

Probing gluon TMDs with quarkonia: Linearly-polarised gluons and J/ψ pairs

J.P. Lansberg

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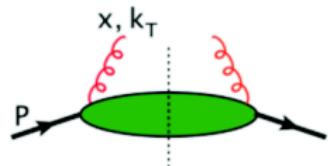
April 16 – 20, 2018, Kobe, Japan

Results obtained in collaboration with W. den Dunnen, M. Echevarria, T. Kasemets, C. Lorcé, C. Pisano, F. Scarpa, M. Schlegel, H.S. Shao, A. Signori

Part I

Generalities on gluon TMDs

Gluon TMDs in unpolarised protons

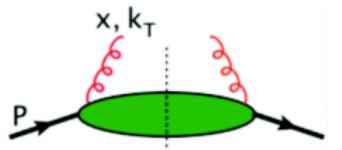


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- Gauge-invariant definition:

$$\Phi_g^{\mu\nu}(x, \mathbf{k}_T, \zeta, \mu) \equiv \int \frac{d(\xi \cdot P) d^2 \xi_T}{(x P \cdot n)^2 (2\pi)^3} e^{i(xP+k_T) \cdot \xi} \langle P | F^{n\nu}(0) \mathcal{U}_{[0,\xi]} F^{n\mu}(\xi) \mathcal{U}'_{[\xi,0]} | P \rangle \Big|_{\xi \cdot P' = 0}$$

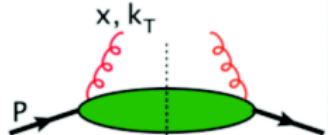
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- Parametrisation:

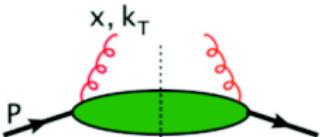
P. J. Mulders, J. Rodrigues, PRD 63 (2001) 094021; D. Boer et al. JHEP 1610 (2016) 013

$$\Phi_g^{\mu\nu}(x, \mathbf{k}_T, \zeta, \mu) = -\frac{1}{2x} \left\{ g_T^{\mu\nu} f_1^g(x, \mathbf{k}_T, \mu) - \left(\frac{k_T^\mu k_T^\nu}{M_p^2} + g_T^{\mu\nu} \frac{\mathbf{k}_T^2}{2M_p^2} \right) h_1^{\perp g}(x, \mathbf{k}_T, \mu) \right\} + \text{suppr.}$$

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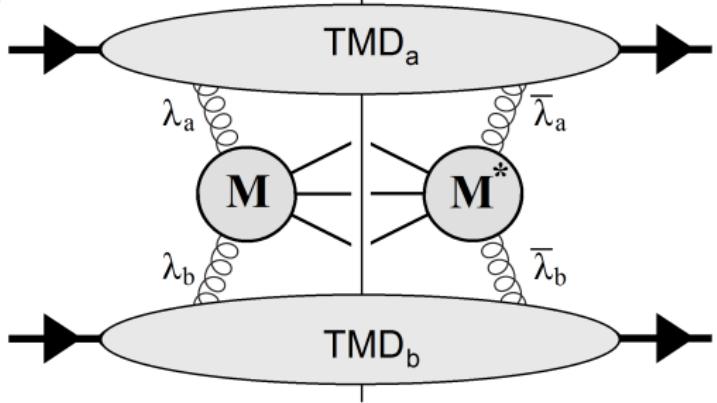
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- f_1^g : TMD distribution of **unpolarised** gluons
- $h_1^{\perp g}$: TMD distribution of **linearly polarised** gluons

[Helicity-flip distribution]

gg fusion in arbitrary unpolarised process [colourless final state]

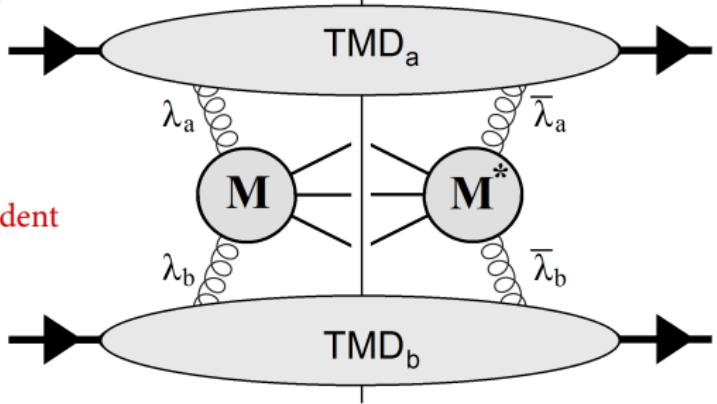
$$d\sigma^{gg} \propto$$



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$$d\sigma^{gg} \propto \underbrace{\left(\sum_{\lambda_a, \lambda_b} \hat{M}_{\lambda_a, \lambda_b} \hat{M}_{\lambda_a, \lambda_b}^* \right)}_{F_1} \mathcal{C}[f_1^g f_1^g]$$

\Rightarrow helicity non-flip, azimuthally independent



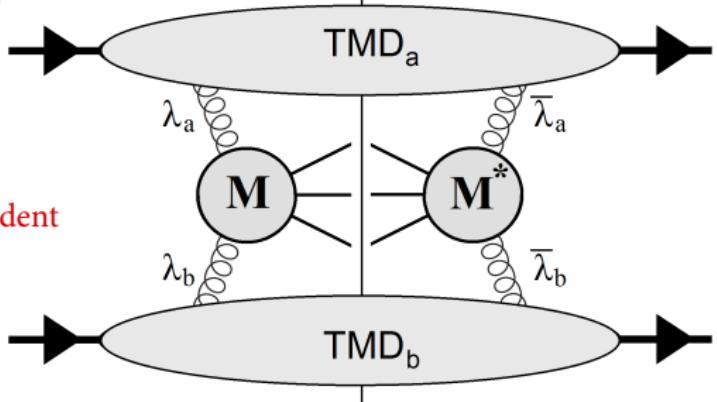
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⇒ helicity non-flip, **azimuthally independent**

$$+ \underbrace{\left(\sum_{\lambda} \hat{\mathcal{M}}_{\lambda, \lambda} \hat{\mathcal{M}}_{-\lambda, -\lambda}^* \right) \mathcal{C}[w_2 \times h_1^{\perp g} h_1^{\perp g}]}_{F_2}$$

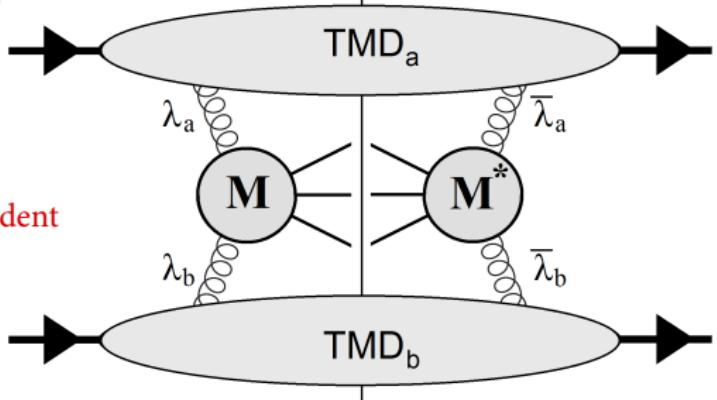
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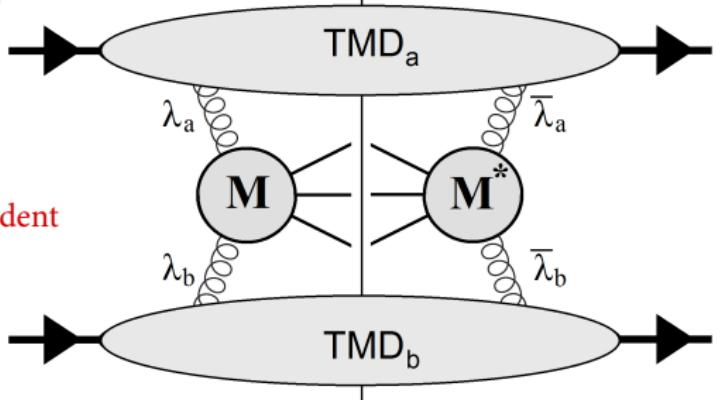
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\Rightarrow double helicity flip, **$\cos(4\phi)$ -modulation**

