Quarkonium Production in the LHC era

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Rencontre de Physique des Particules, LPC Clermont, January 25, 2019

Picture taken by A. Lardeux at ''Quarkonia as Tools'', Aussois, Jan. 2019

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 at mid and large P_T

QCD corrections to the CSM for Υ at colliders

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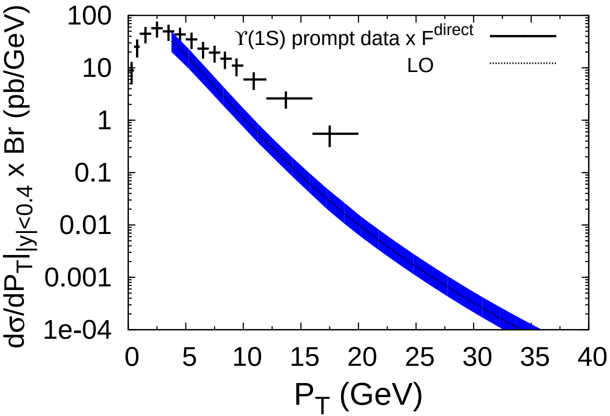

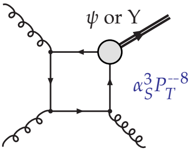

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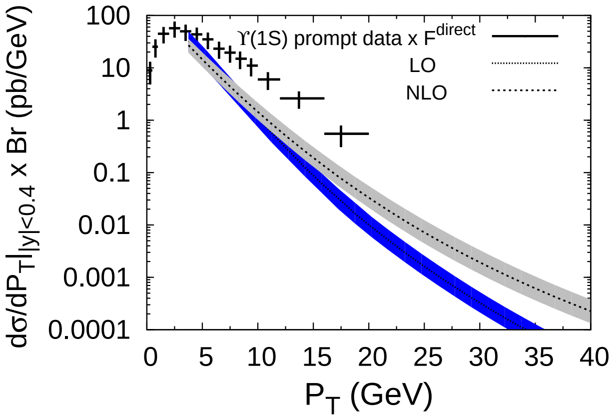

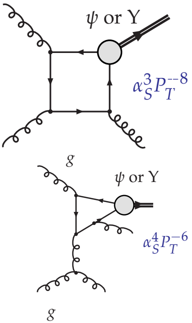

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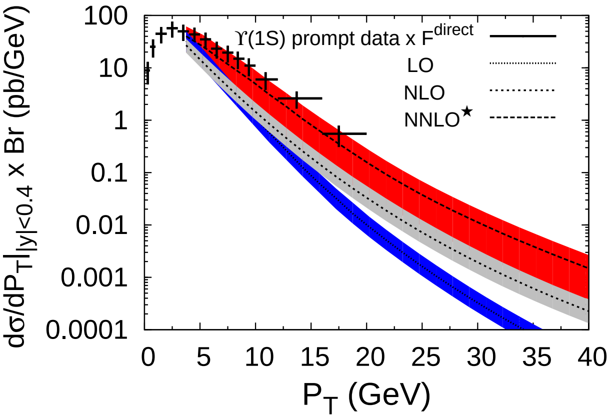

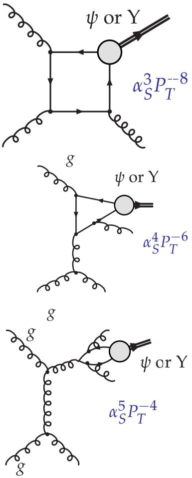

Attention: the NNLO* is not a complete NNLO
See a recent study by H.S. Shao **JHEP 1901 (2019) 112**

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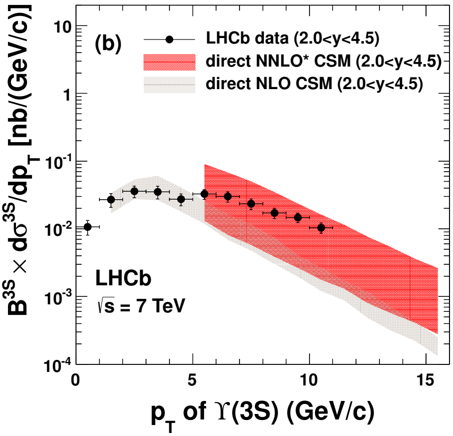

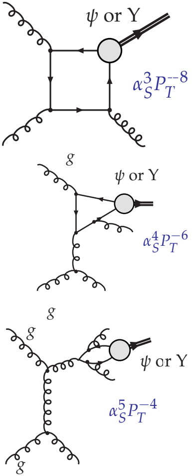

Υ(3S): 60-70 % direct; Υ(2S):60-70 % direct; Υ(1S): 50-70 % direct

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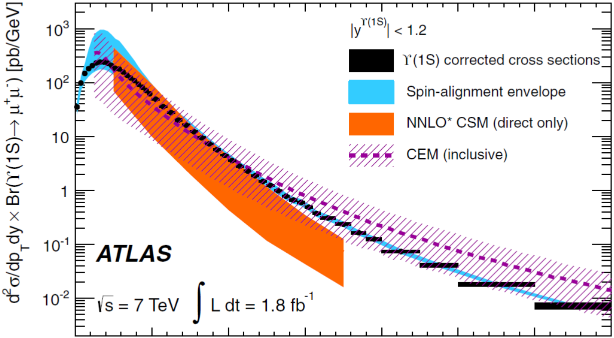

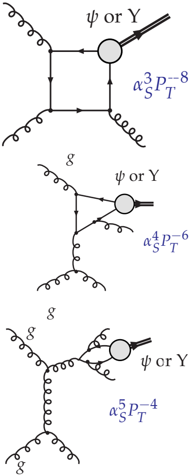

CSM theory curve extrapolated to prompt: × 2

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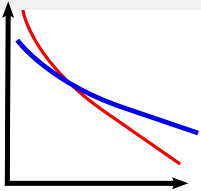

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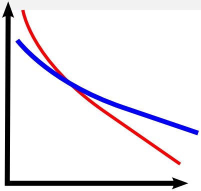

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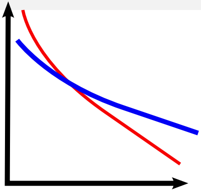

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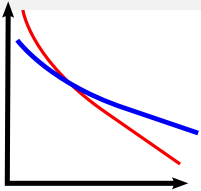

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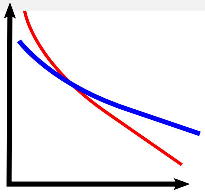

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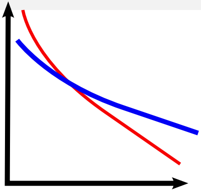

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- Polarisation: ${}^1S_0^{[8]}$: unpolarised; ${}^3S_1^{[8]}$ & ${}^3P_J^{[8]}$: transverse

QCD corrections to the CEM P_T dependence

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

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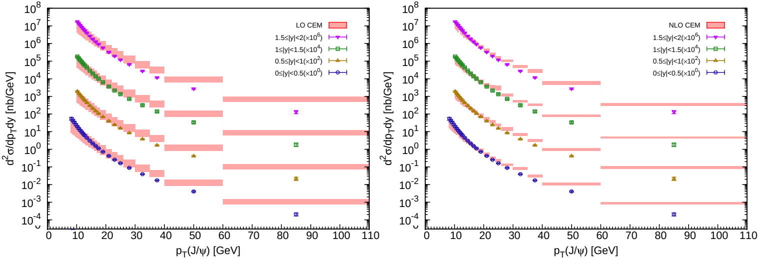

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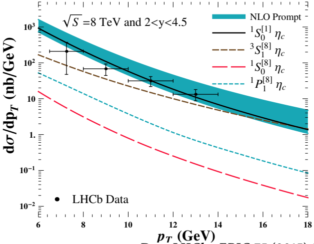
- This motivates the study of new observables

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

The last piece in the puzzle: the η_c



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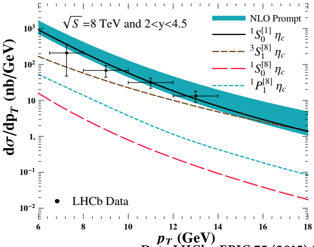

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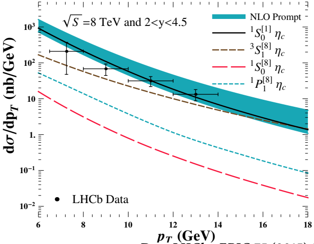

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- Any CO contribution would create a surplus
- Even *neglecting* the *dominant* CS, this induces constraints on CO J/ψ LDMEs

