HQL 2014
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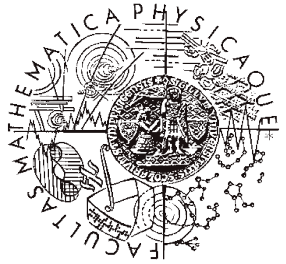
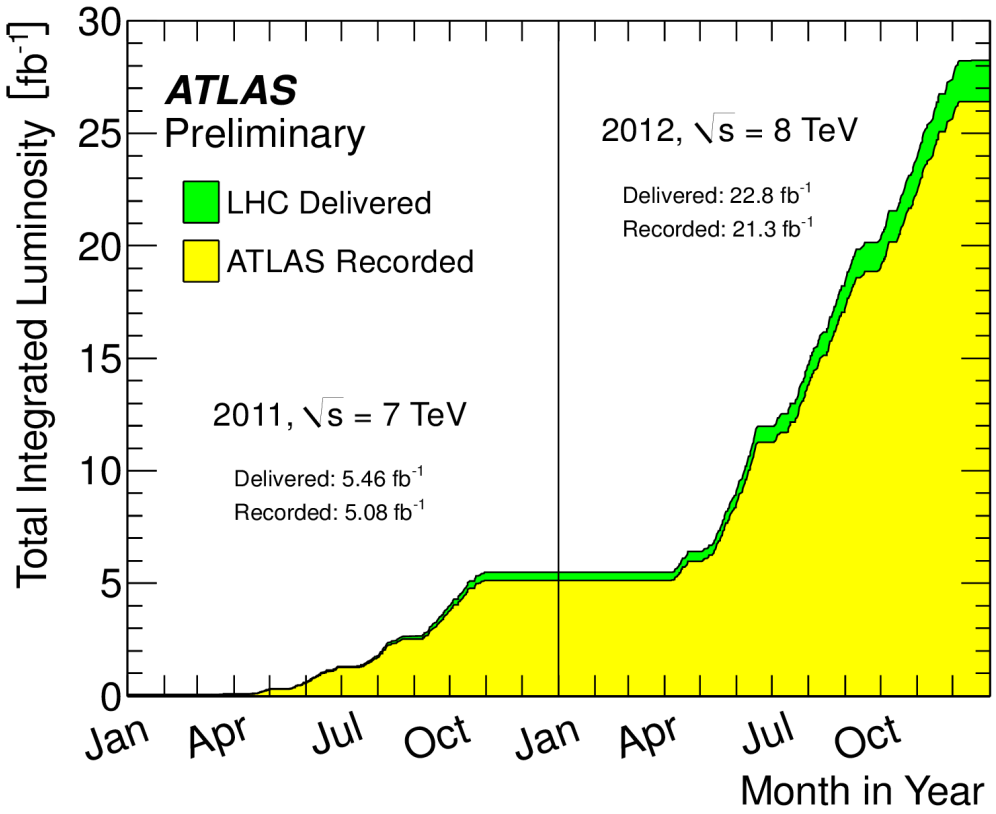
Studies of the B_c Meson with ATLAS and Recent Spectroscopy Results from CMS

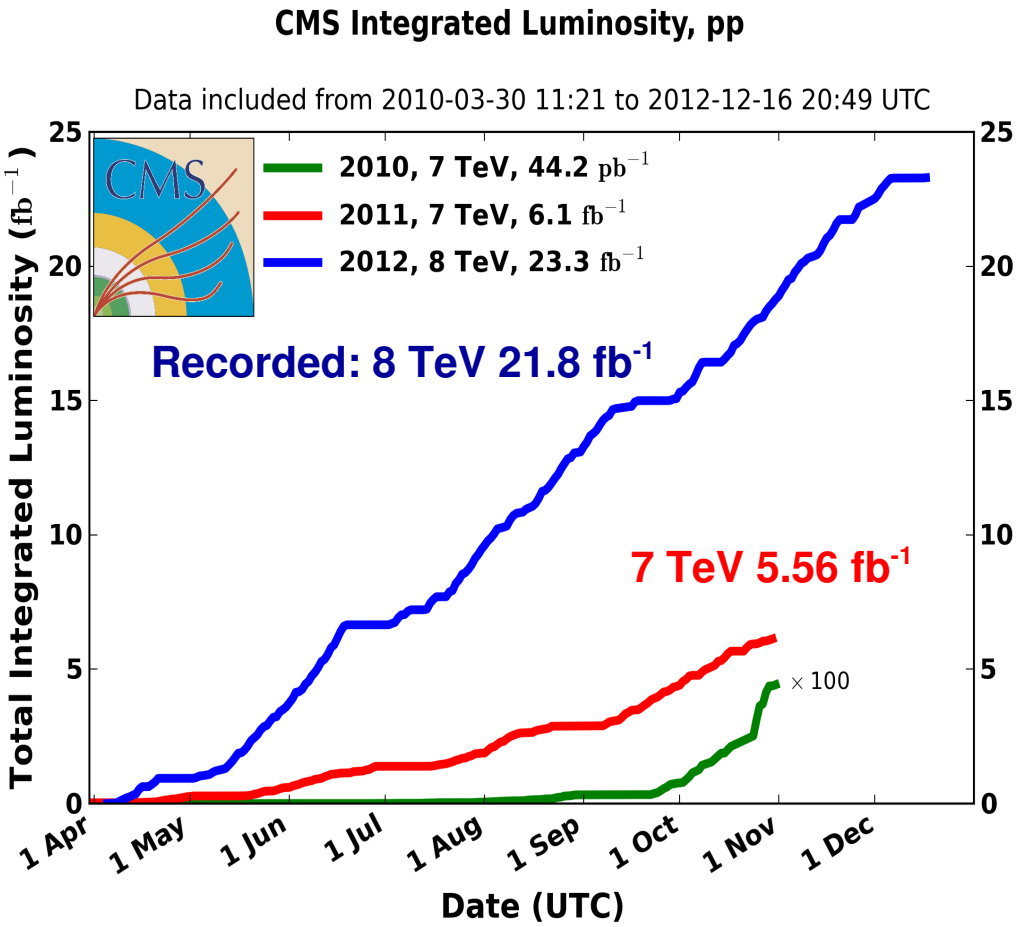
Pavel Řezníček
on behalf of the ATLAS and CMS collaborations



ATLAS & CMS at LHC

Recorded: 7 TeV 5.08 fb^{-1} 8 TeV 21.3 fb^{-1}





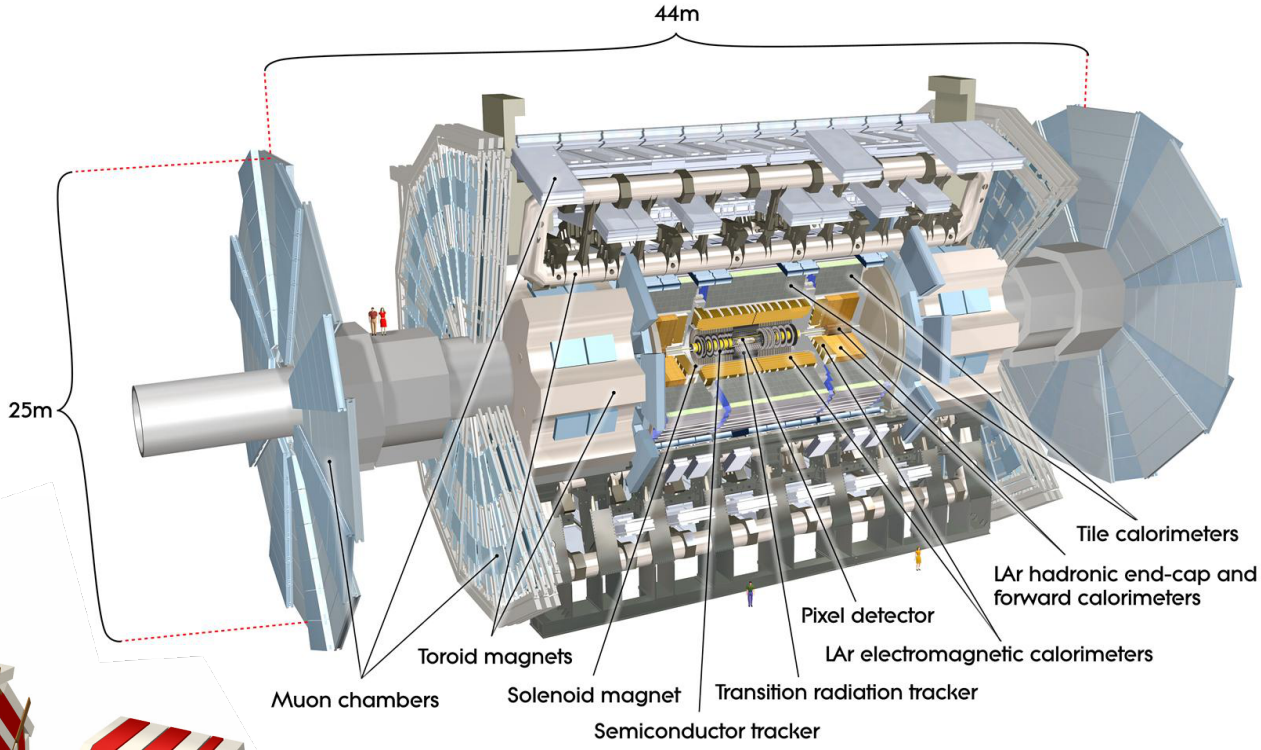
- LHC brought large amount of data at the highest collision energy
- Providing opportunities to search for new phenomena, including exotic hadrons