Part II

Quarkonium production and TMD factorisation applicability/breaking

Approaches to Quarkonium Production

See EPJC (2016) 76:107 for a recent review

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 - ③ COLOUR OCTET MECHANISM (encapsulated in NRQCD): **higher Fock states** of the mesons taken into account; $Q\bar{Q}$ can be produced in octet states with different quantum # as the meson; bleaching with semi-soft gluons ?

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- Different independent $h_1^{\perp g}$ functions correspond to specific colour structures. Depending on the process, one extracts different combinations

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[reactions and kinematics]
- However, if TMD factorisation holds for $H^0 + \text{jet}$ as conjectured by D. Boer-C. Pisano, there should be **no issue** for $\mathcal{Q} + \gamma$, $\mathcal{Q} + Z$ or $\mathcal{Q} + \gamma^*$

Part III

Quarkonia and gluon TMDs at hadron colliders

$2 \rightarrow 2$ vs $2 \rightarrow 1$ processes

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- Hard scale can only be the particle mass : $Q^2 \simeq M^2$
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- **BACK-TO-BACK (LOW q_T) $2 \rightarrow 2$ PROCESS :**
- Produced particles can each have a large \vec{p}_T adding up to make a small \vec{q}_T for the pair. One can impose $|\vec{p}_T|$ large enough for the particle to be detectable
- This renders the TMD “region” ($q_T \ll Q$) virtually as wide as we wish
- Hard scale $Q^2 \simeq (p_1 + p_2)^2$ can be tuned to study the QCD evolution of the TMDs
- Drawback : yield can be populated by Double Parton Scatterings (DPS)

J.P.L., H.S. Shao JHEP 1610 (2016) 153, NPB 900 (2015) 273, PLB 751 (2015) 479

Low P_T quarkonia and TMDs

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PHYSICAL REVIEW D **86**, 094007 (2012)

Polarized gluon studies with charmonium and bottomonium at LHCb and AFTER

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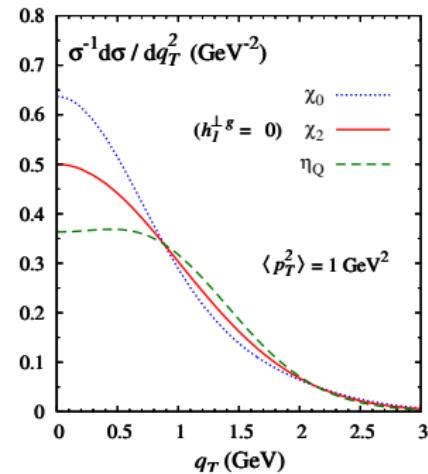
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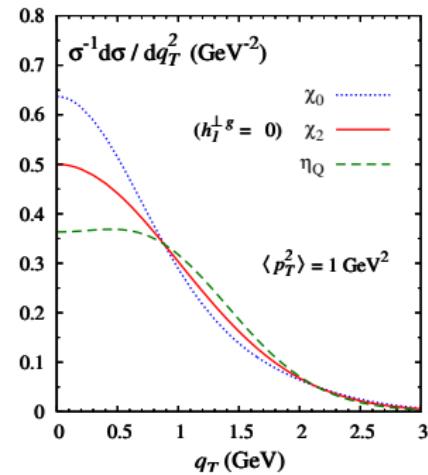
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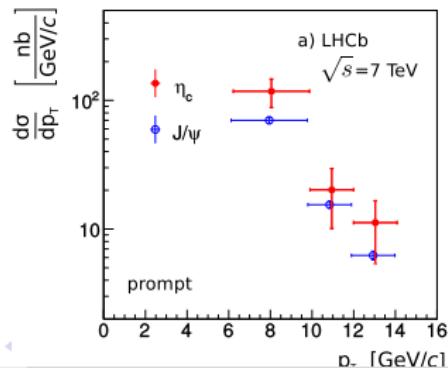
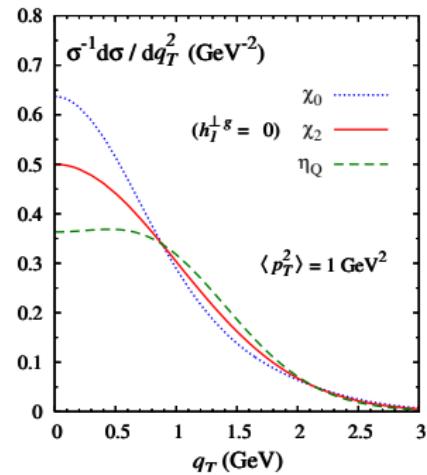
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- Cannot tune Q: $Q \simeq m_Q$
- Low P_T : Experimentally very difficult

First η_c production study at collider ever, only released in 2014

for $P_T^{\eta_c} > 6$ GeV LHCb, EPJC75 (2015) 311



Low P_T quarkonia and TMDs II

- **η_c production at one-loop** : factorisation holds

PHYSICAL REVIEW D 88, 014027 (2013)

Transverse momentum dependent factorization for quarkonium production at low transverse momentum

J. P. Ma,^{1,2} J. X. Wang,³ and S. Zhao¹

¹*Institute of Theoretical Physics, Academia Sinica, P.O. Box 2735, Beijing 100190, China*

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- $\chi_{c0,2}$ factorisation issue ? \leftrightarrow Colour Octet - Colour Singlet mixing

Physics Letters B 737 (2014) 103–108



Breakdown of QCD factorization for P-wave quarkonium production at low transverse momentum



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→ Low $q_T \chi_c$ data exist: empirical check of TMD factorisation possible

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- Evolution taken in account at NNLL
- Considers both the TMD and FO contributions to extend the q_T range
up to the LHCb data

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M.G. Echevarria, T. Kasemets, JPL, C. Pisano, A. Signori - in preparation

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J. Kuhn, E. Mirkes, PRD 48 (1993) 17; A. Petrelli *et al.* NPB 514 (1998) 245; J.P. Ma, J.X. Wang, S. Zhao PRD 88 (2013) 014027

- Evolution taken in account at NNLL
- Considers both the TMD and FO contributions to extend the q_T range up to the LHCb data
- Matching: inverse variance weighted **average** vs. "improved $W + Y$ "

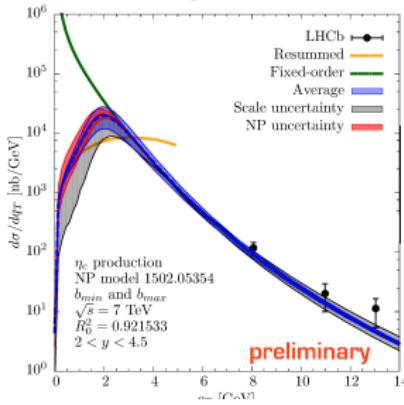
M.G. Echevarria, T. Kasemets, JPL, C. Pisano, A. Signori, PLB 781 (2018) 161; J.C. Collins *et al.* PRD94 (2016) 034014

