Energy dependence of direct-quarkonium production in pp collisions from fixed-target to LHC energies:complete one-loop analysis

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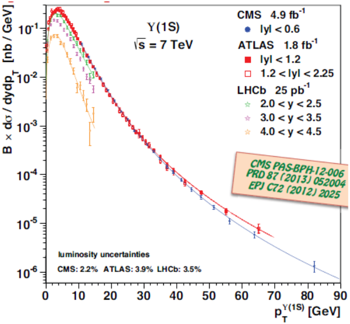
Based on our work:
Eur.Phys.J.C(2015)75:313, Y.Feng, J.P.Lansberg, J.X.Wang

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

- If color is bleaching at short distance (Color Singlet Model), low-P_T quarkonia can be used to extract the distribution of linearly polarized gluon in unpolarized protons, $h_1^{\perp g}(x, k_T, \mu)$
- Different nuclear suppression depending on how the pair hadronizes
- Saturation effects depend on the color state of the propagating pair
- Most of the proton-nucleus and nucleus-nucleus collision data lie at $P_T \lesssim m_{\mathcal{Q}}$
- In the QGP, do quarkonia behave more like colorful gluons or colorless photons?

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

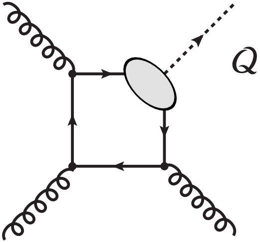
Also because, some very high P_T quarkonia which we study can be as rare as a few millionth of the produced quarkonia



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

Basic pQCD approach: the Color Singlet Model(CSM)

- Perturbative creation of 2 quarks Q and $\overline{Q}$
  - in a color singlet state
  - with a vanishing relative momentum
- Non-perturbative binding of quarks



- Large QCD corrections from new topologies reduce the gap with data at mid and large P_T (Subject for a separate seminar)

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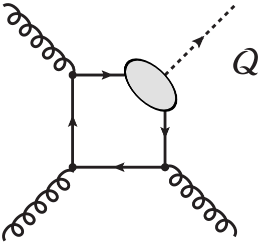
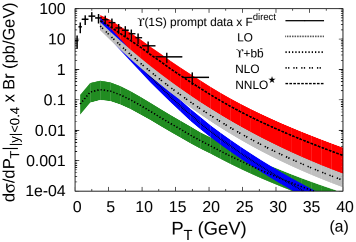




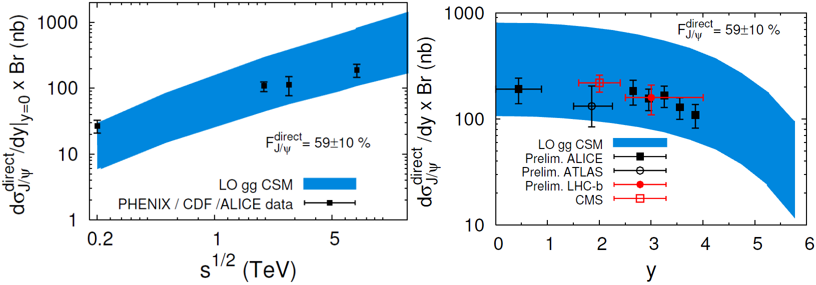
- Large QCD corrections from new topologies reduce the gap with data at mid and large P_T (Subject for a separate seminar)

The LO CSM accounts for the P_T-integrated yield

S.J.Brodsky and J.P.Lansberg, PRD 81, 051502, 2010; JPL,Pos(ICHEP 2010),206(2010);NAP 910-911(2013)470

The yield vs. $\sqrt{s}$, y

- Good agreement with RHIC, Tevatron and LHC data

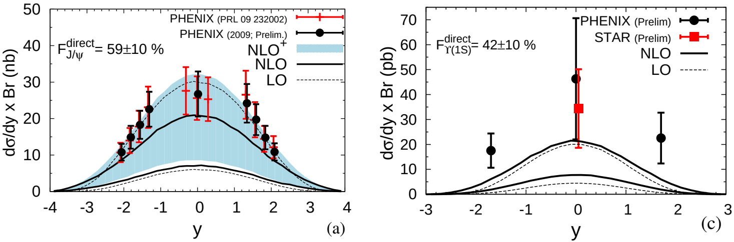


- Unfortunately, very large theory uncertainties: masses, scales(μ_R, μ_F), gluon PDFs at low x and Q^2, ...
- Earlier claims that CSM contribution to $d\sigma/dy$ was small were based on the incorrect assumption that χ_c feed-down was dominant

NLO CSM at RHIC

S.J.Brodsky and J.P.Lansberg,PRD 81 051502,2010.

