Quarkonium production: where do we stand and where to go ?

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Part I

Quarkonium production mechanisms

Approaches to Quarkonium Production

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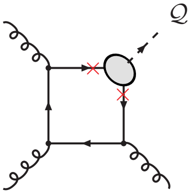
  3. Colour Octet Mechanism (encapsulated in NRQCD): higher Fock states of the mesons taken into account; $Q\bar{Q}$ can be produced in octet states with different quantum # as the meson; bleaching with semi-soft gluons ?

Basic pQCD approach: the Colour Singlet Model (CSM)

C.-H. Chang, NPB172, 425 (1980); R. Baier & R. Rückl Z. Phys. C 19, 251(1983);



LO

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

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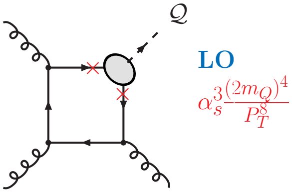

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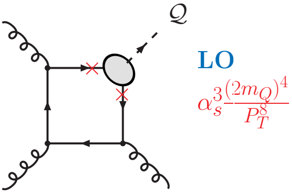

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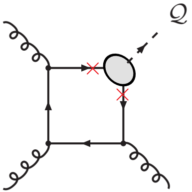

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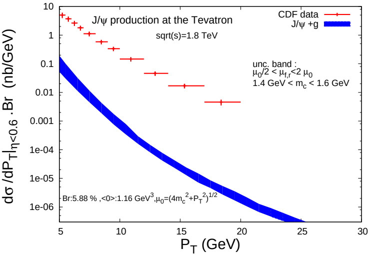

CDF, PRL 79:572 & 578,1997

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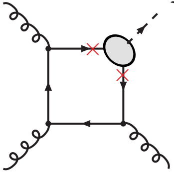

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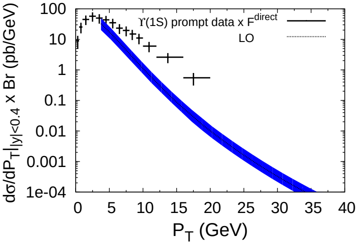

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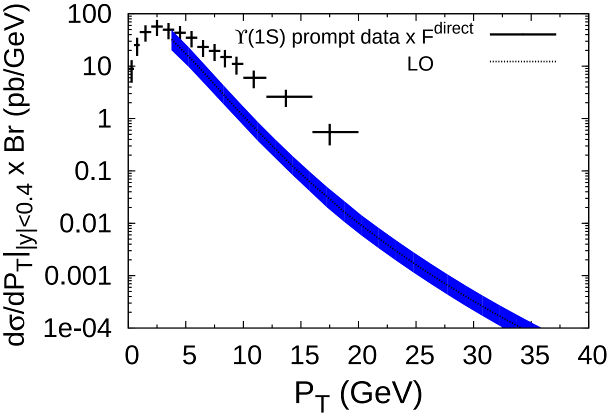

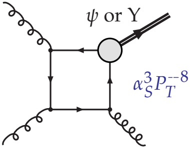

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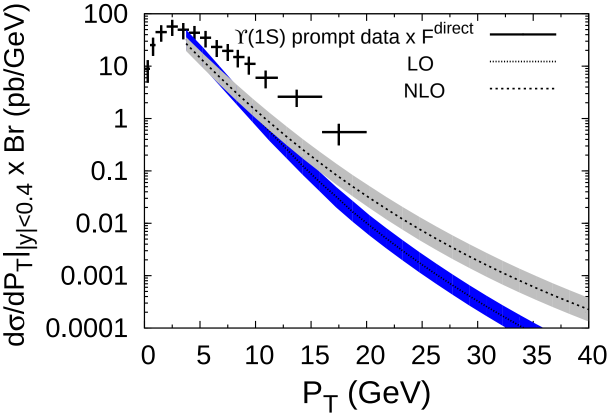

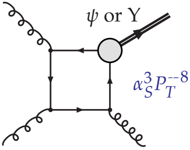

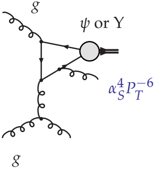

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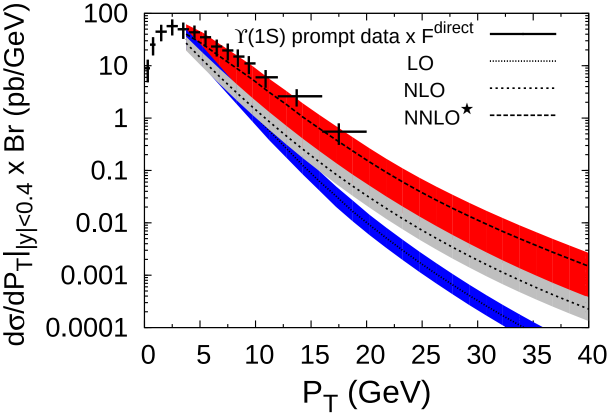

