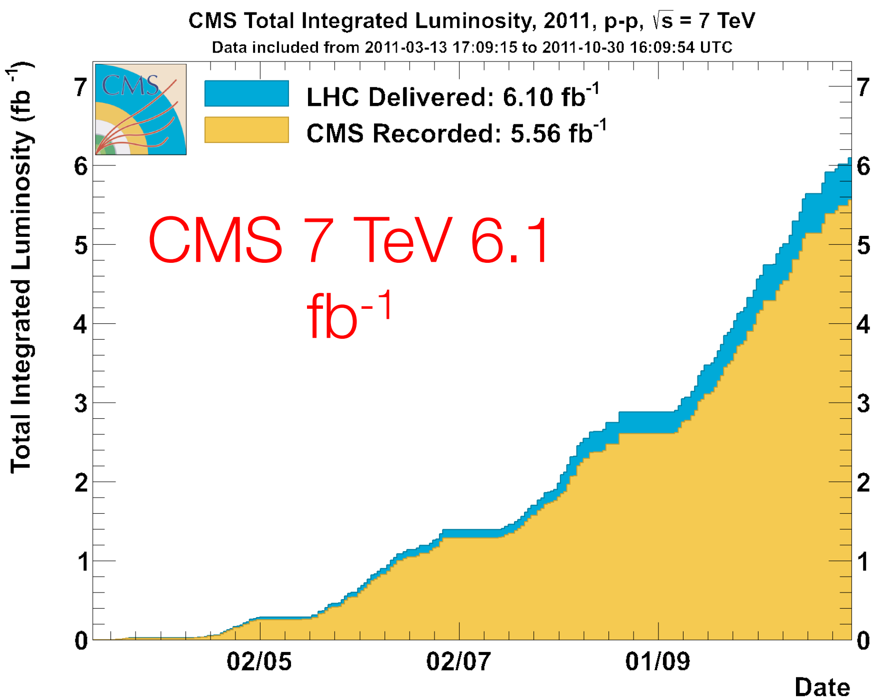
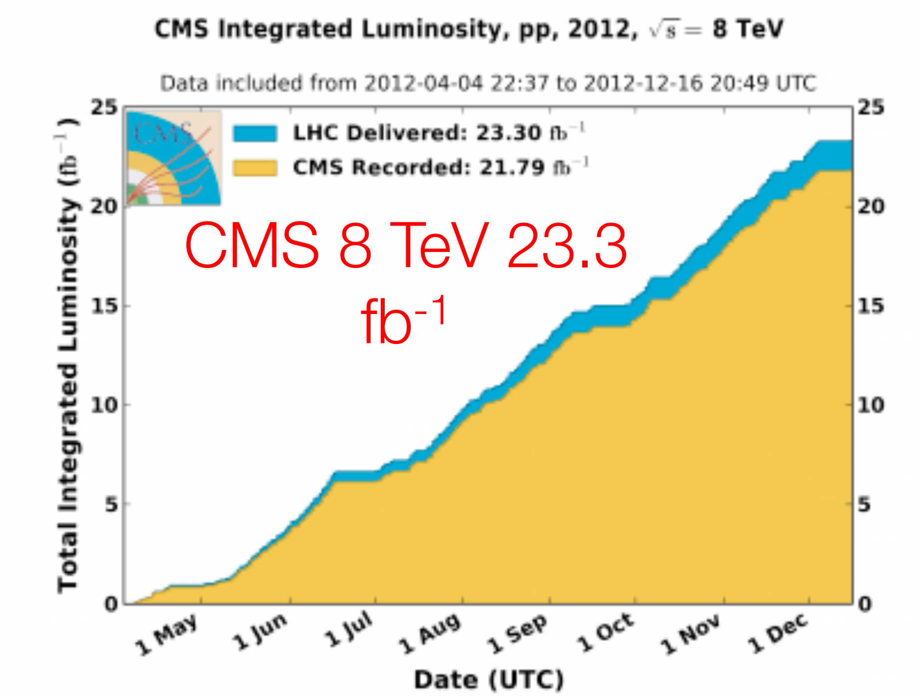
Heavy Meson Production and Spectroscopy at CMS

Meson 2014

Kai Yi
on behalf of the CMS Collaboration
June 3rd, 2014

CMS & LHC



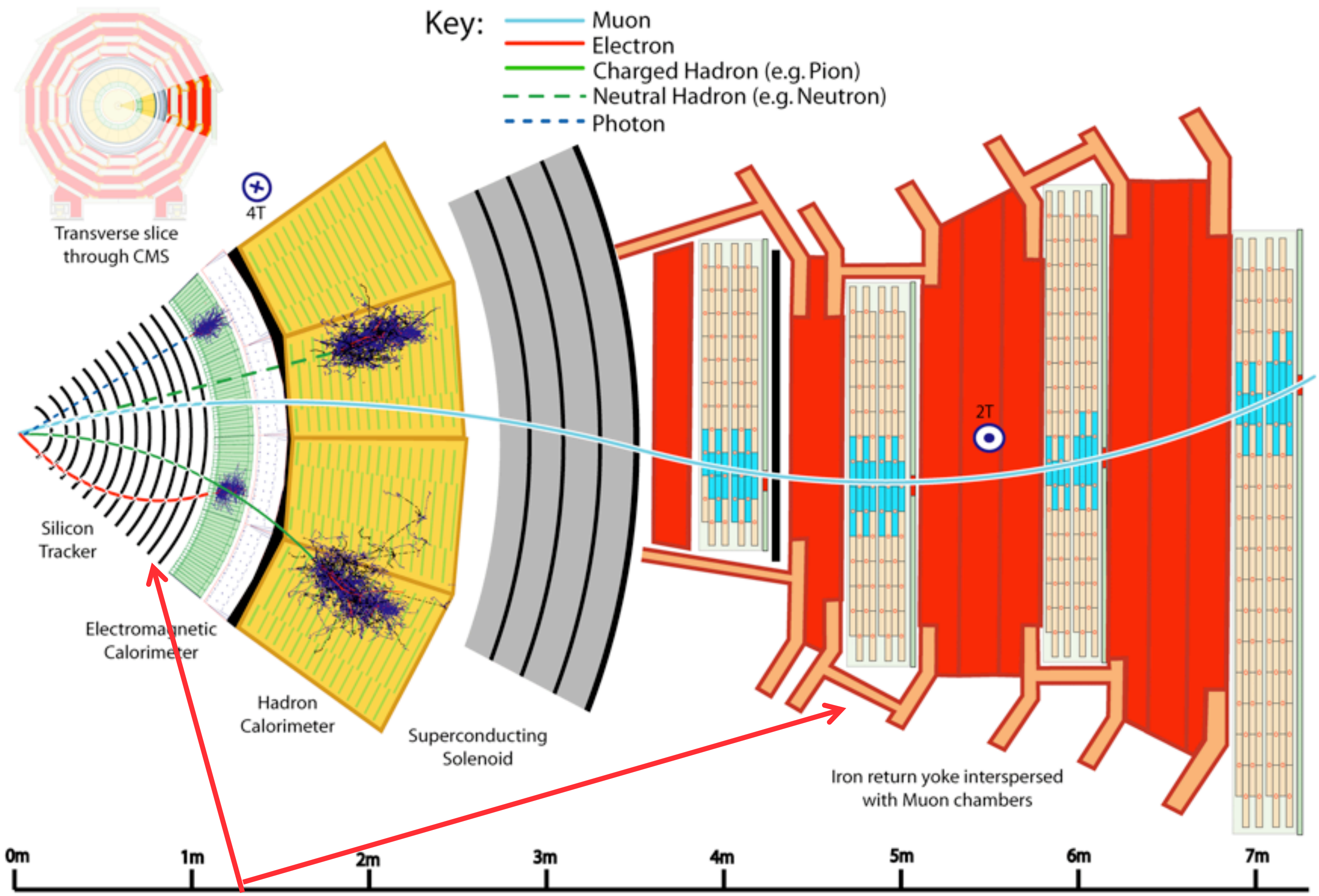


- *LHC Yields large amounts of data at the world's **Highest** Energy*
- *It just discovered the Higgs, confirms & completes the SM*
- *Opportunities to perform SM measurements & search for new phenomena*

Outline

- Introduction
- Observation of $B_s^0 \rightarrow \mu^+\mu^-$
- Observation of peaking structures in $J/\psi\phi$ spectrum
- search for a new state X_b decaying to $Y(1S)\pi^+\pi^-$
- X(3872) production cross section
- χ_{b2} over χ_{b1} cross-section ratio
- $B_c \rightarrow J/\psi\pi^\pm\pi^\pm\pi^\mp$ & $B_c \rightarrow J/\psi\pi^\pm$ branching fractions
- Prompt double J/ψ production
- Summary

