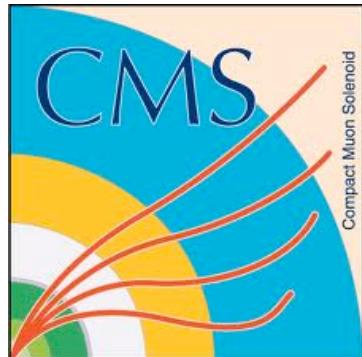


Results on the XYZ states from CMS and ATLAS



Kai Yi (University of Iowa)
for
CMS & ATLAS Collaborations

International Workshop on QCD Exotics
June 8-12, 2015, Shangdong University, Jinan, China

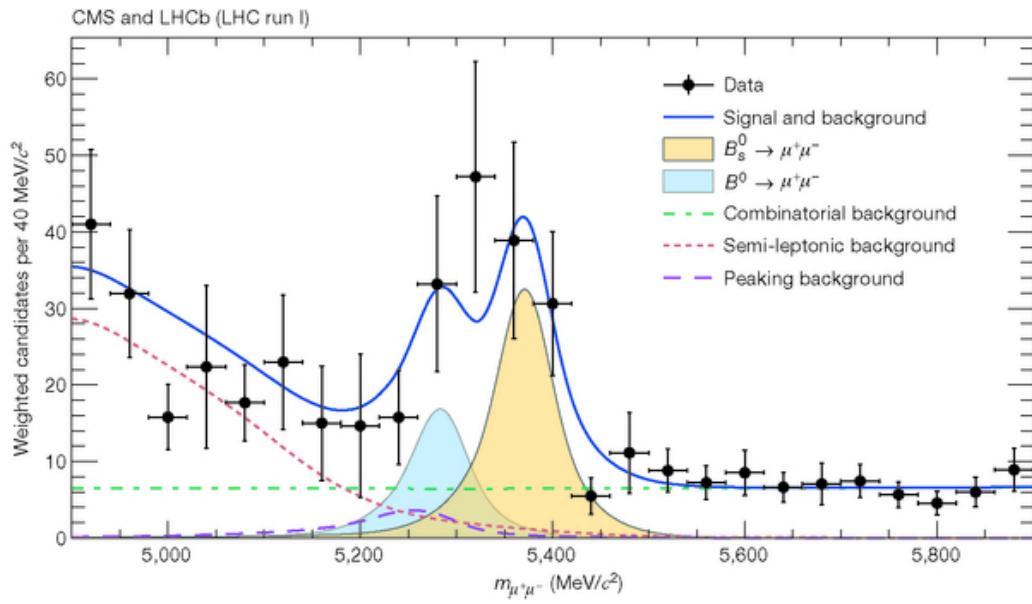
Outline

- General meson studies at LHC
 - search for BSM physics
 - study meson production, properties
 - study explore exotic meson (the topic covered today)
- ATLAS/CMS detectors & triggers
- Exotic meson background
- Exotic meson studies at ATLAS/CMS
- Near VV threshold puzzle?
- Prospect for Run II
- Summary

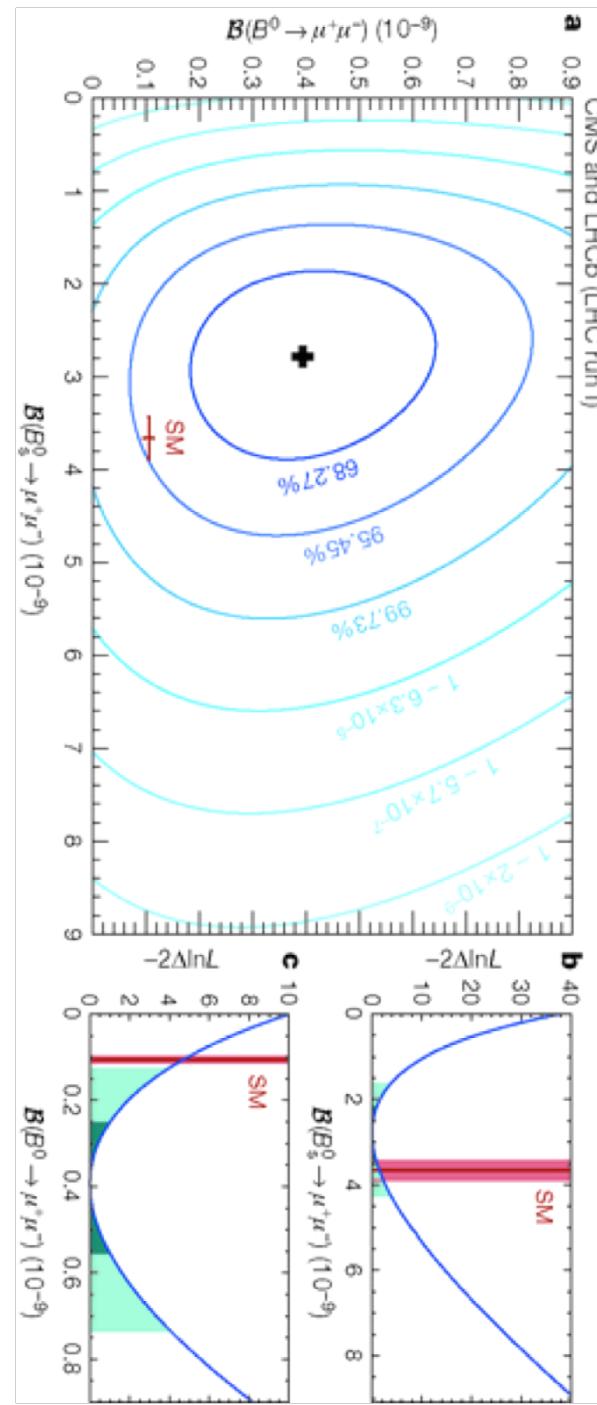
- *General meson studies @LHC*
 - *search for BSM physics*
 - *study meson production, properties*
 - *exotic meson exploration (topic for today)*

Observation of the rare $B_s^0 \rightarrow \mu^+ \mu^-$ decay from the combined analysis of CMS and LHCb data

CMS Collaboration & LHCb Collaboration

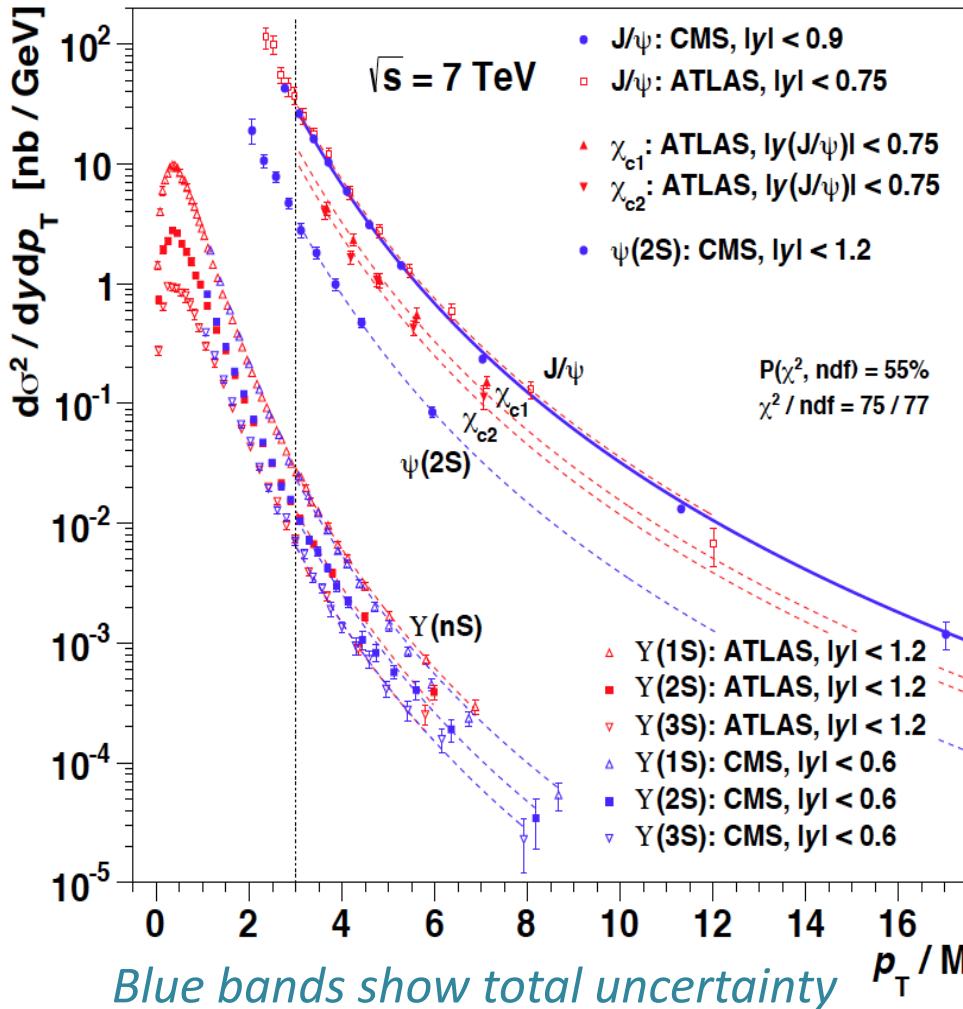


We search for BSM physics via rare decays



LHC data for quarkonium production

[arXiv:1403.3970 \(2014\)](https://arxiv.org/abs/1403.3970)



The double differential cross section as a function of p_T/m over the 7 states.

More accurate data up to high p_T and observables are needed to constraint free parameters and help to understand production rate and polarization

CMS:

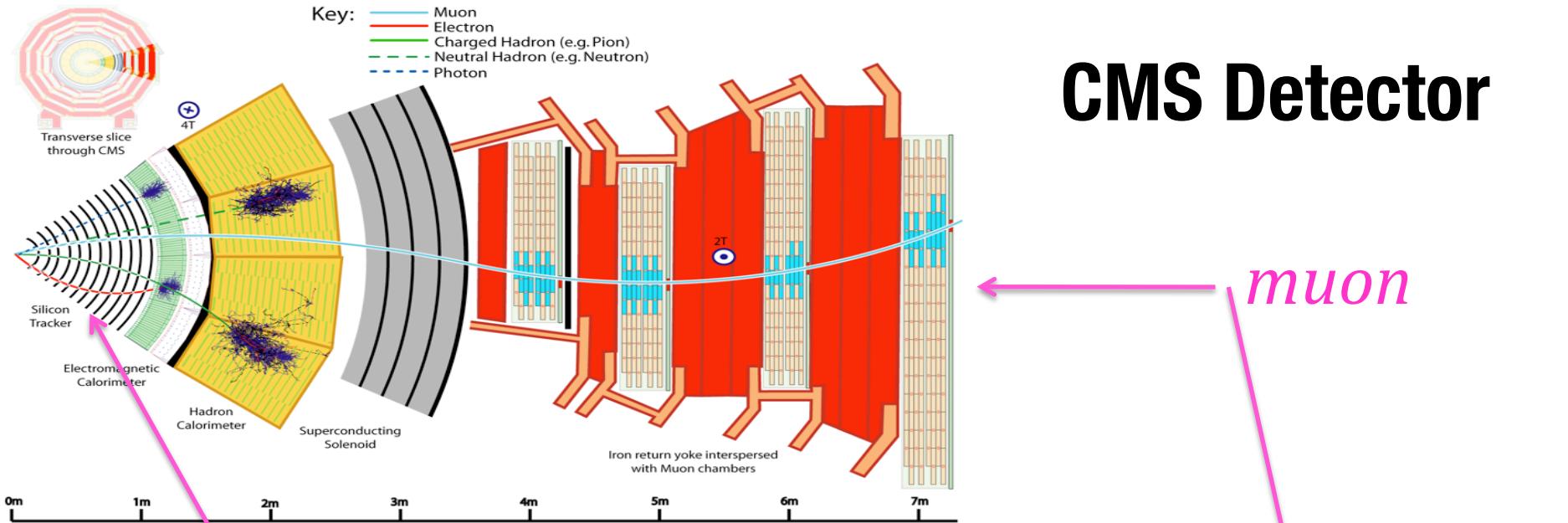
[Phys.Rev.Lett. 110 \(2013\) 8,](https://doi.org/10.1103/PhysRevLett.110.082001)
[JHEP 1202 \(2012\) 011](https://doi.org/10.1007/JHEP02(2012)011)
[arXiv:1501.07750 \[hep-ex\]](https://arxiv.org/abs/1501.07750)

ATLAS:

[Nucl.Phys. B850 \(2011\) 387-444](https://doi.org/10.1016/j.nuclphys.2011.06.025)
[Phys.Rev. D87 \(2013\) 5](https://doi.org/10.1103/PhysRevD.87.032005)
[JHEP 1407 \(2014\) 154](https://doi.org/10.1007/JHEP07(2014)154)

