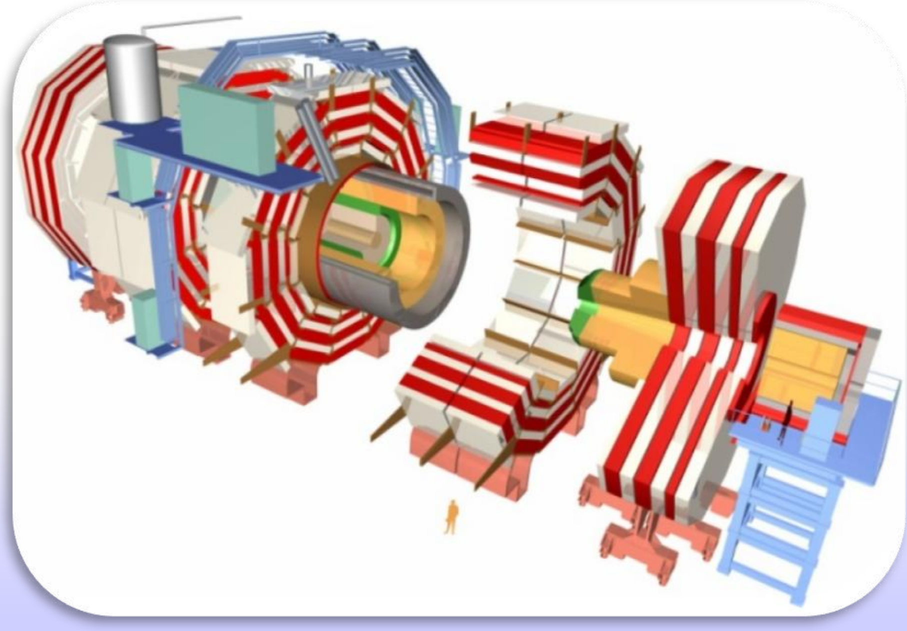
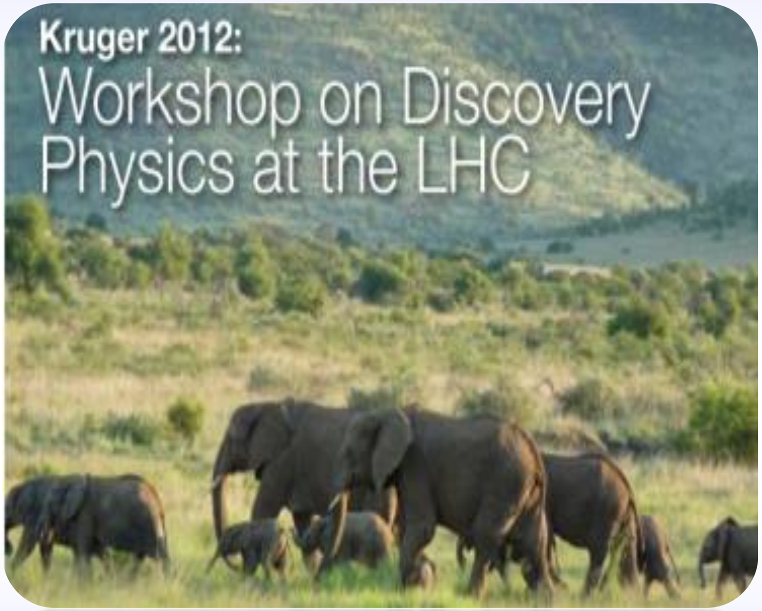
Studies of Exotic Quarkonium States at CMS

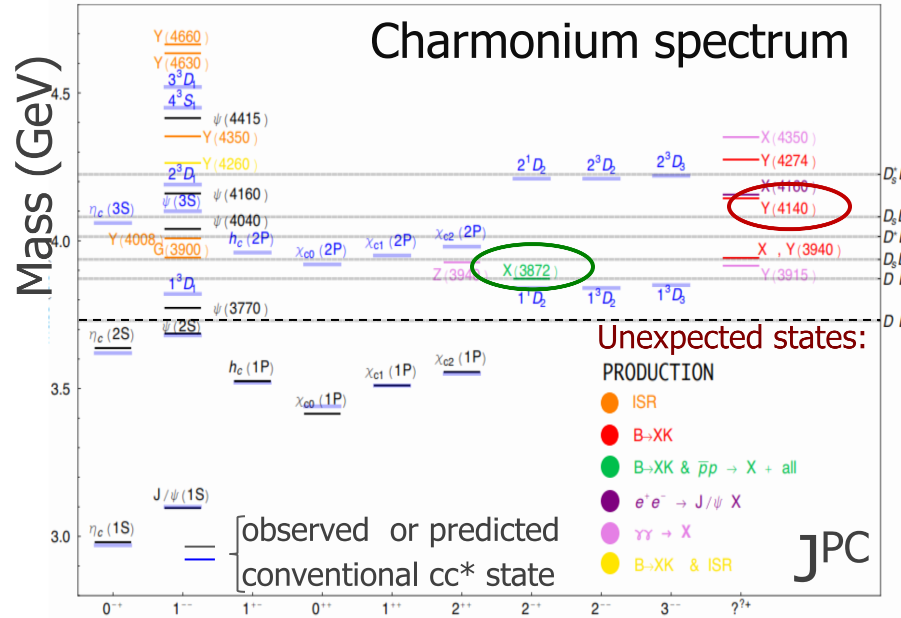
Alessandra Fanfani (Univ. & INFN Bologna)
on behalf of CMS Collaboration





Physical Motivations

- Observation of new states that do not fit into the conventional quark model has renewed the interest in exotic spectroscopy
  - Proliferation of new unconventional states above the open charm threshold
  - Theoretical picture far from being clear!



- Opportunities at LHC to confirm these states and study their properties

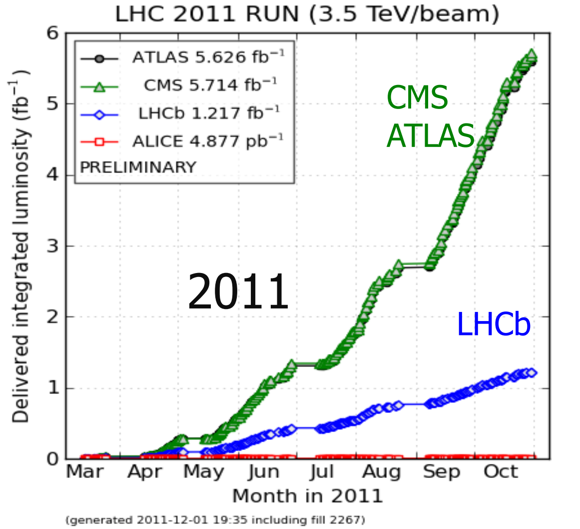
- Focus on first targets in exotic spectroscopy program in CMS:
  - **X(3872)** : First of the exotic charmonium states discovered by Belle (2003)
  - **Y(4140)** : State reported by CDF in $B^+ \rightarrow J/\psi \phi K^+$

presenting recent CMS results on:

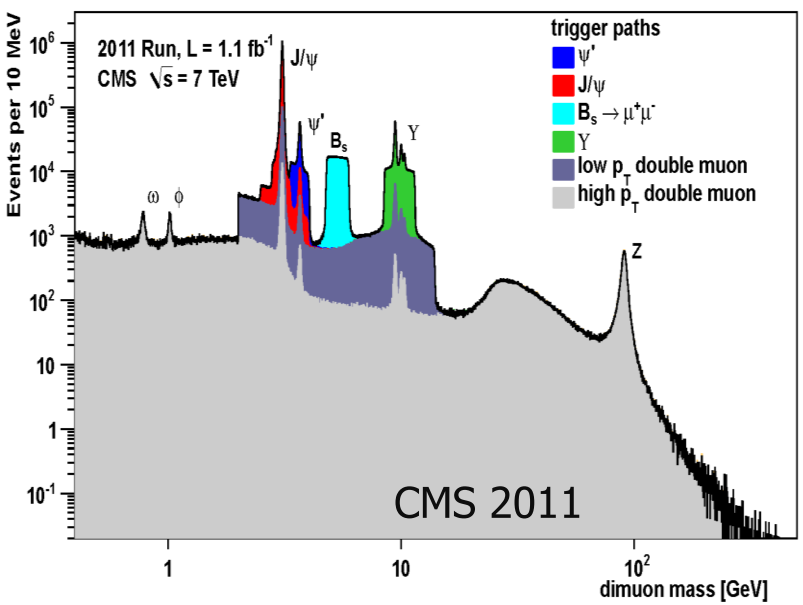
- Production of X(3872) via decay to $J/\psi\pi^+\pi^-$ NEW
- Observation of structures in the $J/\psi\phi$ mass spectrum NEW

CMS Detector Performance

Excellent CMS performances for quarkonium studies



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

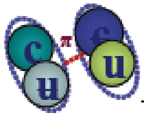


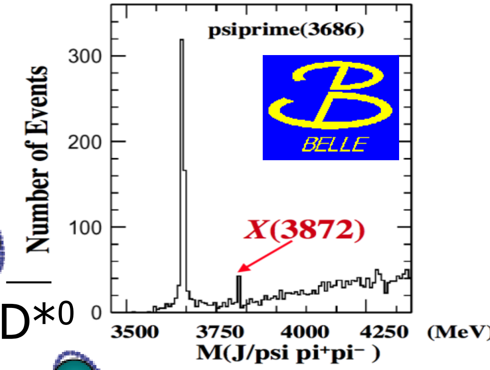
- LHC luminosity and CMS trigger
  - able to collect data at increasing instantaneous luminosity
    - about $5 fb^{-1}$ from 2011 data at $\sqrt{s}$=7 TeV
  - clever triggers are essential ingredients
    - specific trigger paths developed for different analyses

Production of X(3872)

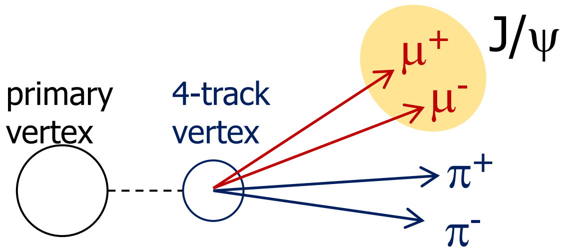
The X(3872) State

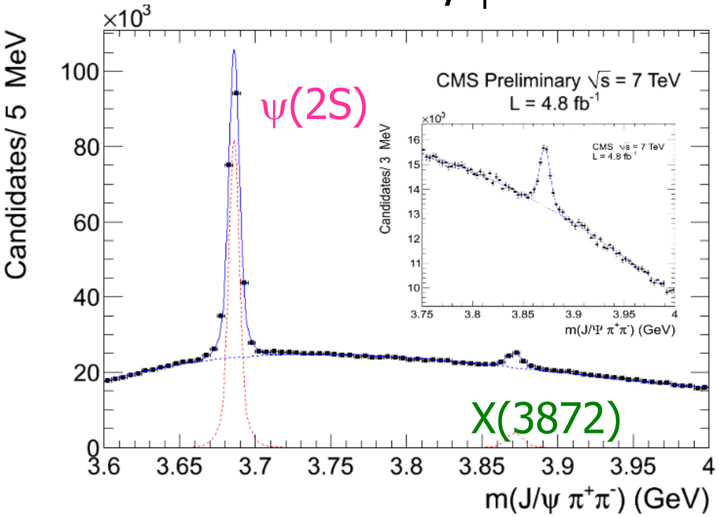
- The X(3872) was discovered by Belle in 2003
  - properties studied at B-factories and Tevatron
  - its nature still remains unclear. Possibilities:
    - a cc(bar) charmonium state
    - a multi-quark molecule: loosely bound state of D^0 and D^{*0}
    - a tetra-quark: bound state of diquark and anti-diquark





- A clean experimental signature for X(3872)→$J/\psi\pi^+\pi^-$ decay
  - J/ψ reconstructed with 2μ and combined with pairs of charged tracks
  - 4 tracks fit to a common vertex with constraint on J/ψ mass to the nominal value

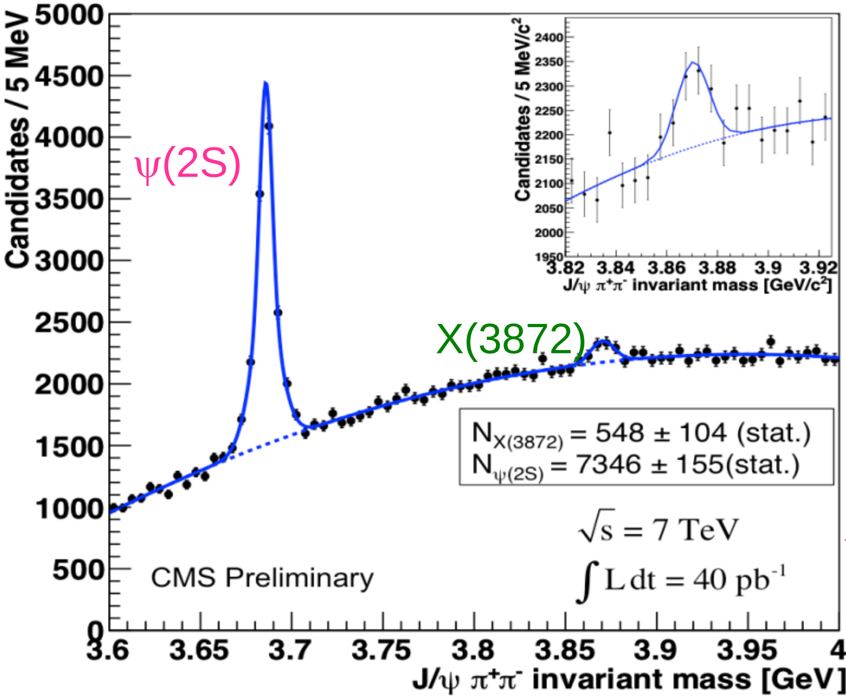




X(3872) Production with 2010 data

- Inclusive production measurement in CMS based on 40 pb^{-1} data sample from 2010

CMS-PAS-BPH-10-018



- Measure the ratio between the X(3872) and ψ(2S) cross sections times branching fractions

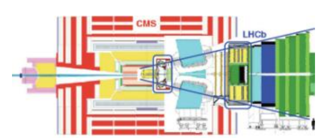
$$R = \frac{\sigma(pp \to X(3872) + \text{anything}) \times BR(X(3872) \to J/\psi\pi^+\pi^-)}{\sigma(pp \to \psi(2S) + \text{anything}) \times BR(\psi(2S) \to J/\psi\pi^+\pi^-)}$$