CMS Detector

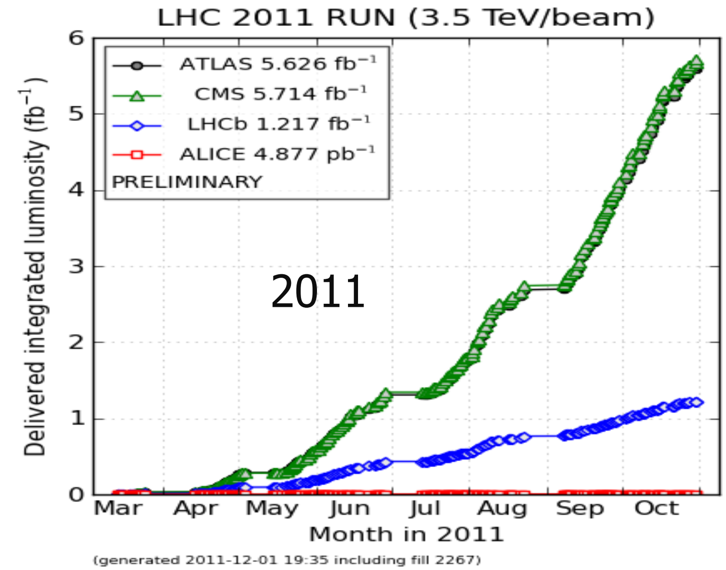


Relevant sub-detectors

CMS Detector Performance

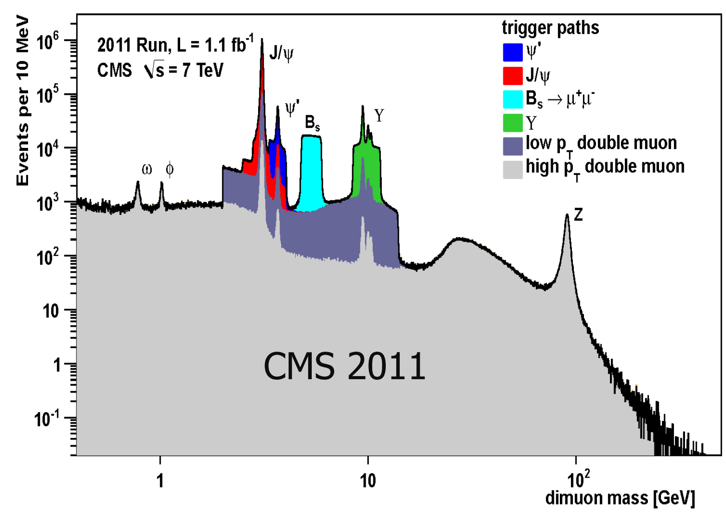
Excellent muon/silicon detectors:

- Muon system
  - High-purity muon identification
  - Good dimuon mass resolution ($\Delta m/m \sim 0.6\%$ for J/Ψ)
- Silicon Tracking detector
  - excellent track momentum resolution ($\Delta p_T / p_T \sim 1\%$)
  - excellent vertex reconstruction and resolution



LHC luminosity & CMS trigger:

- Collect data at increasing instantaneous luminosity
- Triggers are essential ingredients
  - Special triggers for different analysis
  - Combination of dimuon vertex, minimum di(muon) transverse momentum, and displaced dimuon vertex

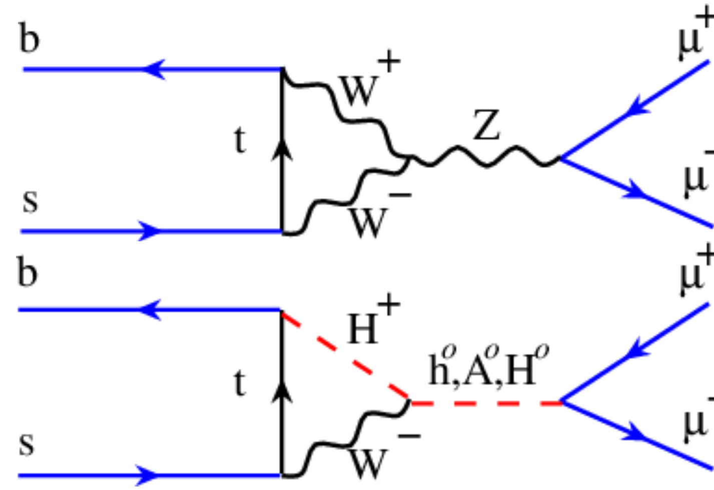


Introduction

- Search for new physics by measuring deviation from standard model
  - Measuring properties of rare decays like $B_s \rightarrow \mu^+\mu^-$, $B \rightarrow K\mu^+\mu^-$…
- Discovery (exotic) states. Help advance our understand of hadron formation
- Test standard model, especially QCD models via precise measurements
  - Measuring heavy meson lifetime, cross section, BF, angular distributions
  - Further study less well-known mesons, like B_c

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH13004
PRL 111 (2013) 101804

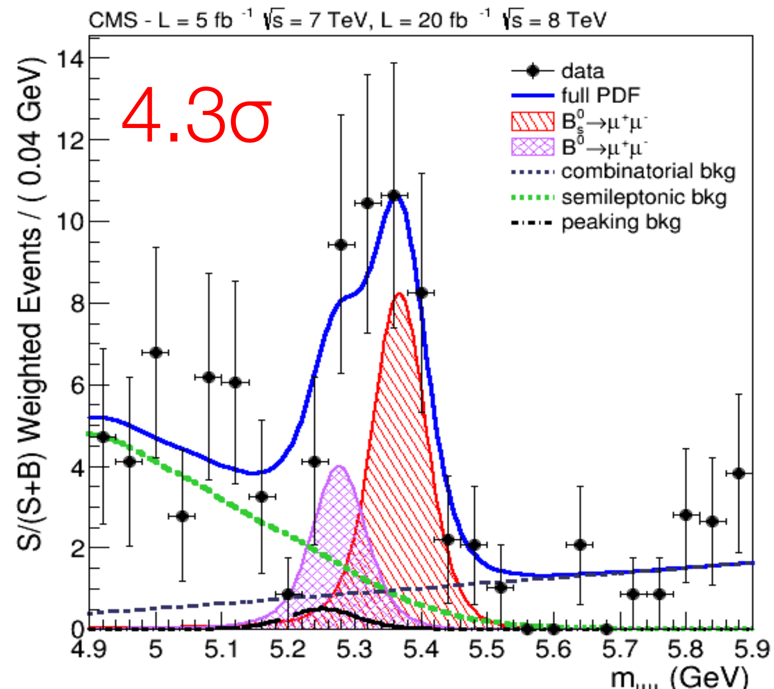
Observation of $B_s^0 \rightarrow \mu^+\mu^-$



- Test SM in the loops:
  - Flavor Changing Neutral Current (FCNC)
  - No tree diagram, only higher orders
- Precise SM prediction:
  - $\beta(B_s^0 \rightarrow \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$
  - $\beta(B_d \rightarrow \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$ PRL 112(2014)101801, PRD 89(2014) 034023
- Possible contribution from NP examples:
  - HDM BF ∝ $\tan^4\beta$ & $m(H^+)$, JHEP 05 (2006) 063; MSSM BF ∝ $\tan^6\beta$, NPB 760 (2007) 38
  - Leptoquarks JHEP 11 (2010) 073

Observation of $B_s^0 \rightarrow \mu^+\mu^-$

- The B_s^0/B signals (MVA--BDT):
  - Displaced dimuon vertex
  - align momentum and flight direction
  - Isolation
- Reference--$B^+ \rightarrow J/\psi K^+$, f_u/f_s from LHCb
- Combine 7&8 TeV data, Barrel & Endcap
- Two approaches:
  - Extract BF from a fit to 12 BDT bins
  - Cut BDT output (1D) as cross check



$\beta(B_s^0 \rightarrow \mu^+\mu^-) = (3.0^{+1.0}_{-0.9})\text{X}10^{-9}$

$\beta(B_d \rightarrow \mu^+\mu^-) < 1.1\text{X}10^{-9}$@95% CL

Consistent with SM @current precision

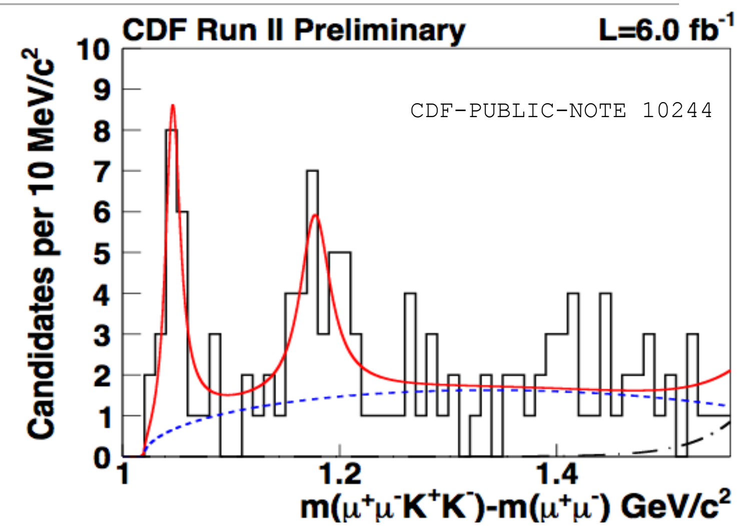
Constraint BSM PS

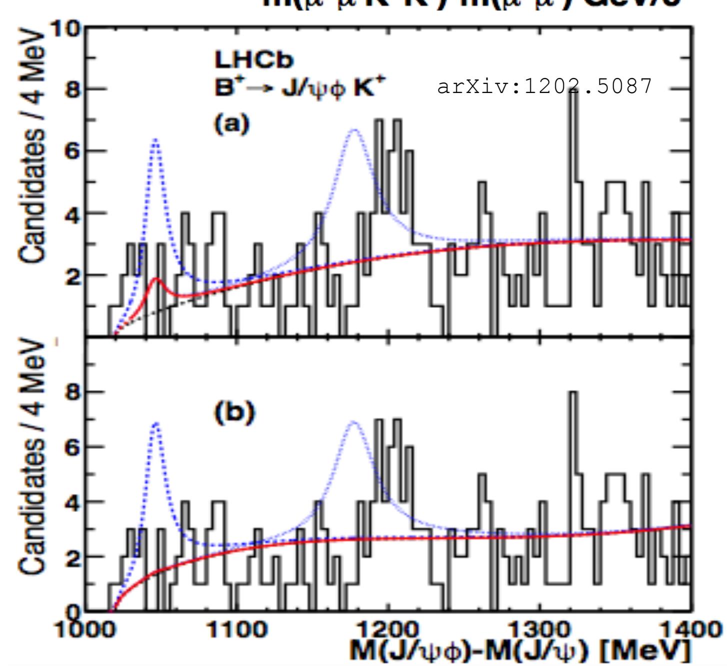
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11026

arXiv 1309.6920 [hep-ex], accepted by PLB

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

- New X/Y/Z states poses a challenge to conventional quark model, possibly a new door is open
- 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
    - LHCb did not confirm the existence of Y(4140) and put an upper limit on its production
  - An independent check at CMS