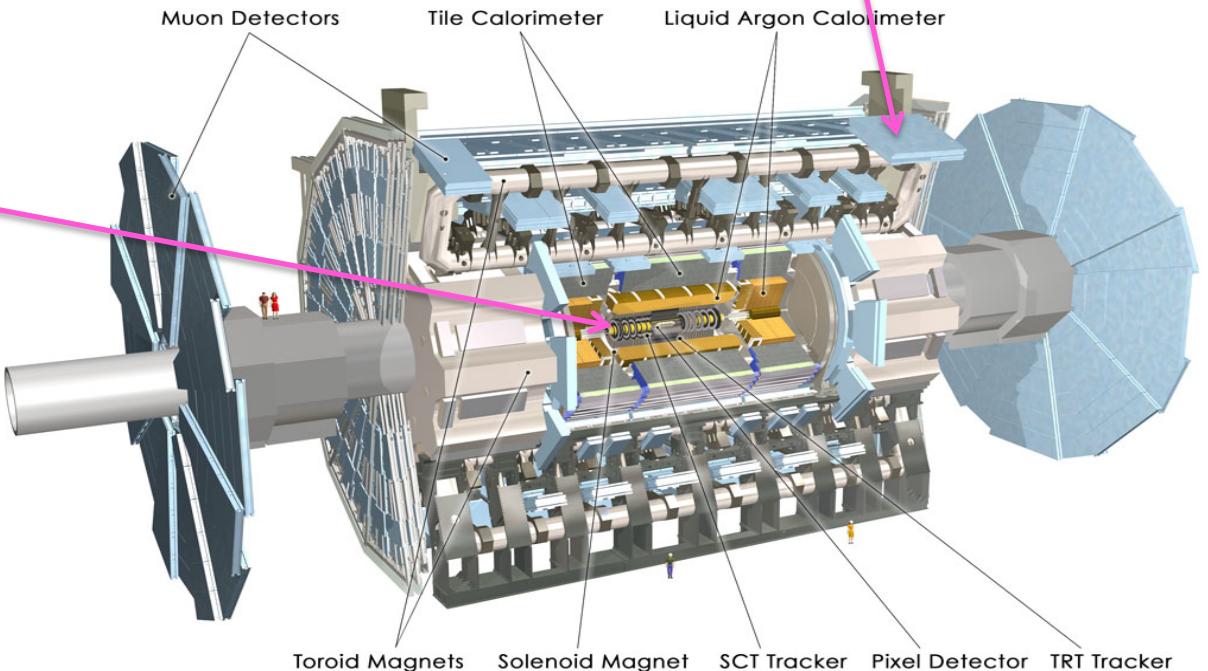
We study meson properties

Main topic today: Exotic meson at CMS & ATLAS



tracker

ATLAS Detector

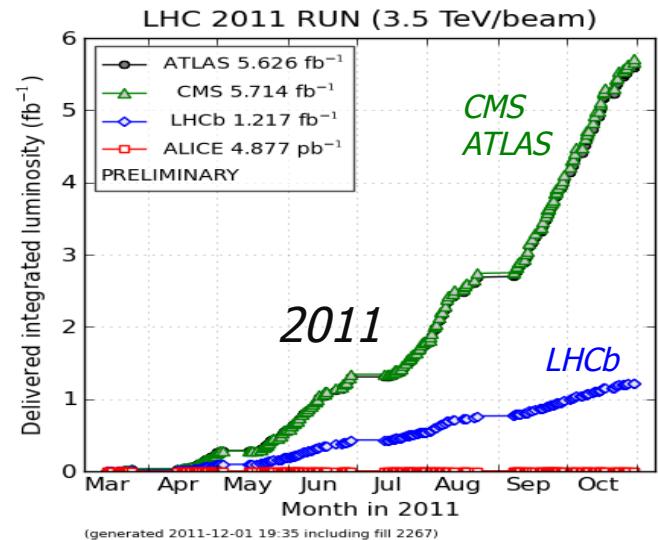


muon

CMS Detector Performance

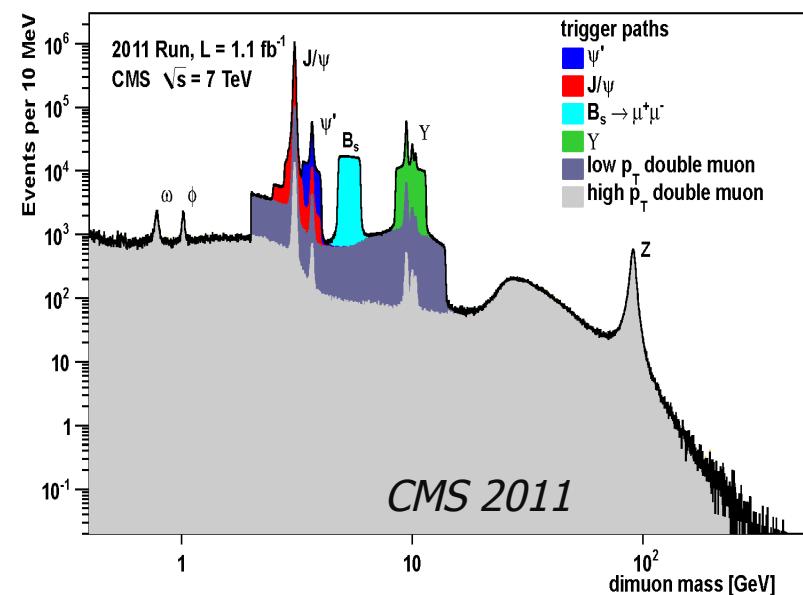
Excellent muon/silicon detectors for quarkonium:

- Muon system
 - High-purity muon identification
 - Good dimu mass resolution ($\Delta m/m \sim 0.6\%$ for J/ψ)
- Silicon Tracking detector, $B=3.8T$
 - excellent track momentum resolution ($\Delta p_T/p_T \sim 1\%$)
 - excellent vertex reconstruction and impact parameter resolution



LHC luminosity and CMS trigger:

- collect data at increasing instantaneous luminosity
- Triggers are essential ingredients
 - Special trigger for different analyses combination of muon p_T , dimu p_T , dimu mass displaced dimuon vertex, and dimu+addiitonal muon



ATLAS Detector Performance

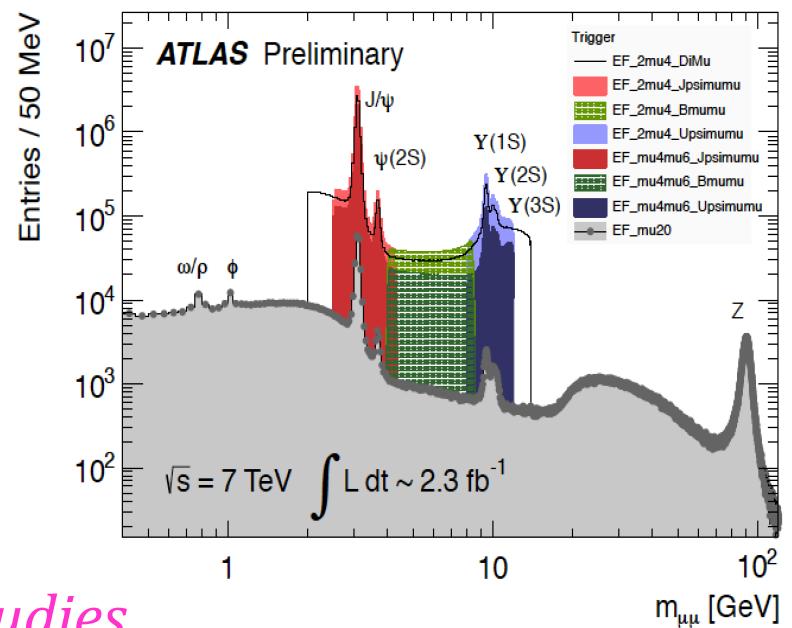
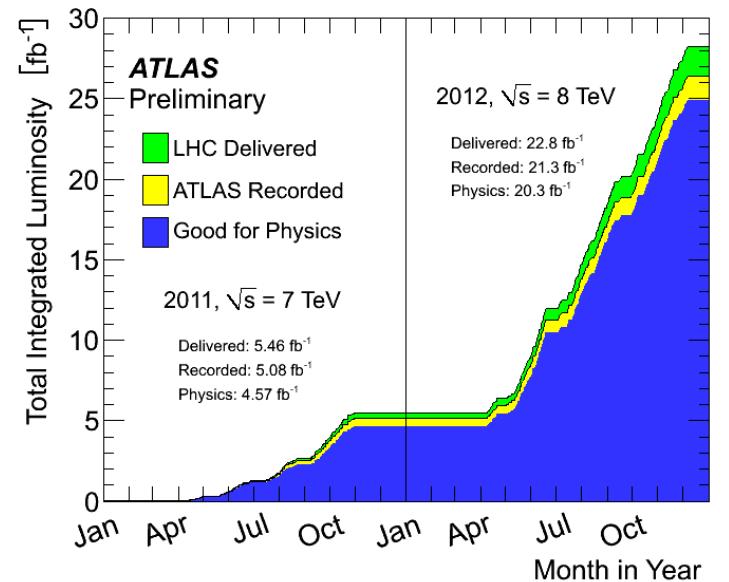
Excellent muon/silicon detectors for quarkonium:

- Muon system
 - High-purity muon identification
 - Good rapidity coverage, up to 2.7 (2.5)
- Silicon Tracking detector, B=2T
 - good track momentum resolution
1.5% plus $3.8 \times 10^{-4} p_T$
 - good vertex reconstruction and impact parameter resolution
15 μm transverse, 100 μm longitudinal

LHC luminosity and ATLAS trigger:

- collect data at increasing instantaneous luminosity
- Triggers are essential ingredients combination of muon pT, dimu mass, impact parameters

*Both ATLAS and CMS detector
are good detectors for exotic meson studies*



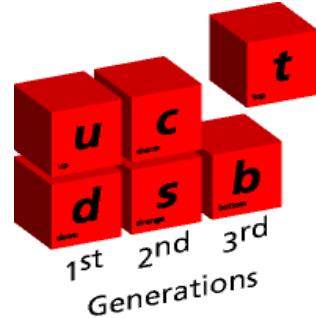
- *About exotic meson*
 - *quarkonium model*
 - *challenge from X(3872)*
 - *exotic models*

Quark Model

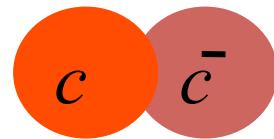
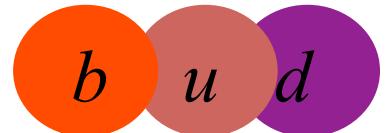
- *The birth of quark model (M. Gell-Mann & G. Zweig):
M. Gell-Mann, Phys. Lett. 8, 214 (1964)*

- *Heavy top decays before forming bound states
light quarks exist as bound states*

– *Baryons:* (qqq)



– *Mesons:* $(q\bar{q})$
quarkonia: $(s\bar{s})$, $(c\bar{c})$ ($b\bar{b}$) (hidden)



- *J/ ψ establishes the quark model, $\Upsilon(1S)$ further confirms it*
- *Gell-Mann also suggested exotic states $(qq\bar{q}\bar{q})$, $(qqqq\bar{q})$ at the birth of quark model, but evidence has never been solidly established*

Revitalized by recently discovered charmonium-like states
despite almost a decade, still mysterious!

Charmonium ($\bar{c}c$) Potential Model (Cornell Model)

- simple QCD-inspired phenomenological potential :

$$V(r) = -\frac{\kappa}{r} + \frac{r}{a^2}, \quad \kappa = 0.61, m_c = 1.84 \text{ GeV}, a = 2.38 \text{ GeV}^{-1}$$

- **non-relativistic** (charm quark is “heavy” compared to binding energy)
- quark confinement (increases linearly with separation)
- extendable to include **spin-dependent** terms, **relativistic** corrections, etc.
- Lattice QCD provides calculation of the masses and widths

[Eichten et. al., PRD 17, 3090 \(1978\)](#)

[Godfrey & Isgur, PRD 32, 189 \(1985\)](#)

[Barnes et. al., PRD 72, 054026 \(2005\)](#)

Charmonium States

Notation:

$^{2S+1}[L]_J$

$L=S, P, D$ (0,1,2)
(No cand. with
 $L \geq 3$)

$J = L+S$

$S(q\bar{q}) = 0$ or 1

Parity: $P = (-1)^{L+1}$

Charge conjugation
eigenvalues:
 $C=(-1)^{L+S}$

N : Radial
Quantum
Numbers

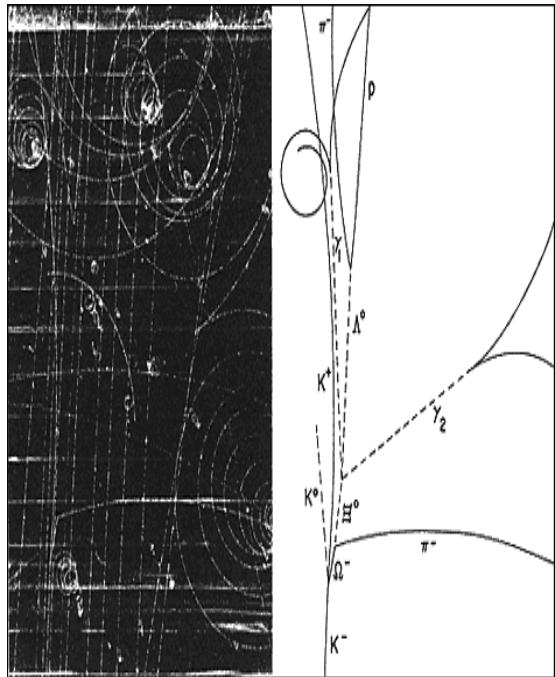
Quantum numbers				Name	Mass (MeV/c ²)	width(MeV)
N	L	J ^{PC}	$N^{2S+1}L_J$			
1	0	0^+	1^1S_0	$\eta_c(1S)$	2980.4 ± 1.2	26.7 ± 3
1	0	1^-	1^3S_1	J/ψ	3096.916 ± 0.011	$93.2 \pm 0.02 \times 10^{-3}$
1	1	0^{++}	1^3P_0	$\chi_{c0}(1P)$	3414.75 ± 0.31	10.2 ± 0.7
1	1	1^{++}	1^3P_1	$\chi_{c1}(1P)$	3510.66 ± 0.07	0.89 ± 0.05
1	1	2^{++}	1^3P_2	$\chi_{c2}(1P)$	3556.20 ± 0.09	2.03 ± 0.12
1	1	1^{+-}	1^1P_1	$h_c(1P)$	3525.93 ± 0.27	<1
1	2	1^-	1^3D_1	$\psi(3770)$	3772.92 ± 0.35	27.3 ± 1.0
2	0	0^+	2^1S_0	$\eta_c(2S)$	3637 ± 4	14 ± 7
2	0	1^-	2^3S_1	$\psi(2S)$	3686.09 ± 0.04	$317 \pm 9 \times 10^{-3}$
2	1	2^{++}	2^3P_2	$\chi_{c2}(2P)$	3929 ± 5	29 ± 10
3	0	1^-	3^3S_1	$\psi(4040)$	4039 ± 1	80 ± 10
2	2	1^-	2^3D_1	$\psi(4160)$	4153 ± 3	103 ± 8
4	0	1^-	4^3S_1	$\psi(4415)$	4421 ± 4	62 ± 20

These states work well with charmonium model, until the appearance of $X(3872)$

From strange to bottom discovery

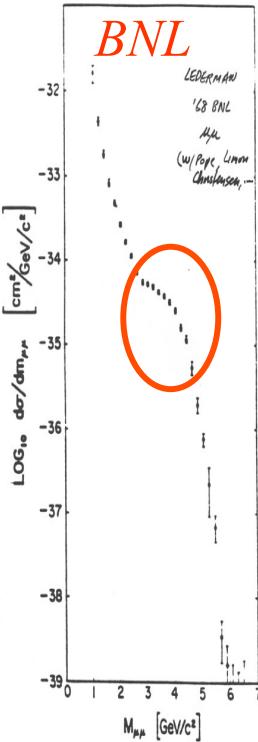
Ω^- discovery

BNL



1964

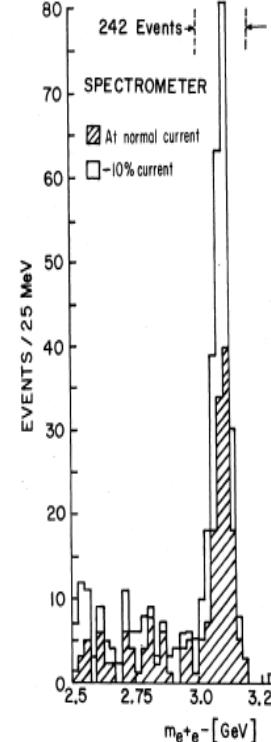
IN THE BEGINNING.....



