Quarkonium production in proton-proton and proton-nucleus collisions

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Program INT-17-1b – Precision Spectroscopy of QGP Properties with Jets and Heavy Quarks
INT Seattle, May 31, 2017

Part I

Introduction

Approaches to Quarkonium Production

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

CEM vs. CSM vs. COM

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3. COLOUR OCTET MECHANISM
   - one non-perturbative parameter per Fock States
   - 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 QCD corrections to the C(S,E,O)M

QCD corrections to the CSM for Υ at colliders

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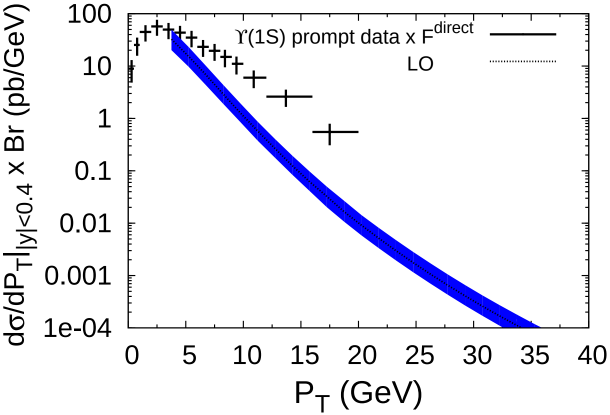

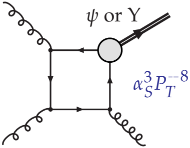

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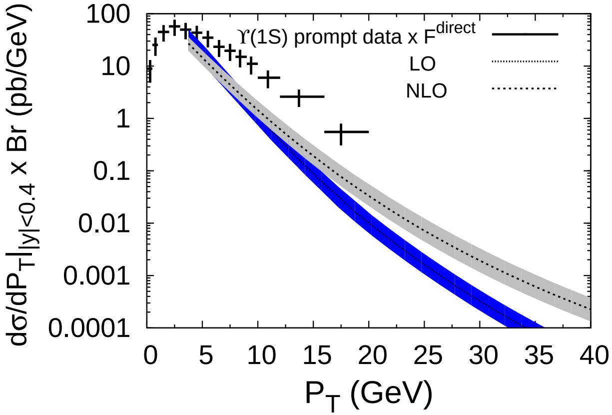

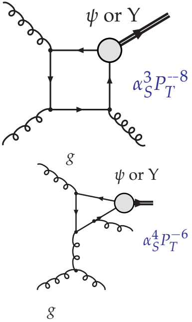

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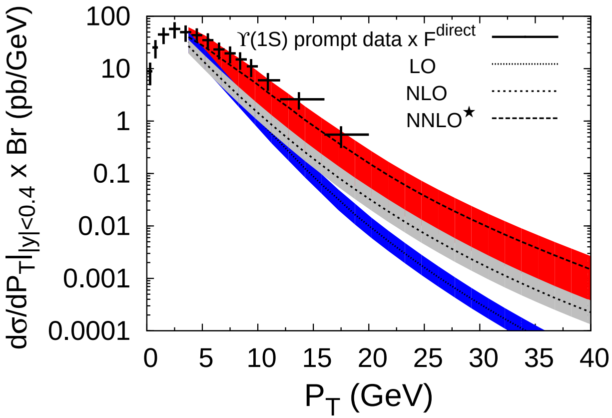

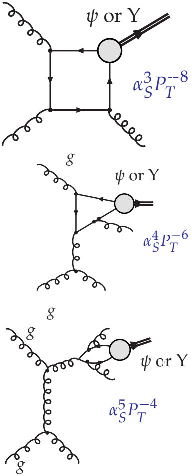

+ double t-channel gluon exchange at α_S^5
Attention: the NNLO* is not a complete NNLO

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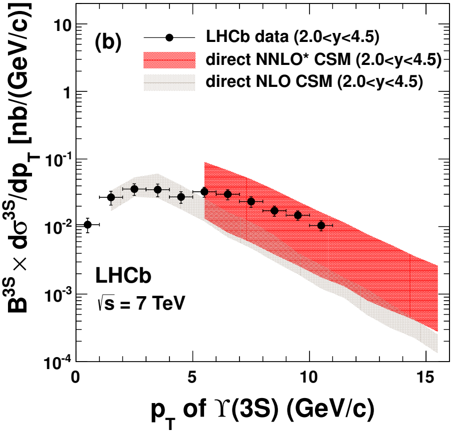

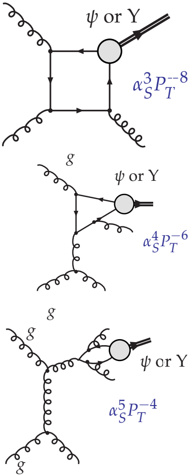

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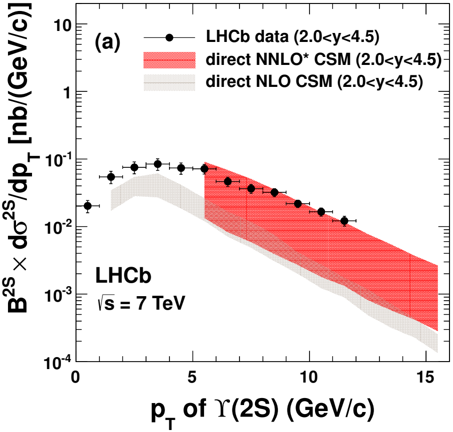

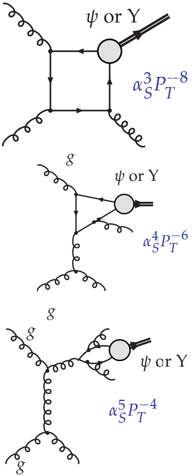

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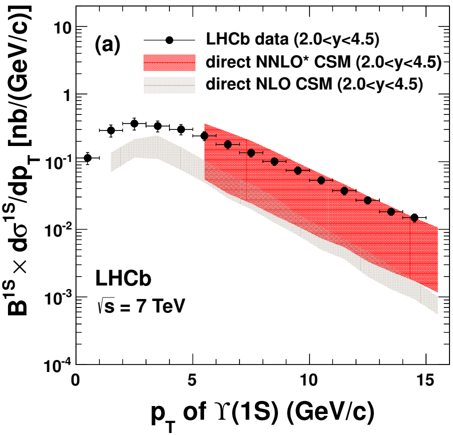

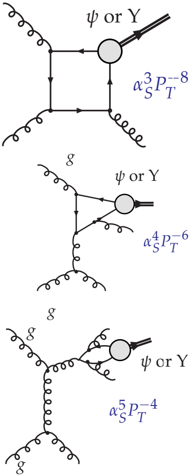

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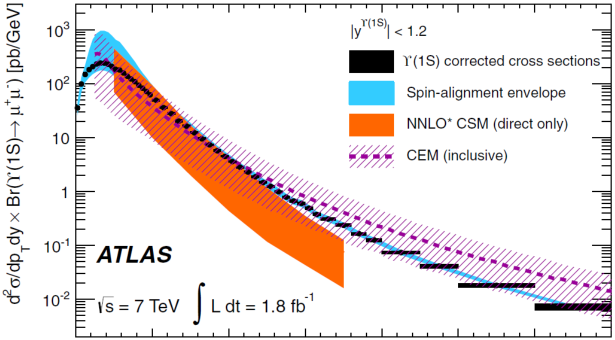

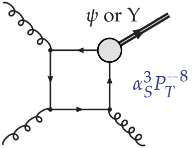

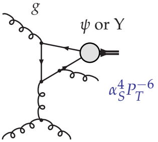

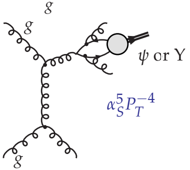

CSM theory curve extrapolated to prompt: × 2

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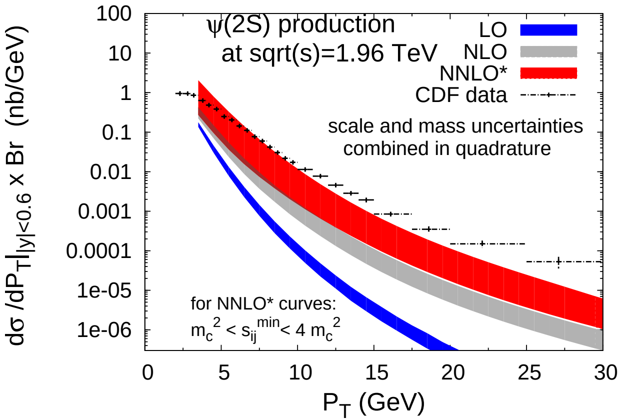

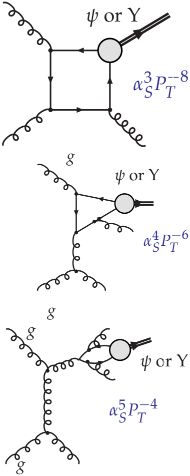

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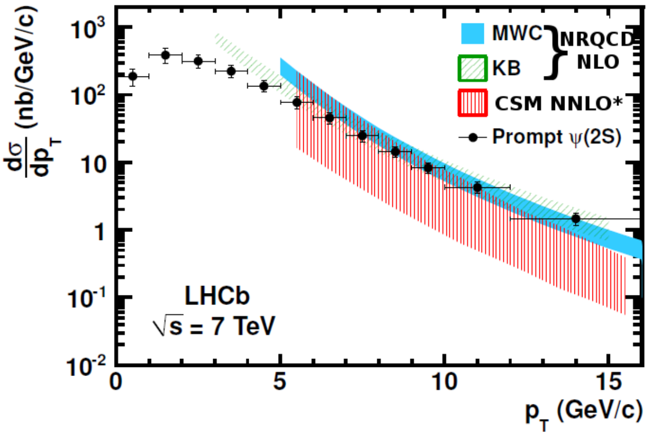

