New Observables in Quarkonium Production at Proton Colliders

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Part I

Introduction

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

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

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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

Part II

Impact of the QCD corrections to the these models

QCD corrections to the CSM for Υ at colliders

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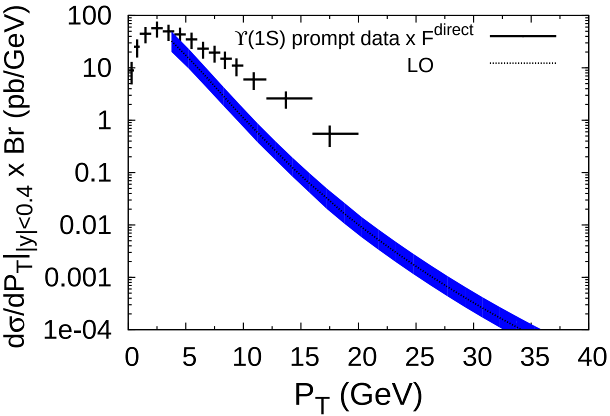

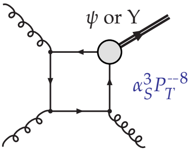

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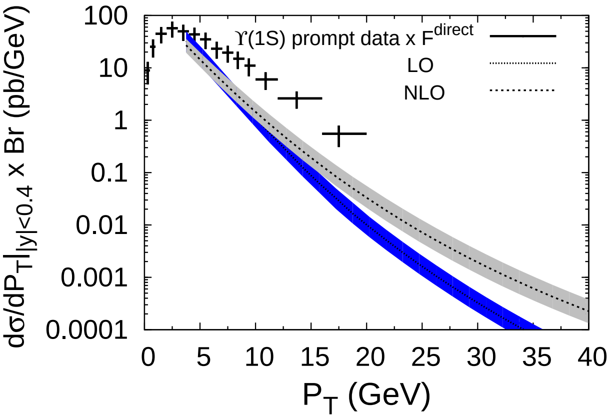

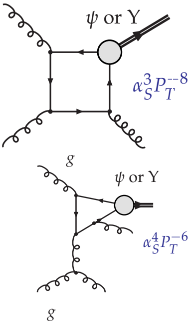

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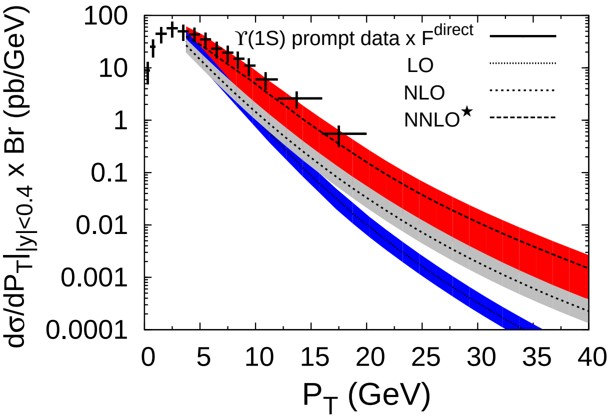

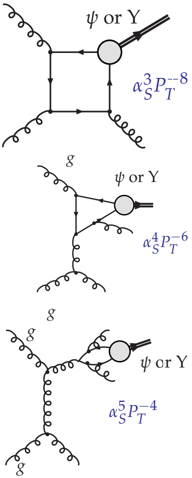

Attention: the NNLO* is not a complete NNLO
See a recent study by H.S. Shao **arXiv:1809.02369 [hep-ph]**

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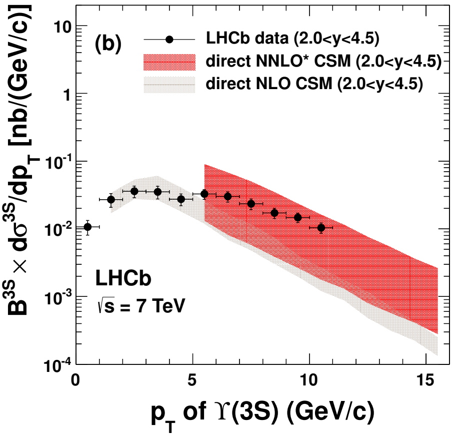

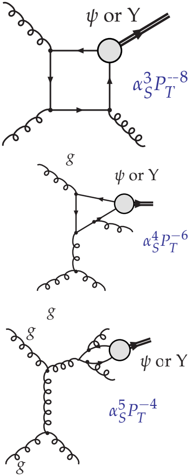

$\Upsilon(3S)$: 60-70 % direct; $\Upsilon(2S)$:60-70 % direct; $\Upsilon(1S)$: 50-70 % direct

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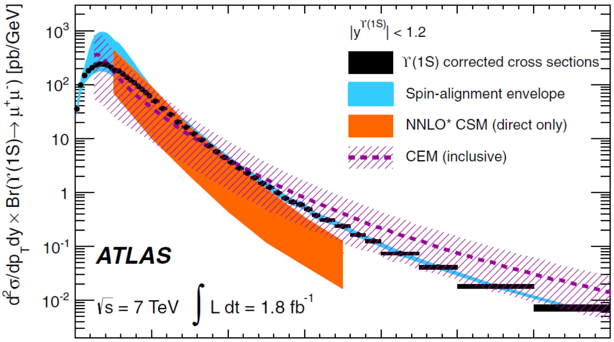

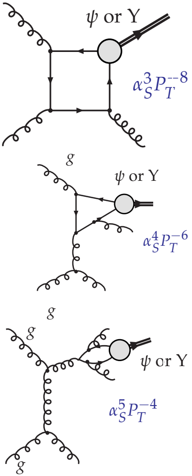

CSM theory curve extrapolated to prompt: × 2

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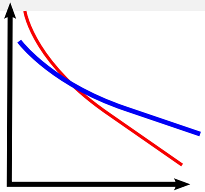

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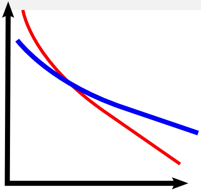

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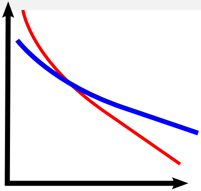

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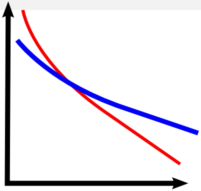

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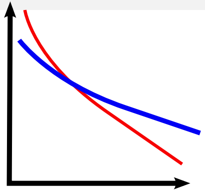

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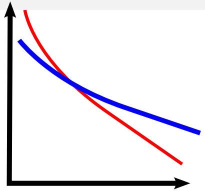

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- Polarisation: ${}^1S_0^{[8]}$: unpolarised; ${}^3S_1^{[8]}$ & ${}^3P_J^{[8]}$: transverse

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

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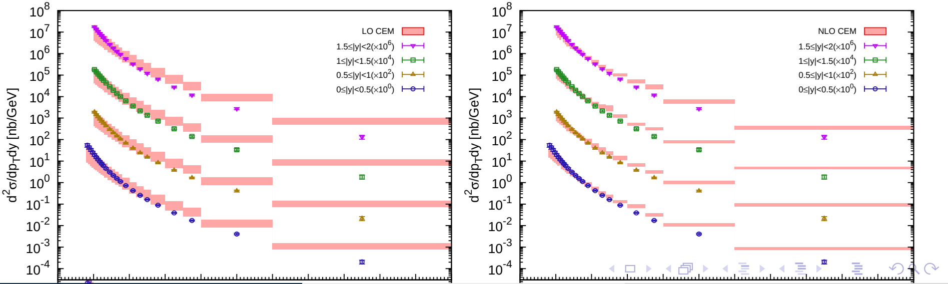

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- All approaches have troubles in describing the polarisation and/or the η_c data
- This motivates the study of new observables

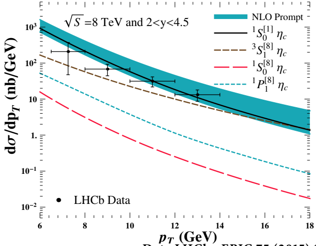
which can be more discriminant for specific effects [e.g. associated production]

Part III

New observables in quarkonium production

III.1 Pseudoscalar quarkonia

From exotic to essential



Data LHCb : EPJC 75 (2015) 311 (plot from H. Han*et al.* PRL 114 (2015) 092005)

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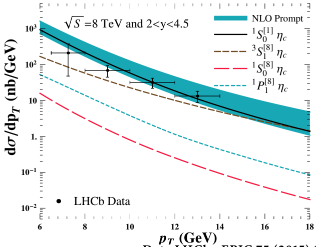

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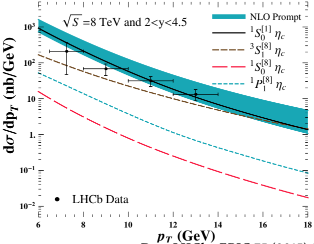

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$$\langle^{J/\psi}(^1S_0^{[8]})\rangle = \langle^{\eta_c}(^3S_1^{[8]})\rangle < 1.46 \times 10^{-2}\ \mathrm{GeV}^3$$

[Additional relations: $\langle^{\eta_c}(^1S_0^{[8]})\rangle = \langle^{J/\psi}(^3S_1^{[8]})\rangle/3$ and $\langle^{\eta_c}(^1P_1^{[8]})\rangle = 3 \times \langle^{J/\psi}(^3P_0^{[8]})\rangle$]

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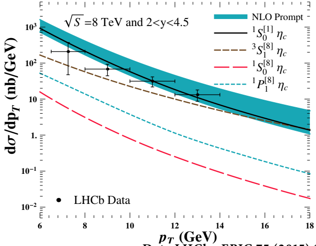

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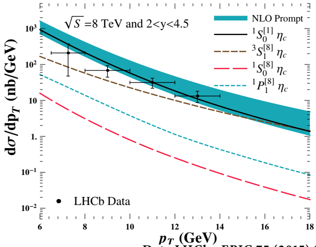
- Even the PKU fit has now troubles to describe CDF polarisation data

[Additional relations: $\langle^{\eta_c}(^1S_0^{[8]})\rangle = \langle^{J/\psi}(^3S_1^{[8]})\rangle/3$ and $\langle^{\eta_c}(^1P_1^{[8]})\rangle = 3 \times \langle^{J/\psi}(^3P_0^{[8]})\rangle$]

From exotic to essential



Data LHCb : EPJC 75 (2015) 311 (plot from H. Han*et al.* PRL 114 (2015) 092005)