1968

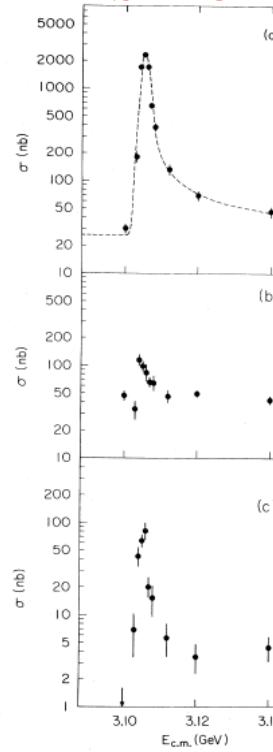
$J/\psi (\bar{c}c)$ discovery

BNL



1974

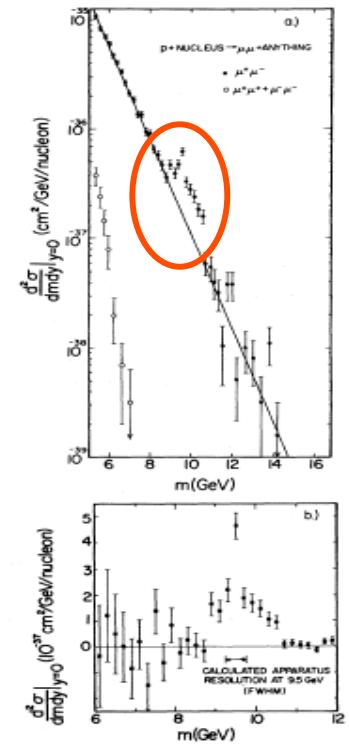
SLAC



1974

$Y(\bar{b}b)$ discovery

FNAL



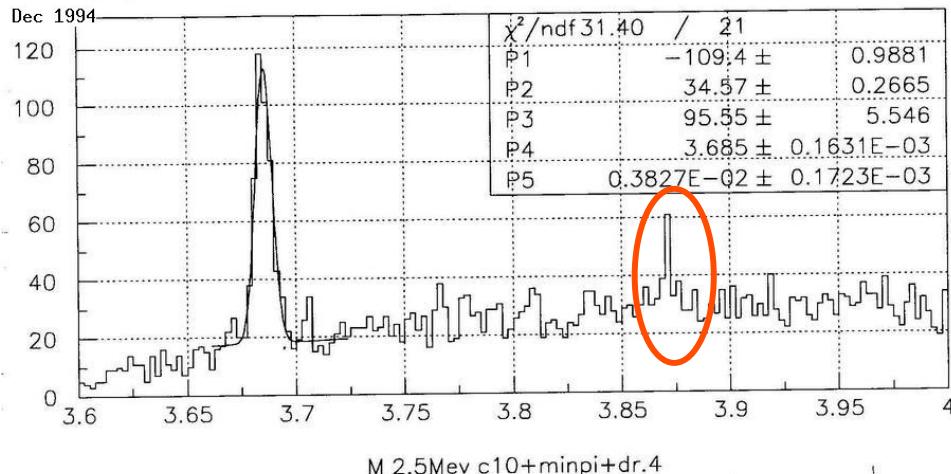
1977

Heavy flavor quarkonium spectroscopy helped turn quarks into a reality!

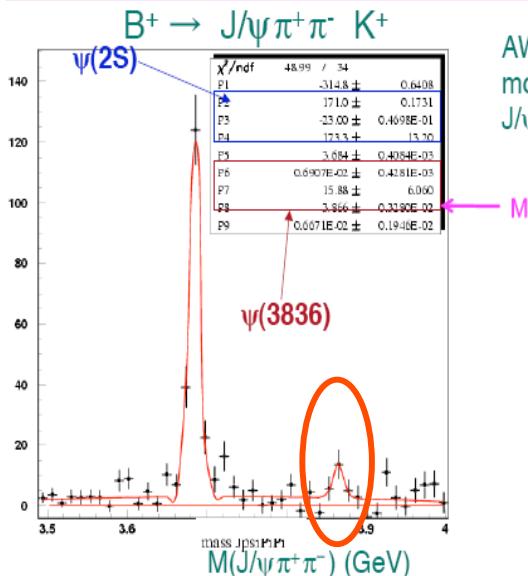
What we can learn from quarkonium-like spectroscopy?

Hints before the discovery of $X(3872) \rightarrow J/\psi\pi^+\pi^-$

CDF internal, 1994



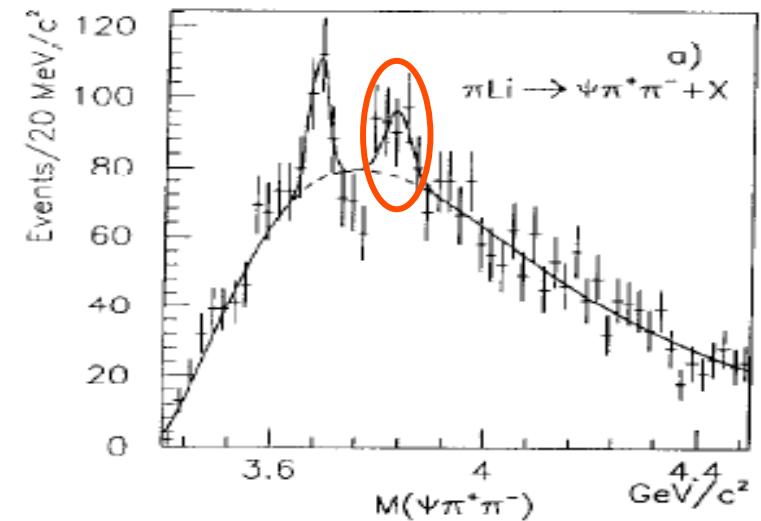
BaBar internal, 2003



From BaBar B-Factory Symposium (C. Hearty)
<http://www-conf.slac.stanford.edu/b-factory-symposium/talks.asp>

E705, PRD 50, 4258 (1994)

E705 saw $\psi(3836)$ in 1994?



CDF saw a hint in 1994, unpublished
 BaBar saw a hint in 2003, unpublished

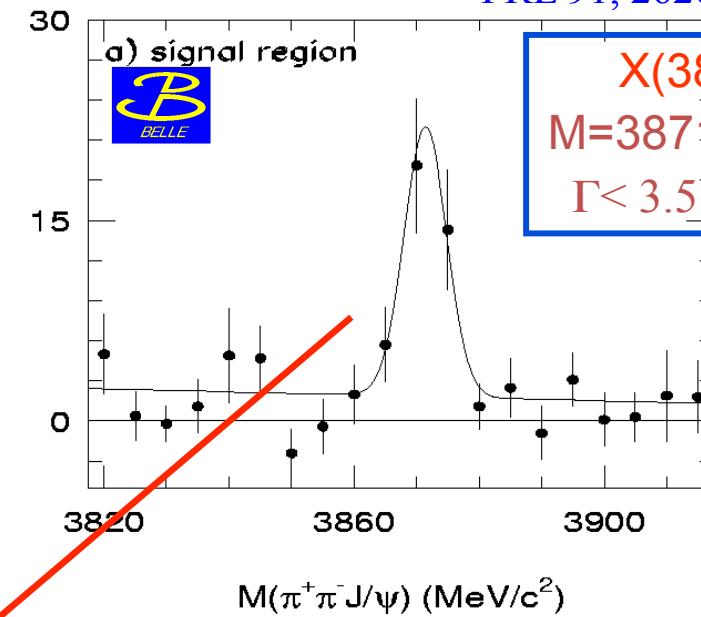
Both CDF and Babar spotted hints of $X(3872)$ before its discovery!

The mass from E705's $\psi(3836)$ is low

History: X(3872)--2003

PRL 91, 262001

$N^{2S+1}L_J$	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^{-+}	$\pi(1800)$		$\eta(1760)$			



$X(3872) \rightarrow J/\psi \pi^+ \pi^-$
 $M = 3871.8 \pm 0.7 \pm 0.4 \text{ MeV}$
 $\Gamma < 3.5 \text{ MeV} @ 90\% \text{ CL}$

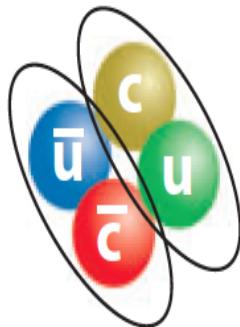
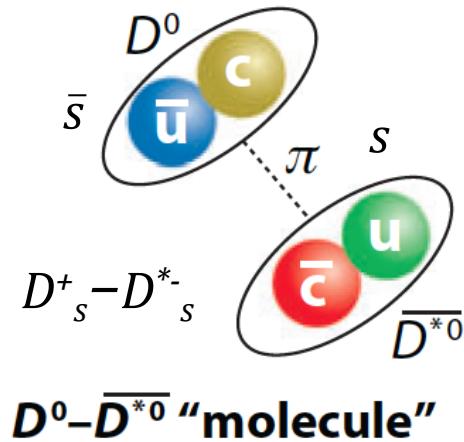
(Problematic) features
mass $\sim 70 \text{ MeV} > 1^3D_2$ charmonium
 $M(\pi^+ \pi^-)$ peaks as a ρ , $C=+$, isospin=1 (charmonium-0)

Mass close to DD^* , molecule is speculated
Recently LHCb determined $J^{PC}=1^{++}$

First particle challenging charmonium model,
Revitalized exotic meson study

CMS has made and is going to make significant contribution!

Exotic Models-I



Diquark-dantiquark

Molecular

Loosely *bound state of a pair of mesons*. The dominant binding mechanism should be **pion exchange**. Being weakly bound the mesons tend to decay as if they were free

Tetraquark

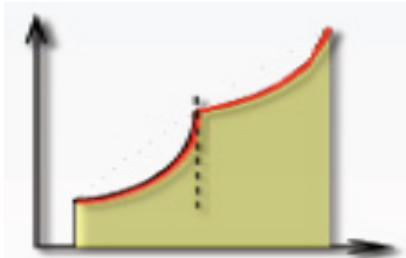
Bound state of *four quarks*, i.e. $qq\bar{q}\bar{q}$ in which the quarks group into color triplet scalar or vector clusters

Strong decays proceed via rearrangement processes

Distinctive features of multi-quark picture with respect to charmonium:

- prediction of many new states
- possible existence of states with non-zero charge, strangeness or both

Exotic Models-II



Charmonium hybrids

States with excited gluonic degrees of freedom;
exotic $J^{PC}=0^{+-}, 1^{-+}, 2^{+-} \dots$ not allowed for charmonium.
Smoking gun for exotic states.

Lattice QCD for 1^{-+} : $m \sim 4.3 \pm 0.05 \text{ GeV}$ (C. Thomas)

Threshold, cusp, or coupled-channel effect giving a cross section enhancement which may not correspond to resonance production at all

Hadro-charmonium

Light hadrons bounded by *van der Waal's force* to a charmonium core in the case where the light hadron is a highly excited resonance.

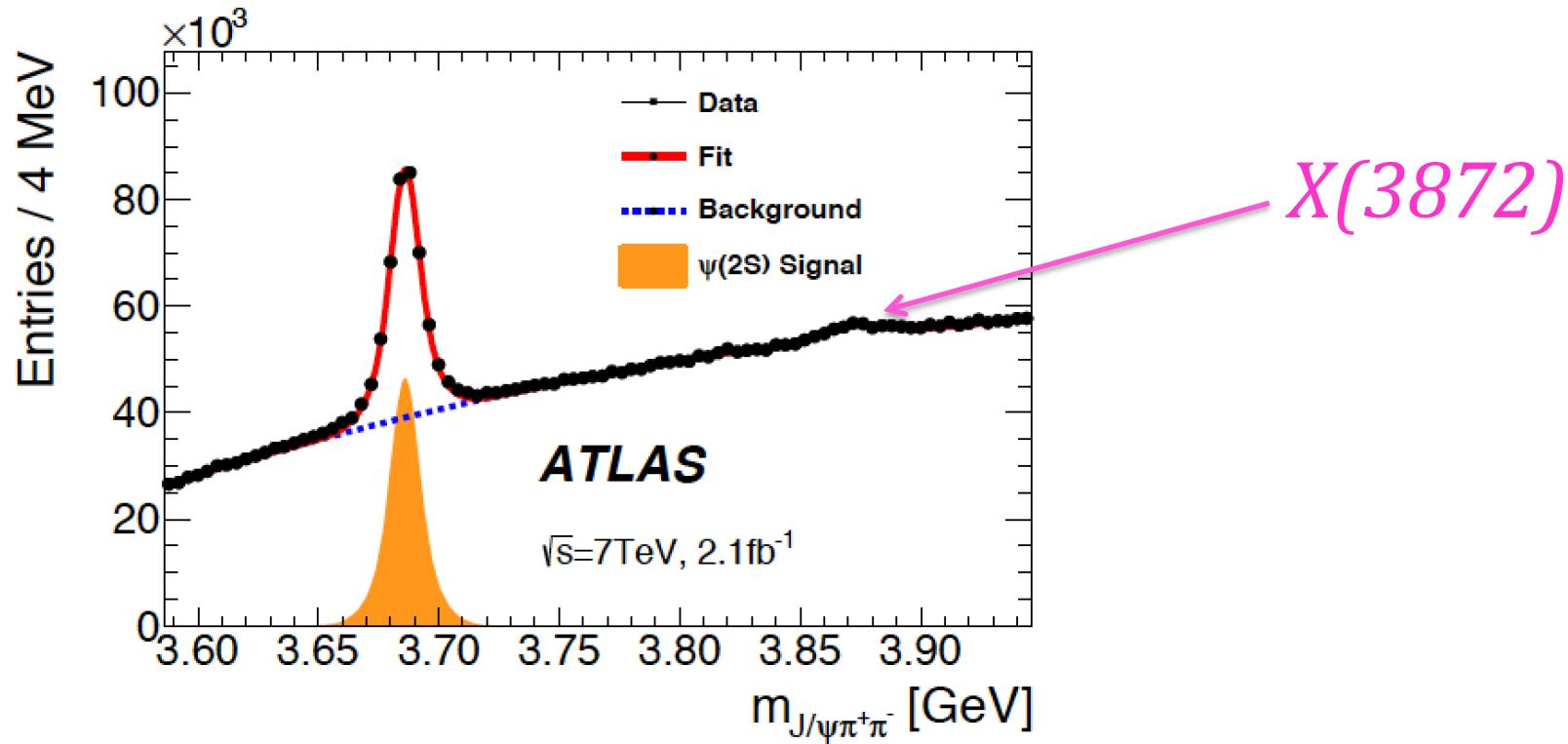
We know something is going on even though we do not know exactly what!

New kind(s) of spectroscopy with complex binding forces?