→ most of the systematics cancel

- kinematic region: $p_T(X)>8$ GeV & $|y(X)|< 2.2$

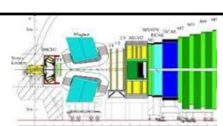
$$R = 0.087 \pm 0.017(stat.) \pm 0.009(syst.)$$

complementary to LHCb



$5 < p_T(X) < 20$GeV

$2.5 < y(X)< 4.5$

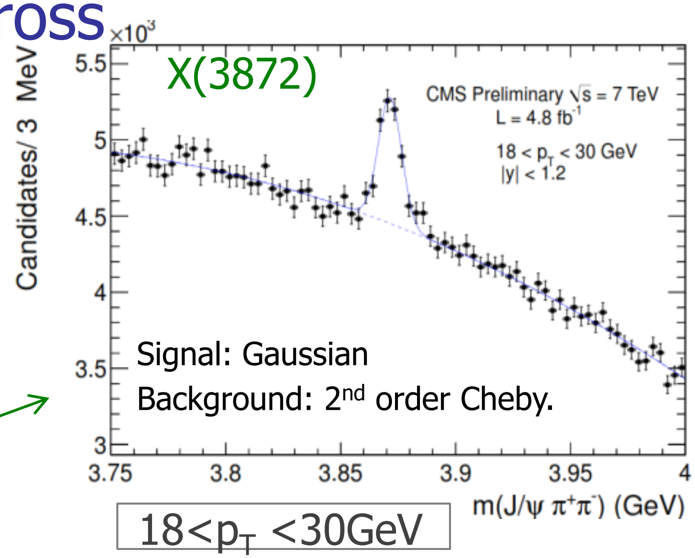


$$\sigma(pp \to X(3872) + \text{anything})B(X(3872) \to J/\psi\pi^+\pi^-) = 5.4 \pm 1.3(\text{stat}) \pm 0.8(\text{syst})\ \text{nb}$$

Eur. Phys. J. C 72 (2012) 1972

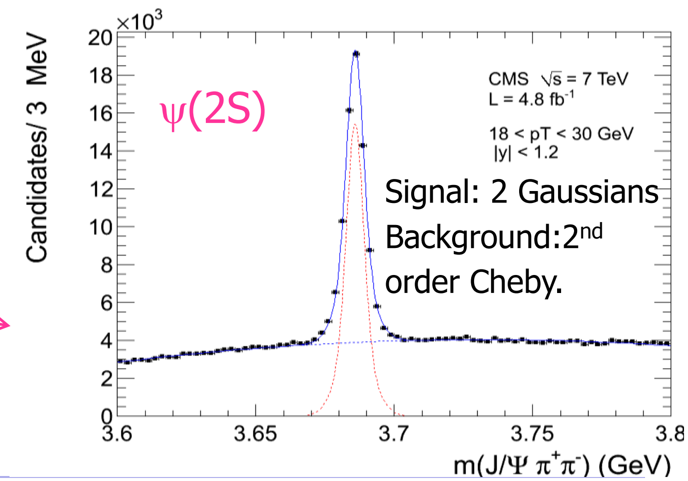
Cross Section ratio of X(3872) wrt ψ(2S)

- The larger event sample collected in 2011 ($4.8 fb^{-1}$) allows for more detailed studies
- Ratio between the X(3872) and ψ(2S) cross sections times *BR*($X(3872) \rightarrow J/\psi\pi^+\pi^-$) is measured as a function of p_T
  - from 10 GeV up to 50 GeV
  - with rapidity |y(X)| < 1.2



- X(3872) and ψ(2S) yields are extracted from fits to the $J/\psi\pi^+\pi^-$ invariant-mass distribution

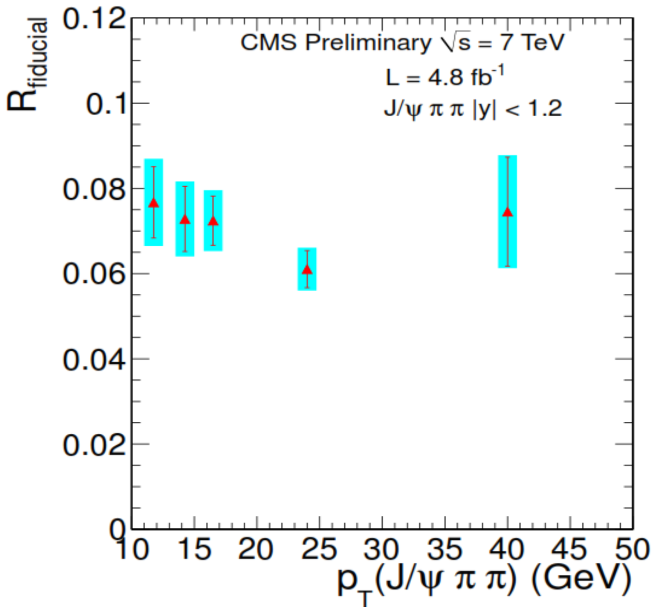
$$R = \frac{N_{X(3872)} \cdot \langle \frac{1}{A \cdot \epsilon} \rangle_{X(3872)}}{N_{\psi(2S)} \cdot \langle \frac{1}{A \cdot \epsilon} \rangle_{\psi(2S)}}$$



- corrected for acceptance and efficiency from simulation
  - data-driven verification of ε evaluation

Results on inclusive Cross Section ratio

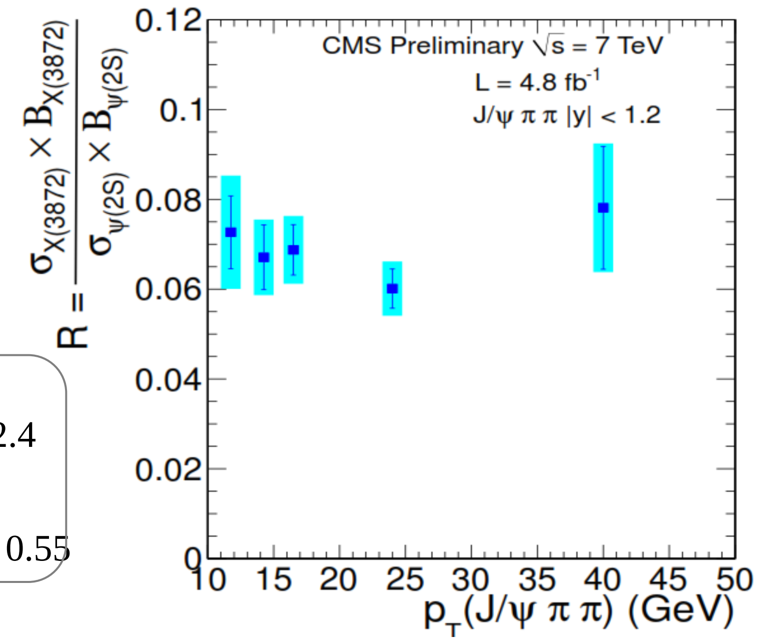
- "fiducial" R within a phase space window defined by kinematical cuts on μ and π



$$R_{fiducial} = 0.0700 \pm 0.0038(\mathrm{stat}) + 0.0038(\mathrm{syst})$$

- $p_T^{\mu} > 4$GeV in $|\eta^{\mu}| < 1.2$
- $p_T^{\mu} > 3.3$GeV in $1.2 <|\eta^{\mu}| < 2.4$
- $p_T^{\mu\mu} > 7$GeV in $|y^{\mu\mu}| < 1.25$
- $p_T^{\pi} > 0.6$GeV & $\Delta R(\pi,\mu\mu) < 0.55$