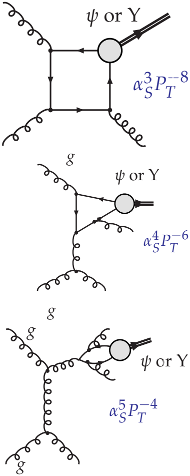

Attention: the NNLO★ is not a complete NNLO

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

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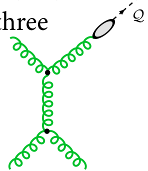

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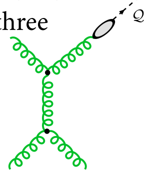

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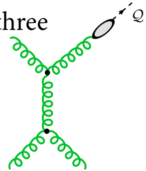

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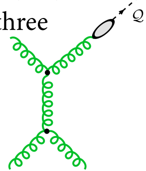

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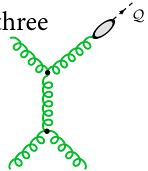

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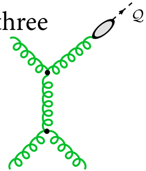

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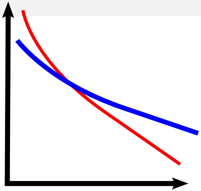

ψ data: a little less hard than the blue curve

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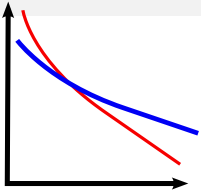

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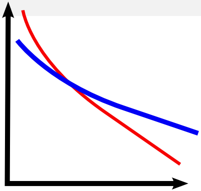

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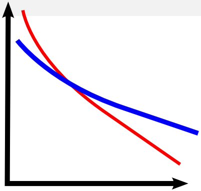

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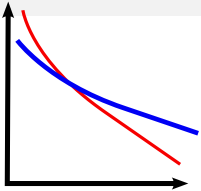

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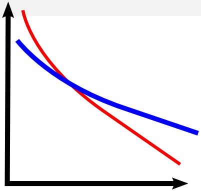

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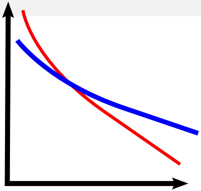

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- Polarisation: ${}^1S_0^{[8]}$: unpolarised; ${}^3S_1^{[8]}$ & ${}^3P_J^{[8]}$: transverse
- As such, it is hazardous to use NLO LDMEs for other processes at LO !

As an illustration, some NLO LDMEs are negative $\Rightarrow \sigma^{\text{LO}} \times \langle \mathcal{O} \rangle < 0$

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

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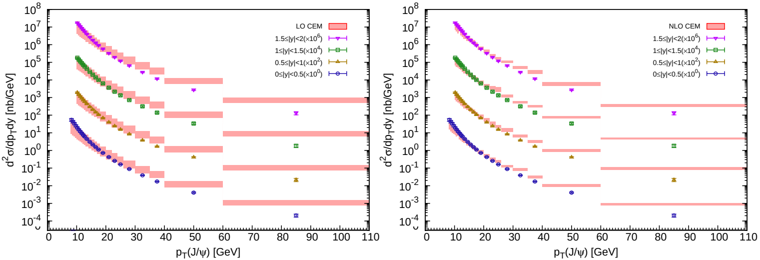
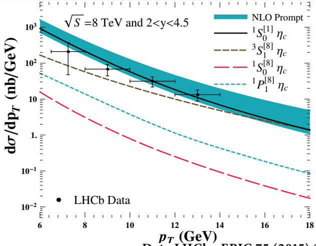
- Tend to overshoot the ψ data at large P_T
- The (LO) ICEM not significantly better at large P_T **Y.Q. Ma, R. Vogt PRD 94 (2016) 114029**



The last piece in the puzzle: the η_c



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

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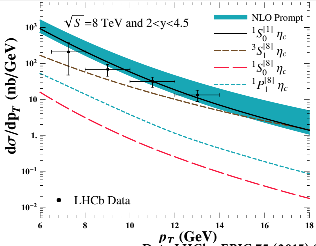

