中國科學院高能物理研究所
Institute of High Energy Physics
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# Experimental Status on Exotic Hadrons

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# Outline

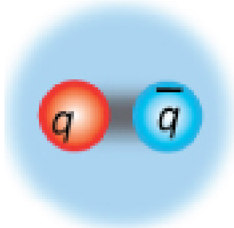
- Introduction
- Selected results on exotic hadron candidates – mainly charmonium sector
  - Observation of structure in J/ψ pair mass spectrum -- $T_{cc\bar{c}\bar{c}}$
  - X(3872)
  - Y(4260)
  - Z states ($Z_c$ and $Z_b$)
  - $P_c$ states
- Summary

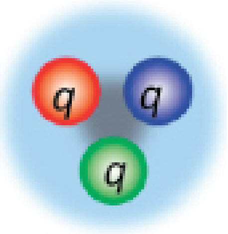
# Exotic hadrons

- Conventional hadrons consist of 2 or 3 quarks：

Naive Quark Model：

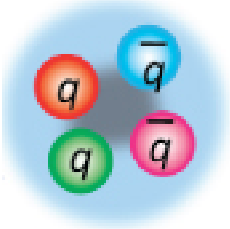
meson

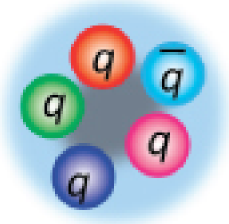


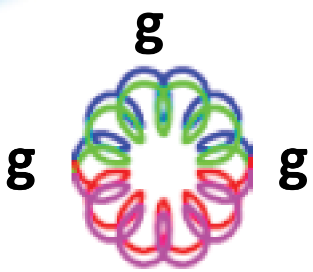

baryon

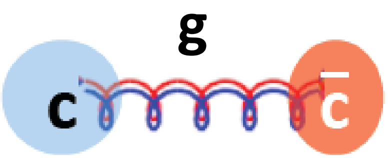
- QCD predicts the new forms of hadrons:
  - Multi-quark states ： Number of quarks >= 4




  - Hybrids ： $q\bar{q}g$， qqqg …
  - Glueballs ： gg， ggg …



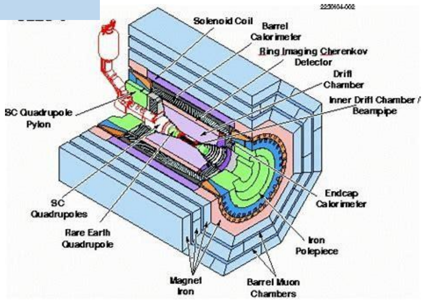




**None of the exotic hadrons is settled！**

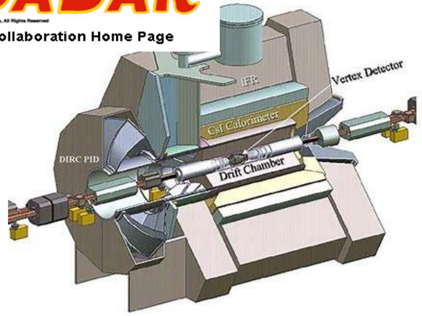
# Main contributors to the exotic hadrons

