Quarkonium Production at LHCb

On behalf of the LHCb collaboration

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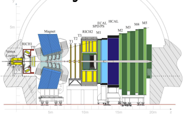
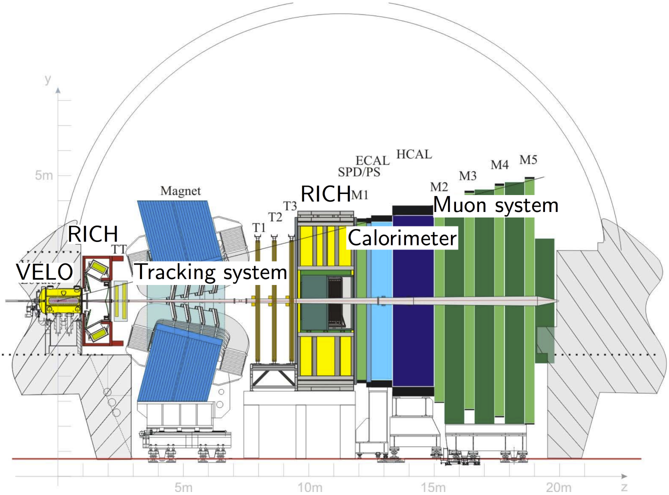


Motivation

- Quarkonia production is an ideal testing ground for QCD.
- Described by NRQCD:
  - Perturbative short distance process.
  - Non-perturbative long distance process.
  - Colour octet (CO) and colour singlet (CS) models.
- Other production models include colour evaporation model (CEM).
- Role of double parton scattering (DPS).
- Models of production cannot describe both the kinematics and polarisation.
- More data from LHC on quarkonia production and polarisation required.

The LHCb Spectrometer

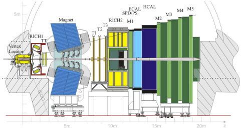


- JINST 3 (2008) S08005

The LHCb Experiment

- LHCb is particularly suited for the study of quarkonium:
  - Excellent separation of primary and secondary vertices.
  - Excellent μ reconstruction and PID.
  - Excellent momentum and mass resolution.
  - Large production cross-sections.
  - Low p_T triggers, e.g. for μ triggers typically used for quarkonium:
    - 1μ: $p_T > 1.8$ GeV/c
    - 2μ: $p_T > 0.56$ GeV/c; $p_T > 0.48$ GeV/c
  - Rapidity complementary to ATLAS and CMS: $2 < y < 4.5$.
- Unless stated all results presented are at 7 TeV.

Year	√s (TeV)	Int. Lumi.
2010	7	36 pb^{-1}
2011	2.76	71 nb^{-1}
2011	7	1 fb^{-1}
2012	8	2.1 fb^{-1}

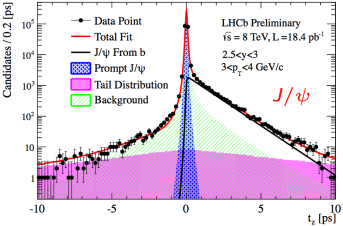


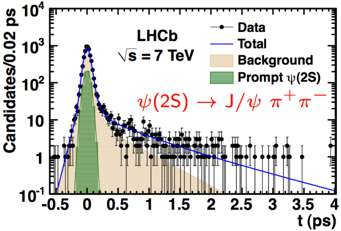
- LHCb-CONF-2010-013

Prompt Charmonium

- $J/\psi \to \mu^+\mu^-$ (5.2 pb^{-1}).
- $\psi(2S) \to \mu^+\mu^-$ and $\psi(2S) \to J/\psi\ \pi^+\pi^-$ (36 pb^{-1}).
- Prompt: produced in PV or from feed-down.
- Separate prompt component exploiting pseudo proper time.

