# Spectroscopy at CMS

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for the CMS Collaboration

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# Outline

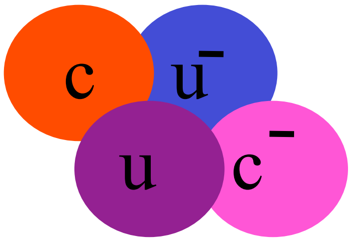
- **Heavy Exotic Meson**
  - **-- CMS Run I Contribution**
  - **-- Prospective @ CMS Run II**

- **B Hadron Spectroscopy**
  - **-- CMS Run I Contribution**
  - **-- Prospective @ CMS Run II**

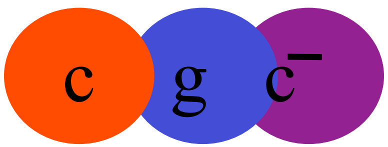
- **Summary**

# Background: What is Exotic mesons

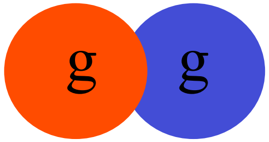
- Multi-quark mesons
  molecule
  diquark-antidiquark




- Hybrid mesons
  quark-antiquark-gluon




- Glueball
  gluonic color singlet states




Candidates: X/Y/Z discovered in the last decade

# X/Y/Z Family

| State | $M$ (MeV) | $\Gamma$ (MeV) | $J^{PC}$ | Process (decay mode) | Experiment (#$\sigma$) | 1st observation |
|---|---|---|---|---|---|---|
| $X(3823)$ | $3823.1 \pm 1.9$ | $< 24$ | $?^{?-}$ | $B \to K + (\chi_{c1}\gamma)$ | Belle [4] (3.8) | Belle 2013 |
| **$X(3872)$** | $3871.68 \pm 0.17$ | $< 1.2$ | $1^{++}$ | $B \to K + (J/\psi\,\pi^+\pi^-)$ | Belle [5, 6] (12.8), *BABAR* [7] (8.6) | Belle 2003 |
| | | | | $p\bar{p} \to (J/\psi\,\pi^+\pi^-) + \ldots$ | CDF [8–10] (np), DØ [11] (5.2) | |
| | | | | $B \to K + (J/\psi\,\pi^+\pi^-\pi^0)$ | Belle [12][a] (4.3), *BABAR* [13][a] (4.0) | |
| | | | | $B \to K + (D^0\bar{D}^0\pi^0)$ | Belle [14, 15][a] (6.4), *BABAR* [16][a] (4.9) | |
| | | | | $B \to K + (J/\psi\,\gamma)$ | Belle [17][a] (4.0), *BABAR* [18, 19][a] (3.6) | |
| | | | | $B \to K + (\psi(2S)\,\gamma)$ | *BABAR* [19][a] (3.5), Belle [17][a] (0.4) | |
| | | | | $pp \to (J/\psi\,\pi^+\pi^-) + \ldots$ | LHCb [20] (np) | |
| **$X(3915)$** | $3917.5 \pm 1.9$ | $20 \pm 5$ | $0^{++}$ | $B \to K + (J/\psi\,\omega)$ | Belle [21] (8.1), *BABAR* [22] (19) | Belle 2004 |
| | | | | $e^+e^- \to e^+e^- + (J/\psi\,\omega)$ | Belle [23] (7.7), *BABAR* [13, 24](7.6 ) | |
| **$\chi_{c2}(2P)$** | $3927.2 \pm 2.6$ | $24 \pm 6$ | $2^{++}$ | $e^+e^- \to e^+e^- + (D\bar{D})$ | Belle [25] (5.3), *BABAR* [26] (5.8) | Belle 2005 |
| $X(3940)$ | $3942^{+9}_{-8}$ | $37^{+27}_{-17}$ | $?^{?+}$ | $e^+e^- \to J/\psi + (D^*\bar{D})$ | Belle [27] (6.0) | Belle 2007 |
| | | | | $e^+e^- \to J/\psi + (\ldots)$ | Belle [28] (5.0) | |
| **$G(3900)$** | $3943 \pm 21$ | $52 \pm 11$ | $1^{--}$ | $e^+e^- \to \gamma + (D\bar{D})$ | *BABAR* [29] (np), Belle [30] (np) | *BABAR* 2007 |
| $Y(4008)$ | $4008^{+121}_{-49}$ | $226 \pm 97$ | $1^{--}$ | $e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$ | Belle [31] (7.4) | Belle 2007 |
| **$Y(4140)$** | $4144.5 \pm 2.6$ | $15^{+11}_{-7}$ | $?^{?+}$ | $B \to K + (J/\psi\,\phi)$ | CDF [32, 33] (5.0), CMS [34] (>5) | CDF 2009 |
| $X(4160)$ | $4156^{+29}_{-25}$ | $139^{+113}_{-65}$ | $?^{?+}$ | $e^+e^- \to J/\psi + (D^*\bar{D}^*)$ | Belle [27] (5.5) | Belle 2007 |

