New Observables in Quarkonium Production

Accessing double parton scatterings with associated-quarkonium production

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Part I

Introduction

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See JPL, arXiv:1903.09185 [hep-ph] 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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- However, as we will now see, these offer new ways to study DPS

Part II

New observables in quarkonium production

Associated-quarkonium production

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See section 3 of JPL, arXiv:1903.09185 [hep-ph]

Observables	Experiments	CSM	CEM	NRQCD	Interest
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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
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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
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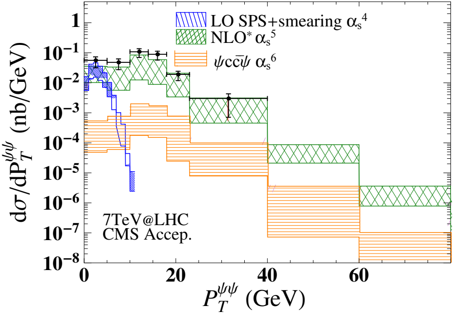

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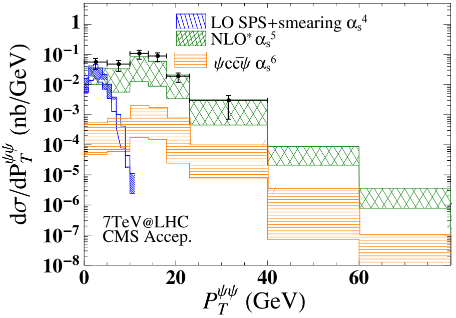

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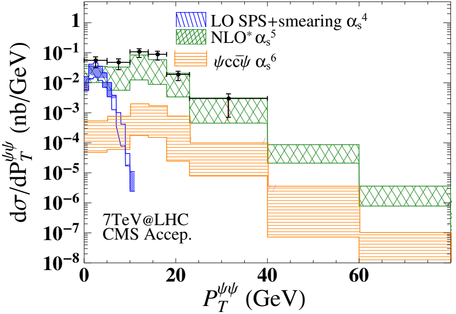

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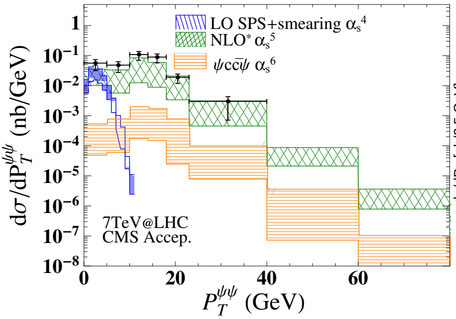

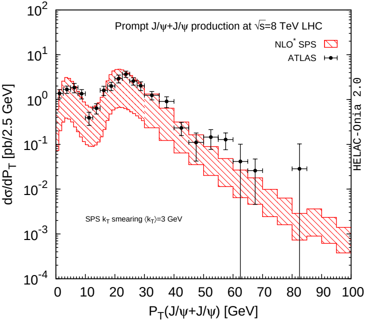

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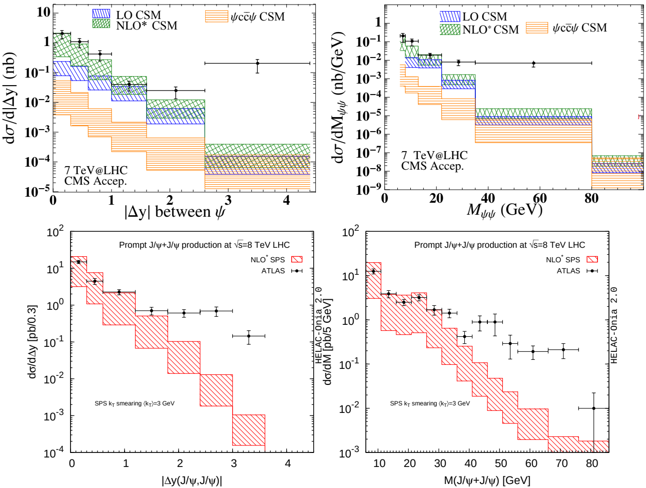

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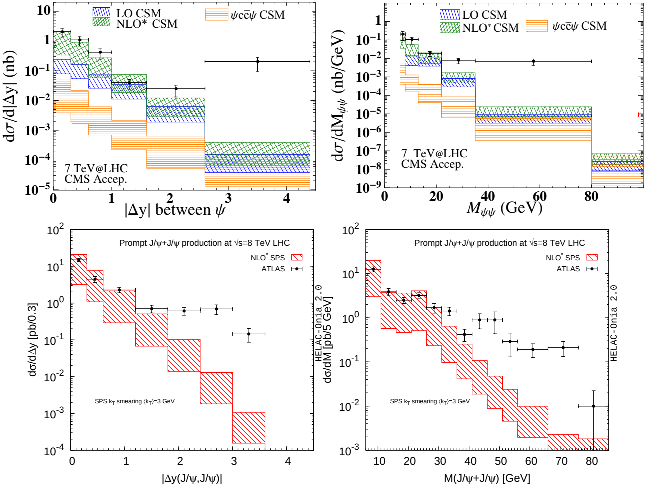

The most natural solution for this excess is the independent production of two J/ψ

→ double parton scattering

Double parton scatterings in double J/ψ production

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NB: Agreement not perfect with the ATLAS kinematical distributions
(yet bins at large $M_{\psi\psi}$ and Δy contain very few events)

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JPL, H.-S.Shao PLB 751 (2015) 479; JPL 1903.09185

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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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- $J/\psi + \eta_c$ can also tell something about DPS and about $\sigma_{\rm eff}$

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

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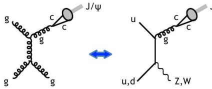

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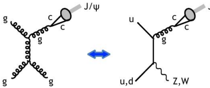

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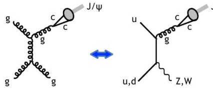

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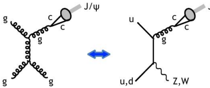

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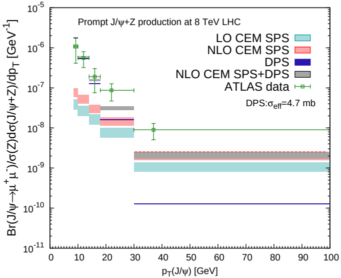

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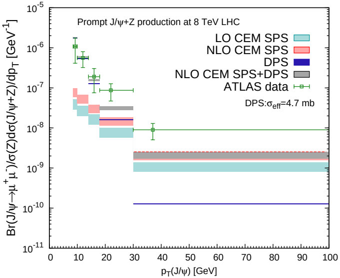

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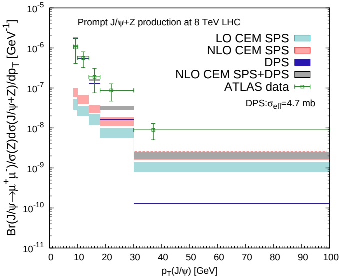

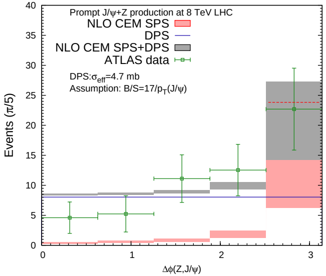

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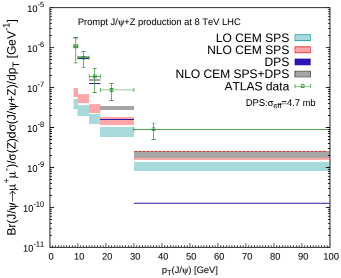

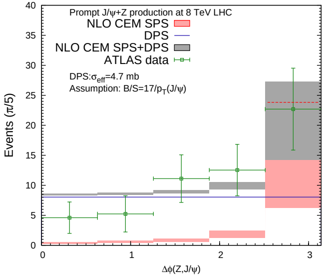

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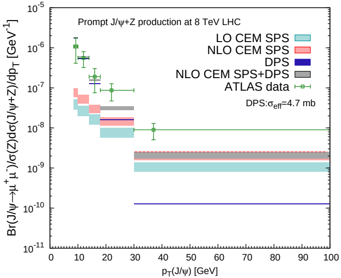

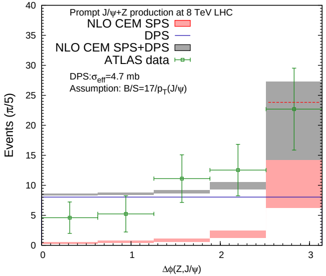

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- We are waiting for an ATLAS update to confirm our explanation

Our analysis of Z+non-prompt J/ψ at NLO and with DPS

JPL, H.S. Shao, Nucl.Phys. B916 (2017) 132

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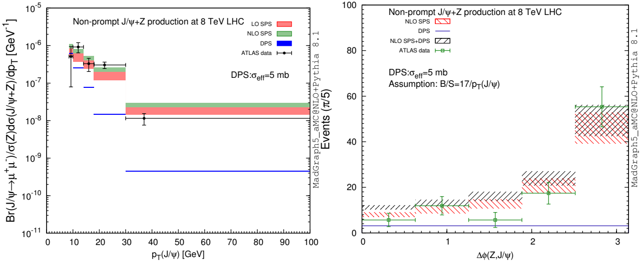

Differential cross section/distributions for non-prompt $J/\psi + Z$ production: p_T distribution of J/ψ (left) and azimuthal angle distribution (right)

- Good agreement. Owing to the data uncertainties at low P_T, we cannot constrain $\sigma_{\rm eff}$ more than with a lower limit, 5.0 mb, at 68 % CL.

