Heavy quarks and quarkonia production in high energy experiments

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Heavy quark production: phenomenological framework

$$\frac{d\sigma}{dX} = \sum_{j,k} \int_{\hat{X}} f_j(x_1,Q) f_k(x_2,Q) \frac{d\hat{\sigma}_{jk}(Q)}{d\hat{X}} F(\hat{X} \to X; Q)$$

Factorization formula

- Parton PDF's *f(x,Q)* (universal)
- The cross section for the scattering of the partons *j*, *k*, computed in *pertubative* series *p*QCD at next to leading order (NLO) in α_S.
- A fragmentation function for the transition to the final state. Includes long-distance effects, taken as universal (e.g., from Z -> b bbar -> B *X*
- *Q* here stands for the mass scales that come into play:
  - Factorization scale
  - Heavy quark mass
  - Renormalization scale
  - p_T scale

- For $p_T \approx m_Q$, the parton cross section is computed for massless light quark [u, d, s (,c)] and g, and heavy b
- For $p_T >> m_Q$ the b quark becomes an active contributor (its mass may be neglected)

Merging low-p_T and high-p_T regions, analytical computations:

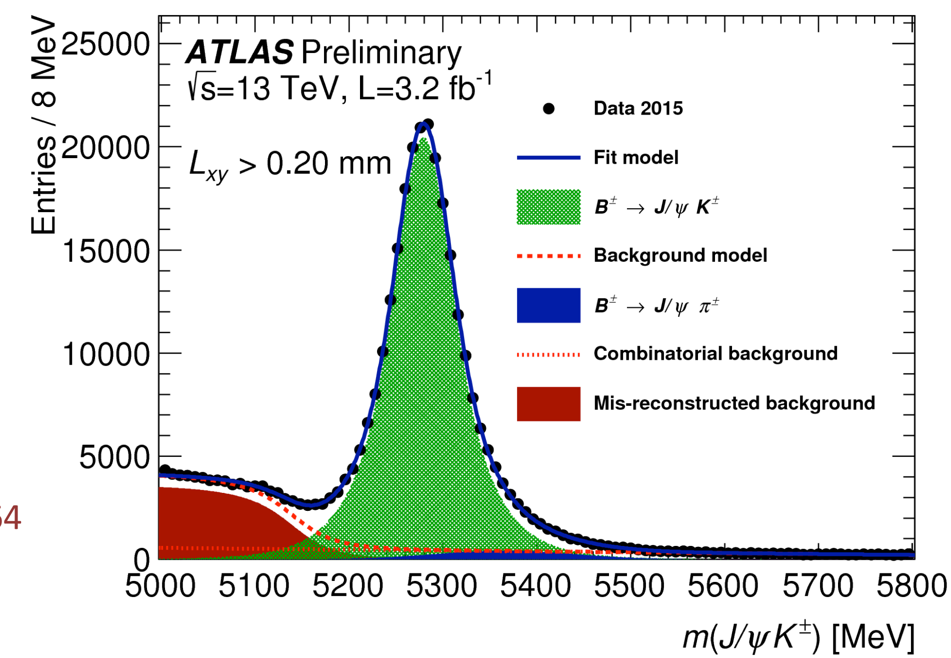
- The General Mass - Variable Flavor Number Scheme (GM-VFNS): similar to methods used in deep inelastic scattering, with NLO and next leading log (NLL) accuracy.
- The Fixed Order plus Next Leading Log (FONLL) scheme, with an empirical matching function for the NLO massive (low p_T) and massless (high p_T) ranges.

The MC generators:

- PYTHIA, HERWIG: LO+LL computation allowing detailed description of the final states
- MC@NLO, POWHEG, MADGRAPH: modeling of the hard scattering, generally NLO + LL, interfaced with the the generators above for parton PDFs and hadronization.

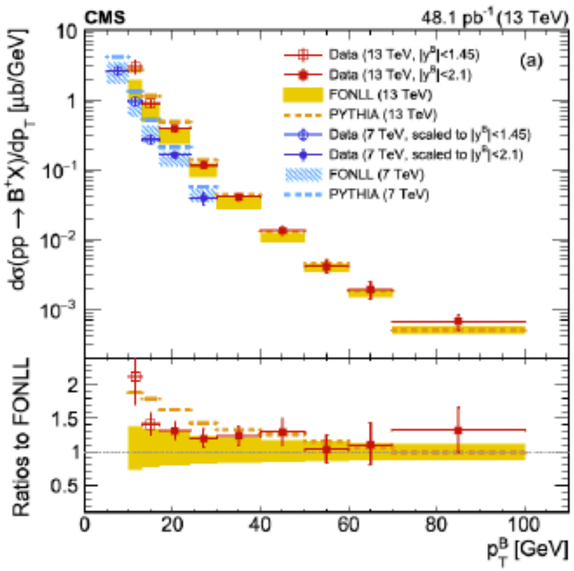
Results on B hadron production at LHC

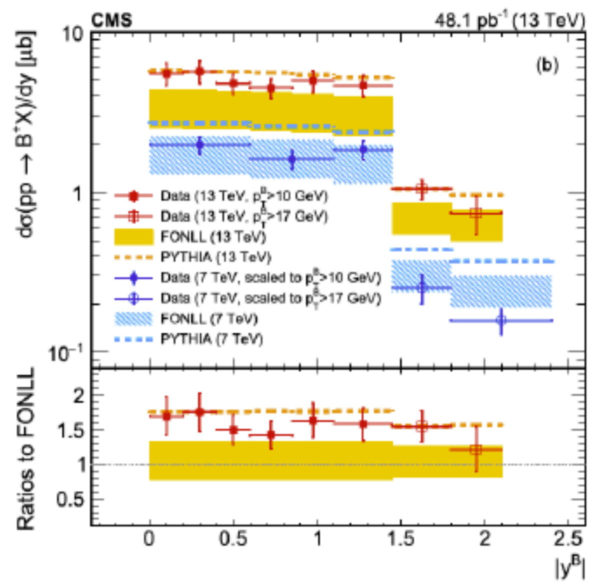
- B^+ differential cross section is the most direct process, in particular for ATLAS and CMS:
  - Decay channel $J/\psi\ K^\pm \to \mu^+\mu^- K^\pm$
  - Selection via muon pairs and displaced vertices
  - Similar techniques used for:
    - $B^0 \to J/\psi\ K^{*0} \to \mu^+\mu^- K^+\pi^-$ (ATLAS has measured the ratio of σ×BR)
    - $B^0 \to J/\psi\ K_S \to \mu^+\mu^-\pi^+\pi^-$ and $B^0_S \to J/\psi\ \phi \to \mu^+\mu^- K^+K^-$ (used for studies of decays)

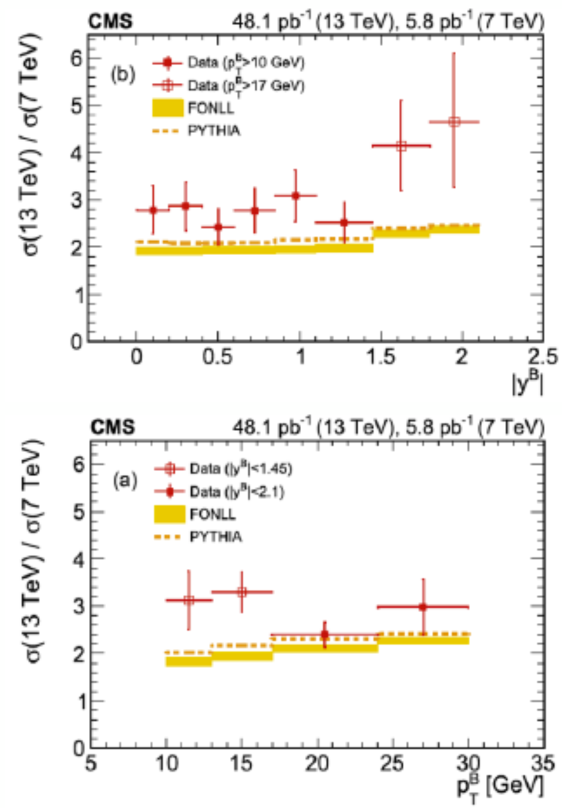


ATLAS-CONF-2015-064

B+ cross section at 13 TeV with CMS





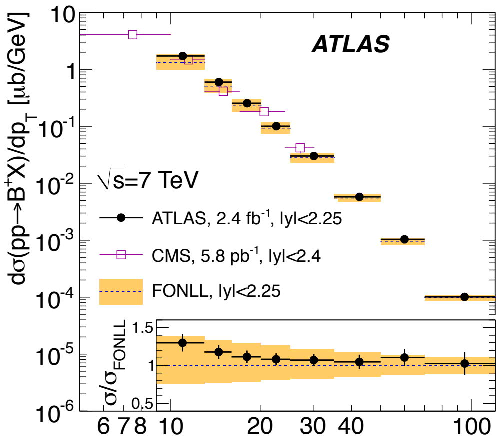


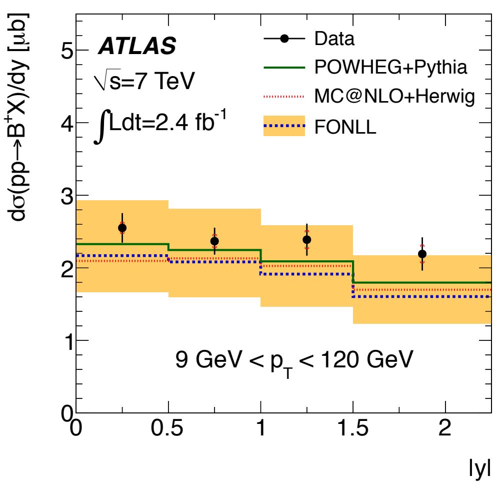
- Shape and normalisation in reasonable agreement with FONLL and PYTHIA
- 13 to 7 TeV ratio tend to prefer higher values wrt predictions

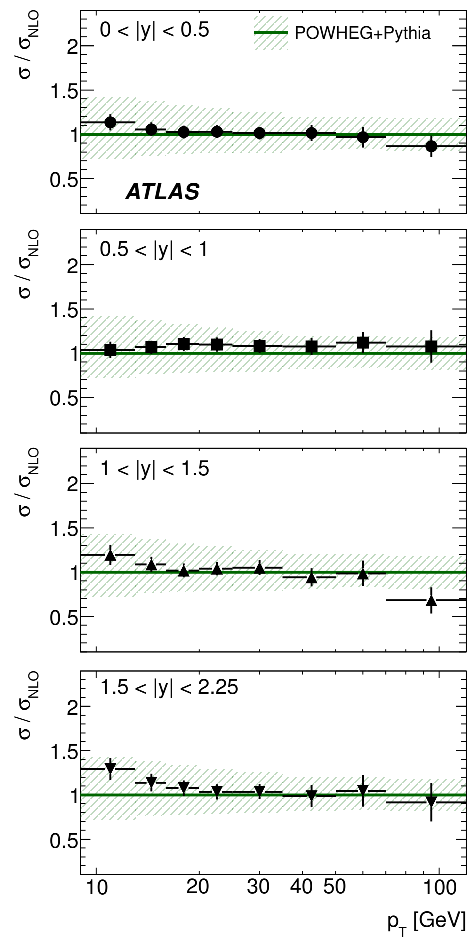
Phys. Lett. B771 (2017) 435 (arXiv:1609.00873)

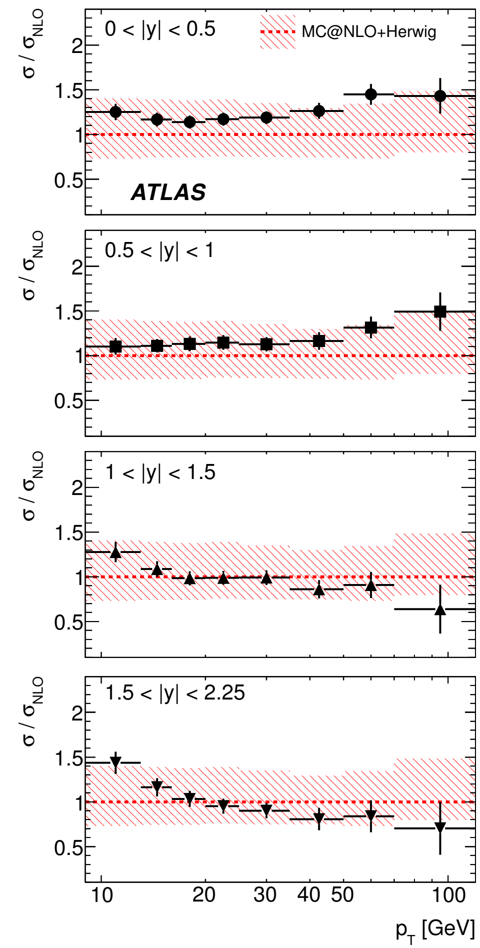
B^+ cross section at 7 TeV (ATLAS)

A comprehensive comparison of data and the different predictions was performed by ATLAS at 7 TeV. JHEP 10 (2013) 042



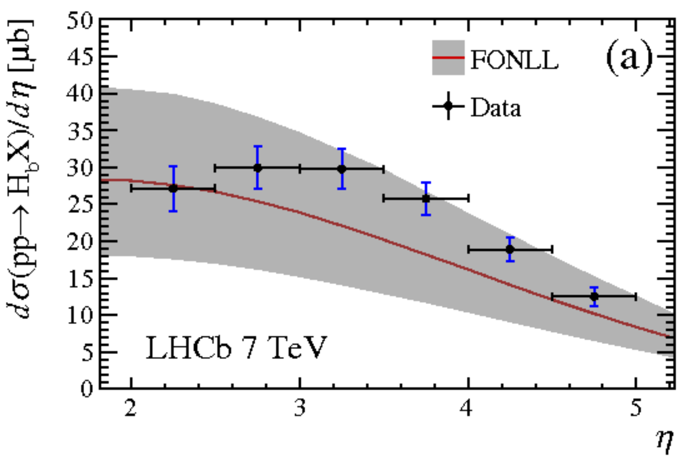


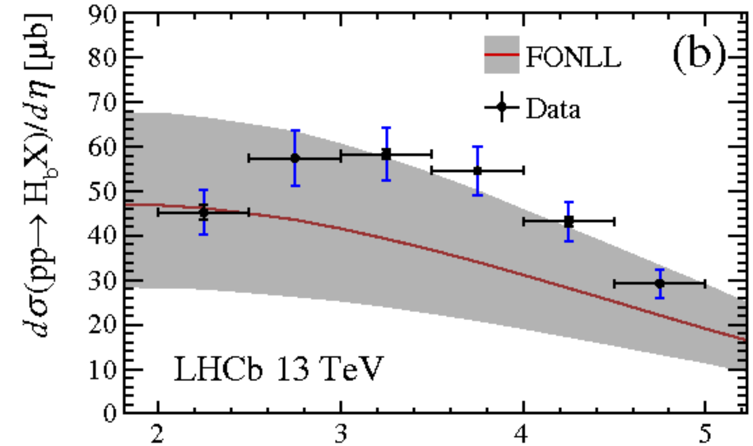


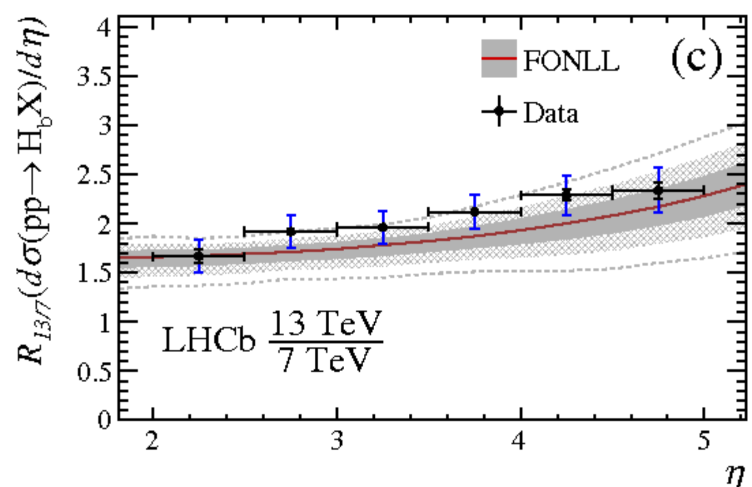


Inclusive *B* production with LHCb

This is an inclusive search for H_b-> H_c μ− X in the forward region. The *c*-hadron may be D^0, D^+, D^+_s, or Λ_c, in a fully reconstructed hadronic decay.