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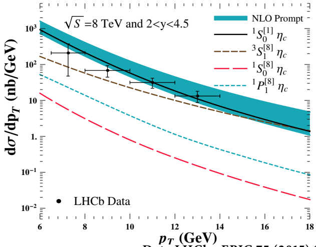

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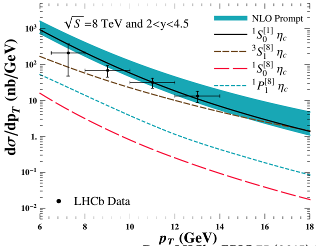
The last piece in the puzzle: the η_c



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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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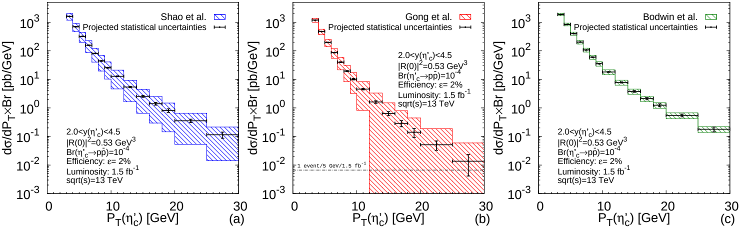

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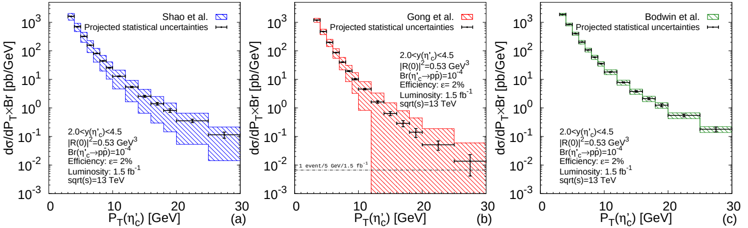

→ Belle-II data on the inclusive $\psi(2S)$ production will also be crucial

Part III

Why is it equally important to understand 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 ...

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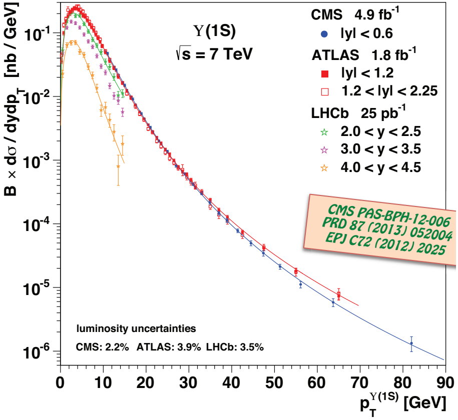

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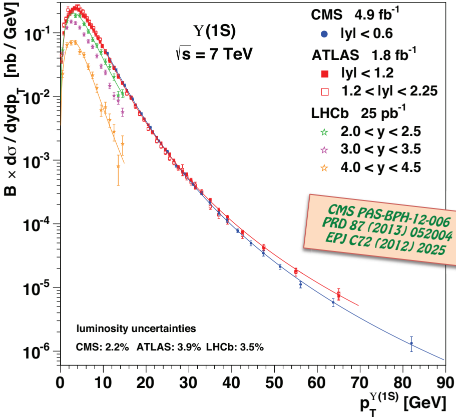

Most probably the production of a Υ with P_T = 90 GeV, even also 20 GeV, has very few things to do with the bulk of Υ

P_T-integrated quarkonium production in a few statements

Y. Feng, JPL, J.X. Wang, EPJC (2015) 75:313

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- All this does not allow one to draw a clear picture about the CO/CS dominance

Part IV

New observables in quarkonium production

Associated-quarkonium production

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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)	--	--	--	Initial vs Final state effects ?
J/ψ in jet.	LHCb, CMS	LO	--	LO	Prod. Mechanism (?)
J/ψ(ϒ) + jet	--	--	--		Prod. Mechanism (QCD corrections)
Isolated J/ψ(ϒ)	--	--	--	--	Prod. Mechanism (CS dominant ?)
J/ψ+b	--	--	--	LO	Prod. Mechanism (CO dominant) + DPS
ϒ+D	LHCb	LO	LO ?	LO	DPS
ϒ+γ	--	NLO, NNLO*	LO ?	LO	Prod. Mechanism (CO LDME mix) + gluon TMD/PDF
ϒ vs mult.	CMS	--	--	--	
ϒ+Z	--	NLO	LO ?	LO	Prod. Mechanism + DPS
ϒ+ϒ	CMS	NLO ?	LO ?	LO ?	Prod. Mechanism (CS dominant ?) + DPS + gluon TMD

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

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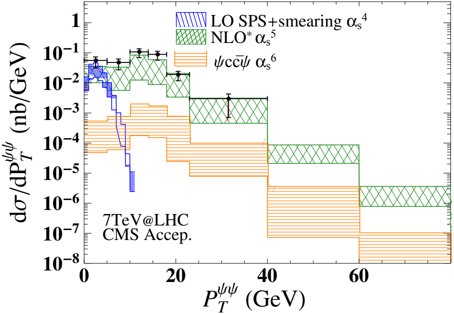

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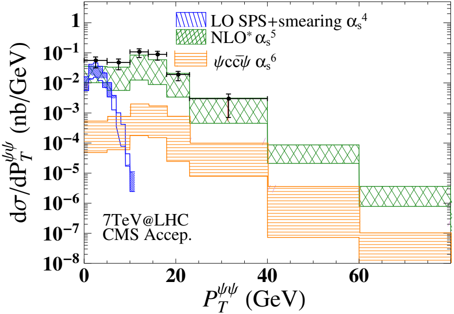

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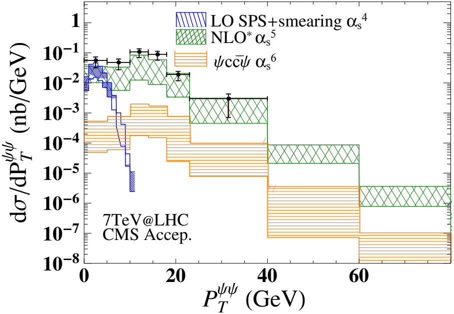

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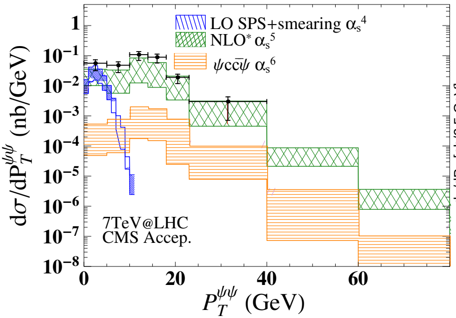

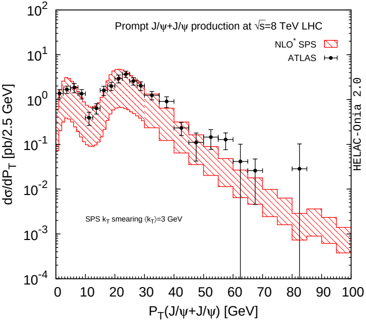

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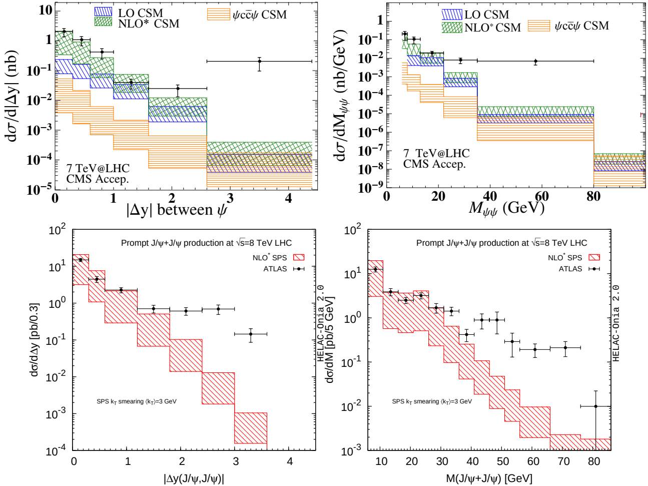

