Heavy Flavor and Spectroscopy in CMS

Les Rencontres de Physique de la Vallée d'Aoste

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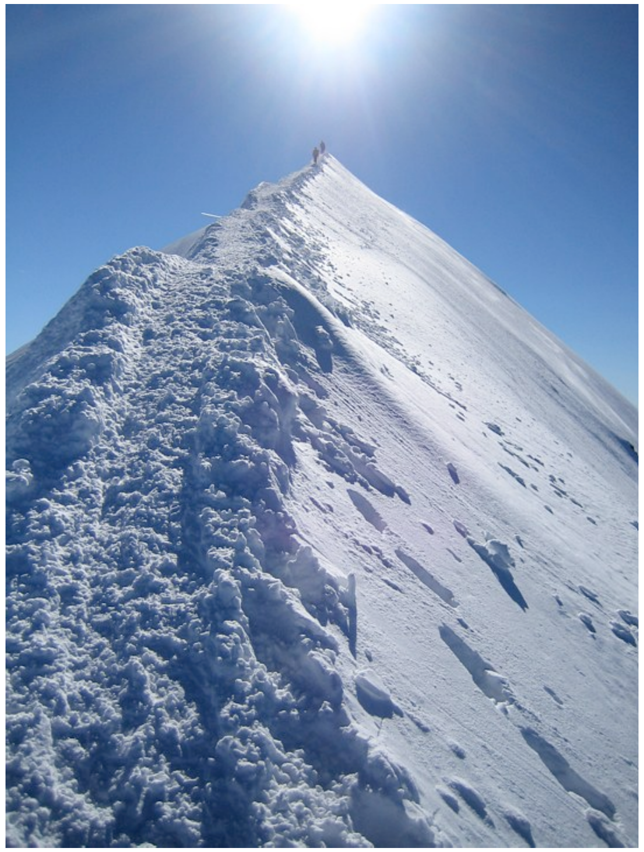
on behalf of the CMS Collaboration

Feb 25th, 2014



Introduction

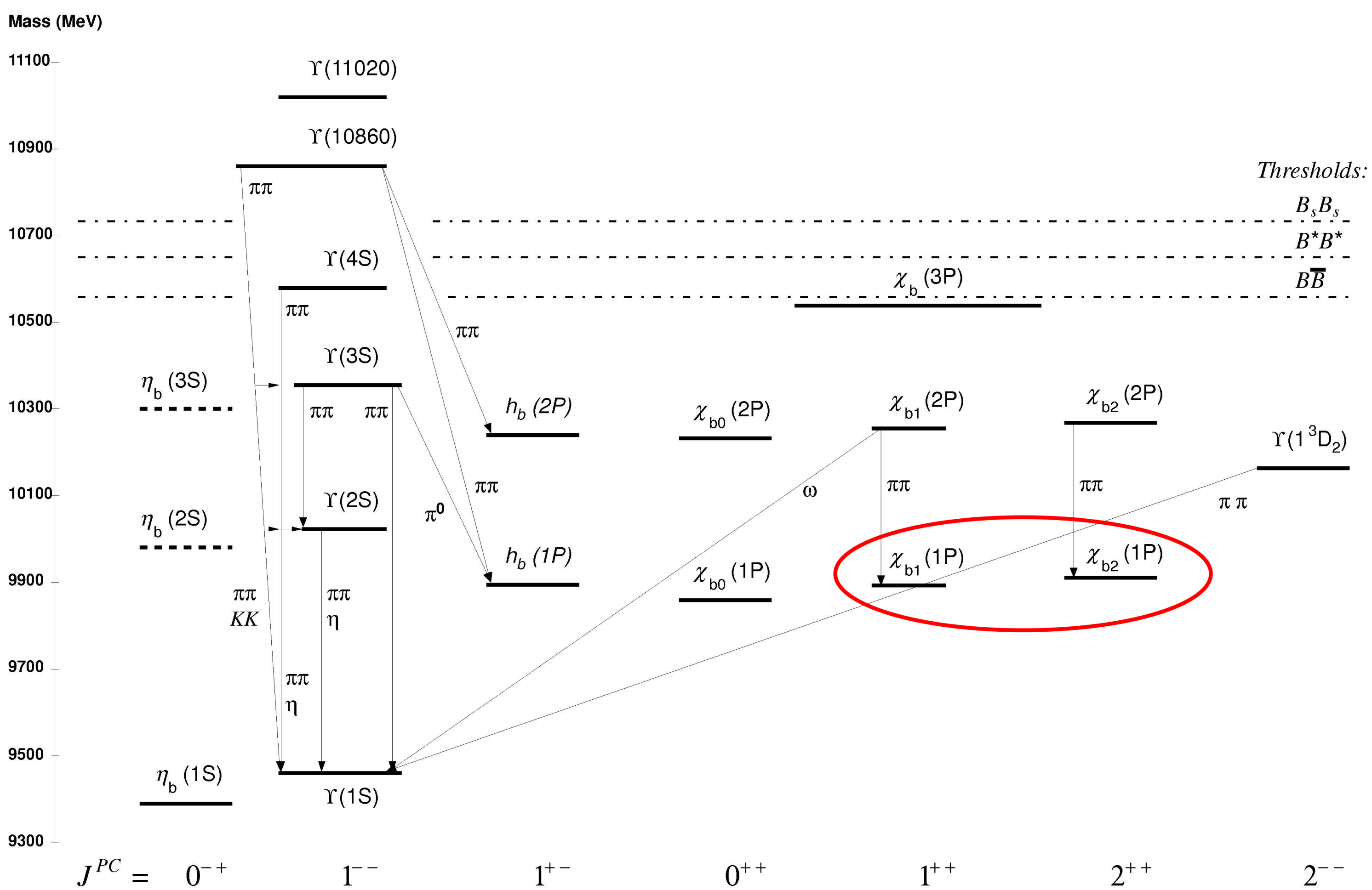
- Measurement of **heavy flavor production** is essential to test QCD models
  - b-hadron properties provide important tests of the SM → any deviation would be indirect indication of New Physics
  - plenty of heavy hadrons produced at hadron colliders → chance to study still not well-known particles
  - knowledge of b-flavored background needed by New Physics studies
- Discovery of **new exotic states** can help understanding hadron formation
- **Outline** of the talk
  - measurement of the χ_{b2} over χ_{b1} cross-section ratio
  - measurement of $B_c \to J/\psi\pi^\pm\pi^\pm\pi^\mp$ and $B_c \to J/\psi\pi^\pm$ branching fractions
  - observation of peaking structures in the $J/\psi\phi$ mass spectrum in B decays
  - search for a new bottomonium state decaying to $\Upsilon(1S)\pi^+\pi^-$

Measurement of the χ_{b2} over χ_{b1} cross-section ratio

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH13005

- Measurements of cross sections and feed-down fractions of P-wave quarkonia are crucial to understand quarkonium production