CMS/ATLAS joined the effort for exotic studies

- *Exotic meson @ ATLAS and CMS*
 - $X(3872)$ production @ CMS
 - $J/\psi\phi$ mass spectrum @ CMS
 - $Xb \rightarrow Y(1S)\pi\pi$ @ CMS and ATLAS

X(3872) signal @ATLAS



ATLAS sees $X(3872)$ signals in data

Measurements of $X(3872)$ are underway within ATLAS

X(3872) cross section @CMS

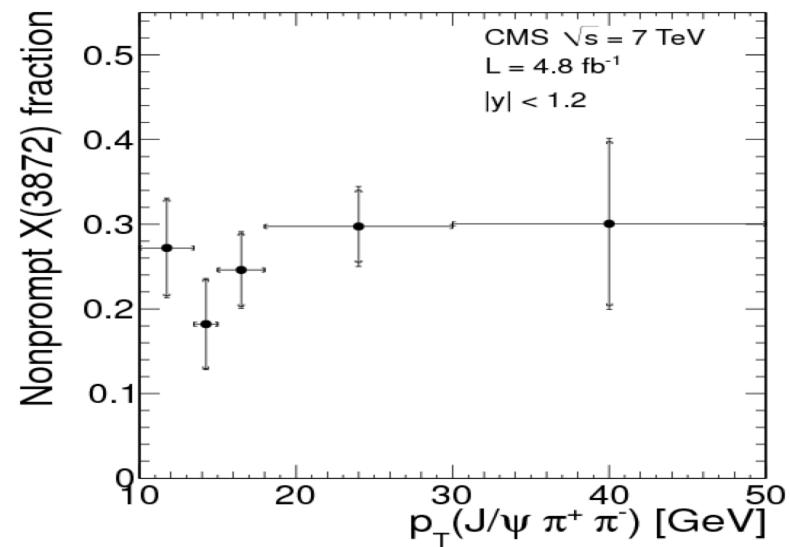
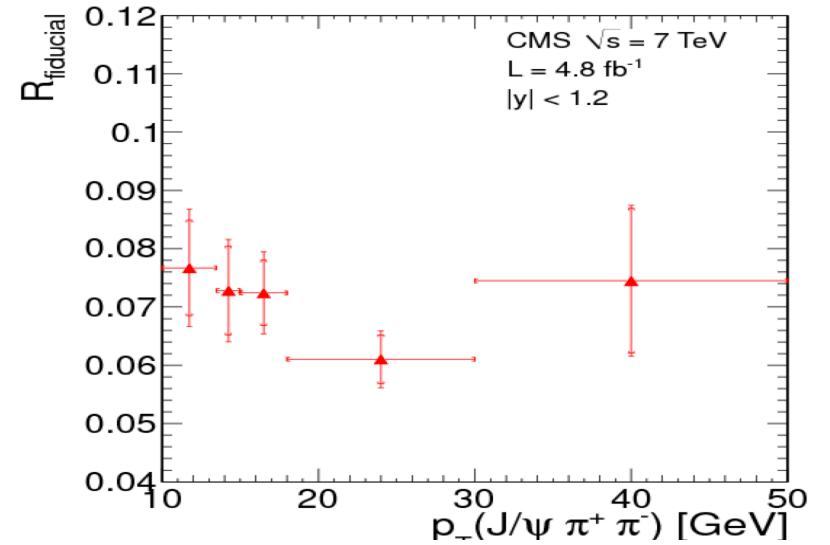
- *The X(3872) was discovered in 2003 by Belle*
 - *Later it was confirmed by CDF, D0, Babar*
 - Its nature is uncertain → exotic candidate
- *Previous analyses (before CMS measurement) prefer JPC=1++ or 2-+*
 - *CMS measurement assumed 1++*
 - *Later LHCb measured its JPC as 1++, PRL 110, 222001 (2013)*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

$X(3872)$ cross section @CMS

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

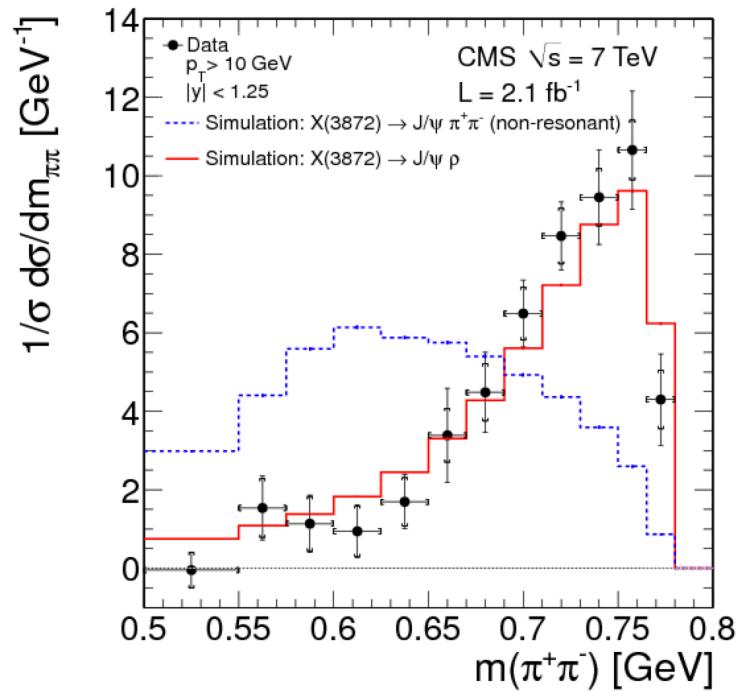
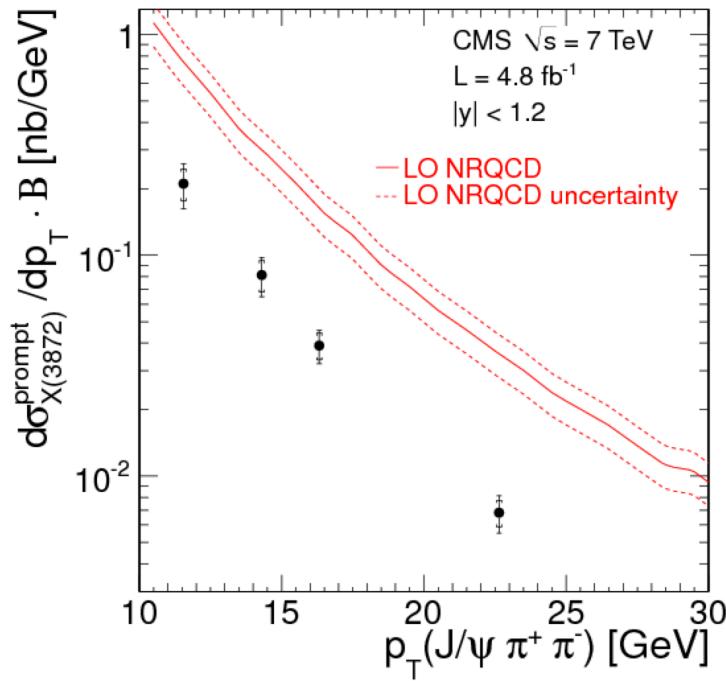
$$l_{xy}^{X(3872)} = \frac{L_{xy}^{X(3872)} \cdot m_{X(3872)}}{p_T}$$

- Non-prompt events ($|l_{xy}| > 100 \mu m$)
- Contribution from prompt < 0.1%
- Cross-checked by 2D fit to the mass and $|l_{xy}|$



$X(3872)$ cross section @CMS

- Prompt cross section compared to NRQCD
JHEP 1304 (2013) 154
- Compared to simulations with and w/o intermediate ρ^0 in the $J/\psi \pi^+\pi^-$ decay

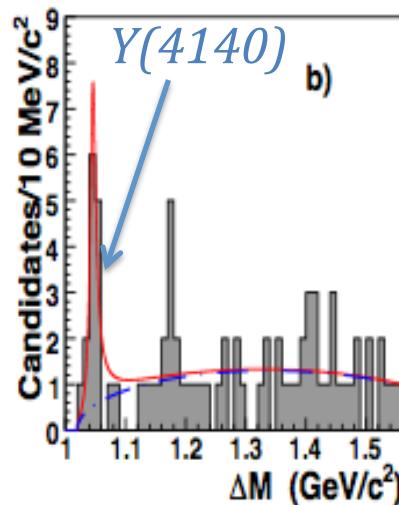
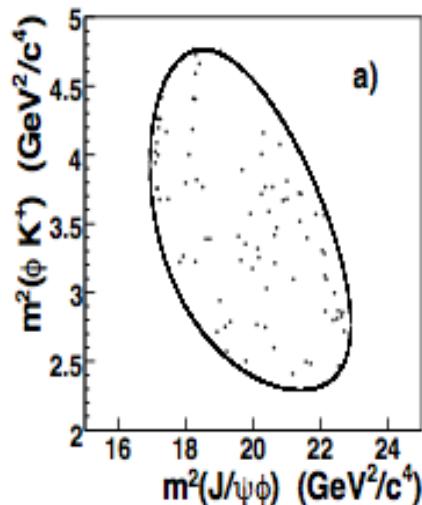


NRQCD predictions significantly exceed the measured value, while p_T dependence is reasonably well described

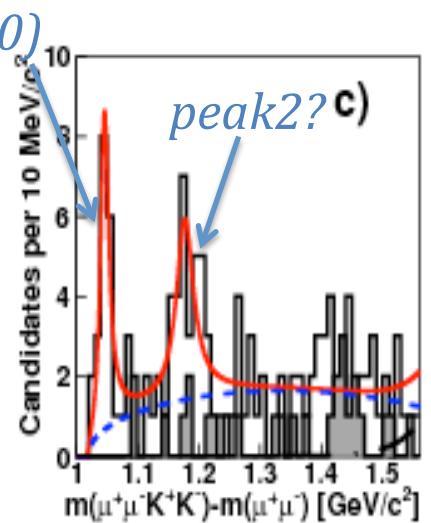
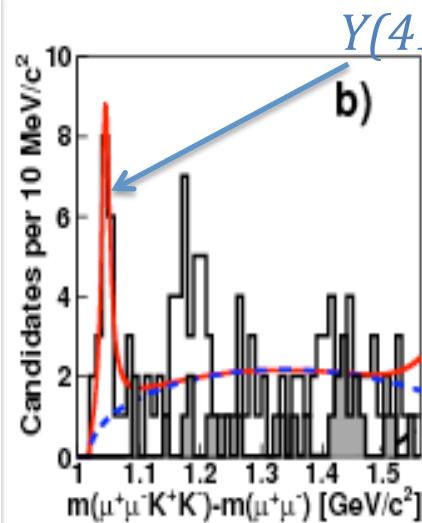
The intermediate ρ^0 decay gives better agreement with data

The Story of $Y(4140)$ —CDF(2009-10)

CDF—PRL102:242002 (2009)



CDF—arXiv:1101.6058 [hep-ex] (2010)



$$M = 4143.0 \pm 2.9(stat) \pm 1.2(syst) \text{ MeV}$$

$$\Gamma = 11.7^{+8.3}_{-5.0}(stat) \pm 3.7(syst) \text{ MeV}$$

Evidence--~ 4σ

Not likely to be charmonium:

High mass w/ narrow width

$$M_1 = 4143.4^{+2.9}_{-3.0}(stat) \pm 0.6(syst) \text{ MeV}$$

$$M_2 = 4277.4^{+8.4}_{-6.7}(stat) \pm 1.9(syst) \text{ MeV}$$

$$\Gamma_1 = 15.3^{+10.4}_{-6.1} \text{ (stat)} \pm 2.5 \text{ (syst)} \text{ MeV}$$

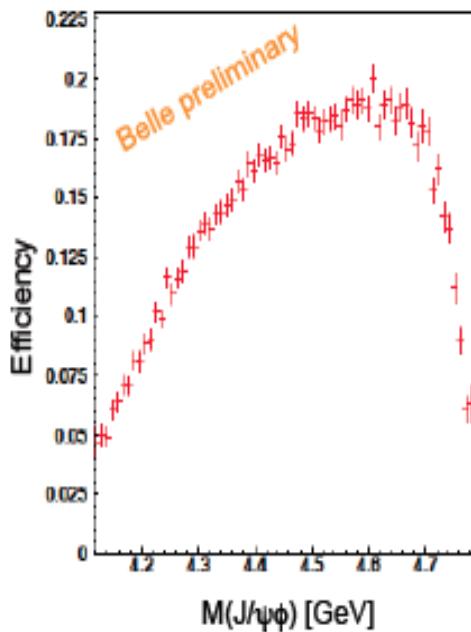
$$\Gamma_2 = 32.3^{+21.9}_{-15.3} \text{ (stat)} \pm 7.6 \text{ (syst)} \text{ MeV}$$

$Y(4140)$ --Observation; $peak2$ —evidence (3.1σ)

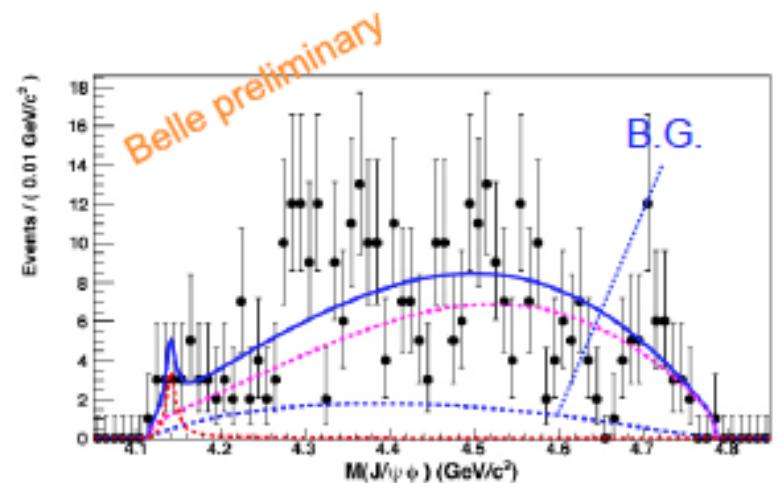
CDF spotted $Y(4140)$, how about other experiments?

