Quarkonia as tools, and tools for quarkonia

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IJCLab Orsay – Paris-Saclay U. – CNRS

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Part I

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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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- What's next ?

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

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 ?

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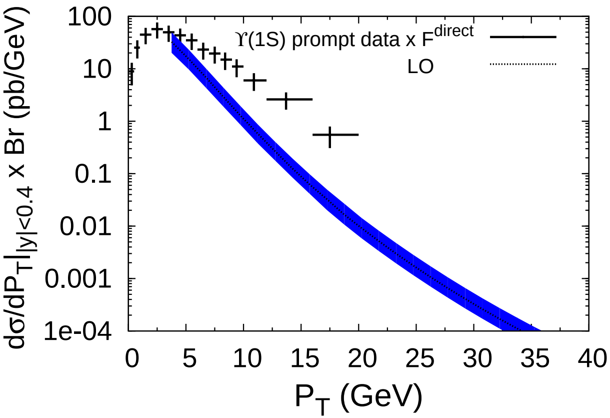

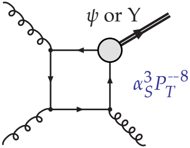

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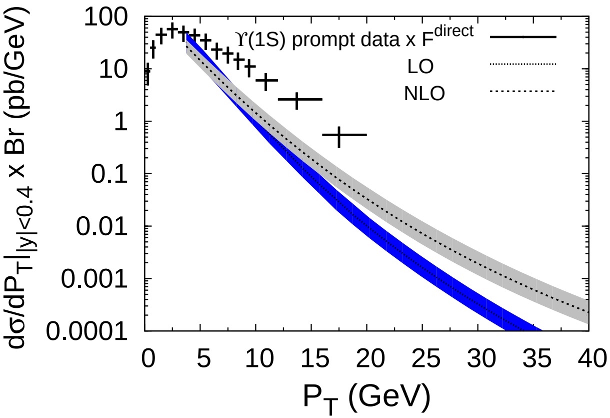

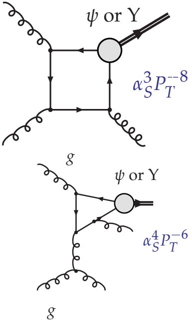

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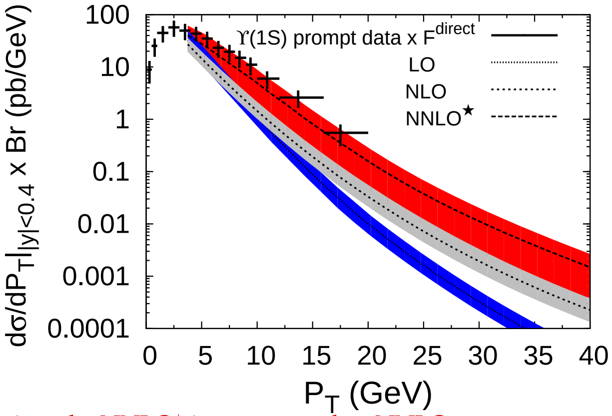

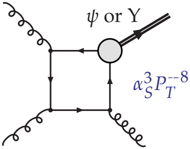

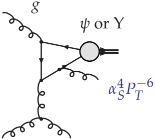

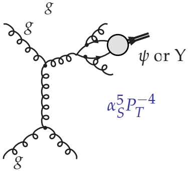

Attention: the NNLO* is not a complete NNLO

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

COM dominance at LO : not so simple

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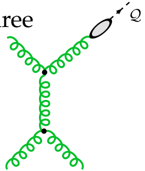

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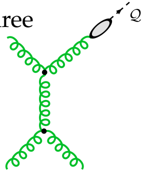

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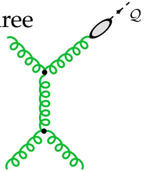

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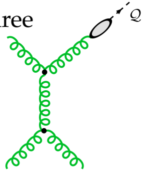

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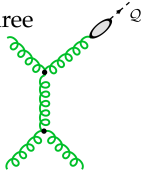

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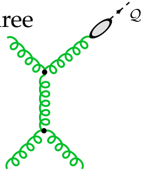

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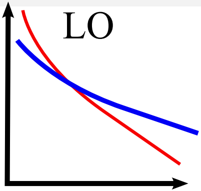

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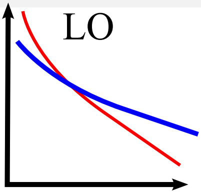

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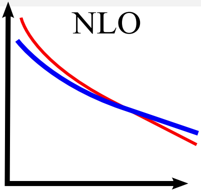

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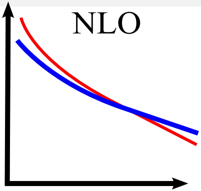

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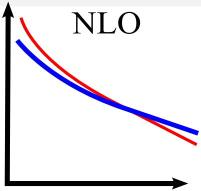

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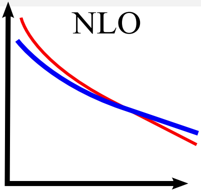

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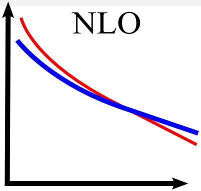

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- As such, it is hazardous to use NLO LDMEs for other processes at LO !

