Quarkonium production: where do we stand and where to go ?

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IJCLab Orsay – Paris Saclay U. – CNRS

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Part I

Quarkonium production mechanisms

Approaches to Quarkonium Production

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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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3. Colour Octet Mechanism
   - one non-perturbative parameter per Fock State
   - expansion in v^2; series can be truncated
   - the phenomenology partly depends on this
   - HQSS relates some non-perturbative parameters to each others and to a specific quarkonium polarisation

Basic pQCD approach: the Colour Singlet Model (CSM)

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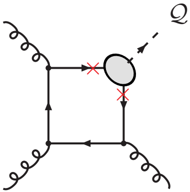

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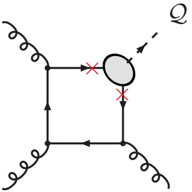

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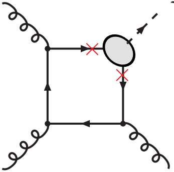

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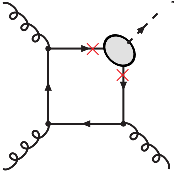

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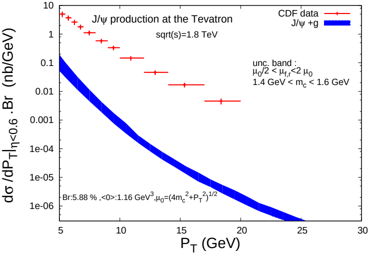

CDF, PRL 79:572 & 578,1997

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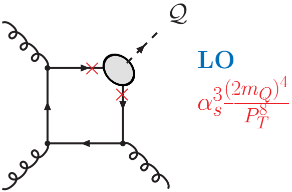

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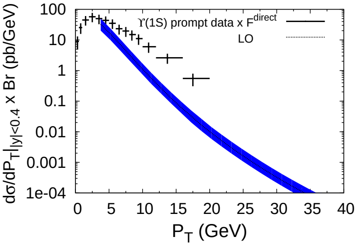

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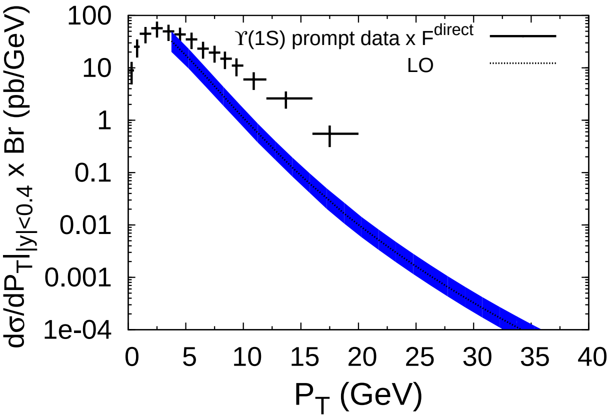

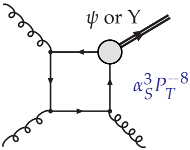

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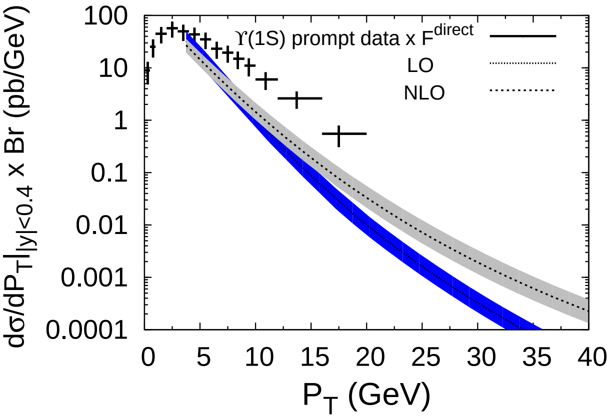

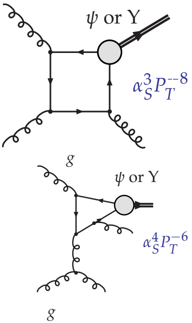

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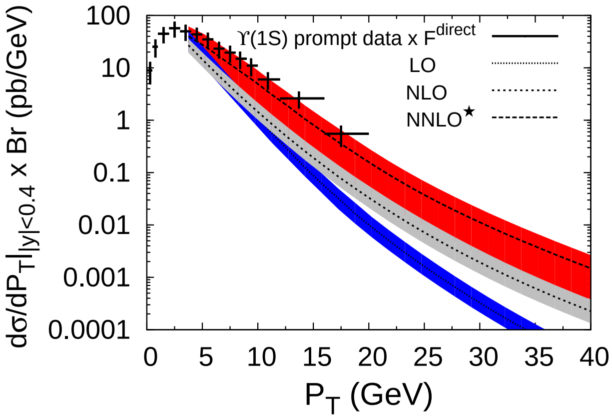

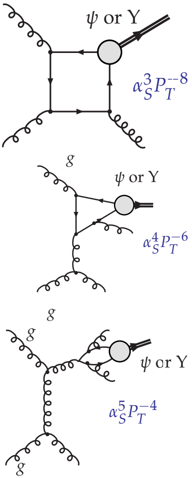

Attention: the NNLO* is not a complete NNLO
See a recent study by H.S. Shao JHEP 1901 (2019) 112

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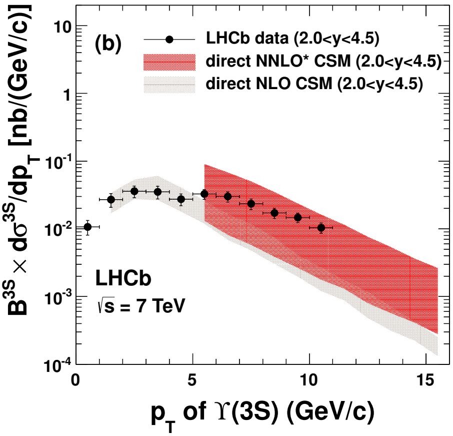

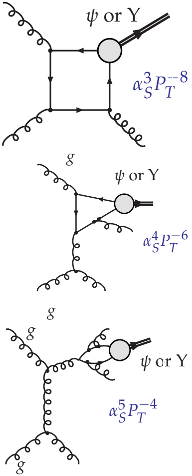

Υ(3S): 60 % direct; Υ(2S):60-70 % direct; Υ(1S): 50-70 % direct

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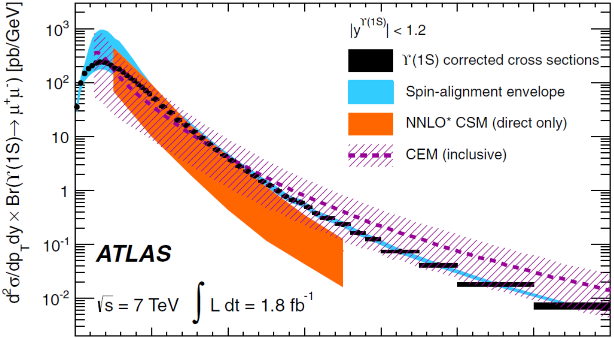

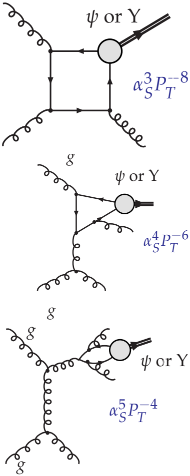

CSM theory curve extrapolated to prompt: × 2

Colour Octet Mechanism Dominance : not so simple

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NRQCD: Bodwin, Braaten, Lepage, 1995; Cho, Leibovich,...

