

CMS Results on Quarkonium Spectroscopy

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Quarkonium 2014

Measurement of the prompt J/ψ pair production in pp collisions at $\sqrt{s} = 7$ TeV

Double J/ψ Production at CMS

- J/ψ mesons are fully reconstructed via their decays into $\mu^+\mu^-$ pairs.
 - $J/\psi J/\psi \rightarrow (\mu^+\mu^-)(\mu^+\mu^-)$
- First time access to the high-transverse-momentum region where model predictions are not yet established
 - Complementary to LHCb measurement (p_T and rapidity)
- Correlation of two J/ψ mesons: SPS (single parton scattering) vs DPS (double parton scattering)
- The total and differential cross sections are measured in a phase space defined by the individual J/ψ transverse momentum and rapidity

$$p_T^{J/\psi} > 6.5 \text{ GeV if } |y^{J/\psi}| < 1.2$$

$$p_T^{J/\psi} > 6.5 \rightarrow 4.5 \text{ GeV if } 1.2 < |y^{J/\psi}| < 1.43$$

$$p_T^{J/\psi} > 4.5 \text{ GeV if } 1.43 < |y^{J/\psi}| < 2.2$$

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

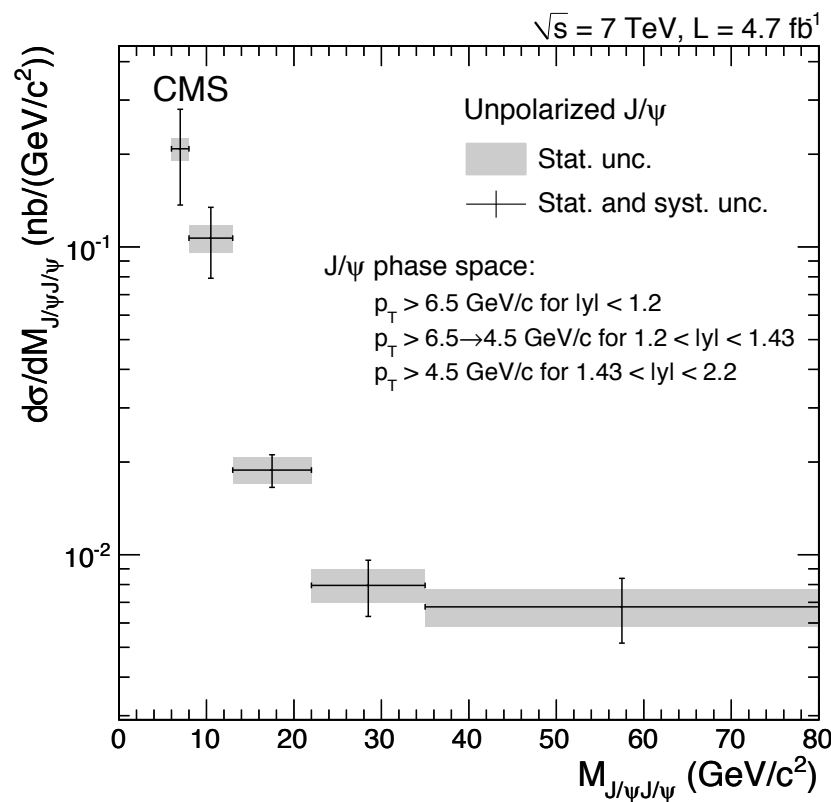
[JHEP 09 \(2014\) 094](#)

Double J/ψ Production at CMS

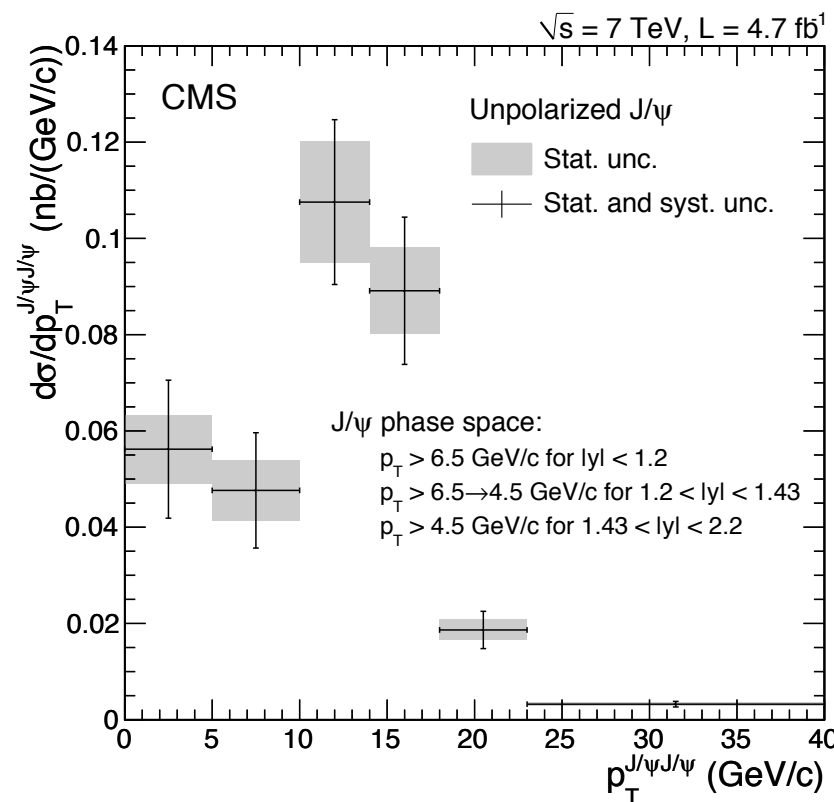
The total cross section assuming unpolarized prompt J/ψ pair production

$$\sigma(pp \rightarrow J/\psi J/\psi + X) = 1.49 \pm 0.07 \pm 0.13 \text{ nb}$$

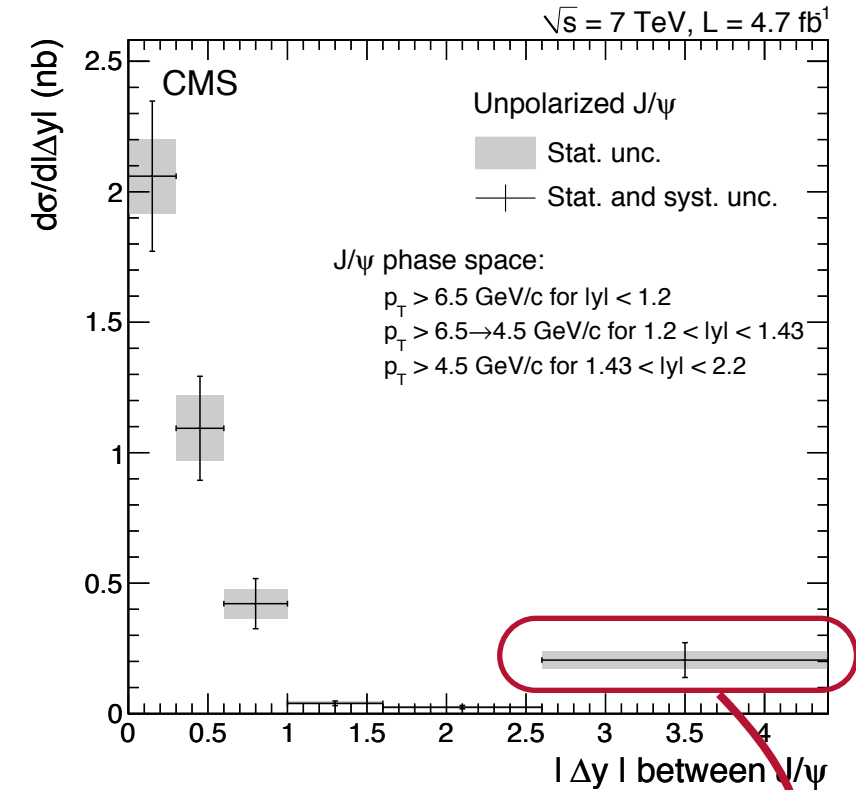
Differential cross section
as a function of $M_{J/\psi J/\psi}$