- fully acceptance corrected R



$$R = 0.0662 \pm 0.0038(\mathrm{stat}) \pm 0.0064(\mathrm{syst})$$

both X(3872) and ψ(2S) assumed unpolarized

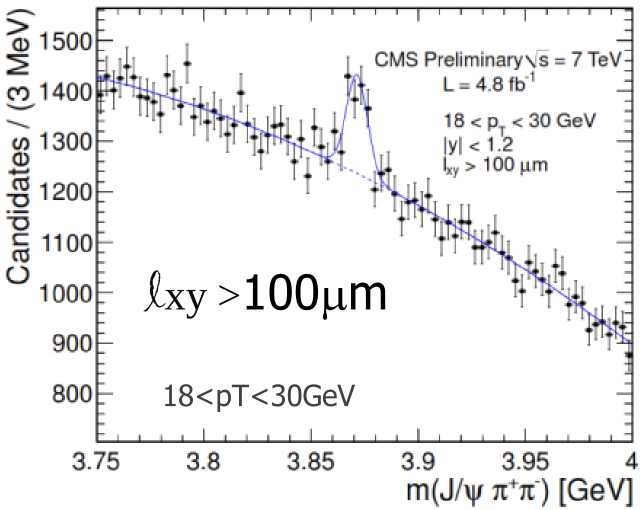
- Typical uncertainty in individual p $_T$ bins ~10% stat. and 6-7% syst.
- Largest systematic uncertainty from lack of knowledge of the X(3872) p_T spectrum

- No significant dependence on p_T

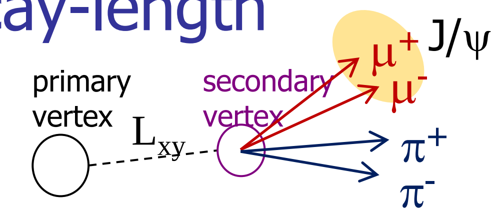
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH11011

Fraction of X(3872) from B Decays

- Based on the study of the "pseudo-proper-decay-length"



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



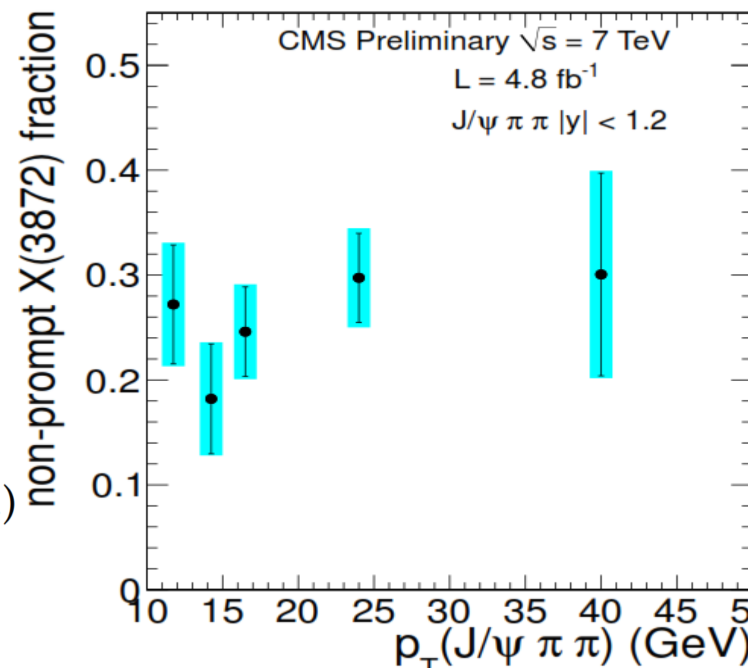
- X(3872) signal yield extracted from $J/\psi\pi^+\pi^-$ invariant-mass fits

$$\text{non-prompt fraction} = \frac{\text{signal yield (B enriched sample)}}{\text{signal yield (entire sample)}}$$

- ψ(2S) data used as control sample
  - to estimate ℓxy resolution and pile-up effects from data

- The non-prompt X(3872) fraction is about half that of the ψ(2S)

non-prompt fraction = $0.259 \pm 0.029\,(\text{stat.}) \pm 0.016\,(\text{syst.})$



- no significant dependence on p_T

Prompt X(3872) Cross Section

- Prompt X(3872) cross-section times BR(X(3872)→J/ψπ+π-) extracted from:

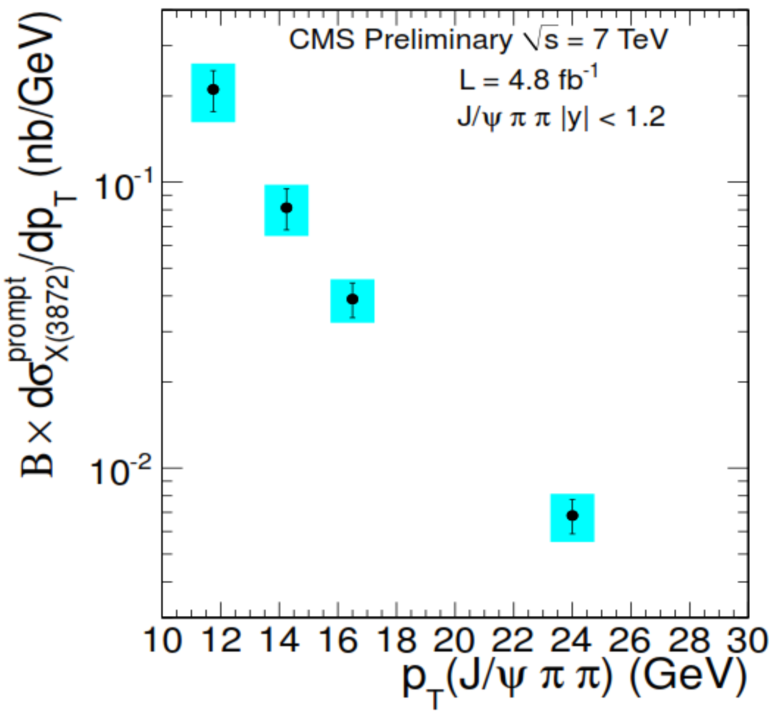
$$\sigma^{\text{prompt}}_{X(3872)} \times \mathcal{B}(X(3872) \to J/\psi\pi\pi) = \frac{1 - f^B_{X(3872)}}{1 - f^B_{\psi(2S)}} \cdot R \cdot \left(\sigma^{\text{prompt}}_{\psi(2S)} \times \mathcal{B}(\psi(2S) \to \mu\mu)\right) \cdot \frac{\mathcal{B}(\psi(2S) \to J/\psi\pi\pi)}{\mathcal{B}(\psi(2S) \to \mu\mu)}$$

non-prompt X(3872) fraction

cross-section ratio R

published CMS results of prompt ψ(2S) cross section (up to 30 GeV, |y| < 1.2) → JHEP 02 (2012) 011

from PDG



Integrated prompt X(3872) cross-section x *B* in $10<p_T(X)<30$GeV $|y(X)|<1.2$:

$$\sigma^{\text{prompt}}(pp \to X(3872) + \text{anything}) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$$