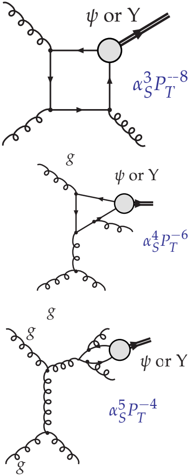

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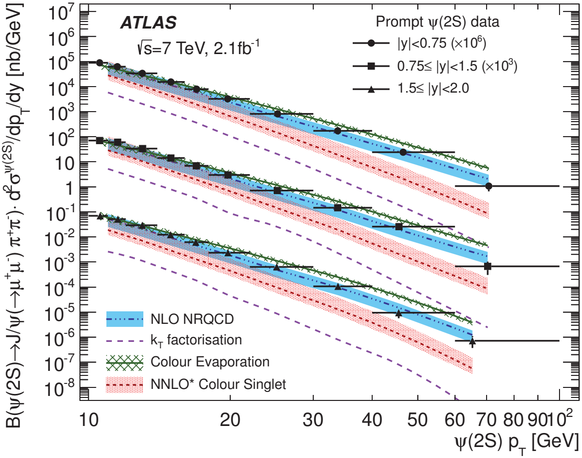
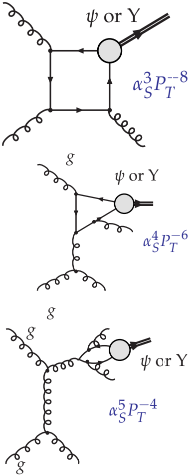
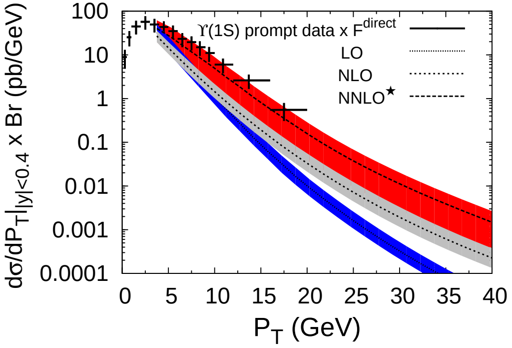
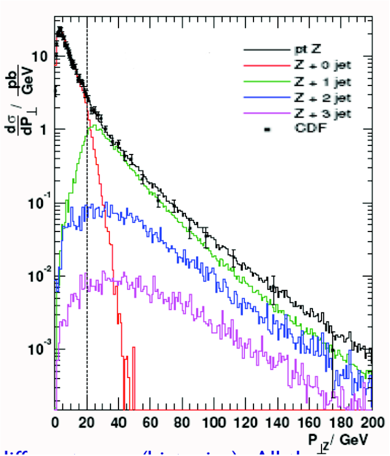


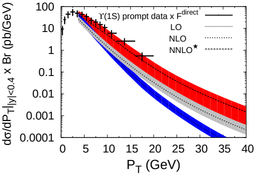


Analogy with the P_T spectrum for the Z^0 boson





Impact of QCD corrections to the CSM at mid and high P_T



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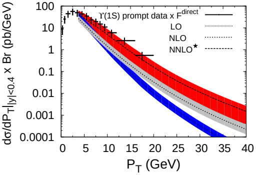

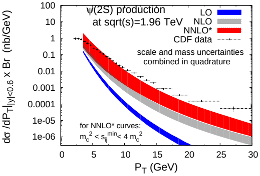

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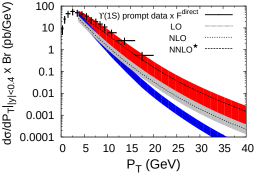

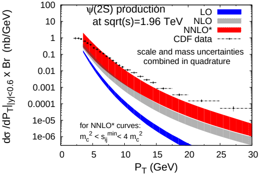

The NNLO* is not a complete NNLO → possibility of uncanceled logs !

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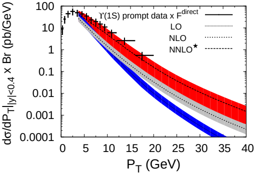

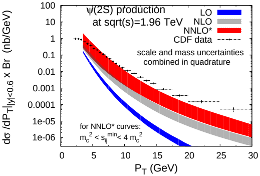

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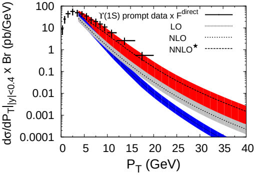

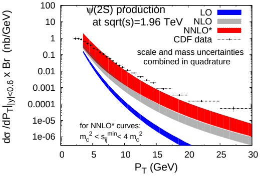

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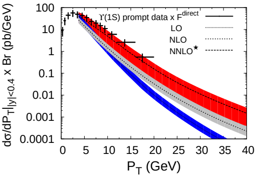

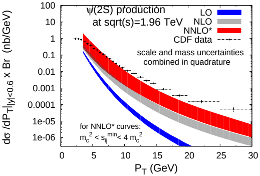

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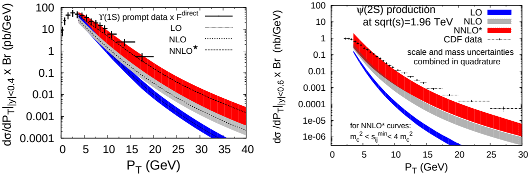

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constraints on ${}^1S_0^{[8]}$ (& ${}^3P_J^{[8]}$): e^+e^-, low P_T pp and η_c	k_T fact. ↔ NNLO Collinear fact. ?

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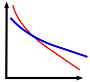

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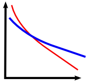

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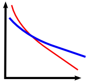

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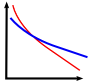

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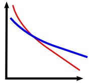

ψ data: a little less hard than the blue curve

2. Colour Evaporation Model

QCD corrections to the COM and CEM

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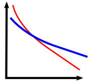

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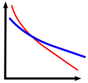

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Confirmed by the first NLO study: JPL, H.S. Shao JHEP 1610 (2016) 153

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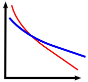

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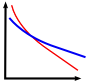

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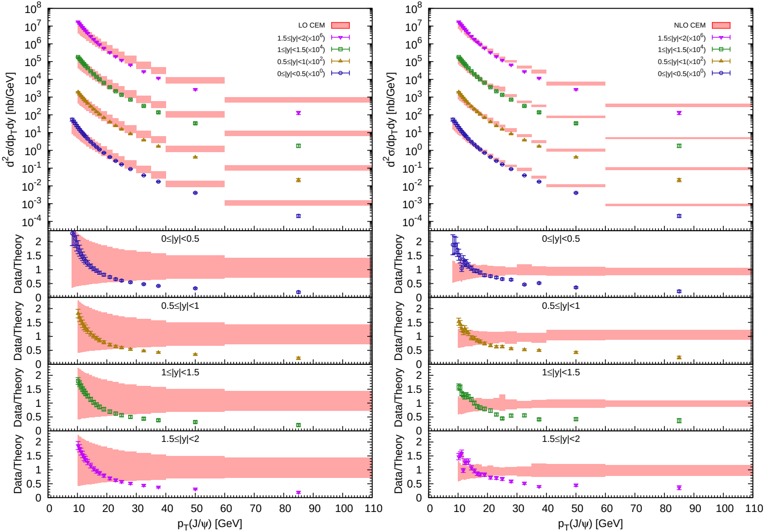
   - The (LO) ICEM not significantly better at large P_T **Y.Q. Ma, R. Vogt PRD 94 (2016) 114029**

QCD corrections (NLO) to the CEM P_T dependence

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



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- Obviously, no consensus on the quarkonium production mechanism, at high, mid and low P_T

The big question: how to treat quarkonium production in *pA* and *AA* collisions ?

Part III

5 lessons from the past

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e.g. **H1,EPJC 25, 2,2002; ZEUS, EPJC 27, 173, 2003**

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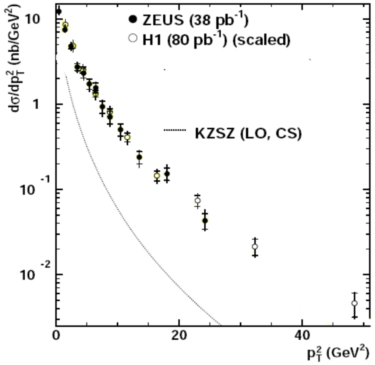

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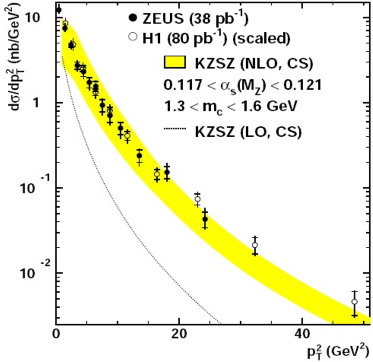

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Followed by data updates :

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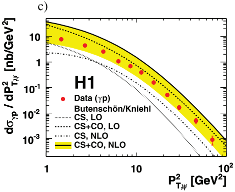

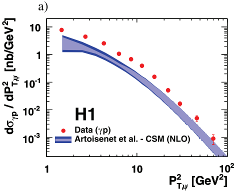

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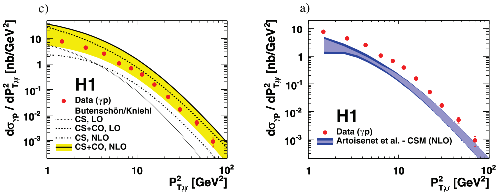

As we say in French: "Tout ça pour ça ..."

Photon-fusion production: from an evidence to a puzzle

VOLUME 89, NUMBER 3 PHYSICAL REVIEW LETTERS 15 JULY 2002

Evidence for the Color-Octet Mechanism from CERN LEP2 $\gamma\gamma \to J/\psi + X$ Data

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(Received 19 December 2001; published 28 June 2002)

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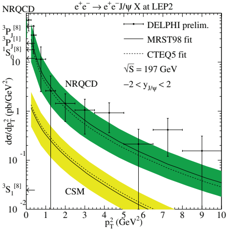

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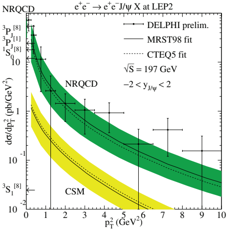

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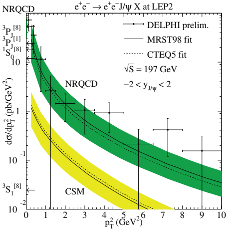

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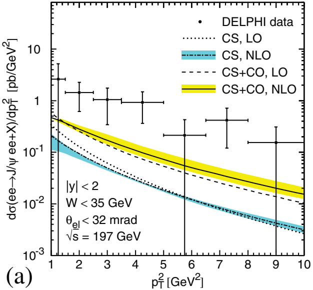

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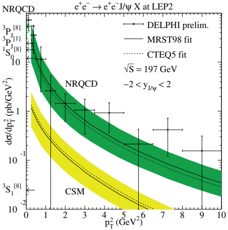

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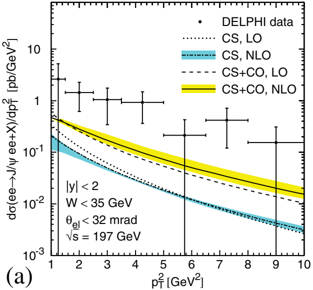