Differential cross section
as a function of $P_T^{J/\psi J/\psi}$



Differential cross section as
a function of $|\Delta y(J/\psi, J/\psi)|$



- The differential cross section decreases rapidly as a function of $|\Delta y|$
 - A non-zero value in 2.6-4.4 $|\Delta y|$ bin \Rightarrow can be populated via DPS production?
- No evidence for the η_b resonance in the J/ψ pair invariant-mass distribution

Observation of the structures in the $J/\psi\phi$ mass spectrum

History of $Y(4140)$

A third independent experimental result was needed to break the deadlock

- **March 2009**

- ✱ CDF report evidence of a narrow peak in $J/\psi\phi$ spectrum in decays of $B^+ \rightarrow J/\psi\phi K^+$ (PRL 102 242002, 2009)

- **August 2009**

- ✱ Belle searched for the same state in the same channel and see no $Y(4140)$ signal. Set limit on production rate, but cannot exclude CDF peak

- **December 2009**

- ✱ Belle searched for direct production $\gamma\gamma \rightarrow J/\psi\phi$, observed no $Y(4140)$ signal, disfavors $D_s^* D_s^*$ meson molecule interpretation, see 3.2σ excess at 4350 MeV (PRL 100 112004, 2010)

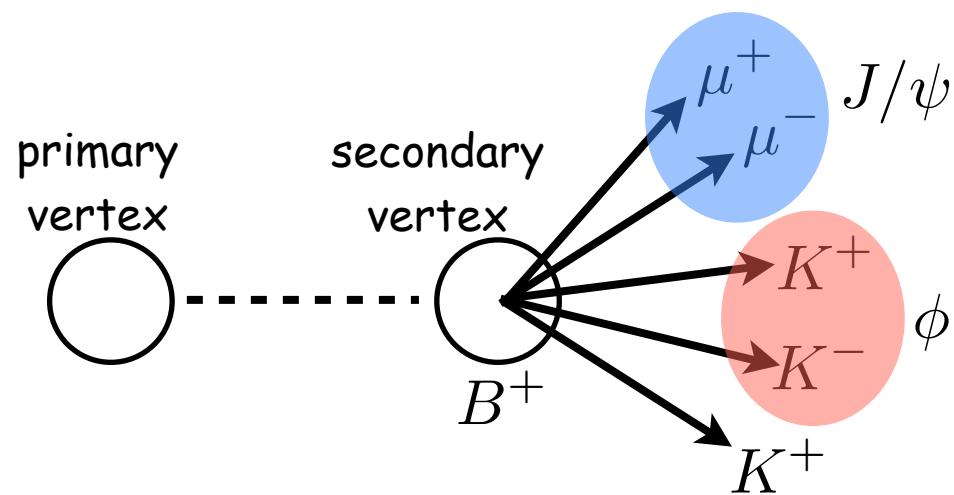
- **January 2011**

- ✱ CDF updated their results with a larger dataset. Observed $Y(4140)$ with 5σ significance (arXiv:1101.6058)

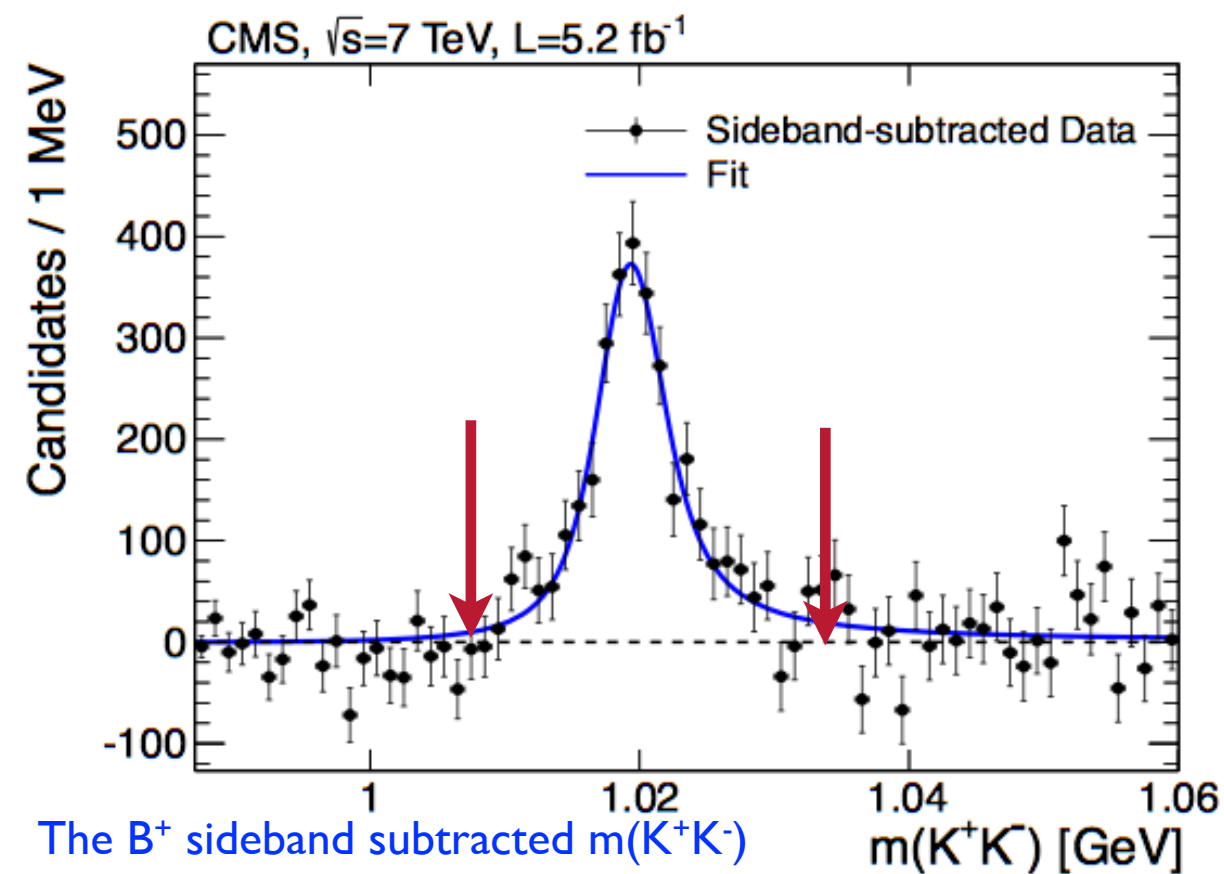
- **February 2011**

- ✱ LHCb searched for the same state in the same channel, no $Y(4140)$ signal, set limit at 2.4σ tension with CDF (PRD 85 091103(R), 2012)

