Studying gluon TMDs with J/ψ pair production at the LHC

F. Scarpa, D. Boer, J.-P. Lansberg, C. Pisano, M. Schlegel

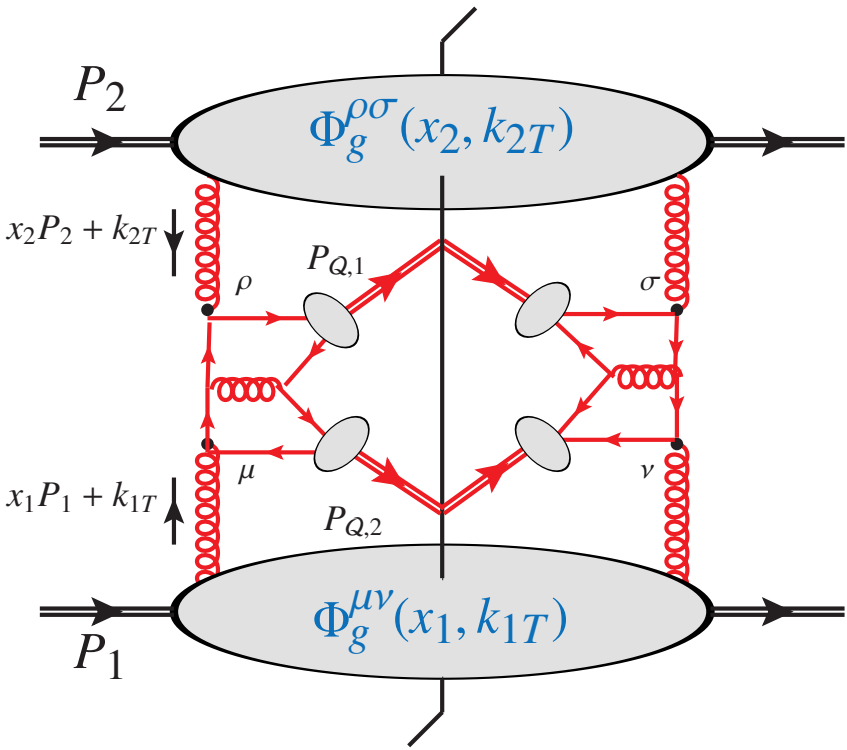
10th of April 2019

DIS 2019 TORINO 8-12 April

XXVII International Workshop on Deep Inelastic Scattering and Related Subjects

TMD factorisation and gluon distributions

TMD correlators & distributions



- Proton beams at the LHC = unpolarised
- Relevant TMDs at twist-2 :
  - f_1^g : TMD distribution of unpolarised gluons
  - $h_1^{\perp g}$: TMD distribution of linearly polarised gluons
- Parametrisation of the TMD correlator for an unpolarised proton :

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

$$d\sigma^{gg} \propto$$

$$F_1\, \mathcal{C}[f_1^g f_1^g]$$

$\Rightarrow$ azimuthally independent

$$+\, F_2\, \mathcal{C}[w_2 \times h_1^{\perp g} h_1^{\perp g}]$$

$\Rightarrow$ azimuthally independent

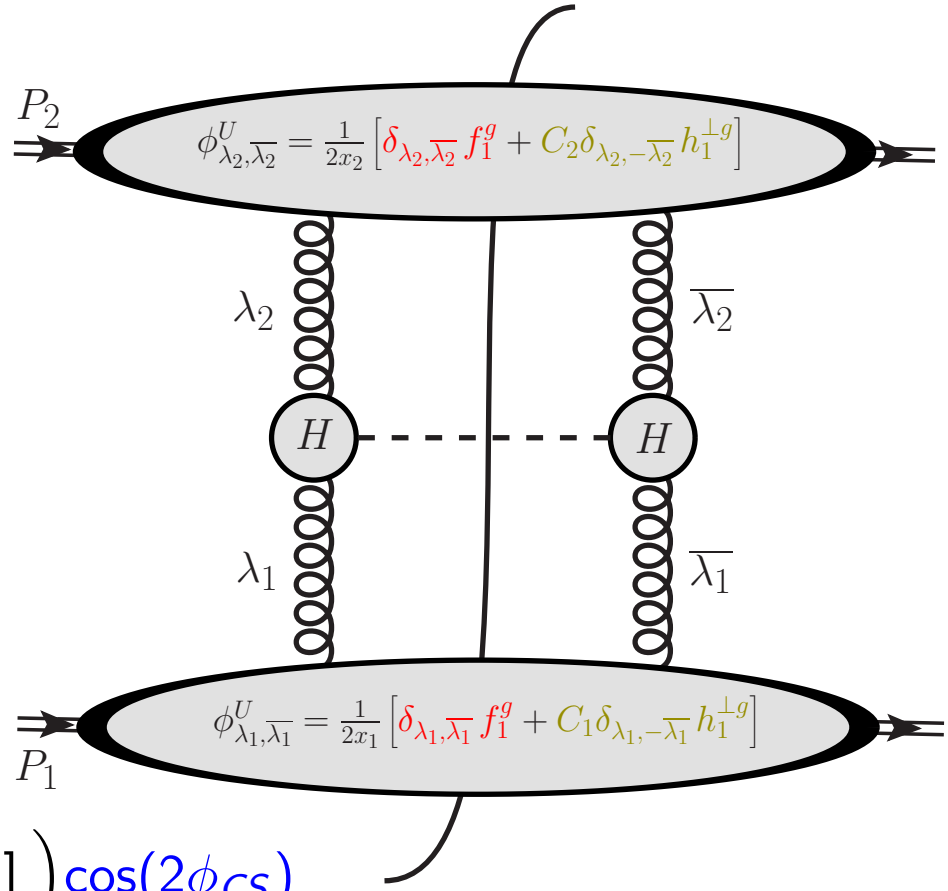
$$+\left(F_3\, \mathcal{C}[w_3 \times f_1^g h_1^{\perp g}] + F_3{}'\, \mathcal{C}[w_3{}' \times h_1^{\perp g} f_1^g] \right)\cos(2\phi_{CS})$$

$\Rightarrow$ $\cos(2\phi_{CS})$-modulation

$$+\, F_4\, \mathcal{C}[w_4 \times h_1^{\perp g} h_1^{\perp g}]\cos(4\phi_{CS})$$

$\Rightarrow$ $\cos(4\phi_{CS})$-modulation

modulations in $\phi_{CS} = (\vec{q}_T, \vec{p}_T)$

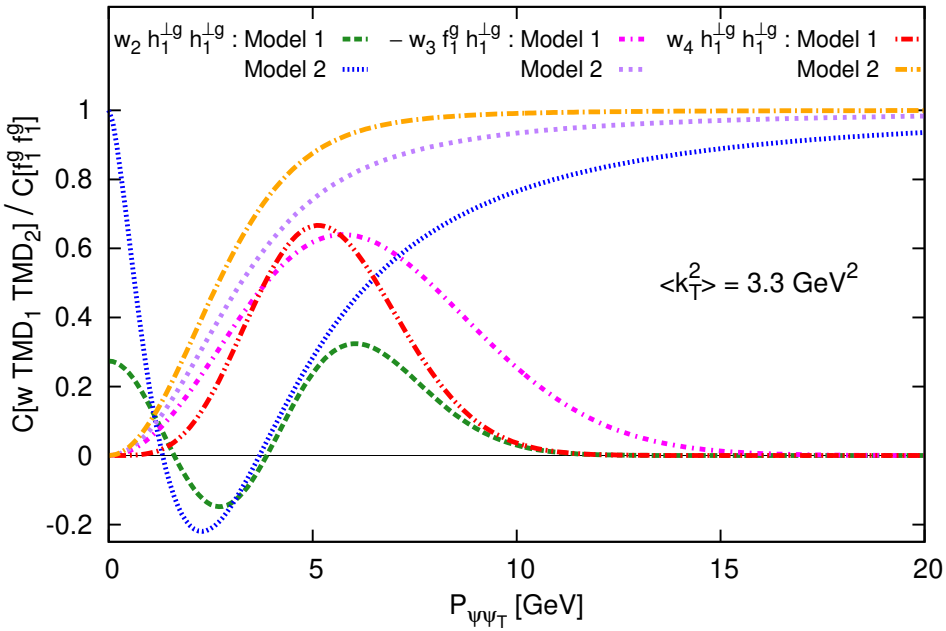


TMD Gaussian modelling :

- f_1^g modelled as a Gaussian in $\vec{k}_T$:

$$f_1^g(x, \vec{k}_T^2) = \frac{g(x)}{\pi \langle k_T^2 \rangle} e^{\frac{-\vec{k}_T^2}{\langle k_T^2 \rangle}}$$

- "Gaussian" $h_1^{\perp g}(x, \vec{k}_T^2) \Rightarrow$ Model 1
  Boer, de Dunnen, Pisano, Schlegel, Vogelsang, PRL 108 (2012) 032002



- Positivity bound : $h_1^{\perp g}(x, \vec{k}_T^2) \leq \frac{2M_p^2}{\vec{k}_T^2} f_1^g(x, \vec{k}_T^2)$ = maximal value (bound saturated) $\Rightarrow$ Model 2

- In order to isolate the different ϕ-dependences, one can define :

$$2\langle \cos(n\phi_{CS}) \rangle = \frac{\int_0^{2\pi} d\phi_{CS} \cos n\phi_{CS}\, d\sigma}{\int_0^{2\pi} d\phi_{CS}\, d\sigma} \simeq \frac{F_n\, \mathcal{C}[w_n TMD_1\, TMD_2]}{F_1\, \mathcal{C}[f_1^g f_1^g]} \qquad n = 2, 4$$

$$= \text{relative amplitude of the azimuthal modulations} \qquad (2)$$

Evolution in b_T space

- TMDs contain UV and rapidity divergences $\Rightarrow$ introduction of a cut-off scale μ and a regulator ζ :

$$f(x, \vec{k}_T^2) \rightarrow f(x, \vec{k}_T^2, \zeta, \mu) \tag{3}$$

- 3 evol. equations $\Rightarrow$ μ and ζ dependence of the TMDs $\Rightarrow$ evaluated at natural scale to minimise large logs :

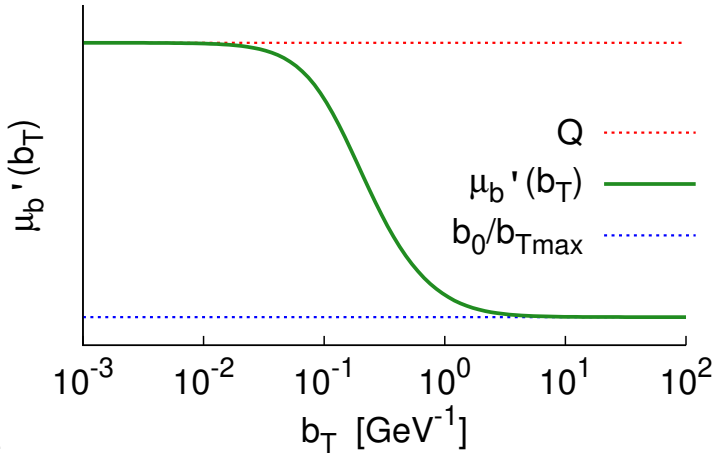
$$\begin{aligned} \mathcal{C}[f_1^g f_1^g] &= \int d^2\vec{k}_{1_T}\, d^2\vec{k}_{2_T}\, \delta^{(2)}(\vec{k}_{1_T} + \vec{k}_{2_T} - \vec{q}_T) f_1^g(x_1, k_{1_T}^2; \zeta_1, \mu) f_1^g(x_2, k_{2_T}^2; \zeta_2, \mu) \\ &= \int \frac{d^2\vec{b}_T}{(2\pi)^2} e^{i\vec{b}_T \cdot \vec{q}_T} \underbrace{e^{-S_A(b_T, Q)}}_{\substack{\text{perturbative} \\ \text{Sudakov factor}}} \tilde{f}_1^g(x_1, b_T^2; \mu_b^2, \mu_b) \tilde{f}_1^g(x_2, b_T^2; \mu_b^2, \mu_b) \end{aligned} \tag{4}$$

natural scale : $\mu_b = \dfrac{b_0}{b_T}$

Large and small b_T regulations

- Small b_T : $\mu_b > Q$ for small $b_T < b_0/Q$

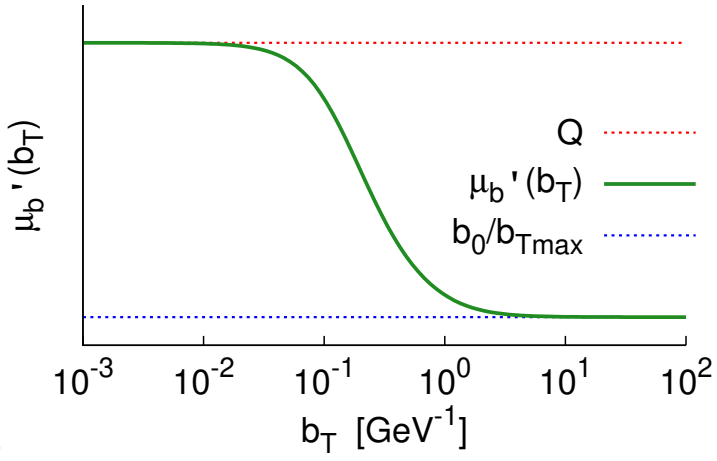
  $\Rightarrow$ regularisation : $\mu_b \to \mu'_b = \dfrac{Q b_0}{\sqrt{Q^2 b_T^2 + b_0^2}}$



