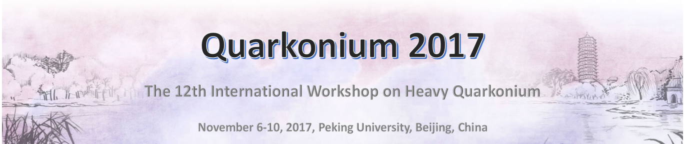
Pinning down the linearly-polarized gluons inside unpolarized protons using J/ψ-pair production at the LHC

Florent SCARPA

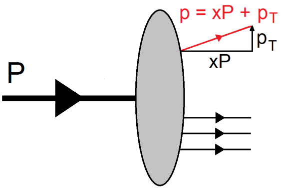
Collaborators : Jean-Philippe Lansberg, Cristian Pisano and Marc Schlegel

arXiv:1710.01684



Generalities on gluon TMDs

Beyond collinear factorisation



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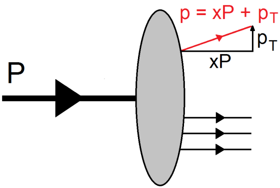

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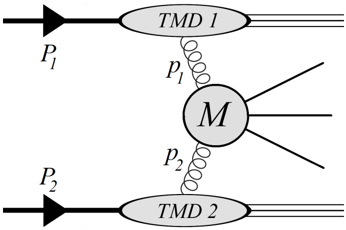
- TMD factorisation : collinear partonic scattering amplitude factorised with k_T-dependent correlators in the cross-section for $q_T \ll Q$



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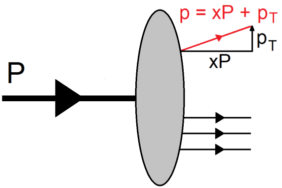

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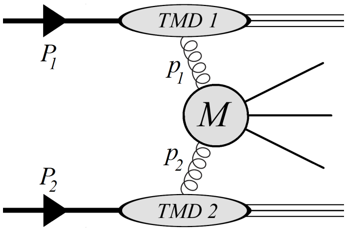
$$d\sigma = \int dx_1 dx_2 d^2\vec{k}_{T1} d^2\vec{k}_{T2} \delta^{(2)}(\vec{k}_{T1} + \vec{k}_{T2} - \vec{q}_T)$$
$$\times \Phi_g^{\mu\nu}(x_1, \vec{k}_{T1}) \Phi_g^{\rho\sigma}(x_2, \vec{k}_{T2}) \left[\hat{\mathcal{M}}_{\mu\rho} \hat{\mathcal{M}}^*_{\nu\sigma} \right] \Big|_{\substack{k_1 = x_1 P_1 \\ k_2 = x_2 P_2}}$$
$$+ \mathcal{O}\left(\frac{q_T^2}{Q^2}\right) \quad (1)$$



TMD distributions & correlators

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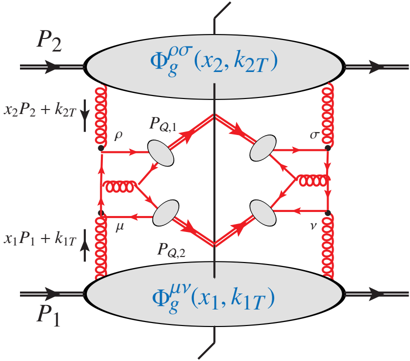

TMD distributions & correlators

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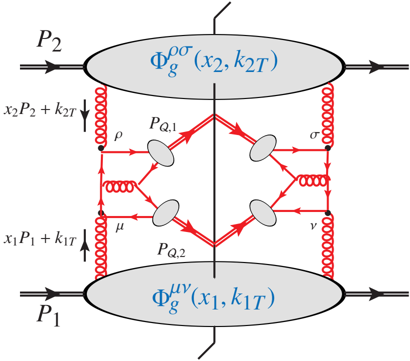
- Relevant TMDs :
  - f_1^g : TMD distribution of unpolarised gluons
  - $h_1^{\perp g}$: TMD distribution of linearly polarised gluons



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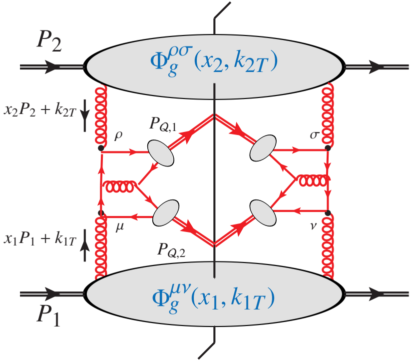

- Parametrisation of the TMD correlator for an unpolarised proton :

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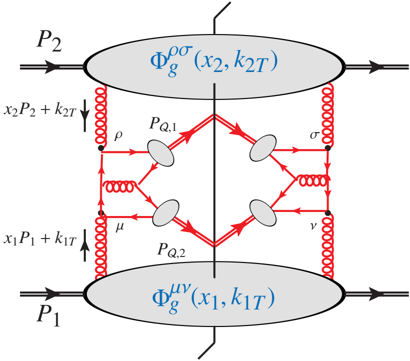

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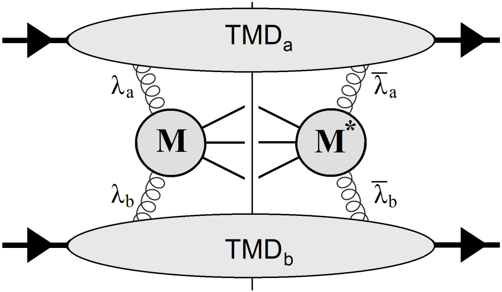