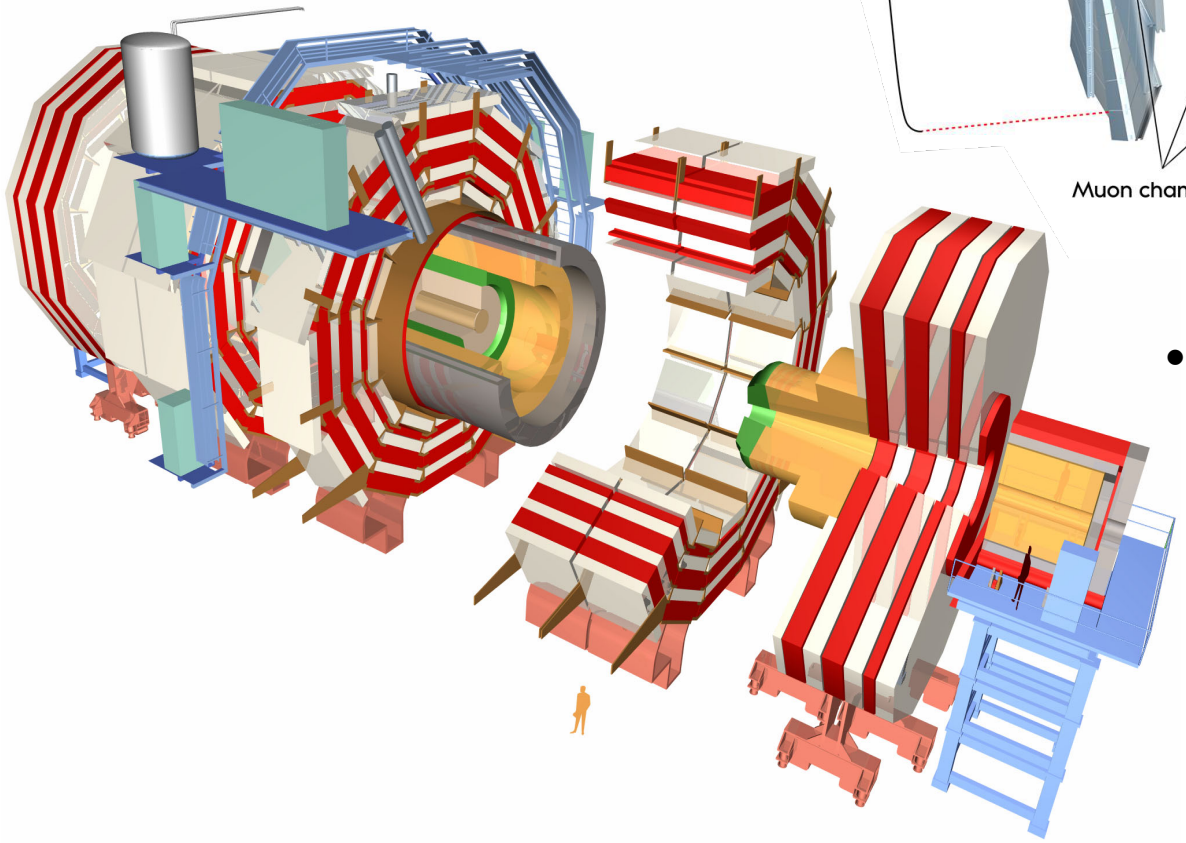
Outline

- Introduction
- Early spectroscopy results at ATLAS and CMS
- B_c observation at ATLAS and CMS
- Observation of $B_c^{\pm}(2S) \rightarrow B_c^{\pm}(1S)\pi^+\pi^-$ at ATLAS
- Search for a new state X_b decaying to $\Upsilon(1S)\pi^+\pi^-$ at CMS
- Peaking structures in the $J/\psi\phi$ mass spectrum in B-decays at CMS
- Summary

ATLAS & CMS Detectors

- High purity muon identification by the muon systems

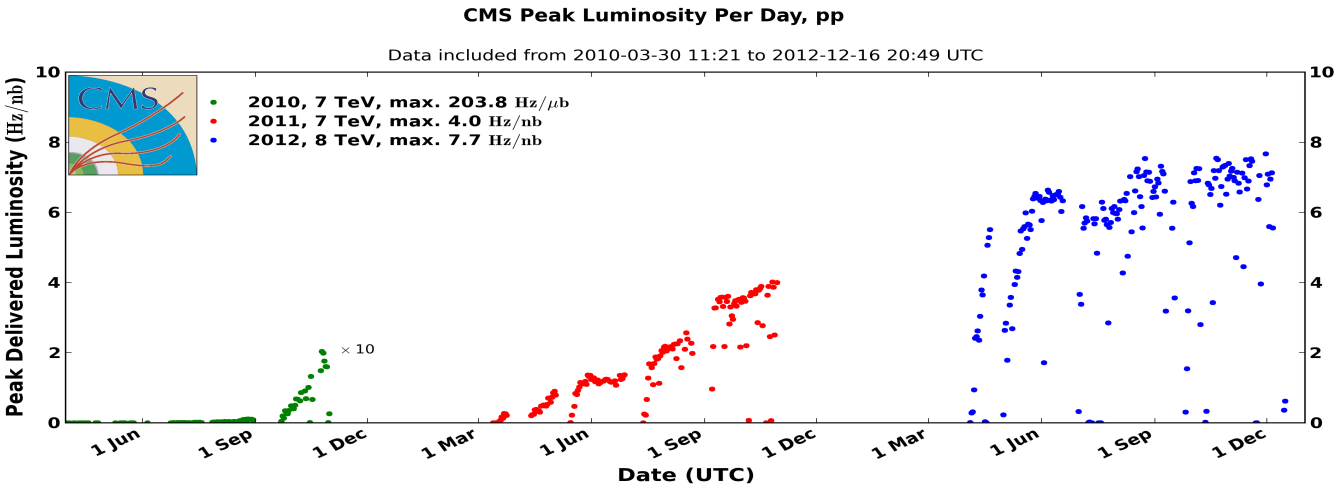




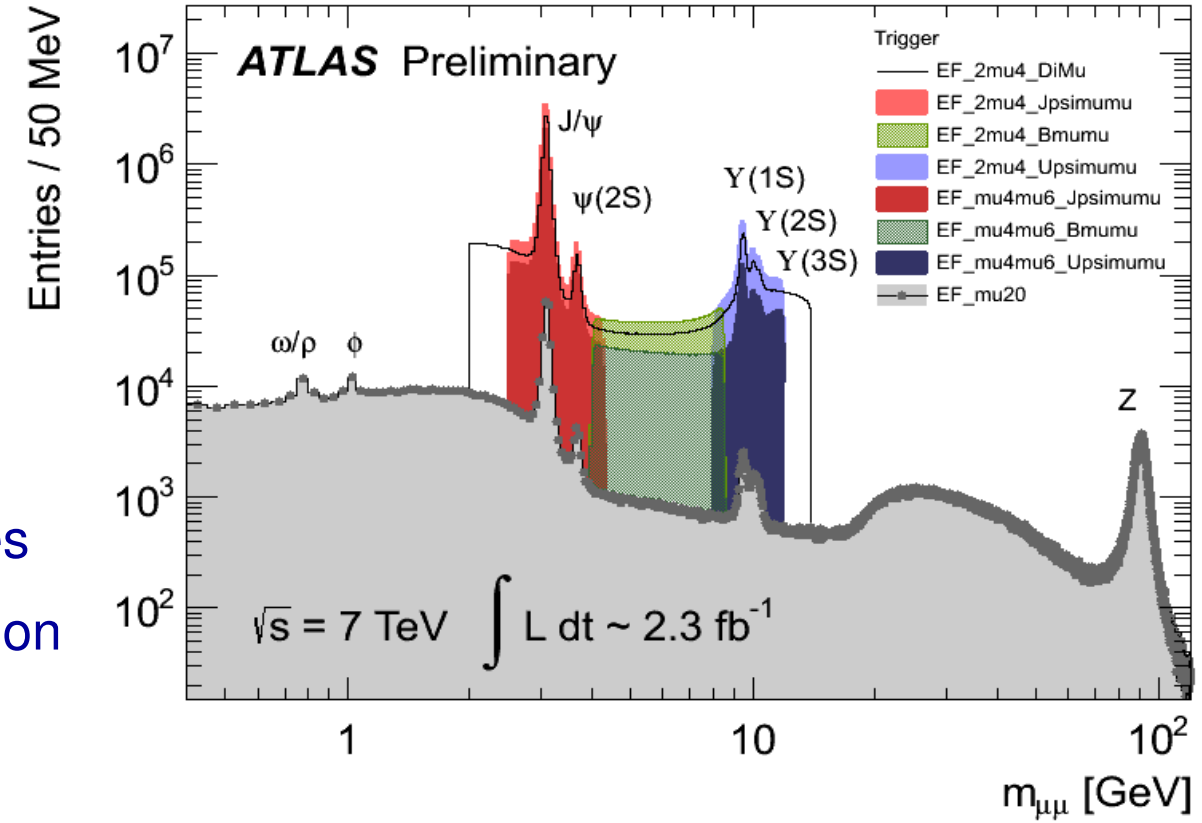
- Tracking detectors in solenoidal magnetic field (2T/4T) providing excellent:
  - track momentum resolution
  - momentum scale
  - vertex reconstruction and resolution

Trigger for Heavy Flavour

- Collecting data at increasing instantaneous luminosity



- Triggers based on di-muon signature:
  - common di-muon vertex
  - muon p_T thresholds
  - di-muon invariant mass window
  - CMS approach: special triggers for different analyses
  - ATLAS: more general di-muon triggers covering several analyses at once

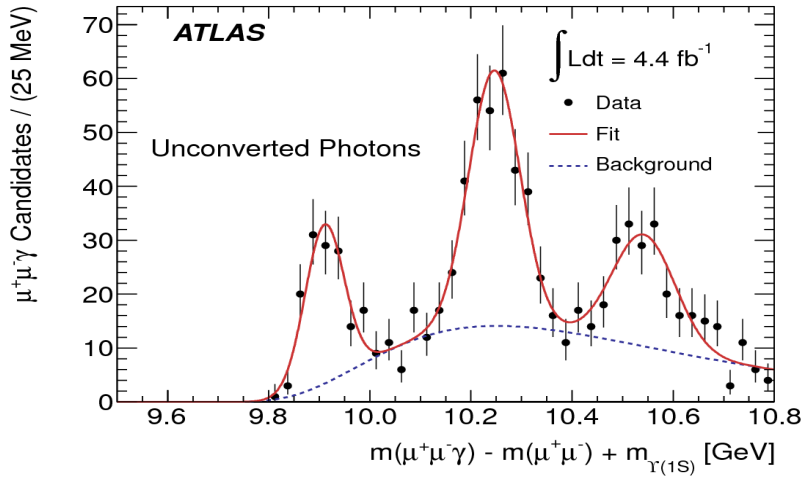


Early Results

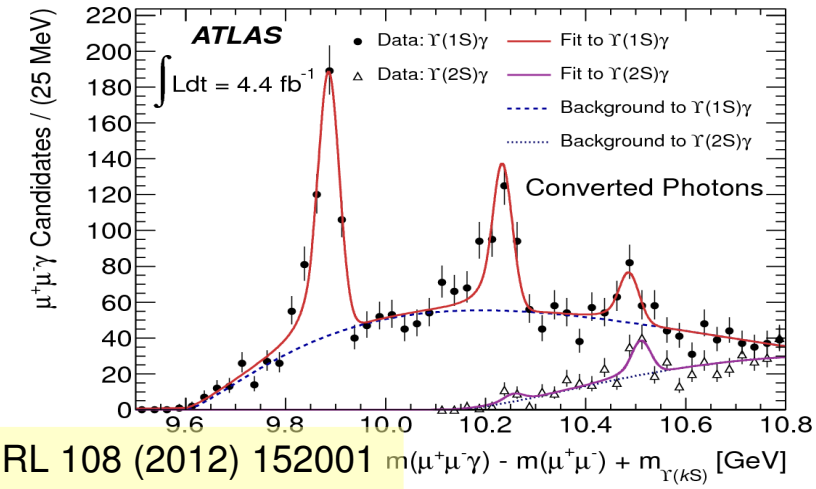
- χ_b observation at ATLAS

$\chi_b(3P) \rightarrow \Upsilon(xS) + \gamma$

$\overline{m}_3 = 10.541 \pm 0.011\ (\text{stat.}) \pm 0.030\ (\text{syst.})\ \text{GeV}$



