Impact of QCD corrections to quarkonium production

J.P. Lansberg
IJCLab Orsay – Paris-Saclay U. – CNRS

Synergies between LHC and EIC for quarkonium physics
ECT*, July 8-12, 2024

This project is supported by the European Union's Horizon 2020 research and innovation programme under Grant agreement no. 824093

Part I

Introduction

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Conversely, other quarkonia (η_Q, χ_Q) or pairs (coupling to 2 g but not to 1 γ) are much less measured, and yet it seems we understand better their production mechanism

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- 2017+2023: Multi-dimensional measurements of J/ψ pairs by ATLAS & LHCb ?

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+ extensions: Improved CEM, Soft Gluon Factorisation, Soft Colour Interaction, ...

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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

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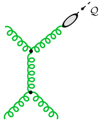

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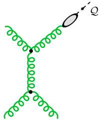

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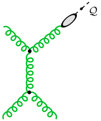

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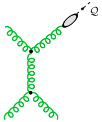

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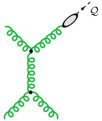

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- Low predictive power, yet overshoots the data at large P_T; issues with the χ_c's

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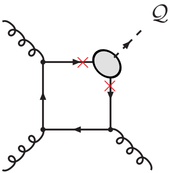

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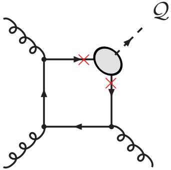

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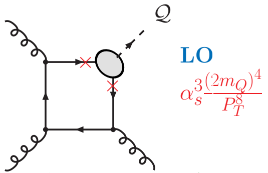

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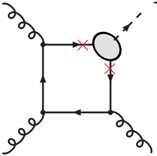

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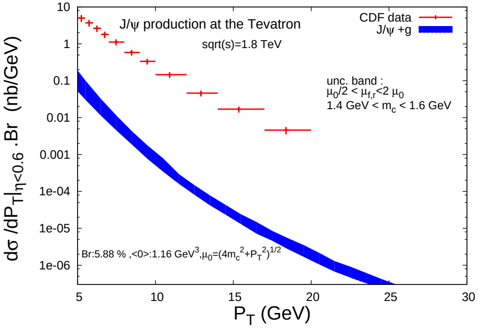

CDF, PRL 79:572 & 578,1997

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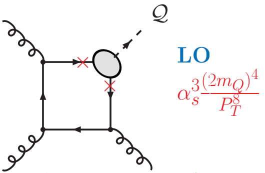

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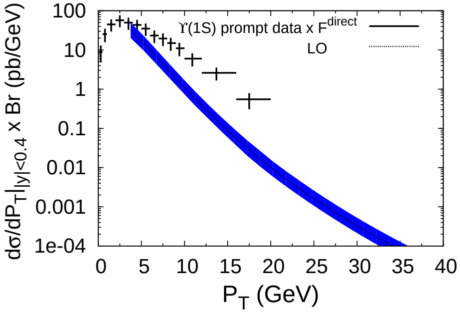

CDF, PRL 88:161802,2002

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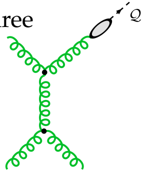

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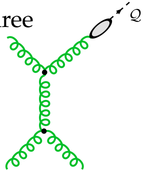

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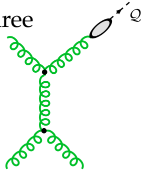

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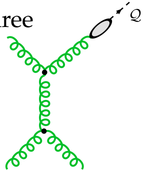

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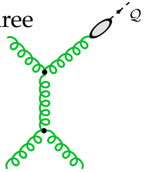

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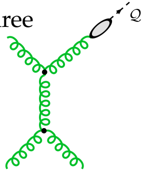