Hardon colliders played critical role

[a] Not included in the averages for $M$ and $\Gamma$.

# X/Y/Z Family

| State | $M$ (MeV) | $\Gamma$ (MeV) | $J^{PC}$ | Process (decay mode) | Experiment (#$\sigma$) | 1st observation |
|---|---|---|---|---|---|---|
| $\boldsymbol{Y(4260)}$ | $4263^{+8}_{-9}$ | $95\pm14$ | $1^{--}$ | $e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$ | *BABAR* [35, 36] (8.0), CLEO [37] (5.4) | *BABAR* 2005 |
| | | | | | Belle [31] (15) | |
| | | | | $e^+e^- \to (J/\psi\,\pi^+\pi^-)$ | CLEO [38] (11) | |
| | | | | $e^+e^- \to (J/\psi\,\pi^0\pi^0)$ | CLEO [38] (5.1) | |
| $Y(4274)$ | $4274.4^{+8.4}_{-6.7}$ | $32^{+22}_{-15}$ | $?^{?+}$ | $B \to K + (J/\psi\,\phi)$ | CDF [33] (3.1) | CDF 2010 |
| $X(4350)$ | $4350.6^{+4.6}_{-5.1}$ | $13.3^{+18.4}_{-10.0}$ | $0/2^{++}$ | $e^+e^- \to e^+e^-\,(J/\psi\,\phi)$ | Belle [39] (3.2) | Belle 2009 |
| $\boldsymbol{Y(4360)}$ | $4361\pm13$ | $74\pm18$ | $1^{--}$ | $e^+e^- \to \gamma + (\psi(2S)\,\pi^+\pi^-)$ | *BABAR* [40] (np), Belle [41] (8.0) | *BABAR* 2007 |
| $X(4630)$ | $4634^{+\ 9}_{-11}$ | $92^{+41}_{-32}$ | $1^{--}$ | $e^+e^- \to \gamma\,(\Lambda_c^+\Lambda_c^-)$ | Belle [42] (8.2) | Belle 2007 |
| $Y(4660)$ | $4664\pm12$ | $48\pm15$ | $1^{--}$ | $e^+e^- \to \gamma + (\psi(2S)\,\pi^+\pi^-)$ | Belle [41] (5.8) | Belle 2007 |
| $\boldsymbol{Z_c^+(3900)}$ | $3898\pm5$ | $51\pm19$ | $1^{?-}$ | $Y(4260) \to \pi^- + (J/\psi\,\pi^+)$ | BESIII [43] (np), Belle [44] (5.2) | BESIII 2013 |
| | | | | $e^+e^- \to \pi^- + (J/\psi\,\pi^+)$ | Xiao *et al.* [45][a] (6.1) | |
| $Z_1^+(4050)$ | $4051^{+24}_{-43}$ | $82^{+51}_{-55}$ | ? | $B \to K + (\chi_{c1}(1P)\,\pi^+)$ | Belle [46] (5.0), *BABAR* [47] (1.1) | Belle 2008 |
| $Z_2^+(4250)$ | $4248^{+185}_{-\ 45}$ | $177^{+321}_{-\ 72}$ | ? | $B \to K + (\chi_{c1}(1P)\,\pi^+)$ | Belle [46] (5.0), *BABAR* [47] (2.0) | Belle 2008 |
| $Z^+(4430)$ | $4443^{+24}_{-18}$ | $107^{+113}_{-\ 71}$ | ? | $B \to K + (\psi(2S)\,\pi^+)$ | Belle [48, 49] (6.4), *BABAR* [50] (2.4) | Belle 2007 |
| $Y_b(10888)$ | $10888.4\pm3.0$ | $30.7^{+8.9}_{-7.7}$ | $1^{--}$ | $e^+e^- \to (\Upsilon(nS)\,\pi^+\pi^-)$ | Belle [51, 52] (2.0) | Belle 2010 |
| $Z_b^+(10610)$ | $10607.2\pm2.0$ | $18.4\pm2.4$ | $1^{+-}$ | $\Upsilon(5S) \to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n=1,2,3$ | Belle [53, 54] (16) | Belle 2011 |
| | | | | $\Upsilon(5S) \to \pi^- + (h_b(nP)\,\pi^+)$, $n=1,2$ | Belle [53, 54] (16) | |
| $Z_b^+(10650)$ | $10652.2\pm1.5$ | $11.5\pm2.2$ | $1^{+-}$ | $\Upsilon(5S) \to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n=1,2,3$ | Belle [53, 54] (16) | Belle 2011 |
| | | | | $\Upsilon(5S) \to \pi^- + (h_b(nP)\,\pi^+)$, $n=1,2$ | Belle [53, 54] (16) | |

