

# Heavy quark production

Jibo HE

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

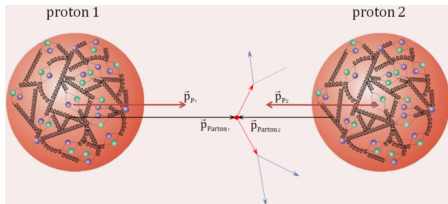
CERN

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

- 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

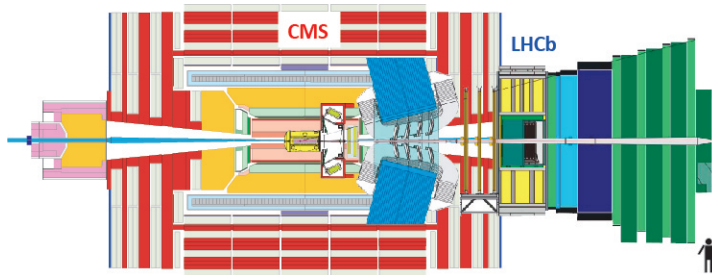
- Measurements of heavy quark(onium) production provide important tests of QCD
  - ▶ Parton distribution function (PDF)
  - ▶ Hard parton scattering
  - ▶ Fragmentation



- 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

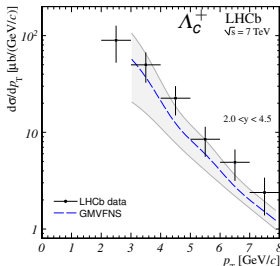
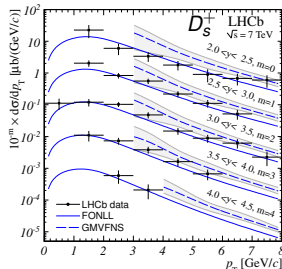
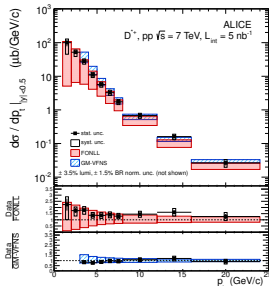
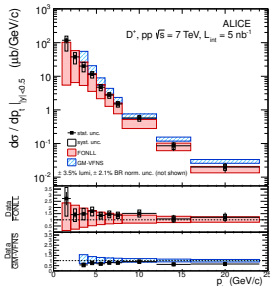
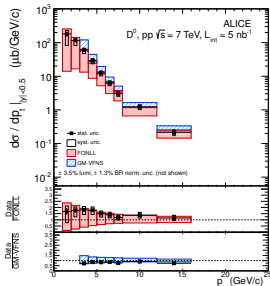


# Charm production

# Open charm production @ 7 TeV

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

- With exclusive decays, in good agreement with theo.

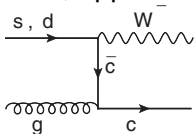


FONLL:  
Fixed Order + Next-to-Leading Log  
[M. Cacciari *et al.*, JHEP 10 (2012) 137]

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

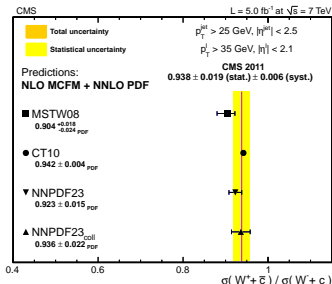
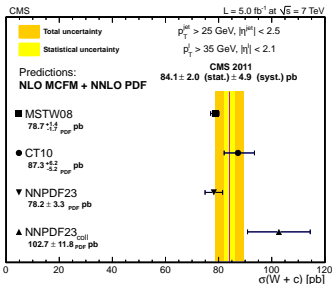
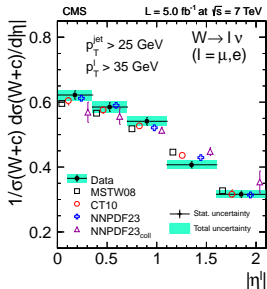
# Associated $W + c$ production

- Sensitive to  $s$ -quark PDF due to  $sg \rightarrow W^- + c$  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]



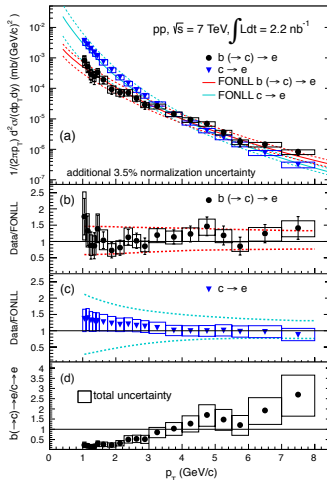
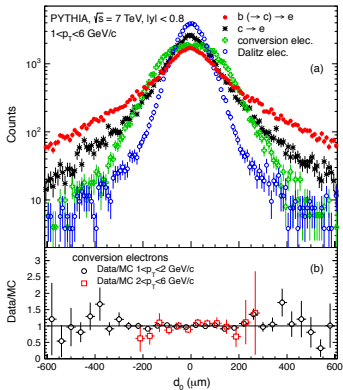
# Bottom production



# Bottom production using electron

[ALICE, PLB 721 (2013) 13]