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Part II

Impact of QCD corrections to the C(S,E,O)M*

*See section 2 of Phys. Rept. 889 (2020) 1 for collinear factorisation

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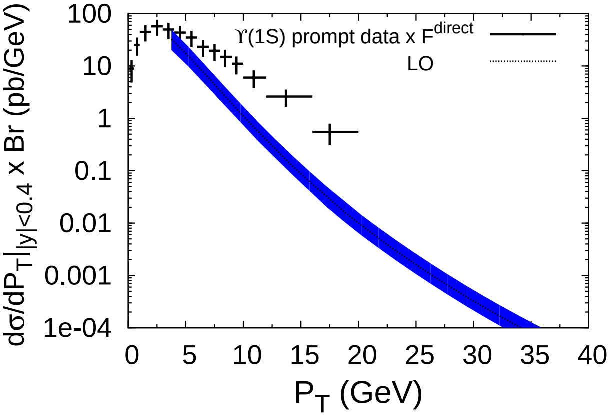

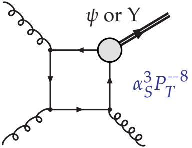

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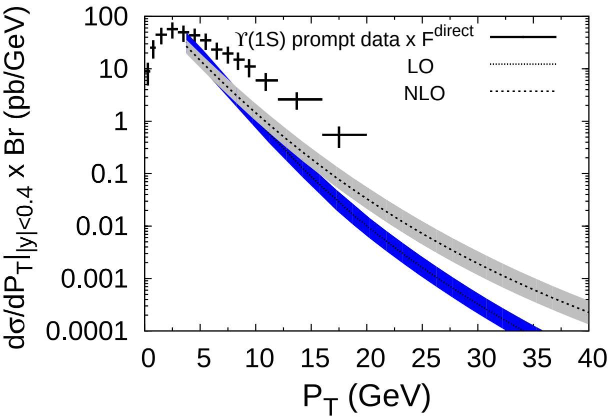

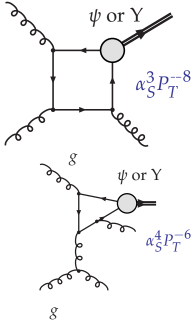

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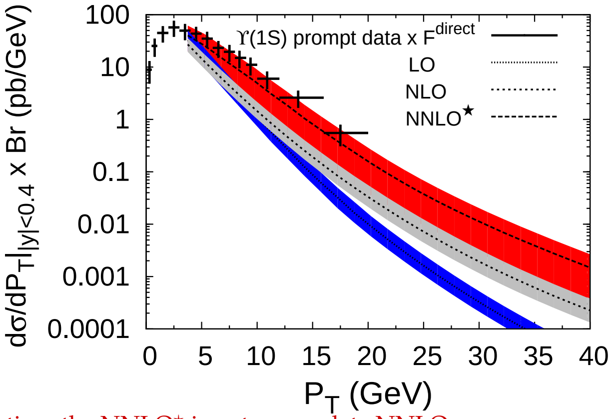

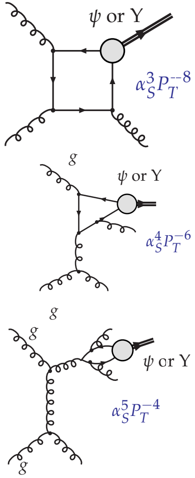

Attention: the NNLO* is not a complete NNLO

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

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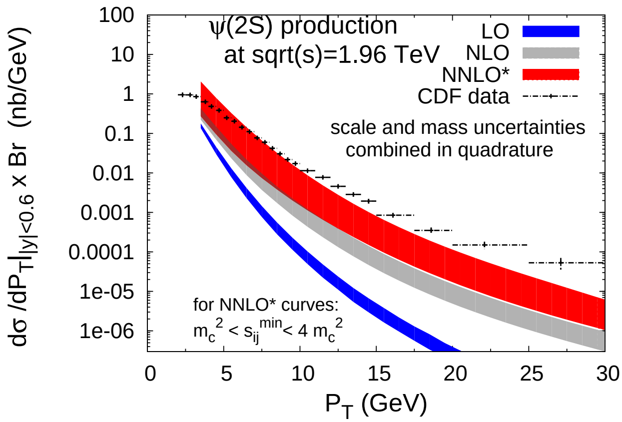