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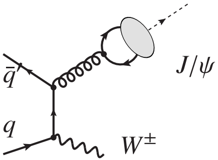

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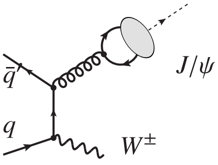

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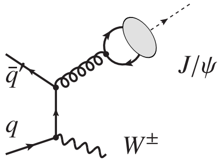

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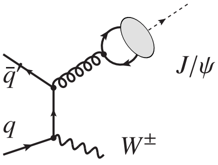

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- Yet the first CSM study shows that the COM and CSM yields are of similar sizes !! a simple α_s counting is not enough **J.P. Lansberg, C. Lorcé, PLB 7 26 (2013) 218**
- $\psi + W$ is not a clean test of CO contributions

"The" Smoking Gun: Polarisation

Quarkonium Working Group CERN Yellow Report, Dec. 2004, CERN-2005-005

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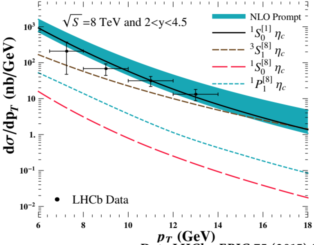
- and this was not anticipated even after the NLO CSM corrections for γp and pp

Part IV

A last lesson from the (close) past: η_c: how not-so-precise data can matter much or The completely unexpected probe

From exotic to essential



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

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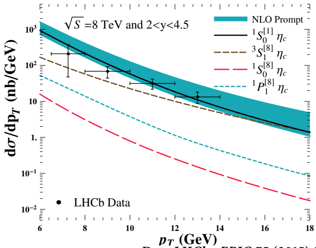

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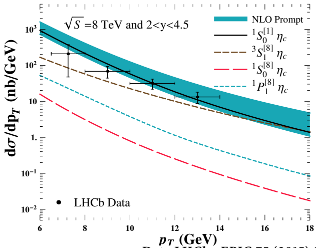

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- Even neglecting the *dominant* CS, this induces constraints on J/ψ LDMEs via HQSS :

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

[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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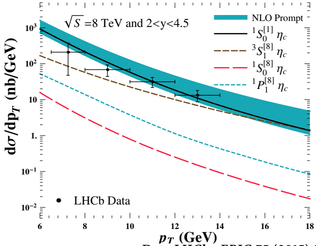

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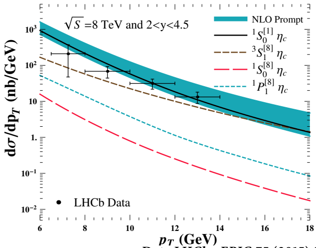

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- Nobody foresaw the impact of measuring η_c yields: 3 PRL published right after the LCHb data came out (Hamburg) M. Butenschoen *et al.* PRL 114 (2015) 092004; (PKU) H. Han *et al.* 114 (2015) 092005; (IHEP) H.F. Zhang *et al.* 114 (2015) 092006

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Part V

Automating the computation of nuclear PDF effects

An automated code to evaluate the impact of nuclear PDF on hard probes I

JPL, H.S. Shao Eur.Phys.J. C77 (2017) 1

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- Not yet interfaced to a Glauber model

  [no centrality and no combinaison with other nuclear effects]

An automated code to evaluate the impact of nuclear PDF on hard probes II

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- Last but not least: the automation of the evaluation allows one to study different nPDF sets AND the scale uncertainties: better control of the theory uncertainties

Fitting the J/ψ pp data

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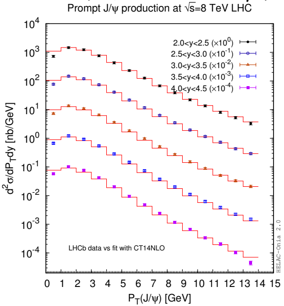

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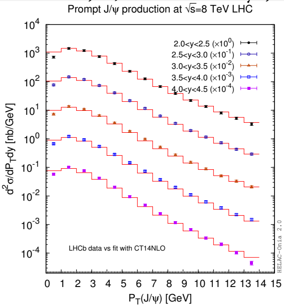

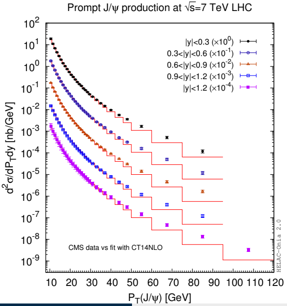

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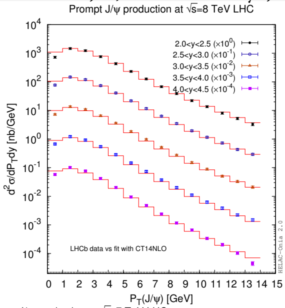

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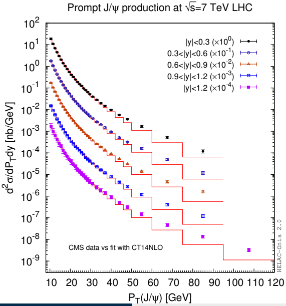

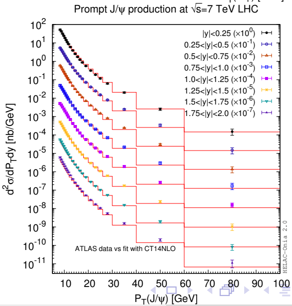

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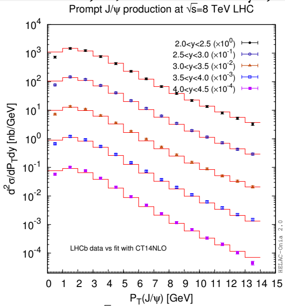

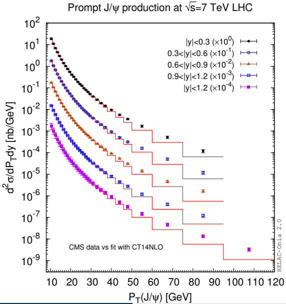

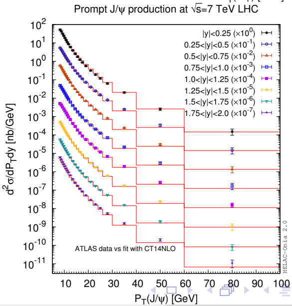

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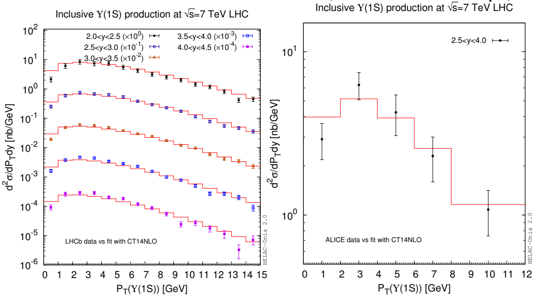

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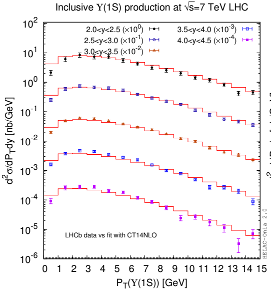

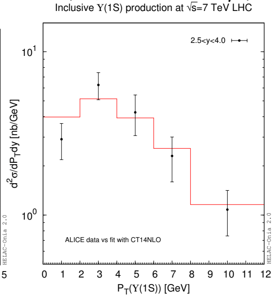

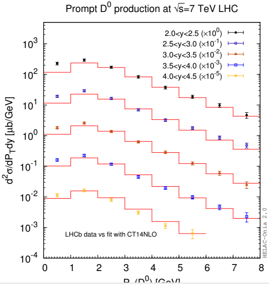

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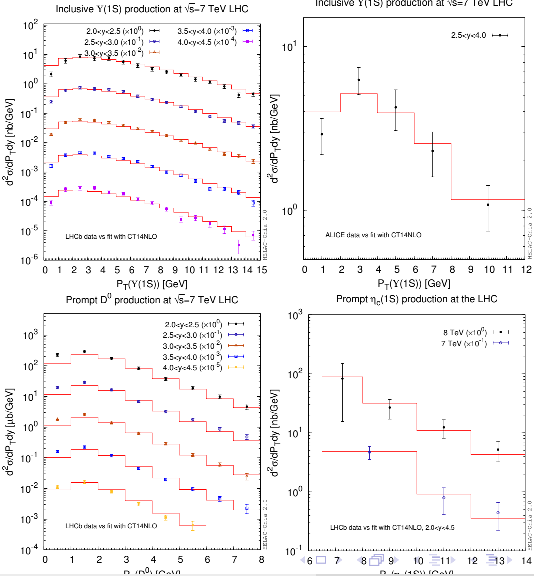
JPL, H.S. Shao Eur.Phys.J. C77 (2017) 1

