Exotic Quarkonium at CMS

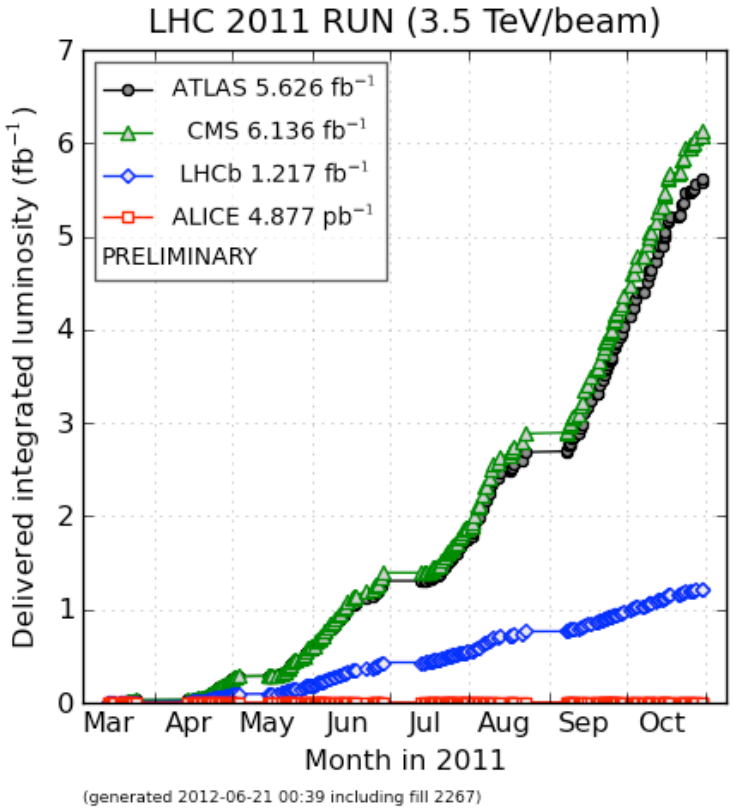
Kai Yi
University of Iowa

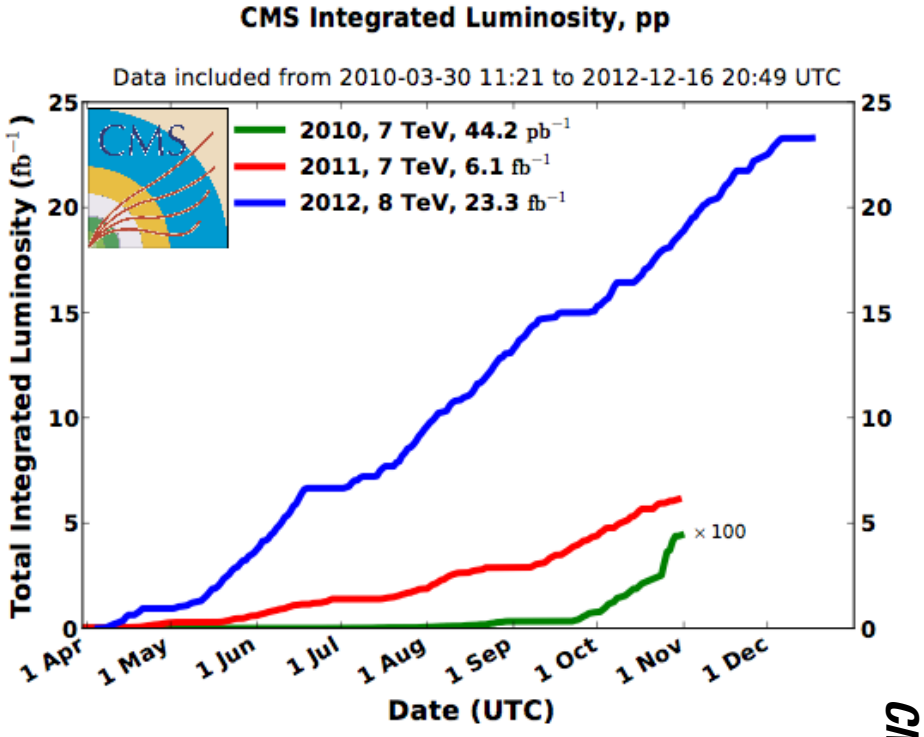
on behalf of the CMS Collaboration

Outline

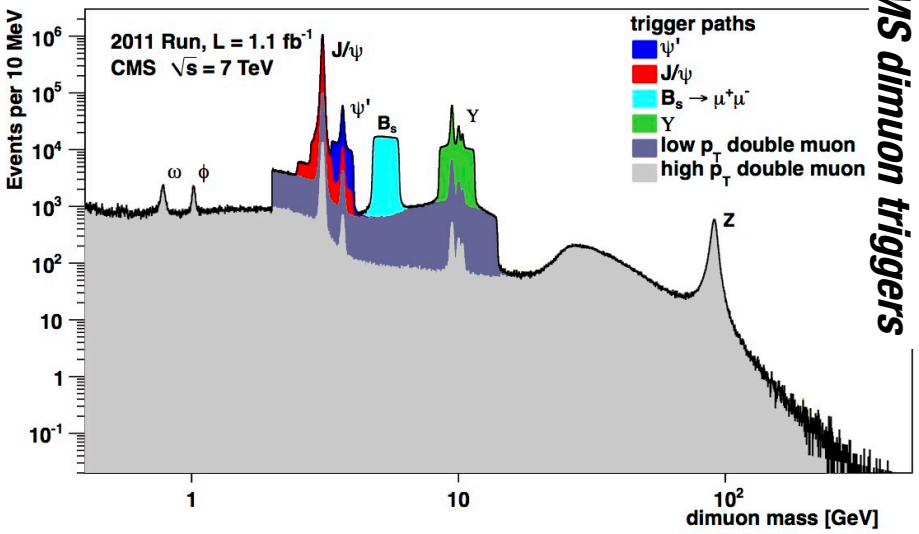
- *Introduction & motivation*
- *LHC & CMS*
- *measurement of the X(3872) production cross section*
- *observation of structures in the $J/\psi\phi$ spectrum*
- *Summary*

LHC and CMS performance





All results presented in this talk are based on proton proton data collected in 2011 @7 TeV



CMS dimuon triggers

X(3872) production cross section

- *The X(3872) was discovered by Belle in 2003*
  - *Later confirmed by BaBar, D0 and CDF*
  - *Its nature still remains unclear. Possibilities:*
    - *a 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*
- *Previous analyses favors $J^{PC}=1^{++}$ or 2^{-+}*

  CMS results are obtained with the assumption that $J^{PC}=1^{++}$
  - *In March 2013, LHCb measured $J^{PC}=1^{++}$* arXiv:1302.6269
- *Produced both in prompt and B→X(3872) feed-down processes &*
  CMS measures both prompt and non-prompt production cross section

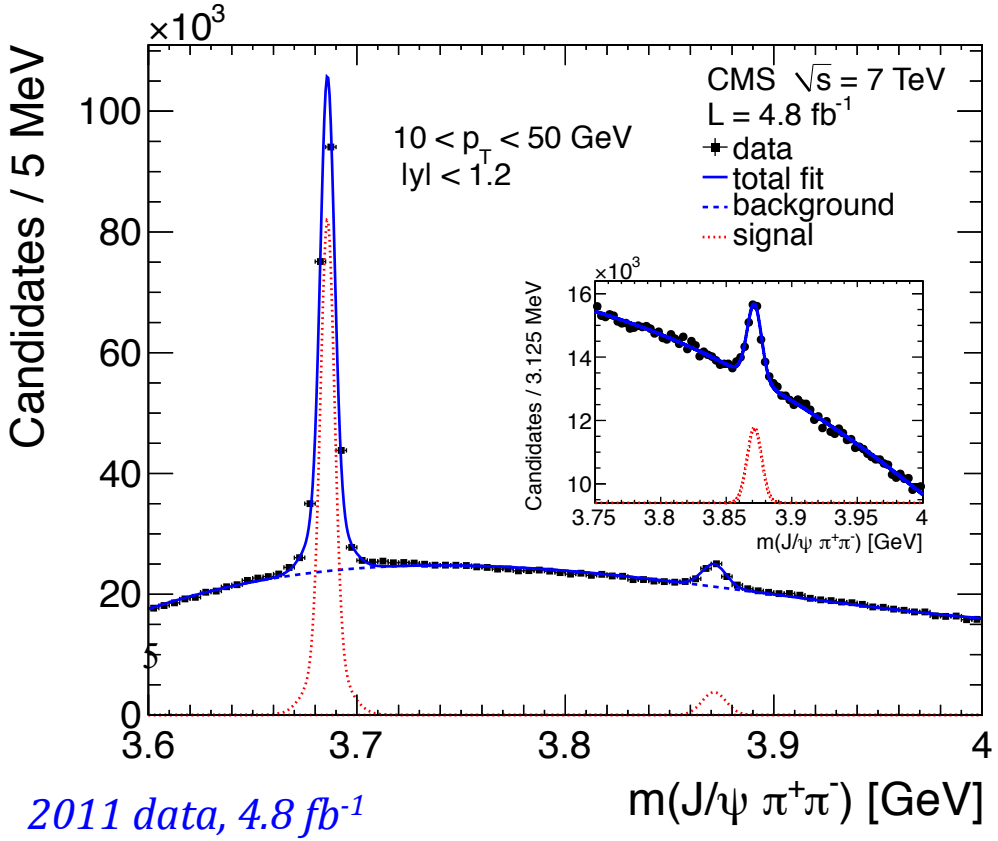
X(3872) production cross section

arXiv:1302.3968, acc. for pub. in JHEP

- *Use the decay X(3872) → J/ψ π⁺π⁻ (J/ψ → μ⁺μ⁻) , 10 < p_T < 50 GeV and |y| < 1.2*
- *Measure the ratio of X(3872) and ψ(2S) cross sections R as:*

$$\frac{N_{X(3872)} \cdot A_{\psi(2S)} \cdot \epsilon_{\psi(2S)}}{N_{\psi(2S)} \cdot A_{X(3872)} \cdot \epsilon_{X(3872)}}$$

signal yield *acceptance* *efficiency*



2011 data, 4.8 fb⁻¹

Event selection:

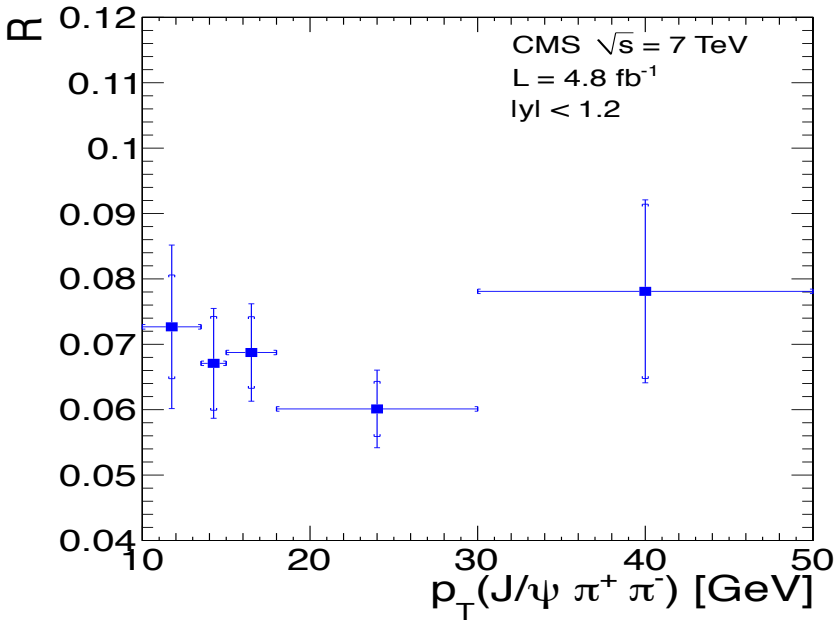
- *p_T(J/ψ) threshold (7 or 10 GeV)*
- *|y(μ⁺μ⁻)| < 1.25, ±75 MeV J/ψ mass*
- *muon p_T threshold depending on |η|*
- *constraining the J/ψ mass to PDG*
- *pion p_T > 0.6GeV*
- *ΔR(J/ψ,π)<0.55*
- *Q value < 300 MeV*