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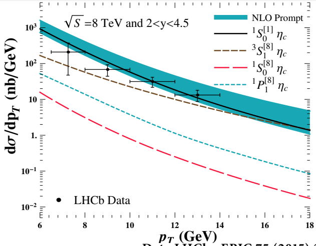

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- Even *neglecting* the *dominant* CS, this induces constraints on CO J/ψ LDMEs

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

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

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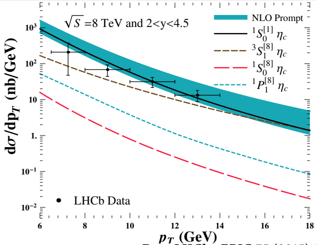

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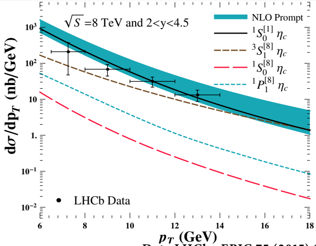

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- Nobody foresaw the impact of measuring η_c yields: 3 PRL published right after the LCHb data came out (Hamburg) M. Butenschoen *et al.* PRL 114 (2015) 092004; (PKU) H. Han *et al.* 114 (2015) 092005; (IHEP) H.F. Zhang *et al.* 114 (2015) 092006

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Part III

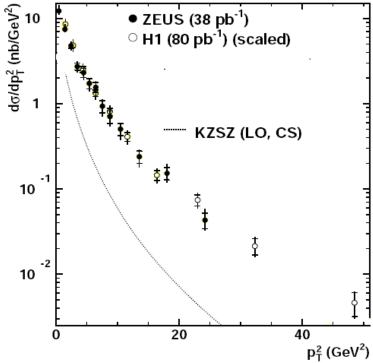
Photoproduction at mid and high P_T: on the importance of QCD and QED corrections

Photoproduction at mid and high P_T

M.Kramer Nucl.Phys.B459:3 1996; e.g. **H1,EPJC 25, 2,2002; ZEUS, EPJC 27, 173, 2003**

LO CSM also fails in photoproduction at HERA

M. Kramer, Nucl.Phys.B459:3 199



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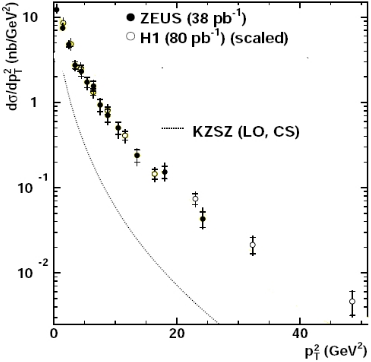

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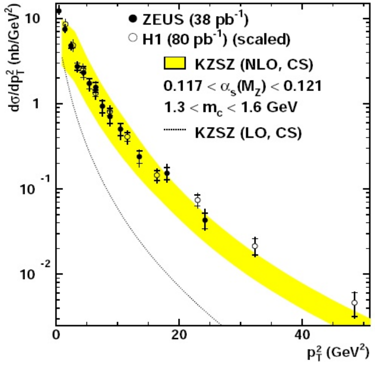

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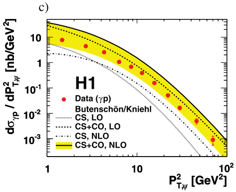
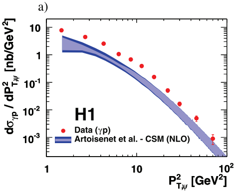
Disagreement not so obvious with the latest H1 data given the theory uncertainties

H1 EPJC (2010) 68: 401





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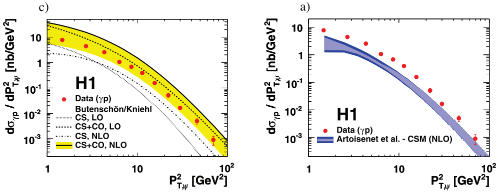
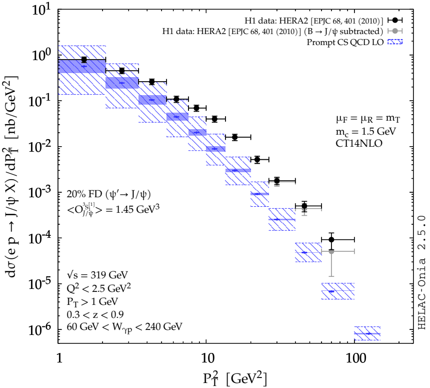
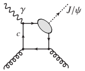


→ Let us revisit this in view of the EIC prospects

Is the CSM after all a good baseline ?

