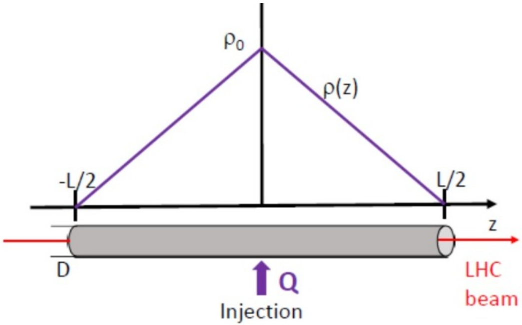
$$F_3' = F_3 = \frac{-2^3 (1-\alpha^2) \mathcal{N}}{\mathcal{D} M_{\Psi\Psi}^2} \sum_{n=0}^{5} f_{3,n} (\cos\theta_{CS})^{2n}$$

$$F_4 = \frac{(1-\alpha^2)^2 \mathcal{N}}{\mathcal{D} M_{\Psi\Psi}^2} \sum_{n=0}^{6} f_{4,n} (\cos\theta_{CS})^{2n} \tag{1}$$

with: $\alpha = \frac{2M_\Psi}{M_{\Psi\Psi}}$, $\mathcal{N} = 2^{11} 3^{-4} (N_c^2 - 1)^{-2} \pi^2 \alpha_s^4 |R_\Psi(0)|^4$, $\mathcal{D} = M_{\Psi\Psi}^4 (1 - (1-\alpha^2)\cos\theta_{CS}^2)^4$ and $R_\Psi(0)$ is the J/ψ radial wave function at the origin and $N_c = 3$.

Tabular storage cell SMOG2

Scheme of a tubular storage cell of length L and inner diameter D. Injection is in the center with flow rate Q, resulting in a triangular density distribution $\rho(z)$ with maximum ρ_0 at the center



(http://cds.cern.ch/record/2673690)