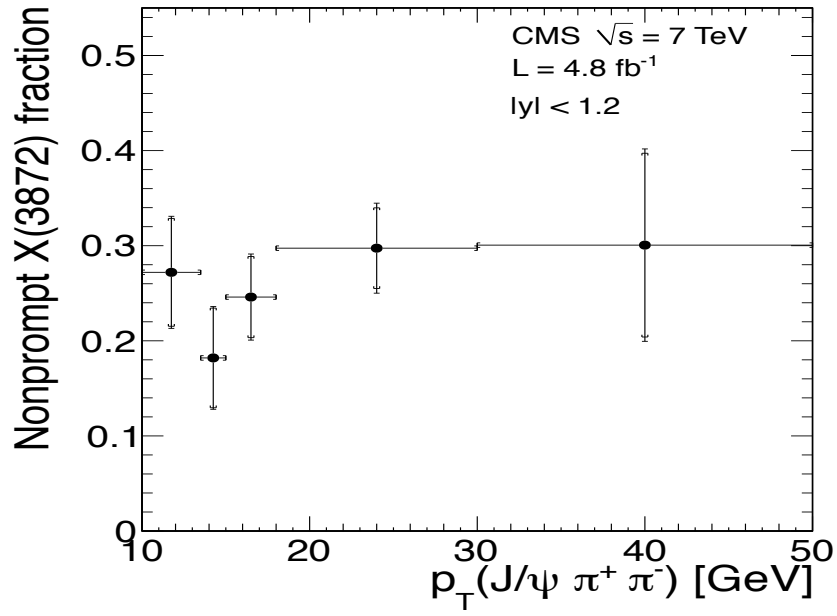
X(3872) production cross section

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

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

  - *Non-prompt events (l_{xy} > 100 μm)*
  - *Contribution from prompt X(3872) <0.1%*
  - *Cross-checked by a 2D fit to the mass vs l_{xy}*
  - *Measurement limited by statistics*



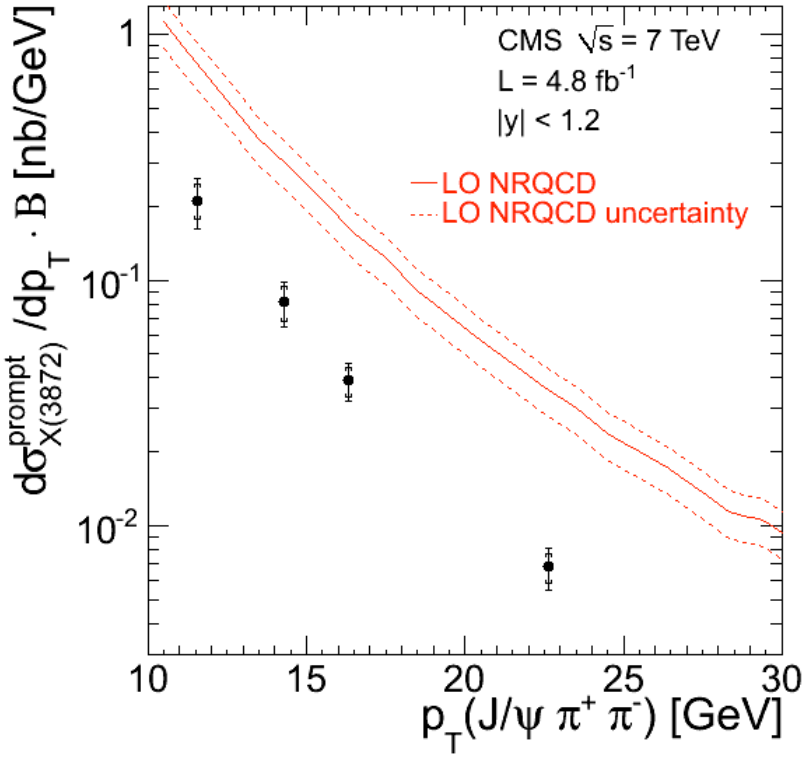


X(3872) production cross section

– Prompt Xsection

- *compared to NRQCD theoretical prediction*

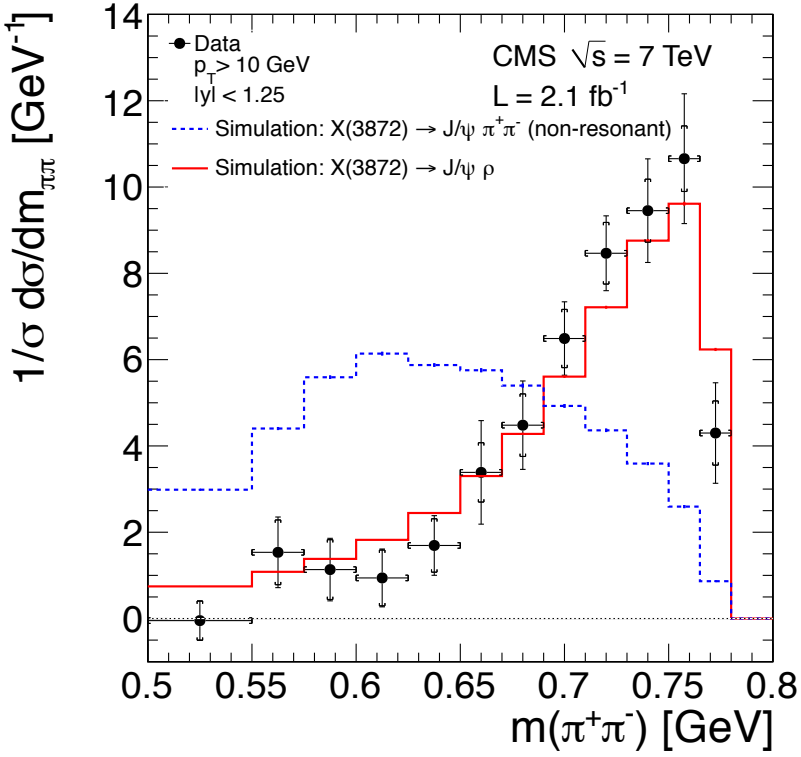
JHEP 02 (2012) 011 *Phys Rev D81 114018*



– *NRQCD predictions significantly exceed the measured value, while p_T dependence is reasonably well described*

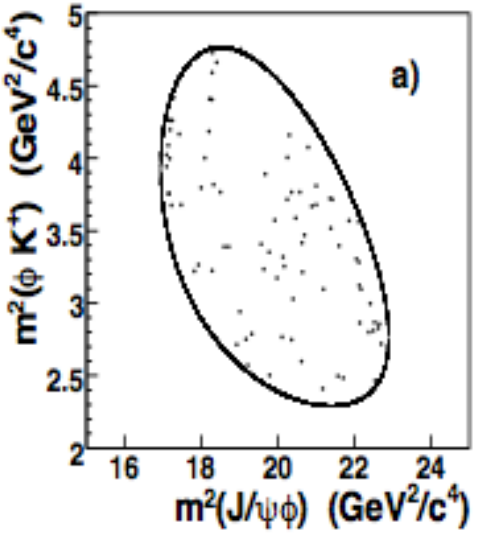
Dipion invariant mass

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

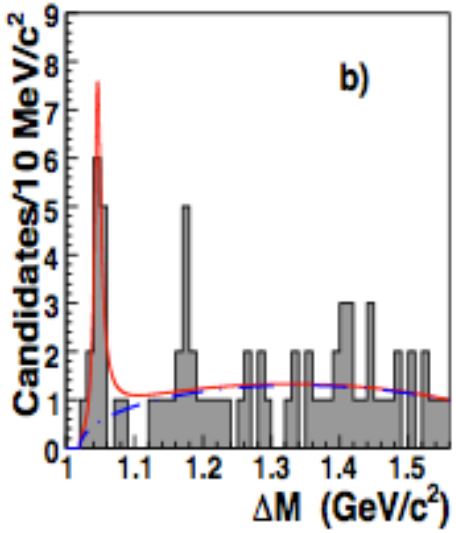


- *The intermediate ρ^0 decay gives better agreement with data*

Structures in J/ψφ Spectrum (CDF 09)



Dalitz plot



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

2.7 fb^{-1}

PRL 102:242002, 2009

Purity ~80% in B$^+$ region

Nice φ shape

Near threshold peak, called Y(4140)

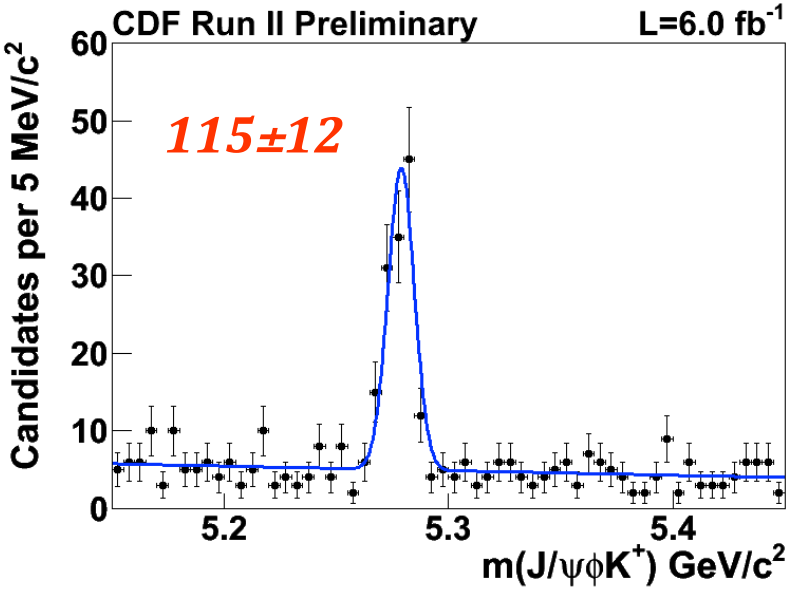
Significance: ~4σ, Yield =14±5

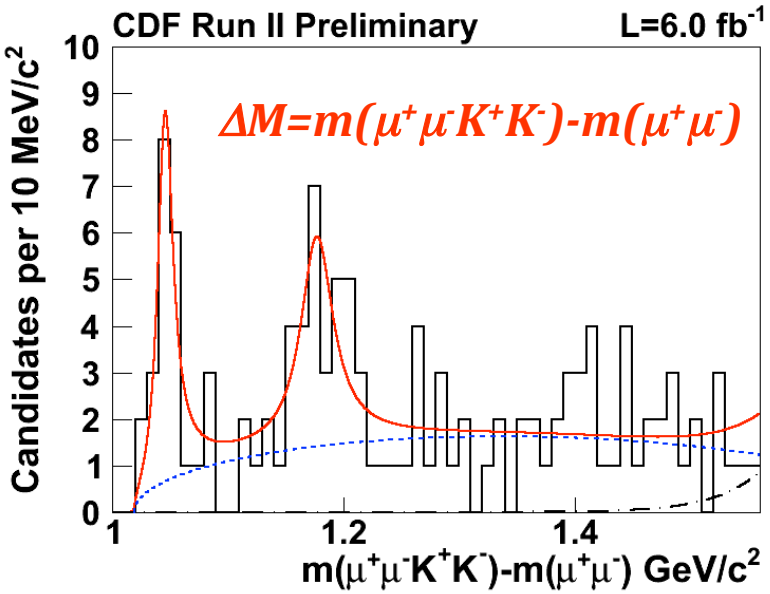
M= 4143.0 ± 2.9 (stat)± 1.2 (syst) MeV

Γ = 11.7 $^{+8.3}_{-5.0}$ (stat) ± 3.7(syst) MeV

Not likely to be charmonium: high mass w/ narrow width

Structures in J/ψφ Spectrum (CDF 10)





arXiv:1101.6058 [hep-ex]