- η_c x-section measured by LHCb very well described by the CS contribution (Solid Black Curve)
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- Even the PKU fit has now troubles to describe CDF polarisation data
- 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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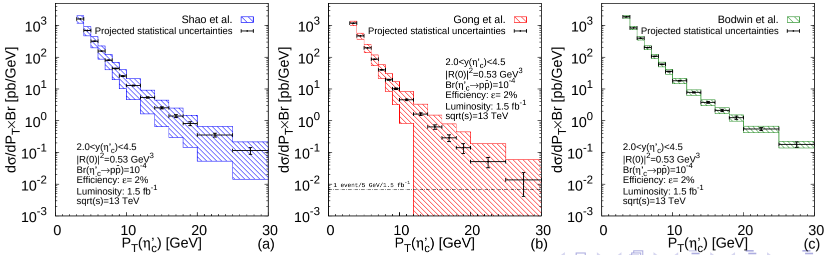

III.2 Quarkonium Pairs

On the importance of α_s^5 contributions to $J/\psi + J/\psi$ & $J/\psi + \eta_c$

JPL, H.S. Shao PRL 111, 122001 (2013)

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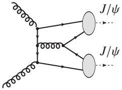

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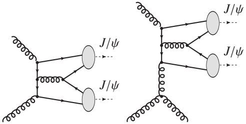

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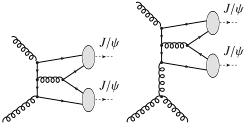
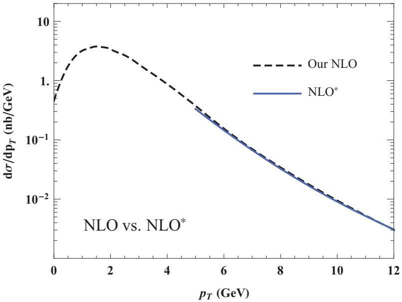


[**nicely confirmed by a full NLO**]

L.P. Sun *et al.* **arXiv:1404.4042 [hep-ph]**



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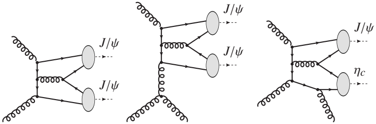

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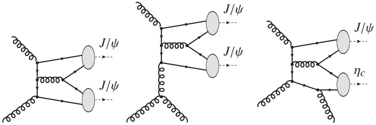

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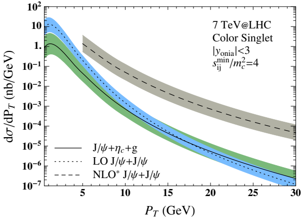

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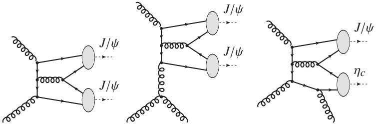

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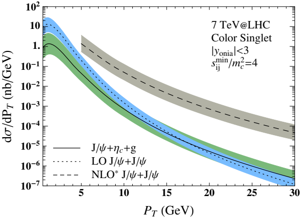

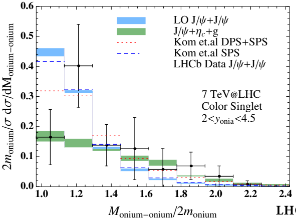

LHCb PLB 707 (2012) 52

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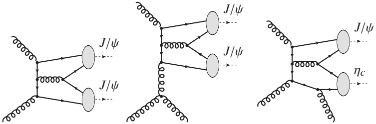

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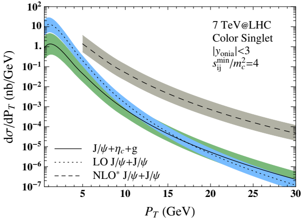

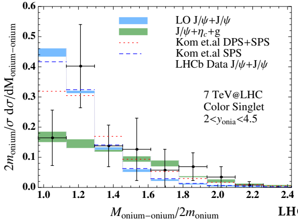

LHCb PLB 707 (2012) 52

- The P_T & $M_{\psi\psi}$ distributions depend very much on the topology (see later)
- $J/\psi + J/\psi$: $\sigma^{\rm central}_{\rm LO\ SPS} = 4.83$ nb; $\sigma^{\rm central}_{\rm NLO\ SPS} = 5.34$ nb; $\sigma^{\rm LHCb}_{\rm measured} = 5.1 \pm 1.0 \pm 1.1$ nb

On the importance of QCD corrections : P_T enhanced topologies

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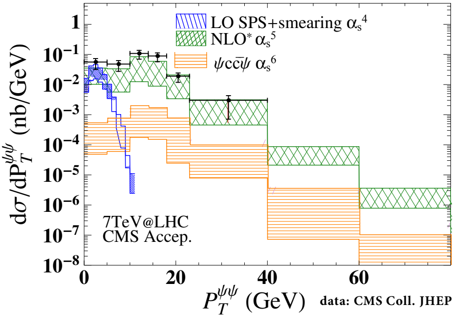

data: CMS Coll. JHEP 1409 (2014) 094

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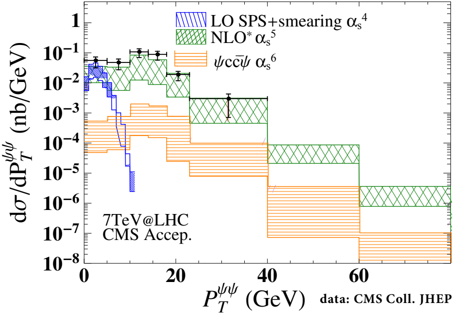

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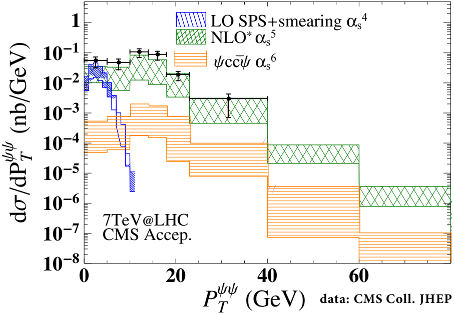

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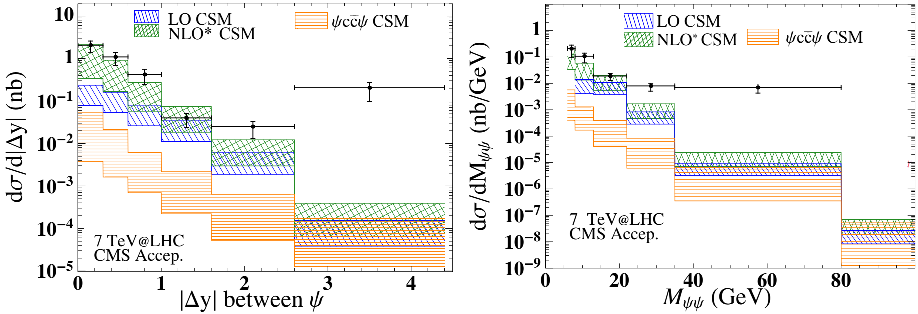
- We do not expect NNLO (α_s^6) contributions to matter where one currently has data

[the orange histogram shows one class of leading P_T α_s^6 contributions]

The so-called CMS puzzle



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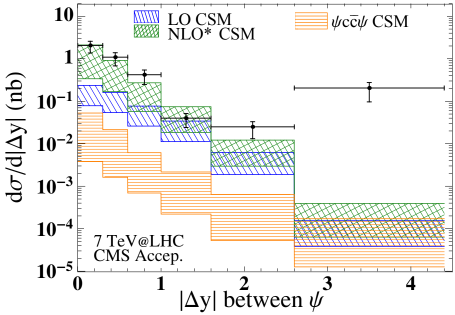

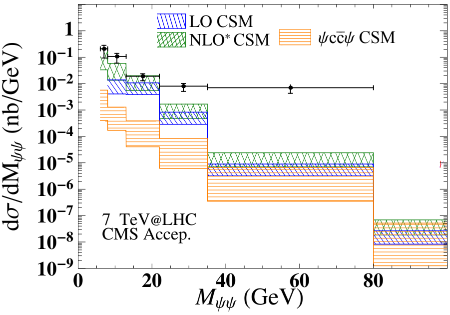

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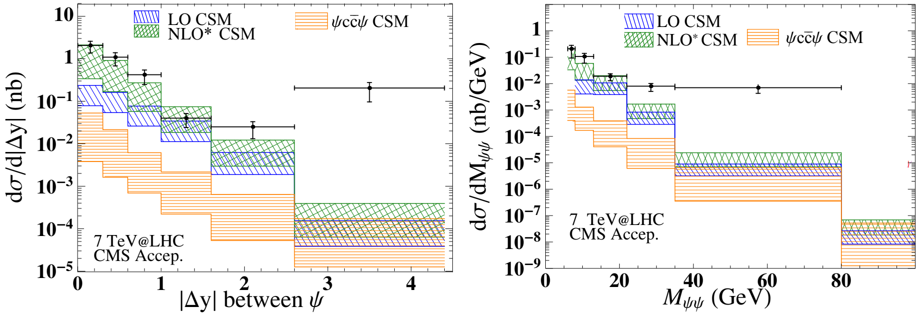

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[At $\Delta y = 3.5$ and $P_T = 6$ GeV, $M_{\psi\psi} \simeq 40$ GeV.]