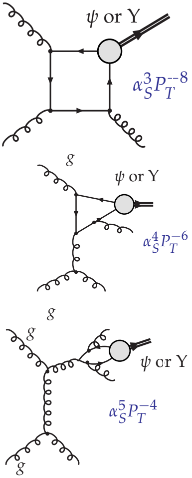

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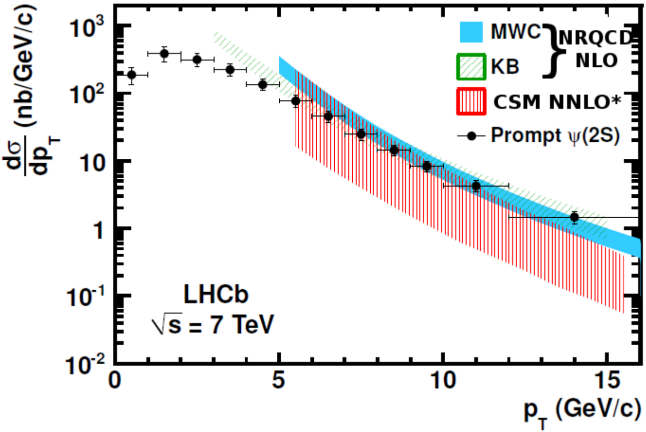

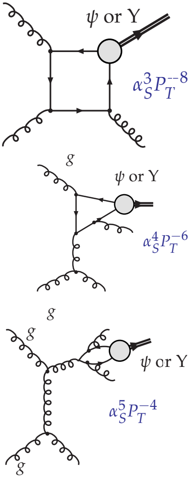

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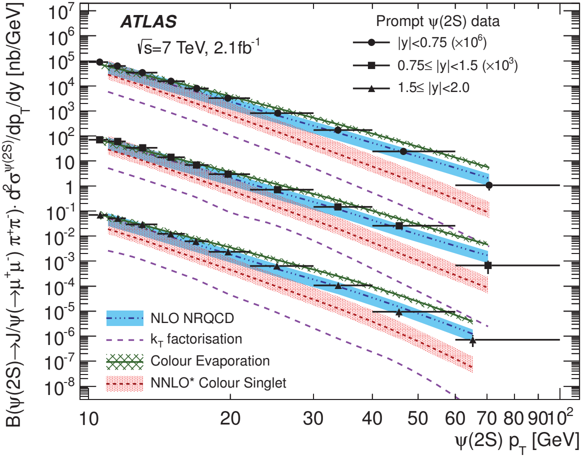

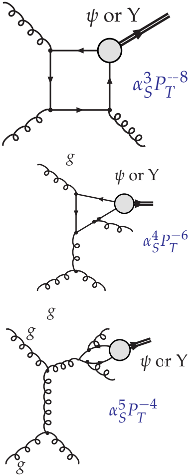

QCD corrections to the CEM P_T dependence

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

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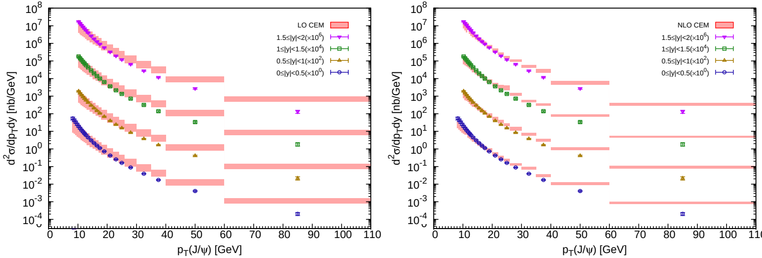

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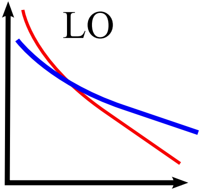

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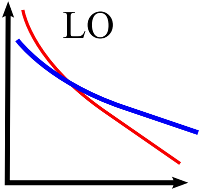

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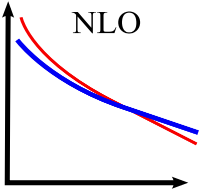