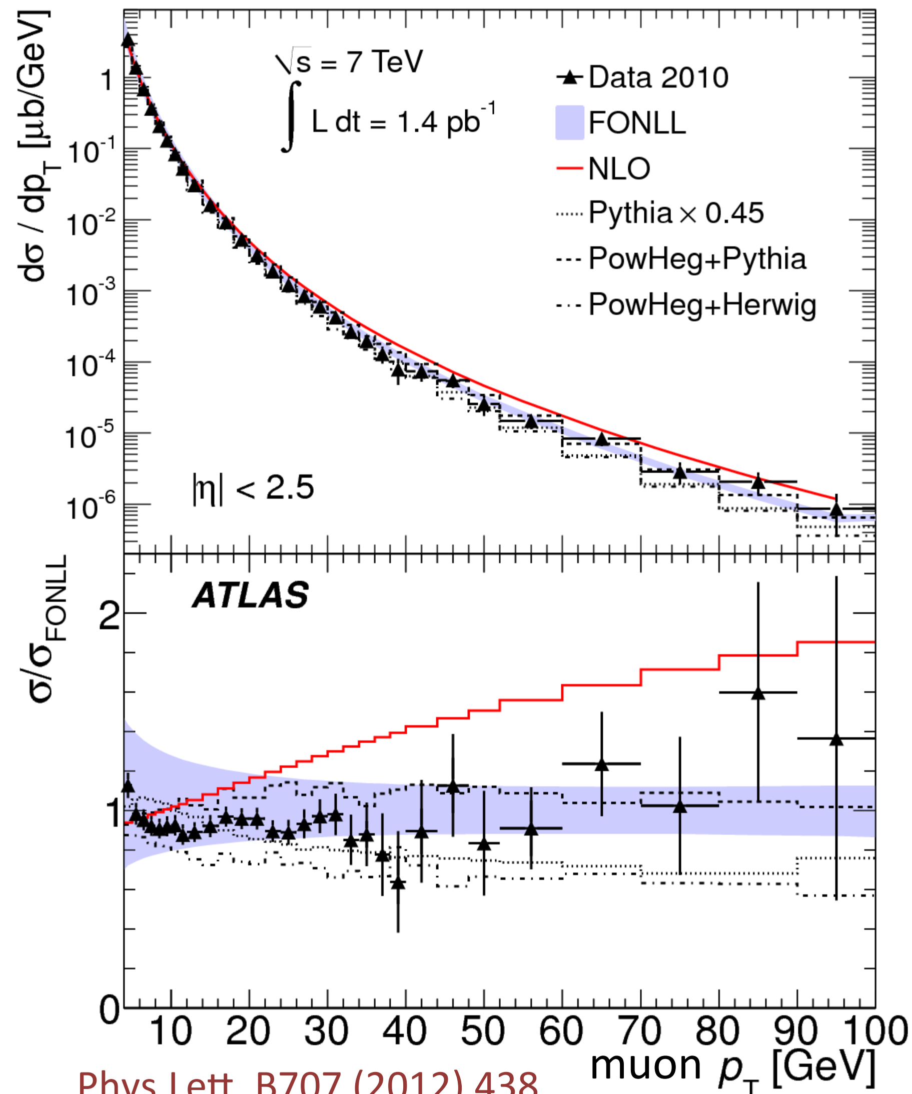


Phis. Rev. Lett. 118, 052002 (2017) (arxiv:1612.05140)

Lepton momentum spectrum

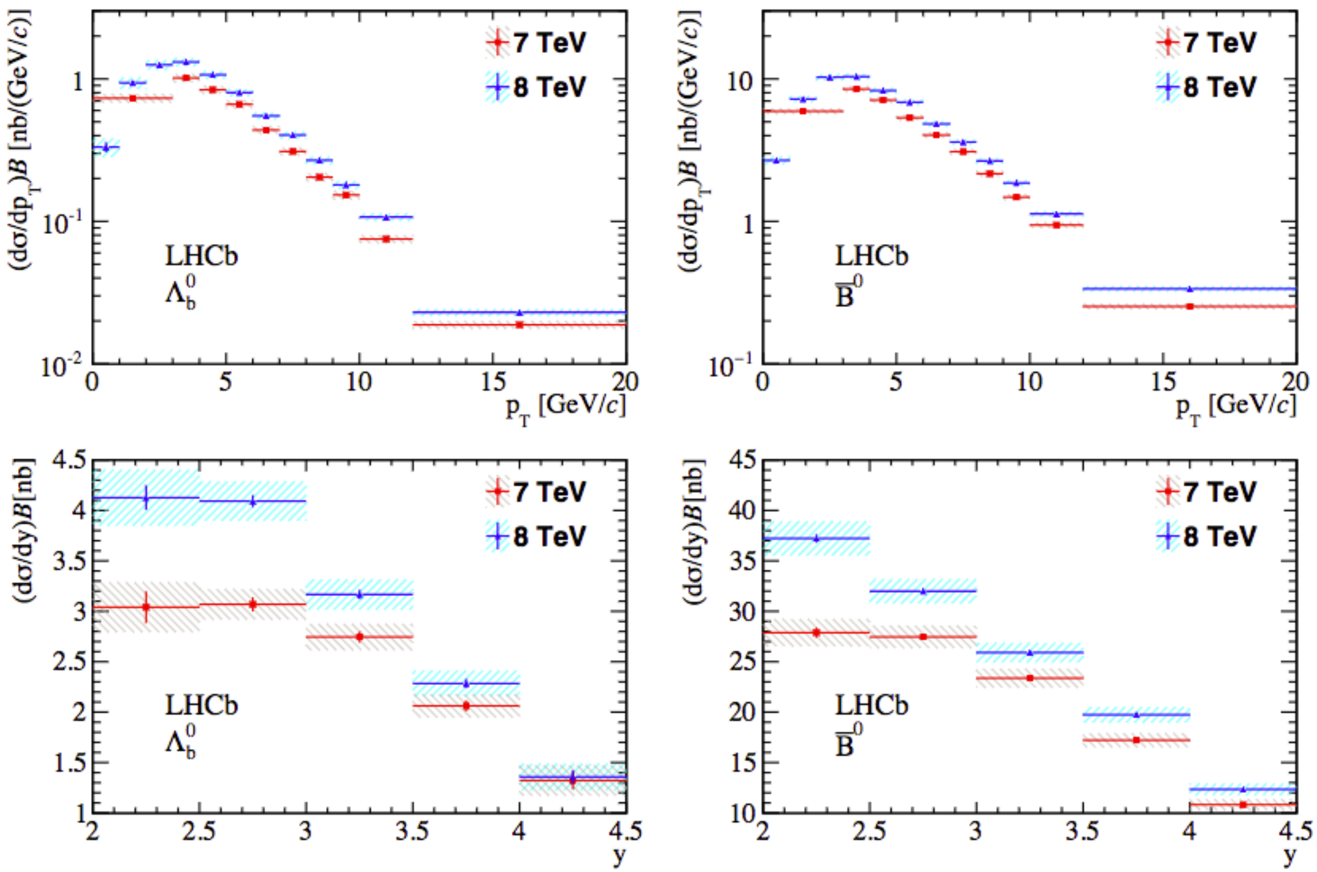
$H_b + H_c$ production at high p_T can be related to the spectrum of muon from inclusive decays. ATLAS and CMS can reach large values of p_T.

An early measurement of the spectrum of $p_{T\mu}$ from a few GeV to 100 GeV. The plot shows explicitly the effect of the NLL component in FONLL.



Phys.Lett. B707 (2012) 438

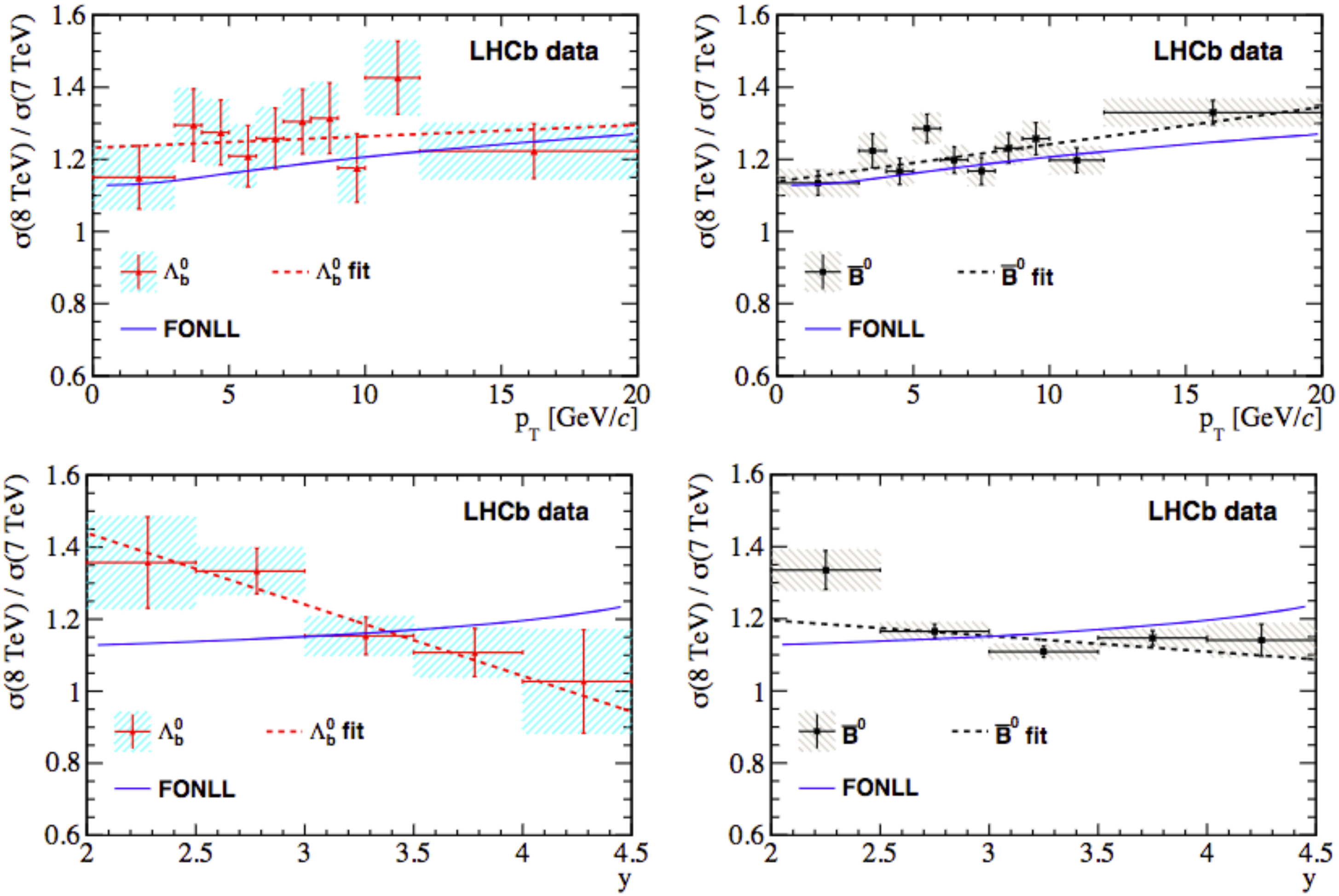
Λ_b and B^0 production with LHCb



Chin.Phys. C40, n.1 (2016) 011001 (arXiv:1509.00292)

CMS at 7 TeV in Phys.Lett. B714 (2012)136)[arXiv:1205.0594](arXiv:1205.0594))

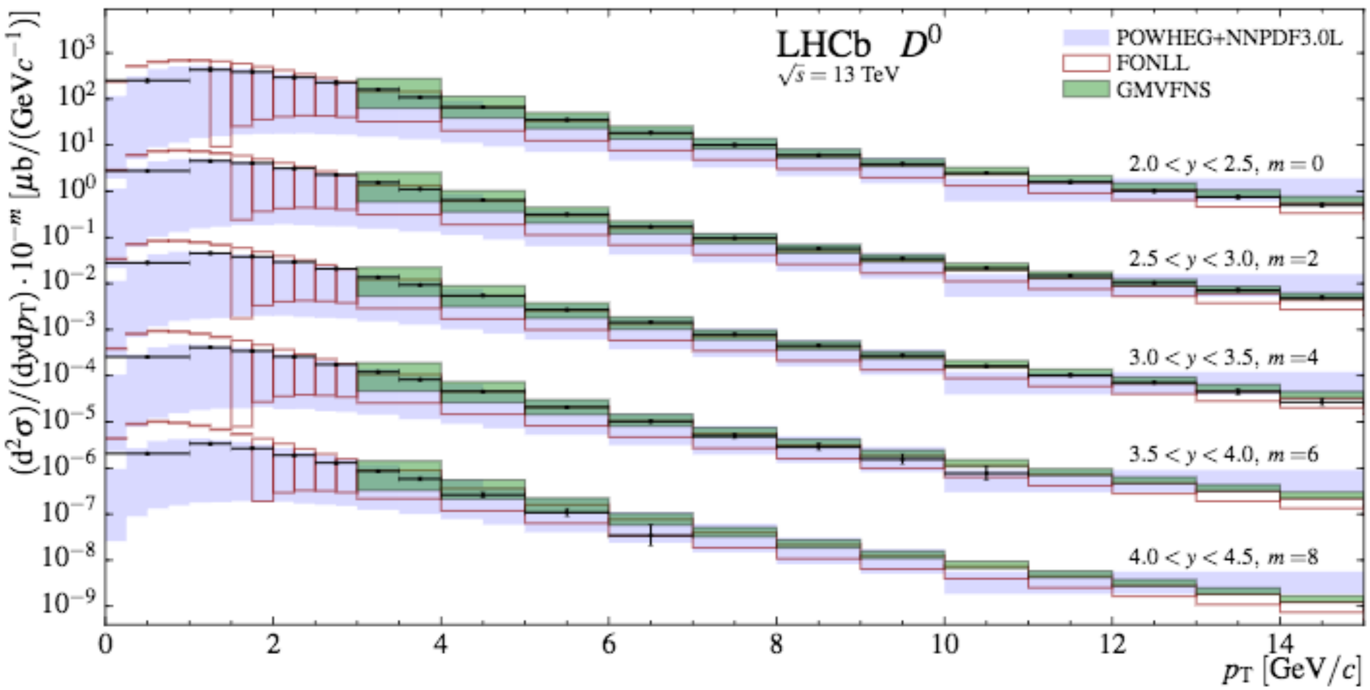
Λ_b and B^0 production with LHCb – continued



Deviation from FONLL prediction in the y dependence.