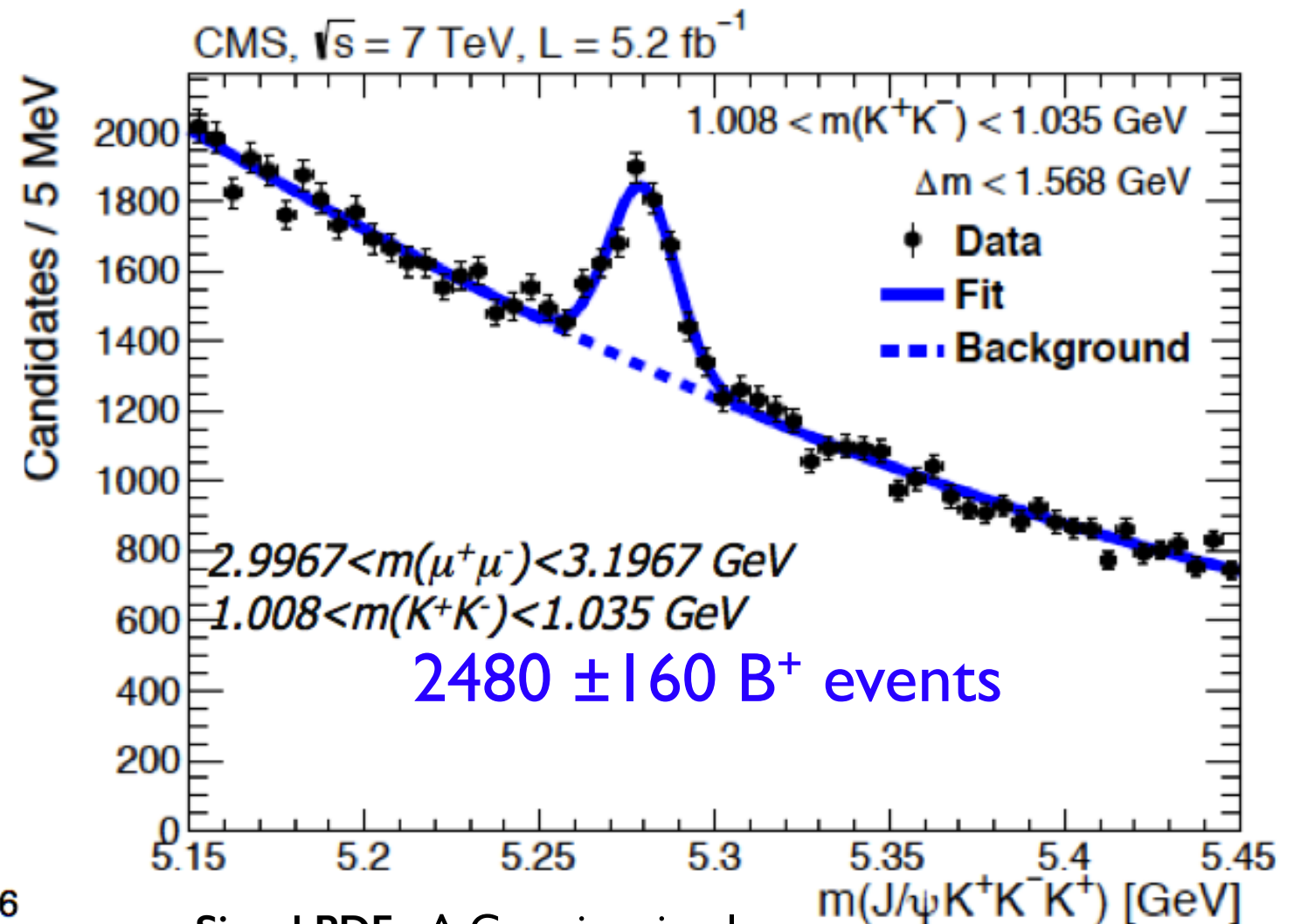
CMS Search in the $J/\psi\phi$ Mass Spectrum



Largest $B^+ \rightarrow J/\psi\phi K^+$ sample
collected in the world up to date.



The B^+ sideband subtracted $m(K^+K^-)$
where $m(J/\psi\phi)$ is within $\mp 3\sigma$ of $m(B^+)$



$2480 \pm 160 B^+$ events

Signal PDF: A Gaussian signal

Background PDF: A second order Chebychev polynomial

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

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Observation of Peaks in the $J/\psi\phi$ Mass Spectrum in B Decays

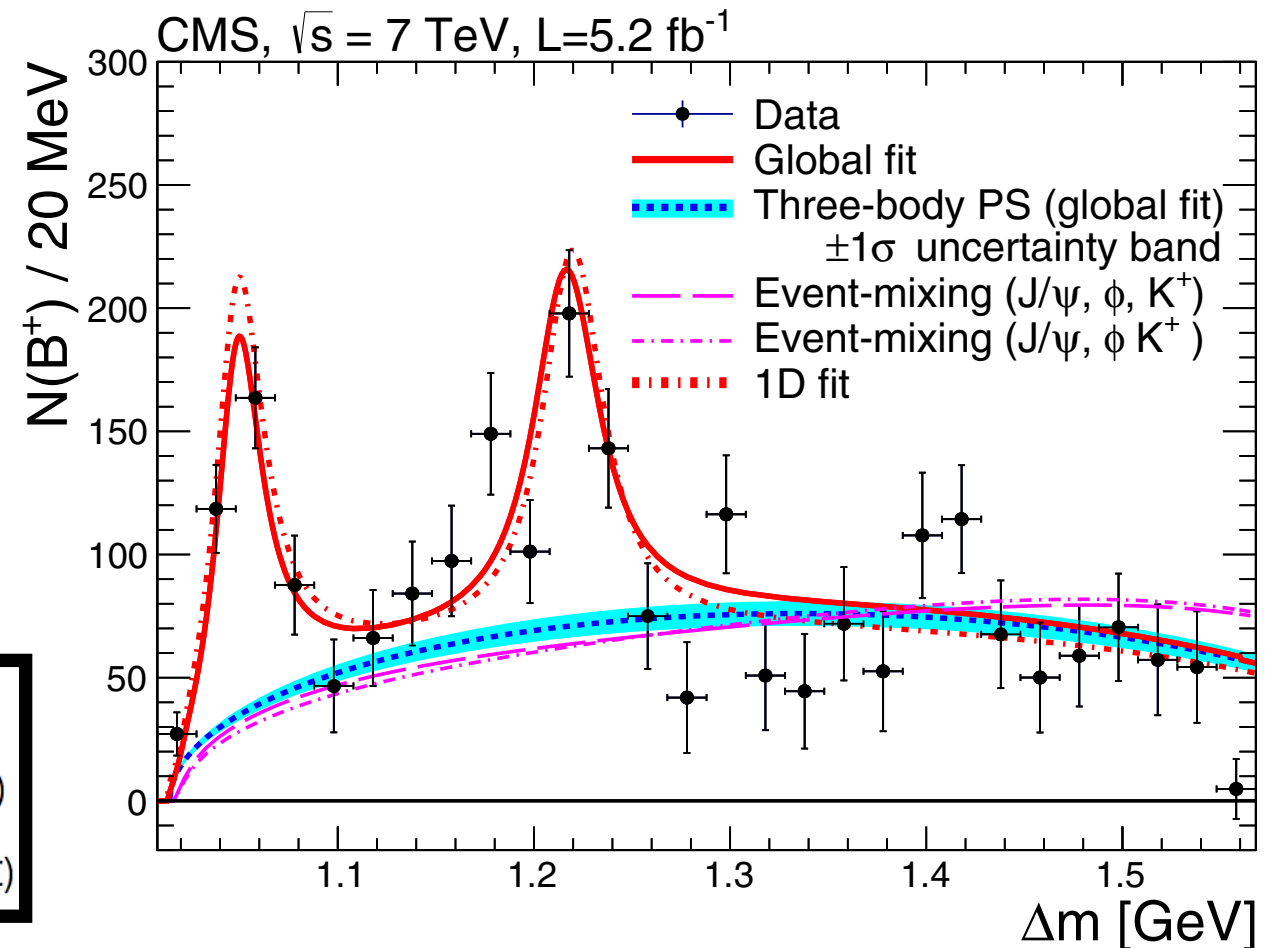
The $\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$ is used to investigate the possible structures

