New quarkonium studies with the LHCb detector

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Implications of LHCb measurements and future prospects,
17-19 October, CERN

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See Y. Zhang's talk on Wednesday

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- What's next ?

Part I

pp collisions

χ_{Q1}/χ_{Q2}: does the Landau-Yang theorem apply ?

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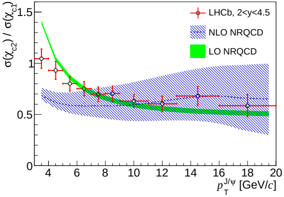

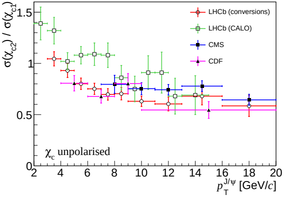

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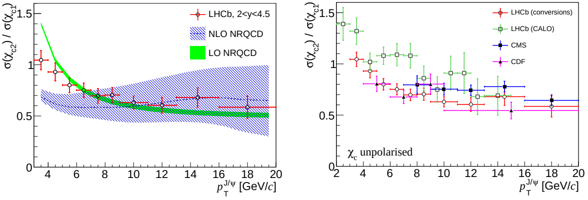

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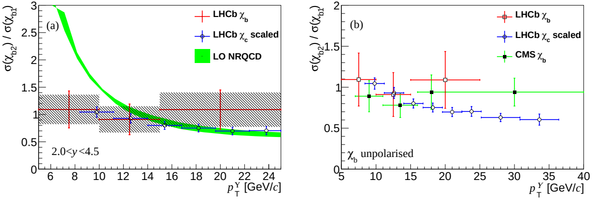

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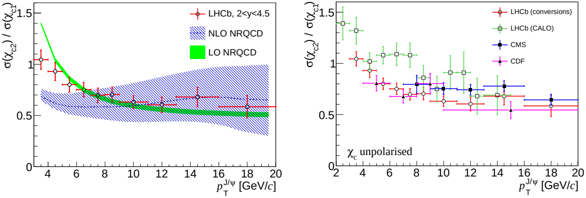

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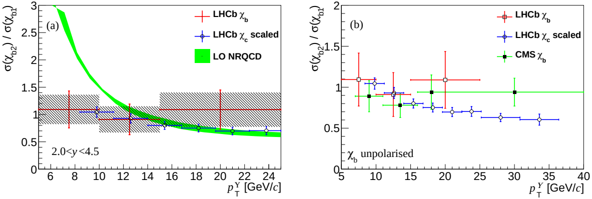

- Low P_T/m_Q region to be better understood,

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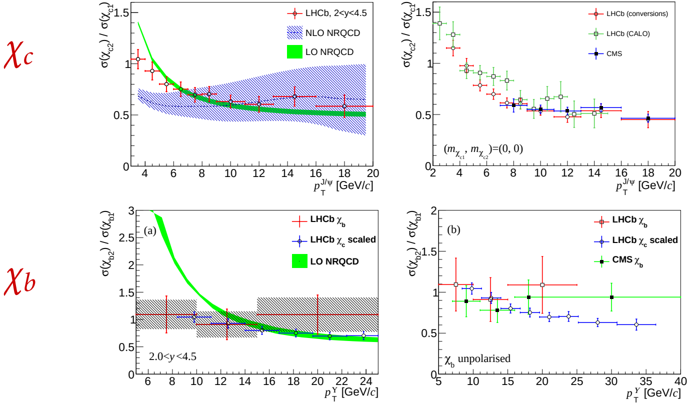

- Low P_T/m_Q region to be better understood,

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- Significant χ_Q polarisation effect on the yield ratio (acceptance effect)

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JPL, H.S. Shao, H.F. Zhang, PLB 786 (2018) 342

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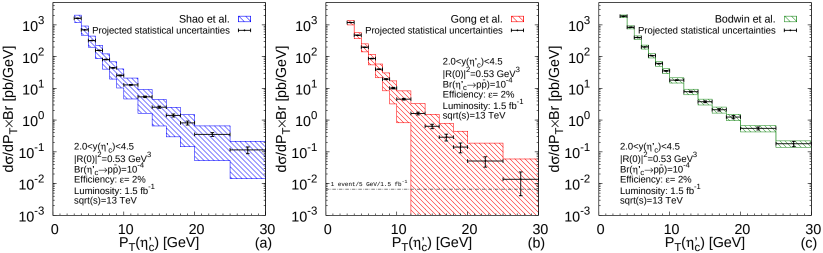

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- η_b ?

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J/ψ+J/ψ	LHCb, CMS, ATLAS, D0 (+NA3)	NLO, NNLO*	LO ?	LO	Prod. Mechanism (CS dominant) + DPS + gluon TMD
J/ψ+D	LHCb	LO	LO ?	LO	Prod. Mechanism (c to J/psi fragmentation) + DPS
J/ψ+ϒ	D0	(N)LO	LO ?	LO	Prod. Mechanism (CO dominant) + DPS
J/ψ+hadron	STAR	LO	--	LO	B feed-down; Singlet vs Octet radiation
J/ψ+Z	ATLAS	NLO	NLO	Partial NLO	Prod. Mechanism + DPS
J/ψ+W	ATLAS	LO	NLO	NLO (?)	Prod. Mechanism (CO dominant) + DPS
J/ψ vs mult.	ALICE,CMS (+UA1)	--	--	--	
J/ψ+b	-- (LHCb, D0, CMS ?)	--	--	LO	Prod. Mechanism (CO dominant) + DPS
ϒ+D	LHCb	LO	LO ?	LO	DPS
ϒ+γ	--	NLO, NNLO*	LO ?	LO	Prod. Mechanism (CO LDME mix) + gluon TMD/PDF
ϒ vs mult.	CMS	--	--	--	
ϒ+Z	--	NLO	LO ?	LO	Prod. Mechanism + DPS
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J/ψ+Υ	D0	(N)LO	LO ?	LO	**Prod. Mechanism (CO dominant) + DPS**
J/ψ+hadron	STAR	LO	--	LO	**B feed-down; Singlet vs Octet radiation**
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Υ+γ	--	NLO, NNLO*	LO ?	LO	**Prod. Mechanism (CO LDME mix) + gluon TMD/PDF**
Υ vs mult.	CMS	--	--	--	
Υ+Z	--	NLO	LO ?	LO	**Prod. Mechanism + DPS**
Υ+Υ	CMS	NLO ?	LO ?	LO ?	**Prod. Mechanism (CS dominant ?) + DPS + gluon TMD**

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- $J/\psi + J/\psi$: **JPL, C. Pisano, F. Scarpa, M. Schlegel, PLB 784(2018)217**
    - $d\sigma/dP_T^{\psi\psi}$ in different bins of $M_{\psi\psi}$ to study the gluon TMD f_1^g
    - Measure the azimuthal modulations to extract $h_1^{\perp g}$ [the distribution of linearly polarised gluons]
    - Feed-down pattern to confirm SPS/DPS dominance **J.P.L., H.S. Shao PLB 751 (2015) 479**

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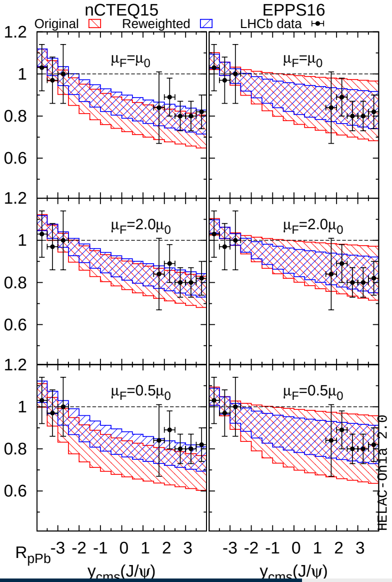
- $\Upsilon + b$ via for instance Υ + nonprompt J/ψ

Part II

pA collisions

Nuclear PDF reweighting with $B \to J/\psi$ data

A. Kusina, JPL, I. Schienbein, H.S. Shao, PRL 121 (2018) 052004

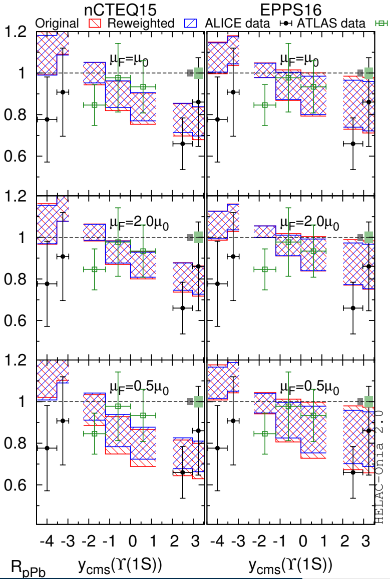


LHCb [PLB 774 (2017) 159, `1706.07122`]

- Scale uncertainty is reduced compared to the D^0 and J/ψ case.
- Data are not yet precise enough to give substantial constraints on nPDFs (but if the precision rises there is big potential).

