CEPC opportunities for Quarkonium production studies

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Part I

Quarkonium production mechanisms

Approaches to Quarkonium Production

For a recent review, see JPL. arXiv:1903.09185 [hep-ph] (Phys. Rept. 2020, In Press)

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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

QCD corrections to the CEM P_T dependence

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

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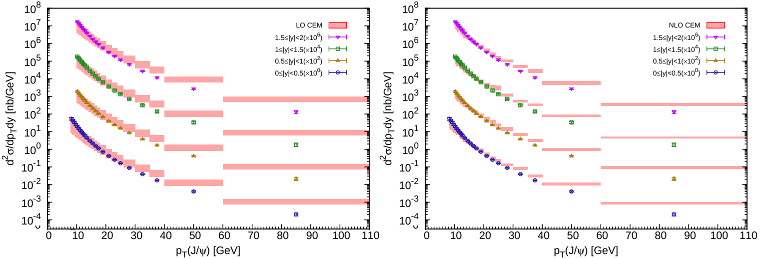

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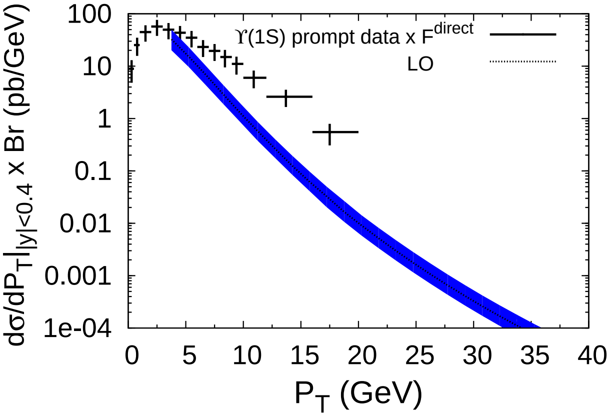

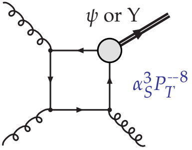

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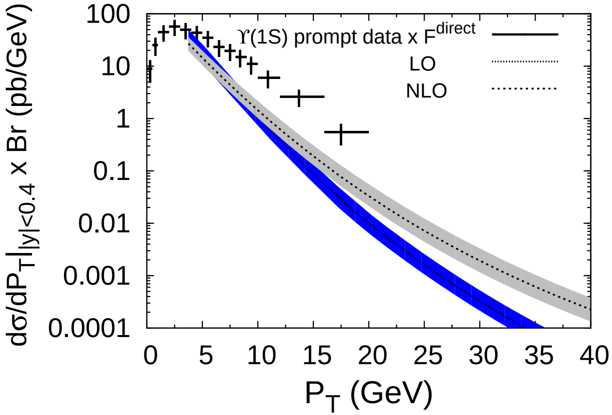

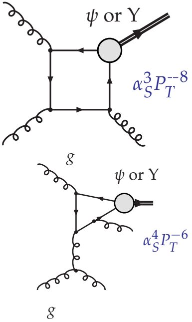

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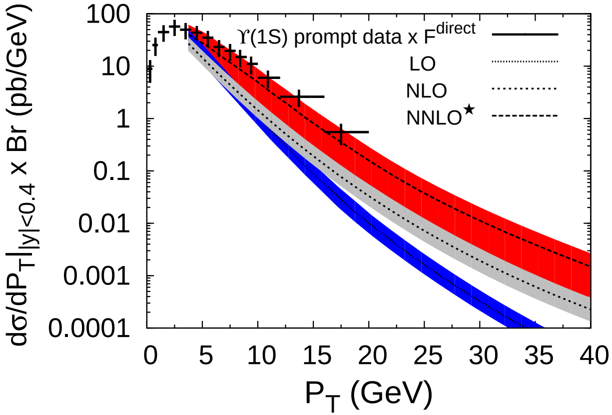

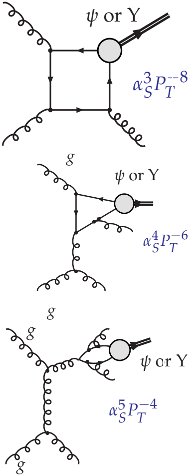

Attention: the NNLO⋆ is not a complete NNLO

See a recent study by H.S. Shao JHEP 1901 (2019) 112

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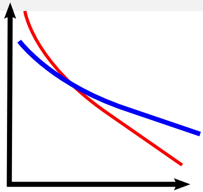

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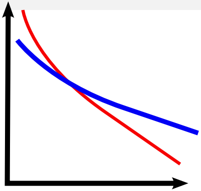

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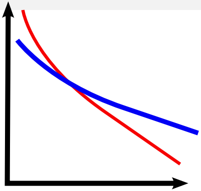

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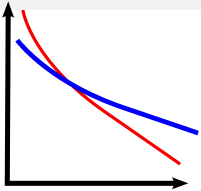
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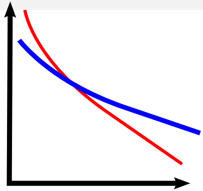