[a]Not included in the averages for $M$ and $\Gamma$.

Extended to bottom sector

# Some Facts about the X/Y/Z Family

- The first heavy exotic candidate: X(3872) (2003)

- The first charged exotic candidate: Z+(4430) (2006)

- The first exotic candidate discovered in Hadron collider: Y(4140)

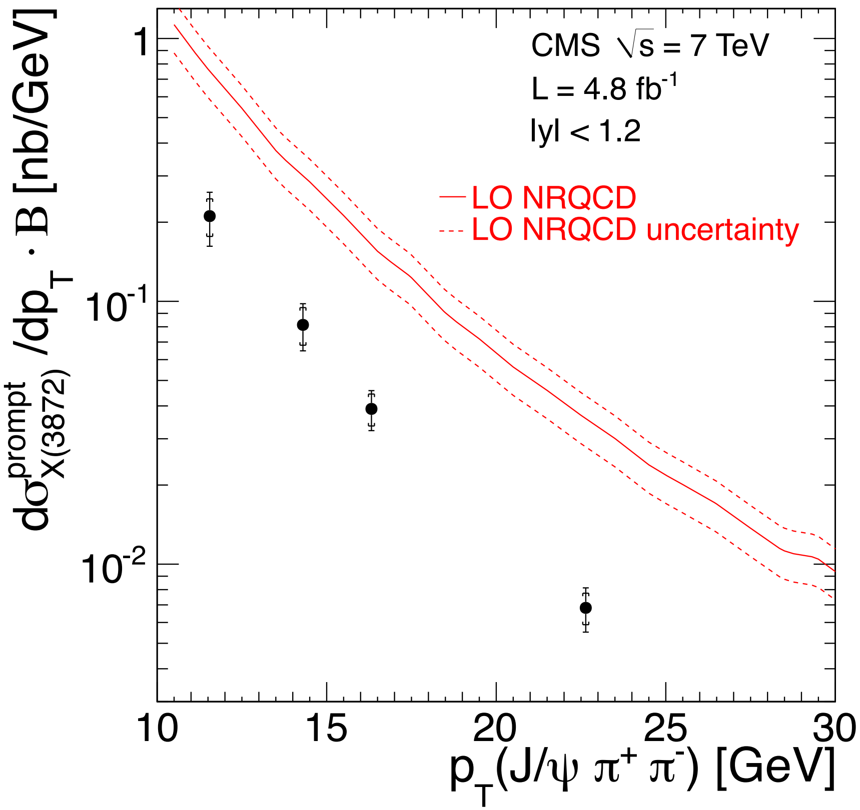
- The first exotic candidate in bottom sector: $Y_b$(10888)