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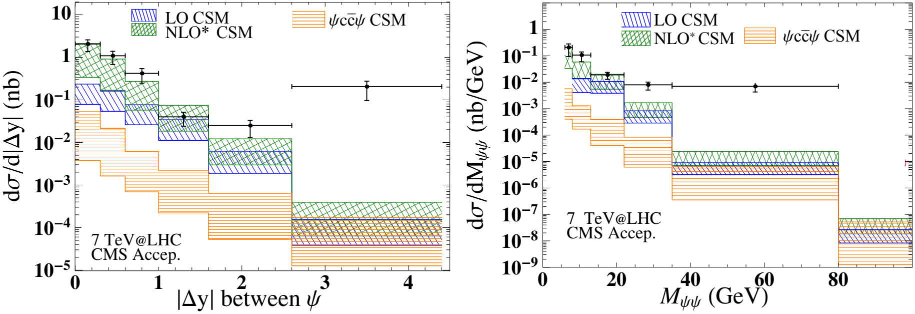

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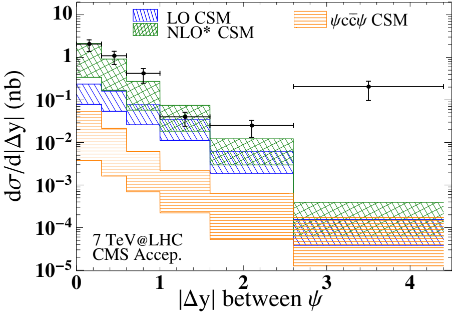

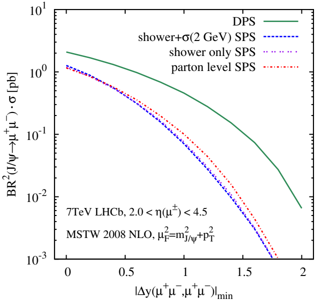

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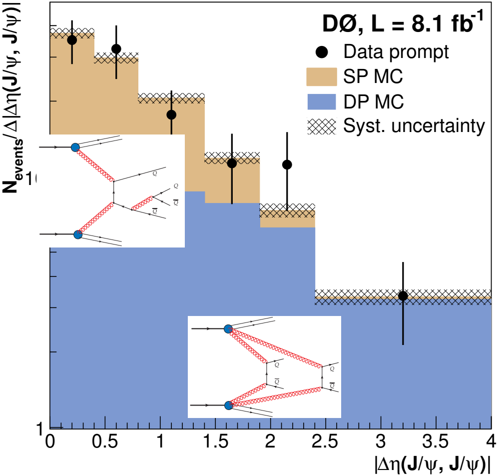
- Predictions for LHCb, DPS ≫ SPS at large Δy C.H. Kom, A. Kulesza, W.J. Stirling PRL 107 (2011) 082002

On the importance of double parton scatterings at large Δy I

In fact, the argument of C.H. Kom, A. Kulesza, and W.J. Stirling was used by D0 to separate out DPS from SPS contributions



D0 Coll. PRD 90 (2014) 111101

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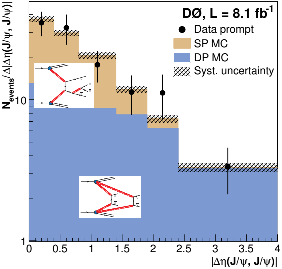

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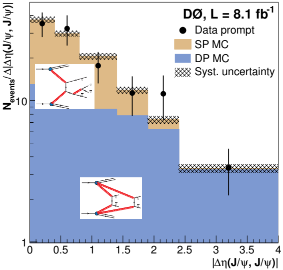

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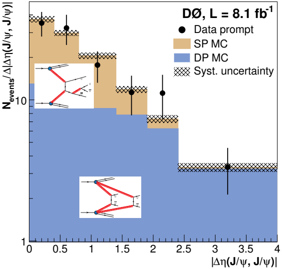

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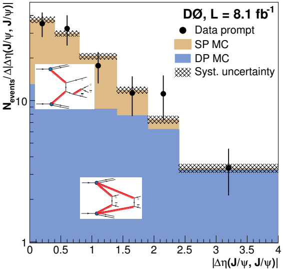

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- A question arises: using $\sigma^{\rm DPS} = \frac{1}{2}\frac{\sigma_\psi \sigma_\psi}{\sigma_{\rm eff}}$ and $\sigma_{\rm eff} = 4.8 \pm 2.5$ mb, can one account for the large Δy CMS data ?

On the importance of double parton scatterings at large Δy II

On the importance of double parton scatterings at large Δy II

- Let us investigate the consistency
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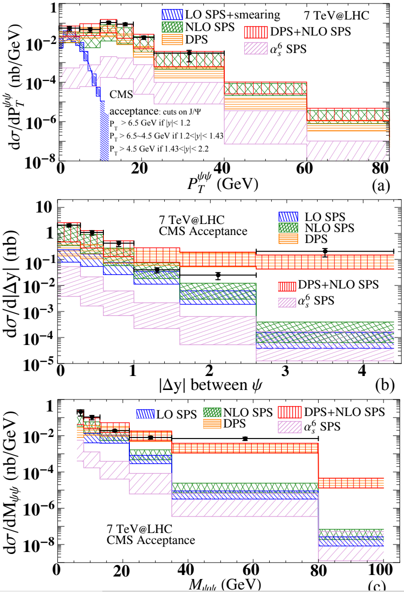

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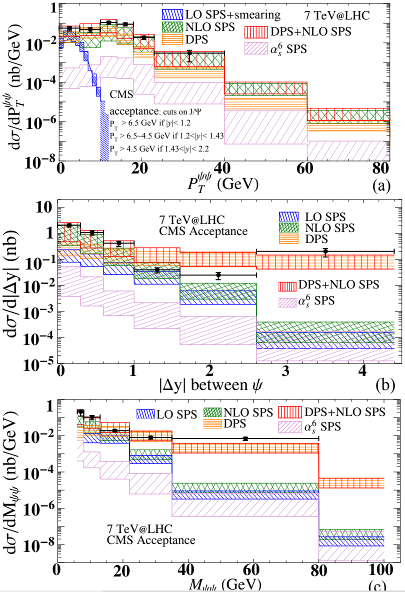

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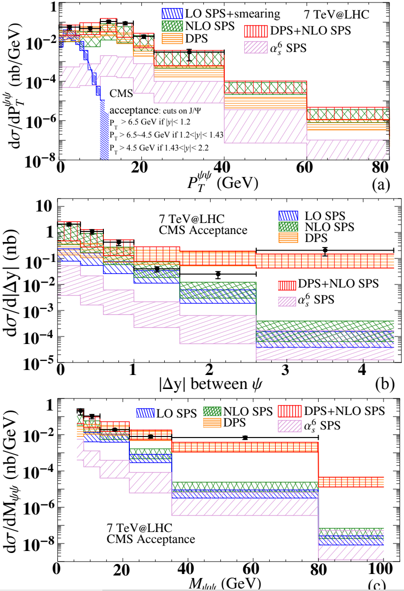

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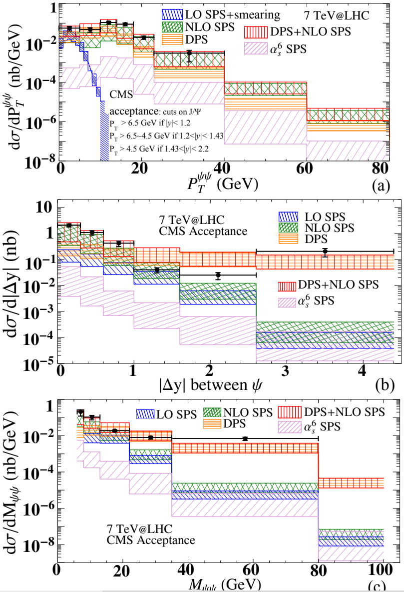

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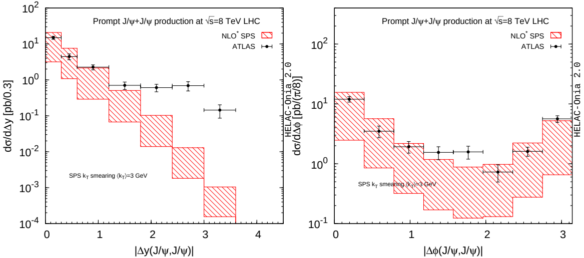

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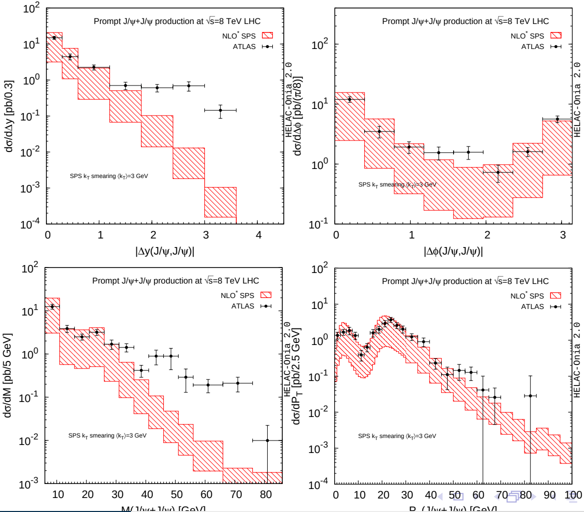

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JPL, H.-S.Shao PLB 751 (2015) 479

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

III.3 Quarkonium and Vector Bosons

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

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

- Significant tensions between the ATLAS measurement and the SPS NRQCD yields: normalisation, P_T and $\Delta\phi$ distributions

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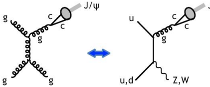

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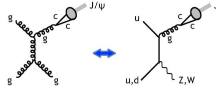

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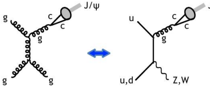

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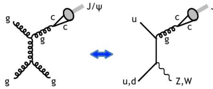

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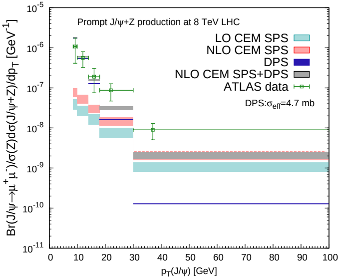

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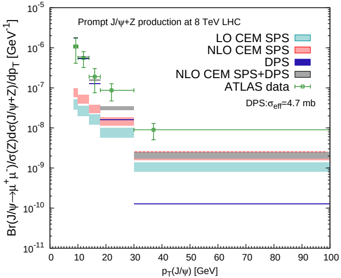

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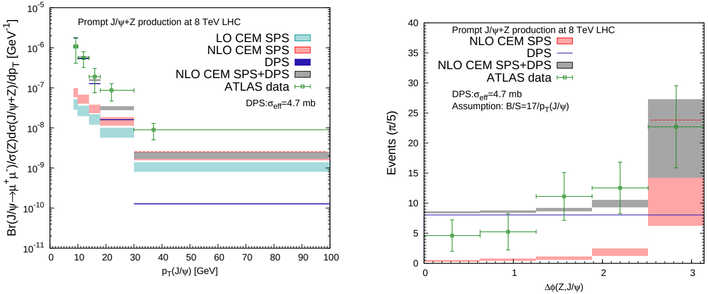

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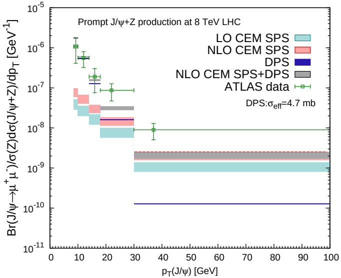

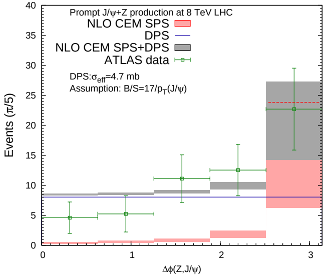

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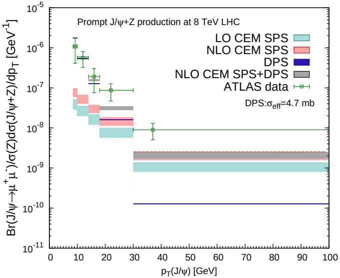