Yield$_1$ =19±6; >5σ *Yield$_2$ =22±8; 3.1σ*

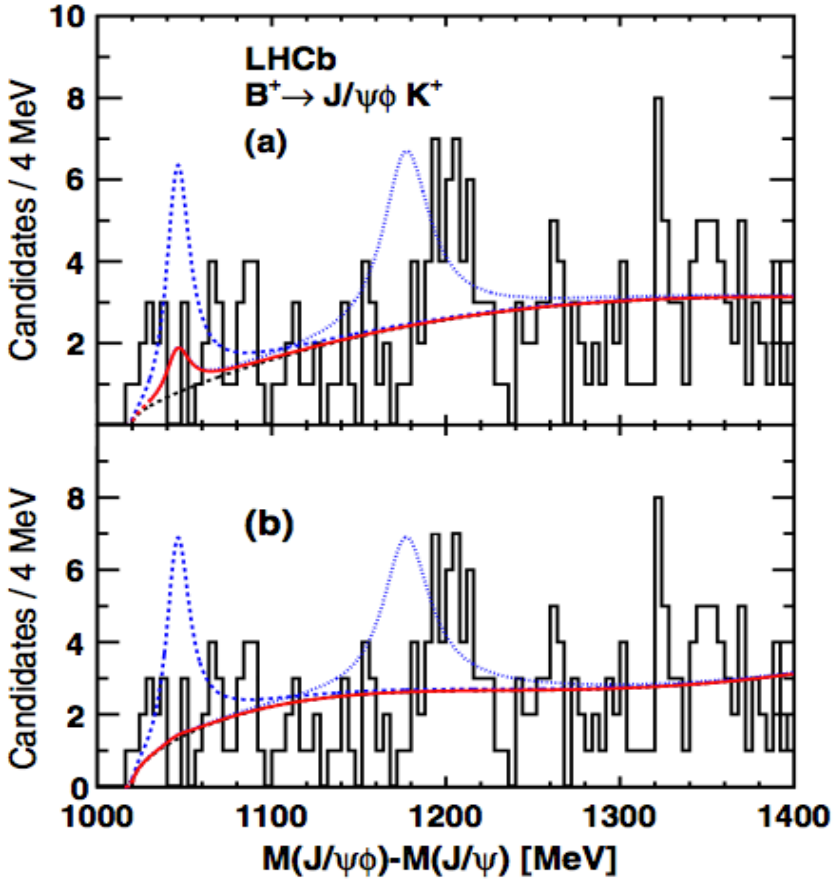
M_1= $4143.4^{+2.9}_{-3.0}$ (stat)± 0.6 (syst) MeV *M_2= $4277.4^{+8.4}_{-6.7}$ (stat)± 1.9 (syst) MeV*

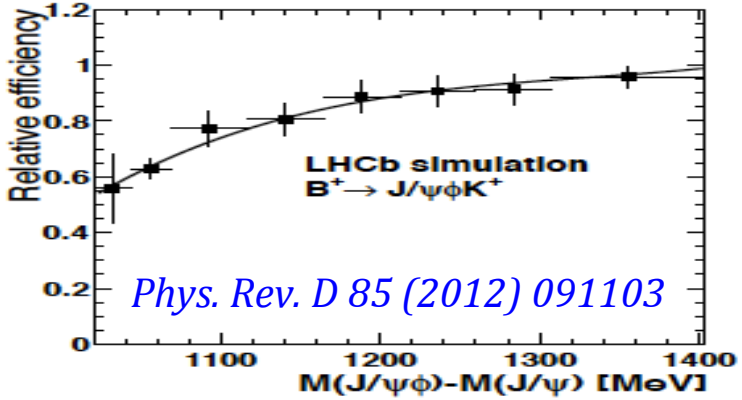
Γ_1 = $15.3^{+10.4}_{-6.1}$ (stat) ± 2.5(syst) MeV *Γ_2= $32.3.7^{+21.9}_{-15.3}$ (stat) ± 7.6(syst) MeV*

χ^2/dof between old and new Δm is 7.2/3, p-value=6.5% w/ four regions

$$\frac{\mathcal{B}(B^+ \to Y(4140)K^+, Y(4140) \to J/\psi\phi)}{\mathcal{B}(B^+ \to J/\psi\phi K^+)} = 0.149 \pm 0.039(\text{stat}) \pm 0.034(\text{syst})$$

LHCb: does not confirm





Phys. Rev. D 85 (2012) 091103

LHC_b confirms neither structure(s)

2.4σ disagreement with CDF measurement @90% CL:

$$\frac{\mathcal{B}(B^+ \to X(4140)K^+) \times \mathcal{B}(X(4140) \to J/\psi\phi)}{\mathcal{B}(B^+ \to J/\psi\phi K^+)} < 0.07.$$

$$\frac{\mathcal{B}(B^+ \to X(4274)K^+) \times \mathcal{B}(X(4274) \to J/\psi\phi)}{\mathcal{B}(B^+ \to J/\psi\phi K^+)} < 0.08$$

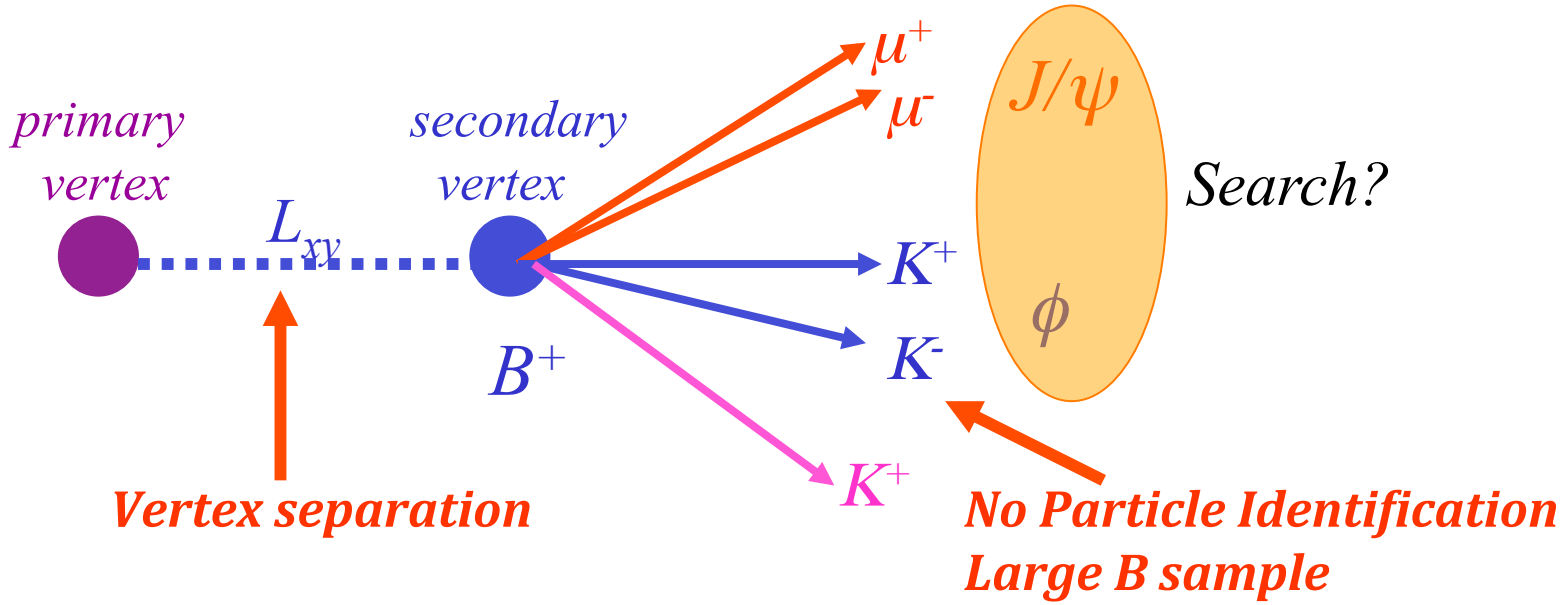
Need an independent result, CMS?

J/Ψϕ analysis strategy (CMS 2012)

- *I) Reconstruct B^+ as:*

$$B^+ \rightarrow J/\psi\phi\, K^+$$
$$J/\psi \rightarrow \mu^+\mu^-$$
$$\phi \rightarrow K^+K^-$$

- *II) Search for structure in J/ψϕ mass spectrum inside B^+ mass window*



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

CMS: BPH-11-026

Event Selections (CMS 2012)

--$|\eta|$ for all tracks <=2.4

--probability(χ^2) for J/ψ vertex fit>10%, probability(χ^2) for B^+ vertex fit>1%

--p_T(kaon track)>1 GeV

--J/ψ vertex flight length significance >=3

&

Dataset A: $p_T(J/\psi)$>7 GeV [first part of the run w/ low lumi, pileup]

Dataset B: $p_T(J/\psi)$>7 GeV & both muon p_T>4 GeV

[second part of the run w/ high lumi, pileup]

--mass window:

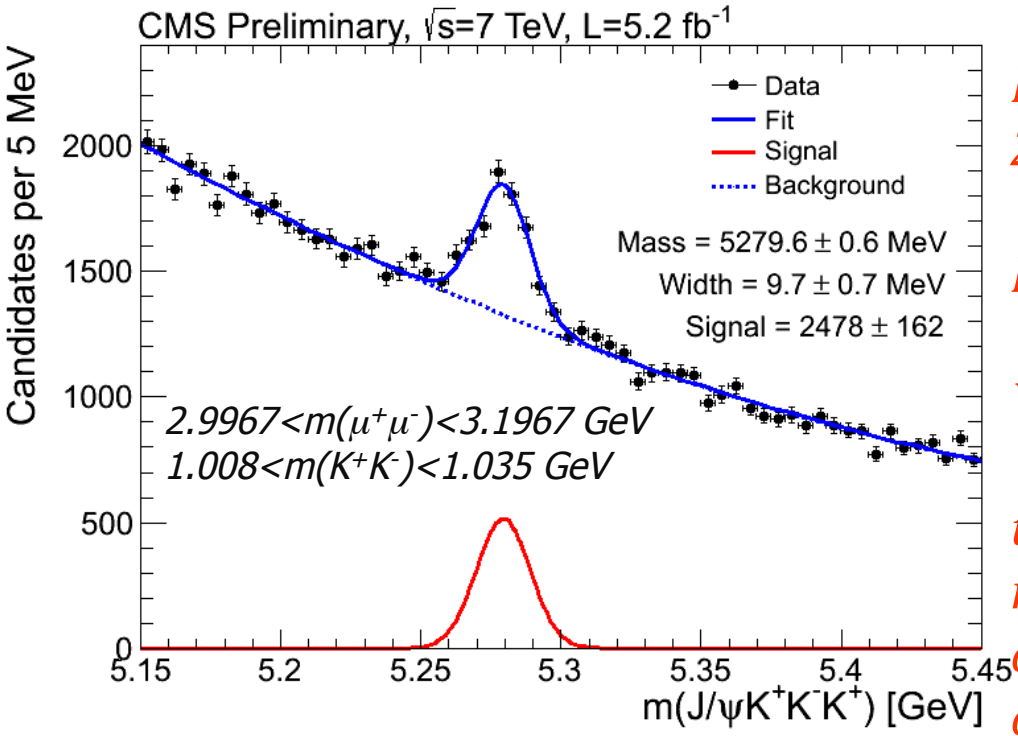
J/ψ (±150 MeV) and ϕ in [1.008, 1.035] GeV (Breit-Wigner shape)

constrain $\mu^+\mu^-$ to J/ψ PDG mass value

Requirements are designed to maximum B yield, confirm trigger requirements

The B Signal (CMS 2012)