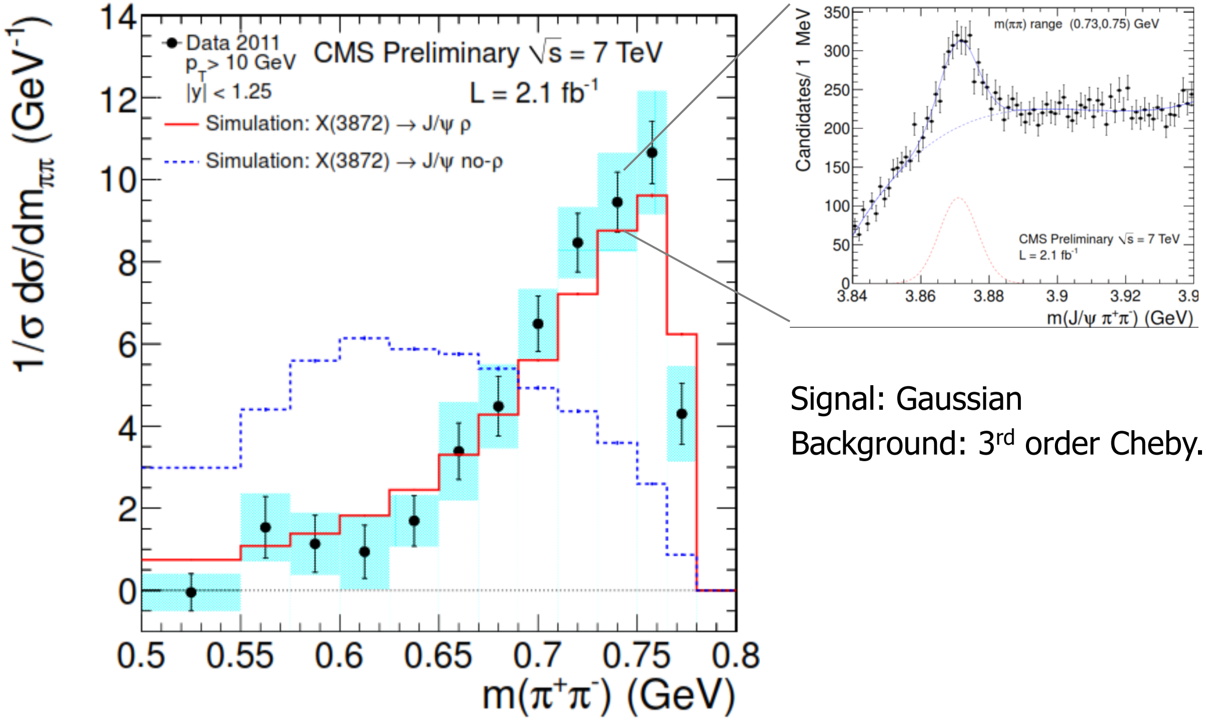
$$1.03 \pm 0.11\,(\text{stat.}) \pm 0.15\,(\text{syst.})\ \text{nb}$$

- First time the X(3872) production is measured differentially in pT

Dipion Invariant-Mass Distribution

- Decay properties are investigated by measuring the $\pi^+\pi^-$ invariant-mass distribution from the decays to $J/\psi\ \pi^+\pi^-$

- X(3872) yields are extracted from $J/\psi\pi^+\pi^-$ invariant-mass fit for slices of $m(\pi^+\pi^-)$
- corrected by relative acceptance and efficiency



Signal: Gaussian
Background: 3rd order Cheby.

normalized to the integrated cross section for $0.5 < m_{\pi\pi} < 0.78$GeV

- Data shows better agreement with predictions from simulation for intermediate resonant $\rho^0 \rightarrow \pi^+\pi^-$ decay, confirming previous indications by CDF and Belle

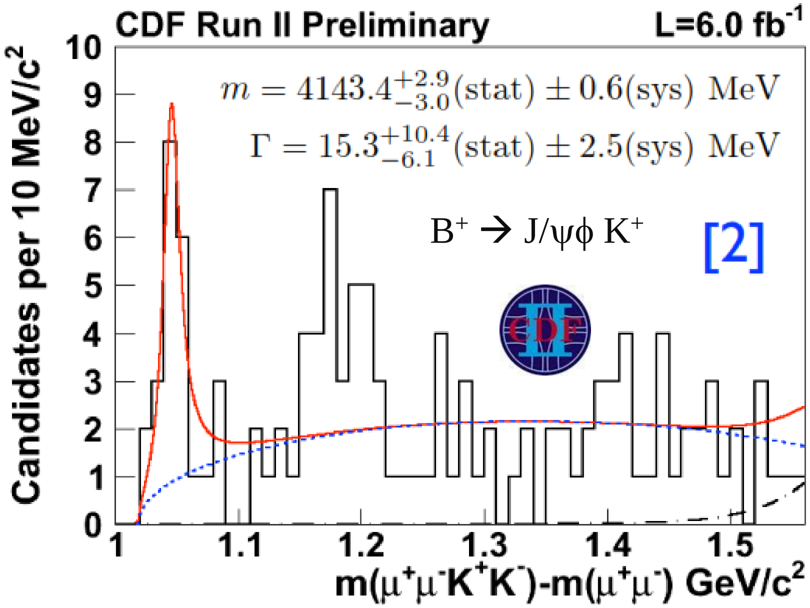
Search for structures in the J/ψφ Mass Spectrum

Search for structures near J/ψϕ threshold

- The observation of Y(3930) [1] near the J/ψω threshold motivated searches for similar structures near J/ψϕ threshold

- CDF observed a narrow peak with a significance greater than 5σ [2]

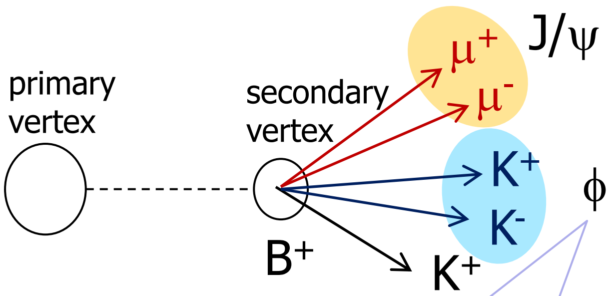
- LHCb did not confirm the existence of Y(4140) [3]



[1] BELLE Phys. Rev. Lett. 94, 182002 (2005), BABAR Phys. Rev. Lett. 101, 082001 (2008)
[2] http://www-cdf.fnal.gov/physics/new/bottom/100701.blessed-jpsiphi6.0/myFig11.eps , arXiv:1101.6058v1
[3] Phys. Rev. D85 (2012) 091103

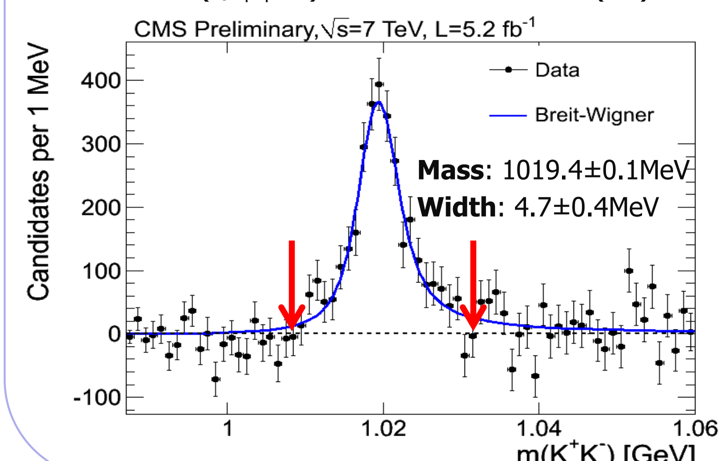
CMS Search in the $J/\psi\phi$ Mass Spectrum