C.Flore, JPL, H.S. Shao, Y. Yedelkina, PLB 811 (2020) 135926





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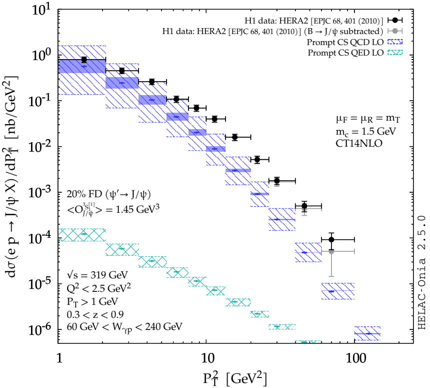

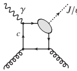

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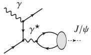

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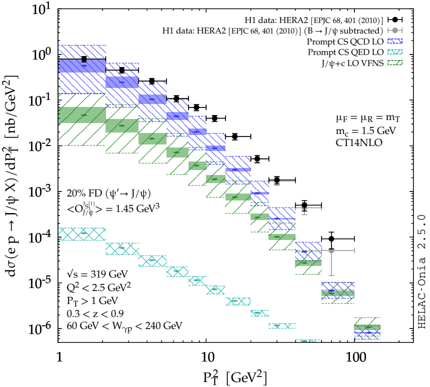

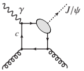

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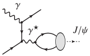

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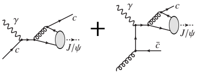

$\begin{cases} \gamma+c\to\psi+c \,@\, \alpha\alpha_s^2 \text{ w. 4 Flav.} \\ \gamma+g\to\psi+c+\bar{c} \,@\, \alpha\alpha_s^3 \text{ w. 3 Flav.} \end{cases}$

[also NEW !]

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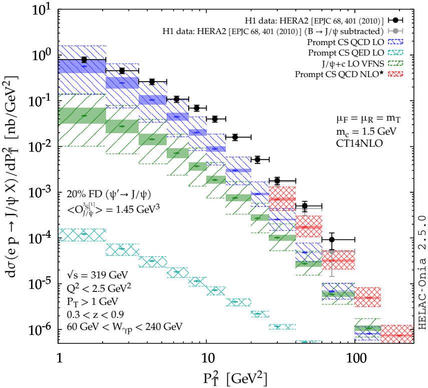

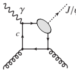

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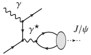

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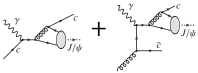
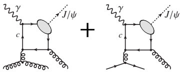


$\gamma + c \to \psi + c \,@\, \alpha\alpha_s^2$ w. 4 Flav.
$\gamma + g \to \psi + c + \bar{c} \,@\, \alpha\alpha_s^3$ w. 3 Flav.

[also NEW !]



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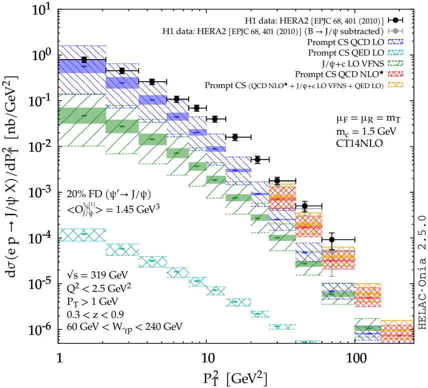

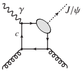

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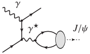

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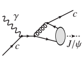
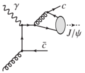
 + 

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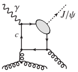
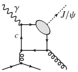
 + 

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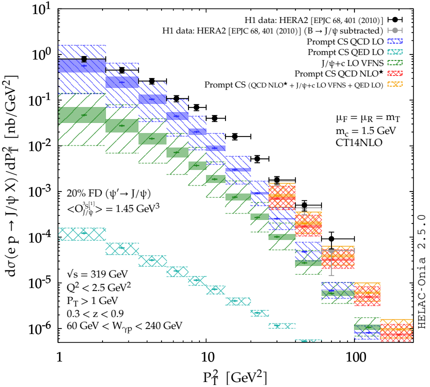
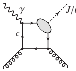
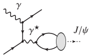
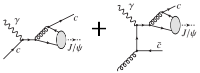




$\gamma + g \to \psi + g\,@\,\alpha\alpha_s^2$ [LO]



$\gamma + q \to \psi + q\,@\,\alpha^3$ [NEW !]