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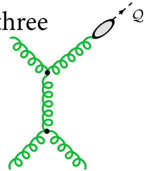

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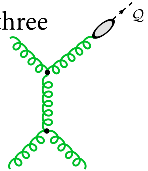

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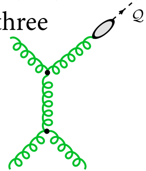

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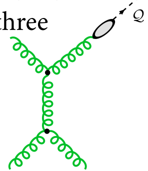

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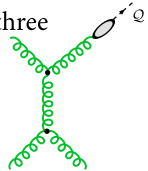

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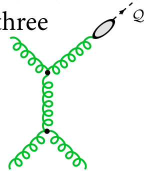

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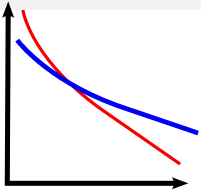

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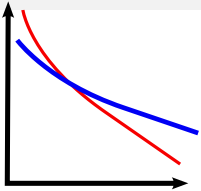

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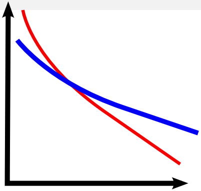

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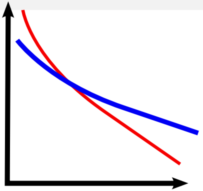

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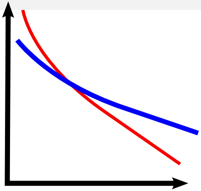
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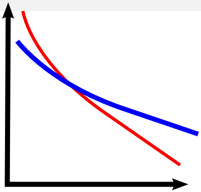

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- Polarisation: ${}^1S_0^{[8]}$: unpolarised; ${}^3S_1^{[8]}$ & ${}^3P_J^{[8]}$: transverse

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JPL, H.S. Shao JHEP 1610 (2016) 153

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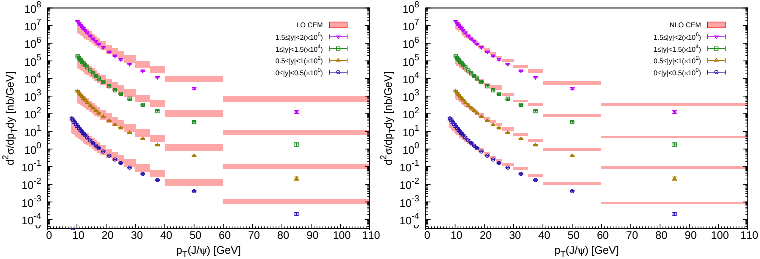
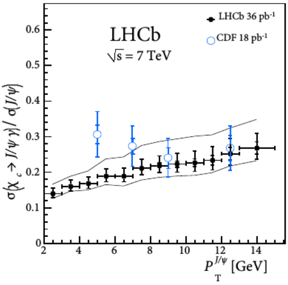


Feed downs from the excited states

JPL. arXiv:1903.09185 [hep-ph] (Phys. Rept. 2020, In Press)



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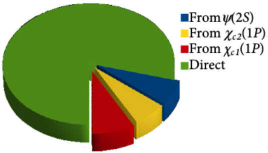
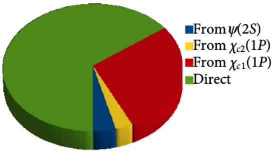


(b) Low P_T J/ψ



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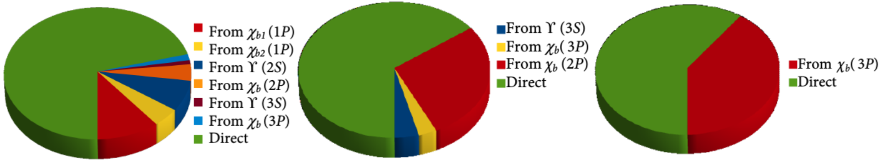

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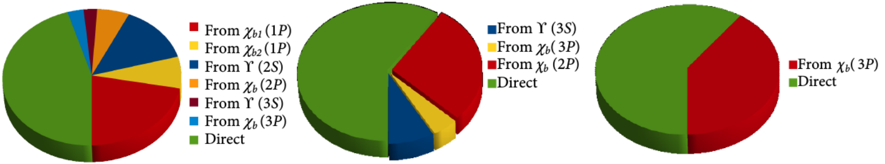
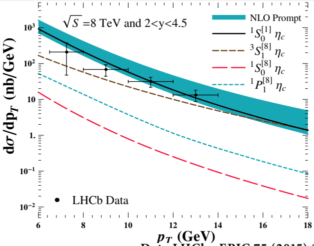


(d) High P_T $\Upsilon(1S)$ (e) High P_T $\Upsilon(2S)$ (f) High P_T $\Upsilon(3S)$

The last piece in the puzzle: the η_c



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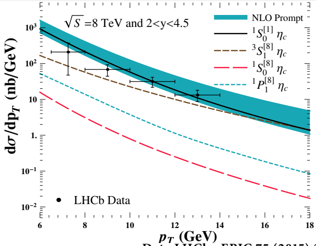

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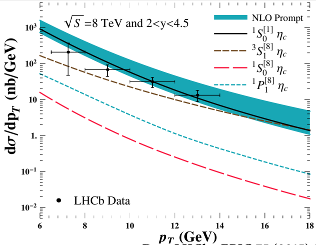

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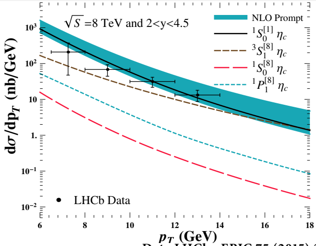

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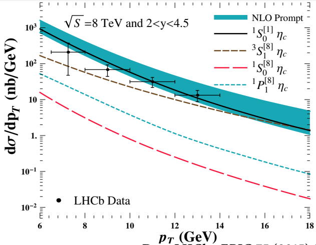

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came out **(Hamburg) M. Butenschoen** *et al.* **PRL 114 (2015) 092004; (PKU) H. Han** *et al.* **114 (2015) 092005; (IHEP) H.F. Zhang** *et al.* **114 (2015) 092006**

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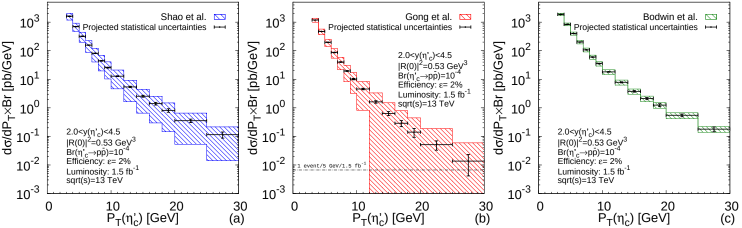

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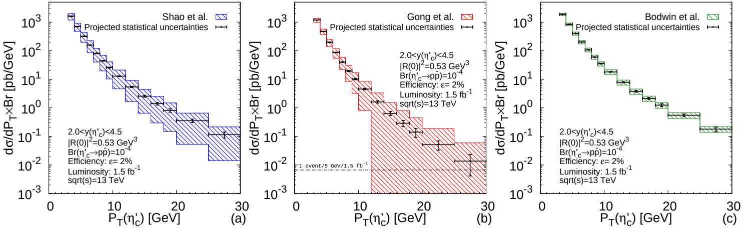

→ Belle-II data on the inclusive $\psi(2S)$ production will also be crucial

The current situation in one slide ...