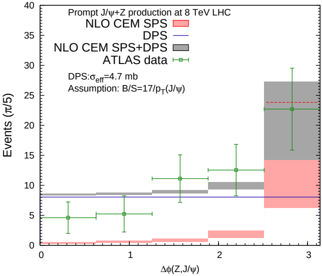

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ATLAS Collaboration, JHEP 1404 (2014) 172
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ATLAS inclusive	$4.5^{+1.9}_{-1.5}$ pb	0.16 ± 0.05	0.28 ± 0.07	1.7

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Comparisons with the differential distributions

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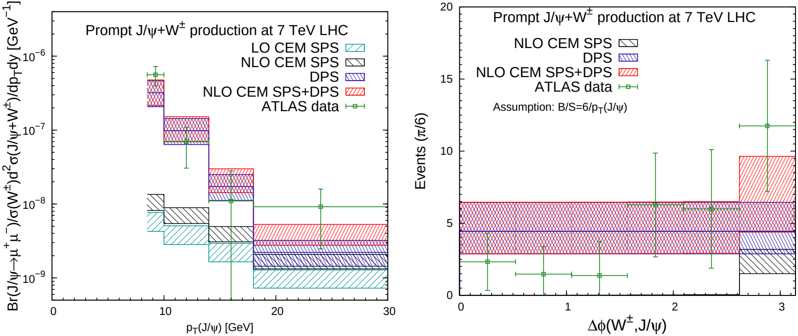
- Like for $Z + J/\psi$, DPS dominate at low P_T and SPS at large P_T in the ATLAS acceptance, [black histogram vs. the blue one]



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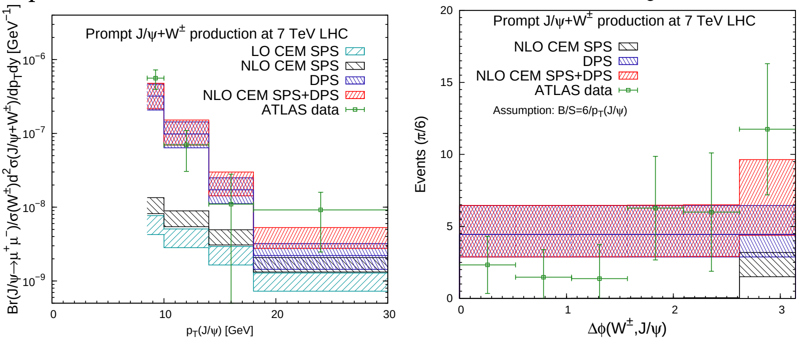

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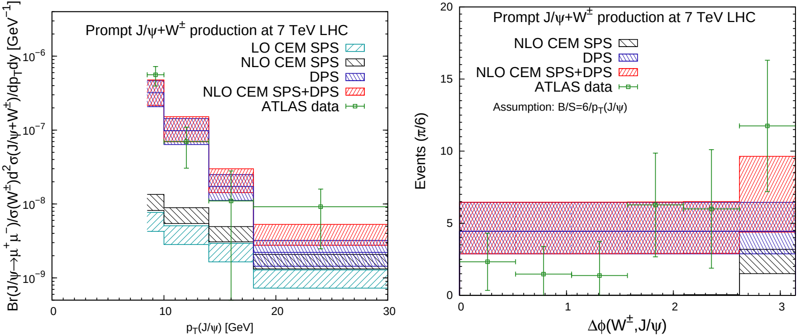

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- We are waiting for ATLAS data at 13 TeV

III.4 Altogether

Harvesting quarkonium data: 4 extractions using theory

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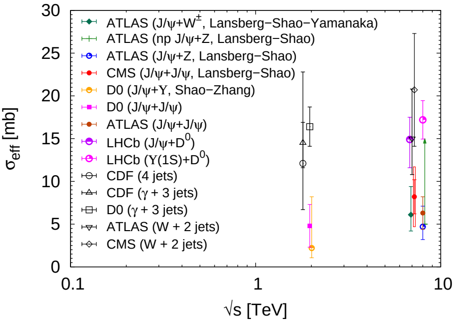

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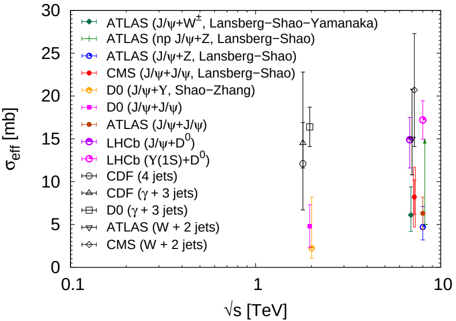

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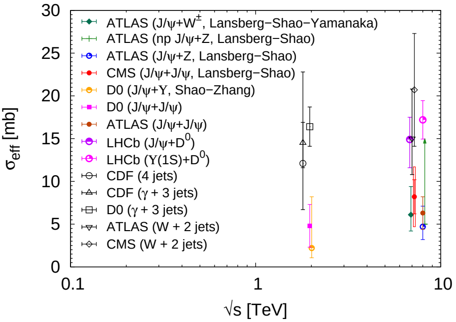

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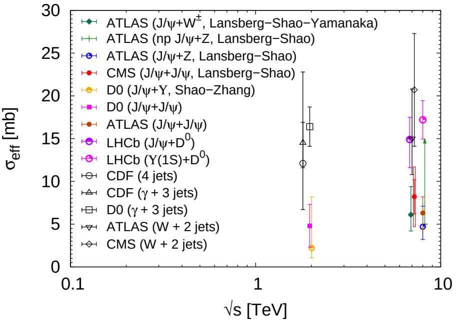

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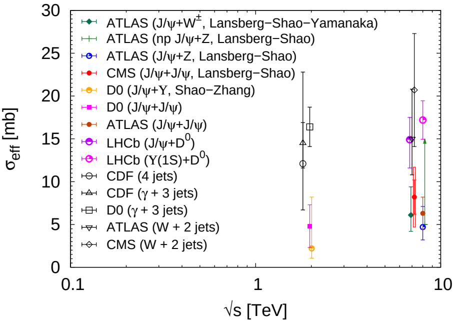

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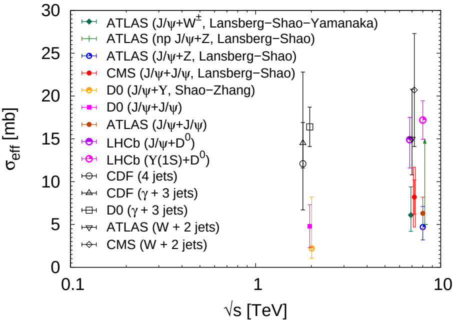

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CMS JHEP05(2017)013

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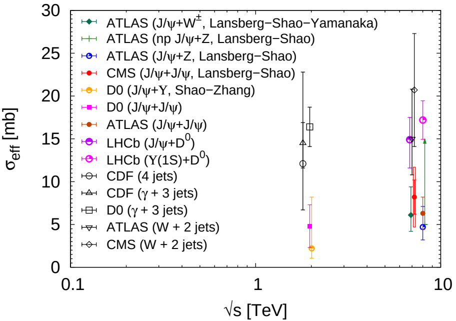

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CMS JHEP05(2017)013

- 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

Part IV

Conclusion

Summary

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

Prospects

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Observables	Experiments	CSM	CEM	NRQCD	Interest
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+hadron	STAR	LO	--	LO	B feed-down; Singlet vs Octet radiation
J/ψ+Z	ATLAS	NLO	NLO	Partial NLO	Prod. Mechanism + DPS
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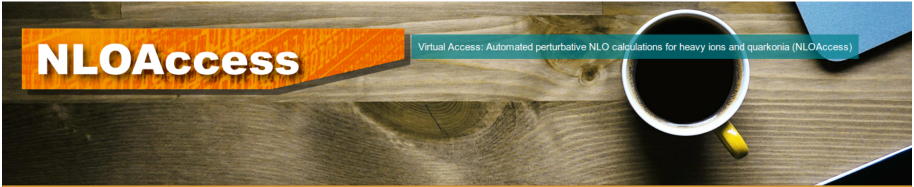
ϒ+Z	--	NLO	LO ?	LO	**Prod. Mechanism + DPS**
ϒ+ϒ	CMS	NLO ?	LO ?	LO ?	**Prod. Mechanism (CS dominant ?) + DPS + gluon TMD**

NLOAccess [in2p3.fr/nloaccess]



General description   Participants   Tasks   Links and resources

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

Show more

This project has been included in the STRONG2020 submission for EU funding.

To search type and hit enter

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

HELAC-Onia Web   Request Registration   References   Contact us   Login

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.

Do you not have an account? Make a registration request.

Part V

Backup

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	$15.4 \pm 2.2^{+51}_{-12}$	$14.8 \pm 1.7^{+53}_{-12}$	$6.8 \pm 0.6^{+22}_{-5}$
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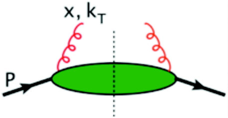
- REMINDER: it is not an option to "switch off"/ignore the NLO CS contribution [parameter free]
- Yet, room for DPS; however tension if $\sigma_{\rm eff} \simeq 7$ mb
- Tension between LHCb and other di-J/ψ extractions [rapidity effect ?]

Gluon TMDs in unpolarised protons



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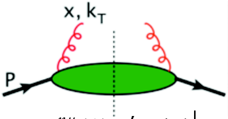

- Gauge-invariant definition:

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

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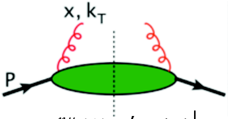

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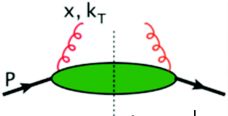
Gluon TMDs in unpolarised protons



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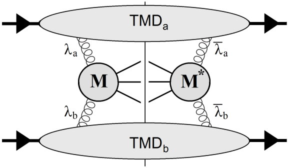
- f_1^g: TMD distribution of unpolarised gluons
- $h_1^{\perp g}$: TMD distribution of linearly polarised gluons

[Helicity-flip distribution]

gg fusion in arbitrary unpolarised process [colourless final state]

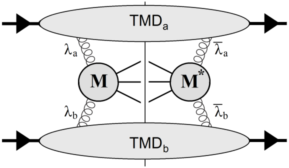
$d\sigma^{gg} \propto$



gg fusion in arbitrary unpolarised process [colourless final state]

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

⇒ helicity non-flip, azimuthally independent



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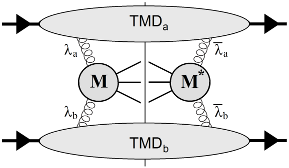

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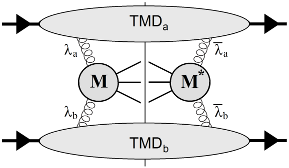

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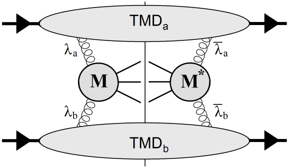

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None are measured so far ...