J/ψ and Υ



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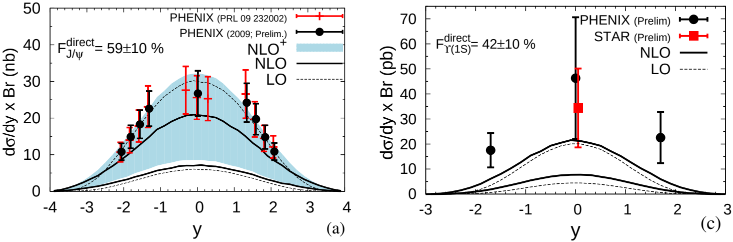
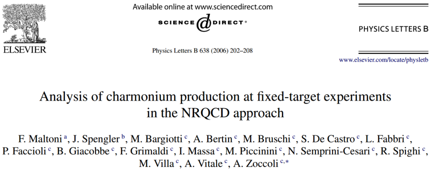


Perform good!

NLO NRQCD up to RHIC



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Analysis of charmonium production at fixed-target experiments in the NRQCD approach

F. Maltoni [a], J. Spengler [b], M. Bargiotti [c], A. Bertin [c], M. Bruschi [c], S. De Castro [c], L. Fabbri [c],
P. Faccioli [c], B. Giacobbe [c], F. Grimaldi [c], I. Massa [c], M. Piccinini [c], N. Semprini-Cesari [c], R. Spighi [c],
M. Villa [c], A. Vitale [c], A. Zoccoli [c,*]

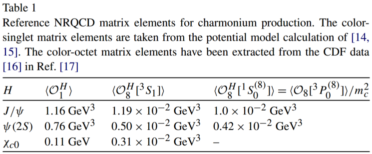


Table 1
Reference NRQCD matrix elements for charmonium production. The color-singlet matrix elements are taken from the potential model calculation of [14, 15]. The color-octet matrix elements have been extracted from the CDF data [16] in Ref. [17]

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	–

- Analysis based on the hard partonic cross sections computed at NLO in

  A.Petrelli, M.Cacciari, M.Greco, F.Maltoni and M.L.Mangano, Nucl.Phys.B 514(1998)245

- At α_s^2, one only has CO contributions ($\rightarrow$ virtual correction at α_s^3):

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

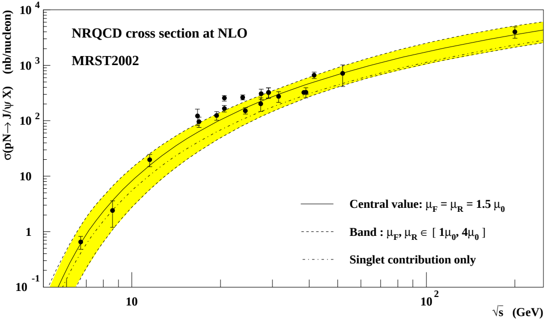
- At α_s^3, one has in addition real emissions (including one CS process)

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

  $q + \bar{q} \rightarrow Q\bar{Q}[^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_J^{[8]}] + g$ and $g + g \rightarrow Q\bar{Q}[^3S_1^{[1]}] + g$

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

NLO NRQCD up to RHIC II



- Good fit but with ten times less CO than expected from Tevatron $d\sigma/dP_T$ data
- CSM could describe the data alone (no uncertainty on CS shown; no surprise: se)
- No similar analysis for Υ
- Never done for $\sqrt{s} > 200$ GeV
- Never update with LDMEs fitted at NLO

What we did Y.Feng, J.P.Lansberg, J.X.Wang, EPJC(2015)75:313

We used

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

  *FDC J.-X.Wang, Nucl.Instrum.Meth.A 534(2004) 241

- only direct J/ψ, $\psi(2S)$ and $\Upsilon(1S)$ yields
- Nota: in principle, we can also predict total-yield polarisation
- an updated data set with:
  - only pp and p$\overline{p}$ data with more than 100 events (no pA data), only for y=0
  - CDF results after a small P_T extrapolation from 1.5 GeV to 0
  - LHC data
- constant feed-down (FD) fractions
  - $F^{direct}_{J/\psi} = 60 \pm 10$
  - $F^{direct}_{\Upsilon(1S)} = 66 \pm 6$
  - $F^{direct}_{\Upsilon(1S+2S+3S)} = 60 \pm 10$
  - Uncertainty on F^{direct} combined in quadrature with that of data

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	2.1×10^{-2}	3.5×10^{-2}	5.8×10^{-3}
B.Gong,*et al*. PRL 110(2013) 042002	-2.2×10^{-2}	9.7×10^{-2}	-4.6×10^{-3}
M.Butenschoen, B.Kniehl. PRD84(2011)051501	-9.1×10^{-3}	3.0×10^{-2}	1.7×10^{-3}

