Heavy quark production

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on behalf of the LHCb collaboration, including results from the ALICE, ATLAS, CMS, CDF and D0 collaborations

CERN

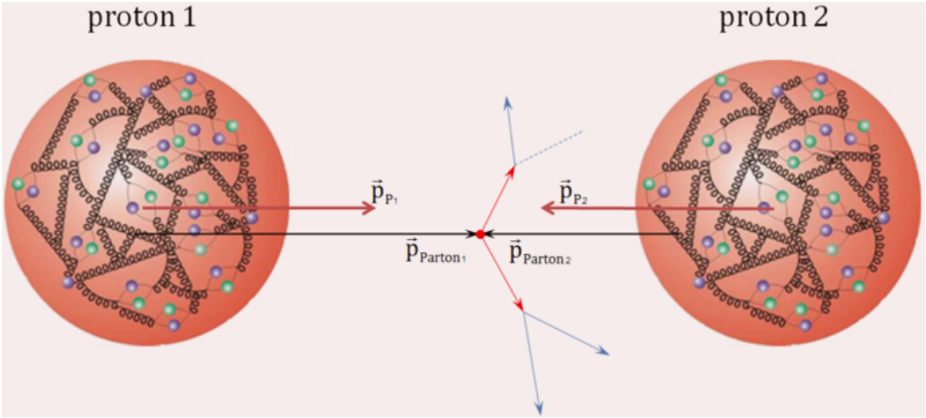
ISVHECRI 2014 @ CERN (Geneva), 18/08/2014

Outline

- Overview of heavy quark(onium) hadroproduction in $pp(p\bar{p})$
  - In heavy-Ion collisions, covered by B. Donigus
  - Via diffraction, covered by I. Katkov
- Heavy quark (associated) production
  - Charm
  - Bottom
- Heavy quarkonium (associated) production
  - Charmonium
  - Bottomonium
  - Polarization
- Impossible to cover all results, sorry for missing your favorite ones

Introduction

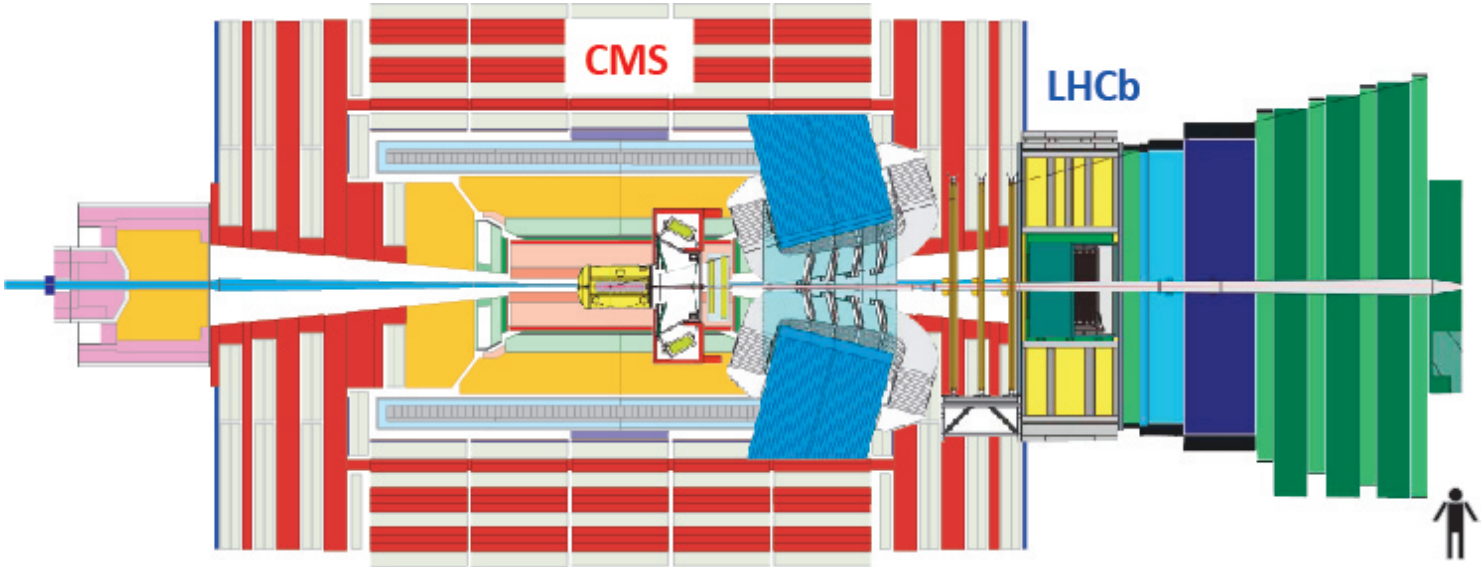
- Measurements of heavy quark(onium) production provide important tests of QCD
  - Parton distribution function (PDF)
  - Hard parton scattering
  - Fragmentation



- Production cross-section at new energies also required to guide relevant studies, e.g., search for new physics
- Measurements of heavy flavor production in *pp* collisions provide mandatory baseline for nucleus-nucleus collisions

Experiments at Tevatron and LHC

- Tevatron
  - p+$\bar{p}$, beam energy: 980 (900) GeV, $\sqrt{s} = 1.96\,(1.8)$ TeV
  - Two General Purpose Detector (GPD), D0 and CDF
- LHC
  - p+p, beam energy: 4 (3.5) TeV, $\sqrt{s} = 8\,(7)$ TeV
  - Two GPDs, ATLAS, CMS
  - ALICE (Heavy-Ion physics), LHCb (Beauty/Charm physics)
- LHCb covers forward region ($2 < \eta < 5$), while other experiments mostly cover central region

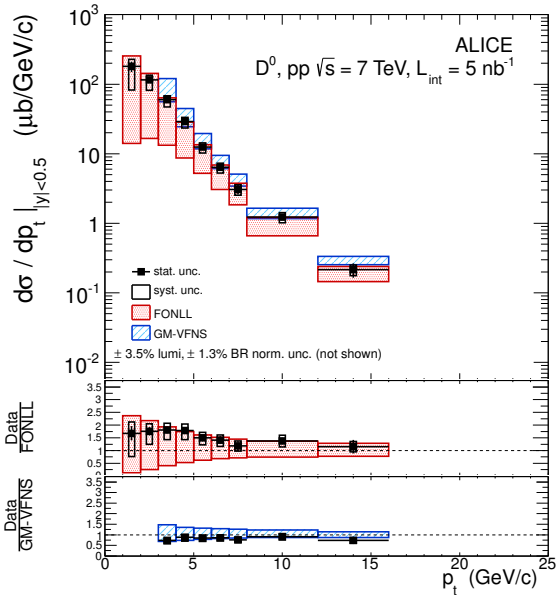


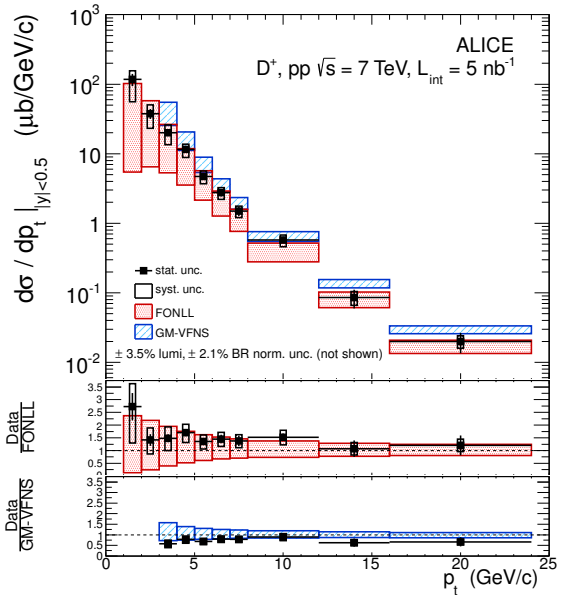
Charm production

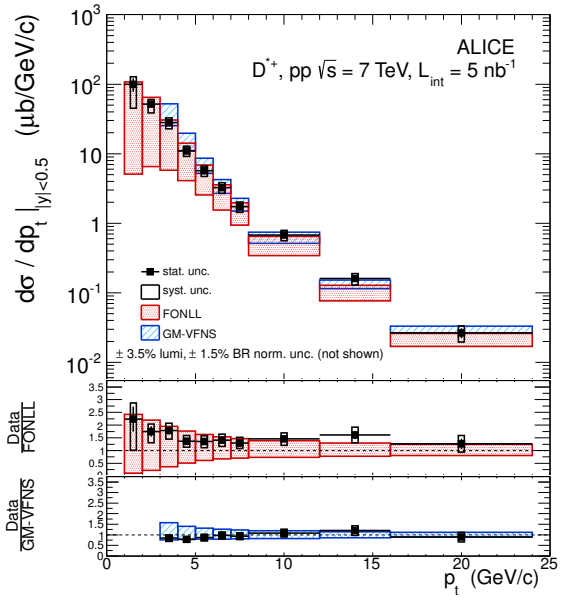
Open charm production @ 7 TeV

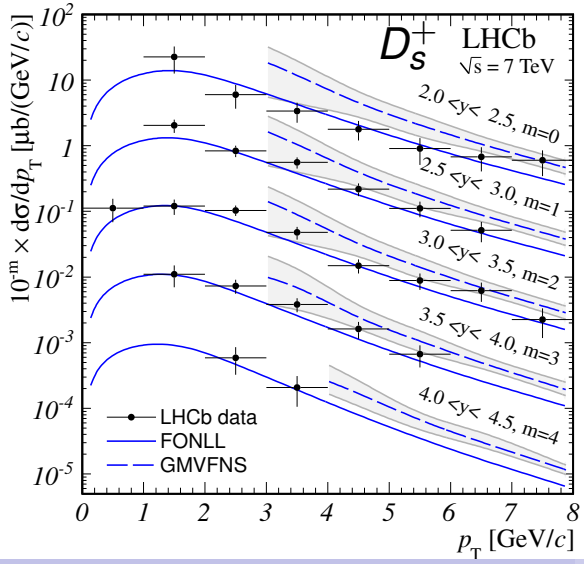
[ALICE, JHEP 01 (2012) 128] [LHCb, NPB 871 (2013) 1]

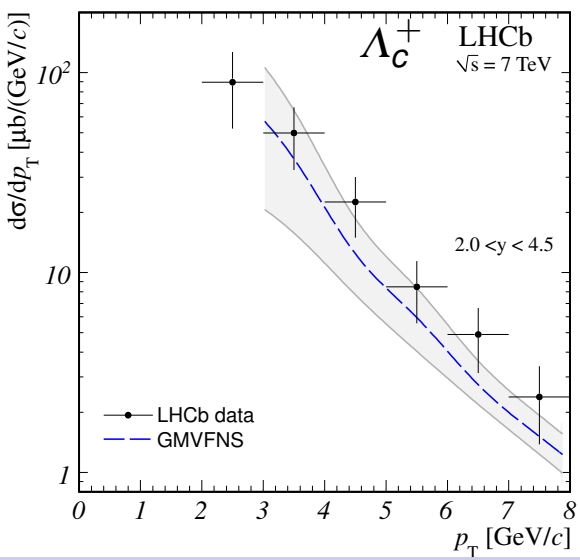
- With exclusive decays, in good agreement with theo.









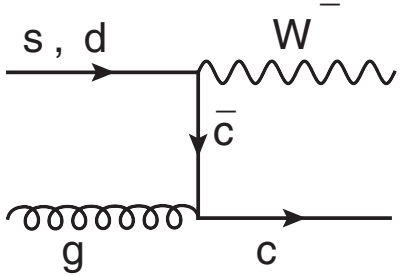


FONLL:
Fixed Order + Next-to-Leading Log
[M. Cacciari *et al.*, JHEP 10 (2012) 137]

GMVFNS:
General Mass Variable Flavor Number Scheme
[B.A. Kniehl *et al.*, EPJC 72 (2012) 2082]

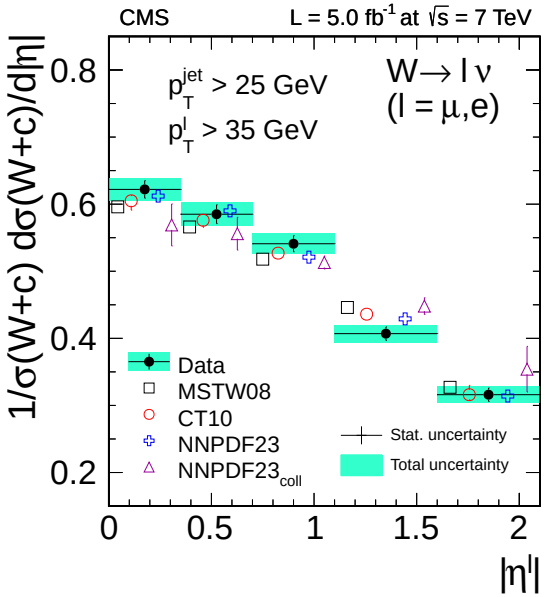
Associated $W + c$ production

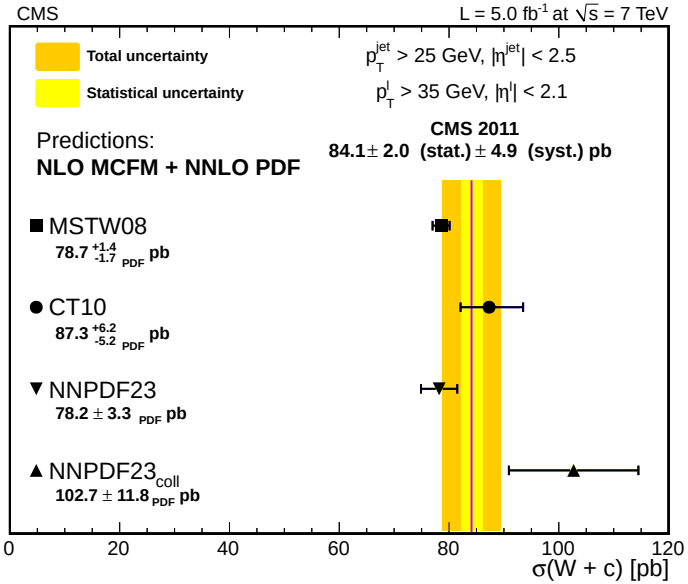
- Sensitive to s-quark PDF due to $sg \to W^- + c$ dominance
- Exploit intrinsic charge correlation of $W + c$, opposite sign (OS)

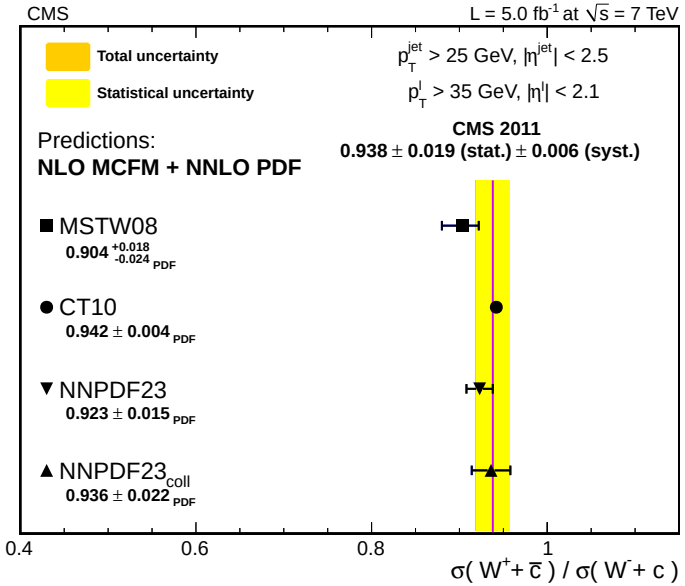


MCFM: Monte Carlo for FeMtobarn processes

[CMS, JHEP 02 (2014) 013] [ATLAS, JHEP 05 (2014) 068]





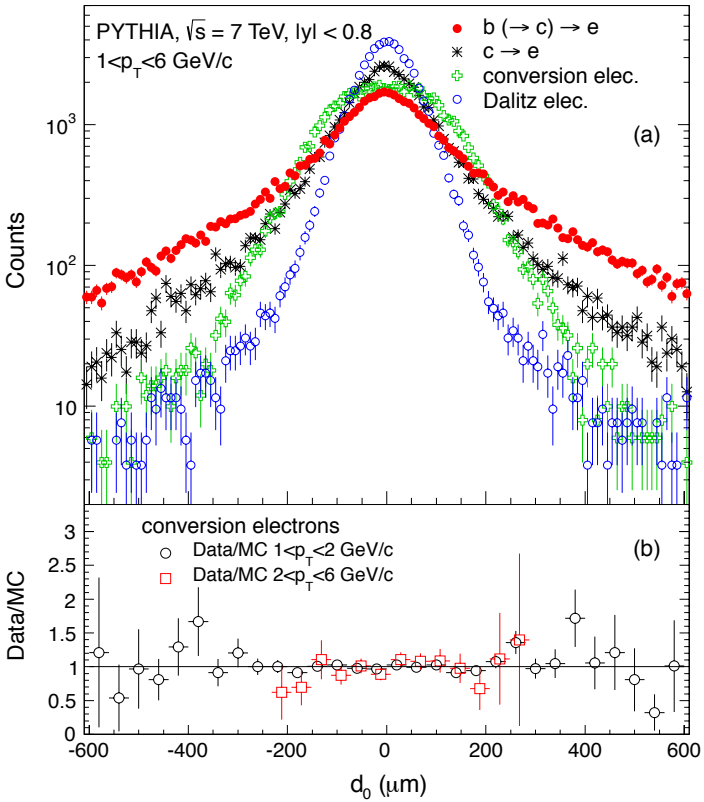


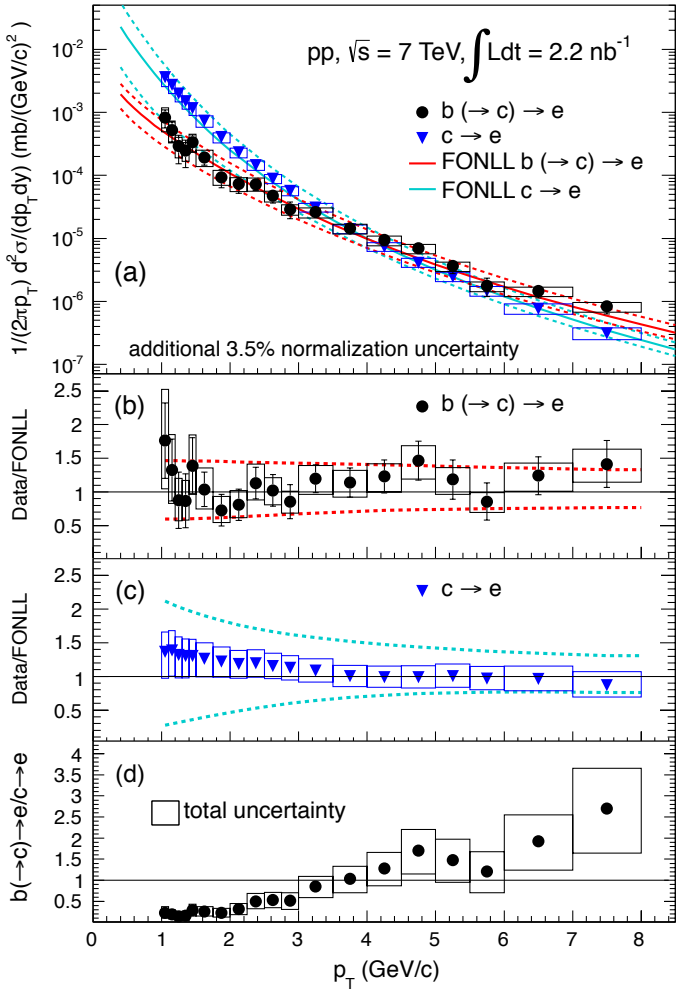
Bottom production

Bottom production using electron

[ALICE, PLB 721 (2013) 13]