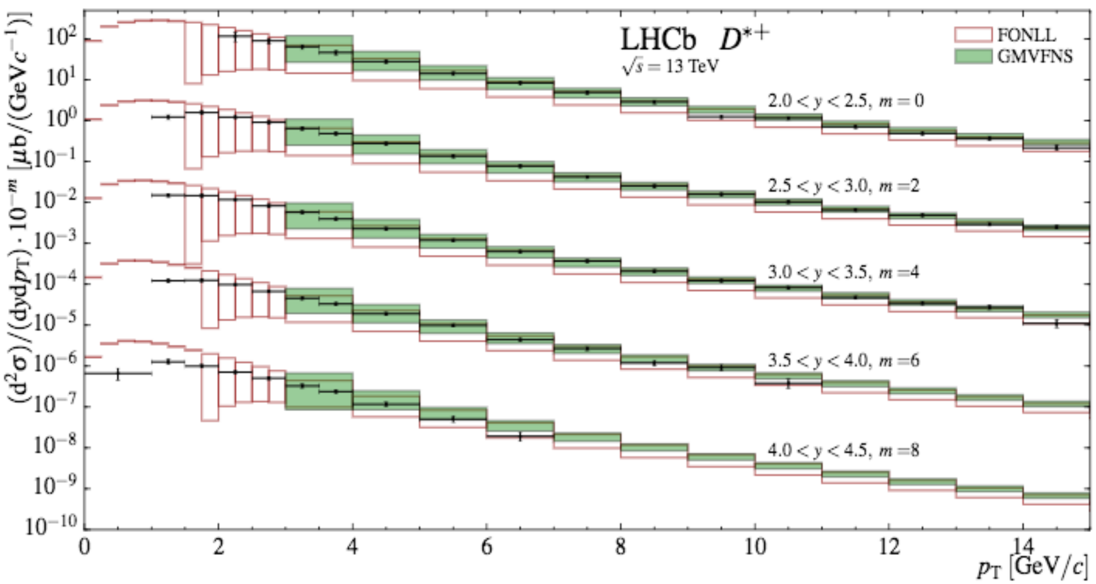
Charm production with LHCb

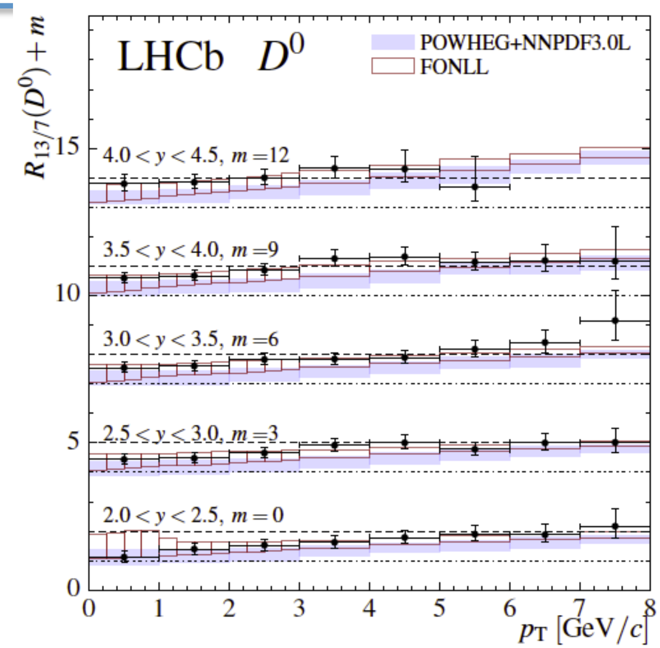
- LHCb studies HQ production in the region $2 < y < 4.5$ and $p_T < 15$ GeV.
- Few-body decays are reconstructed from secondary vertices are reconstructed, with hadron identification and no need for leptons.
- Charm production has been studied for D^0, D^+, D^+_S and D^{*+}.

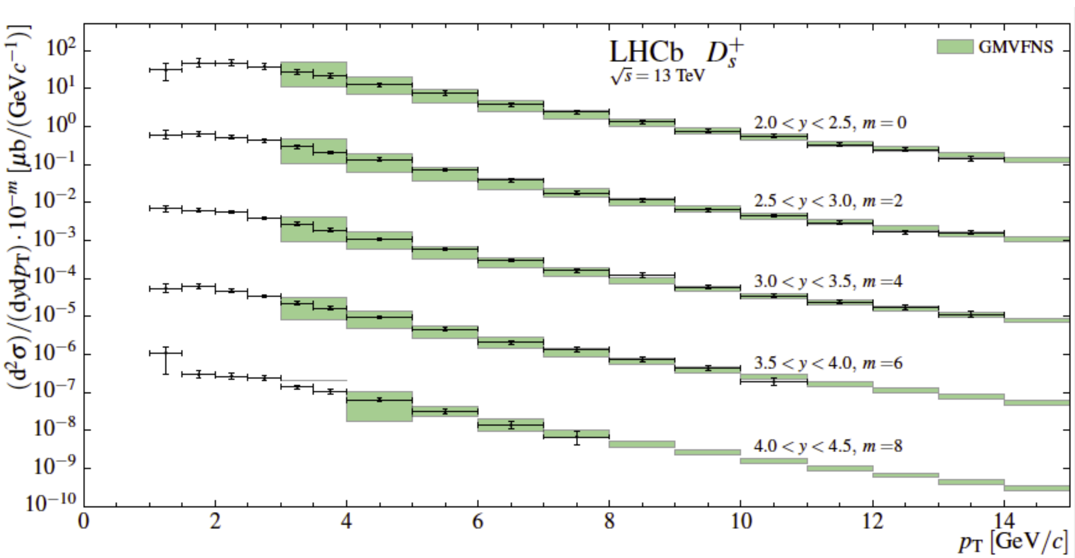


- D mesons from B decays are removed,
- Forward production is sensitive to $x_F < 10^{-4}$, these measurements contribute to the determination of the gluon PDF

arxiv:1510.01707







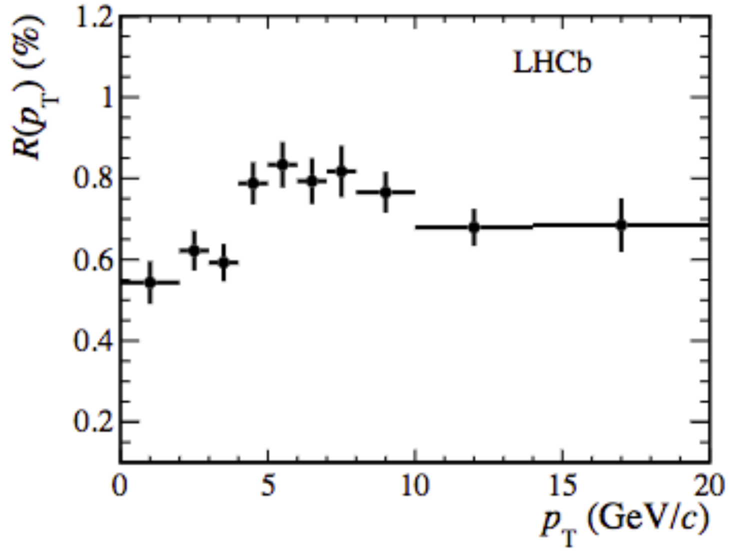
Ratio of differential cross sections at 13 TeV over 7 TeV, with offsets (lines corresponds to equal value and factor 2 increase).

Charm production also at 5 TeV (LHCb) in JHEP 02 (2014) 072 (arXiv:1308.6729)

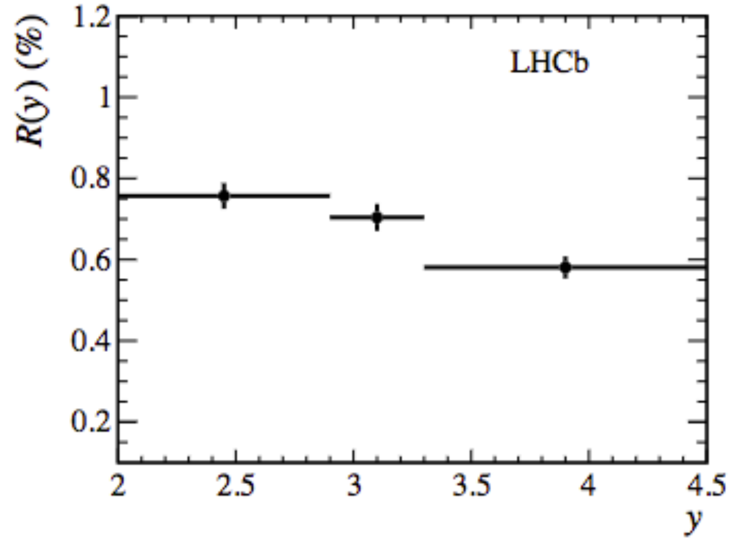
B_c production cross section

Measured at 8 TeV in the decay to $J/\psi\ \pi^+$, and expressed as a ratio to $B^+ \to J/\psi\ K^+$

$$R(p_T) = \frac{d\sigma(B_c)}{dp_T} BR(B_c \to J/\psi\,\pi) \Big/ \frac{d\sigma(B^+)}{dp_T} BR(B^+ \to J/\psi\,K)$$



$$R(y) = \frac{d\sigma(B_c)}{dy} BR(B_c \to J/\psi\,\pi) \Big/ \frac{d\sigma(B^+)}{dy} BR(B^+ \to J/\psi\,K)$$



The shapes agree with computatiosn based on complete order-α_S^4

Phys. Rev. Lett. 114, 132001 (2015) (arXiv:1411.2943)

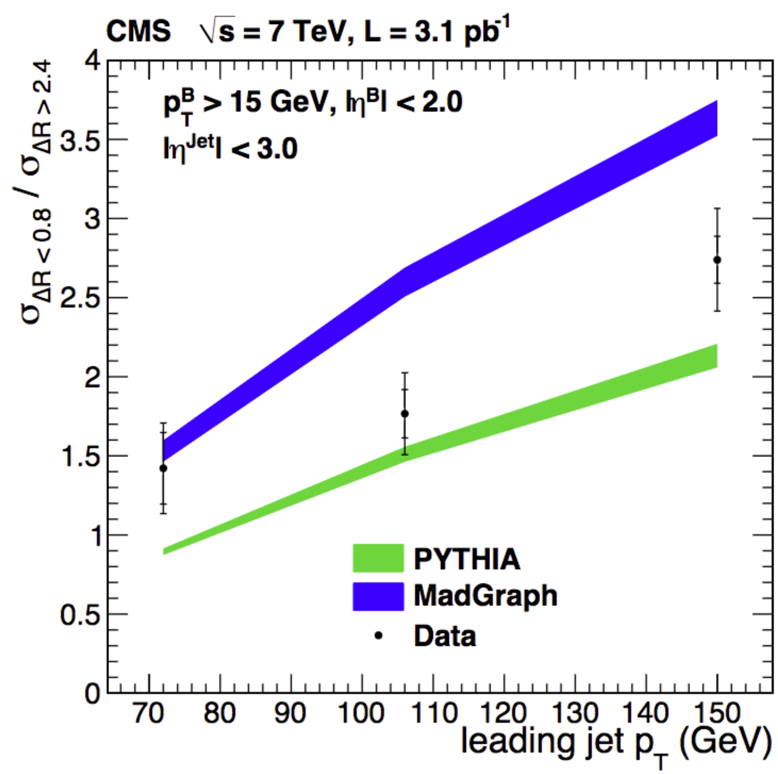
CMS result at 7 TeV: JHEP 01(2015) 063 (arXiv:1410.5729)

Correlations in B-Bbar production

The effects of higher order diagrams are expected to become more visible in the kinematical correlations, in particular at small opening angle (contribution of the *gluon splitting* diagram).