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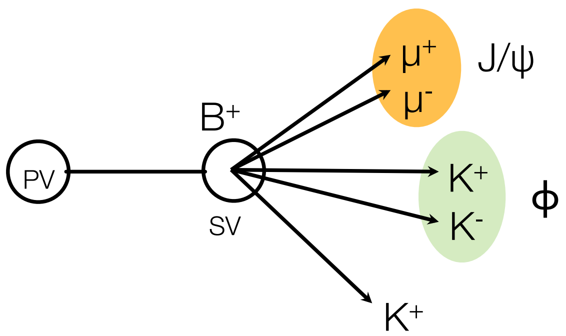
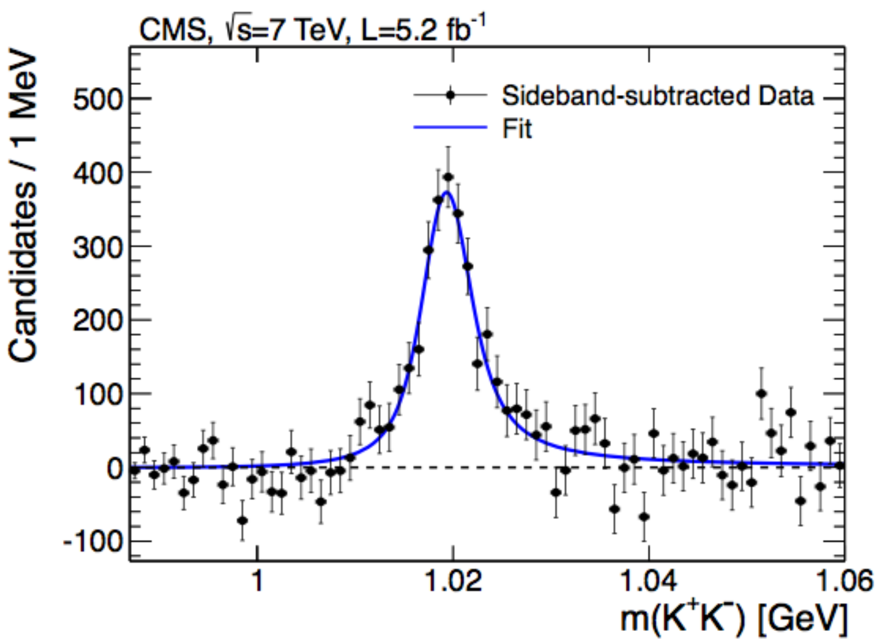
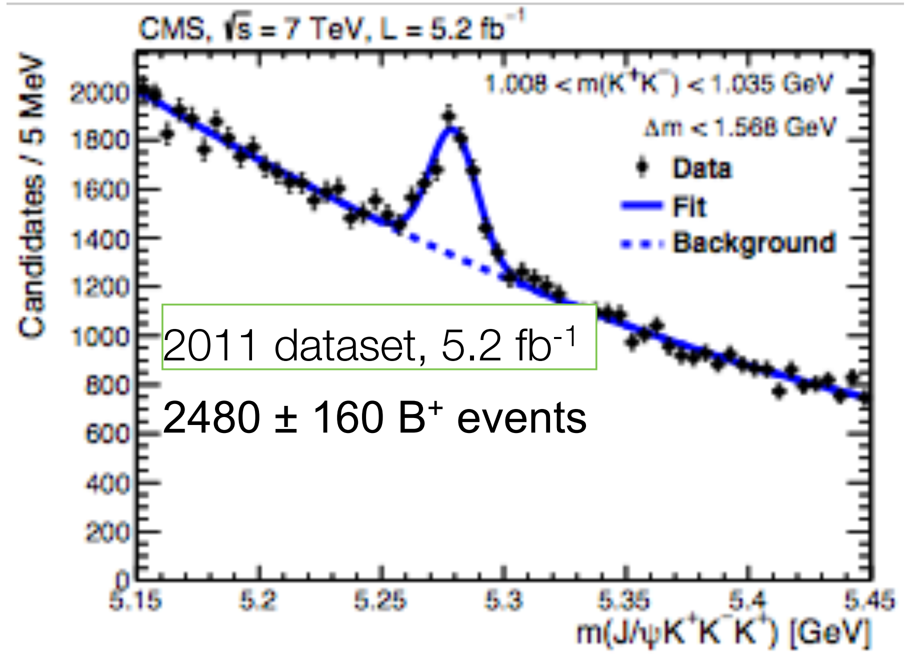
Observation of peaks in the J/ψϕ mass spectrum in B decays





Negligible non-ϕ components.



Largest $B^+ \rightarrow J/\psi \phi K^+$ sample to date.

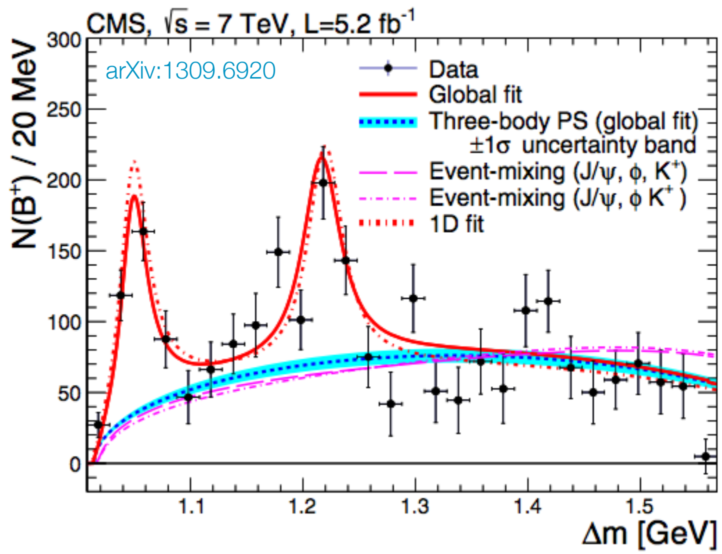
Observation of peaks in the J/ψϕ mass spectrum in B decays

Investigating the $\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$

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

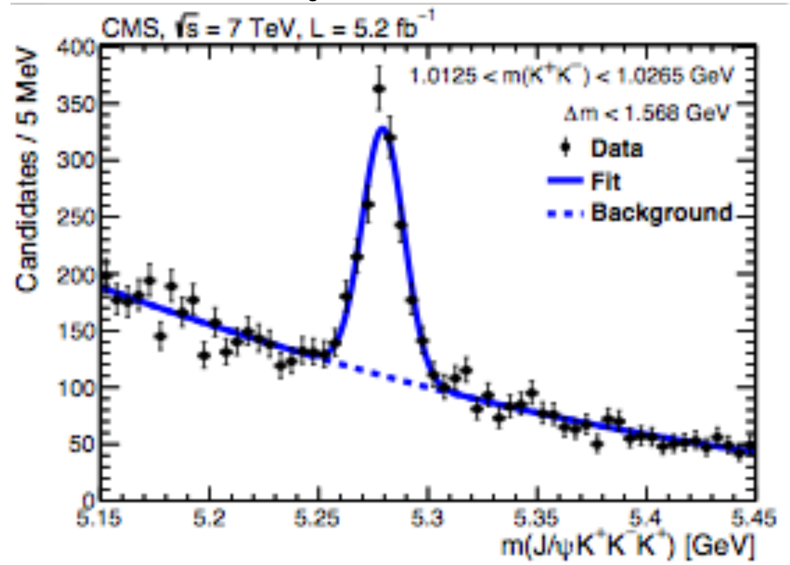


Yield	Mass (MeV)	Γ (MeV)
310 ± 70	4148.0 ± 2.4(stat) ± 6.3(syst)	28^{+15}_{-11}(stat) ± 19(syst)
418 ± 170	4313.8 ± 5.3(stat) ± 7.3(syst)	38^{+30}_{-15}(stat) ± 16(syst)

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

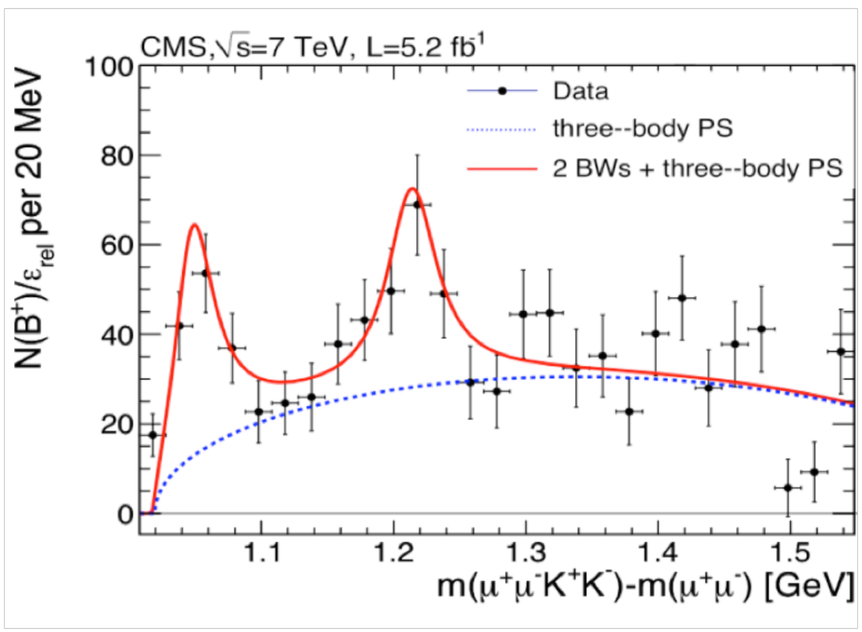
Later D0 also confirmed Y(4140) with a significance of 3σ

Cross Check with clean $B^+ \to J/\psi\phi K$ Sample



Additional requirements:

- kaon $p_T > 1.5$ GeV
- B^+ vertex CL > 10%
- B^+ vertex detachment: >7X from beamspot
- m(K+K-) within 7 MeV of ϕ mass