Y(4140) @ Belle (2010)

Kenkichi Miyabayashi
(Nara Women's Univ.)
2010 May QWG7



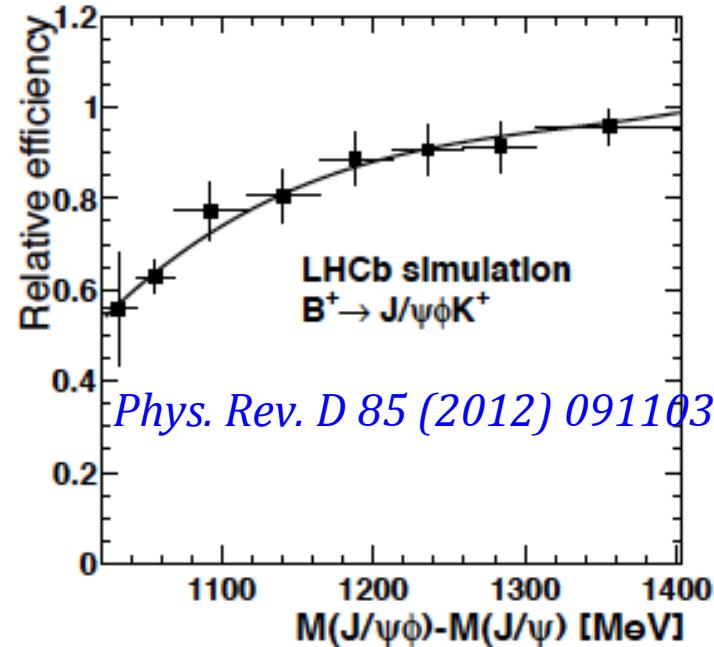
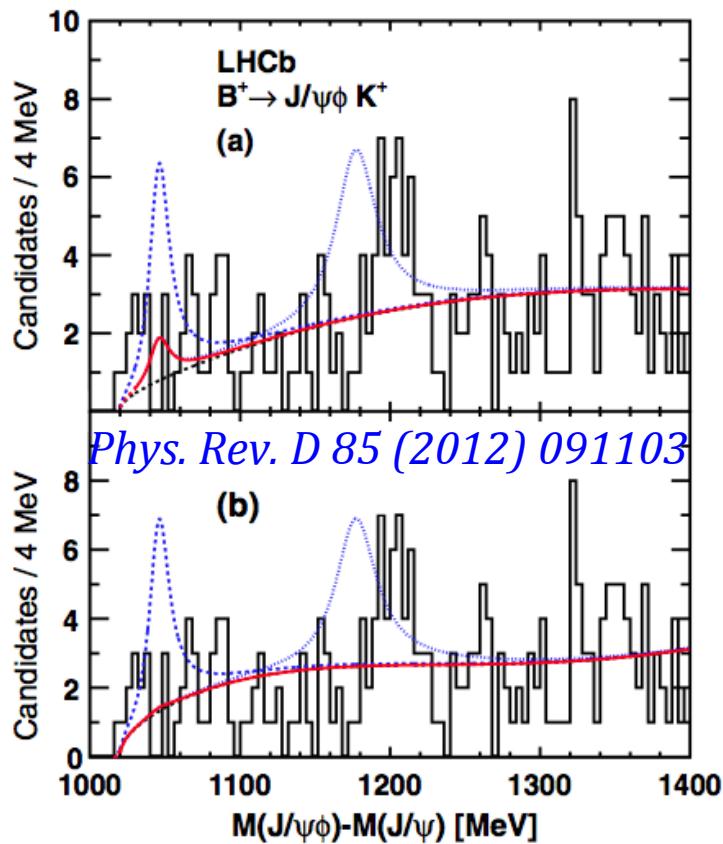
Note: CDF and Belle do not contradict each other.
In Belle, B meson at rest on $\Upsilon(4S)$ rest frame, Kaon momentum from ϕ decay is low, especially just above $J/\psi\phi$ threshold
→ lower reconstruction efficiency.



$Y(4140): 7.5 +4.9/-4.4$ events
Statistical significance : 1.9σ
Signal could not be identified.

Belle cannot confirm or deny the existence of $Y(4140)$

Y(4140) @ LHCb (2011)



*LHCb confirms neither structure
2.4 σ disagreement with CDF result*

LHCb Versus CDF: Two Punches In The Face!

By Tommaso Dorigo | July 27th 2011 05:48 AM | 10 comments | [Print](#) | [E-mail](#) | [Track](#)

result. Note that, as reported in the figure, if the CDF signal were as estimated by CDF, LHCb would have been able to fit 39+-9+-6 events. The Y(4140) is on very shaky ground at the moment, and the new PDG will likely change its status in the particle zoo... This is punch number 1.

What blogger says?

$Y(4140)$ @ CMS (2012)

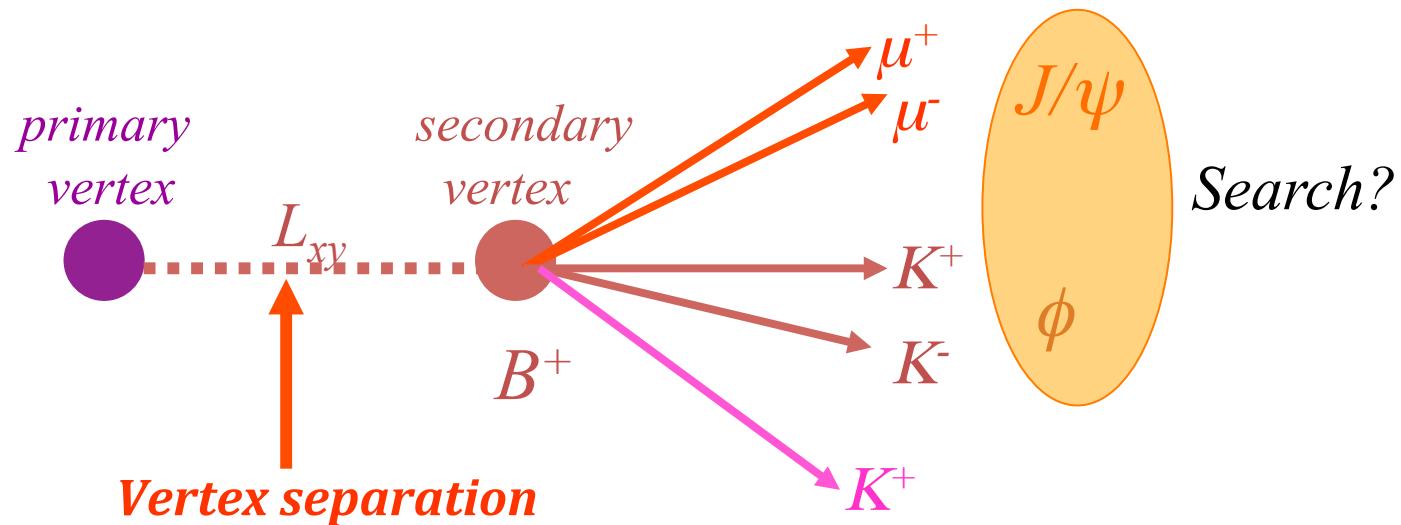
- I) Reconstruct B^+ as:

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

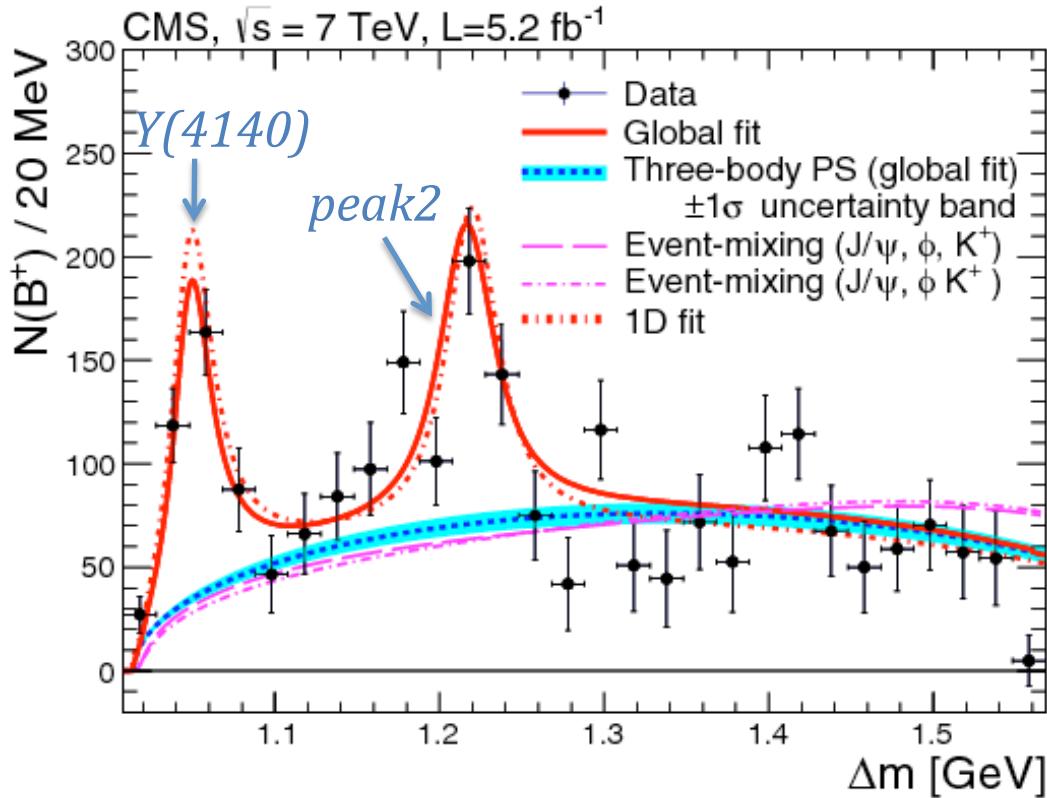
$$J/\psi \rightarrow \mu^+ \mu^-$$

$$\phi \rightarrow K^+ K^-$$

- II) Search for structure in $J/\psi \phi$ mass spectrum inside B^+ mass window



$Y(4140)$ @ CMS (2012)



$$M_1 = 4148.0 \pm 2.4(\text{stat}) \pm 6.3(\text{syst}) \text{ MeV}$$

$$M_2 = 4313.8 \pm 5.3(\text{stat}) \pm 7.3(\text{syst}) \text{ MeV}$$

$$\Gamma_1 = 28^{+15}_{-11}(\text{stat}) \pm 19(\text{syst}) \text{ MeV}$$

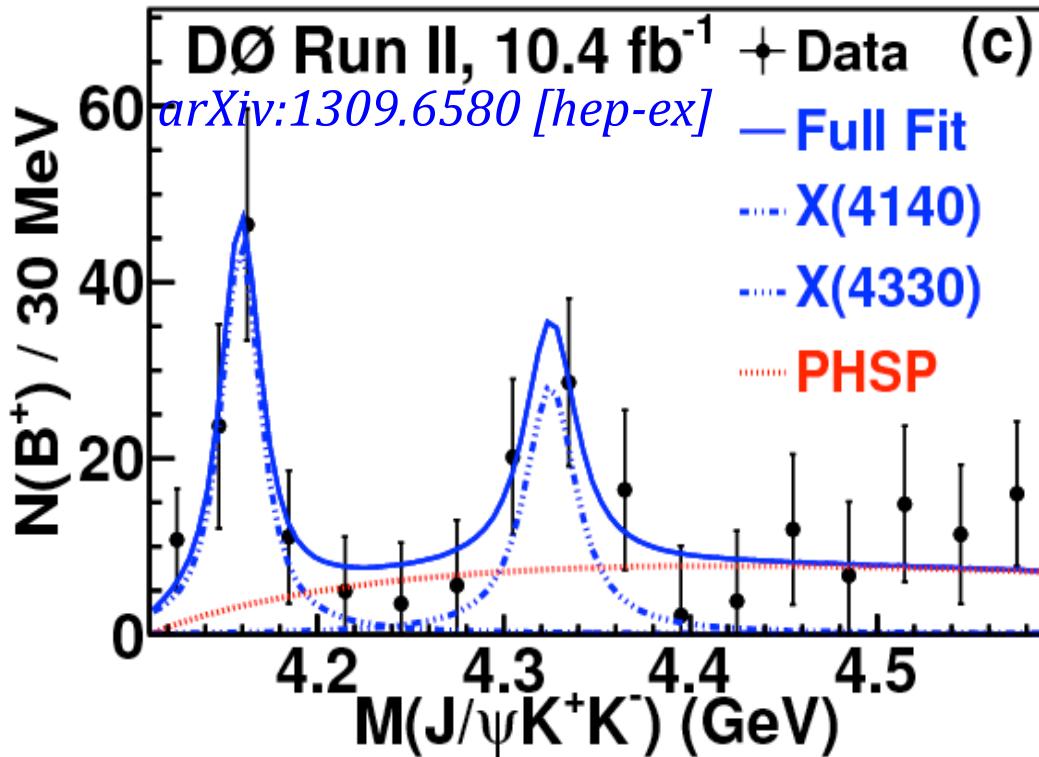
$$\Gamma_2 = 38^{+30}_{-15}(\text{stat}) \pm 16(\text{syst}) \text{ MeV}$$

$Y(4140)$ —Observation ($>5\sigma$),
consistent with CDF $Y(4140)$ result

Peak2 —evidence
Width/BF (estimation) consistent
with CDF result, mass is higher

CMS provides the first independent confirmation of $Y(4140)$ with $>5\sigma$ significance
The largest sample up to date, X20 of CDF statistics, X7 of LHCb statistics

Y(4140) @ D0 (2013)



$$M_1 = 4159.0 \pm 4.3(\text{stat}) \pm 6.6(\text{syst}) \text{ MeV}$$

$$M_2 = 4328.5 \pm 12.0(\text{stat}) \text{ MeV}$$

$$\Gamma_1 = 19.9 \pm 12.6(\text{stat})^{+1.0}_{-8.0}(\text{syst}) \text{ MeV}$$

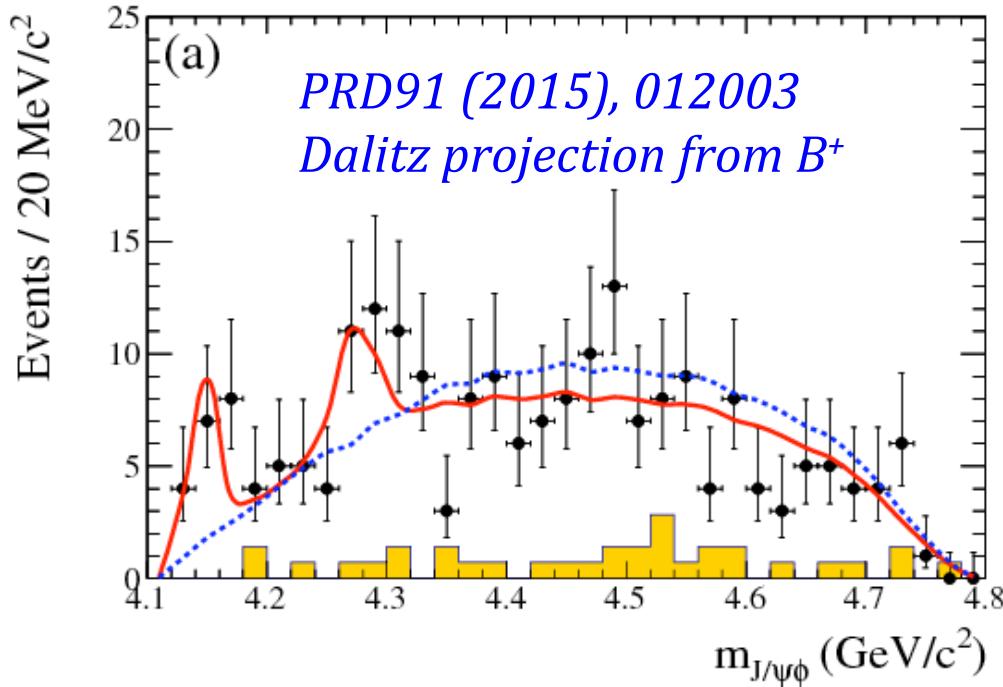
$$\Gamma_2 = ? \text{ MeV}$$

*Y(4140)—Evidence (3.1σ),
 consistent with CDF Y(4140) result*

Peak2 — hint w/ fixed width

*D0 provides the second independent confirmation of Y(4140) with 3.1σ significance
 It is experimentally established!*