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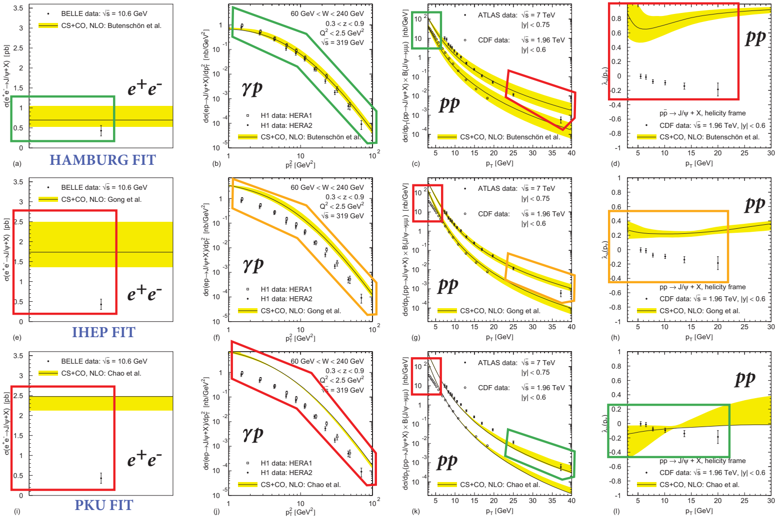
- However, as we will now see, these offer new ways to study DPS

Universality of NLO NRQCD fits ?

Plot from M. Butenschön (ICHEP 2012); Discussion in JPL, arXiv:1903.09185



Further caveats: η_c data !

Part III

Photoproduction at mid and high P_T

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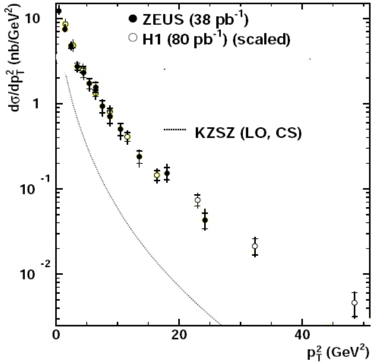

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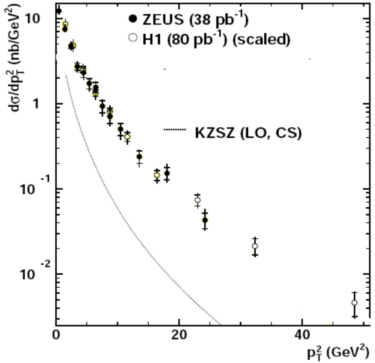

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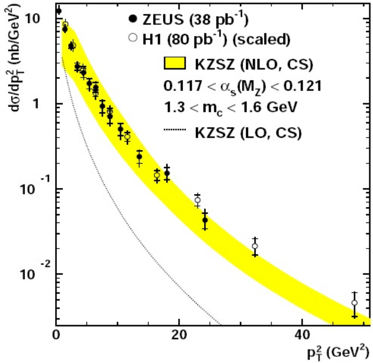

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P. Artoisenet *et al.* **PRL 102 (2009) 142001**

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Photoproduction at mid and high P_T

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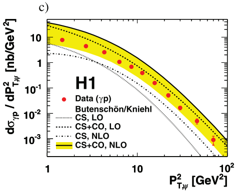
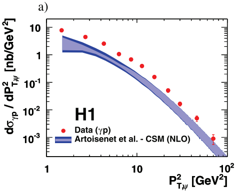
H1 EPJC (2010) 68: 401





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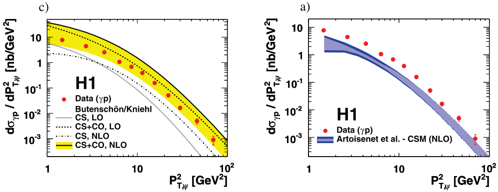
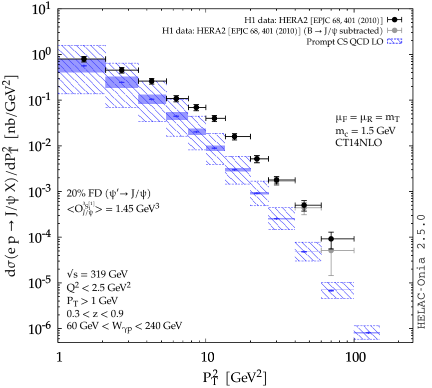
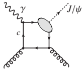


→ Let us revisit this in view of the EIC prospects

Is the CSM after all a good baseline ?

C.Flore, JPL, H.S. Shao, Y. Yedelkina, 2009.08264





$$\gamma + g \to \psi + g \,@\, \alpha \alpha_s^2 \text{ [LO]}$$

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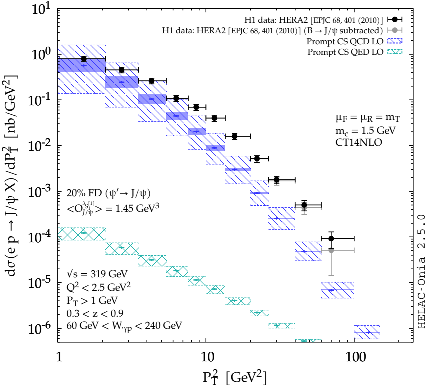
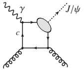
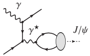




$\gamma + g \to \psi + g \,@\, \alpha\alpha_s^2$ [LO]



$\gamma + q \to \psi + q \,@\, \alpha^3$ [NEW !]

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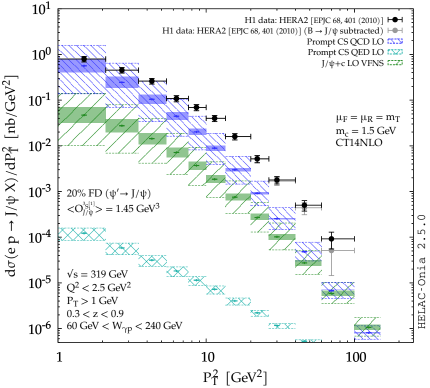

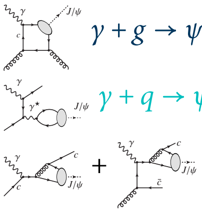

$\gamma + g \to \psi + g @ \alpha\alpha_s^2$ [LO]

$\gamma + q \to \psi + q @ \alpha^3$ [NEW !]

$\gamma + c \to \psi + c @ \alpha\alpha_s^2$ w. 4 Flav.

$\gamma + g \to \psi + c + \bar{c} @ \alpha\alpha_s^3$ w. 3 Flav.

