Emi Kou, Sergey Barsuk

LAL Orsay

IPNO seminar, February 19, 2015

Measurement of η_c production via the decay $\eta_c \to p\bar{p}$

First inclusive analysis of charmonium on hadron machines, with hadronic decays of charmonium

Main results :

in the LHCb acceptance ($2 < y < 4.5$) and for pT > 6.5 GeV/c

- ❑ Ratio of prompt production of η_c relative to that of J/ψ
- ❑ Three or four pT bins, no binning in rapidity
- ❑ Relative η_c inclusive branching fraction from b-hadron decays
- ❑ Mass of η_c relative to that of J/ψ

PRD 86 (2012) 034011

arXiv:1409.3612

Ph.D. thesis of Maksym Teklishyn

Charmonia production using hadronic decays

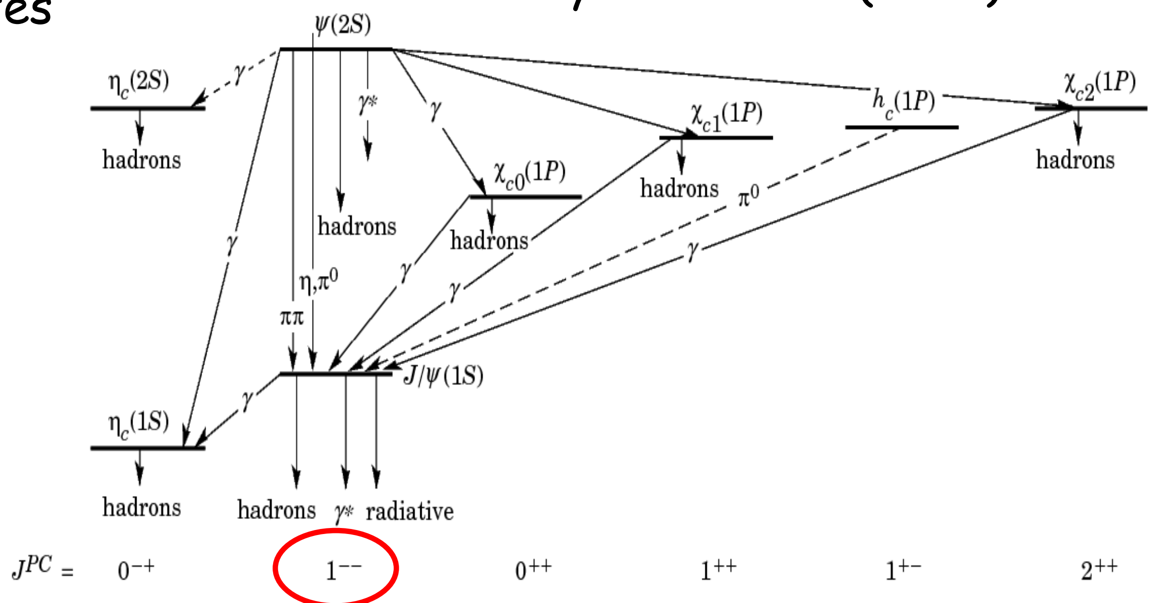
Phys. Rev. D86 (2012) 034011

- Decays to hadronic final states to access production of charmonia, other than those having $J^{PC} = 1^{--}$

- Charmonia decays to the $p\bar{p}$ final states

- + other final states : φφ, $\varphi f_{0,2}$, K*K*, φKK, φππ, ΛΛ, ΞΞ (baryon-antibaryon forbidden by pQCD at LO), …

- Particular case of η_c : hadronic decays only $BR(\eta_c \to \gamma\gamma) \sim 10^{-4}$



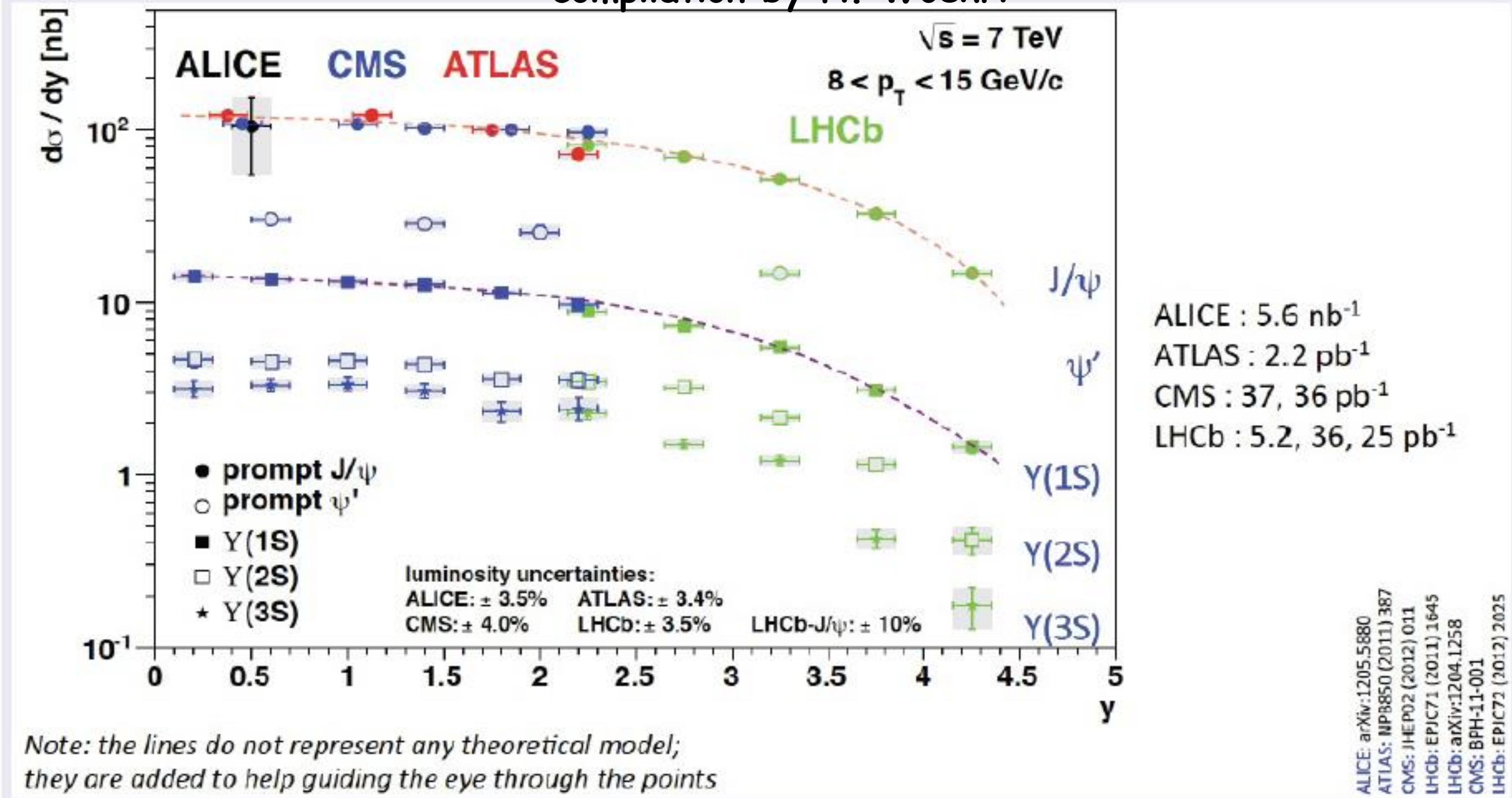
	Mass, MeV/c^2	$\mathcal{B}(c\bar{c} \to p\bar{p})$, $\times 10^{-3}$
η_c (1S)	2980.5 ± 1.47	1.51 ± 0.16
J/ψ (1S)	3096.916 ± 0.011	2.120 ± 0.029
χ_{c0} (1P)	3414.75 ± 0.31	0.213 ± 0.012
χ_{c1} (1P)	3510.66 ± 0.07	0.073 ± 0.004
h_c(1P)	3525.67 ± 0.32	not seen
χ_{c2} (1P)	3556.20 ± 0.09	0.071 ± 0.004
η_c (2S)	3638.9 ± 1.3	< 0.29 at 90% CL
$\psi(2S)$	3686.09 ± 0.04	0.275 ± 0.012
$\psi(3770)$	3773.15 ± 0.33	not seen

3.2 ± 0.5 (Emi Kou)

Studies of prompt charmonia production at the LHC

- Important effort to accommodate observed J/ψ production since 1997: NRQCD developments, higher-order corrections, CS, CO
- Consistent and complementary measurements from all LHC experiments

compilation by H. Woehri



- However, comprehensive model describing charmonia production still missing (e.g. J/ψ production rates AND polarization)

Charmonia production measurements

- Measure production cross-sections, study pT dependences, as a by-product measure masses and natural widths
- Production of η_c is studied relative to the J/ψ production (measured using di-muon final state)
- Distinguish **prompt charmonium production** and **charmonium inclusive production in b-hadron decays** using separation between reconstructed b-production and decay vertices

Disclaimer/definitions

- Promptly produced charmonia include charmonia directly produced in parton interactions and those originating from the decays of heavier quarkonium states, which are in turn produced in parton interactions.
- In all studies production rates include charmonia from the decays of heavier states