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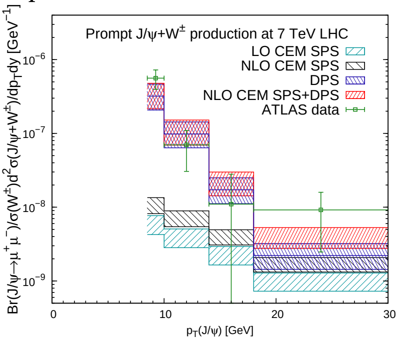

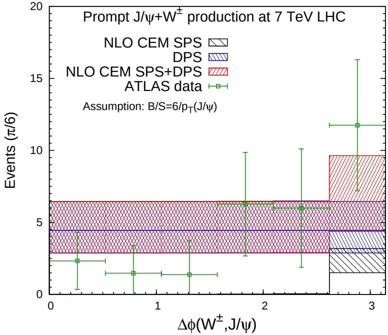

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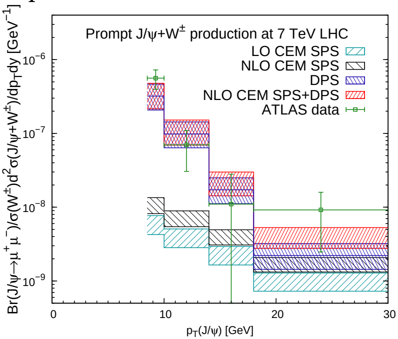

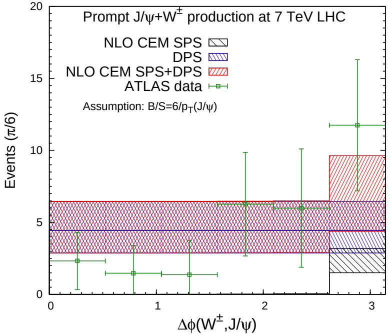

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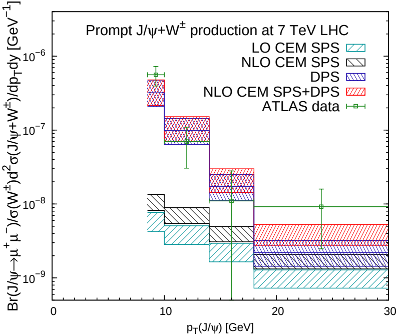

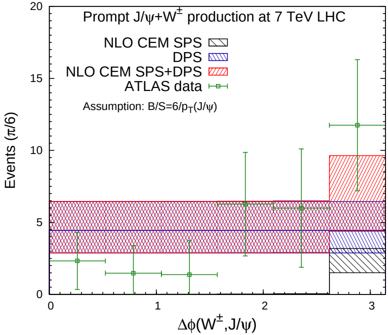

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CMS JHEP05(2017)013

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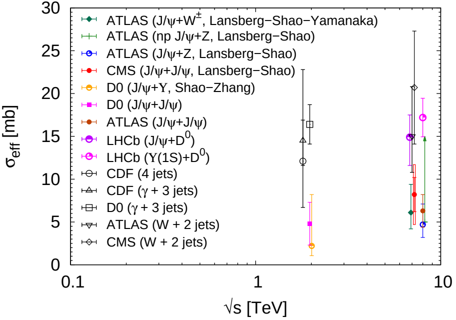

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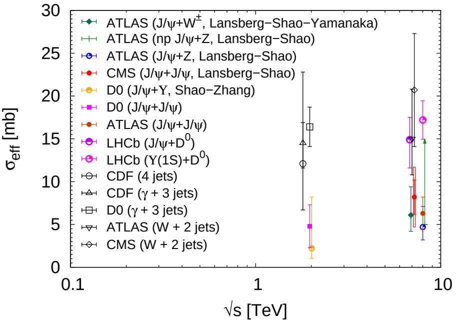

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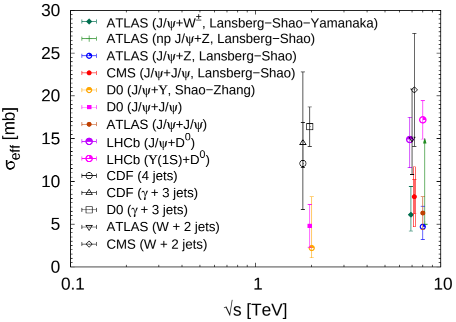

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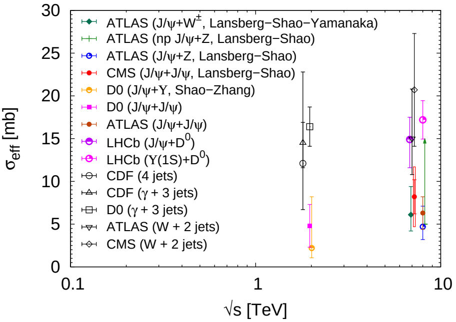

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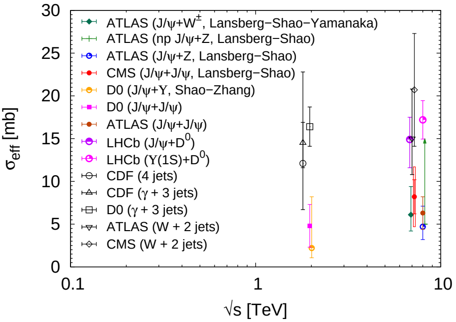

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D0 PRL 116 (2016) 082002 + H.S. Shao - Y. J. Zhang PRL 117 (2016) 062001

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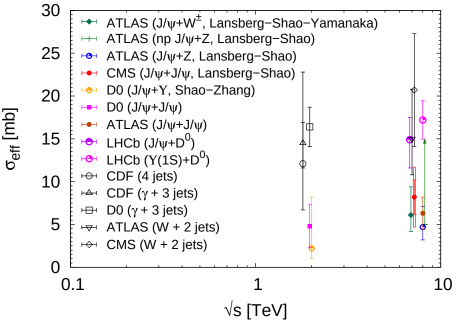

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- Except for both LHCb extractions, all the quarkonium-based extraction point at very small σ_{eff} values: dependence on the flavour, the rapidity or the scale(s) ?

Part III

Conclusion

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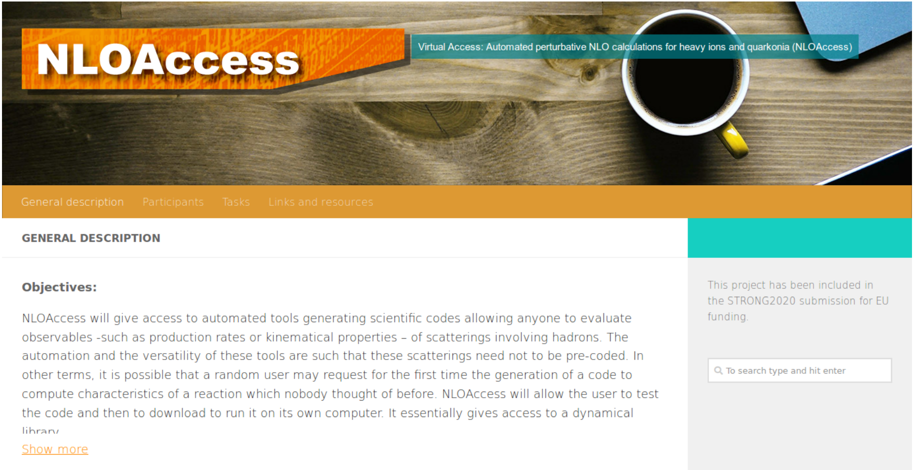
- They also start to tell us new information on the gluon Transverse Momentum Distribution distributions

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

NLOAccess [in2p3.fr/nloaccess]



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

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Automated perturbative NLO 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.

Already registered to the portal? Please login.

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Part IV

Backup

CEM vs. CSM vs. COM in a little more details

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3. COLOUR OCTET MECHANISM
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   - 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

QCD corrections to the COM – NRQCD

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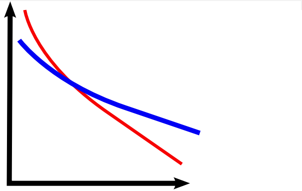

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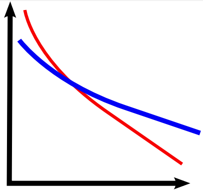

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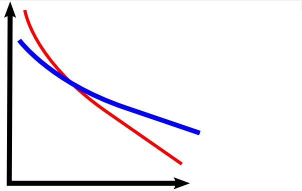
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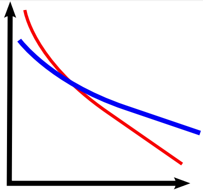

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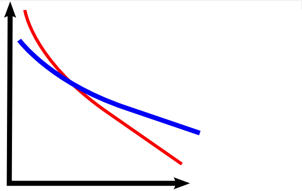

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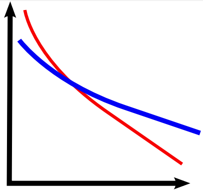

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- Polarisation: ${}^1S_0^{[8]}$: unpolarised; ${}^3S_1^{[8]}$ & ${}^3P_J^{[8]}$: transverse