First study on this subject by CMS:

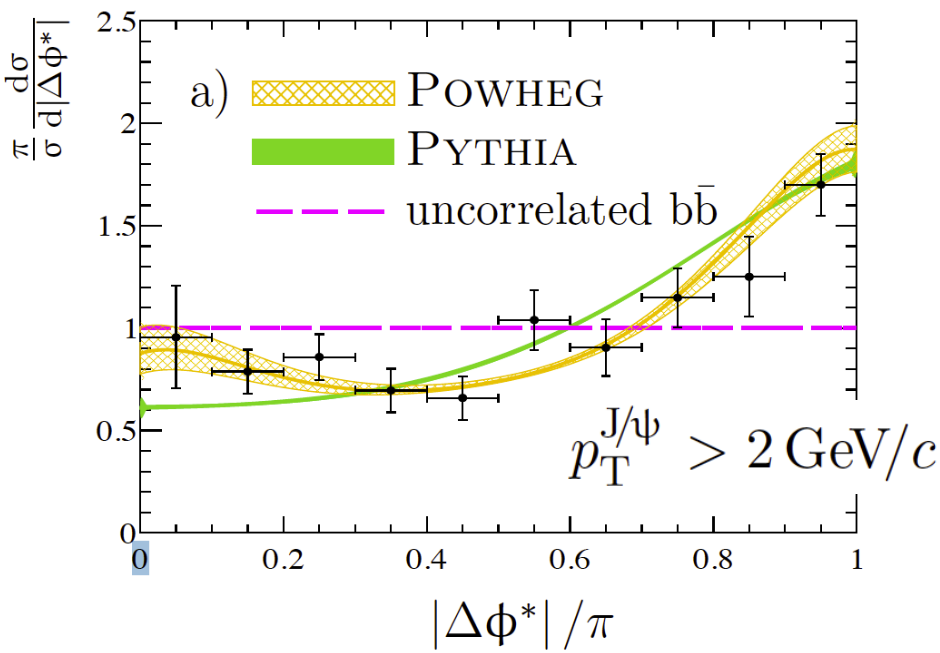
- Using B Bbar identified via secondary vertices. CMS found a significant small-angle (gluon splitting contribution).
- The data is not reproduced accurately by the generators, and appears to be in between MADGRAPH and PYTHIA. (JHEP 03 (2011) 136, arXiv:1101.3194)

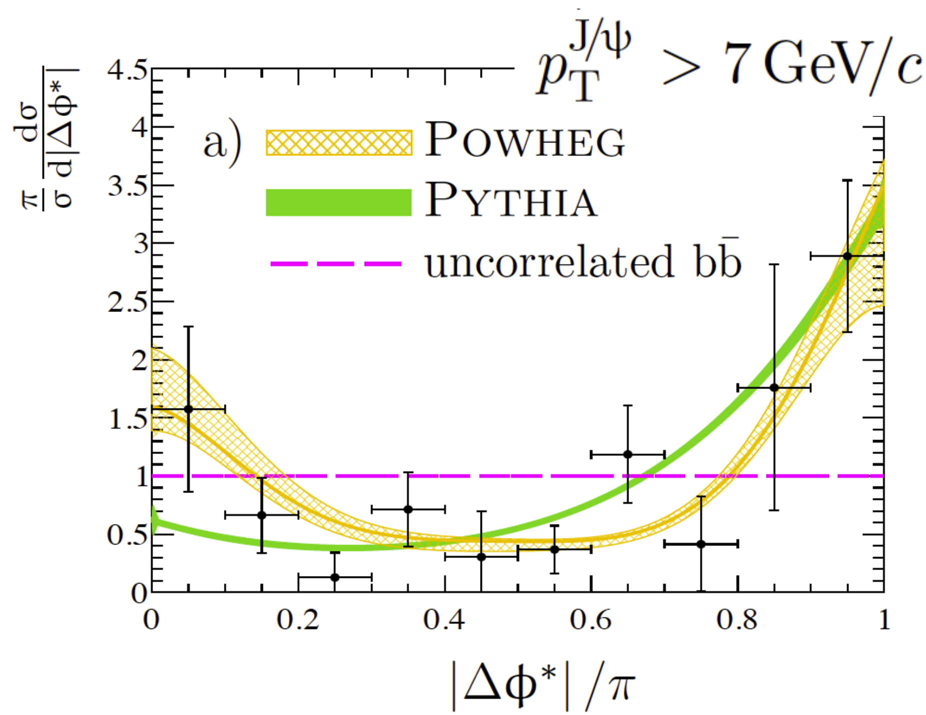


New result on B Bbar correlations from LHCb

Recent LHCb result (7+8 TeV): J/ψ are used a proxy for H_b through the inclusive decay H_b -> J/ψ X.

Comparison is made with PPWHEG (NLO) and PYTHIA (LO).



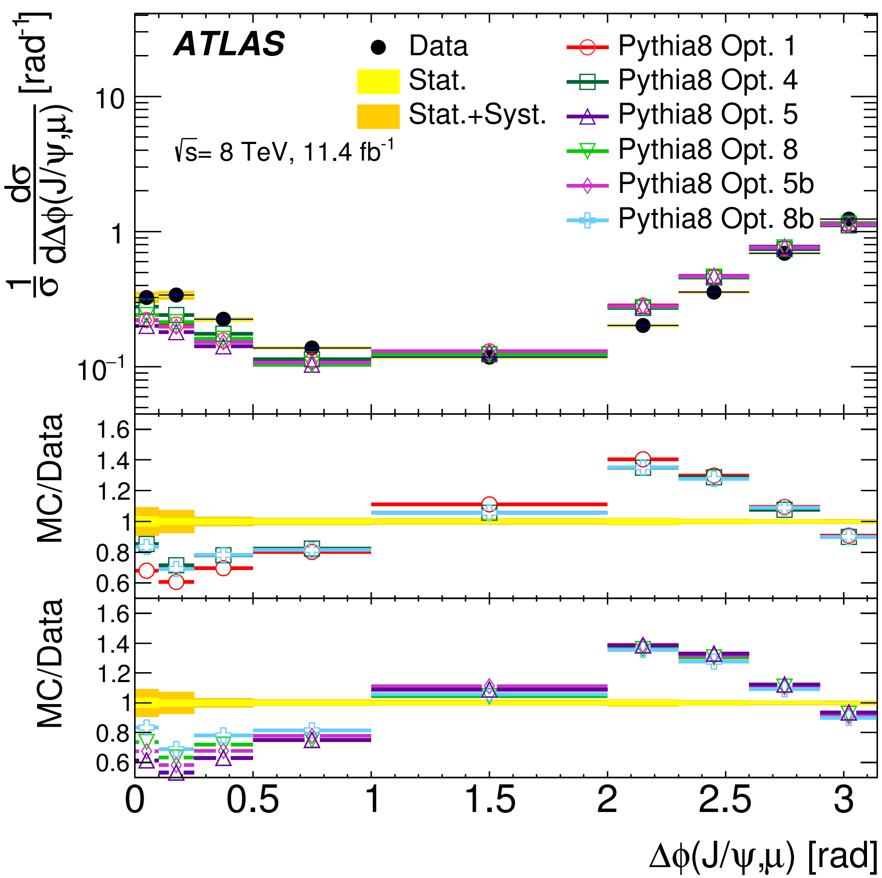


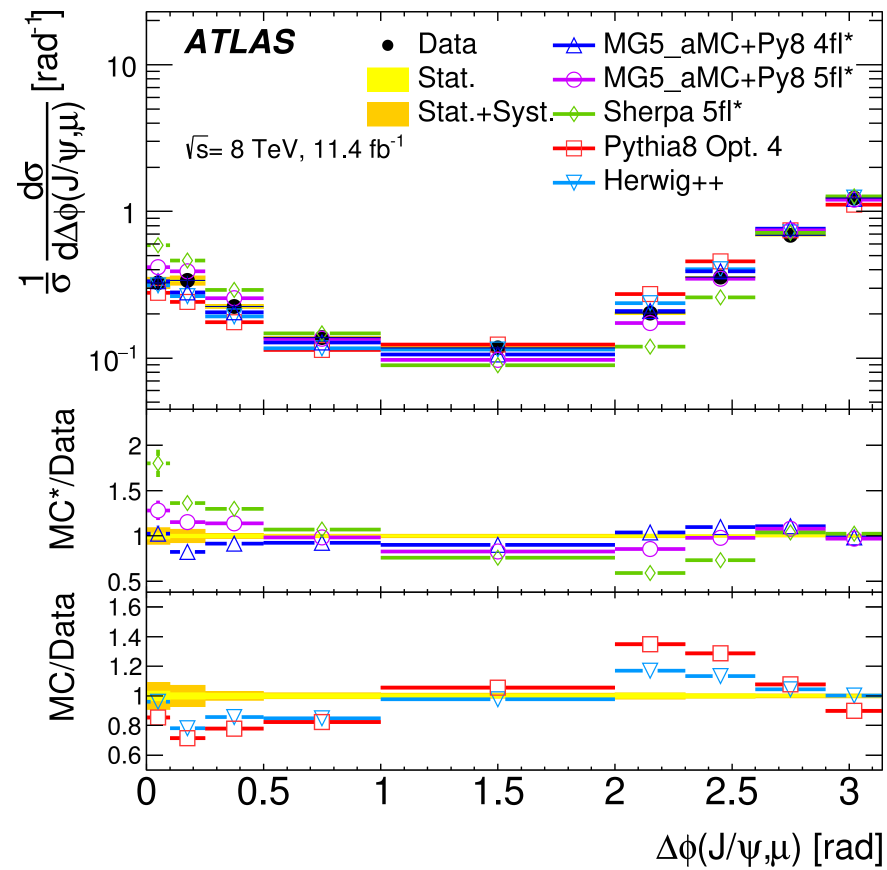
From this and other observables, the authors claim substantial agreement with either prediction.

arXiv:1708.05994

New result on B Bbar correlations from ATLAS

Here the B's are tagged though the decays to J/ψ *X* and $\mu^{\pm}$ [arxiv:1705.03374](https://arxiv.org/abs/1705.03374).
NLO computation are appear generally more accurate than LO, with the 4-flavour MadGraph5_aMC@NLO+Pythia8 behaving better than others.





Quarkonia production: theoretical framework

Long-range, non perturbative effects enter for the production of a bound-state [Q-Qbar] : a *p*QCD approach is s co cope with:

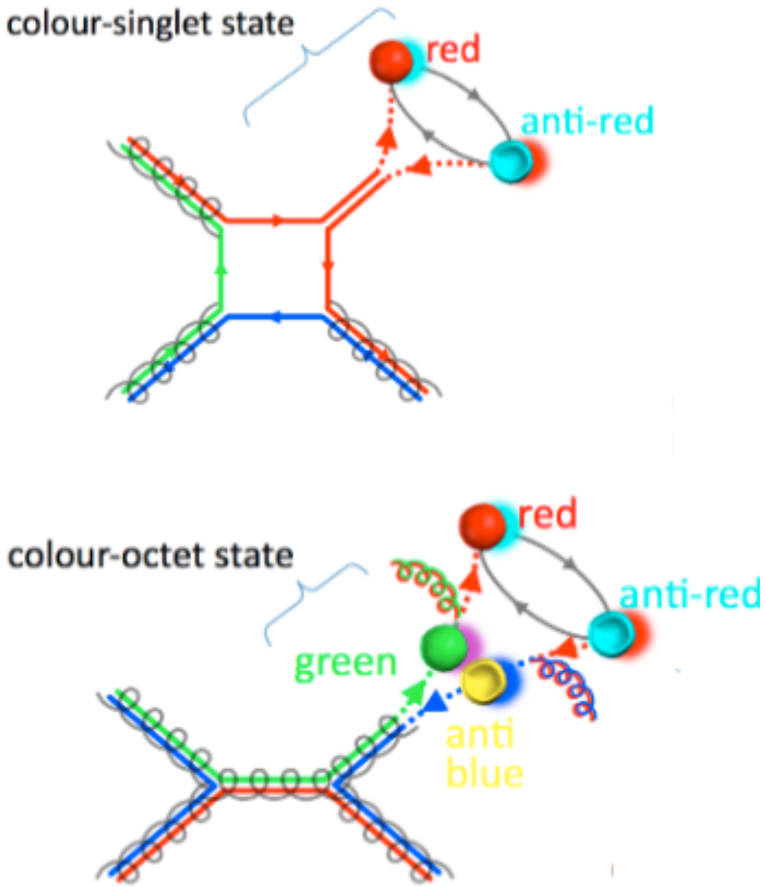
- Q and Qbar have to end up at nearly relative rest
- The final [QQbar] state is in a *color singlet* configuration

Models developed to include these requirements:

- **Color Evaporation Model**: $d\sigma_{[QQbar]}$ is related to $d\sigma_{Q,\ Qbar}$ for $2m_Q < m_{Q,Qbar} < 2m_{H(Q)}$, modulo a $1/N_{colors}$ factor.

- **Color Singlet Model (CSM)**: here the *p*QCD hard scattering process is selected to include directly both requirements. The model is predictive to the extent the the required bound state wave function probability $|\psi_{[QQbar]}|^2$, which can be extracted from decay widths.

- **The Non-Relativistic QCD** approach (Color-Octet) includes also diagrams with colored Q Qbar production. Long-Distance Matrix Elements to correct for this, via soft gluon exchange. LDMEs are typically extracted from fits to data. .



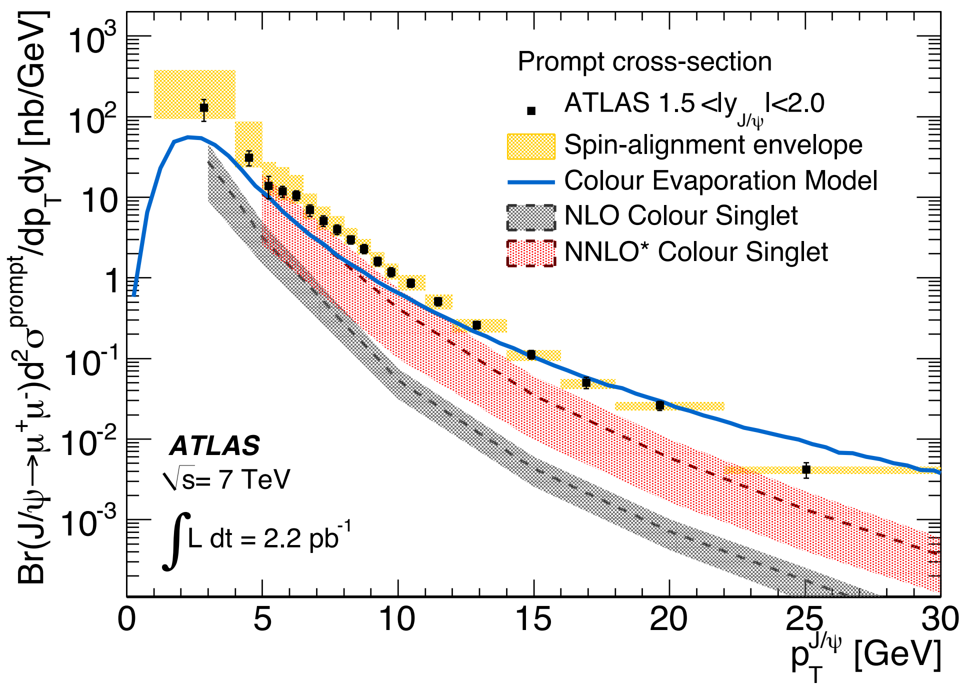
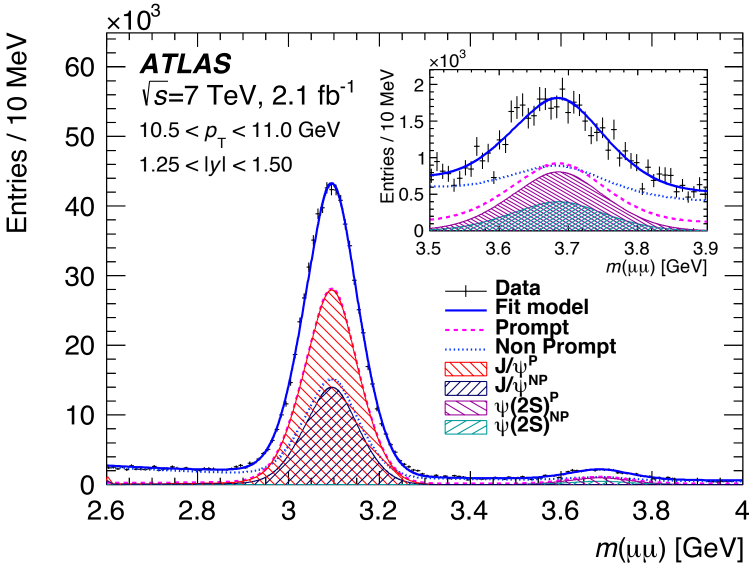
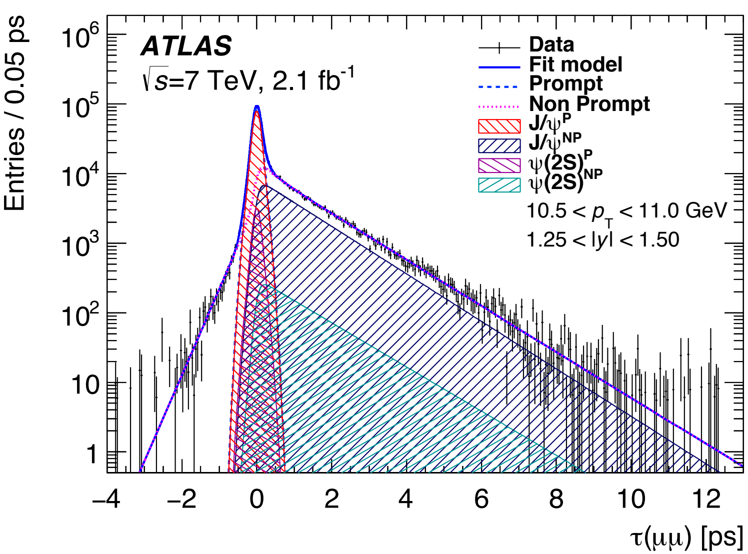


Illustration of CEM and CSM predictions for the differential production cross section of prompt J/ψ (Nucl.Phys. B850(2011) 387).

