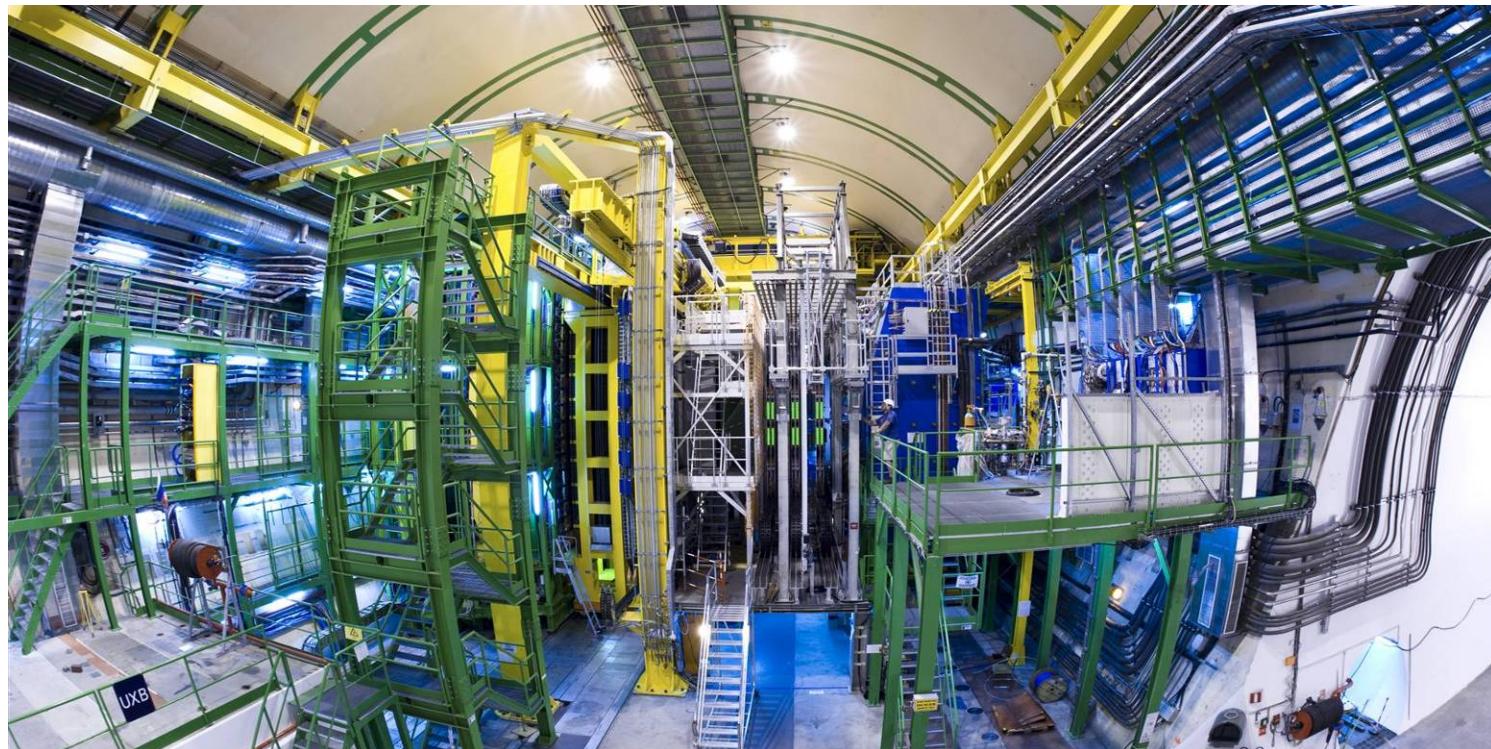


Heavy flavour production and spectroscopy at LHCb



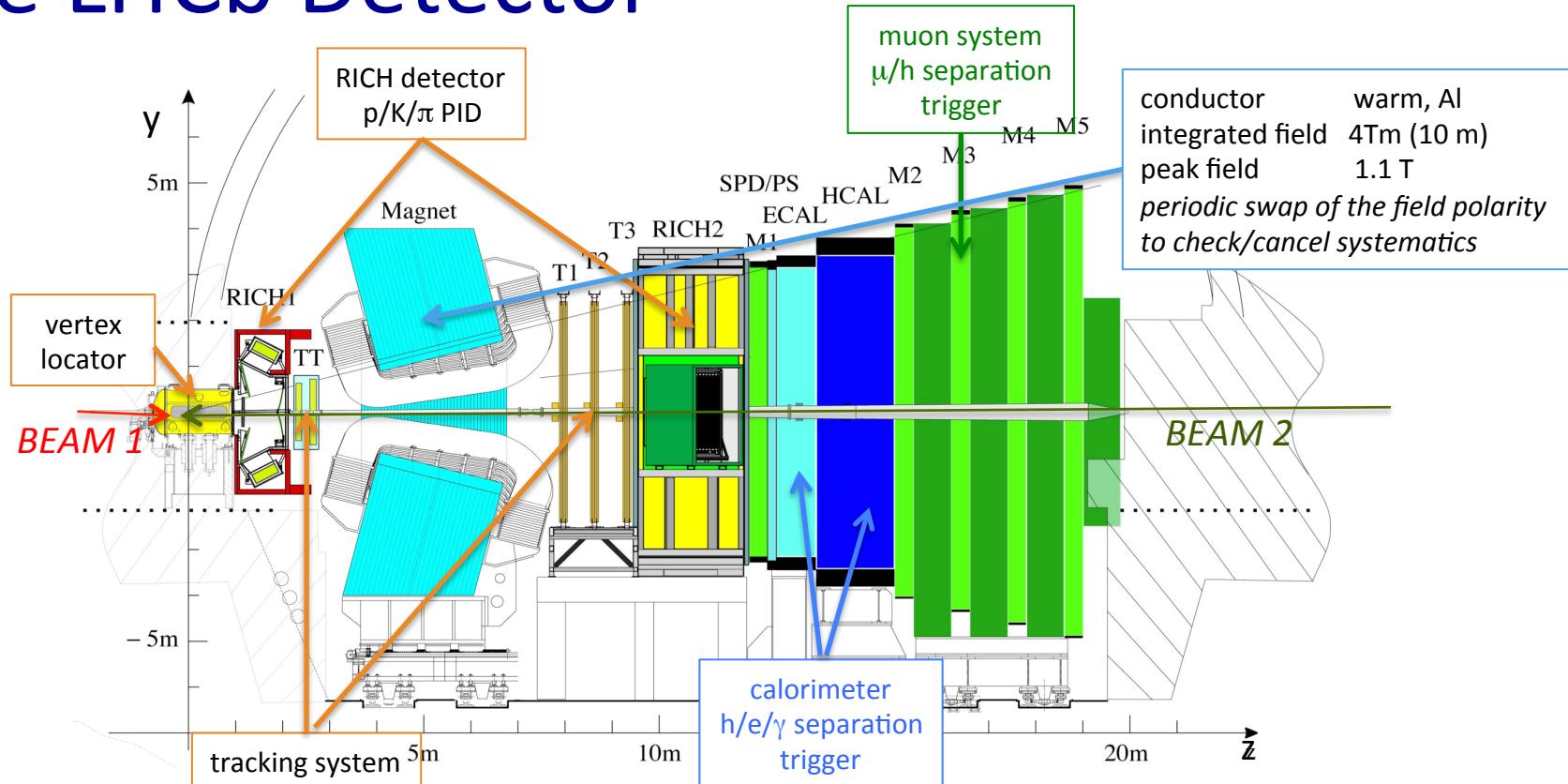
Patrizia de Simone (*INFN LNF*)
on behalf of the LHCb Collaboration
BEACH 2012, Wichita, July 23-28 2012

Outline



- The LHCb detector
- Overview of heavy flavour physics at LHCb
- Results
 - Quarkonia
 - c-hadrons
 - b-hadrons
- Conclusions

The LHCb Detector

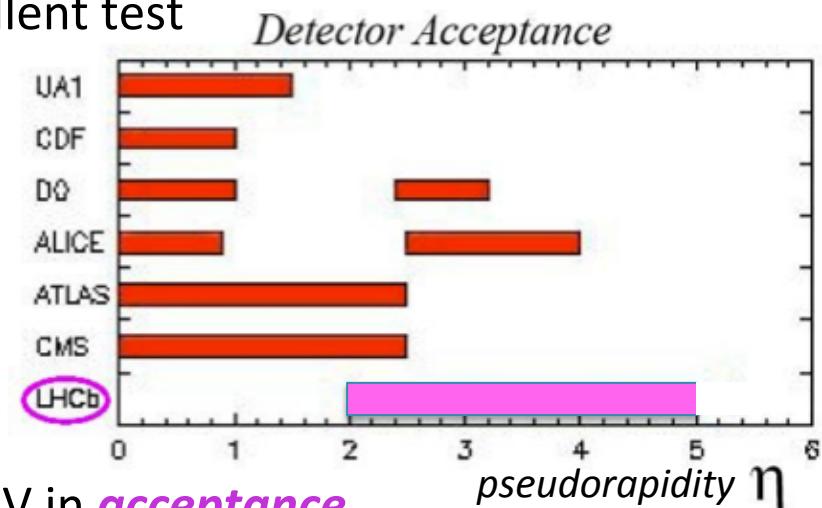


multi-stage trigger first hardware, subsequent two levels are software

- **Vertexing** proper time resolution 30-50 fs
- **Tracking** $\Delta p/p = 0.35 - 0.55 \%$ $\sigma(\text{mass}) = 10 - 25 \text{ MeV}/c^2$
- **RICH** KaonID $\epsilon(K \rightarrow K) \approx 95\%$ misID rate ($\pi \rightarrow K$) $\approx 5\%$
- **ECAL** $\sigma(E)/E = 10\%/\sqrt{E} \oplus 1. \%$ **HCAL** $\sigma(E)/E = 69\%/\sqrt{E} \oplus 9\%$
- **MuonID** $\epsilon(\mu \rightarrow \mu) \approx 97\%$ misID rate ($\pi \rightarrow \mu$) = 1-3 %

Heavy Flavour Physics at LHCb

- quarkonia and heavy hadrons production processes are valuable tests of perturbative and non-perturbative QCD models
- furthermore different QCD models predict different masses, BR, lifetime, etc., c and b hadron spectroscopy provides excellent test
- due to the unique coverage of LHCb, the results are complementary to the GPDs, and essential to obtain a complete picture (underlying event modeling)
- large production cross sections at $\sqrt{s} = 7 \text{ TeV}$ in *acceptance*



$$\sigma(c\bar{c}) = 1742 \pm 267 \mu\text{b} \quad \text{LHCb-CONF-2010-013}$$

$$\sigma(b\bar{b}) = 75.3 \pm 5.4 \pm 13 \mu\text{b} \quad \text{PLB 694 (2010)209}$$

data samples		2010 (7 TeV)	2011 (2.8 TeV)	2011 (7 TeV)	2012 (8 TeV)	expected end 2012 (8 TeV)
Int. Lumi.		37 pb^{-1}	71 nb^{-1}	1 fb^{-1}	0.73 fb^{-1}	2.2 fb^{-1}

- uncertainty on integrated luminosity for all analyses is 3.5% [J. Instr. 7 \(2012\) P01010](https://doi.org/10.1088/1748-0221/7/01/P01010)



- Quarkonia

Charmonia and Bottomonium at $\sqrt{s} = 7$ TeV

- LHCb has published the production rates of prompt and non-prompt quarkonia at 7 TeV

EPJC 71 (2011) 1645

$$\sigma_{prompt}(J/\psi) = 10.52 \pm 0.04(stat) \pm 1.40(syst)^{+1.64}_{-2.20}(pol)\mu b$$

$$\sigma_b(J/\psi) = 1.14 \pm 0.01(stat) \pm 0.16(syst)\mu b$$

data sample of 5.2 pb^{-1}

use $J/\psi \rightarrow \mu^+\mu^-$

cross sections integrated over the ranges
 $p_T < 14.$ GeV/c and $2.0 < y < 4.5$

arXiv: 1204.1258

$$\sigma_{prompt}(\psi(2S)) = 1.44 \pm 0.01(stat) \pm 0.12(syst)^{+0.20}_{-0.40}(pol)\mu b$$

$$\sigma_b(\psi(2S)) = 0.25 \pm 0.01(stat) \pm 0.02(syst)\mu b$$

$$BR(b \rightarrow \psi(2S)X) = (2.73 \pm 0.06 \pm (stat) \pm 0.16(syst) \pm 0.24(BR)) \times 10^{-3}$$

data sample of $36. \text{ pb}^{-1}$

use $\psi(2S) \rightarrow \mu^+\mu^-$ and
 $\psi(2S) \rightarrow J/\psi (\mu^+\mu^-)\pi^+\pi^-$

cross sections integrated over the ranges
 $p_T < 16.$ GeV/c and $2.0 < y < 4.5$

EPJC 72 (2012) 2025

$$\sigma_{prompt}(Y(1S)) \times Br(Y(1S) \rightarrow \mu^+\mu^-) = 2.29 \pm 0.01(stat) \pm 0.10(syst)^{+0.19}_{-0.37}(pol)nb$$

$$\sigma_{prompt}(Y(2S)) \times Br(Y(2S) \rightarrow \mu^+\mu^-) = 0.562 \pm 0.007(stat) \pm 0.023(syst)^{+0.048}_{-0.092}(pol)nb$$

$$\sigma_{prompt}(Y(3S)) \times Br(Y(3S) \rightarrow \mu^+\mu^-) = 0.283 \pm 0.005(stat) \pm 0.012(syst)^{+0.025}_{-0.048}(pol)nb$$

data sample of $25. \text{ pb}^{-1}$

use $Y(iS) \rightarrow \mu^+\mu^-$ ($i=1,2,3$)
cross sections integrated over the ranges