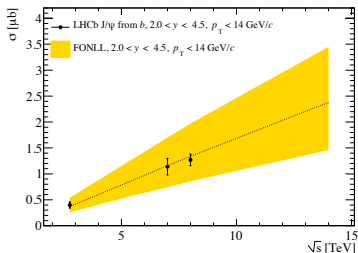
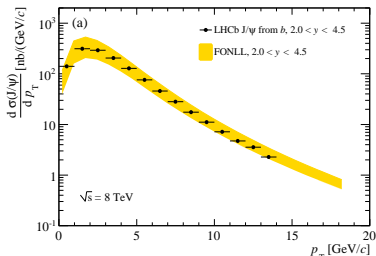
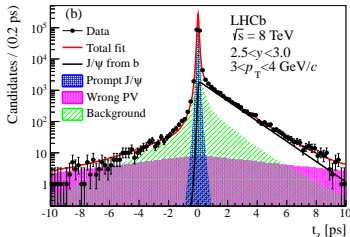
- Different sources of electrons separated using impact parameter
- Bottom and charm differential cross-section described well by FONLL prediction



# Bottom production using $J/\psi$

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

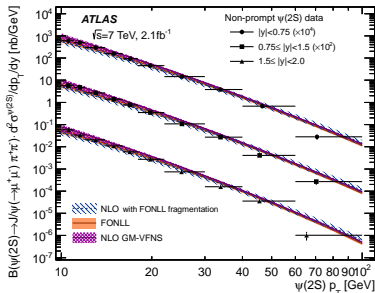
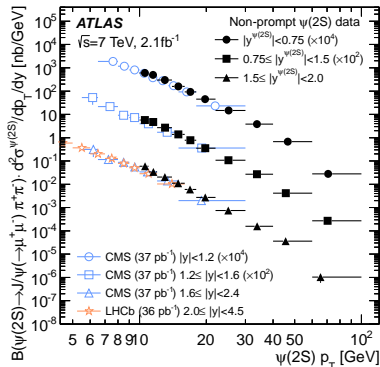
- LHCb measured bottom production using  $b \rightarrow J/\psi X$  at  $\sqrt{s} = 2.76$  and 8 TeV, apart from that at 7 TeV
- $b \rightarrow J/\psi X$  separated from prompt  $J/\psi$  using 
$$t_z = \frac{(z_{J/\psi} - z_{PV}) \times M_{J/\psi}}{p_z}$$
- Good agreements with FONLL



# Bottom production using $\psi(2S)$

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

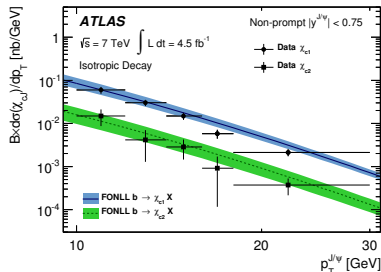
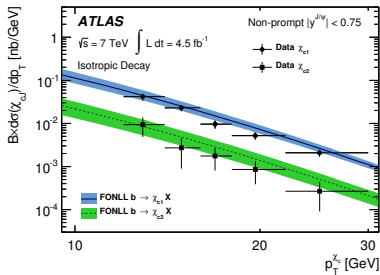
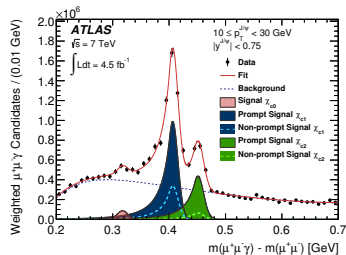
- ATLAS measured bottom production using  $b \rightarrow \psi(2S)X$  with  $\psi(2S) \rightarrow J/\psi(\mu\mu)\pi^+\pi^-$ , overlaid with CMS and LHCb results (note: different rapidity ranges)
- Compared to NLO, FONLL & GM-VFNS, discrepancy at high  $p_T$ ?



# Bottom production using $\chi_c$

[ATLAS, JHEP 07 (2014) 154]

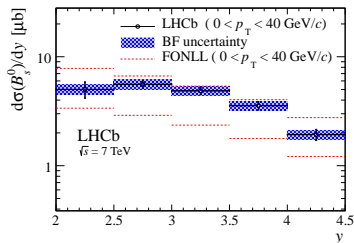
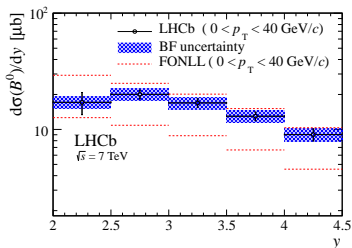
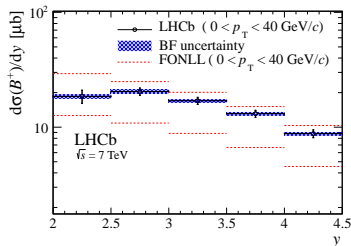
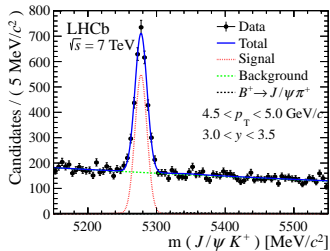
- ATLAS measured bottom production using  $b \rightarrow \chi_c X$  with  $\chi_c \rightarrow J/\psi(\mu\mu)\gamma(e^+e^-)$