$$t_z = \frac{(z_{J/\psi} - z_{PV}) \times M_{J/\psi}}{p_z} \quad (1)$$

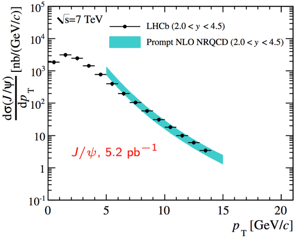


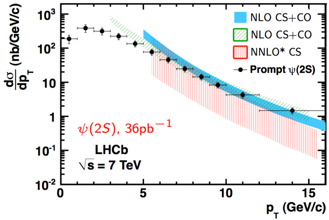


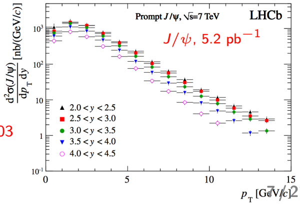
- J/ψ: EPJ C71(2011) 1645
- $\psi(2S)$: EPJ C72(2012) 2100

Prompt Charmonium

- Unknown polarisation significantly affects accept & reco efficiencies.
- Calculate for unpolarised, longitudinal and transverse polarisation.
- $\sigma(J/\psi_{prompt} = 10.52 \pm 0.04(\text{stat}) \pm 1.40\ (\text{syst})^{+1.64}_{-2.20}(\text{pol})\mu\text{b}.$
- Theory models p_T distribution well, especially CO models.



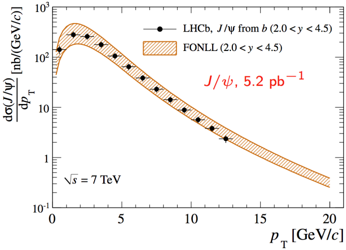


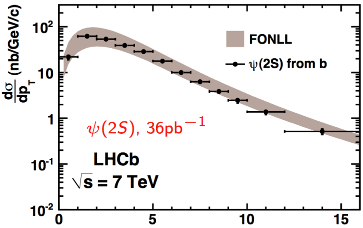


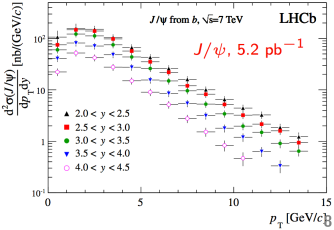
- NNLO CS: P. Artoisenet et al. PRL (2008)152001
- NNLO CS: J.-P. Lansberg, EPJ C61 (2009)693.
- NLO CS+CO (blue): Y.-Q. Ma et al. PRD 84(2011)114001
- NLO CS+CO (green): B. Kniehl et al. PRL 106(2011)022003

Non-Prompt Charmonium

- Non-prompt J/ψ and $\psi(2S)$ from B hadrons.
- FONLL is in good agreement with results.



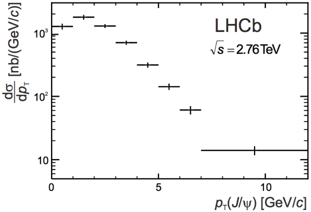




- FONLL: M.Cacciari et al; JHEP 05 (1998) 007
- FONLL: M.Cacciari et al; CERN-PH-TH/2011-227

Charmonium at 2.76 TeV

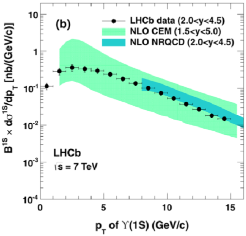
- J/ψ, $p_T < 12$ GeV, $2.0 < y < 4.5$ ($71\ \text{nb}^{-1}$).
- $\sigma_{J/\psi} = 5.6 \pm 0.1\ (\text{stat}) \pm 0.4\ (\text{syst})\ \mu\text{b}$.
- Good Agreement with ALICE $2.0 < y < 4.0$: $\sigma_{J/\psi} = 3.34 \pm 0.13\ (\text{stat}) \pm 0.53\ (\text{syst})\ \mu\text{b}$.
- $\sigma_{(J/\psi_{fromb})} = 400 \pm 35\ (\text{stat}) \pm 49\ (\text{syst})\ \text{nb}$.
- Good agreement with NLO prediction: $370^{+170}_{-110}\text{nb}$.