Experimental situation: prompt and non-prompt J/ψ



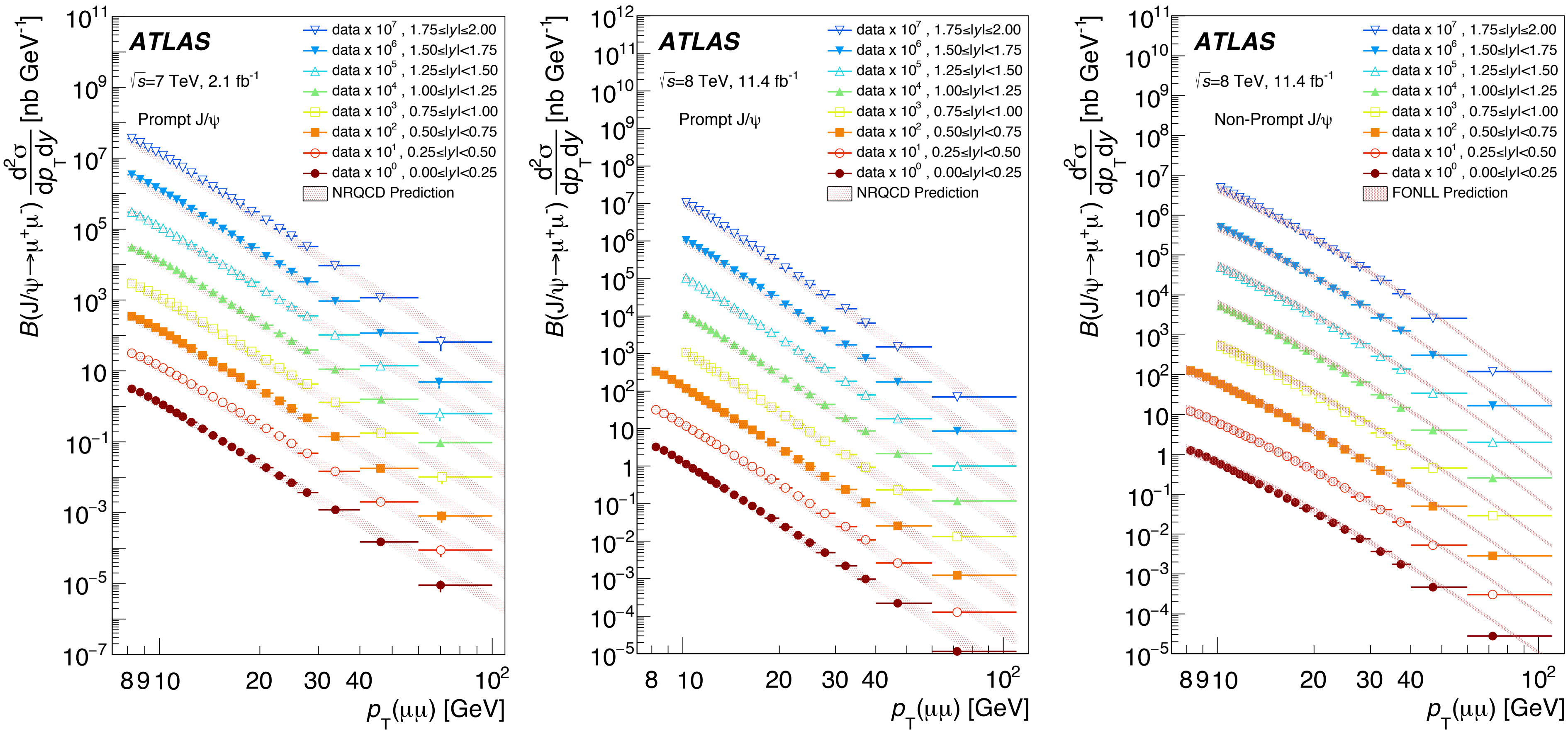


Charmonium states are produced by two mechanisms with comparable contributions:

- **Prompt production**: the [QQbar] state is produced in the hard scattering process, with the muon pairs originating from the primary interaction
- **Non-prompt production**: the [QQbar] state is produced in the decay of a B hadron, with a decay vertex separated from the primary vertex.

- Prompt and non-prompt J/ψ, ψ(2S) are identified with a simultaneous fit to the *mass* and *decay proper time* of the muon pair.

J/ψ and ψ(2S) production at 7, 8 TeV



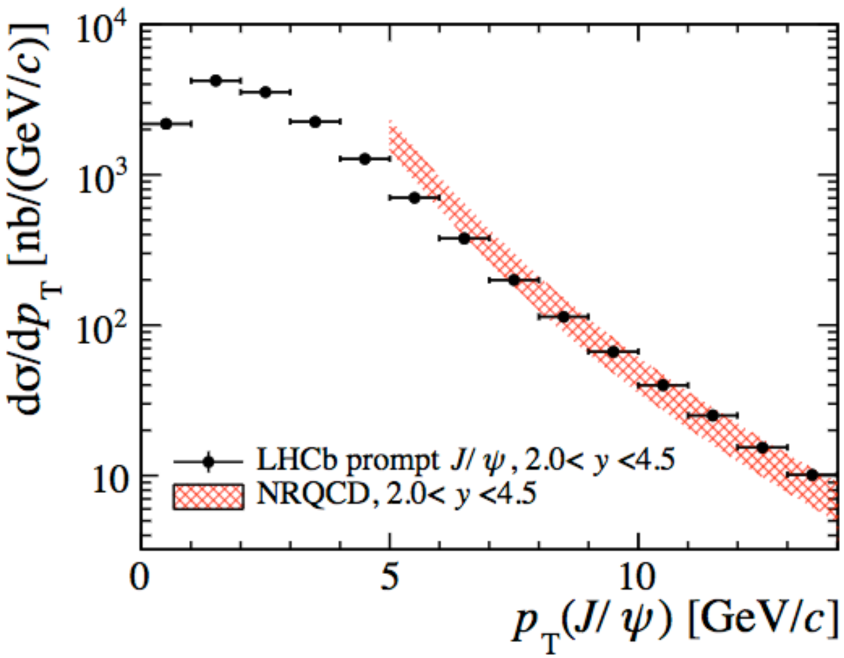
ATLAS: Eur. Phys. J. C76 (5) 1 (2016) arXiv:1512.03657
(CMS, 7 TeV: PRL 114 (2015) 191802 arXiv:1502.04155)

The measurements are in good agreement with predictions based on

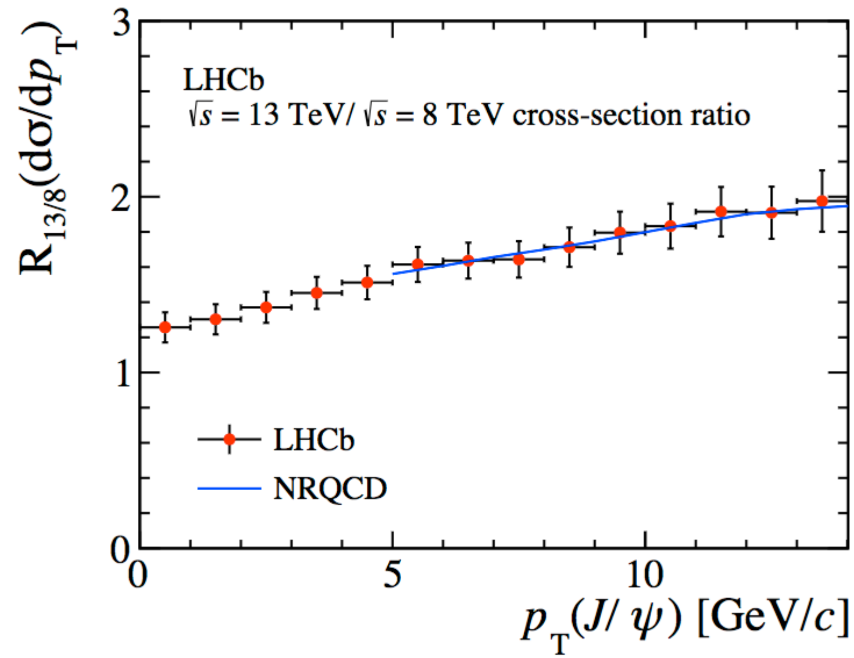
- NRQCD (for the prompt component)
- FONLL (non-prompt component)

Recent measurements of prompt J/ψ from LHCb

Differential production cross section at 13 TeV



Cross section ratio between 13 and 8 TeV



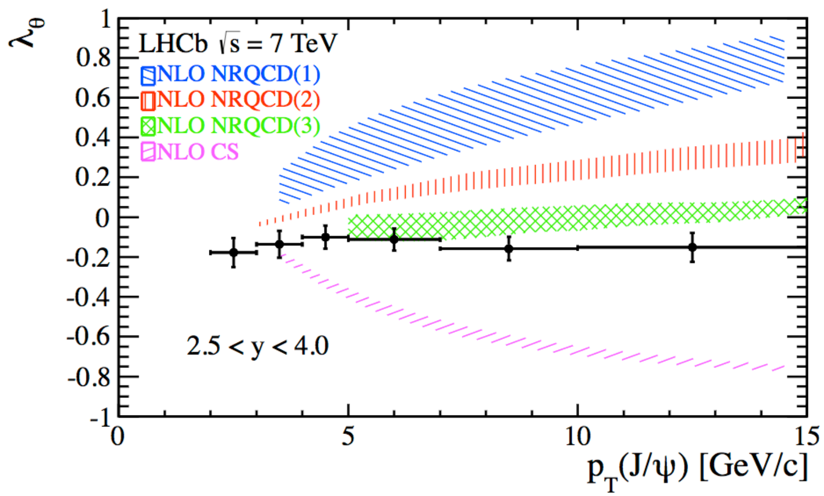
JHEP 10 (2015) 172 (arXiv:1509.00771)

Preliminary results on J/ψ, ψ(2S), Υ(nS) (n=1, 2, 3) at 13 TeV (2.4 fb^{-1}) in CMS-PAS-BPH-15-005

Quarkonia polarization

Polarization observables:

- CSM predicts longitudinal polarization of the $J^P=1^-$ (J/ψ, Υ) states, at large p_T.
- NRQCD predicts that in the hadronization of the Q Qbar pair the different LDMEs produce different polarization (e.g. $^3S_1^{octet}$ generates transverse polarization), with possibly significant transverse polarization (at large p_T)

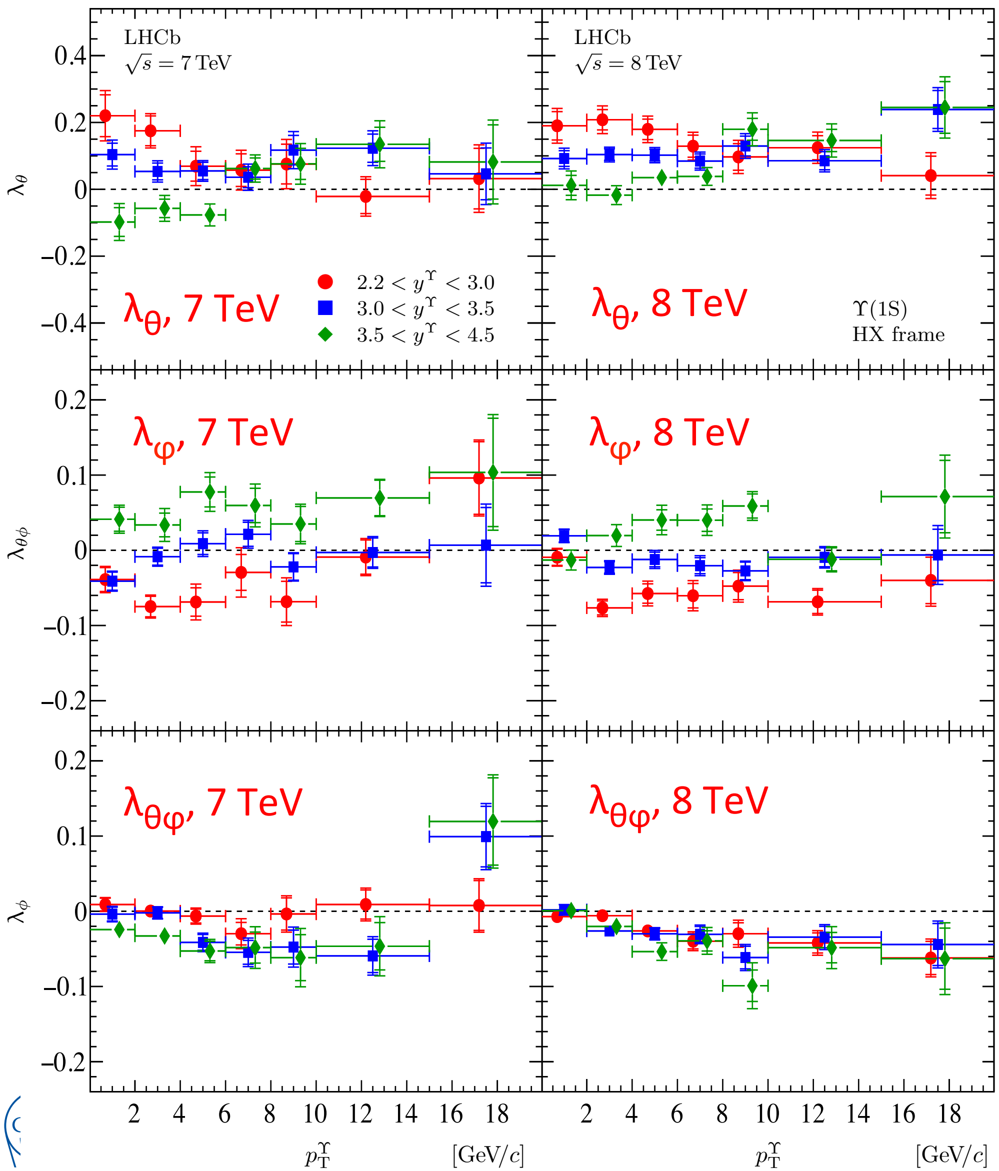


Eur.Phys.J. C 73, 11 (2013) (arXiv:1307.6379)

$$dN/d\Omega = [1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos(2\phi) + \lambda_{\theta\phi} \sin(2\theta) \cos\phi]/(1 + \lambda_\theta/3)$$

For spin-1 state decaying to lepton pairs

Polarization of (prompt) quarkonia



All measurements so far have shown only small deviations from not polarized production.