- Large b_T : S_A expression only valid at $b_T \ll \Lambda_{QCD}^{-1}$

  $\Rightarrow$ b_* prescription : $\tilde{W}(b_T) \equiv \tilde{W}(b_*) e^{-S_{NP}(b_T)}$ with $b_* = \dfrac{b_T}{\sqrt{1 + \frac{b_T^2}{b_{Tmax}^2}}}$

Large and small b_T regulations



- Small b_T : $\mu_b > Q$ for small $b_T < b_0/Q$

  $\Rightarrow$ regularisation : $\mu_b \to \mu_b' = \dfrac{Q b_0}{\sqrt{Q^2 b_T^2 + b_0^2}}$

- Large b_T : S_A expression only valid at $b_T \ll \Lambda_{QCD}^{-1}$

  $\Rightarrow$ b_* prescription : $\tilde{W}(b_T) \equiv \tilde{W}(b_*) e^{-S_{NP}(b_T)}$ with $b_* = \dfrac{b_T}{\sqrt{1 + \frac{b_T^2}{b_{Tmax}^2}}}$

- S_A analytical and identical for f_1^g and $h_1^{\perp g}$

  S_{NP} encodes all the nonperturbative (NP) information on the TMDs ; different between f_1^g and $h_1^{\perp g}$

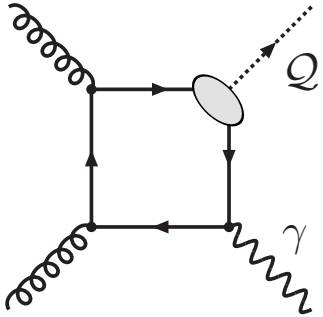
- Perturbative component of the TMDs :

$$\tilde{f}_1^g(x, b_T^2; \mu_b'^2, \mu_b') = f_{g/P}(x; \mu_b') + \mathcal{O}(\alpha_s)$$

$$\tilde{h}_1^{\perp g}(x, b_T^2; \mu_b'^2, \mu_b') = \frac{\alpha_s(\mu_b') C_A}{\pi} \int_x^1 \frac{d\hat{x}}{\hat{x}} \left(\frac{\hat{x}}{x} - 1 \right) f_{g/P}(\hat{x}; \mu_b') + \mathcal{O}(\alpha_s^2)$$

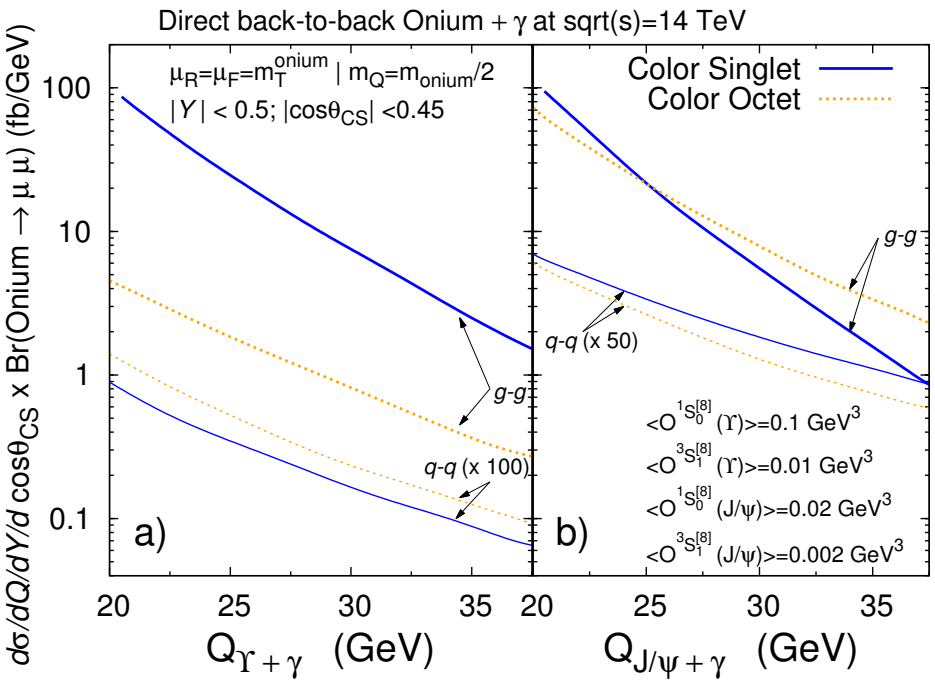
Processes of interest

$gg \to \mathcal{Q} + \gamma$



- $q\bar{q}$ contributions negligible $\Rightarrow$ gluon sensitive process
- The possibility of isolating the quarkonium can eliminate the CO contributions ; the photon is isolated
- CO (orange) smaller than CS (blue); isolation not needed for Υ
- At 14 TeV, $\sigma(J/\psi|\Upsilon+\gamma)|_{Q>20\ GeV} \simeq 100$ fb; about half at 7 TeV

W. den Dunnen, J.P. Lansberg, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)

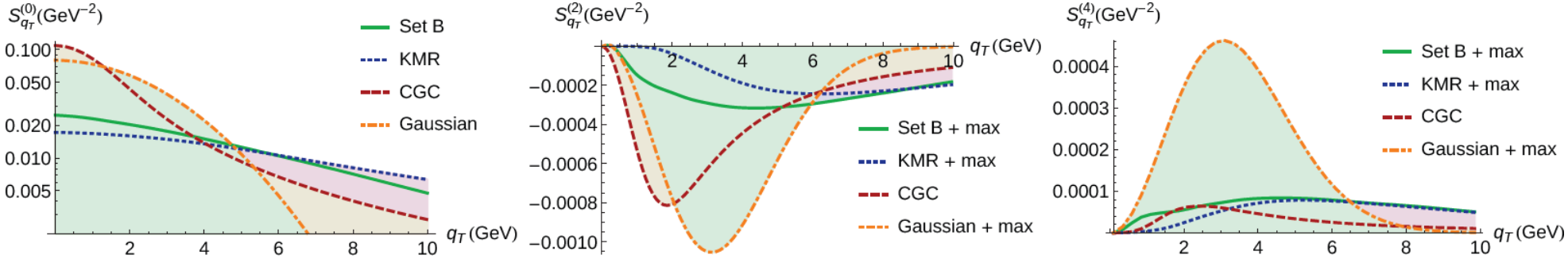


- With the $\mathcal{L} \simeq 20$ fb^{-1} of pp data on tape, one expects up to 2000 events
- ATLAS has looked for $H^0 \to J/\psi\,(\Upsilon) + \gamma$ at $Q \simeq 125$ GeV

Results with UGDs as Ansätze for TMDs

- Observable $S_{q_T}^{(n)} = \dfrac{F_n}{F_1} \dfrac{\mathcal{C}[w_n \; TMD_1^{(n)} \; TMD_2^{(n)}]}{\int d^2\vec{q}_T \mathcal{C}[f_1^g f_1^g]} \quad \Rightarrow S_{q_T}^{(0)}, S_{q_T}^{(2)}, S_{q_T}^{(4)}$

W. den Dunnen, JPL, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)



- $S_{q_T}^{(2)}, S_{q_T}^{(4)} \neq 0 \Rightarrow$ nonzero gluon polarisation in unpolarised protons
- $S_{q_T}^{(0)}$: $f_1^g(x, k_T)$ from the q_T-dependence of the yield
- $\displaystyle\int d^2\vec{q}_T S_{q_T}^{(2,4)}$ probably measurable (few percent : ok with 2000 events)

$gg \to \eta_c + \eta_c$

- Theoretically simple, low $q\bar{q}$ contribution
- No reason for significant CO : $\langle 0| \mathcal{O}_1^\eta(^1S_0) |0\rangle \Rightarrow$ factorisation expected to hold

	$Q(GeV) \in (6.0, 10.0)$	$(10.0,\ 15.0)$	$(15.0,\ 20.0)$	$(20.0,\ 40.0)$
$\langle 1\rangle (pb)$	2.3×10^4	1.7×10^3	1.8×10^2	1.3×10^2
$\lvert\langle \cos 2\phi\rangle\rvert (pb)$	2.4×10^3	4.6×10^2	0.72×10^2	0.63×10^2
$\langle \cos 4\phi\rangle (pb)$	0.20×10^2	9.1	2.5	3.3

Guang-Peng Zhang / Phys.Rev. D 90 (2014) 9, 094011. The η_c weighted differential cross-sections obtained from Gaussian model at $\sqrt{s} = 7$ TeV and $\Delta y = 0$ with $\alpha_s = 0.15$ and $M_{\eta_c} = 3.0$ GeV

- At $\sqrt{s} = 14$ TeV, cross-sections will increase by a 2 factor ($\langle 1\rangle \sim \sigma$)

  $\langle 1, \cos 2\phi\rangle \times Br^2(\eta_c \to p\bar{p}) \simeq 1 - 50$ fb (observable at LHC Run II ?)

  $\langle \cos 4\phi\rangle$ negligible

- However η_c remain hard to see in experiments

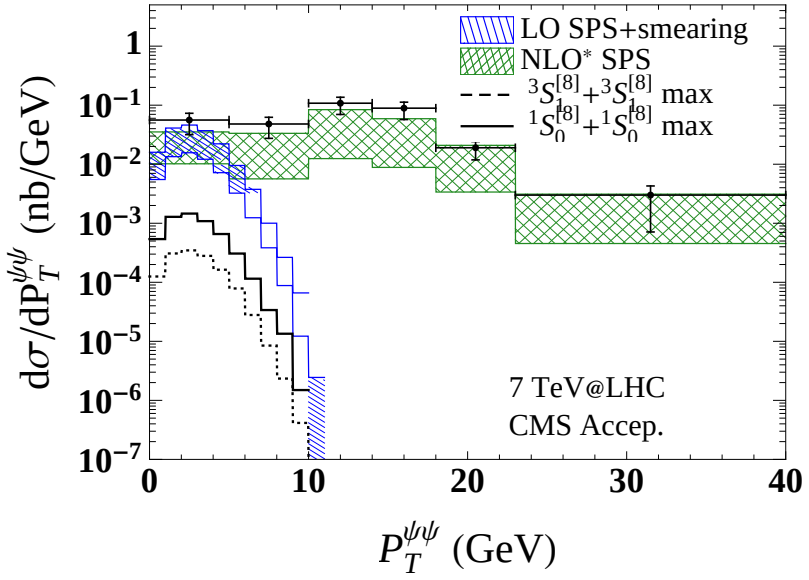
J/ψ pair production

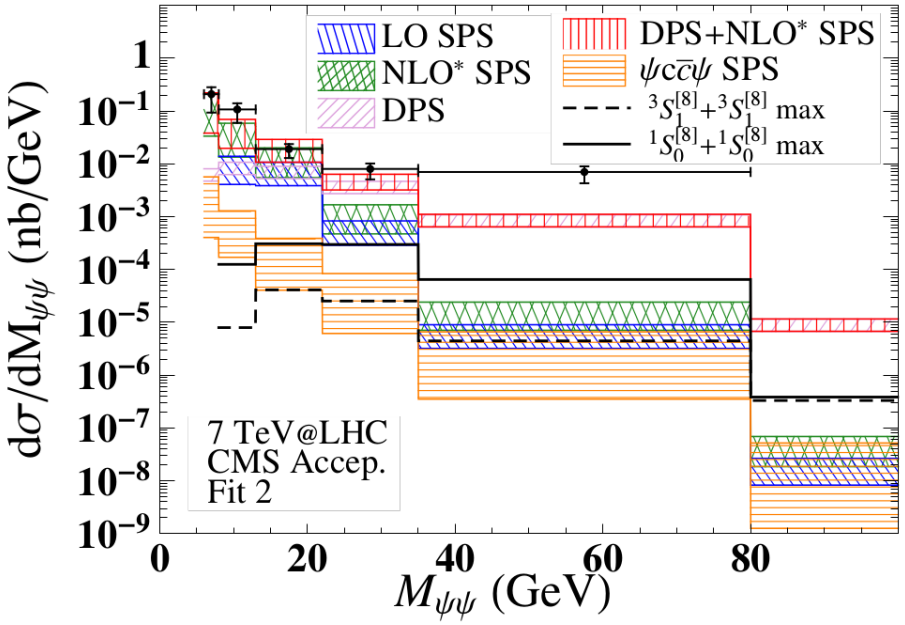
$gg \to J/\psi + J/\psi$: SPS

- J/ψ rather easy to detect $\Rightarrow$ Pair prod. already studied by 4 collaborations :