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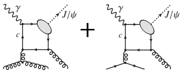

$\gamma + g \to \psi + g + g\,@\,\alpha\alpha_s^3$
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+ LO

- LO QCD does a good job at low P_T
- LO QED much harder but small normalisation [will matter at EIC]
- J/ψ+charm: starts to matter at high P_T [will also matter at EIC]
- NLO$^{(\star)}$ close the data, the overall sum nearly agrees with them
- Agreement when the expected $B \to J/\psi$ feed down (always overlooked) is subtracted

→ CSM accounts for the data and can be used for EIC predictions

Predictions for the EIC : inclusive production

C.Flore, JPL, H.S. Shao, Y. Yedelkina, PLB 811 (2020) 135926

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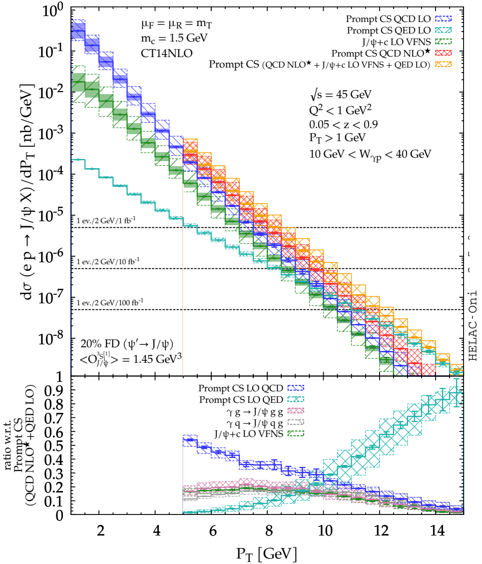

- At $\sqrt{s_{ep}} = 45$ GeV, one enters the valence region
- Yield measurable up to $P_T = 10$ GeV with $\mathcal{L} = 100\ \text{fb}^{-1}$

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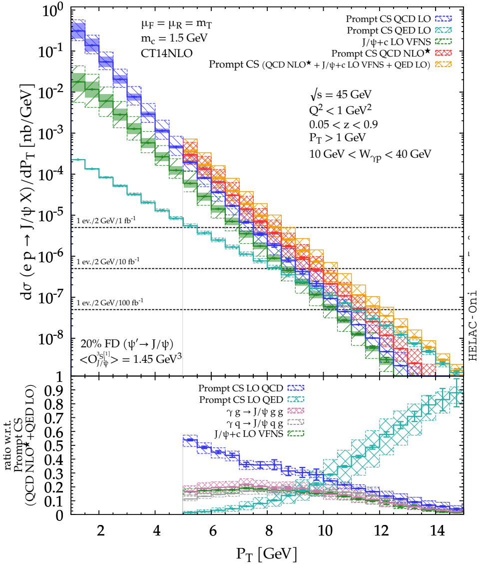
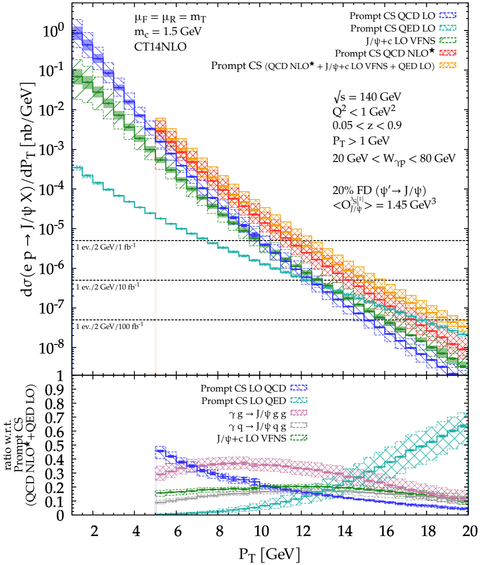


- At $\sqrt{s_{ep}} = 45$ GeV, one enters the valence region
- Yield measurable up to $P_T = 10$ GeV with $\mathcal{L} = 100$ fb^{-1}
- QED contribution leading at the largest measurable P_T