First phenomenological study of η_c production with TMDs

M.G. Echevarria, T. Kasemets, JPL, C. Pisano, A. Signori - in preparation

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- ' $gg' \rightarrow H^0 + \text{jet}$ ' : D. Boer, C. Pisano, PRD 91 (2015) 074024
- $gg \rightarrow (J/\psi, \Upsilon) + Z/\gamma^*$: JPL , C. Pisano, M. Schlegel, NPB 920 (2017) 192

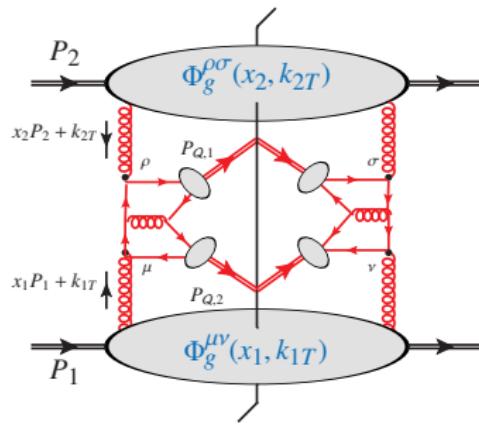
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None are measured so far ...

Part IV

The case of quarkonium pair production in more details



$J/\psi + J/\psi$ at low $P_T^{\psi\psi}$

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- J/ψ : relatively easy to detect. Already studied by LHCb, CMS, ATLAS & D0

LHCb PLB 707 (2012) 52; JHEP 1706 (2017) 047; CMS JHEP 1409 (2014) 094;
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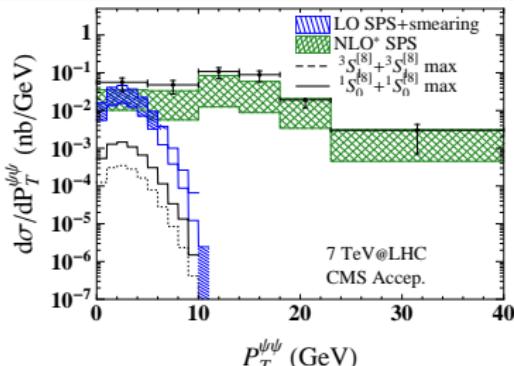
J.P.L., H.S. Shao NPB 900 (2015) 273

- Negligible CO contributions, in particular at low $P_T^{\psi\psi}$ [black/dashed curves vs. blue]

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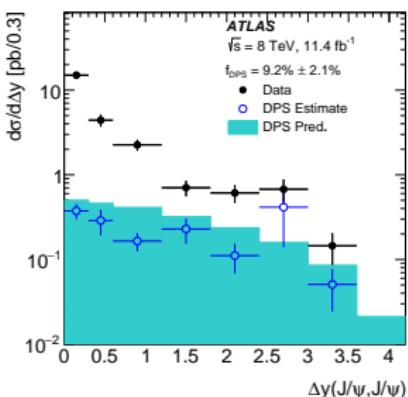
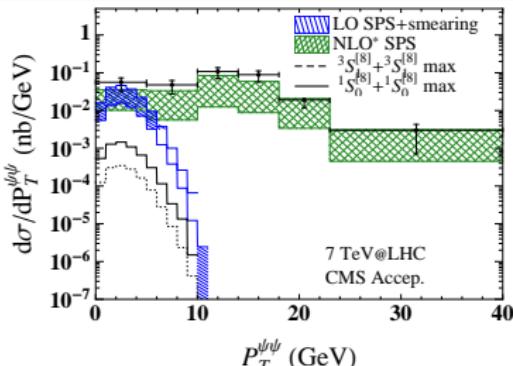
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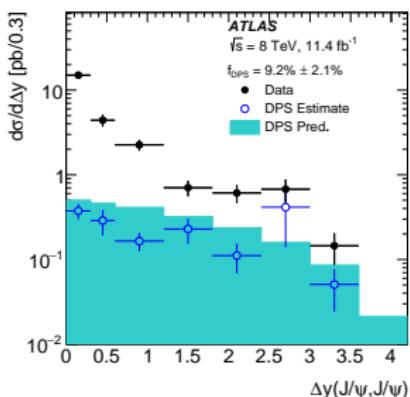
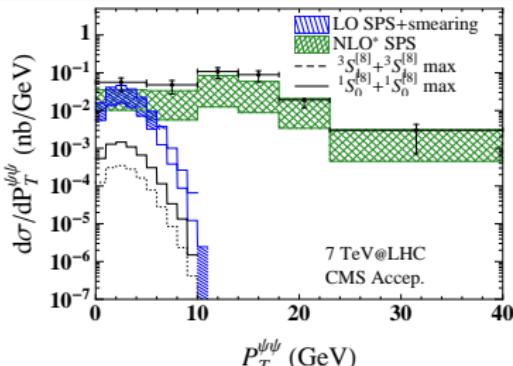
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- DPS in LHCb data [kinematical distributions well controlled : independent scatterings]



What is special about double vector onium production ?

JPL, C. Pisano, F. Scarpa, M. Schlegel, arXiv:1710.01684

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$$F_4 = F_1 \text{ at large } M_{QQ}$$

\Rightarrow di- J/ψ (or di- Υ) **maximise** the observability of $\cos 4\phi$ modulations
in a kinematical region where **data are already taken !**

TMD modelling : f_1^g and the relevance of the LHCb data

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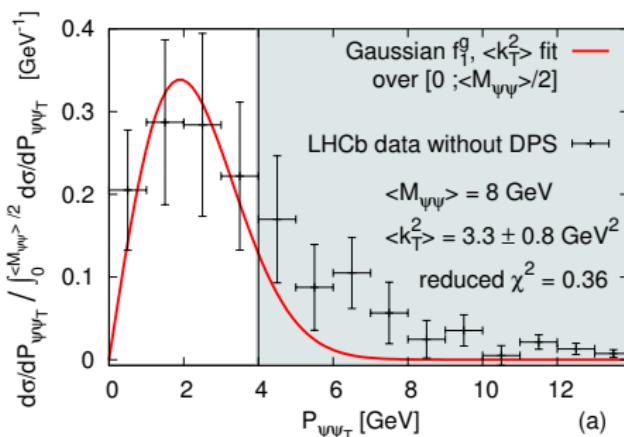
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- f_1^g modelled as a Gaussian in \vec{k}_T : $f_1^g(x, \vec{k}_T^2) = \frac{g(x)}{\pi \langle k_T^2 \rangle} \exp\left(\frac{-\vec{k}_T^2}{\langle k_T^2 \rangle}\right)$
where $g(x)$ is the usual collinear PDF
- First experimental determination [with a pure colorless final state] of $\langle k_T^2 \rangle$
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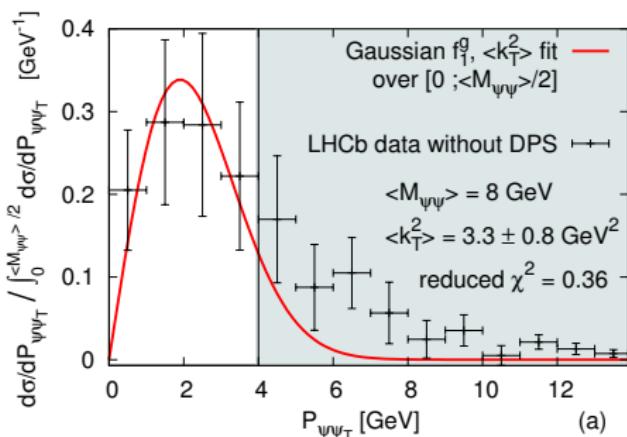
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- Integration over $\phi \Rightarrow \cos(n\phi)$ -terms cancel out
- $F_2 \ll F_1 \Rightarrow$ only $\mathcal{C}[f_1^g f_1^g]$ contributes to the cross-section
- No evolution so far: $\langle k_T^2 \rangle \sim 3 \text{ GeV}^2$ accounts both for non-perturbative and perturbative broadenings at a scale close to $M_{\psi\psi} \sim 8 \text{ GeV}$
- Disentangling such (non-)perturbative effects requires data at different scales