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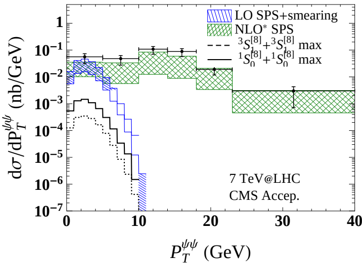

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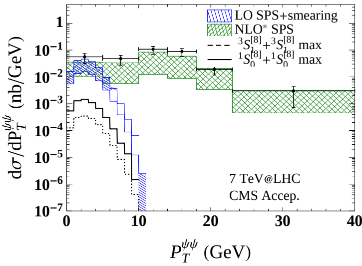

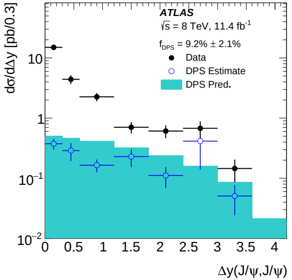

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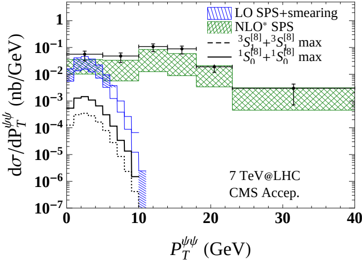

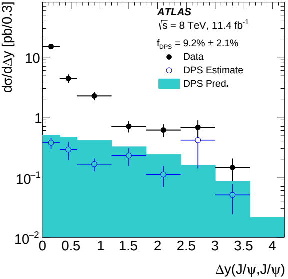

- DPS in LHCb data [kinematical distributions well controlled : independent scatterings]

What's special about double vector onium production ?

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

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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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  where $g(x)$ is the usual collinear PDF
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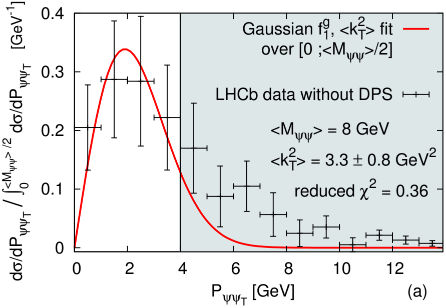

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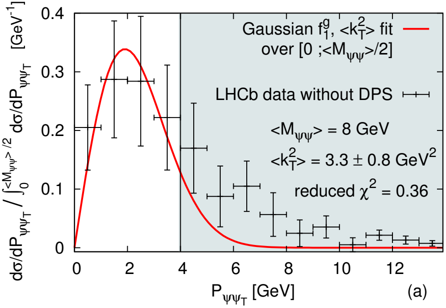

- Integration over $\phi \Rightarrow \cos(n\phi)$-terms cancel out
- $F_2 \ll F_1 \Rightarrow$ only $\mathcal{C}[f_1^g f_1^g]$ contributes to the cross-section
- No evolution so far: $\langle k_T^2\rangle \sim 3$ GeV^2 accounts both for non-perturbative and perturbative broadenings at a scale close to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

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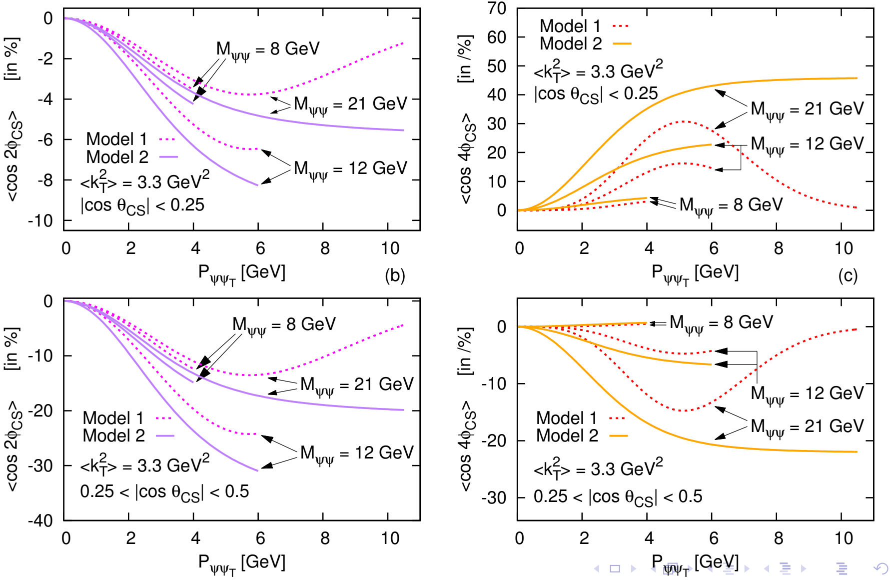

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- If regeneration is at work, how does it happen ? statistically ? according to the charm-quark distribution in the charmonium (wave-function) ?
- etc ...

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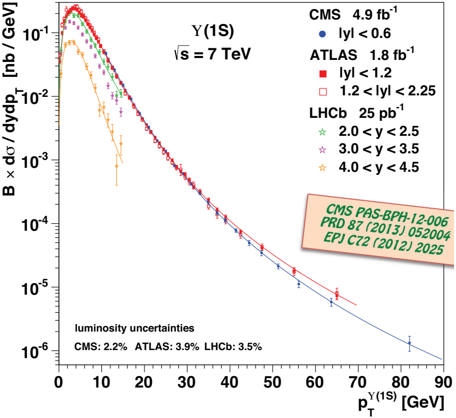

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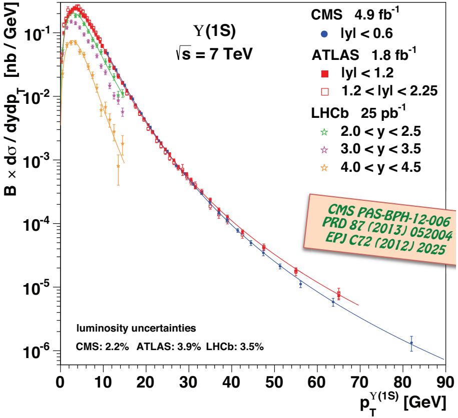

Most probably the production of a Υ with $P_T = 90$ GeV, even also 20 GeV, has very few things to do with the bulk of Υ

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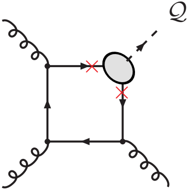

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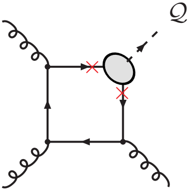

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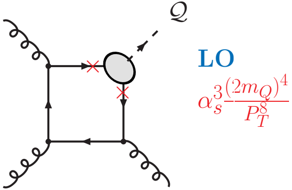

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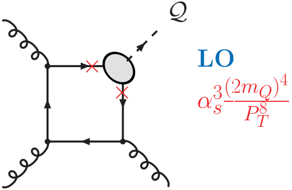

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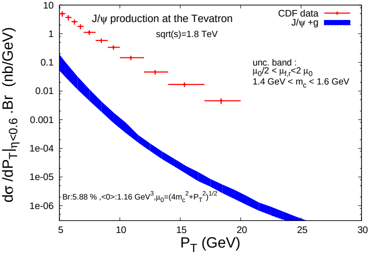

CDF, PRL 79:572 & 578,1997

Basic pQCD approach: the Colour Singlet Model (CSM)

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

- Perturbative creation of 2 quarks Q and $\bar{Q}$ BUT
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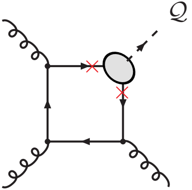

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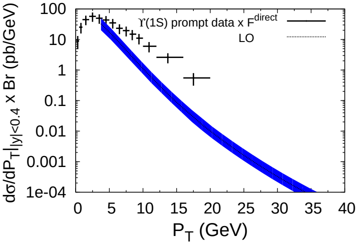

CDF, PRL 88:161802,2002

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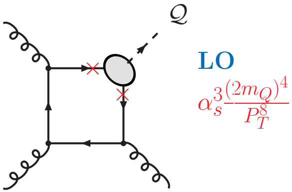

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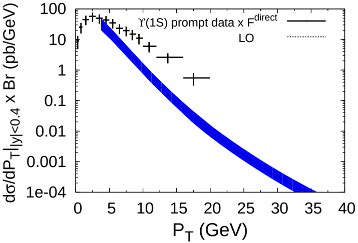

- Large QCD corrections from new topologies reduce the gap with data at mid and large P_T

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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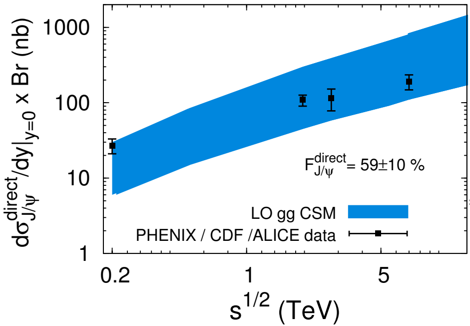

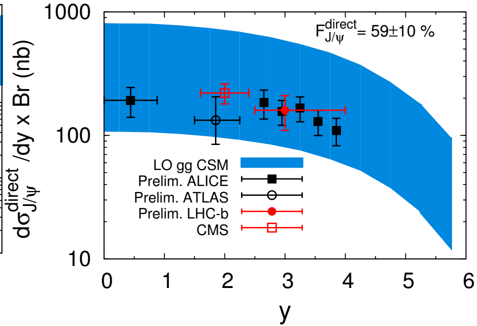

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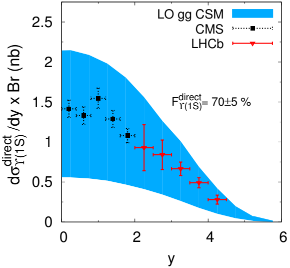

CMS PRD 83 (2011) 112004; LHCb EPJC 72 (2012) 2025

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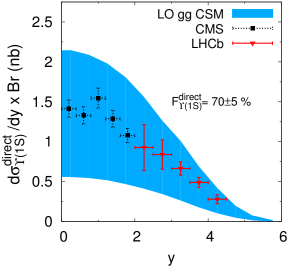

CMS PRD 83 (2011) 112004; LHCb EPJC 72 (2012) 2025

- Unfortunately, very large th. uncertainties: masses, scales (μ_R, μ_F), gluon PDFs at low x and Q^2, …

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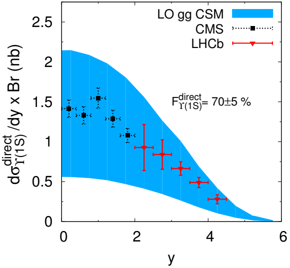

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- Unfortunately, very large th. uncertainties: masses, scales (μ_R, μ_F), gluon PDFs at low x and Q^2, …
- Earlier claims that CSM contribution to $d\sigma/dy$ was small were based on the incorrect assumption that χ_c feed-down was dominant

NLO CSM at RHIC

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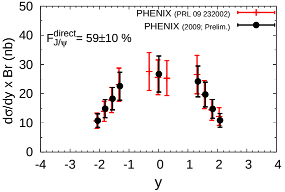
→ J/ψ



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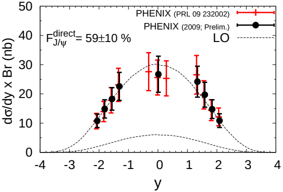

LO: $gg \to J/\psi g$ (see slide 5, nothing new !)