$p_T < 15.$ GeV/c and
 $2.0 < y < 4.5$

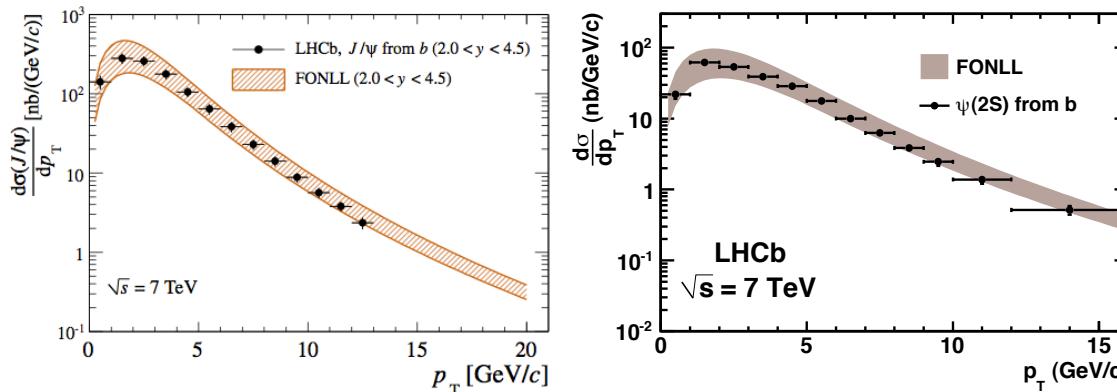
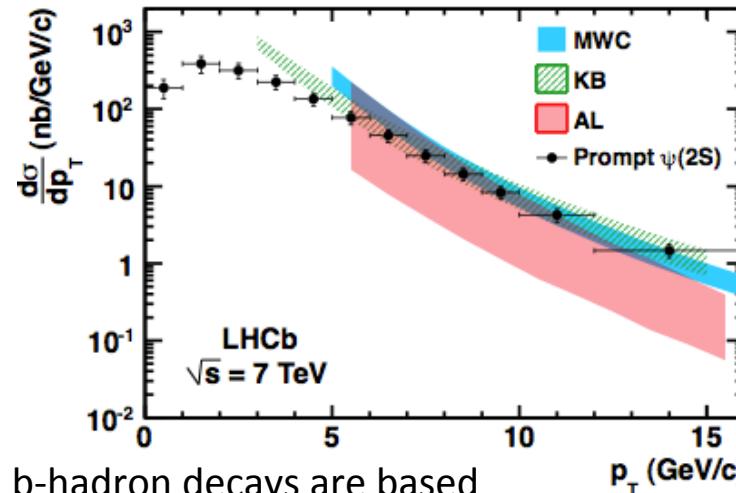
- the largest error on the prompt cross sections is due to the unknown quarkonia states polarizations
- differential cross sections have been measured as a function of p_T and y of the quarkonia states
- the inclusive $BR(b \rightarrow \psi(2S)X)$ has been obtained combining $\sigma_b(\psi(2S))$ and $\sigma_b(J/\psi)$, and the last error is due to the uncertainty on $BR(b \rightarrow J/\psi X)$ [PDG]

Comparison with theory

- as already seen by Tevatron production σ 's are larger than NRQCD calculations based on LO CSM
- recent QCD calculations are found to be in good agreement with all our measurements*
- prompt $\psi(2S)$ production measurement is directly compared with theory prediction because has no appreciable feed-down from higher mass states

MWC [[arXiv:hep-ph/1012.1030](https://arxiv.org/abs/hep-ph/1012.1030)] and
KB [[PRL 106\(2011\)022003](https://doi.org/10.1103/PhysRevLett.106.022003)] are NLO calculations
in NRQCD including CS and CO
AL [[PRL 101\(2008\)152001](https://doi.org/10.1103/PhysRevLett.101.152001), [EPJ C61\(2009\)693](https://doi.org/10.1140/epjc/s10050-009-0693-7)] is a
CS model including the dominant NNLO terms

- QCD predictions for charmonia production from b-hadron decays are based on the **Fixed-Order-Next-to-Leading-Log (FONLL)** approximation

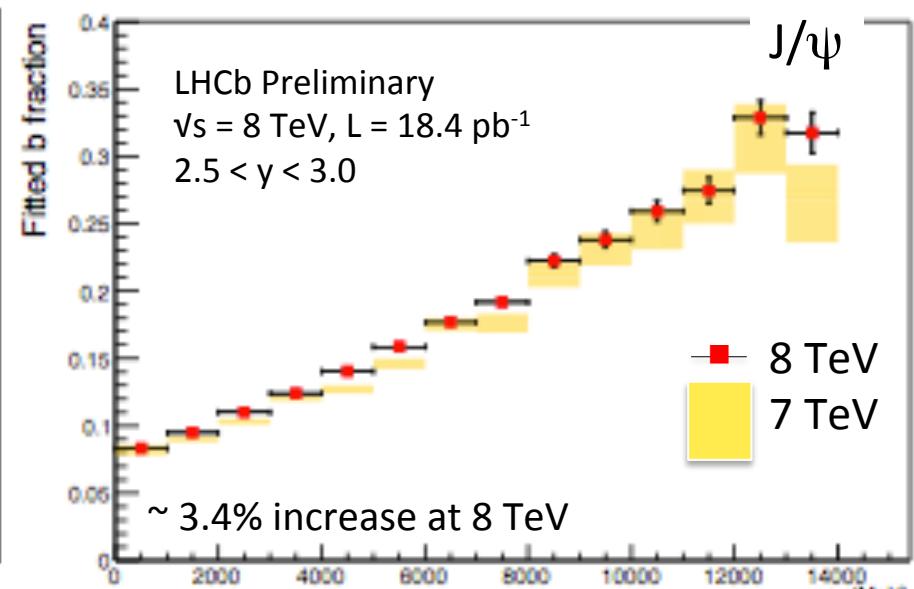
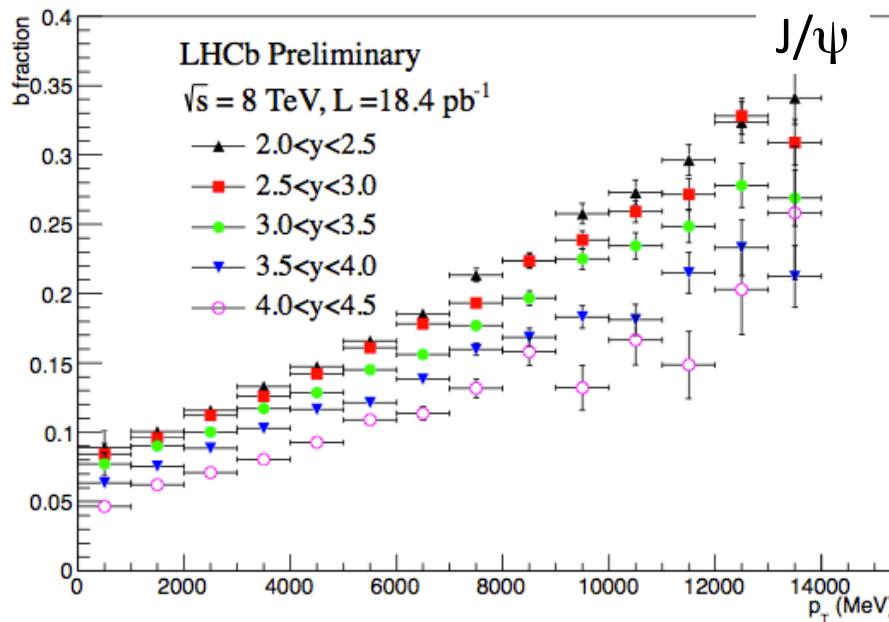


Charmonia and Bottomonium at 8 \sqrt{s} = TeV (Preliminary)

- LHCb is performing extremely well at 8 TeV
- $\sigma(m_{J/\psi}) \approx 14.5 \text{ MeV}/c^2$
- $\sigma(m_Y) \approx 43 \text{ MeV}/c^2$
- $\sigma(\text{proper time}) \approx 61 \text{ fs}$
- fraction of J/ψ and $\psi(2S)$ from b extracted from fit to the mass and pseudo proper time
- cross section expected to increase by $\sim 15\%$

LHCb-CONF-2012-25

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



Double charm production

- besides the quarkonia differential cross sections other observables will be necessary to discriminate amongst the various models
 - Color Singlet vs Color Octet, NLO vs NNLO terms, ...
- quarkonia polarization measurements *analysis ongoing*
- double J/ ψ , J/ ψ open charm and double open charm production

production of multiple heavy
flavour states tests ➔

1. Leading Order calculations for the gg \rightarrow J/ ψ c \bar{c} process in perturbative QCD
2. the Double Parton Scattering approach, DPS
3. sea charm quarks from the interacting protons

may not be mutually exclusive

if DPS picture dominates

we would expect

$$\sigma_{DPS}(C_1 C_2) = \begin{cases} \frac{1}{2} \frac{\sigma(C_1) \times \sigma(C_2)}{\sigma_{eff}^{DPS}} & , \text{for } C_1 = C_2 \\ \frac{\sigma(C_1) \times \sigma(C_2)}{\sigma_{eff}^{DPS}} & , \text{for } C_1 \neq C_2 \end{cases}$$

where $\sigma_{eff}(DPS) \approx 15$ mb has been measured with multi-jet events at the Tevatron

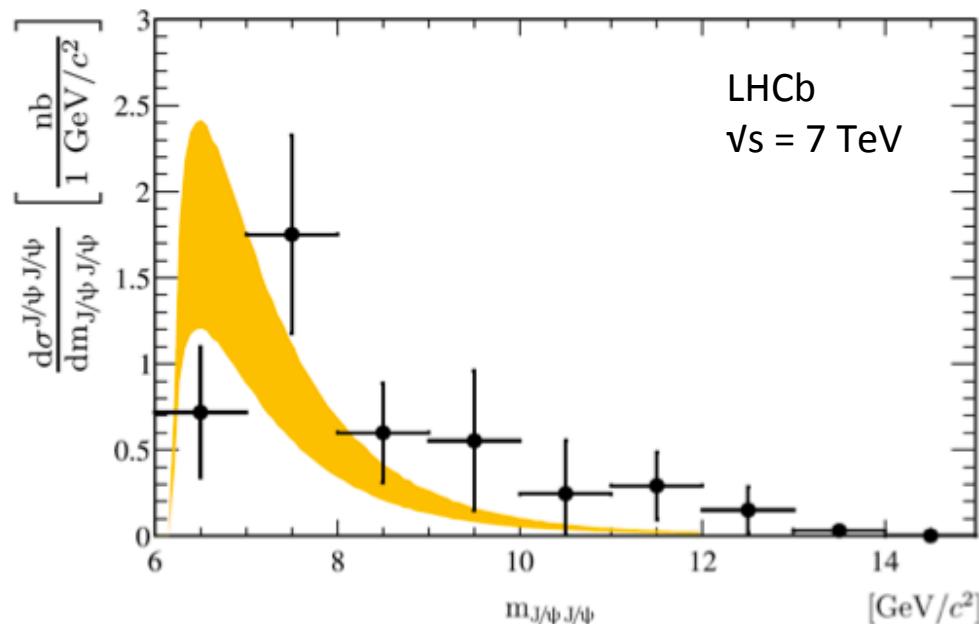
Double J/ ψ production

PLB 707 (2012) 52-59

$$\sigma^{J/\psi J/\psi} = 5.1 \pm 1.0(stat) \pm 1.1(syst) nb$$

data sample of 37.5 pb^{-1}
reconstruct prompt $J/\psi \rightarrow \mu^+\mu^-$
cross sections integrated over the ranges
 $p_T < 10 \text{ GeV}/c$ and $2.0 < y < 4.5$

- differential production cross section as a function of the invariant mass of J/ψ pairs compared with LO calculations for the $gg \rightarrow J/\psi J/\psi$ process in perturbative QCD
 $\sigma^{J/\psi J/\psi} = 4.1 \pm 1.2 \text{ nb}$ [*arXiv:1101.5881*]



- LHCb results might indicate a contribution from the Double Parton Scattering (DPS) production mechanism
 $2. \pm 1. \text{ nb}$ [*arXiv:1106.2184*]

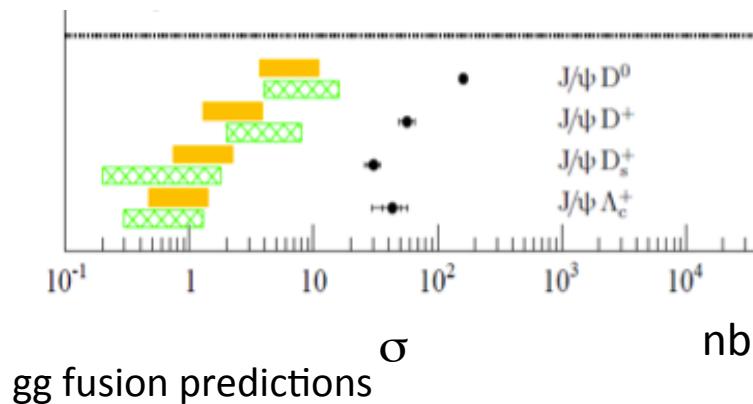
result to be updated with full statistics at 7 TeV