Nuclear PDF reweighting with $\Upsilon(1S)$ data

A. Kusina, JPL, I. Schienbein, H.S. Shao, PRL 121 (2018) 052004



ALICE [PLB 740, 105 (2015), `1410.2234`]
ATLAS [ATLAS-CONF-2015-050 (updated in: `1709.03089`)]

- With the current precision we don't get any additional constraints on the nPDFs.

Wishlist for *pA* collisions

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- Improved precision on the R_{pA} for Υ and J/ψ from b

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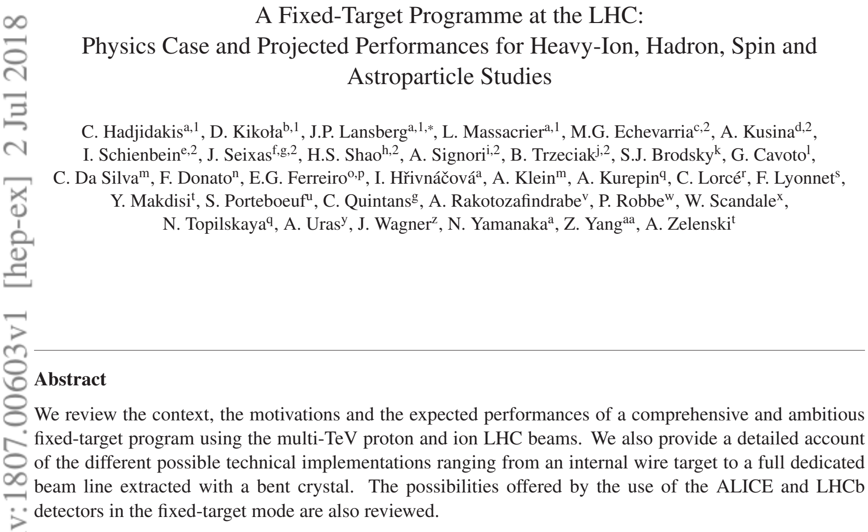
- R_{pA} vs. $\cos\theta$ to look at possible modifications of the J/ψ polarisation

Part III

Fixed-target mode

The AFTER@LHC programme



A Fixed-Target Programme at the LHC: Physics Case and Projected Performances for Heavy-Ion, Hadron, Spin and Astroparticle Studies

C. Hadjidakis[a,1], D. Kikoła[b,1], J.P. Lansberg[a,1,*], L. Massacrier[a,1], M.G. Echevarria[c,2], A. Kusina[d,2],
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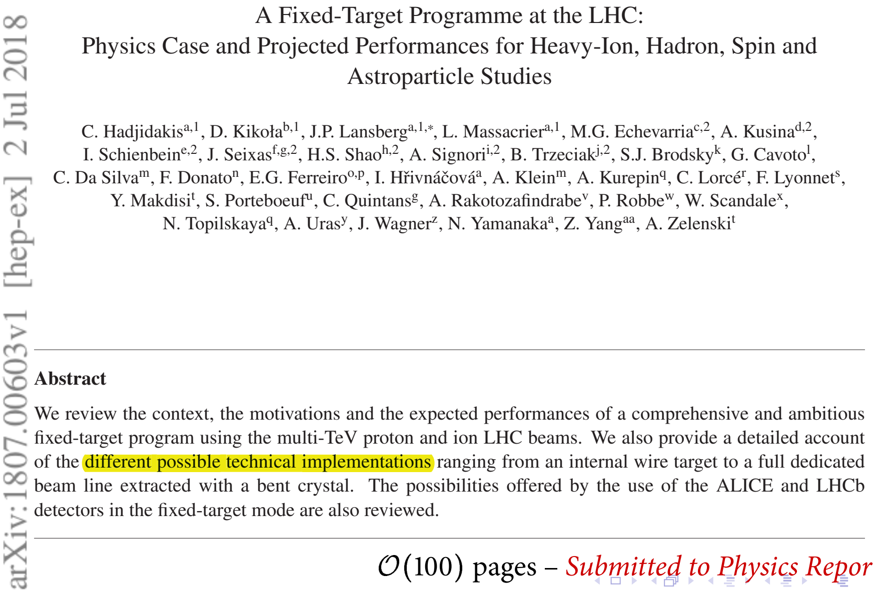
N. Topilskaya[q], A. Uras[y], J. Wagner[z], N. Yamanaka[a], Z. Yang[aa], A. Zelenski[t]

Abstract

We review the context, the motivations and the expected performances of a comprehensive and ambitious fixed-target program using the multi-TeV proton and ion LHC beams. We also provide a detailed account of the different possible technical implementations ranging from an internal wire target to a full dedicated beam line extracted with a bent crystal. The possibilities offered by the use of the ALICE and LHCb detectors in the fixed-target mode are also reviewed.

$\mathcal{O}(100)$ pages – Submitted to Physics Reports

The AFTER@LHC programme



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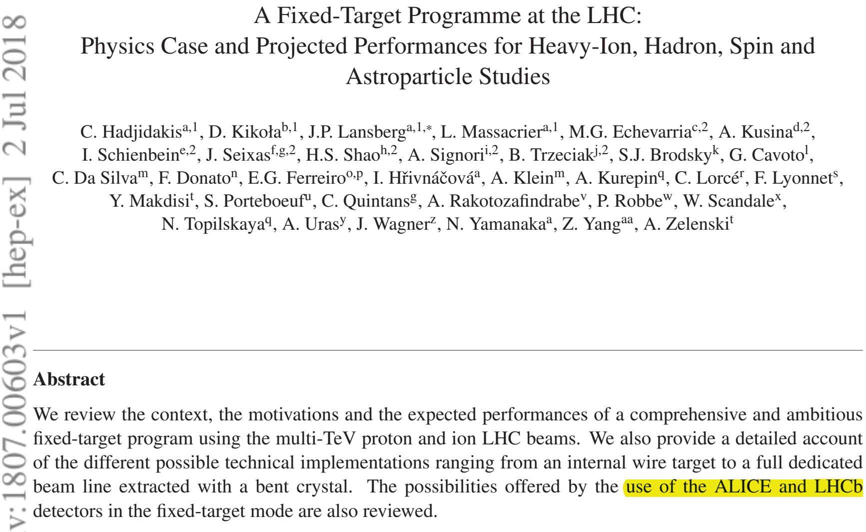

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High-x gluon, antiquark and heavy-quark content in the nucleon & nucleus

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- Gluon EMC effect to understand the quark EMC effect
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↔ high-energy neutrino & cosmic-ray physics

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$$\boxed{\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \mathcal{L}_g + \mathcal{L}_q}$$

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Heavy-ion collisions towards large rapidities

- A complete set of heavy-flavour studies between SPS and RHIC energies
- Test the formation of azimuthal asymmetries thanks to a broad rapidity reach
- Test the factorisation of cold nuclear effects from $p + A$ to $A + B$ collisions with Drell-Yan

Quarkonium Projections: heavy-ion collisions

B.Trzeciak *et al.***Few-Body Syst (2017) 58:148**

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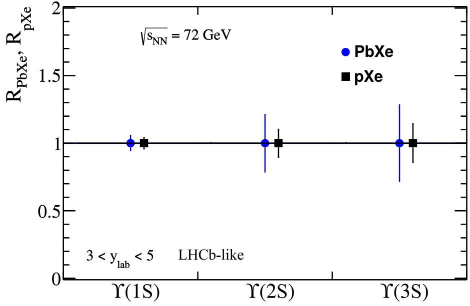

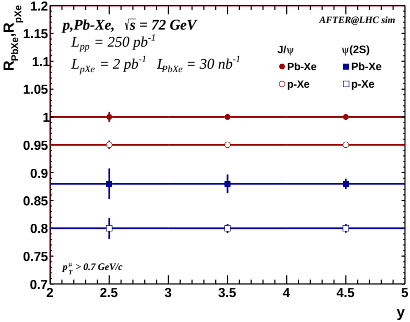

Gluons at the high-x frontier

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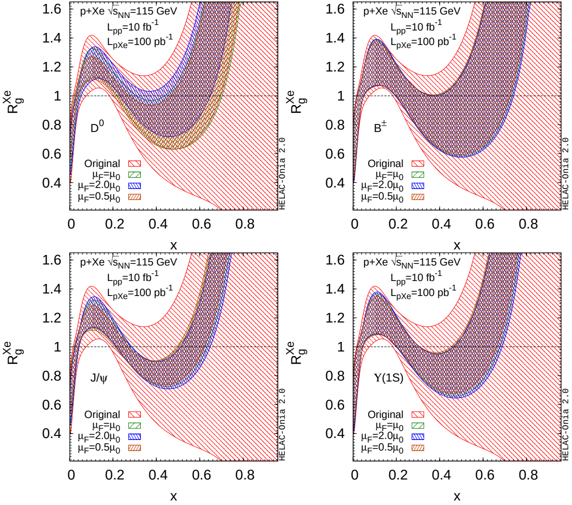
- First extremely promising projections
  [NB: *initial nPDF uncertainties for* $x > 0.1$ *(red band) are underestimated; simply no data exist there. Projection done assuming that other nuclear effect are under control.]*