$\overline{m}_3 = 10.530 \pm 0.005\ (\text{stat.}) \pm 0.009\ (\text{syst.})\ \text{GeV}$

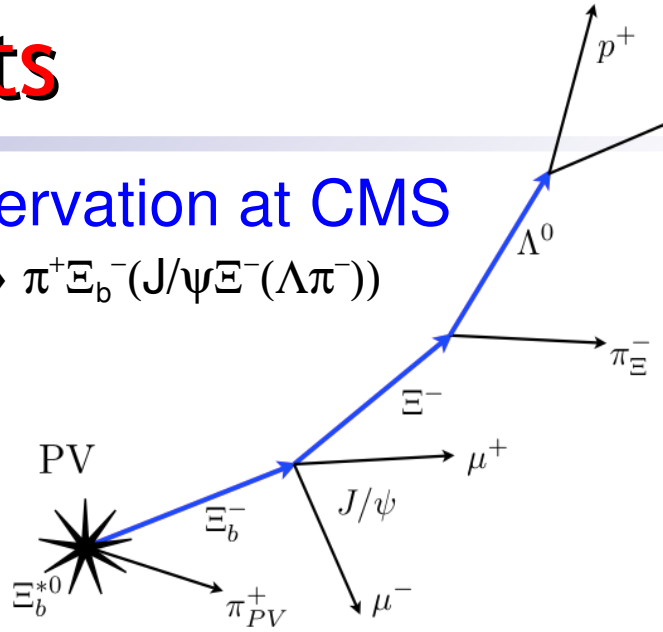


PRL 108 (2012) 152001

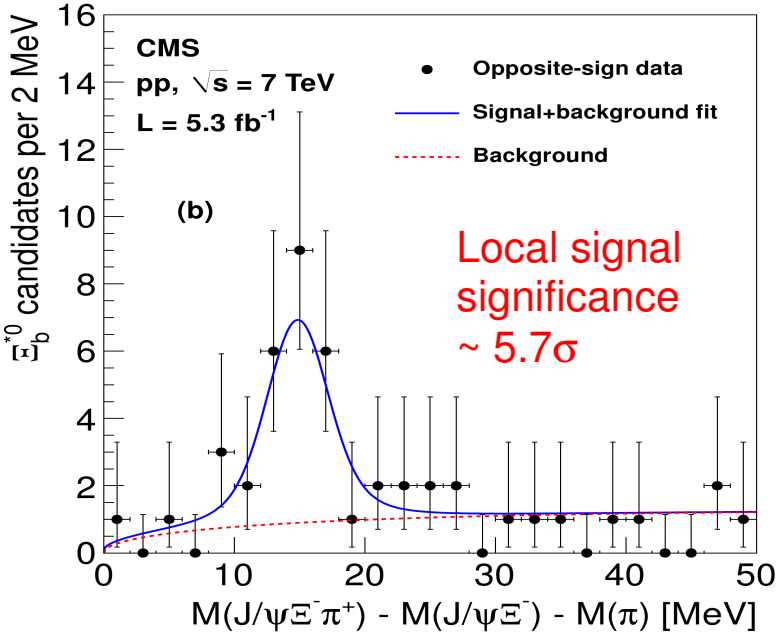
$\chi_b(3P)$ expected below $B\bar{B}$ threshold, predicted CoG mass 10,525 GeV

- Ξ_b^* observation at CMS

$\Xi_b^* \rightarrow \pi^+\Xi_b^-(J/\psi\Xi^-(\Lambda\pi^-))$



$5945.0 \pm 0.7(\text{stat}) \pm 0.3(\text{syst}) \pm 2.7(\text{PDG})\ \text{MeV}$

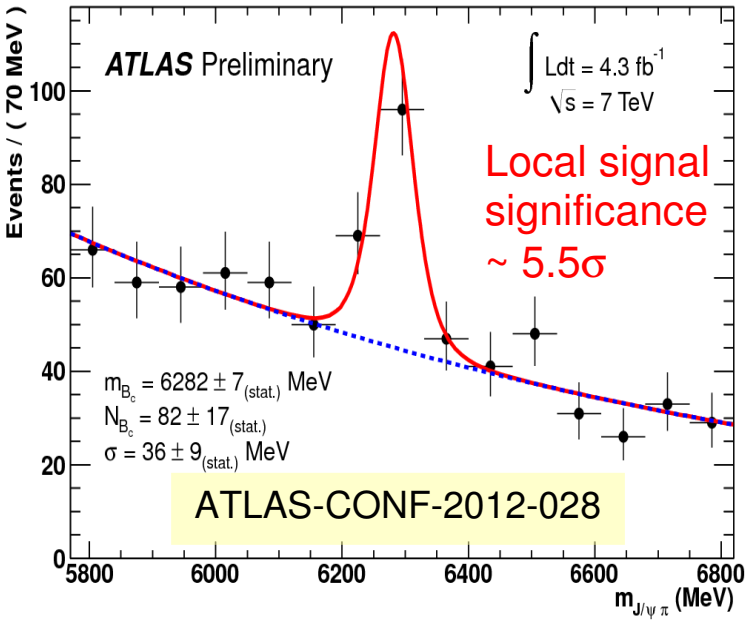


PRL 108 (2012) 252002

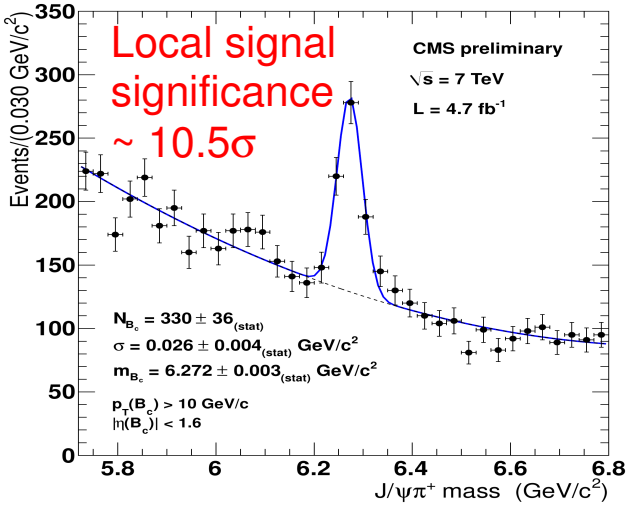
→ mass and decay width and mode => most likely $J^P=3/2^+$ state

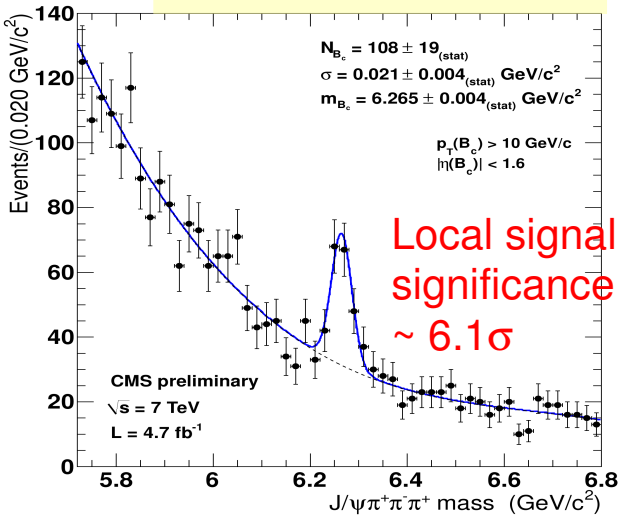
$B_c^{\pm}$ Observation

- Two different heavy flavours → study heavy quark production dynamics
- $B_c^{\pm}$ lifetime measurement → test $B_c^{\pm}$ decay model (**b** and **c** quark decays compete)
- First observed by CDF in 1998, lifetime measured by CDF (2006) and DØ (2009) in semileptonic decay channel including neutrino; LHCb measured relative x-section to $B^{\pm}$
- ATLAS/CMS observation in $B_c^{\pm} \to J/\psi\pi^{\pm}$, CMS also in $B_c^{\pm} \to J/\psi\pi^{+}\pi^{-}\pi^{\pm}$ CMS-PAS-BPH-11-003
- **main selection:**
  $B_c^{\pm}$ vertex quality,
  decay length significance (CMS)
  π track d_0 significance (ATLAS)



ATLAS-CONF-2012-028





- CMS also measured relative production and BR

$$\frac{\sigma(B_c^{\pm}) \times \mathrm{Br}(B_c^{\pm} \to J/\psi\pi^{\pm})}{\sigma(B^{\pm}) \times \mathrm{Br}(B^{\pm} \to J/\psi K^{\pm})} = (0.48 \pm 0.05\,(stat) \pm 0.04\,(syst)\,^{+0.05}_{-0.03}\,(\tau_{B_c})) \times 10^{-2}$$

$$\frac{\mathrm{Br}(B_c^{\pm} \to J/\psi\pi^{\pm}\pi^{\pm}\pi^{\mp})}{\mathrm{Br}(B_c^{\pm} \to J/\psi\pi^{\pm})} = 2.43 \pm 0.76\,(stat)^{+0.46}_{-0.44}\,(syst)$$

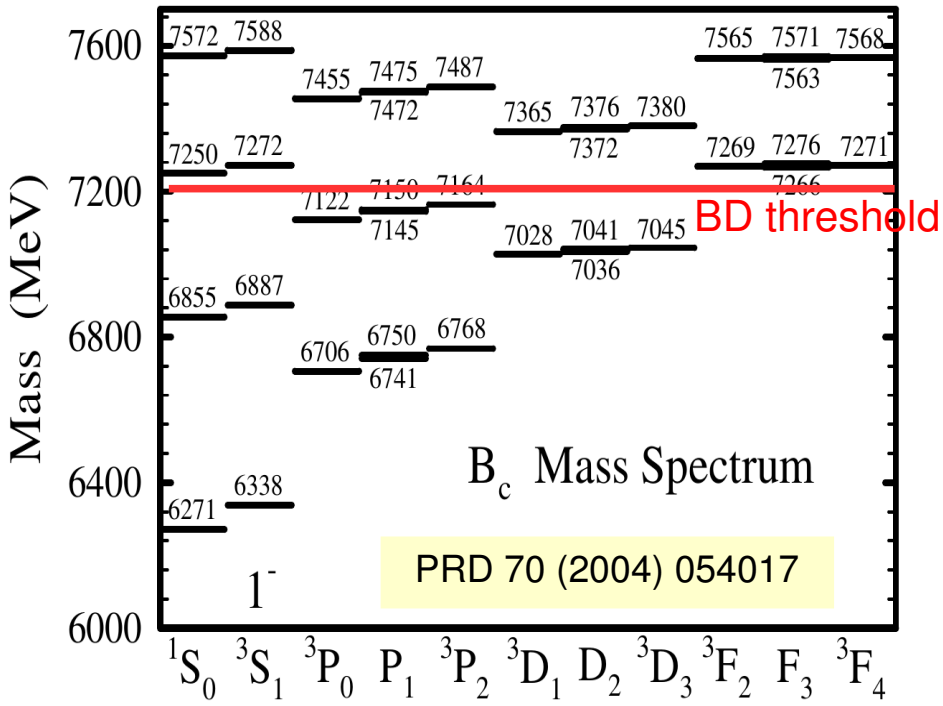
CMS-PAS-BPH-12-011

Observation of $B_c^{\pm}(2S)$ at ATLAS

ArXiv: 1407.1032

- $B_c^{\pm}$ has been observed in both semileptonic and hadronic decay modes, not excited states reported previously
- Spectrum and properties of $B_c^{\pm}$ predicted by NRQCD and lattice calculations. Measurement of both ground and excited states provides test of the models