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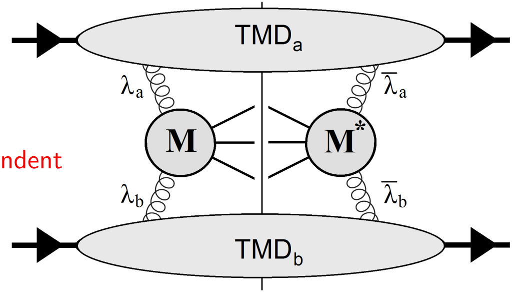
$\Rightarrow$ helicity non-flip, azimuthally independent



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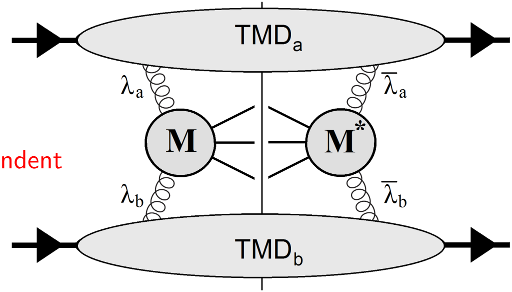

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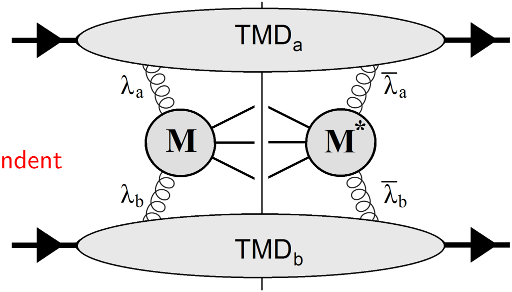

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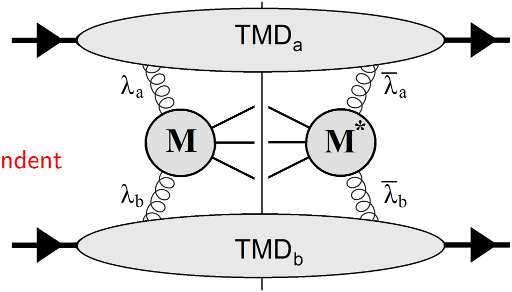

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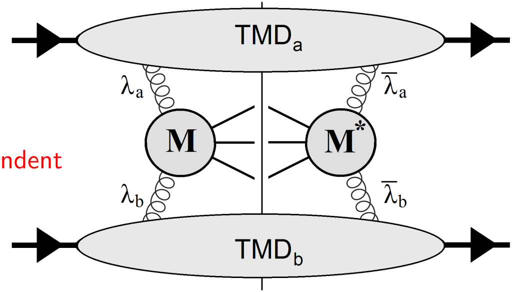

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} modulations in $\phi_{CS} = (\vec{P}_{\psi\psi_T}, \vec{P}_{\psi_T})$

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

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LHCb JHEP 1706 (2017) 047
CMS JHEP 1409 (2014) 094
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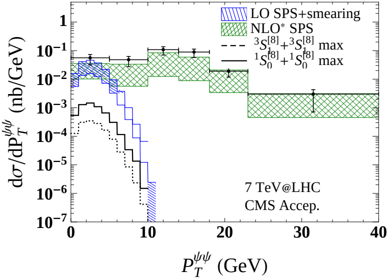
J.-P. Lansberg, H.-S. Shao / Physics Letters B 751 (2015) 479-486



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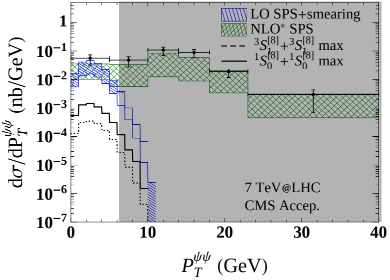

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- For $\Delta y \leq 2$: DPS $<$ SPS

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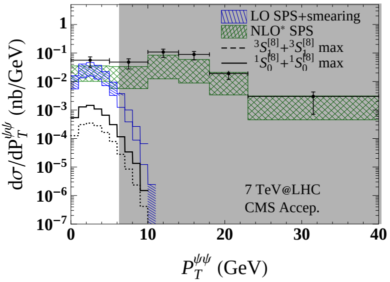

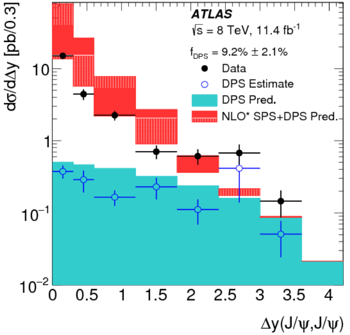

$2 \to 2$ processes computed in the TMD framework

- $gg \to \gamma\gamma$: J.W Qiu, M. Schlegel, W. Vogelsang, PRL 107, 062001 (2011)
- $gg \to \mathcal{Q} + \gamma$: W. den Dunnen, J.P. Lansberg, C. Pisano, M. Schlegel, PRL 112, 212001 (2014)
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$$\text{Hard scattering coefficients bound :} \quad F_1 \geq F_{2,3,4} \tag{3}$$