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

*The Δm Spectrum is extracted by
BACKGROUND SUBTRACTION*

- ➡ Divide the dataset into the 20 MeV Δm bins
- ➡ Extract the number of B signal for each Δm by fitting the $J/\psi\phi K$ spectrum
- ➡ Mean is fixed to the PDG value of B mass
- ➡ RMS is fixed to the number predicted by simulation

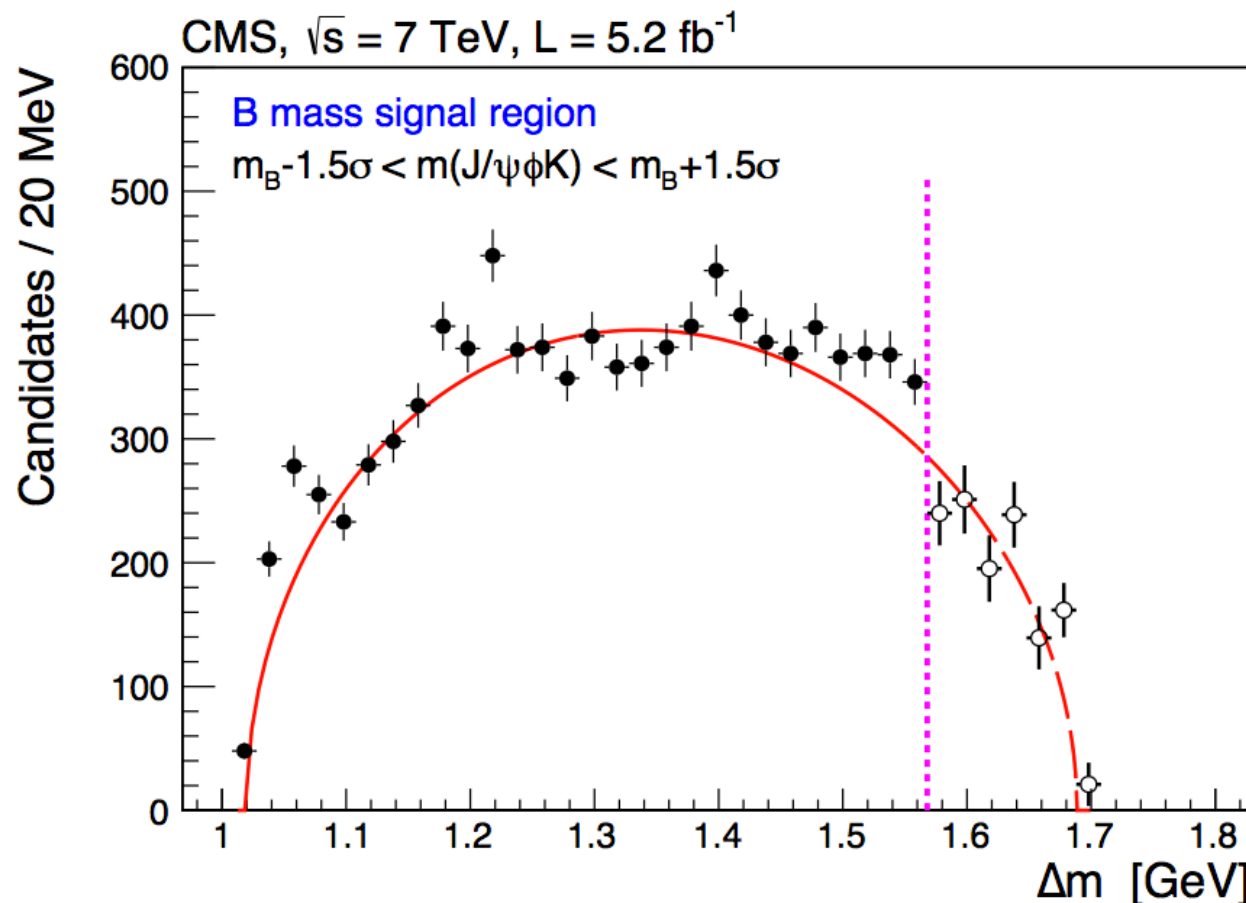
Yield	Mass (MeV)	Γ (MeV)
310 ± 70	$4148.0 \pm 2.4(\text{stat}) \pm 6.3(\text{syst})$	$28^{+15}_{-11}(\text{stat}) \pm 19(\text{syst})$
418 ± 170	$4313.8 \pm 5.3(\text{stat}) \pm 7.3(\text{syst})$	$38^{+30}_{-15}(\text{stat}) \pm 16(\text{syst})$