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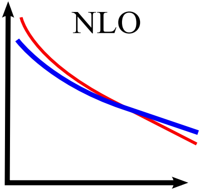

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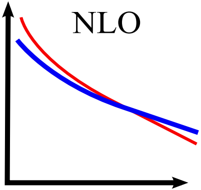

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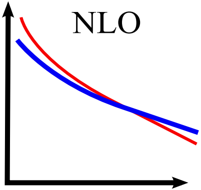

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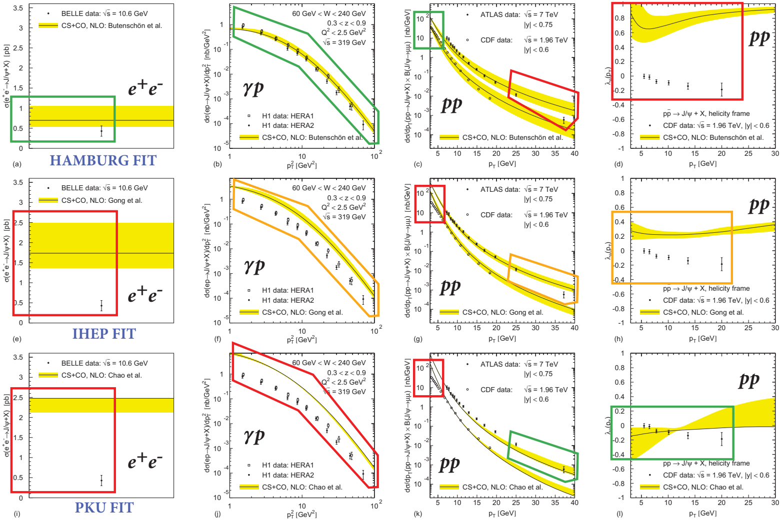
- Polarisation: ${}^1S_0^{[8]}$: unpolarised; ${}^3S_1^{[8]}$ & ${}^3P_J^{[8]}$: transverse

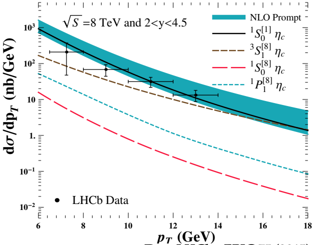
Universality of NLO NRQCD fits ?

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



Further caveats: LDME upper limit from η_c data clearly violated by the 3 fits !

The last piece in the puzzle: the η_c



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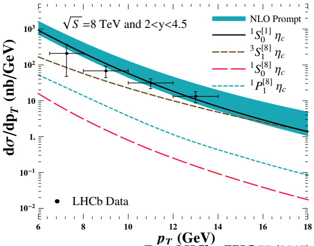

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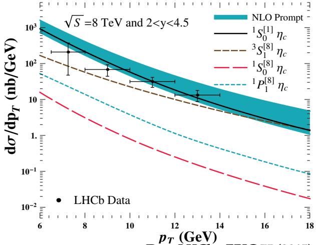

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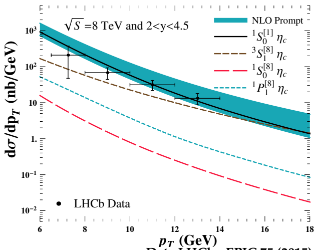

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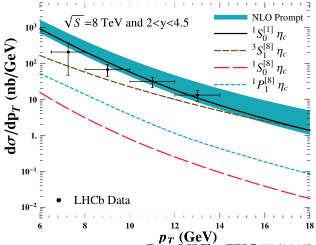

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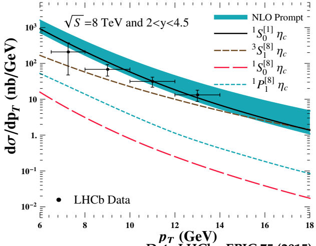
- Yet, the constraints actually is $\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle = \langle \mathcal{O}^{\eta_c}(^3S_1^{[8]})\rangle \lesssim 5 \times 10^{-3}\ \text{GeV}^3$ when the CS contribution is appropriately accounted for