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

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

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

TMD modelling : f_1^g

f_1^g modelled as a Gaussian in $\vec{k}_T$:$f_1^g(x, \vec{k}_T^2) = \frac{g(x)}{\pi \langle k_T^2 \rangle} e^{\frac{-\vec{k}_T^2}{\langle k_T^2 \rangle}}$ (5)

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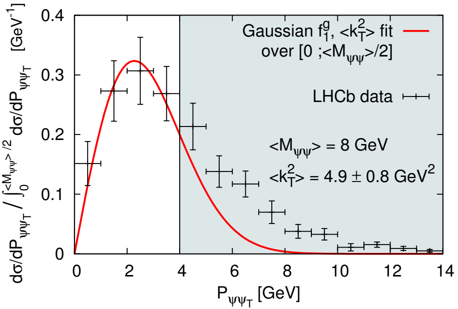

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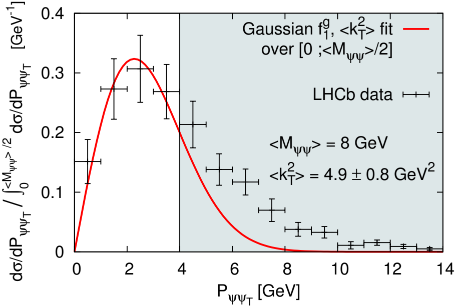

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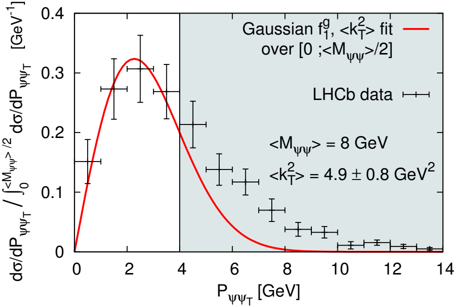

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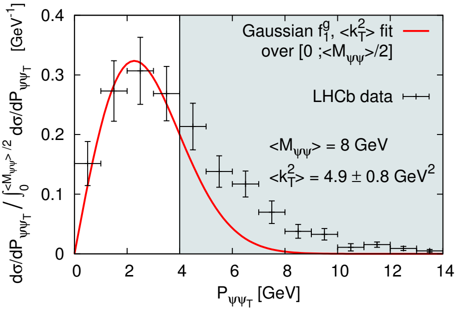

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- No evolution so far

TMD modelling : the mysterious $h_1^{\perp g}$

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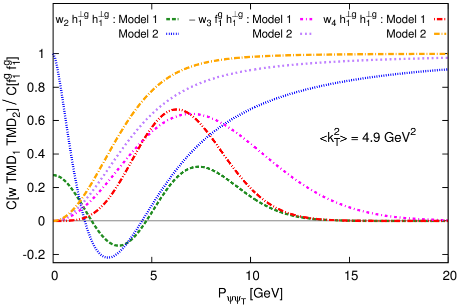

- In order to isolate the different ϕ-dependences, one can define :

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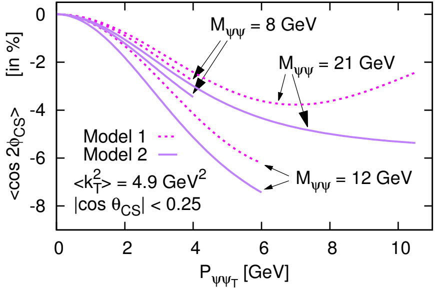
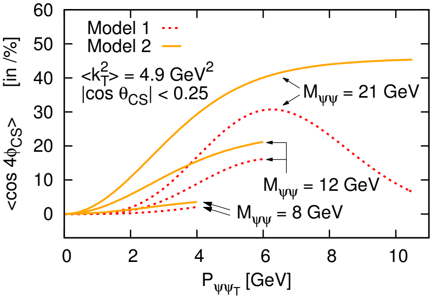
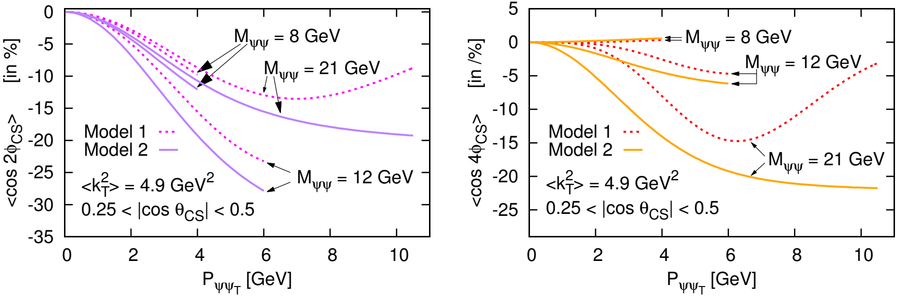




- $\cos 4\phi$-modulations up to 50% !