# $b$ meson production

[LHCb, JHEP 08 (2013) 117]

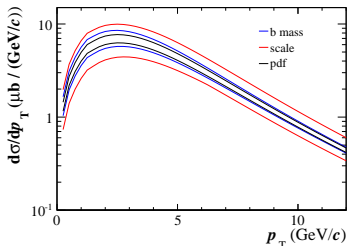
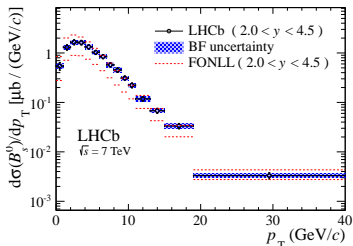
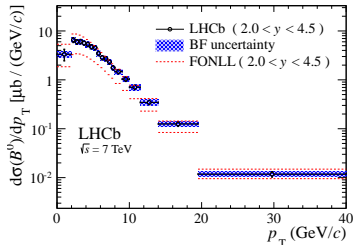
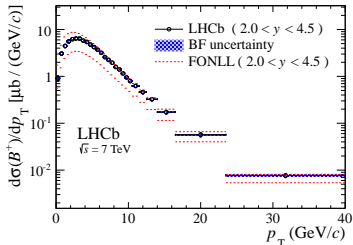
- LHCb measured  $B^+ \rightarrow J/\psi K^+$ ,  $B^0 \rightarrow J/\psi K^{*0}$ , and  $B_S^0 \rightarrow J/\psi \phi$  production for  $2 < y(B) < 4.5$ , in agreement with FONLL



# $b$ meson production (cont.)

[LHCb, JHEP 08 (2013) 117]

- $d\sigma/dp_T$ , good agreement with FONLL
- Theo. uncertainty includes  $m_b$ ,  $\mu_R$ ,  $\mu_F$  and PDF

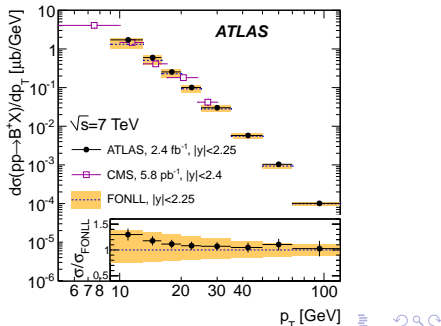
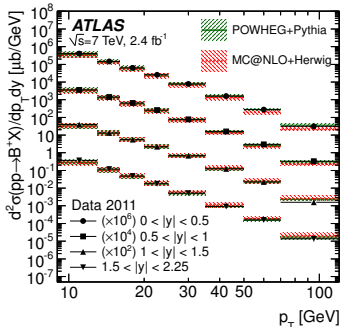
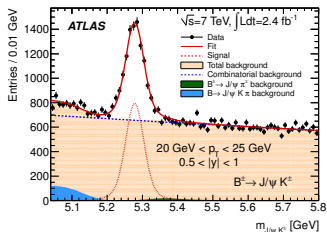


# $B^+$ production by ATLAS

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

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

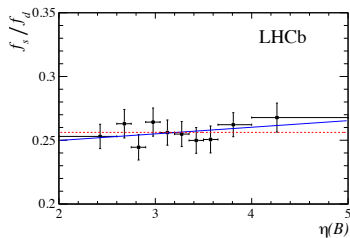
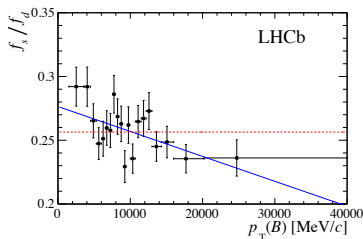
[M. Cacciari et al., JHEP 10 (2012) 137]



# Fragmentation fraction ratio $f_s/f_d$

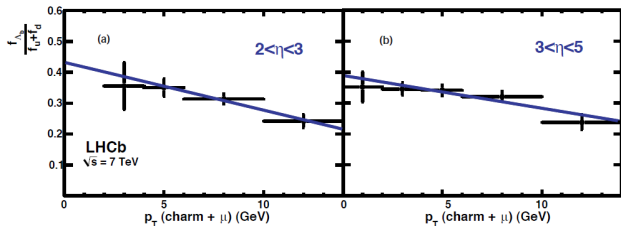
[LHCb, JHEP 04 (2013) 001]

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

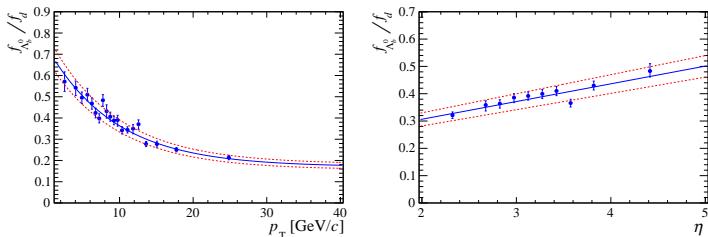




- With  $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \bar{\nu} X$ , dependence on  $p_T$