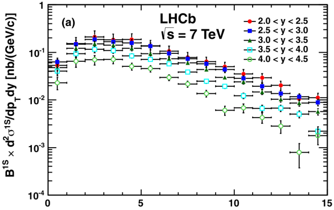


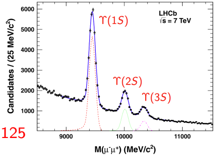
- J/ψ: LHCb-PAPER-2012-039
- ALICE Phys.Lett.B718(2012) 295
- NLO: M.Cacciari et al JHEP 10(2012) 137

Bottomonium

- $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ via decay to $\mu^+\mu^-$ (25 pb^{-1}):
  - $\sigma(pp \to (1S)X)xB(\Upsilon(1S) \to \mu^+\mu^-) = 2.29 \pm 0.01(\text{stat}) \pm 0.10(\text{syst})\ ^{+0.19}_{-0.037}(\text{pol})$ nb.
  - $\sigma(pp \to (2S)X)xB(\Upsilon(2S) \to \mu^+\mu^-) = 0.562 \pm 0.007(\text{stat}) \pm 0.023(\text{syst})\ ^{+0.048}_{-0.092}(\text{pol})$ nb.
  - $\sigma(pp \to (3S)X)xB(\Upsilon(3S) \to \mu^+\mu^-) = 0.283 \pm 0.005(\text{stat}) \pm 0.012(\text{syst})\ ^{+0.025}_{-0.048}(\text{pol})$ nb.
- Good agreement with theory



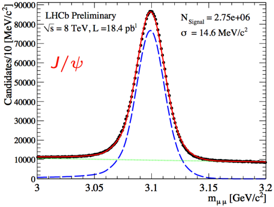


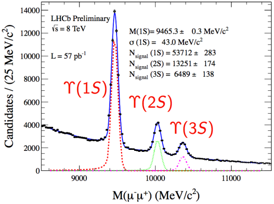


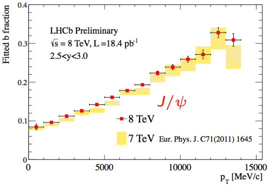
- ϒ: EPJ C72(2012) 2025
- CEM: Y.-Q. Ma et al. PRD 84 (2011) 114001
- NRQCD: A.D. Frawley et al. Phys.Rep. 462 (208) 125

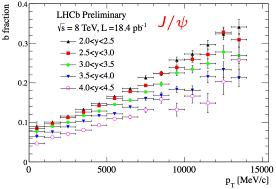
Charmonium and Bottomonium at 8 TeV

- LHCb performing well at 8 TeV.
- Cross-sections expected to increase by $\sim$ 10%.
- J/ψ and Υ ($57 pb^{-1}$).





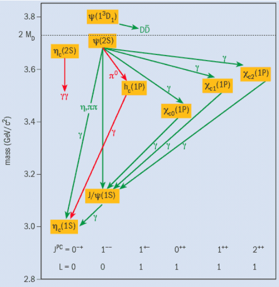


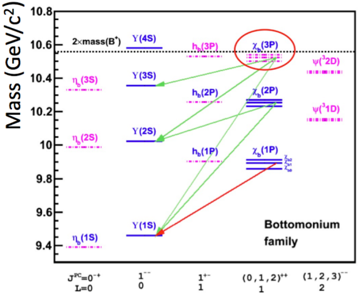


- LHCb-CONF-2012-025

P-wave Onia: Motivation

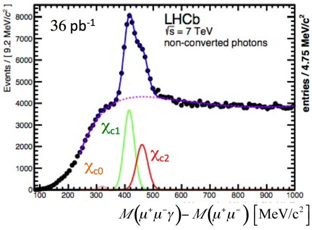
- χ_c and χ_b.
- Provide important tests of CS and CO production mechanisms:
  - ratios of $\chi_{c,bJ}$(J=0,1,2) spin states.
- Needed for polarisation measurements.
  - Feeddown fractions ($\chi_c \rightarrow J/\psi$, $\chi_b \rightarrow \Upsilon$).