J/ ψ C and CC production

JHEP 06(2012) 141

- data sample 355 pb^{-1}
- signals with a statistical significance in excess of 5σ have been observed for
 - ✓ J/ ψ C \rightarrow J/ ψ D 0 , J/ ψ D $^+$, J/ ψ D $_s^+$, J/ ψ Λ_c^+
 - ✓ CC \rightarrow D 0 D 0 , D 0 D $^+$, D 0 D $_s^+$, D $^+$ D $^+$, D $^+$ D $_s^+$, D 0 Λ_c^+
 - ✓ c \bar{c} \rightarrow D 0 \bar{D}^0 , D 0 D $^-$, D 0 D $_s^-$, D $^+$ D $^-$, D $^+$ D $_s^-$, D 0 $\bar{\Lambda}_c^-$, D $^+$ $\bar{\Lambda}_c^-$ (*Control Sample*)

in the acceptance region $\rightarrow p_T(\text{J}/\psi) < 12. \text{ GeV}/c$, $3. < p_T(C) < 12. \text{ GeV}/c$, and $2 < y_{\text{J}/\psi}, Y_C < 4$

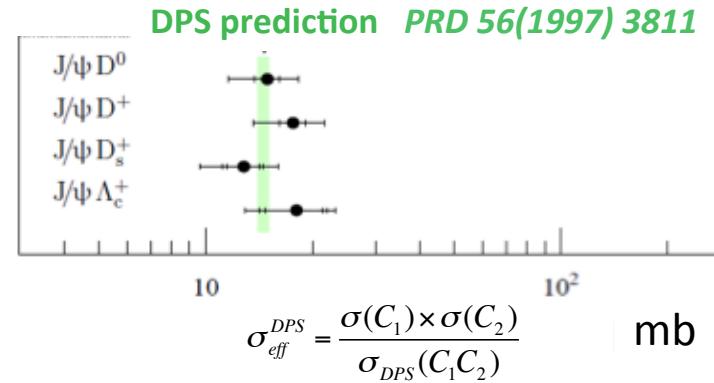


gg fusion predictions

PRD 57 (1998) 4385

EPJC 61 (2009) 693

significantly lower than the measurements



DPS prediction works well for J/ ψ C modes

many more channels to explore with the increasing statistics, also at new \sqrt{s}

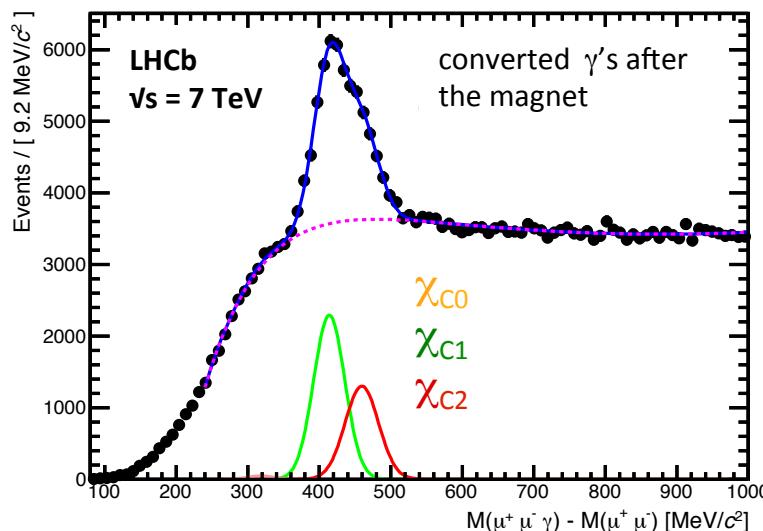
Heavy Onia: $\sigma(\chi_{c2})/\sigma(\chi_{c1})$

arXiv:1202.1080
accepted by PLB

P-wave charmonia $\chi_c(1P)$, with $J = 0, 1, 2$

- 1) give substantial feed-down contributions to the J/ψ_{prompt} production through $\chi_c \rightarrow J/\psi \gamma$
- 2) can have impact on the measurement of the J/ψ polarization
- 3) $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ is sensitive to the CS and CO production mechanisms

- data sample 36 pb^{-1}
- prompt χ_c reconstructed through $\chi_c \rightarrow J/\psi \gamma$, and $J/\psi \rightarrow \mu^+ \mu^-$
- $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ as a function of $p_T(J/\psi)$ in the acceptance region $2 < p_T(J/\psi) < 15 \text{ GeV}/c$ and $2 < \gamma(J/\psi) < 4.5$



$p_T(\gamma) > 650 \text{ MeV}/c$
 $p(\gamma) > 5 \text{ GeV}/c$
likelihood $CL_{\gamma_{ID}} > 0.5$

χ_{c0} peak is barely visible, its BR is ~ 30 times smaller than those of χ_{c1} and χ_{c2}

Heavy Onia: $\sigma(\chi_{c2})/\sigma(\chi_{c1})$

*arXiv:1202.1080
accepted by PLB*

$$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = \frac{N_{\chi_{c2}}}{N_{\chi_{c1}}} \frac{\varepsilon^{\chi_{c1}}}{\varepsilon^{\chi_{c2}}} \frac{BR(\chi_{c1} \rightarrow J/\psi\gamma)}{BR(\chi_{c2} \rightarrow J/\psi\gamma)}$$

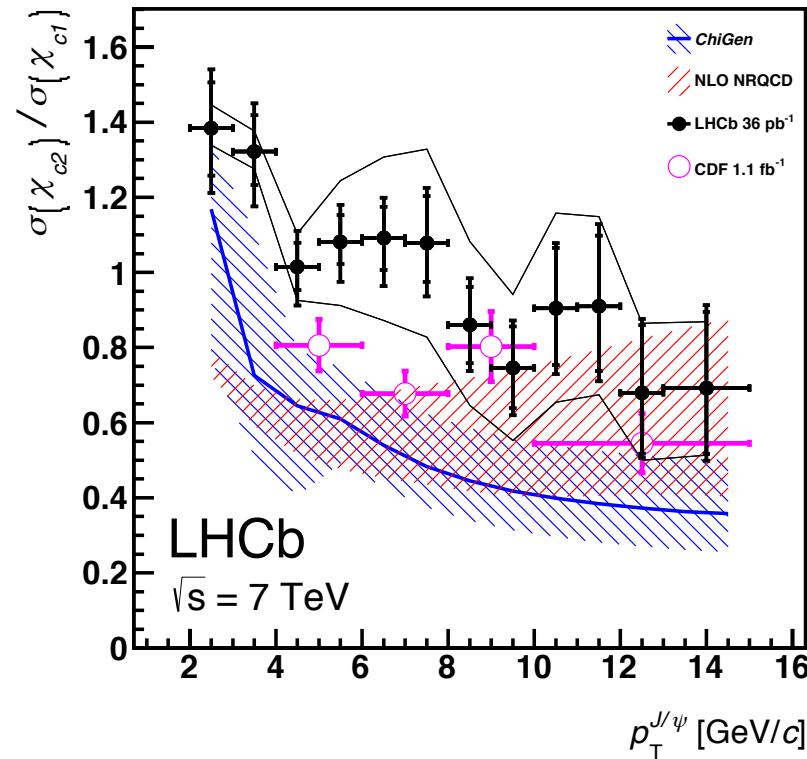
*from an unbinned maximum likelihood fit
to the $(M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-))$ distribution*

$$N_{\chi_2} = 26110 \pm 620$$

$$N_{\chi_1} = 38630 \pm 550$$

$\frac{\varepsilon^{\chi_{c1}}}{\varepsilon^{\chi_{c2}}}$ obtained from simulation

BR's from PDG



- internal error bars = statistical errors, external error bars = systematic uncertainties (apart of polarization)
- lines surrounding the data points show the maximum effect due to the unknown χ_c polarization
- CDF data points at $\sqrt{s} = 1.96$ TeV, *PRL 98 (2007) 232001*
- red hatched band: NLO NRQCD calculation in agreement for $p_T(J/\psi) > 8$ GeV/c [*arXiv:1002.3987*]
- blue hatched band: *ChiGen* Monte Carlo which uses LO CS model describes the shape reasonably well, but consistently below the data



- c-hadrons

$D_s^+ - D_s^-$ production asymmetry

arXiv:1205.0897

- CP violation asymmetries can be determined at LHCb if production and detection asymmetries are known
- while production diagrams are flavour symmetric the hadronization process may not be
- D_s^\pm prompt production cross section asymmetry using $D_s^\pm \rightarrow \phi\pi^\pm$, and $\phi \rightarrow K^+K^-$

$$A_p = \frac{\sigma(D_s^+) - \sigma(D_s^-)}{\sigma(D_s^+) + \sigma(D_s^-)}$$

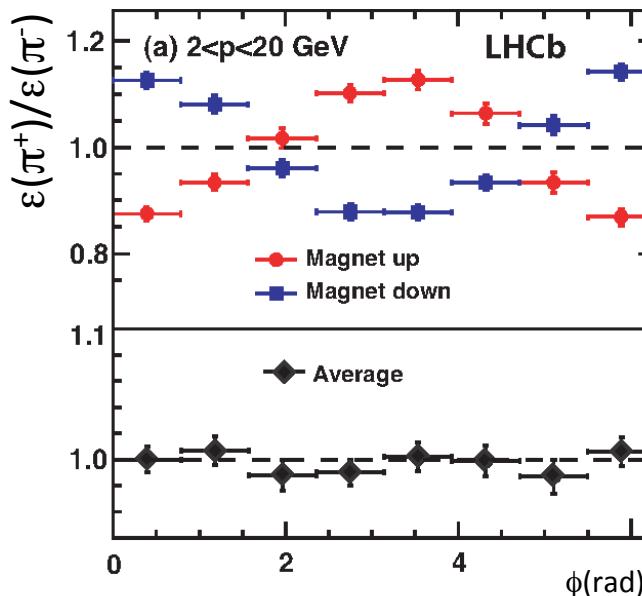
- since $D_s^\pm \rightarrow \phi\pi^\pm$ is Cabibbo favoured, no significant CP asymmetry is expected and A_p is determined after correcting for the relative D_s^+ and D_s^- detection efficiencies
- since final states are symmetric in K production, we have to determine only $\varepsilon(\pi^+)/\varepsilon(\pi^-)$

use the decay sequence from PV

$$D^{*+} \rightarrow \pi^+ D^0$$

$$D^0 \rightarrow K^-\pi^+\pi^+\pi^-$$

the ratio of fully to partially reconstructed decays provides →

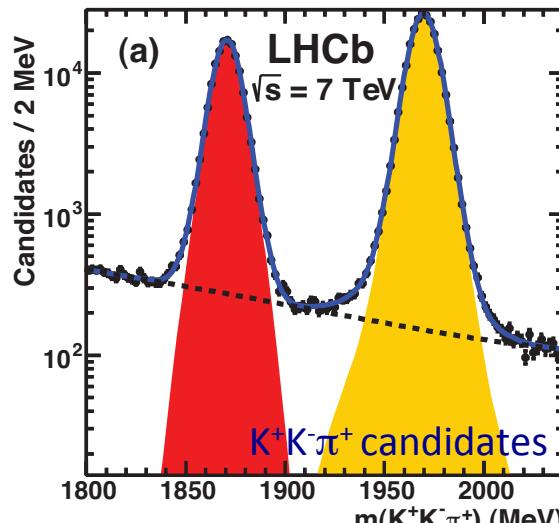


D⁺ and D⁻ decays examined separately
magnet UP data separately from magnet DOWN data

$D_S^+ - D_S^-$ production asymmetry

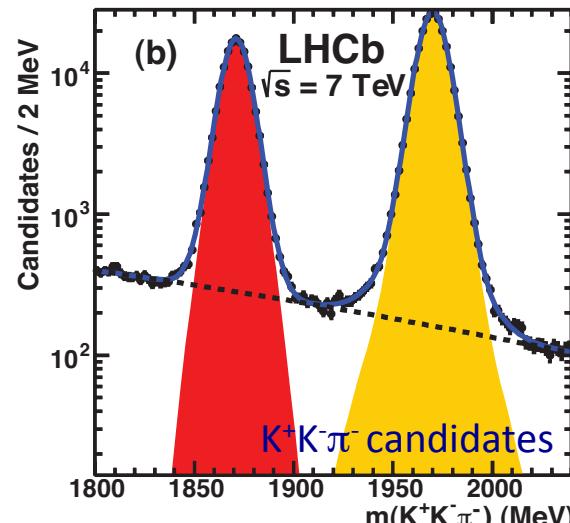
arXiv:1205.0897

- data sample $1.\text{fb}^{-1}$
- 3 candidates tracks, identified by the RICH, with $p_T > 2 \text{ GeV}/c$, must form a vertex detached from PV
- the momentum of the reconstructed D_S^\pm must point to the PV which reduces contamination from b decays to few percent



$A_p(\%)$ as a function of y and p_T

p_T (GeV)	y		
	2.0 – 3.0	3.0 – 3.5	3.5 – 4.5
2.0 – 6.5	0.2 ± 0.5	-0.7 ± 0.5	-0.9 ± 0.4
6.5 – 8.5	-0.3 ± 0.4	0.1 ± 0.5	-1.2 ± 0.5
8.5 – 25.0	0.2 ± 0.3	-0.3 ± 0.5	-1.0 ± 0.8



overall production asymmetry

$$A_P = (-0.33 \pm 0.22(\text{stat}) \pm 0.10(\text{syst}))\%$$

consistent with theoretical expectations [PLB 298(1993)218], [EPJC 17(2000)137] provide constraints on D_S^\pm production models, and can be used as input for CP violation measurements