QCD corrections to the CEM P_T dependence

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

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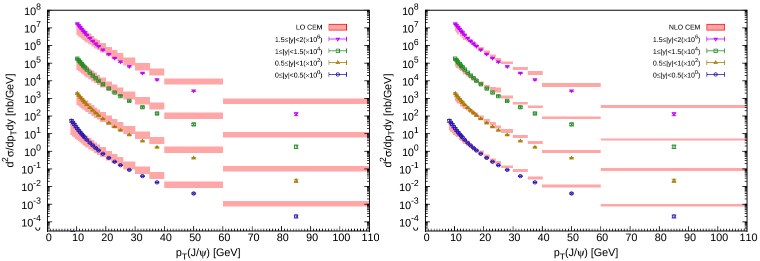
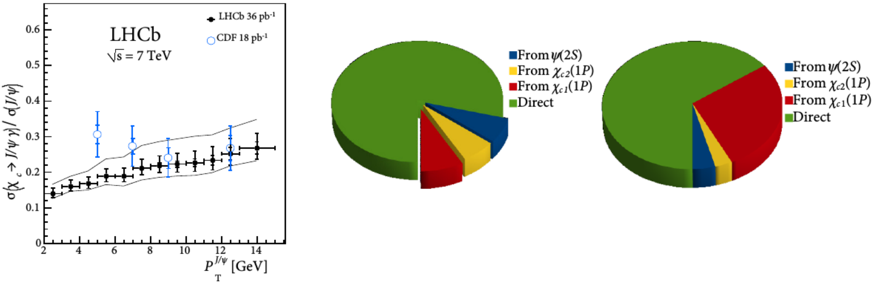


Feed downs from the excited states

JPL, arXiv:1903.09185 [hep-ph]



(a) (b) Low P_T J/ψ (c) High P_T J/ψ

Feed downs from the excited states

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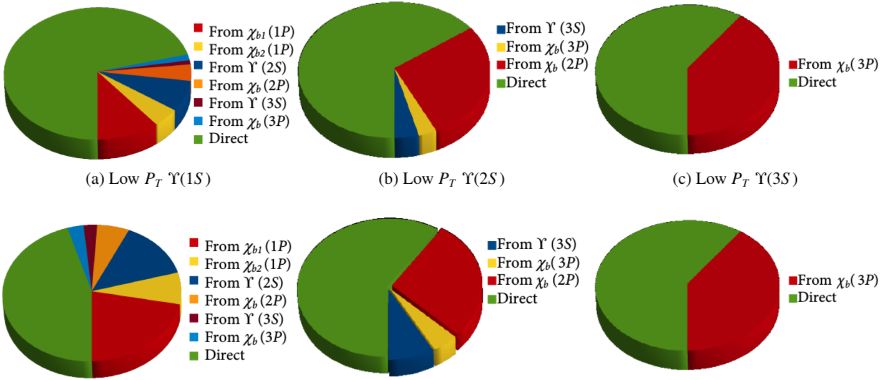

(a) Low P_T $\Upsilon(1S)$ (b) Low P_T $\Upsilon(2S)$ (c) Low P_T $\Upsilon(3S)$

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

QCD corrections to the CSM for Υ at colliders

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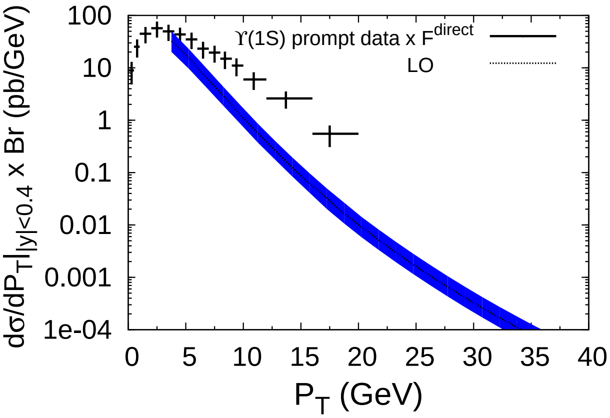
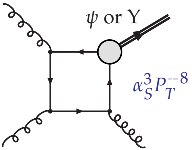
CDF PRL 88 (2002) 161802; LHCb EPJC 72 (2012) 2025





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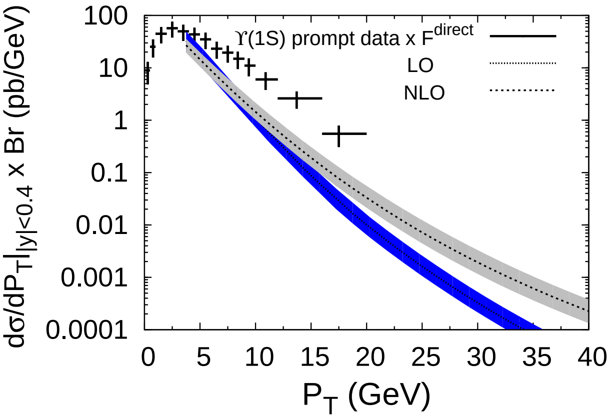

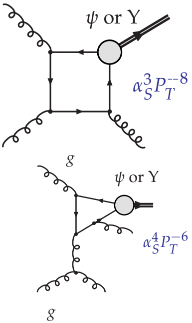

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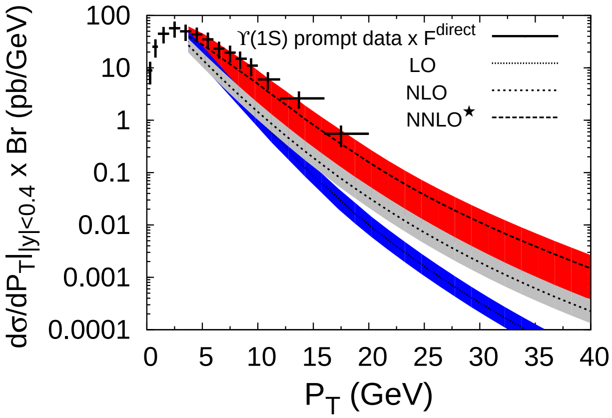

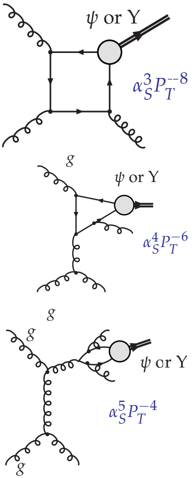

Attention: the NNLO⋆ is not a complete NNLO
See a recent study by H.S. Shao **JHEP 1901 (2019) 112**

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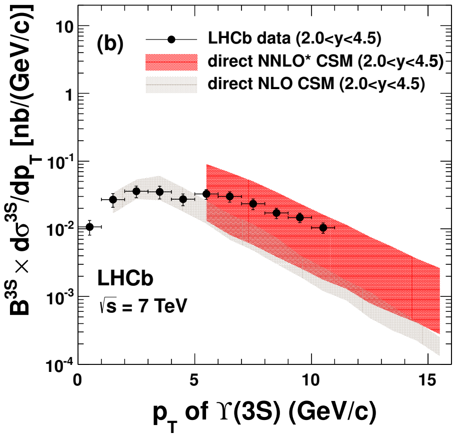

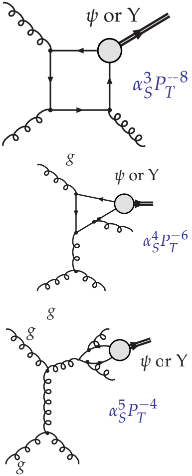

Υ(3S): 60 % direct; Υ(2S):60-70 % direct; Υ(1S): 50-70 % direct

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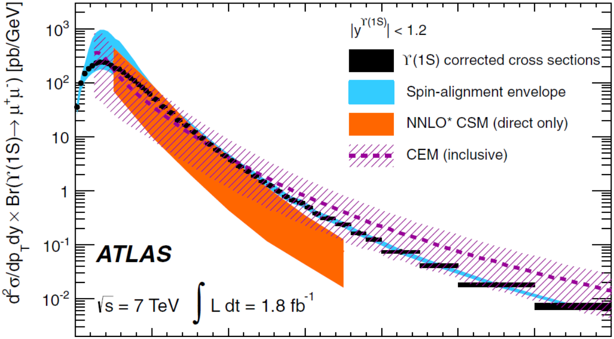
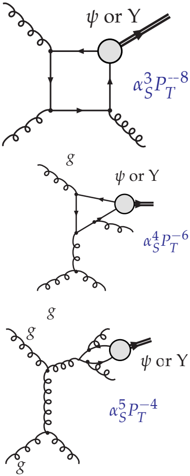
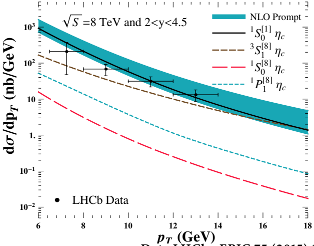




CSM theory curve extrapolated to prompt: × 2

The last piece in the puzzle: the η_c



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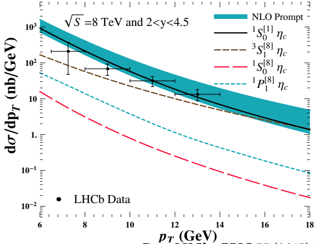

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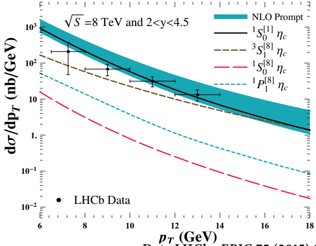

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  via Heavy-Quark Spin Symmetry : $\langle^{J/\psi}(^1S_0^{[8]})\rangle = \langle^{\eta_c}(^3S_1^{[8]})\rangle < 1.46 \times 10^{-2}\ \text{GeV}^3$

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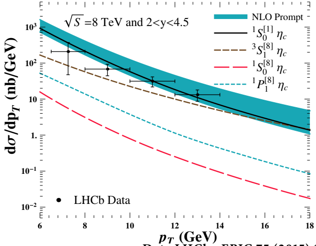

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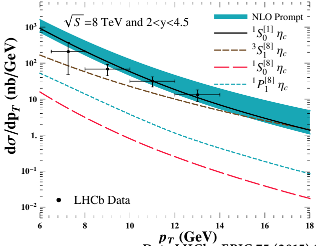