- $e^+e^-$ collider

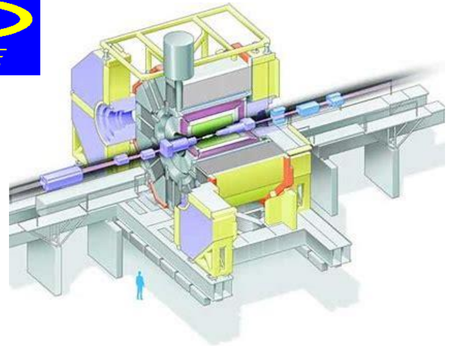
CLEO-c



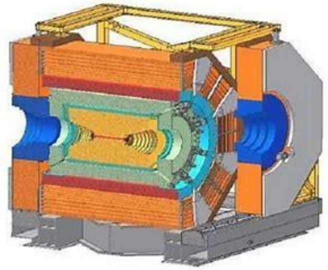

BABAR
Collaboration Home Page




BELLE

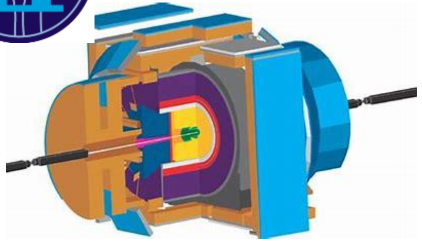


BESIII



- Hadron collider

CDF II



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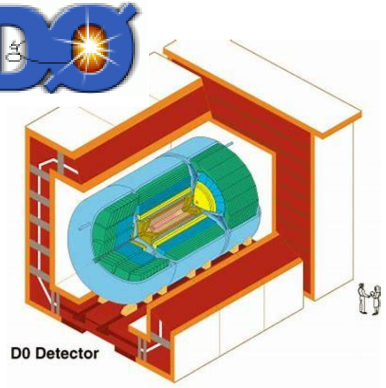
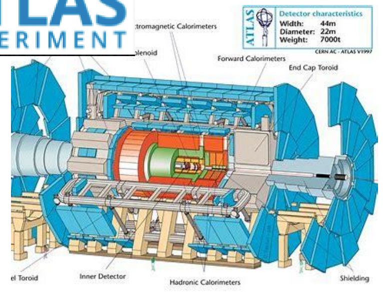
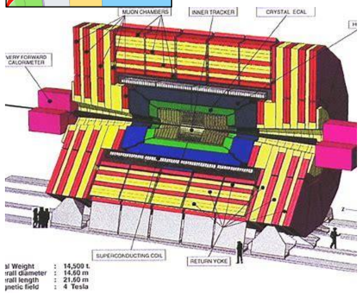