Predictions for the EIC : inclusive production

C.Flore, JPL, H.S. Shao, Y. Yedelkina, PLB 811 (2020) 135926



- At $\sqrt{s_{ep}} = 140$ GeV, P_T range up to 15-20 GeV
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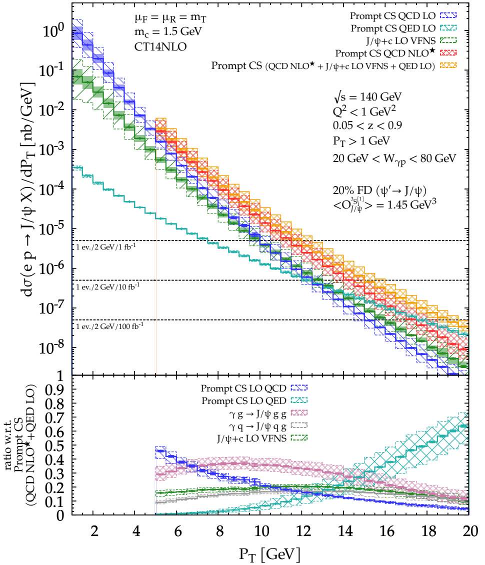


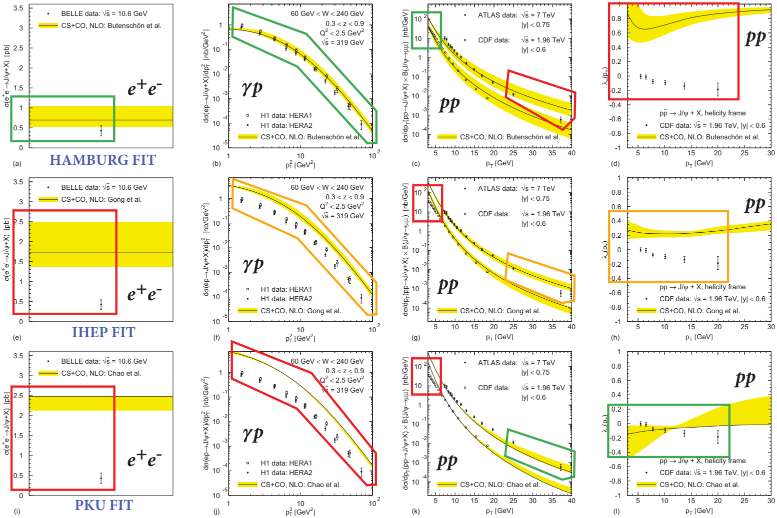
- At $\sqrt{s_{ep}}$ = 140 GeV, P_T range up to 15-20 GeV
- photon-gluon fusion remains dominant
- J/ψ + 2 hard partons dominant for $P_T \sim 10 - 15$ GeV
- Could lead to J/ψ + 2 jets with moderate P_T
- A priori the leading jet$_1$ recoils on the J/ψ+ jet$_2$ pair
- $d\sigma$ should scale with $M_{J/\psi+\text{jet}_2} - M_{J/\psi}$

Part IV

Overall

Universality of NLO NRQCD fits ?

Plot from M. Butenschön (ICHEP 2012); Discussion in JPL, Phys.Rept. 889 (2020) 1



Further caveats: η_c data !

The current situation in one slide ...

See JPL. arXiv:1903.09185 [hep-ph] (Phys.Rept. 889 (2020) 1)

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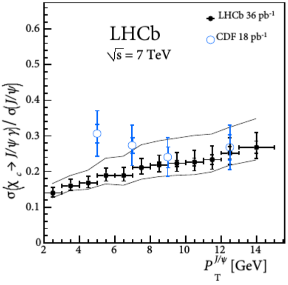
- As we will see, these also offer new ways to study DPS

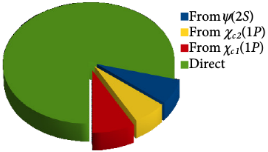
Feed downs from the excited states

Non trivial kinematical effects

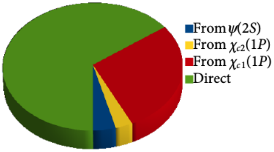
JPL. arXiv:1903.09185 [hep-ph] (Phys.Rept. 889 (2020) 1)



(a)



(b) Low P_T J/ψ



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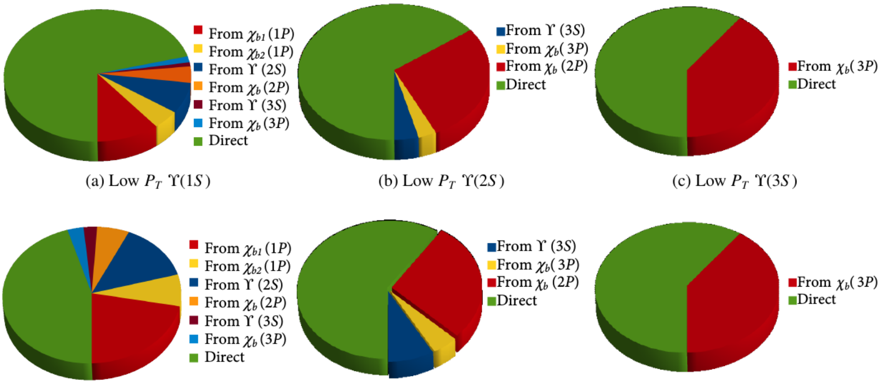