Y(4140) @ BaBar (2015)



Same searches via B decays

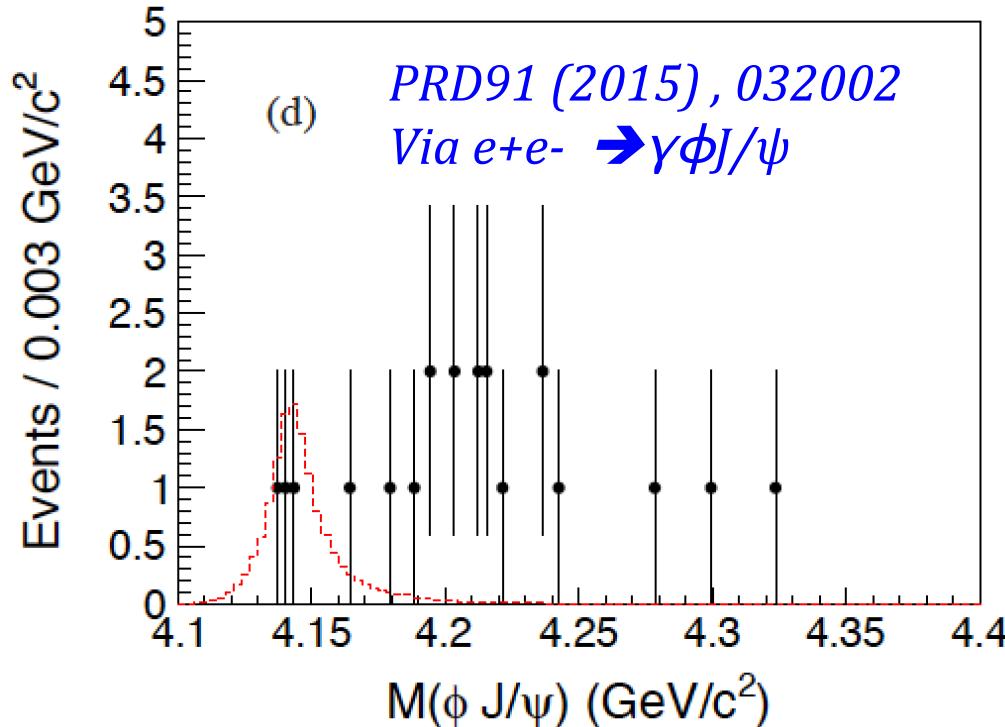
Mass & width are fixed to CDF values

*No significance for both structures
even though there seems hints*

*Babar sets limits for both, compatible
with all experiments*

BaBar provides useful information even though there is no significant signals

Y(4140) @ BES (2015)



No significance for Y(4140)

Three events @4.15 GeV

BES sets limits, cannot compare because it is from a different process

BES provides additional information: under the assumption of molecule interpretation, the BF of $Y(4140) \rightarrow J/\psi \phi$ is estimated to be about 30%

Mini summary of Y(4140) :

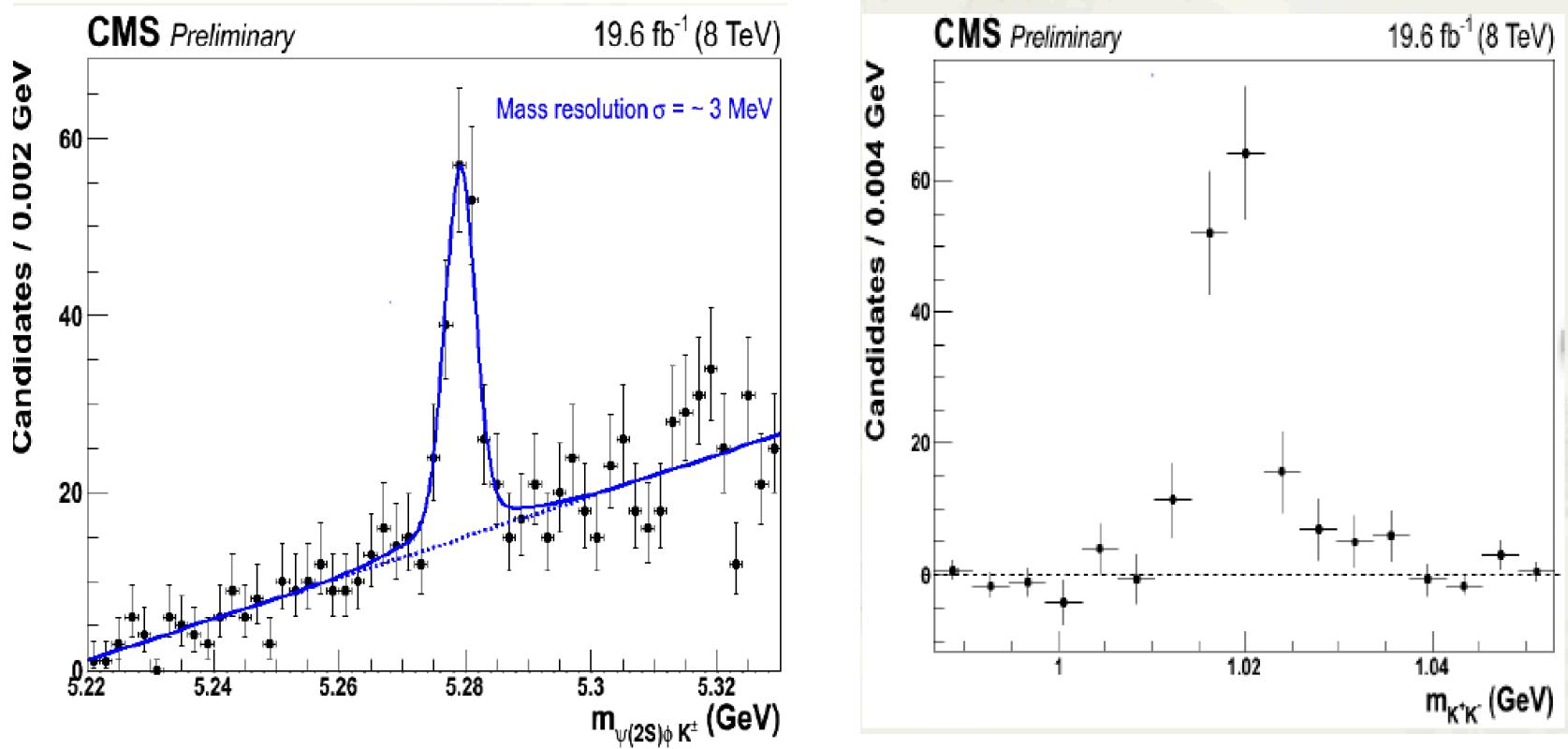
See signal from CDF, CMS, D0

No significant signal from Belle, Babar, BES, but no conflicts

2.4 σ tension between LHCb (0.3 fb⁻¹ data) and CDF

Anything at $\psi(2S)\phi$?—Quarkonium 2014

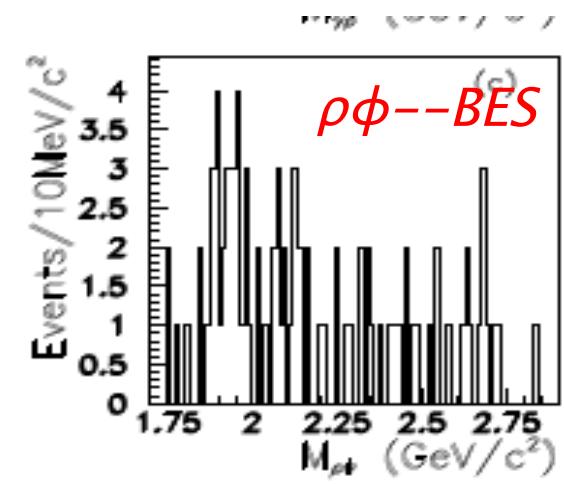
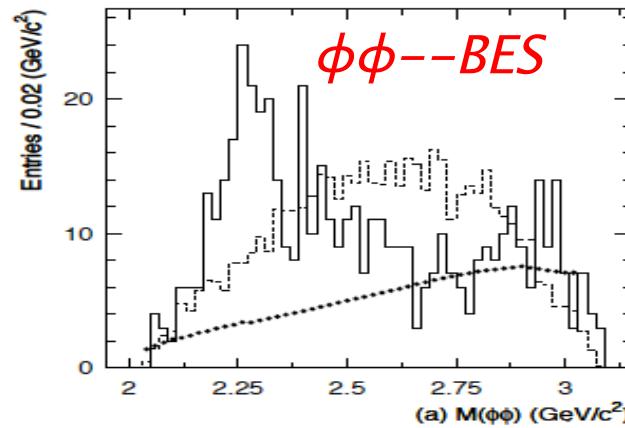
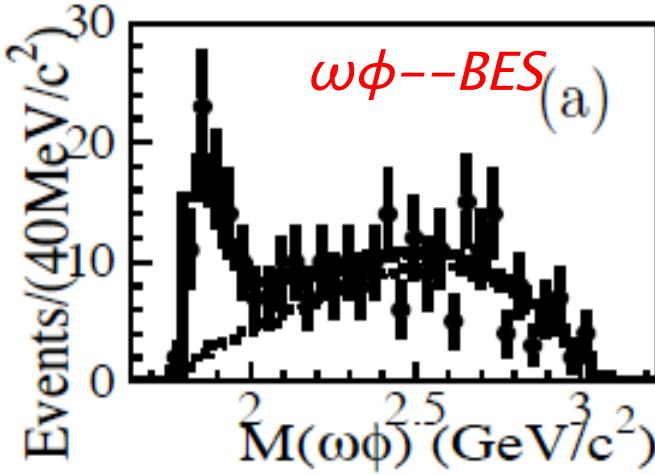
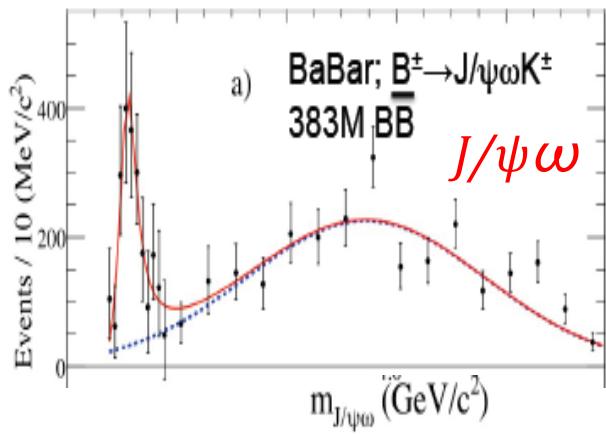
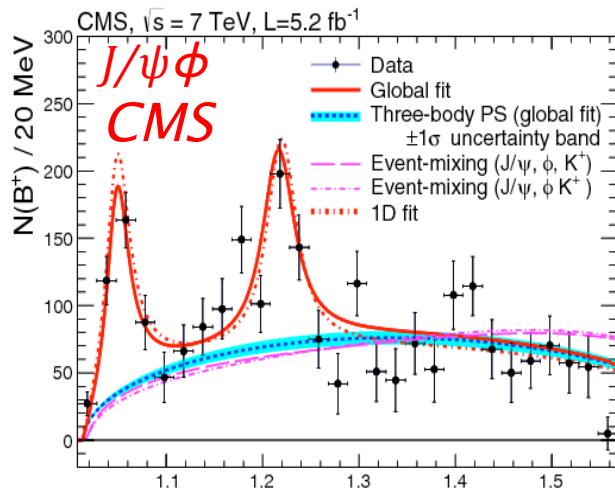
<https://indico.cern.ch/event/278195/session/2/contribution/53/material/slides/0.pdf>



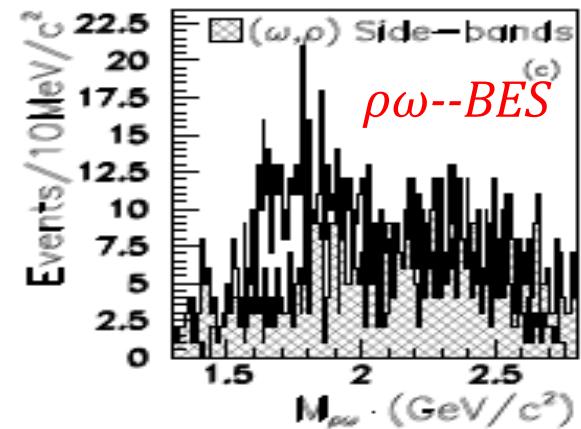
$B^+(\psi(2s)\phi K^+$ signal is clearly observed at CMS, no report on possible structures—very narrow phase space.

Near VV threshold puzzle?

How CMS findings fit into big picture



PRD 77, 012001(2008)



Near VV threshold puzzle

--Observed near threshold narrow $V(I=0)V$ ($I=0$) enhancement

--No clear enhancement if one of the V ($I!=0$) or due to wide width of ρ

Near VV threshold puzzle

- How about near threshold of $J/\psi J/\psi$, $J/\psi Y$, YY threshold? Need Run II data
- Systematically investigate it as a function of VV mass?

Why it is interesting? Very clean system:

- cannot bound by exchanging
pion— V isospin zero ; photon— V charge zero; one gluon— V is color singlet;
- two gluons possible--Pomeron exchange? Final state scattering?
- learn back to nuclear scattering mechanism? Van de Waals bounding?