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- Nobody foresaw the impact of measuring η_c yields: 3 PRL published right after the LCHb data came out (Hamburg) M. Butenschoen *et al.* PRL 114 (2015) 092004; (PKU) H. Han *et al.* 114 (2015) 092005; (IHEP) H.F. Zhang *et al.* 114 (2015) 092006

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

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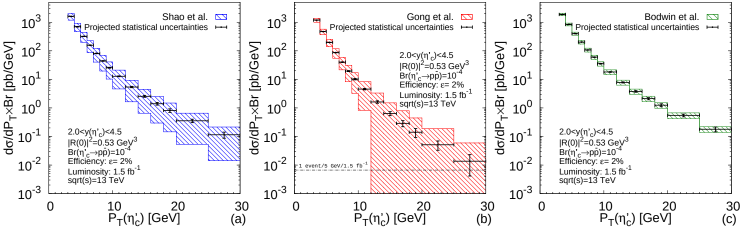

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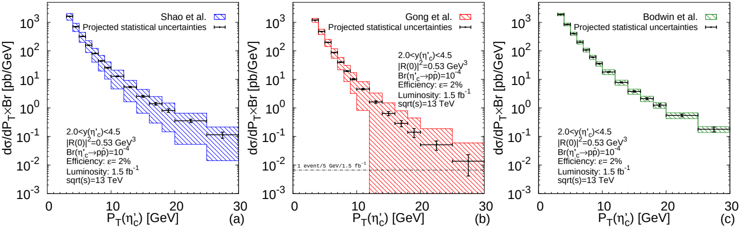

→ Belle-II data on the inclusive $\psi(2S)$ production will also be crucial

On the importance of understanding low-P_T production

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- If regeneration is at work, how does it happen ? statistically ? according to the charm-quark distribution in the charmonium (wave-function) ?
- etc ...

Why is it important to know how low-P_T quarkonia are produced

Also because, some very high P_T quarkonia which we study can be as rare as a few millionth of the produced quarkonia

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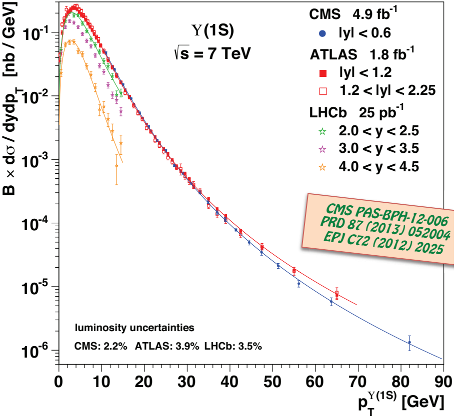

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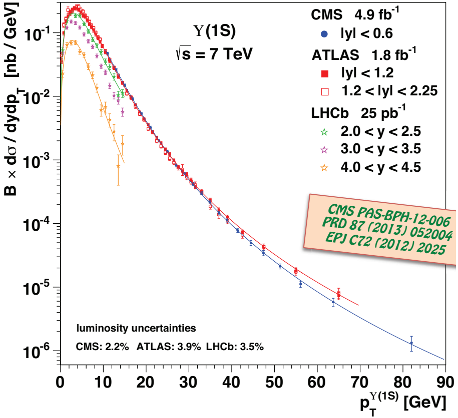

Most probably the production of a Υ with P_T = 90 GeV, even also 20 GeV, has very few things to do with the bulk of Υ

Comparison with the new LHCb data at 13 TeV

LHCb JHEP06(2017)047

$\sigma(\psi\psi)$nb	no P_T cut	$P_T > 1$ GeV	$P_T > 3$ GeV
NLO* CS	$15.4 \pm 2.2^{+51}_{-12}$	$14.8 \pm 1.7^{+53}_{-12}$	$6.8 \pm 0.6^{+22}_{-5}$
NLO CS	$11.9^{+4.6}_{-3.2}$	—	—
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- Large scale uncertainty for the NLO*, greatly reduced at NLO
- REMINDER: it is not an option to "switch off"/ignore the NLO CS contribution [parameter free]

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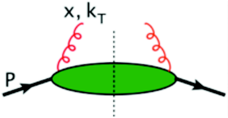
- REMINDER: it is not an option to "switch off"/ignore the NLO CS contribution [parameter free]
- Yet, room for DPS; however tension if $\sigma_{\rm eff} \simeq 7$ mb
- Tension between LHCb and other di-J/ψ extractions [rapidity effect ?]

Gluon TMDs in unpolarised protons



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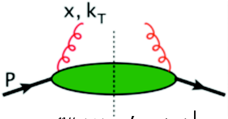
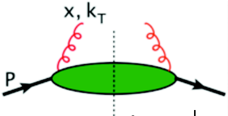


- Gauge-invariant definition:

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

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

Gluon TMDs in unpolarised protons



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

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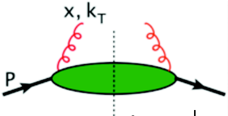

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- f_1^g: TMD distribution of unpolarised gluons
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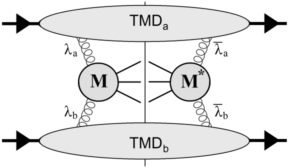
[Helicity-flip distribution]

gg fusion in arbitrary unpolarised process [colourless final state]

$d\sigma^{gg} \propto$



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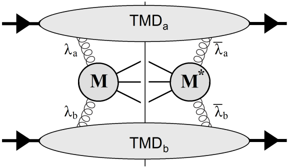
$$d\sigma^{gg} \propto \overbrace{\left(\sum_{\lambda_a,\lambda_b} \hat{\mathcal{M}}_{\lambda_a,\lambda_b} \hat{\mathcal{M}}^*_{\lambda_a,\lambda_b}\right)}^{F_1} \mathcal{C}[f_1^g f_1^g]$$

$\Rightarrow$ helicity non-flip, azimuthally independent



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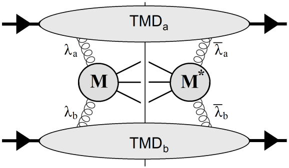

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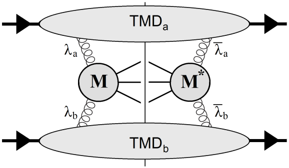

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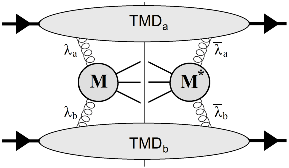

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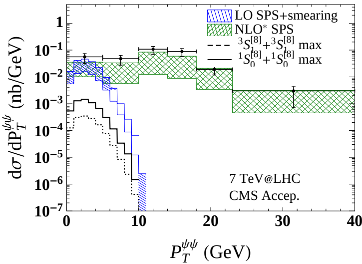

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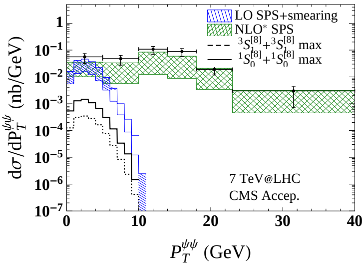

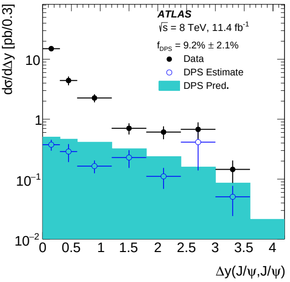

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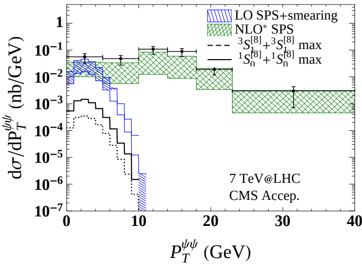

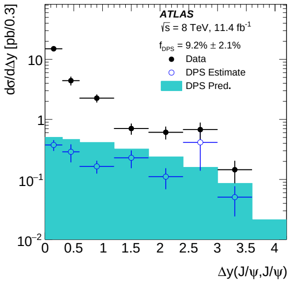

- DPS in LHCb data [kinematical distributions well controlled : independent scatterings]

What's special about double vector onium production ?

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

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

$\Rightarrow$ 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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- 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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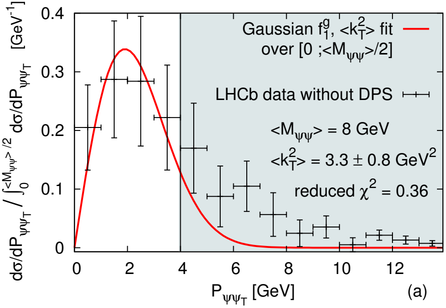

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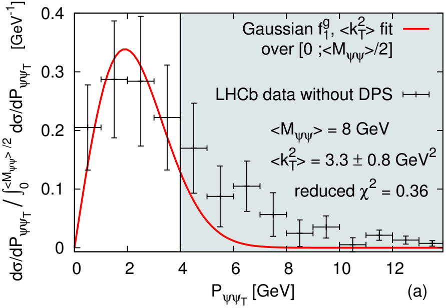

- Integration over $\phi \Rightarrow \cos(n\phi)$-terms cancel out
- $F_2 \ll F_1 \Rightarrow$ only $\mathcal{C}[f_1^g f_1^g]$ contributes to the cross-section
- No evolution so far: $\langle k_T^2\rangle \sim 3$ GeV^2 accounts both for non-perturbative and perturbative broadenings at a scale close to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