- Different sources of electrons separated using impact parameter
- Bottom and charm differential cross-section described well by FONLL prediction

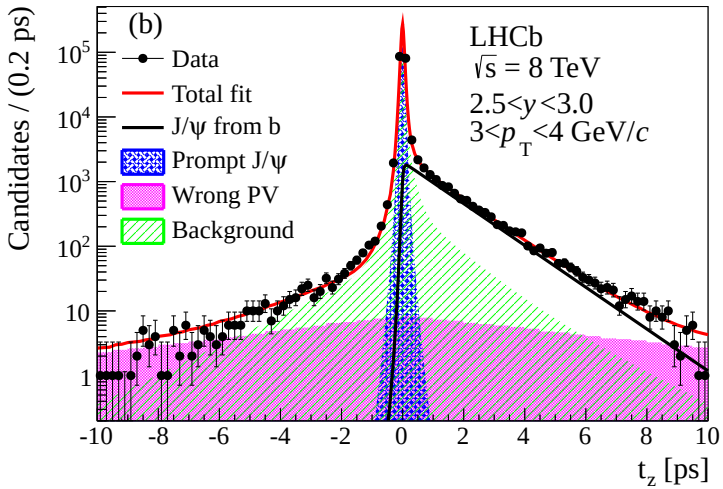


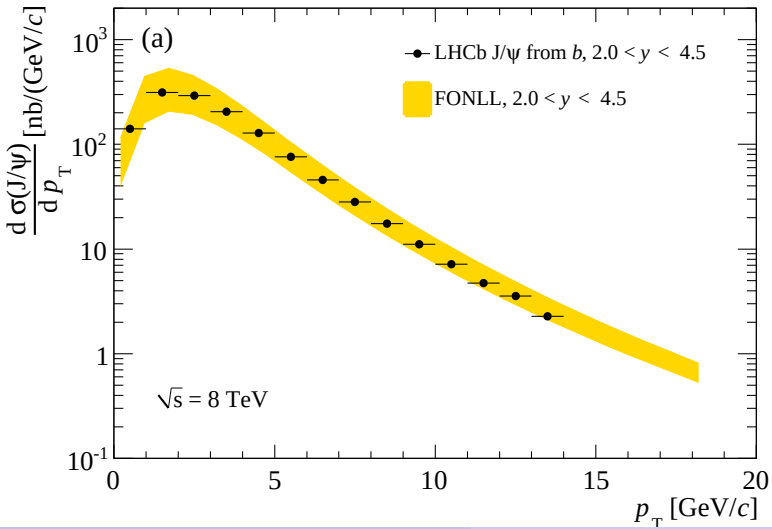


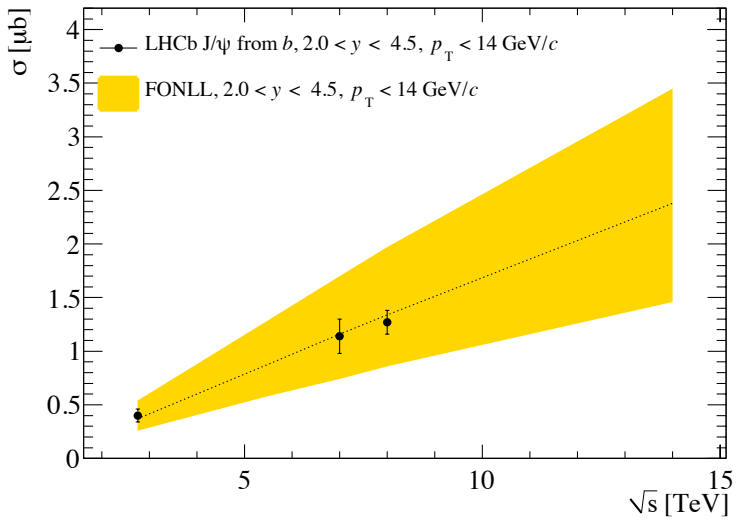
Bottom production using J/ψ

[LHCb, EPJC 71 (2011) 1645] [LHCb, JHEP 02 (2013) 041] [LHCb, JHEP 06 (2013) 064]

- LHCb measured bottom production using $b \to J/\psi X$ at $\sqrt{s} = 2.76$ and 8 TeV, apart from that at 7 TeV
- $b \to J/\psi X$ separated from prompt J/ψ using
  $t_z = \frac{(z_{J/\psi} - z_{\rm PV}) \times M_{J/\psi}}{p_z}$
- Good agreements with FONLL



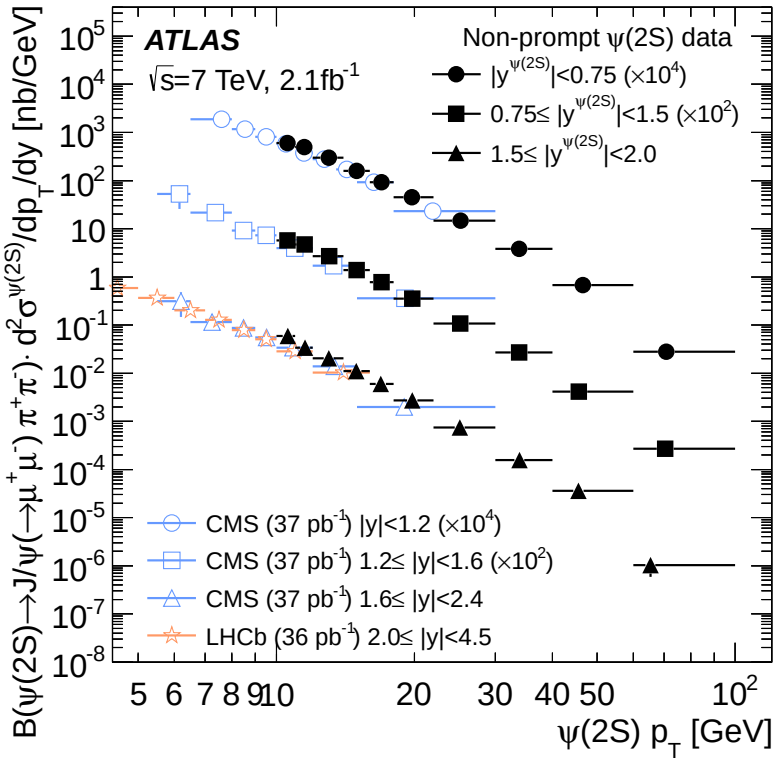


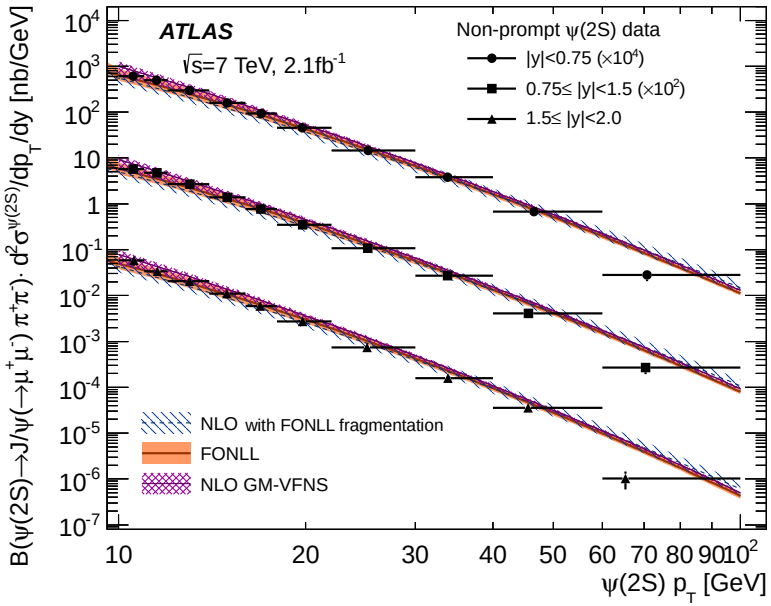


Bottom production using $\psi(2S)$

[ATLAS, arXiv:1407.5532] [CMS, JHEP 02 (2012) 011] [LHCb, EPJC 72 (2012) 2100]

- ATLAS measured bottom production using $b \to \psi(2S)X$ with $\psi(2S) \to J/\psi(\mu\mu)\pi^+\pi^-$, overlaid with CMS and LHCb results
  (note: different rapidity ranges)
- Compared to NLO, FONLL & GM-VFNS, discrepancy at high p_T?

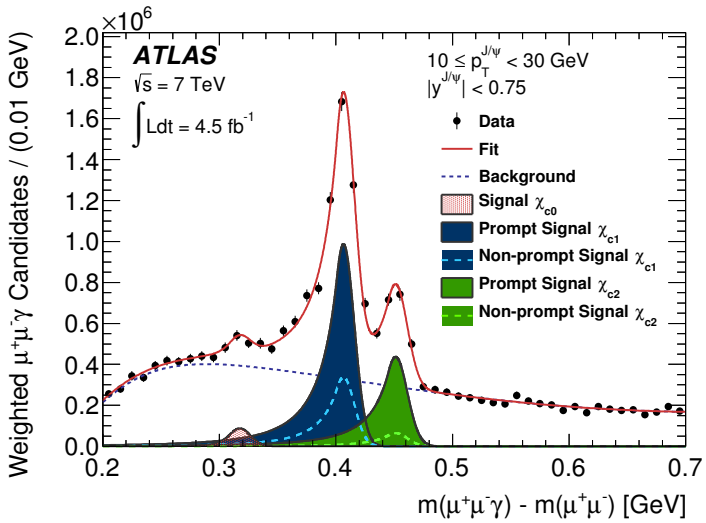


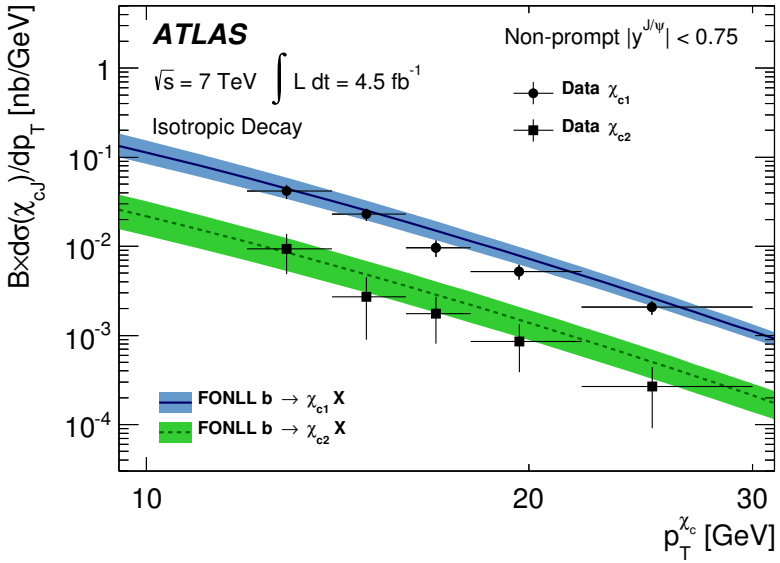


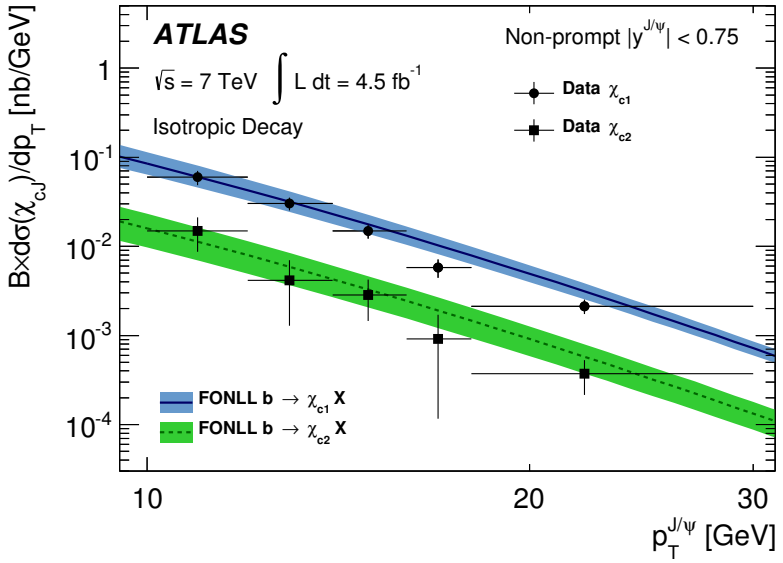
Bottom production using χ_c

[ATLAS, JHEP 07 (2014) 154]

- ATLAS measured bottom production using $b \to \chi_c X$ with $\chi_c \to J/\psi(\mu\mu)\gamma(e^+e^-)$



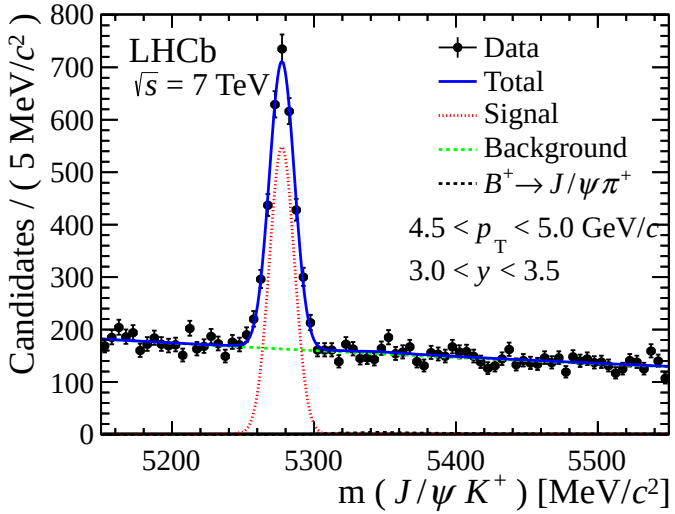


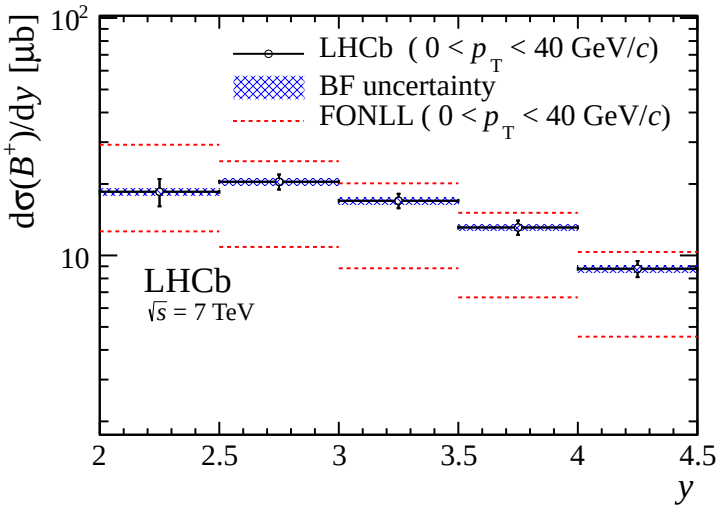


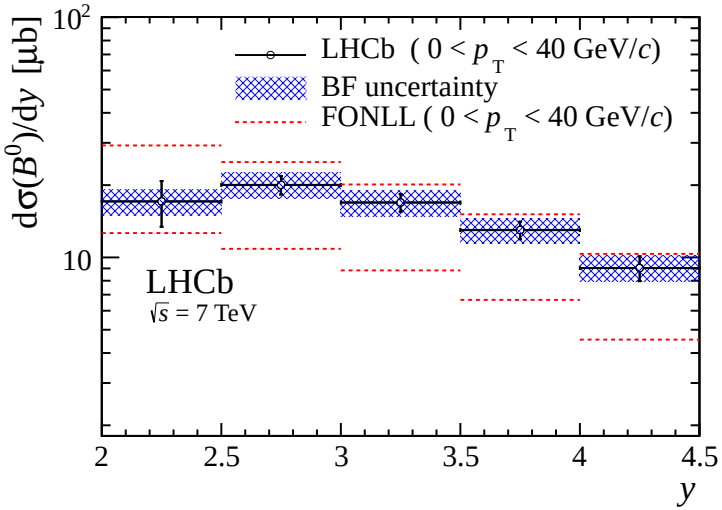
b meson production

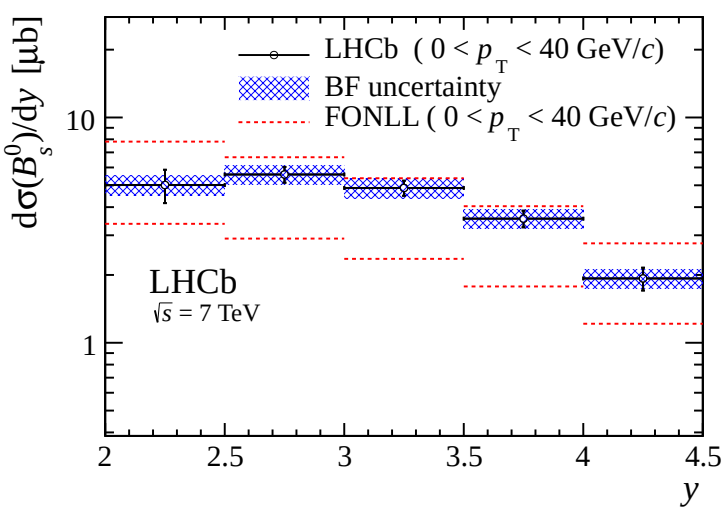
[LHCb, JHEP 08 (2013) 117]