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

Problem of negative NLO quarkonium cross sections

[Y. Feng, JPL, J.X. Wang, Eur.Phys.J. C75 (2015) 313]; JPL, M.A. Ozcelik, EPJC 81 (2021) 6, 497; A. Colpani Serri, Y. Feng, C. Flore, JPL, M.A. Ozcelik, H.S. Shao, Y. Yedelkina PLB 835 (2022) 137556

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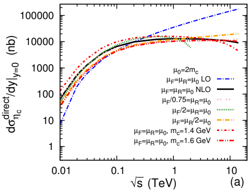

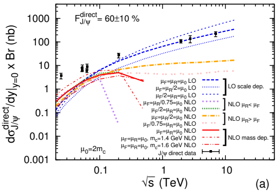

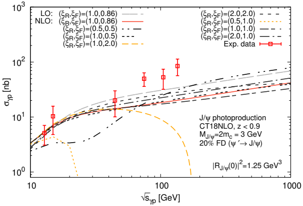

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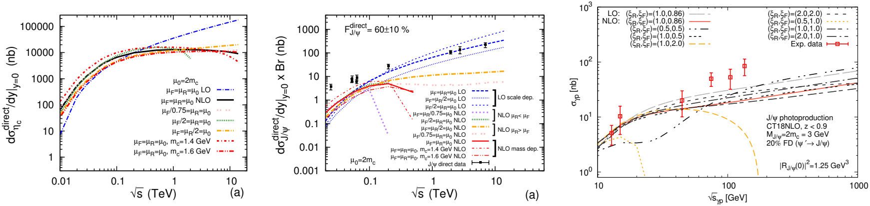

Origin: process-dependent subtraction of collinear divergences vs universal DGLAP PDF evolution

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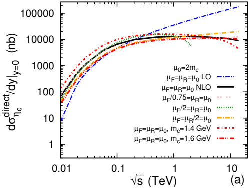

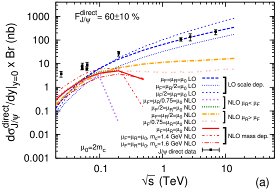

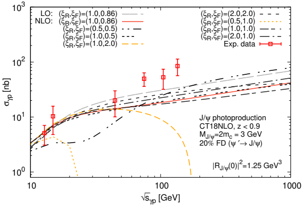

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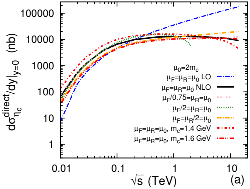

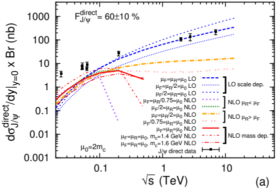

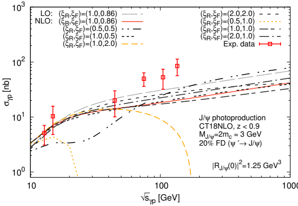

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Confirmation: HEF expanded up to NLO in α_s (for η_Q):

J.P. Lansberg, M. Nefedov, M.A.Ozcelik, JHEP 05 (2022) 083 + arXiv:2306.02425 [hep-ph]

$$\hat{\sigma}_{gg}^{[m],\,\mathrm{HEF}}(z \to 0) = \sigma_{\mathrm{LO}}^{[m]} \left\{ A_0^{[m]} \delta(1-z) + \frac{\alpha_s}{\pi} 2C_A \left[A_1^{[m]} + A_0^{[m]} \ln \frac{M^2}{\mu_F^2} \right] \right.$$

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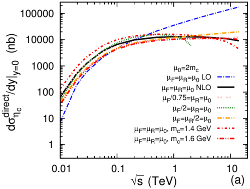

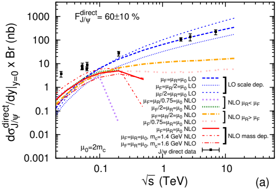

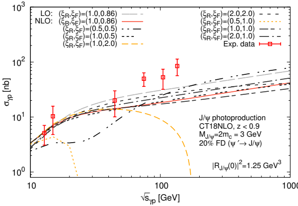

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The current situation in one slide ...

For an up-to-date review, see JPL. arXiv:1903.09185 [hep-ph] (Phys.Rept. 889 (2020) 1)

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

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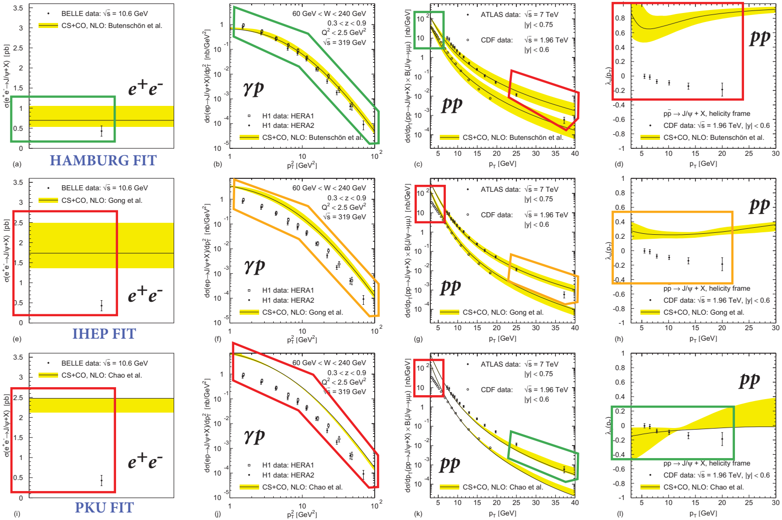
All approaches have troubles with *ep*, *ee* or *pp* polarisation and/or the η_c data

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 !