LHCb JHEP 1706 (2017) 047
CMS JHEP 1409 (2014) 094
ATLAS Eur. Phys. J. C (2017) 77:76
D0 PRD 90 (2014) 111101

J.-P. Lansberg, H.-S. Shao / Physics Letters B 751 (2015) 479-486



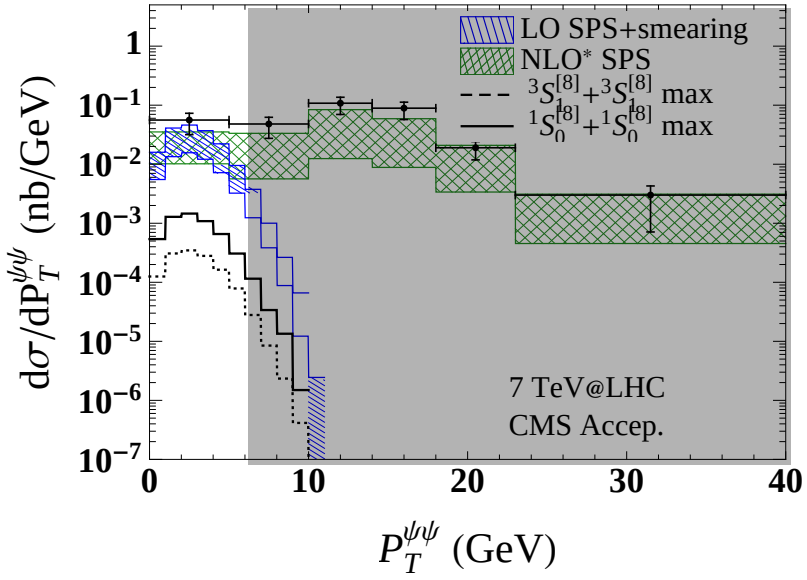


$gg \to J/\psi + J/\psi$: SPS

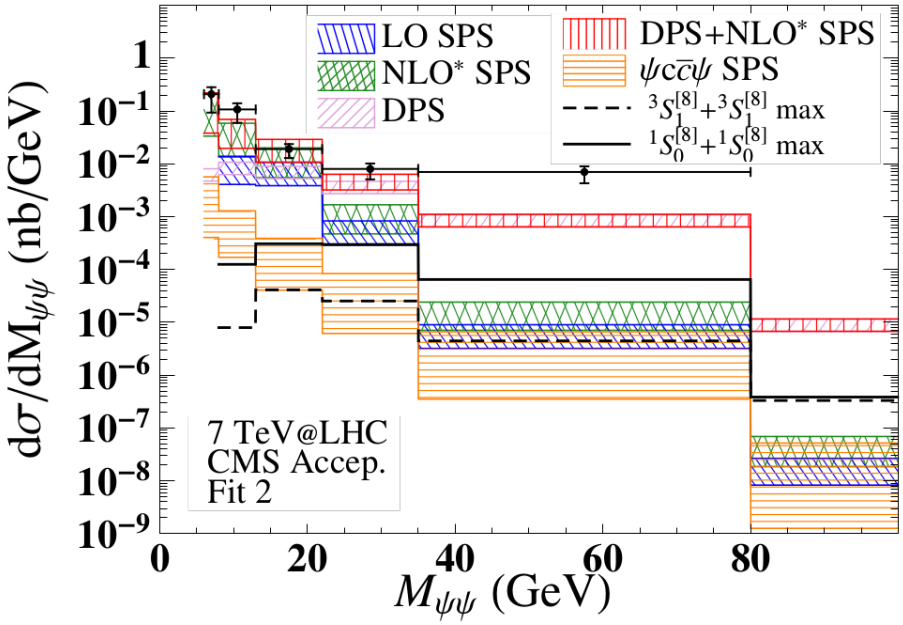
- J/ψ rather easy to detect $\Rightarrow$ Pair prod. already studied by 4 collaborations :

LHCb JHEP 1706 (2017) 047
CMS JHEP 1409 (2014) 094
ATLAS Eur. Phys. J. C (2017) 77:76
D0 PRD 90 (2014) 111101

J.-P. Lansberg, H.-S. Shao / Physics Letters B 751 (2015) 479-486



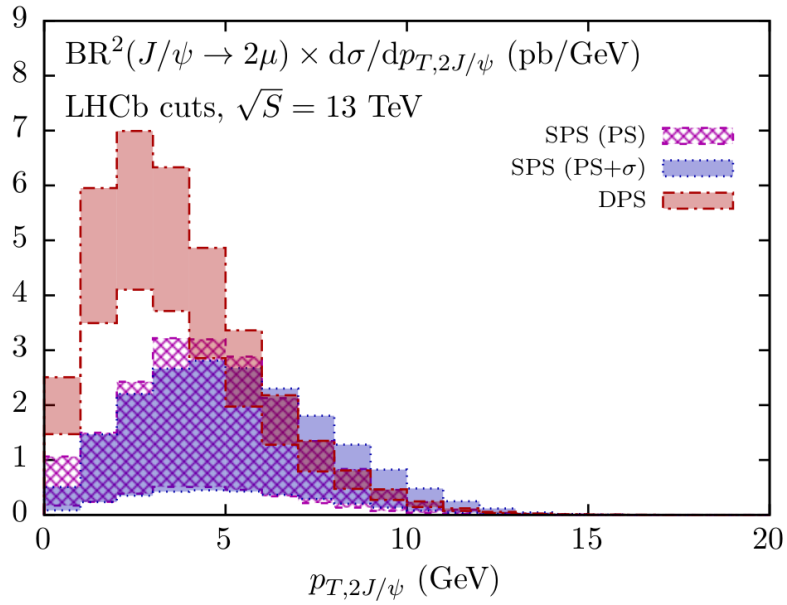
- LO dominant for $P_{\psi\psi_T} \leq 6$ GeV
- Larger $P_{\psi\psi_T} \Rightarrow$ NLO* dominates : the pair recoils against a real gluon
- CO channels are negligible $\Rightarrow$ FSI do not break TMD factorisation



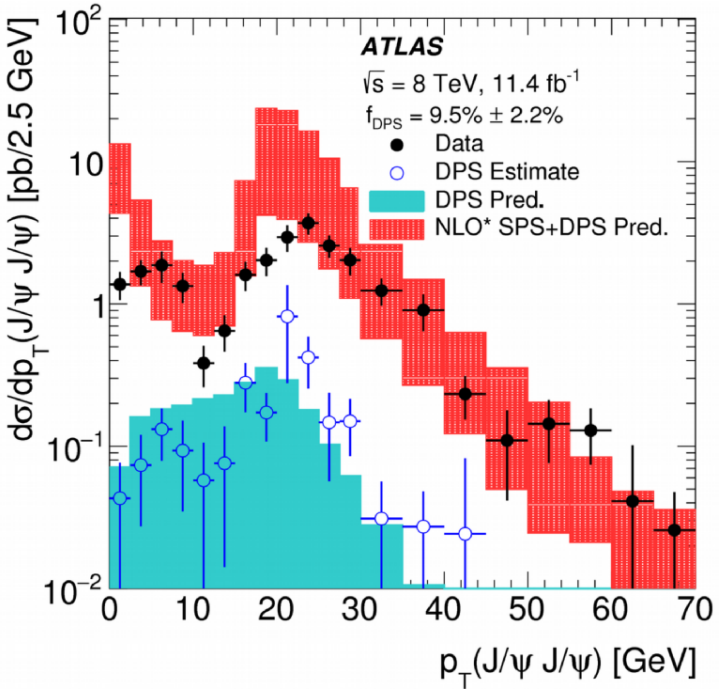
$gg \to J/\psi + J/\psi$: DPS

- Double Parton Scattering (DPS) should compete with Single Parton Scattering (SPS) at LHCb
- Large uncertainties : a clear way to extract the DPS distribution is still lacking

C. Borschensky, A. Kulesza / Phys. Rev. D 95, 034029 (2017)



- ATLAS : p_T-cut on the J/ψ's ; small DPS
- Large $P_{\psi\psi_T}$: TM of the pair generated perturbatively from recoil against a real hard gluon $\Rightarrow$ wipes out TMD effects



$2 \to 2$ processes computed in the TMD framework

- $gg \to \gamma\gamma$: J.W Qiu, M. Schlegel, W. Vogelsang, PRL 107, 062001 (2011)
- $H^0 +$ jet : D. Boer, C. Pisano, Phys. Rev. D91 no. 7, (2015) 074024
- $gg \to \mathcal{Q} + Z/\gamma^*$: J.P. Lansberg , C. Pisano, M. Schlegel, Nucl.Phys. B920 (2017) 192

$2 \to 2$ processes computed in the TMD framework

- $gg \to \gamma\gamma$: J.W Qiu, M. Schlegel, W. Vogelsang, PRL 107, 062001 (2011)
- $H^0 +$ jet : D. Boer, C. Pisano, Phys. Rev. D91 no. 7, (2015) 074024
- $gg \to \mathcal{Q} + Z/\gamma^*$: J.P. Lansberg , C. Pisano, M. Schlegel, Nucl.Phys. B920 (2017) 192

$$\text{Hard scattering coefficients bound :} \quad F_1 \geq F_{2,3,4} \tag{6}$$

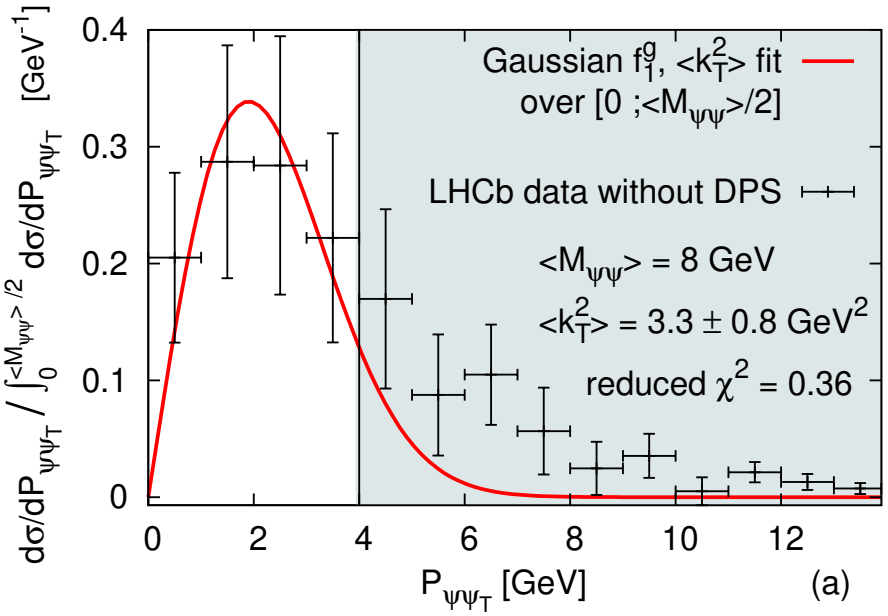
- $gg \to J/\psi + J/\psi$ limit at $M_{\psi\psi} \gg M_\psi$ and $\cos(\theta_{CS}) \to 0$:

$$F_{1,4} \to \frac{256\mathcal{N}}{M_{\mathcal{Q}\mathcal{Q}}^4 M_{\mathcal{Q}}^2}, \quad \frac{F_2}{F_1} \to \frac{81 M_{\mathcal{Q}}^4 \cos(\theta_{CS})^2}{2 M_{\mathcal{Q}\mathcal{Q}}^4}, \quad \frac{F_3}{F_1} \to \frac{-24 M_{\mathcal{Q}}^2 \cos(\theta_{CS})^2}{M_{\mathcal{Q}\mathcal{Q}}^2} \tag{7}$$