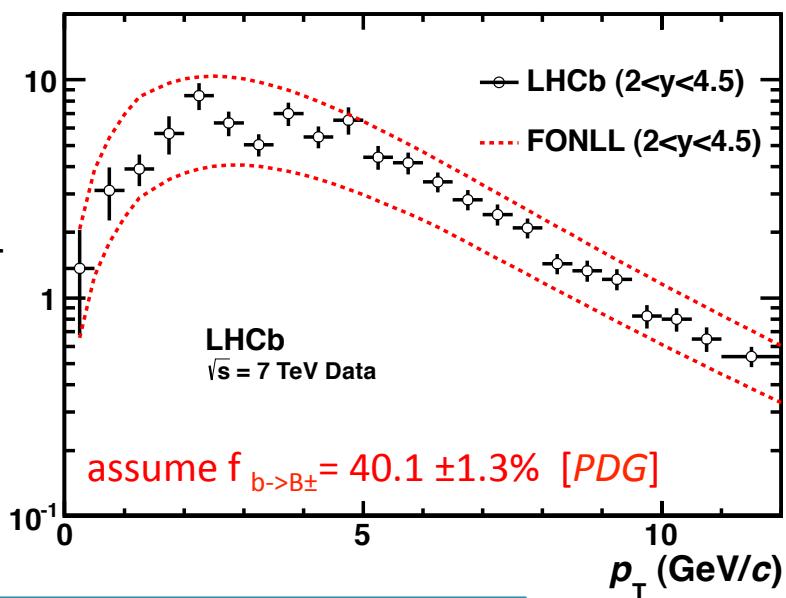
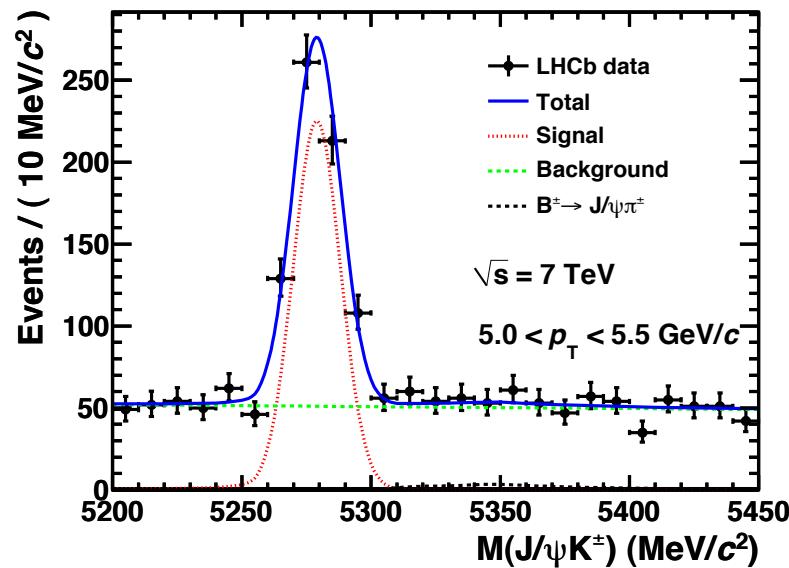
- b-hadrons

B⁺ production

JHEP 04(2012)093

- measurements of $\sigma(pp \rightarrow b\bar{b}X)$ provide powerful test of pQCD (NLO and FONLL approximations)
- data sample 35 pb⁻¹
- B[±] prompt production cross section using ~9K B[±] → J/ψ(μ⁺μ⁻)K[±] candidates *selected in the acceptance region 2 < y < 4.5 and p_T < 40 GeV/c*

M(J/ψK[±]) of selected candidates in one p_T bin



$$\sigma(pp \rightarrow B^\pm X) = 41.4 \pm 1.5(\text{stat}) \pm 3.1(\text{syst}) \mu\text{b}$$

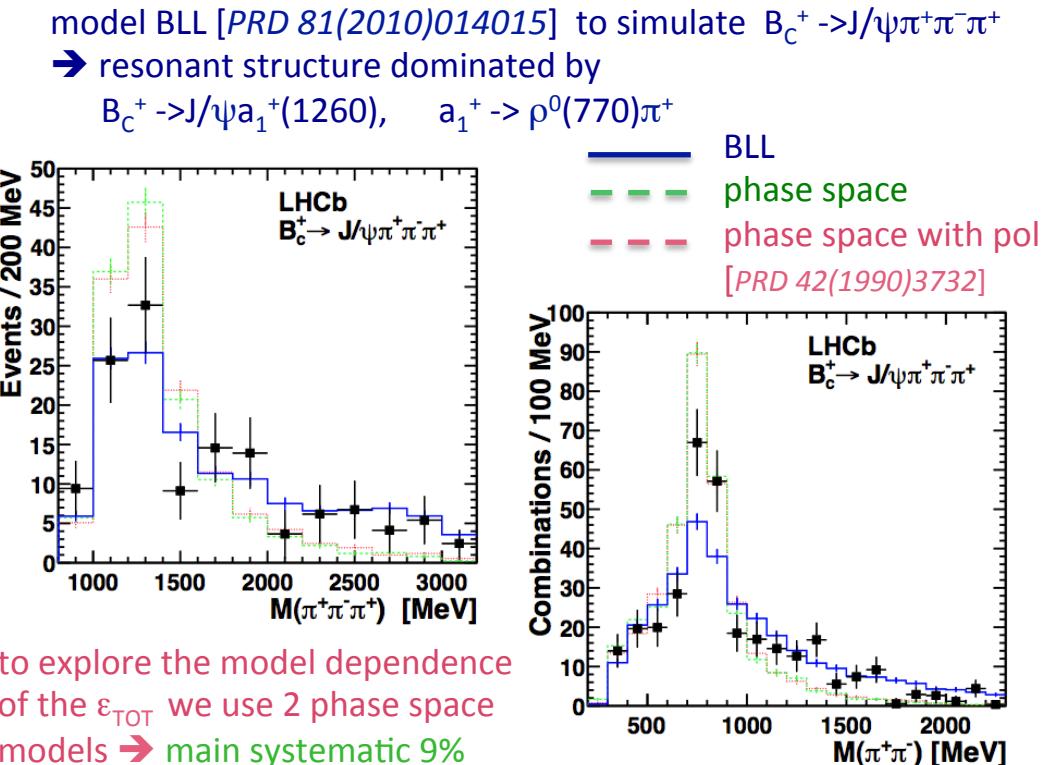
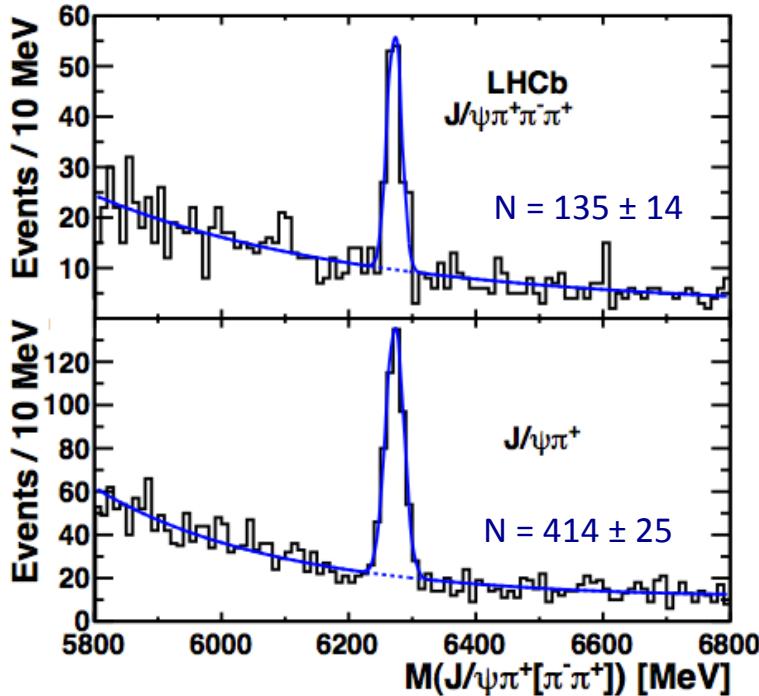
- systematics mainly due to ε_{tracking} (4%) and μID (2.5%)

first measurement of B production in the forward region, will be updated with more luminosity + B_S and B⁰

first observation of $B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$

*arXiv:1204.0079
accepted by PRL*

- BR expected to be 1.5- 2.3 times higher than for $B_c^+ \rightarrow J/\psi \pi^+$ [PRD 81(2010)014015]
- larger number of π 's \rightarrow smaller ϵ_{TOT} due to the limited detector acceptance
- measure of the BR($B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$) relative to that for $B_c^+ \rightarrow J/\psi \pi^+$ with a data sample 0.8 fb^{-1}

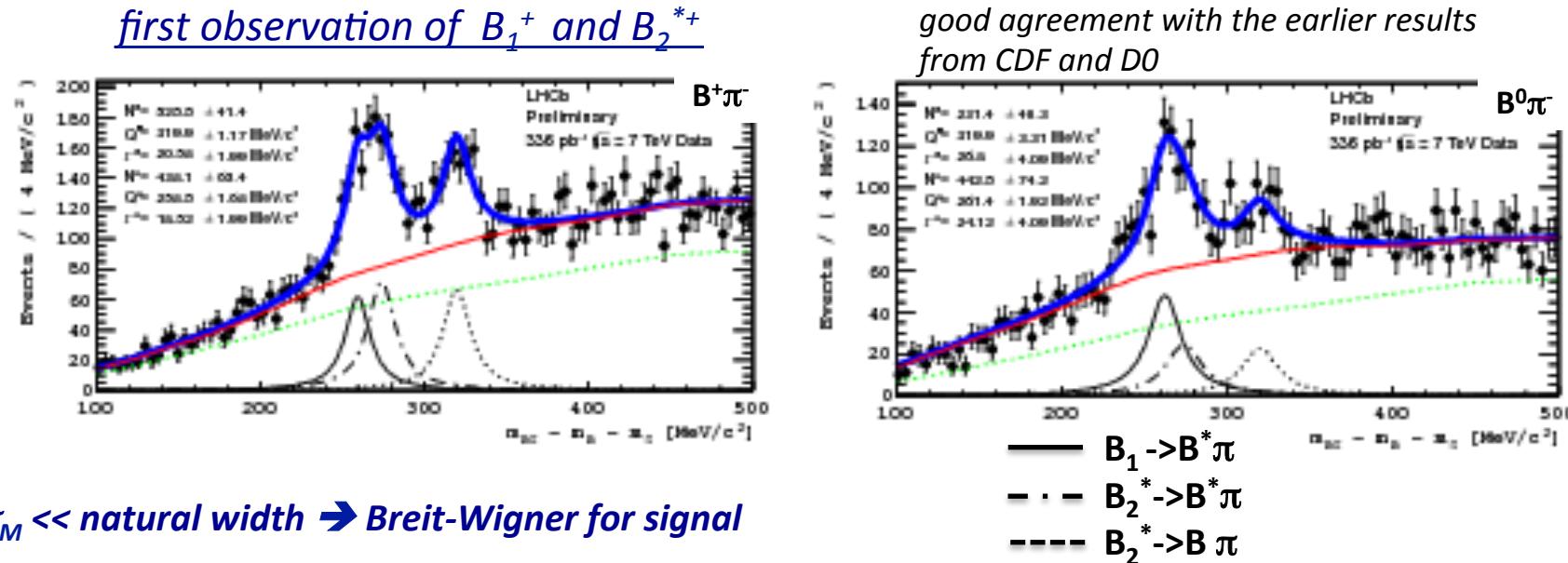


$$\frac{BR(B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+)}{BR(B_c^+ \rightarrow J/\psi \pi^+)} = 2.41 \pm 0.30(\text{stat}) \pm 0.33(\text{syst})$$

Observation of excited $B_{(s)}^{**}$ (Preliminary)

LHCb-CONF-2011-053

- properties of excited $B_{(s)}$ ($L=1$) are predicted by Heavy Quark Effective Theory [PRD 64(2001)114004]
- $B_1(5721)^0$, $B_2^*(5830)^0$, $B_{s1}(5830)^0$, $B_{s2}(5840)^0$ observed by CDF and D0
[PRL 102(2009)102003, 99(2007)172001, 100(2008)082001/082002]
- B mesons reconstructed in $J/\psi K^*$ $D\pi$ and $D\pi\pi\pi$ modes
- search for $B_{(s)}^{**}$ states in the invariant mass distributions of B^+K^- , $B^+\pi^-$ and $B^0\pi^+$
 $B^{**} \rightarrow B h$ and $B^{**} \rightarrow B^*(B\gamma)h$, the invariant masses of the 2 decays are shifted because we do not reconstruct the soft γ ($M_{B^*} - M_B \sim 46 \text{ MeV}/c^2$)
- study the spectrum $Q = m(Bh) - m(B) - m(h)$
- data sample 336 pb^{-1}



the measured Q values are translated into masses

$$M_{B_{s1}^0} = (5828.99 \pm 0.08_{\text{stat}} \pm 0.13_{\text{syst}} \pm 0.45_{\text{syst}}^{B \text{ mass}}) \text{ MeV}/c^2,$$

$$M_{B_{s2}^{*0}} = (5839.67 \pm 0.13_{\text{stat}} \pm 0.17_{\text{syst}} \pm 0.29_{\text{syst}}^{B \text{ mass}}) \text{ MeV}/c^2,$$

$$M_{B_1^0} = (5724.1 \pm 1.7_{\text{stat}} \pm 2.0_{\text{syst}} \pm 0.5_{\text{syst}}^{B \text{ mass}}) \text{ MeV}/c^2,$$

$$M_{B_1^+} = (5726.3 \pm 1.9_{\text{stat}} \pm 3.0_{\text{syst}} \pm 0.5_{\text{syst}}^{B \text{ mass}}) \text{ MeV}/c^2,$$

$$M_{B_2^{*0}} = (5738.6 \pm 1.2_{\text{stat}} \pm 1.2_{\text{syst}} \pm 0.3_{\text{syst}}^{B \text{ mass}}) \text{ MeV}/c^2,$$