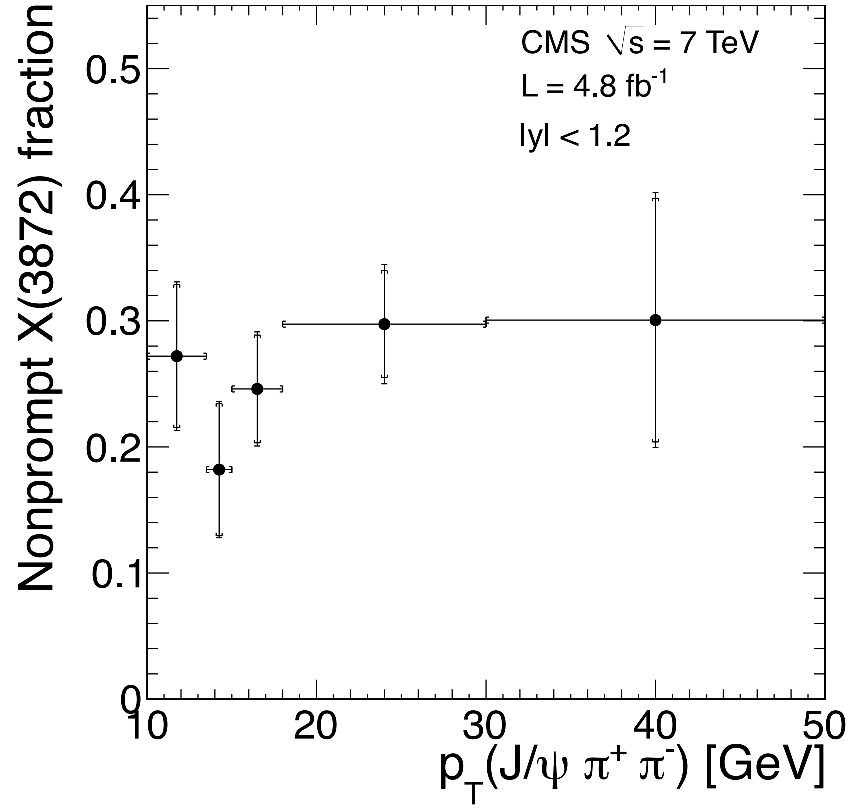
- The first exotic candidate discovered from decay of an exotic candidate: Zc(3900) from Y(4260)

There are about 20 such candidates now.
The charged ones are identified as four-quark states, no solid explanations for others.

# CMS Run I Contribution-X(3872)

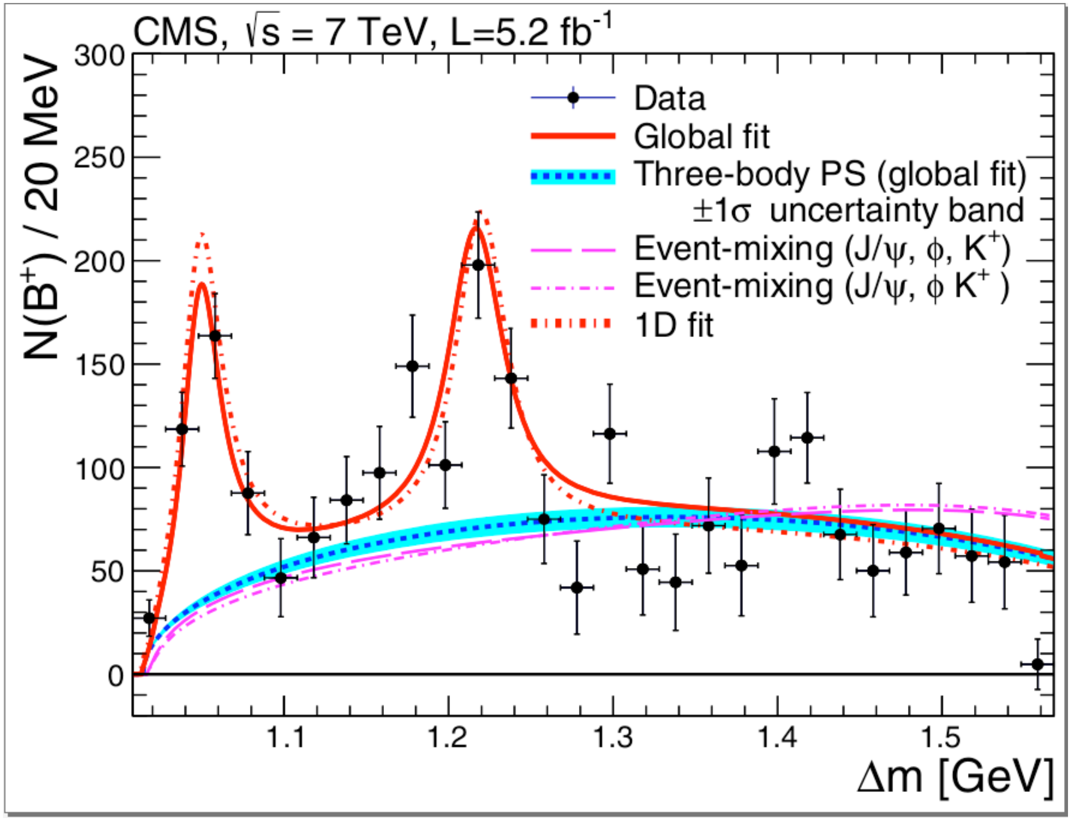
JHEP 1304 (2013) 154, cited 62 times




Non-prompt production ratio ~30%, differential cross section significantly lower than theoretical prediction.

