Quarkonium Production in the LHC era

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

Part I

Introduction

Approaches to (Inclusive) Quarkonium Production

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

- No consensus on the mechanism at work in quarkonium production
- Yet, nearly all approaches assume a factorisation between the production of the heavy-quark pair, $Q\bar{Q}$, and its hadronisation into a meson
- Different approaches differ essentially in the treatment of the hadronisation
- 3 fashionable models:
  1. Colour Evaporation Model: application of quark-hadron duality; only the invariant mass matters; bleaching via (numerous) soft gluons ?
  2. Colour Singlet Model: hadronisation w/o gluon emission; each emission costs $\alpha_s(m_Q)$ and occurs at short distances; bleaching at the pair-production time
  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 ?

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

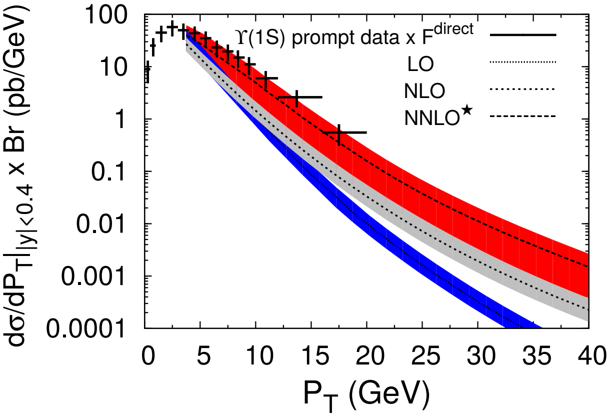
1. **Colour Evaporation Model**
   - any $Q\bar{Q}$ state contributes to a specific quarkonium state
   - colourless pair via a simple 1/9 factor
   - one non-perturbative parameter per meson, supposedly universal
2. **Colour Singlet Model**
   - colourless pair via colour projection; quantum numbers enforced by spin projection
   - one non-perturbative parameter per meson but equal to the Schrödinger wave function at the origin → no free parameter
   - this parameter is fixed by the decay width or potential models and by heavy-quark spin symmetry (HQSS)
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

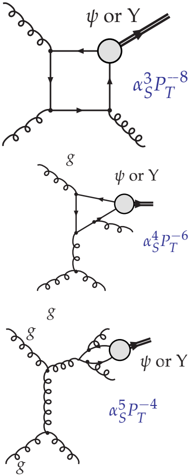
Part II

Impact of the QCD corrections to the these models at mid and large P_T

QCD corrections to the CSM for Υ at colliders

J.Campbell, F. Maltoni, F. Tramontano, Phys.Rev.Lett. 98:252002,2007
P.Artoisenet, J.Campbell, JPL, F.Maltoni, F. Tramontano, Phys. Rev. Lett. 101, 152001 (2008)
CDF PRL 88 (2002) 161802; LHCb EPJC 72 (2012) 2025





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

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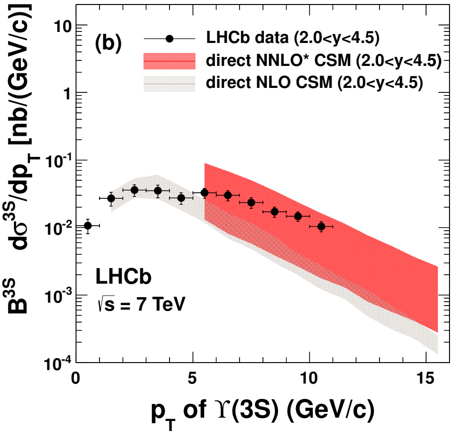
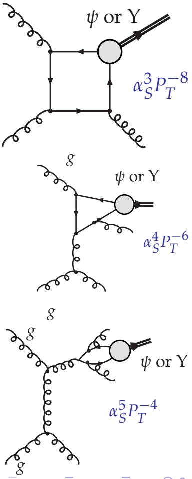
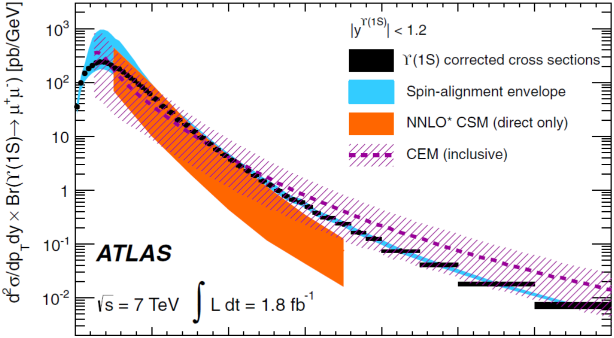