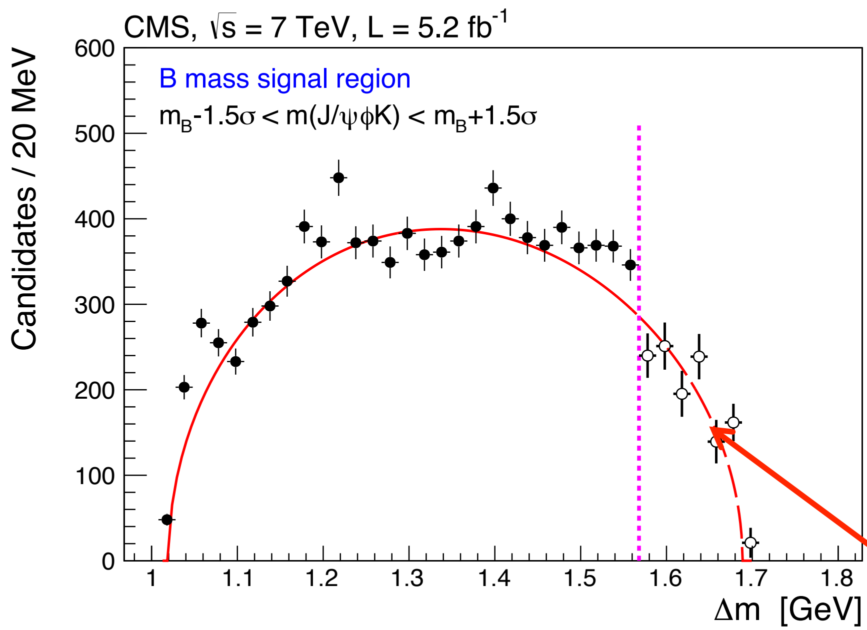


Solid structures appear in clean B sample.

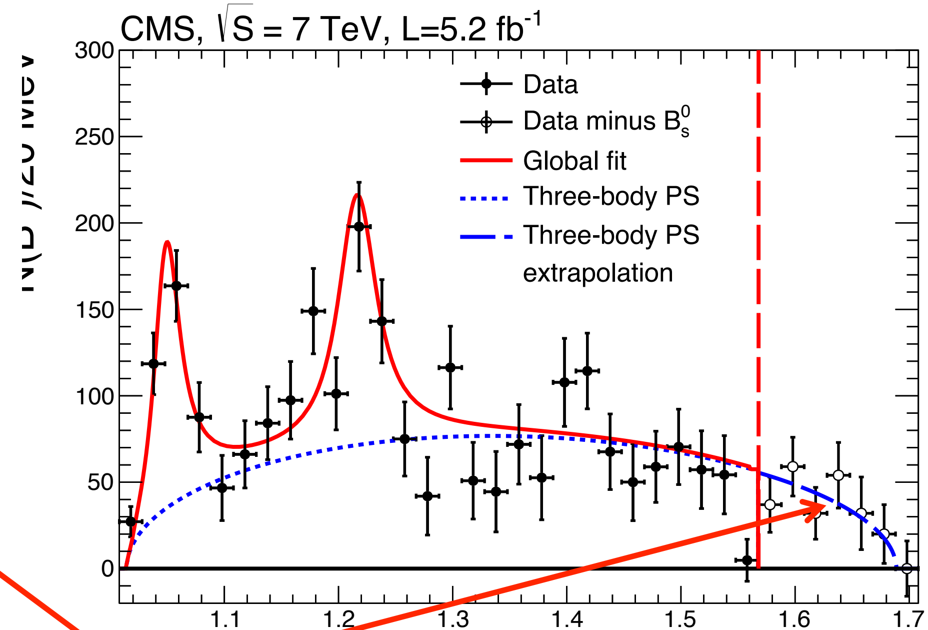
40% of default B signal, 10X less non-B background

Further Investigation in the whole Δm region

The Δm spectrum after subtracting B^0_s contribution but including non-B evens, within 1.5σ *(σ = 9.3MeV) of the B mass.*



The extension of the Δm spectrum, after subtracting non-B background, to the full phase space.



The events in pervious cutoff region are consistent with phase space.

Δm [GeV]

The absence of strong activity in the high- Δ m region reinforces our conclusion that the near-threshold narrow structure is not due to a reflection of other resonances.

Demands an explanation

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11016
PLB 727 (2013) 57

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

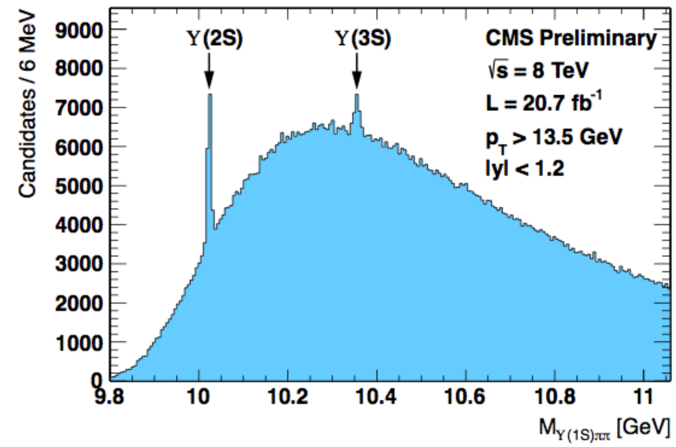
- Exotic resonance X(3872) discovered in the final state $J/\psi\pi^+\pi^-$
- A **bottomonium counterpart X_b** may exist and decays into $Y(1S)\pi^+\pi^-$
  - Mass close to the $B\bar{B}$ or $B\bar{B}^*$ threshold,10.562 and 10.604 GeV
  - Similar to X(3872), narrow width and sizable branching ratio into $Y(1S)\pi^+\pi^-$
  - Look for a peak in the $Y(1S)(\mu^+\mu^-)\pi^+\pi^-$ invariant mass spectrum
    - **Measure** $R = \frac{\sigma_{X_b} \times BR(X_b \to Y(1S)\pi^+\pi^-)}{\sigma_{Y(2S)} \times BR(Y(2S) \to Y(1S)\pi^+\pi^-)}$ **as a function of X_b mass—[10,11] GeV**
    - kinematic region: $p_T(Y(1S)\pi^+\pi^-) > 13.5$ GeV and $|y(Y(1S)\pi^+\pi^-)| < 2.0$

2012 dataset ~20 fb^{-1}

X_b candidate reconstruction

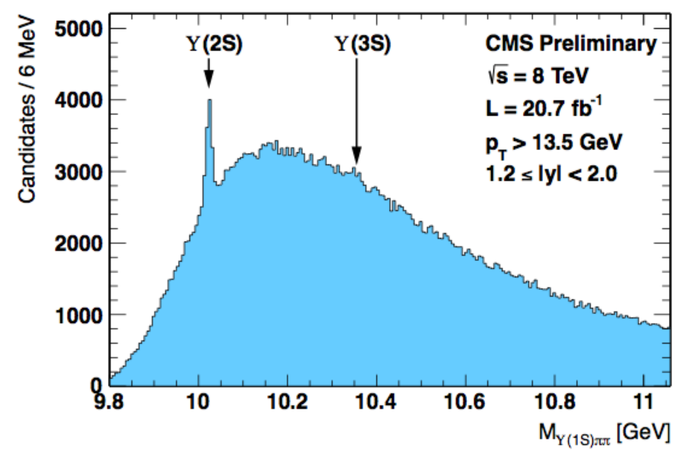
- X_b candidates reconstructed by associating the Υ(1S) to 2 pion tracks
  - optimized to maximize expected signal significance near Υ(2S) mass
  - Expected significance > 5σ if X_b BR * cross-section > 6.56% of the corresponding Υ(2S) → Υ(1S)$\pi^+\pi^-$ value (analogous to X(3872) → J/ψ$\pi^+\pi^-$)

    JHEP **04** (2013) 154



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

- **No 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
    - Fix signal width to value from the simulation (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

Assumptions:

- same production mechanism for Y(2S) and X_b
- both produced unpolarized
- same dipion mass distribution for X_b and Y(2S)

X_b Limit

- 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

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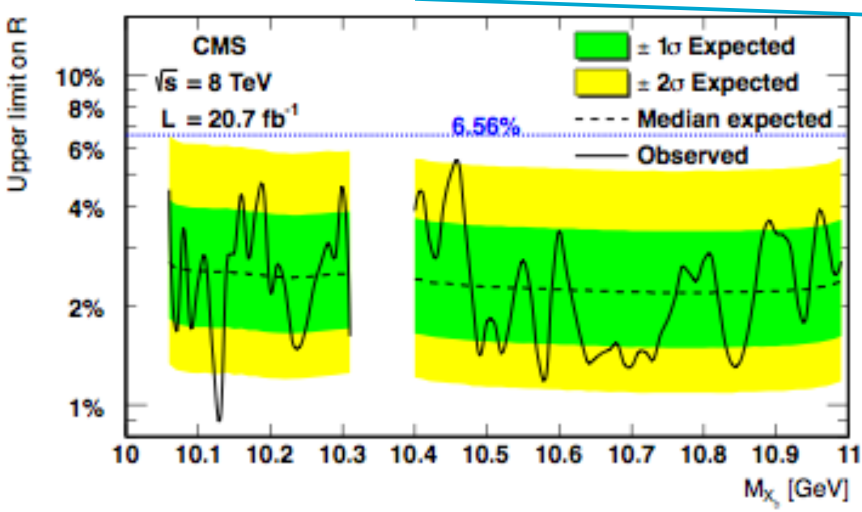
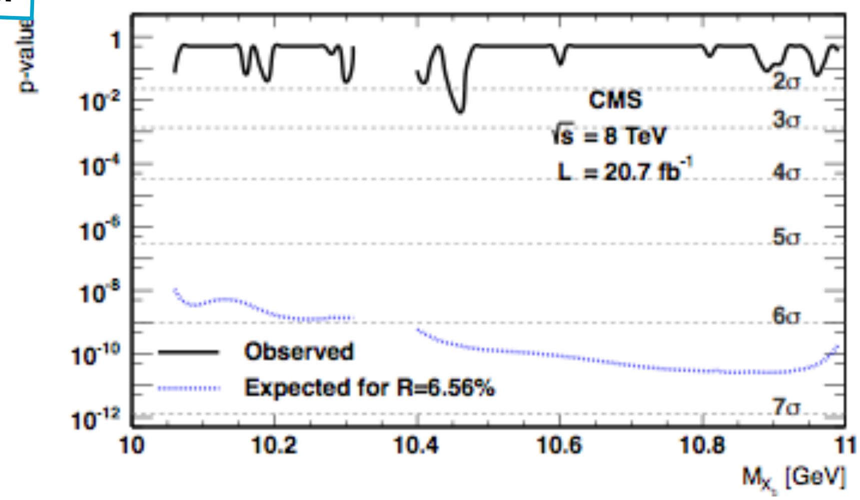