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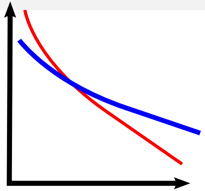

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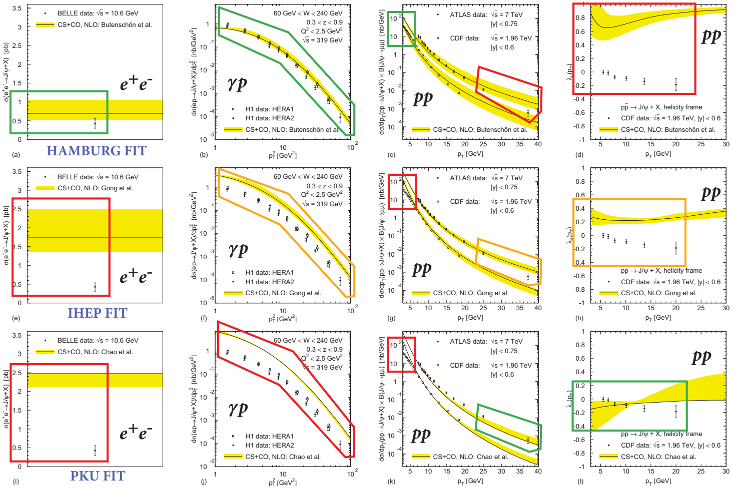
- Polarisation: ${}^1S_0^{[8]}$: unpolarised; ${}^3S_1^{[8]}$ & ${}^3P_J^{[8]}$: transverse

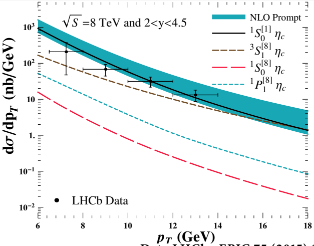
Universality of NLO NRQCD fits ?

Plot from M. Butenschön (ICHEP 2012); Discussion in JPL, arXiv:1903.09185



→ Need to assess if CEPC can confirm inclusive e^+e^- Belle data and that on $J/\psi + c\bar{c}$

The last piece in the puzzle: the η_c



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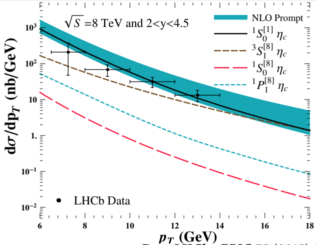

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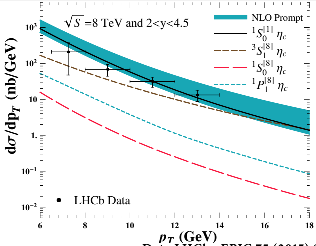

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  via Heavy-Quark Spin Symmetry : $\langle^{J/\psi}(^1S_0^{[8]})\rangle = \langle^{\eta_c}(^3S_1^{[8]})\rangle < 1.46 \times 10^{-2}\ \mathrm{GeV}^3$

[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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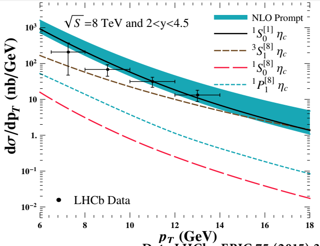

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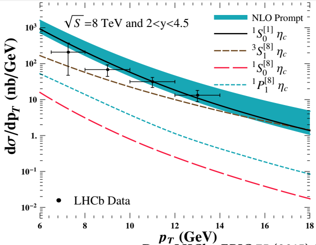

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- Nobody foresaw the impact of measuring η_c yields: 3 PRL published right after the LCHb data came out **(Hamburg) M. Butenschoen *et al.* PRL 114 (2015) 092004; (PKU) H. Han *et al.* 114 (2015) 092005; (IHEP) H.F. Zhang *et al.* 114 (2015) 092006**

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

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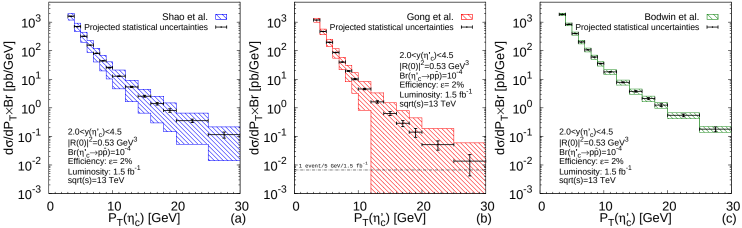

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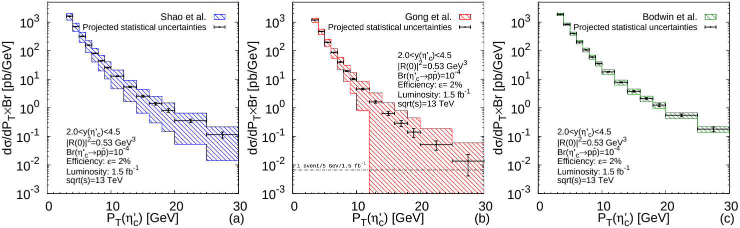
JPL, H.S. Shao, H.F. Zhang, PLB 786 (2018) 342

- 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 $\mathcal{O}(10^{-4})$
  - 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.