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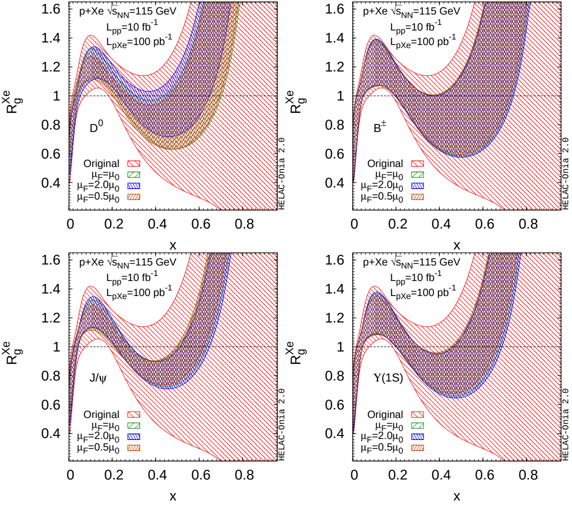
  PROSA Coll. Eur.Phys.J. C75 (2015) 396; R. Gauld, J. Rojo 118 (2017) 072001



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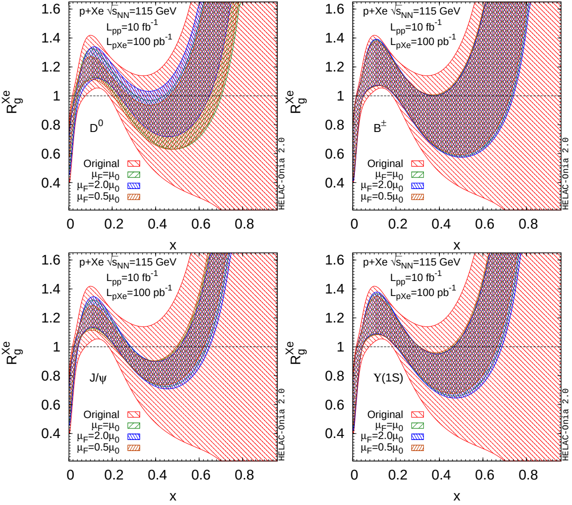

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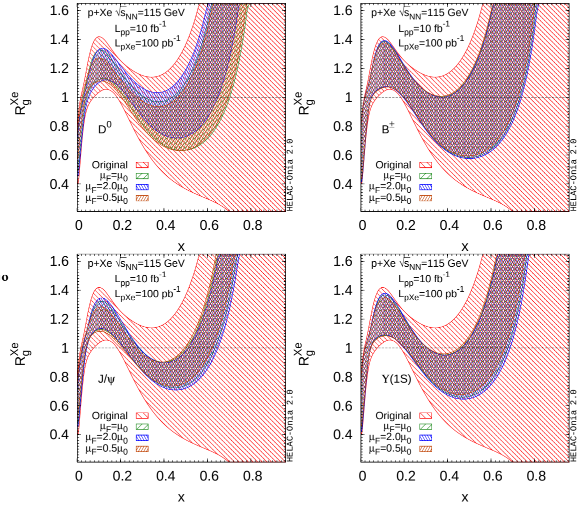


Reward: unique constraints on gluon PDFs at high x and low scales

Wishlist for the fixed-target mode : just too long

- *Quarkonium Physics at a Fixed-Target Experiment using the LHC Beams.* By J.P. Lansberg, S.J. Brodsky, F. Fleuret, C. Hadjidakis. [arXiv:1204.5793 [hep-ph]]. Few Body Syst. 53 (2012) 11.
- *Physics Opportunities of a Fixed-Target Experiment using the LHC Beams* By S.J. Brodsky, F. Fleuret, C. Hadjidakis, J.P. Lansberg. [arXiv:1202.6585 [hep-ph]]. Phys.Rept. 522 (2013) 239
- *A Fixed-Target Programme at the LHC: Physics Case and Projected Performances for Heavy-Ion, Hadron, Spin and Astroparticle Studies* By C. Hadjidakis, D. Kikola, J.P. Lansberg, L. Massacrier, *et al.*[arXiv:1807.00603 [hep-ex]].

Conclusion

LHCb remains the most competitive detector
for quarkonium-production studies

Part IV

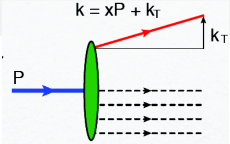
Backup

Part V

Generalities on gluon TMDs

Beyond collinear factorisation

Beyond collinear factorisation



- Observed final-state q_T from
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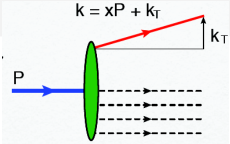
Beyond collinear factorisation



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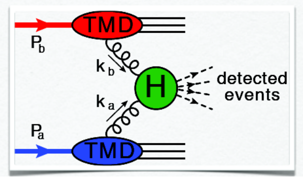

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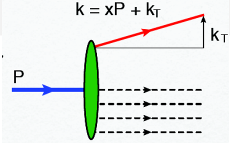

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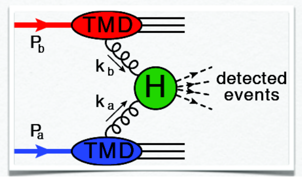
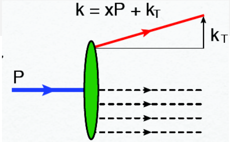


H (or M) is free of q_T

Beyond collinear factorisation



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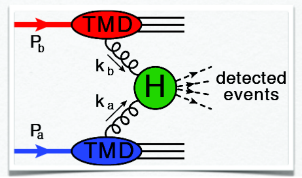
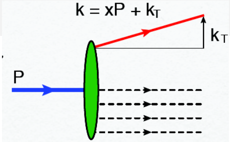


H (or M) is free of q_T

$$d\sigma = \frac{(2\pi)^4}{8s^2}\int d^2\boldsymbol{k}_{1T}\,d^2\boldsymbol{k}_{2T}\,\delta^2(\boldsymbol{k}_{1T}+\boldsymbol{k}_{2T}-\vec{q}_T)\,M_{\mu\rho}\,(M_{\nu\sigma})^* \times$$

$$\Phi_g^{\mu\nu}(x_1,\boldsymbol{k}_{1T},\mu)\,\Phi_g^{\rho\sigma}(x_2,\boldsymbol{k}_{2T},\mu)\,d\mathcal{R} + \mathcal{O}\left(\frac{q_T^2}{Q^2}\right)$$

Beyond collinear factorisation



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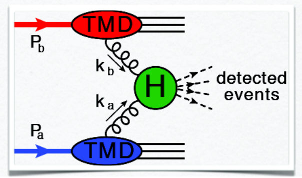

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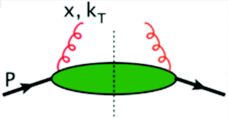
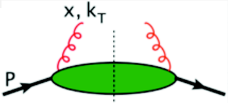
- Should work for SIDIS + pp reactions with colour singlet final states

Collins; Ji, Ma, Qiu; Rogers, Mulders, ...

Gluon TMDs in unpolarised protons



Gluon TMDs in unpolarised protons

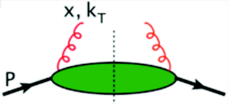


- Gauge-invariant definition:

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

- $\mathcal{U}$ and $\mathcal{U}'$ are process dependent gauge links

Gluon TMDs in unpolarised protons



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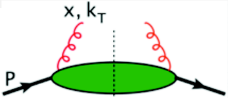
- $\mathcal{U}$ and $\mathcal{U}'$ are process dependent gauge links
- Parametrisation: **P. J. Mulders, J. Rodrigues, PRD 63 (2001) 094021; D. Boer** ***et al.*** **JHEP 1610 (2016) 013**

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

Gluon TMDs in unpolarised protons



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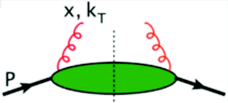
- f_1^g: TMD distribution of unpolarised gluons
- $h_1^{\perp g}$: TMD distribution of linearly polarised gluons

[Helicity-flip distribution]

Gluon TMDs in unpolarised protons



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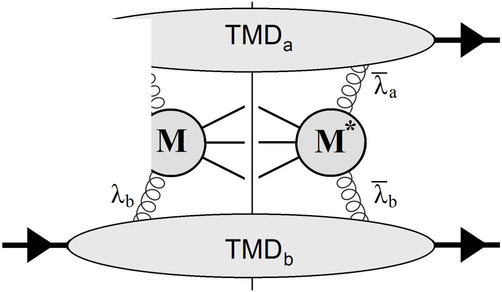
[Helicity-flip distribution]

- Both enter the computation of the q_T dependence of e.g. H^0 production

gg fusion in arbitrary unp d process [colourless final state]