$B^+ \rightarrow J/\psi\phi\, K^+$ decay



Signal PDF: Gaussian

Background PDF: 2nd-order Chebyshev polynomial

Mass: consistent with PDG value

Width: consistent with simulation

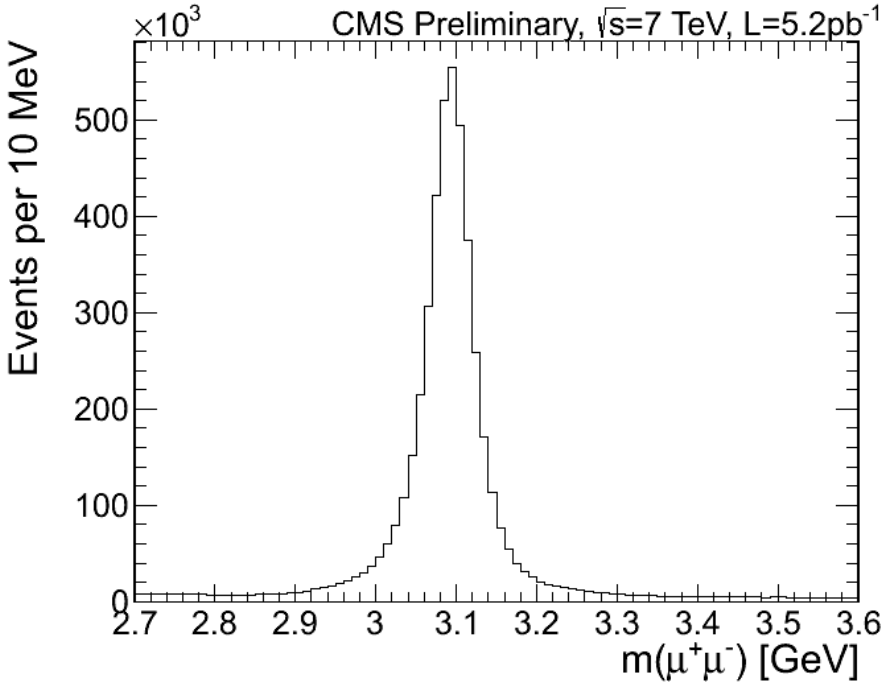
two (K^+K^-) combinations, only keep $m(K^+K^-)_{min}$ as ϕ candidate, negligible contribution from another combination based on MC

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

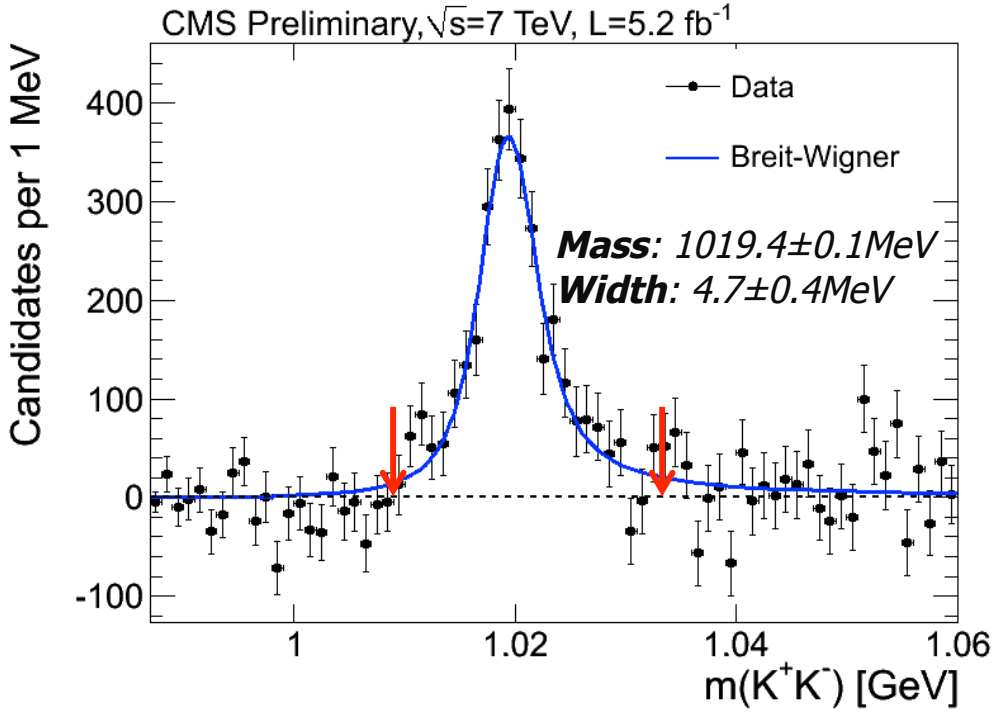
~20 times CDF statistics (115±12); ~7.2X LHCb statistics (346±20)

J/Ψ and ϕ Signal (CMS 2012)

$m(\mu^+\mu^-)$ before forming the B signal



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



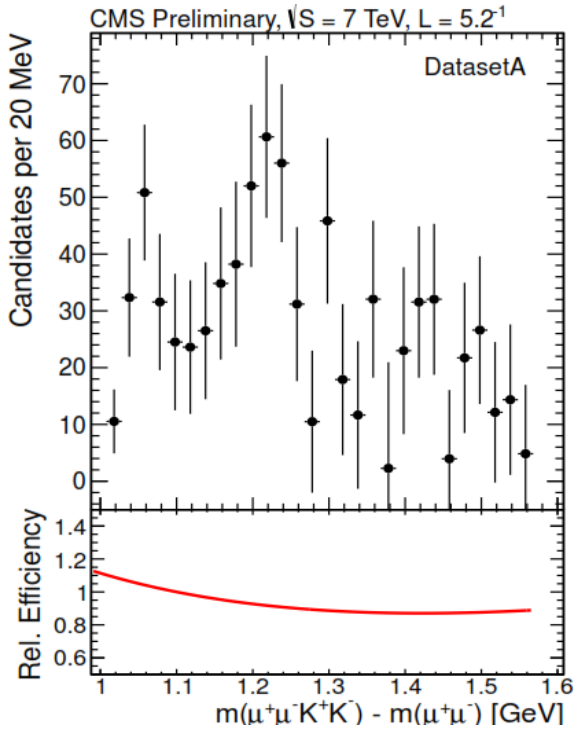
- *A clear and clean J/Ψ signal*
- *Nice ϕ lineshape, consistent with PDG parameters*
- *$B(J/\Psi\phi K^+)$ dominates after ϕ mass restriction*

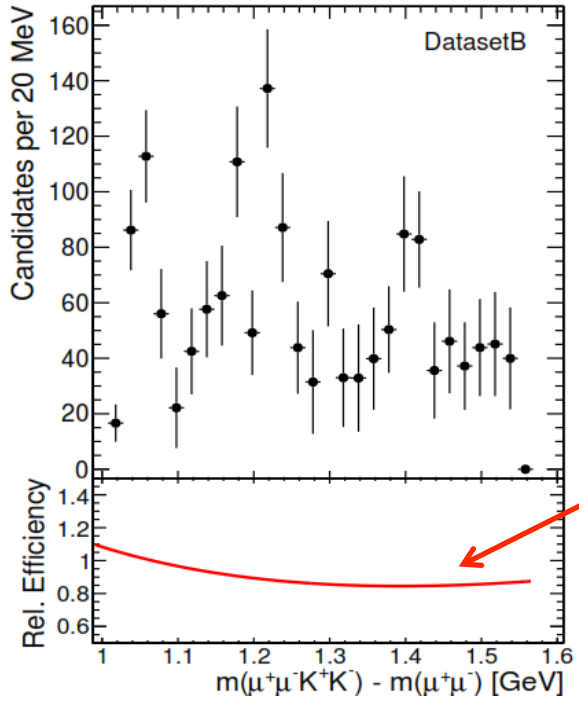
$J/\psi\phi$ Invariant Mass Spectrum(CMS 2012)

- The mass difference $\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$ is used

- Extracting the Δm spectrum
  - Divide the dataset into 20 MeV Δm bins
  - Extract the number of B events for each Δm by fitting the $J/\psi\phi K$ spectrum
    - Means fixed to the PDG B mass
    - RMS fixed to the signal MC values
  - Plot the B yield as a function of Δm

$p_T(J/\psi)>7GeV$ $p_T(J/\psi)>7GeV$ & $p_T(\mu)>4GeV$



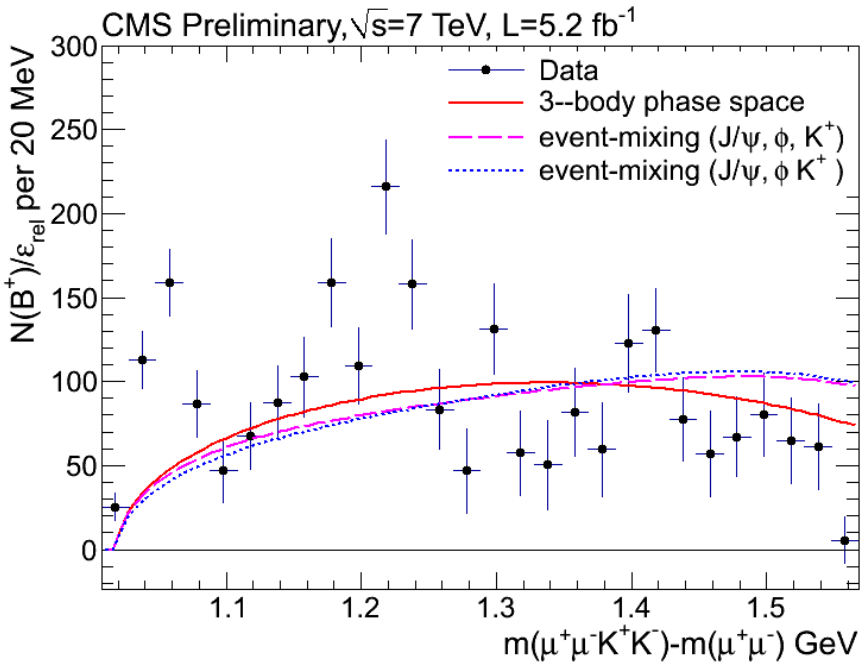


We cut-off $\Delta m>1.568$ GeV
Region to avoid background
From $B_s \rightarrow \psi'\phi$, $\psi' \rightarrow J/\psi\pi\pi$

correct the spectrum
by efficiency before fitting

Relative efficiency over Δm :
approx. flat

Background Shape Studies(CMS 2012)



Event mixing to study the Δm shape

--J/Ψ, ϕ, K⁺ from different event

--ϕ, K⁺ from the same event, J/Ψ from different event. This is to get the impact on Δm from possible ϕK⁺ resonances