# CMS Run I Contribution-Y(4140)



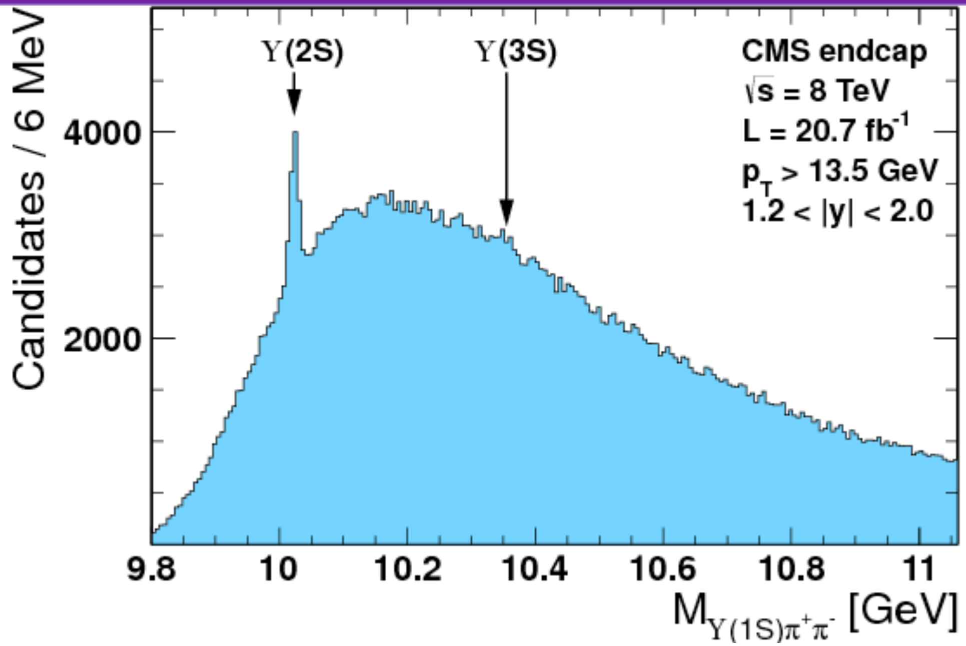

PLB 734 (2014) 261-281
Cited 45 times

CMS spotted a second structure at a higher position in the same spectrum

CMS played critical role to establish its existence due to the conflict between LHCb (PRD85 (2012) 091103) and CDF (PRL102 (2009) 242002).

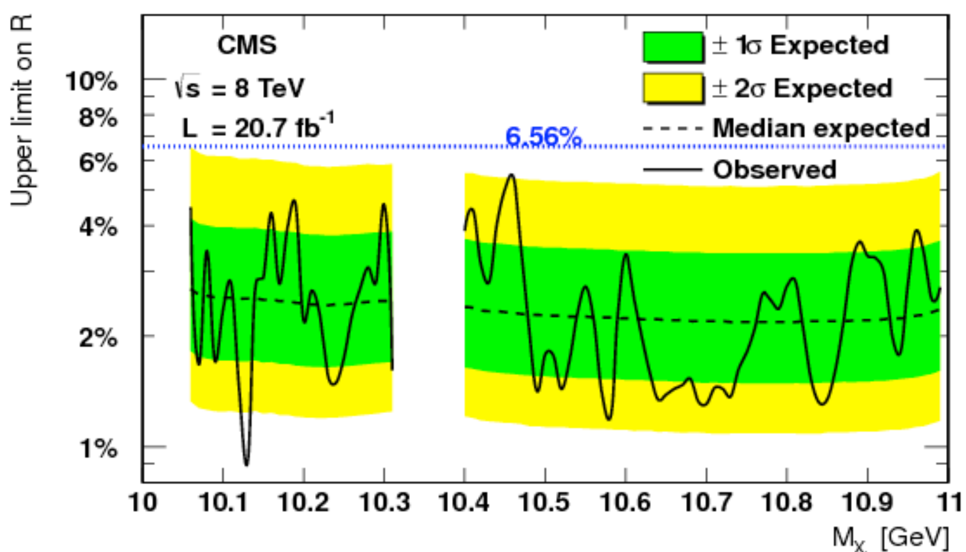
Do not really know its nature! CMS will contribute more!