$d\sigma^{gg} \propto$



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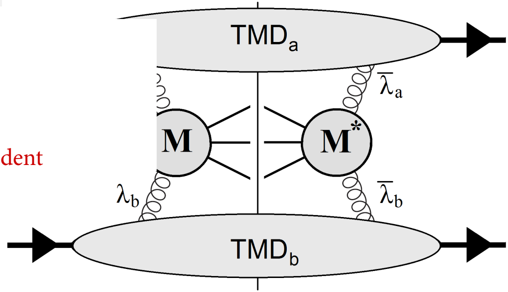
$$d\sigma^{gg} \propto \overbrace{\left(\sum_{\lambda_a,\lambda_b} \hat{\mathcal{M}}_{\lambda_a,\lambda_b}\hat{\mathcal{M}}^*_{\lambda_a,\lambda_b}\right)}^{F_1} \mathcal{C}[f_1^g f_1^g]$$

⇒ helicity non-flip, azimuthally independent



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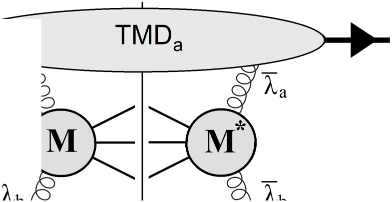

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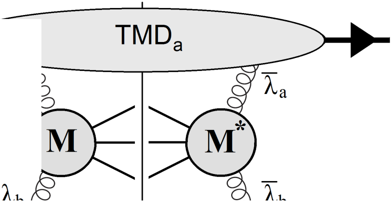

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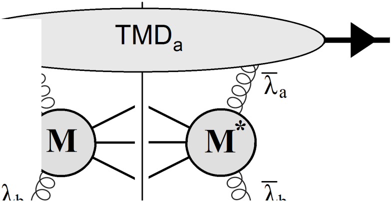

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Part VI

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Buffing, Mukherjee, Mulders, PRD 88 (2013) 054027);
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- However, if TMD factorisation holds for H^0+jet as conjectured by D. Boer-C. Pisano, there should be no issue for $\mathcal{Q}+\gamma$, $\mathcal{Q}+Z$ or $\mathcal{Q}+\gamma^\star$

D. Boer, C. Pisano PRD 91 (2015) 074024

Part VII

Quarkonia and gluon TMDs at hadron colliders

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- BACK-TO-BACK (LOW q_T) $2 \to 2$ 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

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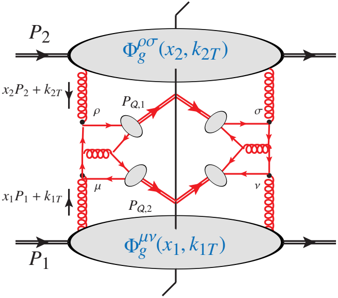
None are measured so far …

Part VIII

The case of quarkonium-pair production in more details



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

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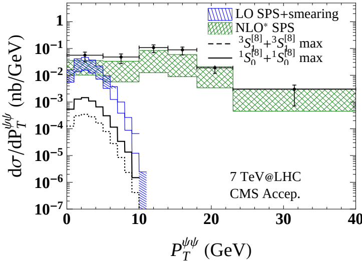

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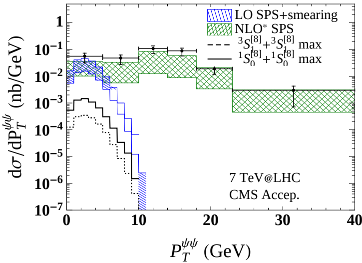

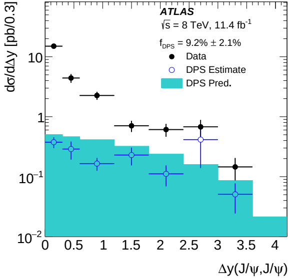

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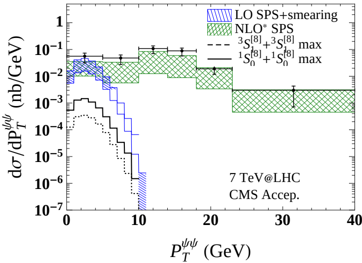

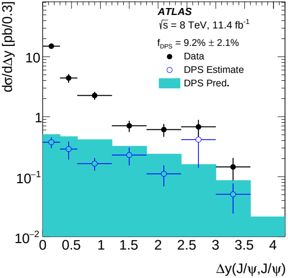

- DPS in LHCb data [kinematical distributions a priori under-control : independent scatterings]

What is special about double vector onium production ?

JPL, C. Pisano, F. Scarpa, M. Schlegel, PLB 784(2018)217

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$$\boxed{F_4 = F_1 \text{ at large } M_{\mathcal{Q}\mathcal{Q}}}$$

⇒ 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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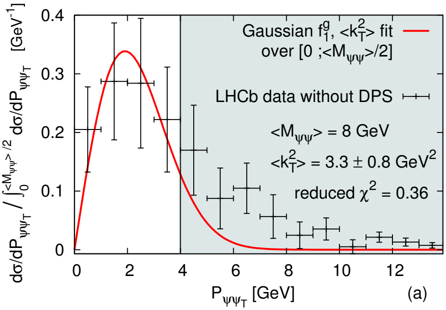

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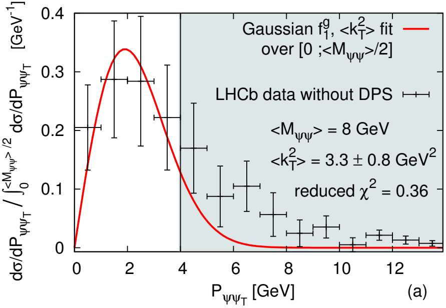

- Integration over $\phi \Rightarrow \cos(n\phi)$-terms cancel out
- $F_2 \ll F_1 \Rightarrow$ only $\mathcal{C}[f_1^g f_1^g]$ contributes to the cross-section
- No evolution so far: $\langle k_T^2 \rangle \sim 3$ GeV^2 accounts both for non-perturbative and perturbative broadenings at a scale close to $M_{\psi\psi} \sim 8$ GeV
- Disentangling such (non-)perturbative effects requires data at different scales

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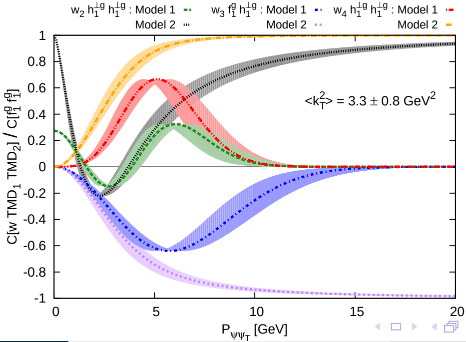

Expected azimuthal asymmetries

JPL, C. Pisano, F. Scarpa, M. Schlegel, PLB 784(2018)217

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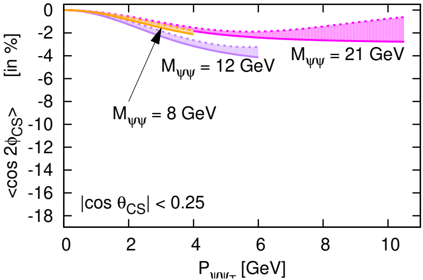
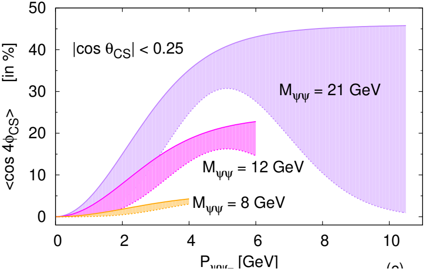


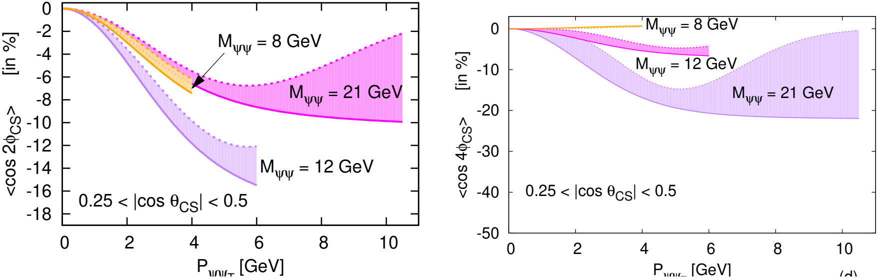


- $\langle \cos 4\phi_{\rm CS} \rangle$: largest values ever predicted ! (up to 40 %)

Expected azimuthal asymmetries

JPL, C. Pisano, F. Scarpa, M. Schlegel, PLB 784(2018)217

$$\langle \cos n\phi_{CS} \rangle = \frac{\int d\phi_{CS} \cos n\phi_{CS} \frac{d\sigma}{dM_{\mathcal{Q}\mathcal{Q}}dY_{\mathcal{Q}\mathcal{Q}}d^2\vec{q}_T d\Omega}}{\int d\phi_{CS} \frac{d\sigma}{dM_{\mathcal{Q}\mathcal{Q}}dY_{\mathcal{Q}\mathcal{Q}}d^2\vec{q}_T d\Omega}}, n = 2, 4$$