0
-5
-10
-15
-20
-25
-30
-35
0
2
4
6
8
10
$M_{\psi\psi}$ = 8 GeV
$M_{\psi\psi}$ = 21 GeV
$M_{\psi\psi}$ = 12 GeV
Model 1
Model 2
$<k_T^2>$ = 4.9 GeV^2
0.25 < |cos θ_{CS}| < 0.5
<cos 2ϕ_{CS}> [in %]
$P_{\psi\psi_T}$ [GeV]
5
0
-5
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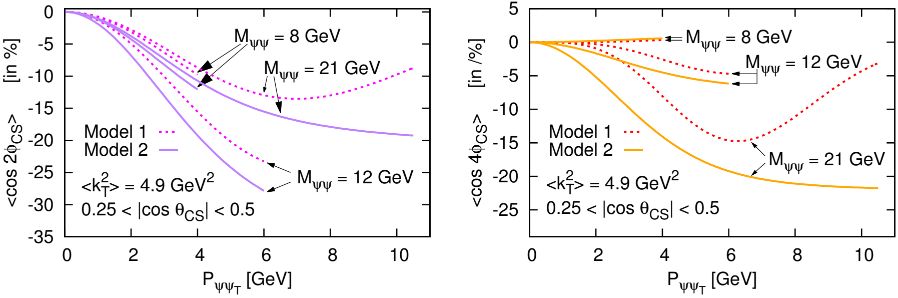
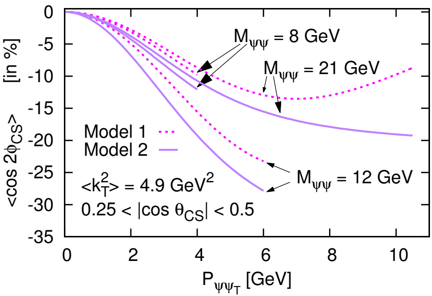
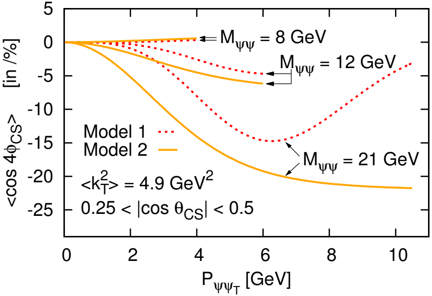


- $\langle \cos 2\phi_{CS} \rangle$ reaches 30% $\Rightarrow$ important to determine the sign of $h_1^{\perp g}$





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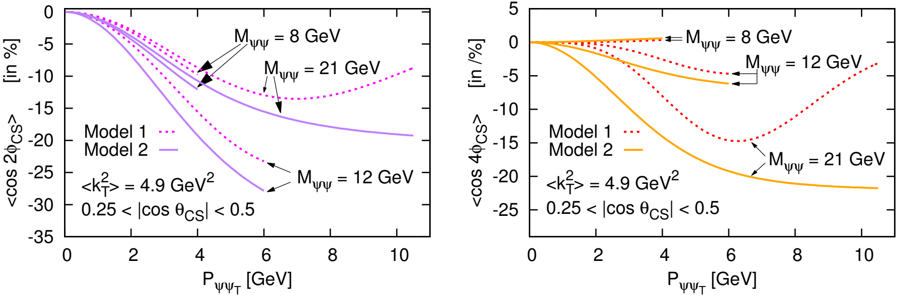

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- $\langle \cos 4\phi_{CS} \rangle$ changes sign $\Rightarrow$ one must be careful when integrating over the phase space
- Modulations measurable at different energies $\Rightarrow$ possibility to study TMD evolution

Summary

- TMD factorisation = systematic method to take into account the TM of partons inside *pp* reactions
- The features of quarkonia make them good probes for the study of gluon TMD-induced effects
- $gg \to J/\psi + J/\psi$ is a promising channel to investigate :
  - LHC data already available to realise the first extraction of the gluon TMDs
  - Computations show that neither CO nor DPS contributions should complicate the extraction
  - di-J/ψ prod. is a real gluon TMDs laboratory : magnitude, sign, k_T-dependence and evolution can be studied
- $\cos(4\phi)$-modulations can be measured at ATLAS and CMS !

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Backup slides

J/ψ pairs as probes of TMDs

- Heavy flavours at the LHC mainly come from gluons $\Rightarrow$ allows for study of gluon TMDs with low $q\bar{q}$ contamination
- Their large masses allow to evaluate the partonic scattering process in perturbative QCD
- Interest in producing a pair :
  - Produced J/ψ's can each have a large $\vec{P}_{\psi_T}$ adding up to a small $\vec{P}_{\psi\psi_T}$ for the pair $\Rightarrow$ TMDs relevant for a wide range of final-state momenta
  - Hard scale $Q^2 = M^2_{\mathcal{QQ}}$ can be tuned to study TMD evolution
- CS vs. CO contributions should be analysed case by case [reactions and kinematics]

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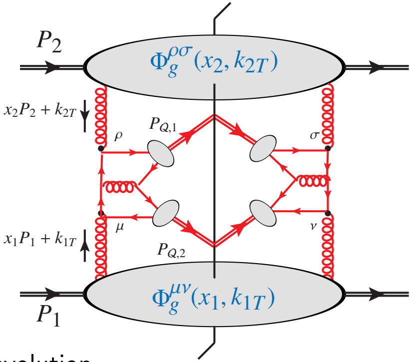
  [reactions and kinematics]

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

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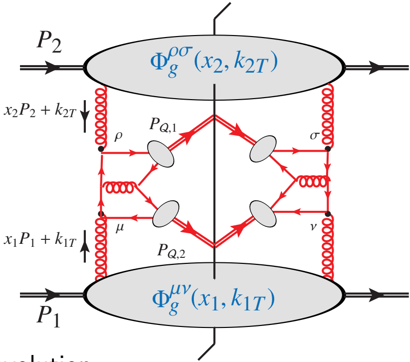