- LHCb measured $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$, and $B_s^0 \to J/\psi \phi$ production for $2 < y(B) < 4.5$, in agreement with FONLL





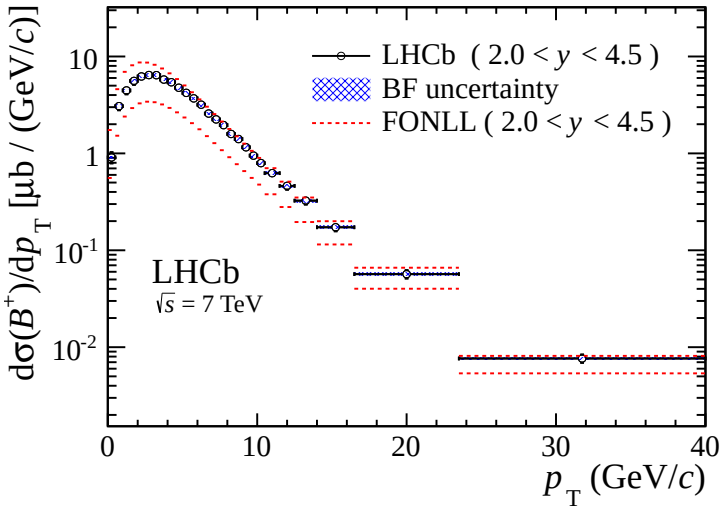


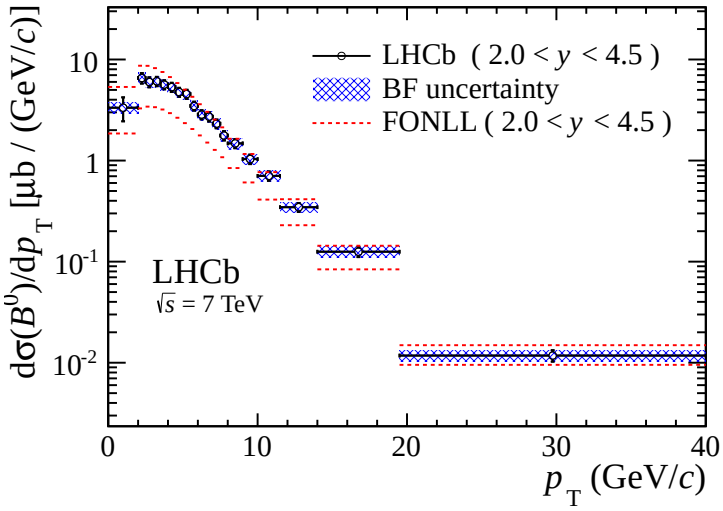


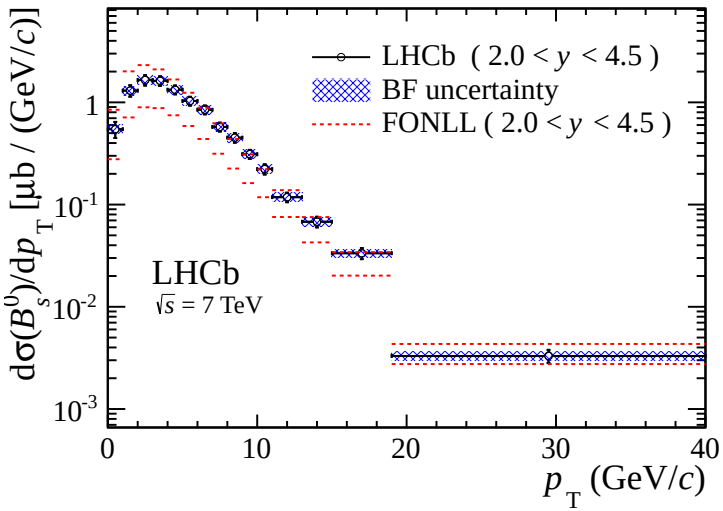
b meson production (cont.)

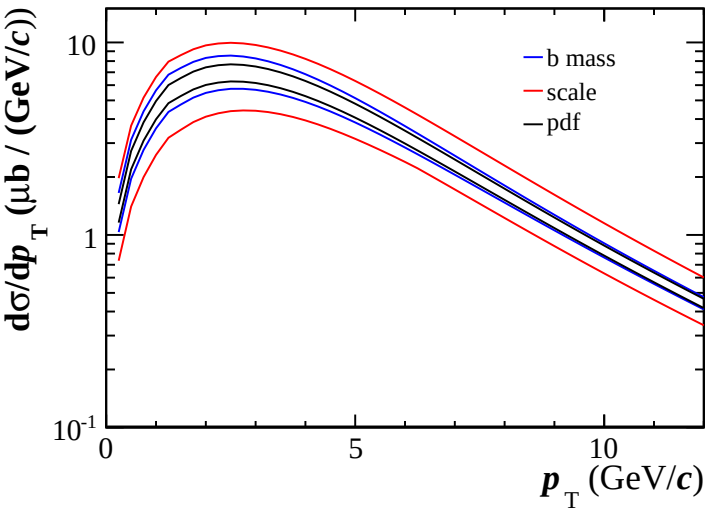
[LHCb, JHEP 08 (2013) 117]

- $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}$, good agreement with FONLL
- Theo. uncertainty includes m_b, $\mu_{\mathrm{R}}, \mu_{\mathrm{F}}$ and PDF







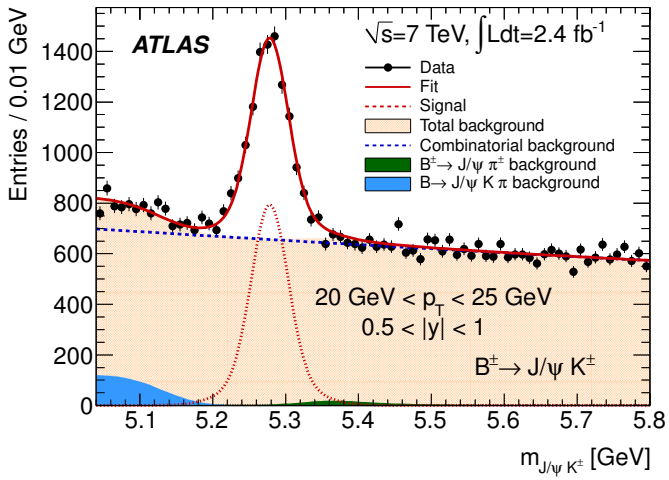


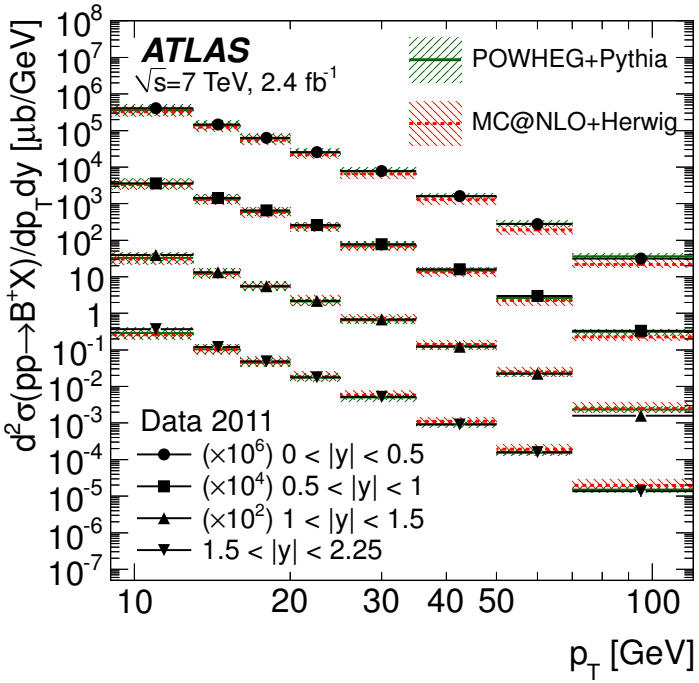
B^+ production by ATLAS

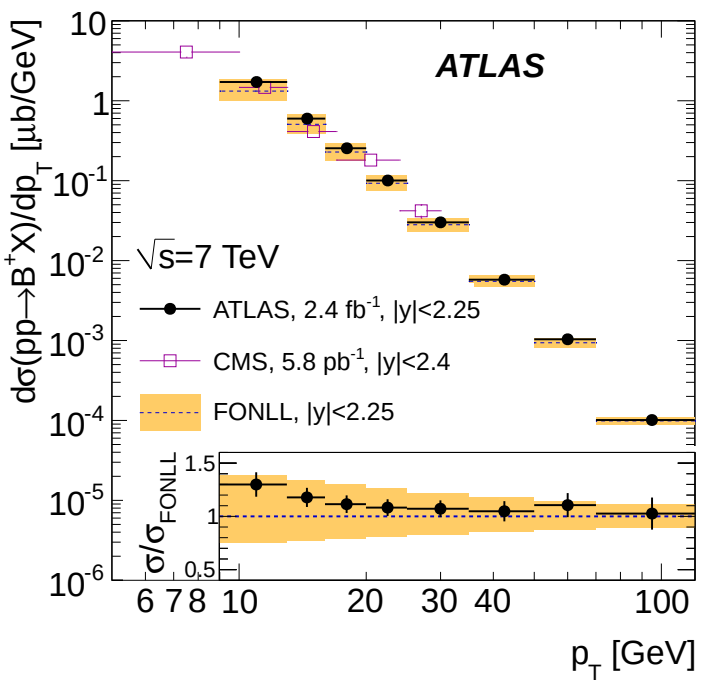
[ATLAS, JHEP 10 (2013) 042] [CMS PRL 106 (2011) 112001]

- ATLAS measured $B^+ \to J/\psi K^+$ in the central region
- Compared to CMS results, FONLL, POWHEG, and MC@NLO

[M. Cacciari et al., JHEP 10 (2012) 137]



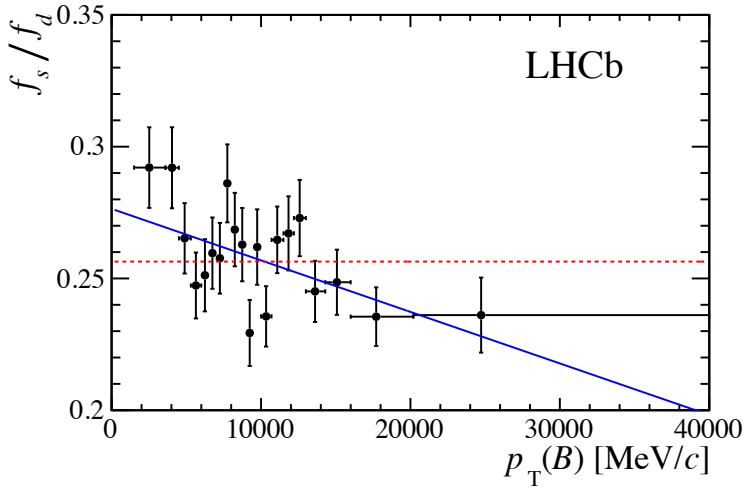


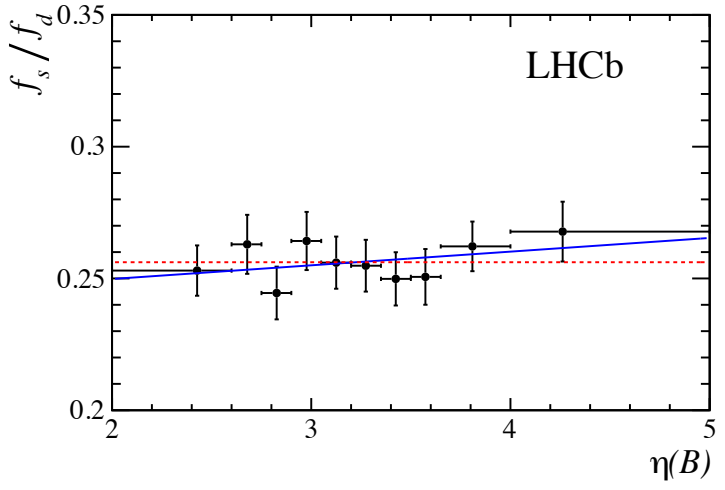


Fragmentation fraction f_s/f_d

[LHCb, JHEP 04 (2013) 001]

- Fragmentation fraction $f_s = \frac{\sigma(B_s^0)}{\sigma(b\bar{b})}$, $f_d = \frac{\sigma(B^0)}{\sigma(b\bar{b})}$
- f_s/f_d needed for normalization of $B_s^0 \to \mu^+\mu^-$
- LHCb updated measurement of f_s/f_d with $B_s^0 \to D_s^- \pi^+$ and $B^0 \to D^- K^+$ using 2011 data (1 fb^{-1})
- Evidence (3σ) of dependence on $p_T(B)$, while no indication of dependence on $\eta(B)$

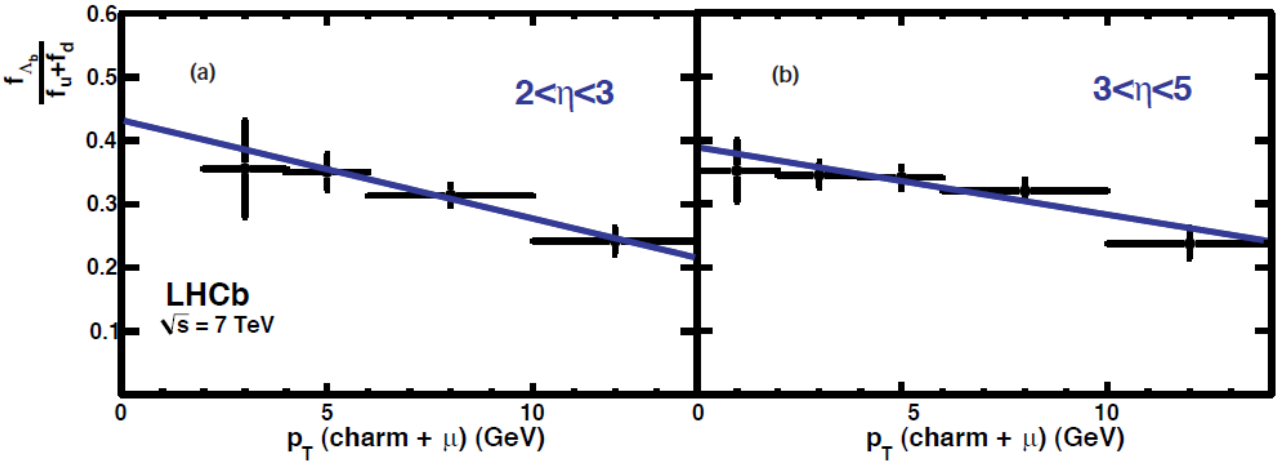




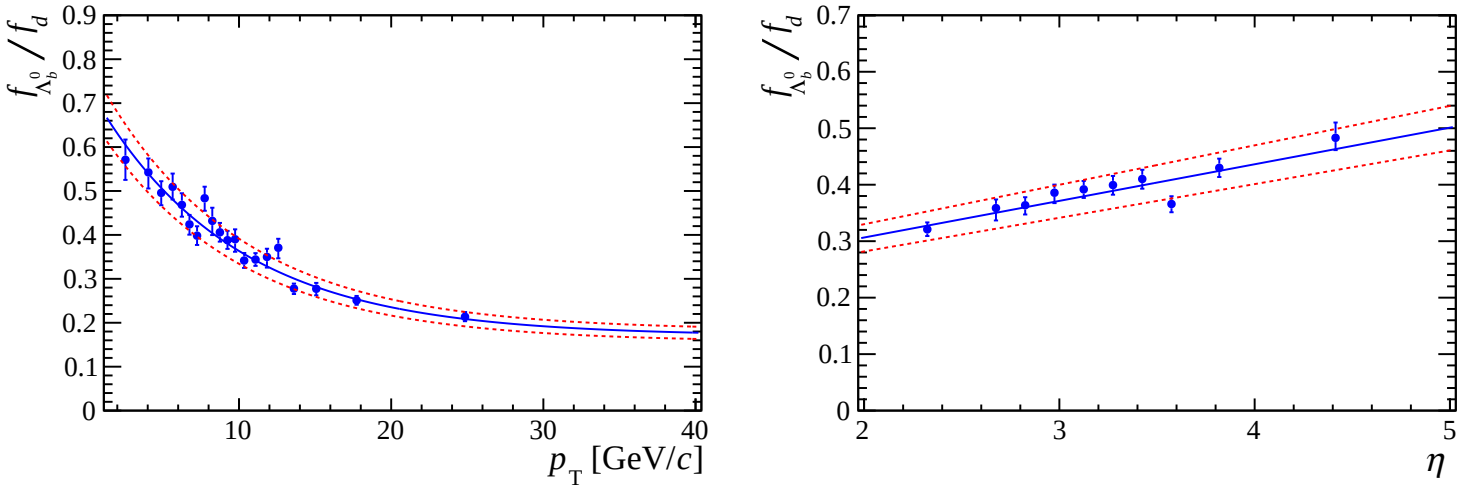
Λ_b^0 production

[LHCb, PRD 85 (2012) 032008] [LHCb, arXiv:1405.6842]