[also NEW !]

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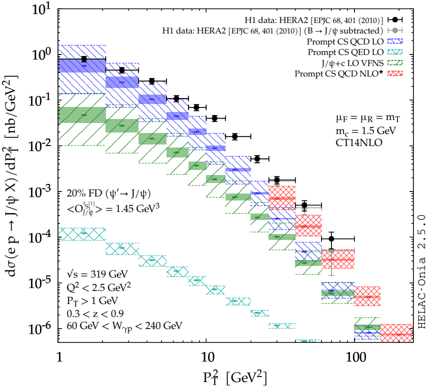
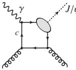
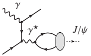




$\gamma + g \to \psi + g\,@\,\alpha\alpha_s^2$ [LO]



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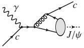
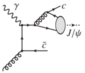
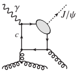
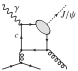
 + 

$\begin{cases} \gamma+c\to\psi+c\,@\,\alpha\alpha_s^2 \text{ w. 4 Flav.} \\ \gamma+g\to\psi+c+\bar{c}\,@\,\alpha\alpha_s^3 \text{ w. 3 Flav.} \end{cases}$

[also NEW !]

 + 

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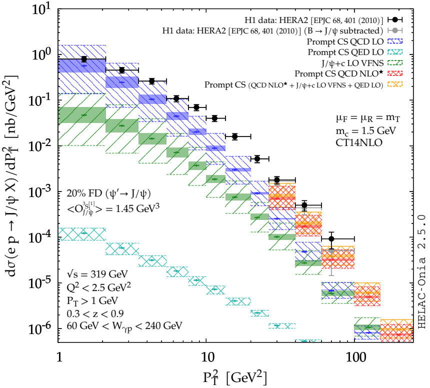
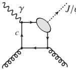
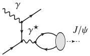




$\gamma + g \to \psi + g \,@\, \alpha\alpha_s^2$ [LO]



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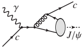
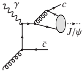
 + 

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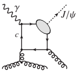
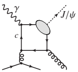
[also NEW !]

 + 

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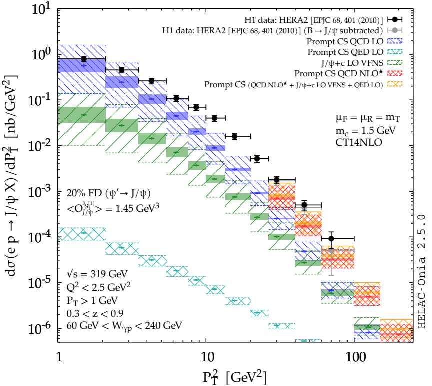

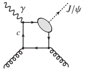

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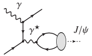
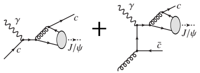


$\gamma + q \to \psi + q \,@\, \alpha^3$ [NEW !]



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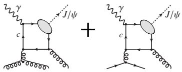
[also NEW !]



$\gamma + g \to \psi + g + g \,@\, \alpha\alpha_s^3$
$\gamma + q \to \psi + g + q \,@\, \alpha\alpha_s^3$ + LO

- LO QCD does a good job at low P_T
- LO QED much harder but small normalisation [will matter at EIC]
- J/ψ+charm: starts to matter at high P_T [will also matter at EIC]
- NLO$^{(\star)}$ close the data, the overall sum nearly agrees with them
- Agreement when the expected $B \to J/\psi$ feed down (always overlooked) is subtracted

→ will restrict to CSM for EIC predictions

Predictions for the EIC : inclusive production

C.Flore, JPL, H.S. Shao, Y. Yedelkina, 2009.08264

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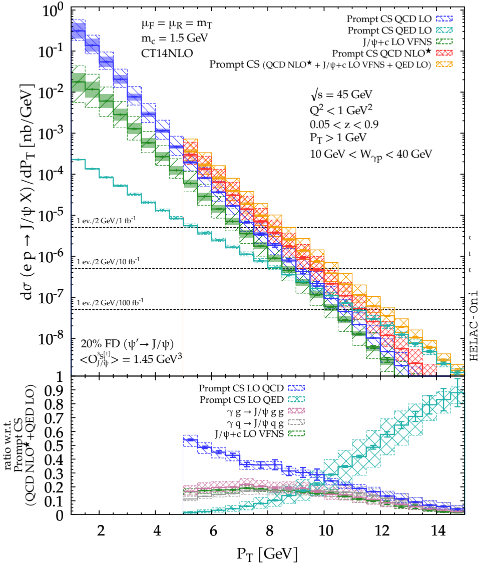

- At $\sqrt{s_{ep}} = 45$ GeV, one enters the valence region
- Yield measurable up to $P_T = 10$ GeV with $\mathcal{L} = 100$ fb^{-1}

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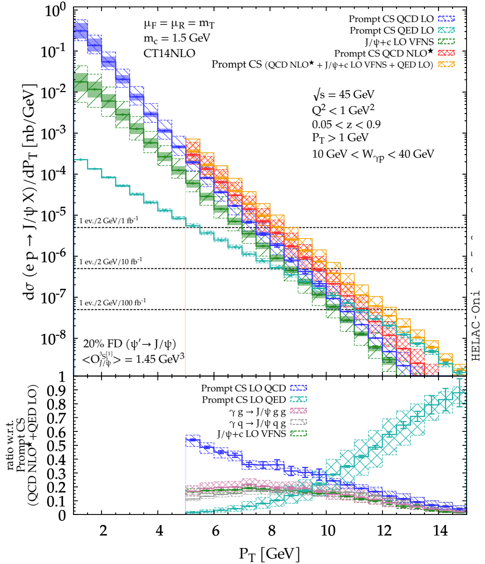

- At $\sqrt{s_{ep}}$ = 45 GeV, one enters the valence region
- Yield measurable up to P_T = 10 GeV with $\mathcal{L}$ = 100 fb^{-1}
- QED contribution leading at the largest measurable P_T

Predictions for the EIC : inclusive production

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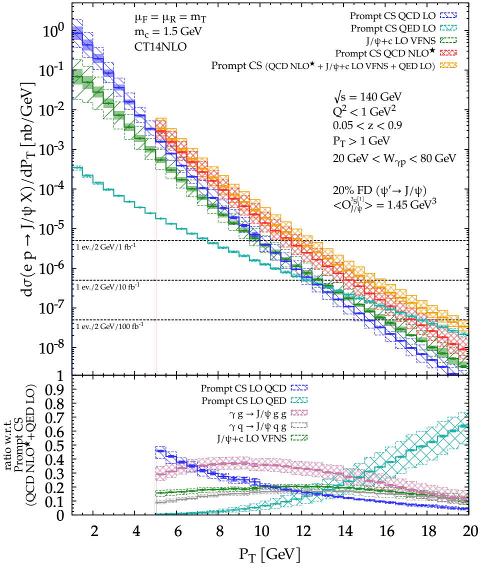