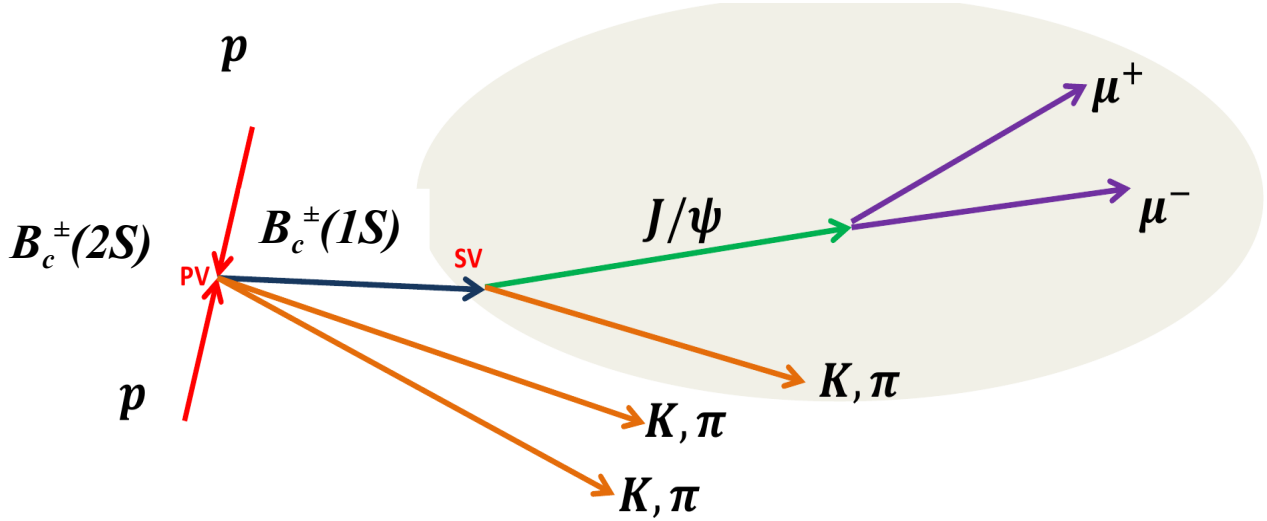
- 1S ground state: both 1^1S_0, 1^3S_1; mass difference ~20-70 MeV, transition via soft gamma
- 2P states: soft gamma radiation to 1S; E_γ ~ 500 MeV
  - soft γ invisible => contributes to the ground state
- 2S state:
  - $B_c^{\pm}(2S)$ predicted mass in 6835-6916 MeV
  - $B_c^{\pm}(2S_0) \rightarrow B_c^{\pm}(1S_0) + \pi\pi$
  - $B_c^{\pm}(2S_1) \rightarrow B_c^{\pm}(1S_1) + \pi\pi$
    $B_c^{\pm}(1S_1) \rightarrow B_c^{\pm}(1S_0) + \gamma_{invisible}$
  - mass difference m(2S)-m(1S) ~ 600 MeV
  - $\pi\pi$ from PV should follow $B_c^{\pm}(1S)$ direction



$B_c^{\pm}(2S)$ Reconstruction Overview

ArXiv: 1407.1032

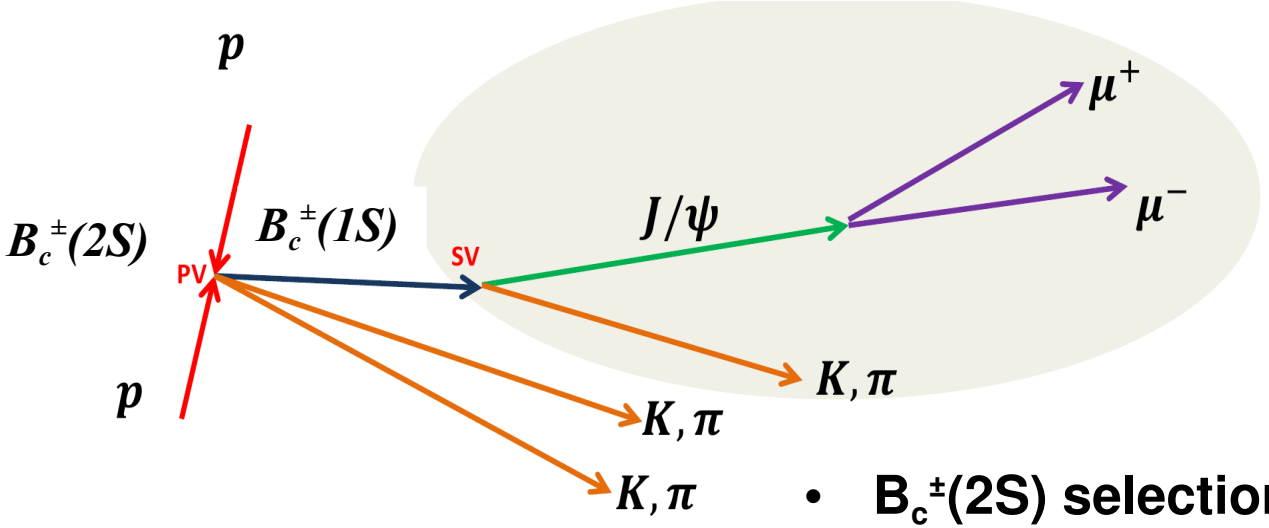
- Using 7 TeV and 8 TeV pp collision data (4.9^{-1} and 19.2 fb^{-1})
- Optimization of $B_c^{\pm}(1S)$ $S/\sqrt{(S+B)}$ on MC, including various peaking backgrounds; separated optimization for 7 TeV and 8 TeV analyses



- J/ψ candidates constructed from $\mu^+\mu^-$ pairs, requiring common vertex
- $B_c^{\pm}(1S)$ candidates constructed combing J/ψ with a hadronic track using both π and K hypotheses; forming a secondary vertex
- $B_c^{\pm}(2S)$ formed from the $B_c^{\pm}(1S)$ candidate and two oppositely charged hadron tracks from PV, using both π and K hypotheses
- Wrong-sign $B_c^{\pm}(2S)$ candidates formed from the same sign charged hadrons; kept for background control

$B_c^{\pm}(1S)$ and $B_c^{\pm}(2S)$ Reconstruction

ArXiv: 1407.1032



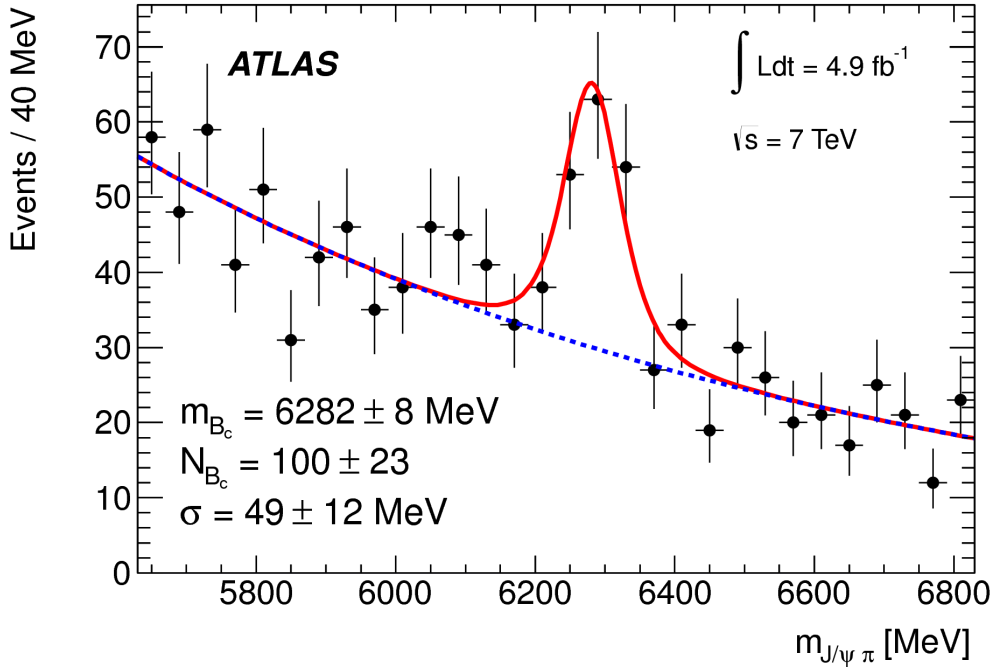
- **$B_c^{\pm}(1S)$ selection (7TeV or 8TeV):**
  - J/ψ vertex quality: $\chi^2/\text{NDoF} < 15$
  - Hadronic track $p_T > 4$ GeV
  - $p_T(B_c^{\pm}) > 15$ GeV or 18 GeV
  - Cut on hadron track impact parameter w.r.t. PV: $d_0/\sigma(d_0) > 5$ mm or 4.5 mm
  - $B_c^{\pm}$-vertex quality $\chi^2/\text{NdoF} < 2$ or 1.5

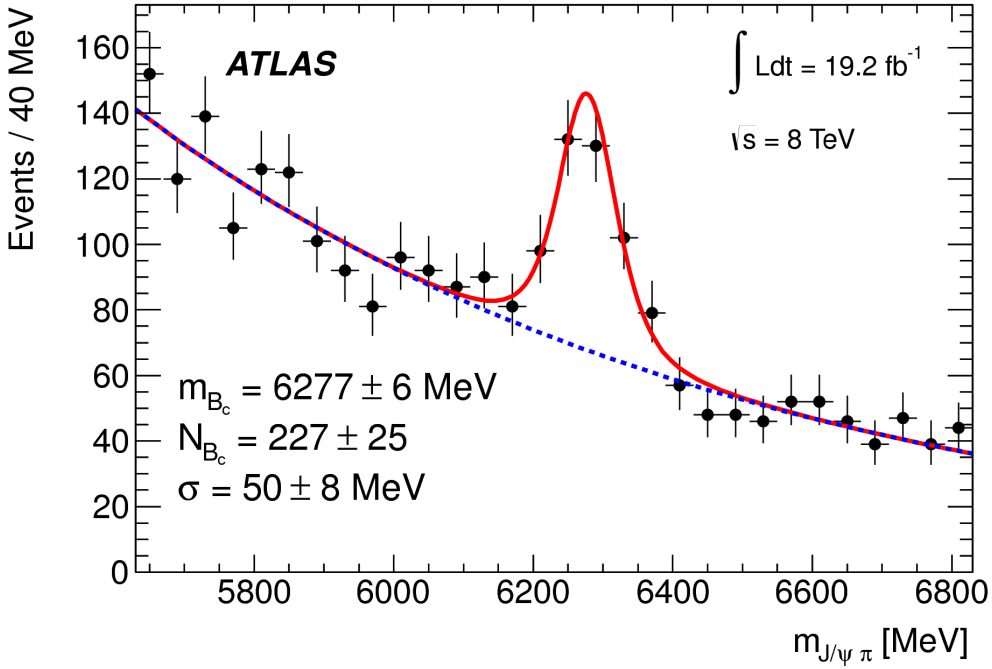
- **$B_c^{\pm}(2S)$ selection:**
  - Previously found $B_c^{\pm}(1S)$ candidate within 3σ mass window of the fitted signal
  - 3 tracks from the $B_c^{\pm}(1S)$ candidate and 2 tracks from the PV are fitted simultaneously; muon pair mass constrained to J/ψ mass
  - $B_c^{\pm}(1S)$ and $B_c^{\pm}(2S)$ must have significantly displaced vertices
  - In case of more $B_c^{\pm}(2S)$ candidates in an event, keep only the one with best cascade vertices fit (best χ^2)