$F_4 = F_1$ at large $M_{\psi\psi} \Rightarrow$ unique feature of di-J/ψ

The $P_{\psi\psi_T}$-spectrum and azimuthal asymmetries

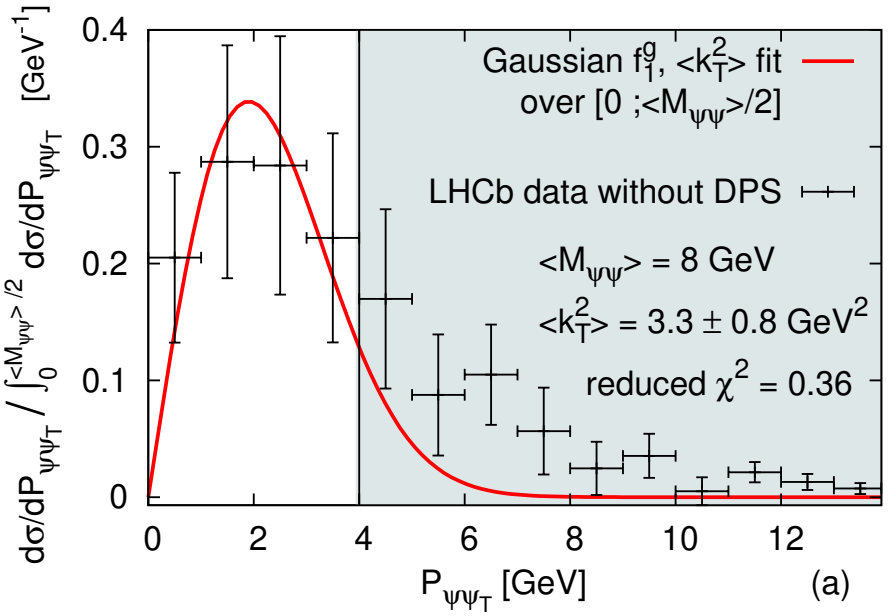
- $\langle k_T^2 \rangle$ fit over normalised LHCb's $d\sigma/dP_{\psi\psi_T}$ data using the analytical expression of $\mathcal{C}[f_1^g f_1^g]$:



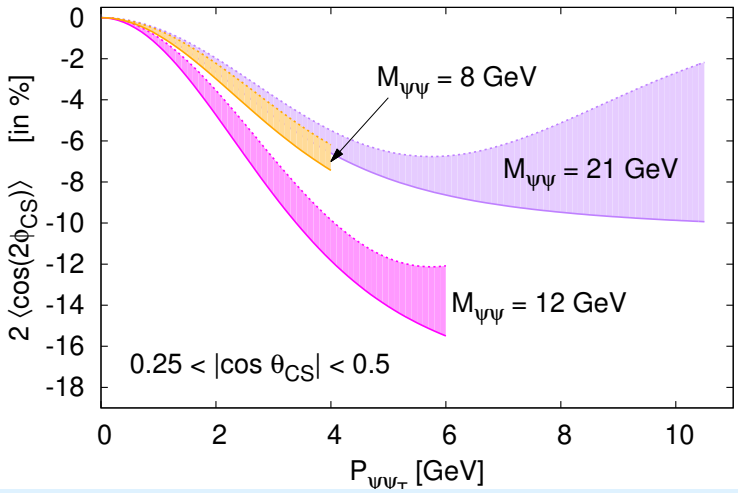
- Integration over $\phi \Rightarrow \cos(n\phi)$-contributions cancelled out
- $F_2 \ll F_1 \Rightarrow$ only $\mathcal{C}[f_1^g f_1^g]$ contributes to the cross-section
- Large value of $\langle k_T^2 \rangle$: indication for evolution effects ?

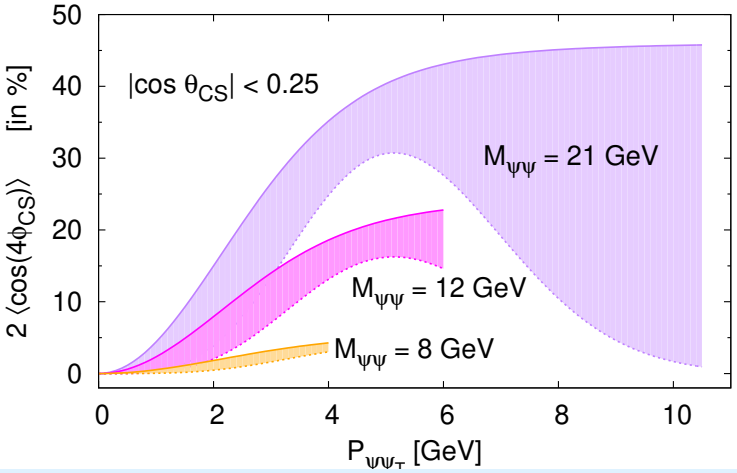
The $P_{\psi\psi_T}$-spectrum and azimuthal asymmetries

- $\langle k_T^2 \rangle$ fit over normalised LHCb's $d\sigma/dP_{\psi\psi_T}$ data using the analytical expression of $\mathcal{C}[f_1^g f_1^g]$:



- Integration over $\phi \Rightarrow \cos(n\phi)$-contributions cancelled out
- $F_2 \ll F_1 \Rightarrow$ only $\mathcal{C}[f_1^g f_1^g]$ contributes to the cross-section
- Large value of $\langle k_T^2 \rangle$: indication for evolution effects ?



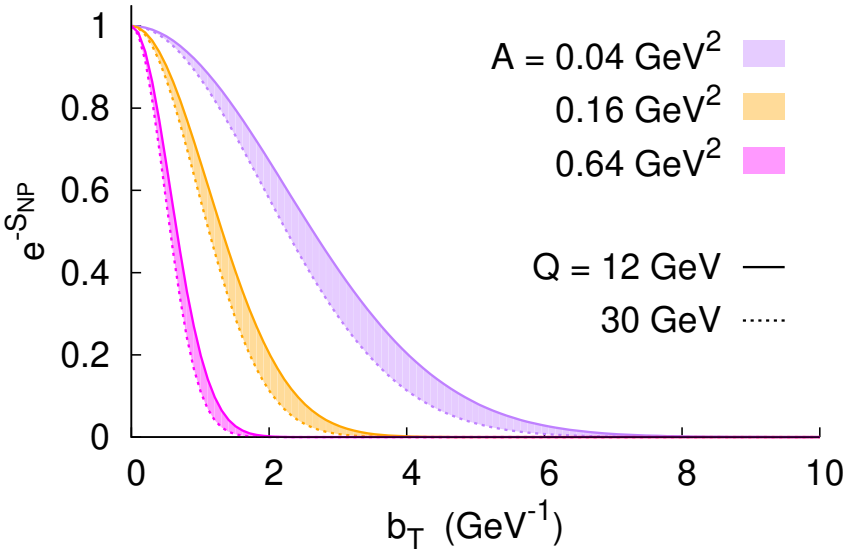


$\cos 4\phi$-mod. up to 50% !

Evolution : the $P_{\psi\psi_T}$-spectrum

A (GeV^2)	b_{Tlim} (GeV^{-1})	$\langle k_T^2 \rangle$ (GeV^2)	r (fm)
0.64	2	3.18	0.2
0.16	4	0.80	0.4
0.04	8	0.20	0.8

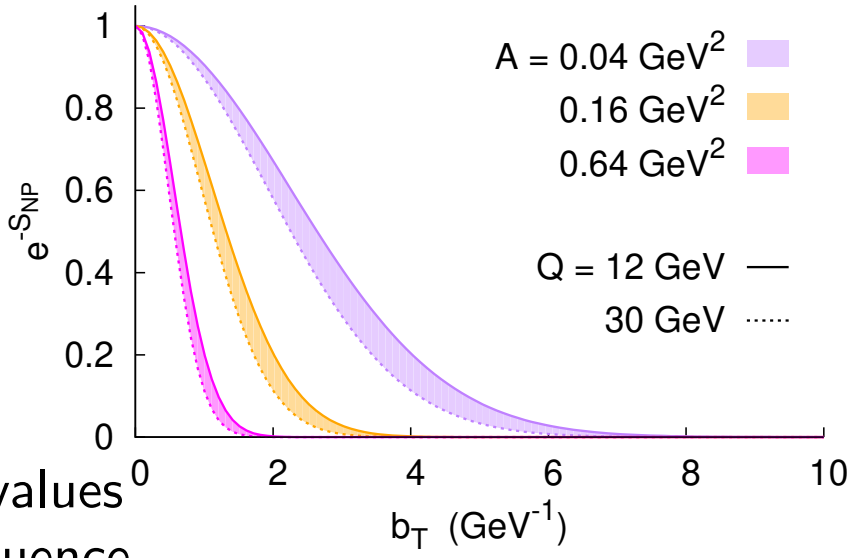
- The TMD scale μ'_b, the perturbative and NP Sudakov factors contribute to the broadening of the $P_{\psi\psi_T}$-spectrum
- Narrow b_T-spectrum $\leftrightarrow$ broad $P_{\psi\psi_T}$-spectrum
- S_{NP} unconstrained for gluons
  $\Rightarrow S_{NP} = A \ln(M_{\psi\psi})\, b_T^2$

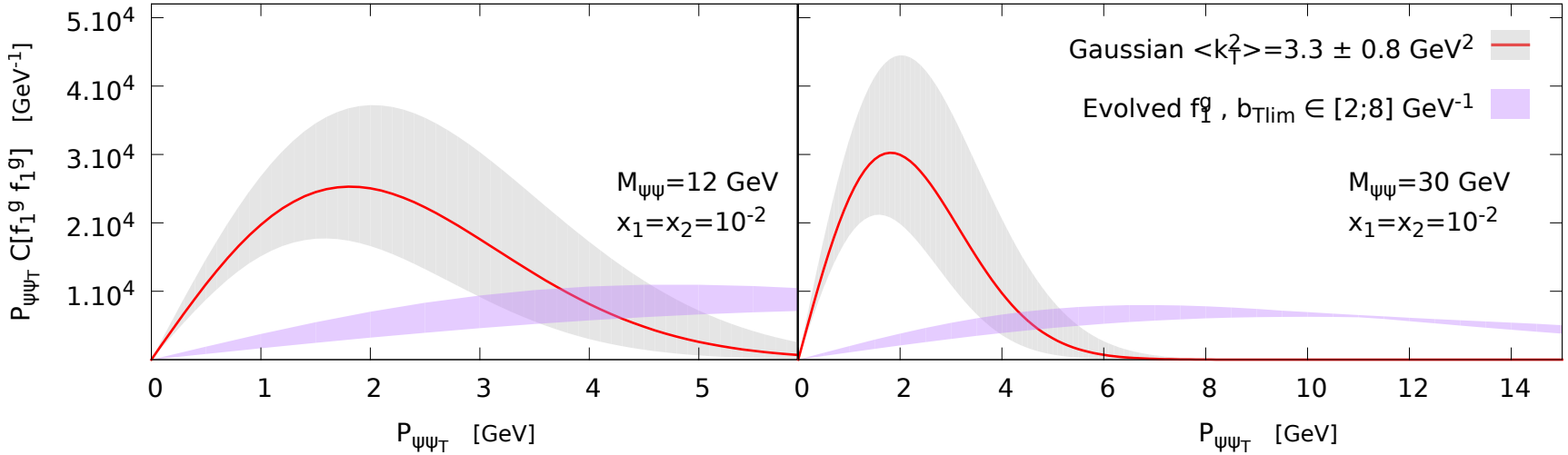


Evolution : the $P_{\psi\psi_T}$-spectrum

A (GeV^2)	b_{Tlim} (GeV^{-1})	$\langle k_T^2 \rangle$ (GeV^2)	r (fm)
0.64	2	3.18	0.2
0.16	4	0.80	0.4
0.04	8	0.20	0.8

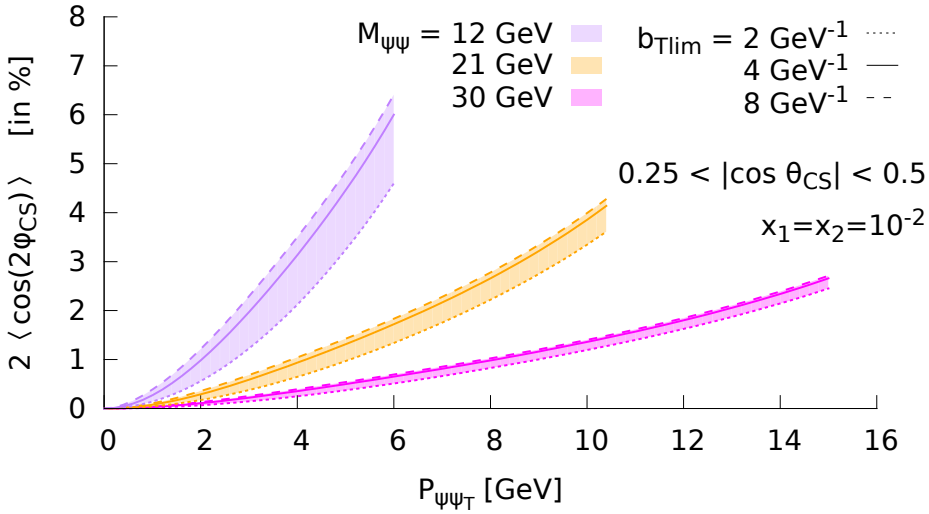
- The TMD scale μ_b', the perturbative and NP Sudakov factors contribute to the broadening of the $P_{\psi\psi_T}$-spectrum
- Narrow b_T-spectrum $\leftrightarrow$ broad $P_{\psi\psi_T}$-spectrum
- S_{NP} unconstrained for gluons
  $\Rightarrow S_{NP} = A \ln(M_{\psi\psi})\, b_T^2$
- Large $M_{\psi\psi}$: S_A strongly suppresses large b_T values
  $\Rightarrow$ broader spectrum, weaker NP Sudakov influence