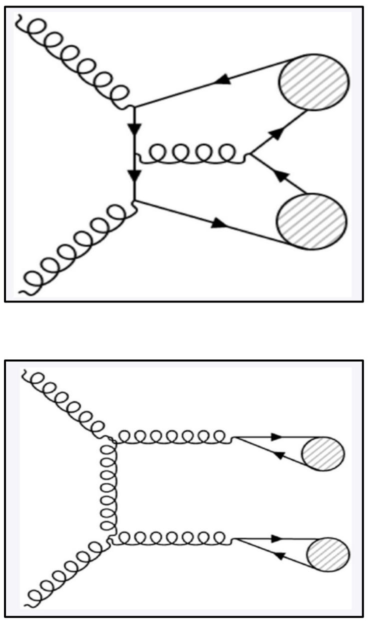
Here data from LHCb (arXiv:1709.01301): Y(1S), Y(2S) and Y(3S) polarization (results provided in *helicity*, *Collins-Soper* and *Gottfried-Jackson* reference frames)

Similar conclusions reached by:

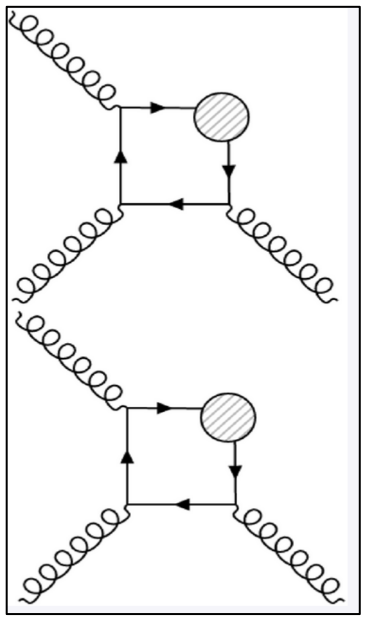
- CMS, for 7 TeV, |y|<1.2, p_T=10-50 GeV, PRL 110(2013) 081802 (arXiv:1209.2922),
- (CMS) J/ψ, ψ(2S) in Phys.Lett. B 727 (2013) 381 (arXiv:1307.6070),
- LHCb for ψ(2S) in Eur.Phys.J. C (2014)74:2872 (arxiv:1403.1339)

Processes with associated production

- Studied as J/ψ+J/ψ, J/ψ+W, J/psi+Z, Y+Y
- Two contributions to these processes:



Higher-order *real* associated production (Single Parton Scattering, SPS)



Double Parton Scattering (DPS)

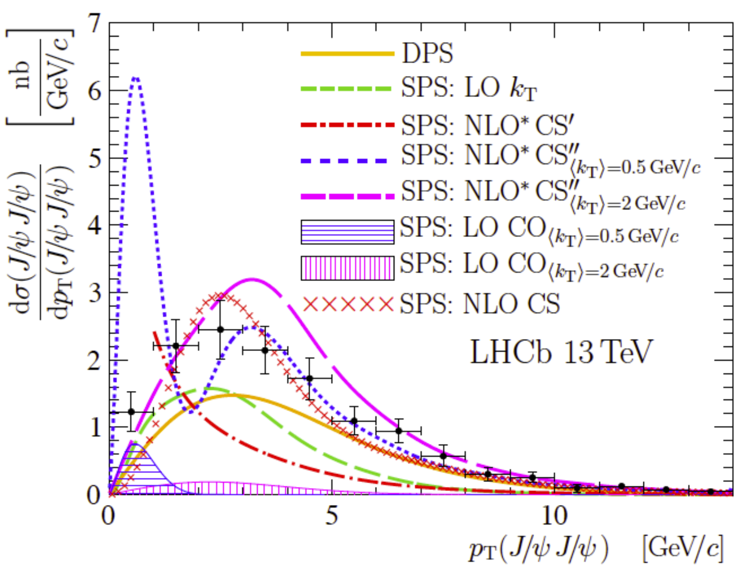
The *effective cross section* σ_{eff} for DPS (here for J/ψ+J/ψ):

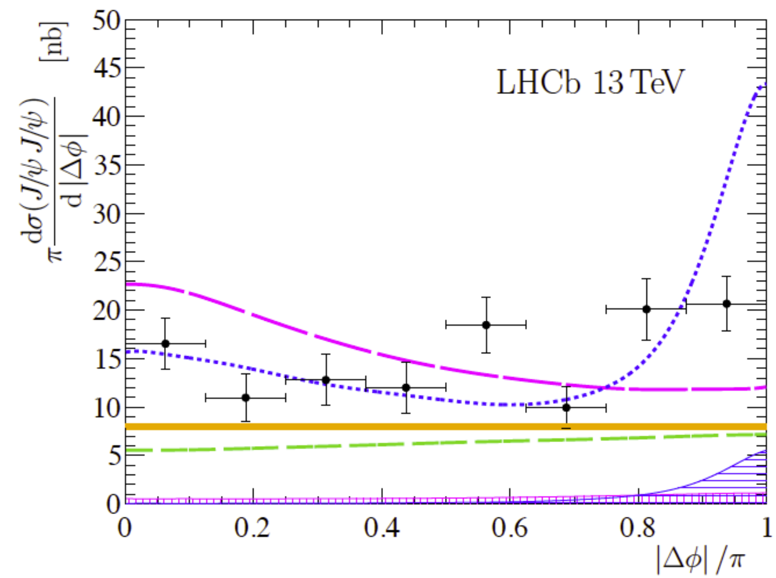
$$\sigma_{\text{eff}} = \frac{1}{2}\frac{{\sigma_{J/\psi}}^2}{\sigma_{\text{DPS}}}$$

First observations of double J/ψ production at 7 TeV:

- LHCb (PL B707 (2012) 52)
- CMS (JHEP 09 (2014) 094.

Recent result on J/ψ J/ψ with LHCb

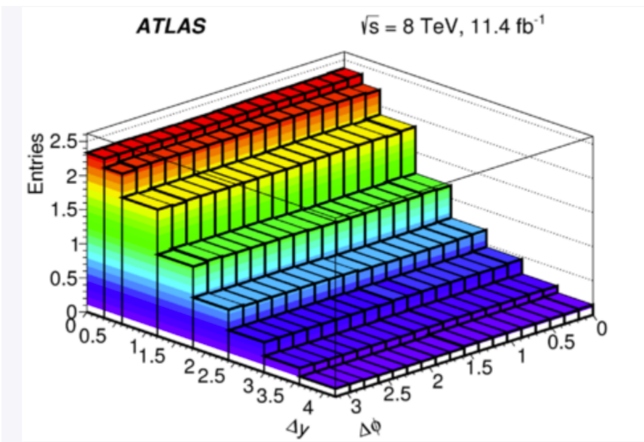




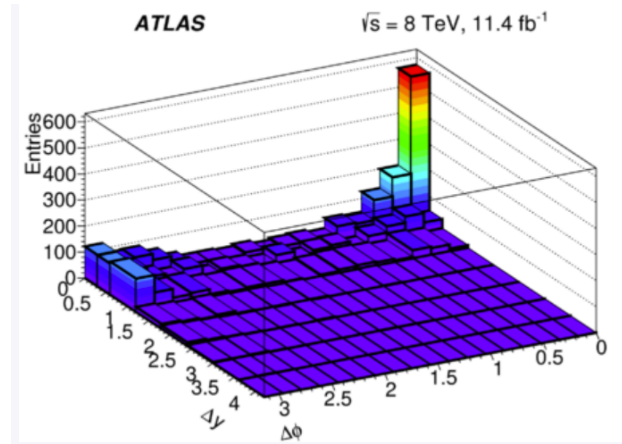
LHCb (JHEP 06 (2017) 047 (arxiv:1612.07451):

- Evidence of SPS and DPS contributions:
  - SPS compared with NRQCD and color-singlet/NLO predictions
  - DPS with σ_{eff} in the range 10.0 – 12.5 mb (model dependent).

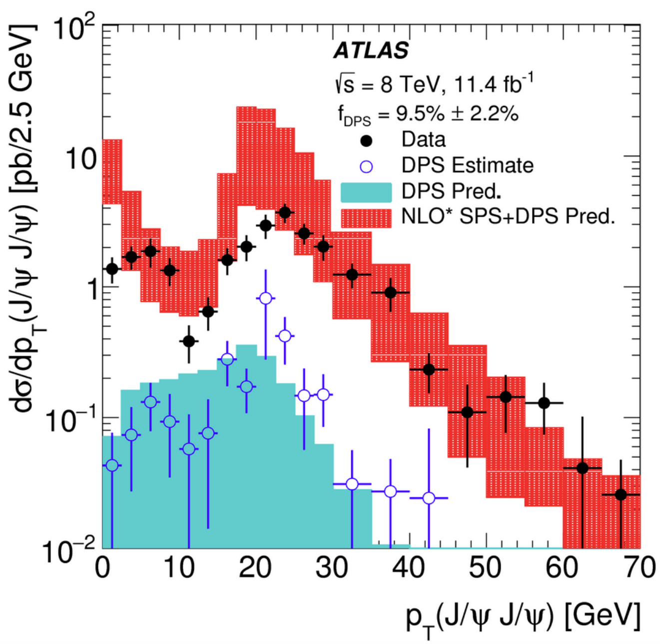
J/ψ J/ψ with ATLAS



Template for DPS obtained from random superposition of J/ψ from different collisions.



SPS distribution from data after subtracting DPS (normalised in DPS dominated regions).

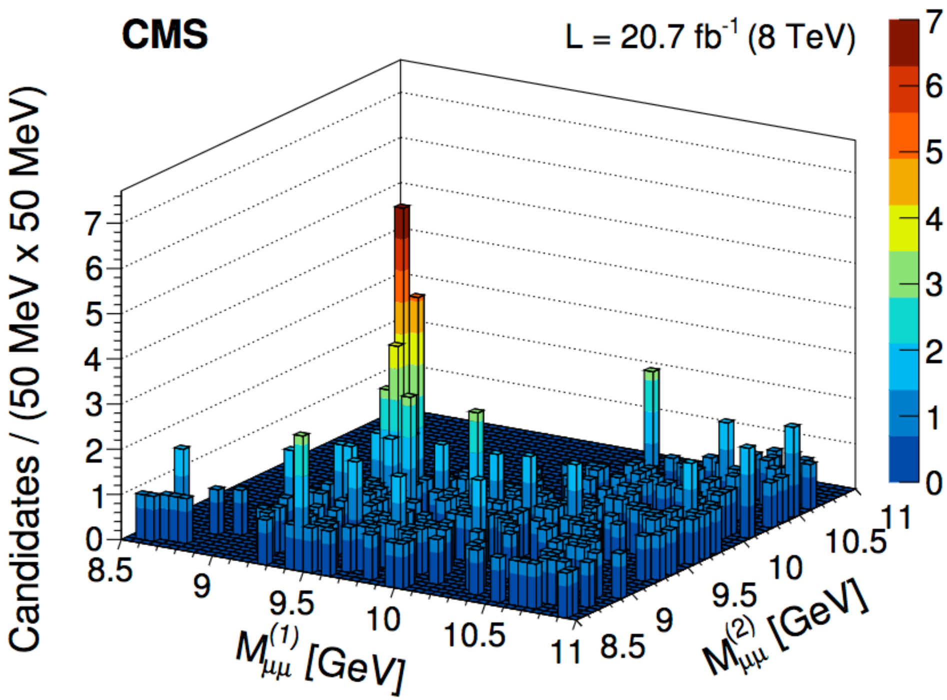


8 TeV data sample.

- SPS: a small-angle contribution is well visible. NLO color-singlet prediction provides a fair description of the result.
- SPS: $\sigma_{eff} = 6.3 \pm 1.6 \pm 1.0$ mb

EPJ C77 (2017) 76, arxiv:1612.02950

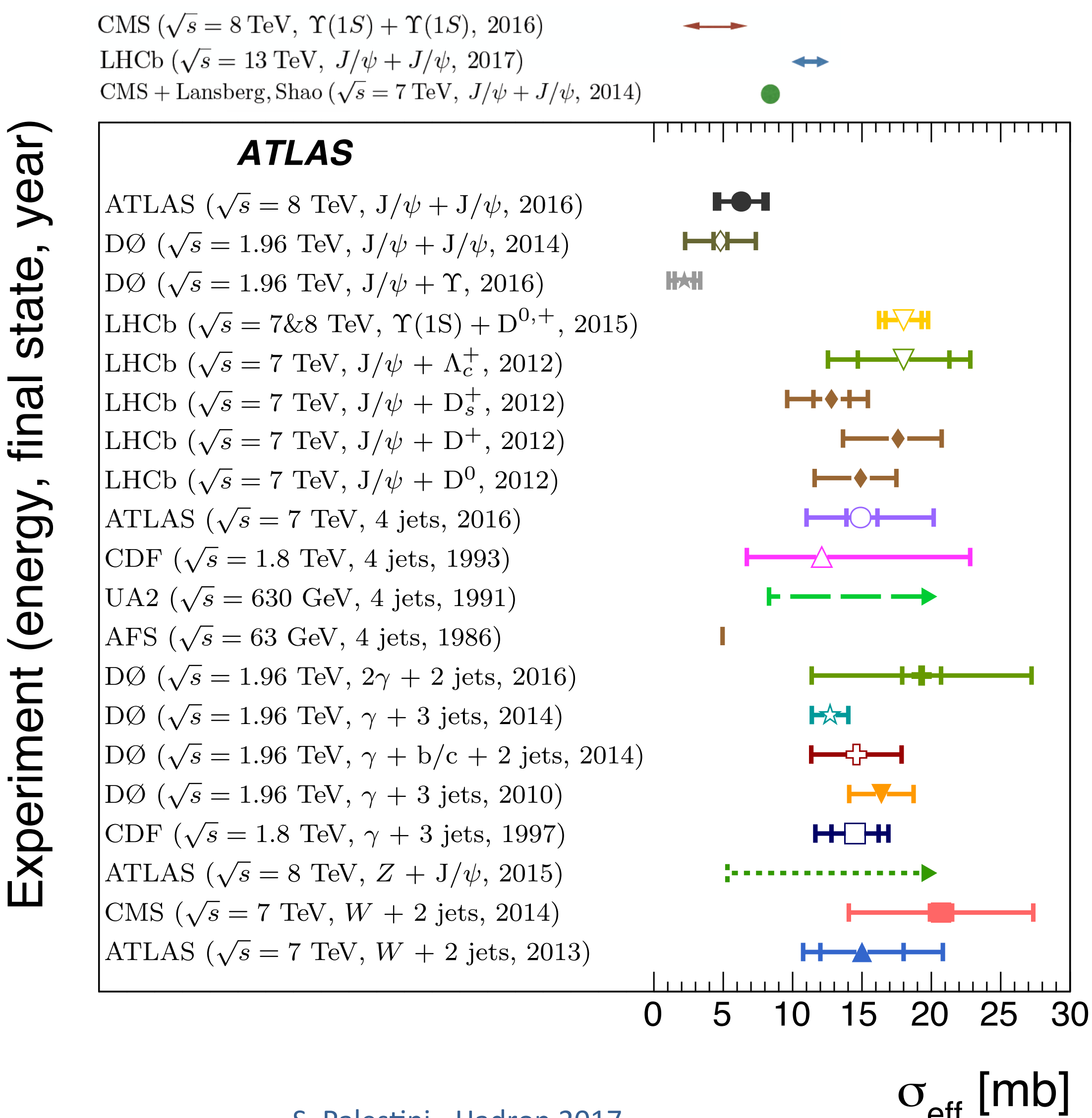
Double Υ production in CMS



38±7 events of Υ(1S) Υ(1S), corresponding to a fiducial production cross section σ_{fid}=68.8±12.7±7.4±2.8 pb for |y(Υ)|<2.0.
The result is in agreement with SPS calculations, together with a DPS contribution of about 10% to 30% of the total (which suggests $\sigma_{eff} \approx$ 2 to 7 mb).