Prompt η_c production

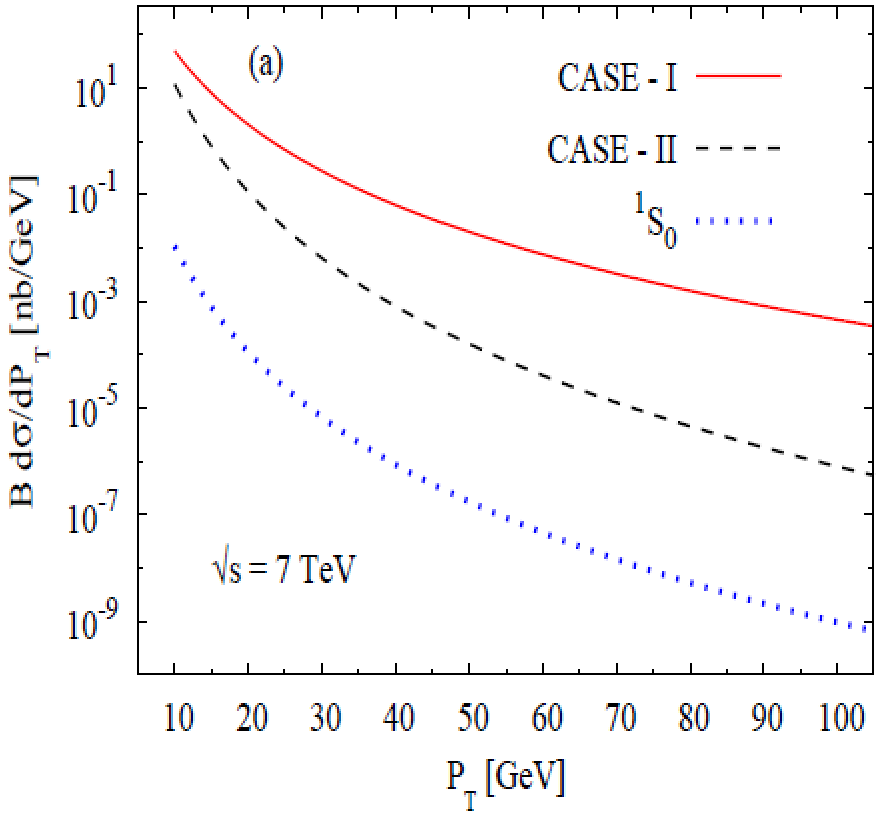
- Test relation between the η_c and J/ψ matrix elements within the heavy quark spin-symmetry, further constraint on QCD matrix elements (E. Kou)
- NLO (Maltoni et al.) computations lead to a different pT dependence of the production rates for the spin singlet (η_c) and triplet (J/ψ, χ_{cJ}) states
- Recent LHCb comparison of pT spectrum for χ_{c0}, χ_{c2} production with respect to χ_{c1} production, another important comparison is that between χ_{c0} and η_c
- Indirect information on the properties of heavier states production, e.g. $\sigma(\eta_c(2S)) \times BR(\eta_c(2S) \rightarrow \eta_c(1S)\,X)$

Prompt η_c production

- The only theoretical prediction (LO only !) before the LHCb analysis:

S. Biswal, K. Sridhar, **J.Phys. G39 (2012) 015008**

7 TeV, -2 < y < 2



B = 3 x 10^{-4}

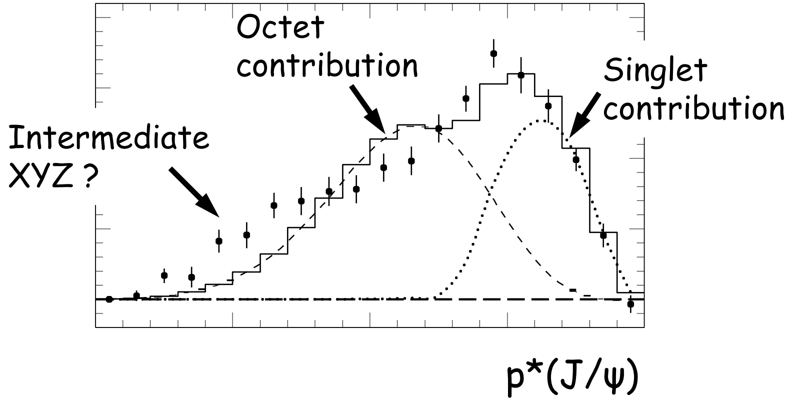
CTEQ 5L LO parton densities

Case I: $^3S_0 + {}^3S_1^{[8]}$

Case II: $^3S_0 + {}^1P_1^{[8]}$

Inclusive η_c production in b-hadron decays

- Theory of inclusive production: delicate NLO calculations of singlet contribution
- Compare data on the η_c and J/ψ production in inclusive b-hadron decays to extract information on the octet matrix elements / test matrix element universality (Emi Kou)
- While BR(b → J/ψ X) is in reasonable agreement with models, the only available (CLEO) experimental UL on BR(b → η_c X) is below model predictions
- Many missing (inclusive) measurements



	$B^-/\overline{B}^0$ admixture	$B^-/\overline{B}^0/\overline{B}^0_s$/b-baryon admixture
η_c (1S)	$< 0.9@90\%CL$	–
J/ψ (1S)	1.094 ± 0.032	1.16 ± 0.10
χ_{c0} (1P)	–	–
χ_{c1} (1P)	0.386 ± 0.027	1.4 ± 0.4
h_c(1P)	–	–
χ_{c2} (1P)	0.13 ± 0.04	–
η_c (2S)	–	–
$\psi(2S)$	0.307 ± 0.021	0.283 ± 0.029

Table 4.2: Branching fractions (in %) of the inclusive b-hadron decays into charmonium states [57]. Admixture of light B^+ and $\overline{B}^0$ mesons is shown for the measurements of the e^+e^- experiments operating at a centre-of-mass energy around $\Upsilon(4S)$resonance, while admixtures of B^-, $\overline{B}^0$, $\overline{B}^0_s$ and b-baryons are considered for measurements from experiments at LEP, Tevatron and LHC

The LHCb experiment

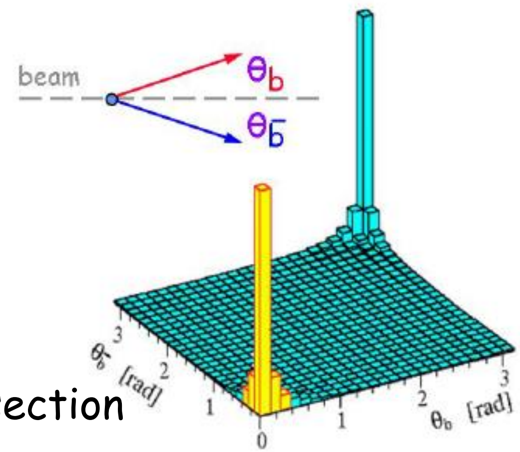
- LHCb physics
  - Precision studies of rare effects in b- and c-physics
  - Production measurements at new energy scale in the forward region
- Large $c\bar{c}$ and $b\bar{b}$ production cross section at LHC with **ALL c- and b-species produced**

$\sigma(b\bar{b})$ ~75 μb at $\sqrt{s}$ = 7 TeV in the LHCb acceptance

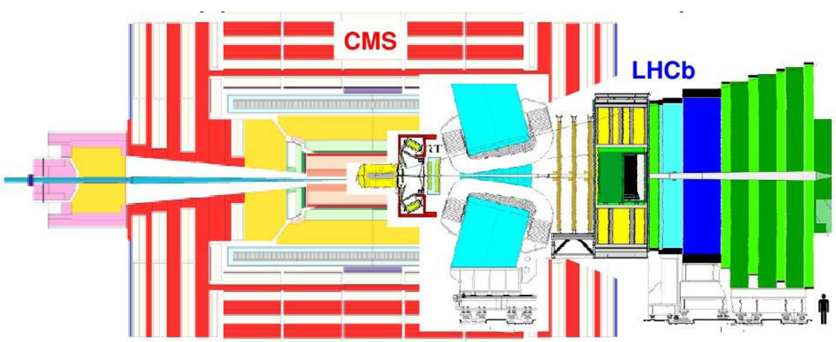
a long LHC fill yields ~1.5 x 10^9 $b\bar{b}$ pairs

(C.f.: 1.4 x 10^9 $b\bar{b}$ pairs in Belle + BaBar over 10 years)