Require the J/ΨϕK⁺ mass around B mass

Event-mixing Δm shapes are slightly distorted compared to three-body phase space

However, *the possible effect is on high Δm region and the three-body phase space shape is more conservative at low Δm region where the two structures are observed.*

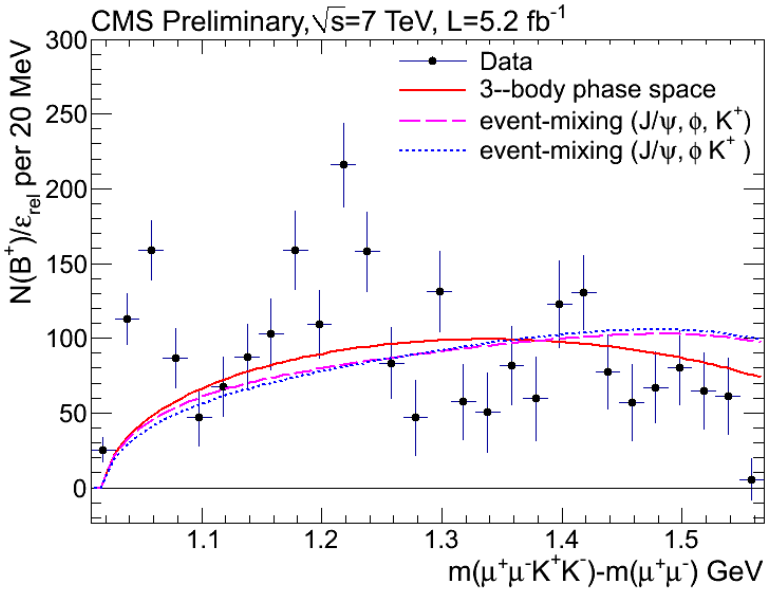
Null- and Signal-hypothesis Fits

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

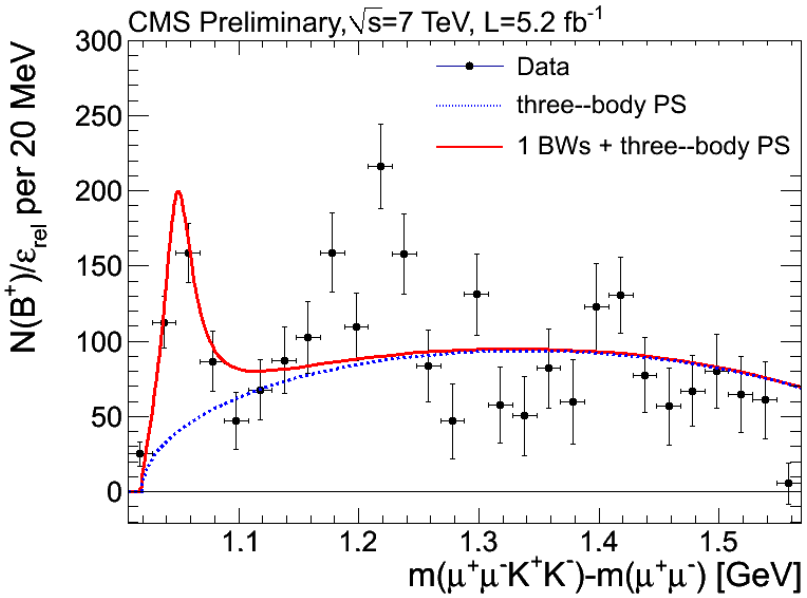
Background: 3-body phase space
Signal: S-wave relativistic Breit-Wigner functions convolved with a Gaussian resolution function

Significance: >5σ for 1st peak
evidence for 2nd peak

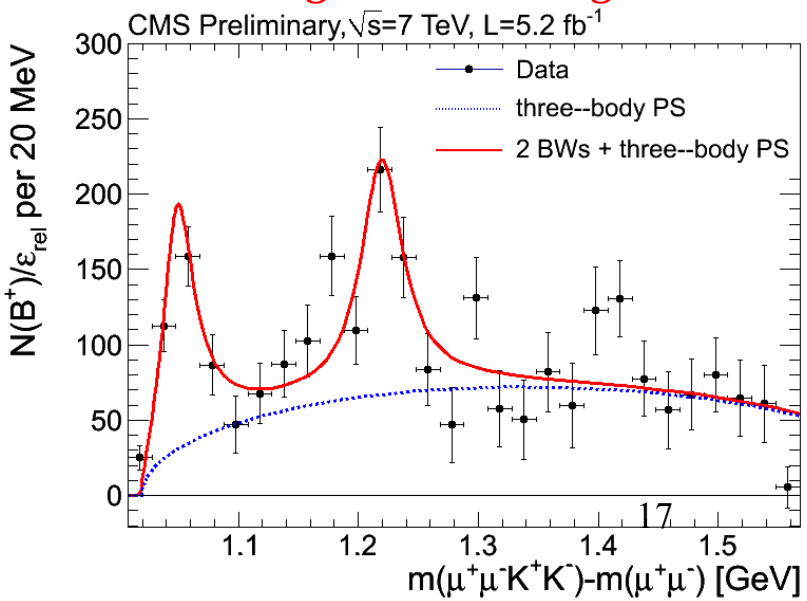
background only hypothesis



background + 1 signal

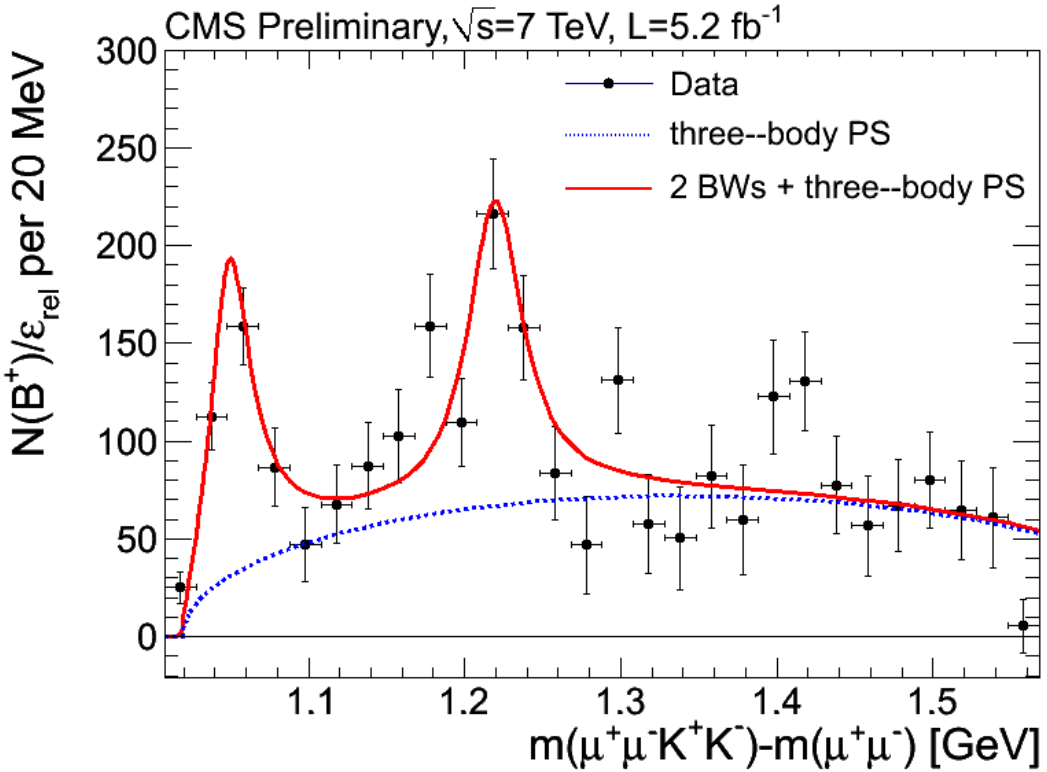


background + 2 signal



CMS Results on $J/\psi\phi$ Structures

- *The efficiency-corrected* $\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$



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

m_1= 4148.2±2.0(stat.)±4.6 (syst.) MeV
m_2= 4316.7±3.0(stat.)±7.3 (syst.) MeV

- *CMS observed a* $J/\psi\phi$ *structure at 4148MeV with a significance greater than* 5σ *consistent with CDF results on Y(4140)*

- *CMS finds evidence for a second structure at ~4317MeV*

Summary

- *Excellent LHC and CMS performances, able to do important studies on exotic charmonium with data @ 7 TeV collision*

- *CMS provides production measurement of X(3872)*

- *CMS observes two structures in the $J/\psi\phi$ spectrum*
  --confirm the existence of the Y(4140)
  --find evidence for a second structure

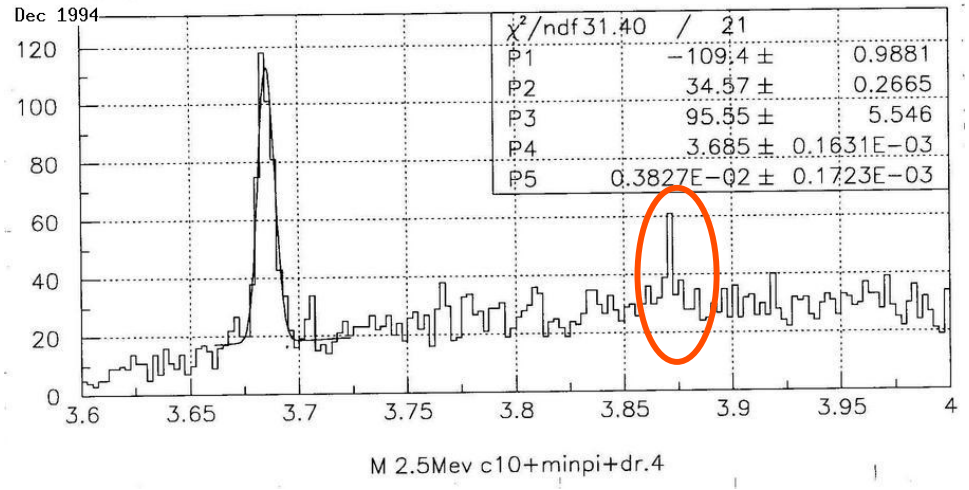
- *More to be expected with the large data sample from 2012*

Stay tuned!

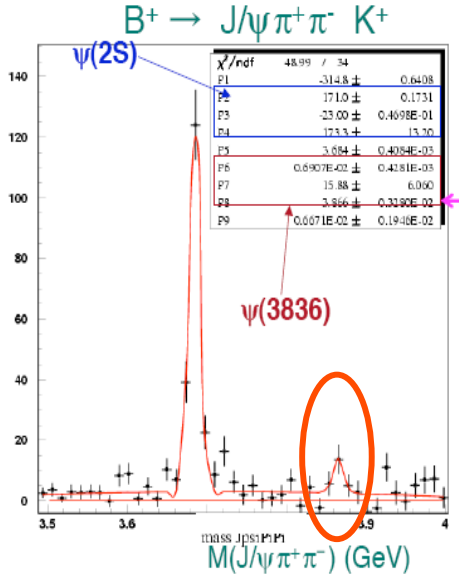
Backup

Hints before the discovery of X(3872)→J/ψπ⁺π⁻

CDF internal, 1994



BaBar internal, 2003

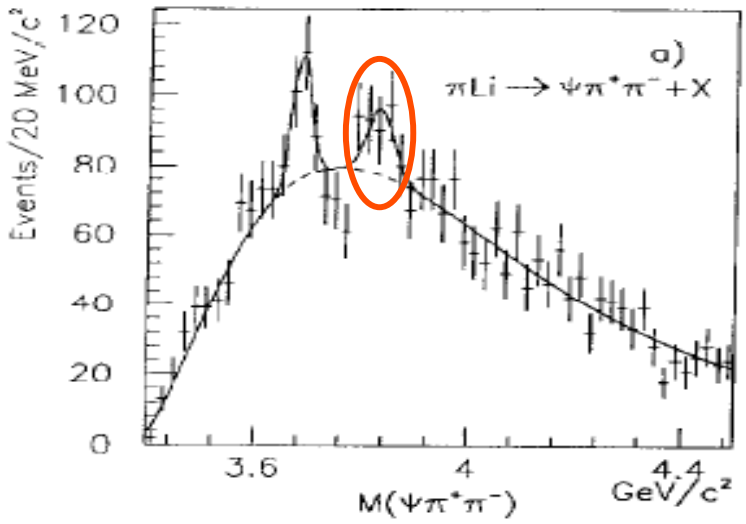


AWG meeting June 2003
motivation: background to $J/\psi K_L$; test factorization…

Mass = 3866 ± 6

E705, PRD 50, 4258 (1994)

E705 claimed ψ(3836) in 1994



CDF saw a hint in 1994*, unpublished*

BaBar saw a hint in 2003*, unpublished*

Both CDF and Babar spotted hints of X(3872) before its discovery!