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)	${}^3S_1^{[1]}$	${}^3S_1^{[8]}$	${}^1S_0^{[8]}$	${}^3P_J^{[8]}$	${}^3P_J^{[1]}$
${}^3S_1^{[1]}$	α_s^4/p_T^8	$\alpha_s^4 v^4/p_T^8$	$\alpha_s^4 v^3/p_T^8$	$\alpha_s^4 v^4/p_T^8$	0
${}^3S_1^{[8]}$	$\cdots$	$\alpha_s^4 v^8/p_T^4$	$\alpha_s^4 v^7/p_T^6$	$\alpha_s^4 v^8/p_T^6$	$\alpha_s^4 v^8/p_T^6$
${}^1S_0^{[8]}$	$\cdots$	$\cdots$	$\alpha_s^4 v^6/p_T^8$	$\alpha_s^4 v^7/p_T^8$	$\alpha_s^4 v^7/p_T^8$
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${}^1S_0^{[8]}$	$\cdots$	$\cdots$	$\alpha_s^4 v^6/p_T^8$	$\alpha_s^4 v^7/p_T^8$	$\alpha_s^4 v^7/p_T^8$
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- Different scaling in the litterature v^3 vs v^4 for ${}^1S_0^{[8]}$, but similar pictures

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- CO are NNLO in v^2 for single ψ, N^{4}LO in v^2 for double ψ

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${}^1S_0^{[8]}$	$\cdots$	$\cdots$	$\alpha_s^4 v^6/p_T^8$	$\alpha_s^4 v^7/p_T^8$	$\alpha_s^4 v^7/p_T^8$
${}^3P_J^{[8]}$	$\cdots$	$\cdots$	$\cdots$	$\alpha_s^4 v^8/p_T^8$	$\alpha_s^4 v^8/p_T^8$
${}^3P_J^{[1]}$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\alpha_s^4 v^8/p_T^8$

- Different scaling in the litterature v^3 vs v^4 for ${}^1S_0^{[8]}$, but similar pictures
- CO are NNLO in v^2 for single ψ, N^{4}LO in v^2 for double ψ
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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)	${}^3S_1^{[1]}$	${}^3S_1^{[8]}$	${}^1S_0^{[8]}$	${}^3P_J^{[8]}$	${}^3P_J^{[1]}$
${}^3S_1^{[1]}$	α_s^4/p_T^8	$\alpha_s^4 v^4/p_T^8$	$\alpha_s^4 v^3/p_T^8$	$\alpha_s^4 v^4/p_T^8$	0
${}^3S_1^{[8]}$	...	$\alpha_s^4 v^8/p_T^4$	$\alpha_s^4 v^7/p_T^6$	$\alpha_s^4 v^8/p_T^6$	$\alpha_s^4 v^8/p_T^6$
${}^1S_0^{[8]}$	...	...	$\alpha_s^4 v^6/p_T^8$	$\alpha_s^4 v^7/p_T^8$	$\alpha_s^4 v^7/p_T^8$
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- "0" can be misleading, it just means that it start at α_s^5, like $J/\psi + \eta_c$
- Indeed, rule of thumb, for $c\bar{c}$, $\alpha_S \sim v^2$, but do not forget the P_T scaling

Part II

J/ψ-pair production at the LHC

Progress in Particle and Nuclear Physics 122 (2022) 103906

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Review

Prospects for quarkonium studies at the high-luminosity LHC

Émilien Chapon[1,a], David d'Enterria[2,a], Bertrand Ducloué[3,a], Miguel G. Echevarria[4,a], Pol-Bernard Gossiaux[5,a], Vato Kartvelishvili[6,a], Tomas Kasemets[7,a], Jean-Philippe Lansberg[8,*,a,b], Ronan McNulty[9,a], Darren D. Price[10,a], Hua-Sheng Shao[11,a], Charlotte Van Hulse[9,a], Michael Winn[12,a], Jaroslav Adam[13], Liupan An[14], Denys Yen Arrebato Villar[5], Shohini Bhattacharya[15], Francesco G. Celiberto[16,17,18,19], Cvetan Cheshkov[20], Umberto D'Alesio[21], Cesar da Silva[22], Elena G. Ferreiro[23], Chris A. Flett[24,25], Carlo Flore[8], Maria Vittoria Garzelli[26,14,27], Jonathan Gaunt[28,10], Jibo He[29], Yiannis Makris[17], Cyrille Marquet[30], Laure Massacrier[8], Thomas Mehen[31], Cédric Mezrag[12], Luca Micheletti[32], Riccardo Nagar[33], Maxim A. Nefedov[34], Melih A. Ozcelik[8], Biswarup Paul[21], Cristian Pisano[21], Jian-Wei Qiu[35], Sangem Rajesh[21], Matteo Rinaldi[36], Florent Scarpa[8,37], Maddie Smith[6], Pieter Taels[30], Amy Tee[6], Oleg Teryaev[38], Ivan Vitev[22], Kazuhiro Watanabe[35], Nodoka Yamanaka[39,40], Xiaojun Yao[41], Yanxi Zhang[2,42]

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New observables in inclusive production of quarkonia

Jean-Philippe Lansberg

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A R T I C L E I N F O

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Tevatron
HERA

A B S T R A C T

After an introduction motivating the study of quarkonium production, we review the recent developments in the phenomenology of quarkonium production in inclusive scatterings of hadrons and leptons. We naturally address data and predictions relevant for the LHC, the Tevatron, RHIC, HERA, LEP, B factories and EIC. An up-to-date discussion of the contributions from feed downs within the charmonium and bottomonium families as well as from b hadrons to charmonia is also provided. This contextualises an exhaustive overview of new observables such as the associated production along with a Standard Model boson (γ, W and Z), with another quarkonium, with another heavy quark as well as with light hadrons or jets. We address the relevance of these reactions in order to improve our understanding of the mechanisms underlying quarkonium production as well as the physics of multi-parton interactions, in particular the double parton scatterings. An outlook towards future studies and facilities concludes this review.