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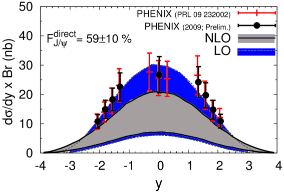

NLO: $gg \to J/\psi gg, gq \to J/\psi gq, ...$

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

NLO CSM at RHIC

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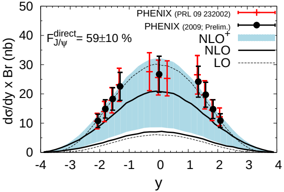

NLO$^+$: possible new contribution at LO $cg \to J/\psi c$

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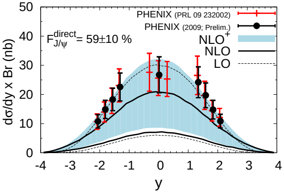

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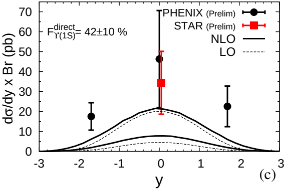

* Sorry: I should update these plots (updated data and fraction is about 60 %)

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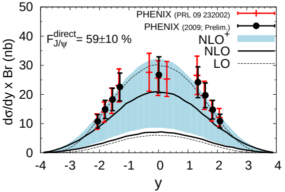

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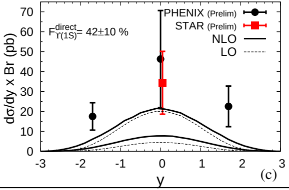

A priori, good convergence NLO w.r.t. LO

[I will come back to that later]

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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**)

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

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

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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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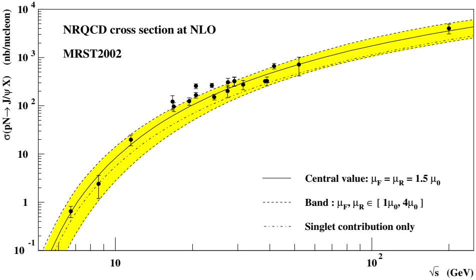

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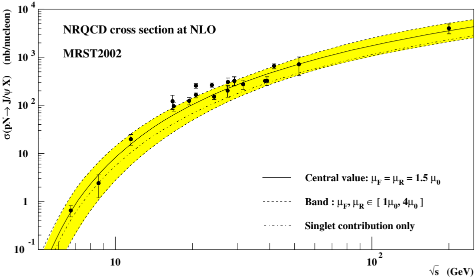

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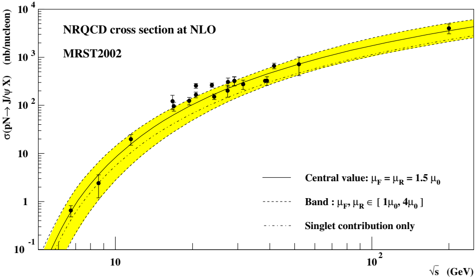

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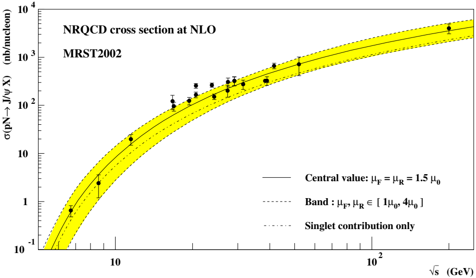

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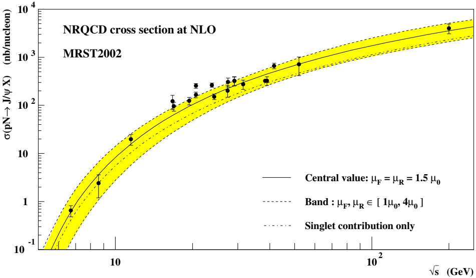

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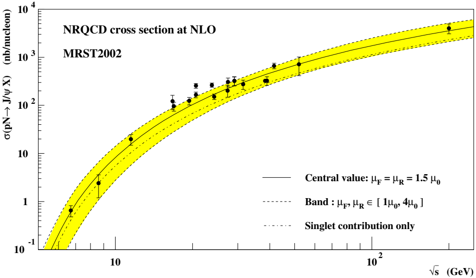

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What we did[Y. Feng, JPL, J.X. Wang, EPJC (2015)75:313]

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- FDC* after complete cross-check of the Petrelli *et al.* results

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- only direct J/ψ, ψ' and $\Upsilon(1S)$ yields

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- 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'

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B. Gong,*et al.* PRL 110 (2013) 042002	9.5×10^{-3}	-1.2×10^{-4}	3.4×10^{-3}
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- $\Upsilon(1S)$

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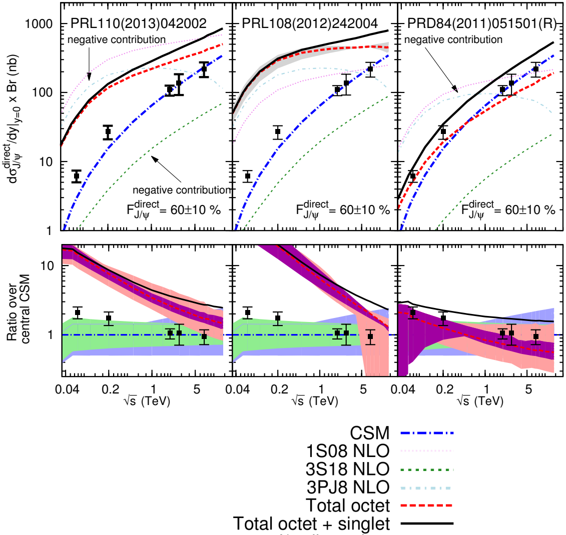
B. Gong, *et al.* PRL 112 (2014) 3, 032001.	-10.36×10^{-2}	11.15×10^{-2}	-4.1×10^{-2}

[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



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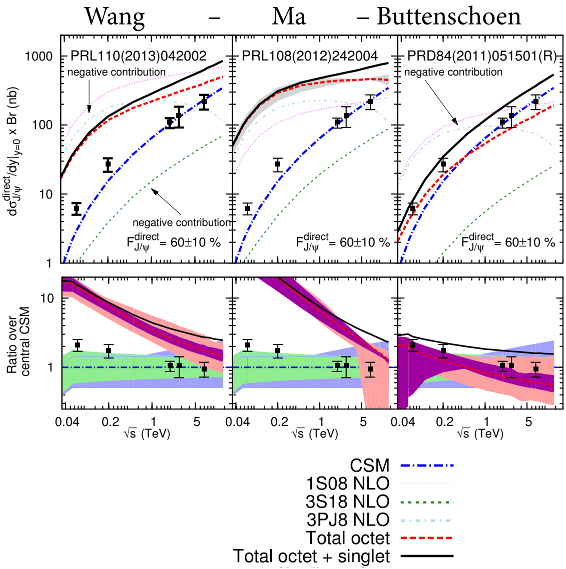

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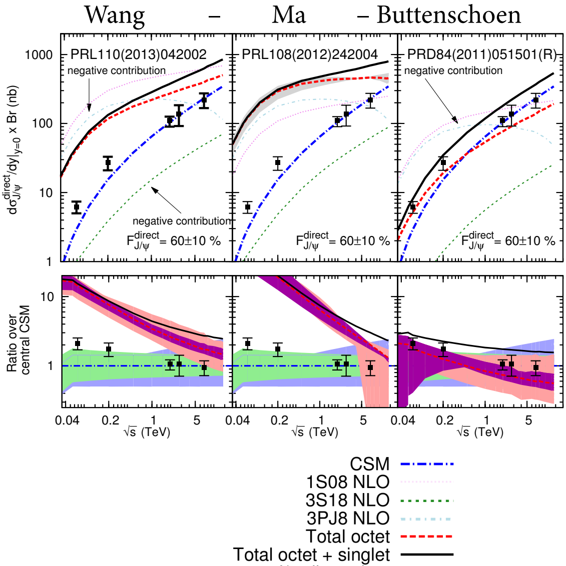

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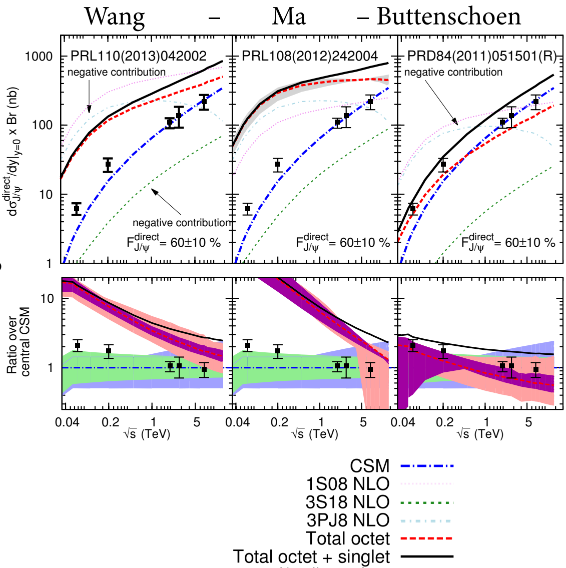