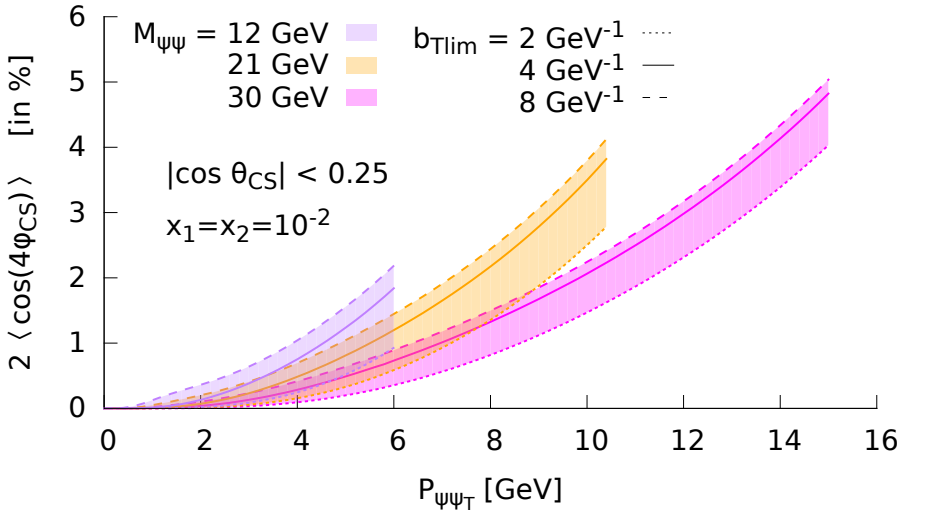




Evolution : Azimuthal asymmetries

- Asymmetries quite smaller: α_s-suppression of $h_1^{\perp g}$
- Double α_s-suppression in $\mathcal{C}[w_4\, h_1^{\perp g}\, h_1^{\perp g}]$ compensated by large hard-scattering coefficient F_4





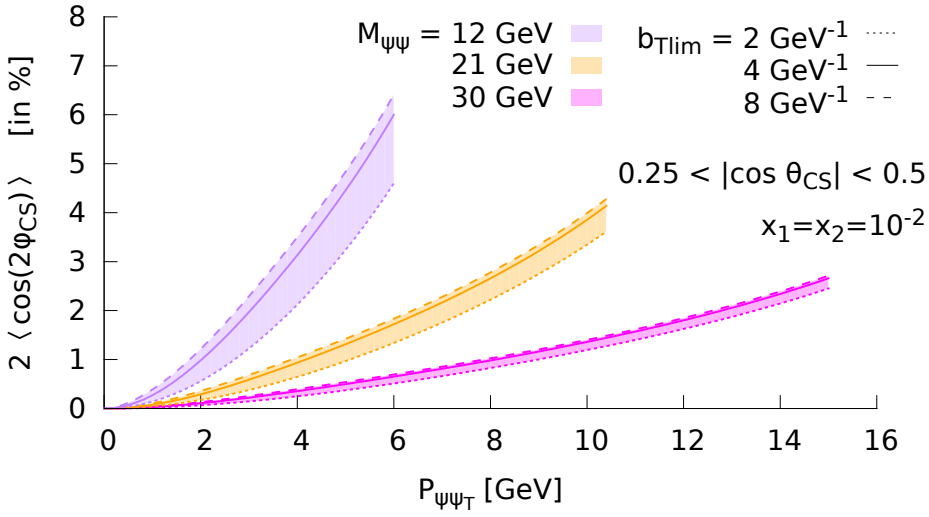
Evolution : Azimuthal asymmetries

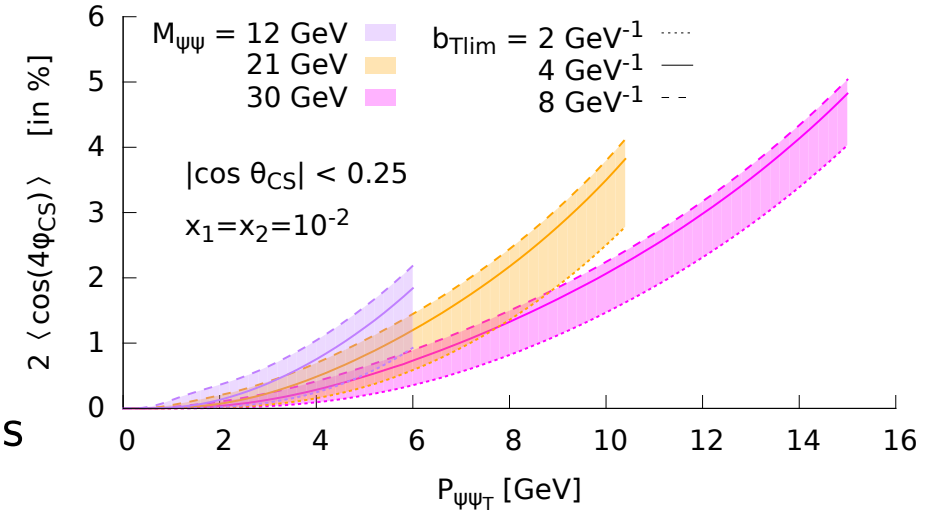
- Asymmetries quite smaller: α_s-suppression of $h_1^{\perp g}$
- Double α_s-suppression in $\mathcal{C}[w_4\, h_1^{\perp g} h_1^{\perp g}]$ compensated by large hard-scattering coefficient F_4
- Ratios increasing with $P_{\psi\psi_T}$

$$\Downarrow$$

Convolutions involving $h_1^{\perp g}$ fall slower with $P_{\psi\psi_T}$ than $\mathcal{C}[f_1^g f_1^g]$

- Size of asymmetries sensitive to width of $S_{NP} \Rightarrow$ constraint on $\langle k_T^2 \rangle$ for both TMDs



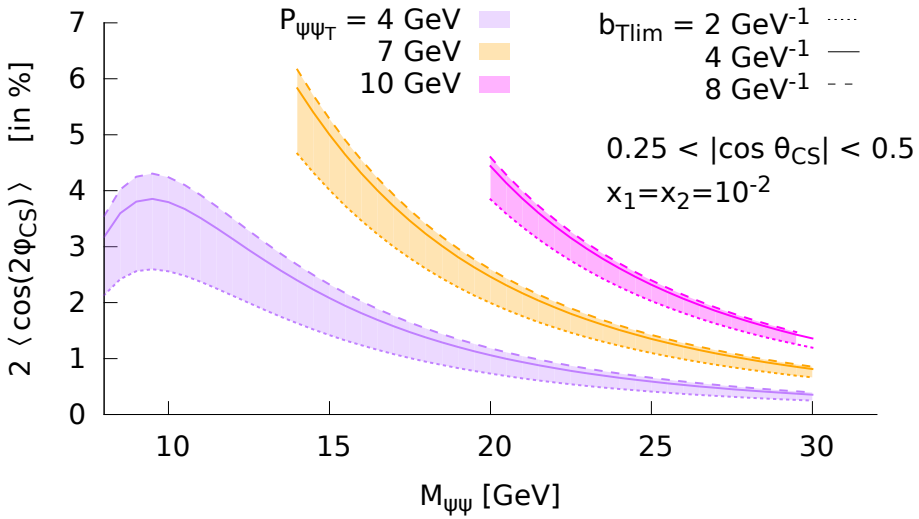


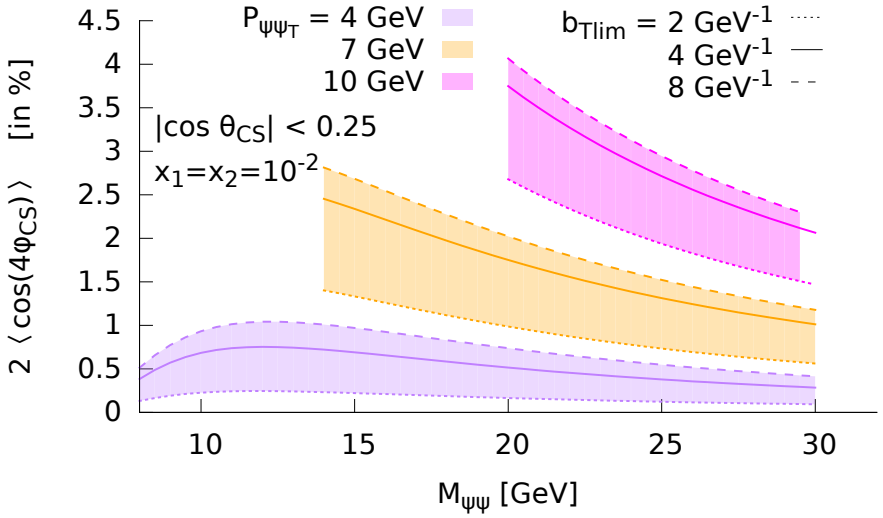
Evolution : Azimuthal asymmetries

- $\mathcal{C}[w_3\, f_1^g\, h_1^{\perp g}]$ and $\mathcal{C}[w_4\, h_1^{\perp g}\, h_1^{\perp g}]$ more Sudakov-suppressed than $\mathcal{C}[f_1^g\, f_1^g]$

$$\Downarrow$$

- Convol. ratios and asymmetries fall with $M_{\psi\psi}$



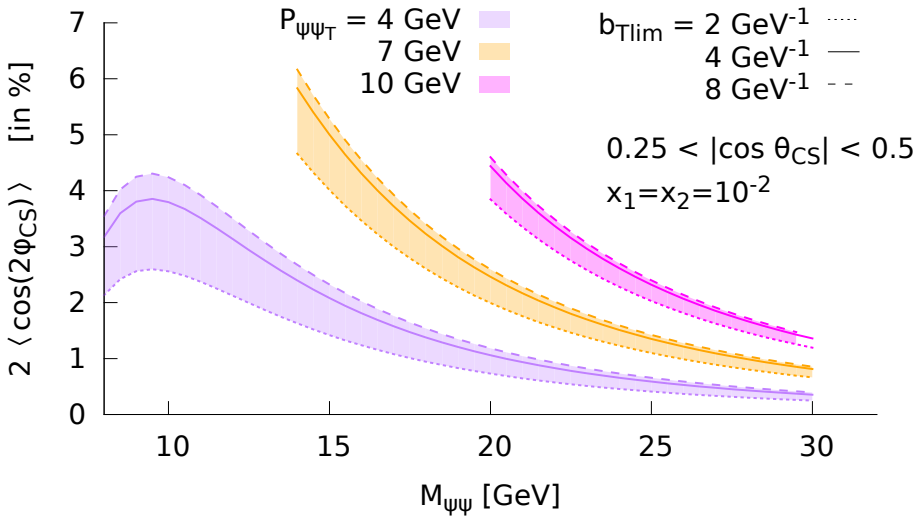


Evolution : Azimuthal asymmetries

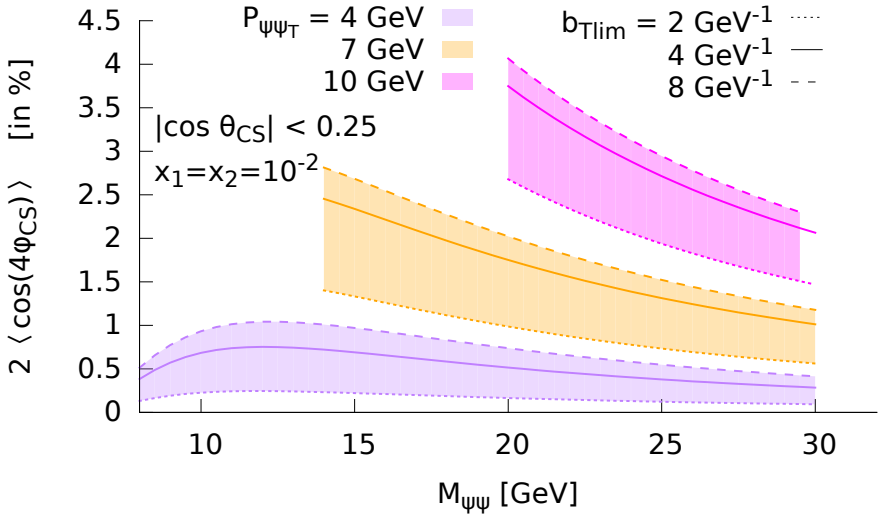
- $\mathcal{C}[w_3\, f_1^g\, h_1^{\perp\, g}]$ and $\mathcal{C}[w_4\, h_1^{\perp\, g}\, h_1^{\perp\, g}]$ more Sudakov-suppressed than $\mathcal{C}[f_1^g\, f_1^g]$

$$\Downarrow$$

- Convol. ratios and asymmetries fall with $M_{\psi\psi}$



- Combined with $M_{\psi\psi}$-dependence of hard-scattering coefficients ratios
- $M_{\psi\psi}$-shape of asymmetries = test of evolution, access to the NP component