$J/\psi + J/\psi$ at low $P_T^{\psi\psi}$ (more generally $P_T^{\psi\psi} \ll M_{\psi\psi}$)

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LHCb PLB 707 (2012) 52; JHEP 1706 (2017) 047; CMS JHEP 1409 (2014) 094; ATLAS EPJC 77 (2017) 76; D0 PRD 90 (2014) 111101; NA3 PLB 158 (1985) 85

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- Negligible $q\bar{q}$ contributions even at AFTER@LHC ($\sqrt{s} = 115$ GeV) energies

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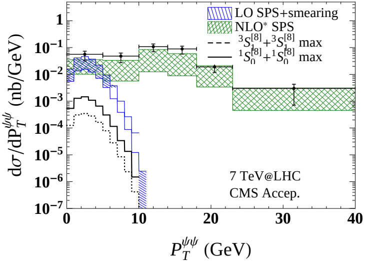

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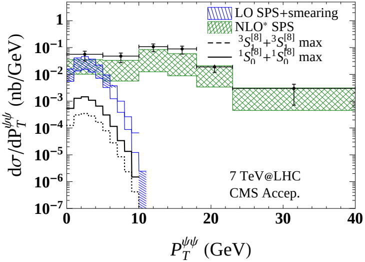
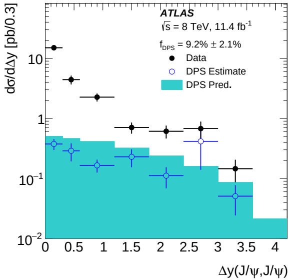
- In the CMS & ATLAS acceptances (P_T cut), small DPS effects, but required by the data at large Δy





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

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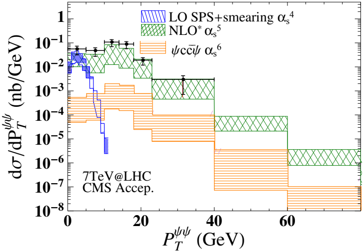

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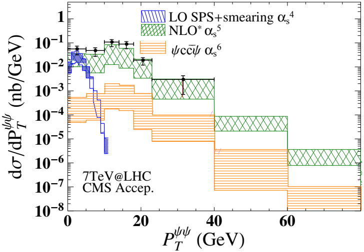

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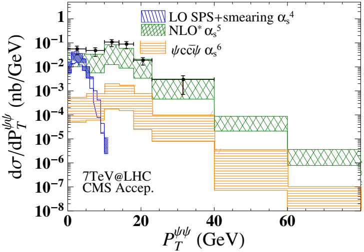

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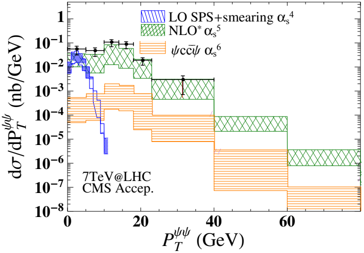

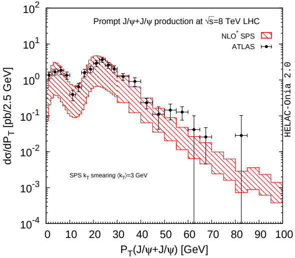

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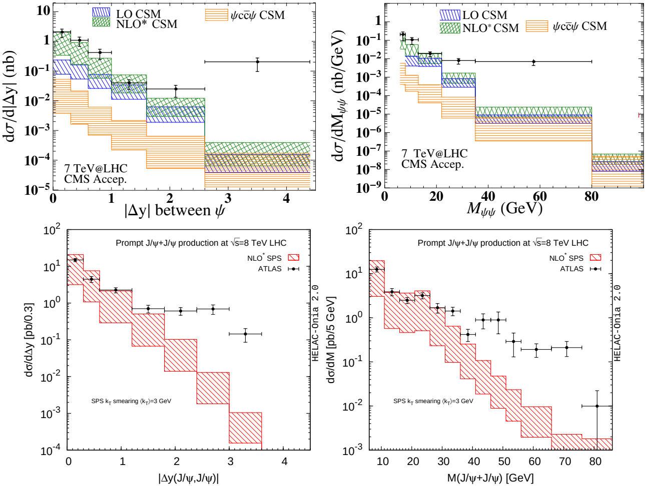
[the orange histogram shows one class of leading P_T α_s^6 contributions]

- Confirmation at larger $P_T^{\psi\psi}$ with ATLAS data !

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

An excess at large Δy (or $M_{\psi\psi}$) ?



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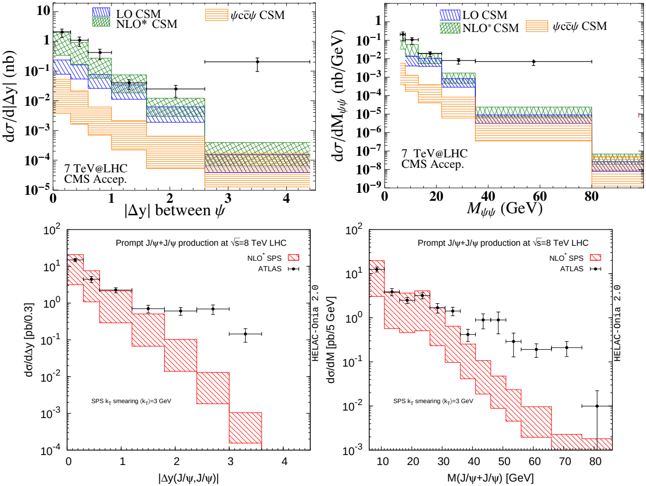

Origin of this excess: **double parton scattering** [not CO]

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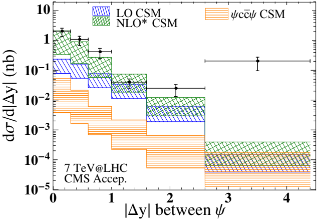