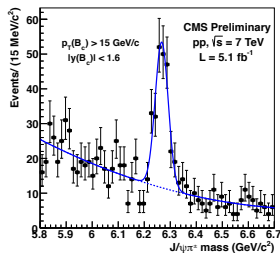
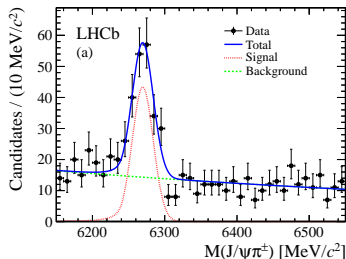
- With  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ , dependence on both  $p_T$  and  $\eta$



# $B_c^+$ production

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

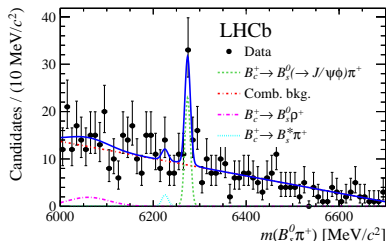
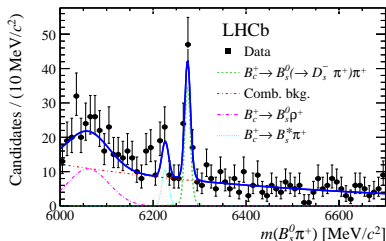
- Production at  $\sqrt{s}=1.96$  TeV,  $\frac{\sigma(B_c^+) \times \mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu)}{\sigma(B^+) \times \mathcal{B}(B^+ \rightarrow J/\psi K^+)}$   
 $= 0.211 \pm 0.012_{-0.020}^{+0.021}$  for  $p_T(B) > 6$  GeV/c and  $|y| < 0.6$  by CDF
- Production at  $\sqrt{s}=7$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



# $B_c^+$ production (cont.)

[LHCb, PRL 111 (2013) 181801]

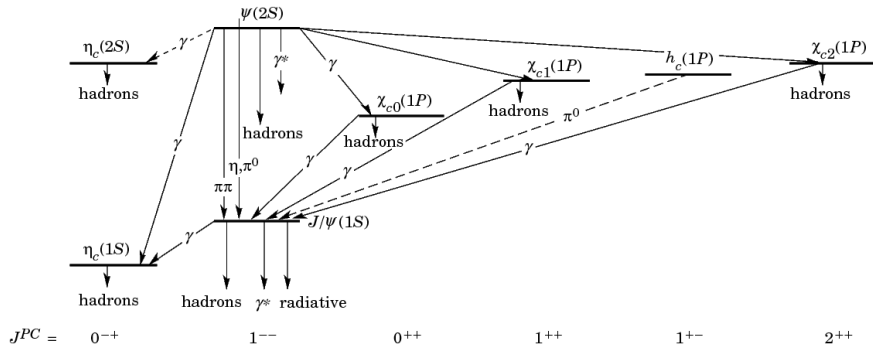
- LHCb measured  $\frac{f_c}{f_s} \cdot \mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+)$  using 2011 + 2012 data, for  $2 < \eta(B) < 5$ .
- Measured with  $B_s^0 \rightarrow D_s^- \pi^+$  and  $B_s^0 \rightarrow J/\psi \phi$  independently, results consistent with each other
- Combined results  
$$\frac{f_c}{f_s} \cdot \mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+) = \left( 2.37 \pm 0.31 \pm 0.11^{+0.17}_{-0.12} (\tau_{B_c^+}) \right) \times 10^{-3}$$



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

# Quarkonium production

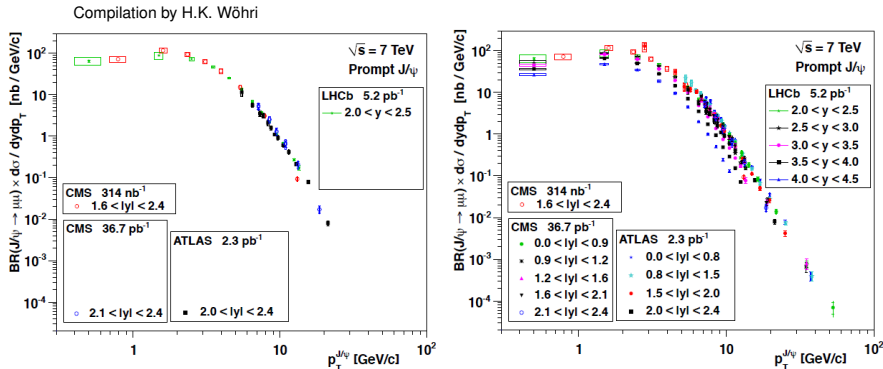
# Charmonium



# Prompt $J/\psi$ differential cross-section

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

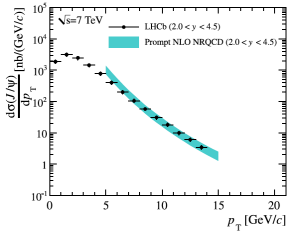
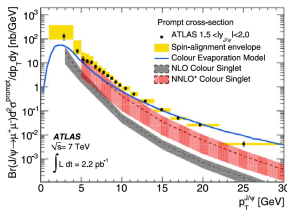
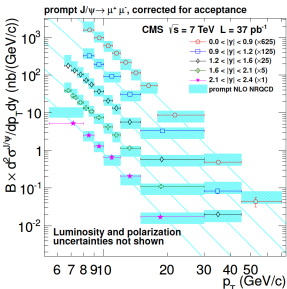
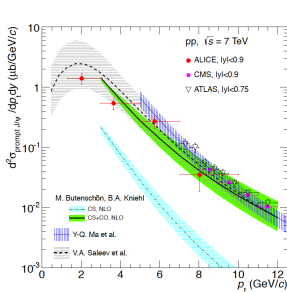
## ● Results of three experiments agree well