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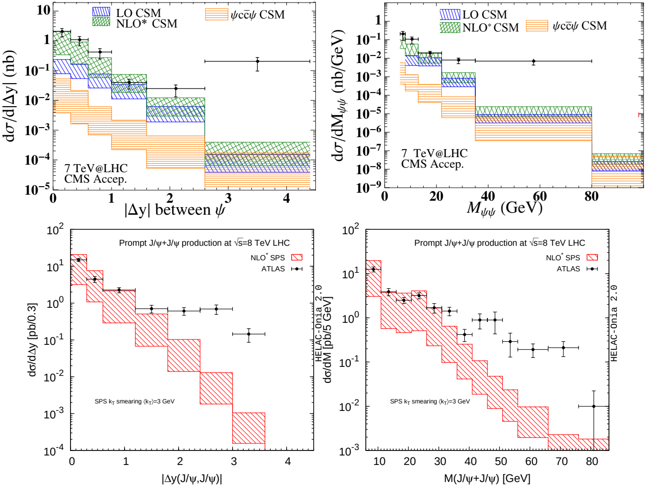

The most natural solution for this excess is the independent production of two J/ψ

→ double parton scattering

Double parton scatterings in double J/ψ production

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

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NB: Agreement not perfect with the ATLAS data

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

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- Hence the importance of measuring $J/\psi + \psi'$ and $J/\psi + \chi_c$
- $J/\psi + \eta_c$ can also tell something about DPS and about $\sigma_{\rm eff}$

Z+prompt J/ψ and W+prompt J/ψ

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

ATLAS Collaboration, Eur. Phys. J. C 75 (2015) 229; JHEP 1404 (2014) 172
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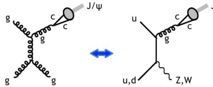

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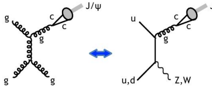

- Tensions are confirmed

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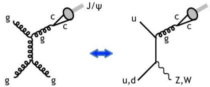
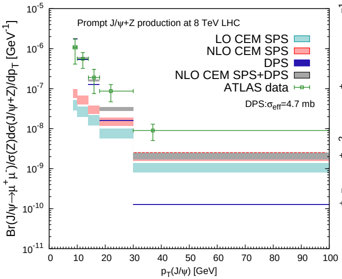
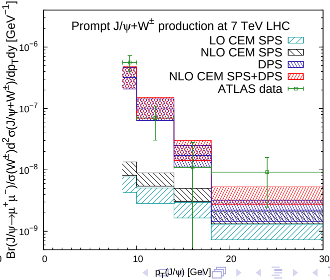


- Tensions are confirmed but can be solved by introducing a DPS yield with $\sigma_{\text{eff}} = 4.7^{+2.4}_{-1.5}$ mb for $\psi + Z$ and $\sigma_{\text{eff}} = 6.1^{+3.3}_{-1.9}$ mb for $\psi + W$

JPL, H.S. Shao, JHEP 1610 (2016) 153; JPL, H.S. Shao, N. Yamanaka, PLB 781 (2018) 485





Harvesting quarkonium data: 5 extractions using theory

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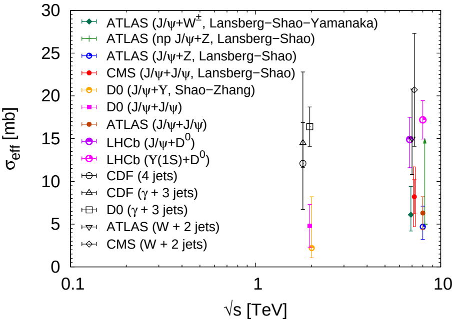

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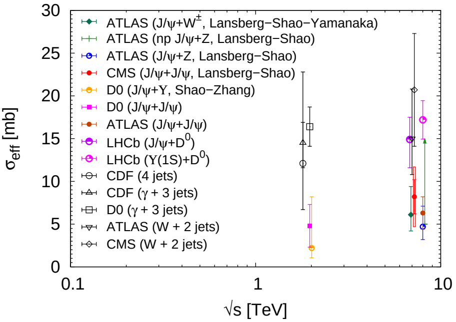

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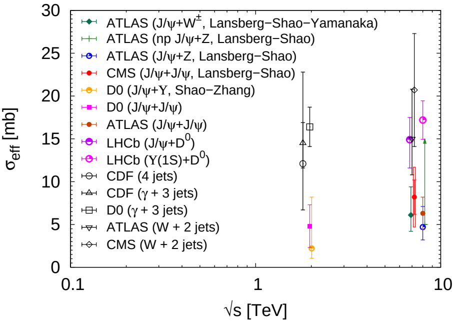

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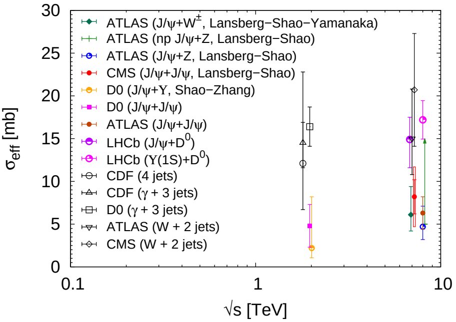

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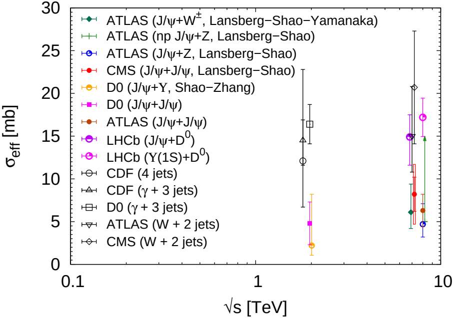

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CMS JHEP05(2017)013

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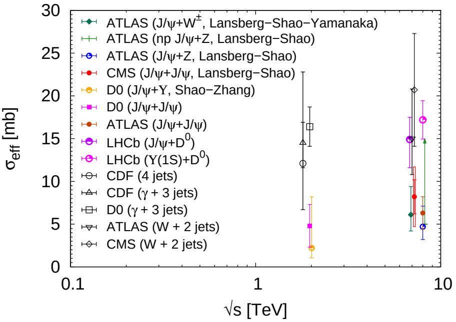

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CMS JHEP05(2017)013

- 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 V

Conclusion

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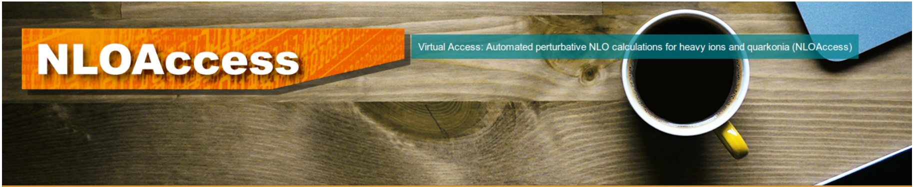
- They also start to tell us new information on the gluon Transverse Momentum Distribution distributions

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 VI

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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DPS $[\sigma_{\rm eff} = 14.5 \pm 1.7^{+1.7}_{-2.3}$ mb$]$	$8.1 \pm 0.9^{+1.6}_{-1.3}$	$7.5 \pm 0.8^{+1.5}_{-1.2}$	$4.9 \pm 0.5^{+1.0}_{-0.8}$
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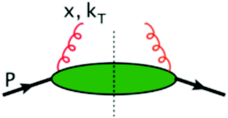
- REMINDER: it is not an option to "switch off"/ignore the NLO CS contribution [parameter free]
- Yet, room for DPS; however tension if $\sigma_{\rm eff} \simeq 7$ mb
- Tension between LHCb and other di-J/ψ extractions [rapidity effect ?]