- Search for states in the $J/\psi\phi$ mass spectrum via the $B^+ \to J/\psi\phi K^+$ decay

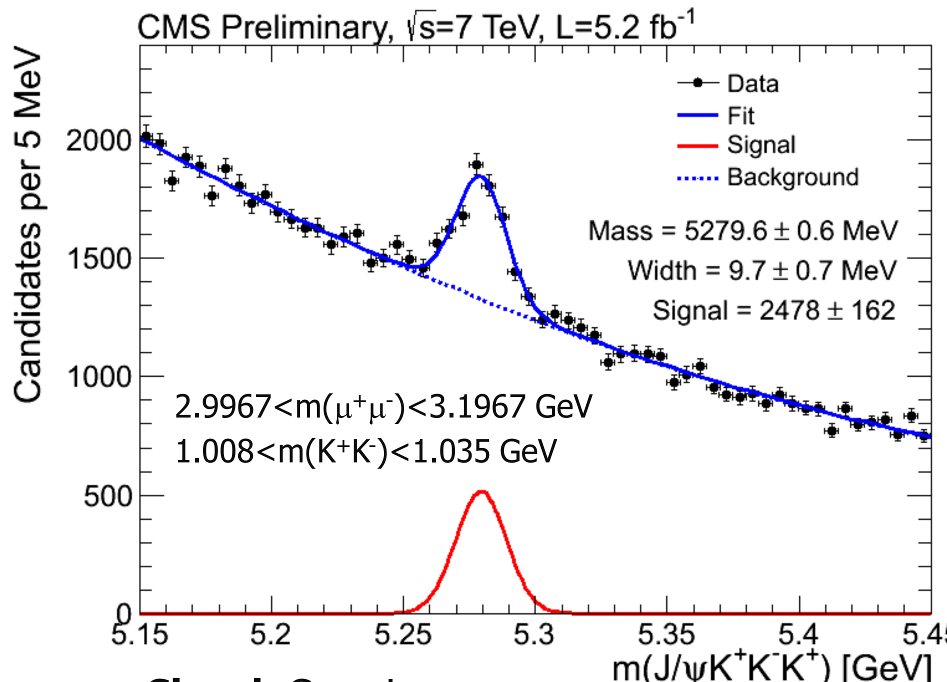


The B^+ sideband subtracted $m(K^+K^-)$

where $m(J/\psi\phi K^+)$ is within $\pm 3\sigma$ of $m(B^+)$



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



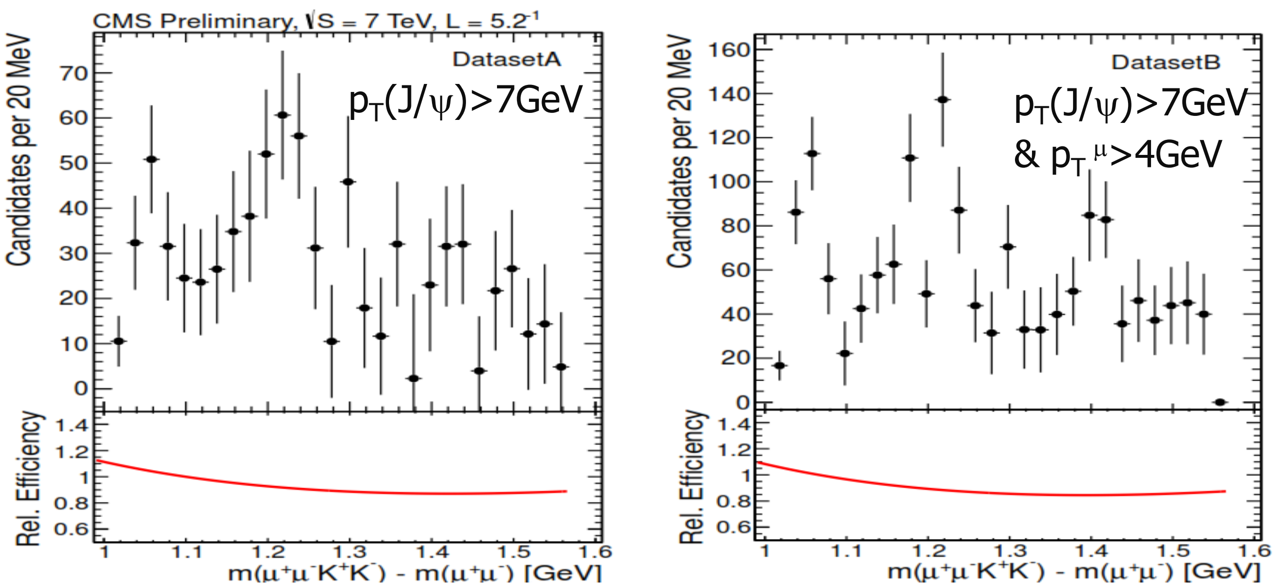
Signal: Gaussian

Background: 2nd-order Chebyshev polynomial

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

$J/\psi\phi$ Invariant-mass Spectrum

- To search for possible structures in $J/\psi\phi$ using the $B^+ \to J/\psi\phi K^+$ decay, the mass difference $\Delta m = m(\mu^+\mu^- K^+K^-) - m(\mu^+\mu^-)$ is used
- Extracting the Δm spectrum
  - Divide the dataset into the 20 MeV Δm bins
  - Extract the number of B events for each Δm by fitting the $J/\psi\phi K$ spectrum
    - Mean fixed to the PDG B mass
    - RMS fixed to the signal MC prediction
  - Plot the B yield as a function of Δm

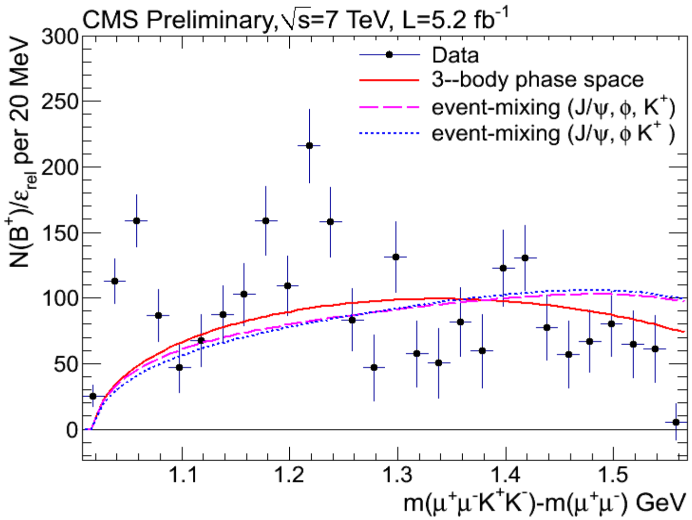


  - Correct the spectrum by relative efficiency

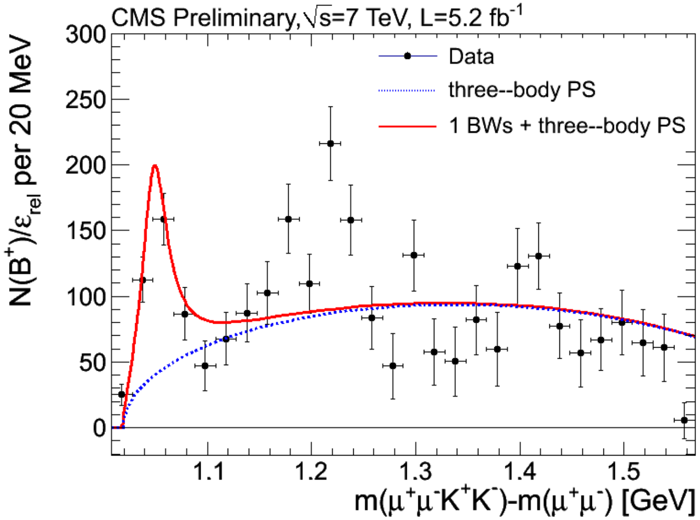
- The relative-efficiency-corrected Δm distribution from $B^+ \rightarrow J/\psi\phi K^+$ decays