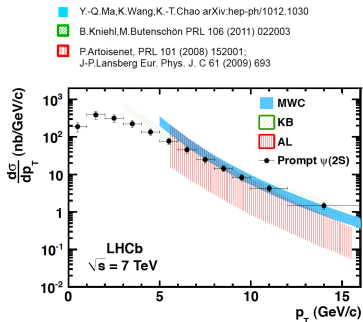
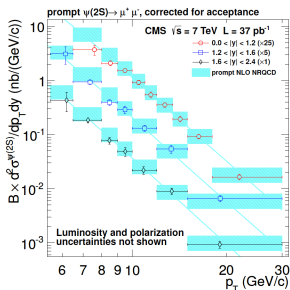
# Prompt $J/\psi$ , compare with theo.

[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



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

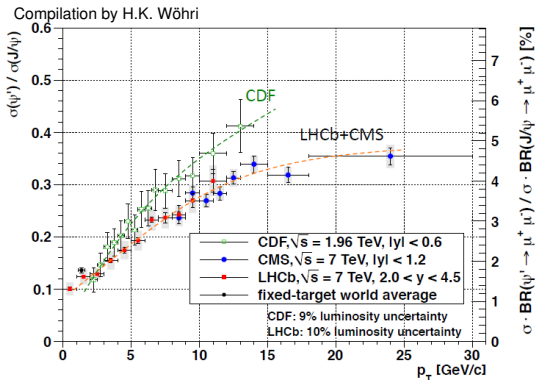




# Ratio of prompt $\psi(2S)$ to $J/\psi$

[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

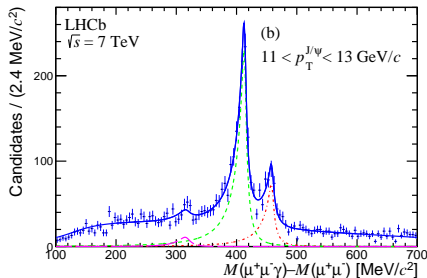
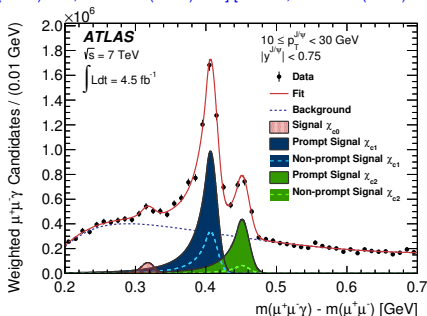
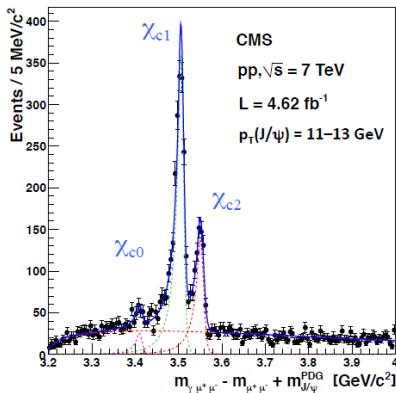


Note: the lines do not represent any theoretical model;  
they are added to help guiding the eye through the points

# $\chi_c$ production

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

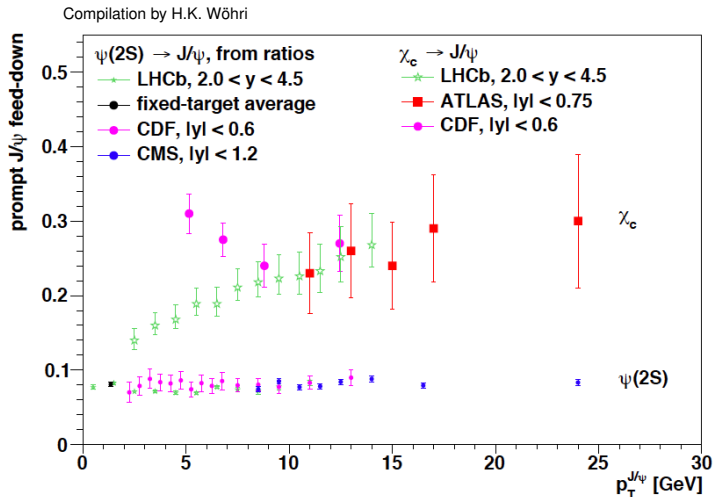
- Using  $\chi_c \rightarrow J/\psi \gamma$ , with  $\gamma \rightarrow e^+ e^-$ . Good resolution,  $\chi_c$ 's peaks are separated