Summary

- The features of quarkonia make them good probes for the study of poorly known gluon TMDs
- $gg \to J/\psi + J/\psi$ is a promising channel to investigate :
  - LHC data already available to realise an extraction of the gluon TMDs
  - Hard-scattering coefficients are large enough to allow for various sizeable azimuthal asymmetries
  - Including evolution effects allows extracting the intrinsically non-perturbative component of TMDs ; asymmetries suffer suppression but remain reasonably large

Summary

- The features of quarkonia make them good probes for the study of poorly known gluon TMDs
- $gg \to J/\psi + J/\psi$ is a promising channel to investigate :
  - LHC data already available to realise an extraction of the gluon TMDs
  - Hard-scattering coefficients are large enough to allow for various sizeable azimuthal asymmetries
  - Including evolution effects allows extracting the intrinsically non-perturbative component of TMDs ; asymmetries suffer suppression but remain reasonably large

Summary

- The features of quarkonia make them good probes for the study of poorly known gluon TMDs
- $gg \to J/\psi + J/\psi$ is a promising channel to investigate :
  - LHC data already available to realise an extraction of the gluon TMDs
  - Hard-scattering coefficients are large enough to allow for various sizeable azimuthal asymmetries
  - Including evolution effects allows extracting the intrinsically non-perturbative component of TMDs ; asymmetries suffer suppression but remain reasonably large

Summary

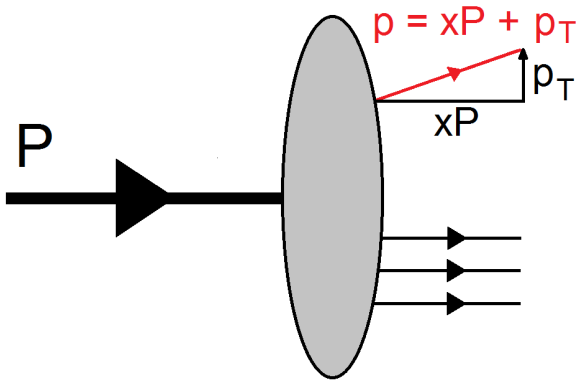
- The features of quarkonia make them good probes for the study of poorly known gluon TMDs
- $gg \to J/\psi + J/\psi$ is a promising channel to investigate :
  - LHC data already available to realise an extraction of the gluon TMDs
  - Hard-scattering coefficients are large enough to allow for various sizeable azimuthal asymmetries
  - Including evolution effects allows extracting the intrinsically non-perturbative component of TMDs ; asymmetries suffer suppression but remain reasonably large

Summary

- The features of quarkonia make them good probes for the study of poorly known gluon TMDs
- $gg \to J/\psi + J/\psi$ is a promising channel to investigate :
  - LHC data already available to realise an extraction of the gluon TMDs
  - Hard-scattering coefficients are large enough to allow for various sizeable azimuthal asymmetries
  - Including evolution effects allows extracting the intrinsically non-perturbative component of TMDs ; asymmetries suffer suppression but remain reasonably large

Backup slides

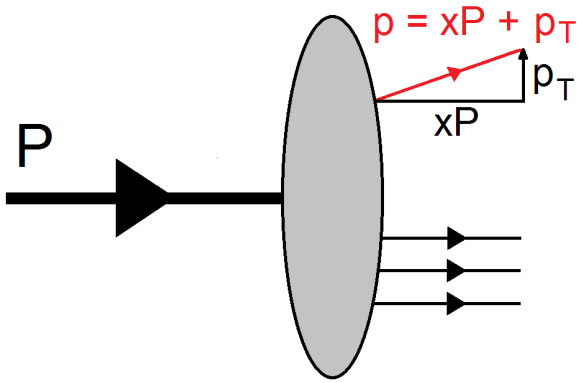
Beyond collinear factorisation



- Observed final-state q_T generated from "intrinsic" k_T from initial partons

- TMD factorisation : collinear partonic scattering amplitude factorised with k_T-dependent correlators in the cross-section for $q_T \ll Q$

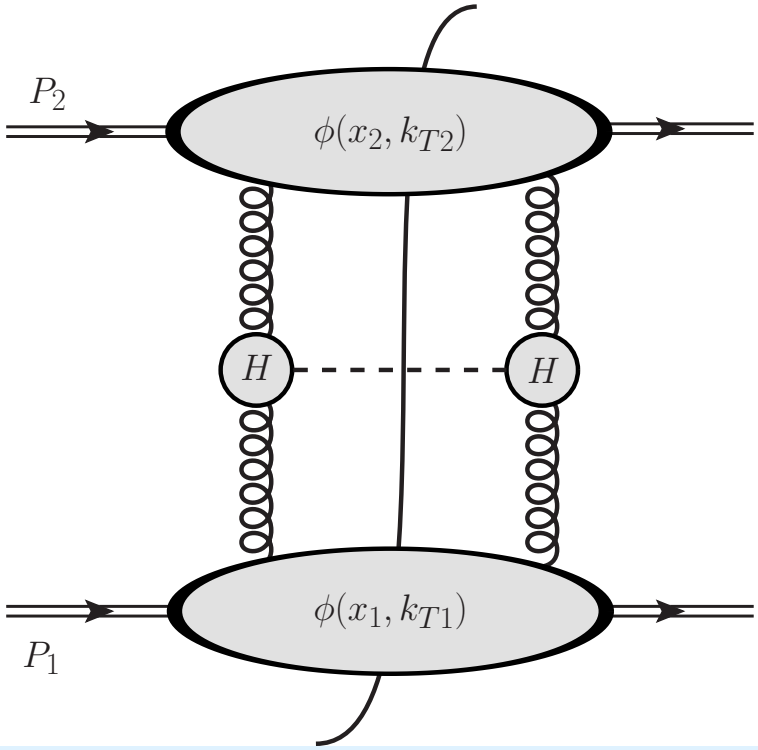
Beyond collinear factorisation



- Observed final-state q_T generated from "intrinsic" k_T from initial partons

- TMD factorisation : collinear partonic scattering amplitude factorised with k_T-dependent correlators in the cross-section for $q_T \ll Q$

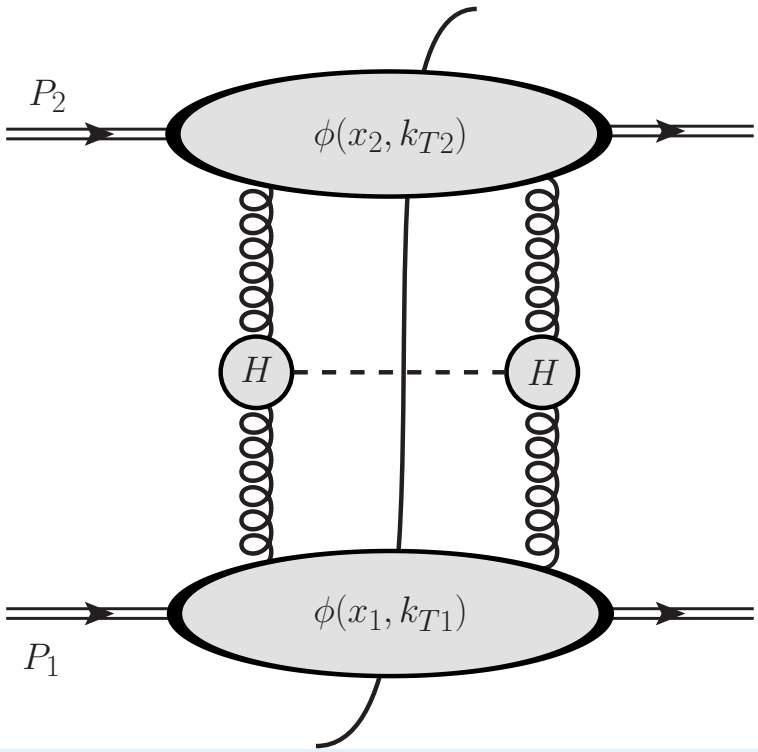
$$d\sigma = \int dx_1 dx_2 d^2\vec{k}_{T1} d^2\vec{k}_{T2}\, \delta^{(2)}(\vec{k}_{T1} + \vec{k}_{T2} - \vec{q}_T)$$
$$\times\, \Phi_g^{\mu\nu}(x_1, \vec{k}_{T1}) \Phi_g^{\rho\sigma}(x_2, \vec{k}_{T2}) \left[\hat{\mathcal{M}}_{\mu\rho}\, \hat{\mathcal{M}}^*_{\nu\sigma} \right]_{\substack{k_1 = x_1 P_1 \\ k_2 = x_2 P_2}}$$
$$+ \mathcal{O}\left(\frac{q_T}{Q}\right) \qquad (8)$$



TMD correlators

- Naive definition of the (fully unintegrated) gluon correlator :

$$\phi_g^{\mu\nu}(k, k', P, S) = \int d^4\xi d^4\eta \, e^{i(k.\xi - k'.\eta)} \langle P, S | A^\mu(\xi) A^\nu(\eta) | P, S \rangle \tag{9}$$



TMD correlators

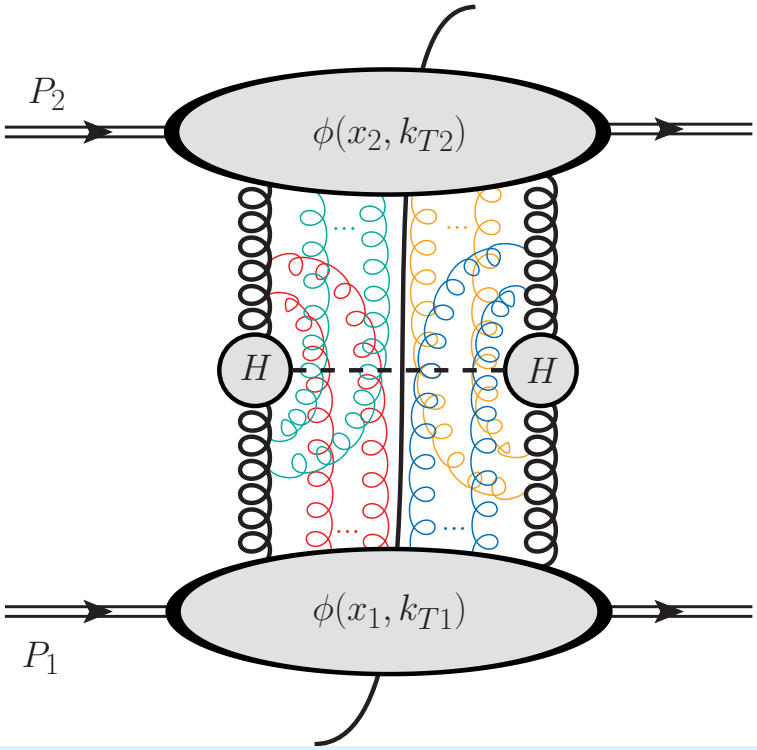
- Naive definition of the (fully unintegrated) gluon correlator :

$$\phi_g^{\mu\nu}(k,k',P,S) = \int d^4\xi d^4\eta \, e^{i(k.\xi - k'.\eta)} \langle P,S| A^\mu(\xi) A^\nu(\eta) |P,S\rangle \tag{9}$$

- Additional contributions of arbitrary numbers of soft gluons : LO in $1/Q$ expansion $\Rightarrow$ need to be resummed to make the correlator gauge-invariant

- Insertion of gauge links in the correlator :

$$U_{a,b}^{[n]} \equiv \mathcal{P} \, e^{-ig \int_{a.P}^{b.P} d(\eta.P) A^n(\eta)} \tag{10}$$



TMD correlators

- Naive definition of the (fully unintegrated) gluon correlator :

$$\phi_g^{\mu\nu}(k,k',P,S) = \int d^4\xi d^4\eta\, e^{i(k.\xi - k'.\eta)} \langle P,S|\, A^\mu(\xi) A^\nu(\eta)\, |P,S\rangle \tag{9}$$