From BaBar B-Factory Symposium (C. Hearty)

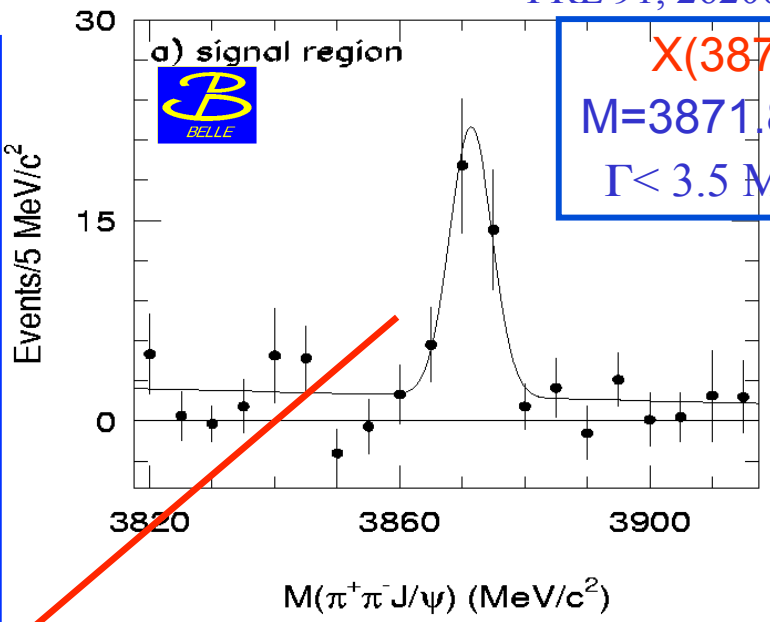
http://www-conf.slac.stanford.edu/b-factory-symposium/talks.asp

X(3872)--2003

$N^{2S+1}L_J$	J^{PC}	$u\bar{d}, u\bar{u}, d\bar{d}$ $I=1$	$u\bar{u}, d\bar{d}, s\bar{s}$ $I=0$	$c\bar{c}$ $I=0$
1^1S_0	0^{-+}	π	η, η'	$\eta_c(1S)$
1^3S_1	1^{--}	ρ	ω, ϕ	$J/\psi(1S)$
1^1P_1	1^{+-}	$b_1(1235)$	$h_1(1170), h_1(1380)$	$h_c(1P)$
1^3P_0	0^{++}	$a_0(1450)^*$	$f_0(1370)^*, f_0(1710)^*$	$\chi_{c0}(1P)$
1^3P_1	1^{++}	$a_1(1260)$	$f_1(1285), f_1(1420)$	$\chi_{c1}(1P)$
1^3P_2	2^{++}	$a_2(1320)$	$f_2(1270), f_2'(1525)$	$\chi_{c2}(1P)$
1^1D_2	2^{-+}	$\pi_2(1670)$	$\eta_2(1645), \eta_2(1870)$	
1^3D_1	1^{--}	$\rho(1700)$	$\omega(1650)$	$\psi(3770)$
1^3D_2	2^{--}			??
1^3D_3	3^{--}	$\rho_3(1690)$	$\omega_3(1670), \phi_3(1850)$	
1^3F_4	4^{++}	$a_4(2040)$	$f_4(2050), f_4(2220)$	
2^1S_0	0^{-+}	$\pi(1300)$	$\eta(1295), \eta(1440)$	$\eta_c(2S)$
2^3S_1	1^{--}	$\rho(1450)$	$\omega(1420), \phi(1680)$	$\psi(2S)$
2^3P_2	2^{++}	$a_2(1700)$	$f_2(1950), f_2(2010)$	
3^1S_0	0^{-+}	$\pi(1800)$	$\eta(1760)$	

$C\bar{C}$

PRL 91, 262001



X(3872)→J/ψπ⁺π⁻
M=3871.8±0.7±0.4 MeV
Γ< 3.5 MeV @ 90% CL

(Problematic) features

mass ~70 MeV > 1^3D_2 charmonium

$M(\pi^+\pi^-)$ peaks as a ρ, C=+, isospin=1 (charmonium--0)

Mass close to DD, molecule is speculated*

What is it?

mixture of a DD molecule and the 2^3P_1 charmonium?*

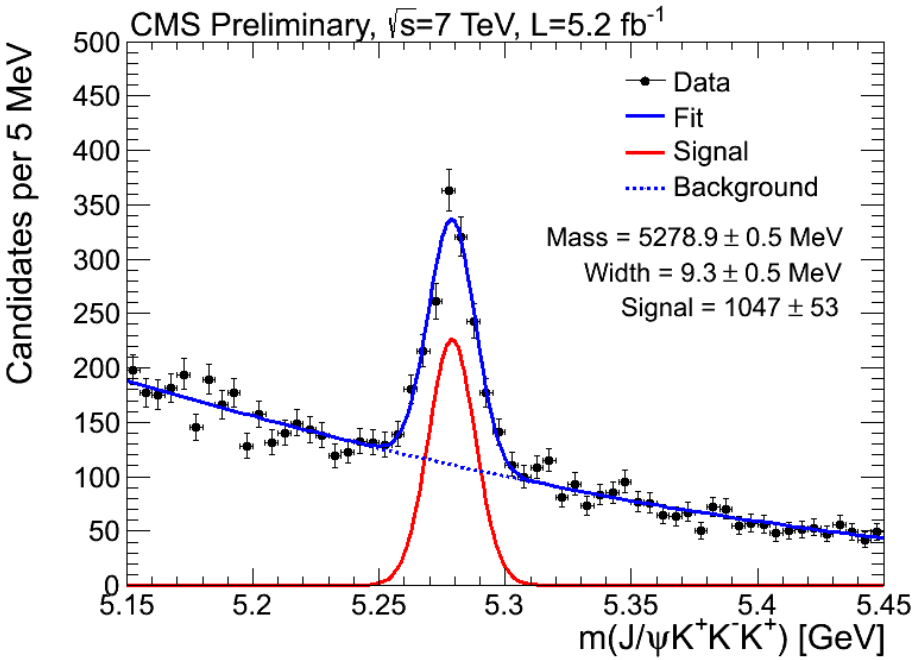
CMS joins the effort to understand the nature of the still mysterious X(3872)

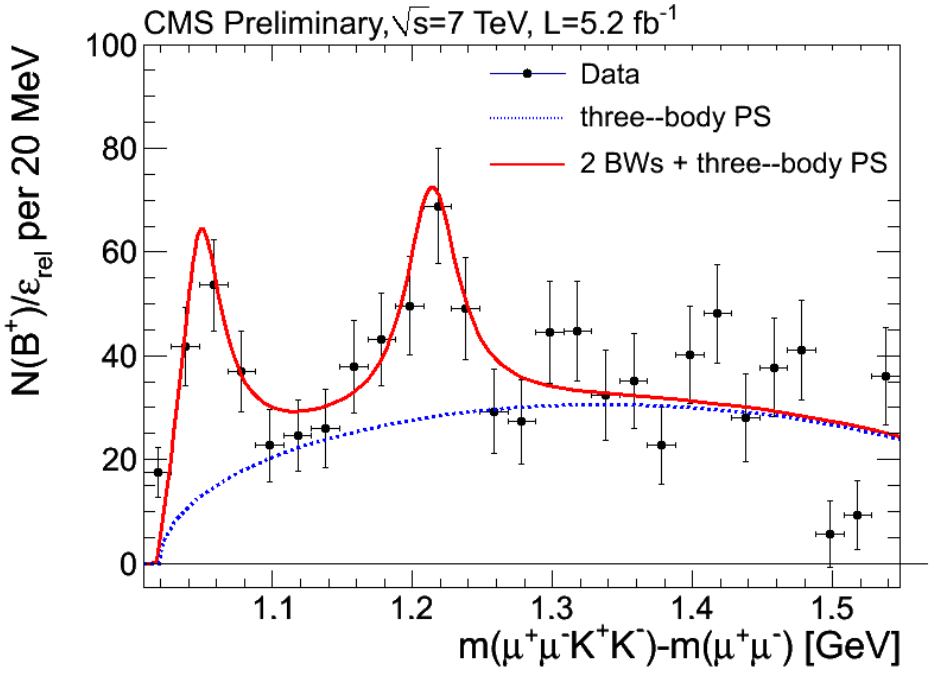
Robust Checks

- *All main requirements are varied step by step to investigate possible bias*
- *Each sideband-subtracted Δm distribution is compared to the default one*
- *No indication of bias was found*

  one example with tighter cuts and purer B sample is shown below:

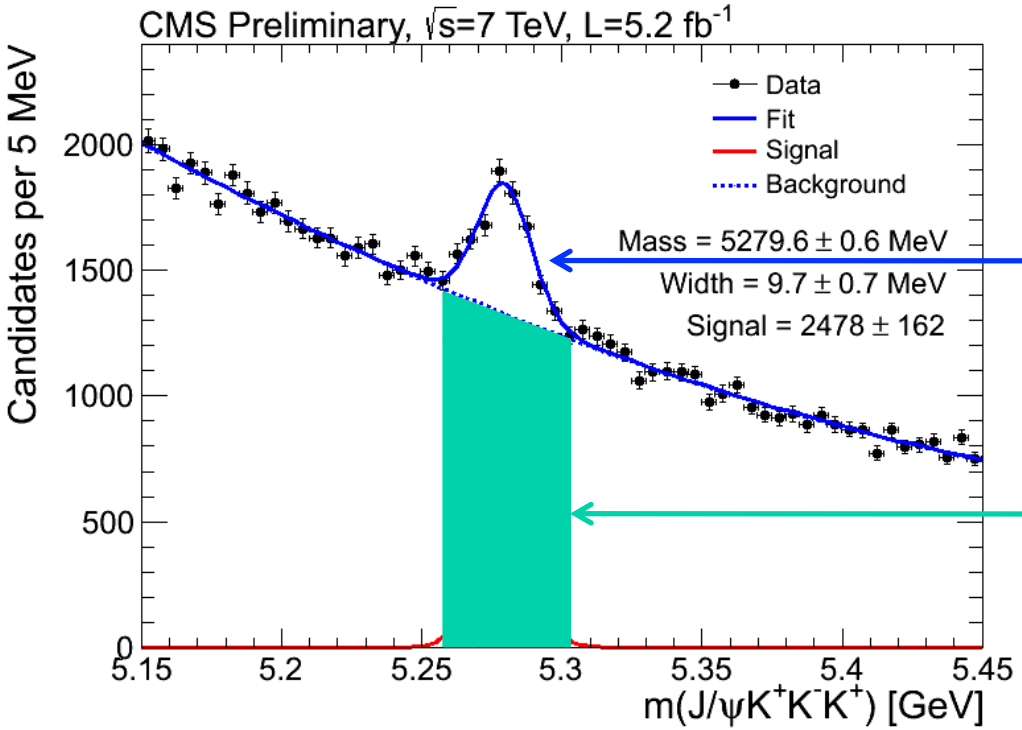
  keep ~40% B signal, reduce background by a factor of 12!