Expected azimuthal asymmetries

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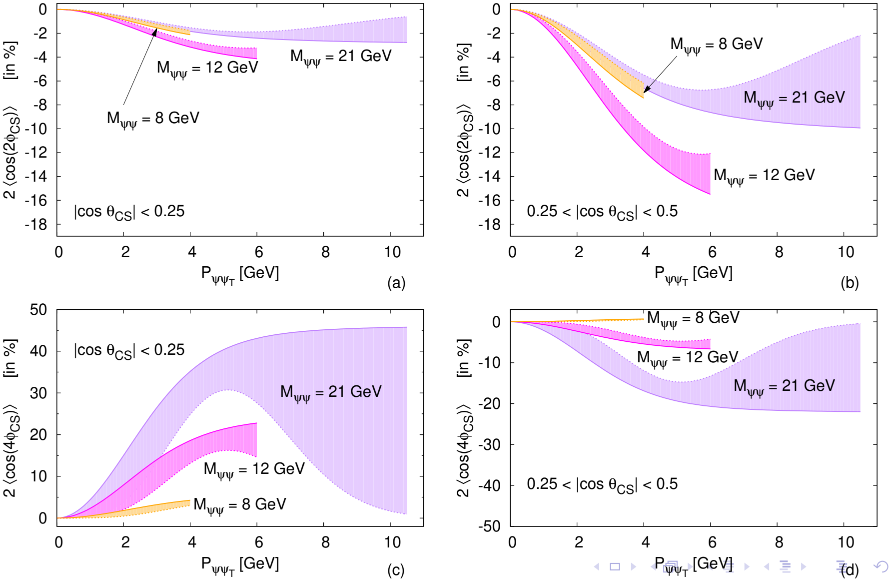

Basic pQCD approach: the Colour Singlet Model (CSM)

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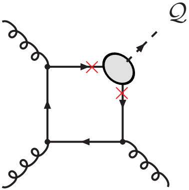

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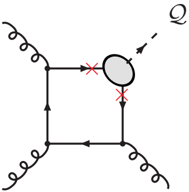

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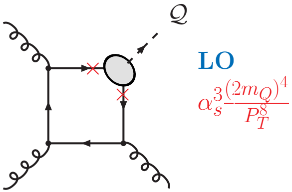

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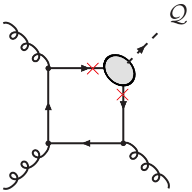

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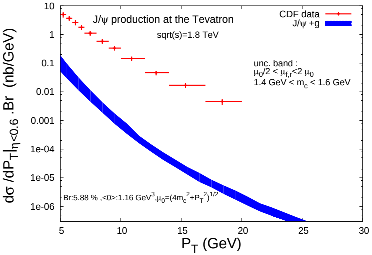

CDF, PRL 79:572 & 578,1997

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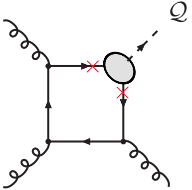

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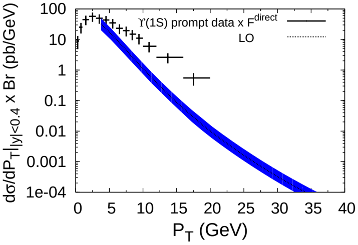

CDF, PRL 88:161802,2002

Basic pQCD approach: the Colour Singlet Model (CSM)

C.-H. Chang, NPB172, 425 (1980); R. Baier & R. Rückl Z. Phys. C 19, 251(1983);

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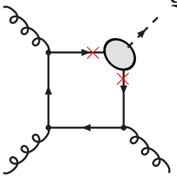

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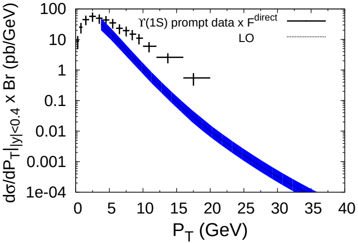

- Large QCD corrections from new topologies reduce the gap with data at mid and large P_T

P.Artoisenet, J.Campbell, JPL, F.Maltoni, F. Tramontano, PRL 101, 152001 (2008

The LO CSM accounts for the P_T-integrated yield

S. J. Brodsky and JPL, PRD 81 051502 (R), 2010; JPL, PoS(ICHEP 2010), 206 (2010); NPA 910-911 (2013) 470

→ The yield vs. $\sqrt{s}$, y

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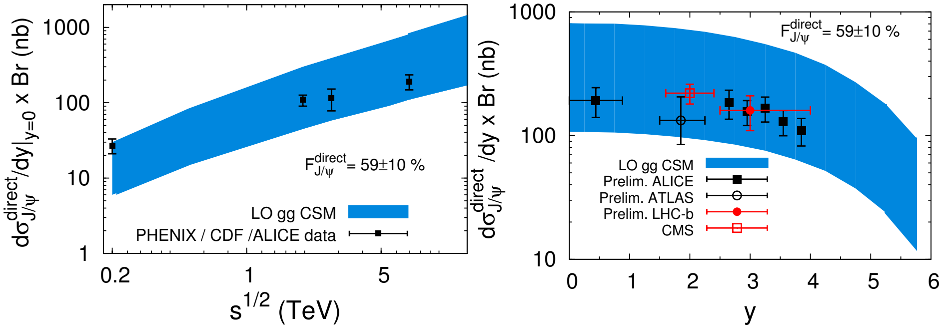

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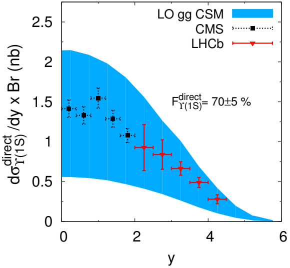

CMS PRD 83 (2011) 112004; LHCb EPJC 72 (2012) 2025

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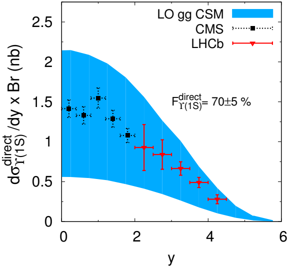

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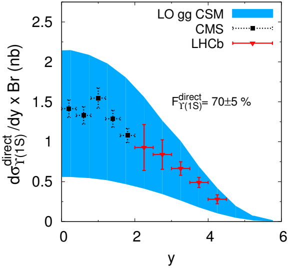

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- Earlier claims that CSM contribution to $d\sigma/dy$ was small were based on the incorrect assumption that χ_c feed-down was dominant

NLO CSM at RHIC

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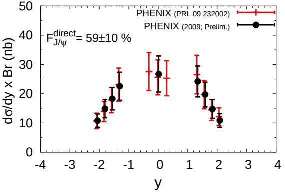
→ J/ψ



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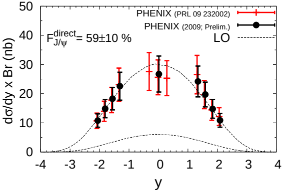

LO: $gg \to J/\psi g$

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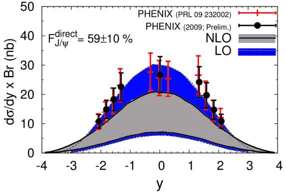

NLO: $gg \to J/\psi gg$, $gq \to J/\psi gq$, ...

using the matrix elements from J.Campbell, F. Maltoni, F. Tramontano, PRL 98:252002,2007

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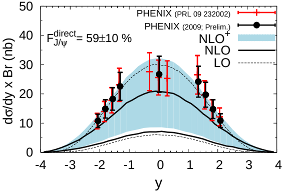

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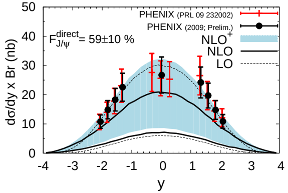

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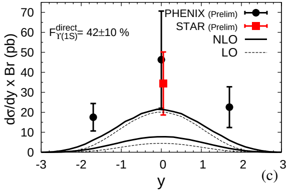

* Sorry: I should update these plots (updated data and fraction is about 60 %)

NLO CSM at RHIC

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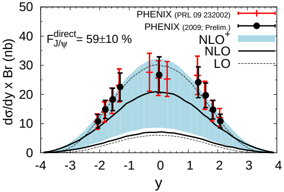
→ J/ψ



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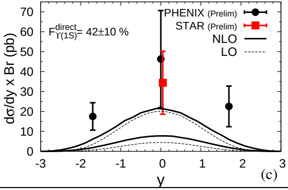
→ $\Upsilon^\star$



A priori, good convergence NLO w.r.t. LO

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NLO NRQCD up to RHIC

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- At α_S^3, one has in addition real emissions (including **one CS process**)

$$g + g \rightarrow Q\bar{Q}[{}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_{J=0,2}^{[8]}] + g, \; g + q(\bar{q}) \rightarrow Q\bar{Q}[{}^1S_8^{[0]}, {}^3S_1^{[8]}, {}^3P_{J=0,2}^{[8]}] + q(\bar{q})$$

$$q + \bar{q} \rightarrow Q\overline{Q}[{}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_{J=0,1,2}^{[8]}] + g \text{ and } \mathbf{g + g \rightarrow Q\overline{Q}[{}^3S_1^{[1]}] + g}$$

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- Done with NRQCD LDMEs fitted **at LO** on P_T spectra from CDF ($\simeq$ 2 TeV)

Table 1
Reference NRQCD matrix elements for charmonium production. The color-singlet matrix elements are taken from the potential model calculation of [14, 15]. The color-octet matrix elements have been extracted from the CDF data [16] in Ref. [17]

H	$\langle \mathcal{O}_1^H \rangle$	$\langle \mathcal{O}_8^H[^3S_1] \rangle$	$\langle \mathcal{O}_8^H[^1S_0^{(8)}] \rangle = \langle \mathcal{O}_8[^3P_0^{(8)}] \rangle / m_c^2$
J/ψ	1.16 GeV^3	1.19×10^{-2} GeV^3	1.0×10^{-2} GeV^3
$\psi(2S)$	0.76 GeV^3	0.50×10^{-2} GeV^3	0.42×10^{-2} GeV^3
χ_{c0}	0.11 GeV	0.31×10^{-2} GeV^3	–