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- $2 \to 2$ process : $\vec{P}_{\mathcal{Q}1_T} \simeq -\vec{P}_{\mathcal{Q}2_T}$
  - Produced particles can each have a large $\vec{P}_{\mathcal{Q}_T}$ adding up to a small $\vec{P}_{\mathcal{Q}\mathcal{Q}_T}$ for the pair $\Rightarrow$ TMDs relevant for a wide range of final-state momenta
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TMD classification

		Parent hadron polarisation		
		Unpolarised	Longitudinal	Transverse
Parton polarisation	U	$f_1(x, \vec{k}_T^2)$ (Number density)		$f_{1T}^{\perp}(x, \vec{k}_T^2)$ (Sivers)
	L		$g_1(x, \vec{k}_T^2)$ (Helicity)	$g_{1T}^{\perp}(x, \vec{k}_T^2)$
	T	$h_1^{\perp}(x, \vec{k}_T^2)$ (Boer-Mulders)	$h_{1L}^{\perp}(x, \vec{k}_T^2)$	$h_1(x, \vec{k}_T^2)$ (Transversity) $h_{1T}^{\perp}(x, \vec{k}_T^2)$ (Pretzelosity)

- f_1, g_1, h_1 give the standard PDFs after integration over $\vec{k}_T$
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Transverse weights

The transverse momentum weights are given by

$$w_2 \equiv \frac{2(\vec{k}_{1T}\cdot\vec{k}_{2T})^2 - \vec{k}_{1T}^2\vec{k}_{2T}^2}{4M_p^4} \quad (8)$$

$$w_3 \equiv \frac{q_T^2\vec{k}_{2T}^2 - 2(\vec{q_T}\cdot\vec{k}_{2T})^2}{2M_p^2 q_T^2} \quad (9)$$

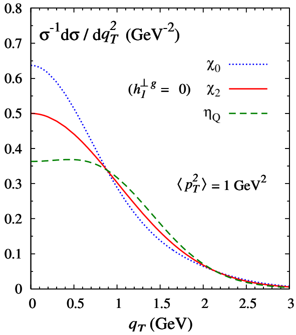
$$w_3' \equiv \frac{q_T^2\vec{k}_{1T}^2 - 2(\vec{q_T}\cdot\vec{k}_{1T})^2}{2M_p^2 q_T^2} \quad (10)$$

$$w_4 \equiv 2\left[\frac{\vec{k}_{1T}\cdot\vec{k}_{2T}}{2M_p^2} - \frac{(\vec{k}_{1T}\cdot\vec{q_T})(\vec{k}_{2T}\cdot\vec{q_T})}{M_p^2 q_T^2}\right]^2 - \frac{\vec{k}_{1T}^2\vec{k}_{2T}^2}{4M_p^4} \quad (11)$$

Processes of interest : $2 \to 1$

$gg \to \eta_Q$ 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:

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

$$\left(R = \frac{\mathcal{C}[w_0^{hh}\, h_1^{\perp g} h_1^{\perp g}]}{\mathcal{C}[f_1^g f_1^g]} \right)$$

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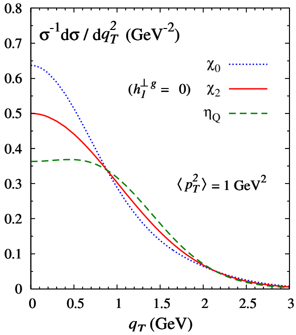

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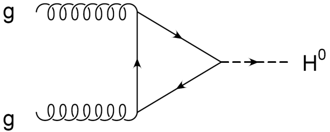
$$\left(R = \frac{\mathcal{C}[w_0^{hh}\, h_1^{\perp g} h_1^{\perp g}]}{\mathcal{C}[f_1^g f_1^g]}\right)$$

- Cannot tune $Q \Rightarrow Q \simeq M_{\mathcal{Q}}$
- Low q_T: experimentally very difficult

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

Higgs production

- Higgs production : very similar to scalar quarkonium production $\Rightarrow$ same method to add gluon-p_T dependence for $gg \to H$ cross-section
- $q\bar{q} \to \mathcal{Q}$ (hadronisation) $\Rightarrow$ replaced by Hqq coupling



- Cross-section structure similar to single η_c production
- The LHC data on Higgs production give access to the value of f_1^g, $h_1^{\perp g}$ for a value of $Q \simeq M_H$

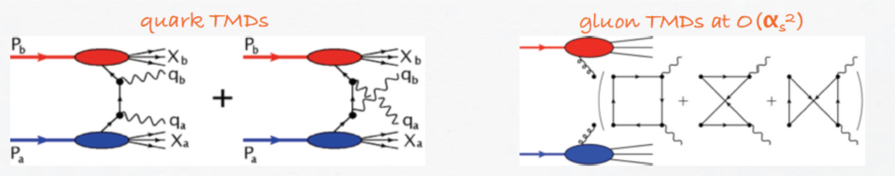
Processes of interest : $2 \to 2$

Di-photon

J.W Qiu, M. Schlegel, W. Vogelsang, PRL 107, 062001 (2011)

- Beside being the QCD background for H^0 studies in the $\gamma\gamma$ channel, $pp \to \gamma\gamma X$ is an interesting process to study gluon TMDs
- Only colour-singlet particles in the final state