→ Important to assess whether CEPC can study inclusive $\psi(2S)$ production

The current situation in one slide ...

See JPL. arXiv:1903.09185 [hep-ph] (Phys. Rept. 2020, In Press)

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- as well as studies in *ep*, *ee* and $\gamma\gamma$ collisions

Going further with associated-quarkonium *hadro*production

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See section 3 of JPL, arXiv:1903.09185 [hep-ph] (Phys. Rept. 2020, In Press)

Observables	Experiments	CSM	CEM	NRQCD	Interest
J/ψ+J/ψ	LHCb, CMS, ATLAS, D0 (+NA3)	NLO, NNLO*	NLO	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	NLO	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 ?	NLO	LO ?	Prod. Mechanism (CS dominant ?) + DPS + gluon TMD

Part II

Quarkonium production in high-energy e^+e^- collisions

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

Michael Klasen, Bernd A. Kniehl, Luminiţa N. Mihaila, and Matthias Steinhauser
II. Institut für Theoretische Physik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany
(Received 19 December 2001; published 28 June 2002)

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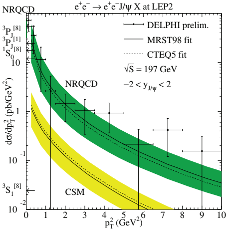

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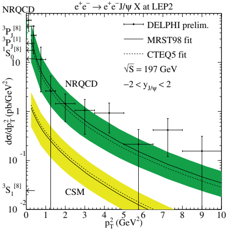

At NLO, these data do not agree any more with NRQCD

Explanation (?): **M. Butenschoen, B. Kniehl, PRD 84, 051501(R) (2011)**

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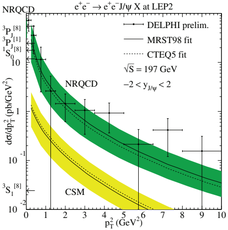

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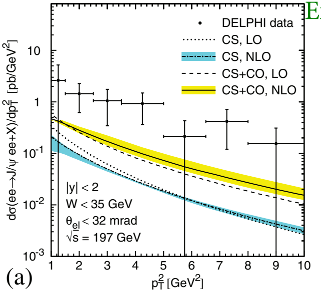

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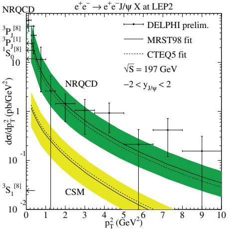

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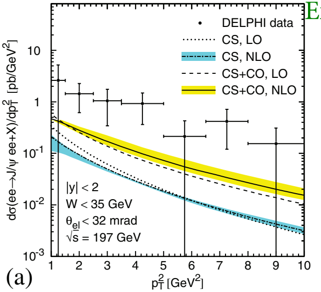

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Still an open issue ...
only an e^+e^- collider like the CEPC can tackle

Opportunities for CEPC in production in Z decays

Operation mode	Z factory	W threshold scan	H^0 factory
E_{cm}(GeV)	91.2	158 – 172	240
$\mathcal{L}(10^{34}\text{cm}^{-2}\text{s}^{-1})$	17 – 32	10	3
Run time (years)	2	1	7
Int. lum.(ab^{-1})	8 – 16	2.6	5.6
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E. Braaten, K. Cheung, T.C. Yuan PRD 48 4230

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- Exclusive decay: rather SM test:

  Expectations : $\mathcal{B}(Z \to J/\psi\gamma) = (9.96 \pm 1.86) \times 10^{-8}$

T.-C. Huang, F. Petriello, PRD 92 (2015) 014007

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$W^+ \to B_c^+ b\bar{s}$	6.3	8.84×10^{-6}
$W^+ \to B_c^{*+} b\bar{s}$	5.4	7.61×10^{-6}
$W^+ \to B_c^+ c\bar{c}$	0.4	3.64×10^{-4}
$W^+ \to B_c^{*+} c\bar{c}$	0.5	5.23×10^{-4}
$W^+ \to \eta_b c\bar{b}$	0.015	1.41×10^{-5}
$W^+ \to \Upsilon c\bar{b}$	0.016	1.49×10^{-5}

C.F. Qiao *et al.* EPJC 71 (2011) 1766

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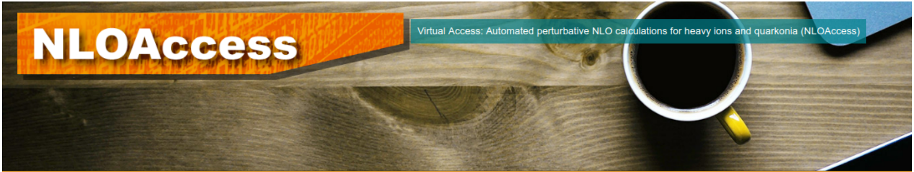
LO predictions for quarkonia → NLOAccess [in2p3.fr/nloaccess]



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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

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STRONG 2020

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 824093.

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

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Automated perturbative 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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