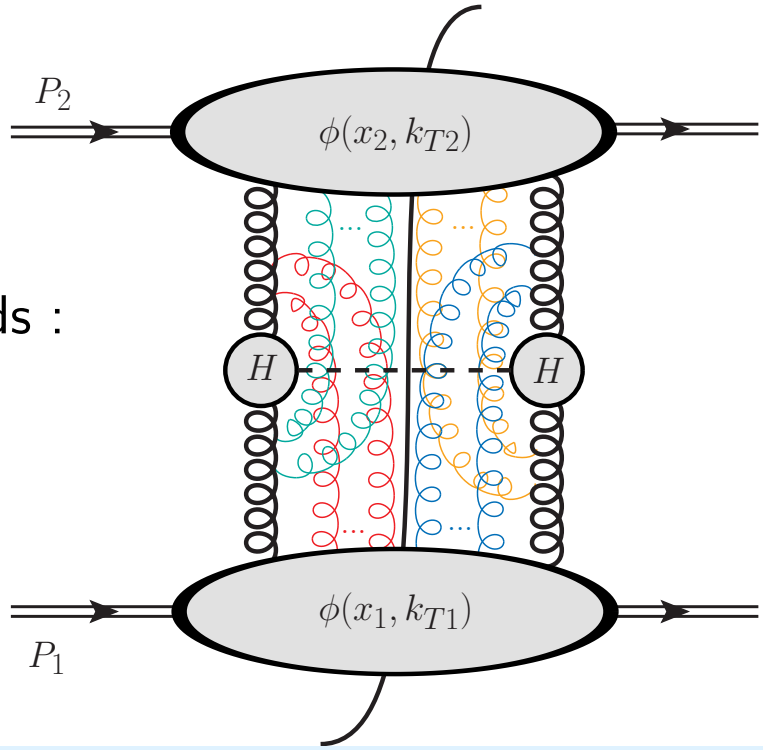
- Additional contributions of arbitrary numbers of soft gluons : LO in $1/Q$ expansion $\Rightarrow$ need to be resummed to make the correlator gauge-invariant

- Insertion of gauge links in the correlator :

$$U_{a,b}^{[n]} \equiv \mathcal{P}\, e^{-ig\int_{a.P}^{b.P} d(\eta.P) A^n(\eta)} \tag{10}$$

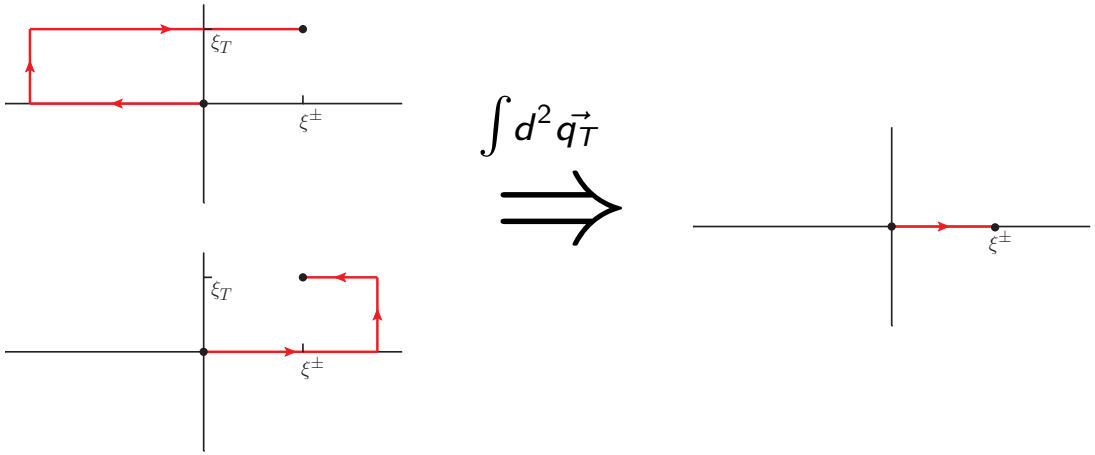
- TMD case : Process dependence of gauge links.
The k_T-dependent correlator for gluon fusion reads :

$$\phi_g^{\mu\nu[-,-]}(x,\vec{k}_T,P,S) = \int \frac{d(\xi.P)d^2\vec{\xi}_T}{(2\pi)^3(k.n)^2} e^{ik.\xi} \times$$
$$2\mathrm{Tr}_c\left[\langle P,S|\, F^{n\nu}(0)\, \mathcal{U}_{0,\xi}^{[-]}\, F^{n\mu}(\xi)\, \mathcal{U}_{\xi,0}^{[-]}\, |P,S\rangle\right]_{LF} \tag{11}$$



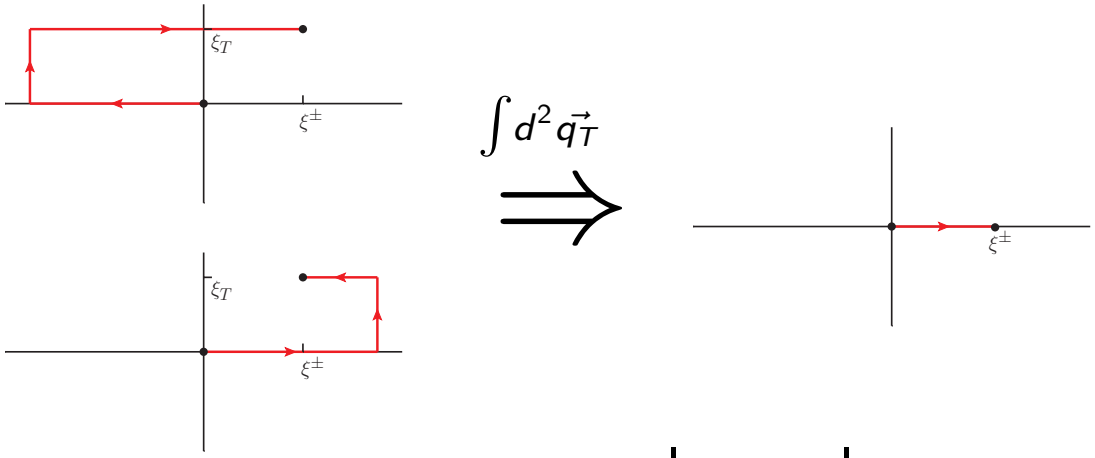
Staple-like links and process dependence

- TMD correlators require "staple-like" gauge links with a transverse component in their path :



Staple-like links and process dependence

- TMD correlators require "staple-like" gauge links with a transverse component in their path :



- The way these links transform under time reversal T allows for the existence of T-odd distributions in the correlator's parametrisation

gluon pol.

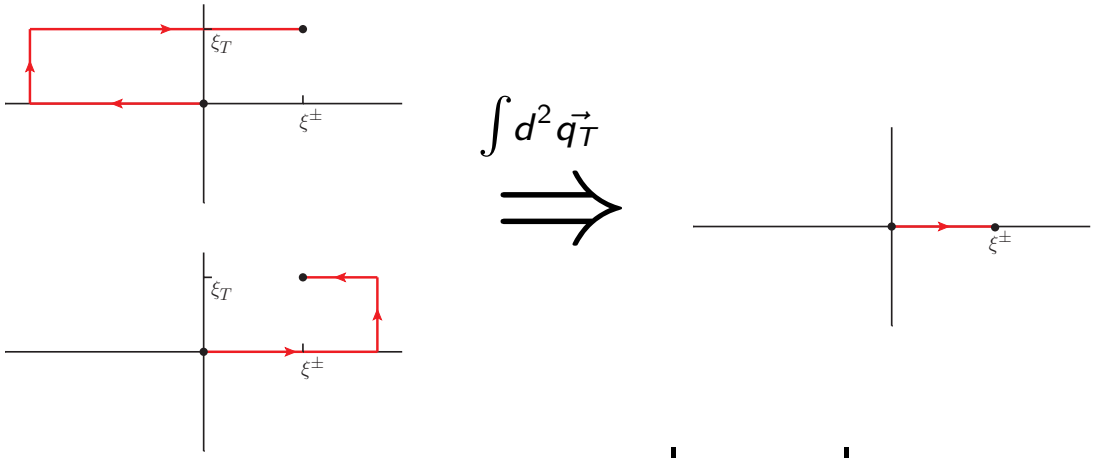
nucleon pol.

	U	circ.	lin.
U	f_1^g		$h_1^{\perp g}$
L		g_1^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_1^g, h_{1T}^{\perp g}$

black : survives $\vec{q_T}$-integration
blue : T-even
red : T-odd

Staple-like links and process dependence

- TMD correlators require "staple-like" gauge links with a transverse component in their path :



- The way these links transform under time reversal T allows for the existence of T-odd distributions in the correlator's parametrisation

gluon pol.

nucleon pol.

	U	circ.	lin.
U	f_1^g		$h_1^{\perp g}$
L		g_1^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_1^g, h_{1T}^{\perp g}$

black : survives $\vec{q_T}$-integration
blue : T-even
red : T-odd

- Sign change between T-odd TMDs extracted in processes with Initial-State Interactions (ISI) or Final State Interactions (FSI) $\Rightarrow$ important prediction of the TMD formalism under investigation

Factorisation breaking and universality

- Non-perturbative interactions of the active quark/gluon with soft spectator partons in the hadron before (Initial-State Interactions) or after (Final-State Interactions) the scattering
- These can make $h_1^{\perp g}$ process dependent and even break factorisation
- Gluon fusion : ISI can be encapsulated in the TMDs
- Colourless final state $\Rightarrow$ no FSI : leptons/photons/Higgs or Colour-Singlet (CS) hadronisation

Factorisation breaking and universality

- Non-perturbative interactions of the active quark/gluon with soft spectator partons in the hadron before (Initial-State Interactions) or after (Final-State Interactions) the scattering
- These can make $h_1^{\perp g}$ process dependent and even break factorisation
- Gluon fusion : ISI can be encapsulated in the TMDs
- Colourless final state $\Rightarrow$ no FSI : leptons/photons/Higgs or Colour-Singlet (CS) hadronisation

Factorisation breaking and universality

- Non-perturbative interactions of the active quark/gluon with soft spectator partons in the hadron before (Initial-State Interactions) or after (Final-State Interactions) the scattering
- These can make $h_1^{\perp g}$ process dependent and even break factorisation
- Gluon fusion : ISI can be encapsulated in the TMDs
- Colourless final state $\Rightarrow$ no FSI : leptons/photons/Higgs or Colour-Singlet (CS) hadronisation

Factorisation breaking and universality

- Non-perturbative interactions of the active quark/gluon with soft spectator partons in the hadron before (Initial-State Interactions) or after (Final-State Interactions) the scattering
- These can make $h_1^{\perp g}$ process dependent and even break factorisation
- Gluon fusion : ISI can be encapsulated in the TMDs
- Colourless final state $\Rightarrow$ no FSI : leptons/photons/Higgs or Colour-Singlet (CS) hadronisation

Transverse weights

The transverse momentum weights are given by

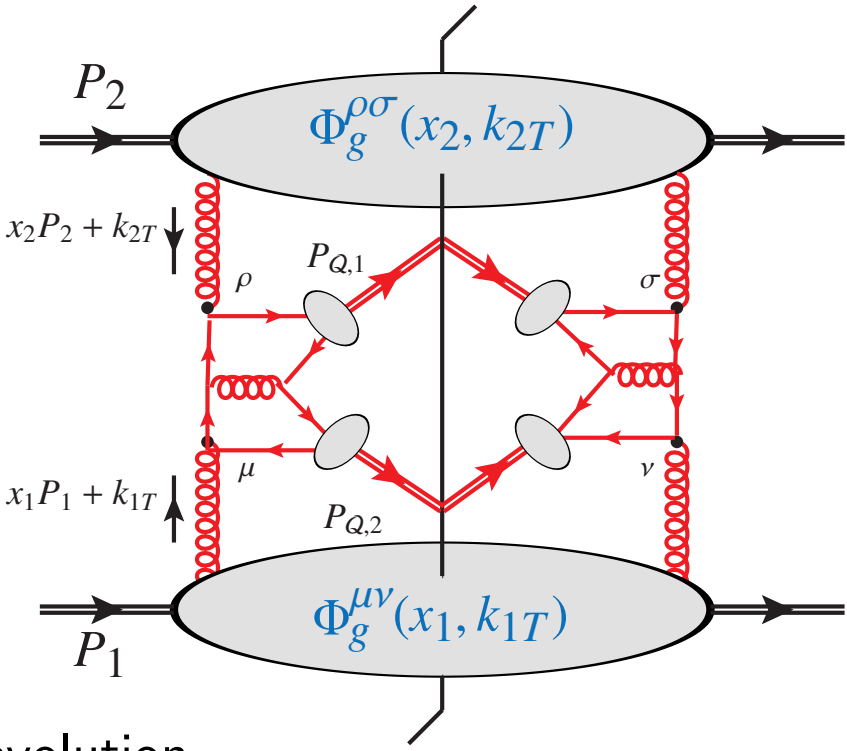
$$w_2 \equiv \frac{2(\vec{k}_{1T}\cdot\vec{k}_{2T})^2 - \vec{k}_{1T}^2\vec{k}_{2T}^2}{4M_p^4} \tag{12}$$

$$w_3 \equiv \frac{q_T^2\vec{k}_{2T}^2 - 2(\vec{q}_T\cdot\vec{k}_{2T})^2}{2M_p^2 q_T^2} \tag{13}$$

$$w_3' \equiv \frac{q_T^2\vec{k}_{1T}^2 - 2(\vec{q}_T\cdot\vec{k}_{1T})^2}{2M_p^2 q_T^2} \tag{14}$$