$\sigma(c\bar{c})$ ~1 mb at $\sqrt{s}$ = 7 TeV in the LHCb acceptance

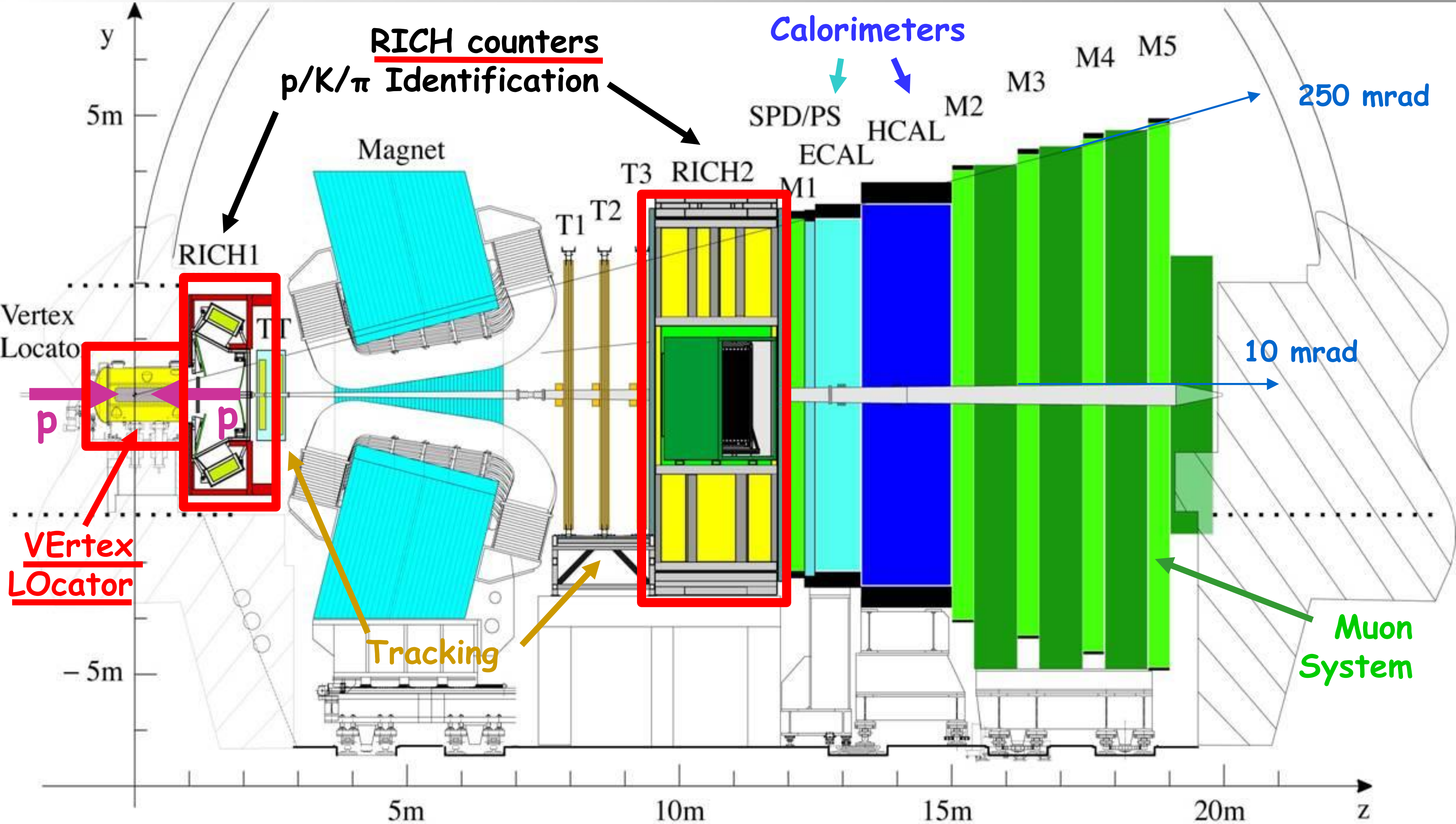


- **Correlated $b\bar{b}$ production**, second b in acceptance once the first b is in (flavour tagging)
- LHCb covers forward region: 1.9 < η < 4.9
  - optimized for forward peaked HQ production at the LHC
  - only ~4% of solid angle, but ~40% of HQ production cross section



- **Unique** (complementary) **acceptance** amongst LHC experiments: explore QCD in the forward region
- LHCb covers forward region: 1.9 < η < 4.9

LHCb detector – single-arm forward spectrometer 10-250 mrad (V), 10-300 mrad (H)



Vertex reconstruction:
VELO

Kinematics:
Magnet
Tracker
Calorimeters

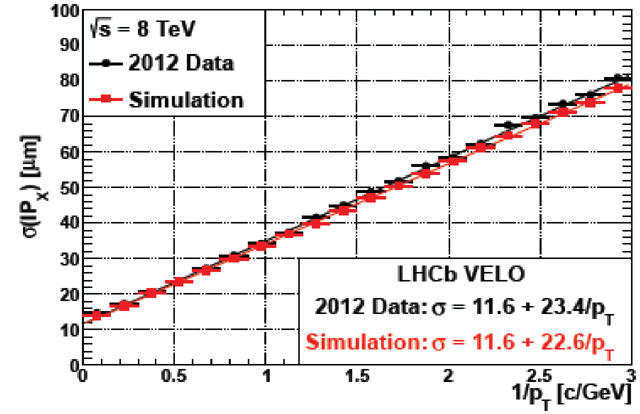
PID:
RICHs
Calorimeters
Muon Chambers

Trigger:
Muon Chambers
Calorimeters
Tracker

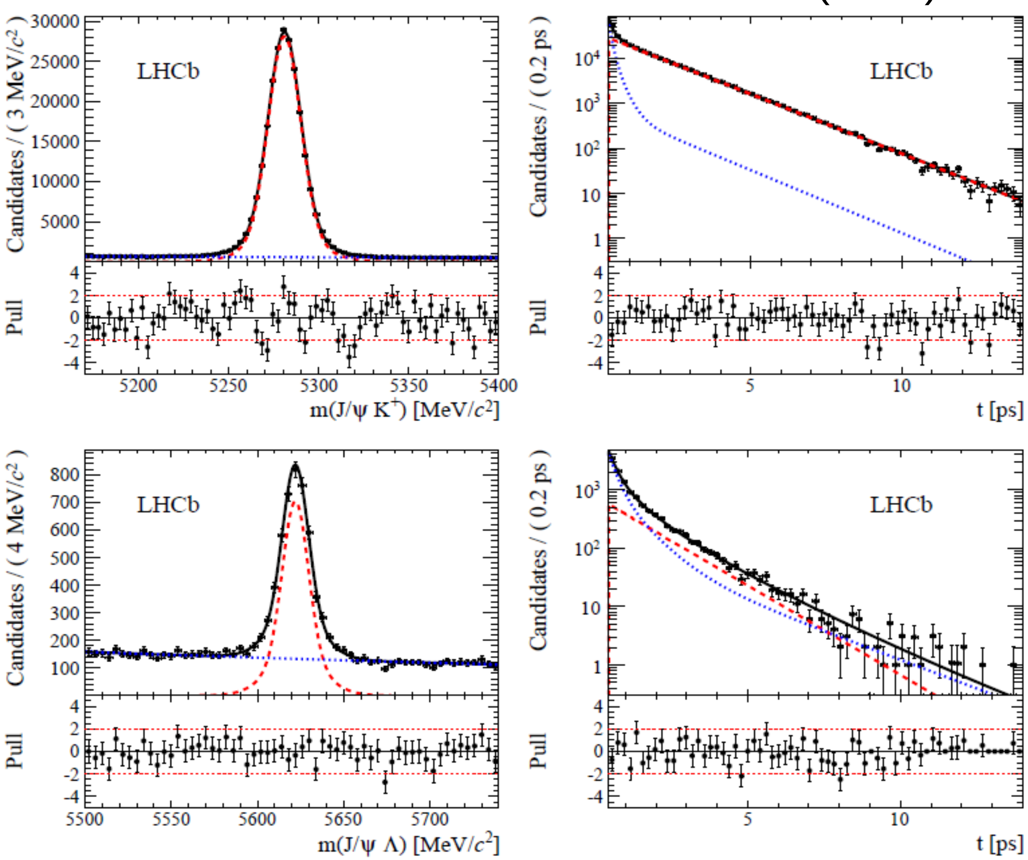
Vertex Locator: precise reconstruction of tracks and vertices

- Excellent spatial resolution, down to 4μ for single tracks
- Precise impact parameter measurement,
  $\sigma_{IP} = 11.6 + 23.4/pT$ [μ]
- Precise primary vertex reconstruction,
  $\sigma_x = \sigma_x = 13\mu$, $\sigma_z = 69\mu$ for a vertex of 25 tracks

Impact parameter resolution



JHEP 04 (2014) 114



- Detector well understood, simulation describes data
- Vertex Locator (VELO) provides excellent proper time resolution

Lifetime	Value [ps]
$\tau_{B^+\to J/\psi K^+}$	$1.637 \pm 0.004 \pm 0.003$
$\tau_{B^0\to J/\psi K^{*0}}$	$1.524 \pm 0.006 \pm 0.004$
$\tau_{B^0\to J/\psi K^0_s}$	$1.499 \pm 0.013 \pm 0.005$
$\tau_{\Lambda^0_b\to J/\psi \Lambda}$	$1.415 \pm 0.027 \pm 0.006$
$\tau_{B^0_s\to J/\psi \phi}$	$1.480 \pm 0.011 \pm 0.005$