No significant excess is observed

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

X(3872) cross section

- The X(3872) was discovered in 2003 by Belle
  - Later it was confirmed by CDF, D0, Babar
  - Its nature is uncertain➔exotic candidate
- Previous analyses (before CMS measurement) prefer JPC=1++ or 2-+
  - CMS measurement assumed 1++
  - Later LHCb measured its JPC as 1++, PRL 110, 222001 (2013)
- It is produced both promptly and from B decays at LHC
  - CMS measures both prompt and non-prompt cross section

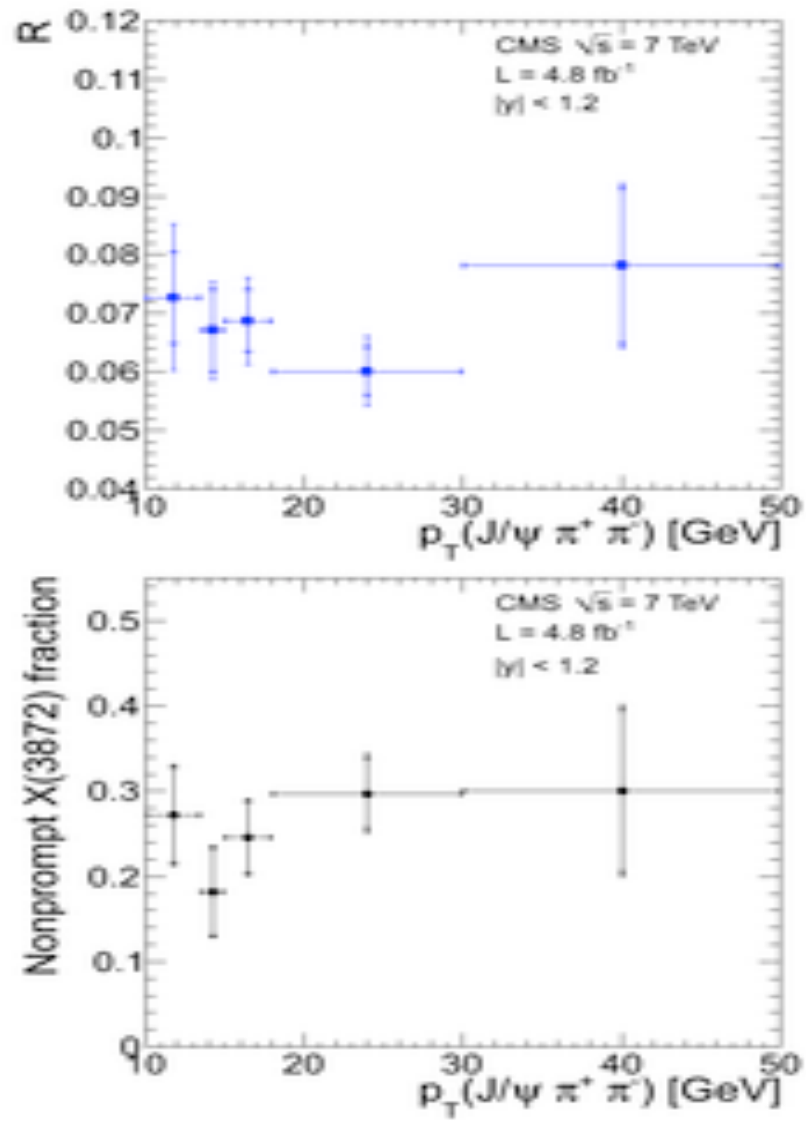
JHEP02 (2012) 011 Phys Rev D81 114018

X(3872) cross section

- R=X(3872)/ψ(2S) cross section ratio
  - X(3872) and ψ(2S) are assumed unpolarized
  - Variation up to 90% due to polarization
- Non-prompt fraction (B decays)
  - Separated based on L_{xy}

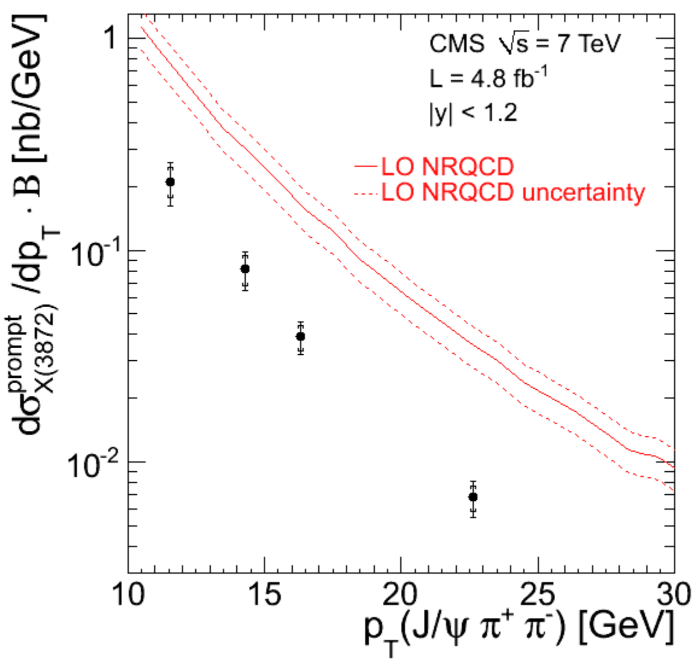
$$l_{xy}^{X(3872)} = \frac{L_{xy}^{X(3872)} \cdot m_{X(3872)}}{p_T}$$

  - Non-prompt events (lxy>100 μm)
  - Contribution from prompt <0.1%
  - Cross-checked by 2D fit to the mass and $_{lxy}$



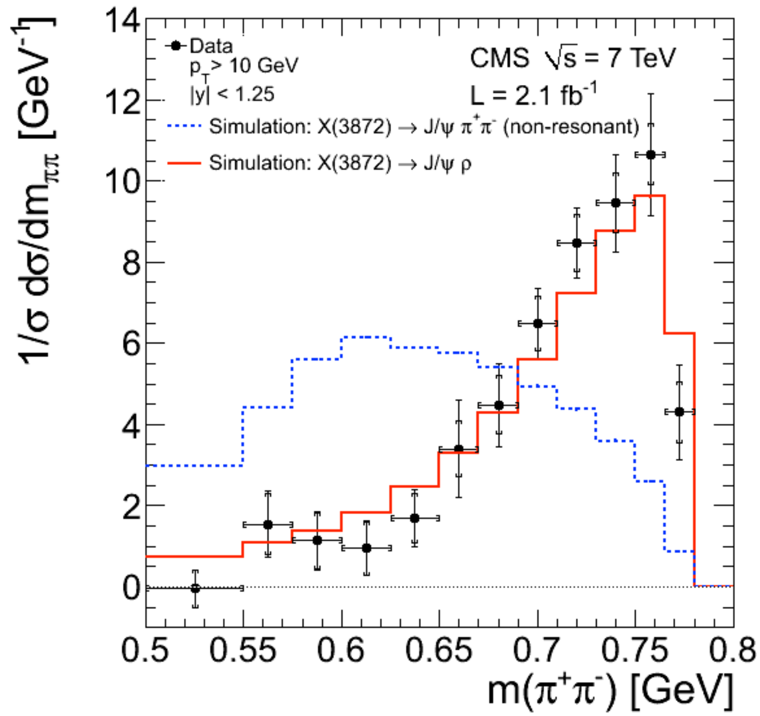
X(3872) cross section

- Prompt cross section compared to NRQCD
  JHEP02 (2012) 011 Phys Rev D81 114018



NRQCD predictions significantly exceed the measured value, while p_T dependence Is reasonably well described

- Compared to simulations with and w/o intermediate ρ^0 in the $J/\psi\ \pi^+\pi^-$ decay



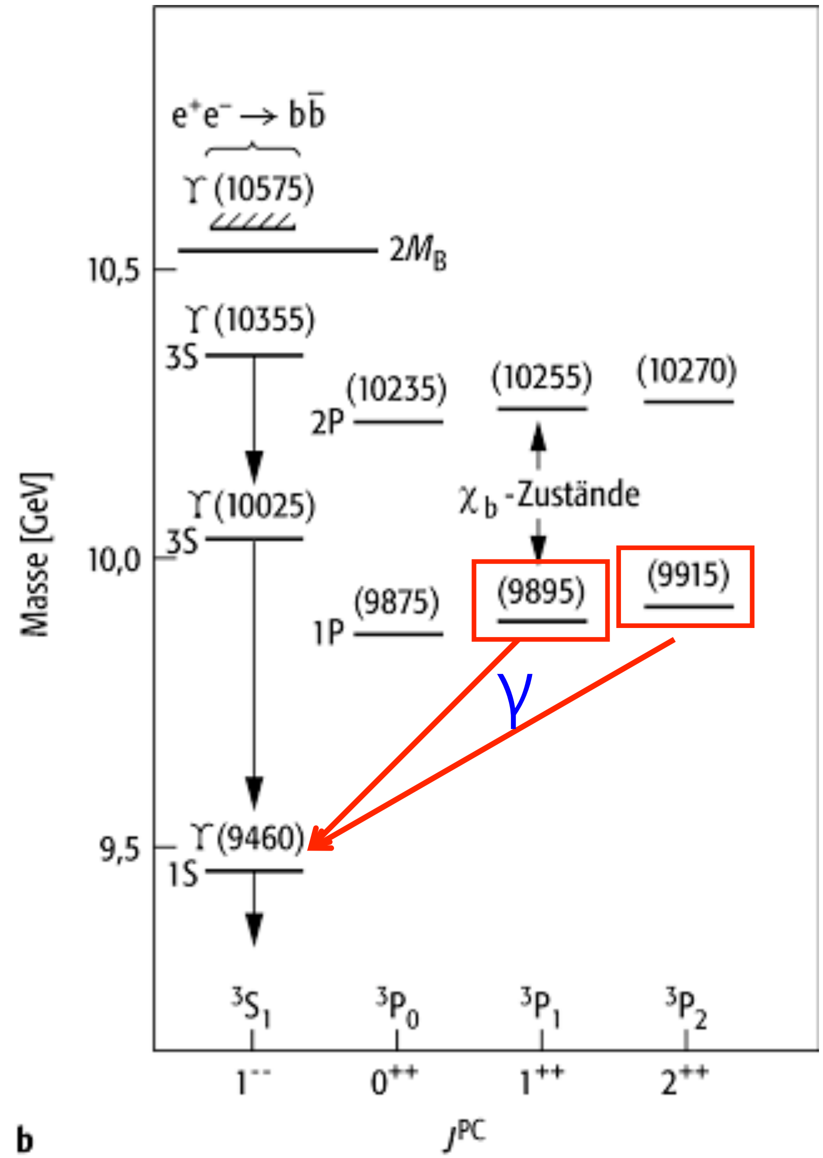
The intermediate ρ^0 decay gives better agreement with data