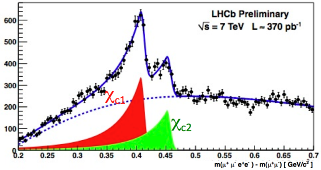


P-wave Onia: $\sigma(\chi_{c2})/\sigma(\chi_{c1})$

- Reconstruct χ_c via radiative decay $\chi_c(\text{nP}) \rightarrow \text{J}/\psi\ \gamma$.
- Two studies:
  - 2010: 36 pb^{-1}, photons reconstructed in calorimeter system.
  - 2011: 370 pb^{-1}, photons converted in the tracker.



Photons identified in ECAL

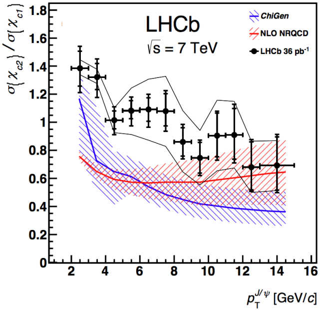


Photons converted in tracker

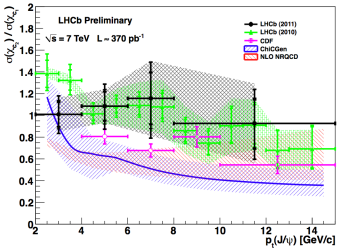
- 2010: Phys.Lett. B 714 (2012) 215-223
- 2011: LHCb-CONF-2011-062

P-wave Onia: $\sigma(\chi_{c2})/\sigma(\chi_{c1})$

- 2010, Results in agreement with NLO NRQCD model for $p_T > 8$ GeV/c.
- 2011, Results in agreement with 2010. More data required.



2010



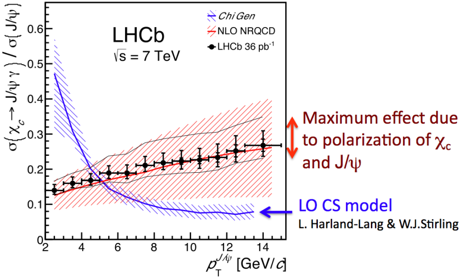
2011

P-wave Onia: J/ψ from χ_c

- J/ψ from χ_c (36pb^{-1}):

$$\frac{\sigma(\chi_c \to J/\psi\gamma)}{\sigma(J/\psi)} = \frac{\sigma(\chi_c \to J/\psi\gamma)}{\sigma^{dir}(J/\psi) + \sigma(\psi(2S) \to J/\psi X) + \sigma(\chi_c \to J/\psi\gamma)} \quad (2)$$

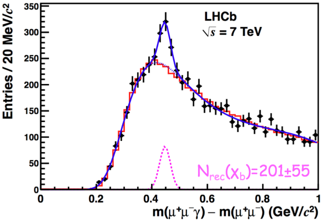
- Good agreement with NLO NRQCD.
- Lies consistently above LO CSM.

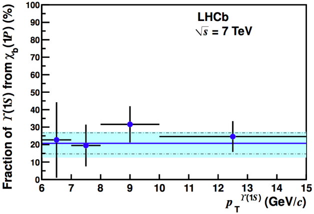


- J/ψ from χ_c: Phys. Lett. B 718 (2012) 431-440
- Ma, Wang & Chao, PRD 83 (2011) 111503

P-wave Onia: χ_b

- Fraction of $\Upsilon(1S)$ from $\chi_b(1P)$ decays (32pb^{-1}).
- Reconstruct: $\chi_b(1P) \rightarrow \Upsilon(1S)\gamma \rightarrow \mu^+ \ \mu^- \ \gamma$
- $20.7 \pm 5.7(\text{stat}) \pm 2.1(\text{syst})^{+2.7}_{-5.4}(\text{pol})$ %
- Consistent with CDF: $27.1 \pm 6.9 \pm 4.4$ %.
- $\chi_b(1P)$ significant source of $\Upsilon(1S)$ in pp collisions.