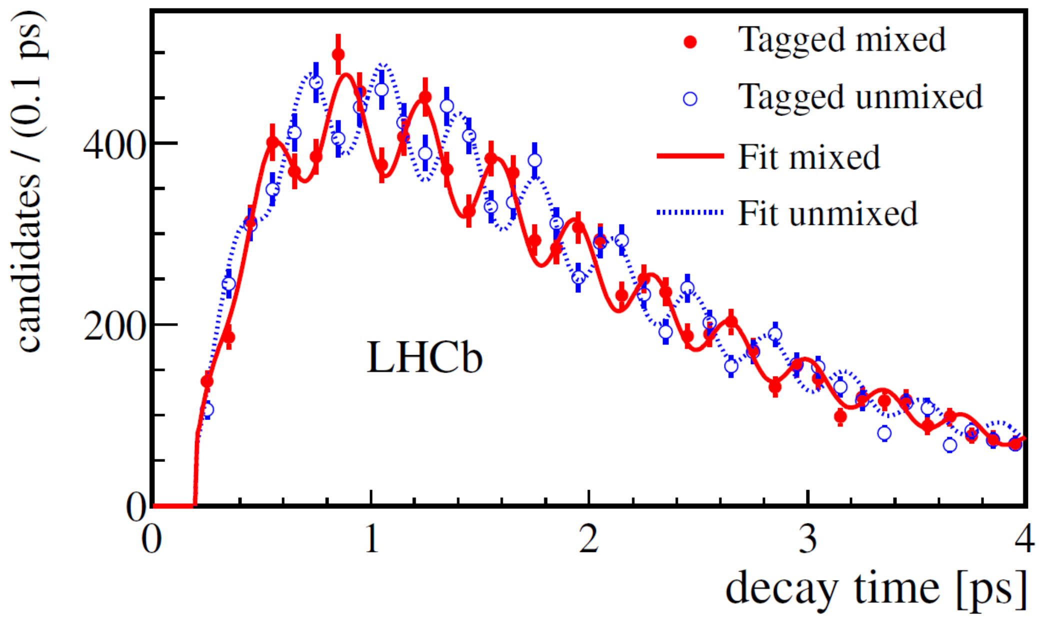
VELO: resolving $B_s\bar{B}_s$ oscillations

- Vertex resolution allows to resolve fast (x~27) $B_s\bar{B}_s$ oscillations

- $B_s^0 \to D_s^- \pi^+$

  $D_s^- \to \phi(K^+K^-)\pi^-$
  $D_s^- \to K^{*0}(K^+\pi^-)K^-$
  $D_s^- \to K^+K^-\pi^-$ nonresonant
  $D_s^- \to K^-\pi^+\pi^-$
  $D_s^- \to \pi^-\pi^+\pi^-$

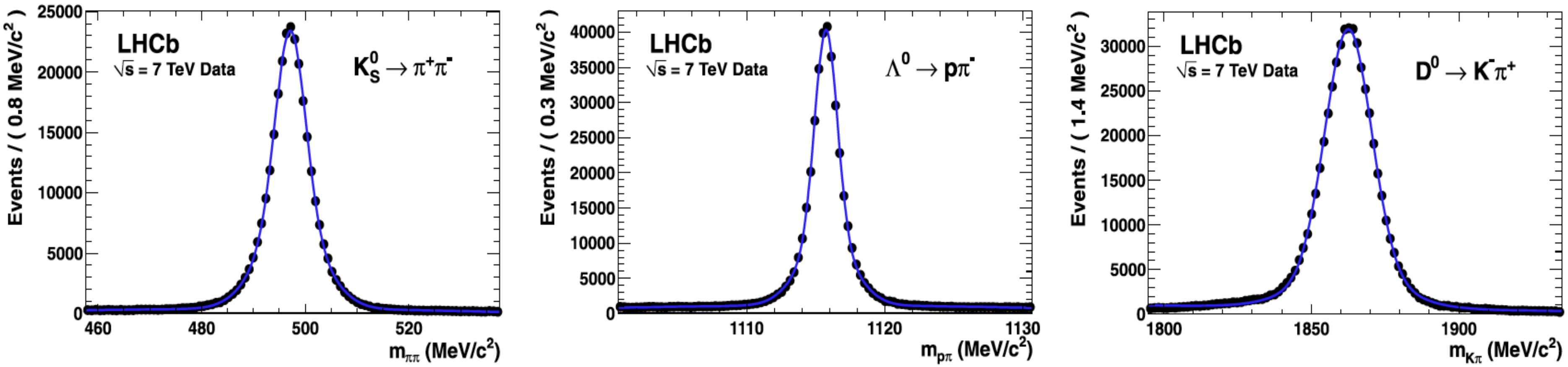
New J. Phys. 15 (2013) 053021



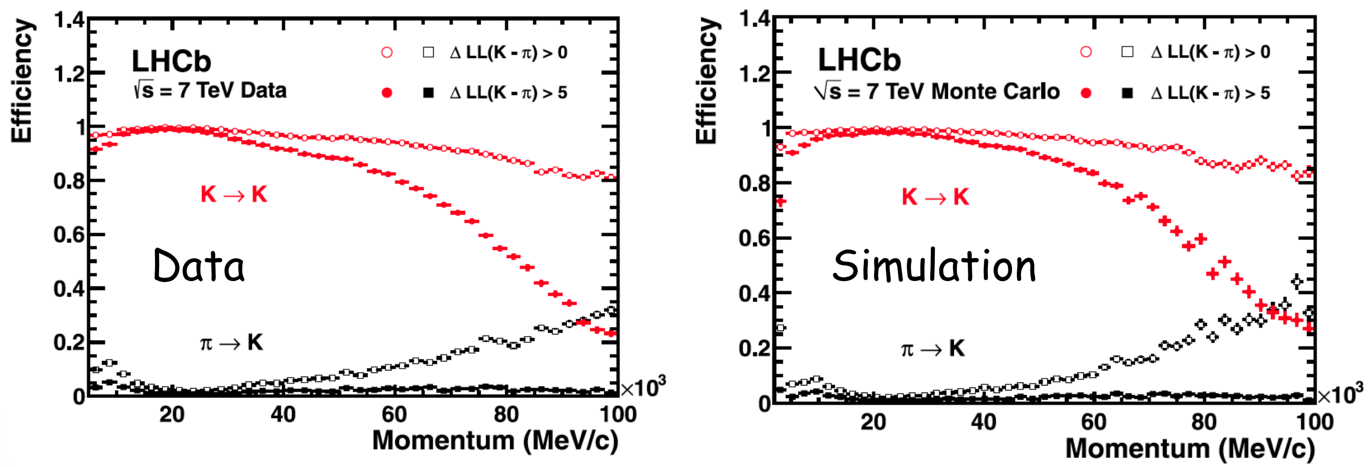
$$\boxed{\Delta m_s = 17.768 \pm 0.023\ (\text{stat}) \pm 0.006\ (\text{syst})\ \text{ps}^{-1}}$$

Charged particles identification performance

- 2 RICH detectors (25-300 mrad, 15-120 mrad), 3 radiators (Aerogel, C_4F_{10}, CF_4), system of light, radiation resistant mirrors, light R-O by HPD
- Genuine π/K/p samples identified from kinematics only
- PID performance evaluated from data



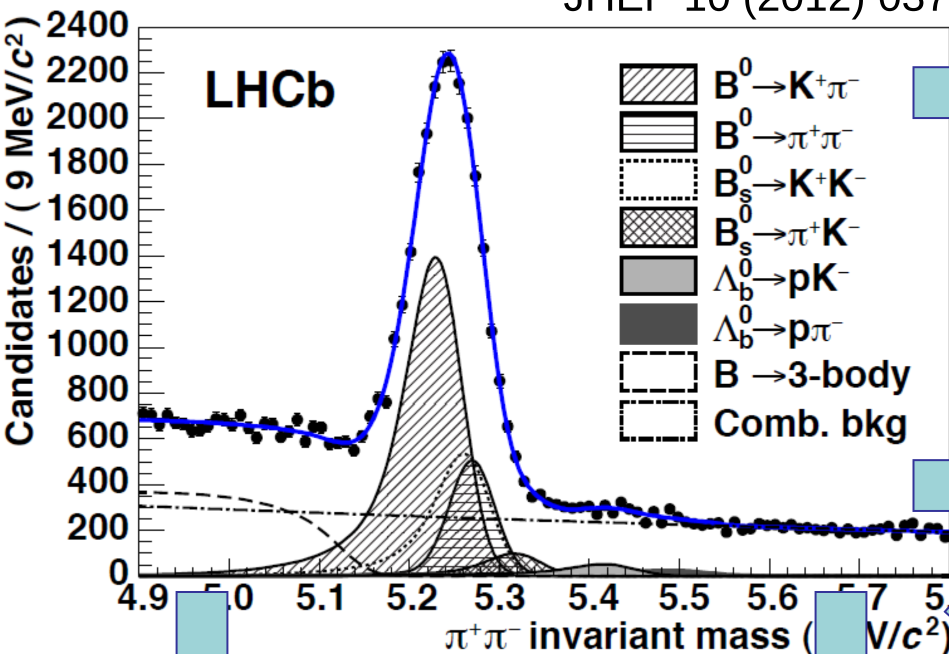
- Efficiency/rejection: reasonable agreement between data and simulation