- At $\sqrt{s_{ep}} = 140$ GeV, P_T range up to 15-20 GeV
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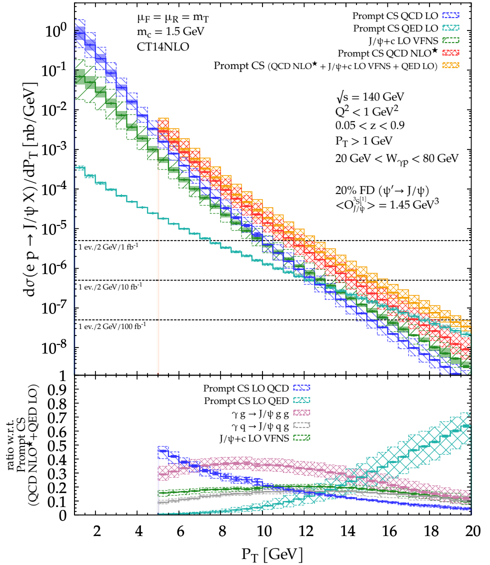

- At $\sqrt{s_{ep}}$ = 140 GeV, P_T range up to 15-20 GeV
- photon-gluon fusion remains dominant
- J/ψ + 2 hard partons dominant for $P_T \sim 10 - 15$ GeV
- Could lead to J/ψ + 2 jets with moderate P_T
- A priori the leading jet$_1$ recoils on the J/ψ+ jet$_2$ pair
- $d\sigma$ should scale with $M_{J/\psi+\text{jet}_2} - M_{J/\psi}$

J/ψ+charm associated production at the EIC

C.Flore, JPL, H.S. Shao, Y. Yedelkina, 2009.08264

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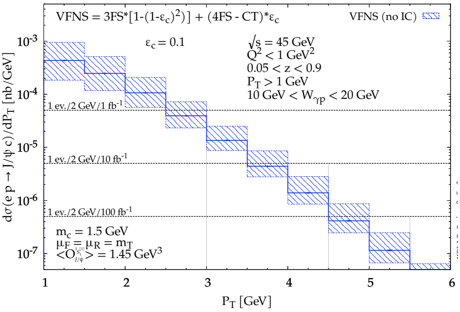

C.Flore, JPL, H.S. Shao, Y. Yedelkina, 2009.08264

- Same LO VFNS computation as for J/ψ+charm contributing to $J/\psi + X$ except for the detection efficiency ϵ: $VFNS =$ $3FS \times \left(1 - (1-\epsilon)^2\right) + \left(4FS - CT\right) \times \epsilon$
- At $\sqrt{s_{ep}} = 45$ GeV, yield limited to low P_T even with $\mathcal{L} = 100$ fb^{-1}
- But it is clearly observable if $\epsilon_c = 0.1$
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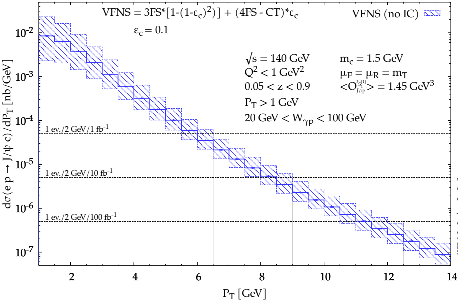

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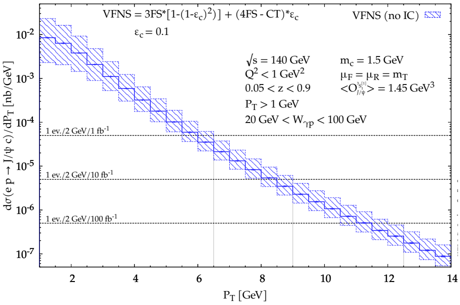

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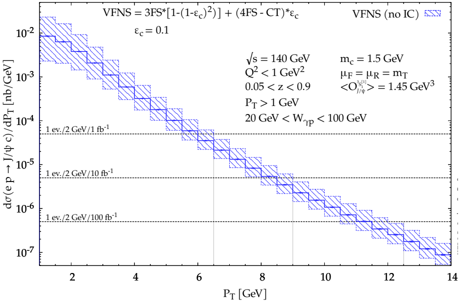

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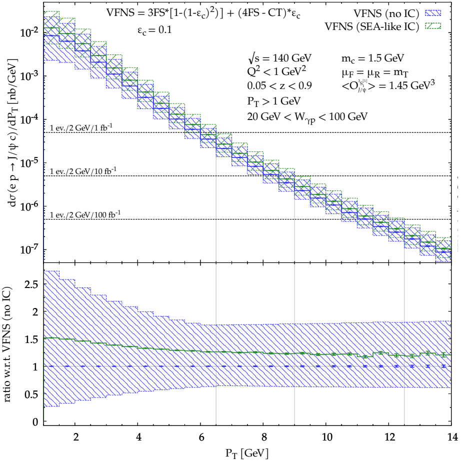

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[We used IC $c(x)$ encoded in CT14NNLO]

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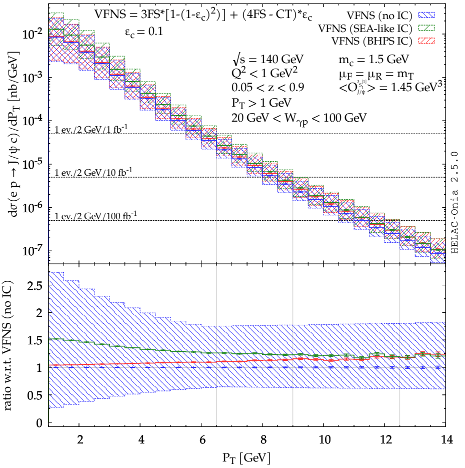

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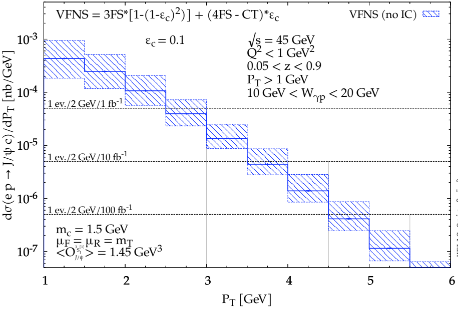

C.Flore, JPL, H.S. Shao, Y. Yedelkina, 2009.08264

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- Azimuthal distribution could be studied
- At $\sqrt{s_{ep}} = 140$ GeV, P_T range up to 10-12 GeV
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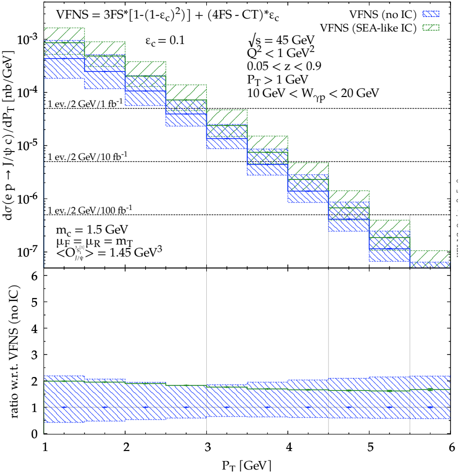