Gluon TMDs in unpolarised protons



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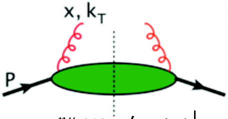

- Gauge-invariant definition:

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

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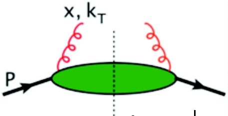

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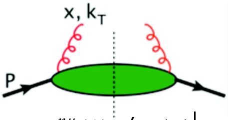
- Parametrisation: **P. J. Mulders, J. Rodrigues, PRD 63 (2001) 094021; D. Boer *et al.* JHEP 1610 (2016) 013**

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

Gluon TMDs in unpolarised protons



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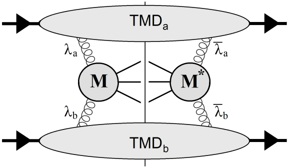
- f_1^g: TMD distribution of unpolarised gluons
- $h_1^{\perp g}$: TMD distribution of linearly polarised gluons

[Helicity-flip distribution]

gg fusion in arbitrary unpolarised process [colourless final state]

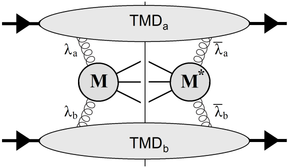
$d\sigma^{gg} \propto$



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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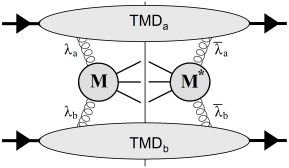
⇒ double helicity flip, azimuthally independent



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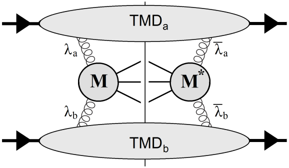

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$\Rightarrow$ single helicity flip, $\cos(2\phi)$-modulation

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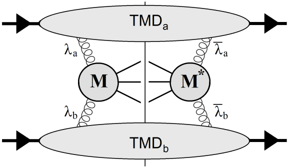

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J.P.L., H.S. Shao NPB 900 (2015) 273

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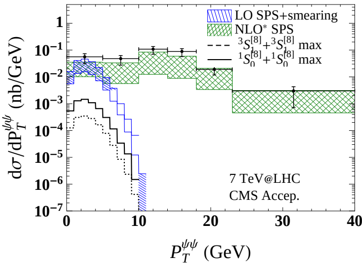

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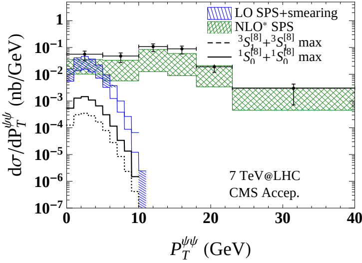

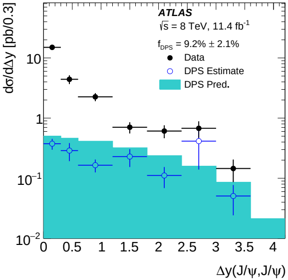

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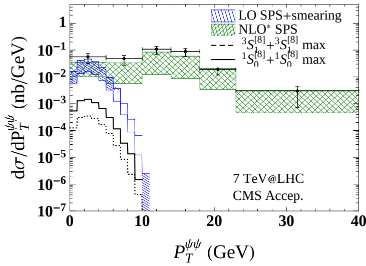

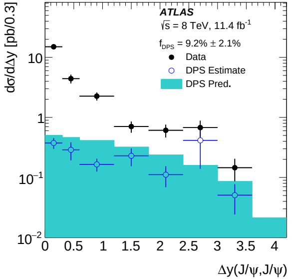

- DPS in LHCb data [kinematical distributions well controlled : independent scatterings]

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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  where $g(x)$ is the usual collinear PDF
- First experimental determination [with a pure colorless final state] of $\langle k_T^2 \rangle$
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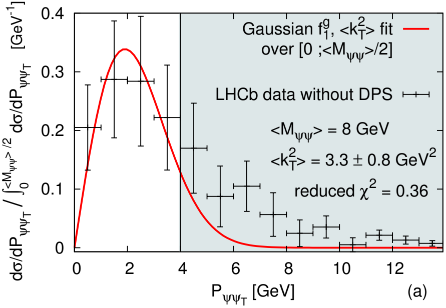

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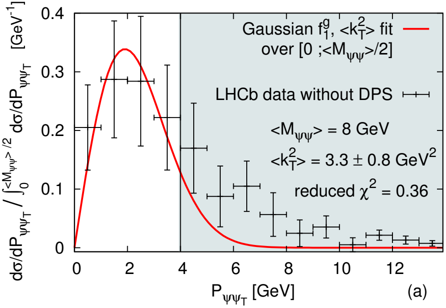

- Integration over $\phi \Rightarrow \cos(n\phi)$-terms cancel out
- $F_2 \ll F_1 \Rightarrow$ only $\mathcal{C}[f_1^g f_1^g]$ contributes to the cross-section
- No evolution so far: $\langle k_T^2 \rangle \sim 3$ GeV^2 accounts both for non-perturbative and perturbative broadenings at a scale close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

Expected azimuthal asymmetries

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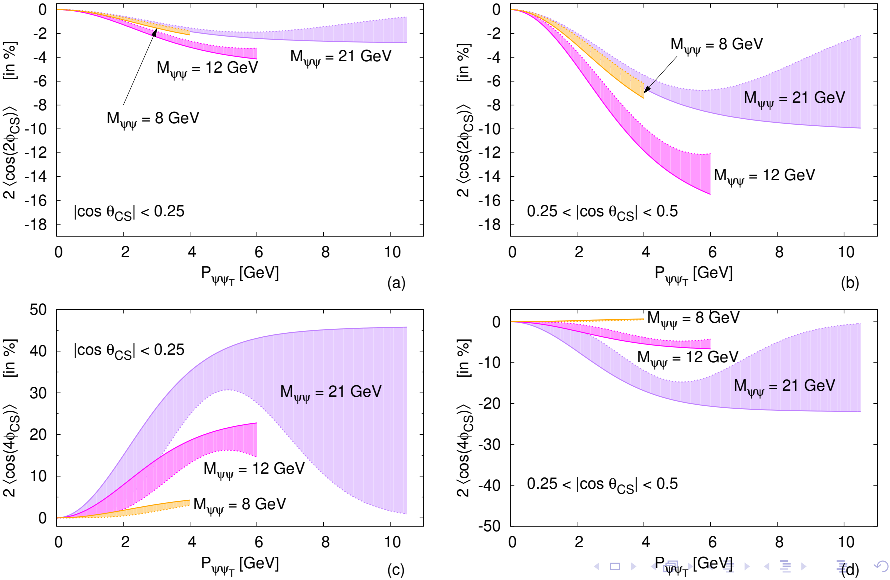

Basic pQCD approach: the Colour Singlet Model (CSM)

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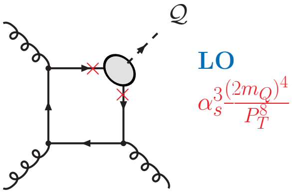

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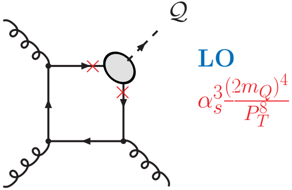

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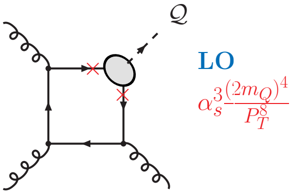

- Non-perturbative binding of quarks → Schrödinger wave function

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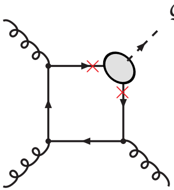

LO

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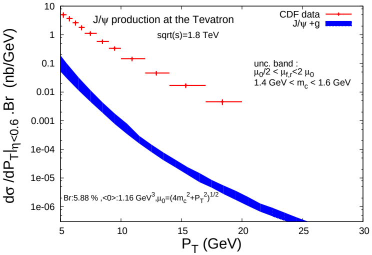

CDF, PRL 79:572 & 578,1997

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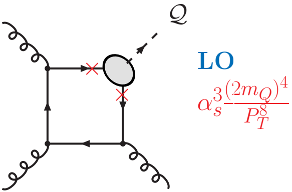

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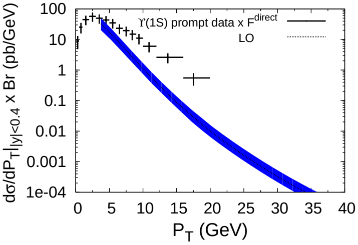

CDF, PRL 88:161802,2002

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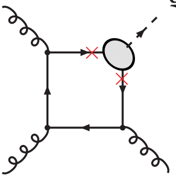
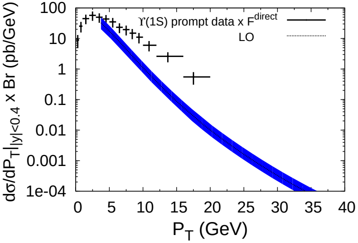


LO

$\alpha_s^3 \frac{(2m_Q)^4}{P_T^8}$

- Non-perturbative binding of quarks → Schrödinger wave function



- 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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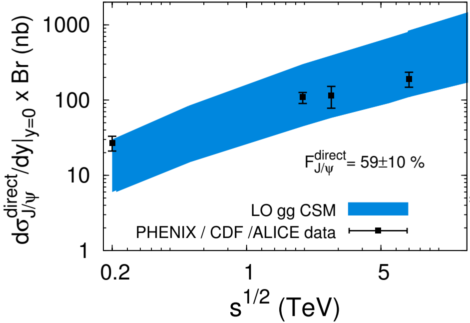