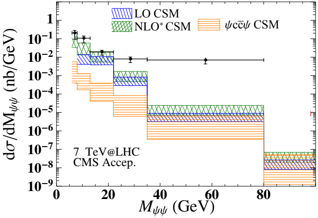

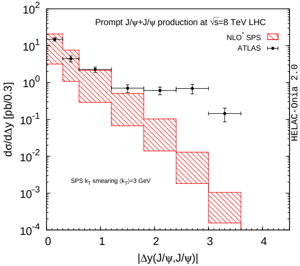

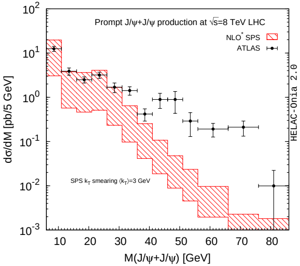

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ATLAS measurement: $\sigma_{\text{eff}} = 6.3 \pm 1.6(stat) \pm 1.0(syst) \pm 0.1(BF) \pm 0.1(lumi)$ mb

Our theory-driven 2015 extraction from CMS data: $\sigma_{\text{eff}} = 8.2 \pm 2.0 \pm 2.9$ mb

New multi-differential analysis of LHCb: I

SPS-DPS separation

See Talk by L. An at EPS-HEP 2023 and [LHCb-PAPER-2023-023]

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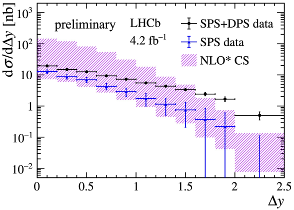

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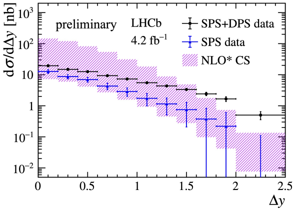

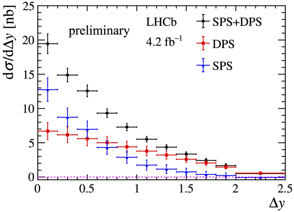

$$\sigma(J/\psi - J/\psi)_{\rm DPS} = 8.6 \pm 1.2(\text{stat}) \pm 1.0(\text{syst})\ \text{nb}$$

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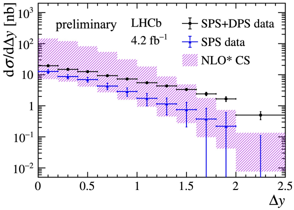

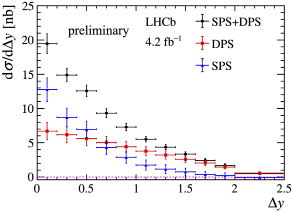

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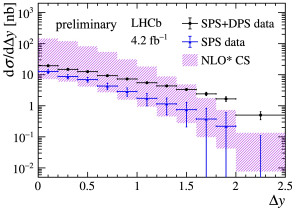
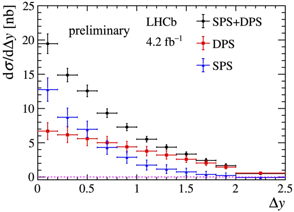
- Taken at face value confirmation that LHCb probes with quarkonia larger σ_{eff} than ATLAS & CMS.





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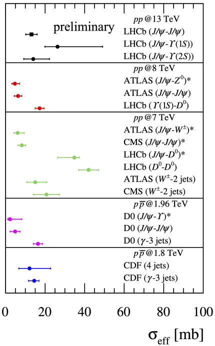
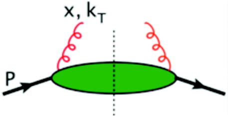


Part III

Double-quarkonium production as tools to probe the gluon transverse dynamics

Gluon TMDs in unpolarised protons



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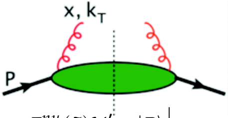

- Gauge-invariant definition:

$$\Phi_g^{\mu\nu}(x,\boldsymbol{k}_T,\zeta,\mu) \equiv \int \frac{\mathrm{d}(\xi\cdot P)\,\mathrm{d}^2\xi_T}{(xP\cdot n)^2(2\pi)^3}\, e^{i(xP+k_T)\cdot\xi}\langle P|F^{n\nu}(0)\mathcal{U}_{[0,\xi]}F^{n\mu}(\xi)\mathcal{U}'_{[\xi,0]}|P\rangle\Big|_{\xi\cdot P'=0}$$

- $\mathcal{U}$ and $\mathcal{U}'$ are process dependent gauge links

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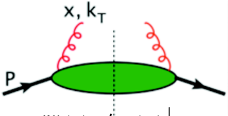

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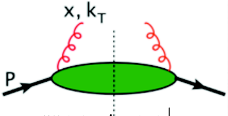
- Parametrisation: **P. J. Mulders, J. Rodrigues, PRD 63 (2001) 094021; D. Boer *et al.* JHEP 1610 (2016) 013**

$$\Phi_g^{\mu\nu}(x,\boldsymbol{k}_T,\zeta,\mu) = -\frac{1}{2x}\left\{g_T^{\mu\nu} f_1^g(x,k_T,\mu) - \left(\frac{k_T^\mu k_T^\nu}{M_p^2} + g_T^{\mu\nu}\frac{\boldsymbol{k}_T^2}{2M_p^2}\right) h_1^{\perp\,g}(x,k_T,\mu)\right\} + \text{suppr.}$$