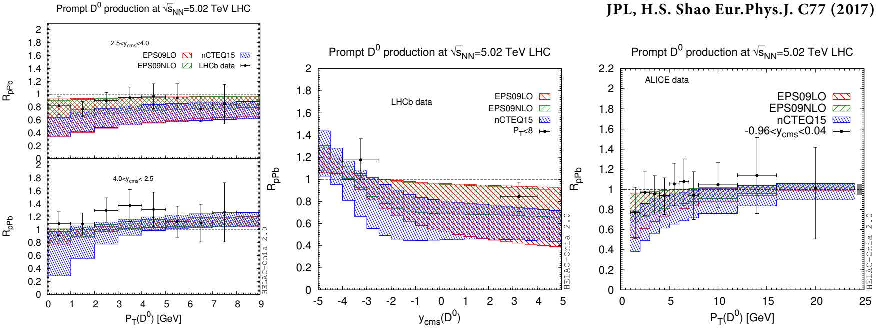


Part VI

Results for *pA* collisions

D^0 results for pA collisions

JPL, H.S. Shao Eur.Phys.J. C77 (2017) 1



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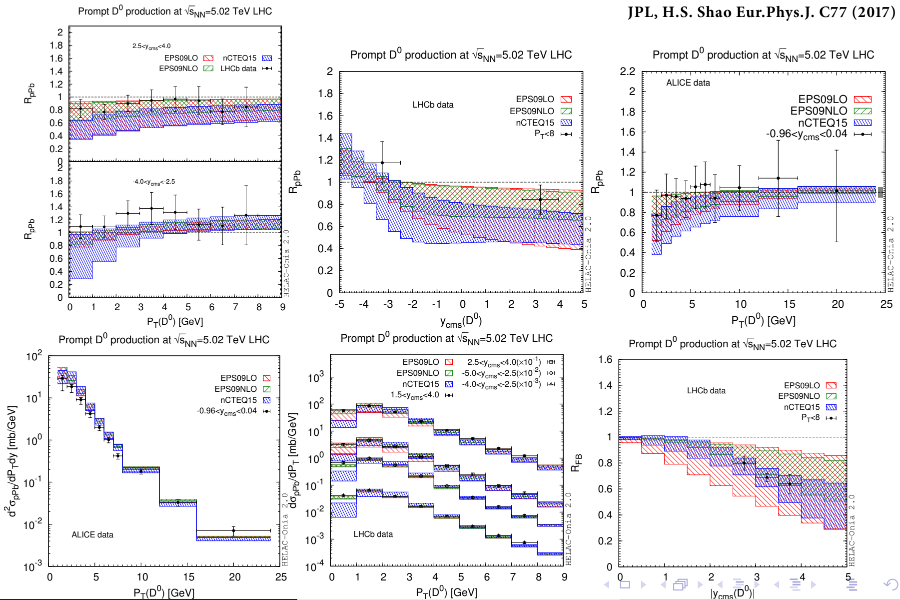
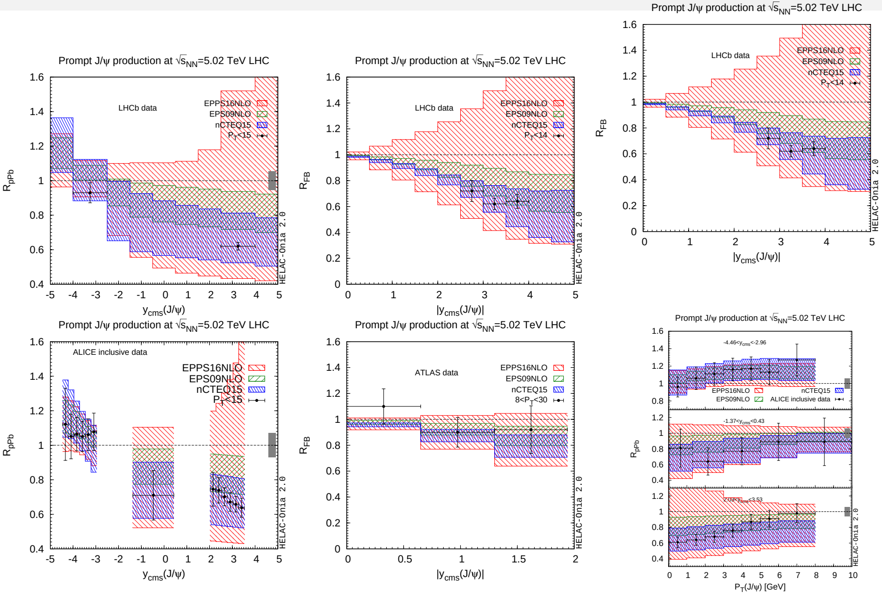
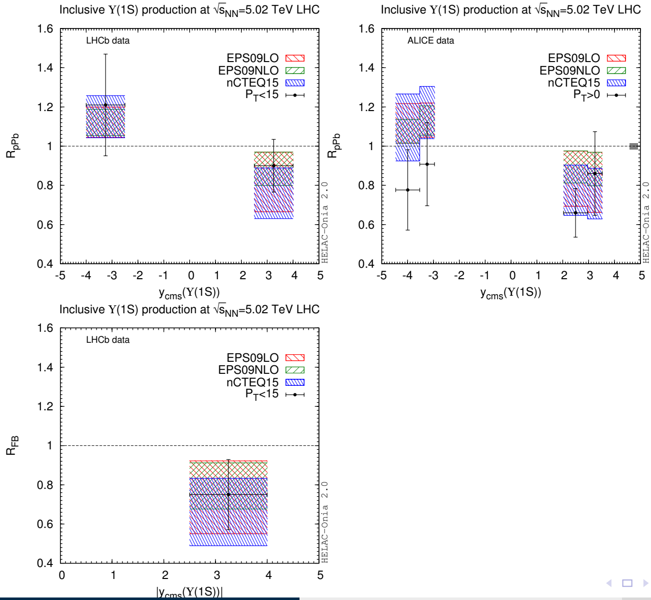


Some J/ψ comparisons (new plots with EPPS16)



More results: $\Upsilon(1S)$ and ... η_c

JPL, H.S. Shao Eur.Phys.J. C77 (2017) 1



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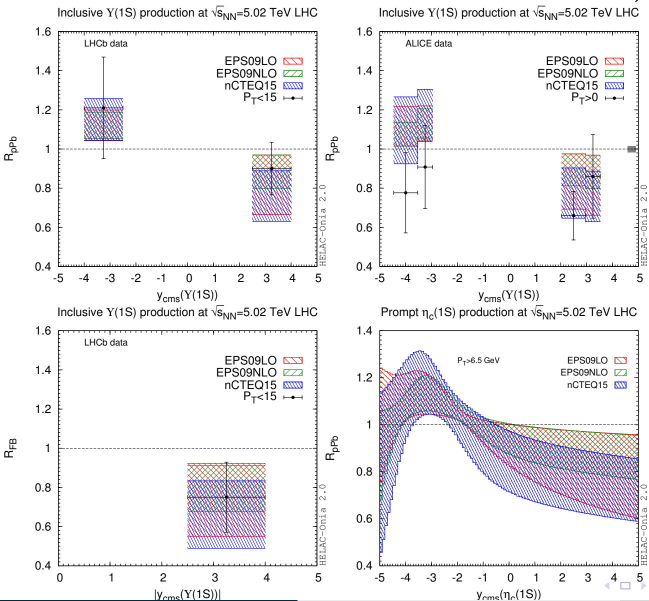
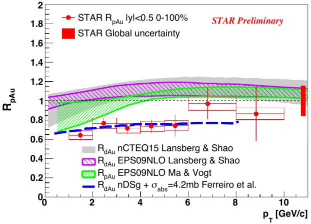
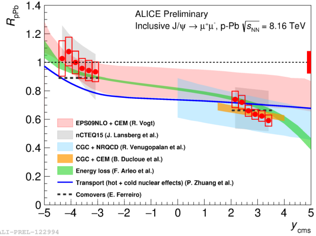
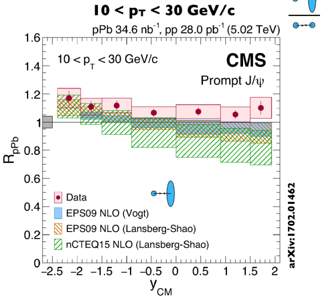


Some recent comparisons [shown at QM2017]

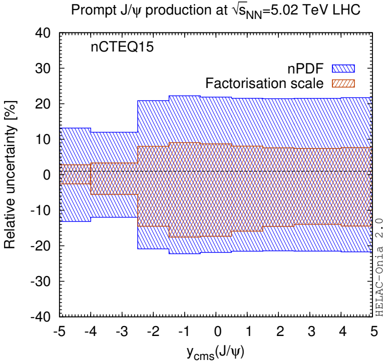


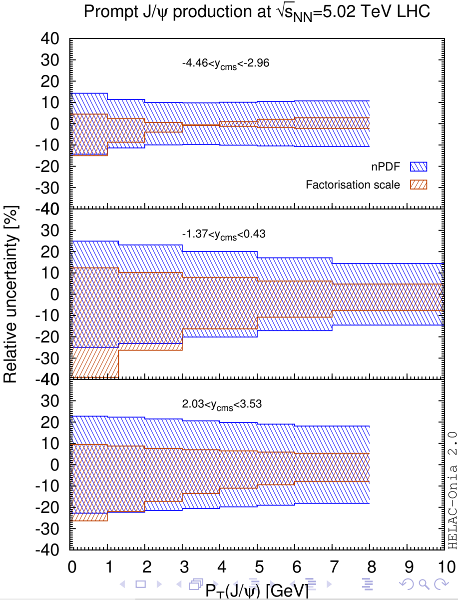




STAR: T.Todoroki; ALICE: M. Tarhini (ALICE-PUBLIC-2017-001); CMS: J. M. Blanco

Uncertainties due to the factorisation scale





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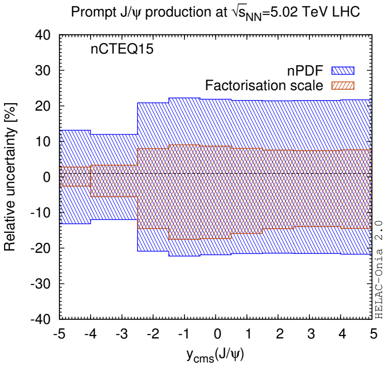
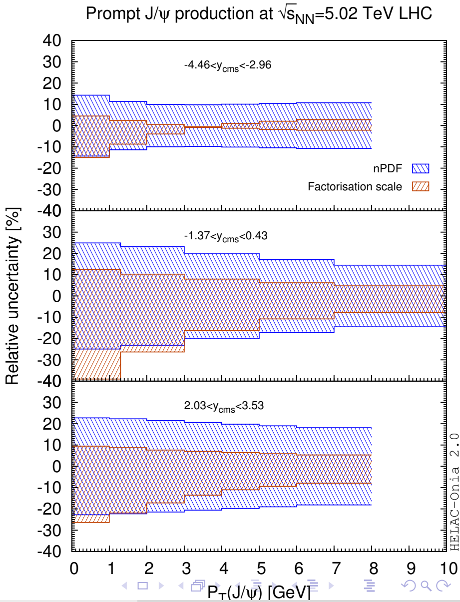
- The strength of the shadowing corrections depends on x_2, but also μ_F





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- The strength of the shadowing corrections depends on x_2, but also μ_F
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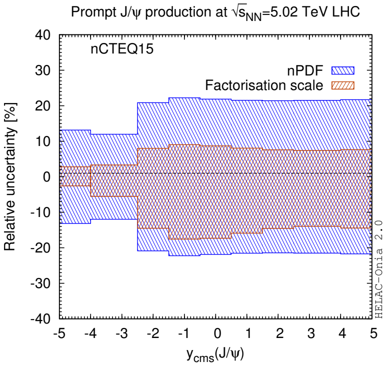