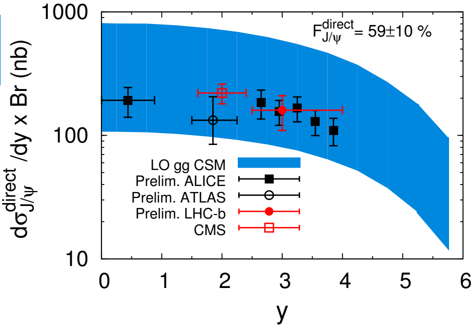

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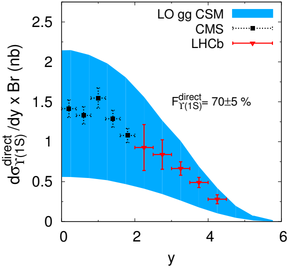

CMS PRD 83 (2011) 112004; LHCb EPJC 72 (2012) 2025

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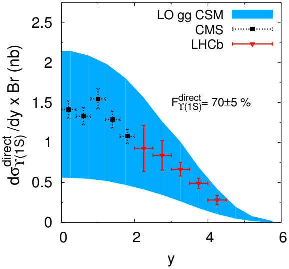

CMS PRD 83 (2011) 112004; LHCb EPJC 72 (2012) 2025

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

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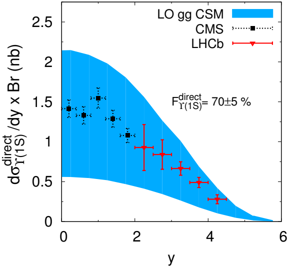


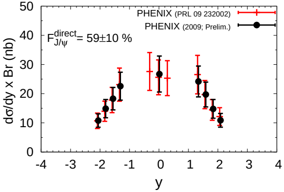
CMS PRD 83 (2011) 112004; LHCb EPJC 72 (2012) 2025

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

S. J. Brodsky and JPL, PRD 81 051502 (R), 2010.

→ J/ψ



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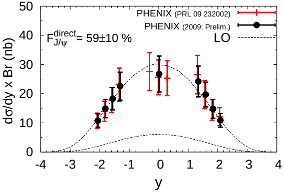

LO: $gg \to J/\psi g$ (see slide 5, nothing new !)

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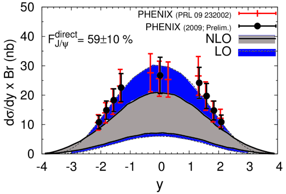
→ J/ψ



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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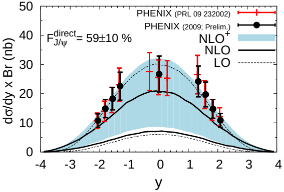

NLO$^+$: possible new contribution at LO $cg \to J/\psi c$

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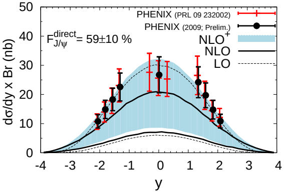

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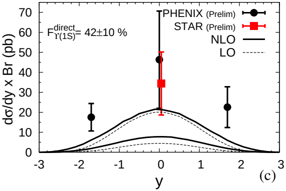

* Sorry: I should update these plots (updated data and fraction is about 60 %)

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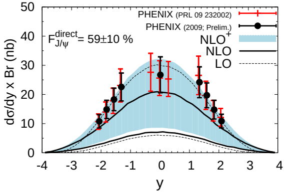
→ J/ψ



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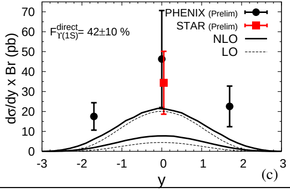

A priori, good convergence NLO w.r.t. LO

[I will come back to that later]

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NLO NRQCD up to RHIC

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

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

- 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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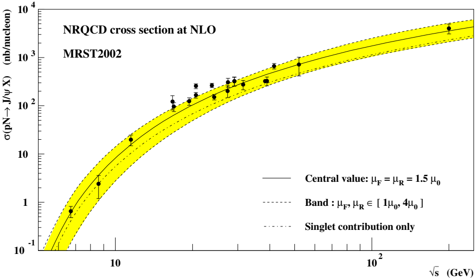

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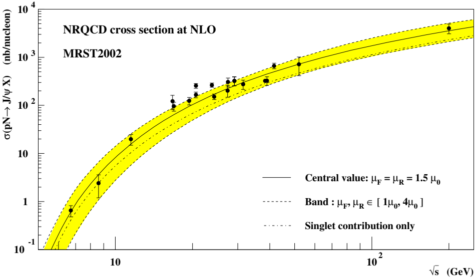

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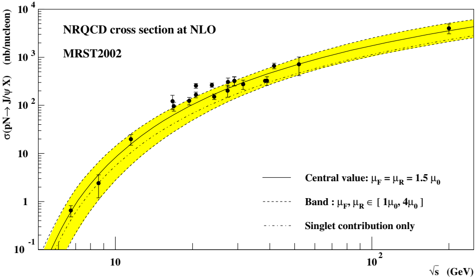

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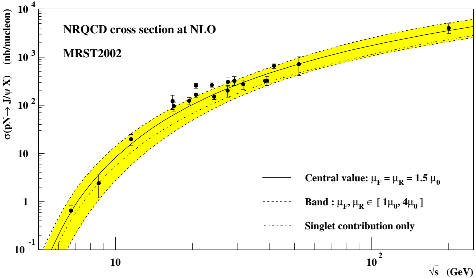

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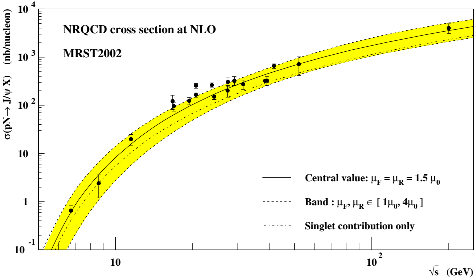

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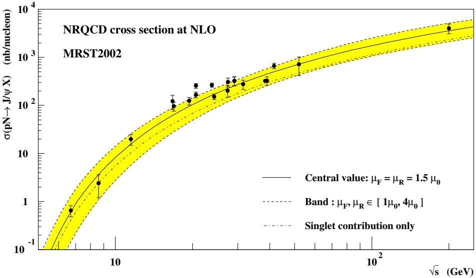

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- Never updated with LDMEs fitted at NLO

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

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- constant feed-down (FD) fractions
  - $F^{\rm direct}_{J/\psi} = 60 \pm 10\%$
  - $F^{\rm direct}_{\Upsilon(1S)} = 66 \pm 10\%$
  - $F^{\rm direct}_{\Upsilon(1S+2S+3S)} = 60 \pm 10\%$
  - Uncertainty on $F^{\rm direct}$ 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}
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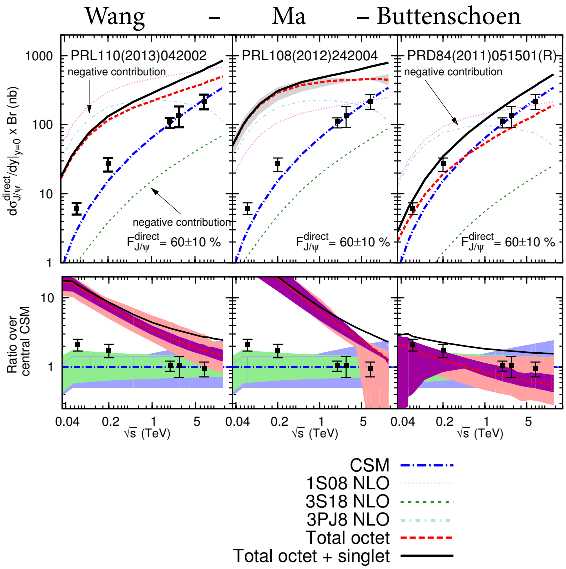
B. Gong, *et al.* PRL 112 (2014) 3, 032001.	-10.36×10^{-2}	11.15×10^{-2}	-4.1×10^{-2}

[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



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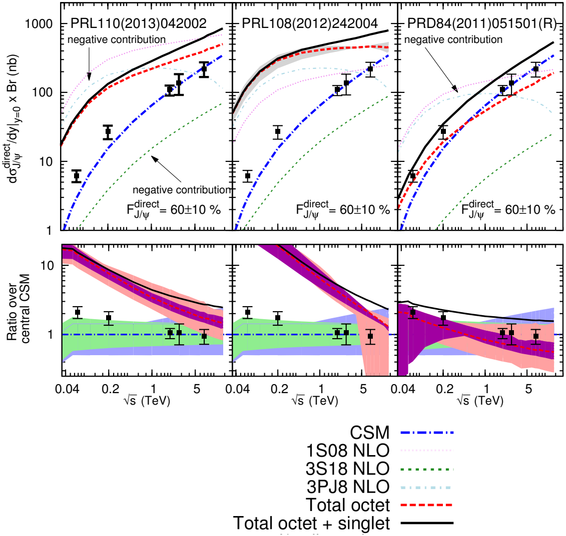