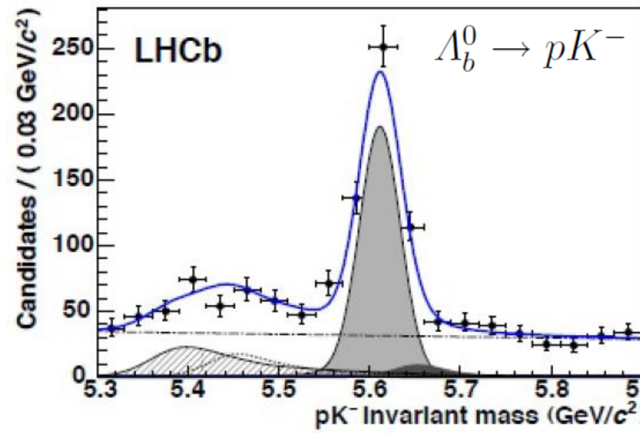


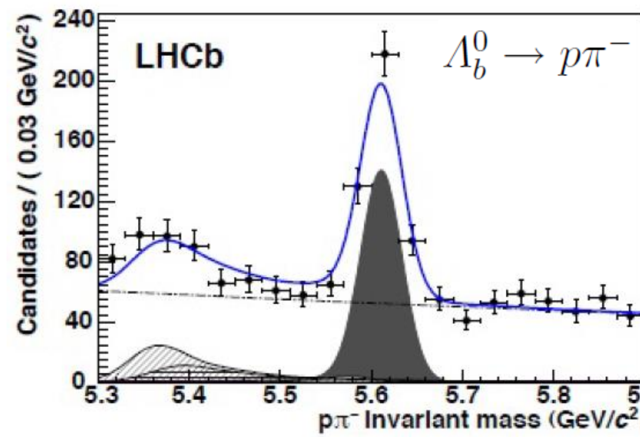
Charged hadron ID with RICH

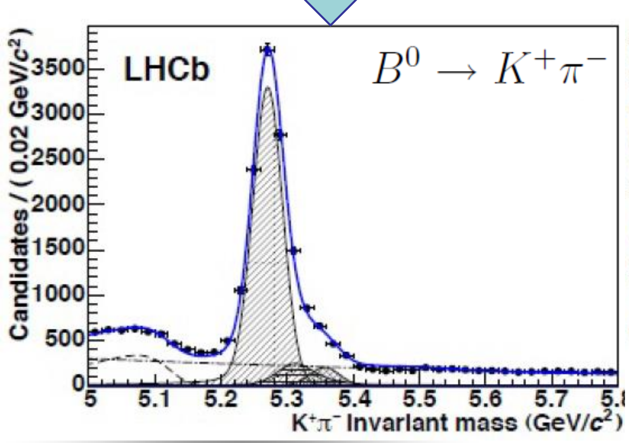
charmless two-body b-hadron decays

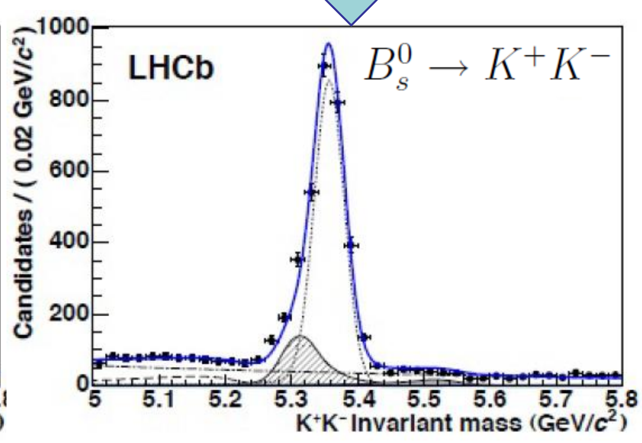
JHEP 10 (2012) 037

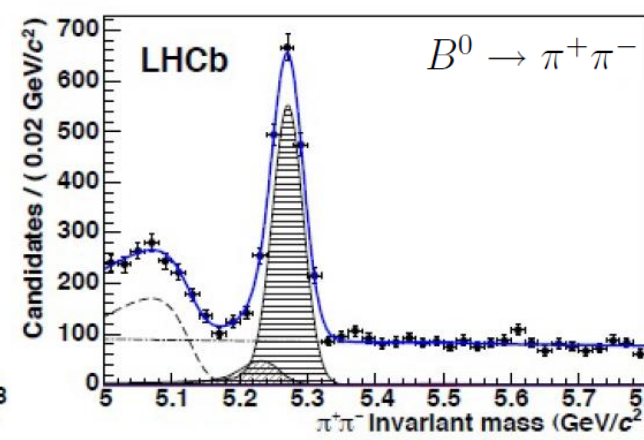






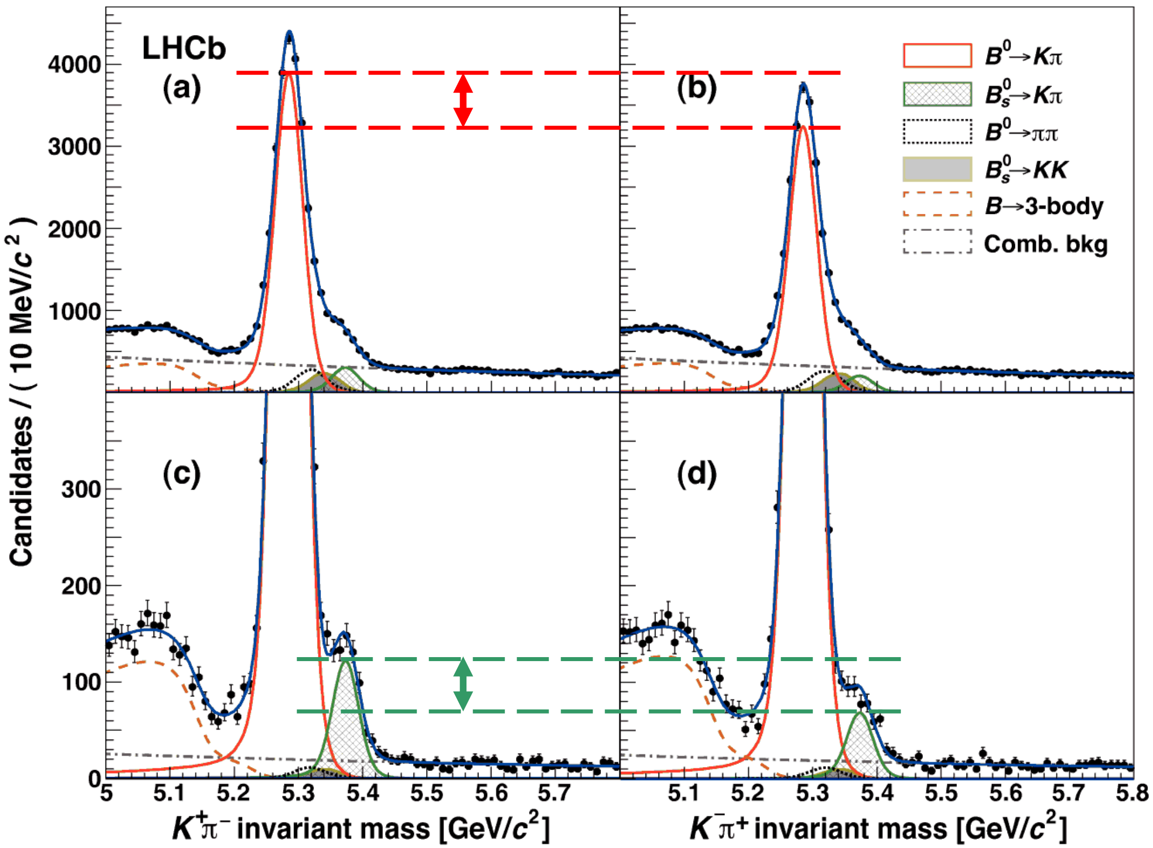






First observation of CP violation in the decays of B_s mesons

PRL 110 (2013) 221601

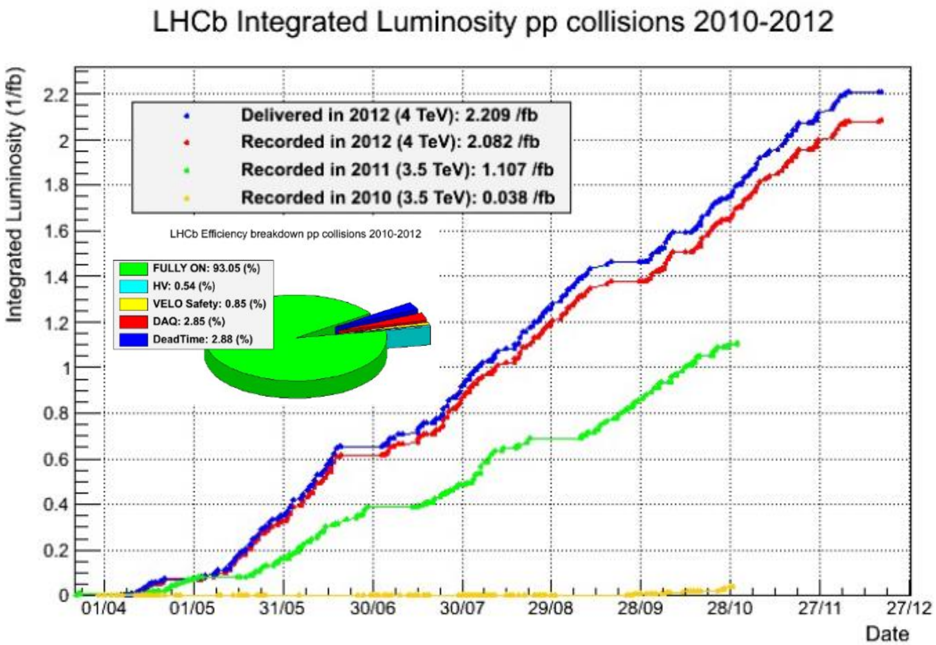


$$A_{CP}(B^0 \to K\pi) = -0.080 \pm 0.007 \pm 0.003$$ *World's best measurement*

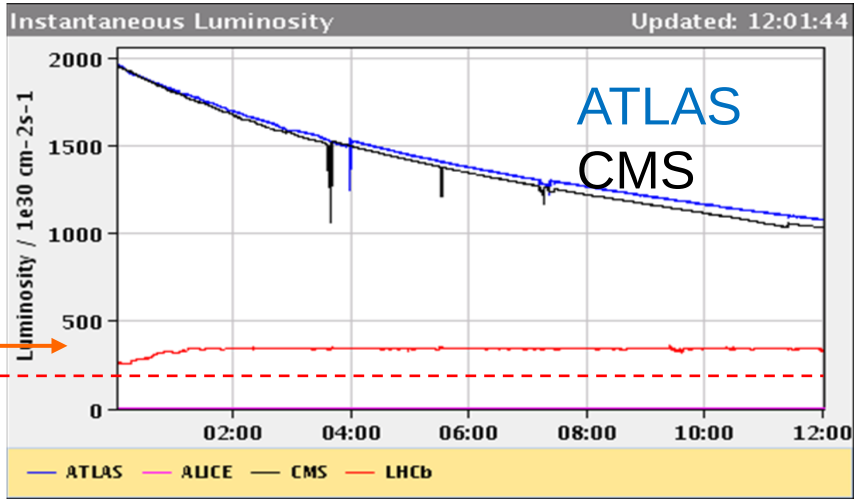
$$A_{CP}(B_s^0 \to K\pi) = 0.27 \pm 0.04 \pm 0.01$$ *First observation*

LHCb operation

- LHCb collected data corresponding to ∫Ldt ~38 pb^{-1} in 2010, 1.1 fb^{-1} in 2011, 2.1 fb^{-1} in 2012



- Stable LHCb operation
- Recording >1pb^{-1}/hour running at up to $L{\sim}4{\times}10^{32}$ $cm^{-2}s^{-1}$ (higher, than nominal, $2{\times}10^{32}$ $cm^{-2}s^{-1}$) in auto-leveling mode



LHCb luminosity levelling

LHCb
(design)

- Visual average **number of vertices** is higher, μ ~1.4, compared to nominal μ =0.4
- Higher μ → higher track multiplicity, 1 PV gives 30 tracks/rapidity range, more difficult reconstruction
  → background for D and B decay vertex reconstruction and matching

average minimum distance between 4 PVs ~12 mm, comparable to average B travel distance ~10 mm

Data analysis: sample and trigger

- **Data sample**: 0.7 fb^{-1} at $\sqrt{s}$ = 7 TeV (2011), 2.0 fb^{-1} at $\sqrt{s}$ = 8 TeV (2012)

- L0Hadron **trigger**, followed by dedicated trigger lines (Jibo He) at the HLT1 and HLT2 levels

- **Signature**: two well-recontructed high-pT tracks, identified as (anti-) protons, forming a good quality vertex, and a high-pT charmonium candidate

- Separate **prompt** and **b-decay production** using pseudo-decay time:

$$\tau_z = \Delta z\, M/p_z\, z$$

- (Almost) all selection (including PID!) at trigger level

- Specifically take into account small feed-down from $J/\psi \rightarrow pp\pi^0$

Selection

- Suppress busy events, SPD multiplicity < 300
- Proton candidates:
  - Track quality, χ^2/ndf < 4
  - Particle ID, DLL_{pK} > 15, $DLL_{p\pi}$ > 20 (result stable against larger values of the cut)