- $\langle \cos 4\phi_{CS} \rangle$: largest values ever predicted ! (up to 40 %)
- $\langle \cos 2\phi_{CS} \rangle$ [sign of $h_1^{\perp g}$] : gets large (30 %) when θ_{CS} moves away from $\pi/2$
- $\langle \cos 4\phi_{CS} \rangle$: changes sign when θ_{CS} moves away from $\pi/2$ [should be careful with the cuts]

On the importance of QCD corrections : P_T enhanced topologies

JPL, H.-S.Shao PRL 111, 122001 (2013); PLB 751 (2015) 479

- At Born (LO) order, the $P_T^{\psi\psi}$ spectrum is $\delta(P_T^{\psi\psi})$: 2 → 2 topologies

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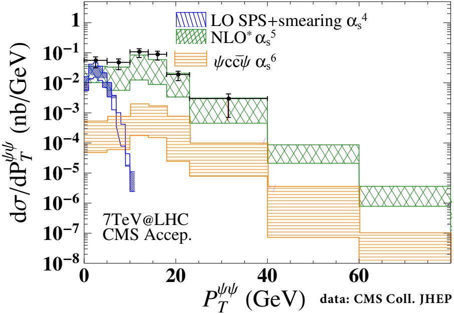

data: CMS Coll. JHEP 1409 (2014) 094

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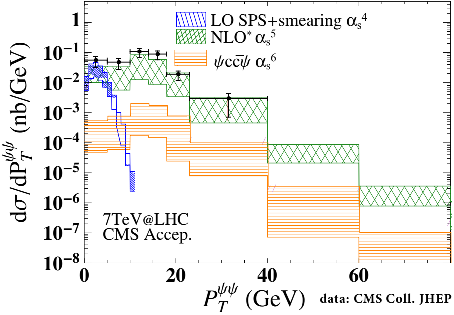

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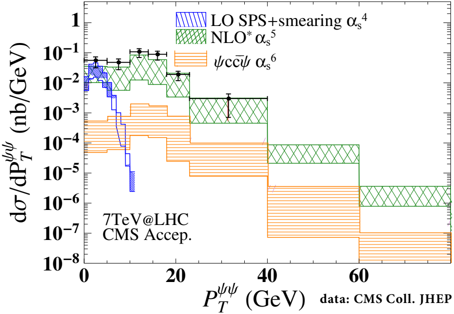

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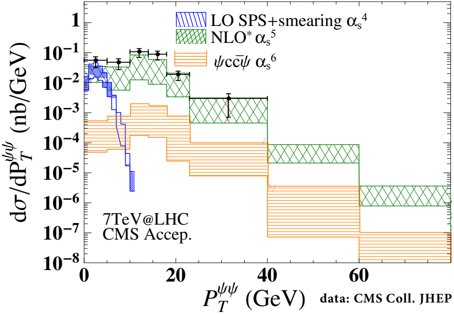

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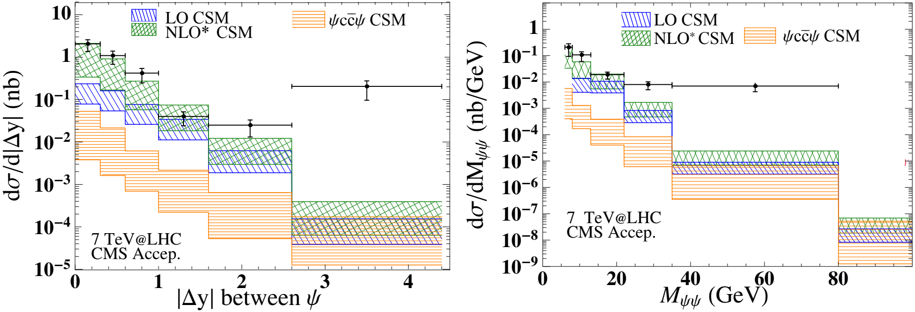
The so-called CMS puzzle



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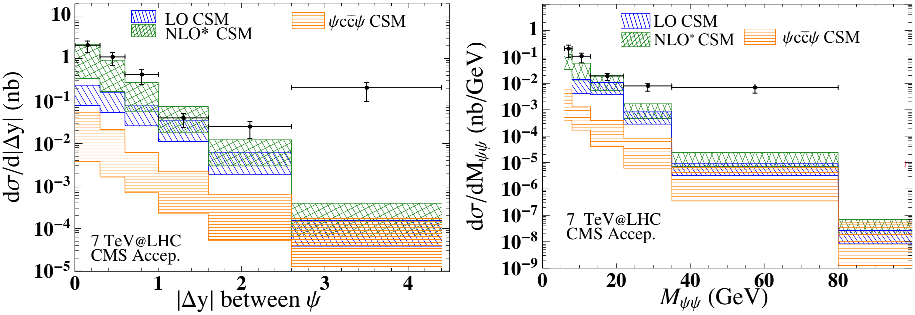

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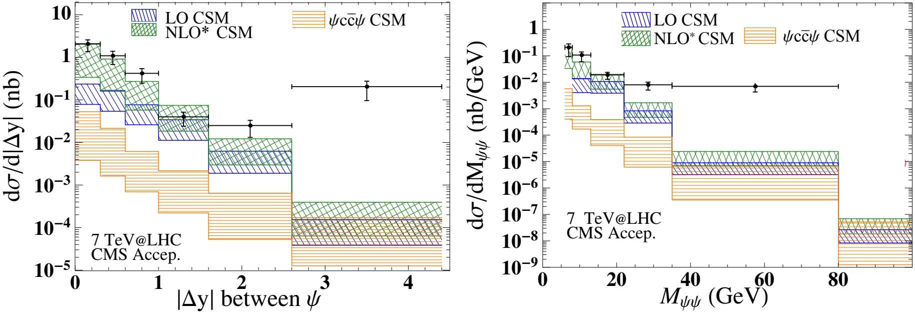

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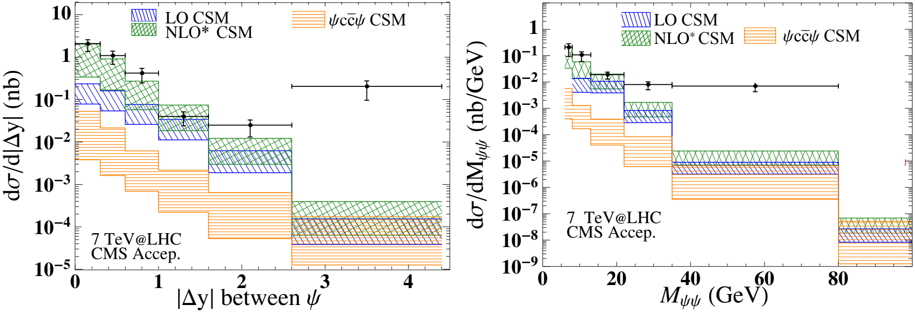

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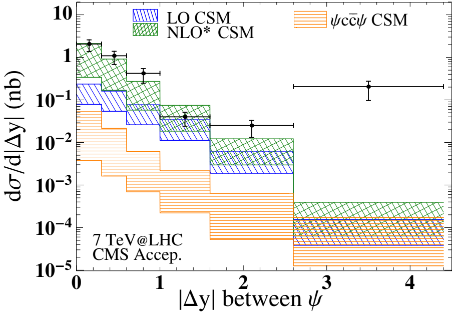

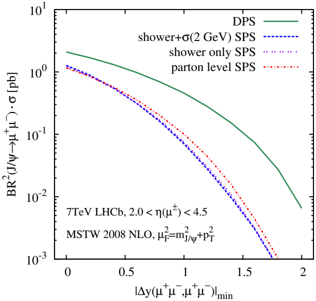

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- Predictions for LHCb, DPS ≫ SPS at large Δy

C.H. Kom, A. Kulesza, W.J. Stirling PRL 107 (2011) 082002

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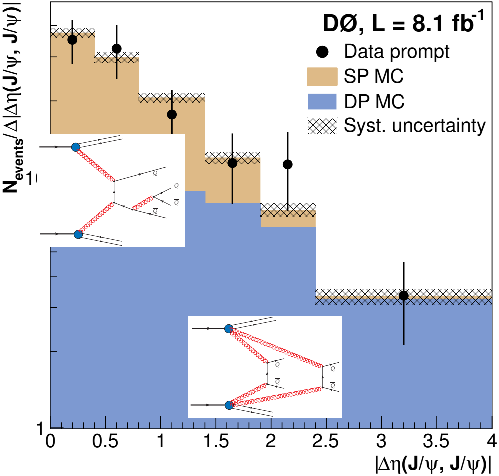

D0 Coll. PRD 90 (2014) 111101

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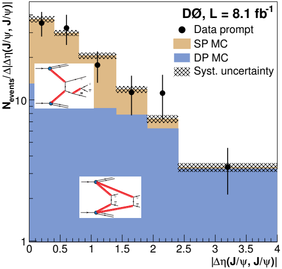

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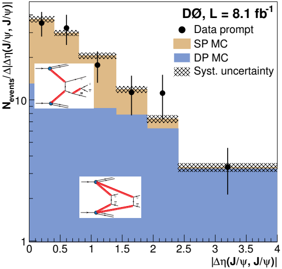

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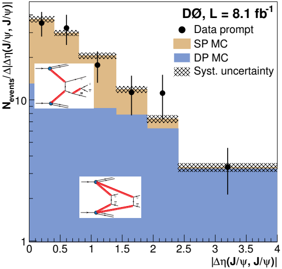

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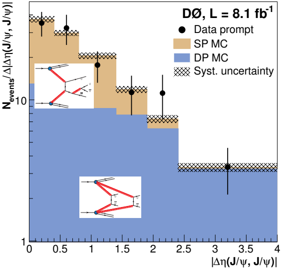

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- A question arises: using $\sigma^{\rm DPS} = \frac{1}{2}\frac{\sigma_\psi \sigma_\psi}{\sigma_{\rm eff}}$ and $\sigma_{\rm eff} = 4.8 \pm 2.5$ mb, can one account for the large Δy CMS data ?