NLO NRQCD up to RHIC II

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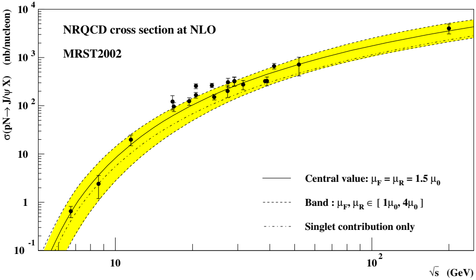

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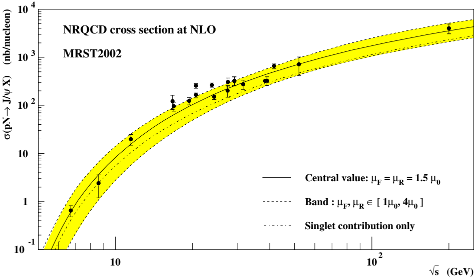

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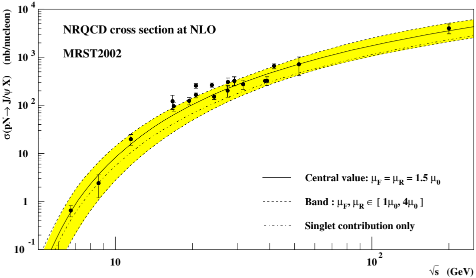

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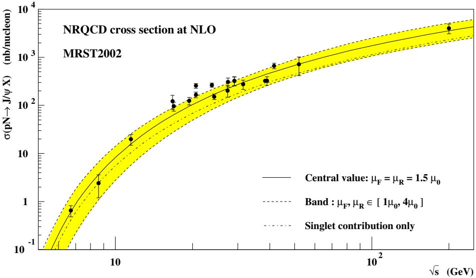

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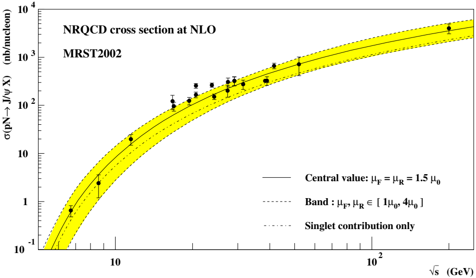

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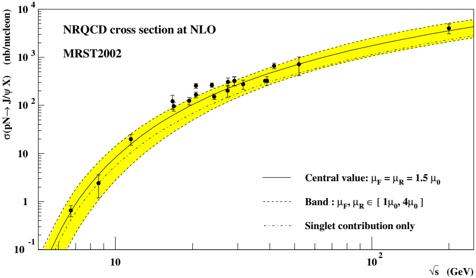

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  - LHC data
- constant feed-down (FD) fractions
  - $F^{\text{direct}}_{J/\psi} = 60 \pm 10\%$
  - $F^{\text{direct}}_{\Upsilon(1S)} = 66 \pm 10\%$
  - $F^{\text{direct}}_{\Upsilon(1S+2S+3S)} = 60 \pm 10\%$
  - Uncertainty on F^{direct} combined in quadrature with that of data

Arguable but accounts for a possible energy dependence of the FD fraction

What we did II

We used LDMEs fitted at NLO/one loop on the P_T spectra

- J/ψ

Ref.	$\langle \mathcal{O}_{J/\psi}(^3P_0^{[8]}) \rangle$ (in GeV^5)	$\langle \mathcal{O}_{J/\psi}(^1S_0^{[8]}) \rangle$ (in GeV^3)	$\langle \mathcal{O}_{J/\psi}(^3S_1^{[8]}) \rangle$ (in GeV^3)
Y.-Q. Ma,*et al.* PRL 106 (2011) 042002.	-2.0×10^{-3}	7.8×10^{-2}	0
	2.1×10^{-2}	3.5×10^{-2}	5.8×10^{-3}
	4.1×10^{-2}	0	1.1×10^{-2}
B. Gong,*et al.* PRL 110 (2013) 042002	-2.2×10^{-2}	9.7×10^{-2}	-4.6×10^{-3}
M.Butenschoen, B.Kniehl. PRD (2011) 051501	-9.1×10^{-2}	3.0×10^{-2}	1.7×10^{-3}

- ψ'

Ref.	$\langle \mathcal{O}_{\psi(2S)}(^3P_0^{[8]}) \rangle$ (in GeV^5)	$\langle \mathcal{O}_{\psi(2S)}(^1S_0^{[8]}) \rangle$ (in GeV^3)	$\langle \mathcal{O}_{\psi(2S)}(^3S_1^{[8]}) \rangle$ (in GeV^3)
B. Gong,*et al.* PRL 110 (2013) 042002	9.5×10^{-3}	-1.2×10^{-4}	3.4×10^{-3}
Y.-Q. Ma,*et al.* PRL 106 (2011) 042002	-4.8×10^{-3}	2.9×10^{-2}	0
	7.9×10^{-3}	5.6×10^{-3}	3.2×10^{-3}
	1.1×10^{-2}	0	3.9×10^{-3}

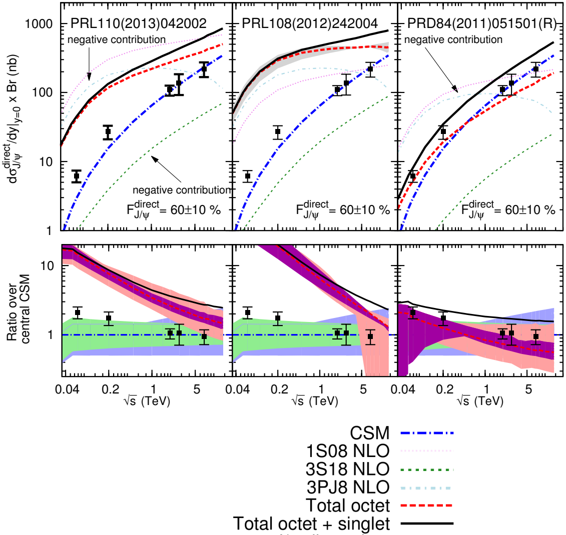
- $\Upsilon(1S)$

Ref.	$\langle \mathcal{O}_{\Upsilon(1S)}(^3P_0^{[8]}) \rangle$ (in GeV^5)	$\langle \mathcal{O}_{\Upsilon(1S)}(^1S_0^{[8]}) \rangle$ (in GeV^3)	$\langle \mathcal{O}_{\Upsilon(1S)}(^3S_1^{[8]}) \rangle$ (in GeV^3)
B. Gong, *et al.* PRL 112 (2014) 3, 032001.	-10.36×10^{-2}	11.15×10^{-2}	-4.1×10^{-2}

[We have also added the fit of G.T. Bodwin, *et al.*, PRL 113, 022001 (2014) even though it is based on a fragmentation function approach]

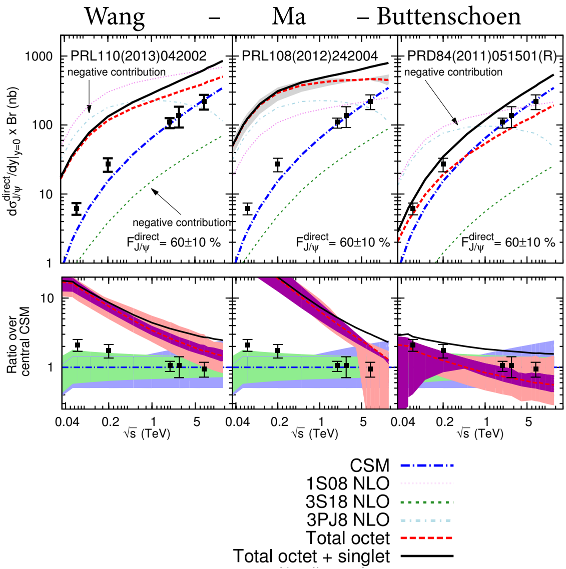
Results for the J/ψ

Wang – Ma – Buttenschoen



Results for the J/ψ

- First 2 fits: 10 times above the data around 200 GeV – as Maltoni *et al.*



Results for the J/ψ

- First 2 fits: 10 times above the data around 200 GeV – as Maltoni *et al.*
- The third fit –which btw has the lowest P_T^{min}– overshoots the least
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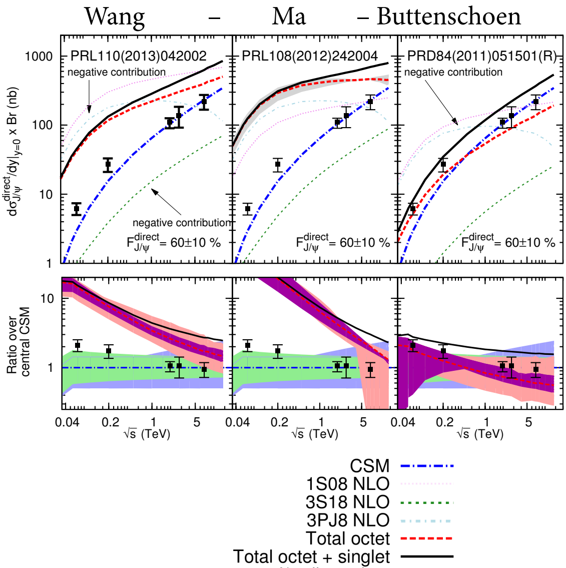