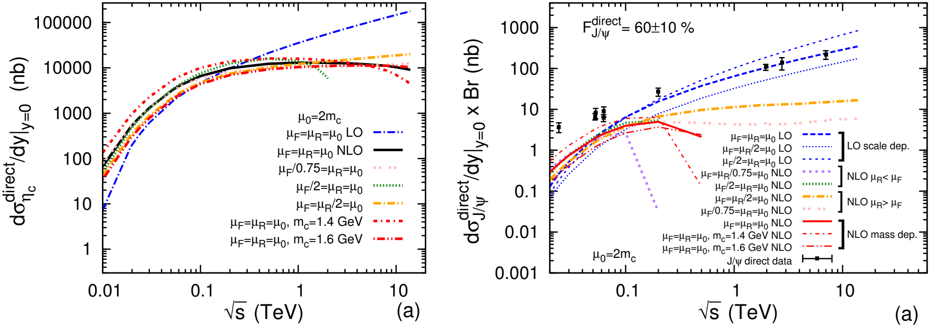
(a) Low P_T $\Upsilon(1S)$ (b) Low P_T $\Upsilon(2S)$ (c) Low P_T $\Upsilon(3S)$

(d) High P_T $\Upsilon(1S)$ (e) High P_T $\Upsilon(2S)$ (f) High P_T $\Upsilon(3S)$

Part V

On the unphysical behaviour of NLO quarkonium production and its cure

Problem of negative cross-sections - η_c and J/ψ at NLO



comparison of η_c (left) and J/ψ (right) differential cross-sections at NLO with different scale choices of μ_R and μ_F with CTEQ6M

[Y. Feng, J.-P. Lansberg, J.X. Wang, Eur.Phys.J. C75 (2015) no.7, 313]

η_c at NLO - historical development

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The partonic high-energy limit is defined as taking $\hat{\sigma}$ at $\hat{s} \to \infty$ or equivalently $z \to 0$ with $z = \frac{M_{\mathcal{Q}}^2}{\hat{s}}$,

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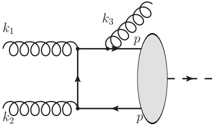
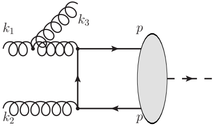
- If PDFs are not steep enough, the large-$\hat{s}$ region dominates and the hadronic cross section becomes negative

Recap of NLO calculation & origin of negative numbers

$\hat{s}$-dependence only present in real corrections $(g(k_1) + g(k_2) \rightarrow \eta_Q(P) + g(k_3))$





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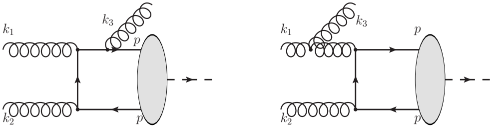

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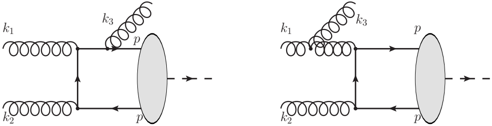

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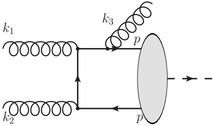

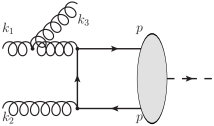

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$$\overline{\sigma}_{gg}^{\text{NLO},z\neq 1}(z) = -\frac{1}{\epsilon_{\text{IR}}}\frac{\alpha_s}{\pi}\left(\frac{4\pi\mu_R^2}{M_Q^2}\right)^{\epsilon}\Gamma(1+\epsilon)\hat{\sigma}_0^{\text{LO}} z P_{gg}(z) + 2C_A\frac{\alpha_s}{\pi}\hat{\sigma}_0^{\text{LO}}\overline{A}_{gg}(z)$$

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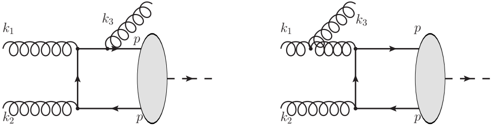