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

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

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

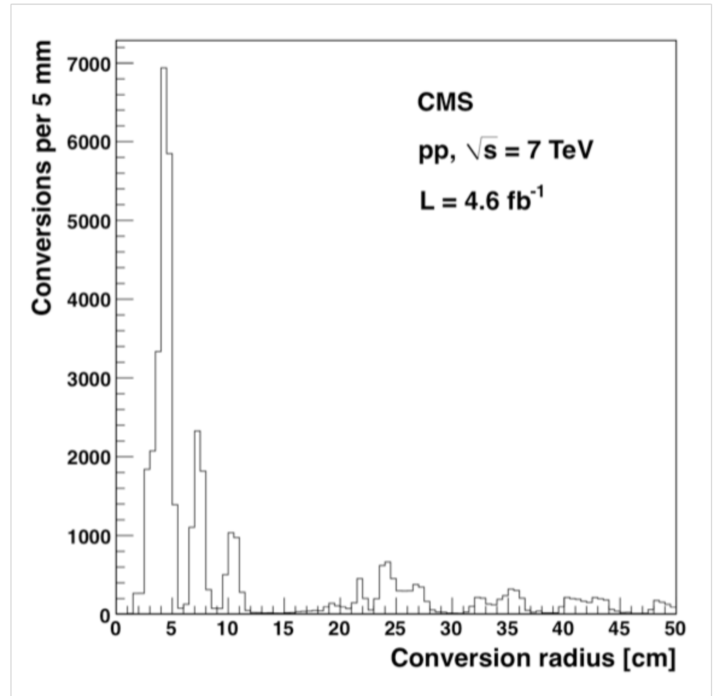
- Relative production cross-section ratios of P-waves are by themselves interesting tests of (NR)QCD



χ_b reconstruction in CMS

- CMS already performed the measurement of χ_c cross section ratio

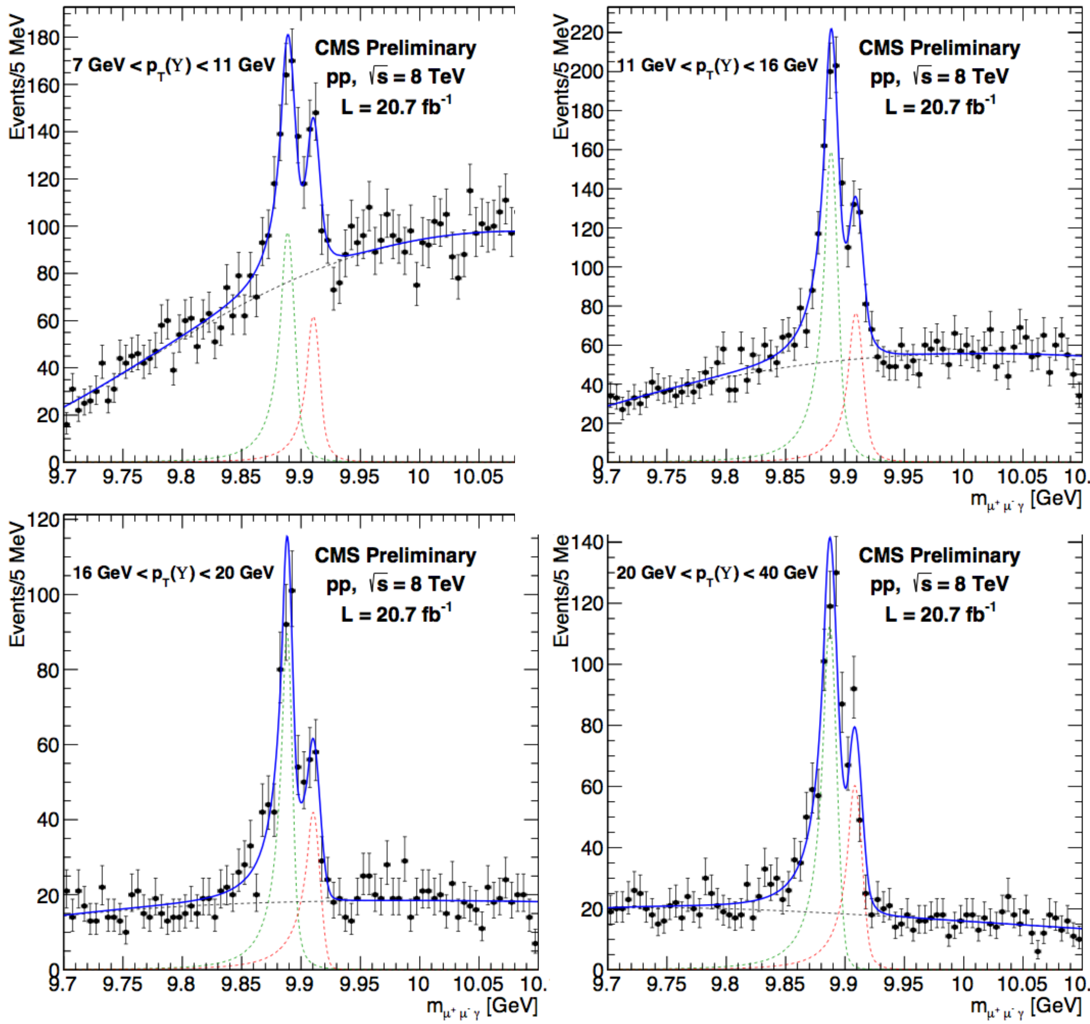
Eur. Phys. J. C72 (2012) 2251



- Same with χ_b using 2012 data (~20 fb^{-1})
- Reconstruct via the **radiative decay**
  - $\chi_{c1,2} \rightarrow J/\psi\ \gamma$
  - $\chi_{b1,2}(nP) \rightarrow \Upsilon(nS)\ \gamma$
- **Small cross section and mass difference** between χ_{b1} and χ_{b2} (19.4 MeV)
  - Use **photon conversions** in the silicon tracker

The $X_{b1,2}$ signals

Divide $X_{b1,2}$ 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

Mass resolution ~5 MeV

χ_{b2}/χ_{b1} cross section ratio

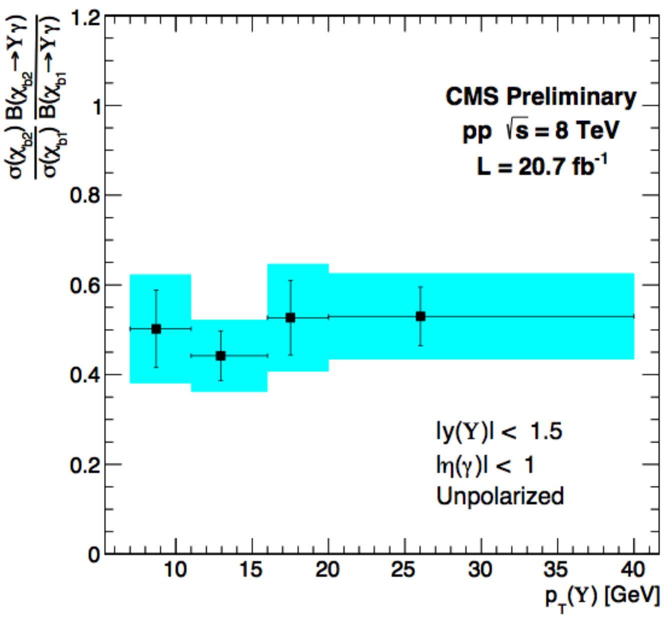
$$\mathcal{R} \doteq \frac{\sigma(pp \to \chi_{b2} + X)}{\sigma(pp \to \chi_{b1} + X)} = \frac{N_{\chi_{b2}}}{N_{\chi_{b1}}} \cdot \frac{\epsilon_1}{\epsilon_2} \cdot \frac{\mathcal{B}(\chi_{b1}(1P) \to \Upsilon(1S) + \gamma)}{\mathcal{B}(\chi_{b2}(1P) \to \Upsilon(1S) + \gamma)}$$