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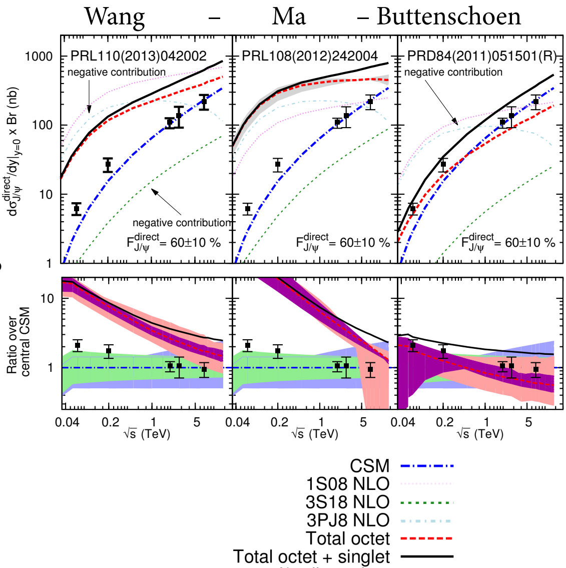

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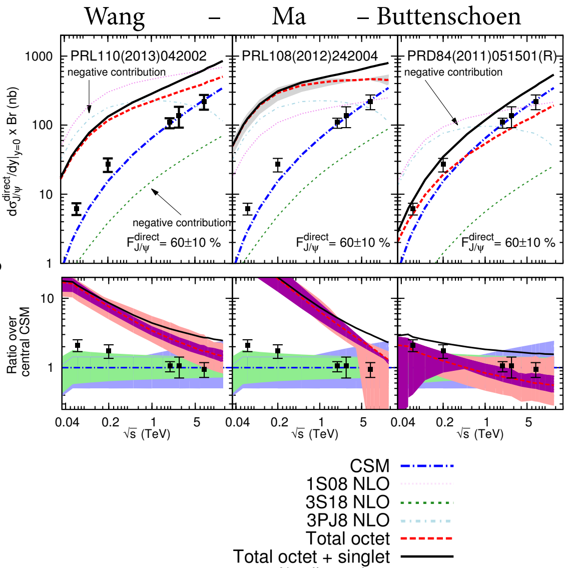

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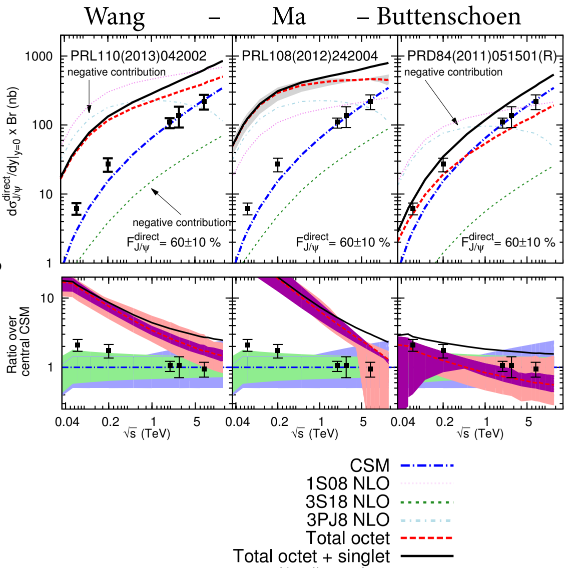

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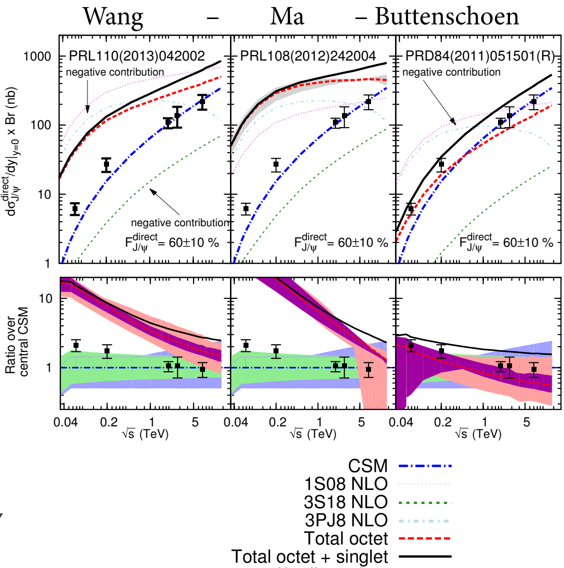
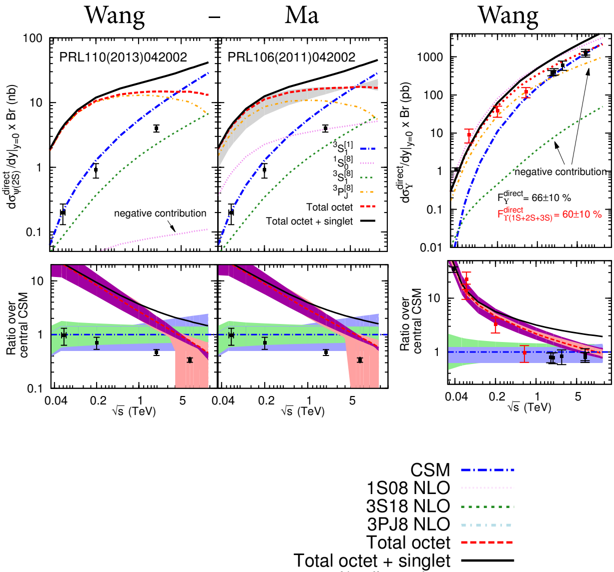
- Taken at face value, these results show a clear violation of NRQCD universality
- Not a surprise since the CSM alone accounts well for the data; adding any contribution creates a "surplus"



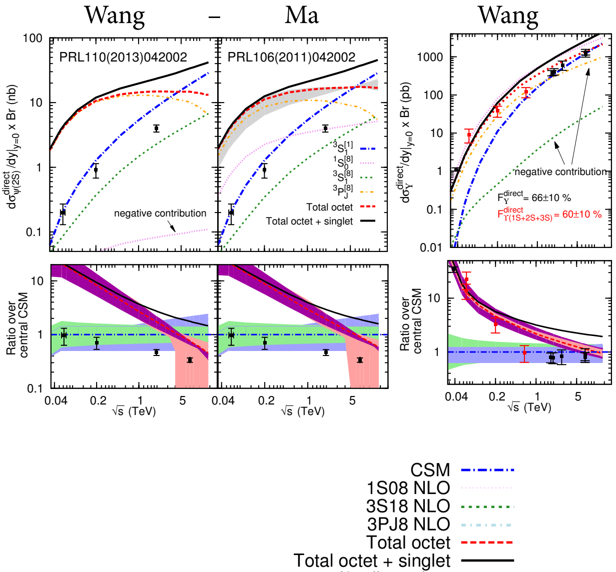
Results for the ψ' and Υ



Results for the ψ' and Υ

For $\psi(2S)$

- Worse than for J/ψ
- CSM even tends to overshoot at large $\sqrt{s}$ – yet in agreement within uncertainties (lower panel)
- CO dominated by the ${}^3P_J^{[8]}$ channel which nearly shows an unphysical behavior



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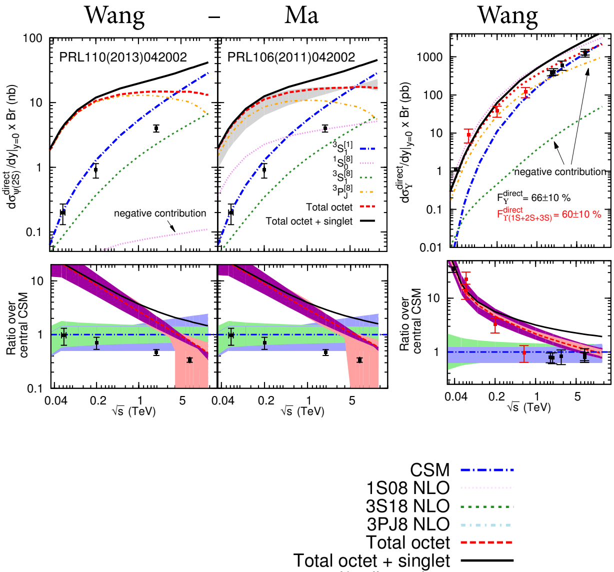
For $\Upsilon(1S)$

- Reasonnable trend for Υ
- CSM is doing a perfect job in the TeV range – note that the RHIC points moved down
- On the other hand, CO needed at low $\sqrt{s}$? High x gluon pdf underestimated ?



A glimmer of hope: Low P_T χ_{Q1}/χ_{Q2}

LHCb, JHEP 10(2013)115 & JHEP 1410 (2014) 88 ; CMS, EPJC, 72, 2257 (2012); ATLAS, JHEP 07(2014)154

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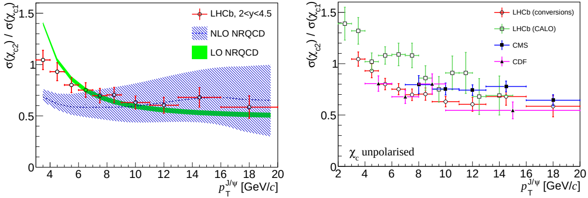

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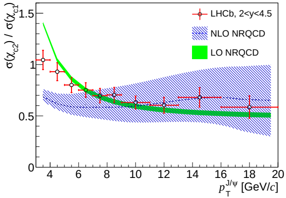
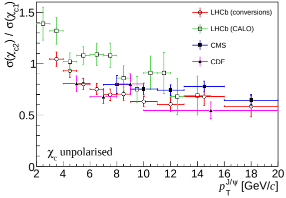
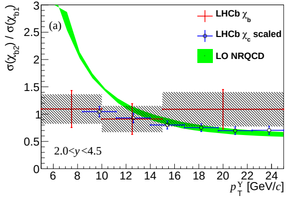
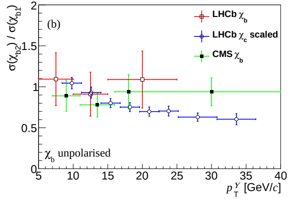