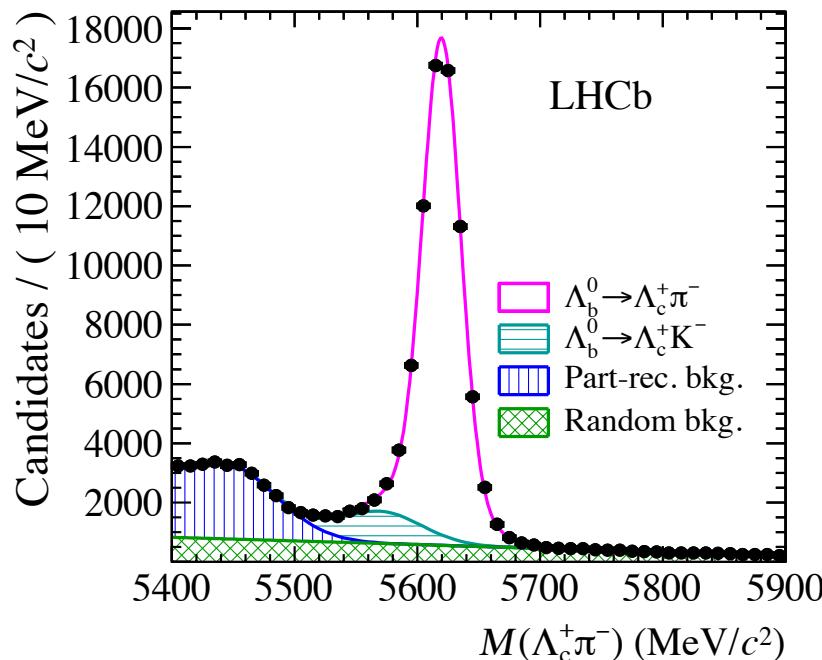
$$M_{B_2^{*+}} = (5739.0 \pm 3.3_{\text{stat}} \pm 1.6_{\text{syst}} \pm 0.3_{\text{syst}}^{B \text{ mass}}) \text{ MeV}/c^2,$$

- all masses are in good agreement with HQET predictions [PRD 64(2001)114004]
- B_1^+ and B_2^{*+} masses are consistent with those of the isospin partners
- the measurement is being updated with 1 fb^{-1}

First observation of excited Λ_b^0 baryons

arXiv:1205.3452

- the quark model predicts two orbitally excited Λ_b^0 states (Λ_b^{0*}) with $J^P = 1/2^-$ and $3/2^-$
- they should decay to $\Lambda_b^0\pi^+\pi^-$ and/or $\Lambda_b^0\gamma$
- properties of Λ_b^{0*} are described by many theoretical models
[PRD 34(1986)2809, NPA 696(2001)638, PLB 659(2008)612, JPG 34(2007)961, AP 324(2009)2, JMP A23(2008)S08005]
predict Λ_b^{0*} mass above $\Lambda_b^0\pi^+\pi^-$ (5900 MeV/c²) but below $\Sigma_b\pi$ threshold (5950 MeV/c²)
- data sample 1. fb⁻¹
- search for Λ_b^{0*} starting from our large sample of $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$ ($\Lambda_c^+ \rightarrow pK^-\pi^+$)



$$N(\Lambda_b^0) = 70540 \pm 330$$

$$S/B = 11$$

background composition →

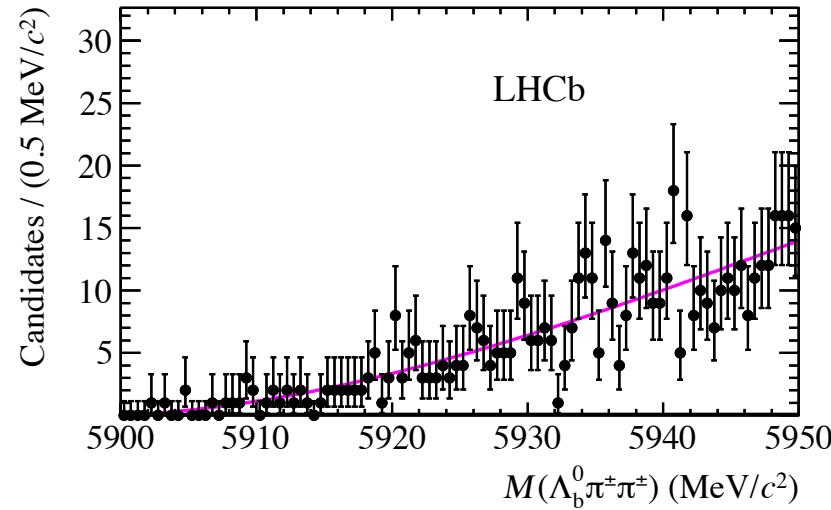
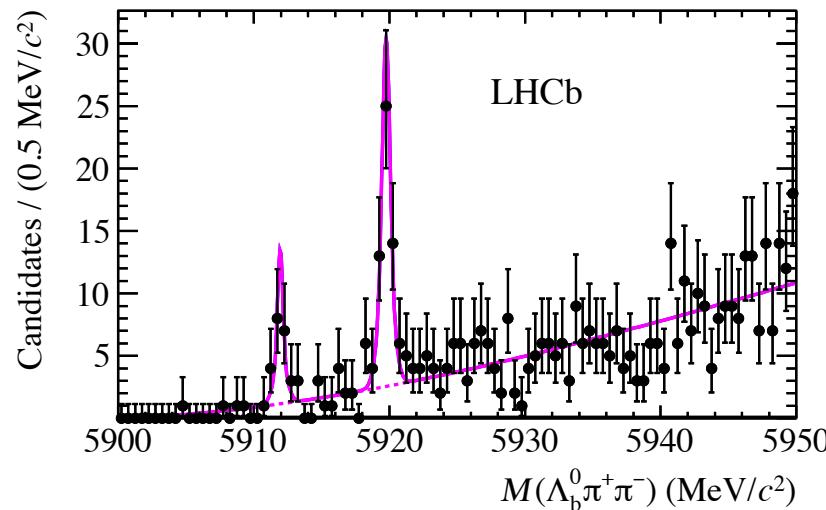
- 1) misreconstructed $\Lambda_b^0 \rightarrow \Lambda_c^+ K^-$
- 2) partially reconstructed decays
- 3) combinatorial background

perfect sample for spectroscopy studies

First observation of excited Λ_b^0 baryons

arXiv:1205.3452

- Λ_b^0 candidates are combined with two charged π from PV
- Λ_b^0 mass constrained to 5619.37 MeV/c² → combination of the world average [PDG] and LHCb measurement [PLB 708(2012)241]
- same sign candidates ($\Lambda_b^0 \pi^\pm \pi^\pm$) are used to model the background shape



two narrow peaks observed slight above the $\Lambda_b^0 \pi^+ \pi^-$ threshold $N(\Lambda_b^{0*}(5912)) = 16.4 \pm 4.7, \text{ 4.6 } \sigma \text{ significance}$
 $N(\Lambda_b^{0*}(5920)) = 45.5 \pm 7.9, \text{ 10.1 } \sigma \text{ significance}$

$$M_{\Lambda_b^{0*}(5912)} = 5911.95 \pm 0.12(\text{stat}) \pm 0.03(\text{syst}) \pm 0.66(\Lambda_b \text{mass}) \text{MeV} / c^2$$

$$M_{\Lambda_b^{0*}(5920)} = 5919.76 \pm 0.07(\text{stat}) \pm 0.02(\text{syst}) \pm 0.66(\Lambda_b \text{mass}) \text{MeV} / c^2$$

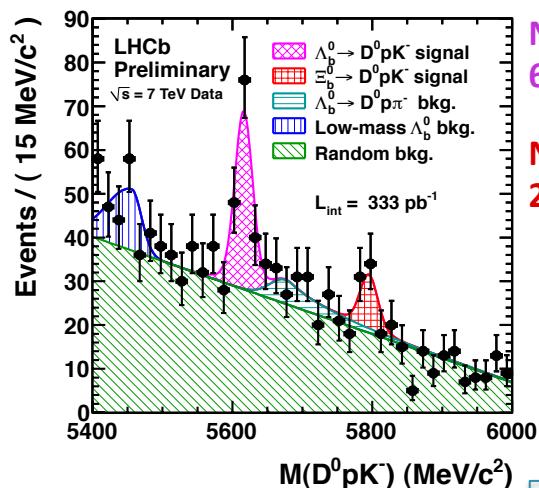
- main systematics due to signal/background modeling, momentum scale
- limit on natural width (95% CL) $\Gamma_{\Lambda_b^{0*}(5912)} < 0.82 \text{MeV}$ and $\Gamma_{\Lambda_b^{0*}(5920)} < 0.71 \text{MeV}$ ($\sigma_M \cong 0.2 - 0.3 \text{ MeV}/c^2$)

$\Lambda_b^0, \Xi_b^0 \rightarrow D^0 p K^-$ (*Preliminary*)

LHCb-CONF-2011-036

- *first observation* of the Cabibbo-suppressed decay $\Lambda_b^0 \rightarrow D^0 p K^-$
- since the $D^0 p K^-$ final state has non-zero strangeness, it may be populated by the Cabibbo-favoured decay of the Ξ_b^0 recently observed by CDF [PRL 107(2011)102001]
- kinematically similar Cabibbo-favoured $\Lambda_b^0 \rightarrow D^0 p \pi^-$ and well established channel $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$ used as normalization and control samples, D mesons reconstructed in the channel $K^- \pi^+$
- data sample 330 pb^{-1}

$$R_{D^0 p \pi^-} = \frac{BR(\Lambda_b^0 \rightarrow D^0 p \pi^-) \times BR(D^0 \rightarrow K^- \pi^+)}{BR(\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-) \times BR(\Lambda_c^+ \rightarrow p K^- \pi^+)} = 0.119 \pm 0.006(\text{stat}) \pm 0.013(\text{syst})$$



$$N(\Lambda_b^0) = 92.1 \pm 14.7$$

6.3 σ significance

$$N(\Xi_b^0) = 26.9 \pm 10.0$$

2.6 σ significance

$$R_{D^0 p K^-} = \frac{BR(\Lambda_b^0 \rightarrow D^0 p K^-)}{BR(\Lambda_b^0 \rightarrow D^0 p \pi^-)} = 0.112 \pm 0.019(\text{stat})^{+0.0011}_{-0.0014}(\text{syst})$$

$$R_{\Xi_b^0} = \frac{f_{b \rightarrow \Xi_b^0}}{f_{b \rightarrow \Lambda_b^0}} \frac{BR(\Xi_b^0 \rightarrow D^0 p K^-)}{BR(\Lambda_b^0 \rightarrow D^0 p \pi^-)} = 0.29 \pm 0.12(\text{stat}) \pm 0.08(\text{syst})$$

$$M(\Xi_b^0) = 5802.0 \pm 5.5(\text{stat}) \pm 1.7(\text{syst}) \text{ MeV}/c^2$$

in good agreement with the CDF result

Measurement of Ξ_b^- and Ω_b^- masses (Preliminary)

LHCb-CONF-2011-060

- search of the strange b-baryon states, Ξ_b^- (bsd) and Ω_b^- (bss), in the decay modes $\Xi_b^- \rightarrow J/\psi \Xi^-$ and $\Omega_b^- \rightarrow J/\psi \Omega^-$ ($J/\psi \rightarrow \mu^+ \mu^-$, $\Xi^- \rightarrow \Lambda^0 \pi^-$, $\Omega^- \rightarrow \Lambda^0 K^-$ and $\Lambda^0 \rightarrow p \pi^-$)
- masses of Ξ_b^- and Ω_b^- already measured by CDF [PRD 80(2009)072003] and D0 [PRL 101(2008)232002]
- Ω_b^- mass measurements by CDF and DO have a discrepancy greater than 6σ
- rich topology, 5 charged tracks and 3 displaced vertices
- data sample 576 pb^{-1}

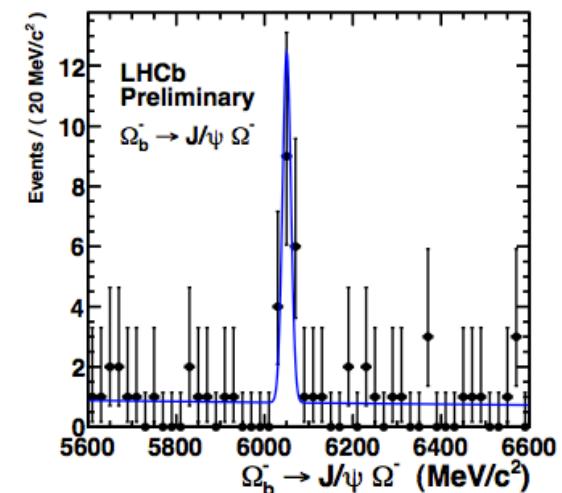
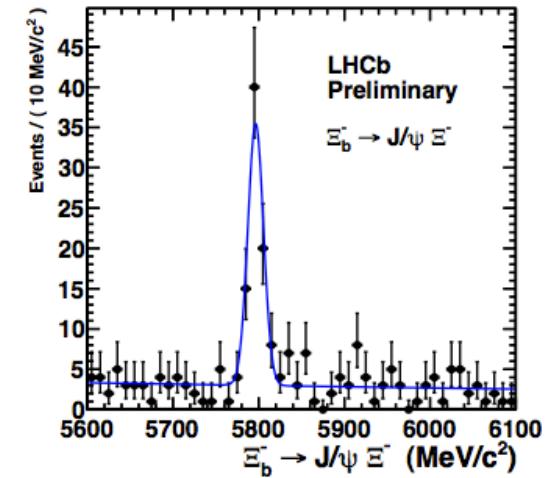
$$M(\Xi_b^-) = 5796.5 \pm 1.2(\text{stat}) \pm 1.2(\text{syst}) \text{ MeV}/c^2$$

$$M(\Omega_b^-) = 6050.3 \pm 4.5(\text{stat}) \pm 2.2(\text{syst}) \text{ MeV}/c^2$$

- systematics dominated by the momentum scale calibration
- best mass measurements up to date, $M(\Omega_b^-)$ measurement favours CDF