# CMS Run I Contribution-$X_B$ Searches




[PLB 727 (2013) 57](#)
Cited 24 times

CMS sets the first time limit at LHC




CMS can certainly continue at RUN II

# The CMS Detector and Trigger

Excellent muon/silicon detectors for spectroscopy:

- Muon system
  - High-purity muon identification, covers rapidity up to 2.5
  - Good dimuon mass resolution ($\Delta m/m \sim 0.6\%$ for $J/\Psi$ @8TeV
- Silicon Tracking detector
  - excellent track momentum resolution ($\Delta p_T/p_T \sim 1\%$)
  - excellent vertex reconstruction and impact parameter resolution, good for B decays

CMS trigger:

- Restriction: muon trigger (before tracker trigger)
- Two types of muon triggers
  - Displaced muon triggers—for B decays
  - Prompt muon triggers—for prompt production, dimuon, triple-muon

Since there is no effective hadron PID @CMS, we should explore more on lepton final states based on CMS muon triggers at Run II!

# CMS Run II—J/ψϕ Spectrum in B Decays

Y(4140) and more via B decays I

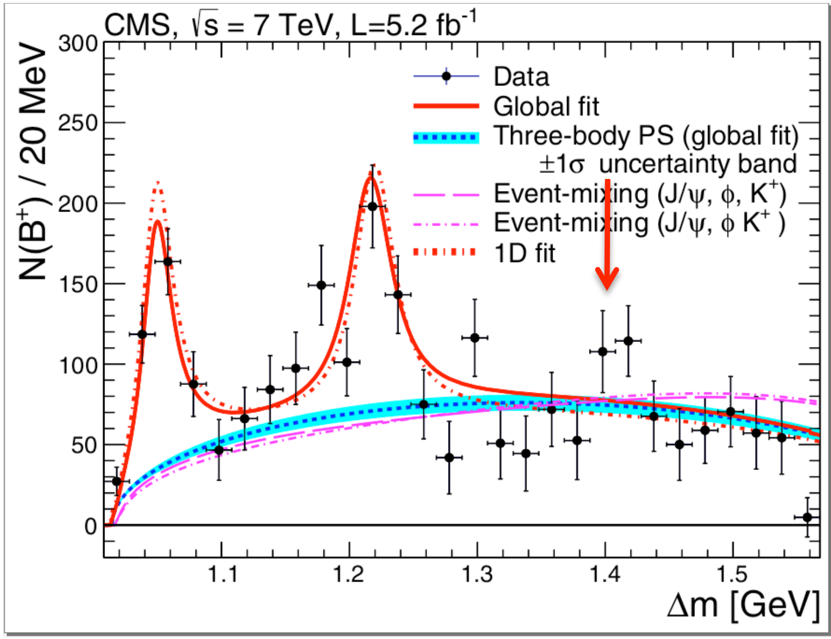
CMS/D0 confirmed its existences, PLB 734 (2014) 261-281, PRD89 012004
arXiv: 1508.07846 (D0 inclusive)

Babar sees a hint (insignificant): PRD91 (2015) 012003

BES search via J/ψ radiative decay
PRD91 (2015) , 032002

Not really understand its nature, $0^{?+}$
Mass/width/BF not well measured.
$J^{PC}$ not measured

Possible a third peak?
Further investigation in $m(\phi K^+)$ & $m(J/\psi K^+)$?