# Fraction of $J/\psi$ from $\chi_c$ decays

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

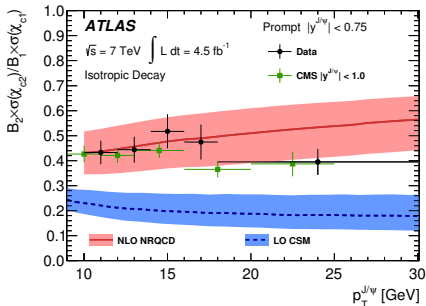
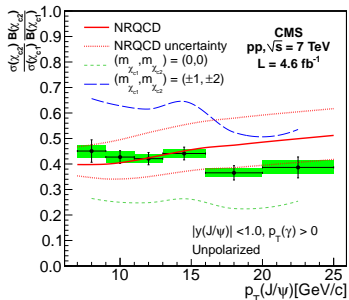
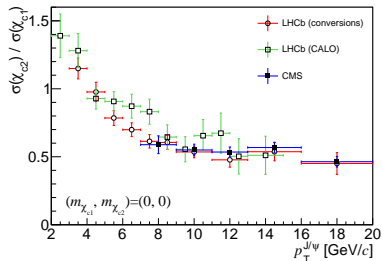
- Big fraction of  $J/\psi$  from feed-down of  $\chi_c$



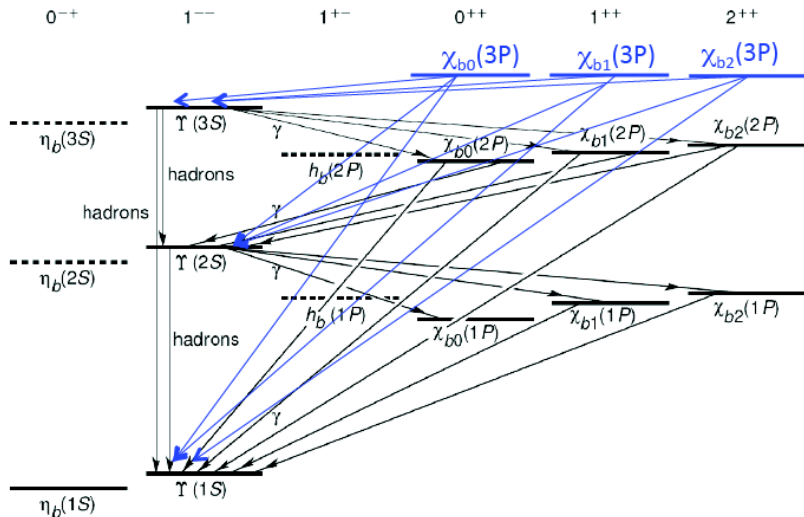
# Ratio of $\chi_{c2}$ to $\chi_{c1}$

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

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



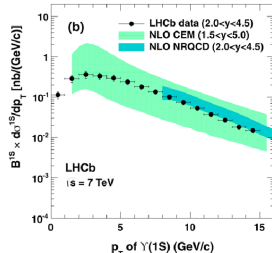
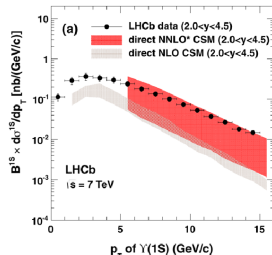
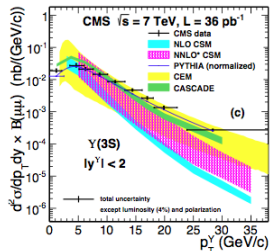
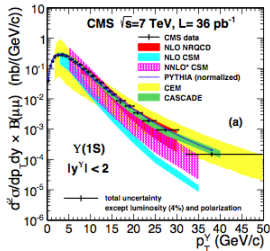
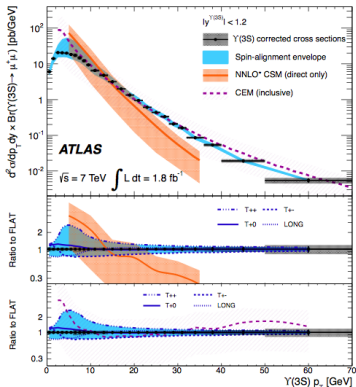
# Bottomonium



# $\Upsilon$ production

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

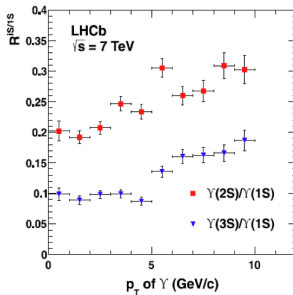
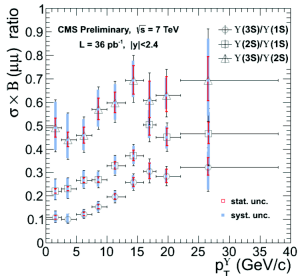
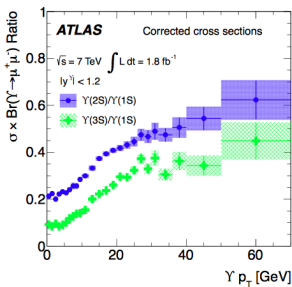
- Good agreement between data and theoretical predictions



# Ratio of $\Upsilon$ 's cross-section

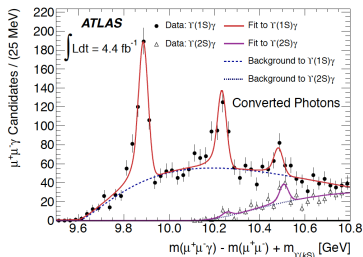
[ATLAS, PRD 87 (2013) 052004] [CMS, PLB 727 (2013) 101] [LHCb, EPJC 72 (2012) 12]

- Clear dependence on  $p_T$ , due to feed-down?