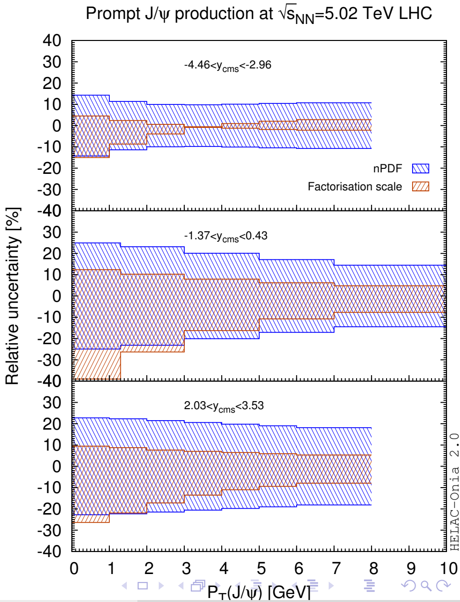

Uncertainties due to the factorisation scale

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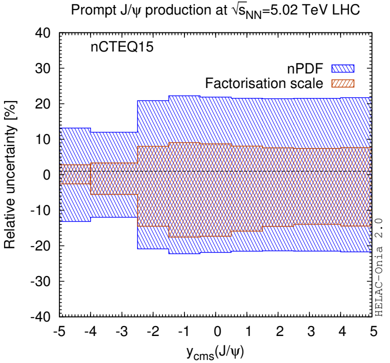
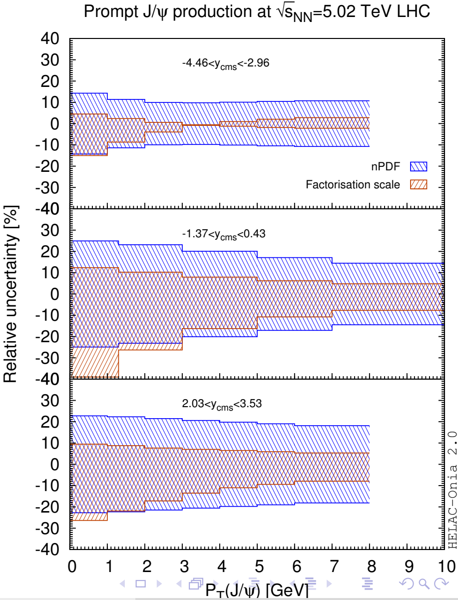
- μ_F is on the order of m_T
- The uncertainty due to μ_F not negligible compared to the nPDF one [nCTEQ shown]





Fit step toward the inclusion of heavy-flavour data in a fit: reweighting

Fit step toward the inclusion of heavy-flavour data in a fit: reweighting

REWEIGHTING FOR HESSIAN PDFS

Giele, Keller '98; Ball et al. '11; Sato, Owens, Prosper '14; Paukkunen, Zurita '14;

1. Convert Hessian error PDFs into replicas

$$f_k = f_0 + \sum_i^N \frac{f_i^{(+)} - f_i^{(-)}}{2} R_{ki},$$

2. Calculate weights for each replica

$$w_k = \frac{e^{-\frac{1}{2}\chi_k^2/T}}{\frac{1}{N_{\mathrm{rep}}}\sum_i^{N_{\mathrm{rep}}} e^{-\frac{1}{2}\chi_k^2/T}}, \qquad \chi_k^2 = \sum_j^{N_{\mathrm{data}}} \frac{(D_j - T_j^k)^2}{\sigma_j^2}$$

3. Calculate observables with new (reweighted) PDFs

$$\langle \mathcal{O} \rangle_{\mathrm{new}} = \frac{1}{N_{\mathrm{rep}}} \sum_{k=1}^{N_{\mathrm{rep}}} w_k \mathcal{O}(f_k),$$

$$\delta \langle \mathcal{O} \rangle_{\mathrm{new}} = \sqrt{\frac{1}{N_{\mathrm{rep}}} \sum_{k=1}^{N_{\mathrm{rep}}} w_k \left(\mathcal{O}(f_k) - \langle \mathcal{O} \rangle\right)^2}.$$

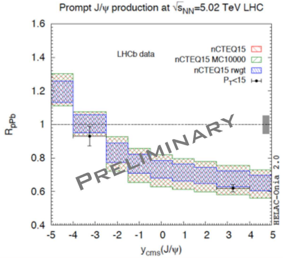
LHCP2017, SHANGHAI 14 HUA-SHENG SHAO

Tuesday, May 30, 17

REWEIGHTING FOR NCTEQ15

Thanks to Kusina, Lansberg, Schienbein, Paukkunen etc

- We used only J/ψ production data from pPb collisions at the LHC
- Only the ratio R_{pPb} has been used here.
  - LHCb arXiv:1308.6729
  - ALICE arXiv:1503.07179, arXiv:1308.6726
- The global uncertainty has been taken into account.



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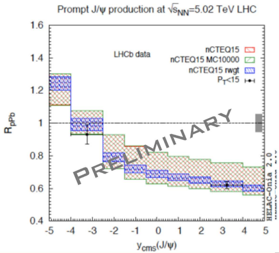

- Replicas reproduce the Hessian PDF
- Data help to reduce the gluon density uncertainty
- Reduction is more striking when including the yield data as well.

Some conclusions

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- Very rich field of theoretical and experimental investigations, just started to be harvested for pseudoscalar (η_c) production [40 years after J/ψ's discovery]
- QCD corrections via new NLO, and perhaps NNLO topologies, matter much for some mechanisms and some observables
- Yet, this may not impact too much the kinematics of single quarkonium production such that J/ψ and Υ (+ open HF) data might be of help to constrain nPDF

Part VII

Backup

Part VIII

The production mechanism(s) at low P_T in proton-proton collisions

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

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- If color is bleaching at short distances (Color Singlet Model), low-P_T quarkonia can be used to extract the distribution of linearly polarised gluon in unpolarised protons, $h_1^{\perp g}(x, k_T, \mu)$ **D. Boer, C. Pisano. PRD 86 (2012) 094007**

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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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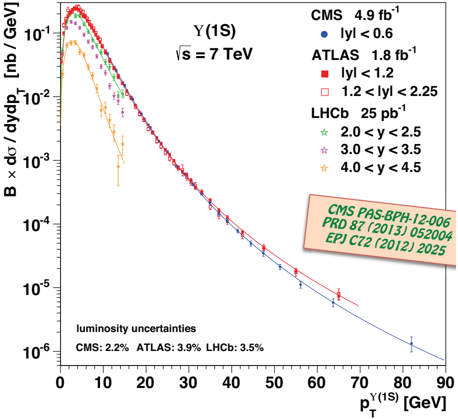

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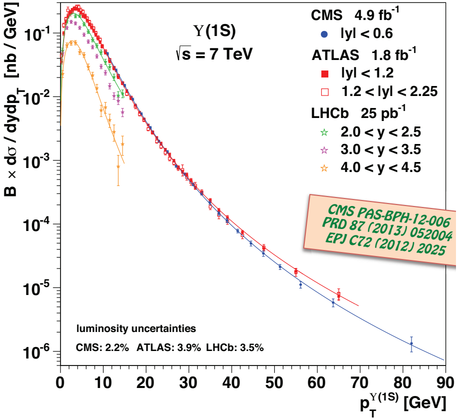
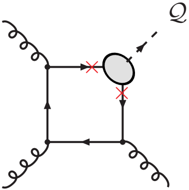


Most probably the production of a Υ with P_T = 90 GeV, even also 20 GeV, has very few things to do with the bulk of Υ

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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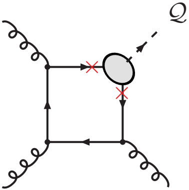

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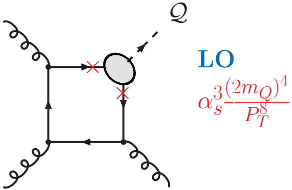

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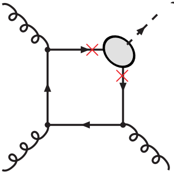

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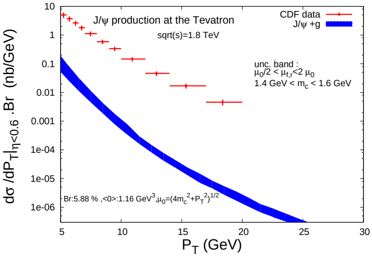

CDF, PRL 79:572 & 578,1997

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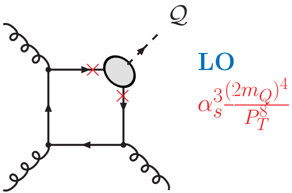

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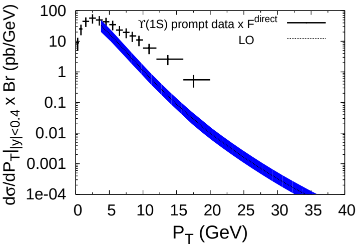

CDF, PRL 88:161802,2002

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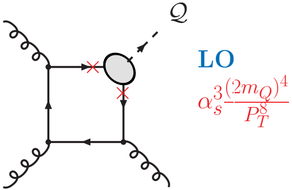

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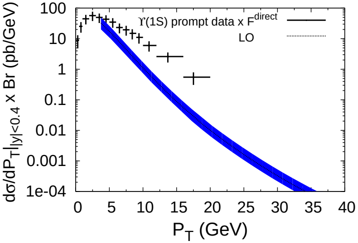

- Large QCD corrections from new topologies reduce the gap with data at mid and large P_T

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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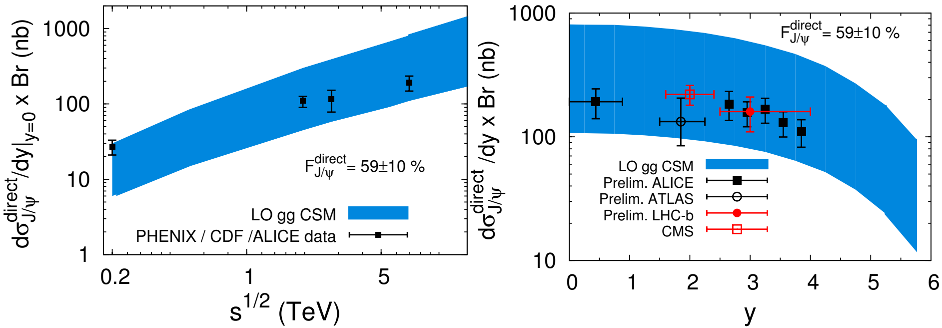

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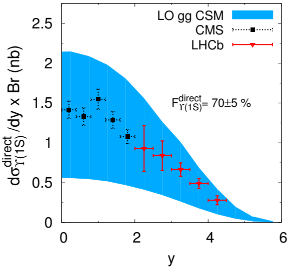

CMS PRD 83 (2011) 112004; LHCb EPJC 72 (2012) 2025

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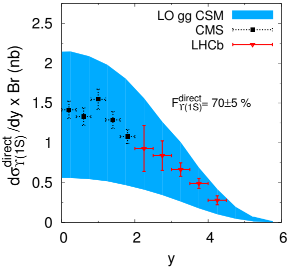

CMS PRD 83 (2011) 112004; LHCb EPJC 72 (2012) 2025

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

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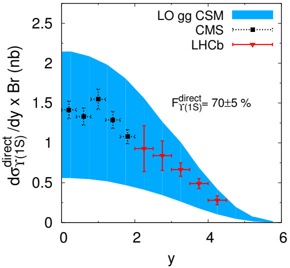


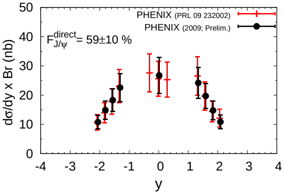
CMS PRD 83 (2011) 112004; LHCb EPJC 72 (2012) 2025

- 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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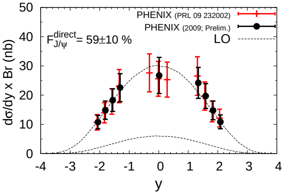

LO: $gg \to J/\psi g$ (see slide 5, nothing new !)