  - Momentum, pT > 2 GeV/c
- Charmonium candidates:
  - Vertex quality, χ^2/ndf < 9
  - Momentum, pT > 6.5 GeV/c

Prompt and b-decay production candidates

- Primary vertex vs. charmonium candidate decay vertex
- Separation between the two samples: pseudo-proper lifetime $\tau_z = \Delta z\, M/p_z\, z$
- Prompt production candidates: τ_z < 80 fs
- b-decay production candidates: τ_z > 80 fs and $\chi^2_{IP}(p)$/ndf > 16
- Results stable against variation of the τ_z cut value

Signal description

- Detector resolution: two Gaussian functions, ratios σ^a/σ^b, $\sigma_{\eta c}/\sigma_{J/\psi}$, and the fraction of narrow Gaussian fixed from MC
- Convolution of Breit-Wigner function with detector resolution for η_c
- In the fit to prompt spectrum:
  - Resolution σ^a and the η_c natural width fixed to the central values from the b-decay production analysis.
  - Gaussian constraint on the η_c and J/ψ masses is applied using the b-decay production analysis.

Procedure

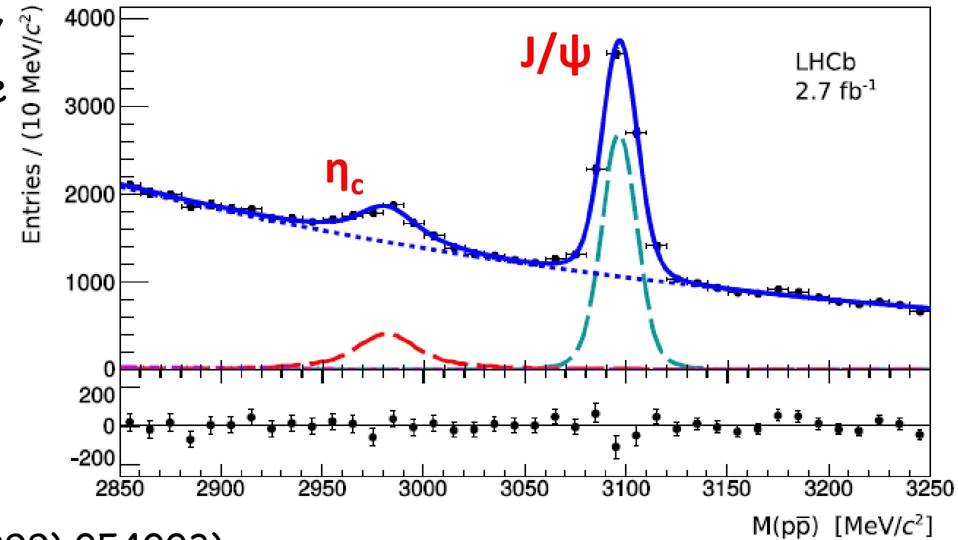
- Extract numbers from the fit
- Re-calculate signal event yields, taking into account cross-feed
- Obtain ratios:

$$\frac{N^p(\eta_c)}{N^p(J/\psi)} = \frac{\sigma(\eta_c) \times BR(\eta_c \to pp)}{\sigma(J/\psi) \times BR(J/\psi \to pp)}$$

$$\frac{N^S(\eta_c)}{N^S(J/\psi)} = \frac{BR(b \to \eta_c X) \times BR(\eta_c \to pp)}{BR(b \to J/\psi X) \times BR(J/\psi \to pp)}$$

Production of $\eta_c(1S)$ in b-hadron decays

- Invariant mass spectra at $\sqrt{s}$ = 7 and 8 TeV are consistent, fit to combined data sample



- BR(b → J/ψ X) is in reasonable agreement with models
- BR(b → η_c X): the only available experimental UL below model predictions
- Theory: talk of E. Kou in charmonium workshop at LAL based on Beneke et al. (Phys. Rev. **D59** (1999) 054003) , Fan et al. (Phys. Rev. **D85** (2012) 034032), Kniehl et al. (Phys. Rev. **D60** (1999) 014006), Bolzoni et al. (Phys. Rev. **D88** (2013) 7 074035): BR(b → η_c X) ~per cent level
- Experiment: for B0/B+ -mixture: BR(b → η_c X) < 0.9% @ 90%CL (CLEO); for b -mixture: no result available.

$$\boxed{\mathcal{B}(b \to \eta_c(1S)X)/\mathcal{B}(b \to J/\psi X) = 0.424 \pm 0.055 \pm 0.015 \pm 0.045_{\mathcal{B}}}$$