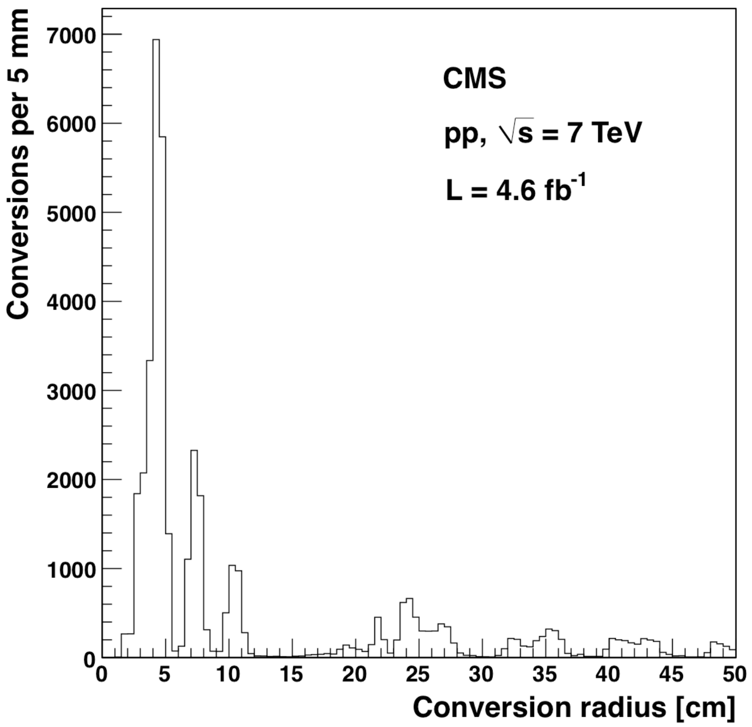
- Relative production cross-section ratios of P-waves are by themselves interesting tests of (NR)QCD



χ_b reconstruction in CMS

- CMS already performed the measurement of χ_c cross section ratio
  Eur. Phys. J. C72 (2012) 2251

- Same measurement in the χ_b sector with 2012 data (~20 fb^{-1})
  - most theoretical and experimental uncertainties cancel out in the ratio

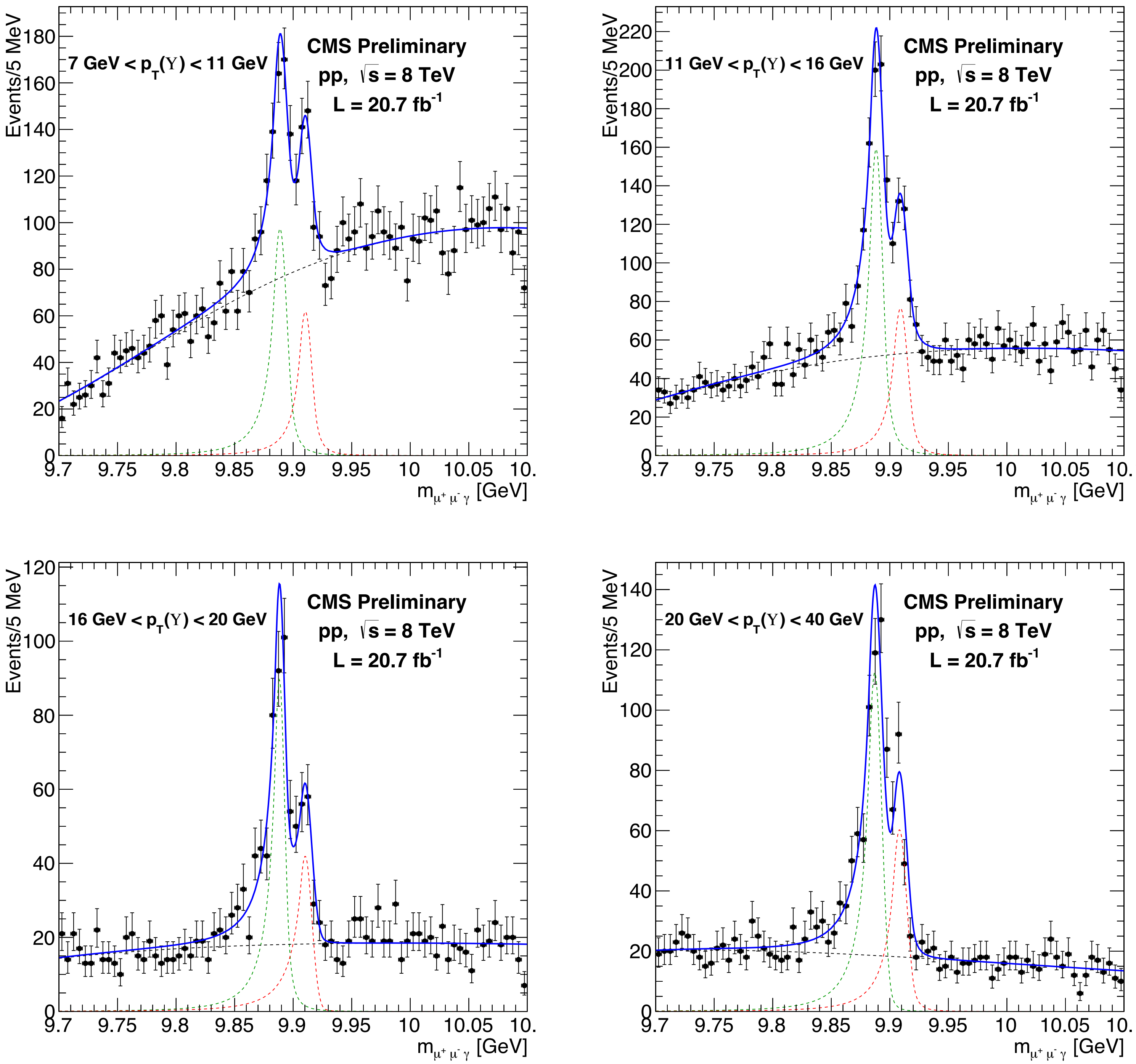


- P-wave quarkonia can be detected via the **radiative decay**
  - $\chi_{c1,2} \rightarrow J/\psi\ \gamma$
  - $\chi_{b1,2}(nP) \rightarrow \Upsilon(nS)\ \gamma$

- **Very challenging because of the small difference** between χ_{b1} and χ_{b2} masses (19.4 MeV) and of their small production cross section
  - Photon calorimetric measurement → not sufficient invariant mass resolution to separate the two states
  - Good photon energy and mass resolution obtained from the **reconstruction of photon conversions in the silicon tracker**

The $\chi_{b1,2}$ signals

$\chi_{b1,2}$ signals are measured in four bins of Υ(1S) transverse momentum in the range 7-40 GeV