$B_c^{\pm}(1S)$ Candidates

ArXiv: 1407.1032

- Projection of the results of unbinned maximum likelihood fit (Gaussian + exponential) to all candidates in range 5620-6820 MeV; separating the background component



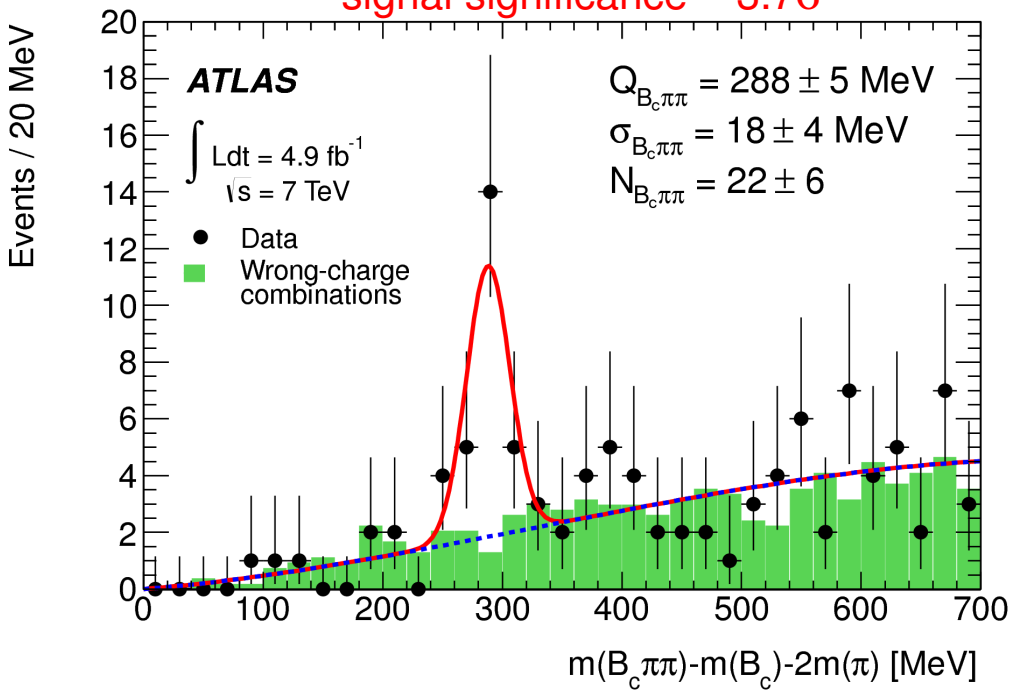


$B_c^{\pm}(2S)$ Candidates

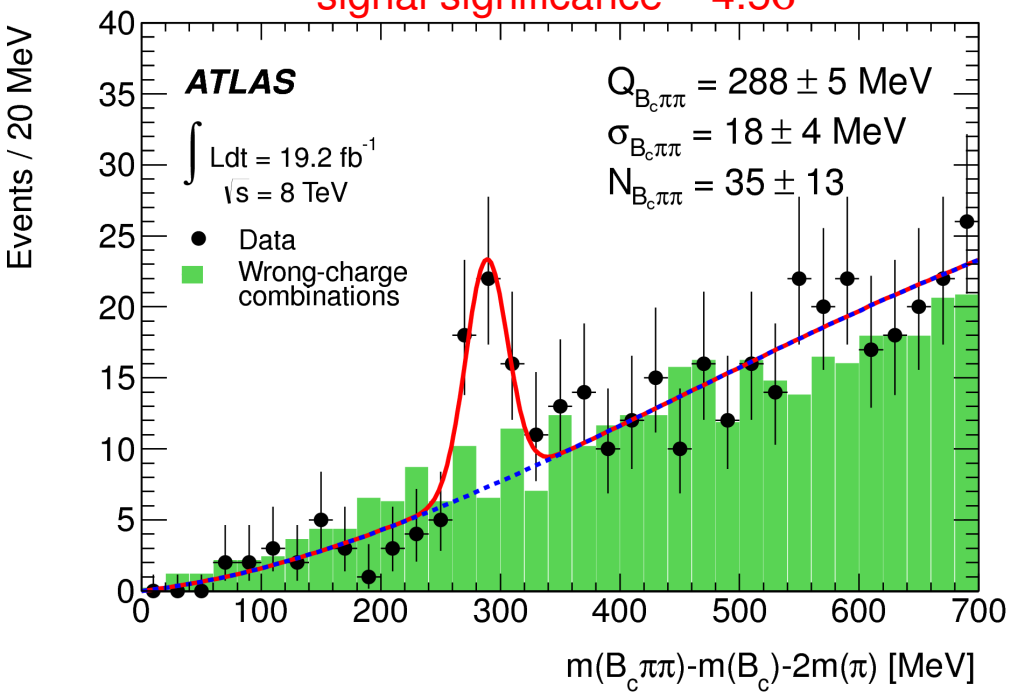
ArXiv: 1407.1032

- Using mass variable: $Q = m(B_c^{\pm}\pi^+\pi^-) - m(B_c^{\pm}) - 2m(\pi^{\pm})$
- Projection of the results of unbinned maximum likelihood fit (Gaussian + 3rd order polynomial) to all candidates in range 0-700 MeV; background component compared to ππ wrong-sign charge combinations (normalized to the same yield)

signal significance ~ 3.7σ



signal significance ~ 4.5σ



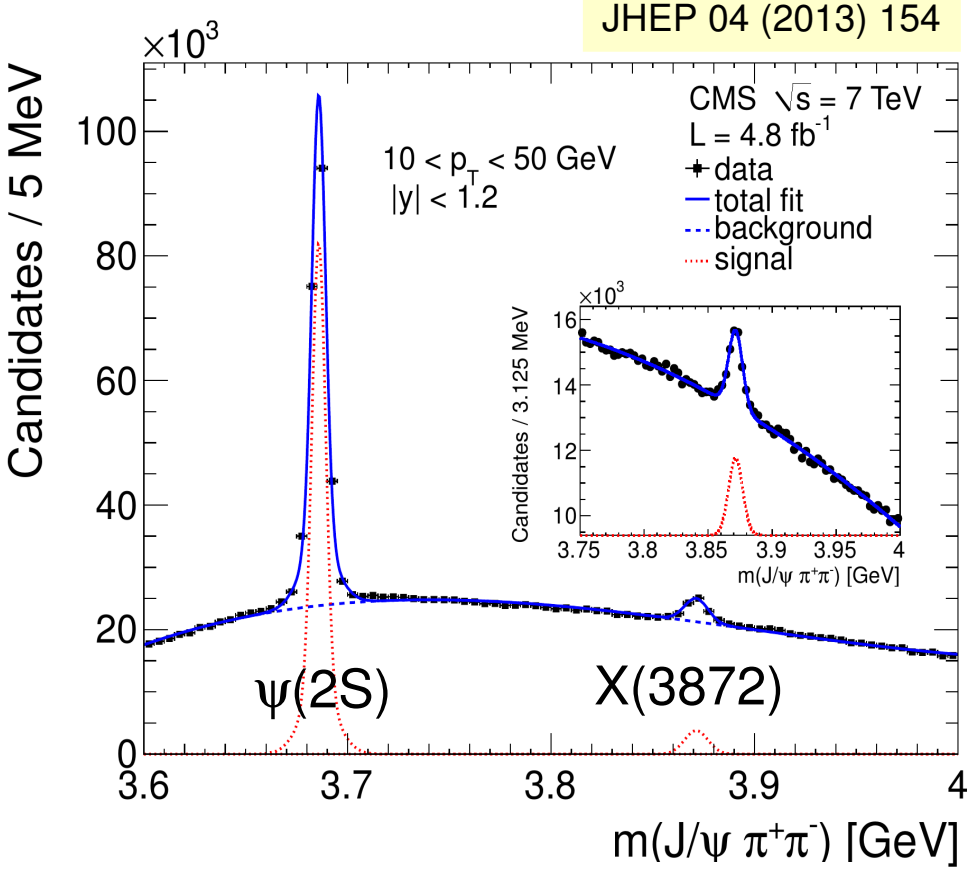
- Significance calculated using pseudo-experiments and accounting for look-elsewhere effect
- New state observed at **Q = 288.3 ± 3.5 ± 4.1 MeV** => **m = 6842 ± 4 ± 5 MeV** with significance of 5.2σ for combined 7 TeV and 8 TeV datasets; consistent with prediction
- Dominating systematics from $B_c^{\pm}(1S)$ ground state uncertainty and mass-fit procedure

Search for $X_b \to \Upsilon(1S)\pi^+\pi^-$

PLB 727 (2013) 57

- Existence of exotic resonance X(3872) discovered in the final state $J/\psi\pi^+\pi^-$ suggest possible bottomonium counterpart X_b decaying to $\Upsilon(1S)\pi^+\pi^-$
- Mass close to the BB or BB* thresholds 10.562 and 10.604 GeV
- Assume, similarly to X(3872), narrow width and sizeable BR

JHEP 04 (2013) 154

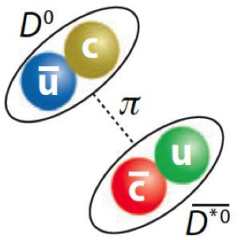


- Look for signal in the $\Upsilon(1S)\pi^+\pi^-$ invariant mass spectrum; measure:

$$R = \frac{\sigma_{X_b} \times BR(X_b \to \Upsilon(1S)\pi^+\pi^-)}{\sigma_{\Upsilon(2S)} \times BR(\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-)}$$

as a function of the X_b mass [10-11] GeV

- Kinematic region covered:
  - $p_T(\Upsilon(1S)\pi\pi) > 13.5$ GeV
  - $|y(\Upsilon(1S)\pi\pi)| < 2.0$



D^0–$\bar{D}^{*0}$ "molecule"