JHEP 05 (2017) 013, arxiv:1610.07095

σ_{eff} for double parton scattering



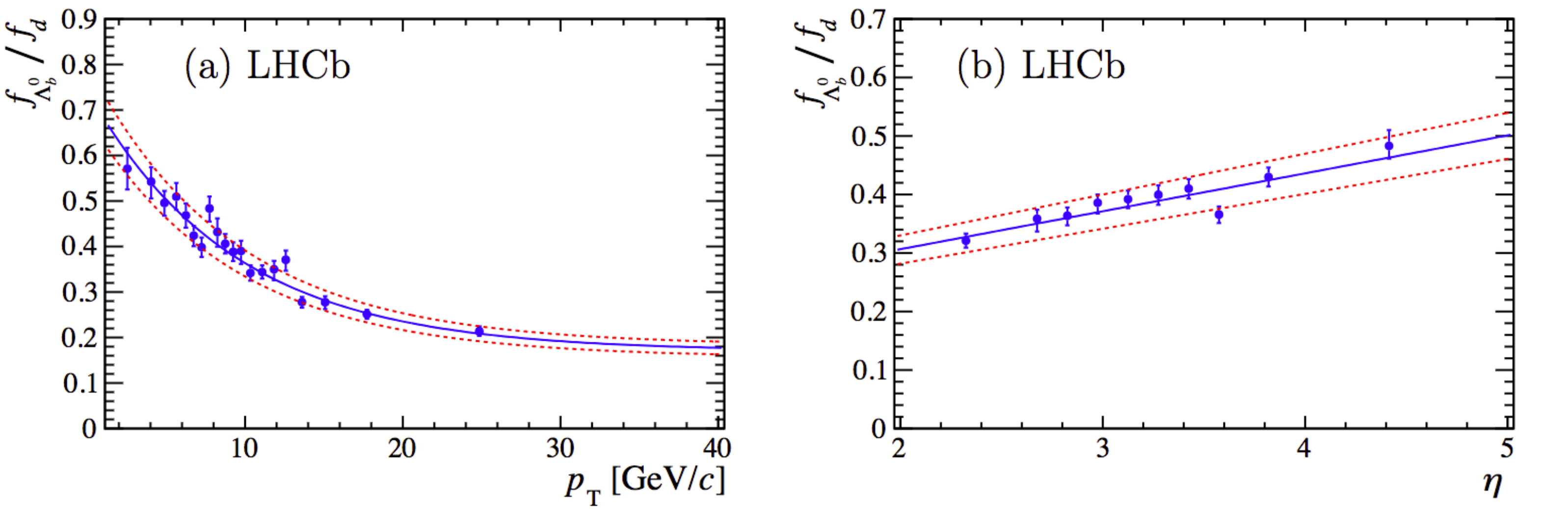
Is there evidence of non universality, with smaller values of σ_{eff} for quarkonia + quarkonia production ?

Conclusions

- The studies of the production of open heavy quark hadrons and of quarkonia in high energy collisions provide important tests of our understanding of the strong interactions.
- The range of the differential cross sections extends up to six order of magnitude across the p_T spectrum. Both central and forward production are studied.
- Substantial agreement is generally found between measurement and recent, detailed predictions. The experimental reach and accuracy underlines the relevance of computations at NLO, NNLO in some cases, NLL.
- Additional observables have been considered, including correlations in B Bbar production, quarkonia polarization, associated production.
- The increase in collision energy in LHC-Run 2, as well current and future increase in luminosity provide ground for further progress.

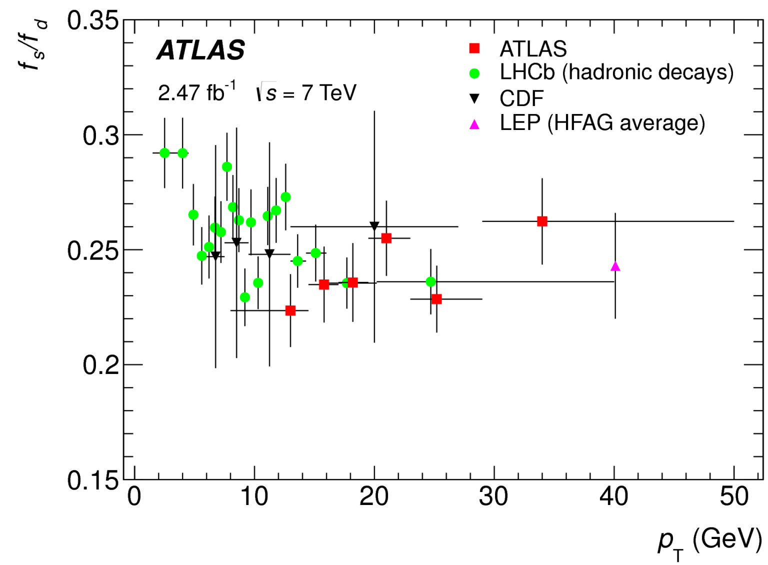
BACKUP AND AUXILIARY MATERIAL

Other results: production fractions

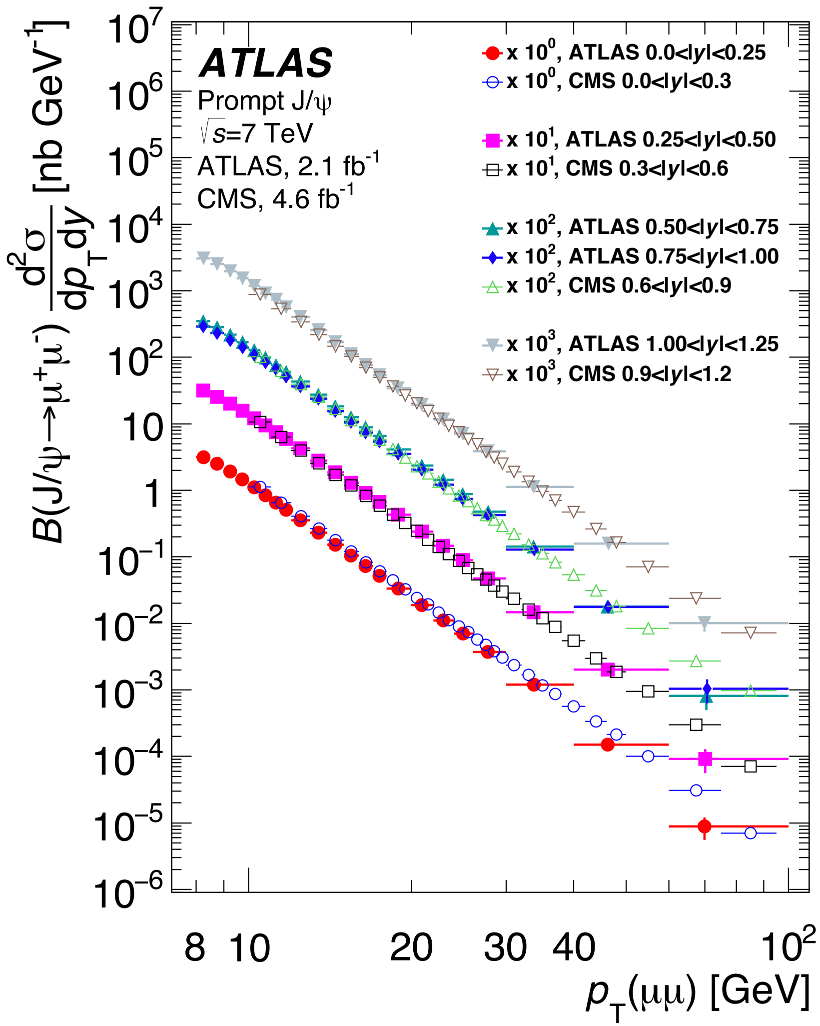


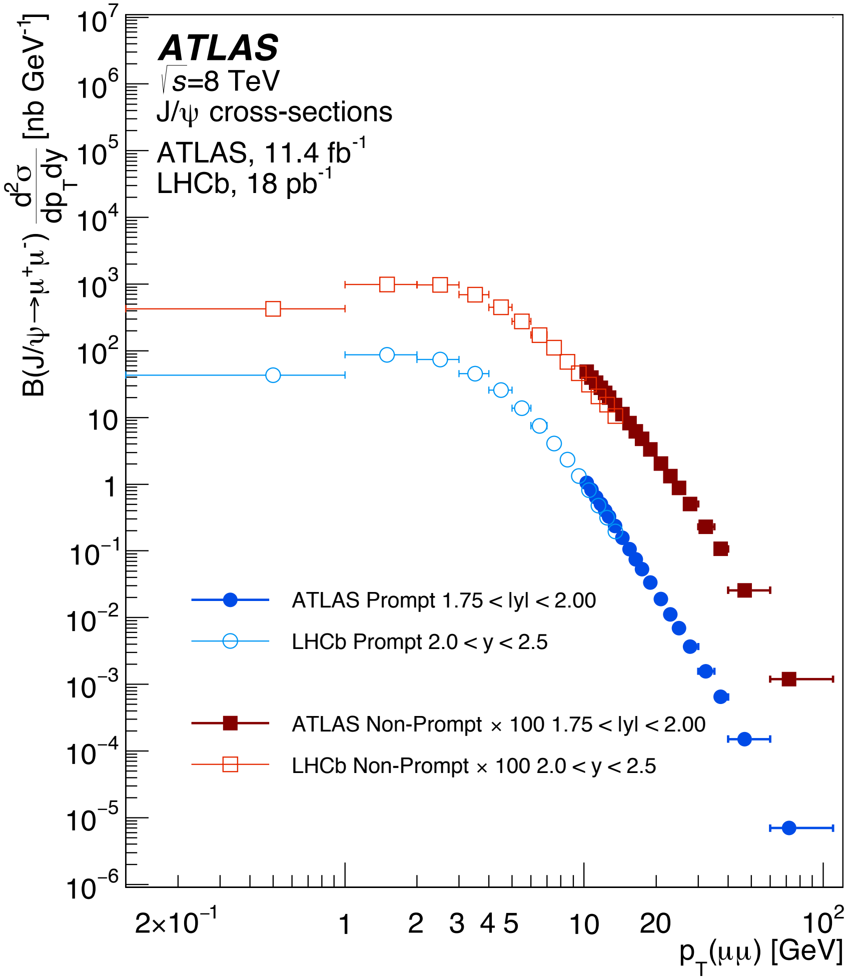
Baryon/meson production fraction measured by LHCb [JHEP 08(2014)143].

B^0_s/B^0 production ratio
ATLAS: PRL 115, 262001(2015)
LHCb: JHEP 04 (2013) 001



J/ψ, ψ(2S) production: comparisons among LHC experiments

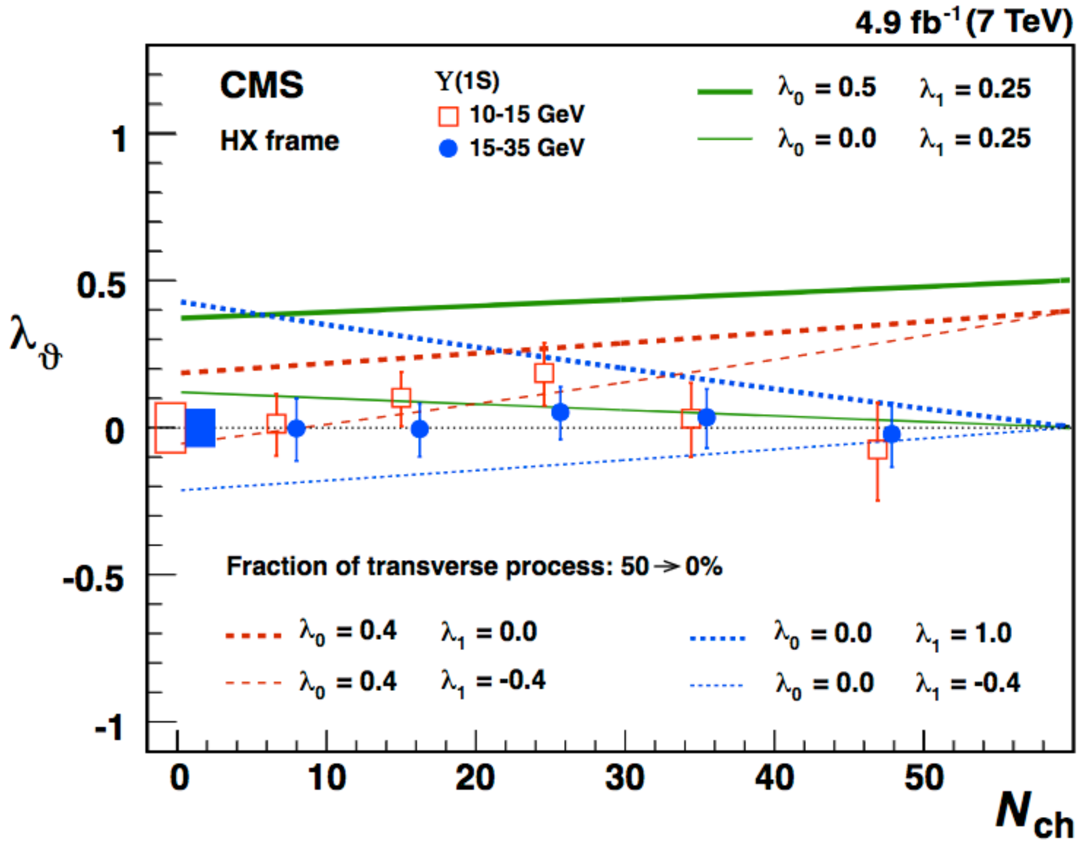




Υ polarization vs. particle multiplicity

CMS has tested a possible dependence of the polarization on the multiplicity of charged tracks ($|\eta|<2.4$, $p_T>500$ MeV), aiming at a correlation of the QQ hadronization process with the complexity of the hadronic environment.
No evidence of such dependence is found.