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

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 : $\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle = \langle \mathcal{O}^{\eta_c}(^3S_1^{[8]})\rangle < 1.46 \times 10^{-2}\ \mathrm{GeV}^3$
- 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
- Yet, the constraints actually is $\langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle = \langle \mathcal{O}^{\eta_c}(^3S_1^{[8]})\rangle \lesssim 5 \times 10^{-3}\ \mathrm{GeV}^3$ when the CS contribution is appropriately accounted for
- 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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Tension between hadro- and photoproduction data

No peak at $z \simeq 1$

Plots courtesy M. Butenschön ; to appear in our EIC Quarkonium Review

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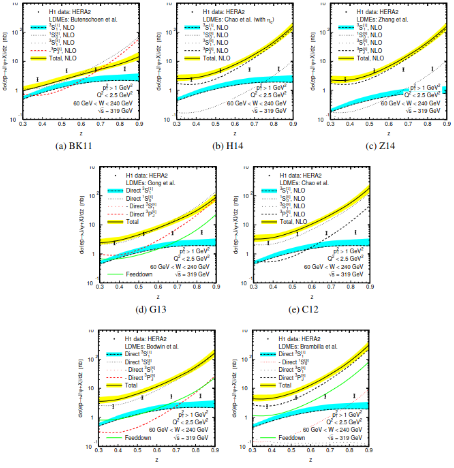


(a) BK11 (b) H14 (c) Z14

(d) G13 (e) C12

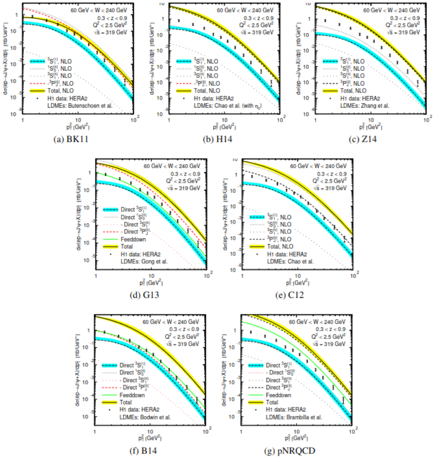
(f) B14 (g) pNRQCD

NB: The small discrepancy of the blue band (CSM) could be fixed by HEF resummation

Tension between hadro- and photoproduction data

Excess at ”any” P_T

Plots courtesy M. Butenschön ; to appear in our EIC Quarkonium Review



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On the importance of QCD corrections to $\psi + \psi$ production at large $P_T^{\psi\psi}$

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

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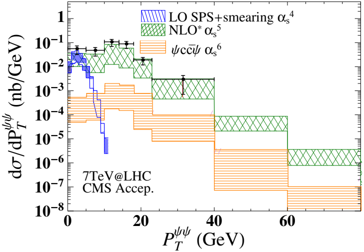

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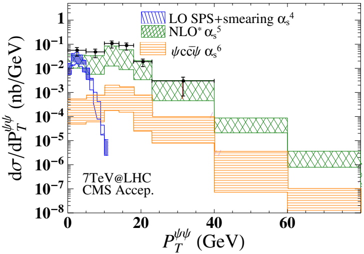

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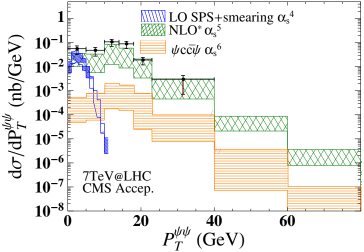

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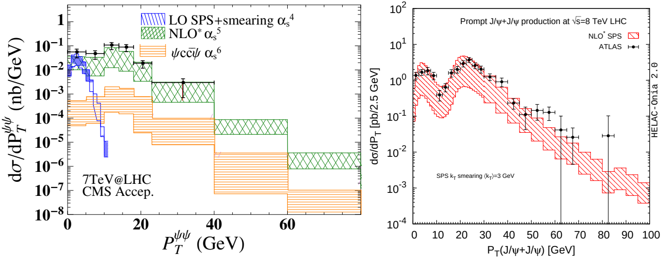

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Note: the NLO* SPS red band in ATLAS EPJC (2017) 77:76 is wrong !