	$M(\Xi_b^-)$	$M(\Omega_b^-)$
DØ	5774 ± 19	6165 ± 16
CDF	5790.9 ± 2.7	6054.4 ± 6.9
PDG	5790.5 ± 2.7	6071 ± 40
LHCb	5796.5 ± 1.7	6050.3 ± 5.0

will be updated with more luminosity



because of time constraints I did not touch ..

heavy onia Preliminary

- χ_b reconstructed via the radiative decays $\chi_{bJ}(nP) \rightarrow Y(1S)\gamma$
 - 1) measured the fraction of $Y(1S)$ from $\chi_b(1P)$ decays **LHCb-PAPER-2012-015**
 - 2) measured the masses **LHCb-CONF-2012-020**

exotic onia

- study of $X(3827)$, measured production cross section and mass **EPJC 72(2012)1972**
- search for $X(4140)$ in $B^+ \rightarrow X(4140)K^+$, $X(4140) \rightarrow J/\psi\phi$ **PRD 85(2012)091103**

D_{sJ} spectroscopy Preliminary **LHCb-PAPER-2012-016**

- the study of D^+K_s and D^0K^+ invariant mass spectra confirms the existence of $D_{sJ}^*(2860)^+$ and $D_{s1}^*(2700)^+$ observed at B-factories

world best measurement of B^+ , B_d , B_s and Λ_b masses **PLB 708(2012)241**

measurement of B_c mass Preliminary **LHCb-CONF-2012-016**

Conclusions



LHCb produced many interesting results with 2010 and 2011 data and will continue to provide precise and competitive measurements in the heavy flavour sector

- several measurements are currently being updated with the full 2011 luminosity
- production measurements will be re-performed at $\sqrt{s} = 8$ TeV (expected 2.2 fb^{-1})
- polarization measurements for J/ψ and other other heavy quarkonia states are in progress
- explore other promising channels for double onia production studies:
 $J/\psi\psi(2S)$, $J/\psi Y(nS)$, $Y(nS)Y(nS)$
- exotic spectroscopy

- B_c studies
- Λ_b^0 , Ξ_b^- and Ω_b^- lifetimes measurements
- Σ_b baryon studies
-

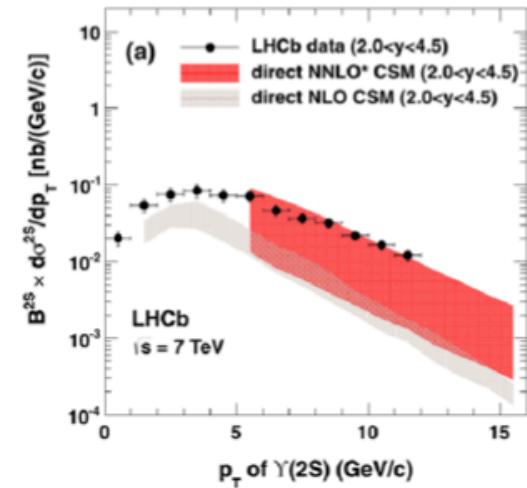
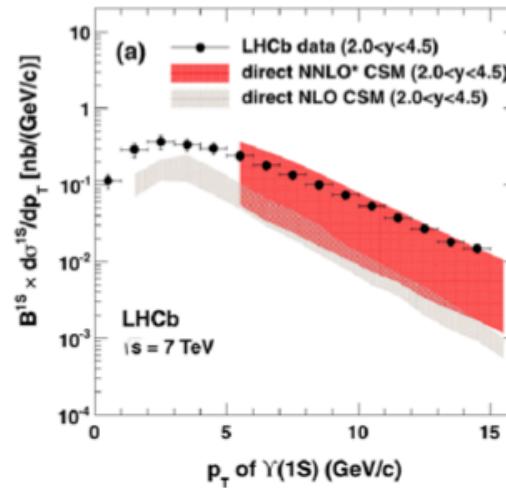
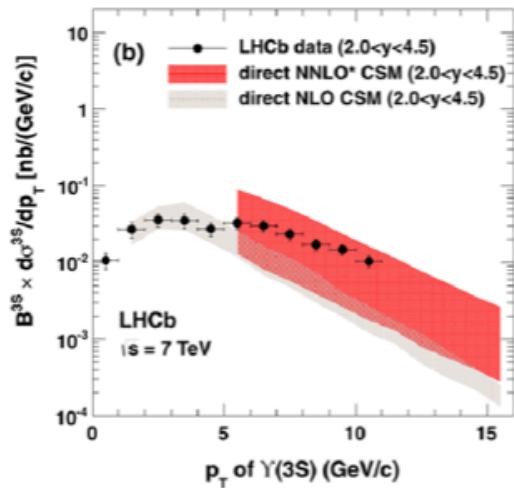
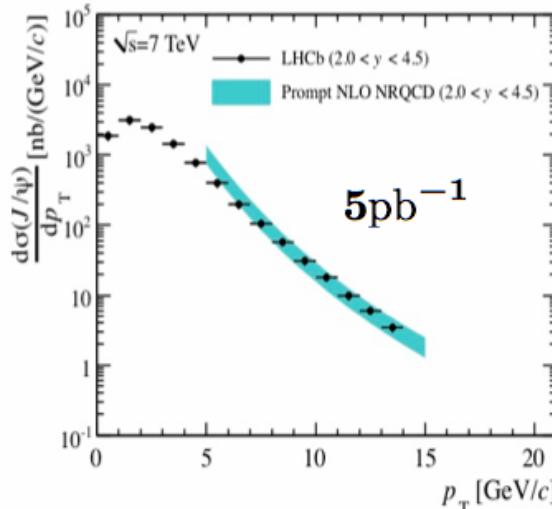
LHCb has a world class heavy flavour production and spectroscopy program

backup slides

Comparison with theory

- as already seen by Tevatron production σ 's are larger than NRQCD calculations based on LO CSM
- recent QCD calculations are found to be in good agreement with all our measurements*

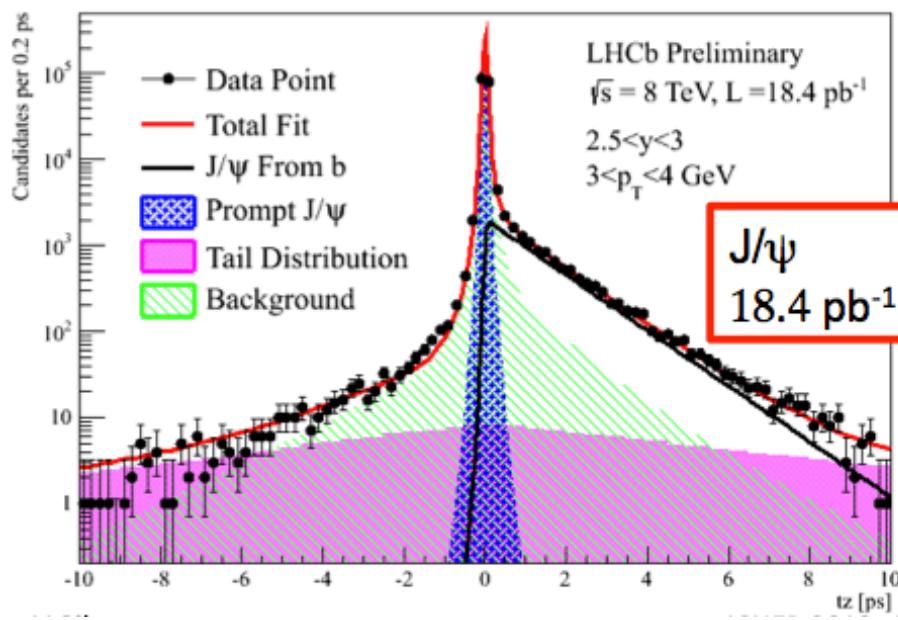
LHCb data vs. CS+CO



Charmonia and Bottomonium at 8 \sqrt{s} = TeV (Preliminary)

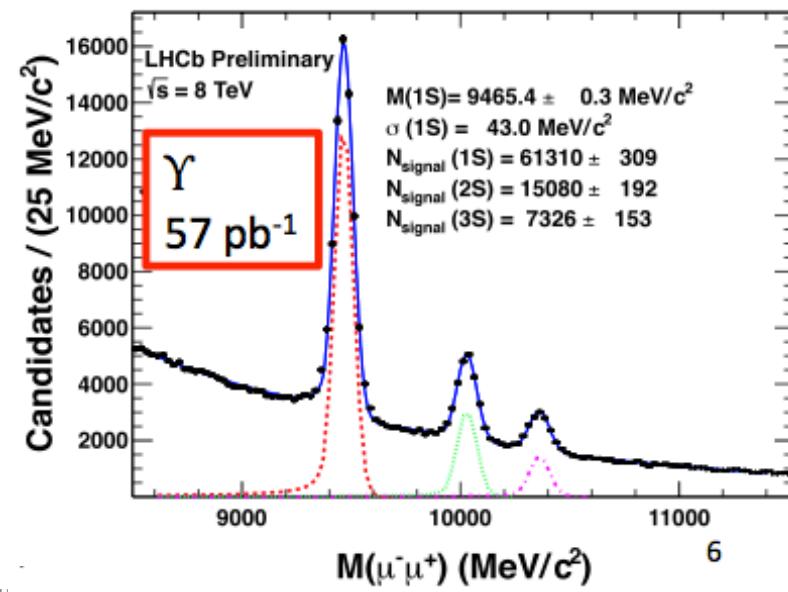
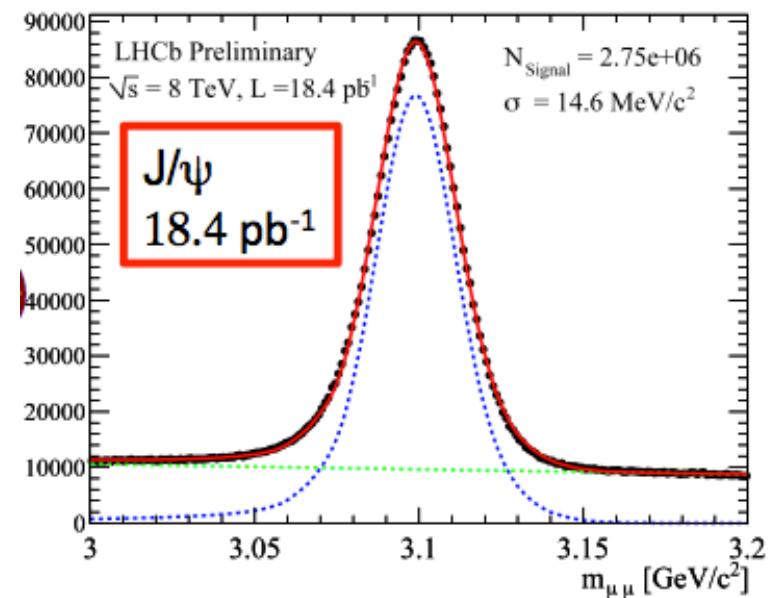
LHCb-CONF-2012-25

- LHCb is performing extremely well at 8 TeV
- $\sigma(m_{J/\psi}) \approx 14.5 \text{ MeV}/c^2$
- $\sigma(m_\gamma) \approx 43 \text{ MeV}/c^2$
- $\sigma(\text{proper time}) \approx 61 \text{ fs}$