First measurement

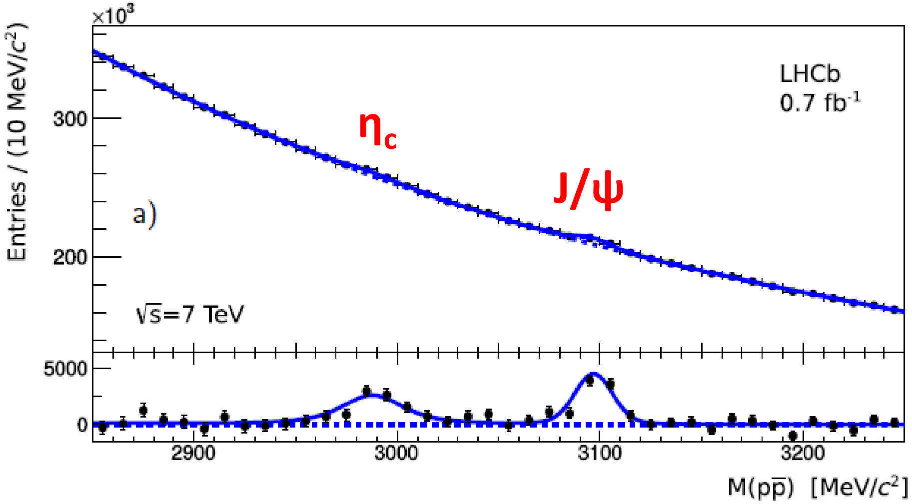
- Assuming that pT requirement does not bias p(J/ψ,η_c) in the b-hadron rest frame, and using B(b→J/ψ X) = (1.16 ± 0.10)%,

$$\boxed{\mathcal{B}(b \to \eta_c(1S)X) = (4.92 \pm 0.64 \pm 0.25 \pm 0.67_{\mathcal{B}}) \times 10^{-3}}$$

First measurement

- No contradiction to CLEO UL

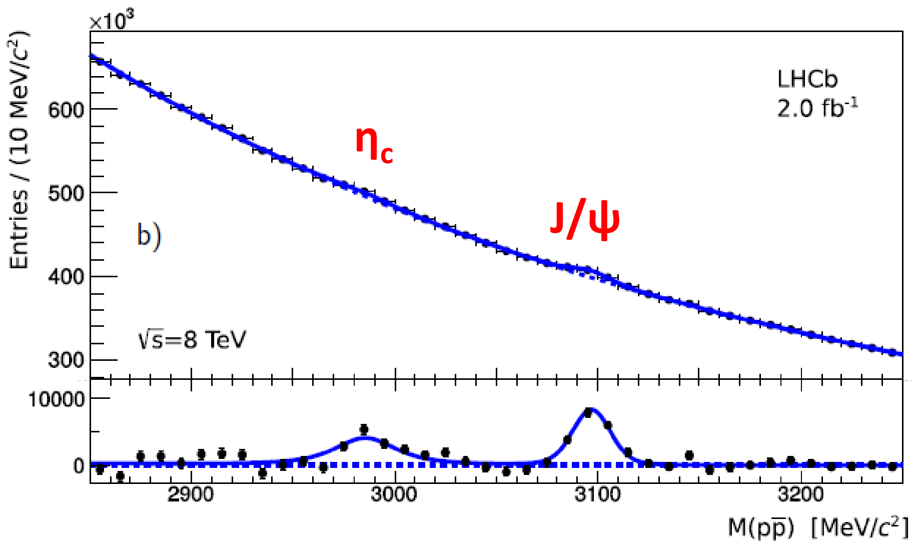
Prompt production of $\eta_c(1S)$



- Important level of combinatorial background
- Relative production cross-section:

$$\left(\sigma_{\eta_c(1S)}/\sigma_{J/\psi}\right)_{\sqrt{s}=7\text{ TeV}} = 1.75 \pm 0.30 \pm 0.28 \pm 0.19_{\mathcal{B}}$$
$$\left(\sigma_{\eta_c(1S)}/\sigma_{J/\psi}\right)_{\sqrt{s}=8\text{ TeV}} = 1.60 \pm 0.29 \pm 0.25 \pm 0.17_{\mathcal{B}}$$

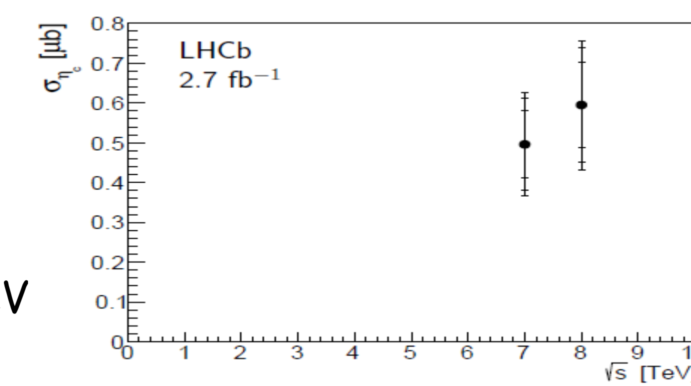
First measurement



- Using LHCb J/ψ production cross-section in di-muon channel (Eur. Phys. J. **C73** (2013) 2631, JHEP **06** (2013) 064):

$$\left(\sigma_{\eta_c(1S)}\right)_{\sqrt{s}=7\text{ TeV}} = 0.52 \pm 0.09 \pm 0.08 \pm 0.06_{\sigma_{J/\psi},\mathcal{B}}\ \mu\text{b}$$
$$\left(\sigma_{\eta_c(1S)}\right)_{\sqrt{s}=8\text{ TeV}} = 0.59 \pm 0.11 \pm 0.09 \pm 0.06_{\sigma_{J/\psi},\mathcal{B}}\ \mu\text{b}$$

First measurement



- Cross-section energy dependence, data at $\sqrt{s}$ = 13-14 TeV
- Few existing results, NLO contribution important
- LO calculations of S.S.Biswal and K.Sridhar (J. Phys. 416 **G39** (2012) 015008): does not contradict to CS, two orders smaller when CO contributions included

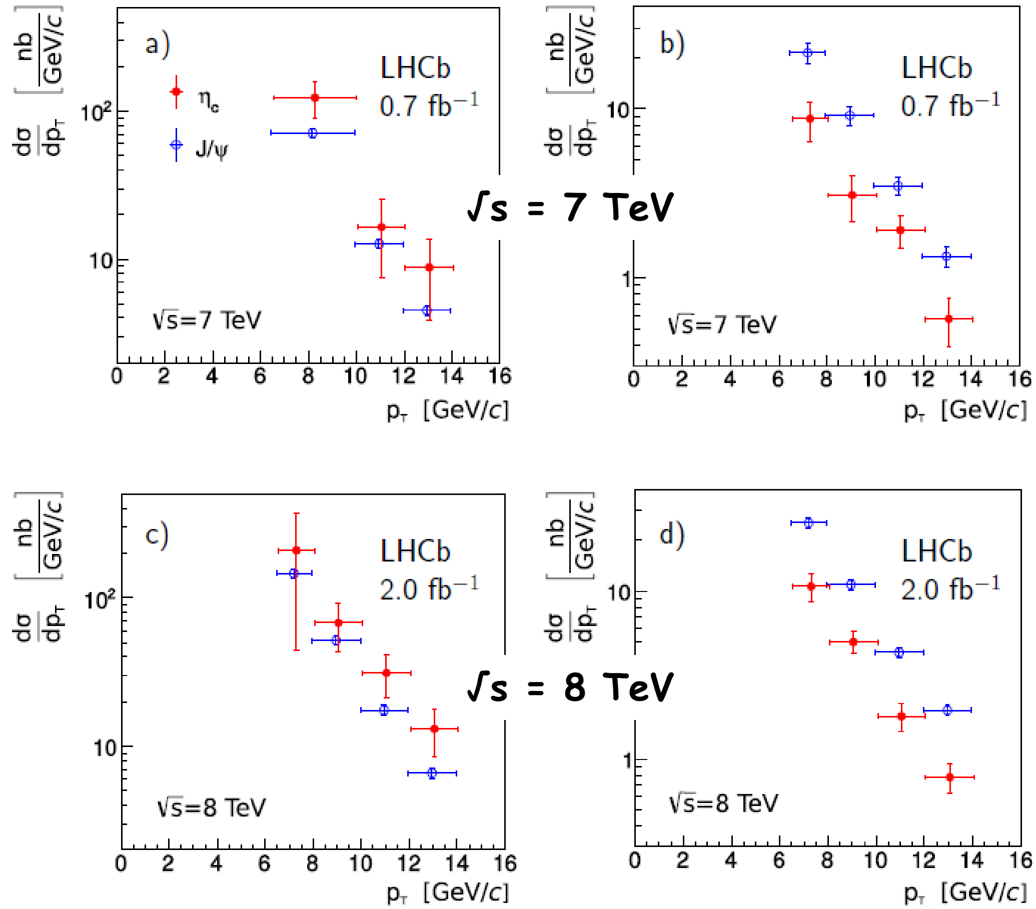
Differential production cross-section

- Differential production cross-section in pT bins
- NLO computations:

  (F. Maltoni and A. Polosa, Phys. Rev. D70 (2004) 054014; A. Petrelli et al., Nucl. Phys. B514 (1998) 245; J. H. Kuhn and E. Mirkes, Phys. Rev. D48 (1993) 179)

  different pT dependence of the production rates for spin singlet (η_c (1S)) and triplet (J/ψ) states

Prompt production | **Production in b-decays**



- Similar pT behaviour of the J/ψ and $\eta_c(1S)$ rates
- **New theory results since then** → Emi Kou