χ_b





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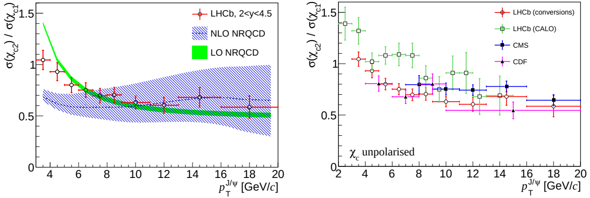
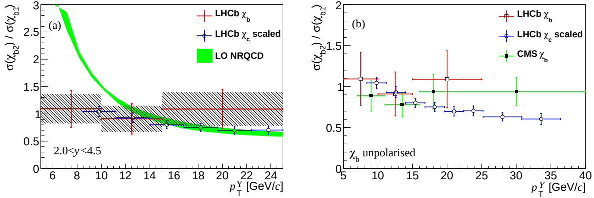


χ_b



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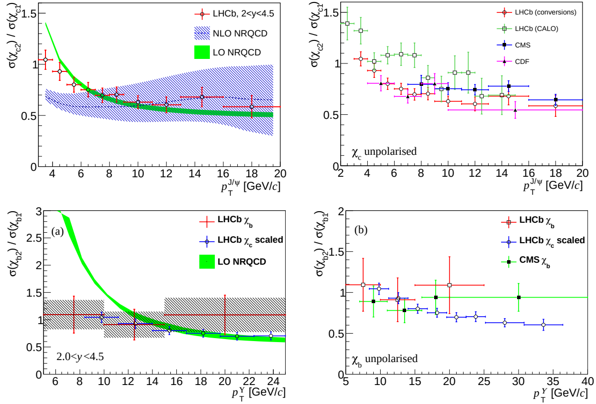
χ_b



- The Landau-Yang suppression shows up for χ_c in the Low P_T/m_Q region
- The nature (quantum #) of the produced final state seems still relevant !

Basics of the Colour Evaporation Model

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- Based on Quark-Hadron duality argument, one writes

H. Fritzsch, PLB 67 (1977) 217; F. Halzen, PLB 69 (1977) 105

$$\sigma_{\mathcal{Q}}^{\text{(N)LO, direct}} = F_{\mathcal{Q}}^{\text{direct}} \int_{2m_Q}^{2m_H} \frac{d\sigma_{Q\bar{Q}}^{\text{(N)LO}}}{dm_{Q\bar{Q}}} dm_{Q\bar{Q}}$$

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- It can easily be check by MCFM at NLO for instance `http://mcfm.fnal.gov/`

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$$\begin{aligned}
\langle \mathcal{O}_{^3S_1}(^3S_1^{[1]})\rangle &= 3 \times \langle \mathcal{O}_{^3S_1}(^1S_0^{[1]})\rangle, \\
\langle \mathcal{O}_{^3S_1}(^1S_0^{[8]})\rangle &= \frac{4}{3} \times \langle \mathcal{O}_{^3S_1}(^1S_0^{[1]})\rangle, \\
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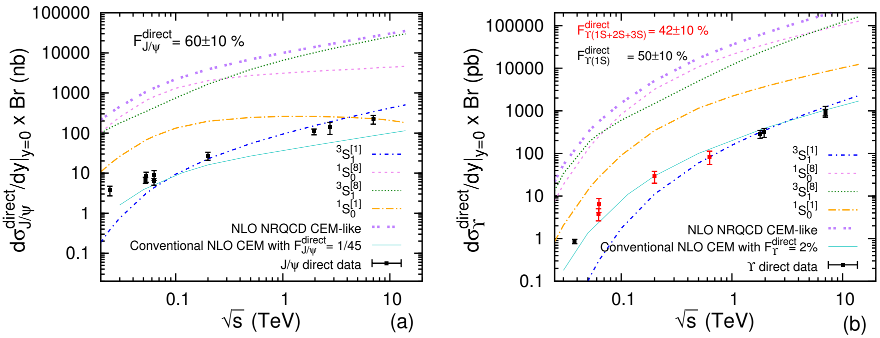
- If, as it should be in NRQCD, $\langle \mathcal{O}_{^3S_1}(^3S_1^{[1]})\rangle$ is the usual CS LDME, *i.e.* $\frac{2N_C}{4\pi}(2J+1)\,|R(0)|^2$, everything is fixed

CEM results



100000
10000
1000
100
10
1
0.1
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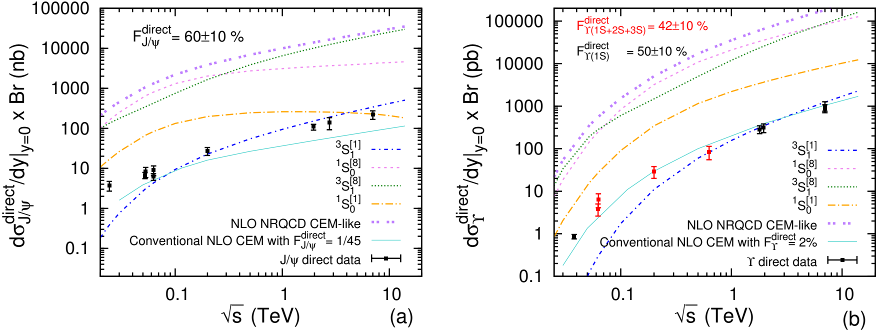
$d\sigma^{direct}_{J/\psi}/dy|_{y=0}$ x Br (nb)
$^3S_1^{[1]}$
$^1S_0^{[8]}$
$^3S_1^{[8]}$
$^1S_0^{[1]}$
NLO NRQCD CEM-like
Conventional NLO CEM with $F^{direct}_{J/\psi}$ = 1/45
J/ψ direct data
0.1
1
10
$\sqrt{s}$ (TeV)
(a)
100000
10000
1000
100
10
1
0.1
$F^{direct}_{\Upsilon(1S+2S+3S)}$ = 42±10 %
$F^{direct}_{\Upsilon(1S)}$ = 50±10 %
$d\sigma^{direct}_{\Upsilon}/dy|_{y=0}$ x Br (pb)
$^3S_1^{[1]}$
$^1S_0^{[8]}$
$^3S_1^{[8]}$
$^1S_0^{[1]}$
NLO NRQCD CEM-like
Conventional NLO CEM with F^{direct}_{Υ} = 2%
Υ direct data
0.1
1
10
$\sqrt{s}$ (TeV)
(b)

CEM results



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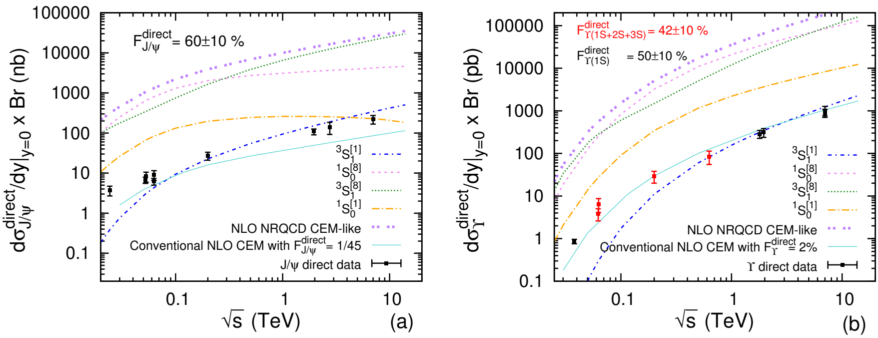

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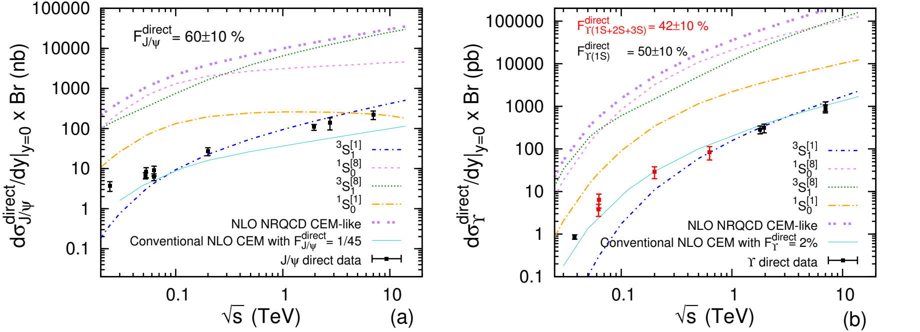

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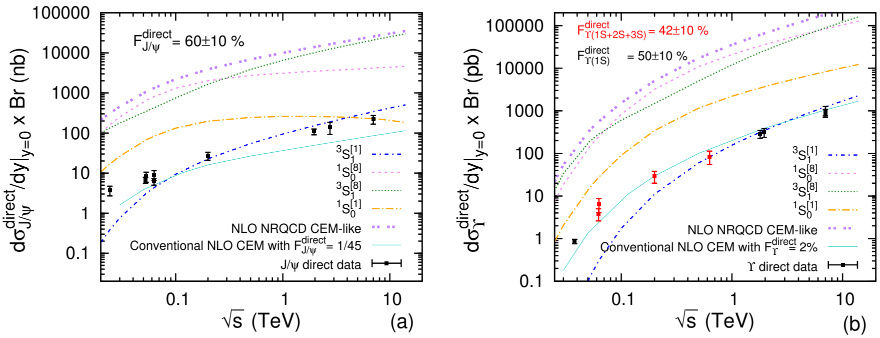

- NRQCD-like CEM badly overshoots the data
  - Expected since CO LDMEs are as large as the CS, whereas the hard parts tend to be larger.
  - Weird energy behaviour
- Conventional CEM does a pretty good job
  - No th. uncertainty shown
  - "Natural" value of $F^{direct}_{J/\psi}$ is ok