Background: 3-body phase space
Signal: S-wave relativistic Breit-Wigner functions convolved with a Gaussian resolution function

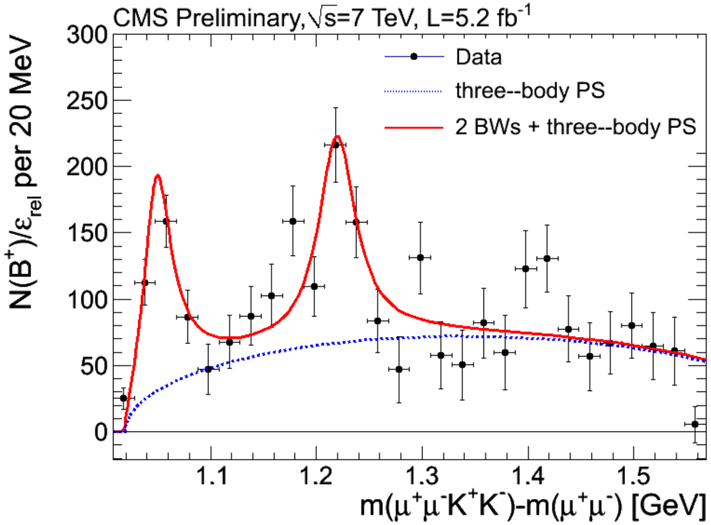
only background hypothesis



background + 1 signal hypothesis

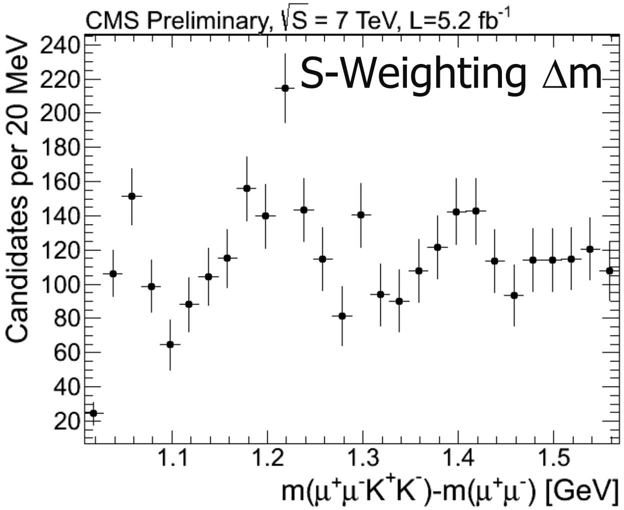


background + 2 signal hypothesis

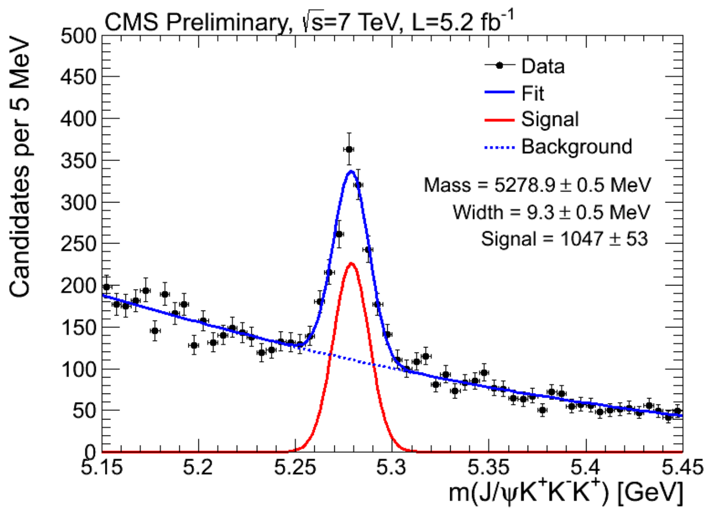


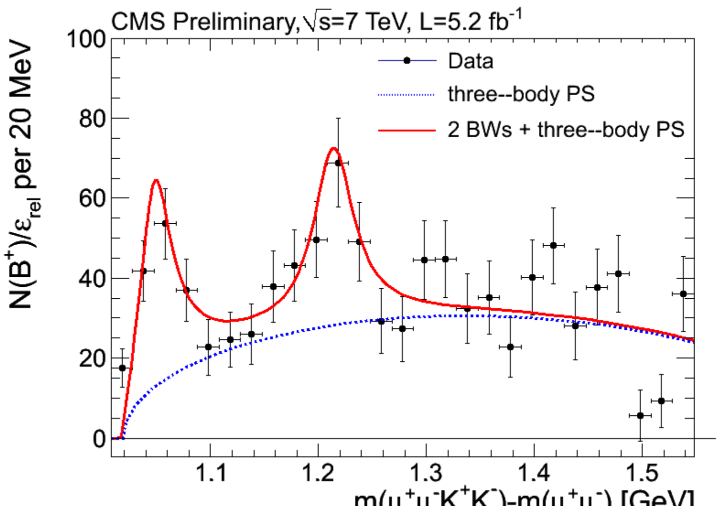
Robustness of the Observed Structures

- Several checks to validate the robustness of the two structures
  - Variations on selection cuts, Δm binning, background and signal shape
  - Background-subtraction technique based on *sPlot* formalism
  - Tighter B selection to reduce the combinatorial background



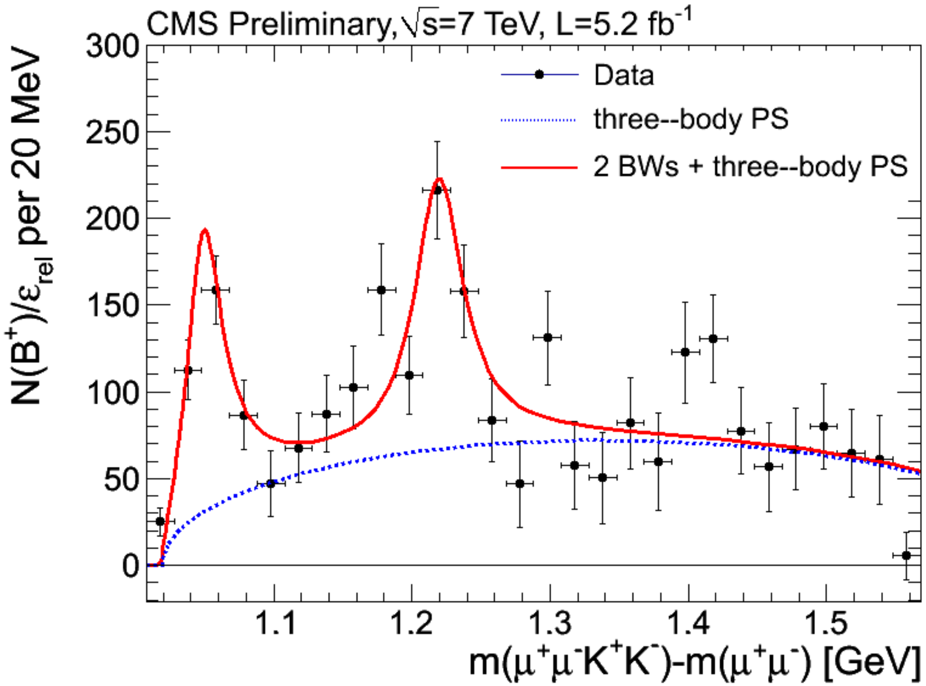
- B purity ~60% within $\pm 1.5\sigma$ of m(B+)
- similar Δm spectrum