- With $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu} X$, dependence on p_{T}



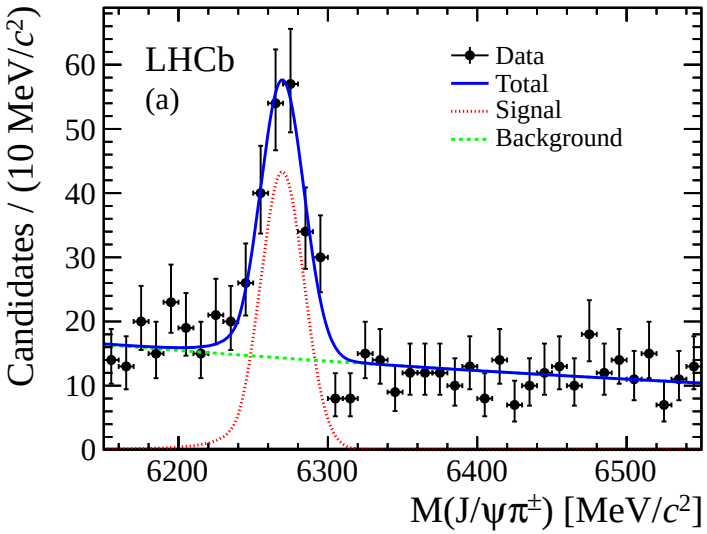
- With $\Lambda_b^0 \to \Lambda_c^+ \pi^-$, dependence on both p_{T} and η

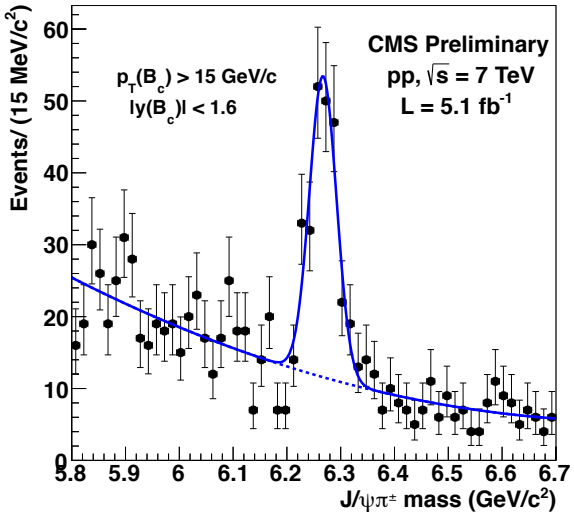


B_c^+ production

[CDF, CDF-note-11083] [LHCb, PRL 109 (2012) 232001] [CMS, CMS-PAS-BPH-12-011]

- Production at $\sqrt{s}$ =1.96 TeV, $\frac{\sigma(B_c^+)\times\mathcal{B}(B_c^+\to J/\psi\,\mu^+\nu)}{\sigma(B^+)\times\mathcal{B}(B^+\to J/\psi\,K^+)}$
  $= 0.211 \pm 0.012^{+0.021}_{-0.020}$ for $p_T(B) > 6$ GeV/c and $|y| < 0.6$ by CDF
- Production at $\sqrt{s}$ =7 TeV, $\frac{\sigma(B_c^+)\times\mathcal{B}(B_c^+\to J/\psi\pi^+)}{\sigma(B^+)\times\mathcal{B}(B^+\to J/\psi K^+)}$
  - $(0.68 \pm 0.10 \pm 0.03 \pm 0.05(\tau_{B_c^+}))\%$
    for $p_T(B) > 4$ GeV/c and $2.5 < \eta(B) < 4.5$, by LHCb
  - $(0.48 \pm 0.05 \pm 0.04\,^{+0.05}_{-0.03}(\tau_{B_c^+}))\%$
    for $p_T(B) > 15$ GeV/c and $|y| < 1.6$, by CMS



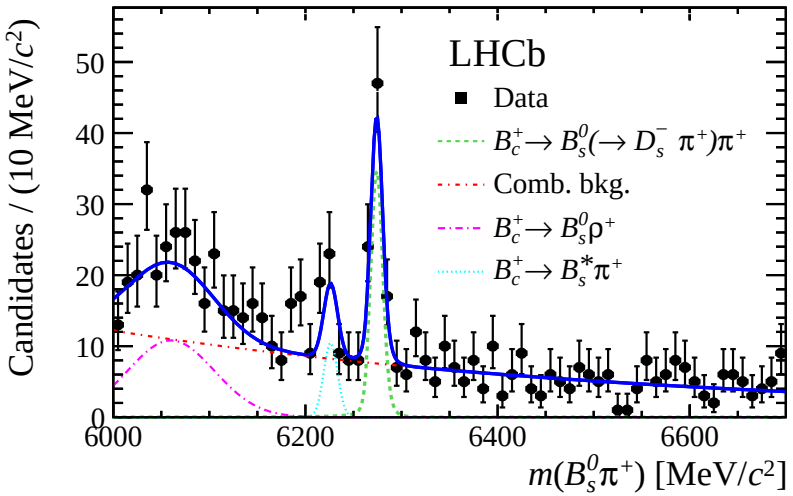


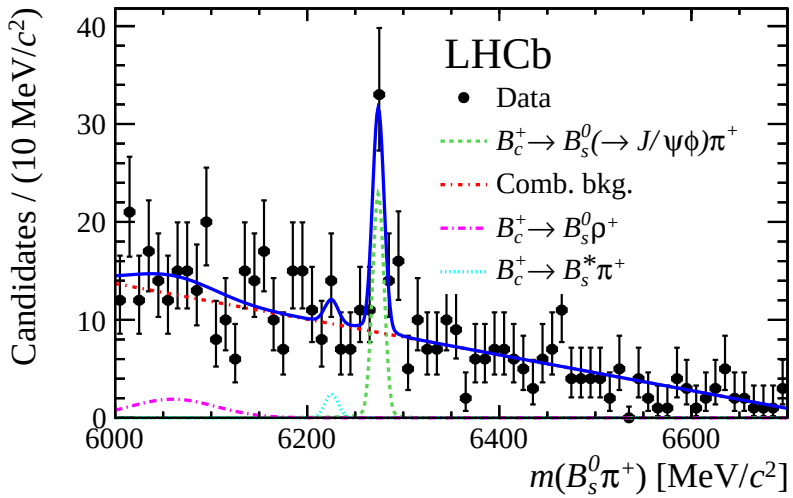
B_c^+ production (cont.)

[LHCb, PRL 111 (2013) 181801]

- LHCb measured $\frac{f_c}{f_s} \cdot \mathcal{B}(B_c^+ \to B_s^0 \pi^+)$ using 2011 + 2012 data, for $2 < \eta(B) < 5$.
- Measured with $B_s^0 \to D_s^- \pi^+$ and $B_s^0 \to J/\psi\phi$ independently, results consistent with each other
- Combined results

$$\frac{f_c}{f_s} \cdot \mathcal{B}(B_c^+ \to B_s^0 \pi^+) = \left(2.37 \pm 0.31 \pm 0.11 \,^{+0.17}_{-0.12}(\tau_{B_c^+})\right) \times 10^{-3}$$

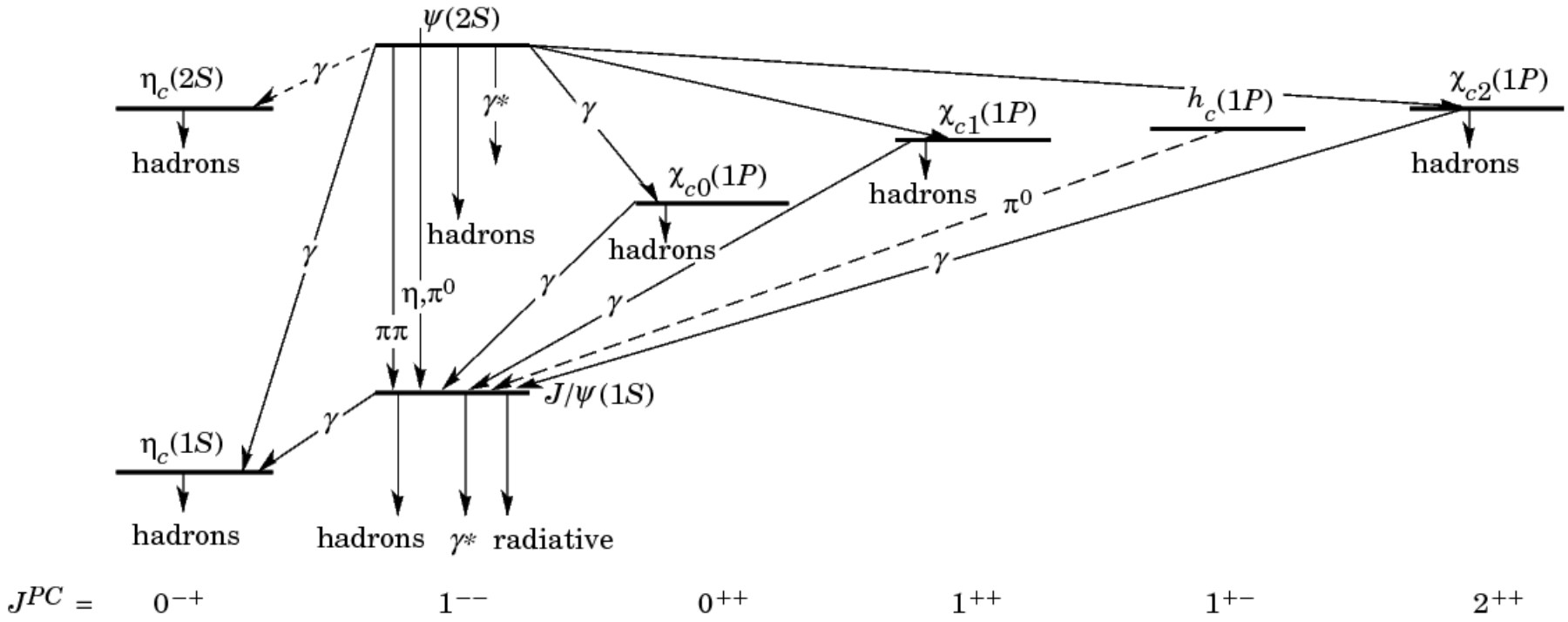




- First observation of $B_c^+ \to B_s^0 \pi^+$

Quarkonium production

Charmonium

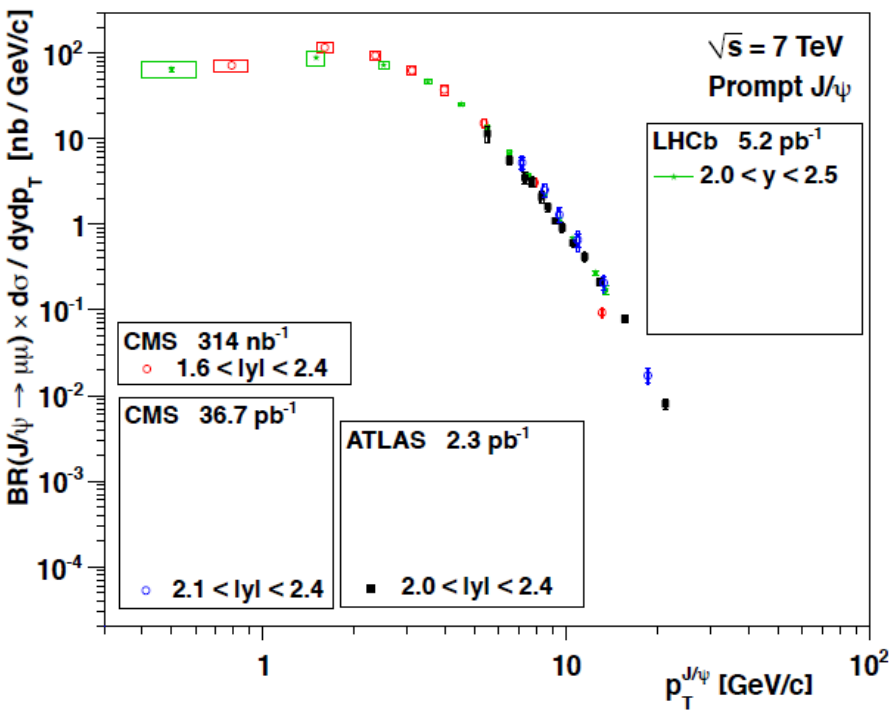

ψ(2S)
η_c(2S)
γ
hadrons
γ*
γ
χ_c0(1P)
χ_c1(1P)
h_c(1P)
χ_c2(1P)
hadrons
hadrons
hadrons
hadrons
π⁰
γ
η,π⁰
ππ
γ
γ
γ
J/ψ(1S)
η_c(1S)
γ
hadrons
hadrons
γ*
radiative
J^PC = 0^-+ 1^-- 0^++ 1^++ 1^+- 2^++

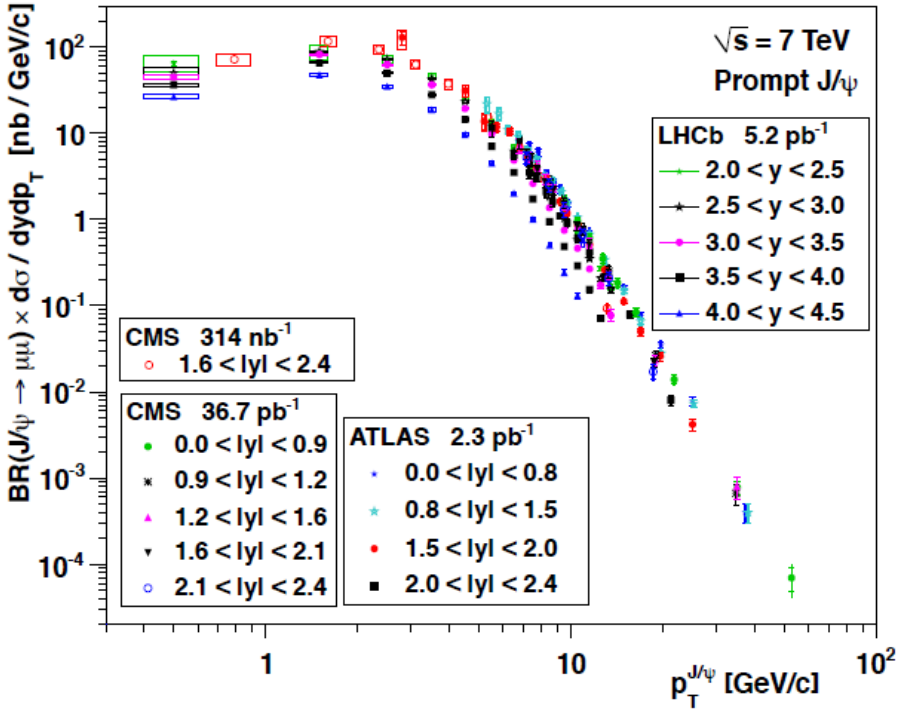
Prompt J/ψ differential cross-section

[ATLAS, NPB 850 (2011) 387] [CMS, JHEP 02 (2012) 011] [LHCb, EPJC 71 (2011) 1645]

- Results of three experiments agree well

Compilation by H.K. Wöhri

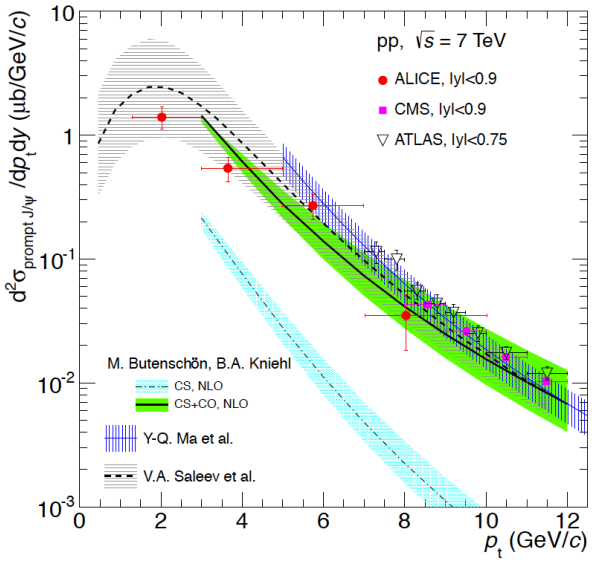


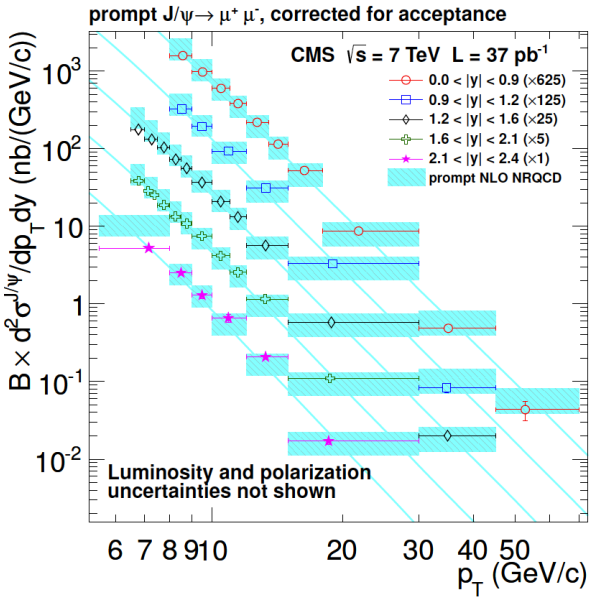


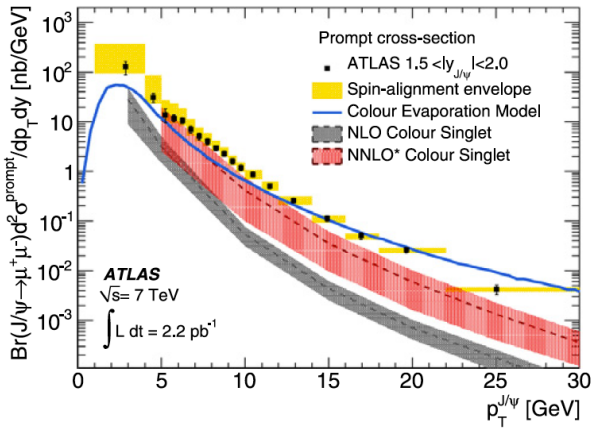
Prompt J/ψ, compare with theo.