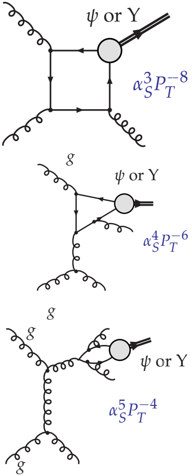


$\Upsilon(3S)$: 60-70 % direct; $\Upsilon(2S)$:60-70 % direct; $\Upsilon(1S)$: 50-70 % direct

QCD corrections to the CSM for Υ at colliders

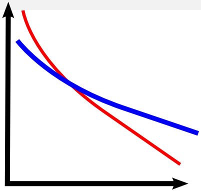
J.Campbell, F. Maltoni, F. Tramontano, Phys.Rev.Lett. 98:252002,2007
P.Artoisenet, J.Campbell, JPL, F.Maltoni, F. Tramontano, Phys. Rev. Lett. 101, 152001 (2008)
ATLAS PRD 87 052004





CSM theory curve extrapolated to prompt: × 2

QCD corrections to the COM – NRQCD



ψ data: a little less hard than the blue curve

- At LO, P_T spectrum driven by the combination of 2 CO components : ${}^3S_1^{[8]}$ vs. ${}^1S_0^{[8]}$ & ${}^3P_J^{[8]}$
- At NLO, the soft component becomes harder (same effect as for CSM)
- ${}^3P_J^{[8]}$ becomes as hard as ${}^3S_1^{[8]}$ and interferes with it; ${}^1S_0^{[8]}$ a little softer
- Due to this interference, it is possible to make the softer ${}^1S_0^{[8]}$ dominant yet with nonzero ${}^3P_J^{[8]}$ and ${}^3S_1^{[8]}$ LDMEs
- Since the 3 associated LDMEs are fit, the combination at NLO still describes the data; hence an apparent stability of NRQCD x-section at NLO
- What significantly changes is the size of the LDMEs
- Polarisation: ${}^1S_0^{[8]}$: unpolarised; ${}^3S_1^{[8]}$ & ${}^3P_J^{[8]}$: transverse

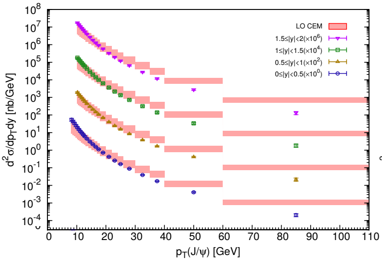
QCD corrections to the CEM P_T dependence

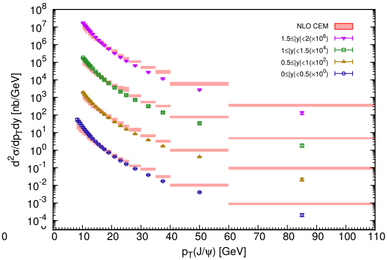
JPL, H.S. Shao JHEP 1610 (2016) 153

- All possible spin and colour combinations contribute
- The gluon fragmentation ($\sim\ ^3S_1^{[8]}$) dominant at large P_T
- No reason for a change at NLO. The fit can yield another CEM parameter value but this will not modify the P_T spectrum

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

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





The current situation in one slide ...