- $\psi(2S)$

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

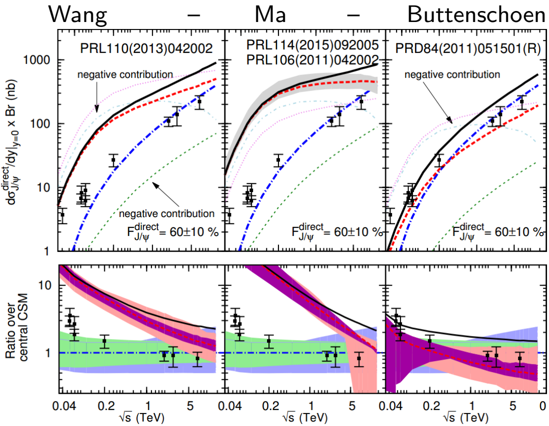
- $\Upsilon(1S)$

Ref.	$\langle\mathcal{O}_{\Upsilon(1S)}(^3P_0^{[8]})\rangle$ (in GeV^5)	$\langle\mathcal{O}_{\Upsilon(1S)}(^1S_0^{[8]})\rangle$ (in GeV^3)	$\langle\mathcal{O}_{\Upsilon(1S)}(^3S_1^{[8]})\rangle$ (in GeV^3)
B.Gong,*et al*. PRL 112 (2014) 3, 032001	-13.6×10^{-2}	11.2×10^{-2}	-4.1×10^{-3}

[For J/ψ, 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

- First 2 fits: 10 times above the data around 200 GeV -as Maltoni *et al.*
- The third fit - which has the lowest P_T^{min}-overshoots the least
- The third fit is however the only which does not account for the polarisation data
- Weird energy behaviour of Ma's fit, due to ${}^3P_J^{[8]}$ channel - we'll come back to that later

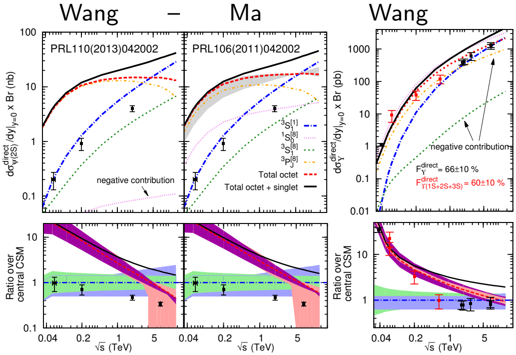


- The CS component alone does a pretty good job, even excellent in the TeV range
- Taken at face value, these results show a clear violation of NRQCD universality

Results for the $\psi(2S)$ and Υ

For $\psi(2S)$

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



For $\Upsilon(1S)$

- Reasonable 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

CSM at one loop

In the previous analysis, the CS contribution to ${}^3S_1$ production was only appearing as a real-emission QCD correction at α_s^3

If we switch off the CO channels - or believe they are negligible-, the tree-level/LO contribution for direct J/ψ is at α_s^3

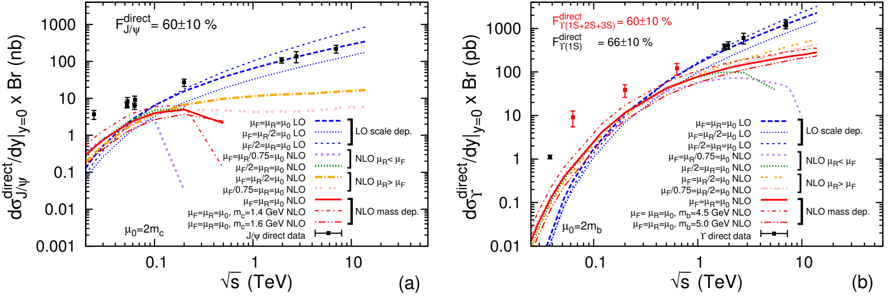
In fact, the total yield at one loop (up to α_s^4) can be computed since 2007

J.Campbell, F.Maltoni, F.Tramontano, PRL98:25200, 2007

One can repeat this for ${}^1S_0$ production for which we have closed-form results for the hard part at one loop (Nucl.Phys.B 514(1998)245)

We checked these with FDC

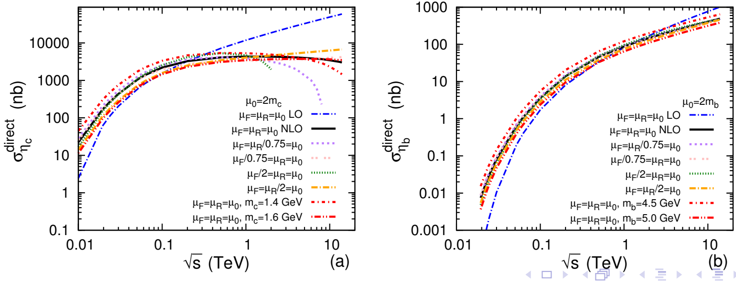
CSM at one loop: Results



- Same weird energy behavior as observed for the ${}^3P_J^{[8]}$ channel (and to a less extent for ${}^1S_0^{[8]}$ channel)
- Non negative cross sections at large $\sqrt{s}$ only for $\mu_R > \mu_F$?
- Is it due to ISR, FSR ? Is NRQCD simply not holding at low P_T?