Gluon TMDs in unpolarised protons

- Gauge-invariant definition:



$$\Phi_g^{\mu\nu}(x,\boldsymbol{k}_T,\zeta,\mu) \equiv \int \frac{\mathrm{d}(\xi\cdot P)\,\mathrm{d}^2\xi_T}{(xP\cdot n)^2(2\pi)^3}\, e^{i(xP+k_T)\cdot\xi}\langle P|F^{n\nu}(0)\mathcal{U}_{[0,\xi]}F^{n\mu}(\xi)\mathcal{U}'_{[\xi,0]}|P\rangle\Big|_{\xi\cdot P'=0}$$

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- $h_1^{\perp g}$: TMD distribution of linearly polarised gluons

[Helicity-flip distribution]

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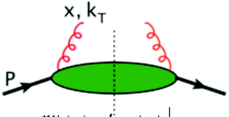

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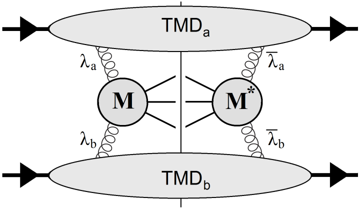
[Helicity-flip distribution]

- Both enter the computation of the q_T dependence of e.g. H^0 production

Accesssing the gluon polarisation with $\mathcal{Q} + \mathcal{Q}$

$d\sigma^{gg} \propto$



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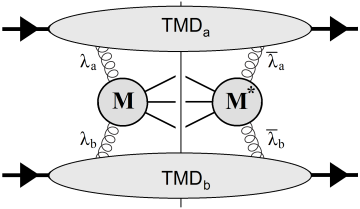
$$d\sigma^{gg} \propto \overbrace{\left(\sum_{\lambda_a,\lambda_b} \hat{\mathcal{M}}_{\lambda_a,\lambda_b} \hat{\mathcal{M}}^*_{\lambda_a,\lambda_b}\right)}^{F_1} \mathcal{C}[f_1^g f_1^g]$$

$\Rightarrow$ helicity non-flip, azimuthally independent



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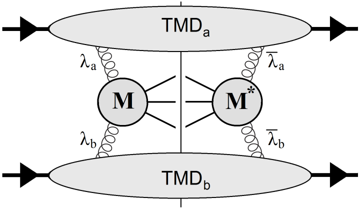
$\Rightarrow$ double helicity flip, azimuthally independent



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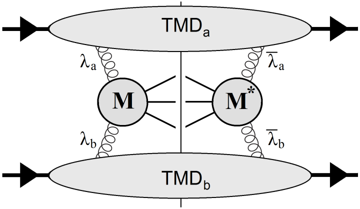
⇒ single helicity flip, $\cos(2\phi)$-modulation



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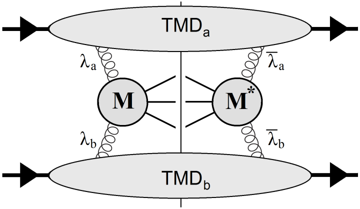
$\Rightarrow$ double helicity flip, $\cos(4\phi)$-modulation



TMD modelling : f_1^g and the 2017 $\psi + \psi$ LHCb data

JPL, C. Pisano, F. Scarpa, M. Schlegel, PLB 784(2018)217

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  where $g(x)$ is the usual collinear PDF
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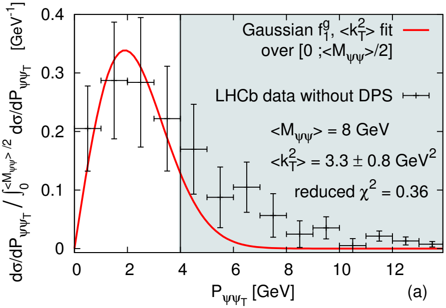

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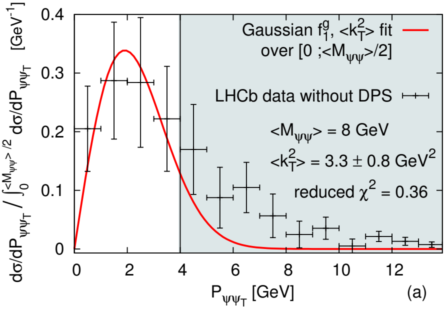

- Integration over $\phi \Rightarrow \cos(n\phi)$-terms cancel out
- $F_2 \ll F_1 \Rightarrow$ only $\mathcal{C}[f_1^g f_1^g]$ contributes to the cross-section
- No evolution here: $\langle k_T^2 \rangle \sim 3\ \mathrm{GeV}^2$ accounts both for non-perturbative and perturbative broadenings at a scale close to $M_{\psi\psi} \sim 8$ GeV
- Disentangling such (non-)perturbative effects requires data at different scales

Switching on TMD evolution

F. Scarpa, D. Boer, M.G. Echevarria, JPL, C. Pisano, M. Schlegel, EPJC (2020) 80:87

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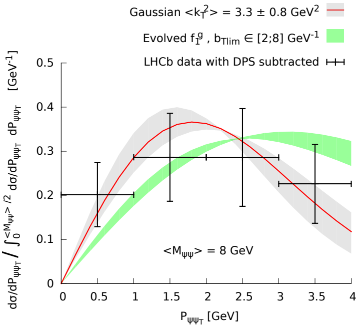

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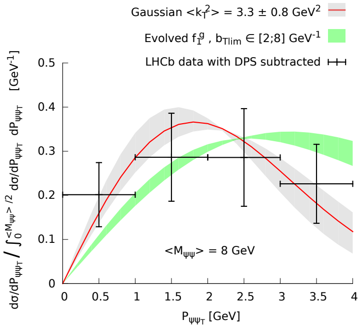