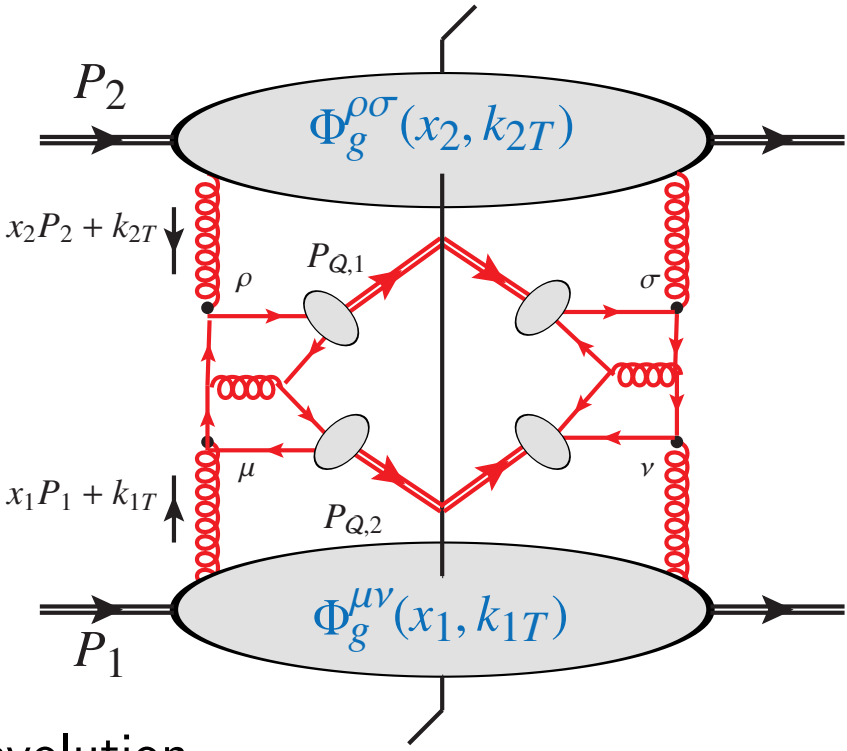
$$w_4 \equiv 2\left[\frac{\vec{k}_{1T}\cdot\vec{k}_{2T}}{2M_p^2} - \frac{(\vec{k}_{1T}\cdot\vec{q}_T)(\vec{k}_{2T}\cdot\vec{q}_T)}{M_p^2 q_T^2}\right]^2 - \frac{\vec{k}_{1T}^2\vec{k}_{2T}^2}{4M_p^4} \tag{15}$$

Advantages of $2 \to 2$ processes



- $2 \to 1$ process :
  - Resulting particle has to be at small $\vec{P}_{\mathcal{Q}_T}$ $\Rightarrow$ likely difficult to measure
  - Hard scale has to be the particle mass : $Q^2 = M_{\mathcal{Q}}^2$ $\Rightarrow$ doesn't help to study TMD evolution

Advantages of $2 \to 2$ processes

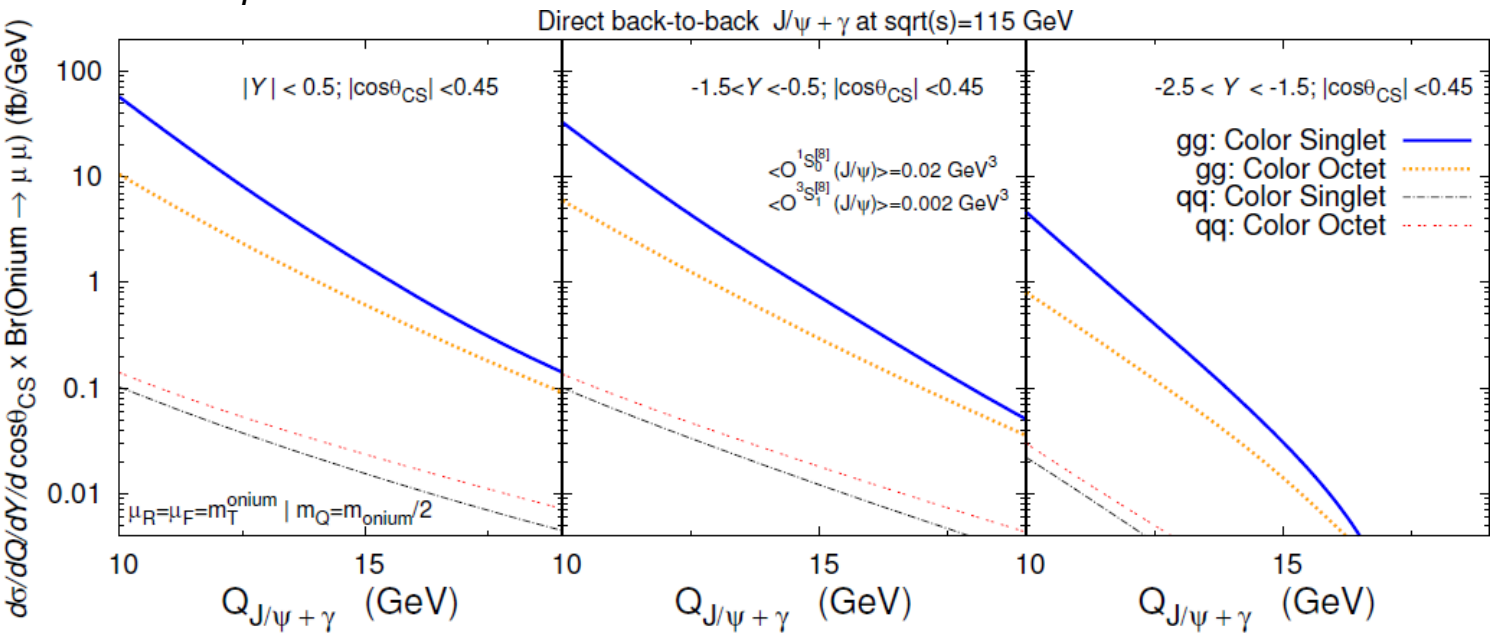


- $2 \to 1$ process :
  - Resulting particle has to be at small $\vec{P}_{\mathcal{Q}_T}$ $\Rightarrow$ likely difficult to measure
  - Hard scale has to be the particle mass : $Q^2 = M_{\mathcal{Q}}^2$ $\Rightarrow$ doesn't help to study TMD evolution
- $2 \to 2$ process : $\vec{P}_{\mathcal{Q}1_T} \simeq -\vec{P}_{\mathcal{Q}2_T}$
  - Produced particles can each have a large $\vec{P}_{\mathcal{Q}_T}$ adding up to a small $\vec{P}_{\mathcal{Q}\mathcal{Q}_T}$ for the pair $\Rightarrow$ TMDs relevant for a wide range of final-state momenta
  - Hard scale $Q^2 = M_{\mathcal{Q}\mathcal{Q}}^2$ can be tuned to study TMD evolution

$\mathcal{Q} + \gamma$ at AFTER@LHC

AFTER@LHC : a fixed-target experiment using the LHC beams

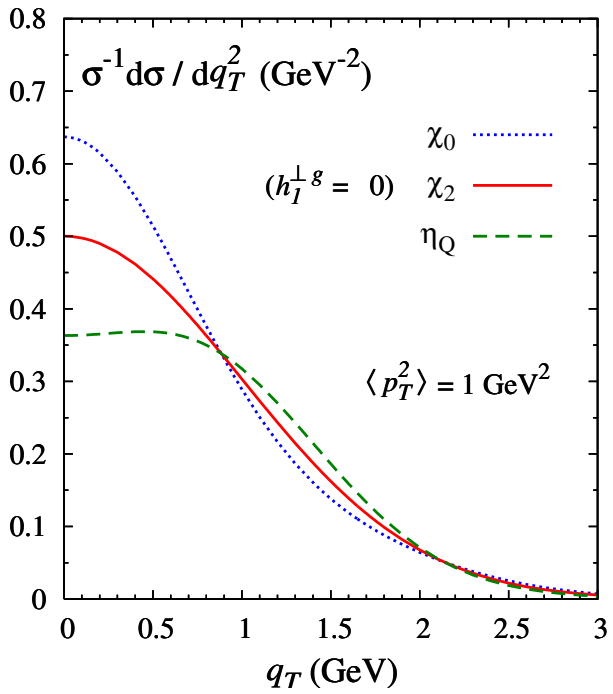
- $\sqrt{2 \times m_N \times E_p} \overset{7\,TeV}{=} 115$ GeV
- Experimental coverage of ALICE or LHCb is about $y_{\rm cms} \in [-3 : 0]$
- For $\psi + \gamma$, smaller yield (14 TeV $\rightarrow$ 115 GeV) compensated by an access to lower P_T



- At $Y_{(\rm cms)} \simeq -2$, $x_2 \simeq 10/115 \times e^2 \simeq 0.65$. Yet, $g - g > q - \bar{q}$!

$gg \to \eta_Q$ and $gg \to \chi_{Q_{0,2}}$

D. Boer, C. Pisano / Physical Review D 86, 094007 (2012)



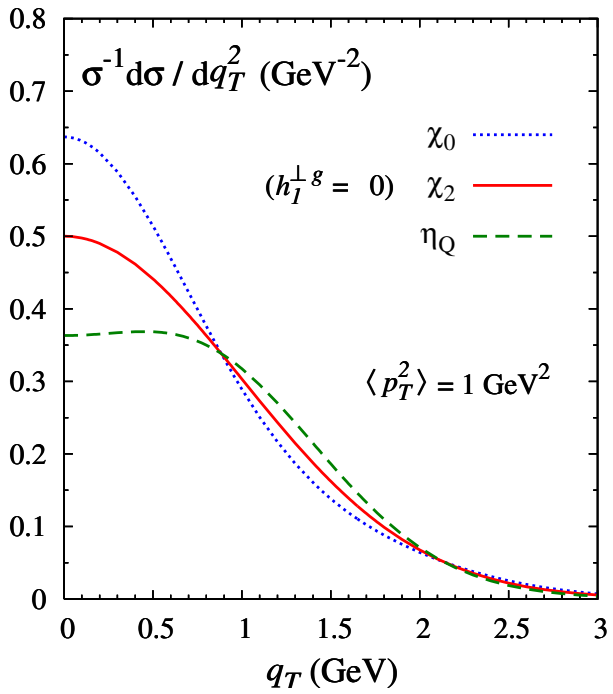
- Low q_T C-even quarkonium production is a good probe of $h_1^{\perp g}$
- Very clean action on the low q_T spectra:

$$\frac{1}{\sigma}\frac{d\sigma(\eta_Q)}{d\vec{q}_T^2} \propto 1 - R(\vec{q}_T^2) \;\&\; \frac{1}{\sigma}\frac{d\sigma(\chi_{Q,0})}{d\vec{q}_T^2} \propto 1 + R(\vec{q}_T^2)$$

$$\left(R = \frac{F_2}{F_1}\frac{\mathcal{C}[w_2\, h_1^{\perp g} h_1^{\perp g}]}{\mathcal{C}[f_1^g f_1^g]} \right)$$

$gg \to \eta_Q$ and $gg \to \chi_{Q_{0,2}}$

D. Boer, C. Pisano / Physical Review D 86, 094007 (2012)



- Low q_T C-even quarkonium production is a good probe of $h_1^{\perp g}$
- Very clean action on the low q_T spectra:

$$\frac{1}{\sigma}\frac{d\sigma(\eta_Q)}{d\vec{q}_T^2} \propto 1 - R(\vec{q}_T^2) \;\&\; \frac{1}{\sigma}\frac{d\sigma(\chi_{Q,0})}{d\vec{q}_T^2} \propto 1 + R(\vec{q}_T^2)$$

$$\left(R = \frac{F_2}{F_1}\frac{\mathcal{C}[w_2\, h_1^{\perp g} h_1^{\perp g}]}{\mathcal{C}[f_1^g f_1^g]} \right)$$

- Cannot tune $Q \Rightarrow Q \simeq M_{\mathcal{Q}}$ (Higgs prod. $\sim \eta_c$ prod. at $Q = 125$ GeV)
- Low q_T: experimentally very difficult

  [Only one η_c production study at collider , for $q_T^{\eta_c} > 6$ GeV LHCb, 1409.3612]

Prospects for the future measurements

- Fixed-Target Program for the LHC (FTP4LHC) :
  - Drell-Yan Single Transverse Spin Asymmetry (STSA) can constraint the quark Sivers effect, especially at large x
  - Other TMDs can be accessed : h_1^q, $h_1^{\perp q}$, $h_{1T}^{\perp q}$
  - Gluon Sivers effect can also be measured in associated quarkonium production : $p^\uparrow p \to J/\psi\, \gamma\, X$, $p^\uparrow p \to J/\psi\, J/\psi\, X$, $p^\uparrow p \to \gamma\, jet\, X$