NLO CSM at RHIC

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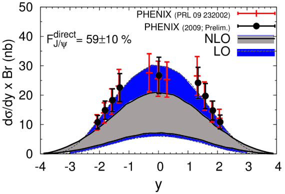
$\rightarrow J/\psi$



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

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

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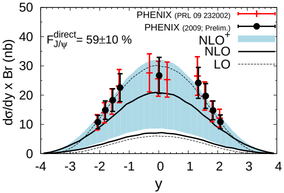

NLO$^+$: possible new contribution at LO $cg \to J/\psi c$

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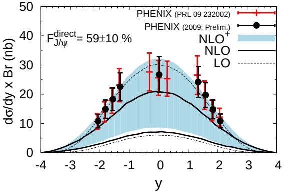

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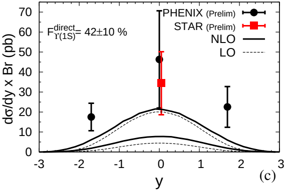

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NLO CSM at RHIC

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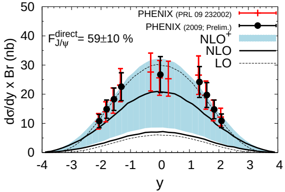

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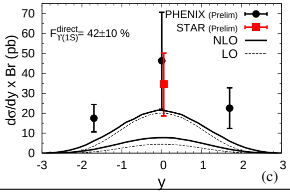

A priori, good convergence NLO w.r.t. LO

[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**)

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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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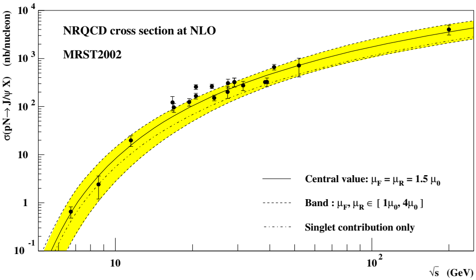

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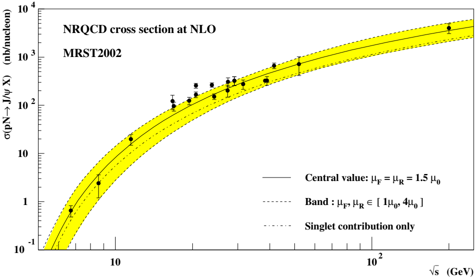

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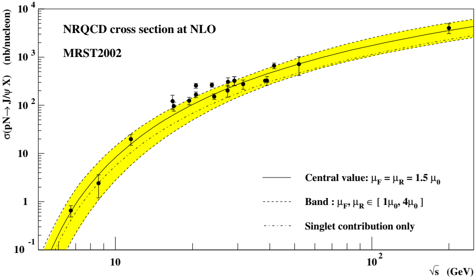

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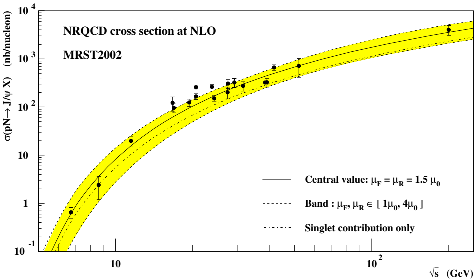

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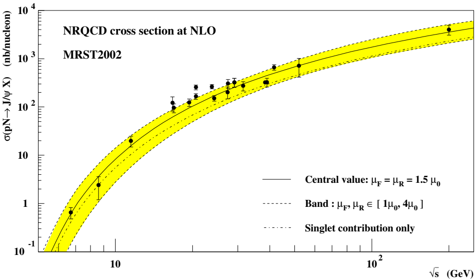

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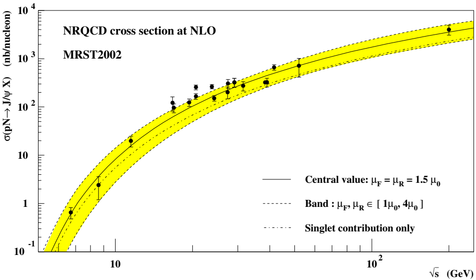

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- constant feed-down (FD) fractions
  - $F^{\text{direct}}_{J/\psi} = 60 \pm 10\%$
  - $F^{\text{direct}}_{\Upsilon(1S)} = 66 \pm 10\%$
  - $F^{\text{direct}}_{\Upsilon(1S+2S+3S)} = 60 \pm 10\%$
  - Uncertainty on F^{direct} combined in quadrature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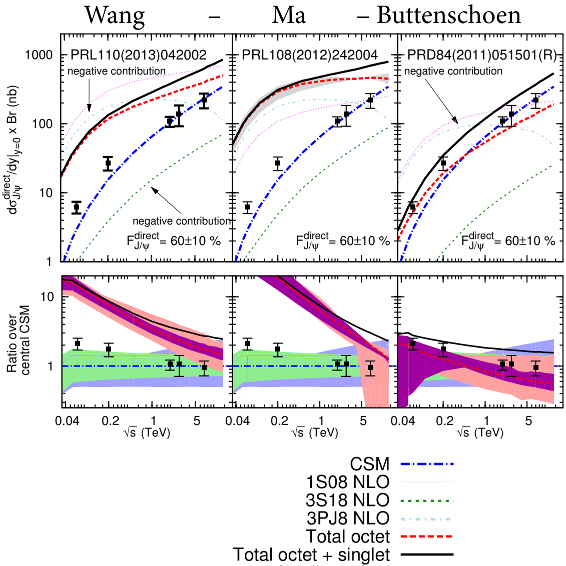
- $\Upsilon(1S)$

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

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

Results for the J/ψ



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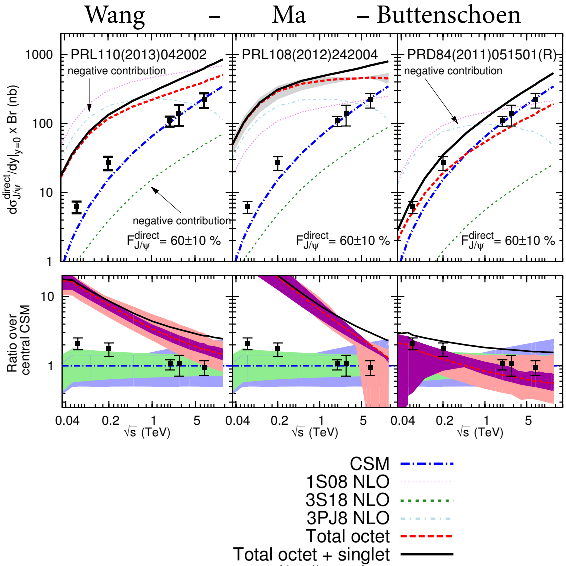

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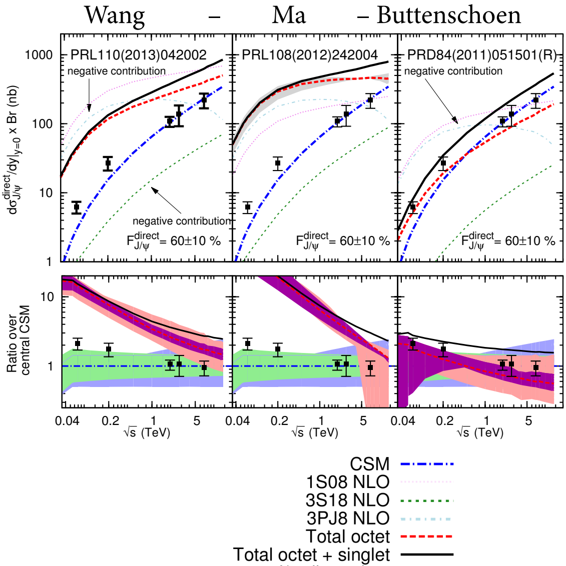

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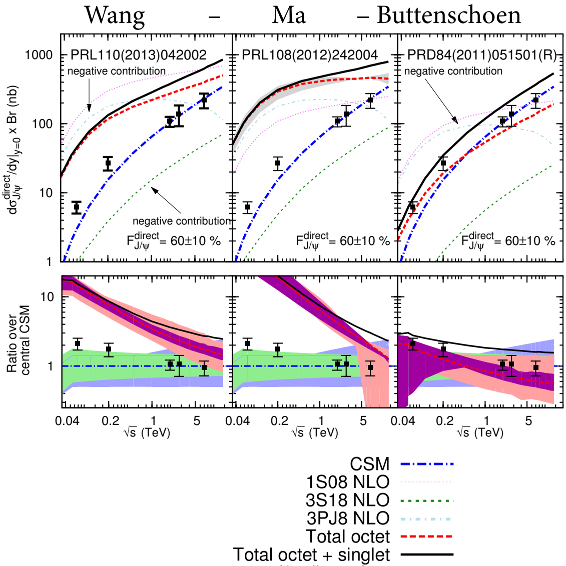

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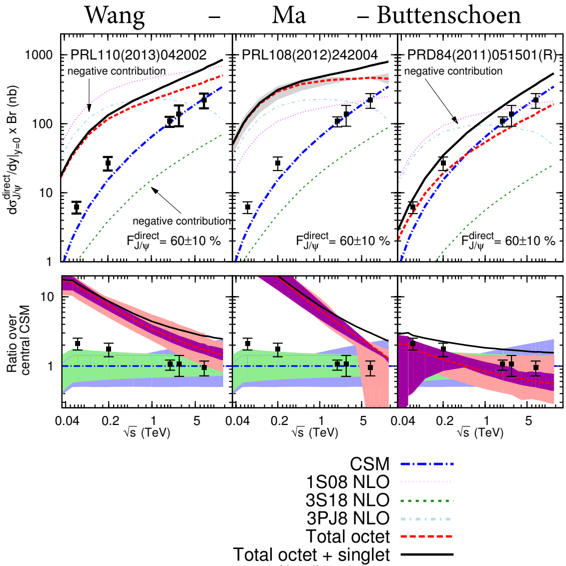
- The CS component alone does a pretty good job, even excellent in the TeV range