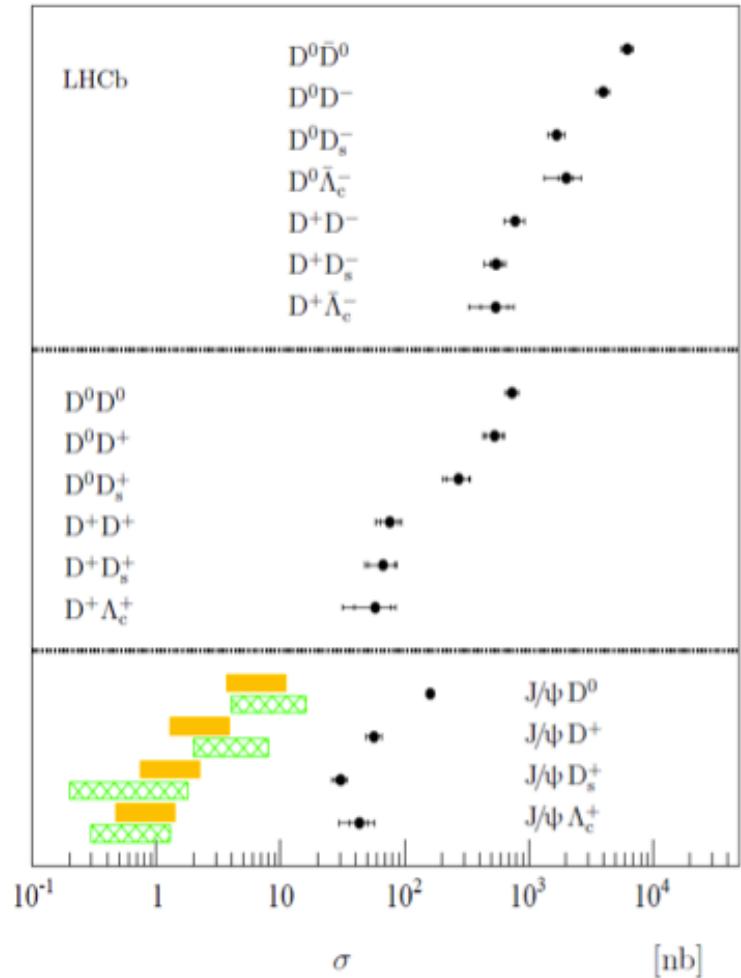
BEACH 2012, Wichita

P. de Simone, LNF-INFN



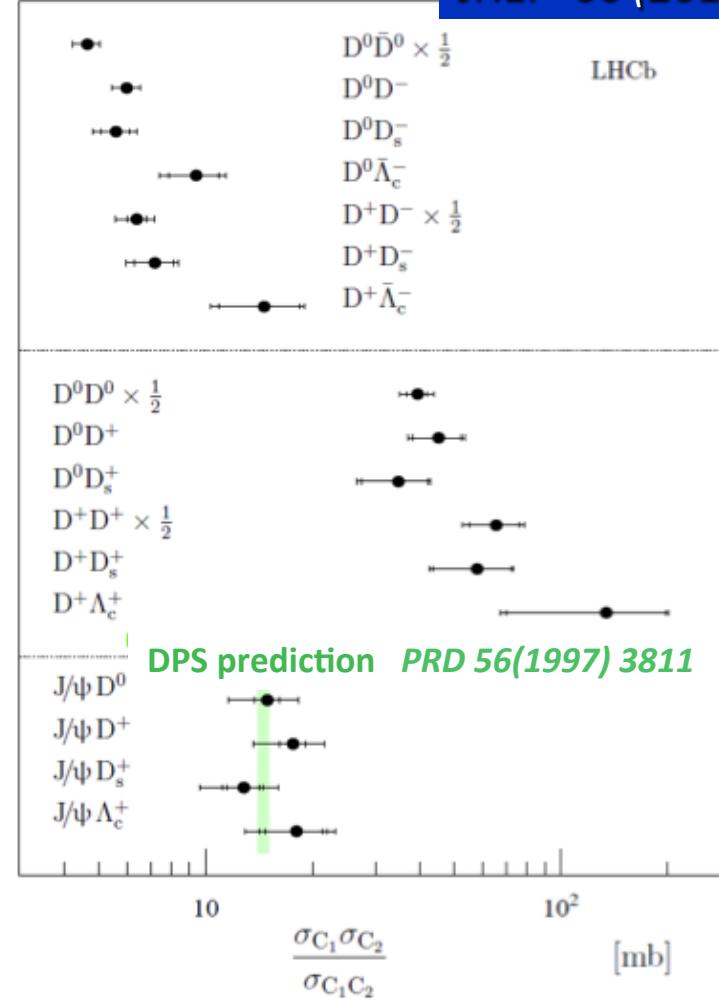
J/ ψ C and CC production: cross sections

JHEP 06 (2012) 141



PRD 57 (1998) 4385
EPJC 61 (2009) 693

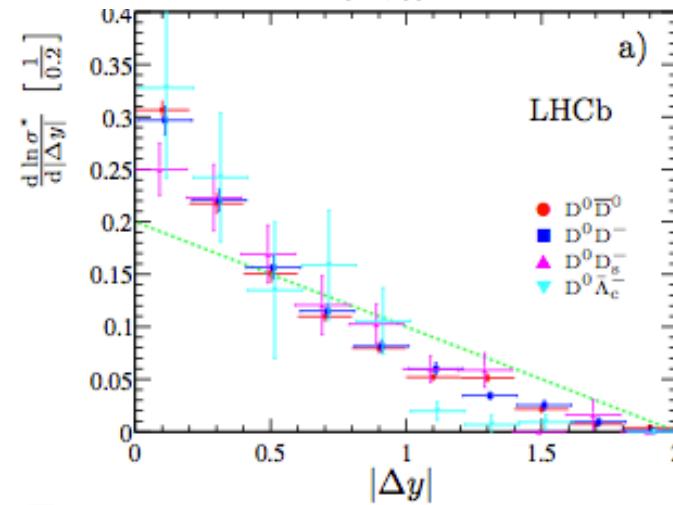
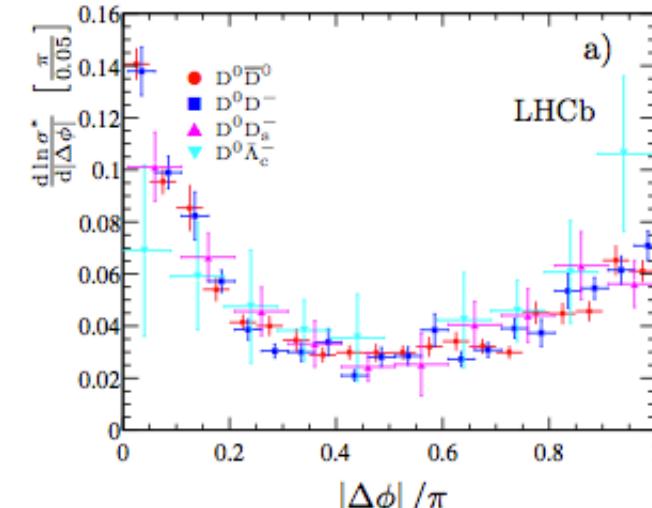
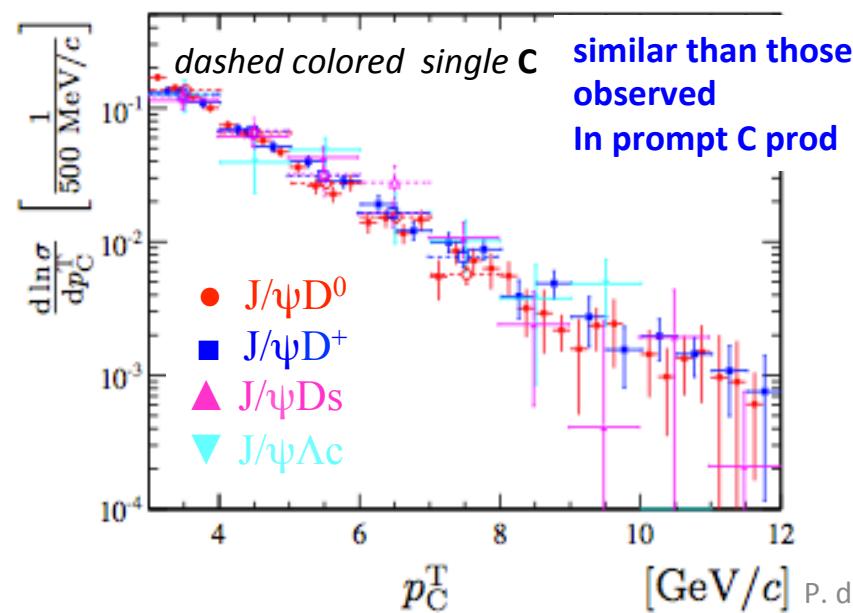
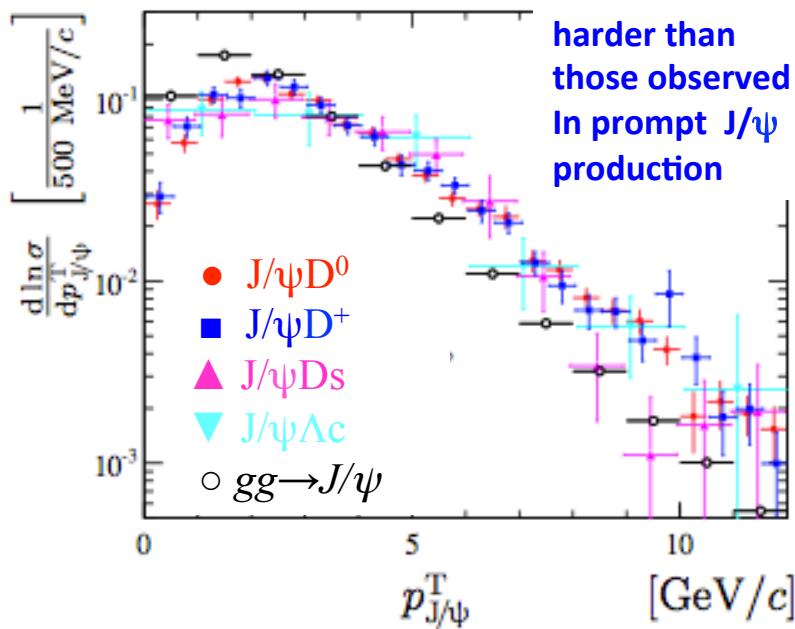
significantly lower than the measurements



DPS prediction works well for J/ ψ C modes,
while CC modes are higher by a factor 2 to 3

$J/\psi C$ and CC production: kinematics

JHEP 06 (2012) 141

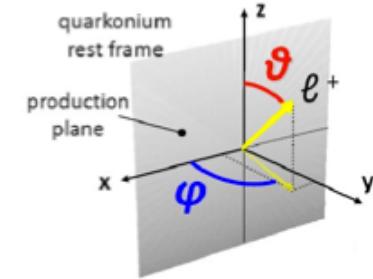


for CC events significant rapidity and azimuthal correlations are observed → suggest a sizeable contribution from the gluon splitting process to charm quark production

Polarization

- polarization measurements are important to improve the accuracy on production measurements, but also represent an important test for production models
- polarization described by three parameters λ_θ , λ_ϕ and $\lambda_{\theta\phi}$
 - θ = polar angle between μ^+ in the J/ ψ rest-frame and the J/ ψ momentum direction
 - ϕ = azimuthal angle between J/ ψ production plane and μ^+ plane

$$\frac{dN}{d \cos \vartheta d\phi} \propto 1 + \lambda_\theta \cos^2 \vartheta + \lambda_\phi \sin^2 \vartheta \cos 2\phi + \lambda_{\theta\phi} \sin^2 \vartheta \cos \phi$$

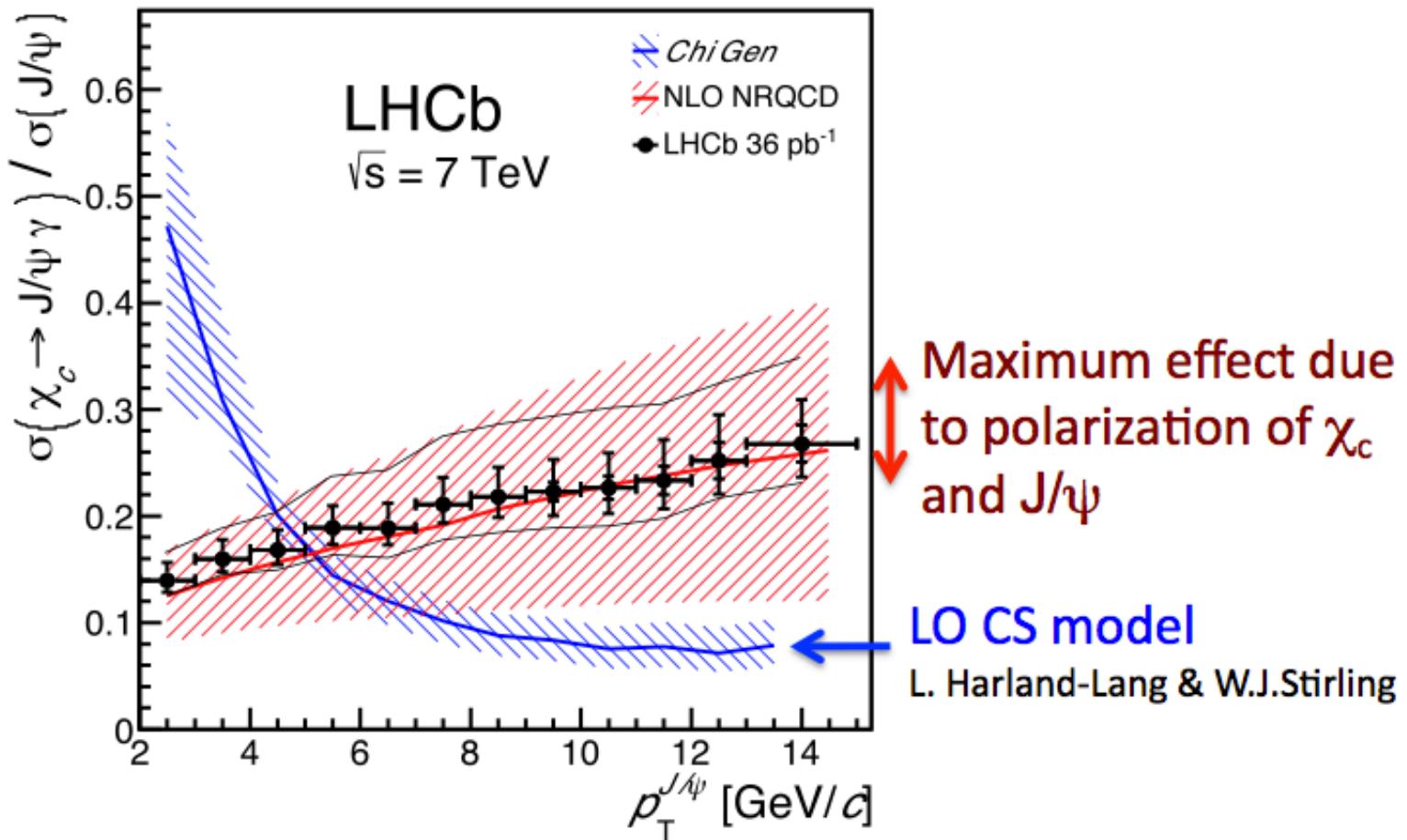


- extract λ_θ , λ_ϕ and $\lambda_{\theta\phi}$ using an unbinned maximum likelihood fit to the μ^+ angular distribution
- result will be given in bins of p_T and y
- **J/ ψ polarization result expected soon**

Heavy Onia

arXiv:1204.1462

fraction of J/ψ from χ_c states



results in remarkable agreement with NLO NRQCD calculation [PRD 83(2011)111503]