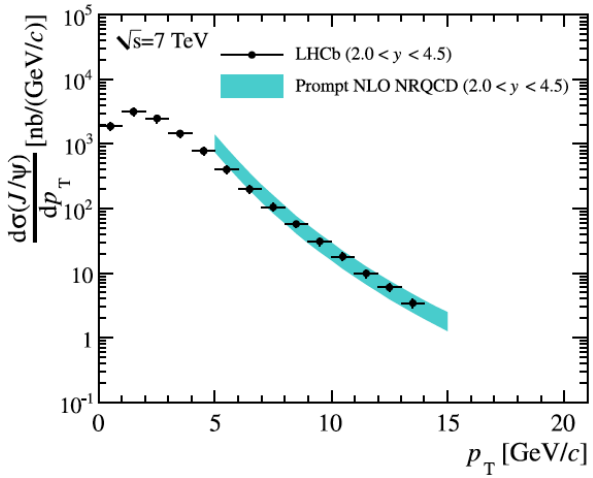
[ALICE, JHEP 11 (2012) 065] [ATLAS, NPB 850 (2011) 387] [CMS, JHEP 02 (2012) 011] [LHCb, EPJC 71 (2011) 1645]

- Theo. predictions in agreement with data





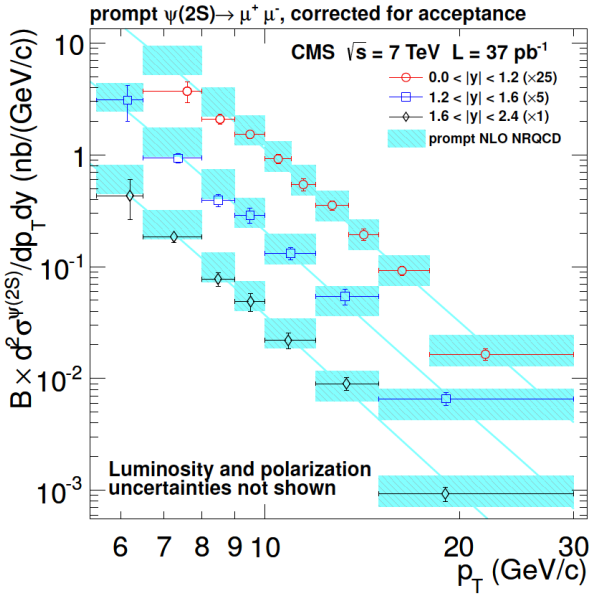


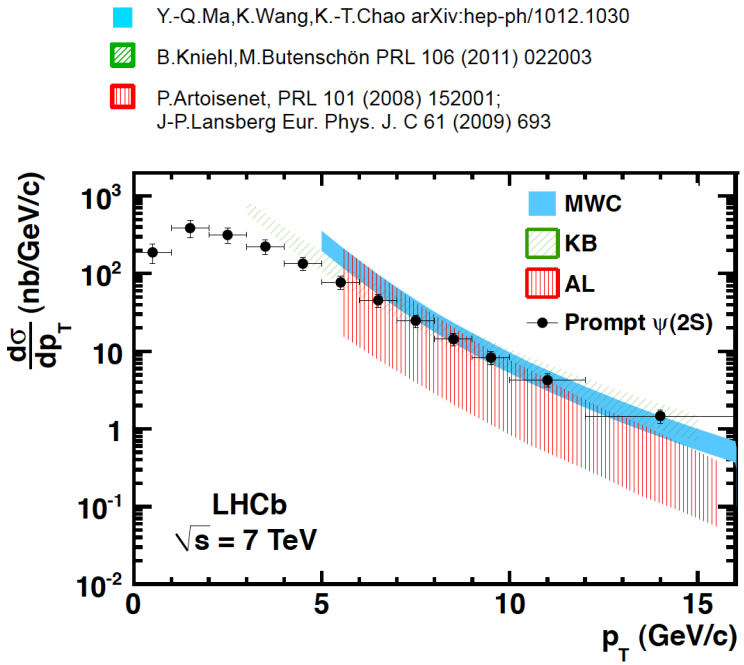


$\psi(2S)$ production

[CMS, JHEP 02 (2012) 011] [LHCb, EPJC 72 (2012) 2100]

- $\psi(2S)$, free from prompt feed-down, more convenient to compare with theoretical prediction

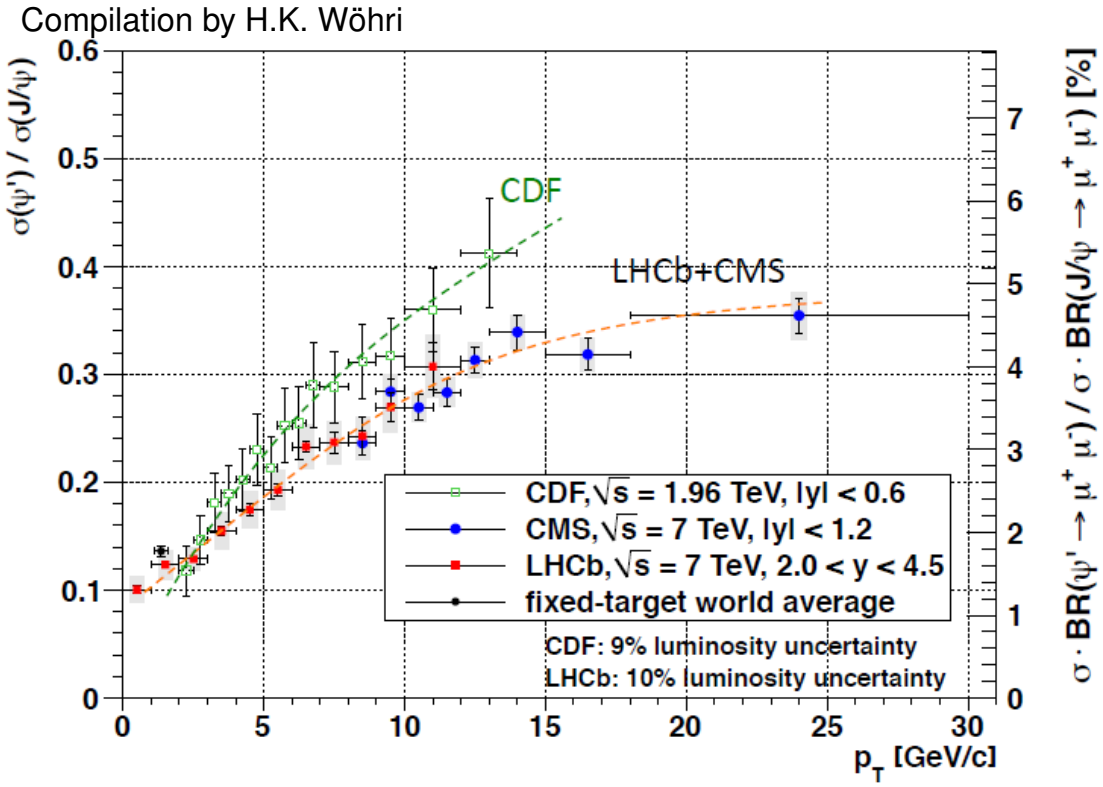




Ratio of prompt $\psi(2S)$ to J/ψ

[CDF, PRD 80 (2009) 031103] [CMS, JHEP 02 (2012) 011] [LHCb, EPJC 72 (2012) 2100] [JHEP10 (2008) 004]

- Ratio in the central region agree with that in the forward region, no strong dependence on rapidity?
- Stronger p_{T} dependence at CDF than at LHC

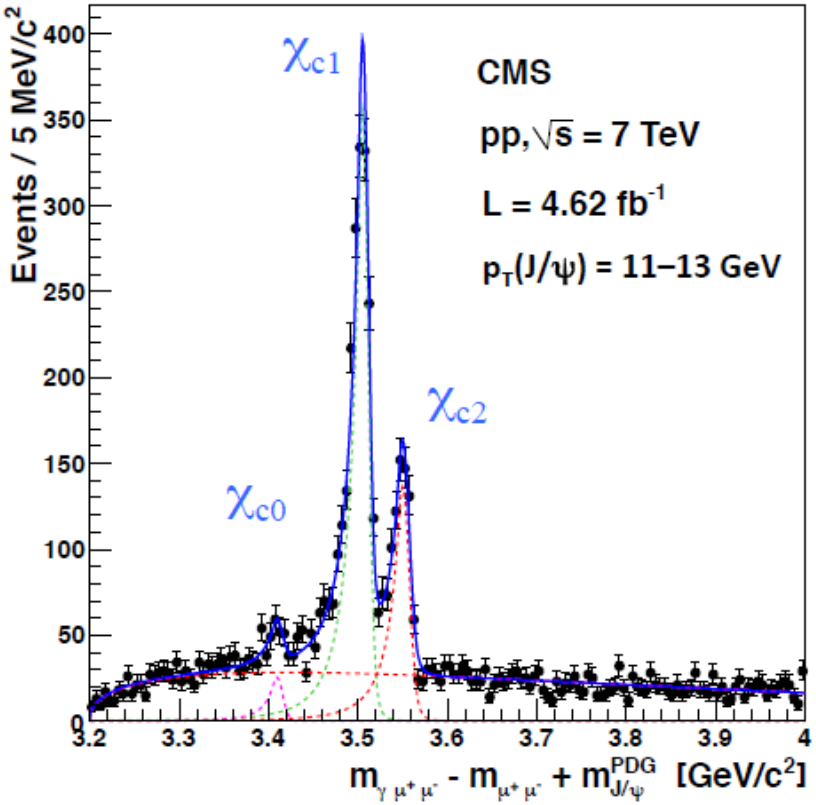


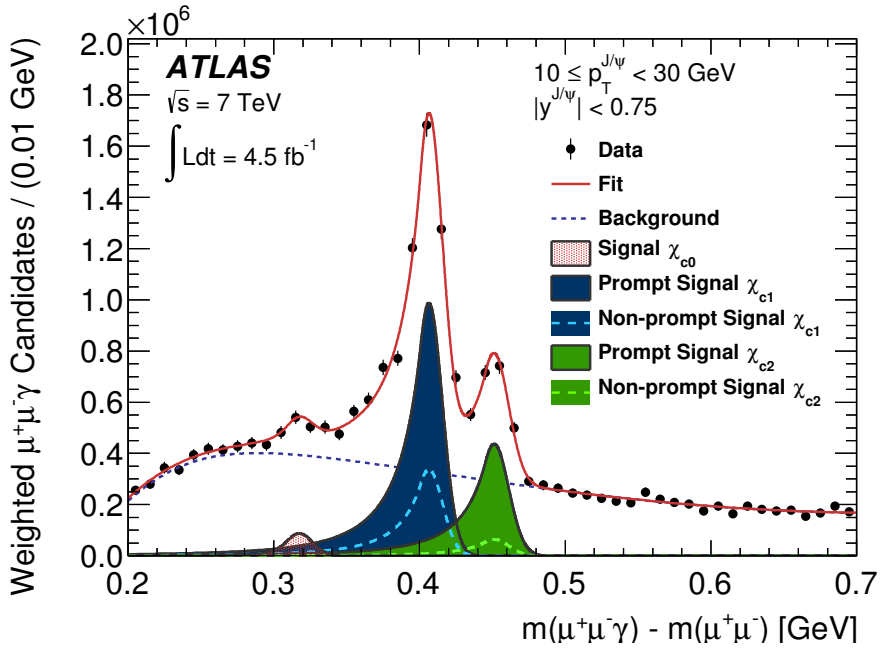
Note: the lines do not represent any theoretical model; they are added to help guiding the eye through the points

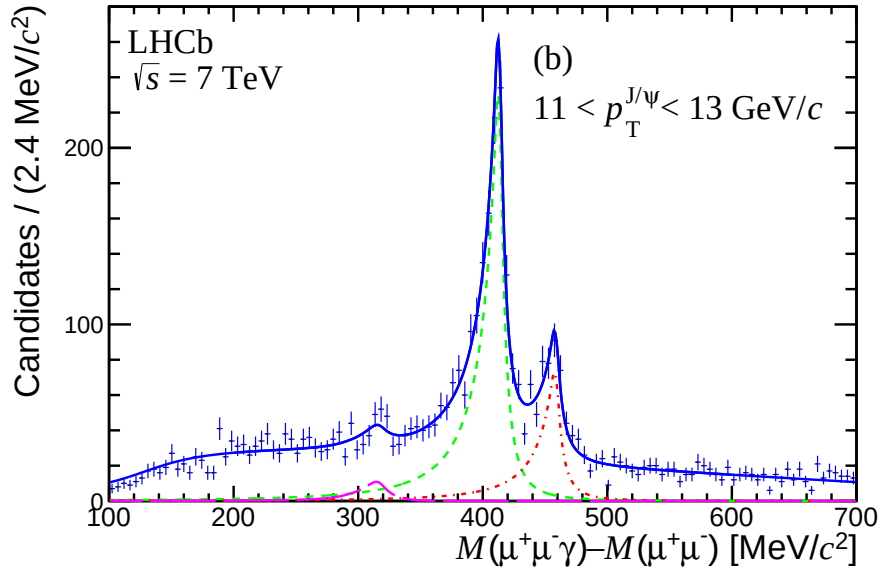
χ_c production

[CMS, EPJC 72 (2012) 2251] [LHCb, PLB 714 (2012) 215, JHEP 10 (2013) 115] [ATLAS, JHEP 07 (2014) 154]

- Using $\chi_c \to J/\psi\gamma$, with $\gamma \to e^+e^-$. Good resolution, χ_c's peaks are separated



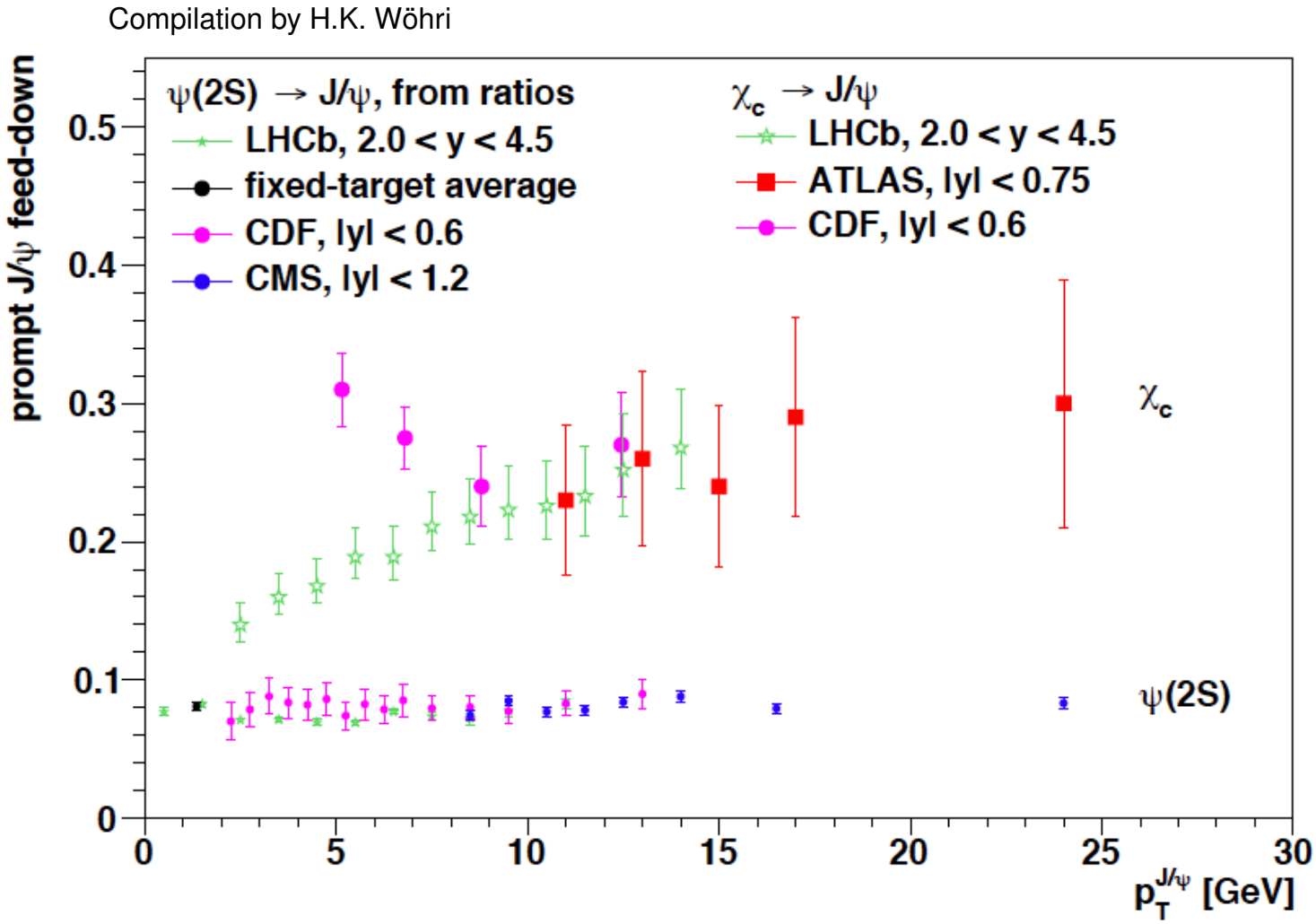




Fraction of J/ψ from χ_c decays

[CDF, PRL 79 (1997) 578] [LHCb, PLB 714 (2012) 215] [ATLAS, JHEP 07 (2014) 154]