Results on Structures in the $J/\psi\phi$ invariant mass

- The efficiency-corrected $\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$ from the exclusive $B^+ \rightarrow J/\psi\phi\, K^+$ decays



	Mass (MeV)	Signal Yield
First Peak	1051.5 ± 2.0	355 ± 46
Second Peak	1220.0 ± 3.0	445 ± 83

Fitted mass of the two structures:

m (1st) = 4148.2 ± 2.0 (stat.) ± 4.6 (syst.) MeV
m (2nd) = 4316.7 ± 3.0 (stat.) ± 7.3 (syst.) MeV

- observed a $J/\psi\phi$ structure at 4148MeV with a significance greater than 5σ
- evidence for a second structure at ~4317MeV in the same mass spectrum

Summary

- The CMS Collaboration has an active exotic spectroscopy program
- Production of X(3872) via decay to $J/\psi\pi^+\pi^-$
  - ratio of cross section times branching fractions of the X(3872) and $\psi(2S)$
    - no p_T dependence up to 50GeV
  - fraction of X(3872) from B decays is measured ←first time at LHC
    - f_B= 0.261 ±0.028 (stat) ±0.016 (sys) about half that of the $\psi(2S)$
  - prompt X(3872) cross section x*BR* measured as a function of p_T ←first time
  - dipion invariant-mass spectrum favors the decay of an intermediate ρ^0
- Structures in the $J/\psi\phi$ mass spectrum at 4148MeV and ~4317MeV
- These results demonstrate the CMS potential in the exotic quarkonium sector
- More to be expected with the large data sample from 2012
  - should help to better understand the nature of the observed structures

BACKUP

Systematic uncertainties on X(3872) results

Systematic uncertainties on cross-section ratio R:

- Signal and background parametrisation→ 1-2%
- Data-Driven estimate of $\pi\pi$ efficiency and muon efficiency→1-2%
- Limited MC statistic → 1%
- ψ(2S) pT dependence → 2-4%
- Lack of knowledge of the pT distribution of the X(3872): 3-10%
- X(3872) decay kinematics→ 1-2%

Polarization scenarios: rough estimate of relative shifts

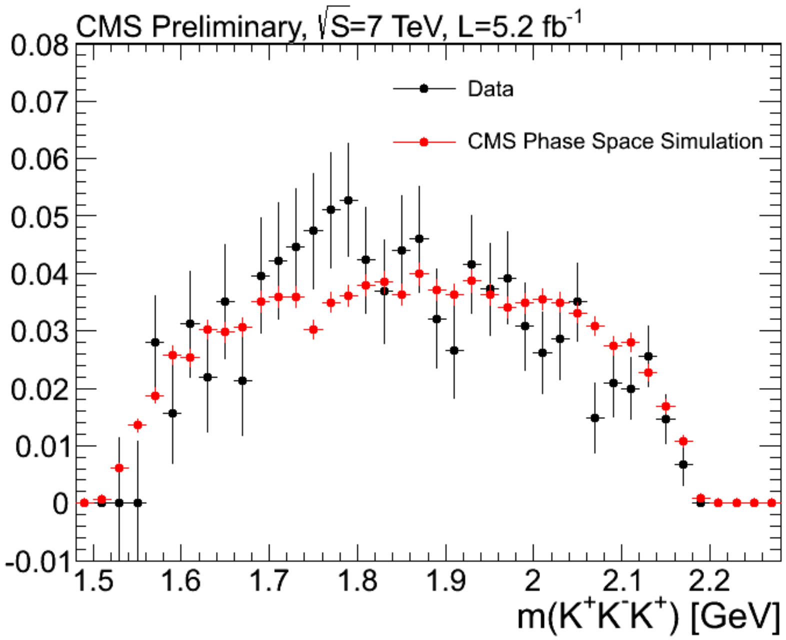
- from few % up to 30% if only one state is assumed polarized in extreme scenarios
- up to 30% (90%) in Collins-Soper (helicity) frame for both states in extreme pol. scenarios

Systematic uncertainties on nonprompt X(3872) fraction:

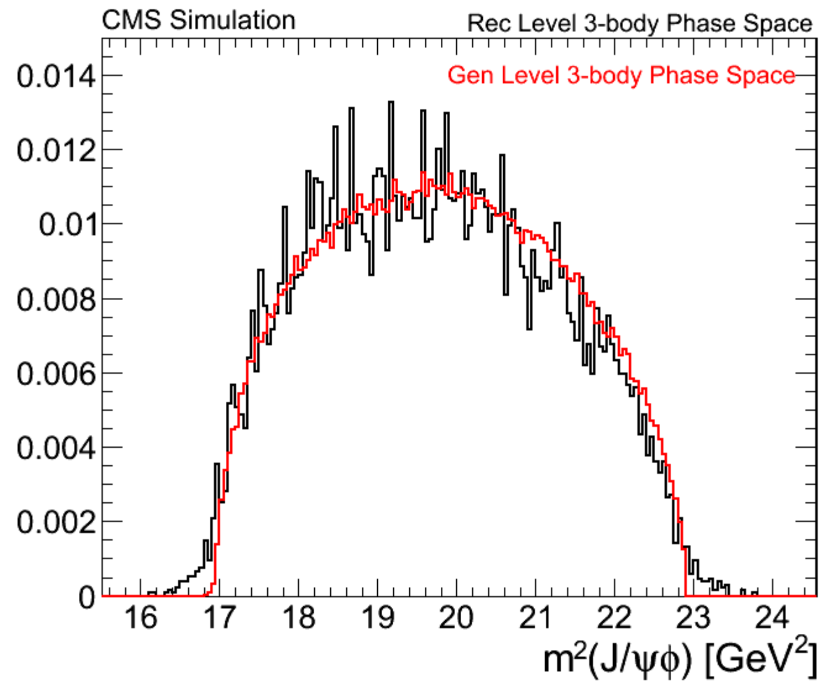
- Primary vertex selection →1%
- Background parametrization → 2-3%
- Difference between prompt and nonprompt efficiencies → 3-4%
- Decay length resolution →4%
- Effect of PileUp → 2%

Structures in the $J/\psi\phi$ mass spectrum

- Sideband subtracted KKK mass distribution in Phase Space MC(red) and in data (black).



- The x projection ($J/\psi\phi$ space) of dalitz plot for the generated events (red) and for the reconstructed events (shown as black, after all event selections). The dalitz plot is obtained from CMS Phase Space MC.



CMS Detector

- Silicon Tracking detector
- Muon system