A puzzle can be resolved at LHC—back to low energy nuclear physics

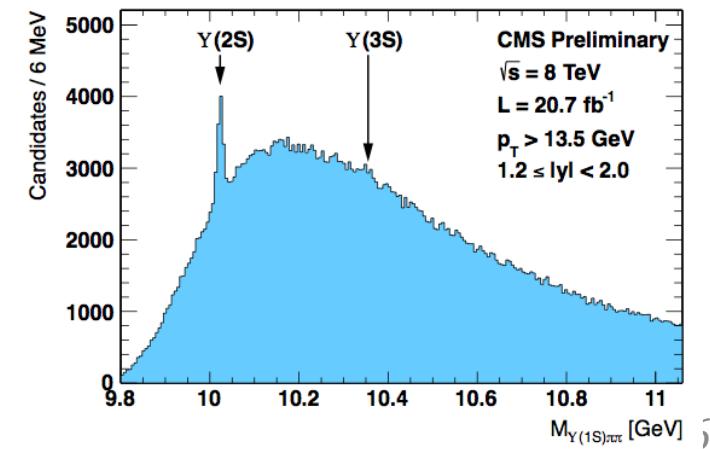
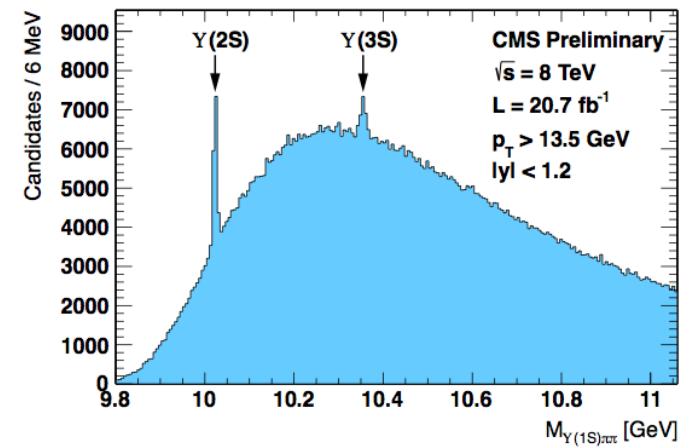
Search for new bottomonium state to $Y(1S)\pi^+\pi^-$

PLB 727 (2013) 57

- 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 BB or BB* 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** $R = \frac{\sigma_{X_b} \times BR(X_b \rightarrow Y(1S)\pi^+\pi^-)}{\sigma_{Y(2S)} \times BR(Y(2S) \rightarrow Y(1S)\pi^+\pi^-)}$ **as a function of X_b mass—[10,11] GeV**
 - kinematic region: $p_T(Y(1S)\pi^+\pi^-) > 13.5$ GeV and $|y(Y(1S)\pi^+\pi^-)| < 2.0$

X_b candidate reconstruction @CMS

- X_b candidates reconstructed by associating the Y(1S) to 2 pion tracks
 - optimized to maximize expected signal significance near Y(2S) mass
 - Expected significance $> 5\sigma$ if $X_b \text{ BR} * \text{cross-section} > 6.56\%$ of the corresponding $Y(2S) \rightarrow Y(1S)\pi^+\pi^-$ value (analogous to $X(3872) \rightarrow J/\psi\pi^+\pi^-$)
- 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 Y(2S) and Y(3S)



X_b search: mass scan @CMS

- 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

$$R = \frac{N_{X_b}^{\text{obs}}}{N_{Y(2S)}^{\text{obs}}} \cdot \frac{\epsilon_{Y(2S)}}{\epsilon_{X_b}}$$

observed yields of X_b
and Y(2S) candidates

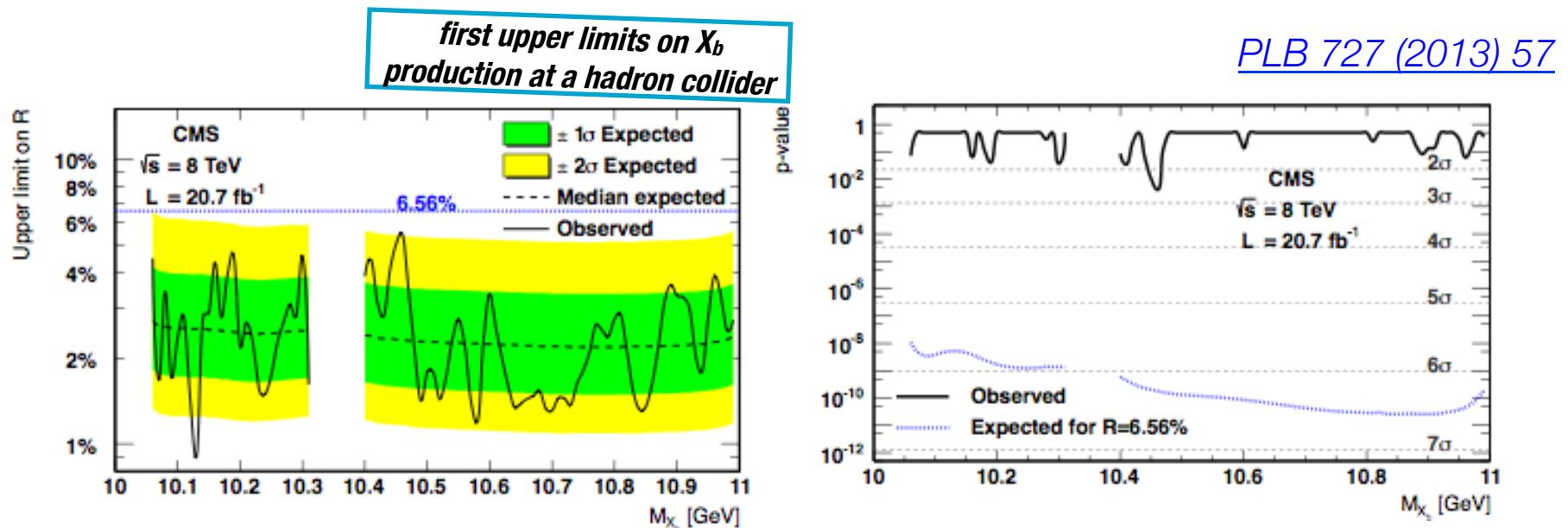
overall efficiencies estimated
from simulation

Assumptions:

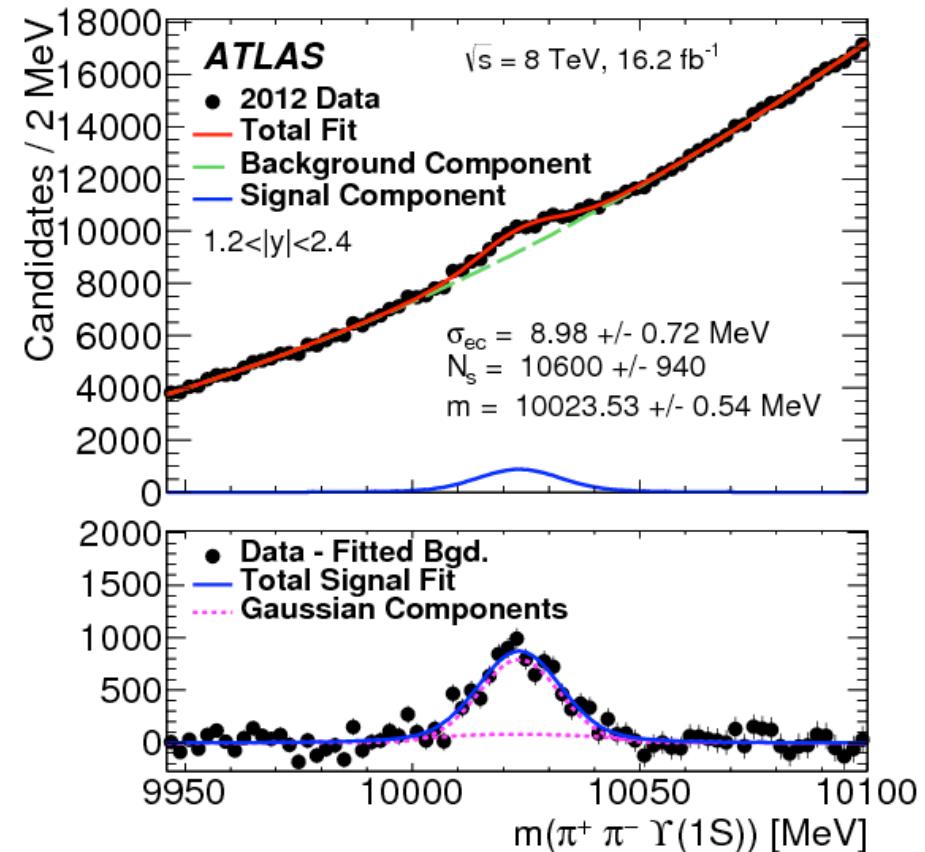
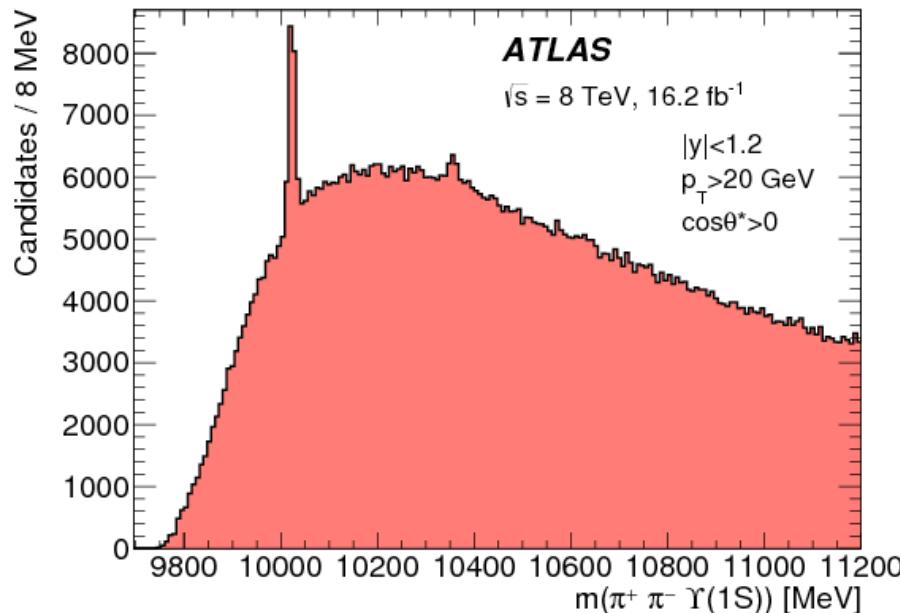
- same production mechanism for Y(2S) and X_b
- both produced unpolarized
- same dipion mass distribution for X_b and Y(2S)

X_b Limit @CMS

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



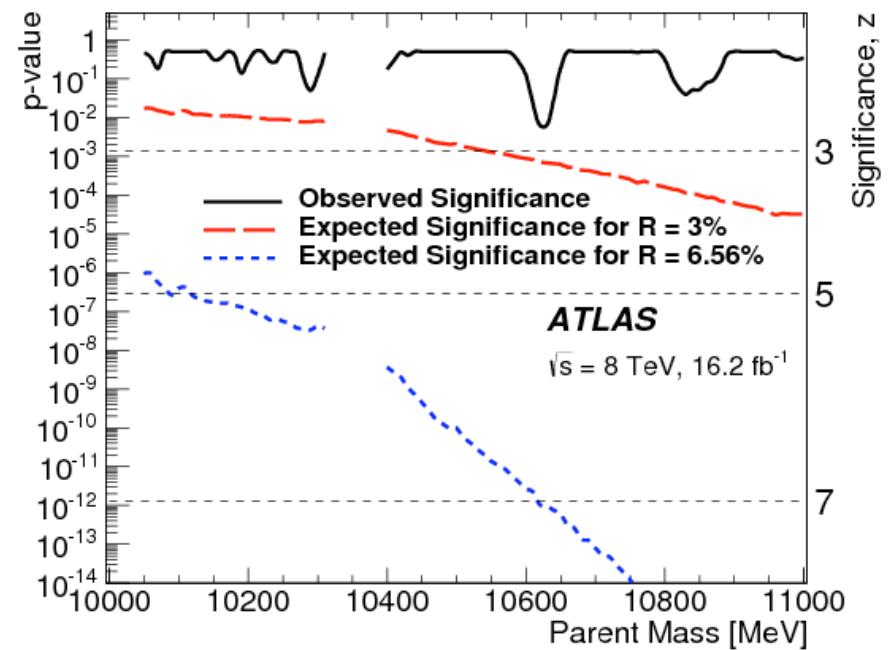
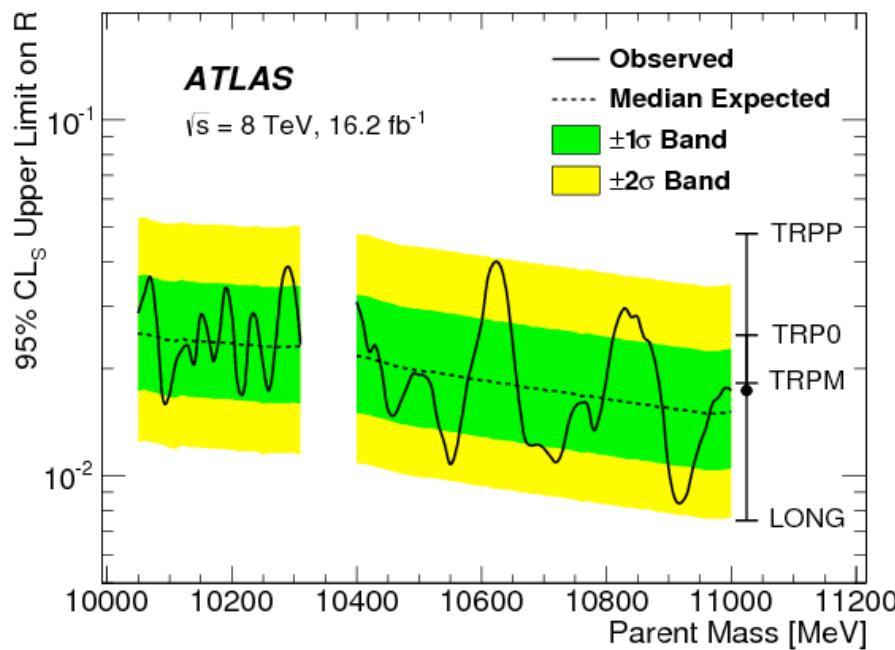
No significant excess is observed
*95% CL upper limit on the cross-sections*branching fractions ratio: 0.9 - 5.4 %*



- Similar to CMS search
- Fit in $2 \times 2 \times 2$ bins of ($|y|$, p_T , $\cos\theta^*$)
- Validated on 34300 ± 800 $Y(2S)$ signal, $Y(3S)$ model for X_b search (8.7σ)
- no significant excess found, set upper limit
- The split of the analysis into bins of ($|y|$, p_T , $\cos\theta^*$) take the advantage of varying bin sensitivity, which allowed for a more restrictive limit than CMS

X_b Limit @ATLAS

- Upper limit is set on R using CLs method
- Most significant fluctuation $<3\sigma$
- Combined barrel and endcap region



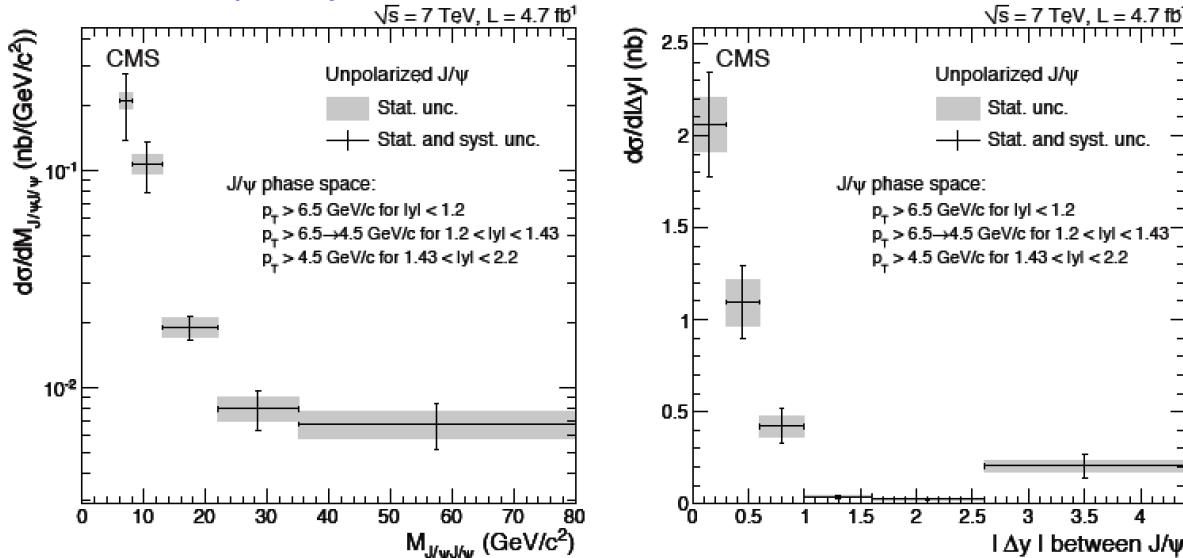
95% CL upper limit on R: $0.8\text{--}4\%$

*take into account the effect of unknown spin-alignment state of the X_b
 $Y(1S)\pi\pi$ is isospin-suppressed at certain assumptions, isospin allowed
 channels under investigation within ATLAS*

- Prospect for Run II

Double J/ ψ and Υ cross section

JHEP 1409 (2014) 094



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

We have observed double J/ψ events and measured its production cross section
Dominated by SPS, hint of DPS.