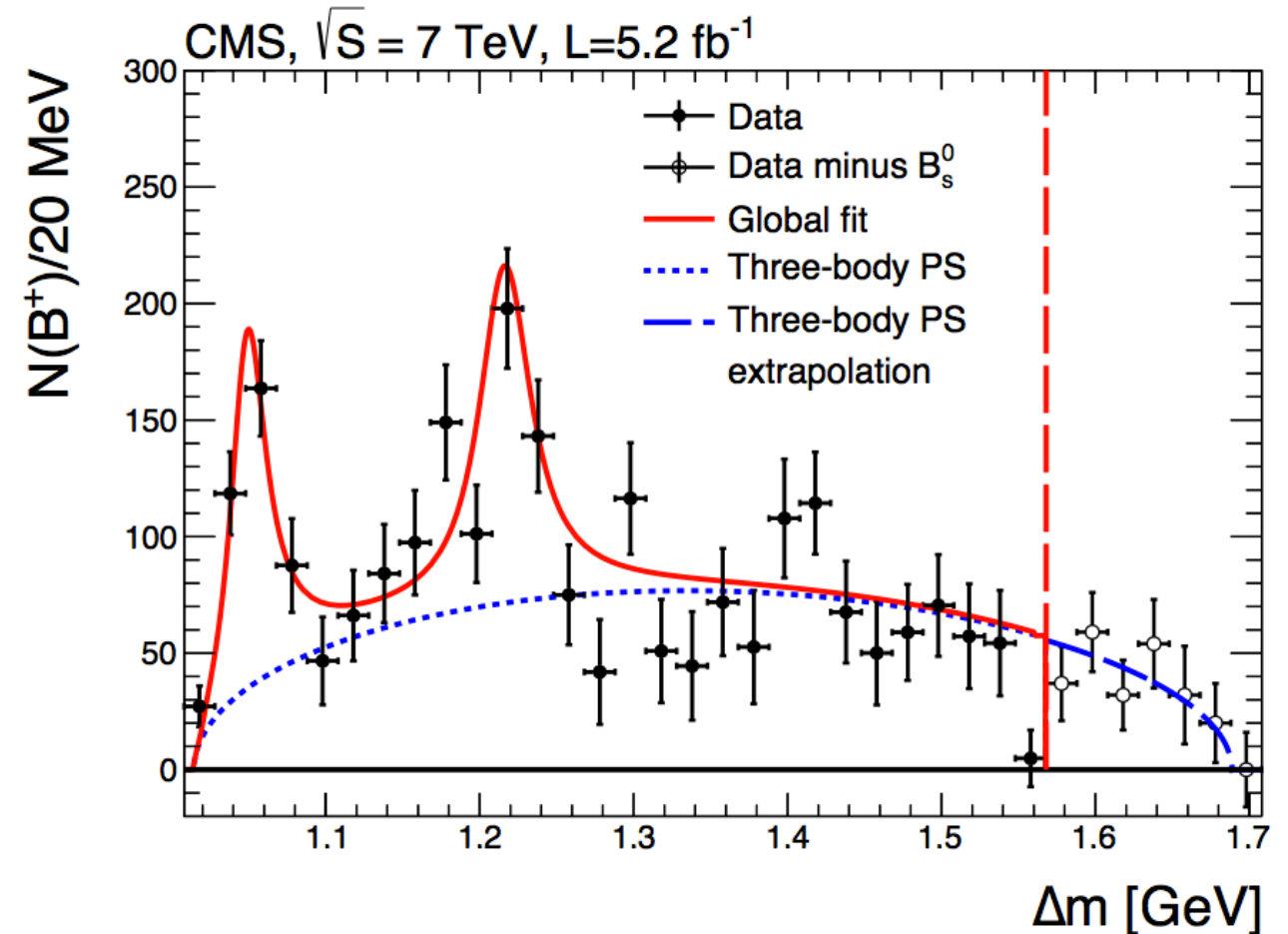
- CMS observed a $J/\psi\phi$ structure at 4148 MeV with a significance greater than 5σ confirms the existence of $Y(4140)$ from CDF
 - CDF $Y(4140)$: $m = 4143.4^{+2.9}_{-3.0}(\text{stat}) \pm 0.6(\text{syst})$, $\Gamma = 15.3^{+10.4}_{-6.1}(\text{stat}) \pm 2.5(\text{syst})$ MeV
- Evidence for a second structure at ~ 4314 MeV in the same mass spectrum
- Later D0 also confirmed $Y(4140)$ with a significance of 3σ

Further Investigation in the Whole Δm Region

The Δm spectrum after subtracting B^0_s contribution but including non-B events, within 1.5σ ($\sigma = 9.3\text{MeV}$) of the B mass



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



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

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

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

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

$X(3872)$ observed in the $J/\psi\pi^+\pi^-$ final state:

A bottomonium counterpart (X_b) may exist and expected to decay into $Y(1S)\pi^+\pi^-$

Predicted to have a mass close to the $B\bar{B}$ (10.562 GeV) or $B\bar{B}^*$ (10.604 GeV) thresholds

Similar to $X(3872)$, should have a narrow resonance with a sizable decay rate in the $Y(1S)\pi^+\pi^-$ final state

Analysis Strategy: searching for a peak, other than the known $Y(2S)$ and $Y(3S)$ resonances, in the $Y(1S)(\mu^+\mu^-)\pi^+\pi^-$ invariant-mass spectrum

The ratio $R = \frac{\sigma_{X_b} \times BR(X_b \rightarrow Y(1S)\pi^+\pi^-)}{\sigma_{Y(2S)} \times BR(Y(2S) \rightarrow Y(1S)\pi^+\pi^-)}$ is measured as a function of X_b mass
(10-11 GeV)

Kinematic Region: $p_T(Y(1S)\pi^+\pi^-) > 13.5 \text{ GeV}$ & $|y(Y(1S)\pi^+\pi^-)| < 2.0$

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

[Phys. Lett. B 727 \(2013\) 57](#)