Mass and natural width of η_c

- Using low background sample of the η_c candidates from b-hadron decays, the mass of η_c relative to that of J/ψ is measured
- For that momentum scale calibration is performed
- The **mass difference** is measured to be

$$\Delta M = 114.7 \pm 1.5 \pm 0.1 \ \text{MeV/c2}$$

- Systematic uncertainty is small with respect to the statistical one and is dominated by the description of the $J/\psi \rightarrow pp\pi^0$ reflection shape
- The results are consistent between the 2011 and 2012 samples
- X-check for absolute J/ψ mass determination:

$$M(J/\psi) = 3096.66 \pm 0.19 \pm 0.02 \ \text{MeV/c2}$$

  in good agreement with the PDG average
- The ΔM result agrees to the PDG average, employs a method different from more precise BES result, and has better uncertainty than other previous measurements
- The **η_c natural width** value $\Gamma(\eta_c) = 25.8 \pm 5.2 \pm 1.9$ MeV also agrees with the PDG value
- Systematic uncertainty is small with respect to the statistical one and is dominated by the detector resolution

Learn more on charmonia production using hadronic decays

- Charmonia decays to hadrons are used to study charmonia production at LHCb. The **η_c prompt production** cross-section and branching fraction of **b-hadron decays into η_c** are measured for the first time.
- More data in 2015+, measure η_c state prompt **production at $\sqrt{s}$ = 13-14 TeV**
- Proposed to favour $\varphi\varphi$ combinations in the **trigger** for 2015+
- Include decays to other **hadronic final states**
- Use hadronic modes for **CEP studies**

Backup

Production yield ratios and systematic uncertainties

7 TeV : $\dfrac{N^P(\eta_c)}{N^P(J/\psi)} = 1.24 \pm 0.21 \pm 0.20$

8 TeV : $\dfrac{N^P(\eta_c)}{N^P(J/\psi)} = 1.14 \pm 0.21 \pm 0.18$

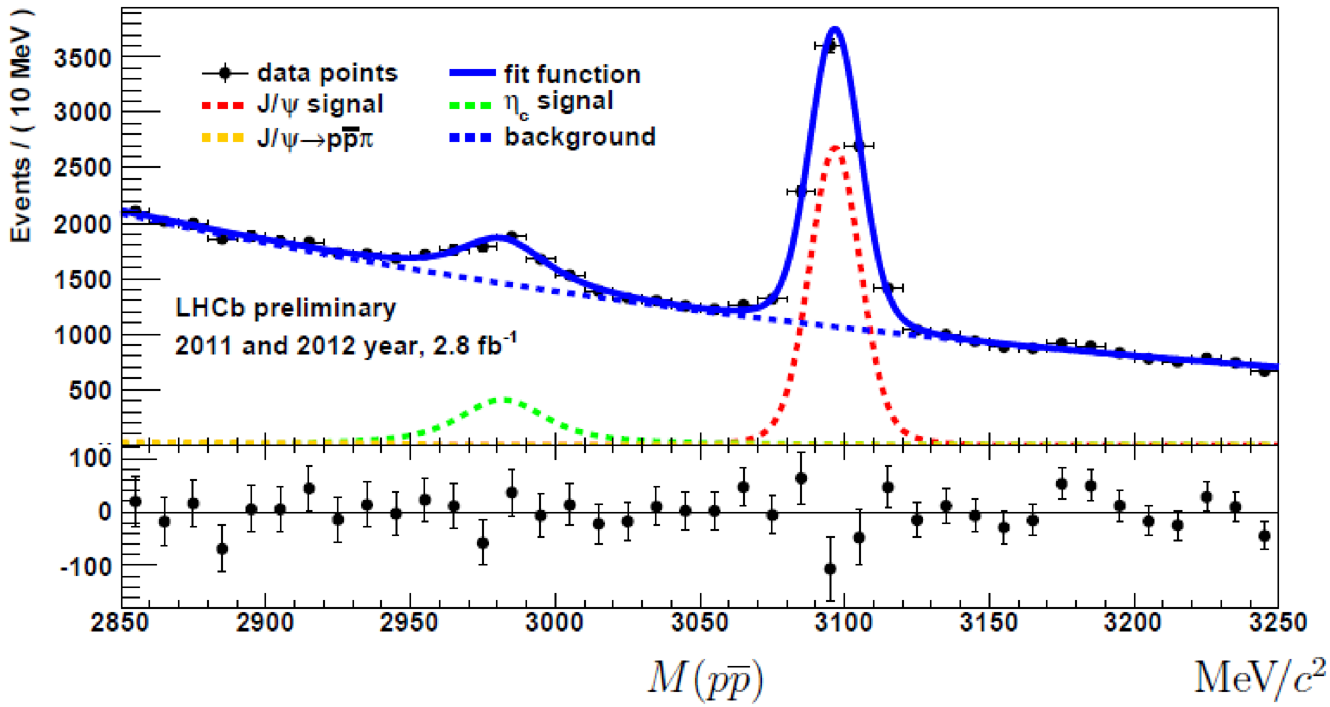
$\dfrac{N^S(\eta_c)}{N^S(J/\psi)} = 0.302 \pm 0.039 \pm 0.015$

	production in b-hadron decays	prompt production $\sqrt{s} = 7\,\text{TeV}$	$\sqrt{s} = 8\,\text{TeV}$
Mean value	0.302	1.24	1.14
Statistical uncertainty	0.039	0.21	0.21
Signal resolution ratio (MC)	0.006	0.04	0.03
Signal resolution variation		0.01	0.01
Prompt production spectrum	0.003	0.07	0.06
Γ_{η_c} variation		0.15	0.14
Fit range variation	0.009	0.06	0.06
Background shape variation	0.004	0.07	0.06
$J/\psi \to p\bar{p}\pi^0$ shape variation	0.005	0.02	0.02
Cross-talk between prompt sample and sample from b-hadron decays	0.008	0.01	0.01
J/ψ polarization		0.02	0.02
Systematic uncertainty, quadratic sum	0.015	0.20	0.18

Table 1: Systematic uncertainty decomposition for the production yield ratio $\frac{N_{\eta_c}}{N_{J/\psi}}$.

Inclusive production from b-decays: pp invariant mass spectrum

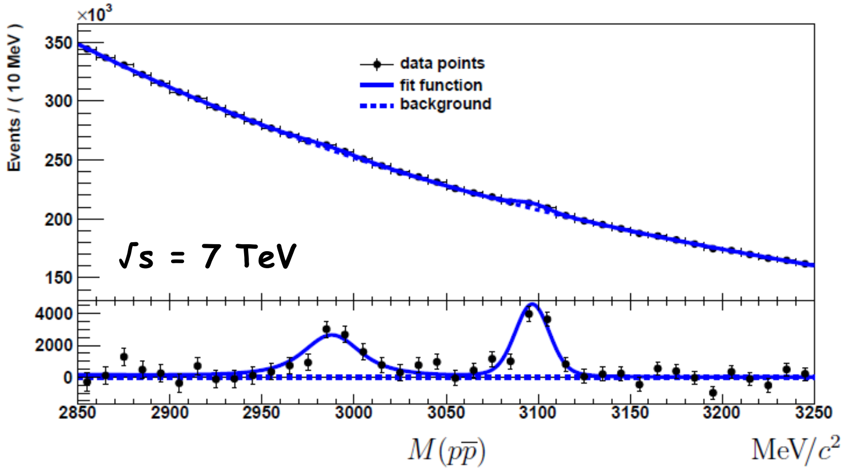
- Samples at $\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 8 TeV are consistent, including background shape, and are combined.

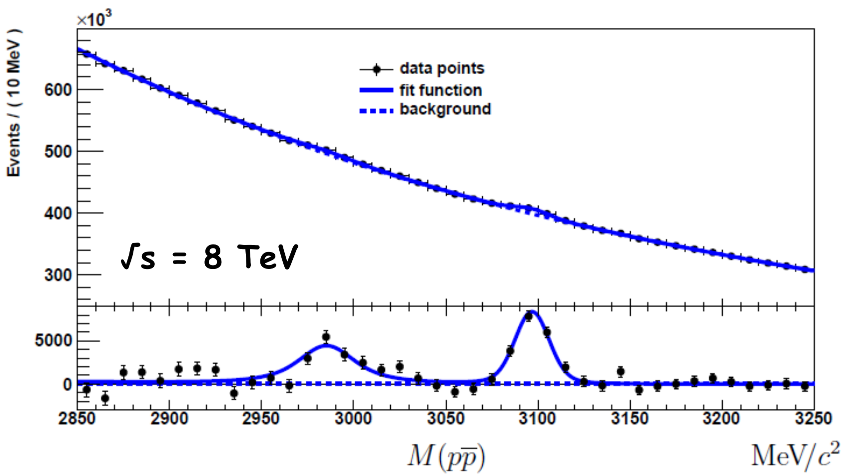


$n^S(\eta_c)$ = 2020 ± 230

$n^S(J/\psi)$ = 6110 ± 116

Prompt production: pp invariant mass spectrum





$\sqrt{s}$ = 7 TeV :

$n^P(\eta_c) = 13370 \pm 2260$

$n^P(J/\psi) = 11052 \pm 1004$

$\sqrt{s}$ = 8 TeV :

$n^P(\eta_c) = 22416 \pm 4072$

$n^P(J/\psi) = 20217 \pm 1403$