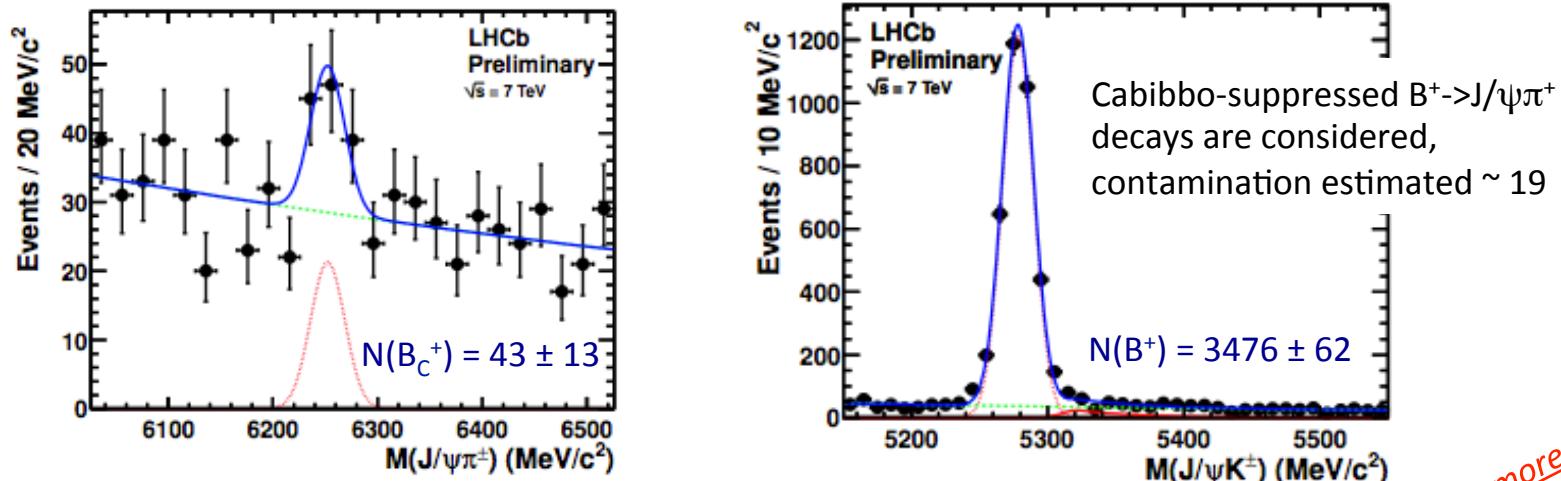
B_C^+ to B^+ production rate (*Preliminary*)

LHCb-CONF-2011-017

- measurements of B_C^+ production, mass and lifetime constrain QCD calculation
- first B_C^+ observation by CDF [*PRL* 81(1998)2432]
- data sample 32.5 pb^{-1}
- B_C^+ absolute BR not measured yet -> the strategy of this analysis is to measure

$$R_{C^+} = \frac{\sigma(B_C^+) \times BR(B_C^+ \rightarrow J/\psi\pi^+)}{\sigma(B^+) \times BR(B^+ \rightarrow J/\psi K^+)}$$

- $B_C^+ \rightarrow J/\psi\pi^+$ and $B^+ \rightarrow J/\psi K^+$ are selected with identical requirements *in the range* $2.5 < y < 4.5$ and $p_T > 4 \text{ GeV}/c$



$$R_{C^+} = 2.2 \pm 0.8(\text{stat}) \pm 0.2(\text{syst})\%$$

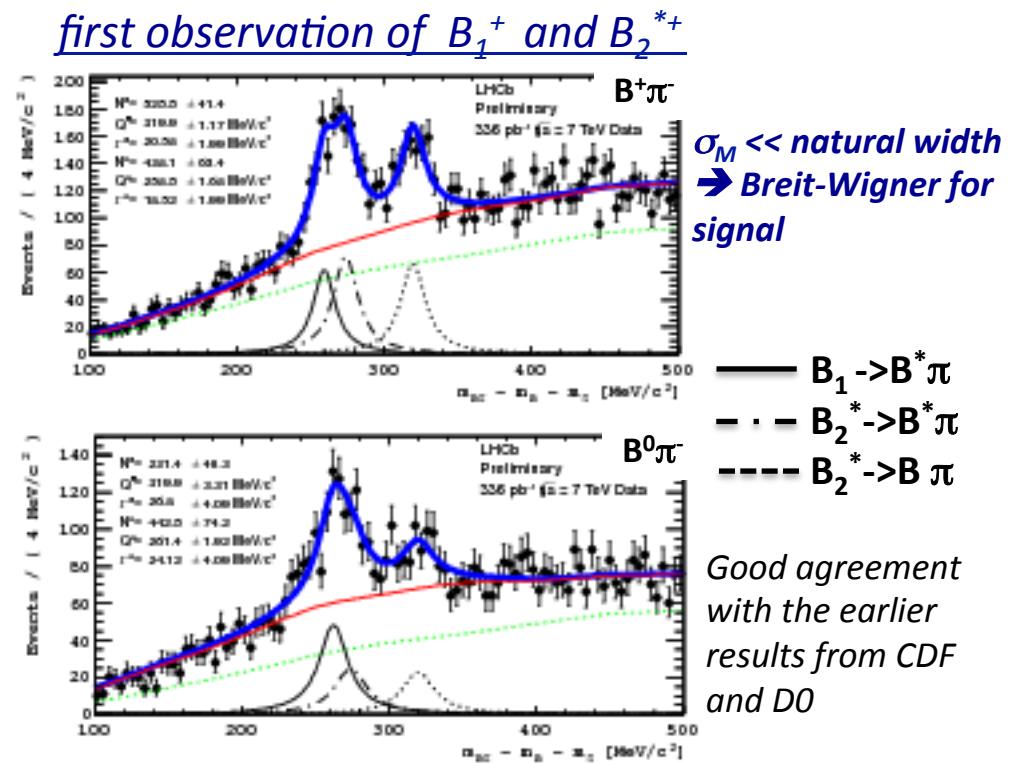
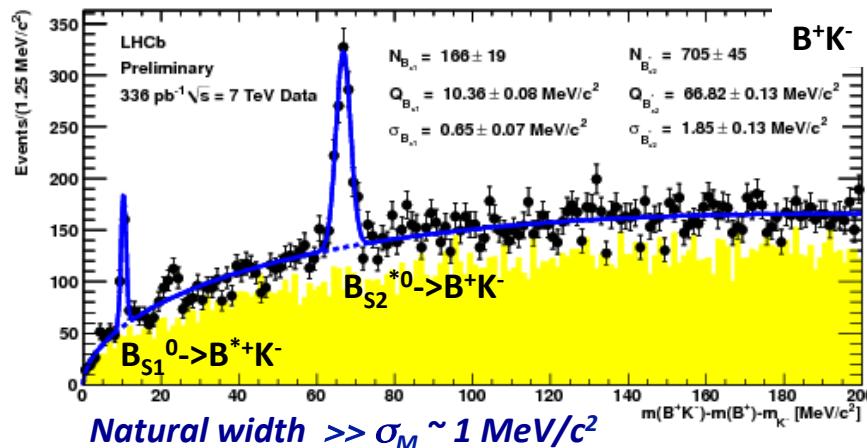
- main systematics (6%) due to B_C^+ lifetime known with a large uncertainty

will be updated with more luminosity

Observation of excited $B_{(s)}^{**}$ (Preliminary)

LHCb-CONF-2011-053

- properties of excited $B_{(s)}$ ($L=1$) are predicted by Heavy Quark Effective Theory [PRD 64(2001)114004]
- $B_1(5721)^0$, $B_2^*(5830)^0$, $B_{s1}(5830)^0$, $B_{s2}(5840)^0$ observed by CDF and D0
[PRL 102(2009)102003, 99(2007)172001, 100(2008)082001/082002]
- B mesons reconstructed in $J/\psi K^*$ $D\pi$ and $D\pi\pi\pi$ modes
- search for $B_{(s)}^{**}$ states in the invariant mass distribution of B^+K^- , $B^+\pi^-$ and $B^0\pi^+$
 $B^{**} \rightarrow B h$ and $B^{**} \rightarrow B^*(B\gamma)h$, the invariant masses of the 2 decays are shifted because we do not reconstruct the soft γ ($M_{B^*} - M_B \sim 46 \text{ MeV}/c^2$)
- study the spectrum
 $Q = m(Bh) - m(B) - m(h)$
- data sample 336 pb^{-1}



Quarkonia

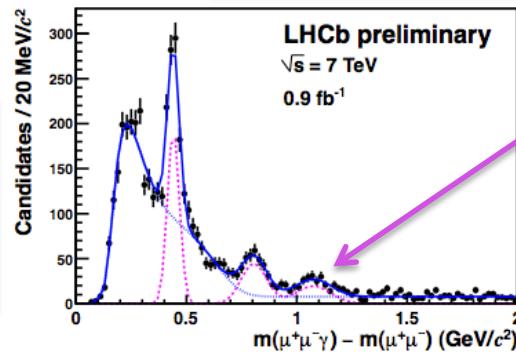
because of time constraints I did not touch ..

heavy onia

Preliminary

- χ_b reconstructed via the radiative decays $\chi_{bJ}(nP) \rightarrow Y(1S)\gamma$
- measured the fraction of $Y(1S)$ from $\chi_b(1P)$ decays $f_{\chi_b \rightarrow Y} = (20.7 \pm 5.7(stat) \pm 2.1(syst)_{-5.4}^{+2.7}(pol))\%$
- measured the masses

$$\begin{aligned} M(\chi_b(1P)) &= (9.901 \pm 0.002) \text{GeV}/c^2 \\ M(\chi_b(2P)) &= (10.266 \pm 0.006) \text{GeV}/c^2 \\ M(\chi_b(3P)) &= (10.535 \pm 0.010) \text{GeV}/c^2 \end{aligned}$$



LHCb-PAPER-2012-015

$N(\chi_b(3P)) = 196 \pm 19$
12.1 σ significance
 $M(\chi_b(3P))$ consistent with ATLAS/D0

LHCb-CONF-2012-020

exotic onia

- study of $X(3827)$, measured the
 - 1) production cross section in the ranges $5 < p_T < 20 \text{ GeV}/c$ and $2.5 < y < 4.5$ $\text{EPJC } 72(2012)1972$
 - 2) $M_{X(3872)} = (3871.95 \pm 0.48(stat) \pm 0.12(syst)) \text{MeV}/c^2$ still unclear if above DD^* threshold or not
 $M(D^0) + M(D^{*0}) = 3871.79 \pm 0.29 \text{ MeV}/c^2$
- search for $X(4140)$ in $B^+ \rightarrow X(4140)K^+$, $X(4140) \rightarrow J/\psi\phi$
 don't find evidence for this state in 2.4σ disagreement with CDF $\text{PRD } 85(2012)091103$
- **work in progress** search for $Z(4430)^+ \rightarrow \psi(2S)\pi^+$ claimed by Belle but not confirmed by BaBar

Heavy hadrons

because of time constraints I did not touch ..

D_{sJ} spectroscopy

Preliminary

- the study of D^+K_s and D^0K^+ invariant mass spectra confirms the existence of $D_{sJ}^*(2860)^+$ and $D_{s1}^*(2700)^+$ observed at B-factories

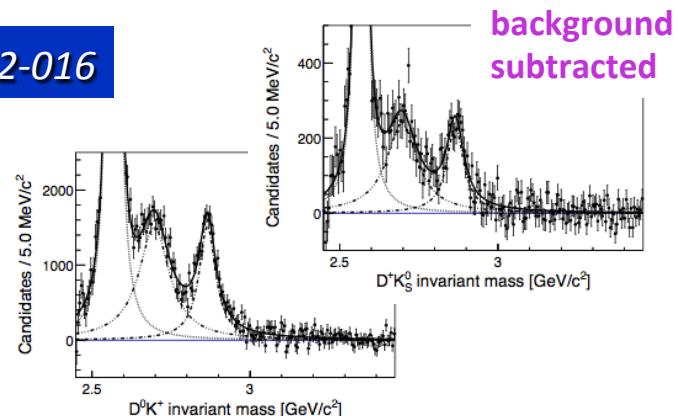
LHCb-PAPER-2012-016

$$M(D_{s1}^*(2700)^+) = (2709.4 \pm 1.9(\text{stat}) \pm 4.5(\text{syst})) \text{MeV}/c^2$$

$$\Gamma(D_{s1}^*(2700)^+) = (121.7 \pm 7.3(\text{stat}) \pm 12.1(\text{syst})) \text{MeV}$$

$$M(D_{sJ}^*(2860)^+) = (2866.7 \pm 1.0(\text{stat}) \pm 6.3(\text{syst})) \text{MeV}/c^2$$

$$\Gamma(D_{sJ}^*(2860)^+) = (64.5 \pm 3.2(\text{stat}) \pm 6.6(\text{syst})) \text{MeV}$$



world best measurement of B^+ , B_d

B_s and Λ_b masses

PLB 708(2012)241

Quantity	LHCb measurement	Best previous measurement	PDG fit
$M(B^+)$	5279.38 ± 0.35	5279.10 ± 0.55 [4]	5279.17 ± 0.29
$M(B^0)$	5279.58 ± 0.32	5279.63 ± 0.62 [4]	5279.50 ± 0.30
$M(B_s^0)$	5366.90 ± 0.36	5366.01 ± 0.80 [4]	5366.3 ± 0.6
$M(\Lambda_b^0)$	5619.19 ± 0.76	5619.7 ± 1.7 [4]	–
$M(B^0) - M(B^+)$	0.20 ± 0.20	0.33 ± 0.06 [15]	0.33 ± 0.06
$M(B_s^0) - M(B^+)$	87.52 ± 0.32	–	–
$M(\Lambda_b^0) - M(B^+)$	339.81 ± 0.72	–	–

[4] CDF PRL 96(2006)202001

[15] BaBar PRD 78(2008)011103

measurement of B_c mass

$$M(B_c^+) = 6268.0 \pm 4.0(\text{stat}) \pm 6.0(\text{syst}) \text{MeV}/c^2$$

Preliminary

LHCb-CONF-2012-016