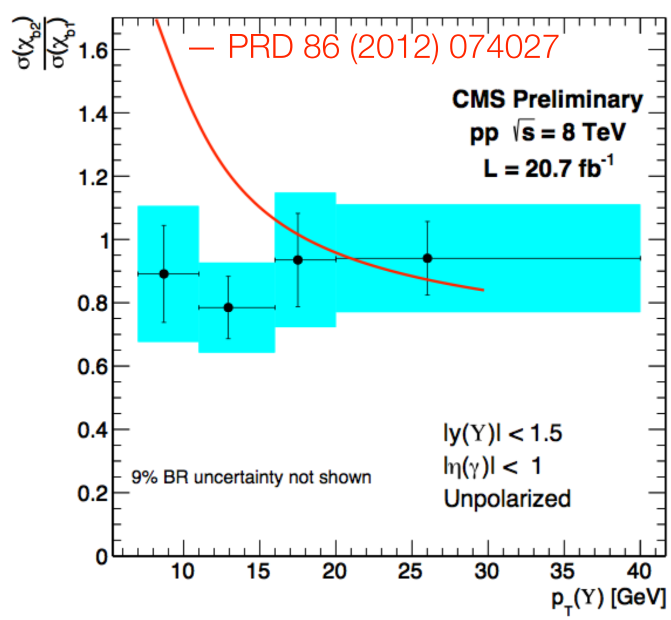
yields of $\chi_{b1,2}$ signal candidates

ε_{12} acceptance and efficiency

Ratio of BR from PDG

No significantly dependent on Υ(1S) transverse momentum





Theoretical prediction:
ratio increase at low p_T.
based on CMS χ_c result

[PRD 86 (2012) 074027]

Uncertainties:
Error bars → statistical

Colored bands → total

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

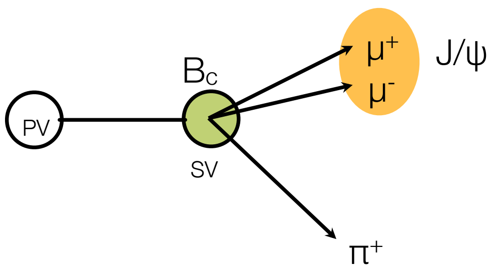
Measurement of B_c Branching Fractions

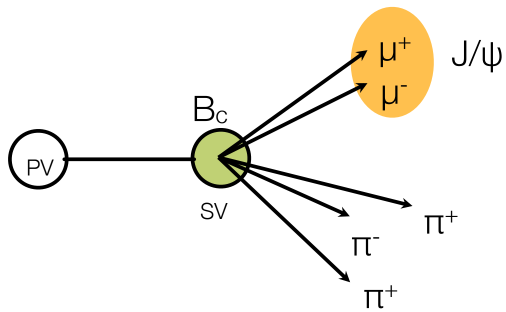
- A unique heavy-quark dynamics from **two different heavy flavors (bc)**
  - Both quarks compete in the decay
- Experimental knowledge rather poor (only produced at hadron colliders)
  - Only few decay channels have been observed so far
  - No cross section measurement is available
- Here we show the CMS measurements of

$$\frac{BR(B_c^\pm \to J/\psi\pi^\pm\pi^\pm\pi^\mp)}{BR(B_c^\pm \to J/\psi\pi^\pm)} = \frac{N(B_c^\pm \to J/\psi\pi^\pm) \times \epsilon_{B^\pm}}{N(B^\pm \to J/\psi K^\pm) \times \epsilon_{B_c^\pm}} = \frac{Y_{B_c}}{Y_B}$$

$$\frac{\sigma(B_c^\pm) \times Br(B_c^\pm \to J/\psi\pi^\pm)}{\sigma(B^\pm) \times Br(B^\pm \to J/\psi K^\pm)} = \frac{N(B_c^\pm \to J/\psi\pi^\pm\pi^\pm\pi^\mp) \times \epsilon_{B_c^\pm \to J/\psi\pi^\pm}}{N(B_c^\pm \to J/\psi\pi^\pm) \times \epsilon_{B_c^\pm \to J/\psi\pi^\pm\pi^\pm\pi^\mp}} = \frac{Y_{3\pi}}{Y_{B_c}}$$

Event selection



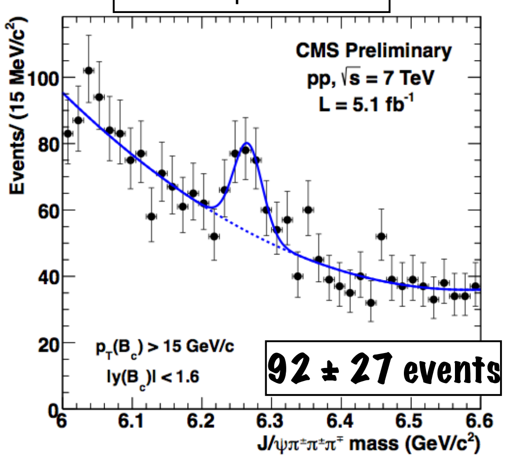


2011 dataset

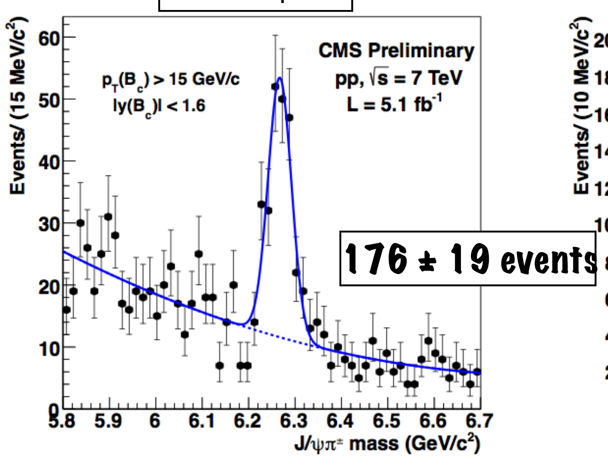
~ 5 fb^{-1}

- 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

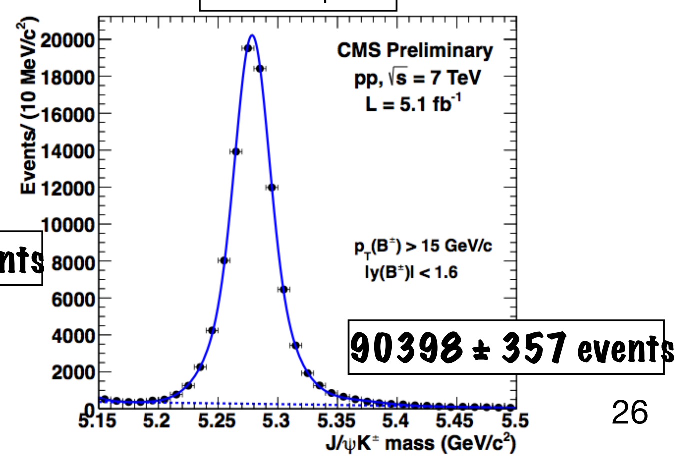
$B_c \to J/\psi\pi^\pm\pi^\pm\pi^\mp$



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



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



Efficiency evaluation

Different strategy for different mesons and different channels:

- $B_c \to J/\psi\pi^\pm$ and $B^\pm \to J/\psi K^\pm$ signals
  - efficiency parametrized as a function of the *B meson* p_T
- $B_c \to J/\psi\pi^\pm\pi^\pm\pi^\mp$ channel
  - Many sub-structures involved--treat as *5-body in entire PS*
  - **Description independent of the decay mode**
  - Efficiency parametrized as

$$\epsilon = |p_0 + p_1 \cdot x + p_2 \cdot y + p_3 \cdot z + p_4 \cdot w + p_5 \cdot r + p_6 \cdot t + p_7 \cdot s|$$

  - Determine 7D free parameters using a ML fit on generated events
  - Use $B_c \to J/\psi 3\pi$ 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

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

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 $2.5 < \eta < 4.5$

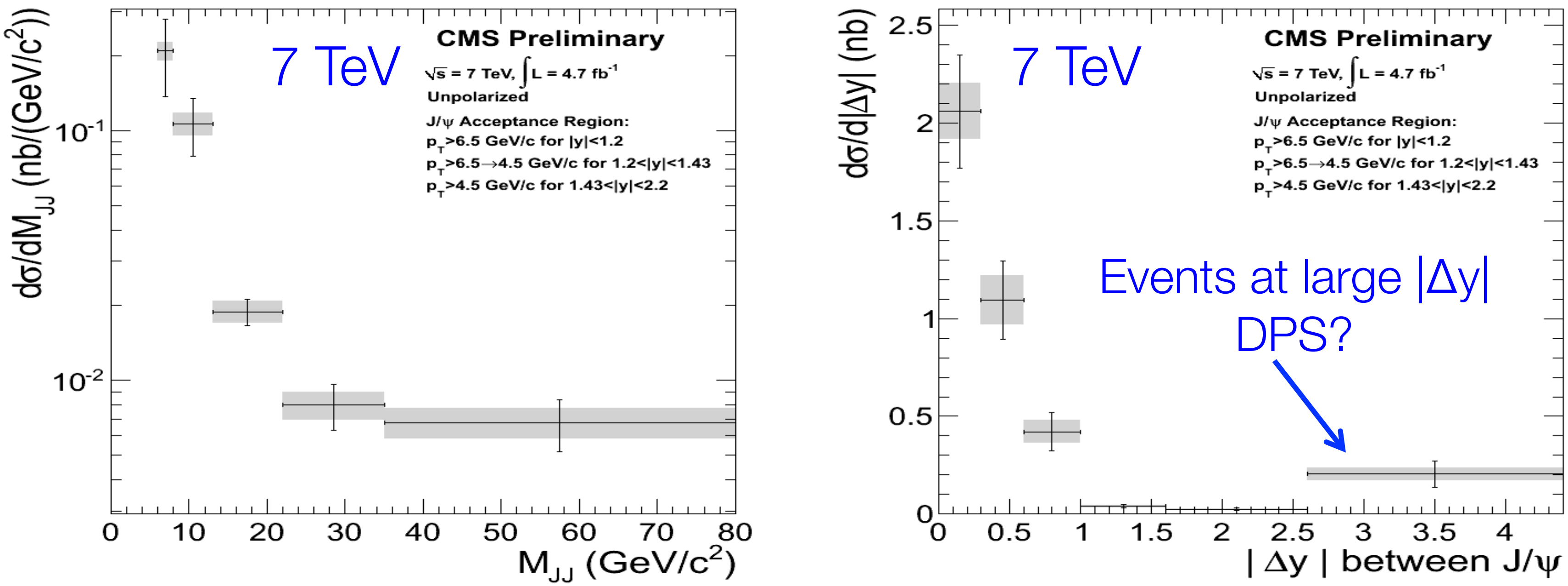
$$R_{c/u} = (0.68 \pm 0.10(\mathrm{stat}) \pm 0.03(\mathrm{syst}) \pm 0.05(\mathrm{lifetime}))\%$$