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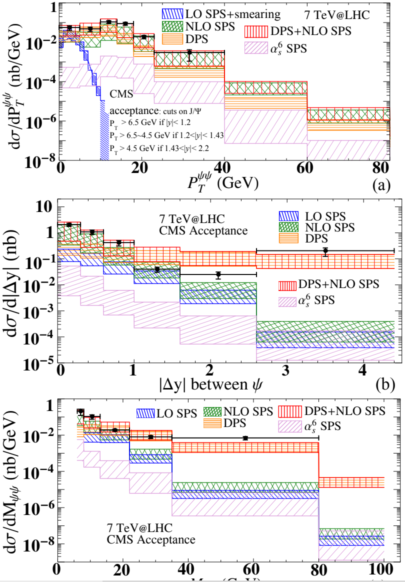

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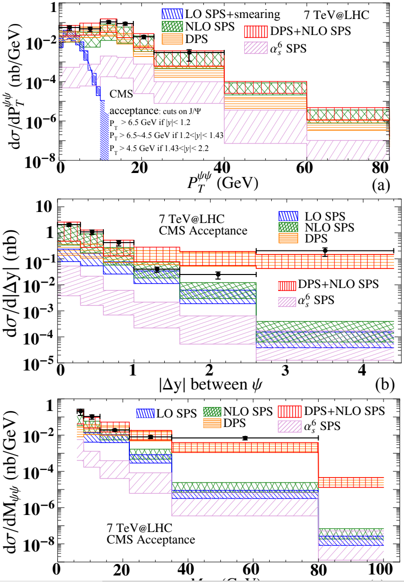

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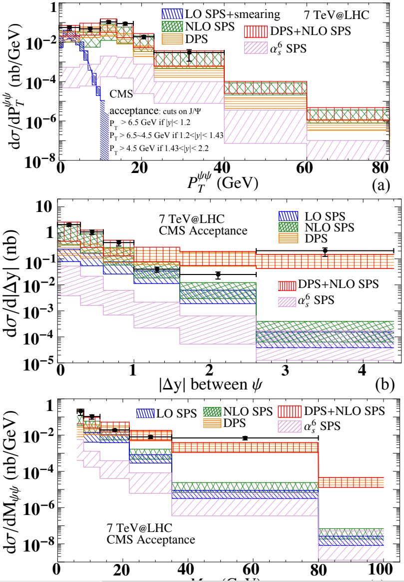

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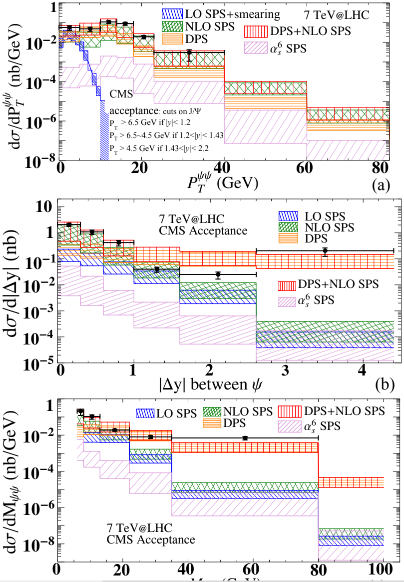
- Fit done prior the ATLAS analysis → good agreement !



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ATLAS Eur. Phys. J. C (2017) 77:76

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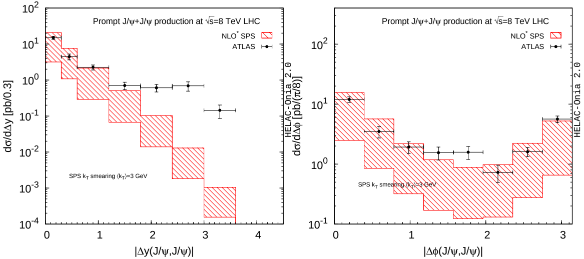

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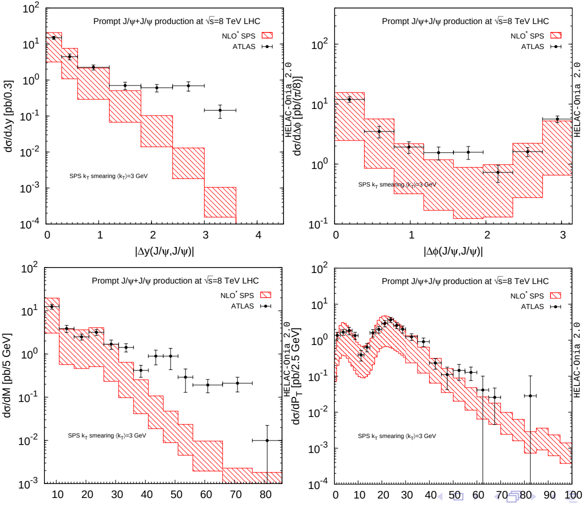

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JPL, H.-S.Shao PLB 751 (2015) 479

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- Overall :

	(CSM) SPS	DPS
$F^{\psi'}_{\psi\psi}$	45%	20%
$F^{\chi_c}_{\psi\psi}$	small	50%

Harvesting quarkonium data: 5 extractions using theory

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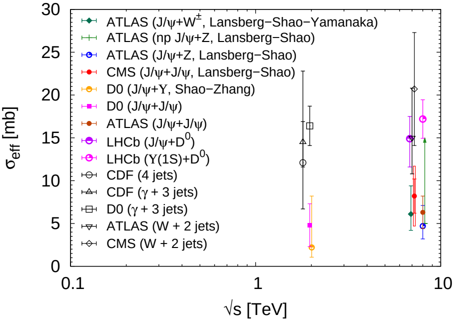

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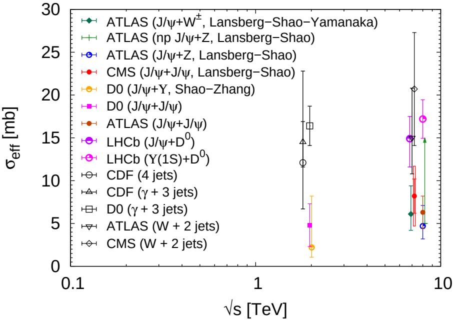

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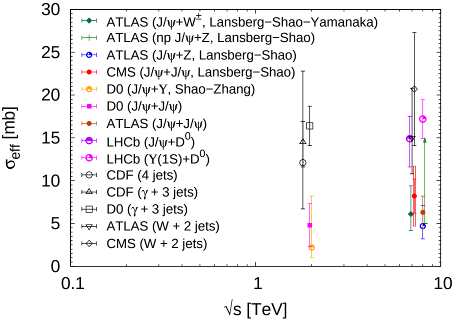

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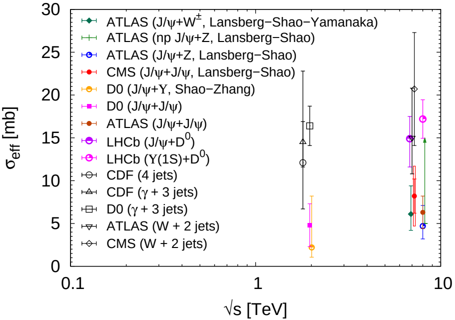

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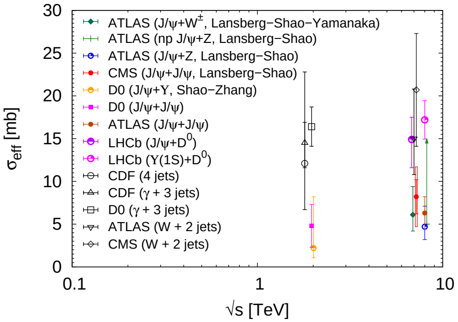