Considered phase space:
$|y^{\Upsilon}| < 1.5$
$|\eta^{\gamma}| < 1.0$

Shape of the signal peaks based on simulation studies

Measurement resolution ~5 MeV

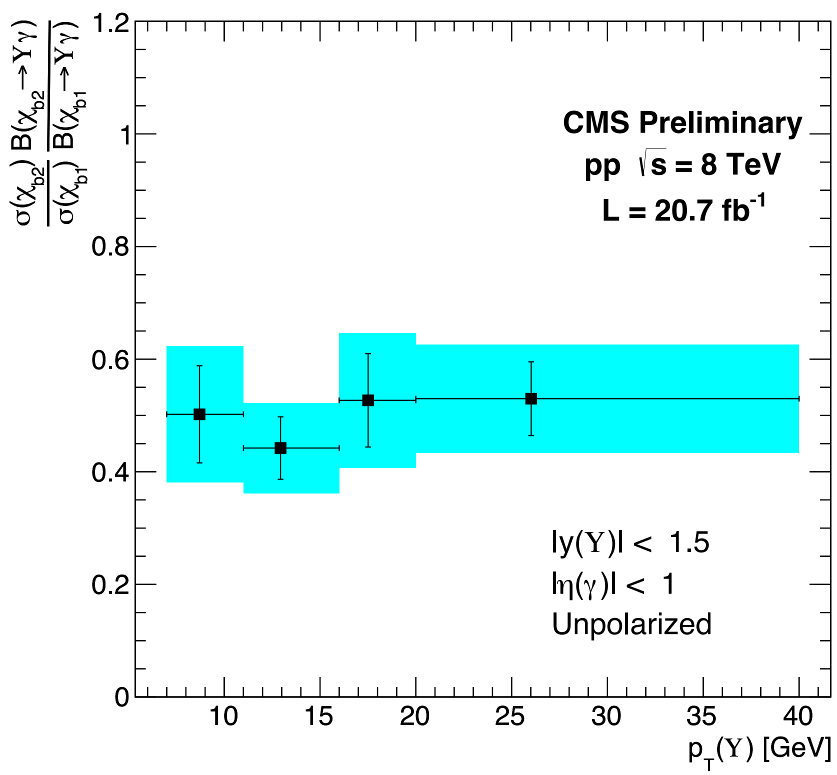
χ_{b2}/χ_{b1} cross section ratio

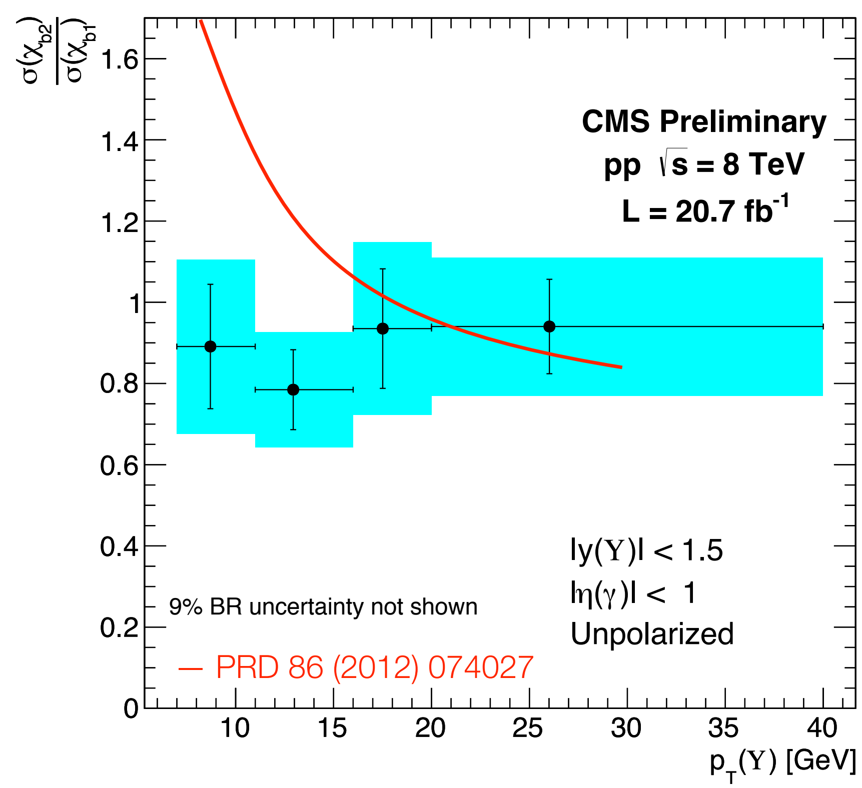
$$\mathcal{R} \doteq \frac{\sigma(pp \to \chi_{b2} + X)}{\sigma(pp \to \chi_{b1} + X)} = \frac{N_{\chi_{b2}}}{N_{\chi_{b1}}} \cdot \frac{\epsilon_1}{\epsilon_2} \cdot \frac{\mathcal{B}(\chi_{b1}(1P) \to \Upsilon(1S) + \gamma)}{\mathcal{B}(\chi_{b2}(1P) \to \Upsilon(1S) + \gamma)}$$

Ratio of BR from PDG

yields of $\chi_{b1,2}$ signal candidates
from unbinned log-likelihood minimization

ε_{12} acceptance and efficiency
obtained from simulation,
assumption of unpolarized χ_b





Systematic uncertainties:

- Signal parametrization and fit strategy
- χ_b p_T spectra
- statistical uncertainty on ε ratio
- uncertainty on BR

Error bars → statistical uncertainties
Colored bands → total uncertainties

Not significantly dependent on the transverse momentum of the Υ(1S)

The most recent theoretical work PRD 86 (2012) 074027, using also the CMS χ_c result, predicts an increase of the ratio at low p_T

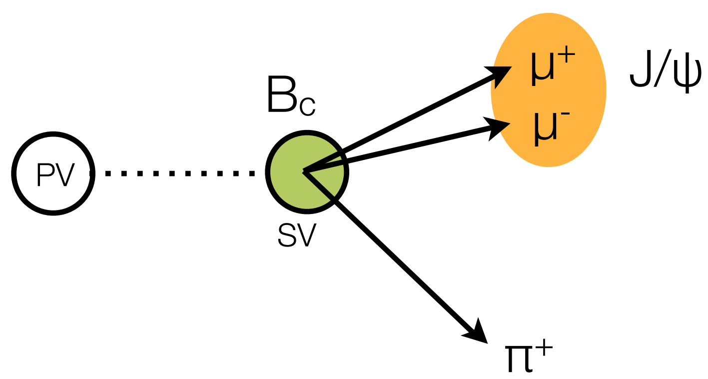
Measurement of B_c Branching Fractions

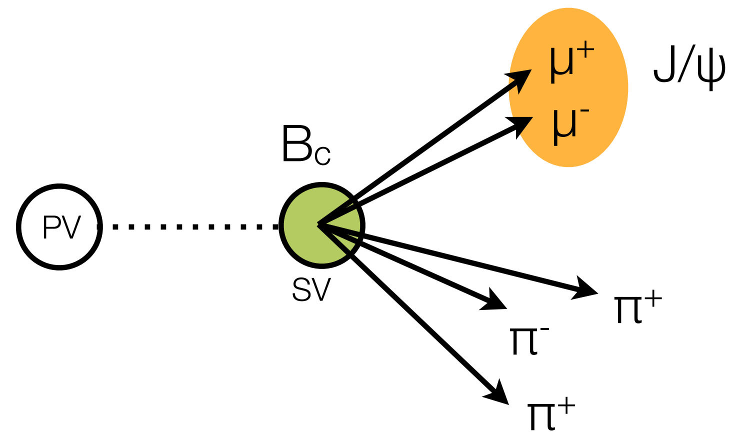
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH13005

- The B_c meson ($\bar{b}c$) is a unique probe for heavy-quark dynamics since it carries **two different heavy flavors**
  - Both quarks compete in the decay
  - b→c transition offers an easy experimental signature (high probability to have a J/ψ meson in the final state)
- Experimental knowledge rather poor (only produced at hadron colliders, need to produce two B_c mesons)
  - Only few decay channels have been observed so far
  - No cross section measurement is available
- Here shown the CMS measurements of
  - $$\frac{BR(B_c^\pm \to J/\psi\pi^\pm\pi^\pm\pi^\mp)}{BR(B_c^\pm \to J/\psi\pi^\pm)} = \frac{N(B_c^\pm \to J/\psi\pi^\pm) \times \epsilon_{B^\pm}}{N(B^\pm \to J/\psi K^\pm) \times \epsilon_{B_c^\pm}} = \frac{Y_{B_c}}{Y_B}$$
  - $$\frac{\sigma(B_c^\pm) \times Br(B_c^\pm \to J/\psi\pi^\pm)}{\sigma(B^\pm) \times Br(B^\pm \to J/\psi K^\pm)} = \frac{N(B_c^\pm \to J/\psi\pi^\pm\pi^\pm\pi^\mp) \times \epsilon_{B_c^\pm \to J/\psi\pi^\pm}}{N(B_c^\pm \to J/\psi\pi^\pm) \times \epsilon_{B_c^\pm \to J/\psi\pi^\pm\pi^\pm\pi^\mp}} = \frac{Y_{3\pi}}{Y_{B_c}}$$