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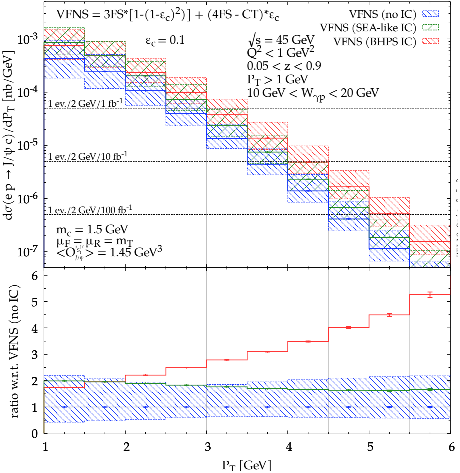

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Part IV

Associated-quarkonium production

Going further with associated-quarkonium production

Going further with associated-quarkonium production

See section 3 of JPL, arXiv:1903.09185 [hep-ph] (Phys. Rept. 2020, In Press)

Observables	Experiments	CSM	CEM	NRQCD	Interest
J/ψ+J/ψ	LHCb, CMS, ATLAS, D0 (+NA3)	NLO, NNLO*	NLO	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	NLO	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)	--	--	--	Initial vs Final state effects ?
J/ψ in jet.	LHCb, CMS	LO	--	LO	Prod. Mechanism (?)
J/ψ(ϒ) + jet	--	--	--		Prod. Mechanism (QCD corrections)
Isolated J/ψ(ϒ)	--	--	--	--	Prod. Mechanism (CS dominant ?)
J/ψ+b	--	--	--	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
ϒ+ϒ	CMS	NLO ?	NLO	LO ?	Prod. Mechanism (CS dominant ?) + DPS + gluon TMD

Part V

Quarkonium-pair production

On the importance of QCD corrections to $J/\psi + J/\psi$ production

JPL, H.-S.Shao PRL 111, 122001 (2013); PLB 751 (2015) 479; CMS JHEP 1409 (2014) 094; ATLAS EPJC (2017) 77:76

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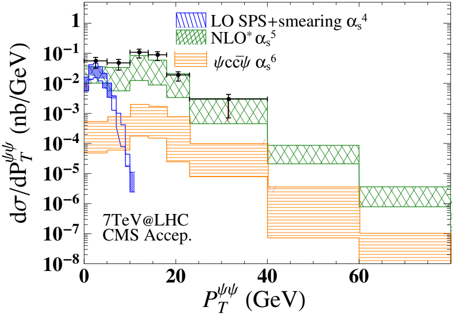
- By far insufficient (blue) to account for the CMS measured spectrum



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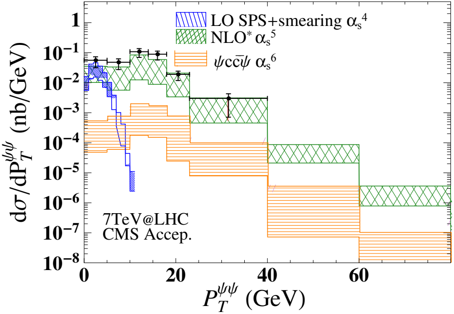

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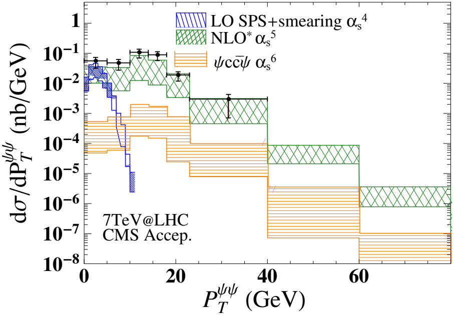

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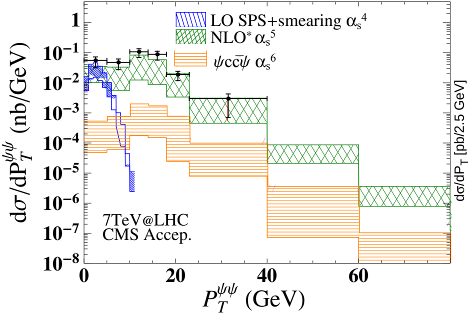

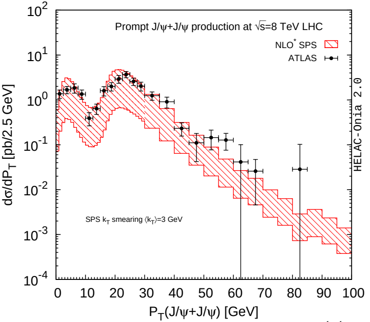

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- Confirmation at larger $P_T^{\psi\psi}$ with ATLAS data !

$J/\psi + J/\psi$ at low $P_T^{\psi\psi}$: where LHCb can contribute

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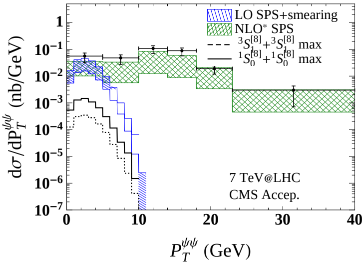

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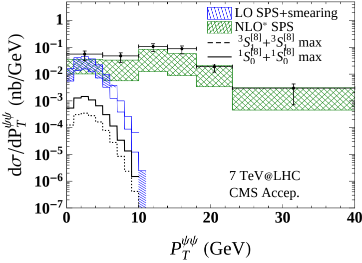

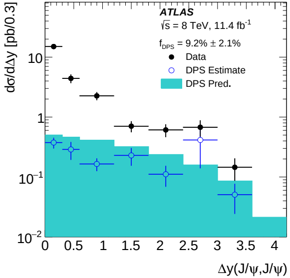

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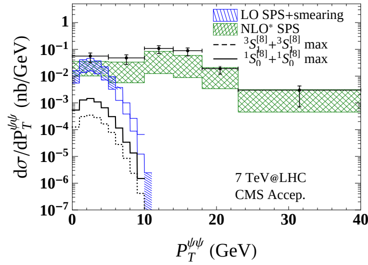
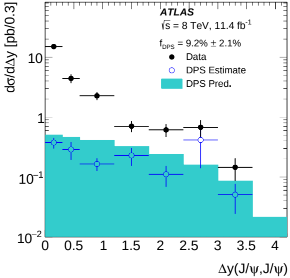
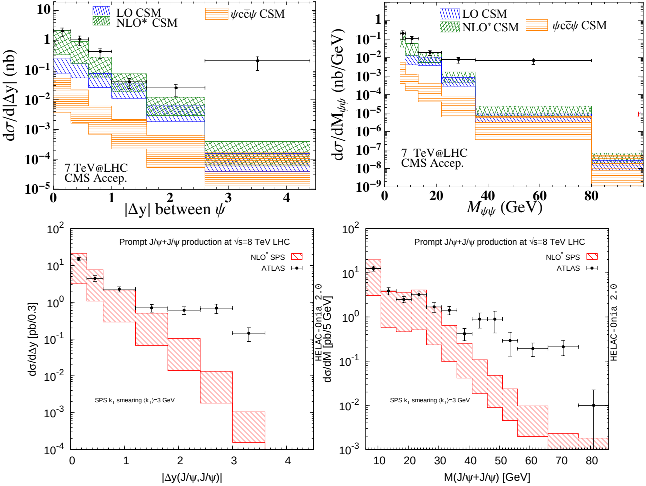




- DPS in LHCb data [kinematical distributions a priori under-control : independent scatterings]

A puzzle at large Δy (or $M_{\psi\psi}$) ?