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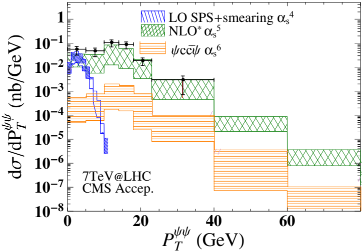

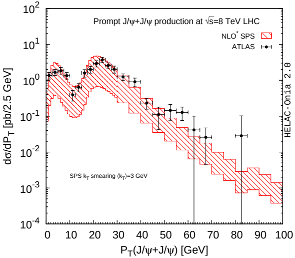

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- Like for η_c, $\psi + \psi$ P_T spectrum is well accounted by the CSM

Table: Scaling with α_s, p_T and v of $d\sigma/dp_T^2$ for $gg \to c\bar{c}(m)c\bar{c}(n)$ times the respective LDMEs and branching fractions for the relevant pairings (m, n) of $c\bar{c}$ Fock states. Note that ${}^3P_J^{[1]}$ are counted separately for $J = 0, 1, 2$. [By B. Kniehl and Z. He]

(m, n)	${}^3S_1^{[1]}$	${}^3S_1^{[8]}$	${}^1S_0^{[8]}$	${}^3P_J^{[8]}$	${}^3P_J^{[1]}$
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${}^3S_1^{[8]}$	$\cdots$	$\alpha_s^4 v^8/p_T^4$	$\alpha_s^4 v^7/p_T^6$	$\alpha_s^4 v^8/p_T^6$	$\alpha_s^4 v^8/p_T^6$
${}^1S_0^{[8]}$	$\cdots$	$\cdots$	$\alpha_s^4 v^6/p_T^8$	$\alpha_s^4 v^7/p_T^8$	$\alpha_s^4 v^7/p_T^8$
${}^3P_J^{[8]}$	$\cdots$	$\cdots$	$\cdots$	$\alpha_s^4 v^8/p_T^8$	$\alpha_s^4 v^8/p_T^8$
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${}^3S_1^{[8]}$	...	$\alpha_s^4 v^8/p_T^4$	$\alpha_s^4 v^7/p_T^6$	$\alpha_s^4 v^8/p_T^6$	$\alpha_s^4 v^8/p_T^6$
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- Indeed, rule of thumb, for $c\bar{c}$, $\alpha_S \sim v^2$, but do not forget the P_T scaling

Part III

Summary and outlook

The current situation in one slide ...

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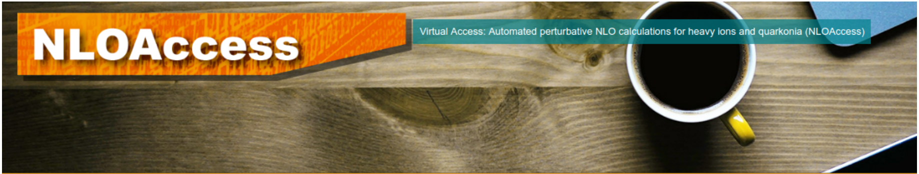
All approaches have troubles with *ep*, *ee* or *pp* polarisation and/or the η_c data

A EU Virtual Access to pQCD tools: 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

FOLLOW:

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 [nloaccess.in2p3.fr/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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MG5@NLO online [nloaccess.in2p3.fr/MG5/]

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Automated perturbative calculation with NLOAccess

MG5_aMC@NLO

MadGraph5_aMC@NLO is a framework that aims at providing all the elements necessary for SM and BSM phenomenology, such as the computations of cross sections, the generation of hard events and their matching with event generators, and the use of a variety of tools relevant to event manipulation and analysis. Processes can be simulated to LO accuracy for any user-defined Lagrangian, an the NLO accuracy in the case of models that support this kind of calculations -- prominent among these are QCD and EW corrections to SM processes. Matrix elements at the tree- and one-loop-level can also be obtained.

Please login to use MG5_aMC@NLO.