Modelling $h_1^{\perp g}$

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- Evolution effect on $h_1^{\perp g} \Rightarrow$ modifications of azimuthal asymmetries

See Y. Zhou's talk earlier this morning

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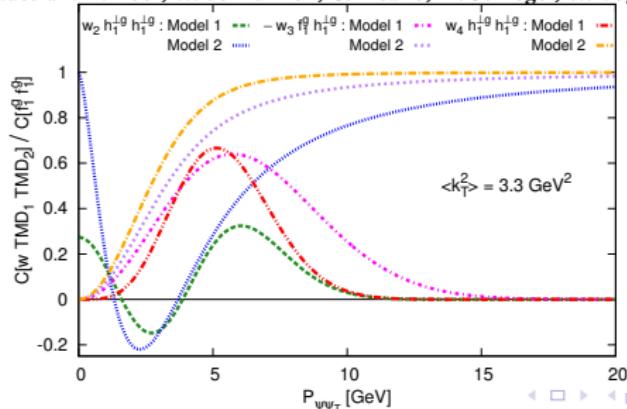
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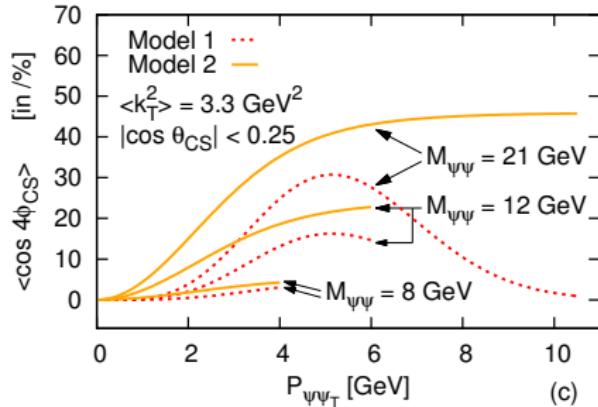
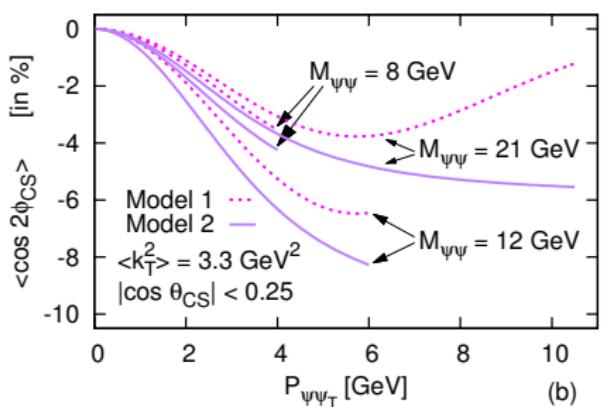
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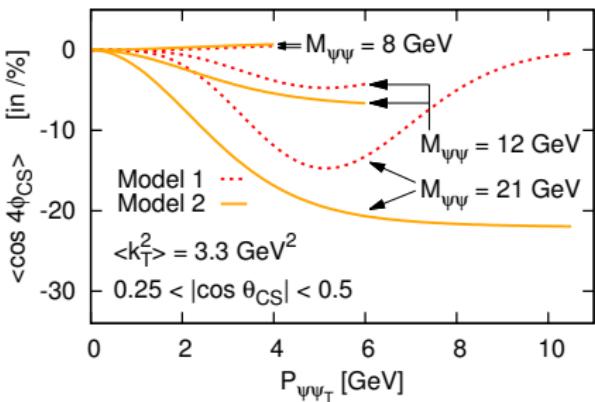
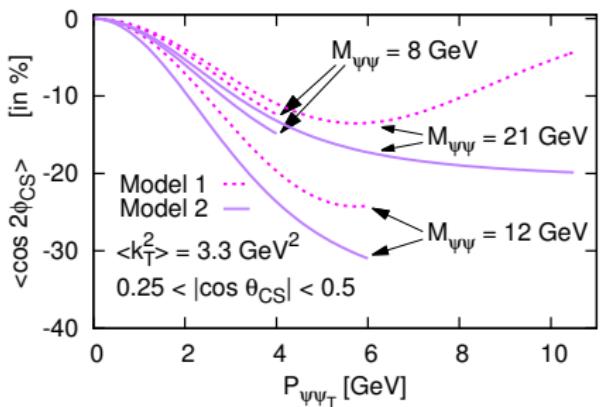


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 - $\langle \cos 2\phi_{\text{CS}} \rangle$ [sign of $h_1^{\perp g}$] : gets large (30 %) when θ_{CS} moves away from $\pi/2$
 - $\langle \cos 4\phi_{\text{CS}} \rangle$: changes sign when θ_{CS} moves away from $\pi/2$ [should be careful with the cuts]

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- Back-to-back $J/\psi + \gamma$ or $\Upsilon + \gamma$ is certainly at reach [events already on tapes]
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See also D. Boer, C. Lorcé, C. Pisano, J. Zhou, Adv.High Energy Phys. 2015 (2015) 371396

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See my talk at 10:35am (WG7) → link; D. Kikola et al. Few Body Syst. 58 (2017) 139

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- $J/\psi + \gamma$ STSA study might also be possible with STAR if very favourable conditions

JPL, C. Pisano, M. Schlegel, in progress



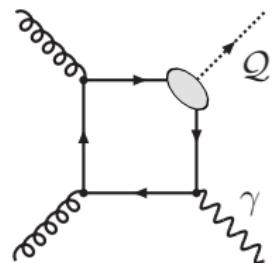
Part V

Backup

$Q + \gamma$ at low $P_T^{\psi-\gamma}$

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

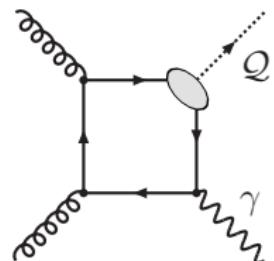
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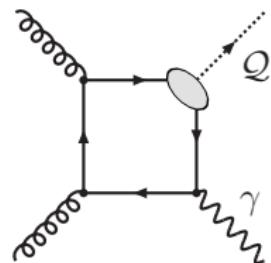
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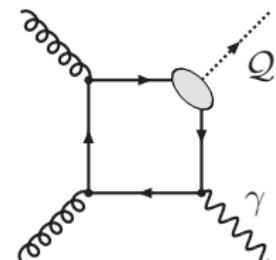
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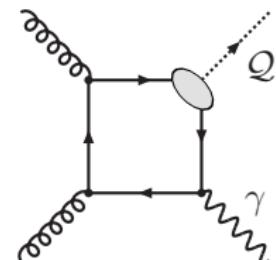
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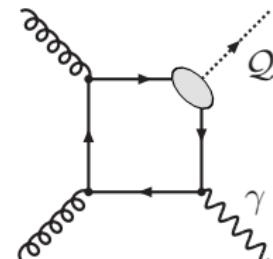
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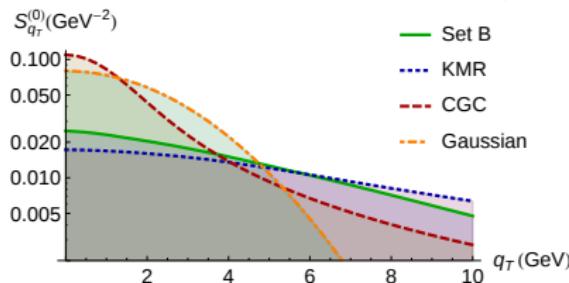