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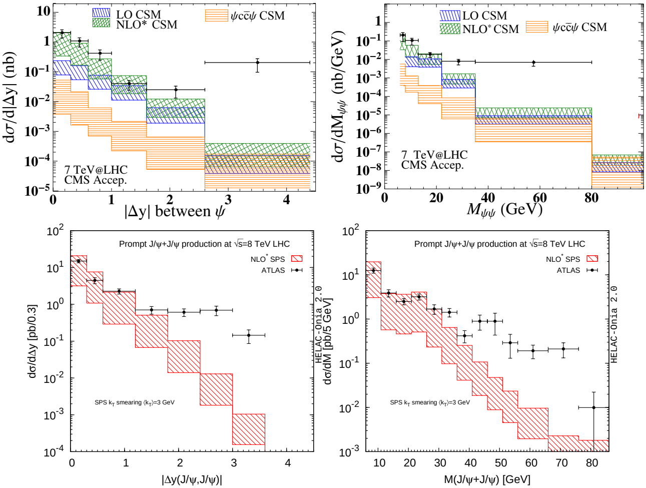

The most natural solution for this excess is the independent production of two J/ψ

→ **double parton scattering**

Predictions: excited states and more

JPL, H.-S.Shao PLB 751 (2015) 479; JPL JPL. arXiv:1903.09185 [hep-ph] (Phys. Rept. 2020, In Press)

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$F^{\psi'}_{\psi\psi}$	50%	15%	15%
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- Hence the importance of measuring $J/\psi + \psi'$ and $J/\psi + \chi_c$

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- We define $F^{\chi_c}_{\psi\psi}$ ($F^{\psi'}_{\psi\psi}$) as the fraction of events containing at least one χ_c (ψ')
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$$F^{\chi_c}_{\psi\psi} = F^{\chi_c}_{\psi} \times \left(F^{\chi_c}_{\psi} + 2F^{\rm direct}_{\psi} + 2F^{\psi'}_{\psi}\right), F^{\psi'}_{\psi\psi} = F^{\psi'}_{\psi} \times \left(F^{\psi'}_{\psi} + 2F^{\rm direct}_{\psi} + 2F^{\chi_c}_{\psi}\right), F^{\rm direct}_{\psi\psi} = \left(F^{\rm direct}_{\psi}\right)^2$$

- Under SPS CSM dominance,
  - $F^{\psi'}_{\psi\psi}$ is slightly enhanced by symmetry factors,
  - $F^{\chi_c}_{\psi\psi}$, unlike single quarkonium production, is not enhanced and is found to be small
- Overall :

	(CSM) SPS	Low P_T DPS	High P_T DPS
$F^{\psi'}_{\psi\psi}$	50%	15%	15%
$F^{\chi_c}_{\psi\psi}$	small	25%	50%

- Based on up-to-date feed-down values (J/ψ is 80% direct at low P_T) JPL. arXiv:1903.09185
- Hence the importance of measuring $J/\psi + \psi'$ and $J/\psi + \chi_c$
- $J/\psi + \eta_c$ can also tell something about DPS and about $\sigma_{\rm eff}$

Harvesting quarkonium data: 5 extractions using theory

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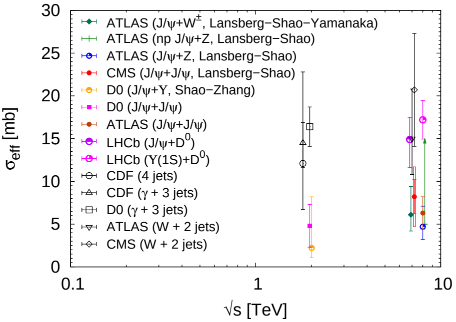

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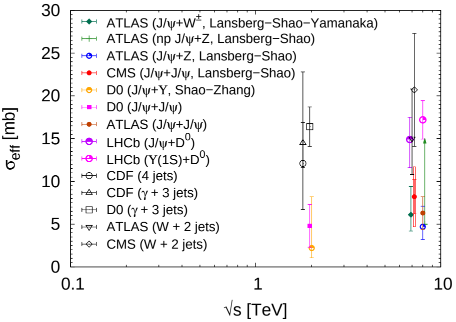

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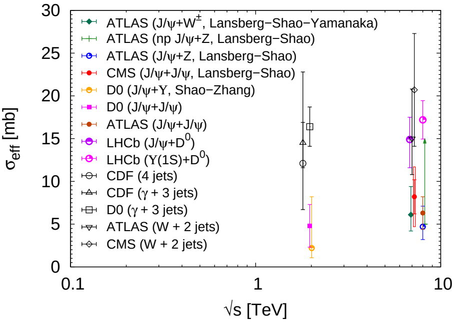

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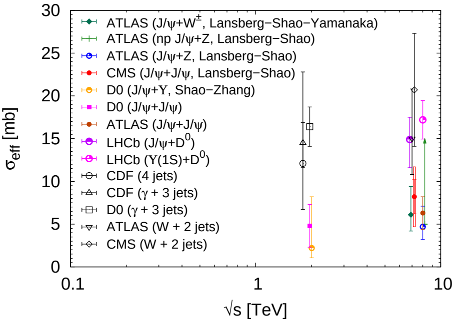

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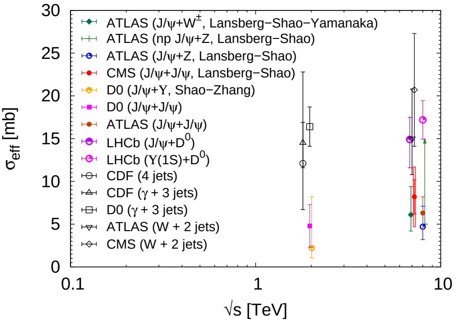

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D0 PRL 116 (2016) 082002 + H.S. Shao - Y. J. Zhang PRL 117 (2016) 062001

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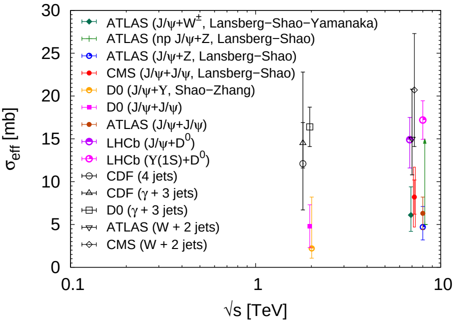

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D0 PRL 116 (2016) 082002 + H.S. Shao - Y. J. Zhang PRL 117 (2016) 062001

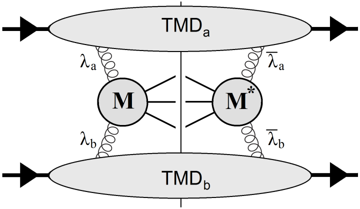
- Except for both LHCb extractions, all the quarkonium-based extraction point at very small $\sigma_{\rm eff}$ values: dependence on the flavour, the rapidity or the scale(s) ?