- Colour-Singlet Model (CSM) long thought to be insufficient

  ...not as clear now

[large NLO and NNLO correction to the P_T spectrum ; but not perfect → need a full NNLO]

P.Artoisenet, J.Campbell, JPL, F.Maltoni, F. Tramontano, PRL 101, 152001 (2008); JPL EPJC 61 (2009) 693

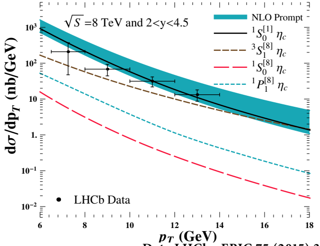
- CSM is doing well for the P_T integrated yield [see later]

S.J. Brodsky, JPL PRD 81 (2010) 051502; Y. Feng, JPL. J.X.Wang Eur.Phys.J. C75 (2015) 313

- Colour-Octet Mechanism (COM) helps in describing the P_T spectrum
- Yet, the COM NLO fits differ a lot in their conclusions owing to their assumptions (data set, P_T cut, polarisation fitted or not, etc.)
- Colour-Evaporation Mechanism (CEM) ↔ quark-hadron duality tends to overshoot the data at large P_T – issue shared by some COM fits
- All approaches have troubles in describing the polarisation and/or the η_c data
- This motivates the study of new observables

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

The last piece in the puzzle: the η_c



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

- η_c x-section measured by LHCb very well described by the CS contribution (Solid Black Curve)
- Any CO contribution would create a surplus
- Even *neglecting* the *dominant* CS, this induces constraints on CO J/ψ LDMEs

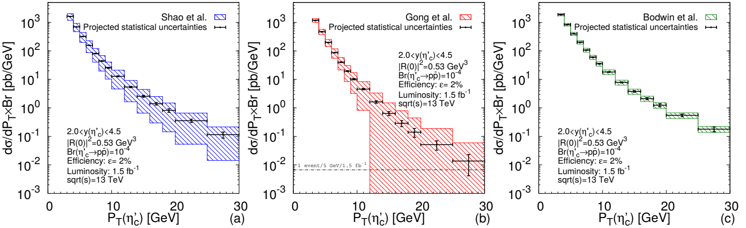
  via Heavy-Quark Spin Symmetry : $\langle^{J/\psi}(^1S_0^{[8]})\rangle = \langle^{\eta_c}(^3S_1^{[8]})\rangle < 1.46 \times 10^{-2}$ GeV^3
- Rules out the fits yielding the $^1S_0^{[8]}$ dominance to get unpolarised yields
- Even the PKU fit has now troubles to describe CDF polarisation data
- Nobody foresaw the impact of measuring η_c yields: 3 PRL published right after the LCHb data came out (Hamburg) M. Butenschoen *et al.* PRL 114 (2015) 092004; (PKU) H. Han *et al.* 114 (2015) 092005; (IHEP) H.F. Zhang *et al.* 114 (2015) 092006

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

The next one : the $\eta_c(2S)$?

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

- HQSS also relates the LDMEs for the $\psi(2S)$ and $\eta_c(2S)$
- To avoid the same situation as with the $\psi(2S)$, we have performed the first study of its possible prompt production at the LHC
  - Thanks to existing (LHCb, e^+e^-) data, we identified tractable branchings on $\mathcal{O}(10^{-4})$
  - Using HQSS, we evaluated the theory uncertainty on $\eta_c(2S)$ production
  - From the expected yields, we evaluated the expected experimental uncertainties
  - A forthcoming (LHCb) measurement would further constrain (or exclude) the existing NLO $\psi(2S)$ LDME fits of Shao *et al.* and Gong *et al.* and confirm/exclude the hypotheses underlying the Bodwin *et al.* fit.



→ 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 ?