CMS is planning an update at Run II with large statistics
via B decays and may be via prompt production

# CMS Run II—Other Analyses in B Decays

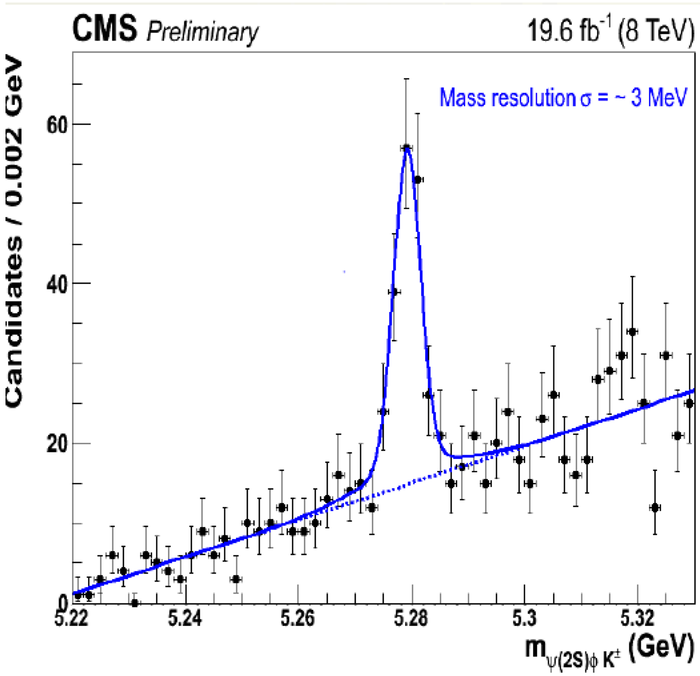
Y(4140) and more via B decays II

Is it just a threshold effect structure or a resonance like structure?

Threshold effect—it has to be channel dependent
Resonance-like structure—Can we find another decay channel?
We know it is negligible for its decay to $J/\psi f_0$ in 2011 data.
How about $J/\psi\gamma$ (conversion) via B decays?
(BF can be measured relative to $\chi_C \rightarrow J/\psi\gamma$ if observed)

Similar structures in other channel?

For instance, $B^+ \rightarrow \psi(2S)\phi K^+$
(phase space too narrow, need large statistics)



# CMS Run II—Prompt Exotic Mesons

pp collision has rich production mechanism, the exotic may be produced promptly, it can help understand their nature through measurement of their production cross section if observed

Measure prompt X(3872) differential cross section at 13 TeV

search for promptly produced Z+(4430), $Z_C(3900)$?

Search for promptly produced Y(4140)?

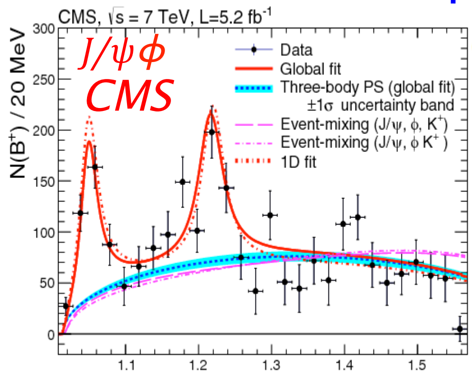
Search for possible structures in $\psi(2S)\phi$ mass spectrum promptly?

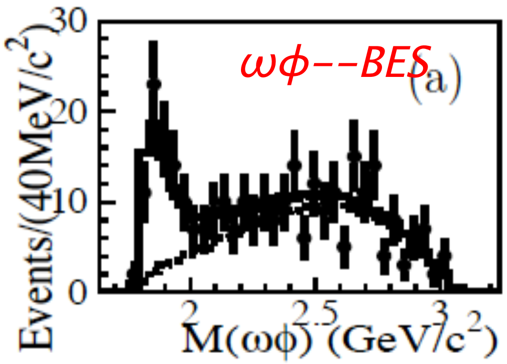
We do not have hadron PID, it may be difficult, but it is worth to try with large statistics.

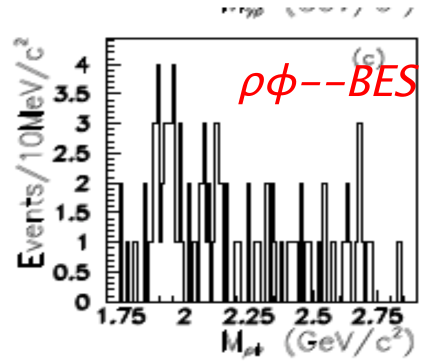
But we do have excellent lepton PID.