- *evaluated on MC*
- *weight data event by event and extract Y_x from an unbinned ML fit to efficiency corrected mass distribution*

Event selection

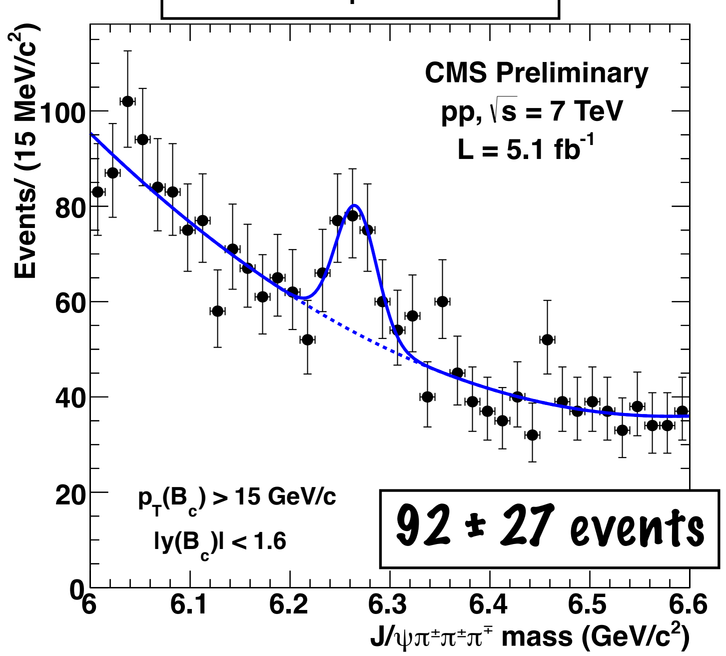




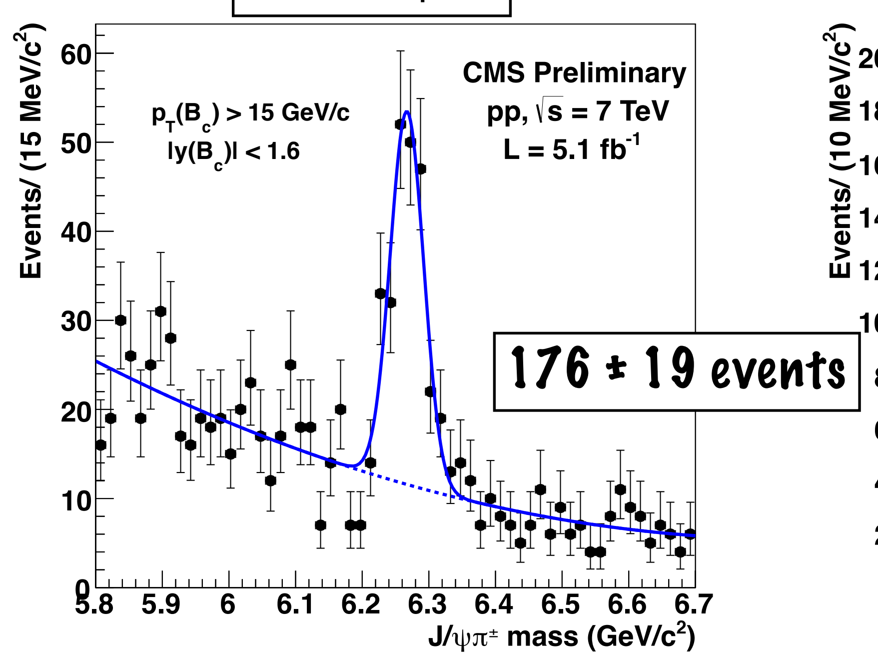
2011 dataset
~ 5 fb^{-1}

- Selection criteria optimized to maximize S/sqrt(S+B)
- Consider the kinematic phase space $p_T(B_c) > 15$ GeV and $|y(B_c)| < 1.6$
  - $p_T(B^+) > 15$ GeV and $|y(B^+)| < 1.6$ for the $B^+ \to J/\psi K^+$ normalization channel

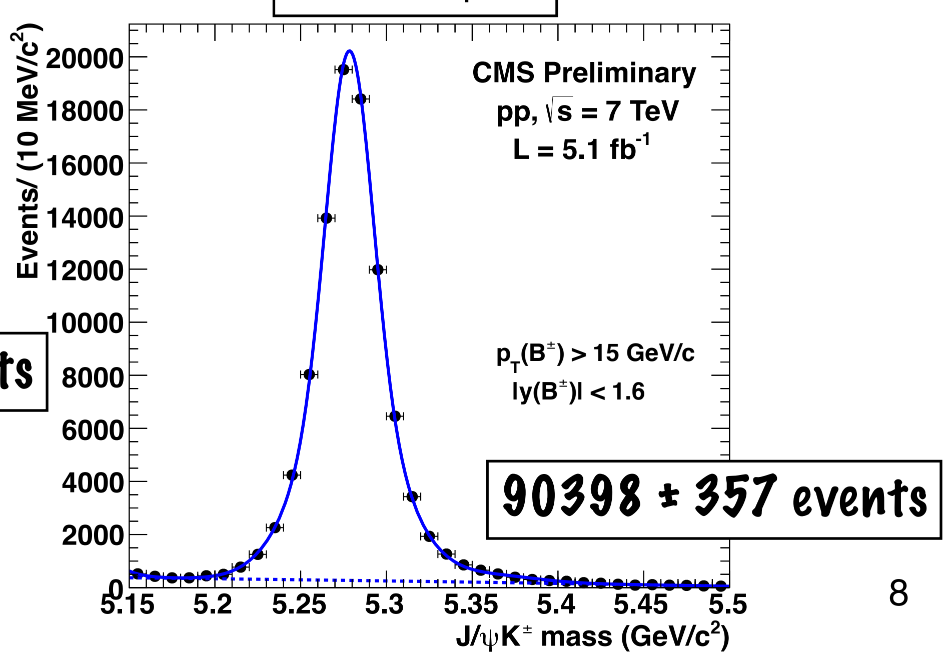
$B_c \to J/\psi\pi^\pm\pi^\pm\pi^\mp$



$B_c \to J/\psi\pi^\pm$



$B^\pm \to J/\psi K^\pm$



Efficiency evaluation

Different strategy depending on the considered meson and decay channel:

- $B_c \rightarrow J/\psi\pi^{\pm}$ and $B^{\pm} \rightarrow J/\psi K^{\pm}$ signals
  - efficiency parametrized as a function of the B_c *(B^{+}) transverse momentum*
- $B_c \rightarrow J/\psi\pi^{\pm}\pi^{\pm}\pi^{\mp}$ channel
  - The decay can go through resonances, and different dynamics could favor (disfavor) different phase space regions
  - Efficiency is studied as a function of a *complete set of variables for the 5 body final state across the entire PS*
  - **Description independent of the decay mode**
  - Efficiency parametrized as $\epsilon = |p_0 + p_1 \cdot x + p_2 \cdot y + p_3 \cdot z + p_4 \cdot w + p_5 \cdot r + p_6 \cdot t + p_7 \cdot s|$
    - free parameters determined with a ML fit on generated events in the 7D space through a binomial probability
    - performed on the $B_c \rightarrow J/\psi 3\pi$ non resonant MC, where all PS configurations are covered

7 independent mass-combinations

- $m^2(\mu^+\pi^+)_{low}$
- $m^2(\pi^+\pi^-)_{high}$
- $m^2(\mu^+\pi^-)$
- $m^2(\pi^+\pi^+)$
- $m^2(\mu^-\pi^+)_{low}$
- $m^2(\mu^-\pi^+)_{high}$
- $m^2(\mu^-\pi^-)$