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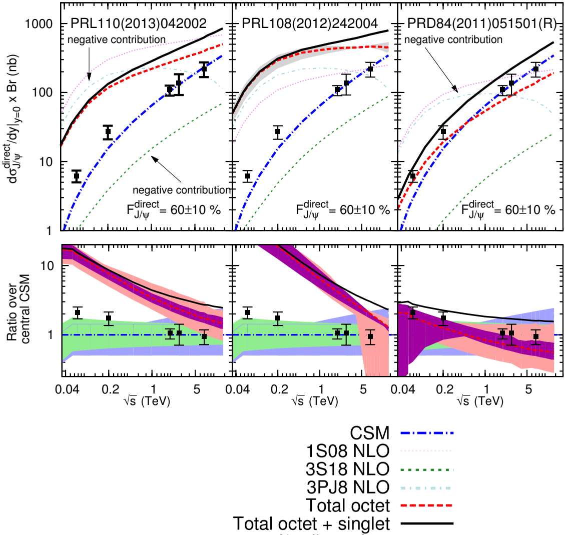

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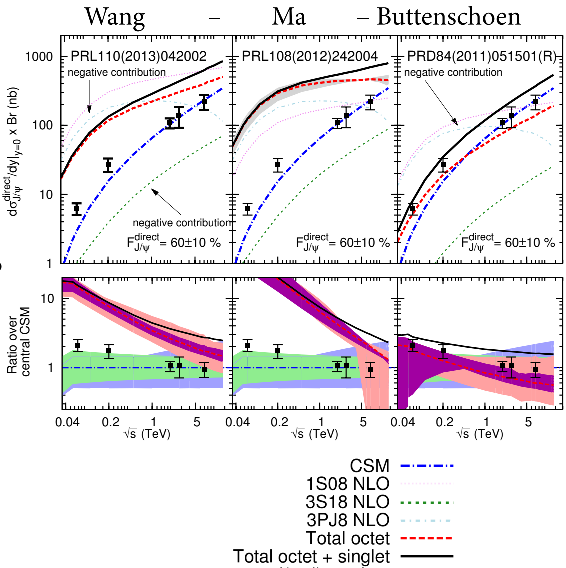

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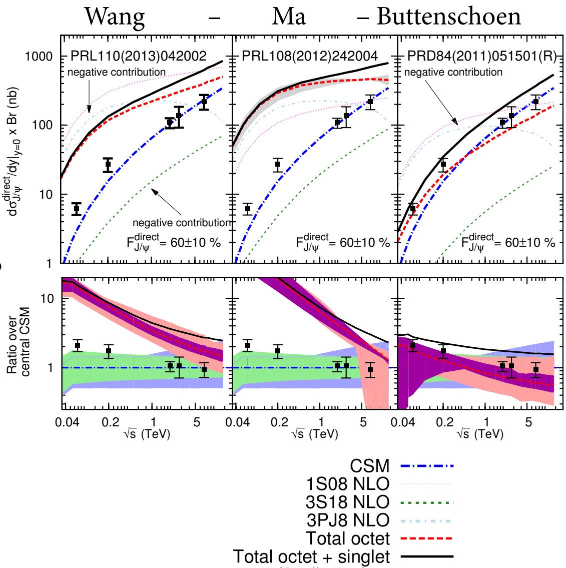

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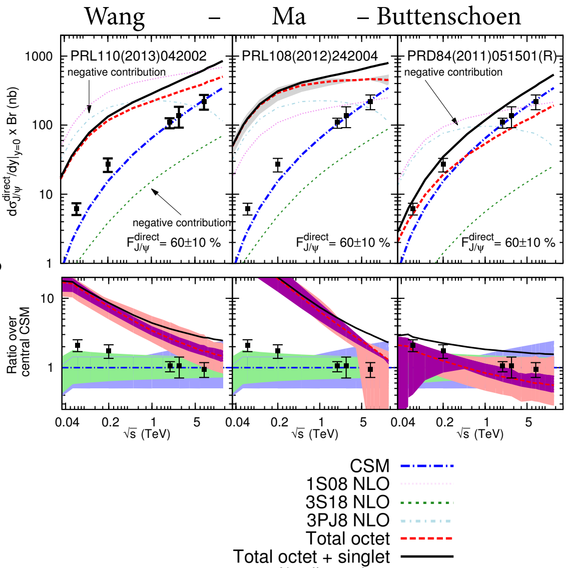

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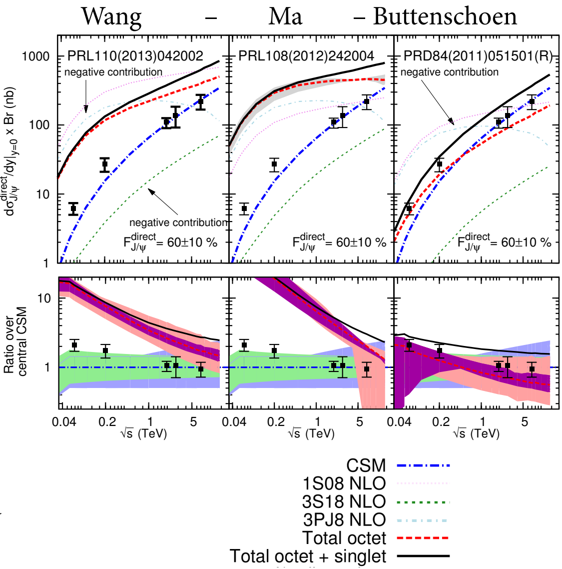
- Not a surprise since the CSM alone accounts well for the data; adding any contribution creates a "surplus"



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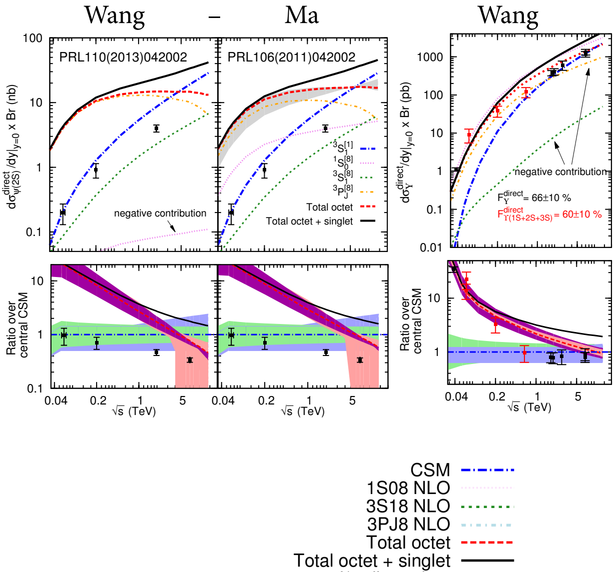

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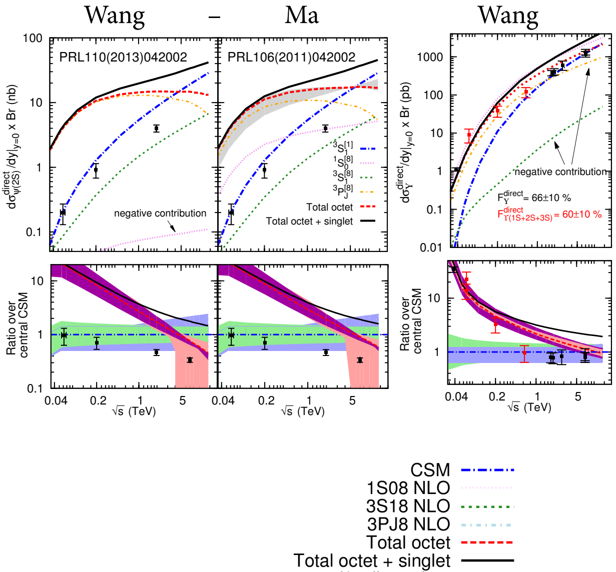