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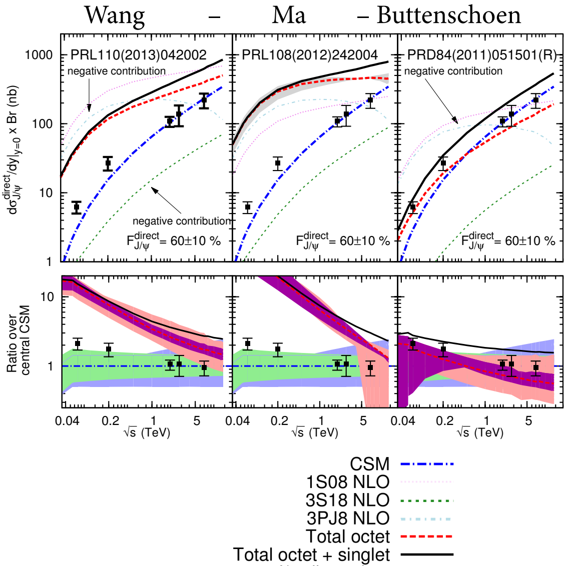

Results for the J/ψ

- First 2 fits: 10 times above the data around 200 GeV – as Maltoni *et al.*
- The third fit –which btw has the lowest P_T^{min}– overshoots the least
- The third fit is however the only which does not account for the polarisation data
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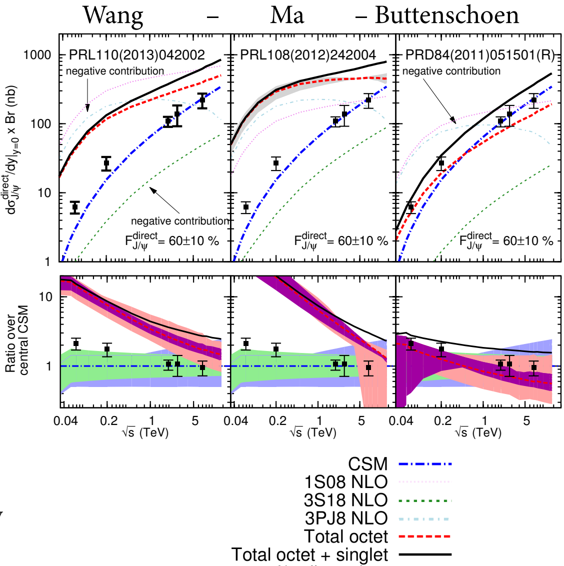
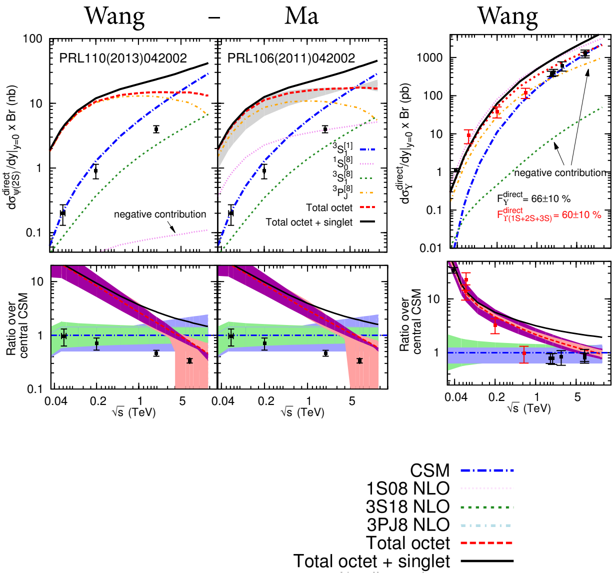
- Not a surprise since the CSM alone accounts well for the data; adding any contribution creates a "surplus"



Results for the ψ' and Υ



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For $\psi(2S)$

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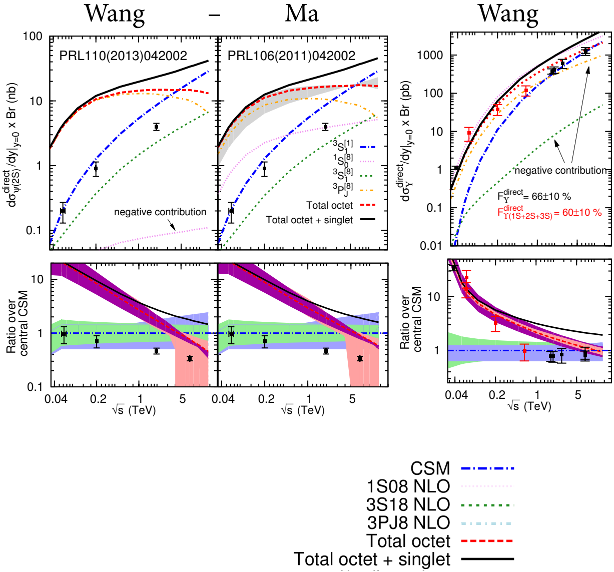

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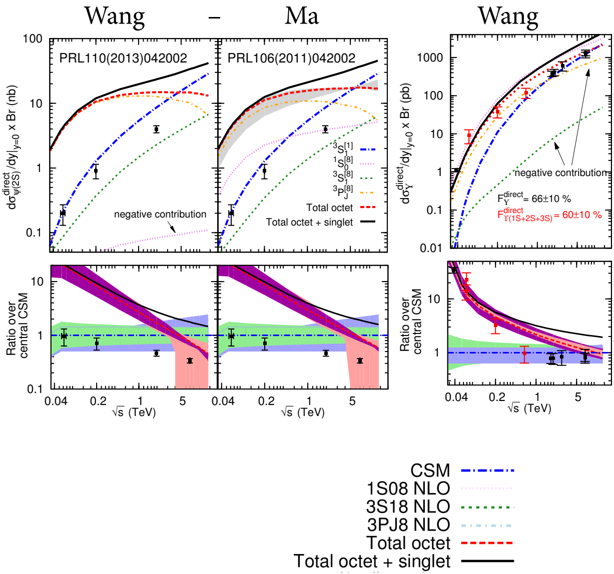
For $\Upsilon(1S)$

- 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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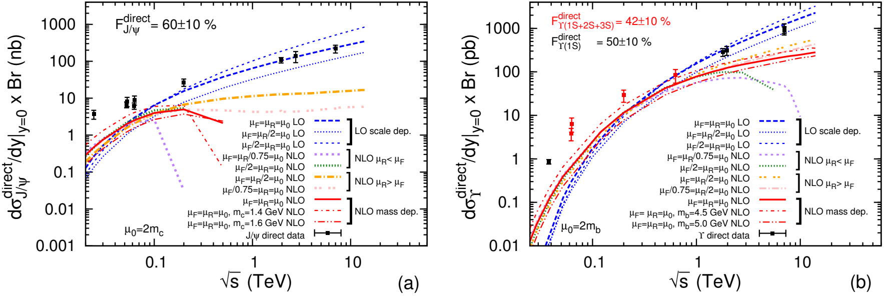
- We checked these with FDC

CSM at one loop: Results



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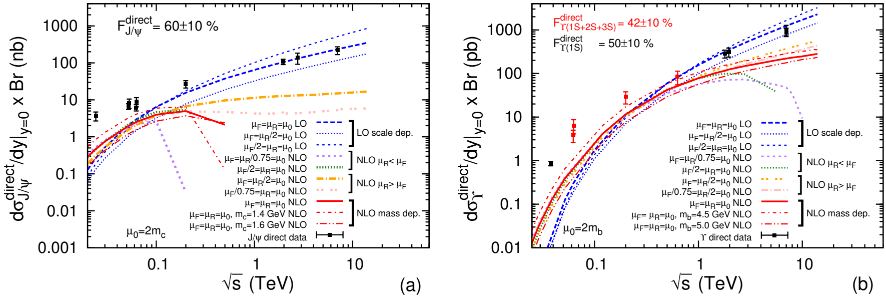

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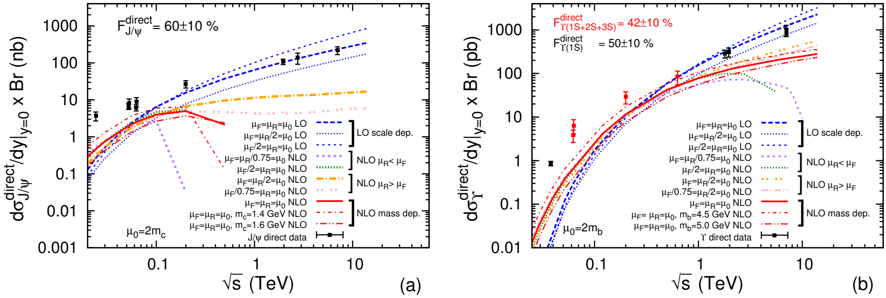

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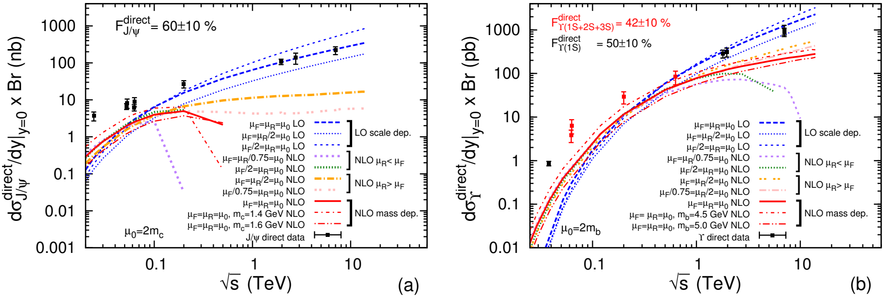

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Is it due to ISR, FSR ? Is NRQCD simply not holding at low P_T ?