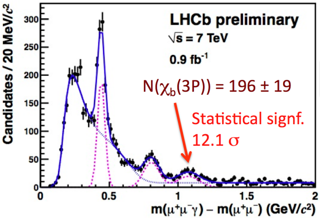




- LHCb: LHCb-PAPER-2012-015
- CDF: PRL 84 (2000) 2094

P-wave Onia: χ_b

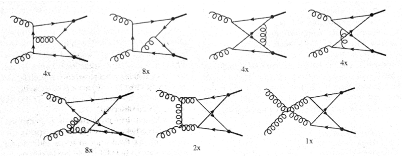
- Observation of new quarkonium $\chi_b(3P)$ state ($0.9 fb^{-1}$).
- Reconstruct: $\chi_b(3P) \to \Upsilon(1S)\gamma \to \mu^+ \mu^- \gamma$.
- $m(\chi_b(3P)) = 10.535 \pm 0.010$ GeV/c^2.
- $m(\chi_b(1P)) = 9.901 \pm 0.002$ GeV/c^2.
- $m(\chi_b(2P)) = 10.266 \pm 0.006$ GeV/c^2.
- Consistent with ATLAS and D0 measurments.



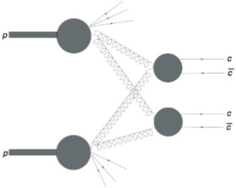
- LHCb: LHCb-CONF-2012-020
- ATLAS: PRL 108(2012) 152001
- D0: PRD 86(2012) 031103

Multiple Onia: Motivation

- Production of Multiple heavy onia tests:
  - pQCD (predominately gluon fusion at LHC).
  - Double parton scattering (DPS).
  - Intrinsic charm of the proton.



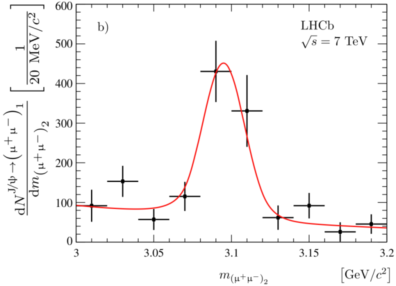
Gluon fusion



DPS

Multiple Onia: Double J/ψ

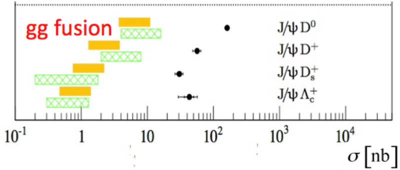
- First observation of 2xJ/ψ at hadron colliders (37.5 pb^{-1}).
- $\sigma^{J/\psi J/\psi} = 5.1 \pm 1.0 \pm 1.1$ nb.
- $\frac{\sigma^{J/\psi J/\psi}}{\sigma^{J/\psi}} = (5.1 \pm 1.0(\text{stat}) \pm 0.6(\text{syst})^{+1.2}_{-1.0}(\text{pol})) \times 10^{-4}$.
- Kinematic properties will be studied with larger dataset.

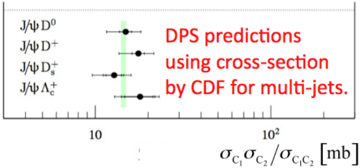


- Phys.Lett.B707(2012) 52

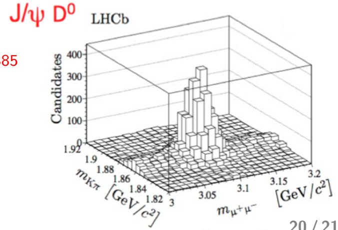
Multiple Onia: J/ψ and Open Charm

- Open charm: D^0, D^+, D_s^+ and Λ_c (355 pb^{-1}).
- Cross-sections suggest DPS needed.





- J/ψ & charm: JHEP 06 (2012) 141
- Yellow gg fusion: A. Berezhnoy et al. PRD 57(1998) 4385
- Yellow gg fusion: S. Baranow PRD 73 (2006) 074021
- Green gg fusion: J-.P. Landsberg EPJ C61 (2009) 693
- CDF: Eur.Phys.J C61 (2009) 693



Summary

- LHCb has produced many important quarkonia results:
  - First observations.
  - Cross section measurements.
  - Evidence for the importance of DPS.
- More important studies on the way:
  - Polarisation studies.
  - 8 TeV data.
  - More detailed studies of kinematic distribution of double charm production.

Many important results with many more on the way.