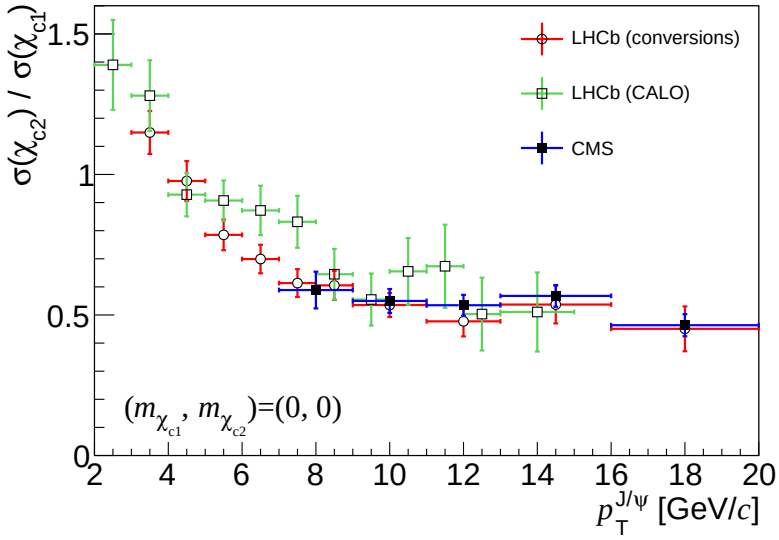
- Big fraction of J/ψ from feed-down of χ_c

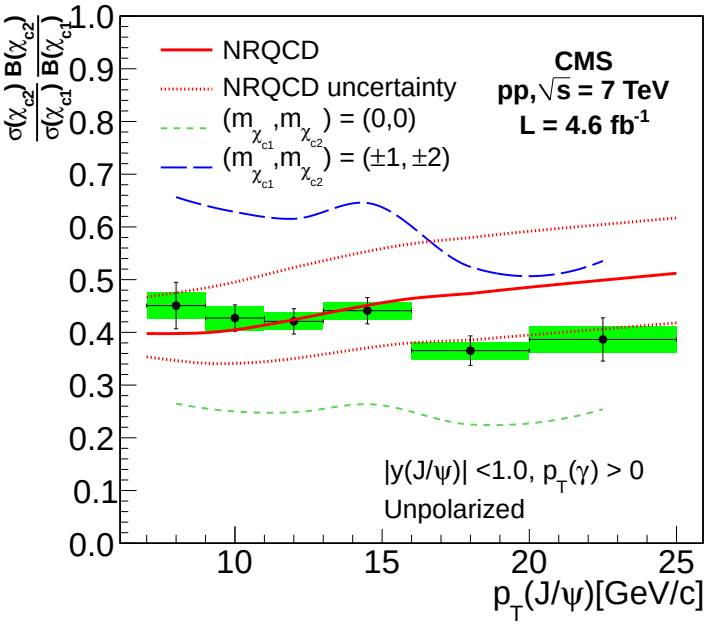


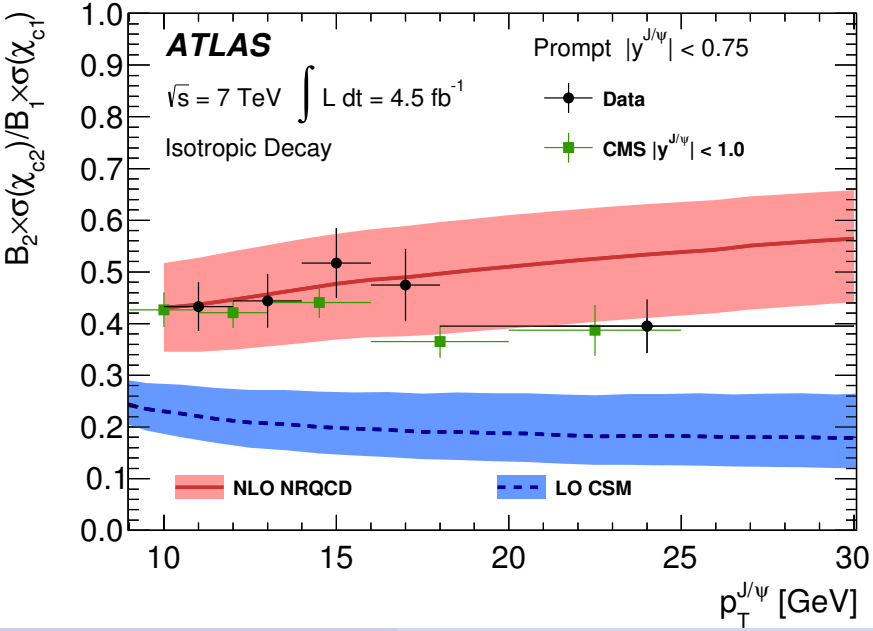
Ratio of χ_{c2} to χ_{c1}

[CMS, EPJC 72 (2012) 2251] [LHCb, PLB 714 (2012) 215, JHEP 10 (2013) 115] [ATLAS, JHEP 07 (2014) 154]

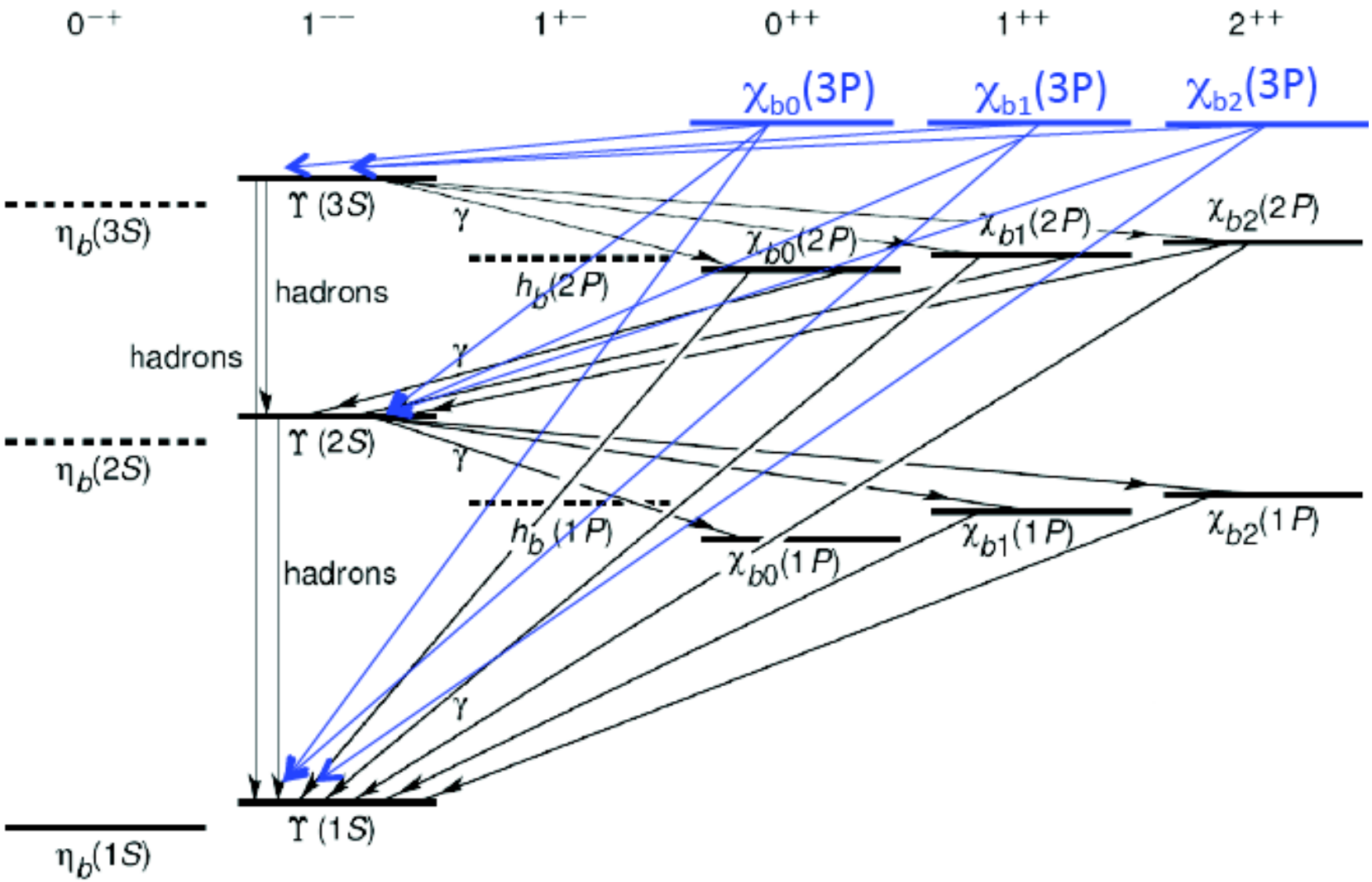
- Assume χ_c are unpolarized
- Big uncertainty due to unknown polarization
- Ratio not consistent with simple spin counting, 5/3







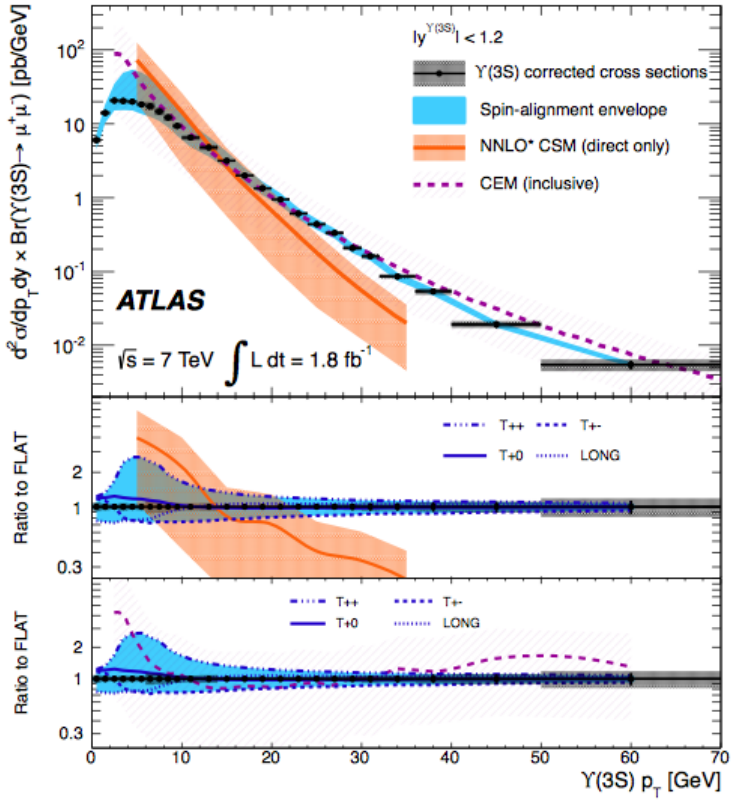
Bottomonium

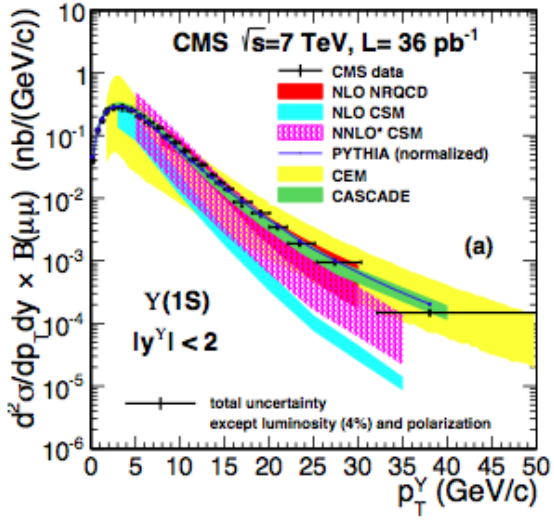


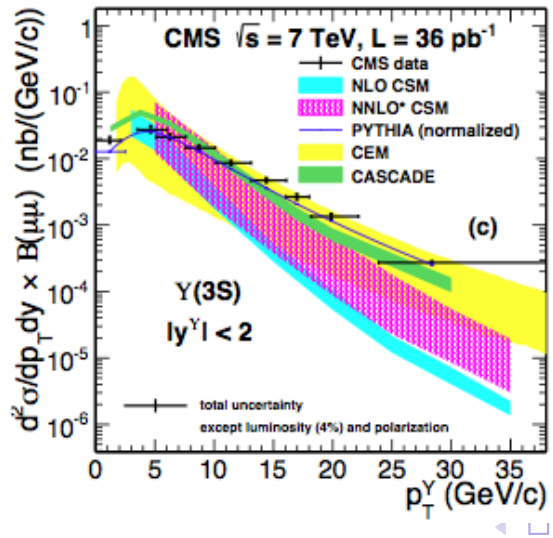
ϒ production

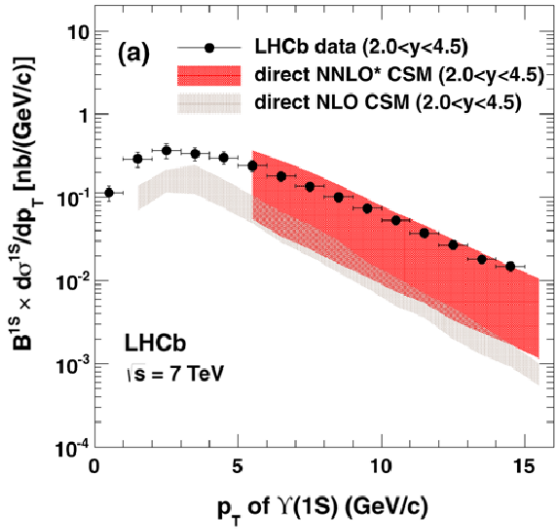
[ATLAS, PRD 87 (2013) 052004] [CMS, PLB 727 (2013) 101] [LHCb, EPJC 72 (2012) 12]

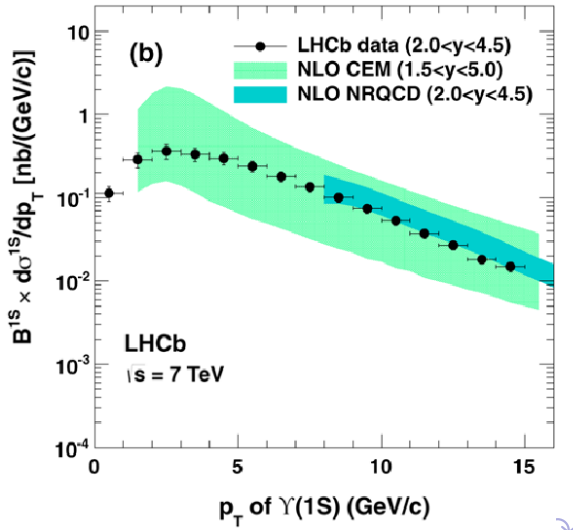
- Good agreement between data and theoretical predictions







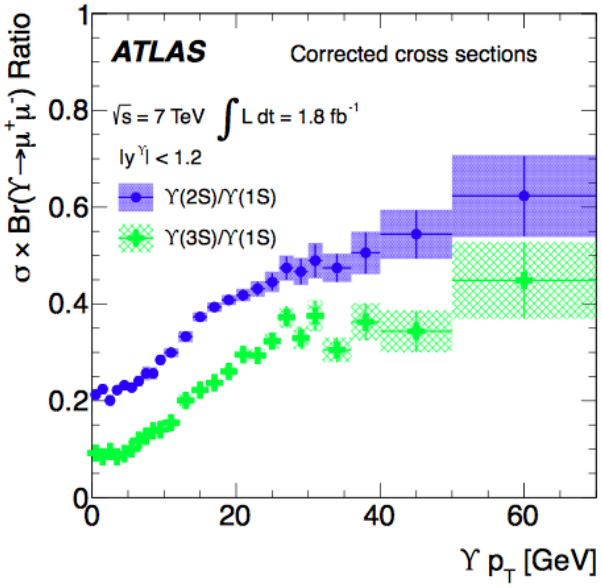


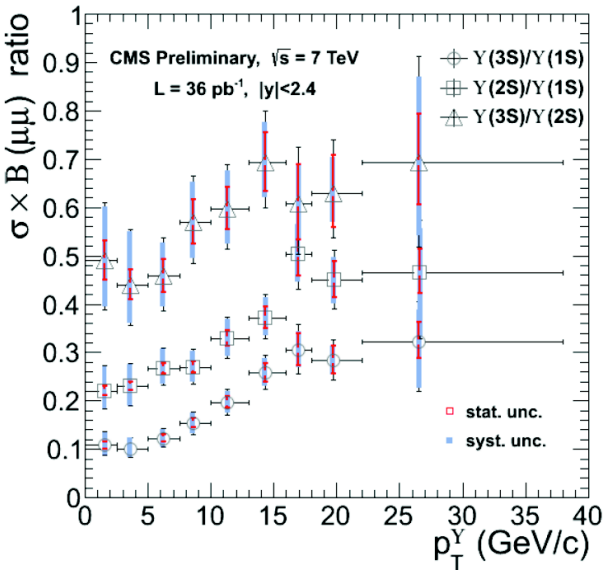


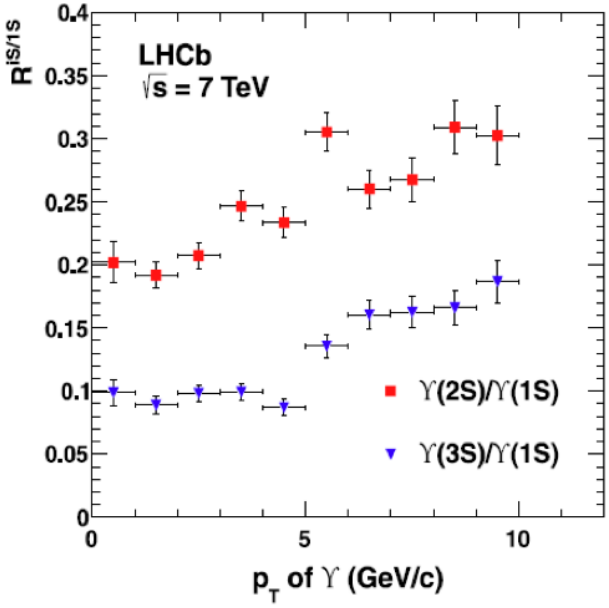
Ratio of ϒs cross-section

[ATLAS, PRD 87 (2013) 052004] [CMS, PLB 727 (2013) 101] [LHCb, EPJC 72 (2012) 12]

- Clear dependence on p_{T}, due to feed-down?