B_c Branching Fraction results

The two ratios are measured to be

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

Systematic uncertainties:

- Signal and bkg parametrization
- Statistical uncertainty on ε
- Experimental uncertainty on B_c lifetime
- Tracking efficiency

in good agreement with LHCb measurement

$$\frac{BR(B_c^\pm \to J/\psi\pi^\pm\pi^\pm\pi^\mp)}{BR(B_c^\pm \to J/\psi\pi^\pm)} = 2.41 \pm 0.30 \pm 0.33$$

Phys. Rev. Lett. 108 (2012) 251802

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

complementary to the LHCb result, which covers $p_T(B_c(B^+)) > 4$ GeV and $2.5 < \eta < 4.5$

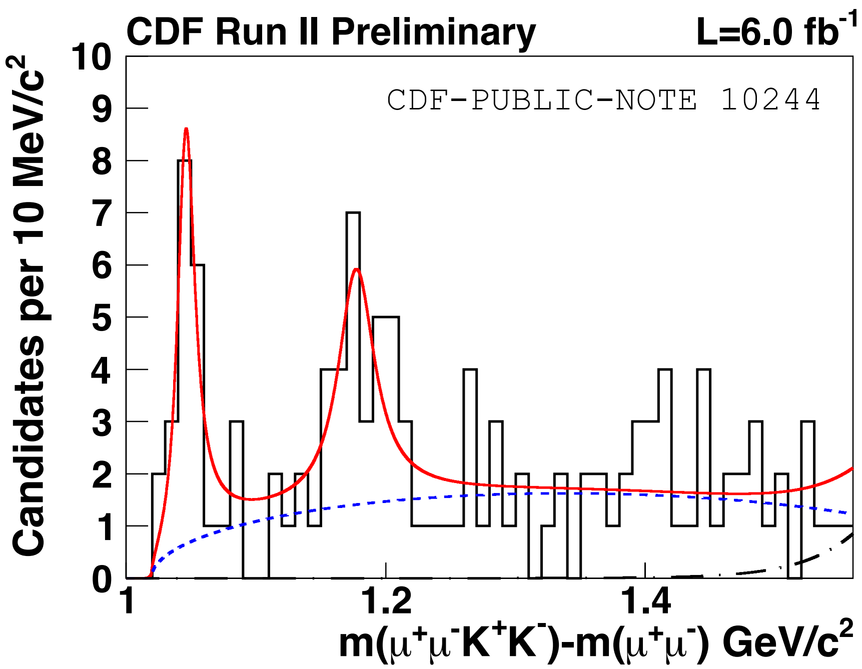
$$R_{c/u} = (0.68 \pm 0.10(\mathrm{stat}) \pm 0.03(\mathrm{syst}) \pm 0.05(\mathrm{lifetime}))\%$$

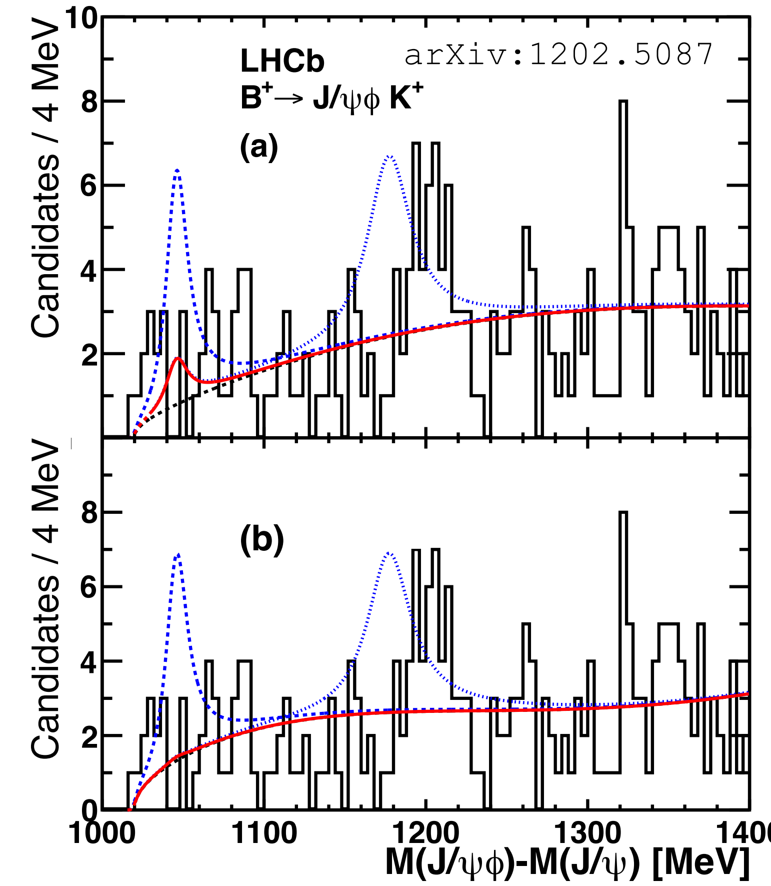
Phys. Rev. Lett. 109 (2012) 232001

Observation of peaks in the J/ψφ mass spectrum in B decays

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11026

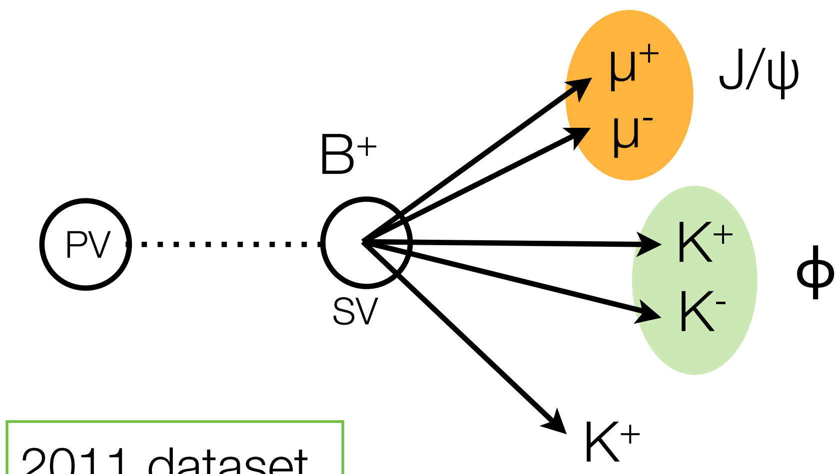
- Discovery of new quarkonium-like states over the last decade poses a challenge to conventional quark model
  - nature of these entities is still a puzzle (charmed hybrids? tetraquarks? molecular states?)
- CDF reported evidence for a structure Y(4140) with mass $4143.4^{+2.9}_{-3.0} \pm 1.2_{(syst)}$ MeV and width $15.3^{+10.4}_{-6.1} \pm 2.5_{(syst)}$ MeV
  - if confirmed, candidate for an exotic meson
    - Belle could not confirm it
    - LHCb did not confirm the existence of Y(4140) and put an upper limit on its production
  - useful to have an independent result
    - **CMS studies the J/ψφ mass spectrum from exclusive $B^+ \to J/\psi\phi K^+$ decays**