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 - $\mathcal{S}_{q_T}^{(0)} = \frac{\mathcal{C}[f_1^g f_1^g]}{\int dq_T^2 \mathcal{C}[f_1^g f_1^g]}$: does not involve $h_1^{\perp g}$ [not always the case]
 - $\mathcal{S}_{q_T}^{(2)} = \frac{F_3 \mathcal{C}[w_2^{fh} f_1^g h_1^{\perp g} + x_1 \leftrightarrow x_2]}{2F_1 \int dq_T^2 \mathcal{C}[f_1^g f_1^g]}$
 - $\mathcal{S}_{q_T}^{(4)} = \frac{F_4 \mathcal{C}[w_4^{hh} h_1^{\perp g} h_1^{\perp g}]}{2F_1 \int dq_T^2 \mathcal{C}[f_1^g f_1^g]}$

$S_{q_T}^{(2)}, S_{q_T}^{(4)} \neq 0 \Rightarrow$ nonzero gluon polarisation in unpolarised protons!

Results with UGDs as Ansätze for TMDs

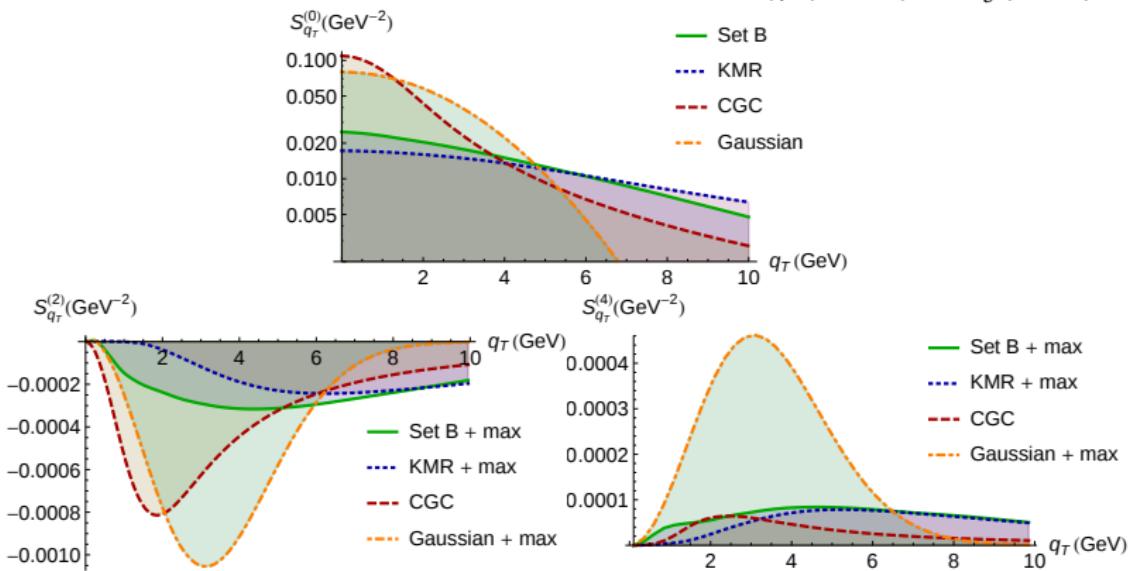
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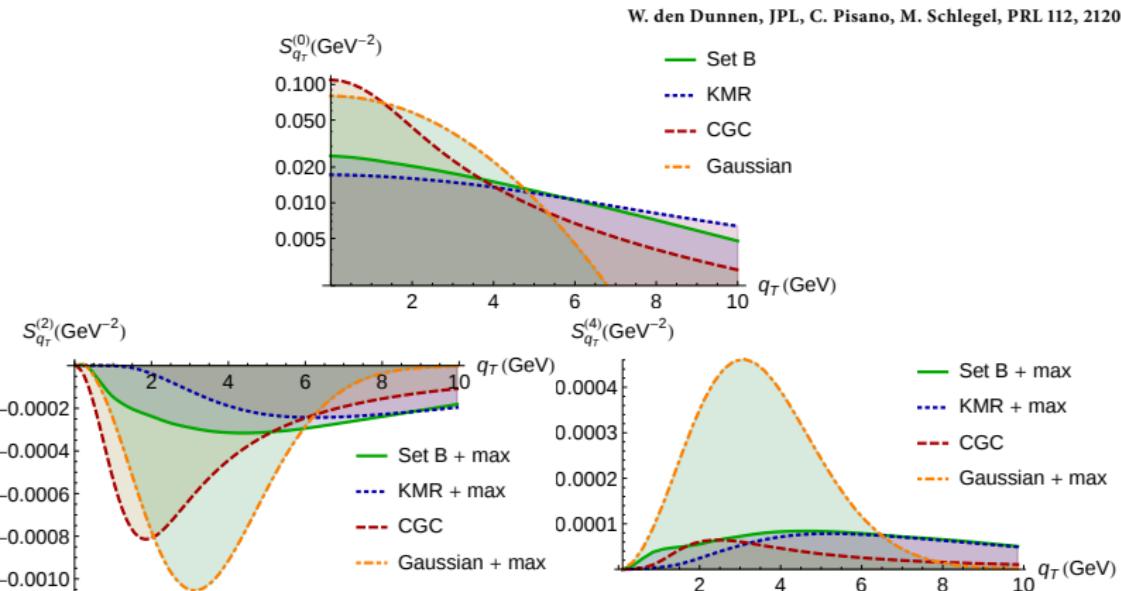
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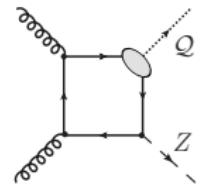


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Extending to $J/\psi/\Upsilon + Z$

- Rates similar for $\Upsilon + Z$ and $J/\psi + Z$ [Same for $Q + \gamma$ for $Q \gtrsim 20$ GeV]