Reconstruction of X_b

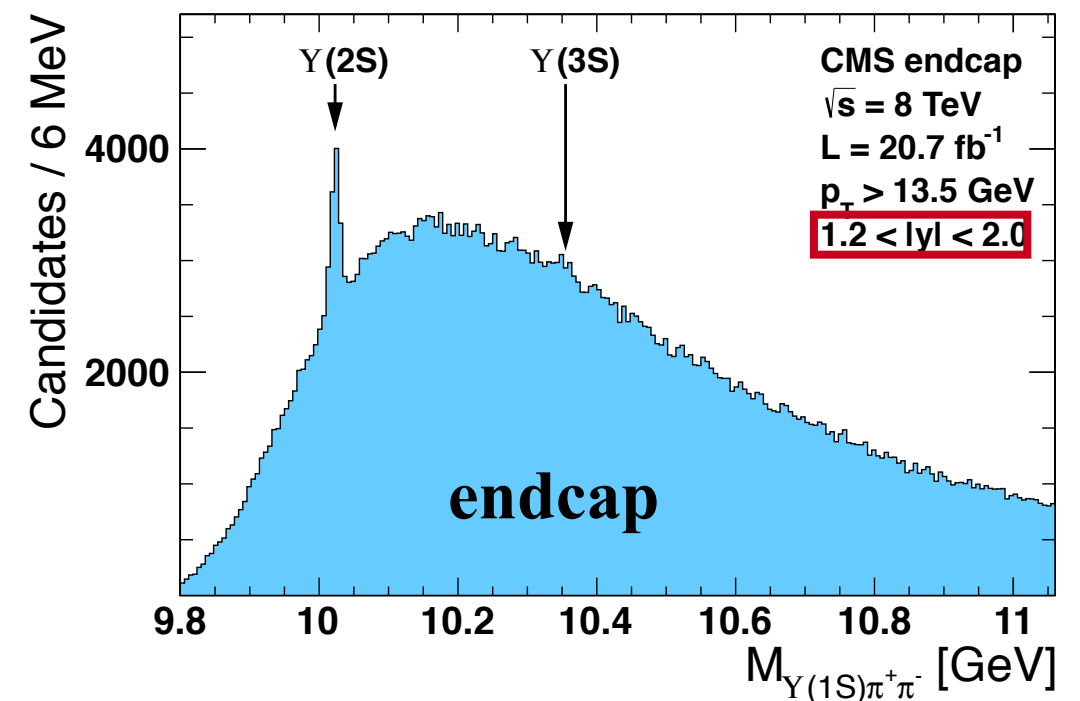
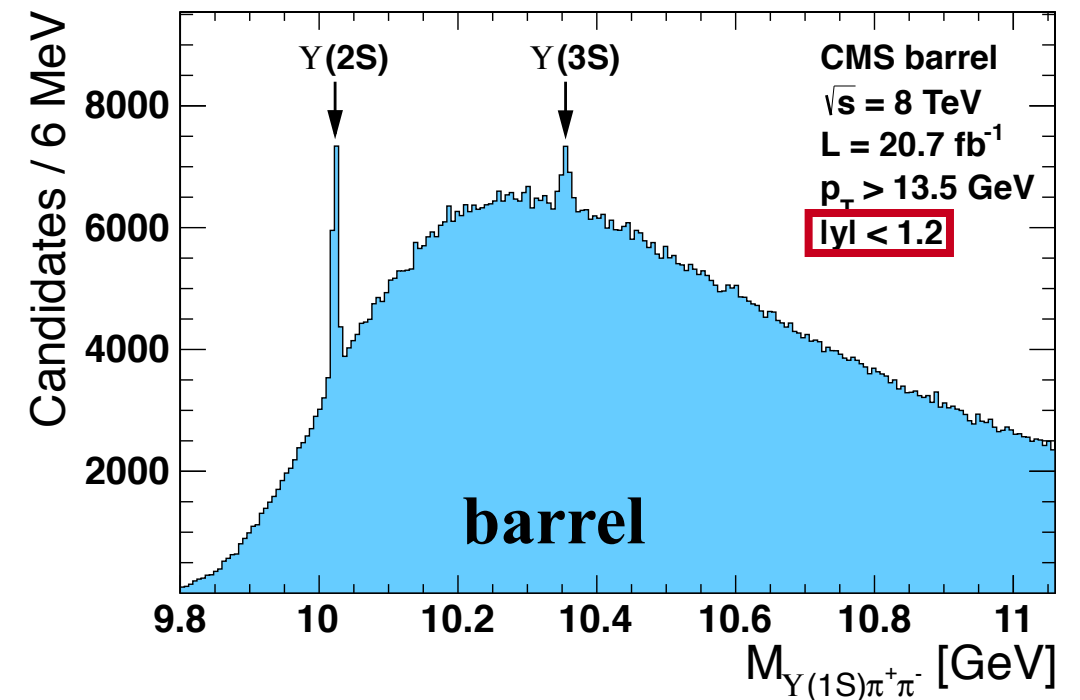
1. Reconstruction of $Y(1S) \rightarrow \mu^+\mu^-$
2. Combine $Y(1S)$ with two oppositely charged pion tracks
3. A common-vertex constrained fit is applied to the 4-tracks ($\mu^+\mu^-\pi^+\pi^-$)
 - dimuon invariant mass is constrained to the world-average $Y(1S)$ mass

Candidate selection is optimized to maximize the expected signal significance near $Y(2S)$ mass

Candidates are separated into the **barrel** ($|y| < 1.2$) and **endcap** ($1.2 < |y| < 2.0$) given different mass resolution

No structure is observed other than $Y(2S) \rightarrow Y(1S)\pi^+\pi^-$ and $Y(3S) \rightarrow Y(1S)\pi^+\pi^-$

invariant mass distributions of the $Y(1S)(\rightarrow\mu^+\mu^-)\pi^+\pi^-$ candidates



Searching for X_b

Exploring 10.06-10.31 and 10.40-10.99 GeV mass intervals excluding the $Y(2S)$ and $Y(3S)$ resonances

Shifting the hypothetical X_b mass in 10 MeV intervals to evaluate signal significance

Unbinned maximum-likelihood fits are performed on the invariant mass distribution

- Signal \rightarrow Single Gaussian function:
 - width is fixed to the values obtained from simulation
- Background \rightarrow 3rd degree polynomial
 - modeled separately for low and high mass intervals

At each X_b mass point the ratio R is evaluated

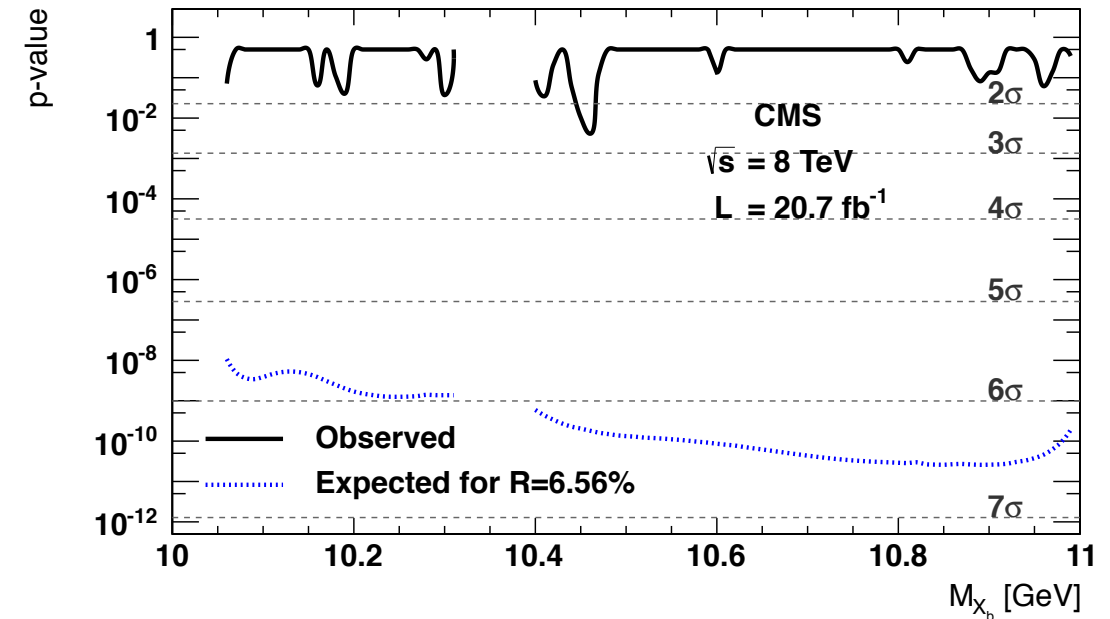
$$R = \underbrace{\frac{N_{X_b}^{obs}}{N_{Y(2S)}^{obs}}}_{\text{ratio of the observed yields}} \times \underbrace{\frac{\epsilon_{Y(2S)}}{\epsilon_{X_b}}}_{\text{ratio of overall efficiencies (simulation)}}$$