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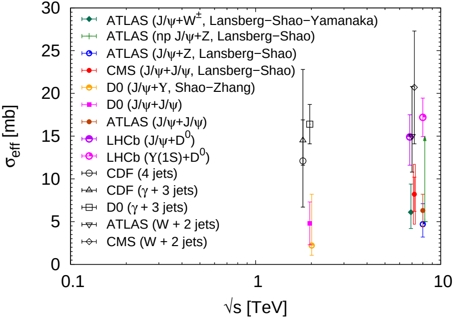

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CMS JHEP05(2017)013

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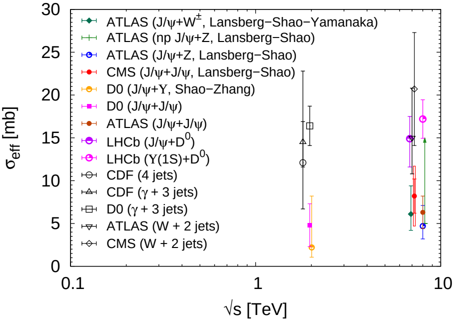

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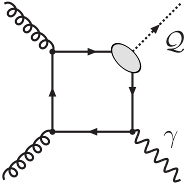
CMS JHEP05(2017)013

- D0 $J/\psi + \Upsilon$ data clearly points at a very large DPS

D0 PRL 116 (2016) 082002 + H.S. Shao - Y. J. Zhang PRL 117 (2016) 062001

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

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



- Unique candidate to pin down the gluon TMDs

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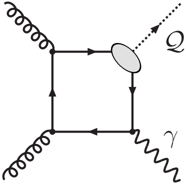

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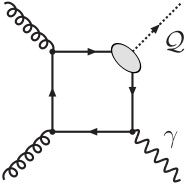

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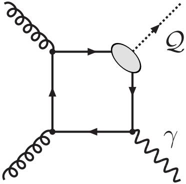

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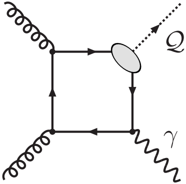

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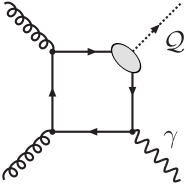

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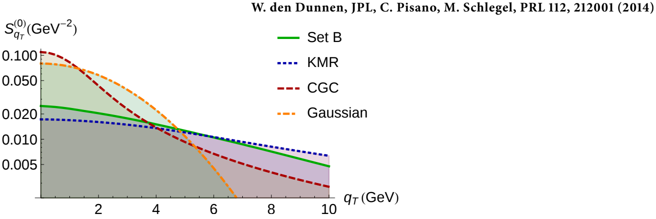
    - $\mathcal{S}^{(0)}_{q_T} = \frac{\mathcal{C}[f_1^g f_1^g]}{\int dq_T^2\, \mathcal{C}[f_1^g f_1^g]}$: does not involve $h_1^{\perp g}$ [not always the case]
    - $\mathcal{S}^{(2)}_{q_T} = \frac{F_3\, \mathcal{C}[w_2^{fh} f_1^g h_1^{\perp g} + x_1 \leftrightarrow x_2]}{2F_1 \int dq_T^2\, \mathcal{C}[f_1^g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

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

Results with UGDs as Ansätze for TMDs



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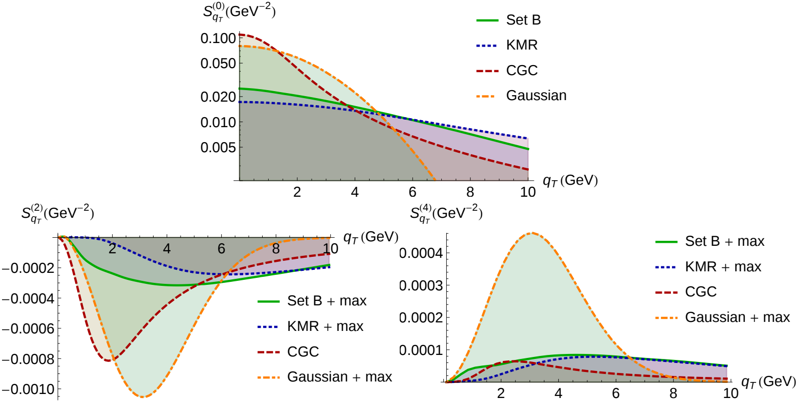

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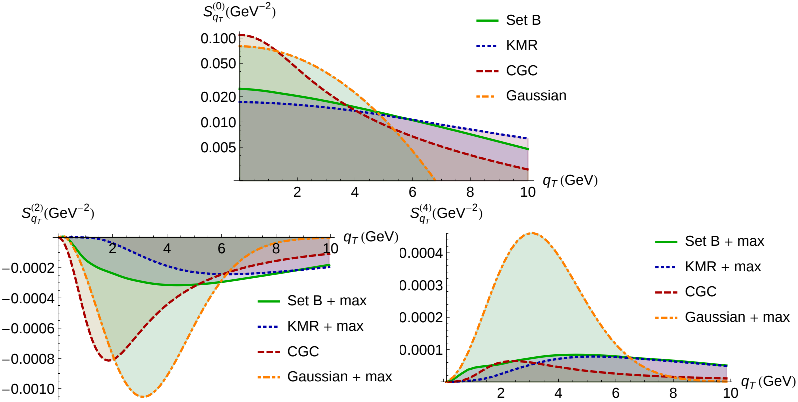

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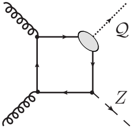
- $\mathcal{S}^{(2)}_{q_T}$: slightly larger than $\mathcal{S}^{(4)}_{q_T}$

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

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

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



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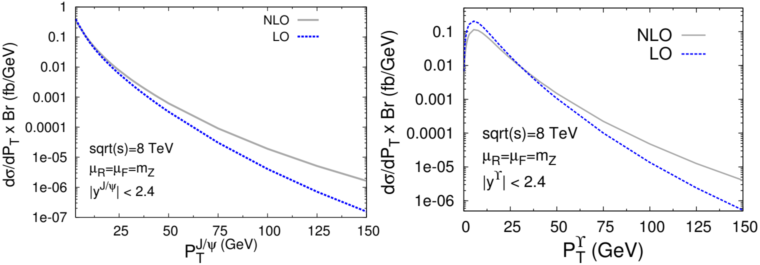

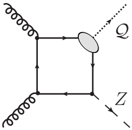

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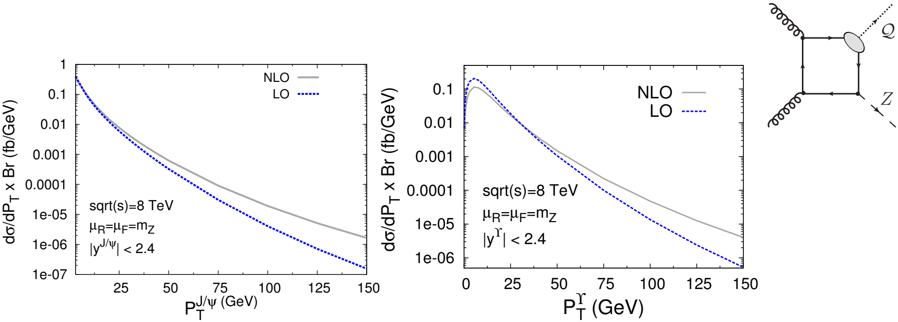

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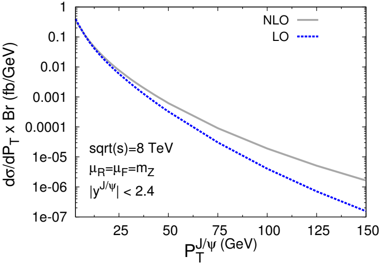

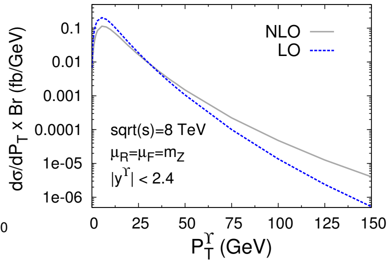

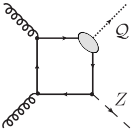

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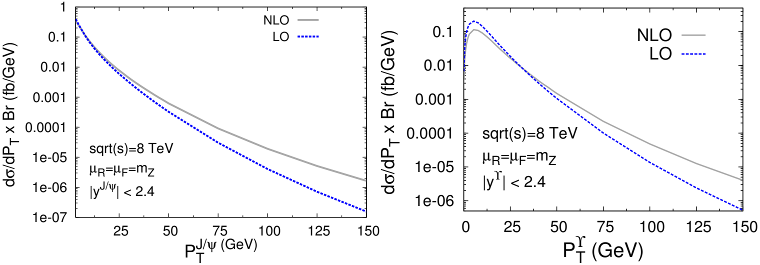

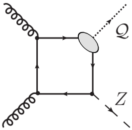

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- Rate clearly smaller than $\mathcal{Q} + \gamma$ even at low P_T; but much better detectability
- First measurement of $J/\psi + Z$ by ATLAS; large DPS yield : unequal p_T cuts ?