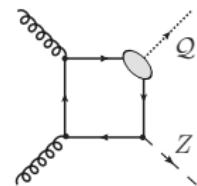
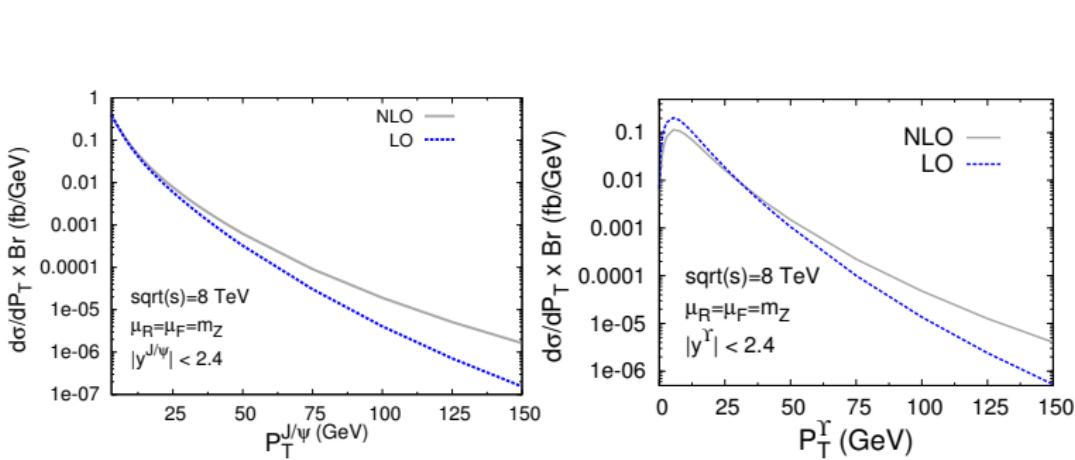
B. Gong, J.P. Lansberg, C. Lorcé, J.X. Wang, JHEP 1303 (2013) 115



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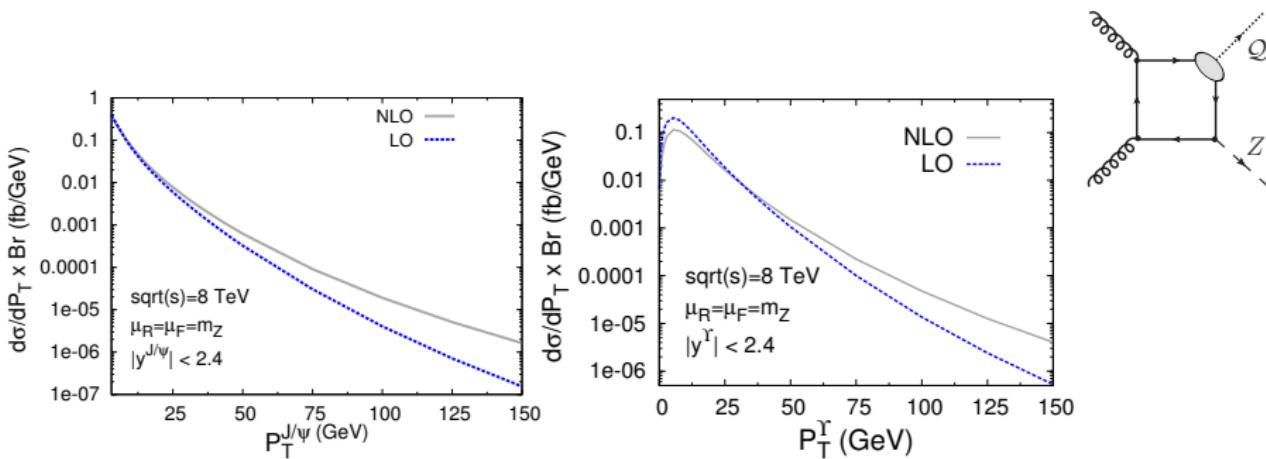
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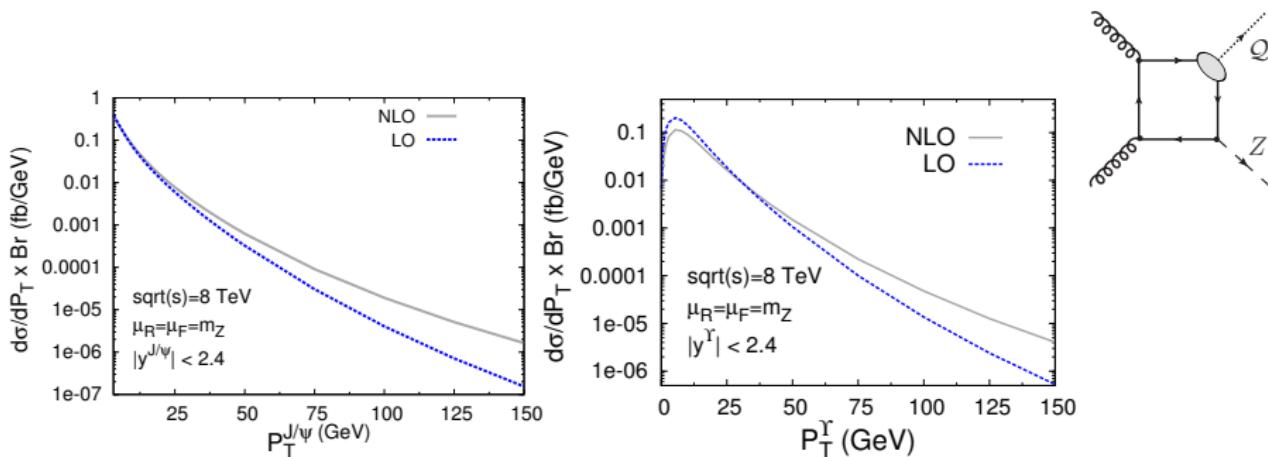


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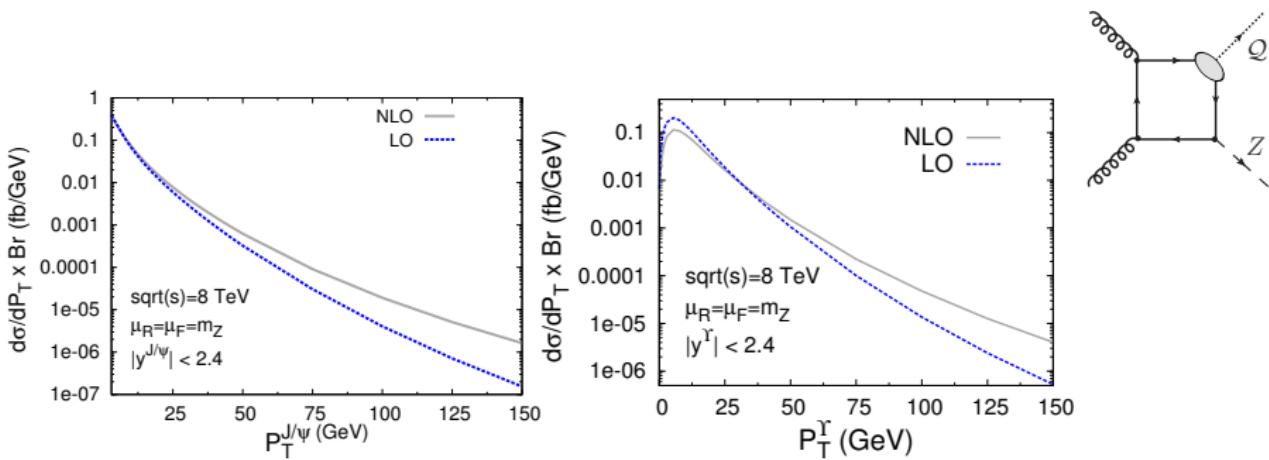


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- First measurement of J/ ψ + Z by ATLAS; large DPS yield : unequal p_T cuts ?