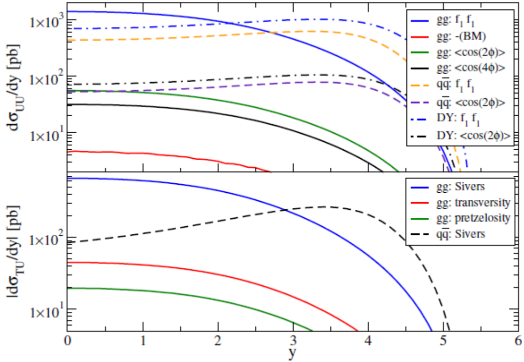
  (also true for ZZ and γZ)
- But contaminations from the $q\bar{q}$ channel (particularly at RHIC)



Di-photon

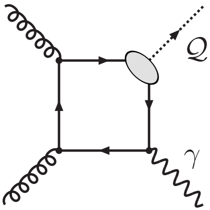
J.W Qiu, M. Schlegel, W. Vogelsang, PRL 107, 062001 (2011)

- At $\sqrt{s} = 500$ GeV,
  for $p_T^\gamma \geq 1$ GeV, $4 \leq Q^2 \leq 30$ GeV, $0 \leq q_T \leq 1$ GeV



- Only F_4 (*i.e.* the $\cos(4\phi)$ modulation) is purely gluonic
- Huge background from $\pi^0 \to$ isolation cuts are needed

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



- The possibility of isolating the quarkonium eliminates the CO contributions ; the photon is isolated

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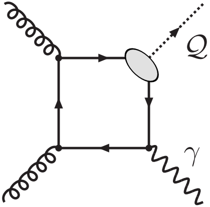
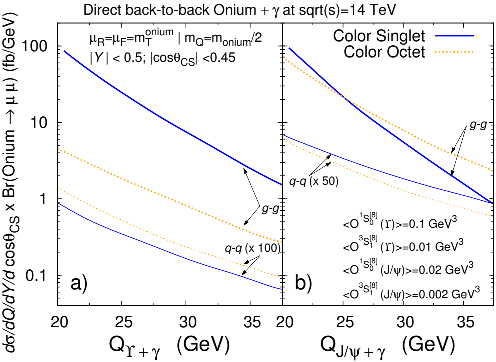


- The possibility of isolating the quarkonium eliminates the CO contributions ; the photon is isolated
- Good candidate to pin down the gluon TMDs :
  - Gluon sensitive process
  - Colourless final state : TMD factorisation applicable
  - Small sensitivity to QCD corrections (most of them in the TMD evolution)

Expected rates for $\mathcal{Q} + \gamma$

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



- $q\bar{q}$ contributions negligible
- CO (orange) smaller than CS (blue); isolation not needed for Υ
- At 14 TeV, $\sigma(J/\psi|\Upsilon{+}\gamma)|_{Q>20\ GeV}$ $\simeq 100\,\text{fb}$; about half at 7 TeV
- With the $\mathcal{L} \simeq 20\ \text{fb}^{-1}$ of *pp* data on tape, one expects up to 2000 events
- ATLAS has looked for $H^0 \to J/\psi\,(\Upsilon) + \gamma$ at $Q \simeq 125\,\text{GeV}$

Results with UGDs as Ansätze for TMDs

- We define $S_{q_T}^{(n)} = \frac{A^{(n)}}{A^f} \frac{\mathcal{C}[w^{(n)}\ TMD_1^{(n)}\ TMD_2^{(n)}]}{\int d^2\vec{q}_T \mathcal{C}[f_1^g f_1^g]} \quad \Rightarrow S_{q_T}^{(0)}, S_{q_T}^{(2)}, S_{q_T}^{(4)}$

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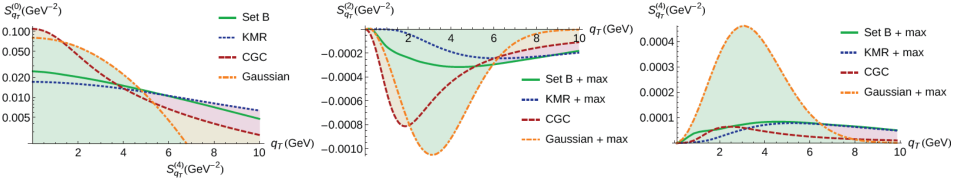
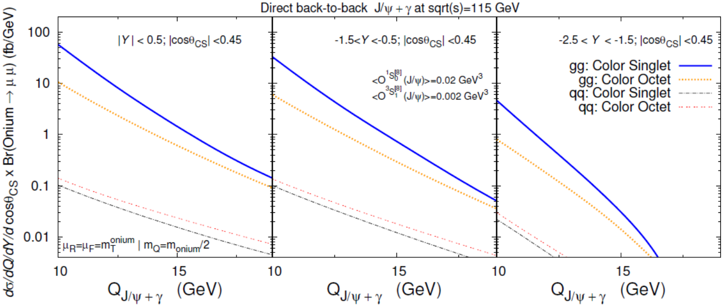


- $S^{(2)}_{q_T}, S^{(4)}_{q_T} \neq 0 \Rightarrow$ nonzero gluon polarisation in unpolarised protons
- $S^{(0)}_{q_T}$: $f_1^g(x, k_T)$ from the q_T-dependence of the yield
- $\int d^2\vec{q}_T S^{(2,4)}_{q_T}$ should be measurable (few percent : ok with 2000 events)

Same 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 $\to$ 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, $g - g > q - \bar{q}$!