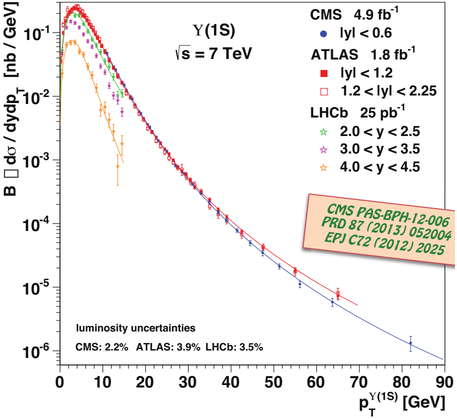
On the importance of understanding low-P_T production

- 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**
- Different nuclear suppression depending on how the pair hadronizes

  J.W. Qiu, J. P. Vary, X.F. Zhang, PRL 88 (2002) 232301
- Saturation effects depend on the colour state of the propagating pair

  D. Kharzeev, *et al.* **PRL 102 (2009) 152301; F. Dominguez,** *et al.* **PLB 710 (2012) 182; Y.Q. Ma,** *et al.* **PRD 92 (2015) 071901**
- Most of the proton-nucleus and nucleus-nucleus collision data lie at $P_T \lesssim m_Q$
- In the QGP, do quarkonia behave more like colorful gluons or colorless photons ?
- If regeneration is at work, how does it happen ? statistically ? according to the charm-quark distribution in the charmonium (wave-function) ?
- etc ...

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 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

- CSM works at LO for J/ψ and $\psi(2S)$ and at LHC energies for $\Upsilon(1S)$
  [$\Upsilon(1S)$ data undershot at low energies: PDF effect ?]
- Most NRQCD/COM NLO fits badly overshoot the data (factor 10+), except that including low P_T data which however cannot describe polarisation data
- The energy dependence of the CEM is good but the normalisation tends to differ to that coming the the P_T dependence
  [also remember that the CEM has a harder spectrum than the data]
- NLO CSM predictions seem not stable at high energies : problem still to be investigated
- Coupling NRQCD with CGC seems to describe the data but the cross-section suppression seems energy independent (surprising for a low-x effect) and seems to appear only for the quarkonia (again surprising) Y.Q Ma, R. Venugopalan, PRL 113 (2014) 192301
- All this does not allow one to draw a clear picture about the CO/CS dominance

Part IV

New observables in quarkonium production

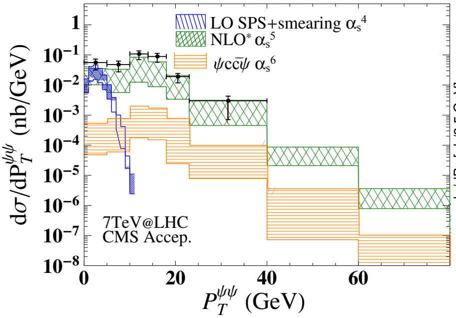
Associated-quarkonium production

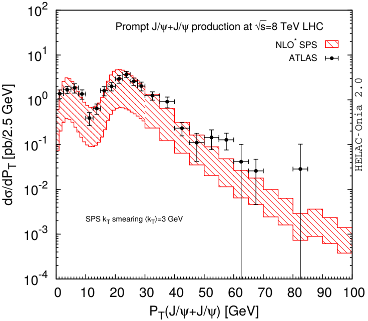
Observables	Experiments	CSM	CEM	NRQCD	Interest
J/ψ+J/ψ	LHCb, CMS, ATLAS, D0 (+NA3)	NLO, NNLO*	LO ?	LO	Prod. Mechanism (CS dominant) + DPS + gluon TMD
J/ψ+D	LHCb	LO	LO ?	LO	Prod. Mechanism (c to J/psi fragmentation) + DPS
J/ψ+ϒ	D0	(N)LO	LO ?	LO	Prod. Mechanism (CO dominant) + DPS
J/ψ+hadron	STAR	LO	--	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

JPL, H.-S.Shao PRL 111, 122001 (2013); PLB 751 (2015) 479; CMS JHEP 1409 (2014) 094; ATLAS EPJC (2017) 77:76

- At Born (LO) order, the $P_T^{\psi\psi}$ spectrum is $\delta(P_T^{\psi\psi})$: $2 \to 2$ topologies
- It can be affected by initial parton k_T [$\leftrightarrow$ interest for TMD studies]
- By far insufficient (blue) to account for the CMS measured spectrum