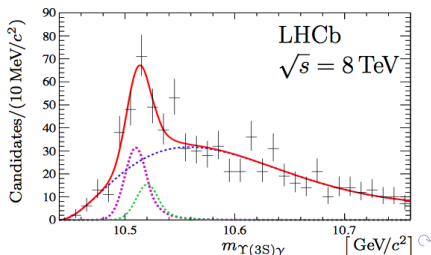
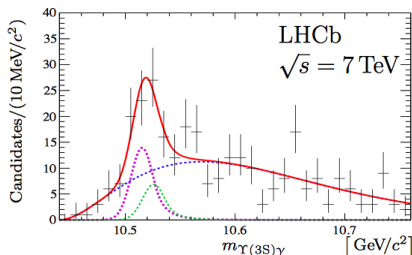


- Observation of  $\chi_b(3P)$  states

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



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

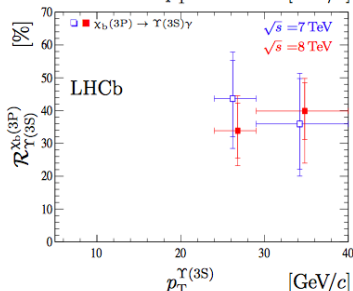
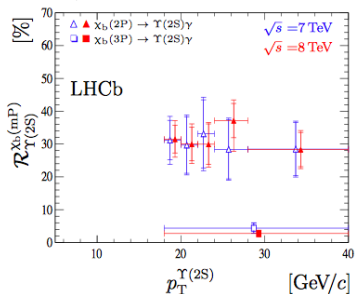
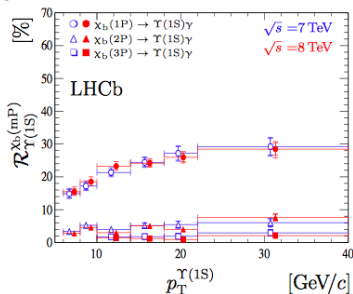




# Fraction of $\Upsilon$ from $\chi_b$ decays

[LHCb, arXiv:1407.7734]

- Big fraction of  $\Upsilon$  from feed-down of  $\chi_b$

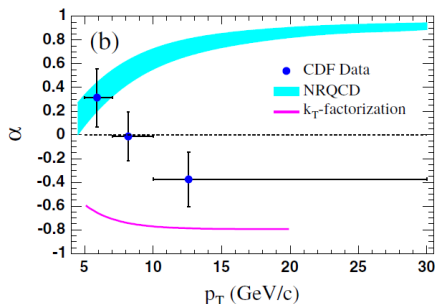
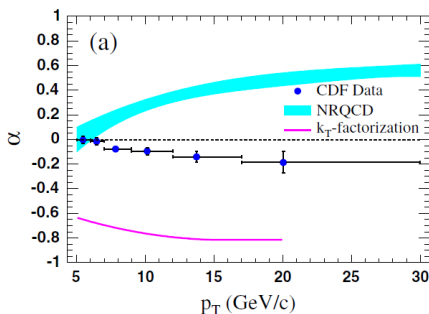
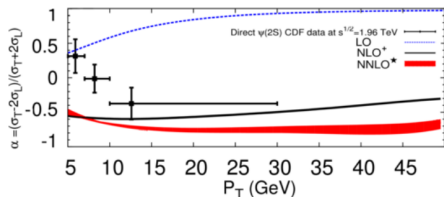


$\Upsilon(3S)$  NOT free from feed-down!

# The $\psi$ polarization puzzle

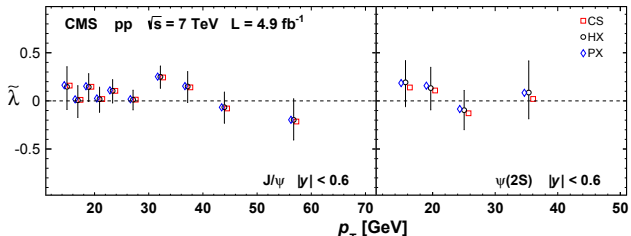
[CDF, PRL 99 (2007) 132001]

- 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)]



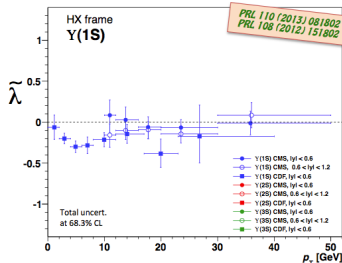
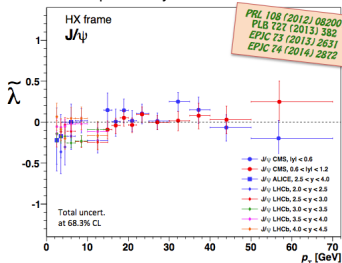
# $J/\psi$ and $\Upsilon(1S)$ polarization