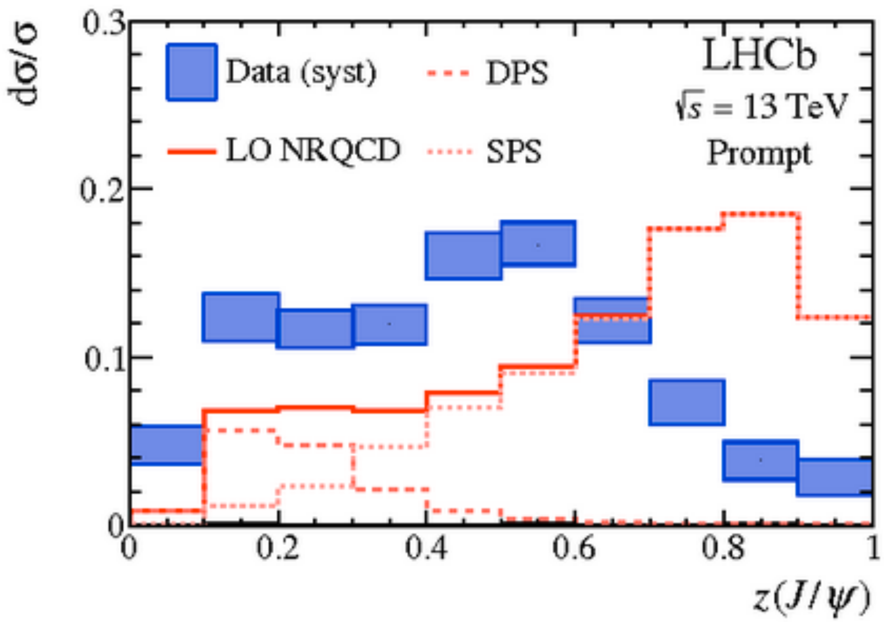
Phis.Lett. B 761 (2016) 31 (arXiv:1603.02913)



Prompt J/ψ and associated jet

- The subject is interesting because it provides new observables for the production mechanism.
- Unfortunately the result of LHCb is for rather low p_T values (of Jet and of J/ψ) and we do not have (yet) results form ATLAS or CMS.

- Phys.Rev.Lett. 118, 192001 (2017)
  arXiv:1701.05116



More on quarkonia polarization

- The case considered more frequently is the decay of a spin 1 particle (e.g., J/ψ) into a lepton pair. In the vector rest frame, the angular distribution of the decay product is given by:

$$dN/d\Omega = [1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos(2\phi) + \lambda_{\theta\phi} \sin(2\theta) \cos\phi]/(1 + \lambda_\theta/3)$$

- The parameter are constrained to have absolute value less than 1 (actually, correlated constraints turn out to be tighter, see below).
- There is some freedom in the choice of the axes, normally chosen as:
  - The production plane is orthogonal to the *y* axis
  - Different choices are possible for the orientation of *z* and *x*, among the most common:
    - *Helicity frame: z* along the momentum of the decaying particle in the laboratory frame
    - *Collins-Soper* (CS) and *Gottfried-Jackson* (GJ) are among other possibilities

Polarization - 2

- All possible frames are related by a rotation about *y*, and corresponding trasformations equation exists for the three coefficients.

– Therefore the one could say that the physical polarization (or spin alignment), depends on two quantities rather than three (and in fact two independent *rotation invariant* quantities are known [*,§]).

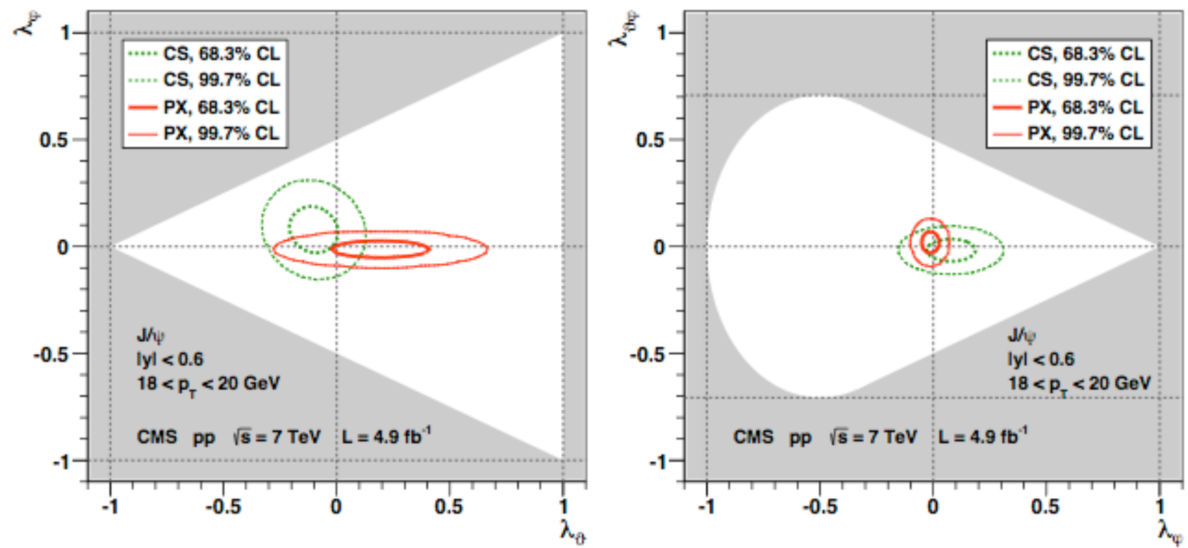
– Different computation may prefer different choices, of the coefficients, and it has been argued that model independent analyses could benefit from the determination of the invariant quantities.

[*] P. Faccioli et al., Phys. Rev. D 83 (211) 056008 (arXiv:1102.3946) and refs. therein,

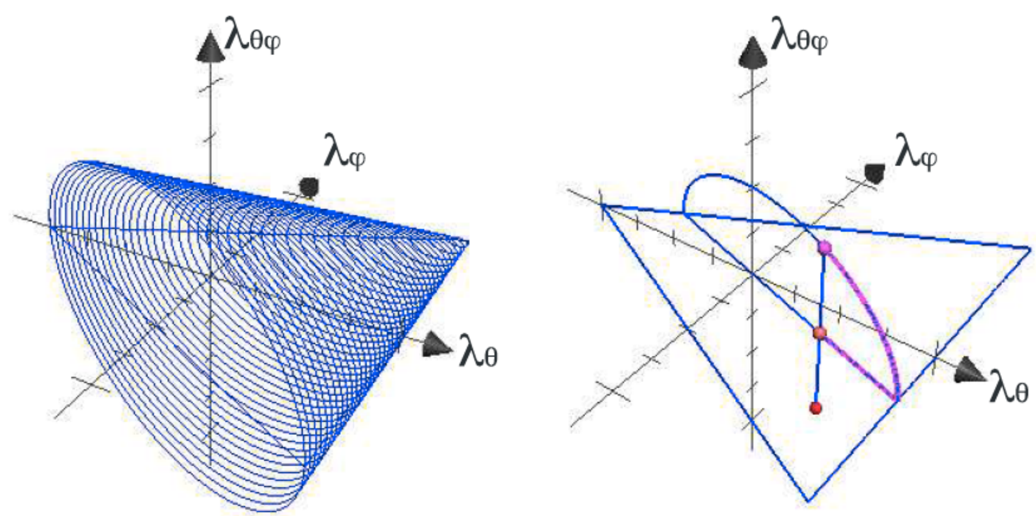
[§] S. P., Phys. Rev. D 83, 031503 (arXiv:1012.2485).

Polarization - 3

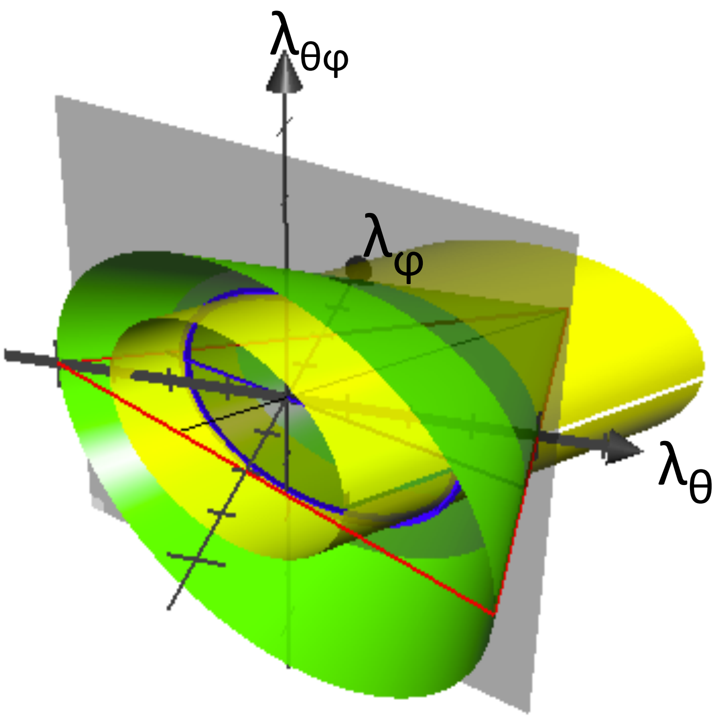
The boundaries on the values of the angular distribution parameters are often given on 2D projections (the grey area is forbidden).



A more complete picture is visible in 3D. For a rotation of frame the values of the parameters change following an ellipse that lies on a plane orthogonal to the λ_θ, λ_φ plane.



Polarization - 4



Geometrical description of the frame-invariant parameters of the angular distribution for J/ψ (ϒ) decay to lepton pairs:

- A plane for the invariant in ref. [*],
- An elliptic cone for the invariant in ref. [§].

The intercepted ellipsis defines the set of values of the angular distribution parameters linked by a different choice of reference frame.

List of recent HQ production results at LHC: LHCb

- LHCb Y production at 7, 8 TeV: http://arxiv.org/abs/1509.02372
- LHCb J/psi roduction at 13 TeCV : http://arxiv.org/abs/1509.00771
- LHCb associated Y and open charm at 7, 8 TeV: http://arxiv.org/abs/1510.05949
- LHCB Lambda_b and B0bar production ; http://arxiv.org/abs/1509.00292]
- LHCb Y exclusive production cross section ay 7 Tev: http://arxiv.org/abs/1505.07024
- LHCb eta_c production : http://arxiv.org/abs/1409.3612
- LHCb χb1(1P) and χb2(1P) relative production: http://arxiv.org/abs/1409.1408
- LHCb χb production at 7, 8 TeV : http://arxiv.org/abs/1407.7734
- LHCb pair of charmonium (produced exclusively?) : http://arxiv.org/abs/1407.5973
- LHCB kinematic dependence of Lambda_b production:
- http://arxiv.org/abs/1405.6842

LHCb results continued

- LHCb ψ(2S) polarisation at 7 TeV : http://arxiv.org/abs/1403.1339
- LHCb polarisation and helicity amplitudes in Lambda_b -> Lambda J/psi : http://arxiv.org/abs/1302.5578

- LHCb Y polarization at 7, 8 TeV http://arxiv.org/abs/1709.01301
- B Bbar correlations http://arxiv.org/abs/1708.05994
- Production asymmetries in B0, B0s, B+ Lambda_b at 7, 8 TeV http://arxiv.org/abs/1703.08464
- J/ψ prompt production in jets http://arxiv.org/abs/1701.05116 PRL 118, 192001 (2017)
- Prompt J/psi pair production at 13 TeV http://arxiv.org/abs/1612.07451 JHEP 2017:47 (June 2017)

CMS recent results on HF production

- Υ pairs production: BPH-14-008 JHEP 05 (2017) 013
- Total and differential B^+ cross section at 13 TeV PLB 771 (2017) 435
- J/ψ and ψ(2S) at 7 TeV BPH-14-001 PRL 114 (2015) 191802
- Υ(1S-3S) production at 7 TeV BPH-12-006 PLB 749 (2015) 14
- B_c/B^+ cross section at 7 TeV BPH-12-011 JHEP 01 (2015) 063
- $\chi_{b2}(1P)/\chi_{b1}(1P)$ at 8 TeV BPH-13-005 PLB 743 (2015) 383
- J/ψ pair productioon BPH-11-021 JHEP 09 (2014) 094
- J/ψ and ψ(2S) polarization at 7 TeV BPH-13-003 PLB 727 (2013) 381

ATLAS results on HF production

- B Bbar correlation in J/ψ +mu https://arxiv.org/abs/1705.03374
- J/ψ + J/ψ at 8 TeV Eur. Phys. J. C77(2017)76
- J/ψ + Z at 8 TeV Eur. Phys. J. C75 (2015) 229
- J/ψ and ψ(2S) production at 7, 8 TeV Eur. Phys. J. C 76 (5) 1-47 (2016)
- *X*(3872) production at 8 TeV JHEP01(2017)117
- Fragmentation ratio f_s / f_d Phys.Rev.Lett.115.262001
- J/ψ π π production at 7 TeV JHEP09(2014)079
- χ_{c1}, χ_{c2} production at 7 TeV JHEP07(2014)154
- $D^{\pm}$,$D^{*\pm}$,D^{+}_{s} production at high pT at 7 TeV Nucl. Phys. B 907 (2016) 717
- J/ψ+W production at 7 TeV JHEP04(2014)172
- B+ cross section JHEP10(2013)042
- ϒ cross section at 7 TeV Phys. Rev. D 87, 052004 (2013)
- B cross section from D*μ events Nucl. Phys. B 864 (2012) 341

Some additional references

Bc differential cross section, agreement in shape in with computations based on a complete order-α_s^4:

- *C.H Chang et al. PR D48 (1993) 4086 and PL B364(1995)78,*
- *Berezhnoy et al. Phys. Atom. Nucl 58 (1995) 672,*
- *Kolodziej et al. PL B355(1995)337*

Predictions for polarization of prompt J/ψ's in NRQCD NLO computations:

M. Butenschoen and B. A. Kniehl, *J/ψ polarization at Tevatron and LHC: Nonrelativistic-QCD factorization at the crossroads*, Phys. Rev. Lett. **108** (2012) 172002, arXiv:1201.1872.

B. Gong, L.-P. Wan, J.-X. Wang, and H.-F. Zhang, *Polarization for prompt J/ψ, $\psi(2S)$ production at the Tevatron and LHC*, Phys. Rev. Lett. **110** (2013) 042002, arXiv:1205.6682.

K.-T. Chao *et al.*, *J/ψ polarization at hadron colliders in nonrelativistic QCD*, Phys. Rev. Lett. **108** (2012) 242004, arXiv:1201.2675; H.-S. Shao and K.-T. Chao, *Spin correlations in polarizations of P-wave charmonia χ_{cJ} and impact on J/ψ polarization*, arXiv:1209.4610.