We have enough statistics to investigate heavy meson pairs

Search for exotic mesons decay into double J/ψ , $J/\psi\mu\mu$, $\Upsilon(nS)\Upsilon(nS)$, $\Upsilon\mu\mu$, $\Upsilon\phi$, ...

Heavy tetra-quark bound states

● Heavy-quark tetra-quark states

Phys. Rev. D 86, 034004 (2012)

---No solid prediction for heavy quarks, but a few simple models, i.e.

$c\bar{c}c\bar{c}$

$0^{++'}$:	$M = 5.966 \text{ GeV},$	$M - M_{\text{th}} = -228. \text{ MeV},$	Above double η_c threshold
$1^{+-'}$:	$M = 6.051 \text{ GeV},$	$M - M_{\text{th}} = -142. \text{ MeV},$	Below double J/ψ threshold
2^{++} :	$M = 6.223 \text{ GeV},$	$M - M_{\text{th}} = 29.5 \text{ MeV}.$	Search via $(\eta_c\eta_c?), J/\psi\mu^+\mu^-, J/\psi^*$

0^{++a} :	$M = 12.359 \text{ GeV},$	$M - M_{\text{th}} = -191. \text{ MeV}$	Above double B_c threshold
0^{++b} :	$M = 12.471 \text{ GeV},$	$M - M_{\text{th}} = -78.7 \text{ MeV},$	$J/\psi Y(1S)$ threshold
$ 1^{+-a}$:	$M = 12.424 \text{ GeV},$	$M - M_{\text{th}} = -126. \text{ MeV}$?
1^{+-b} :	$M = 12.488 \text{ GeV},$	$M - M_{\text{th}} = -62.5 \text{ MeV},$	
1^{++} :	$M = 12.485 \text{ GeV},$	$M - M_{\text{th}} = -64.9 \text{ MeV},$	
2^{++} :	$M = 12.566 \text{ GeV},$	$M - M_{\text{th}} = 16.1 \text{ MeV}.$	Above double B_c threshold

$b\bar{c}\bar{b}\bar{c}$

$0^{++'}$:	$M = 12.359 \text{ GeV},$	$M - M_{\text{th}} = -191. \text{ MeV}$	Above double B_c threshold
0^{++b} :	$M = 12.471 \text{ GeV},$	$M - M_{\text{th}} = -78.7 \text{ MeV},$	$J/\psi Y(1S)$ threshold
$ 1^{+-a}$:	$M = 12.424 \text{ GeV},$	$M - M_{\text{th}} = -126. \text{ MeV}$?
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1^{++} :	$M = 12.485 \text{ GeV},$	$M - M_{\text{th}} = -64.9 \text{ MeV},$	
2^{++} :	$M = 12.566 \text{ GeV},$	$M - M_{\text{th}} = 16.1 \text{ MeV}.$	Above double B_c threshold

$b\bar{b}b\bar{b}$

$0^{++'}$:	$M = 18.754 \text{ GeV},$	$M - M_{\text{th}} = -544. \text{ MeV},$	Below double $Y(1S)$ threshold
$1^{+-'}$:	$M = 18.808 \text{ GeV},$	$M - M_{\text{th}} = -490. \text{ MeV},$	Search via $Y(1S)\mu^+\mu^-$
2^{++} :	$M = 18.916 \text{ GeV},$	$M - M_{\text{th}} = -382. \text{ MeV}.$	

Will be a breakthrough for exotic meson if established

Arguable to call below J/ψ mass events as J/ψ^* since J/ψ is very narrow, same for Y^*

Prospect of exotic meson studies at ATLAS and CMS

Run II data-taking is started, we expect $\sim 500 \text{ fb}^{-1}$ 13 TeV data.

--production of $X(3872)$ @CMS as a function of center-of-mass energy: 7/8/13 TeV

--amplitude analysis of $B^0 \rightarrow \psi(2S)K^+\pi^-$, $B^+ \rightarrow J/\psi\phi K^+$ systems, possible more states

--search for exotic in heavy sector: $J/\psi J/\psi(^*)$, $Y(nS)Y(nS)(^*)$, $Y(nS)\phi$, ...

--tackle the near VV threshold puzzle?

Why it is interesting? Very clean system:

--cannot bound by exchanging

pion— V isospin zero ; photon— V charge zero; one gluon— V is color singlet;

--two gluons possible--Pomeron exchange? Final state scattering?

--learn back to nuclear scattering mechanism? Van de Waals bounding?

A puzzle possibly to be resolved at LHC—back to low energy nuclear physics

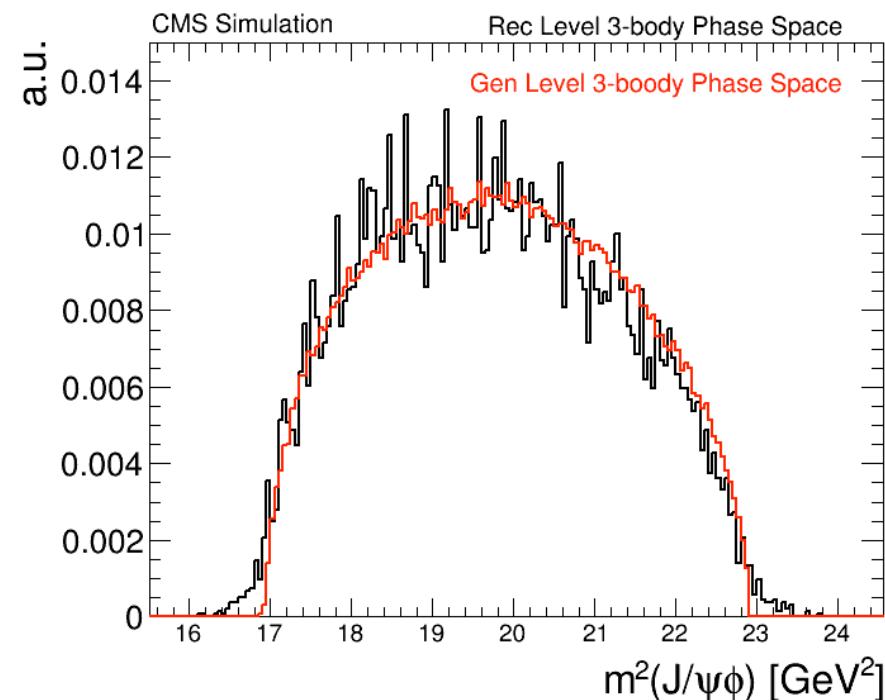
Summary

- *CMS/ATLAS detectors are excellent detectors for exotic studies*
- *CMS/ATLAS produced fruitful results on exotic mesons*
- *A near VV threshold puzzle?*
- *Bright prospects for Run II*

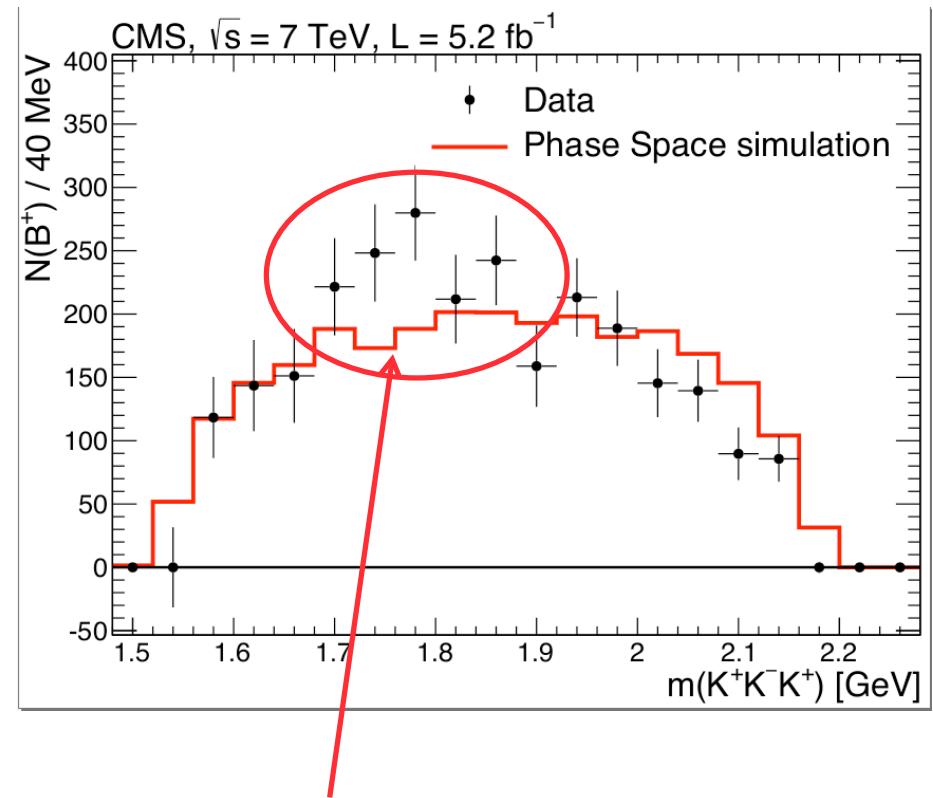
Stay tuned!

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)

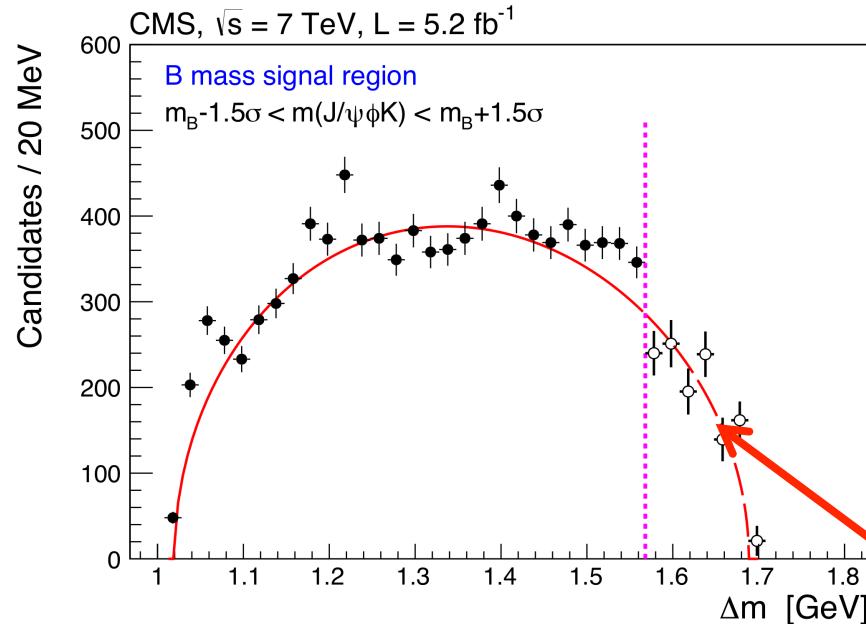


CMS detector does not produce peaks
Also imply relative flat efficiency

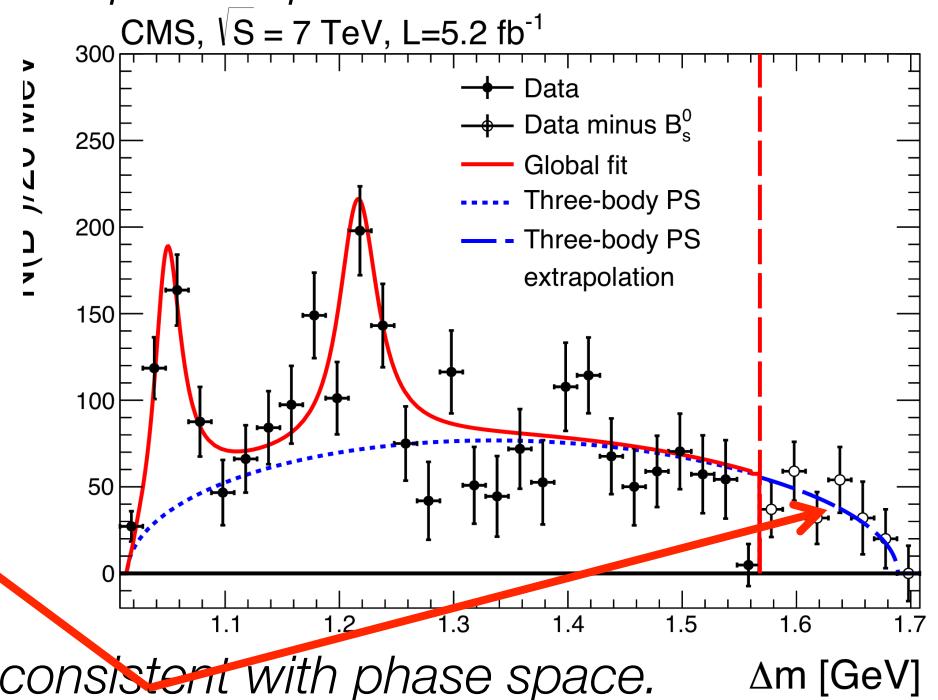
Possible $K^*(1770)$?
Does it effect Δm ?

Further Investigation in the whole Δm region

The Δm spectrum after subtracting B_s^0 contribution but including non- B evens, 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.

Demands an explanation