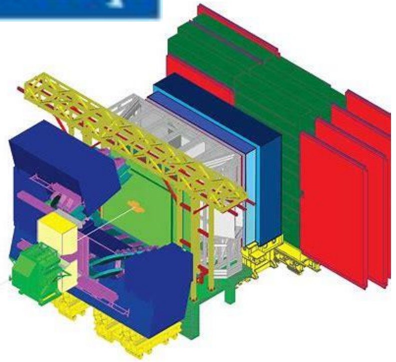

ATLAS EXPERIMENT




CMS

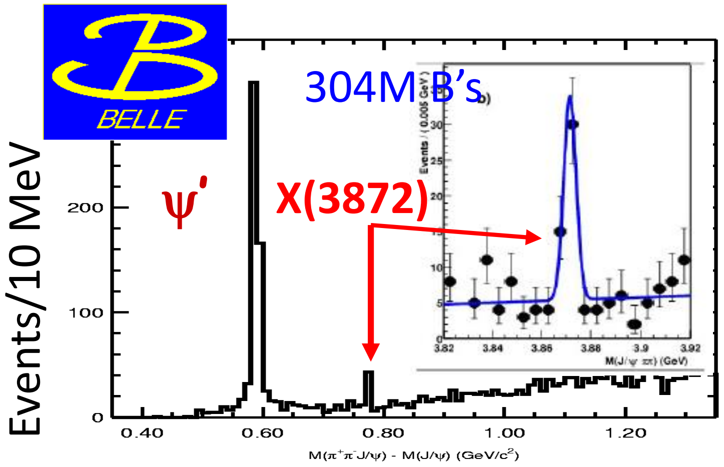


LHCb



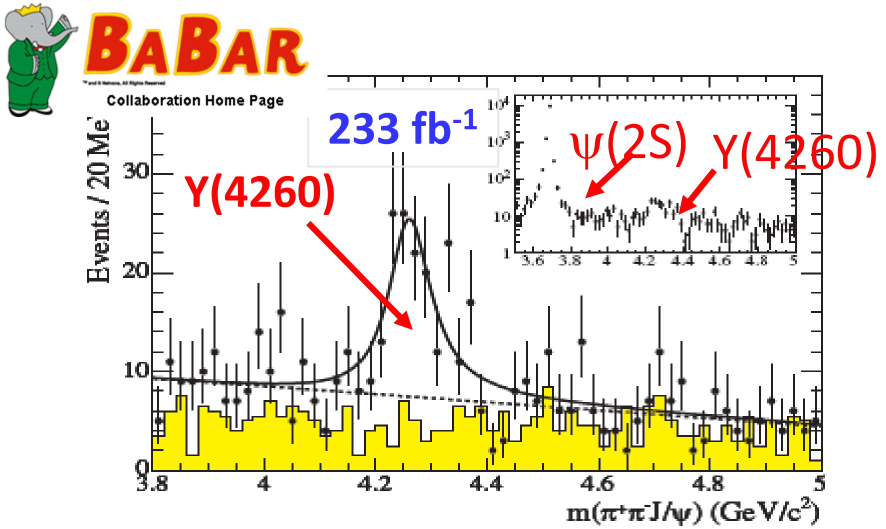
**I apologize for not covering all the experiments and results.**