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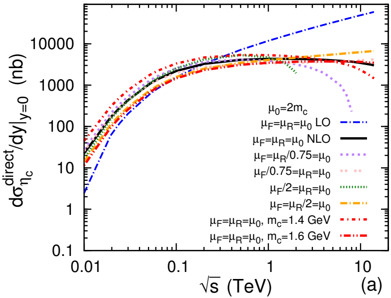

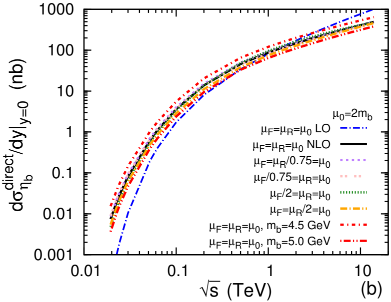

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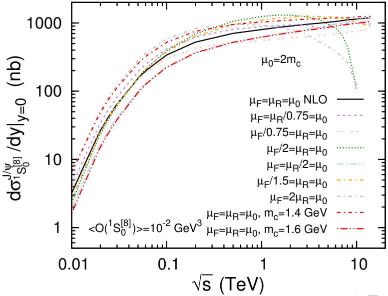

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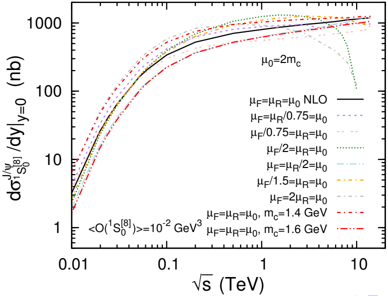
M. Echevarria, T. Kasemets, JPL, C. Pisano A. Signori (in progress); J.P. Ma, J.X. Wang, S. Zhao, PRD 88 (2013) 014027



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

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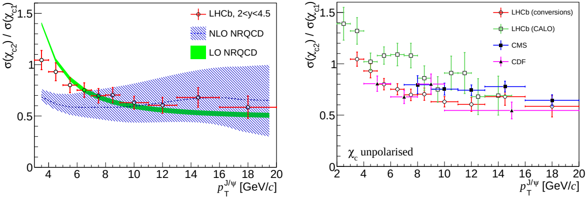

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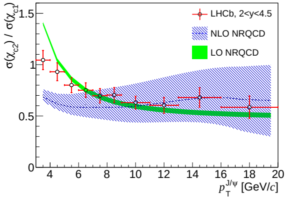
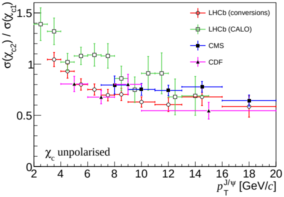
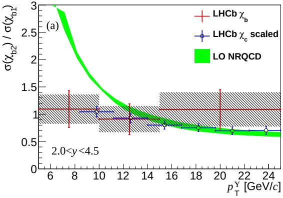
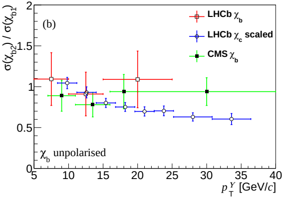




χ_b





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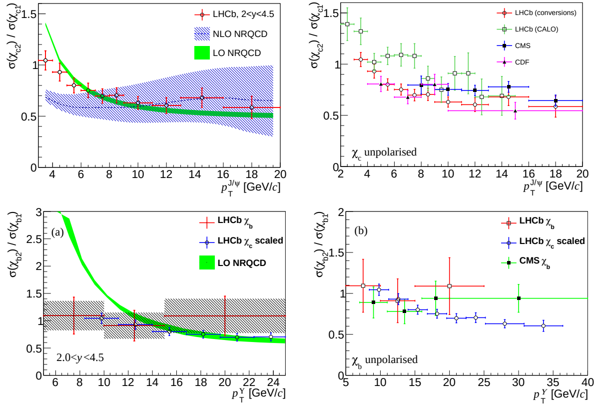

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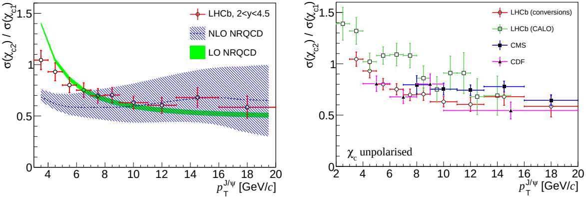

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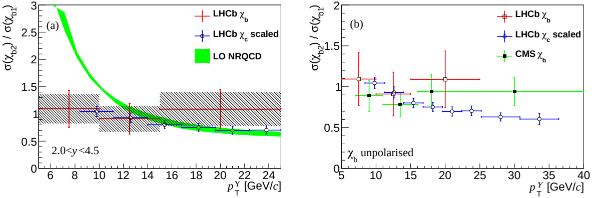

- The Landau-Yang suppression shows up for χ_c in the Low P_T/m_Q region
- The nature (quantum #) of the produced final state seems still relevant !

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

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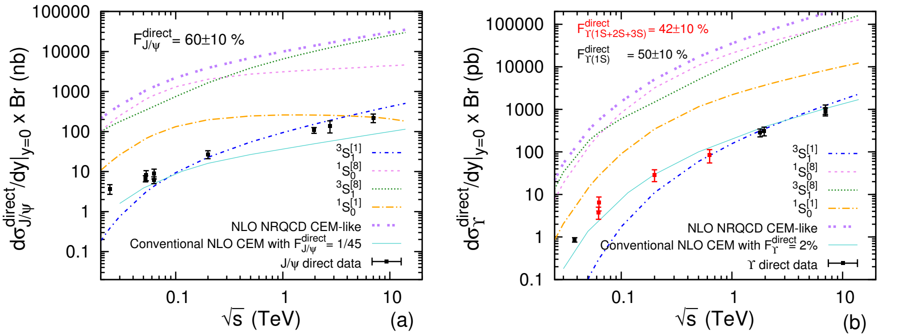
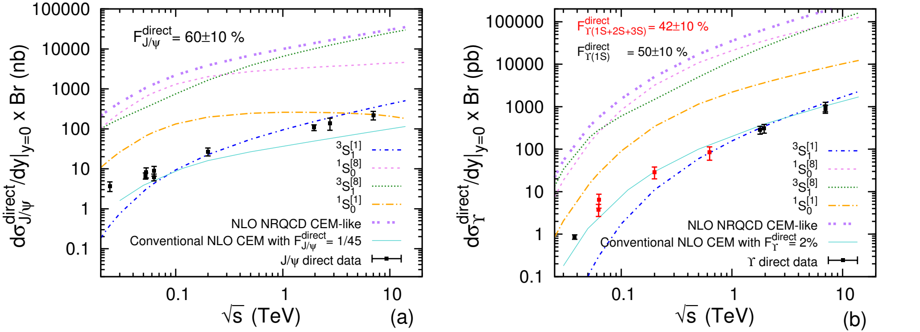
- If, as it should be in NRQCD, $\langle \mathcal{O}_{^3S_1}(^3S_1^{[1]})\rangle$ is the usual CS LDME, *i.e.* $\frac{2N_C}{4\pi}(2J+1)\,|R(0)|^2$, everything is fixed

CEM results



F direct J/ψ = 60±10 %
dσ direct J/ψ /dy|y=0 x Br (nb)
100000
10000
1000
100
10
1
0.1
3S1[1]
1S0[8]
3S1[8]
1S0[1]
NLO NRQCD CEM-like
Conventional NLO CEM with F direct J/ψ = 1/45
J/ψ direct data
0.1
1
10
√s (TeV)
(a)
F direct ϒ(1S+2S+3S) = 42±10 %
F direct ϒ(1S) = 50±10 %
dσ direct ϒ /dy|y=0 x Br (pb)
3S1[1]
1S0[8]
3S1[8]
1S0[1]
NLO NRQCD CEM-like
Conventional NLO CEM with F direct ϒ = 2%
ϒ direct data
√s (TeV)
(b)

CEM results



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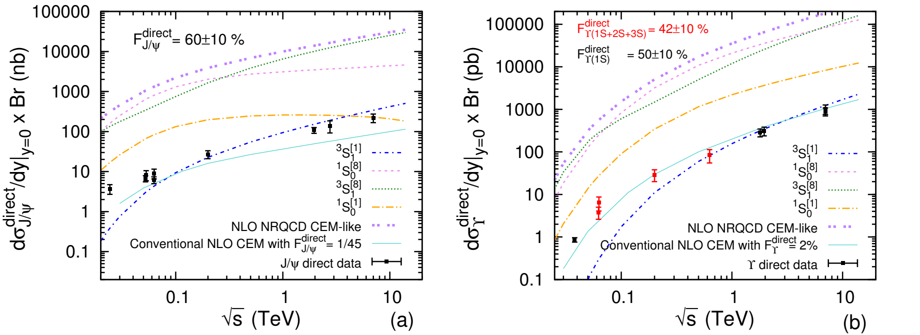

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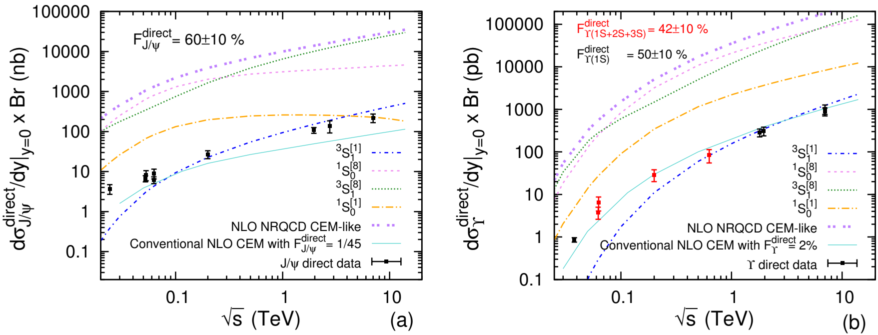

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  - Weird energy behaviour

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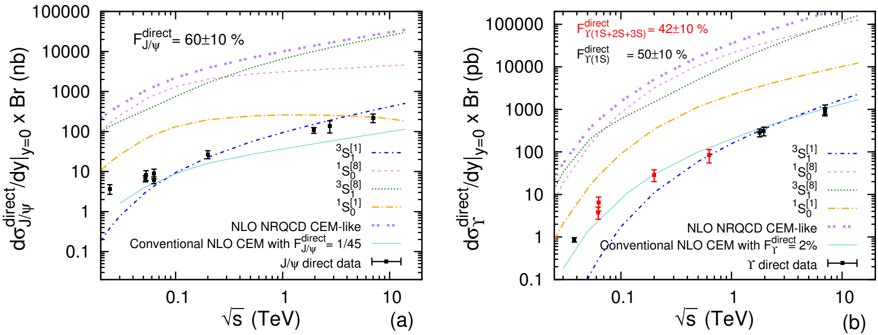

- NRQCD-like CEM badly overshoots the data
  - Expected since CO LDMEs are as large as the CS, whereas the hard parts tend to be larger.
  - Weird energy behaviour
- Conventional CEM does a pretty good job
  - No th. uncertainty shown
  - "Natural" value of $F^{\rm direct}_{J/\psi}$ is ok