ATLAS EPJC 75 (2015) 229 ; J.P.L., H.S. Shao JHEP 1610 (2016) 153

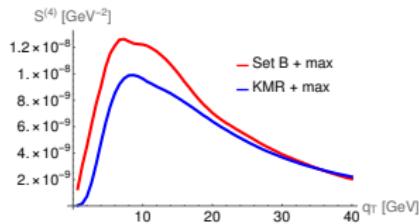
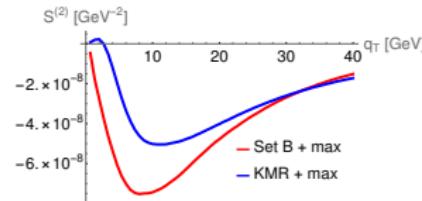
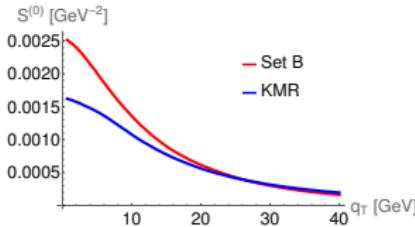
$Y + Z \& Y + \gamma^* @\sqrt{s} = 14 \text{ TeV}$

JPL, C. Pisano, M. Schlegel, NPB 920 (2017) 192

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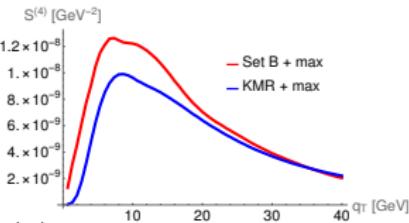
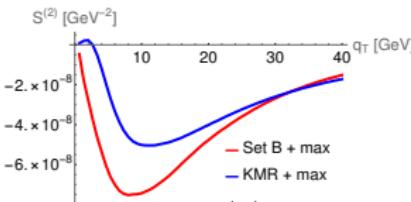
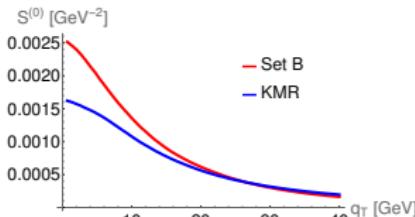
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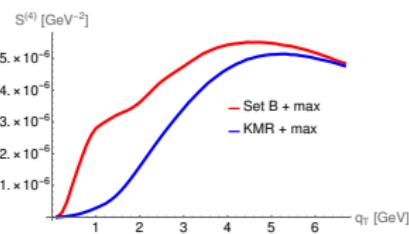
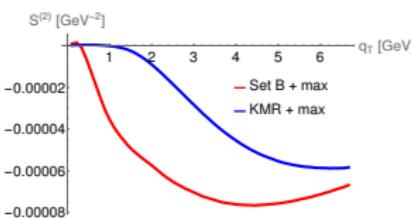
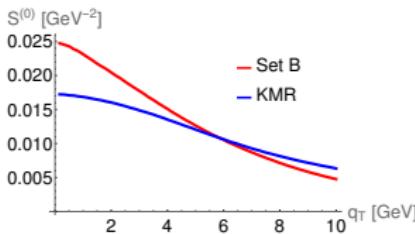
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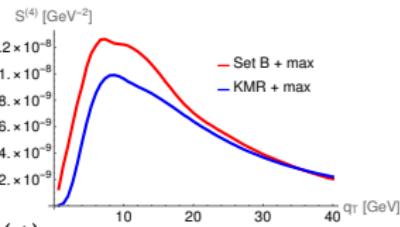
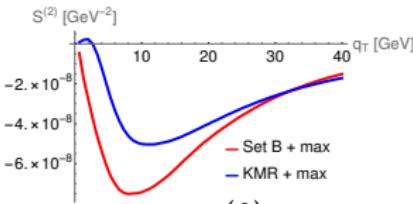
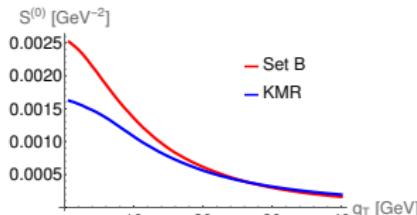
- $Q = 20 \text{ GeV} \& \text{ dilepton mass } [5:7] \text{ GeV } [\int S^{(2)} \sim 0.5\%; \int S^{(4)} \sim 0.05\%]$



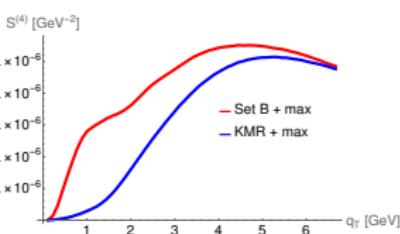
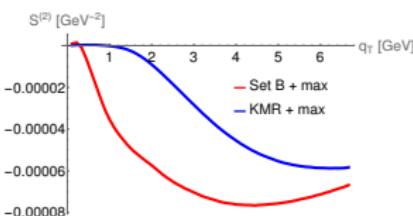
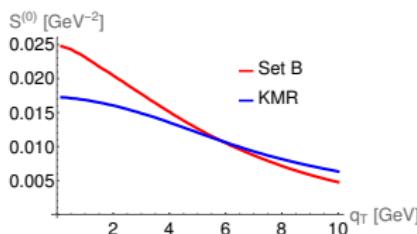
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JPL, C. Pisano, M. Schlegel, NPB 920 (2017) 192

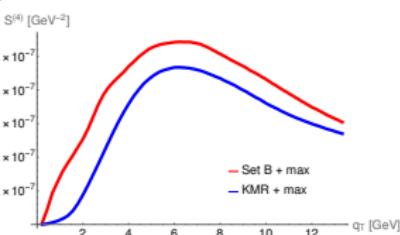
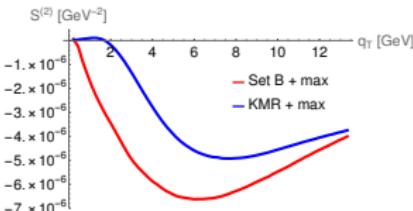
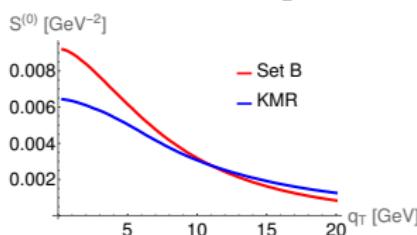
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$\Upsilon + \gamma$ already measured ?

PRL 114, 121801 (2015)

PHYSICAL REVIEW LETTERS

week ending
27 MARCH 2015

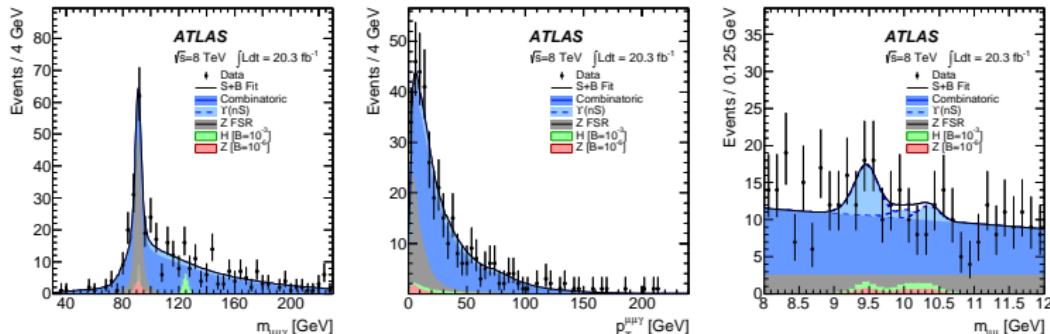
Search for Higgs and Z Boson Decays to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$ with the ATLAS Detector

G. Aad *et al.*^{*}

(ATLAS Collaboration)

(Received 15 January 2015; published 26 March 2015)

A search for the decays of the Higgs and Z bosons to $J/\psi\gamma$ and $\Upsilon(nS)\gamma$ ($n = 1, 2, 3$) is performed with pp collision data samples corresponding to integrated luminosities of up to 20.3 fb^{-1} collected at $\sqrt{s} = 8 \text{ TeV}$ with the ATLAS detector at the CERN Large Hadron Collider. No significant excess of events is observed above expected backgrounds and 95% C.L. upper limits are placed on the branching fractions. In the $J/\psi\gamma$ final state the limits are 1.5×10^{-3} and 2.6×10^{-6} for the Higgs and Z boson decays, respectively, while in the $\Upsilon(1S, 2S, 3S)\gamma$ final states the limits are $(1.3, 1.9, 1.3) \times 10^{-3}$ and $(3.4, 6.5, 5.4) \times 10^{-6}$, respectively.