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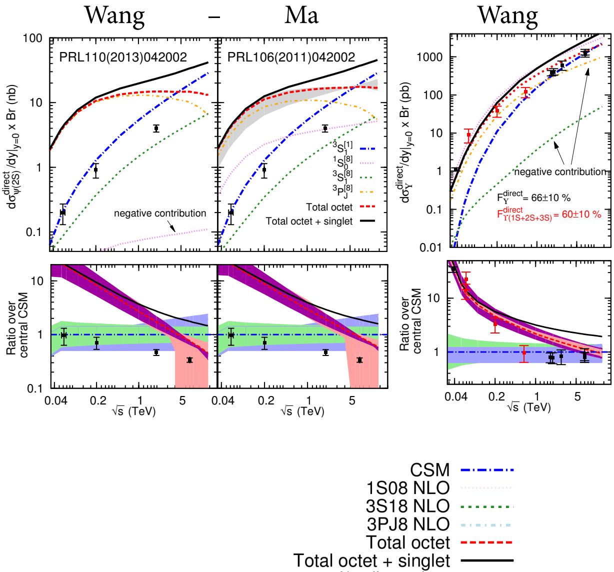
For $\Upsilon(1S)$

- 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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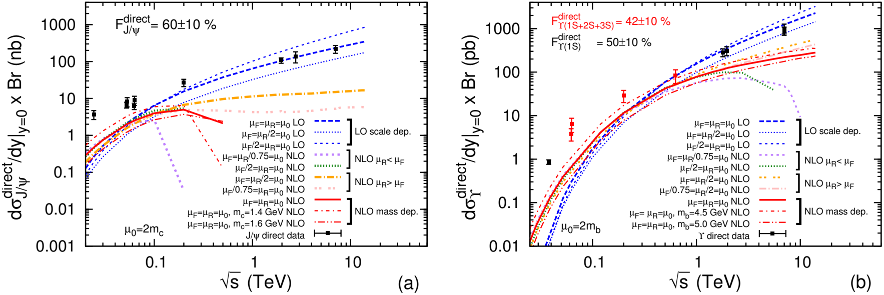

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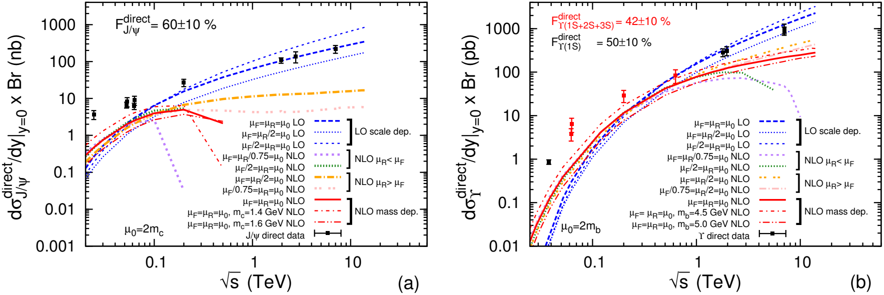

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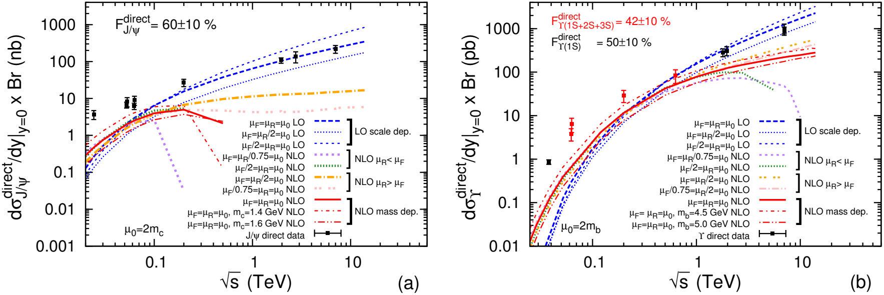

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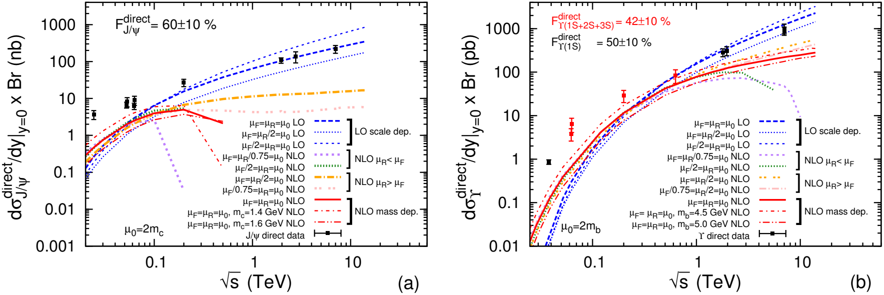

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Is it due to ISR, FSR ? Is NRQCD simply not holding at low P_T ?

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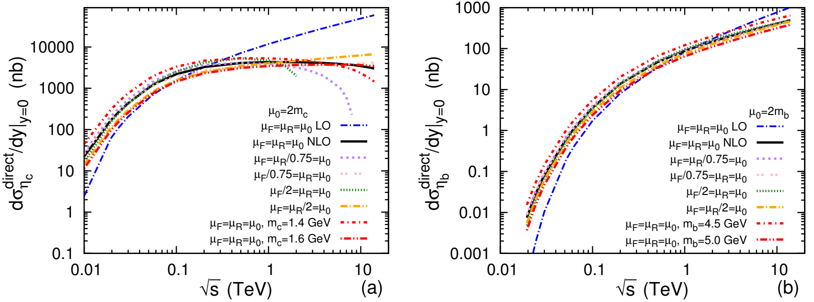

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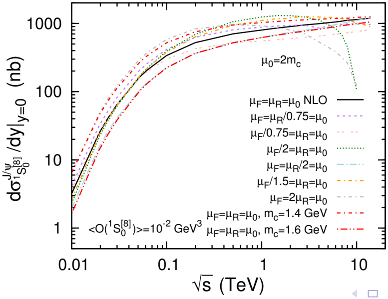

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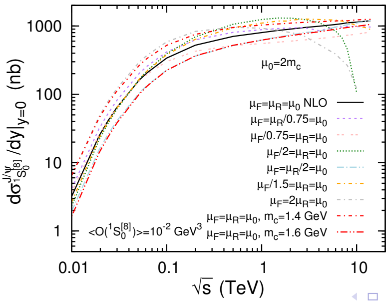
M. Echevarria, T. Kasemets, JPL, C. Pisano A. Signori (in progress); J.P. Ma, J.X. Wang, S. Zhao, PRD 88 (2013) 014027



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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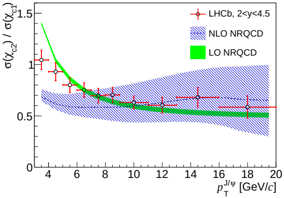

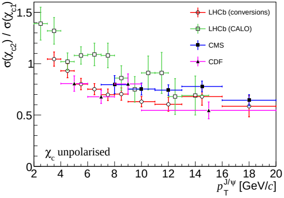

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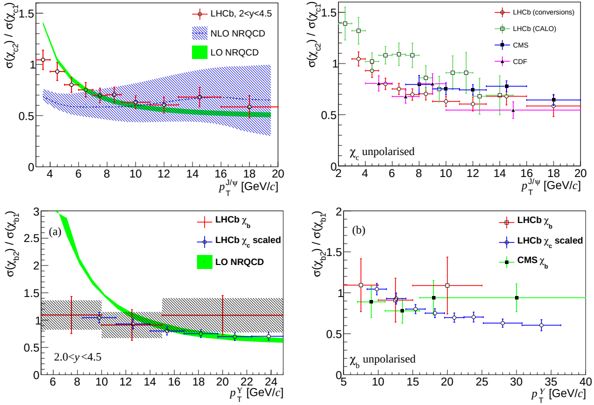

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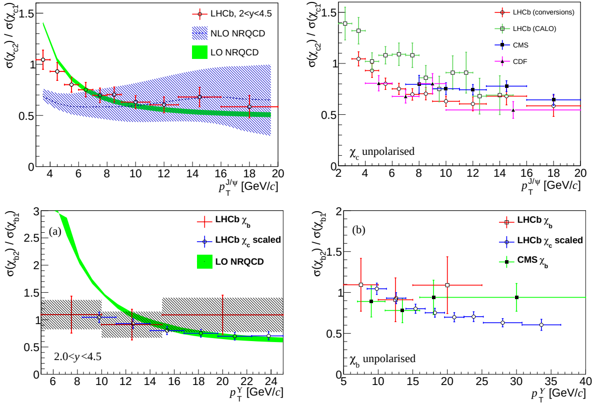

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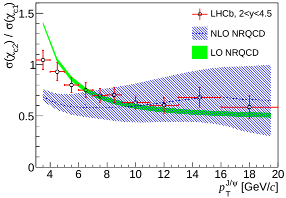

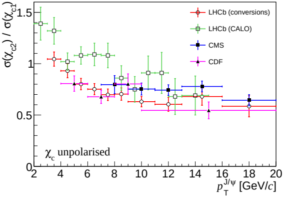

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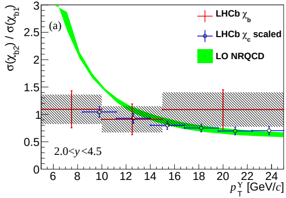

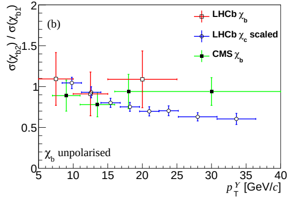

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- The nature (quantum #) of the produced final state seems still relevant !