Assumptions (simulation) for $Y(2S)$ and X_b

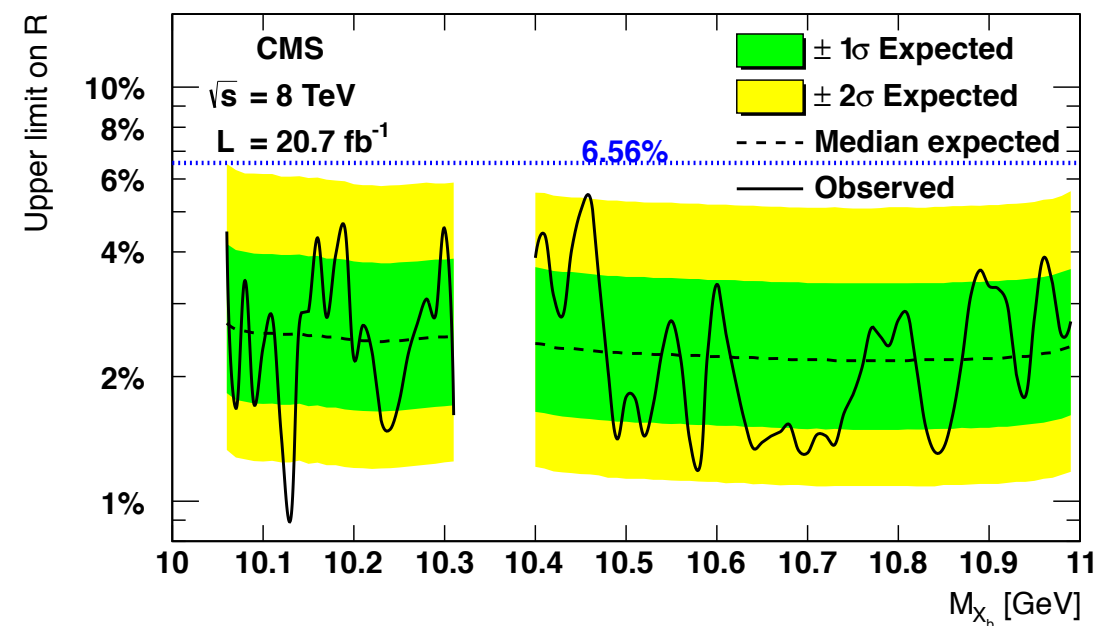
- same production mechanism
- both are unpolarized
- same dipion mass distribution

No strong hint of a signal:

95% CL upper limit on the ratio of the production cross sections times branching fractions of the X_b and $Y(2S)$: 0.9 - 5.4 %



1st upper limit on X_b production measured at a hadron collider



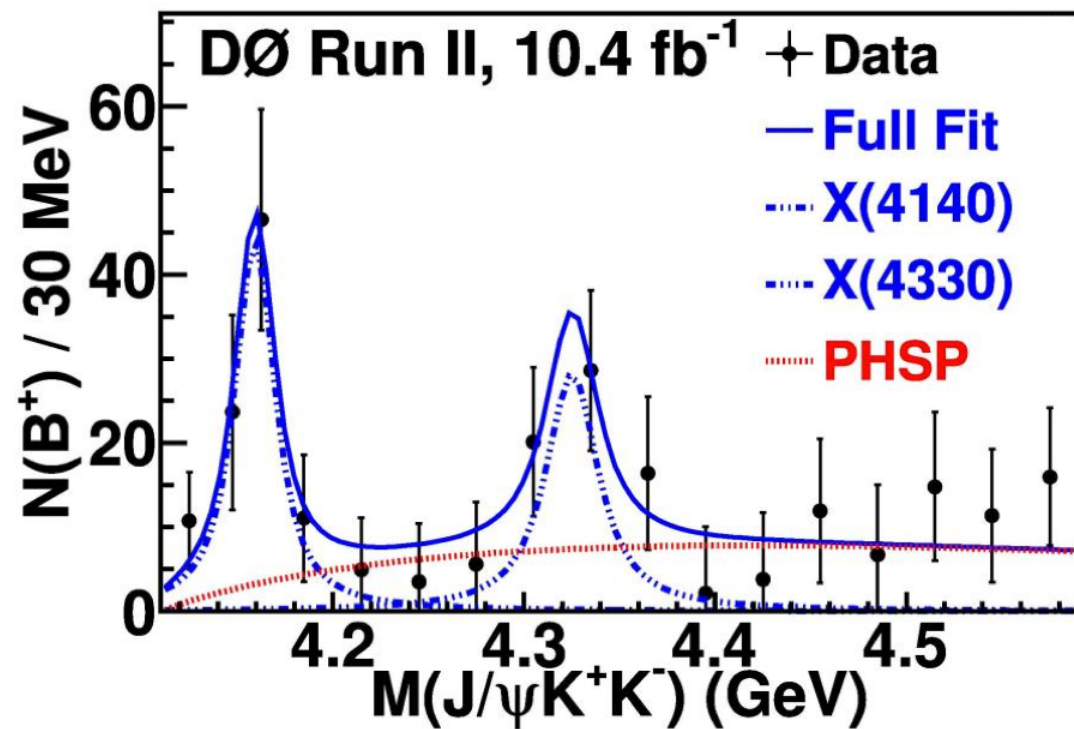
Summary

- ➡ Thanks to the excellent LHC and detector performances, CMS made important measurements in the quarkonium sector, among which:
 - ➡ prompt J/ψ pair production measurement
 - ➡ first time at high p_T region
 - ➡ observation of a peaking structure in the $J/\psi\phi$ mass spectrum
 - ➡ confirmed $Y(4140)$ with a significance $>5\sigma$, and saw evidence for a second structure in the same mass spectrum
 - ➡ D0 also confirmed $Y(4140)$ with a significance of 3σ
 - ➡ searching for a new bottomonium state decaying to $Y(1S)\pi^+\pi^-$
 - ➡ No significant excess is observed
 - ➡ 95% CL upper limit on the $(\sigma \times \text{Br})$ ratio: 0.9 - 5.4 %