$gg \to \eta_c + \eta_c$

- $2 \to 2$ process $\Rightarrow Q^2, q_T$ tuning possible + presence of ϕ-dependent terms
- Theoretically the simplest, low $q\bar{q}$ contribution, no reason for significant CO and no final state gluon needed

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	$Q(GeV) \in (6.0, 10.0)$	$(10.0,\ 15.0)$	$(15.0,\ 20.0)$	$(20.0,\ 40.0)$
$\langle 1 \rangle (pb)$	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

Pion and proton TMDs at COMPASS

Double J/ψ production : First measurements by NA3

- The first evidence for double J/ψ events was reported by NA3 in 1982 in π induced reactions at $p_{\text{lab}} = 150(280)$ GeV, that is $\sqrt{s} = 16.8(22.9)$ GeV **NA3 J. Badier et al., PLB 114 (1982) 457.**

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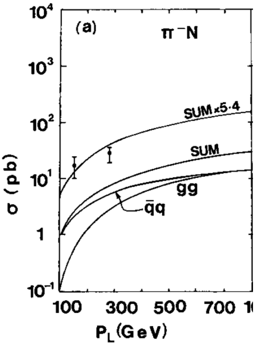
R.E. Ecclestone, D.M. Scott ZPC 19 (1983) 29; B. Humpert, P. Mery PLB 124 (1982) 265



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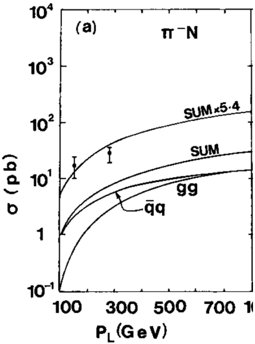

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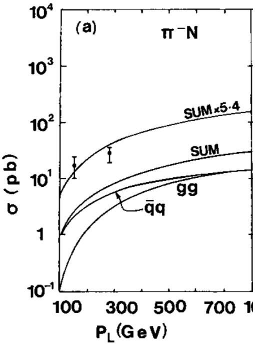

Double J/ψ production : First measurements by NA3

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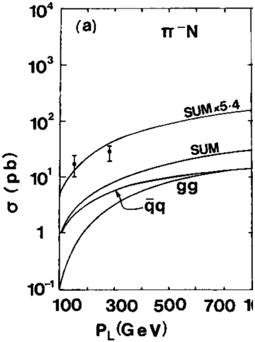
- NA3 also analysed proton induced reactions at $p_{\rm lab} =$ 400 GeV

NA3 PLB 158 (1985) 85



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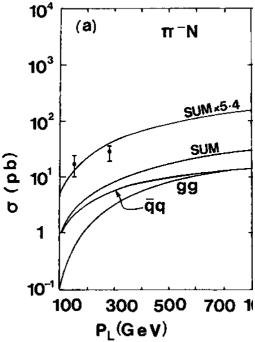

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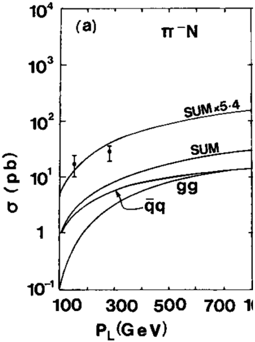

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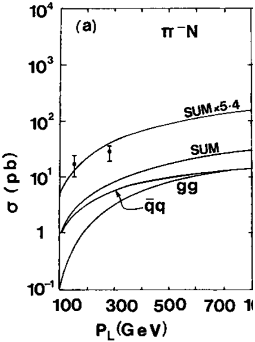
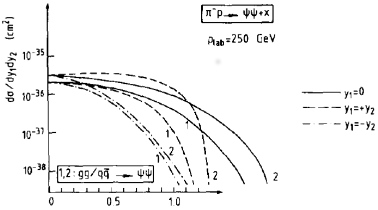


Quark or gluon production ?

- The ratio $q\bar{q}$ vs gg is of course not a flat function of the rapidity
- The QCD corrections for $q\bar{q}$ may be different than gg since the graphs are different
- A modern analysis focused on COMPASS acceptance is therefore needed
- This could be completed with a TMD based evaluation of the azimuthal asymetries



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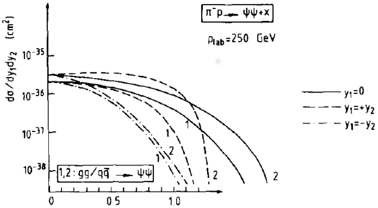

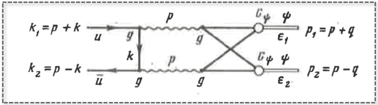

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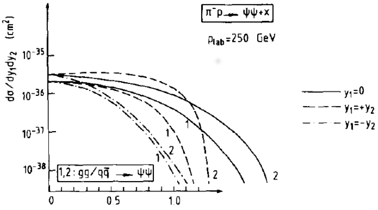

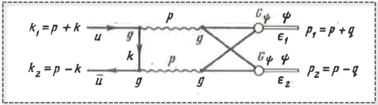

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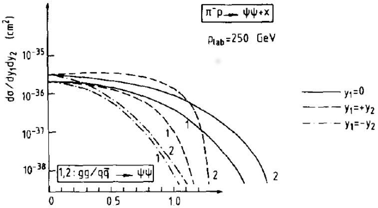