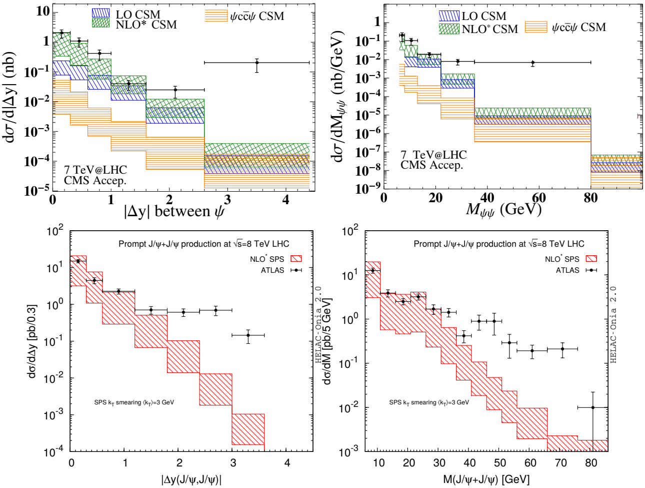




- α_s^5 contributions (green) are crucial here and do a good job even at $P_T^{\psi\psi} \simeq 30$ GeV
- We do not expect NNLO (α_s^6) contributions to matter where one currently has data

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

A puzzle at large Δy (or $M_{\psi\psi}$) ?



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

- If the DPS are independent, one can write

$$\sigma^{\rm DPS}_{\psi\psi} = \frac{1}{2}\frac{\sigma_\psi \sigma_\psi}{\sigma_{\rm eff}}$$

[σ_ψ can either be measured or computed]

- The smaller $\sigma_{\rm eff}$, the larger the DPS yield
  and the larger the parton correlations in the proton
- D0 : $\sigma_{\rm eff} = 4.8 \pm 2.5$ mb **D0 Coll. PRD 90 (2014) 111101**
- CMS: $\sigma_{\rm eff} = 8.2 \pm 2.0 \pm 2.9$ mb **JPL, H.-S.Shao PLB 751 (2015) 479; CMS JHEP 1409 (2014) 094**
- ATLAS : $\sigma_{\rm eff} = 6.3 \pm 1.6(stat) \pm 1.0(syst) \pm 0.1(BF) \pm 0.1(lumi)$ mb

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

NB: Agreement not perfect with the ATLAS data

Predictions: excited states and more

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

- Even though we find it a natural, accounting for DPS introduces another parameter
- How to check that one is not playing with a further d.o.f. on the theory side?
- DPS vs SPS dominance are characterised by different feed-down patterns
- We define $F^{\chi_c}_{\psi\psi}$ ($F^{\psi'}_{\psi\psi}$) as the fraction of events containing at least one χ_c (ψ')
- Under DPS dominance (e.g. large Δy), $\sigma^{\rm DPS}_{ab} = \frac{m}{2}\frac{\sigma_a\sigma_b}{\sigma_{\rm eff}}$ (m: symmetry factor)

$$\boxed{F^{\chi_c}_{\psi\psi} = F^{\chi_c}_{\psi} \times \left(F^{\chi_c}_{\psi} + 2F^{\rm direct}_{\psi} + 2F^{\psi'}_{\psi}\right), F^{\psi'}_{\psi\psi} = F^{\psi'}_{\psi} \times \left(F^{\psi'}_{\psi} + 2F^{\rm direct}_{\psi} + 2F^{\chi_c}_{\psi}\right), F^{\rm direct}_{\psi\psi} = \left(F^{\rm direct}_{\psi}\right)^2}$$

- Under SPS CSM dominance,
  - $F^{\psi'}_{\psi\psi}$ is slightly enhanced by symmetry factors,
  - $F^{\chi_c}_{\psi\psi}$, unlike single quarkonium production, is not enhanced and is found to be small
- Overall :

	(CSM) SPS	DPS
$F^{\psi'}_{\psi\psi}$	45%	20%
$F^{\chi_c}_{\psi\psi}$	small	50%

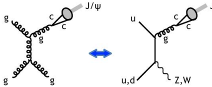
- Hence the importance of measuring $J/\psi + \psi'$ and $J/\psi + \chi_c$
- $J/\psi + \eta_c$ can also tell something about DPS and about $\sigma_{\rm eff}$