Same at AFTER@LHC

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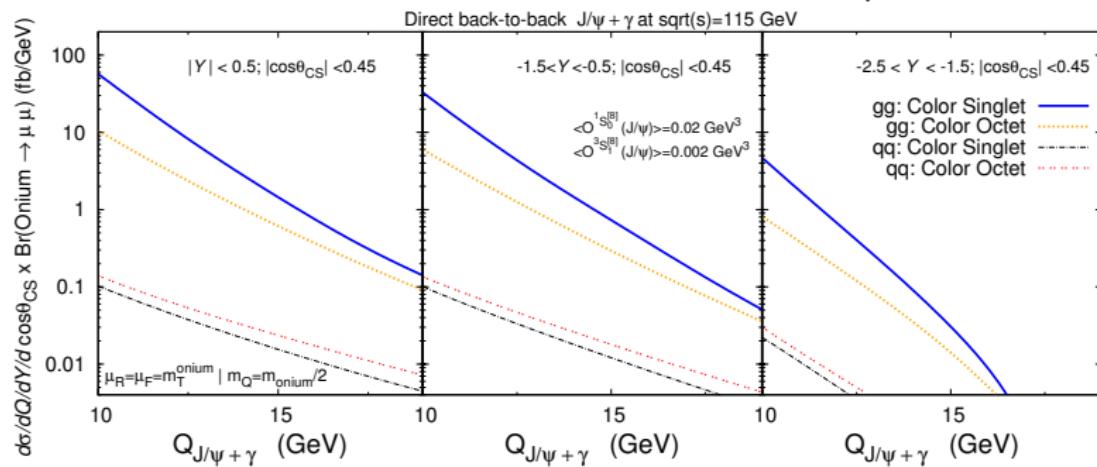
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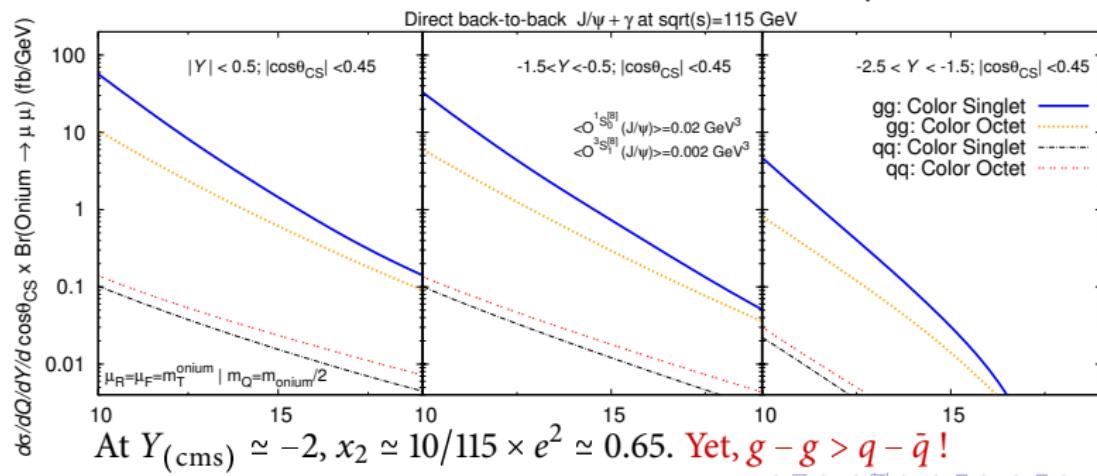
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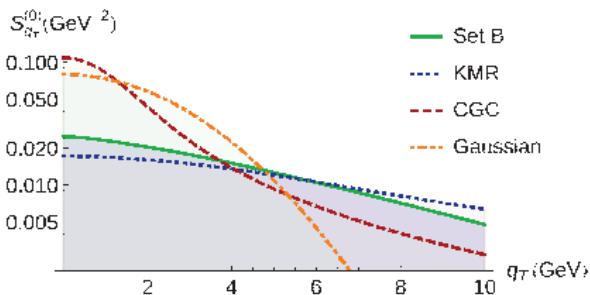
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$S_{q_T}^{(0)}$: Model predictions for $\Upsilon + \gamma$ production at $\sqrt{s} = 14$ TeV

$$Q = 20 \text{ GeV}, \quad Y = 0, \quad \theta_{CS} = \pi/2$$

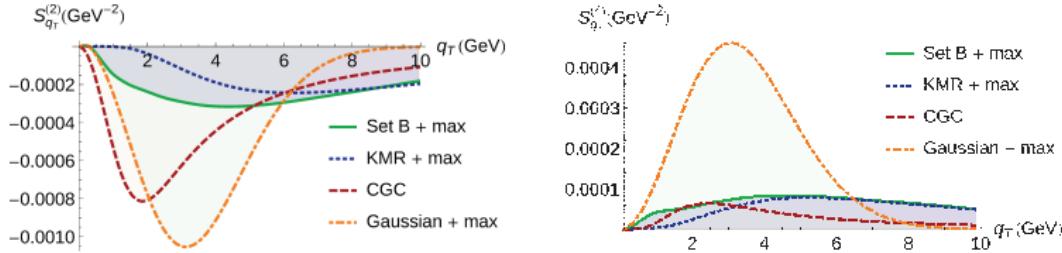


Models for f_1^g : assumed to be the same as for Unintegrated Gluon Distributions

- **Set B:** B0 solution to CCFM equation with input based on HERA data
Jung et al., EPJC 70 (2010) 1237
- **KMR:** Formalism embodies both DGLAP and BFKL evolution equations
Kimber, Martin, Ryskin, PRD 63 (2010) 114027
- **CGC:** Color Glass Condensate Model
Dominguez, Qiu, Xiao, Yuan, PRD 85 (2012) 045003
Metz, Zhou, PRD 84 (2011) 051503

$\mathcal{S}_{q_T}^{(2,4)}$: Model predictions for Y + γ production at $\sqrt{s} = 14$ TeV

$$Q = 20 \text{ GeV}, \quad Y = 0, \quad \theta_{CS} = \pi/2$$



$h_1^{\perp g}$: predictions only in the CGC: in the other models saturated to its upper bound

$\mathcal{S}_{q_T}^{(2,4)}$ smaller than $\mathcal{S}_{q_T}^{(0)}$: can be integrated up to $q_T = 10$ GeV

$$\begin{aligned} 2.0\% \text{ (KMR)} &< |\int dq_T^2 \mathcal{S}_{q_T}^{(2)}| &< 2.9\% \text{ (Gauss)} \\ 0.3\% \text{ (CGC)} &< \int dq_T^2 \mathcal{S}_{q_T}^{(4)} &< 1.2\% \text{ (Gauss)} \end{aligned}$$

Possible determination of the shape of f_1^g and verification of a non-zero $h_1^{\perp g}$