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Recap of NLO calculation & origin of negative numbers

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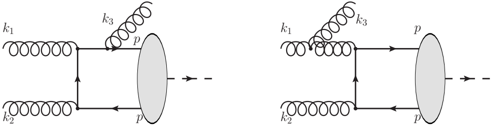

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A new scale-choice prescription

JPL, M.A. Ozcelik, EPJC 81 (2021) 6, 497

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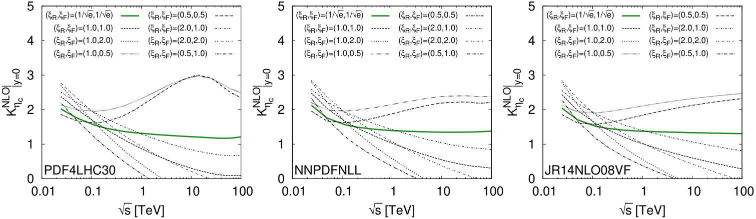

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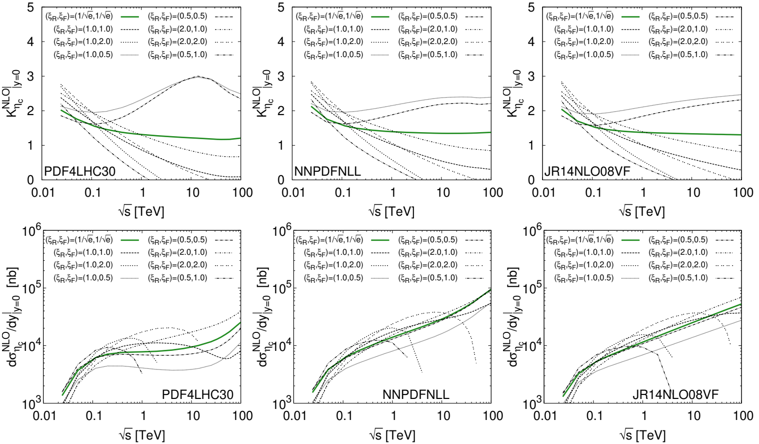

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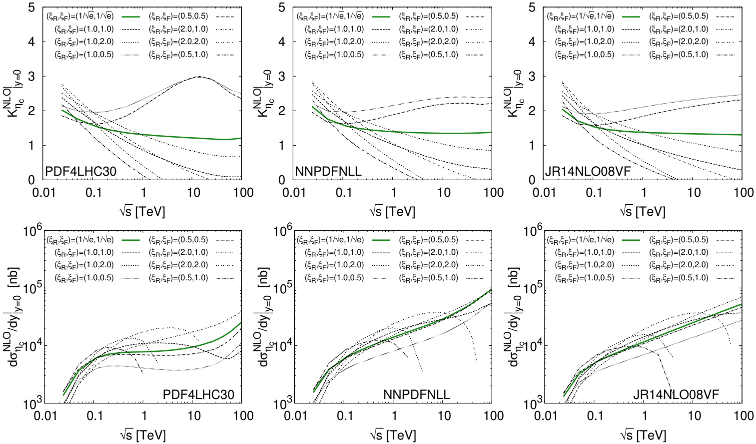

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Measuring η_c total cross sections (at NICA, LHC-FT and LHC) : crucial constraints on gluon PDFs

Part VI

Associated-quarkonium production

Going further with associated-quarkonium production

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See section 3 of JPL, arXiv:1903.09185 (Phys.Rept. 889 (2020) 1) and section 2.5 of E. Chapon arXiv:2012.14161 PPNP (2021) 103906, https://doi.org/10.1016/j.ppnp.2021.103906.

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

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    First observation by ATLAS EPJC 75 (2015) 229
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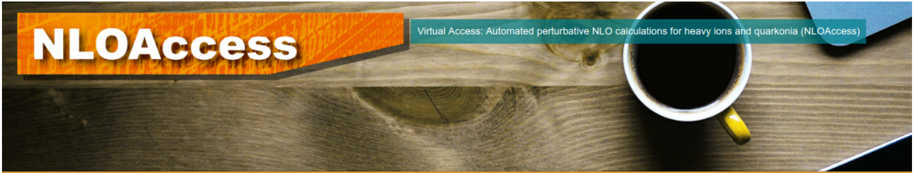
LO predictions for quarkonia → NLOAccess [in2p3.fr/nloaccess]



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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

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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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