# CMS Run II—Prompt Exotic Mesons

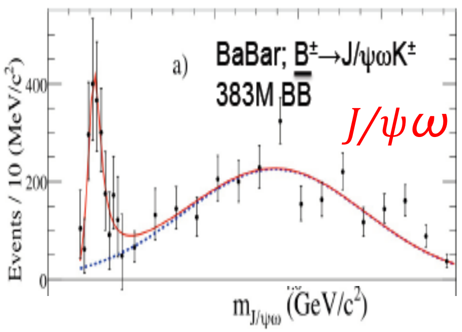
## Near VV threshold puzzle

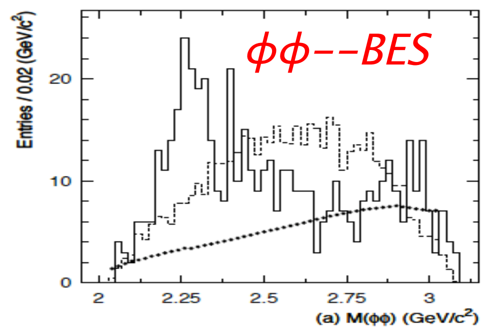


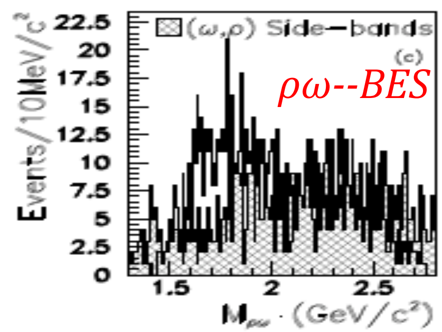




PRD 77, 012001(2008)




*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?*

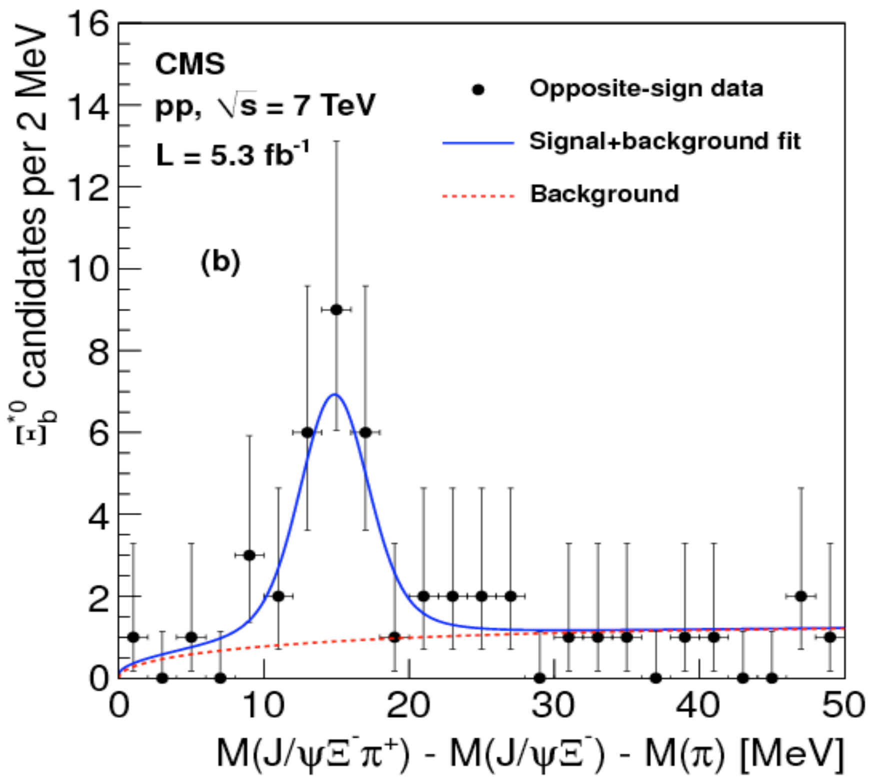
*--learn back to nuclear scattering mechanism? Van de Waals bounding?*



*Extend to other VV states?*

# CMS Run I B Hadron Contribution-Xi(b)

PRL 108 (2012) 252002, cited 56 times




First new particle observed at CMS

Very clean signal

Other activities on B hadrons are going on at CMS, including search for the penta-quark candidate P(4300) discovered by LHCb.

Can do well in some channels, by taking advantage of long life time etc.
Some channels are difficult due to lack of hadron PID

We will continue B Hadron spectroscopy studies at Run II for sure

# Summary

- There are interesting physics in X/Y/Z sage
- CMS has contributed significantly to this topic
- CMS is promising in X/Y/Z physics at Run II
- CMS has contributed to B hadron spectroscopy and is promising at Run II
- Let’s work on it with other LHC experiments together

Thank you

# Backup