- *B purity ~60% within ±1.5σ of m(B⁺)*
- *similar Δm spectrum*

Various Components (CMS 2012)



Two big components:

$B^+ \rightarrow J/\Psi\phi K^+$

Random combinatory background (need to be subtracted, next slide)

Possible components for $B^+ \rightarrow J/\Psi\phi K^+$ *final state (ignoring interference):*

1. *Phase space events: 3-body decay:* $B^+ \rightarrow$ $J/\Psi\phi K^+$
2. *Possible structures in m(*$J/\Psi\phi$*):* $B^+ \rightarrow XK^+,\ X \rightarrow J/\Psi\phi \rightarrow J/\Psi\phi K^+$
3. *Possible structures in m(*$J/\Psi K^+$*):* $B^+ \rightarrow X\phi,\ X \rightarrow J/\Psi K^+ \rightarrow J/\Psi\phi K^+$
4. *Possible structures in m(*ϕK^+*):* $B^+ \rightarrow XJ/\Psi,\ X \rightarrow \phi K^+ \rightarrow J/\Psi\phi K^+$

We need to sort out each component

Reflection in Three-body Decays

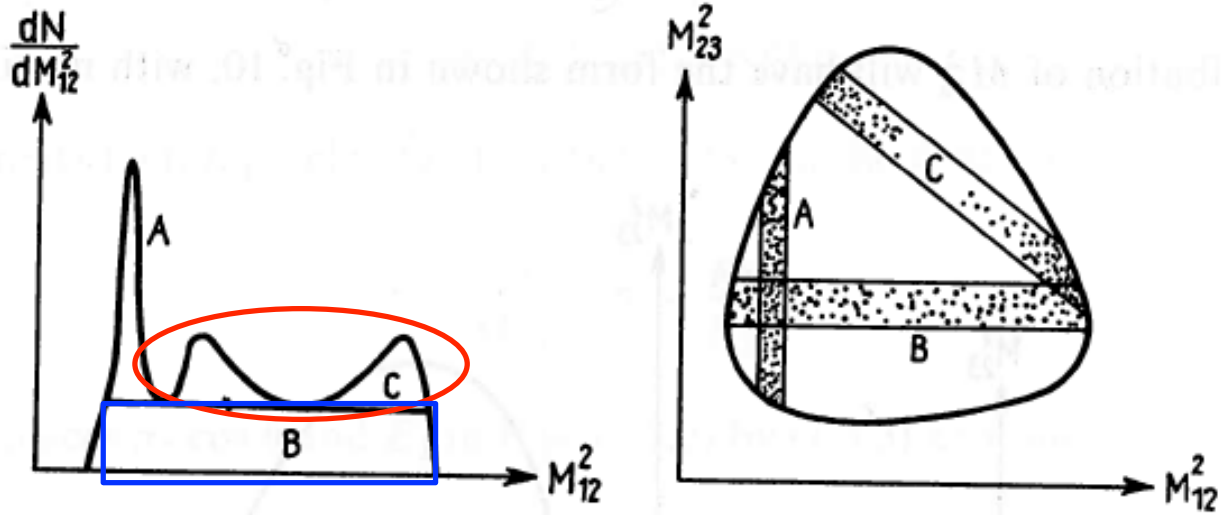


Fig. 11

Three resonances:
$A \rightarrow M_{12}$
$B \rightarrow M_{23}$
$C \rightarrow M_{13}$

Example: ρ^+, N^{*++}, N^{*+} *in*
$\pi^+ + p \rightarrow \pi^+ + \pi^0 + p$

Depending on J^{PC}, *B & C can be structure-less or structures in* M_{12}. *In this example, B shows flat distribution in* M_{12} *and C shows up two structures in* M_{12}.

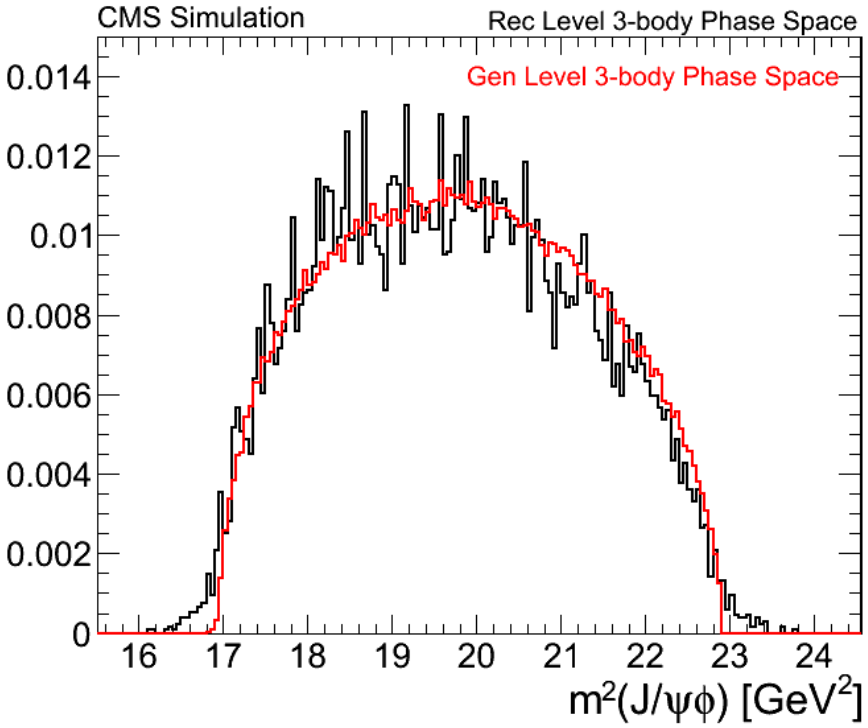
There are no established resonances in $m(\phi K^+)$ *(possible hint for* K_1 *&* K_2*) and* $m(J/\Psi K^+)$, *CDF was limited by statistics and state:*

"We find no evidence for any other structure in the φK^+ *and* $J/\psi K^+$ *spectrum; the only structure [i.e.* $K_2(1770)$*] that has been claimed in the* φK^+ *spectrum by previous experiments is too broad to alter our analysis"* *Re-visit later.*

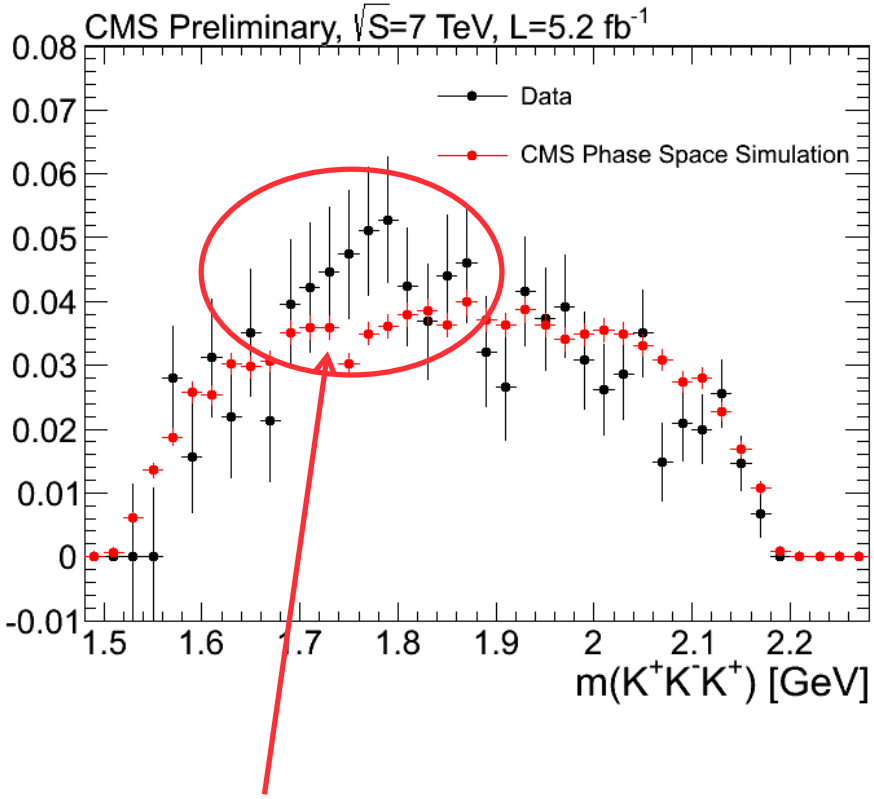
PRL 102:242002, 2009

Background Shape Studies (CMS 2012)

The phase space Dalitz projection on $m^2(J/\psi\phi)$
generated events (red)
Vs
reconstructed events (black)



Sideband subtracted KKK mass
Phase Space MC (red)
Vs
data (black)



CMS detector does not produce peaks
Also imply relative flat efficiency

Possible $K_2(1770)$, $K_2(1820)$?
Does it effect Δm?

ϕK^+ Resonances Studies (CMS 2012)

- *Generated simple Dalitz plot for (ϕK^+) resonances. No similar structures seen in m($J/\Psi\phi$) from reflections.*
- *No evidence of structures or deviation from phase space background shape found in m(ϕK^+) mass distribution after removing the two structures in m($J/\Psi\phi$) in the data*
- *No evidence for m($J/\Psi K^+$) so far*
- *Possible interference ? Could affect lineshape parameters, no big signal*
- *A full amplitude analysis is desirable, limited by statistics and high non-B combinatoric background*