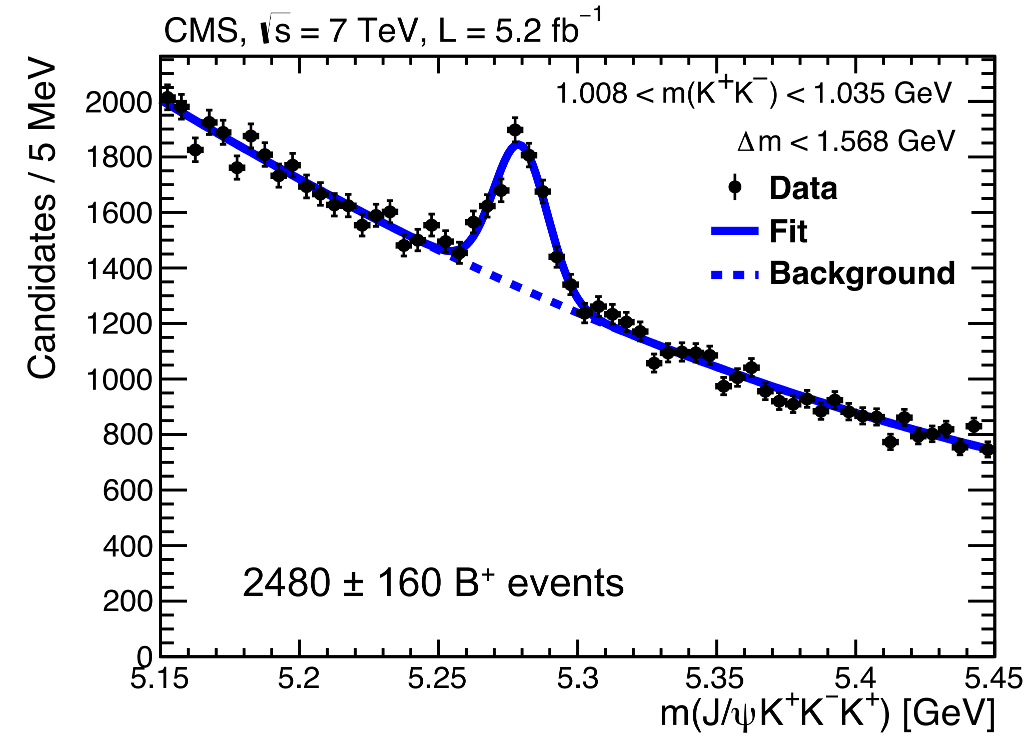


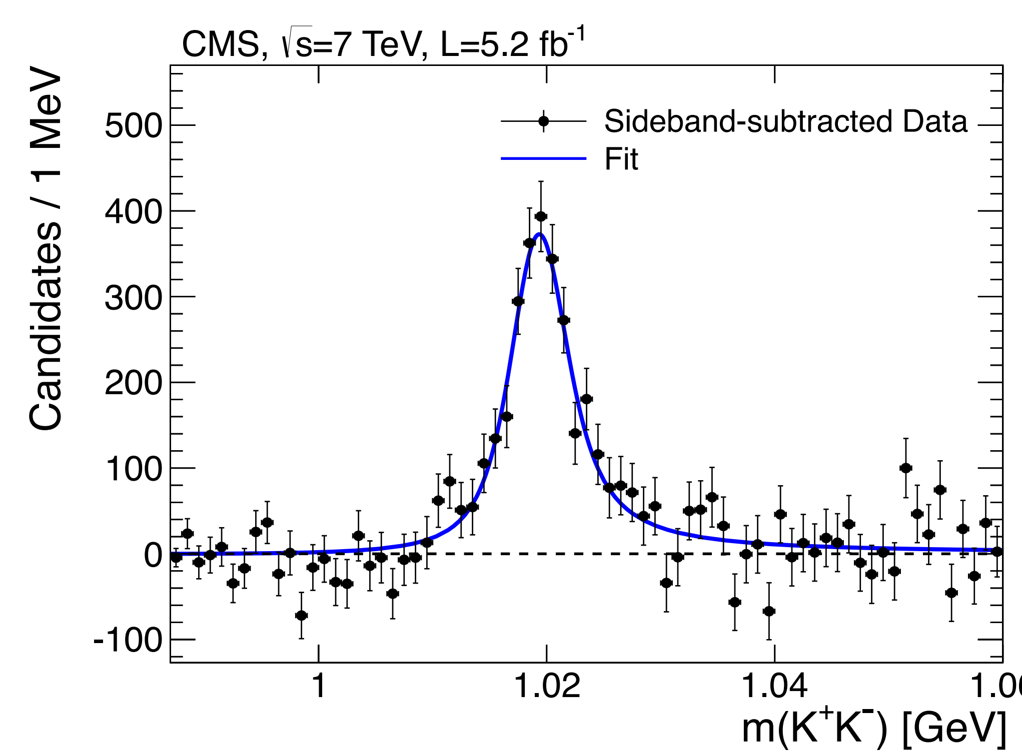
Observation of peaks in the J/ψϕ mass spectrum in B decays

arXiv:1309.6920



2011 dataset,
5.2 fb^{-1}





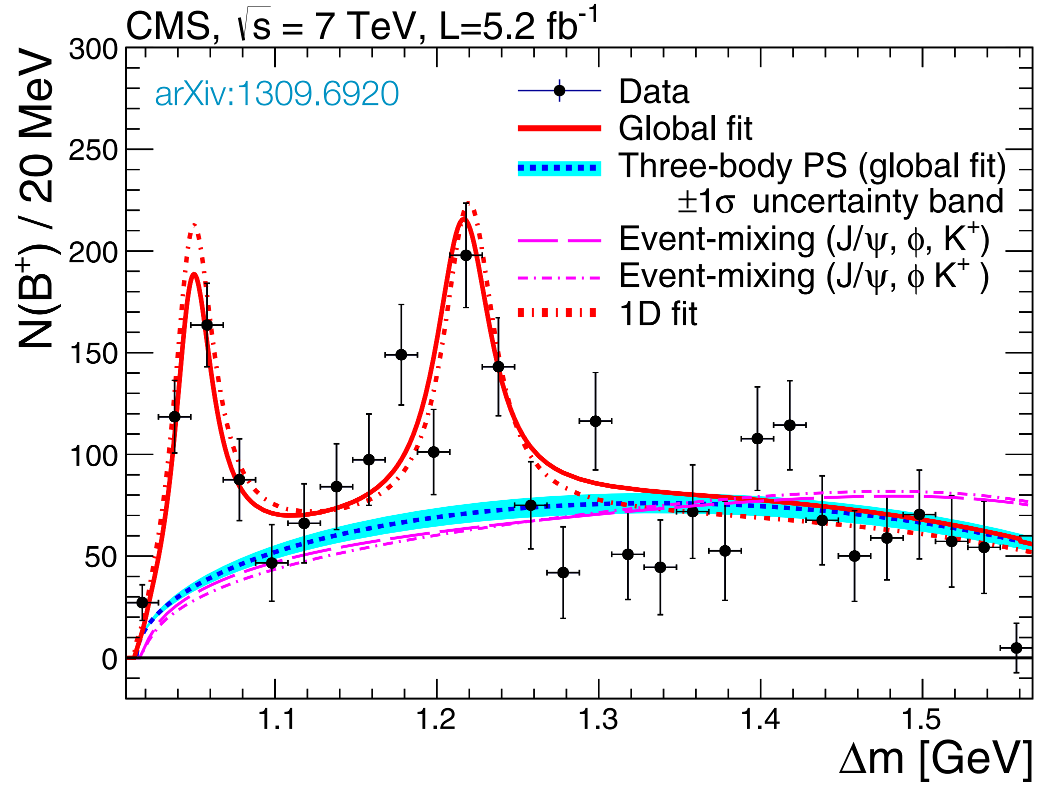
Event selection:

- displaced J/ψ dimuon trigger with $p_T(J/\psi) > 7$ GeV
- run dependent p_T threshold for each muon
- candidate J/ψ associated to 3 additional charged tracks
- vertex constraining J/ψ mass
- K^+K^- pair with lower mass considered as ϕ
  - must lie in ϕ mass window [1.008,1.035] GeV
- **A cleaner sample is also considered as a cross check**
  - retains 40% of B^+ candidates, reduce bkg > 10 times

Observation of peaks in the J/ψϕ mass spectrum in B decays

Presence of possible structures investigated using the $\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$ spectrum

- exclude Δm >1.568 GeV region to avoid bkg from $B_s \to \psi(2S)\phi \to J/\psi\pi^+\pi^-\phi$ decays



Δm spectrum obtained by:

- dividing the dataset in 20MeV Δm bins
- extracting the number of B signal in each Δm bin by fitting the J/ψϕK spectrum
- plotting the B^+ yield corrected by relative efficiency

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

Systematic uncertainties:

- B^+ signal and bkg pdf
- Relative efficiency
- Δm binning
- Δm structure PDF
- Δm mass resolution
- Δm background shape
- Selection requirements

CMS confirmed a structure at 4148 MeV with a significance greater than 5σ and saw an evidence for a second structure in the same mass spectrum

Angular analysis would help to elucidate the nature of these 2 structures

Search for new bottomonium state decaying to $\Upsilon(1S)\pi^+\pi^-$

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11016

- Exotic resonance X(3872) discovered in the final state $J/\psi\pi^+\pi^-$

- The **bottomonium counterpart X_b** is expected to decay into $\Upsilon(1S)\pi^+\pi^-$

  - Predicted mass within 10-11 GeV (or close to the $B\bar{B}$ or $B\bar{B}^*$ threshold,10.562 and 10.604 GeV)

  - In analogy with X(3872), could be a narrow resonance (X(3872) width = 1.2 MeV) and have a sizable branching ratio into $\Upsilon(1S)\pi^+\pi^-$

  - Look for a peak in the $\Upsilon(1S)(\mu^+\mu^-)\pi^+\pi^-$ invariant mass spectrum (excluding the Y(2S) and Y(3S) peak regions)

    - **Measure** $R = \dfrac{\sigma_{X_b} \times BR(X_b \to \Upsilon(1S)\pi^+\pi^-)}{\sigma_{\Upsilon(2S)} \times BR(\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-)}$ **as a function of X_b mass between 10 and 11 GeV**

    - Investigated kinematic region: $p_T(\Upsilon(1S)\pi^+\pi^-) > 13.5$ GeV and $|y(\Upsilon(1S)\pi^+\pi^-)| < 2.0$

Assumptions:

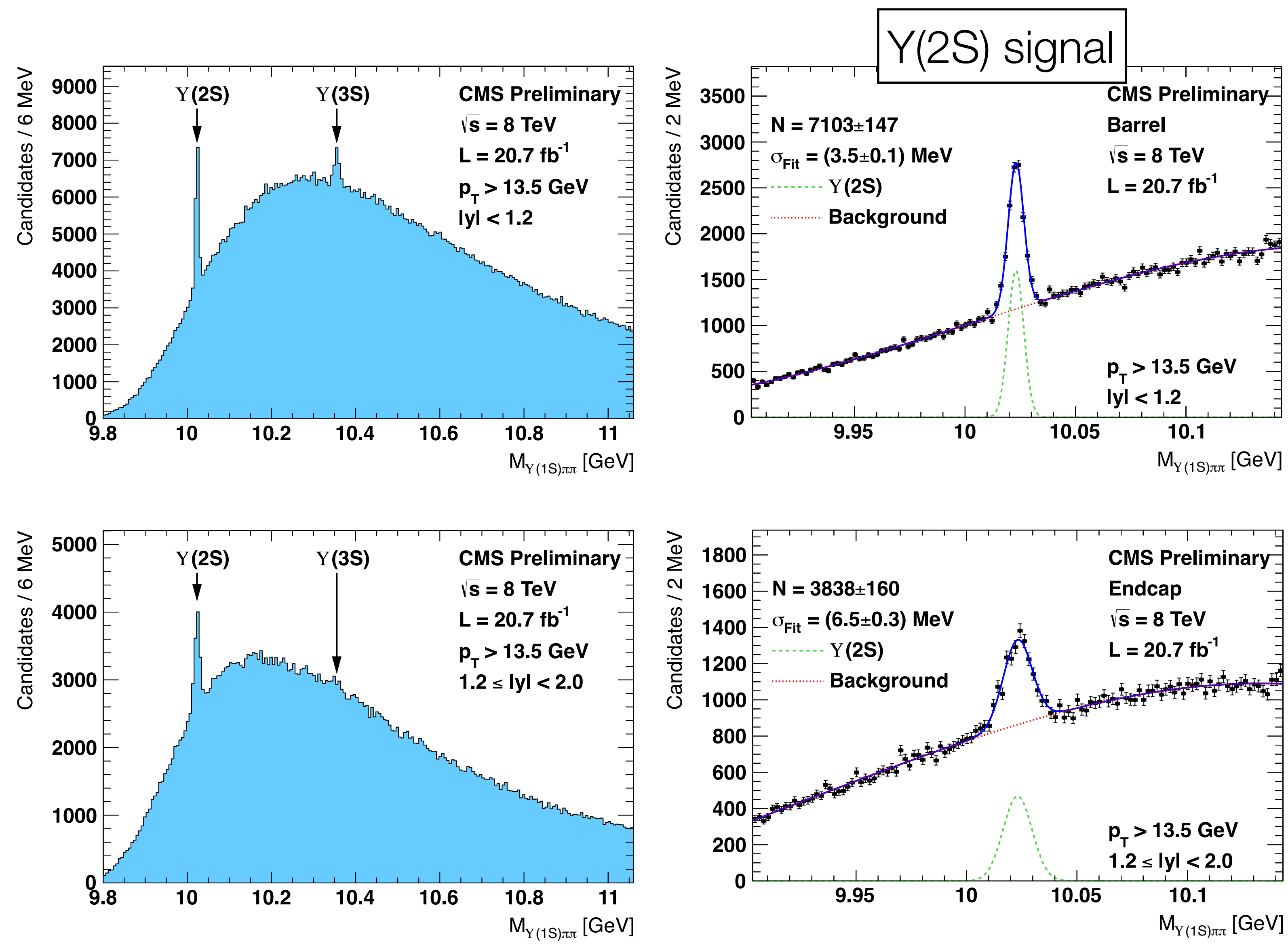
- same production mechanism for Y(2S) and X_b
- both produced unpolarized
- X_b narrow resonance with same quantum numbers as Y(2S)
- same dipion mass distribution for X_b and Y(2S)

X_b candidate reconstruction

2012 dataset
~20 fb^{-1}

- X_b candidates reconstructed by associating the Υ(1S) to 2 tracks (assumed to be pions)
  - selection criteria optimized with a genetic algorithm → maximize expected signal significance near Υ(2S) mass
  - signal statistical significance expected to be > 5σ if X_b BR * cross-section > 6.56% of the corresponding Υ(2S) → Υ(1S)$\pi^+\pi^-$ value (analogous to X(3872) → J/ψ$\pi^+\pi^-$)

    JHEP **04** (2013) 154



- Separate "barrel" and "endcaps" events to exploit better mass resolution and lower background in the barrel region

- **No outstanding structure** apart from Υ(2S) and Υ(3S)