CSM at one loop for $^1S_0$

- At LO, η_Q production occurs without final-state gluon emission
- Empirical way to see if the pathological energy behavior of both CO and CS for $^3S_1$ may be due to final state emissions, typical of quarkonium production
- Colse-form results for the hard part at one loop exit [Nucl.Phys.B 514(1998) 245]



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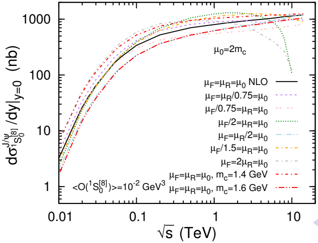
- Colse-form results for the hard part at one loop exit [Nucl.Phys.B 514(1998) 245]
- Same happens with the $^1S_0^{[8]}$
- No sign of negative terms in the TMD factorization approach up to one loop



Basics of the Color Evaporation Model

- Based on Quark-Hadron duality argument, one writes

H.Fritzsch,PLB 67 (1997) 217; F.Halzen,PLB 69 (1997)105

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

- Using a simple statistical counting

[$\sum_i$ runs over all the charmonium states below the $D\bar{D}$ threshold]

J.F.Amundson,*et al*. PLB 372 (1996)

$$F_{J/\psi}^{\mathrm{direct}} = \frac{1}{9}\frac{2J_\psi + 1}{\sum_i (2J_i + 1)} = \frac{1}{45}$$

- Romaona Vogt's fits roughly give the same number for direct $J/\psi's$

R.Vogt *et al*.,hep-ph/0311048

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

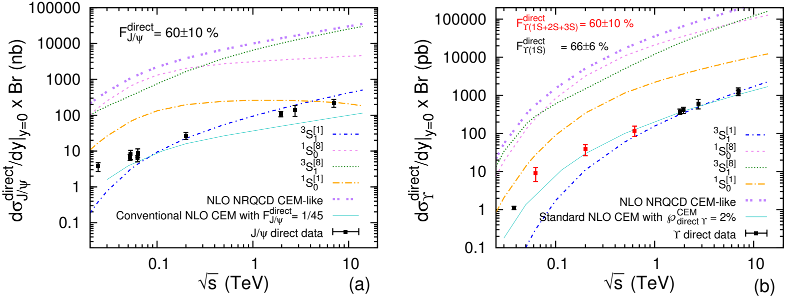
  G.T.Bodwin, E.Braaten, J.Lee, PRD72(2005) 014004

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

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

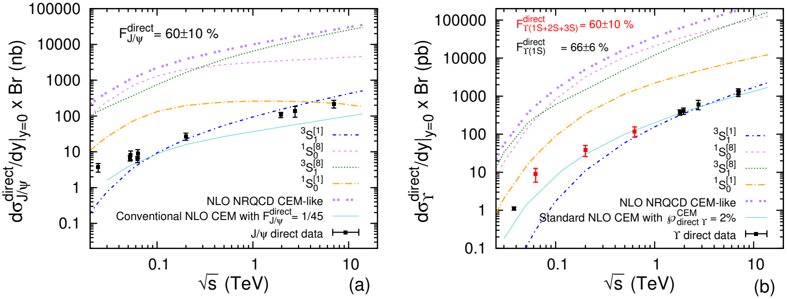
- If, as it should be in NRQCD, $\langle \mathcal{O}_{^3S_1}(^3S_1^{[1]}) \rangle$ is the usual CS LDME, $i.e.$ $\frac{2N_C}{4\pi}\ (2J+1)\ |R(0)|^2$, everything is fixed

CEM results



- 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 behavior

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 behavior
- Conventional CEM does a pretty good job
  - No th. uncertainty shown
  - "natural" value of $F^{direct}_{J/\psi}$ is ok

Conclusion

- The first full analysis for $d\sigma/dy|_{y=0}$ vs. $\sqrt{s}$ at one-loop both in NRQCD and CSM.
- NRQCD: Overshot the data.
- CSM: LO is pretty good, NLO presents unphysical behavior
- CEM: Conventional CEM does a pretty good job

Thank you!