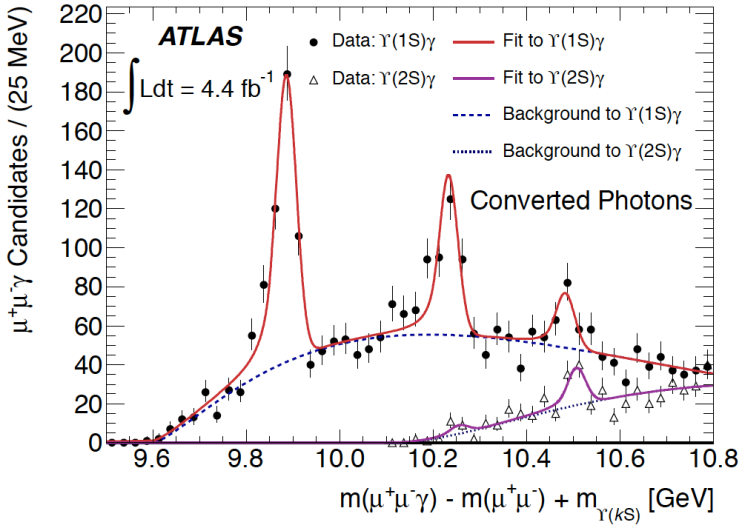




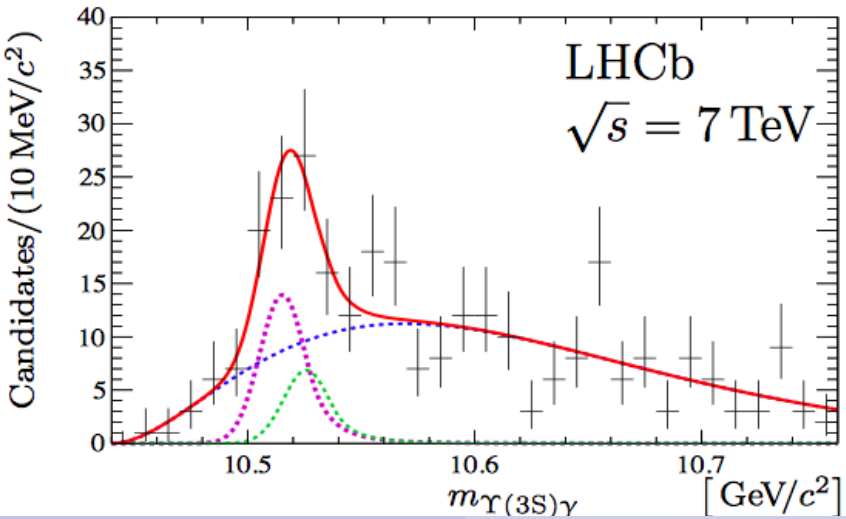
χ_b

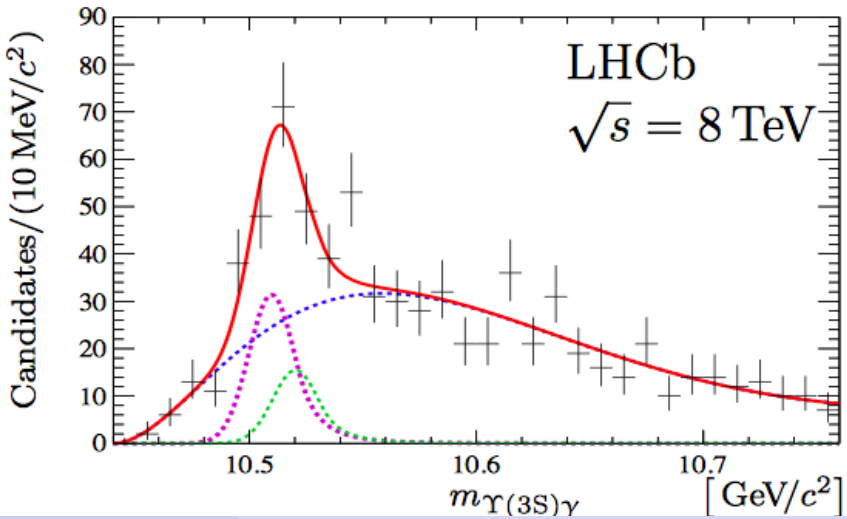
- Observation of $\chi_b(3P)$ states

[ATLAS, PRL 108 (2012) 152001] [LHCb, arXiv:1407.7734]



- LHCb also observed $\chi_b(3P) \to \Upsilon(3S)\gamma$

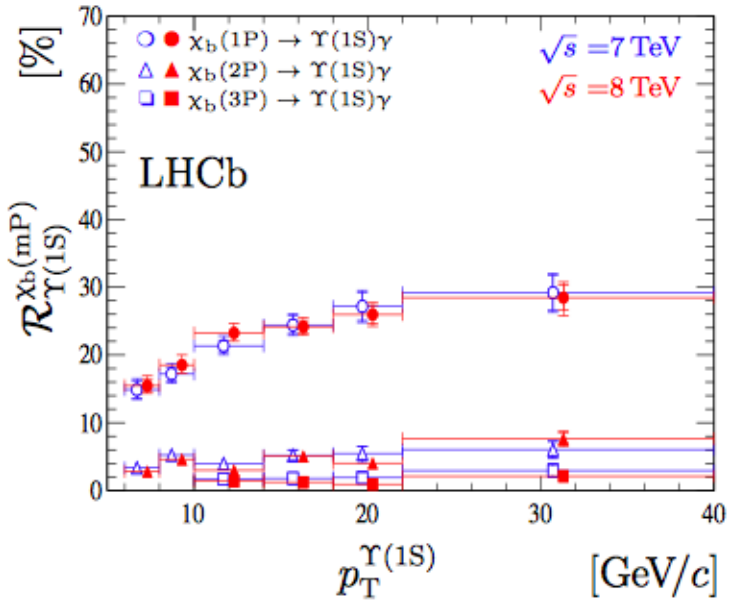


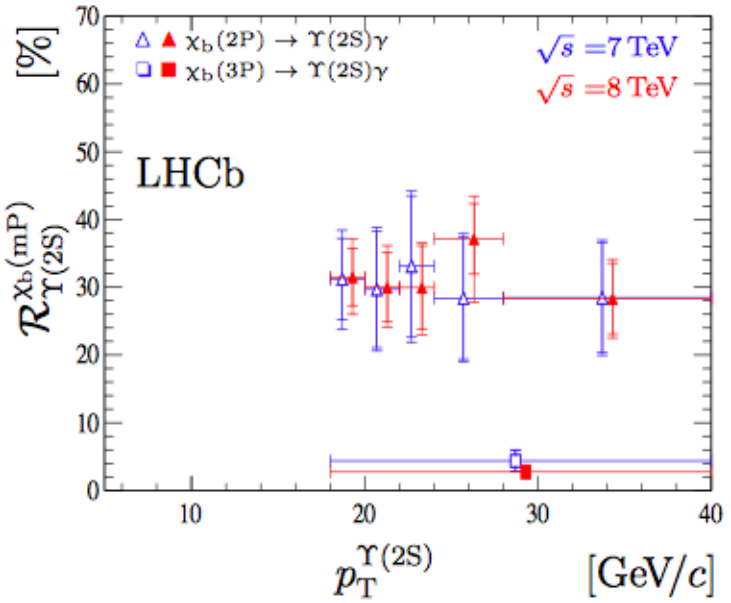


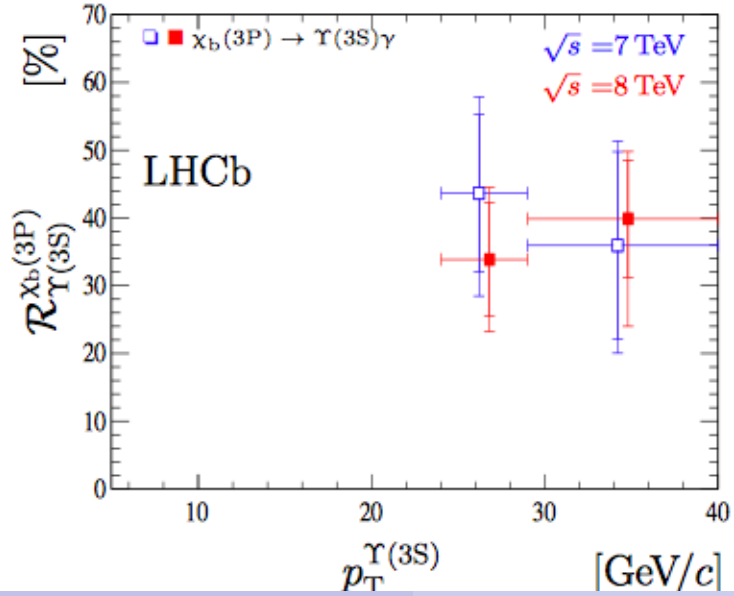
Fraction of Υ from χ_b decays

- Big fraction of Υ from feed-down of χ_b

[LHCb, arXiv:1407.7734]





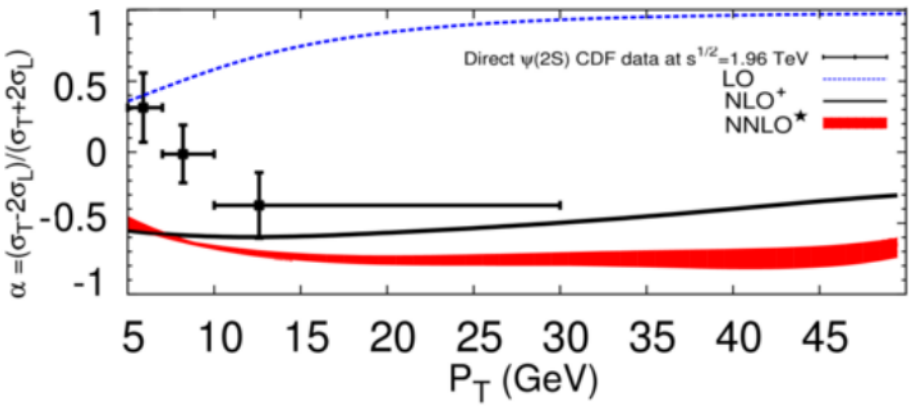


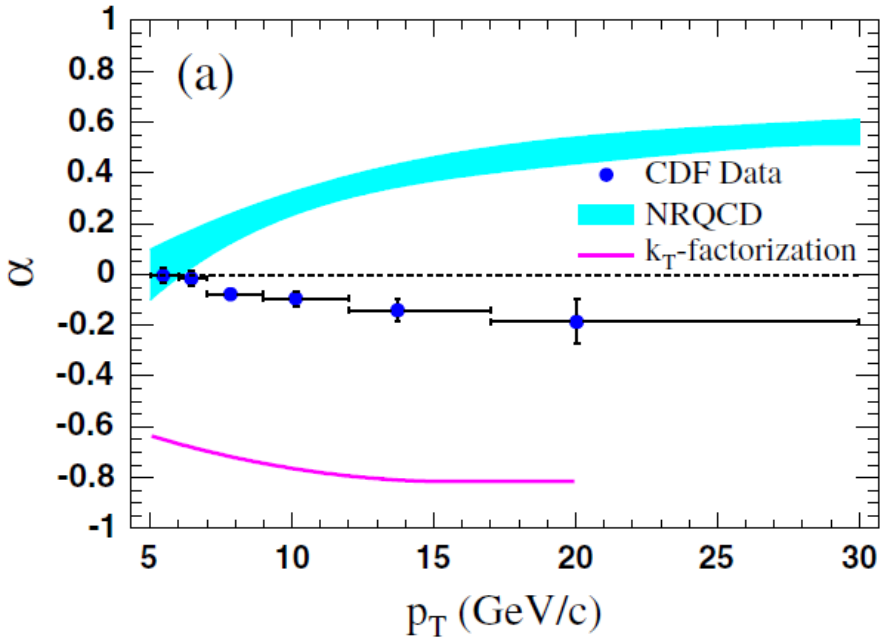
$\Upsilon(3S)$ NOT free from feed-down!

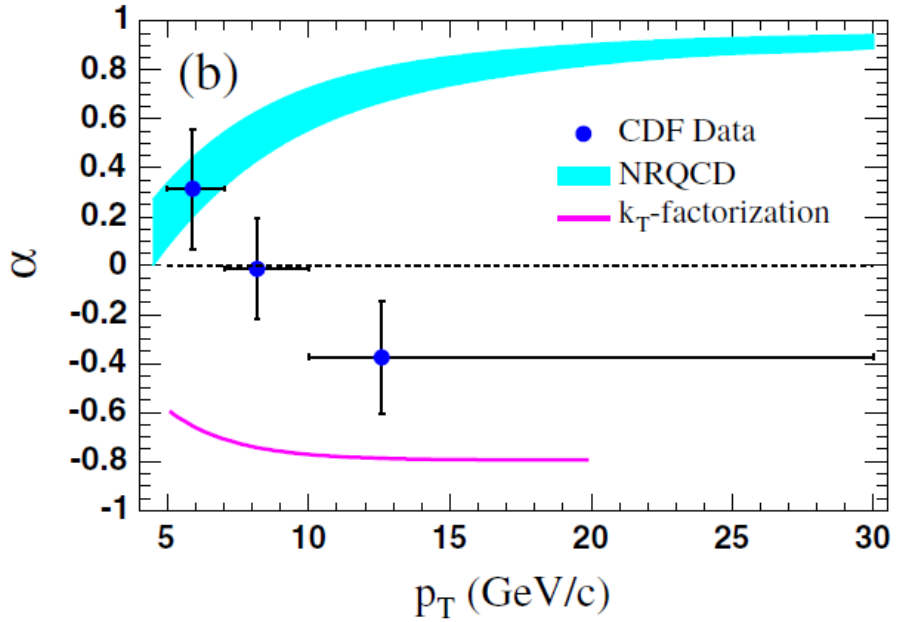
The ψ polarization puzzle

- NRQCD [Braaten, Kniehl & Lee, PRD 62, 094005 (2000)]
- CSM [Gong & Wang, PRL 100,232001 (2008)] [Artoisenet et al., PRL 101, 152001 (2008)]
- k_T fact. [Baranov, Phys. Rev. D 66, 114003 (2002)]

[CDF, PRL 99 (2007) 132001]

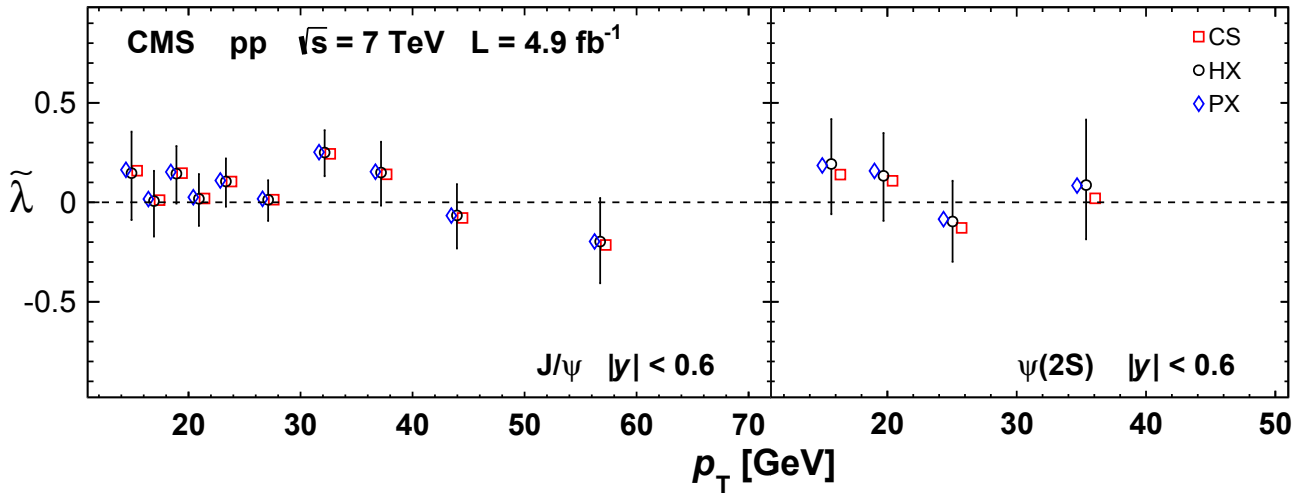






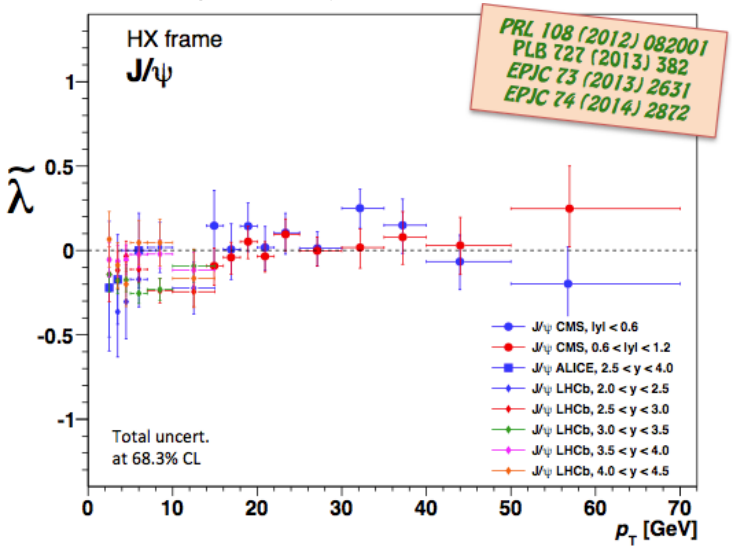
J/ψ and $\Upsilon(1S)$ polarization

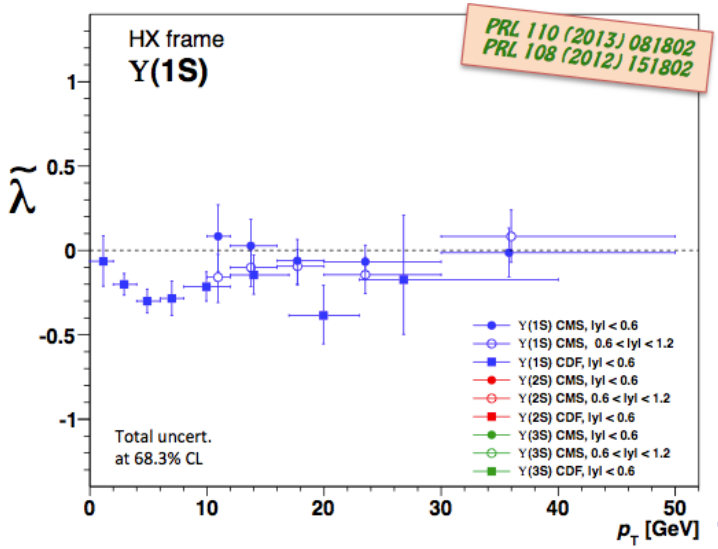
- Frame-invariant variable $\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$