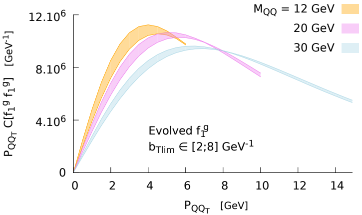

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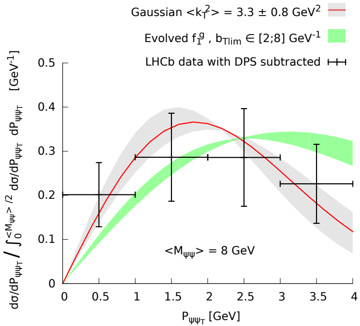
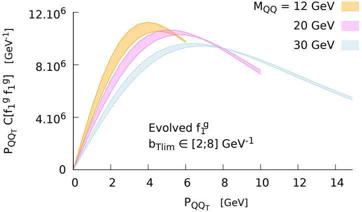


J. Bor, A. Colpani Serri



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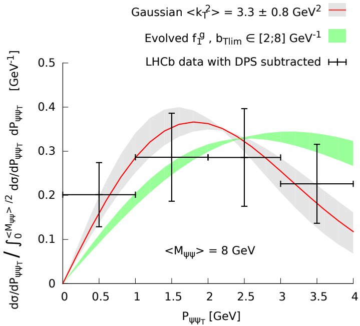
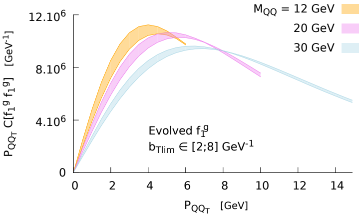
- x dependence J. Bor, A. Colpani Serri
- Besides the $P_T^{\psi\psi}$ broadening, $\langle \cos n\varphi \rangle$ studies give access to the linearly-polarised-gluon distributions

F. Scarpa, D. Boer, M.G. Echevarria, JPL, C. Pisano, M. Schlegel, EPJC (2020) 80:87





New multi-differential analysis of LHCb: II

Looking for scale evolution

See Talk by L. An at EPS-HEP 2023 and [LHCb-PAPER-2023-023]. Theory prediction; D. Boer, J. Bor, A. Colpani Serri, JPL, to appear

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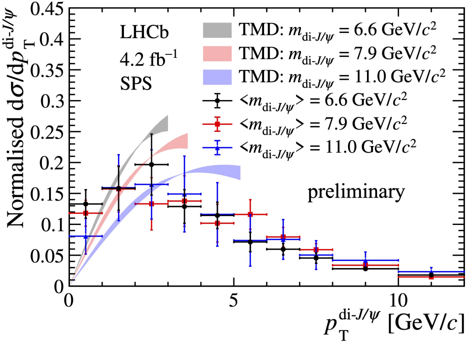
- Likely need a wider lever arm in $M_{\psi\psi}$



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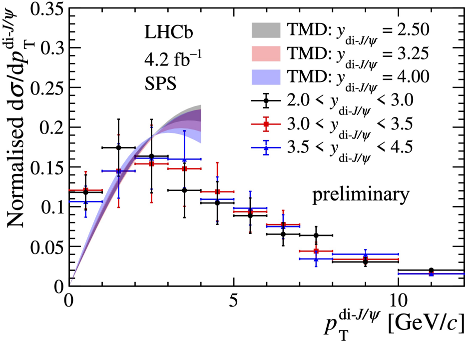
- No x dependence seen in the LHCb acceptance in agreement with our predictions



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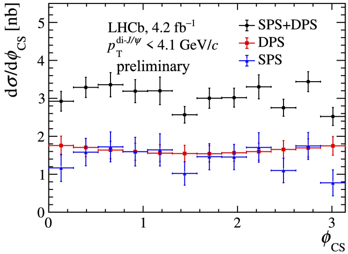

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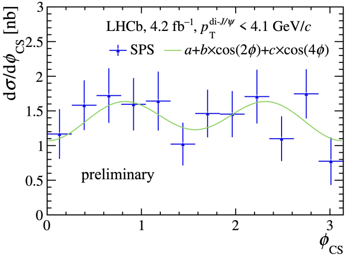

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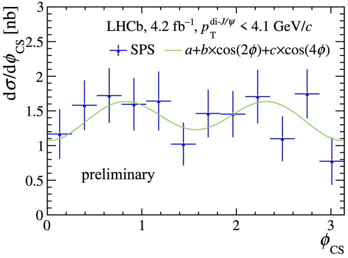
$\Rightarrow$ first hint of linearly polarised gluons in unpolarised protons



[LHCb-PAPER-2023-022]

$$a = F_1 \mathcal{C}[f_1^g f_1^g] + F_2 \mathcal{C}[w_2 h_1^{\perp g} h_1^{\perp g}],$$
$$b = F_3 \mathcal{C}[w_3 f_1^g h_1^{\perp g}] + F_3' \mathcal{C}[w_3' h_1^{\perp g} f_1^g],$$
$$c = F_4 \mathcal{C}[w_4 h_1^{\perp g} h_1^{\perp g}],$$

$\langle \cos(2\phi_{CS}) \rangle = b/2a$
$= -0.029 \pm 0.050 \pm 0.009$

$\langle \cos(4\phi_{CS}) \rangle = c/2a$
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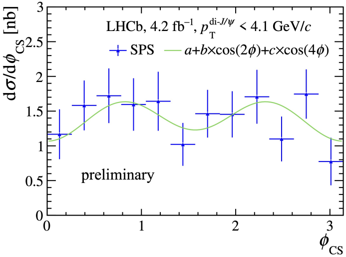