Diquark–diantiquark

$X_b \to \Upsilon(1S)\pi^+\pi^-$ Reconstruction

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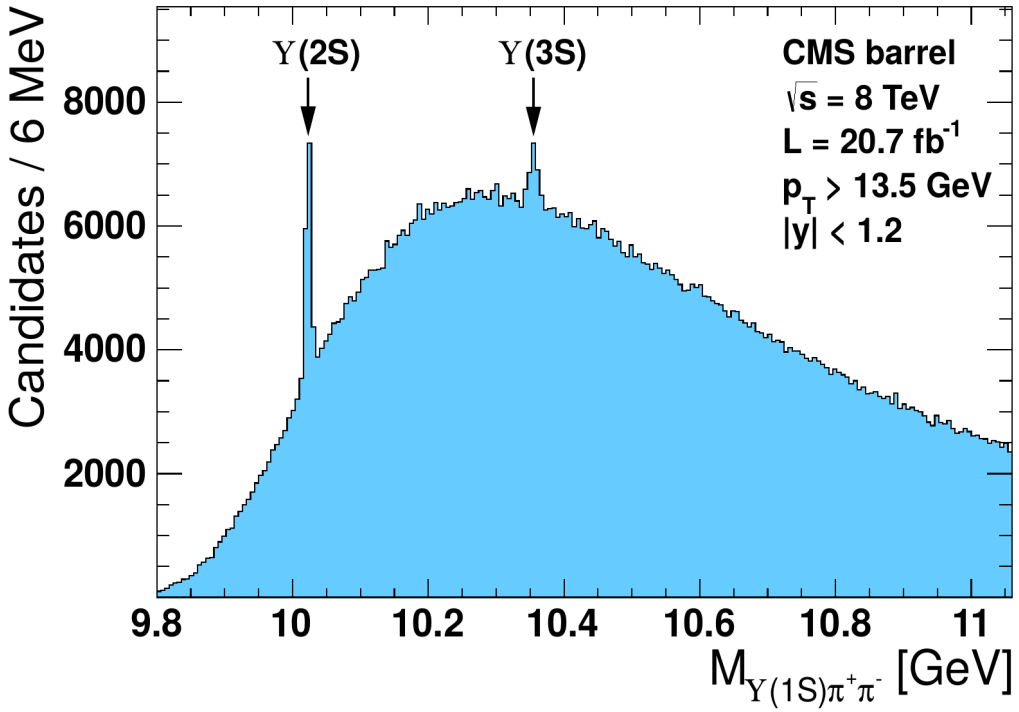
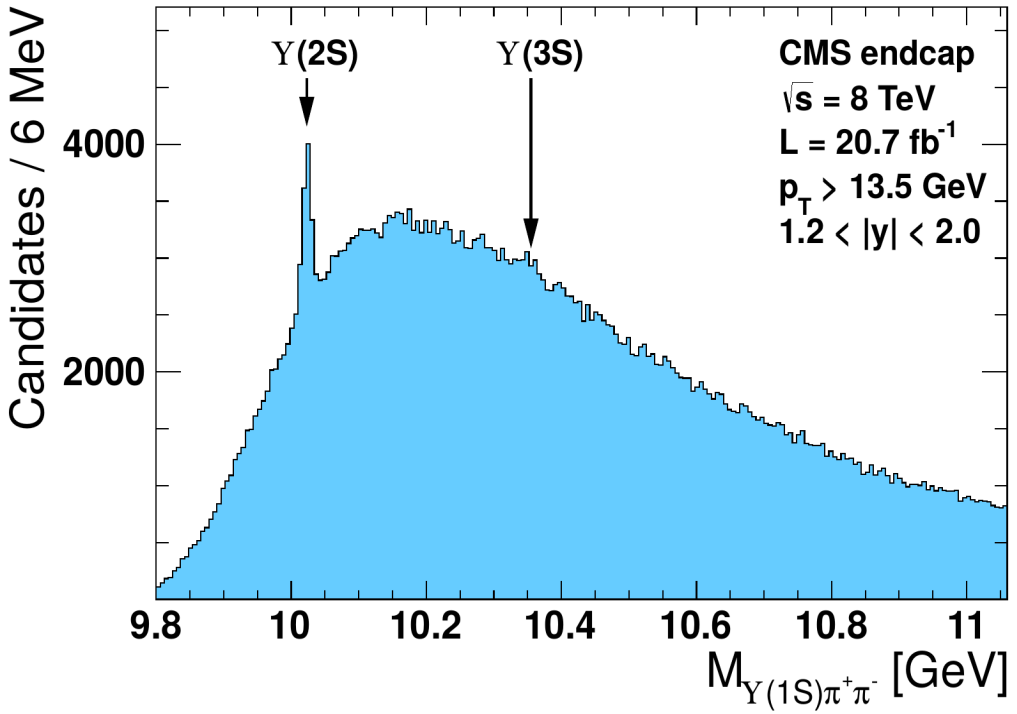
- Combine $\Upsilon(1S) \to \mu\mu$ candidates with pion pairs
  - Optimize selection by maximizing expected signal significance near $\Upsilon(2S)$ mass
- Expect significance **> 5σ** if relative **BR × cross-section > 6.56% of the $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$ value** (analogically as in the X(3872) case JHEP 04 (2013) 154)
- Separate "barrel" and "end-cap" events to better account for varying mass resolution and background level
- No structure seen, apart from $\Upsilon(2S)$ and $\Upsilon(3S)$





X_b Search: Mass Scan

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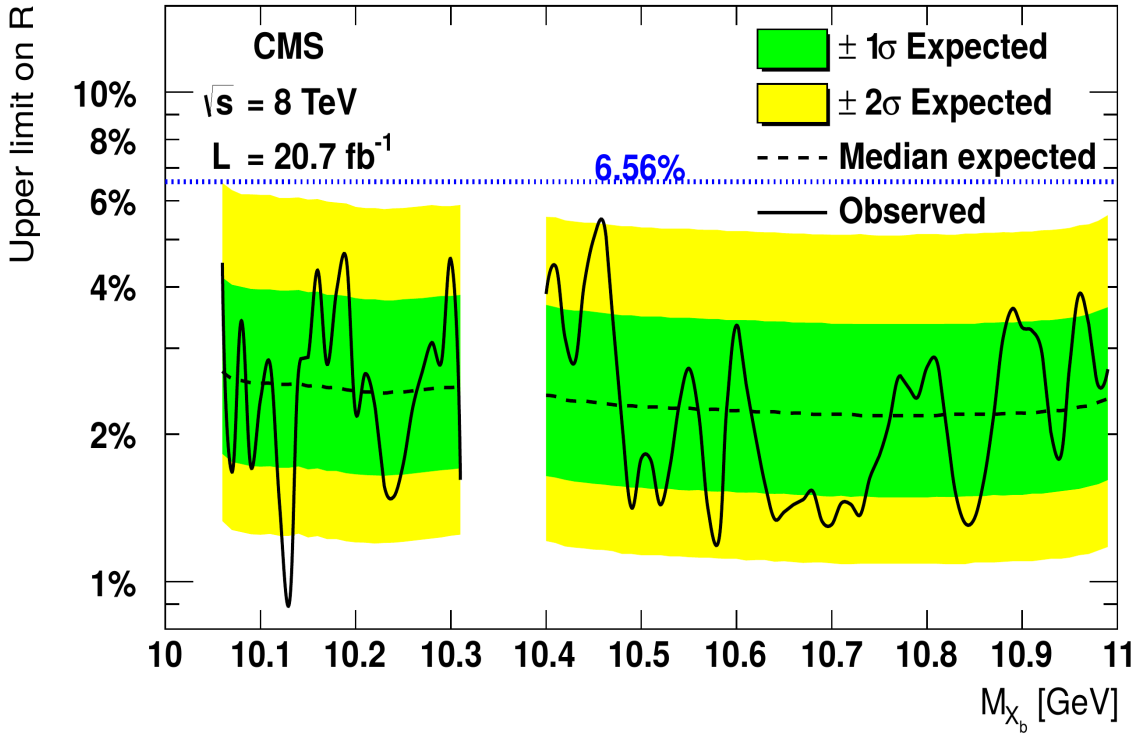
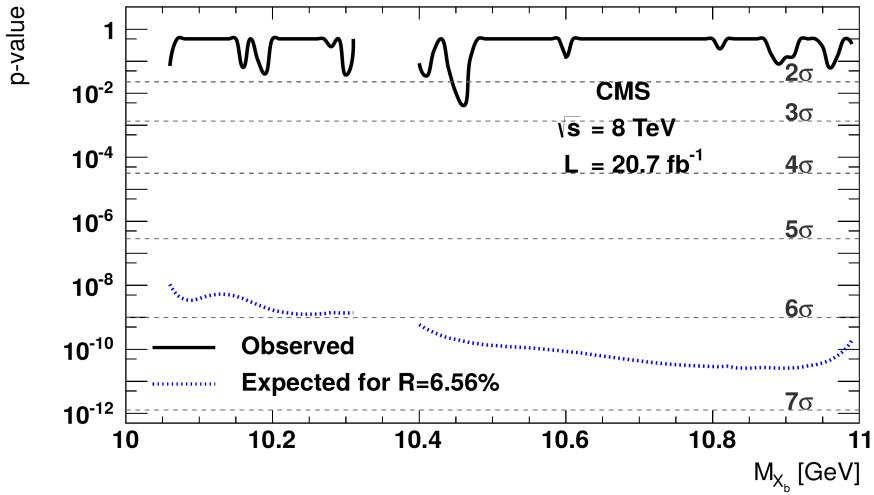
- Explore mass range (10.06-10.31) GeV and (10.40-10.99) GeV
- Shift X_b expected mass in 10 MeV intervals and evaluate signal significance
  - Signal modeled by Gaussian (width fixed to MC simulation: (3.8 – 16.4) MeV)
  - Background as 3rd order polynomial
  - For each mass-point evaluate: (assuming same production mechanism of X_b and $\Upsilon(2S)$, both unpolarized and same di-pion mass distribution)

$$R = \frac{N^{obs}_{X_b}}{N^{obs}_{\Upsilon(2S)}} \frac{\epsilon_{\Upsilon(2S)}}{\epsilon_{X_b}}$$



- local p-values calculated using asymptotic approach
- combining barrel and endcap results
- systematic uncertainties implemented as nuisance parameters



- No significant excess observed; 95% CL upper limit on R (relative BR x cross-section): 0.9% – 5.4%
- This decay mode possibly suppressed by G-parity violation (not in X(3872) case) ArXiv:1402.6236

Peaks in J/ψφ Mass Spectrum in B-decays

- New X/Y/Z states challenges the conventional quark model: origin of these states is not understood
  - If confirmed, would be candidate for an exotic meson
- CDF reported evidence for a structure Y(4140) with mass $4143.4^{+2.9}_{-3.0}$(stat.) ± 1.2(syst.) MeV and width $15.4^{+10.4}_{-6.1}$(stat.) ± 2.5(syst.) MeV
- DØ confirmed observation of the state: M = 4159.0 ± 4.3(stat.) ± 6.6(syst.) and $\Gamma = 19.9 \pm 12.6(\text{stat.})\ ^{+1.0}_{-8.0}$(syst.)
- LHCb did not confirm the existence and have put upper limit on its production
- **This is an independent check by CMS**