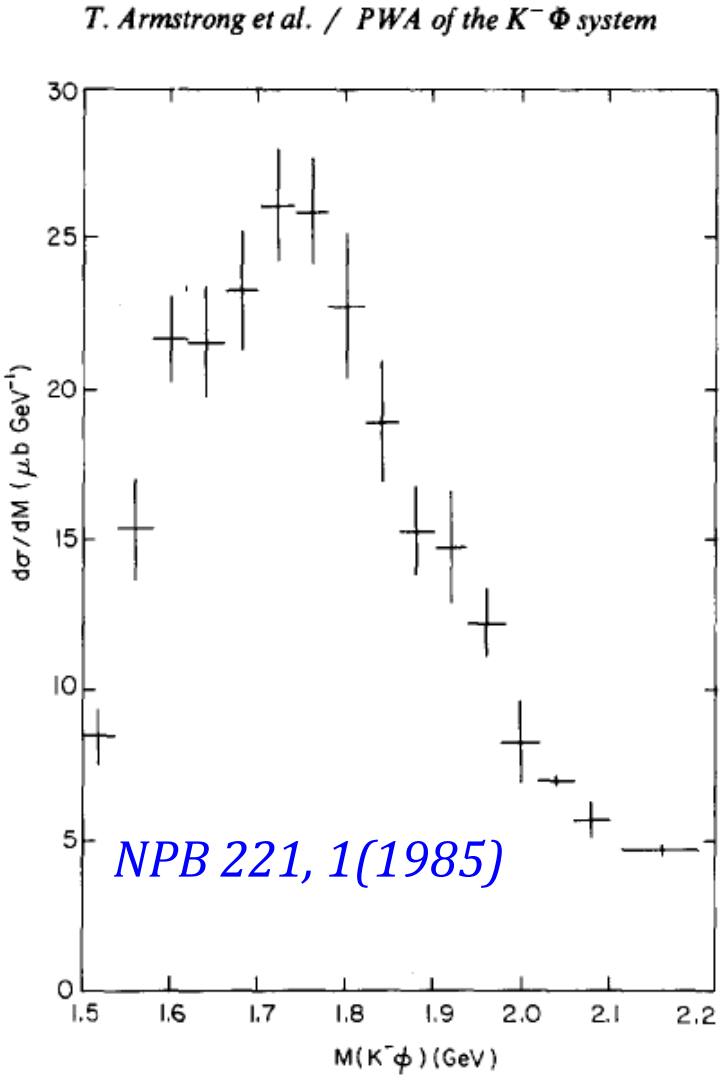
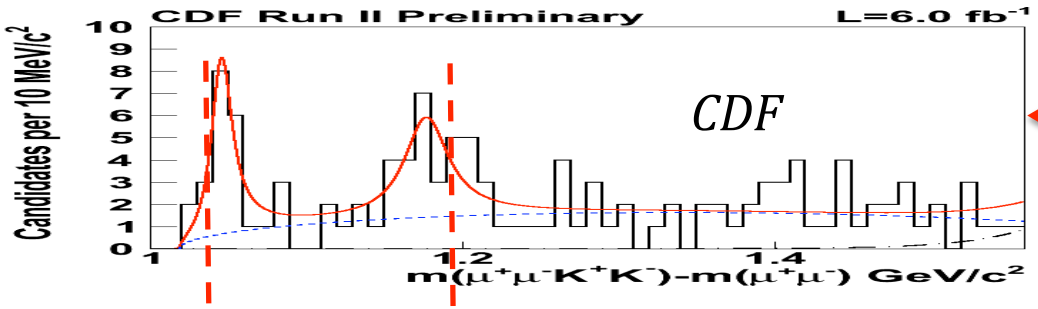
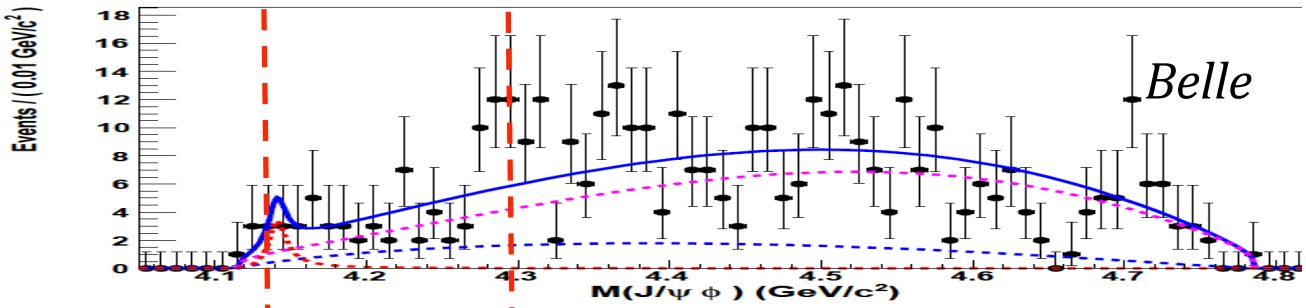


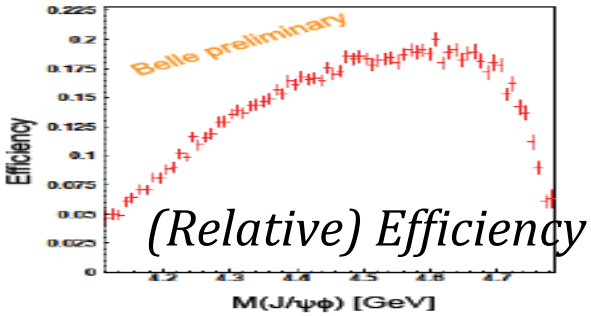
Fig. 7. Corrected $K^-\Phi$ mass spectrum for $t' < 0.8$ GeV^2.



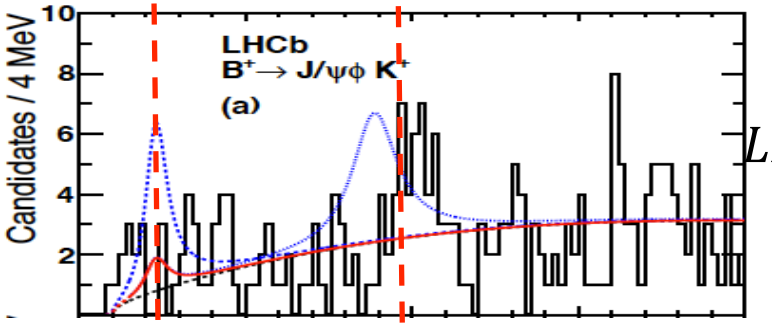
← *flat relative efficiency*

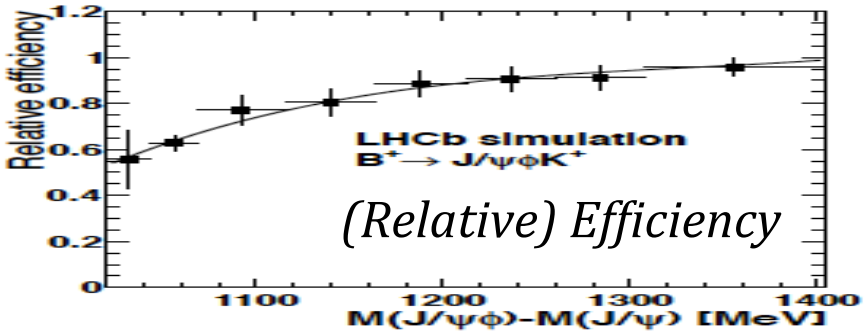


K. Miyabayashi, QWG 2010

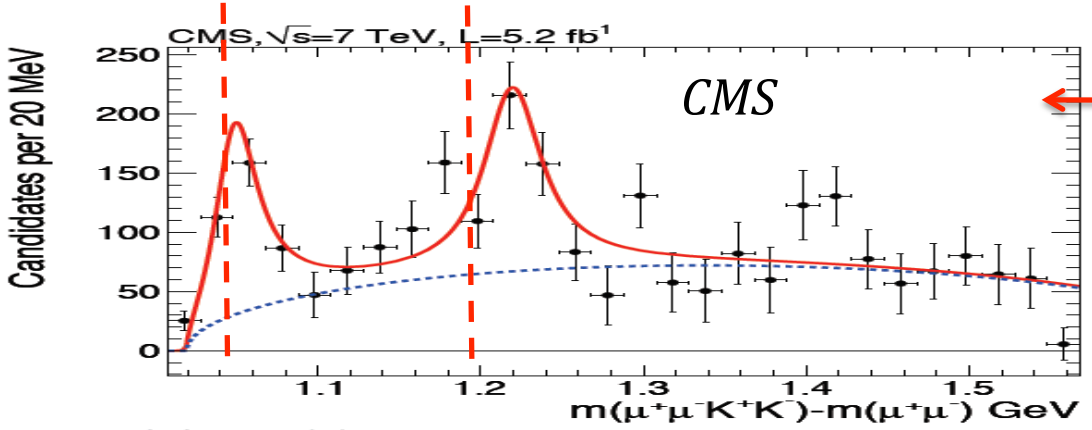


(Relative) Efficiency





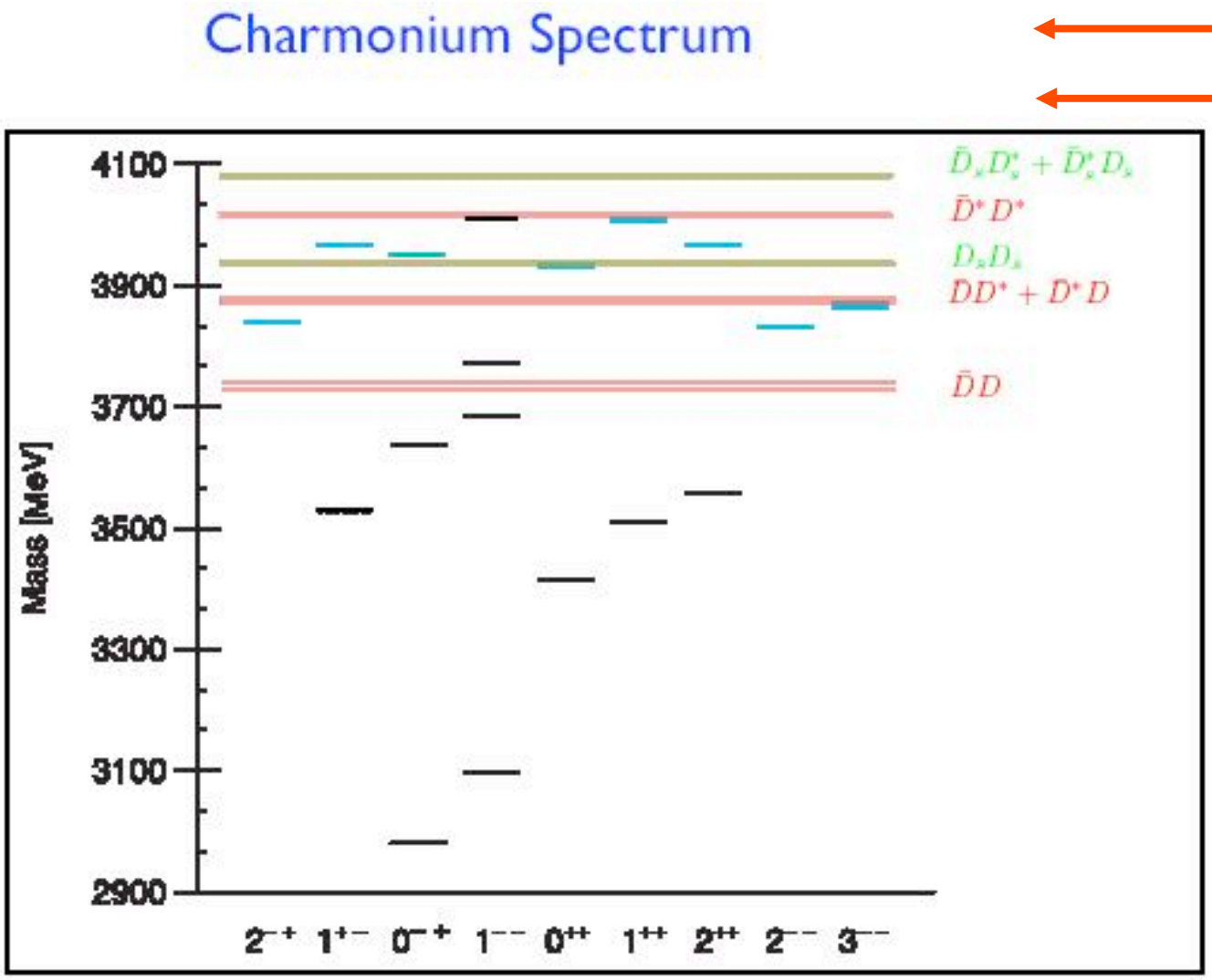
(Relative) Efficiency



← *relative efficiency corrected*

CDF/BELLE/LHCb are raw distributions w/o efficiency correction

What is it?



2^{nd} peak

Y(4140)

- *Well **above** charm pair threshold*
- *Expect **tiny** BF to $J/\psi\phi$*
- *Does **not** fit into charmonium*
- *Close $J/\psi\phi$ threshold like Y(3940)*
- *What is it? Molecule/ hybrid/threshold CUSP?*