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



- No sign of significant polarization in all measurements

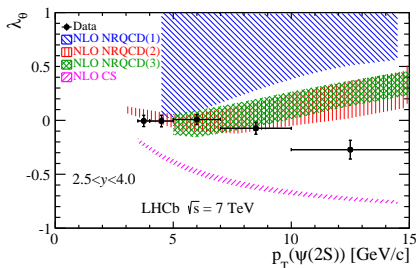
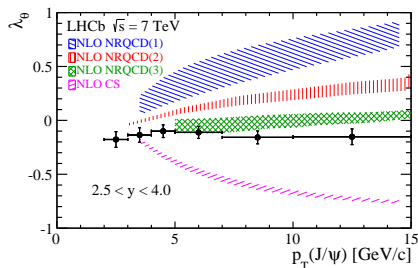
Compilation by H.K. Wöhri



# Polarization, comparisons with theo. predictions

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

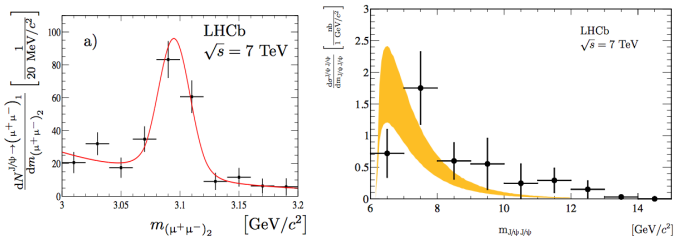
- NLO CSM disfavored
- NLO NRQCD calculations, different selections of experimental data to determine the non-perturbative matrix elements
  - ▶ NLO CS and NLO NRQCD(1) [M. Butenschoen and B. A. Kniehl, PRL 108 (2012) 172002]
  - ▶ NLO NRQCD(2) [B. Gong *et al.*, PRL 110 (2013) 042002]
  - ▶ NLO NRQCD(3)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



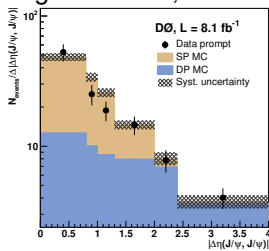
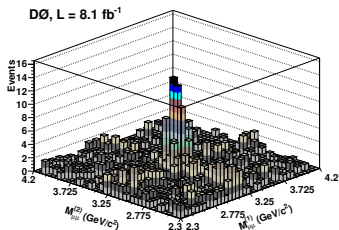
# Double $J/\psi$ production

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

- Double  $J/\psi$  production observed by LHCb and D0



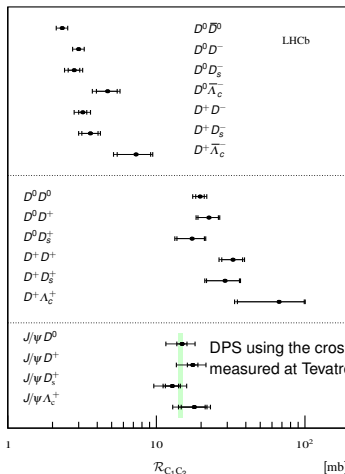
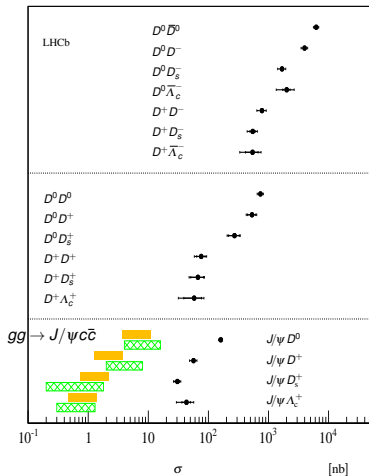
Both Single and Double particle scattering contribute,  $f^{\text{SP}} = 0.70 \pm 0.11$



# Double charm production

[LHCb, JHEP 06 (2012) 141]

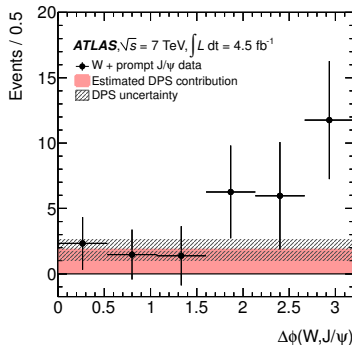
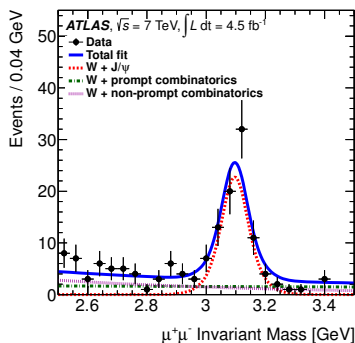
- Double charm production observed, Double Parton Scattering (DPS) needed to explain measured cross-section



# $W + J/\psi$ 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  $p_T$ ...