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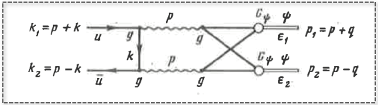
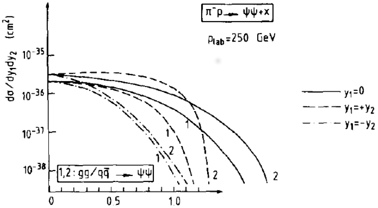
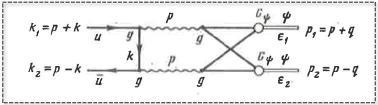


About the extraction of TMDs

- If gg fusion from CS is dominant, the results presented above should apply by just replacing the projectile proton TMDs (f_1 and $h_1^{\perp g}$) by those of the π
- If $q\bar{q}$ fusion dominates, the structure of the azimuthal asymetries needs to be recalculated
- Even with low statistics (a few tens of events expected), it will be of great interest to get these data in order to extract proton and pion TMDs magnitudes





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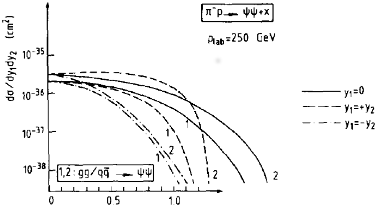

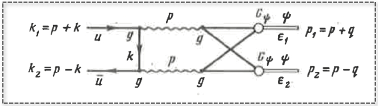

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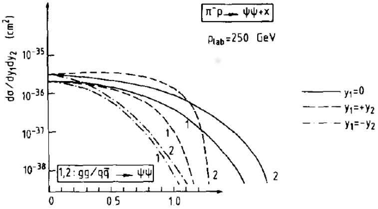

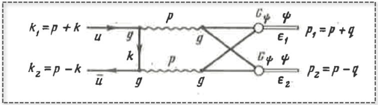

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  R. Vogt and S. J. Brodsky, PLB 349 (1995) 569

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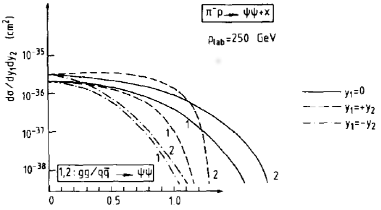

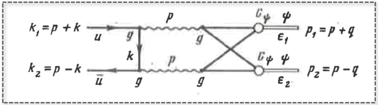

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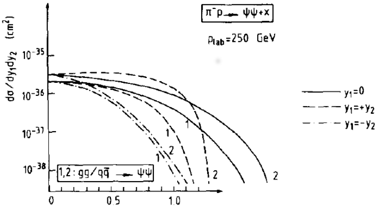

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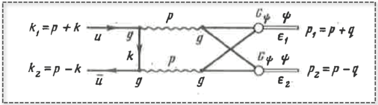

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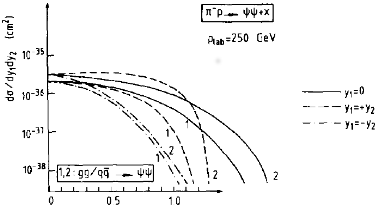
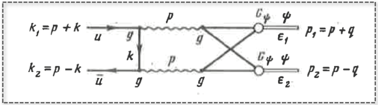




Gaussian $h_1^{\perp g}$ model from Boer, de Dunnen, Pisano, Schlegel, Vogelsang, PRL 108 (2012) 032002

$$h_1^{\perp g}(x, \vec{k}_T^2) = \frac{2M_p^2}{\langle k_T^2 \rangle} \frac{1-r}{r} \frac{g(x)}{\pi \langle k_T^2 \rangle} e^{1 - \frac{\vec{k}_T^2}{r \langle k_T^2 \rangle}} \qquad \text{with} \quad r = 2/3 \qquad (12)$$

Gaussian+tail modelisation of TMDs

We do not know the nature of f_1^g or $h_1^{\perp g}$. We can use a Gaussian + tail model to evaluate some observables :

- f_1^g is written as the product of the usual integrated PDF $f_1^g(x)$ and a function of $\vec{k}_T$:

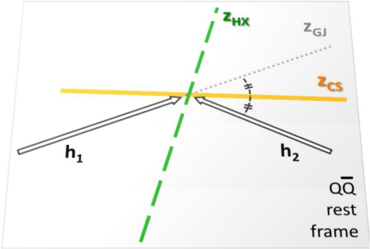
$$f_1^g(x, \vec{k}_T) = \frac{R^2}{2\pi} \frac{1}{1 + \vec{k}_T^2 R^2} f_1^g(x) \quad \text{with } R = 2\,\text{GeV}^{-1} \tag{13}$$

- $h_1^{\perp g}$ knows a positivity bound : $\frac{\vec{k}_T^2}{2M_p^2}|h_1^{\perp g}| \leq f_1^g(x, \vec{k}_T)$. We thus take the positivity bound saturation to get a maximal effect of linearly polarised gluons :

$$|h_1^{\perp g}| \simeq \frac{2M_p^2}{\langle \vec{k}_T^2 \rangle} f_1^g(x, \vec{k}_T) \tag{14}$$

Polarised pair production

- J/ψ = massive vector meson ⇒ can be longitudinally or transversely polarised
- Measuring polarisation of the produced pair = effect on the TMD extraction ?
- Polarisation is frame/axis-dependent : different frames give different cross-sections



Representation of the polarisation axis in the helicity (HX), Gottfried-Jackson (GJ) and Collins-Soper (CS) frames [Faccioli_CERN_3_5_2010]