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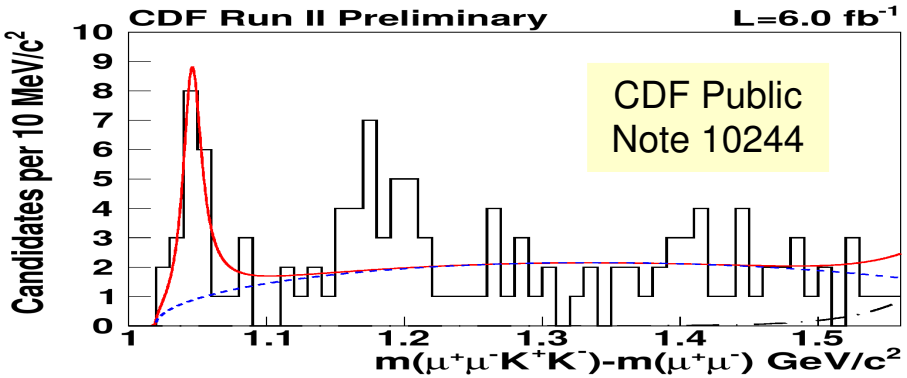

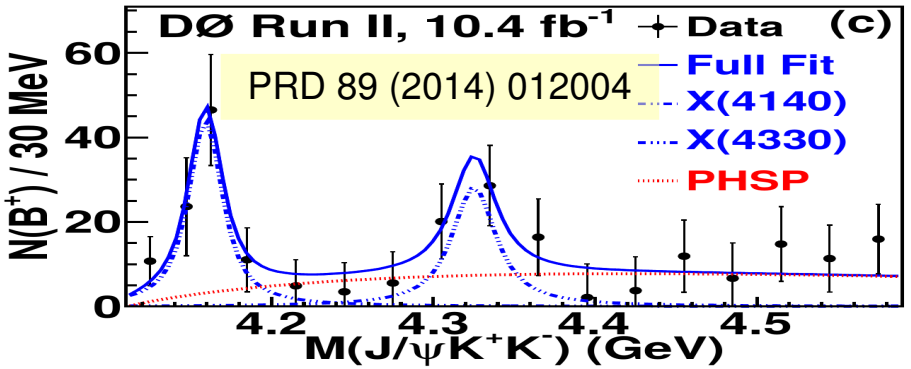

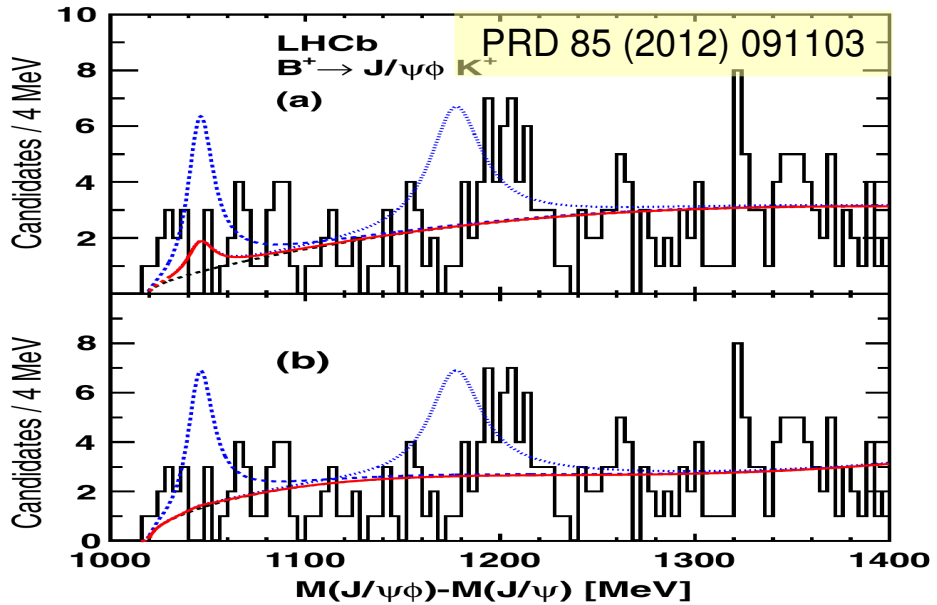

$B^+ \to J/\psi\phi K^+$ Decay Reconstruction

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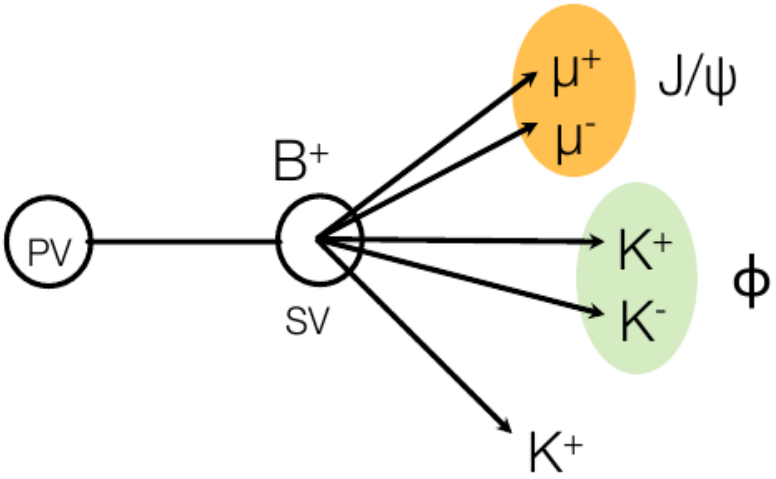

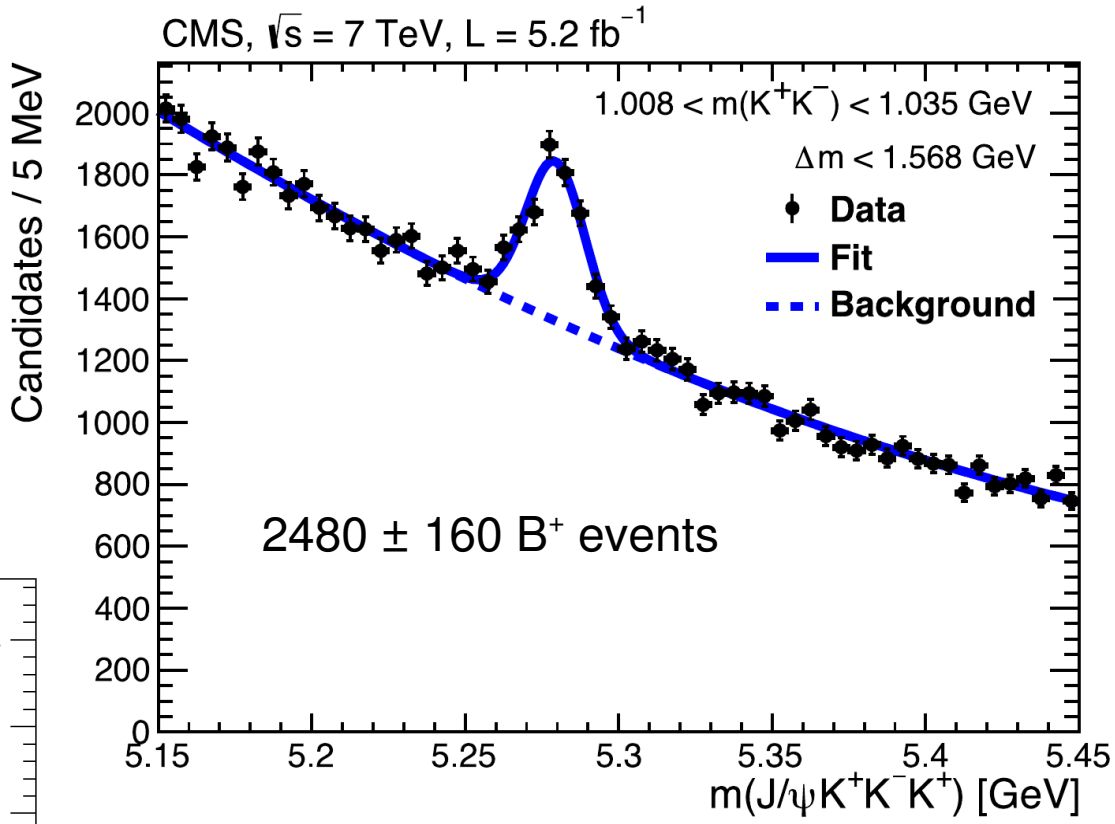

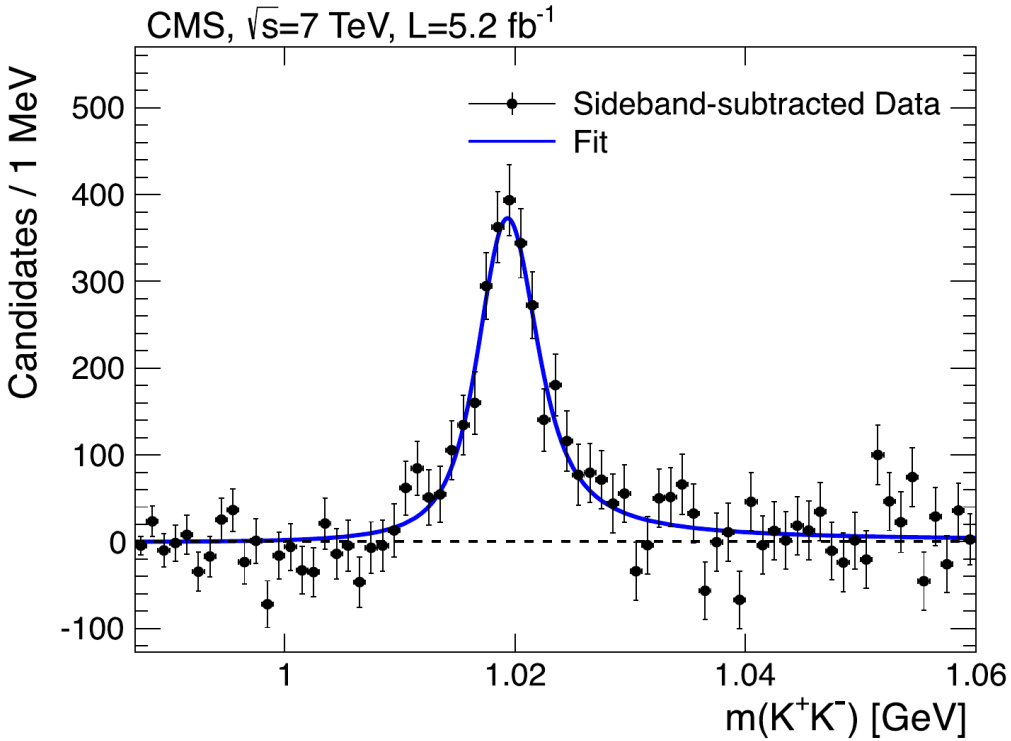

- Largest sample of $B^+ \to J/\psi\phi K^+$ events so far
- Negligible non-ϕ contribution