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

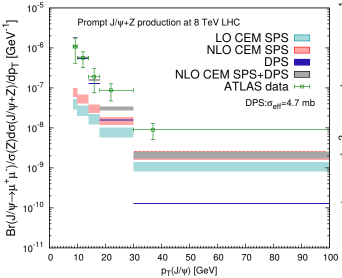
ATLAS Collaboration, Eur. Phys. J. C 75 (2015) 229; JHEP 1404 (2014) 172
L.Gang et al., JHEP 1102 (2011) 071; B. Gong et al., JHEP 1303 (2013) 115;
L. Gang et al., PRD 83 (2011) 014001; J.P. Lansberg, C. Lorce, PLB 726 (2013) 218

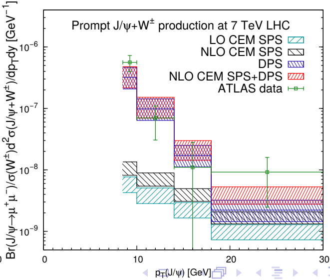
- Just as the CEM tends to produce too many J/ψ at large P_T, we expect it to be the same for $J/\psi + Z$ and $J/\psi + W$ and to provide us with an upper SPS limit.



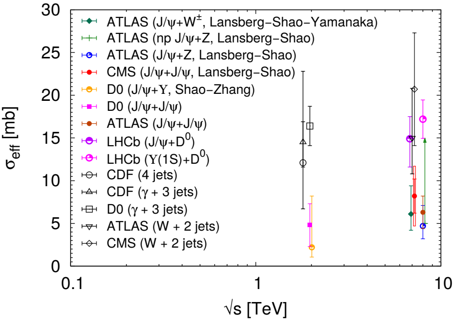
- Tensions are confirmed but can be solved by introducing a DPS yield with $\sigma_{\text{eff}} = 4.7^{+2.4}_{1.5}$ mb for $\psi + Z$ and $\sigma_{\text{eff}} = 6.1^{+3.3}_{1.9}$ mb for $\psi + W$

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



- J/ψ+charm and Υ+charm data point at $\sigma_{\text{eff}} \sim 20$ mb
- $J/\psi + J/\psi$ LHCb region: SPS computations with too large uncertainties to conclude
- Looking at the feed-down pattern likely necessary to check the SPS/DPS ratio
- $\Upsilon + \Upsilon$ data by CMS: same as above about the current theory uncertainties

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

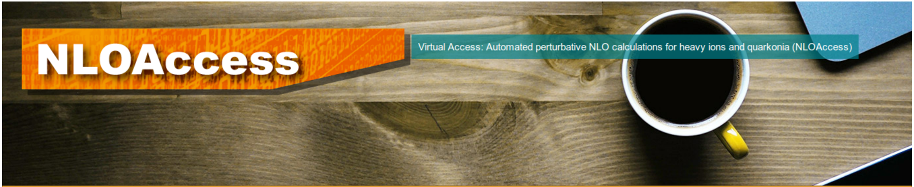
Part V

Conclusion

Summary

- The quarkonium-inclusive-production mechanisms
  not yet the object of a consensus
- QCD corrections via new NLO, and perhaps NNLO topologies,
  matter much for some mechanisms and some observables
- Novel Observables are necessary:
  pseudoscalar states and associated production
- Beside the production-mechanism debate, quarkonia already allow us to probe the parton correlation through DPS studies
- 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

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Automated perturbative NLO calculation with HELAC-Onia Web

Welcome to HELAC-Onia Web!

HELAC-Onia ia an automatic matrix element generator for the calculation of the heavy quarkonium helicity amplitudes in the framework of NRQCD factorization.
The program is able to calculate helicity amplitudes of multi P-wave quarkonium states production at hadron colliders and electron-positron colliders by including new P-wave off-shell currents. Besides the high efficiencies in computation of multi-leg processes within the Standard Model, HELAC-Onia is also sufficiently numerical stable in dealing with P-wave quarkonia and P-wave color-octet intermediate states.

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