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

Backup Slides

Recent Results From D0 and Babar



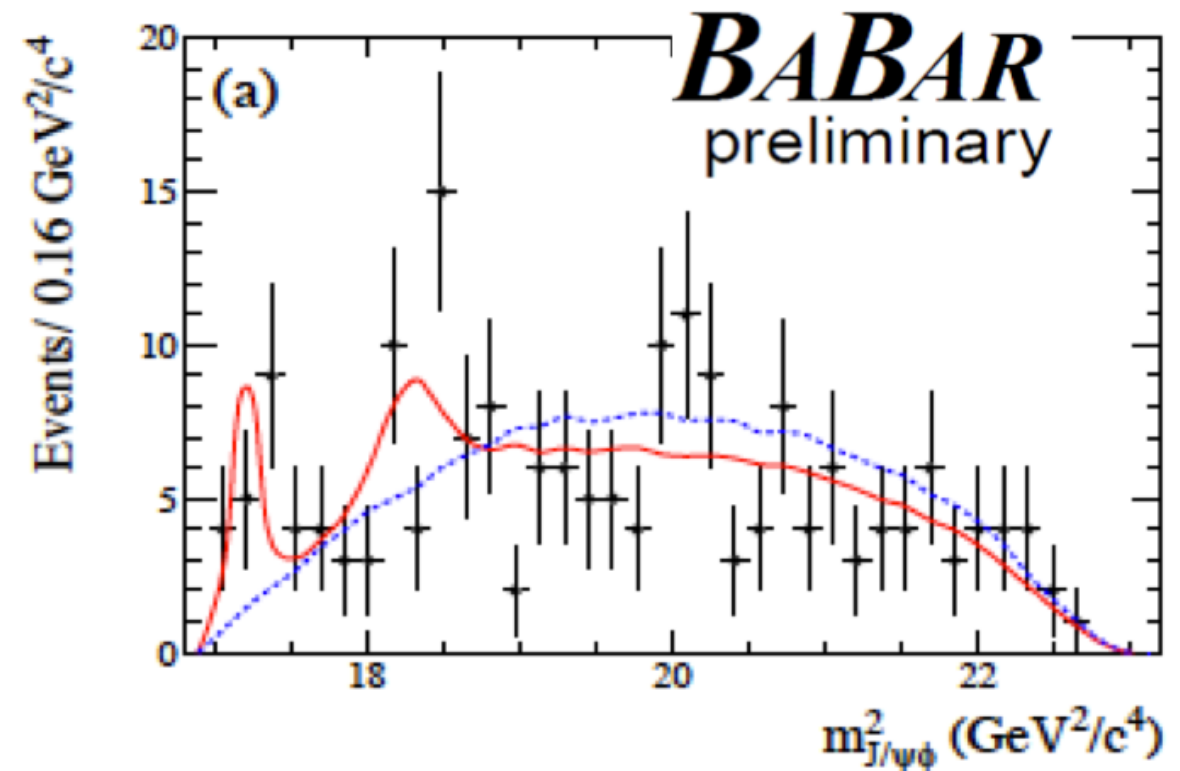
D0 found evidence at $>3\sigma$ significance for the decay $B^+ \rightarrow X(4140)K^+$, $X(4140) \rightarrow J/\psi\phi$

The mass, width, and relative decay branching fraction are measured to be:

$$m_1 = 4159.0 \pm 4.3(\text{stat.}) \pm 6.6(\text{syst.}) \text{ MeV}$$

$$\Gamma_1 = 19.9 \pm 12.6(\text{stat.}) {}^{+1.8}_{-8}(\text{syst.}) \text{ MeV}$$

$$\frac{\mathcal{B}[B^+ \rightarrow X(4140)K^+]}{\mathcal{B}[B^+ \rightarrow J/\psi\phi K^+]} = [21 \pm 8(\text{stat.}) \pm 4(\text{syst.})] \%$$



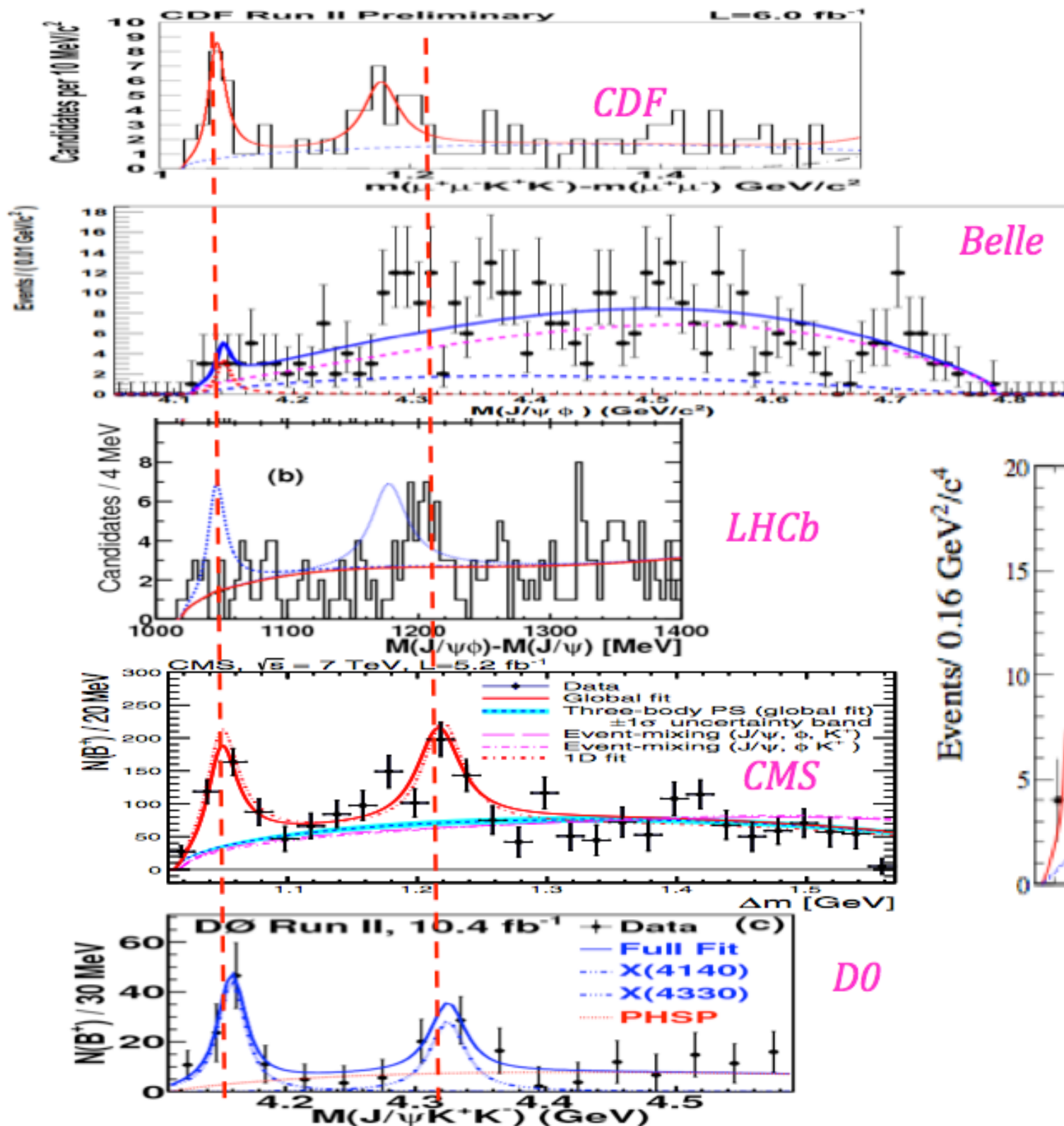
Measured branching fractions, branching ratios and searched for $J/\psi\phi$ mass structure

Fit fractions obtained assuming two resonances

$$f(4140) = (7.3 \pm 2.5 \pm 3.8)\%, \text{ UL @ 90\% C.L. } = 12.1 \%$$

$$f(4270) = (7.7 \pm 3.7 \pm 5.2)\%, \text{ UL @ 90\% C.L. } = 16.4 \%$$

Current Status of $J/\psi\phi$ System



*Belle & LHCb miss the 1st peak
(low efficiency & low statistics)*

*All experiments show activity around
4.3 GeV range, but masses are not
aligned well*