- No sign of significant polarization in all measurements

Compilation by H.K. Wöhri

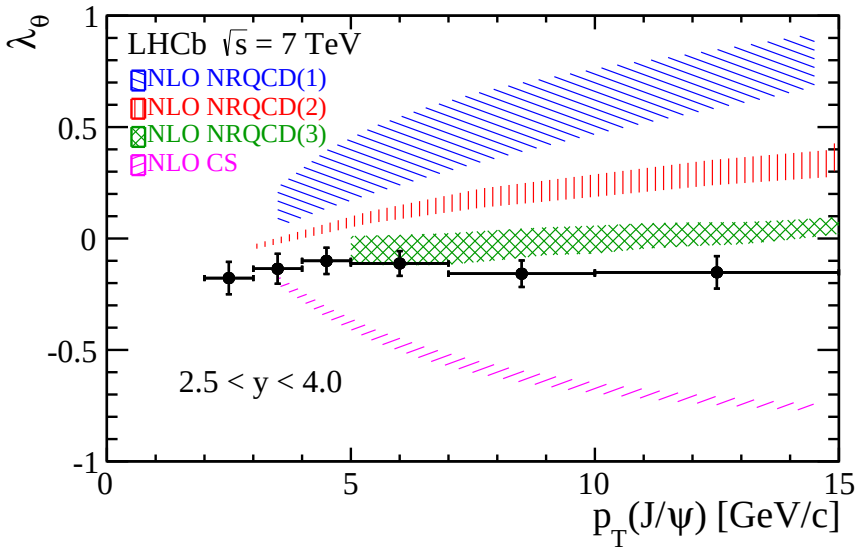


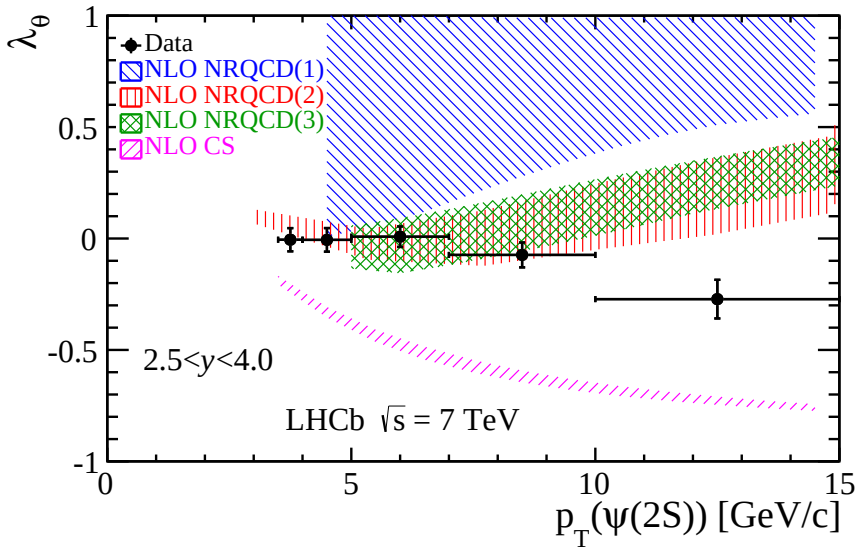


Polarization, comparisons with theo. predictions

[LHCb, EPJC 73 (2013) 2631, arXiv:1403.1339]

- NLO CSM disfavored
- NLO NRQCD calculations, different selections of experimental data to determine the non-perturbative matrix elements
  - NLO CS and NLO NRQCD(1) [M. Butenschoen and B. A. Kniehl, PRL 108 (2012) 172002]
  - NLO NRQCD(2) [B. Gong *et al.*, PRL 110 (2013) 042002]
  - NLO NRQCD(3) [K.-T. Chao *et al.*, PRL 108 (2012) 242004]
- Increasing polarization as p_T predicted by NLO NRQCD not supported by data

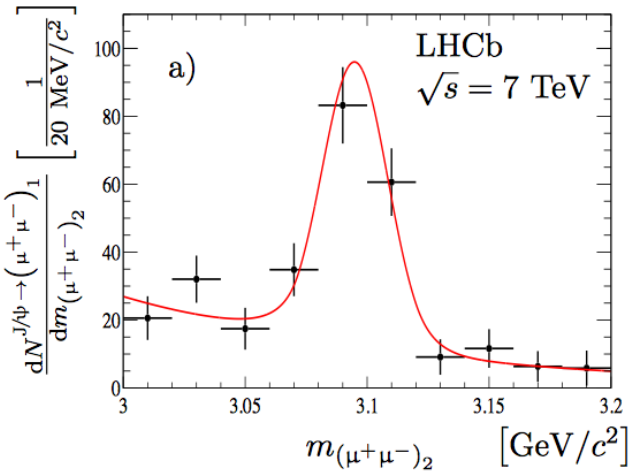


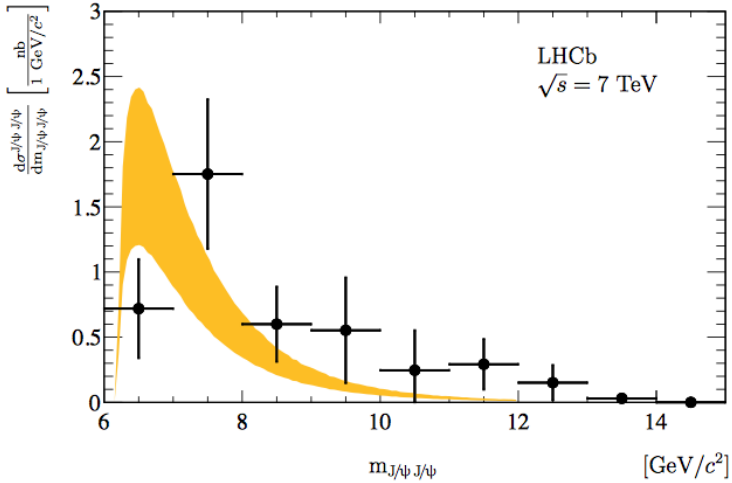


Double J/ψ production

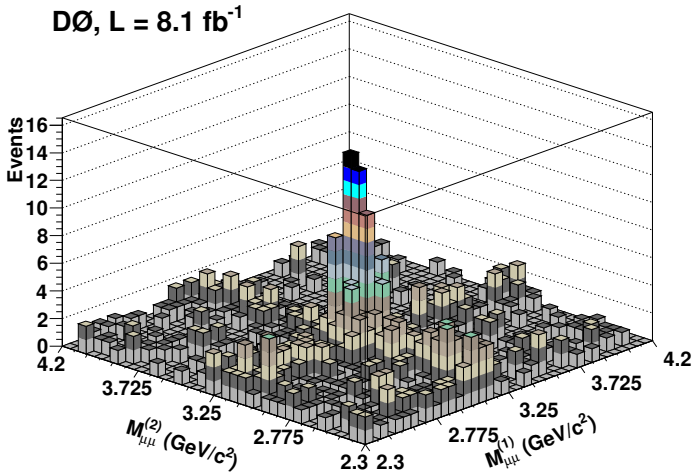
[LHCb, PLB 707 (2012) 52] [D0, arXiv:1406.2380]

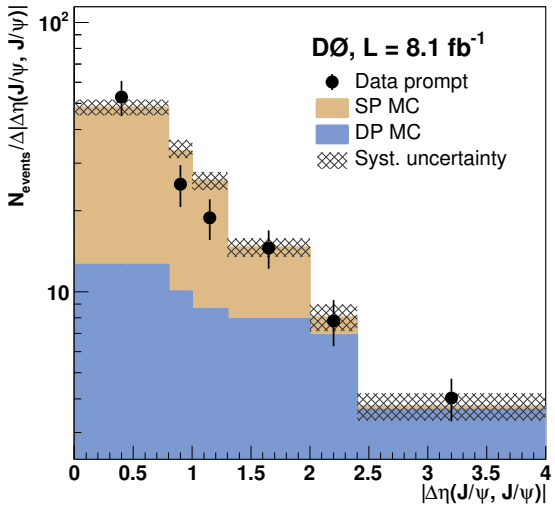
- Double J/ψ production observed by LHCb and D0





Both Single and Double particle scattering contribute, $f^{\mathrm{SP}} = 0.70 \pm 0.11$

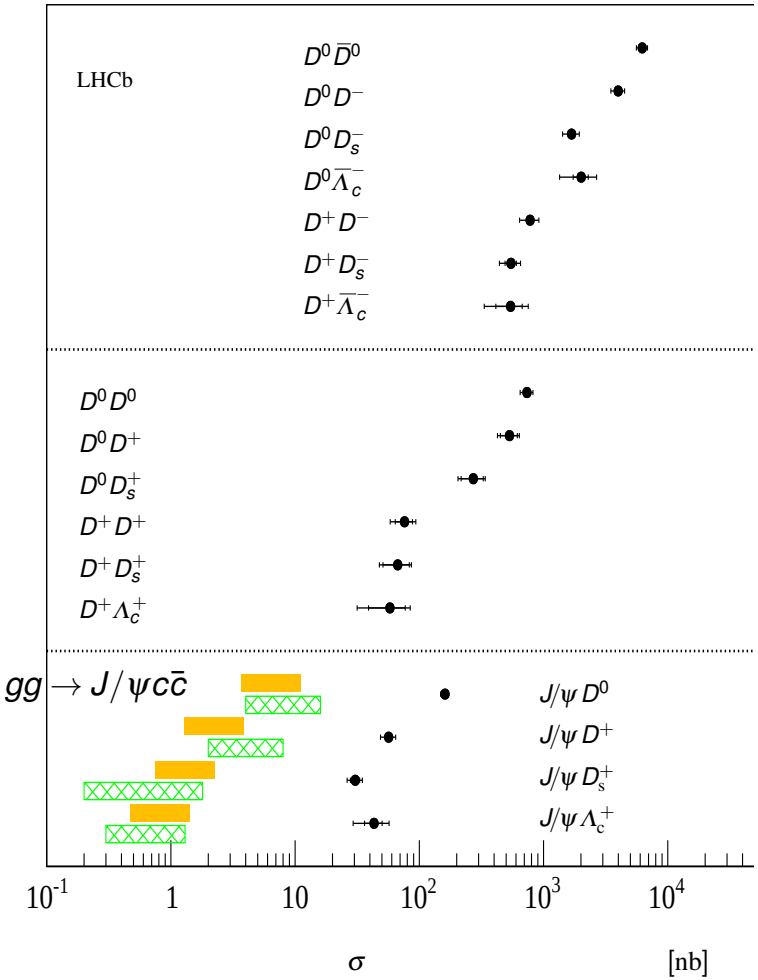


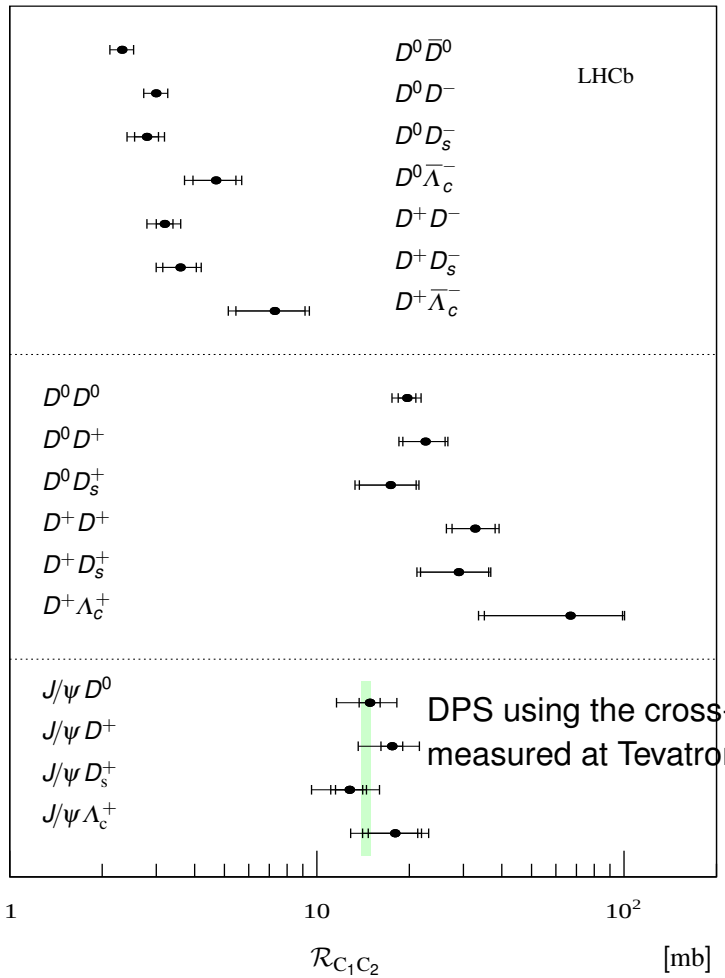


Double charm production

[LHCb, JHEP 06 (2012) 141]

- Double charm production observed, Double Parton Scattering (DPS) needed to explain measured cross-section



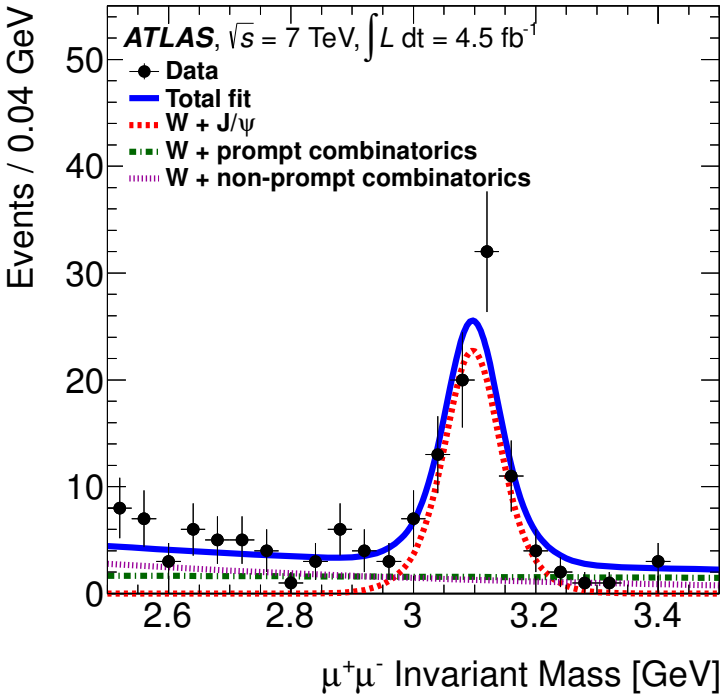


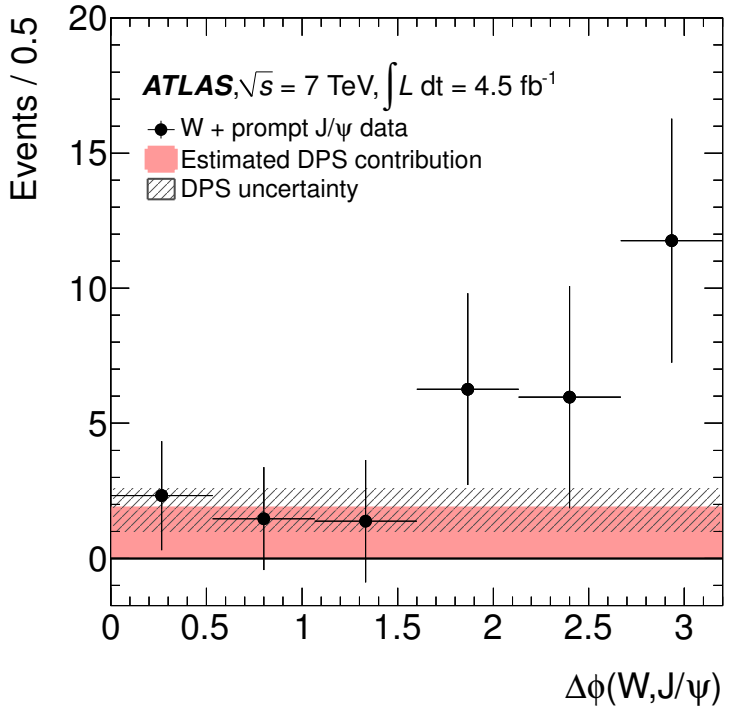
DPS using the cross-section measured at Tevatron for multi-jet events

$W + J/\psi$ associated production

[ATLAS, JHEP 04 (2014) 172]

- Dominated by CO? [B.A. Kniehl *et al.*, PRD 66 (2002) 114002] [G.Li *et al.*, PRD 83 (2011) 014001]
  CS contribution comparable [J.P. Lansberg and C. Lorce, PLB 726 (2013) 218]
- ATLAS observed $W + J/\psi$ associated production
  - DP: two interactions independent and uncorrelated?
  - Data suggest both SPS and DPS contributions
- More data needed to distinguish CS and CO to SPS, and to determine relative rates of SPS and DPS





Summary

- Big progress made on understanding the heavy quark(onium) hadroproduction
  - Production cross-section
  - Feed-down fraction for quarkonium
  - Polarization of quarkonium
  - ...
- New states, production observed
  - $\chi_b(3P)$
  - Double charm(onium) production
  - $W + J/\psi$ associated production
  - ...
- In general, theoretical predictions describe data well. However,
  - Possible to reduce theoretical uncertainty, e.g., due to scales?
  - Polarization of quarkonium...
  - Heavy quark production cross-section at high p_{T}...