Part VI

Quarkonium-pair production at the LHC and gluon TMDs

gg fusion in arbitrary unpolarised process [colourless final state]

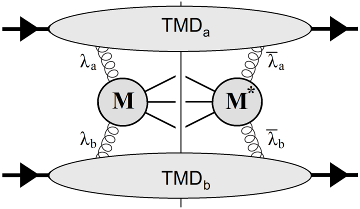
$d\sigma^{gg} \propto$



gg fusion in arbitrary unpolarised process [colourless final state]

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

$\Rightarrow$ helicity non-flip, azimuthally independent



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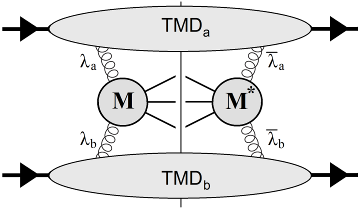
$\Rightarrow$ helicity non-flip, azimuthally independent

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

$\Rightarrow$ double helicity flip, azimuthally independent



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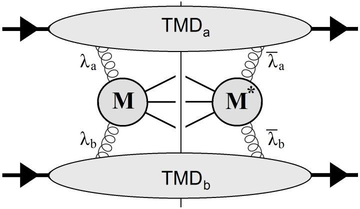
⇒ single helicity flip, $\cos(2\phi)$-modulation



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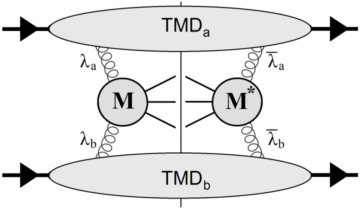
$\Rightarrow$ single helicity flip, $\cos(2\phi)$-modulation

$$+\overbrace{\left(\sum_{\lambda} \hat{\mathcal{M}}_{\lambda,-\lambda}\hat{\mathcal{M}}^*_{-\lambda,\lambda}\right)}^{F_4} \mathcal{C}[w_4 \times h_1^{\perp g} h_1^{\perp g}]$$

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



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

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

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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 $\langle k_T^2\rangle$
  by fitting $\mathcal{C}[f_1^g f_1^g]$ over the normalised LHCb $d\sigma/dP_{\psi\psi_T}$ spectrum at 13 TeV from which we have subtracted the DPS yield determined by LHCb

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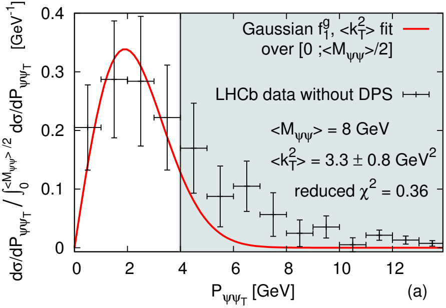

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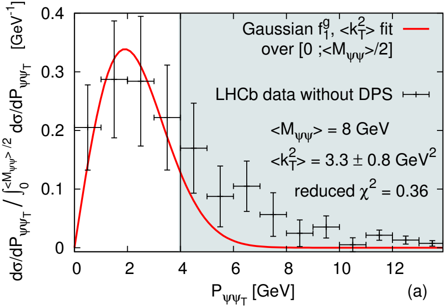

- Integration over $\phi \Rightarrow \cos(n\phi)$-terms cancel out
- $F_2 \ll F_1 \Rightarrow$ only $\mathcal{C}[f_1^g f_1^g]$ contributes to the cross-section
- No evolution so far: $\langle k_T^2\rangle \sim 3$ GeV^2 accounts both for non-perturbative and perturbative broadenings at a scale close to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

Switching on TMD evolution

F. Scarpa, D. Boer, M.G. Echevarria, JPL, C. Pisano, M. Schlegel, EPJC (2020) 80:87

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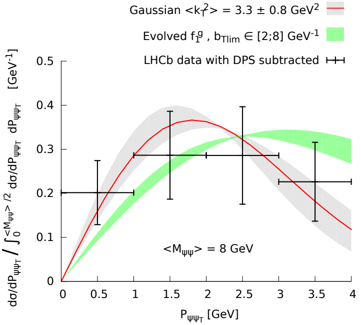

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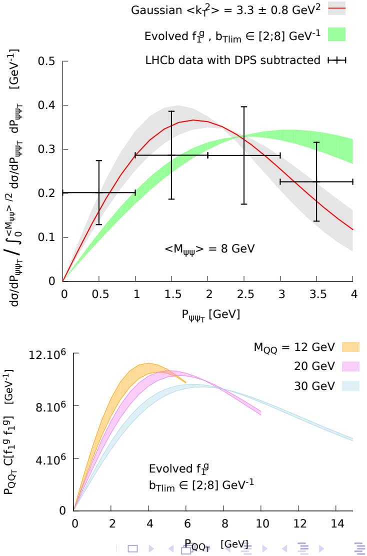

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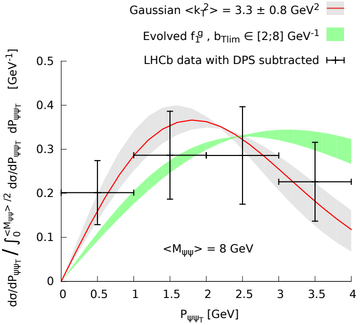
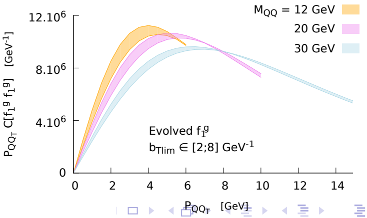
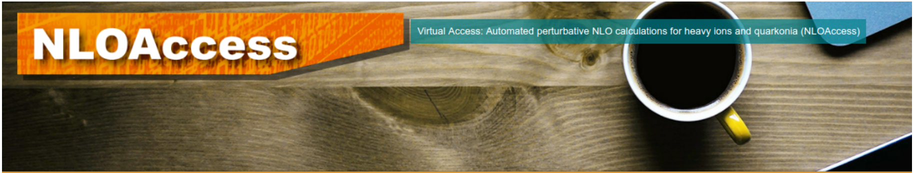
- Evolution effects are measurable
- So far, no x dependence information





LO predictions for quarkonia → NLOAccess [in2p3.fr/nloaccess]



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GENERAL DESCRIPTION

Objectives:

NLOAccess will give access to automated tools generating scientific codes allowing anyone to evaluate observables -such as production rates or kinematical properties – of scatterings involving hadrons. The automation and the versatility of these tools are such that these scatterings need not to be pre-coded. In other terms, it is possible that a random user may request for the first time the generation of a code to compute characteristics of a reaction which nobody thought of before. NLOAccess will allow the user to test the code and then to download to run it on its own computer. It essentially gives access to a dynamical library

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HELAC-Onia Web [in2p3.fr/nloaccess/HO]

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NLOAccess

Automated perturbative calculation with HELAC-Onia Web

Welcome to HELAC-Onia Web!

HELAC-Onia ia an automatic matrix element generator for the calculation of the heavy quarkonium helicity amplitudes in the framework of NRQCD factorization.
The program is able to calculate helicity amplitudes of multi P-wave quarkonium states production at hadron colliders and electron-positron colliders by including new P-wave off-shell currents. Besides the high efficiencies in computation of multi-leg processes within the Standard Model, HELAC-Onia is also sufficiently numerical stable in dealing with P-wave quarkonia and P-wave color-octet intermediate states.

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