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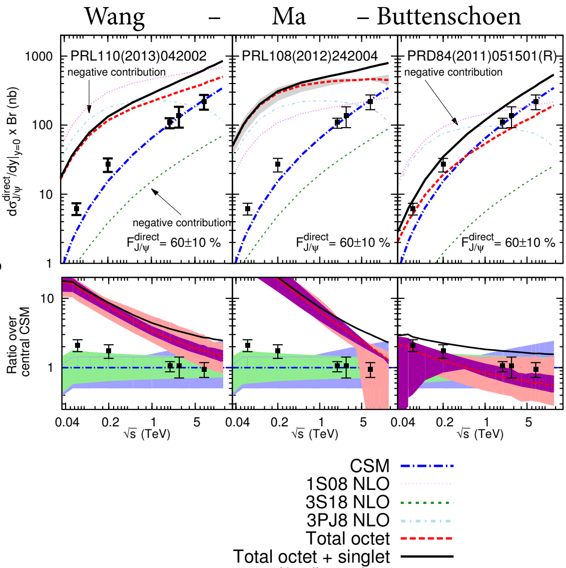

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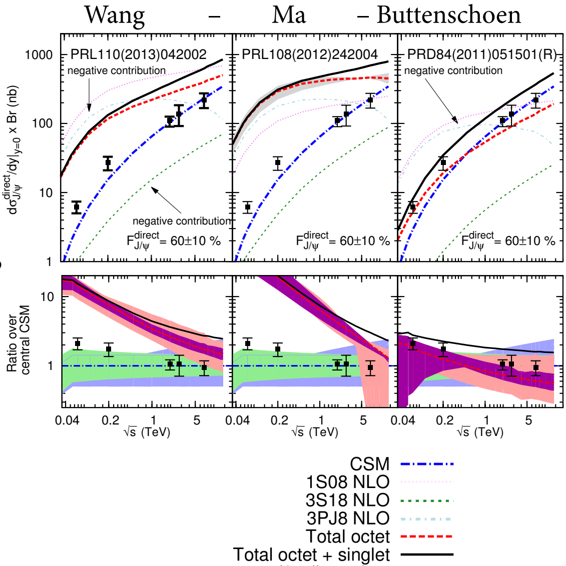

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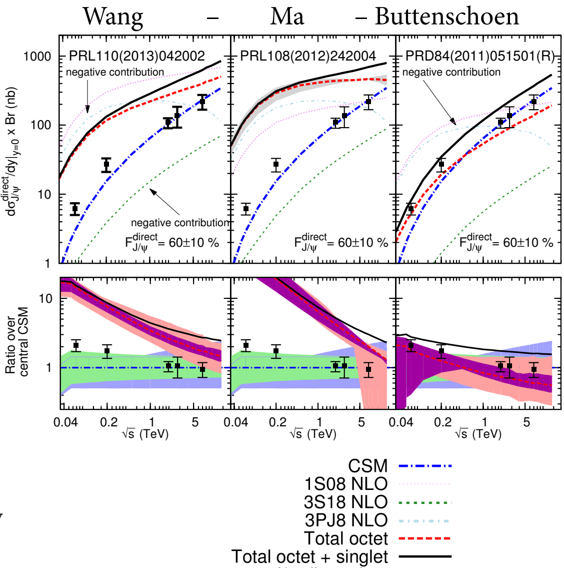
- Not a surprise since the CSM alone accounts well for the data; adding any contribution creates a "surplus"



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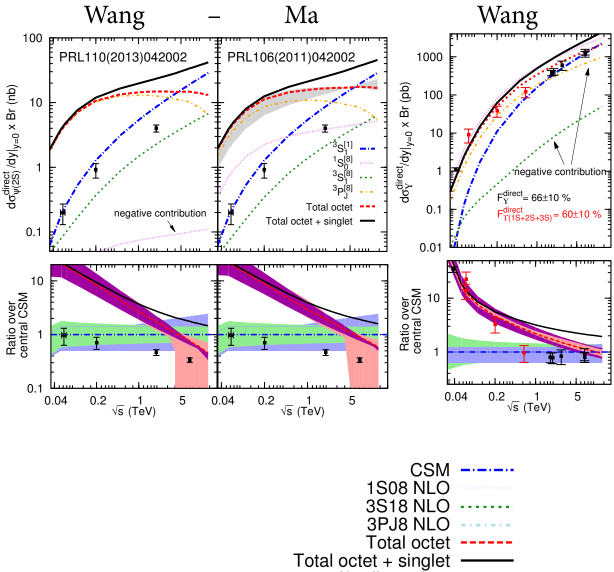

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For $\psi(2S)$

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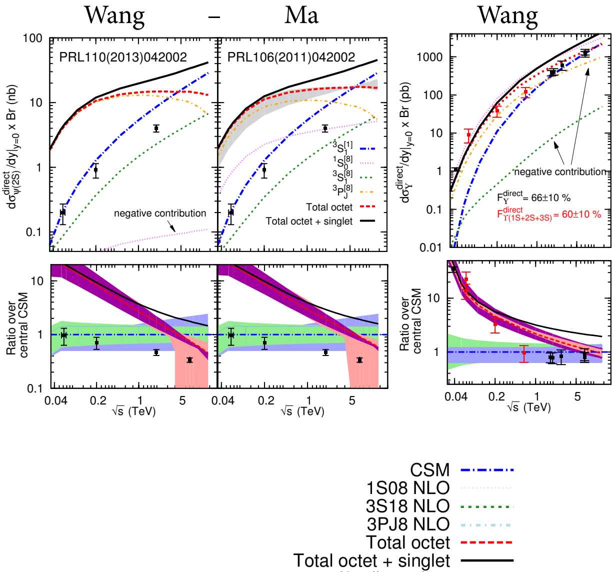

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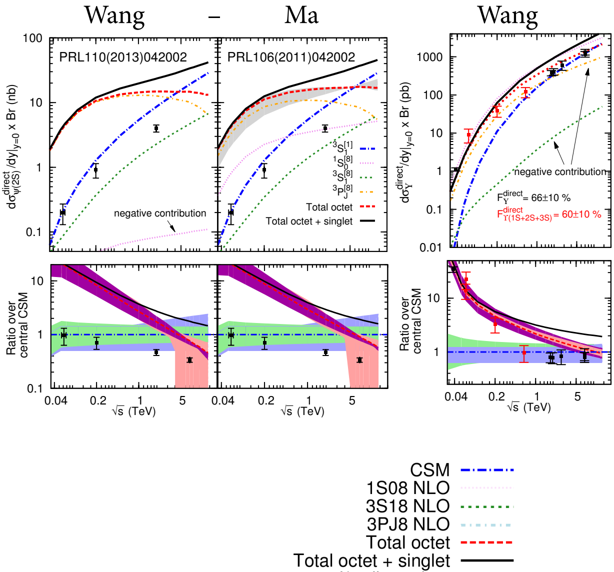
For $\Upsilon(1S)$

- 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 ?



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We checked these with FDC

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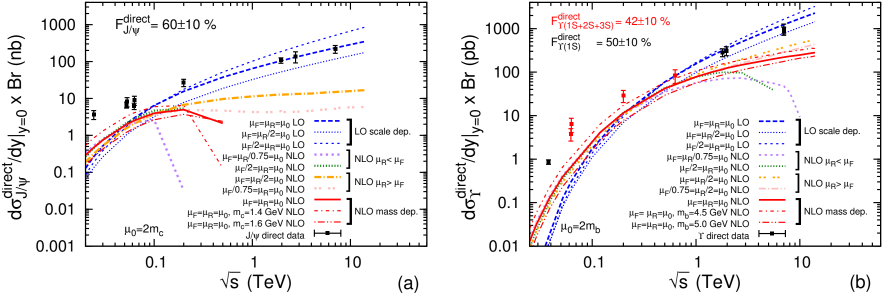

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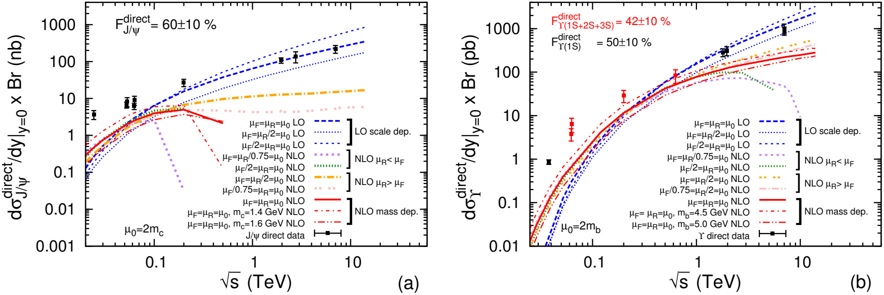

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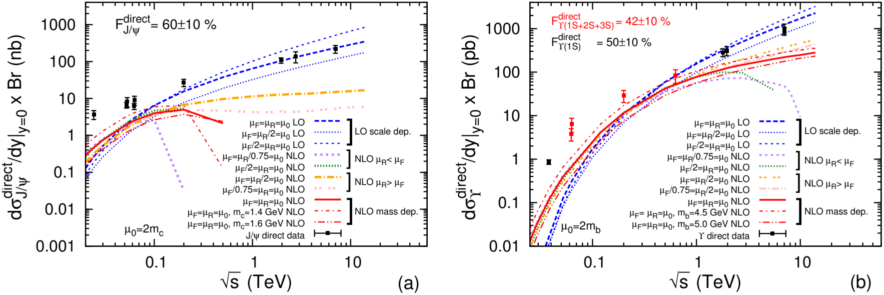

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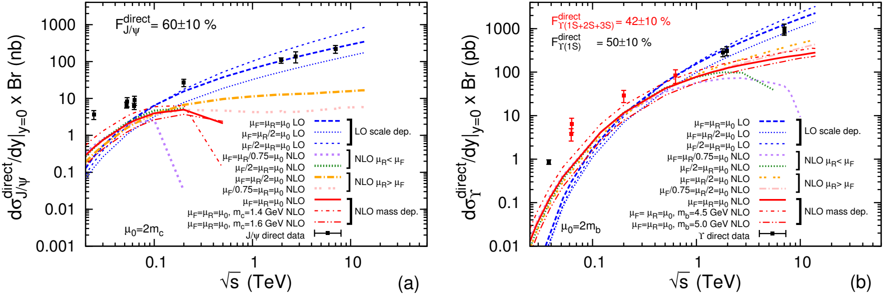

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Is it due to ISR, FSR ? Is NRQCD simply not holding at low P_T ?