X_b search: mass scan

- Explore 10.06-10.31 and 10.40-10.99 GeV mass regions
- Shift X_b expected mass in **10 MeV intervals** and evaluate signal significance
  - X_b signal modeled with a Gaussian function
    - intrinsic width assumed to be small compared to the detector mass resolution
    - for each mass point, fix signal width to value from the simulation (can vary from 3.8 to 16.4 MeV)
  - background parametrized with a 3rd order polynomial
  - for each mass point, evaluate

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

observed yields of X_b and Y(2S) candidates

overall efficiencies estimated from simulation

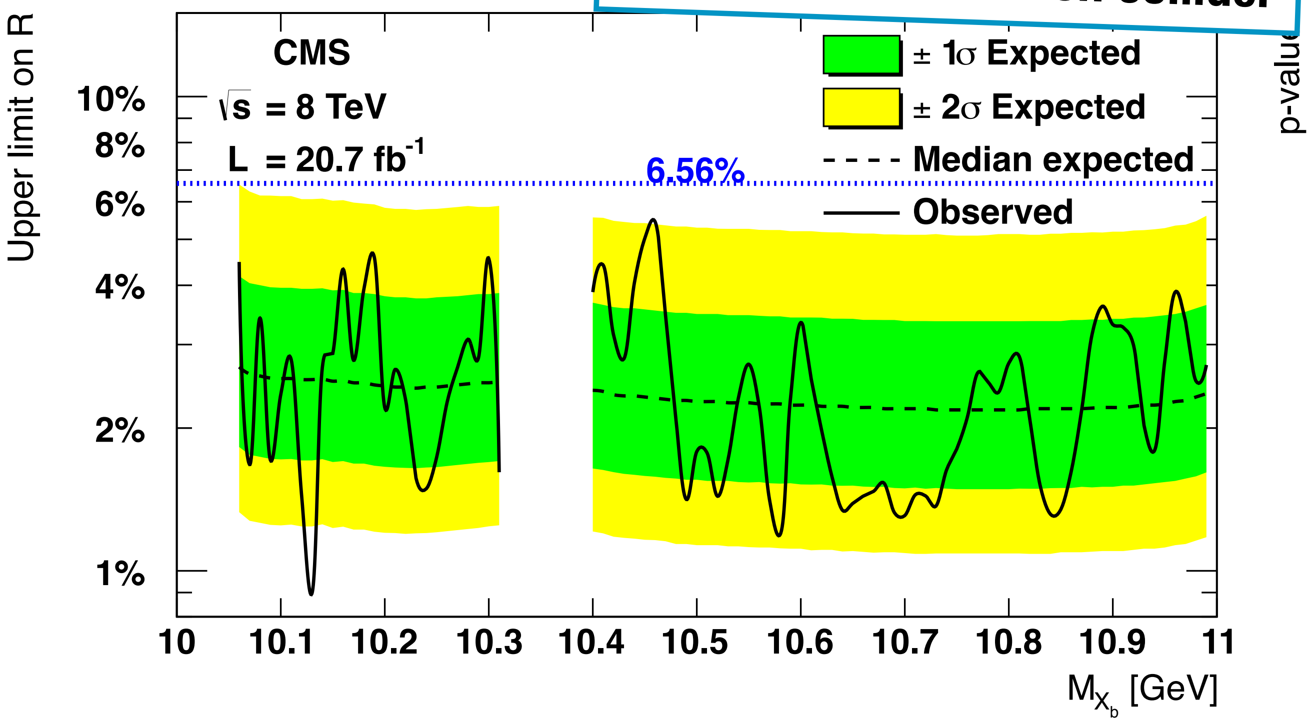
Systematic uncertainties:

- Modeling of the signal decay
  - dipion mass distribution
  - Y(2S) mass resolution
- Signal polarization
- Background shape

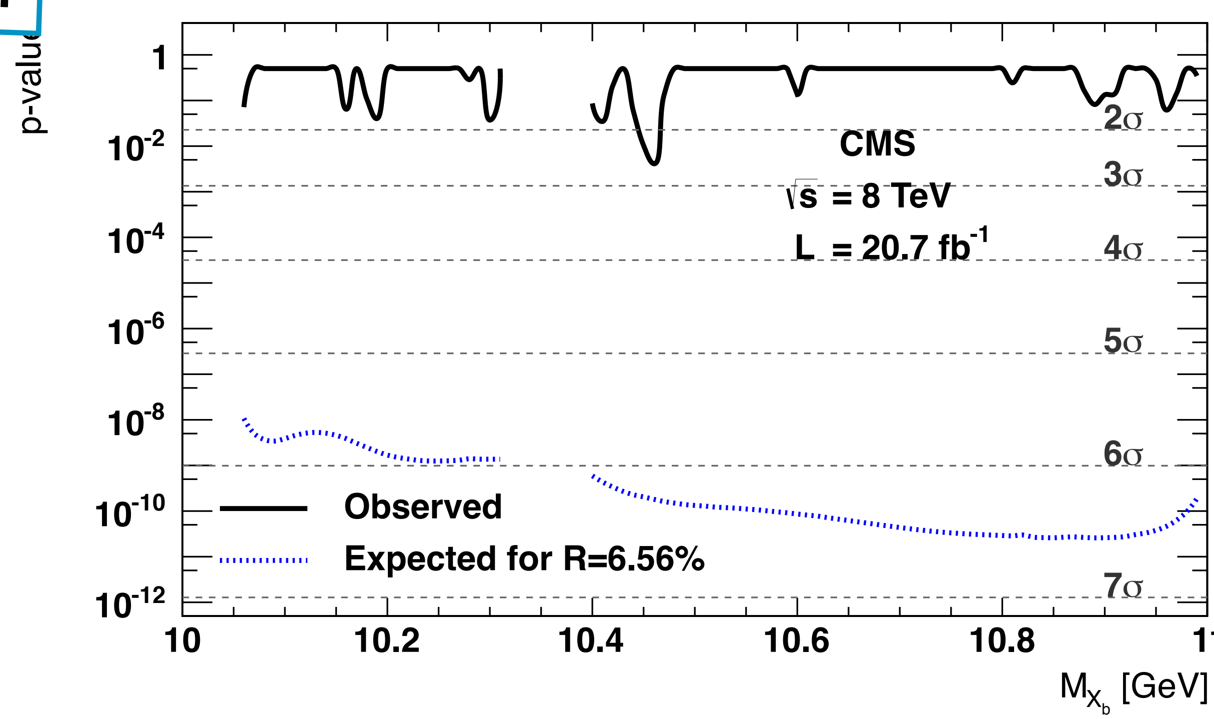
Results

- Local p-values calculated using asymptotic approach and combining results of fits to the barrel and endcap regions
- Systematic uncertainties implemented as nuisance parameters

first upper limits on X_b production at a hadron collider



[PLB 727 (2013) 57](#)



No significant excess is observed

95% CL upper limit on the cross-sections*branching fractions ratio is in the range 0.9 - 5.4 %

Conclusions

- Thanks to the excellent LHC and CMS performances in Run1, important measurements of B-hadrons and quarkonium production and decay rates have been carried out

- We have also exploited the collected data to search for new exotic states

- Shown today:
    - measurement of the χ_{b2} over χ_{b1} cross section ratio
    - measurement of B_c branching fractions
    - observation of peaks in the $J/\psi\phi$ mass spectrum
    - search for a new bottomonium state decaying to $\Upsilon(1S)\pi^+\pi^-$

All CMS B-Physics results are available at
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH

Backup

$B^+ \to J/\psi\phi K$ tight selection

Additional requirements:

- kaon $p_T > 1.5$ GeV
- B^+ vertex CL > 10%
- significance of the B^+ vertex transverse displacement from the PV > 7
- m(K+K-) within 7 MeV from the ϕ meson mass