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

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

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$$\begin{aligned}
\langle \mathcal{O}_{^3S_1}(^3S_1^{[1]})\rangle &= 3 \times \langle \mathcal{O}_{^3S_1}(^1S_0^{[1]})\rangle, \\
\langle \mathcal{O}_{^3S_1}(^1S_0^{[8]})\rangle &= \frac{4}{3} \times \langle \mathcal{O}_{^3S_1}(^1S_0^{[1]})\rangle, \\
\langle \mathcal{O}_{^3S_1}(^3S_1^{[8]})\rangle &= 4 \times \langle \mathcal{O}_{^3S_1}(^1S_0^{[1]})\rangle.
\end{aligned} \tag{1}$$

NRQCD Ersatz of the CEM

- In 2005, Bodwin, Braaten and Lee derived relations between NRQCD LDMEs provided that the CEM is interpreted as part NRQCD

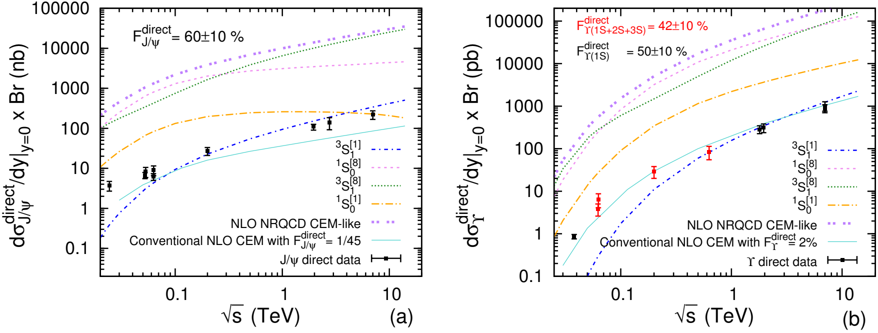
G.T. Bodwin, E. Braaten, J. Lee, PRD 72 (2005) 014004

- These violate the velocity scaling rules also violated by the NLO fits btw
- At LO in v, one has

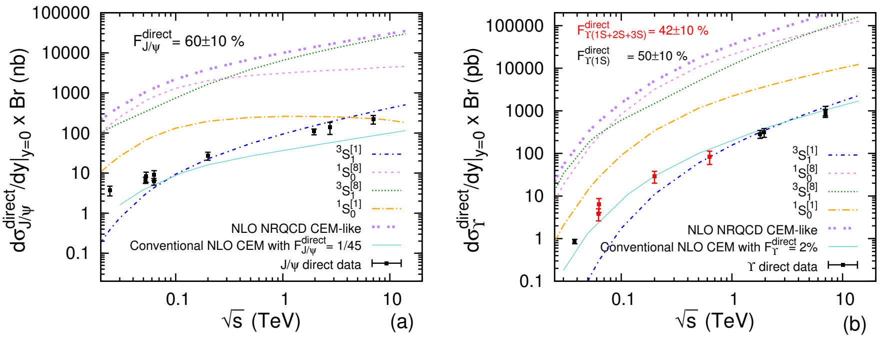
$$\begin{aligned}
\langle \mathcal{O}_{^3S_1}(^3S_1^{[1]})\rangle &= 3 \times \langle \mathcal{O}_{^3S_1}(^1S_0^{[1]})\rangle,\\
\langle \mathcal{O}_{^3S_1}(^1S_0^{[8]})\rangle &= \frac{4}{3} \times \langle \mathcal{O}_{^3S_1}(^1S_0^{[1]})\rangle,\\
\langle \mathcal{O}_{^3S_1}(^3S_1^{[8]})\rangle &= 4 \times \langle \mathcal{O}_{^3S_1}(^1S_0^{[1]})\rangle.
\end{aligned} \quad (1)$$

- 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

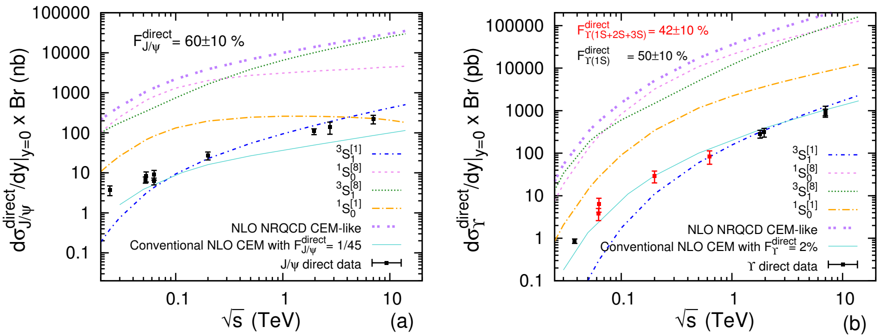

$F^{direct}_{J/\psi}$ = 60±10 %
$d\sigma^{direct}_{J/\psi}/dy|_{y=0}$ x Br (nb)
$^3S_1^{[1]}$
$^1S_0^{[8]}$
$^3S_1^{[8]}$
$^1S_0^{[1]}$
NLO NRQCD CEM-like
Conventional NLO CEM with $F^{direct}_{J/\psi}$ = 1/45
J/ψ direct data
$\sqrt{s}$ (TeV)
(a)
$F^{direct}_{\Upsilon(1S+2S+3S)}$ = 42±10 %
$F^{direct}_{\Upsilon(1S)}$ = 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
$\sqrt{s}$ (TeV)
(b)

CEM results



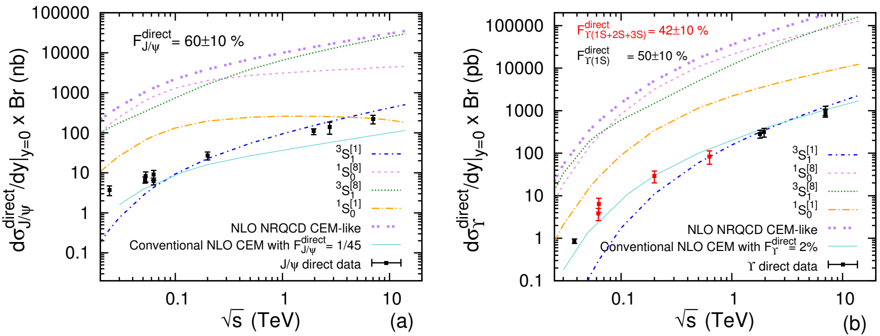
- NRQCD-like CEM badly overshoots the data

CEM results



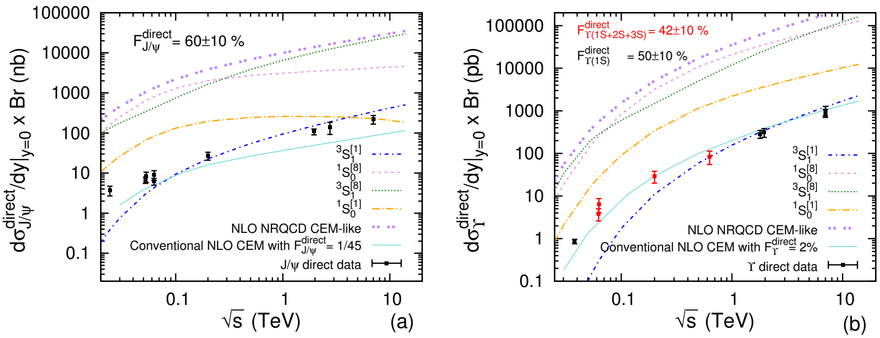
- NRQCD-like CEM badly overshoots the data
  - Expected since CO LDMEs are as large as the CS, whereas the hard parts tend to be larger.

CEM results



- 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

CEM results



- 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