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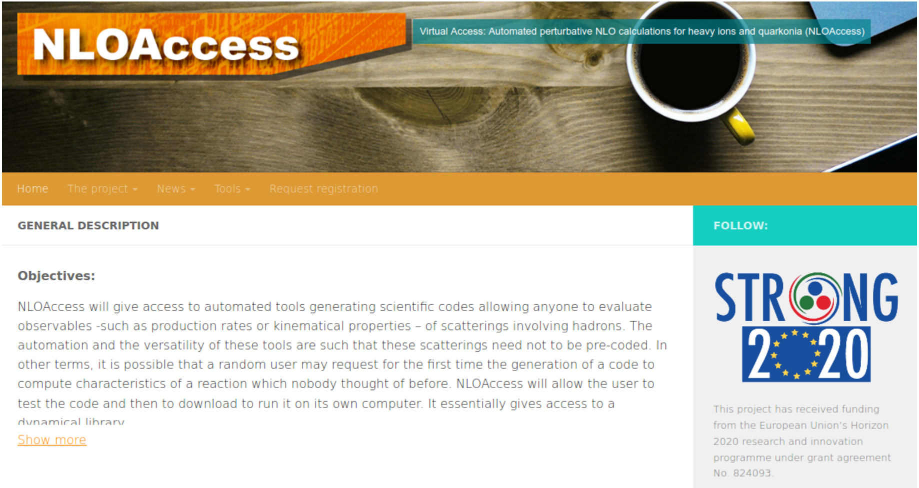
These numbers are compatible with our predictions [asymmetries at the per cent level, not larger] which however depend strongly on the $\cos\theta_{CS}$ region: $\langle \cos 2\phi_{CS} \rangle \propto \cos\theta_{CS}$ whereas $\langle \cos 4\phi_{CS} \rangle$ changes sign around $\cos\theta_{CS} = 0.2$

Part IV

Online tools for future prospects

A EU Virtual Access to pQCD tools: NLOAccess

[in2p3.fr/nloaccess]



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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Automated perturbative calculation with NLOAccess

MG5_aMC@NLO

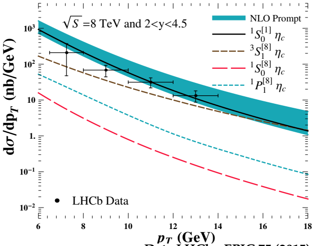
MadGraph5_aMC@NLO is a framework that aims at providing all the elements necessary for SM and BSM phenomenology, such as the computations of cross sections, the generation of hard events and their matching with event generators, and the use of a variety of tools relevant to event manipulation and analysis. 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.

Part V

Backup

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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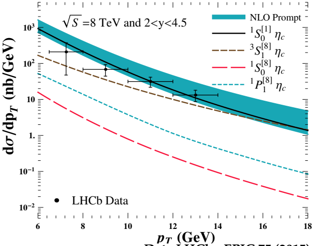

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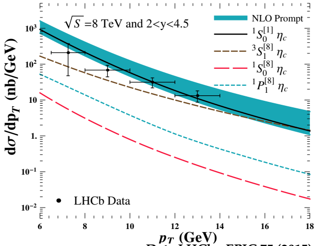

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$$\text{via Heavy-Quark Spin Symmetry : } \langle \mathcal{O}^{J/\psi}(^1S_0^{[8]})\rangle = \langle \mathcal{O}^{\eta_c}(^3S_1^{[8]})\rangle < 1.46 \times 10^{-2}\ \text{GeV}^3$$

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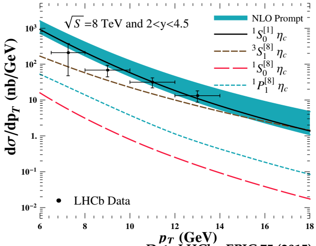

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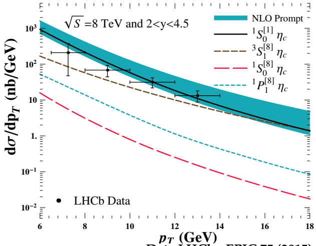

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- Nobody foresaw the impact of measuring η_c yields: 3 PRL published right after the LCHb data came out **(Hamburg) M. Butenschoen** *et al.* **PRL 114 (2015) 092004; (PKU) H. Han** *et al.* **114 (2015) 092005; (IHEP) H.F. Zhang** *et al.* **114 (2015)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

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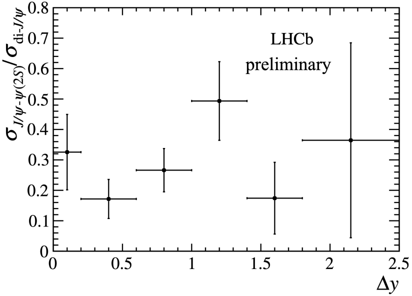
- $J/\psi + \eta_c$ can also tell something about DPS and about $\sigma_{\rm eff}$

New multi-differential analysis of LHCb: II

SPS-DPS separation with $\psi + \psi'$?

See Talk by L. An at EPS-HEP 2023 and [LHCb-PAPER-2023-023]



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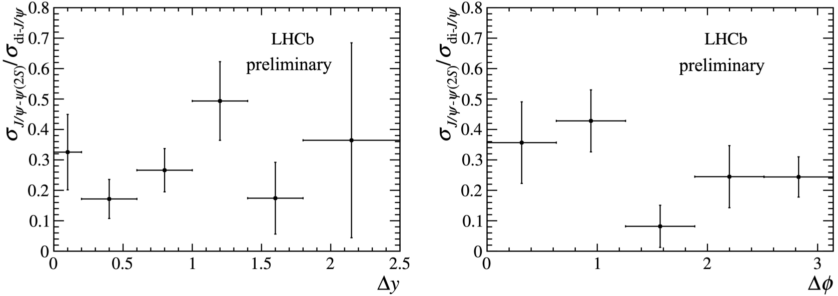

- Not conclusive yet

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Experimental wishlist for new observables in pp collisions :

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