Phys. Rev. Lett. 109 (2012) 232001

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11021

arXiv:1406.0484 [hep-ex]

Double J/ψ Production @CMS



- Separate prompt J/ψ ($\mu^+\mu^-$) pairs based on significance of two J/ψ distance
- First time @high-p_T region, no solid model. Complementary to LHCb (p_T and rapidity)
- SPS (single parton scattering) vs DPS (double parton scattering)?
- Evidence of excess at |Dy| > 2.6 indicative of DPS?

$$\sigma_{tot} = 1.49 \pm 0.07(stat) \pm 0.13(syst)\ \text{nb}$$

|y| < 1.2	pT > 6.5 GeV/c
1.2 <|y|< 1.43	pT > 6.5→4.5 GeV/c
1.43 <|y|< 2.2	pT > 4.5 GeV/c

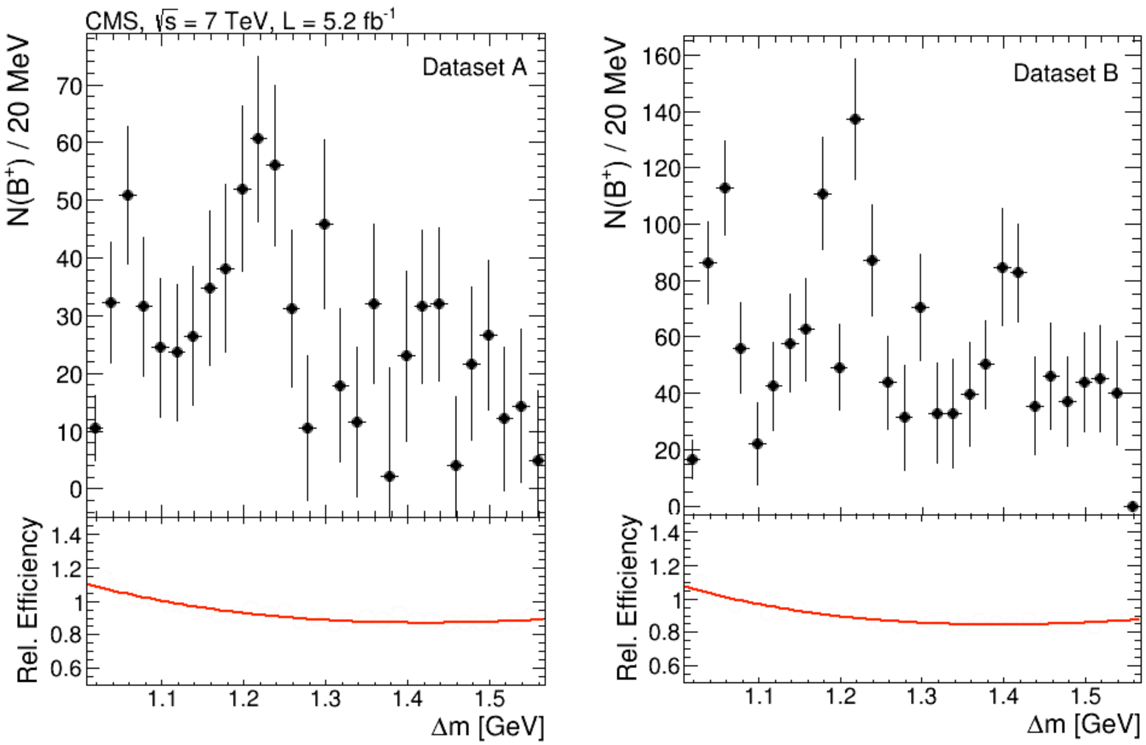
Summary

- Thanks to the excellent LHC and CMS performances
- Made important measurements of B-hadrons and quarkonium
- Demonstrated CMS can/will play important role in new physics searches and exotic states studies

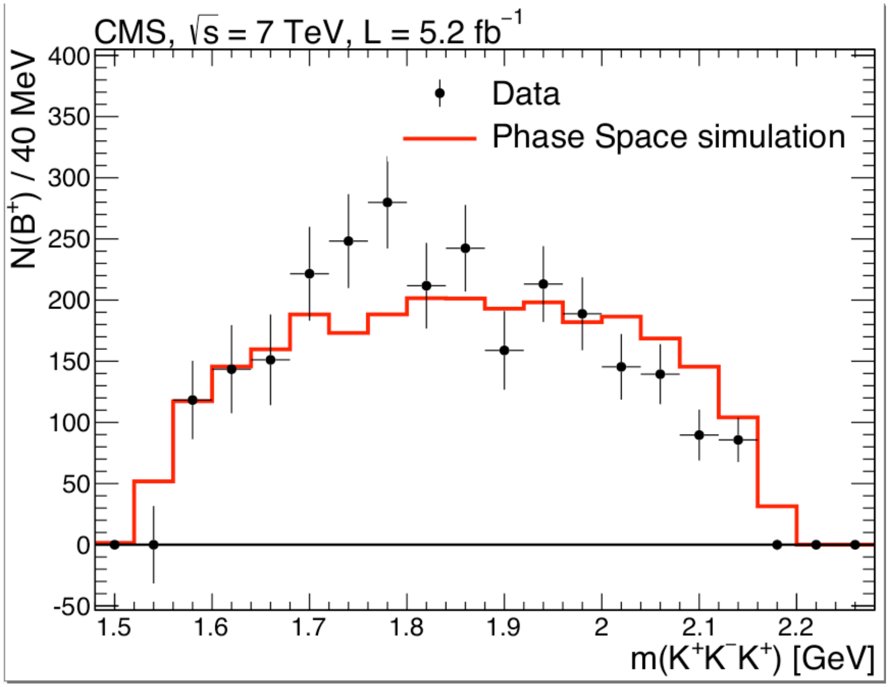
Stay tuned!

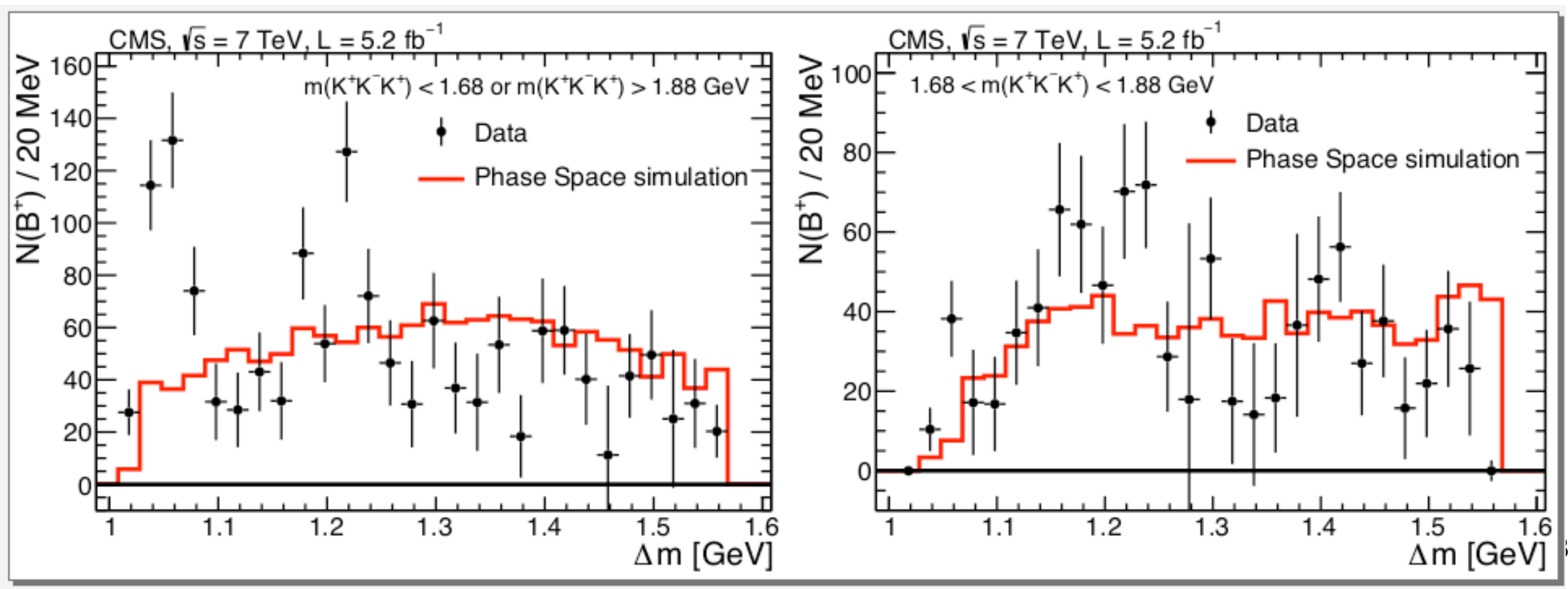
All CMS B-Physics results are available at
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH

Backup



The Δm spectrums for datasetA (left, dimuon pT>7 GeV), datasetB(right, dimuon pT>7 GeV and each muon pT>4 GeV) with corresponding relative efficiency curves


CMS, √s = 7 TeV, L = 5.2 fb⁻¹
Data
Phase Space simulation
N(B⁺) / 40 MeV
m(K⁺K⁻K⁺) [GeV]


CMS, √s = 7 TeV, L = 5.2 fb⁻¹
m(K⁺K⁻K⁺) < 1.68 or m(K⁺K⁻K⁺) > 1.88 GeV
Data
Phase Space simulation
N(B⁺) / 20 MeV
Δm [GeV]
CMS, √s = 7 TeV, L = 5.2 fb⁻¹
1.68 < m(K⁺K⁻K⁺) < 1.88 GeV
Data
Phase Space simulation
N(B⁺) / 20 MeV
Δm [GeV]