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

$\Upsilon + Z$ & $\Upsilon + \gamma^\star$ @$\sqrt{s} = 14$ TeV

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

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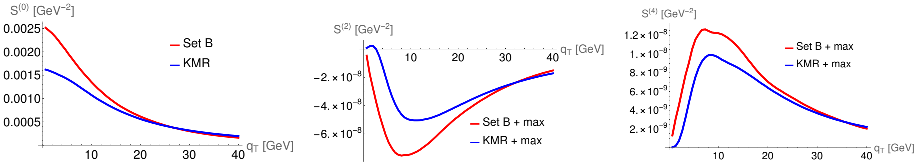

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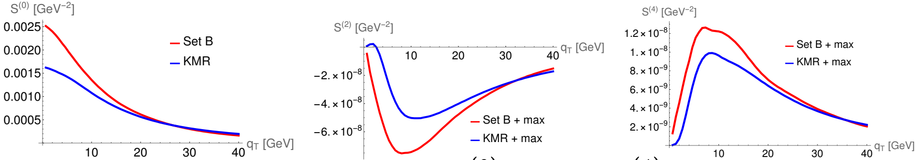
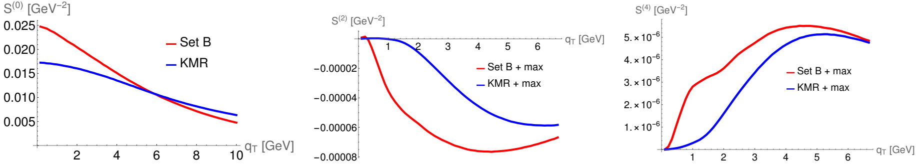


- $Q = 20$ GeV & dilepton mass [5:7] GeV $[\int \mathcal{S}^{(2)} \sim 0.5\%; \int \mathcal{S}^{(4)} \sim 0.05\%]$



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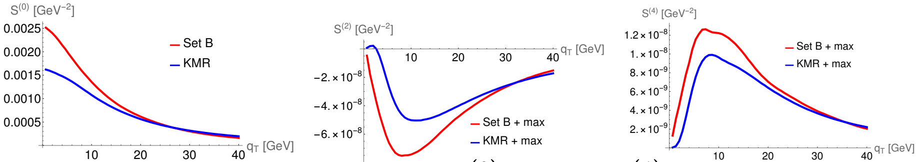

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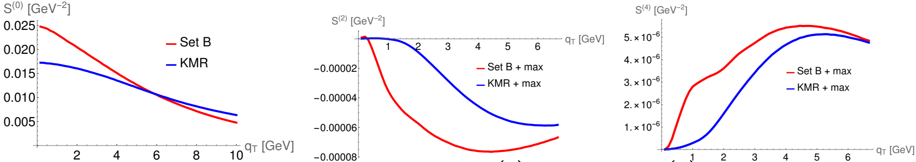
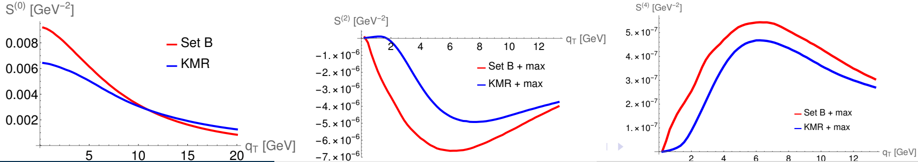
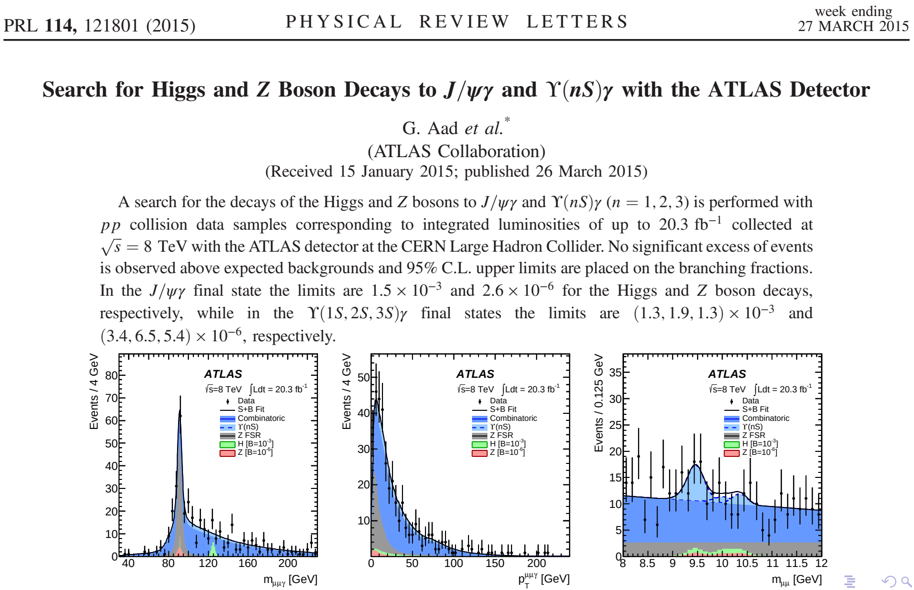


- $Q = 40$ GeV & dilepton mass [20:25] GeV [$\int \mathcal{S}^{(2)} \sim 0.15\%$; $\int \mathcal{S}^{(4)} \sim 0.01\%$]



$\Upsilon + \gamma$ 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 $\sqrt{s} = 8$ 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

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

- $\sqrt{2 \times m_N \times E_p} \overset{7\,TeV}{=} 115$ GeV

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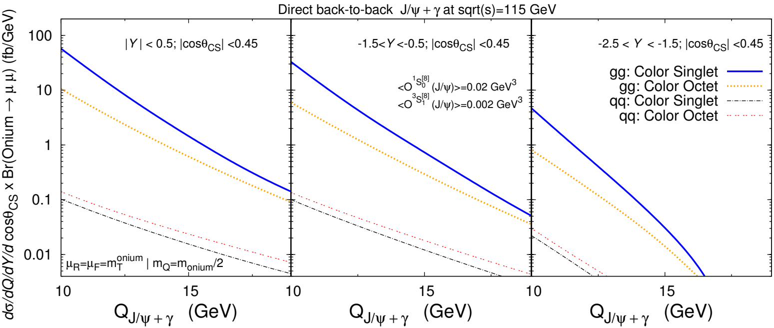

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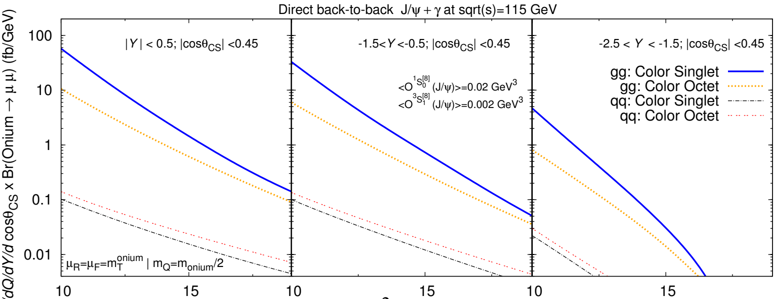
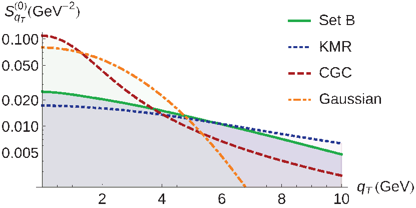


At $Y_{\rm (cms)} \simeq -2$, $x_2 \simeq 10/115 \times e^2 \simeq 0.65$. Yet, $g - g > q - \bar{q}$!

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

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

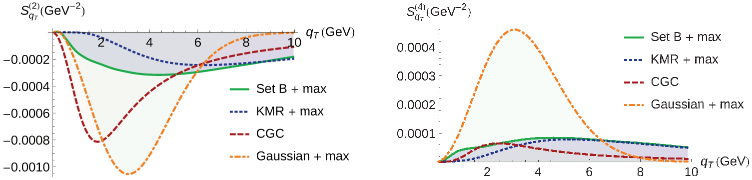


Models for f_1^g: assumed to be the same as for Unintegrated Gluon Distributions

- 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* $\Upsilon + \gamma$ *production at* $\sqrt{s} = 14$ *TeV*

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



$h_1^{\perp g}$: 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

$$2.0\%\ (\text{KMR}) < \quad |\int \mathrm{d}q_T^2 \mathcal{S}_{q_T}^{(2)}| \quad < 2.9\%\ (\text{Gauss})$$

$$0.3\%\ (\text{CGC}) < \quad \int \mathrm{d}q_T^2\ \mathcal{S}_{q_T}^{(4)} \quad < 1.2\%\ (\text{Gauss})$$

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