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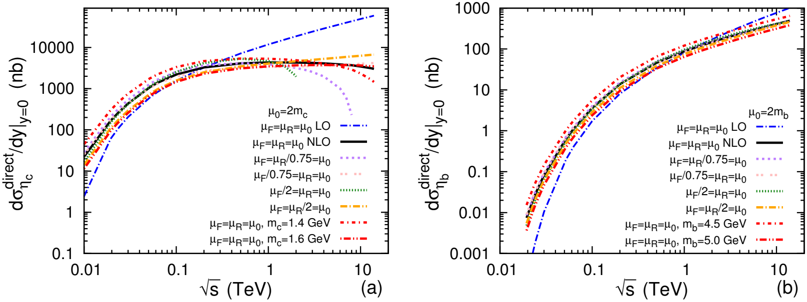

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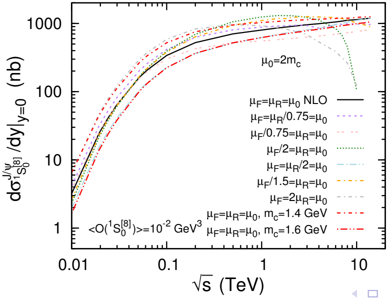

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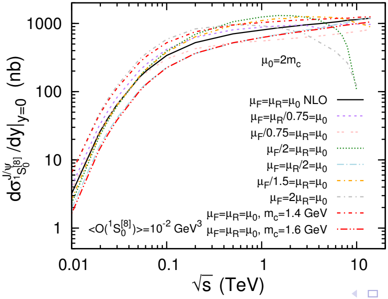
- No sign of negative terms in the TMD factorisation approach up to one loop

M. Echevarria, T. Kasemets, JPL, C. Pisano A. Signori (in progress); J.P. Ma, J.X. Wang, S. Zhao, PRD 88 (2013) 014027



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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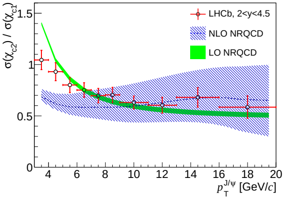

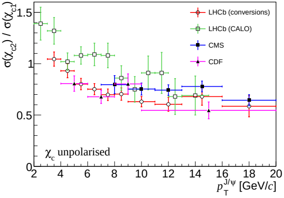

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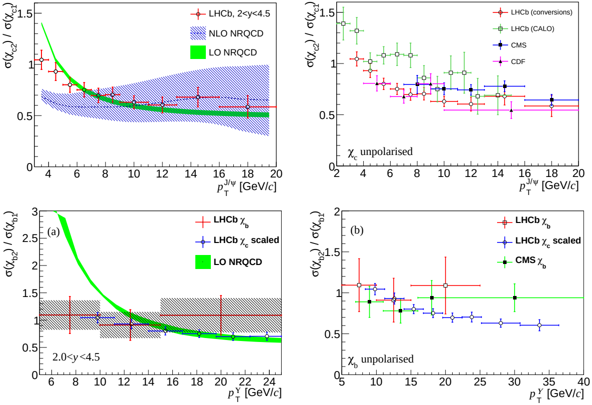

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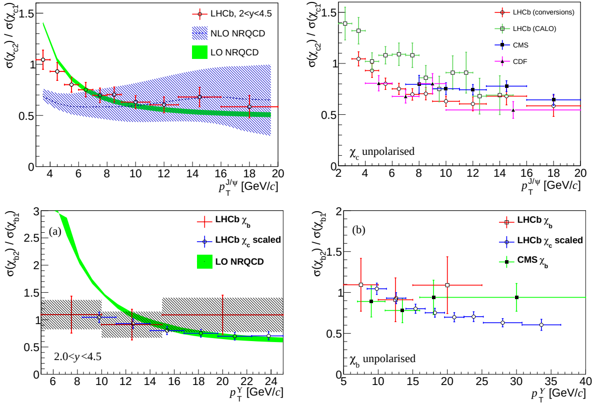

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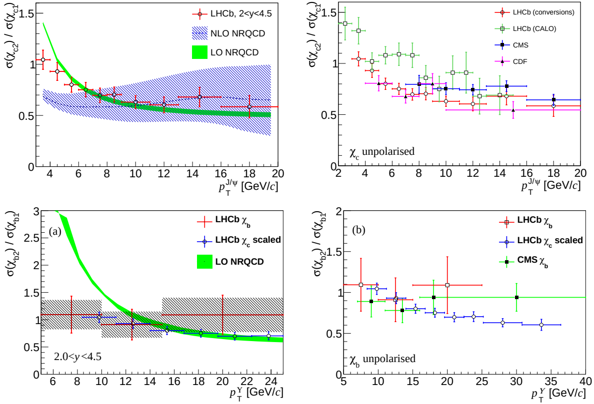

- The Landau-Yang suppression shows up for χ_c in the Low P_T/m_Q region
- The nature (quantum #) of the produced final state seems still relevant !

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

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M. Bedjidian, [..], R. Vogt *et al.*, **hep-ph/0311048**

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- Ramona Vogt's fits roughly give the same number for direct J/ψ's

M. Bedjidian, [..], R. Vogt *et al.*, **hep-ph/0311048**

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

NRQCD Ersatz of the CEM

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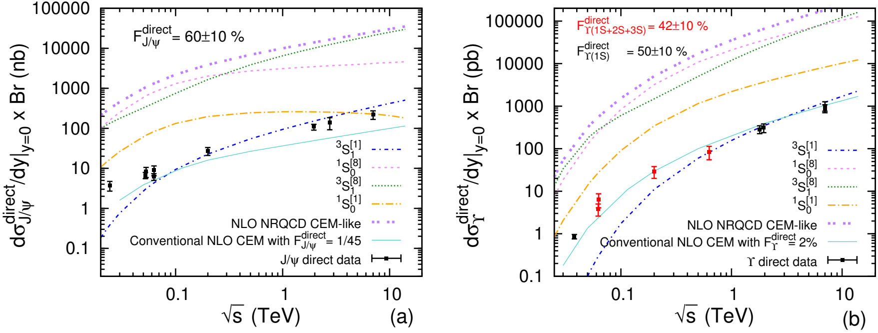
- If, as it should be in NRQCD, $\langle \mathcal{O}_{^3S_1}(^3S_1^{[1]})\rangle$ is the usual CS LDME, *i.e.* $\frac{2N_C}{4\pi}(2J+1)|R(0)|^2$, everything is fixed

CEM results



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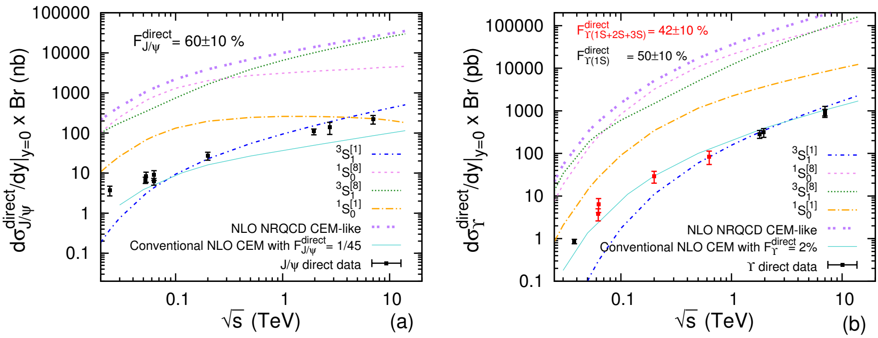

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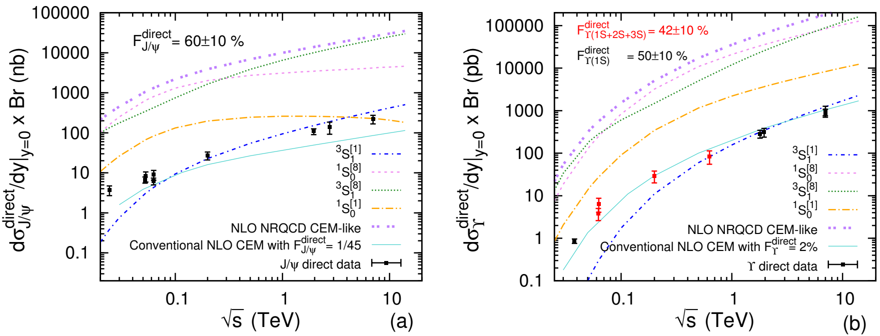

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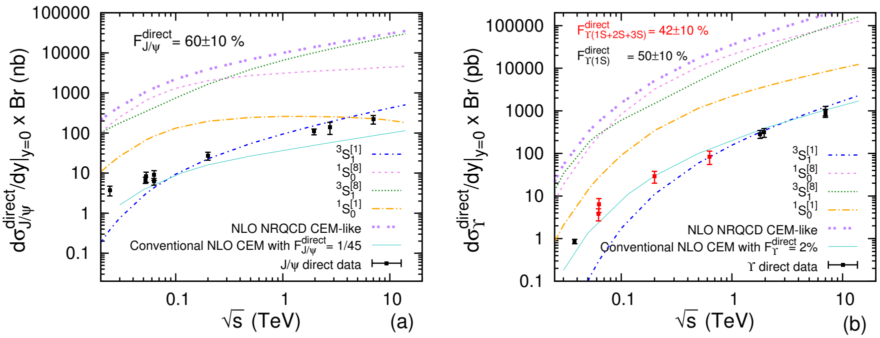

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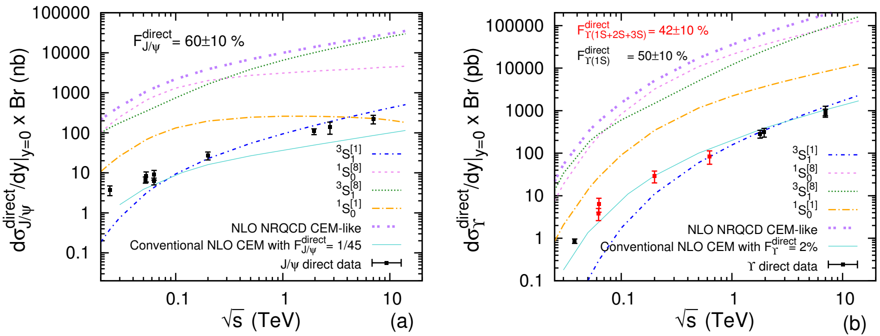

- NRQCD-like CEM badly overshoots the data
  - Expected since CO LDMEs are as large as the CS, whereas the hard parts tend to be larger.
  - Weird energy behaviour
- Conventional CEM does a pretty good job
  - No th. uncertainty shown
  - "Natural" value of $F^{direct}_{J/\psi}$ is ok