$J/\psi\phi$ Mass Spectrum in $B^+ \to J/\psi\phi K^+$ Decays

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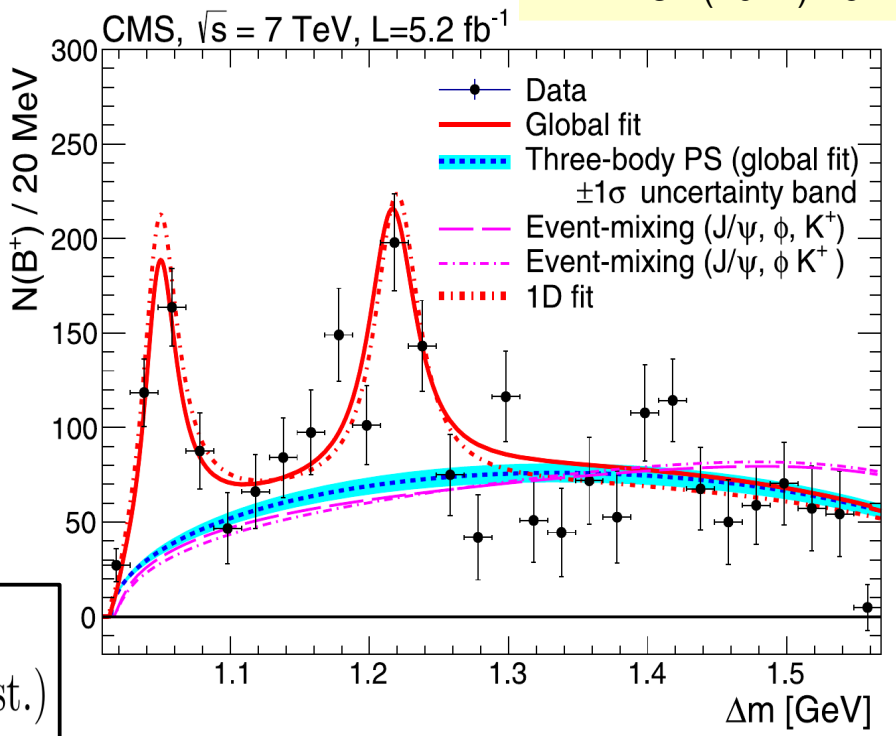
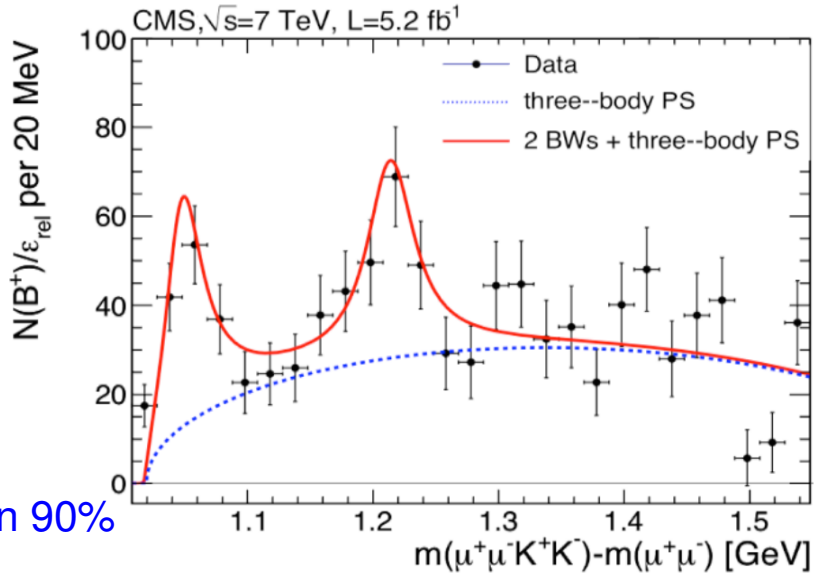
- Investigating $\Delta m = m(\mu\mu KK) - m(\mu\mu)$
  - Exclude $\Delta m > 1.568$ GeV region to reject background from $B_s \to \psi(2S)\phi \to J/\psi\pi\pi\phi$
- Δm spectrum obtained by:
  - Dividing the dataset in 20 MeV Δm bins
  - Extract B^+ signal in each Δm bin by fit



Yield	Mass [MeV]	Γ [MeV]
310 ± 70	$4148.0 \pm 2.4(\text{stat.}) \pm 6.3(\text{syst.})$	$28^{+15}_{-11}(\text{stat.}) \pm 19(\text{syst.})$
418 ± 170	$4313.8 \pm 5.3(\text{stat.}) \pm 7.3(\text{syst.})$	$38^{+30}_{-15}(\text{stat.}) \pm 16(\text{syst.})$

- CMS confirmed Y(4140) with significance > 5σ and saw evidence for a second structure in the same mass spectrum



- Cross-checked with cleaner B^+ sample (tighter selection – kaon p_T, B^+ vertex quality and separation from beam spot, tight ϕ mass window cut)
- Signal efficiency ~40%, further background rejection 90%
- Studied possible contribution from reflections

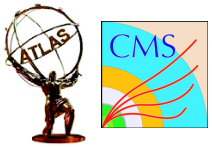
Summary

- **The excellent performance of the LHC and the CMS and ATLAS detectors allowed to study exotic states in heavy flavour, resulting in:**
  - Observation of / evidence for new states: χ_b, Ξ_b^*, $B_c(2S)$
  - Confirmation of previously observed, but still very rare, states: B_c, X(3872), structures in $J/\psi\phi$ mass spectrum from $B^+ \rightarrow J/\psi\phi K^+$ decays
  - Setting up upper limits on possibly existing states: bottomonium counter part of X(3872)

… further Run 1 analyses still running, as well as preparation for spectroscopy measurements in next phases of LHC …

All ATLAS and CMS B-physics public results are available at:

- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH



Backup

Investigating Whole Mass Spectrum

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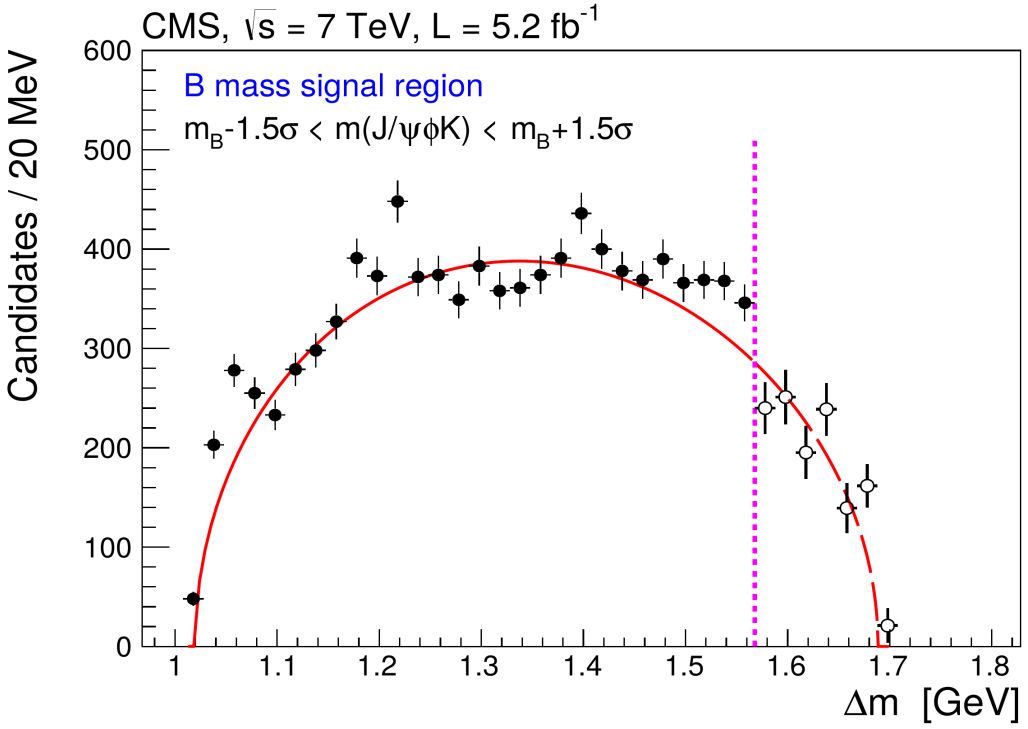
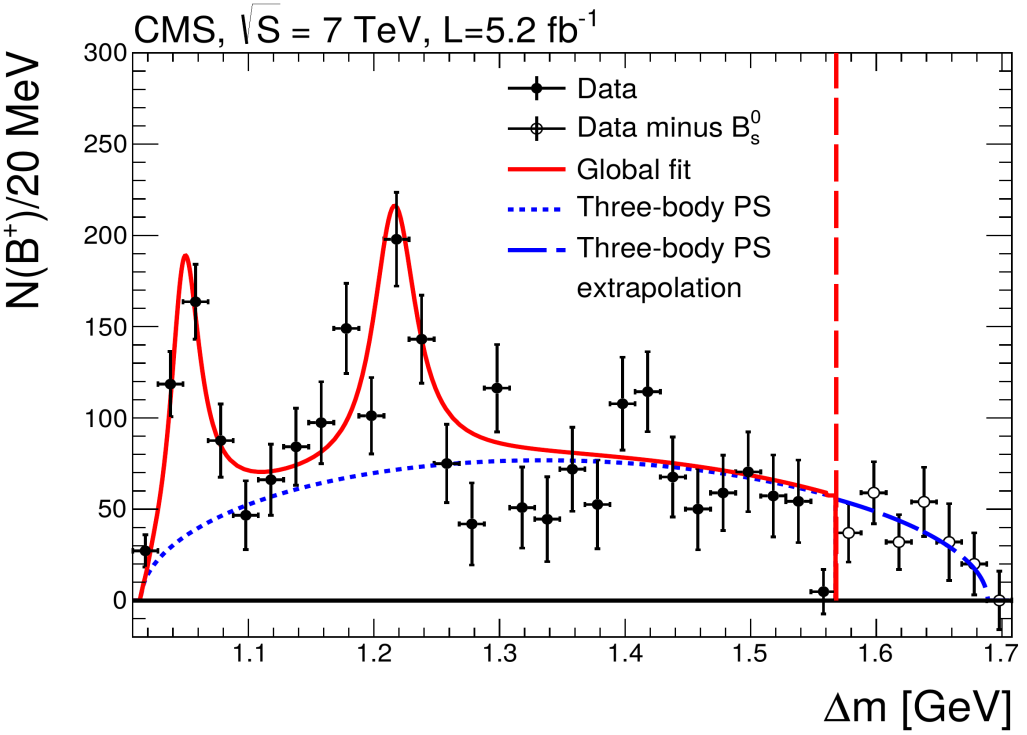
- Δm subtracting $B_s \rightarrow \psi(2S)\phi$ contribution, but including non-B events within 1.5σ of the B-mass



- Extension of the Δm spectrum after subtracting non-B background



- No strong activity => peaks should not appear due to reflections of other resonances