# XYZ particles at the beginning (charmonium sector)



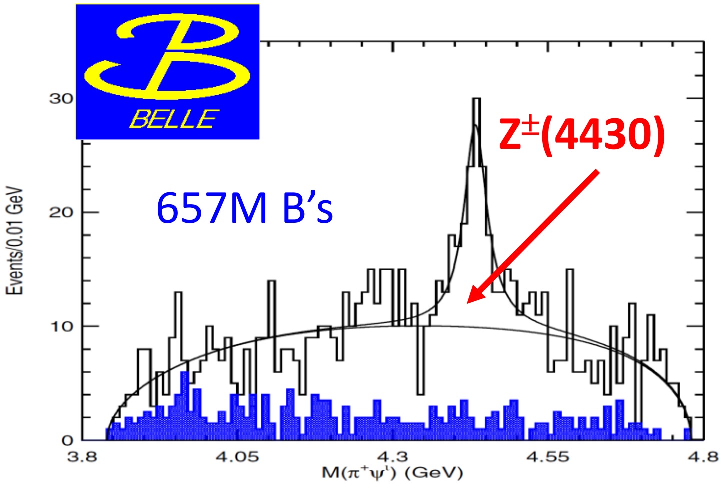

PRL 91 (2003) 262001

$B^{\pm} \to K^{\pm} \pi^{+} \pi^{-} J/\psi$




PRL 95 (2005) 142001

$e^{+} e^{-} \to \gamma_{\rm ISR} \pi^{+} \pi^{-} J/\psi$



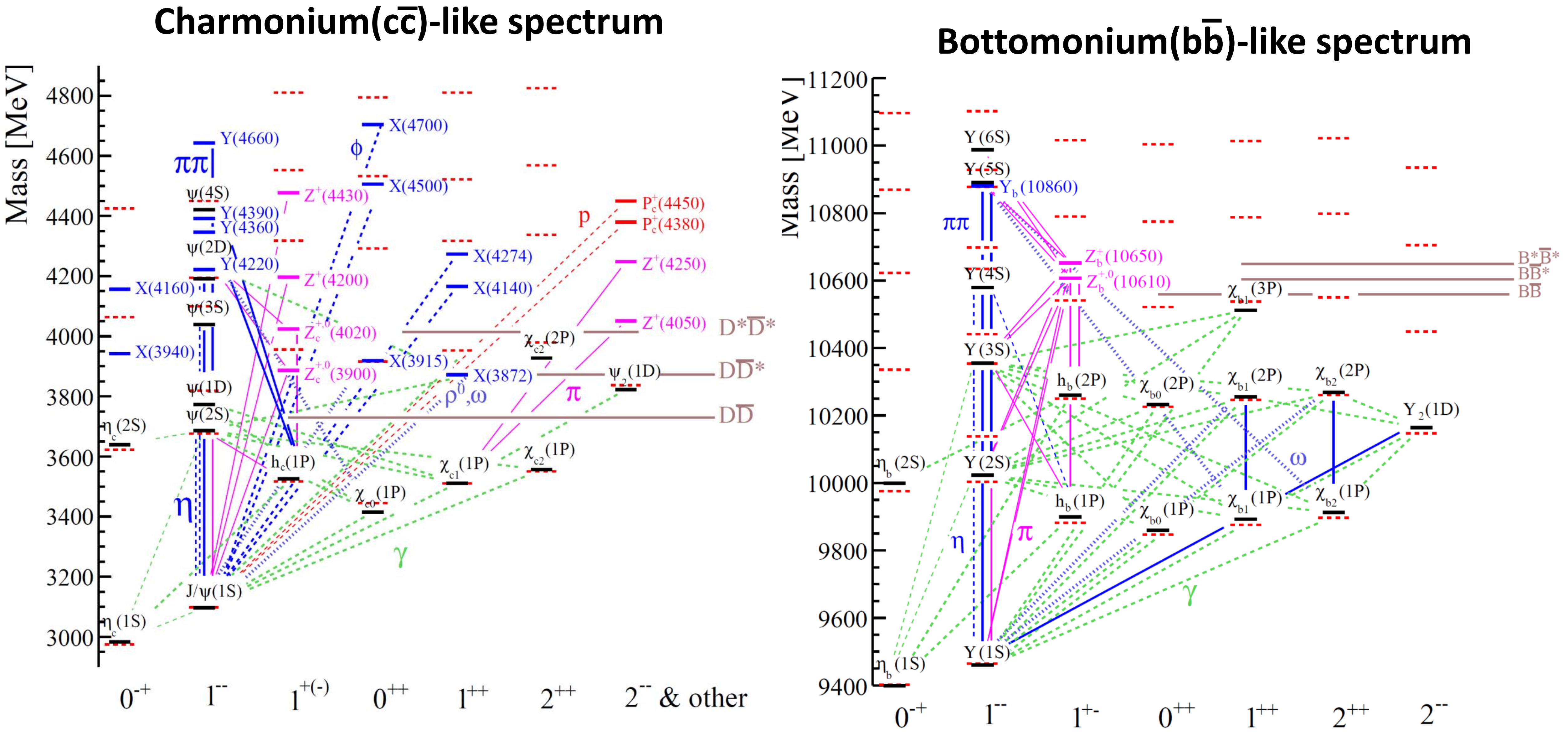

PRL 100 (2008) 142001

$B \to K \pi^{\pm} \psi'$

- X(3872) was first observed by Belle, then confirmed by other exps.
- Y(4260) was first observed by Babar, then confirmed by other exps.
- $Z^{\pm}$(4430) was first observed by Belle, not in Babar, confirmed by LHCb

Inspired the observation of lots of exotic hadron candidates in many exps.
Opened a new era of exotic, quakonium-like spectroscopy.

From Stephen L. Olsen et al., Rev. Mod. Phys. 90, 15003(2018)



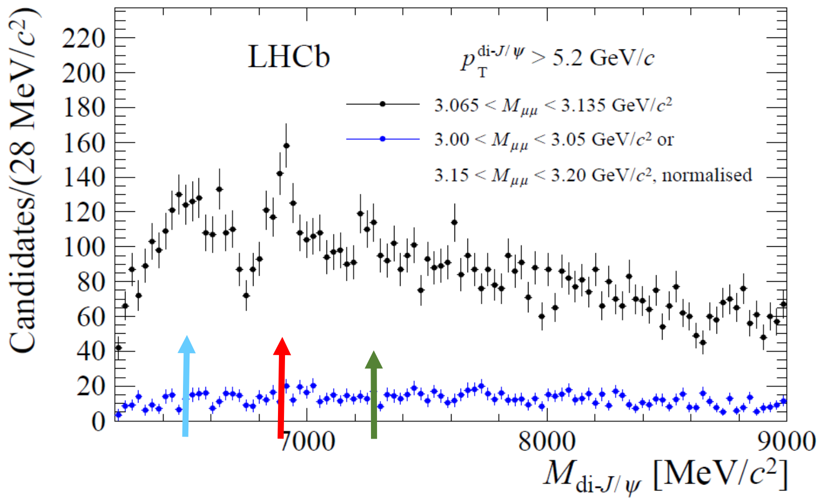

**Mainly focus on the results in charmonium sector**

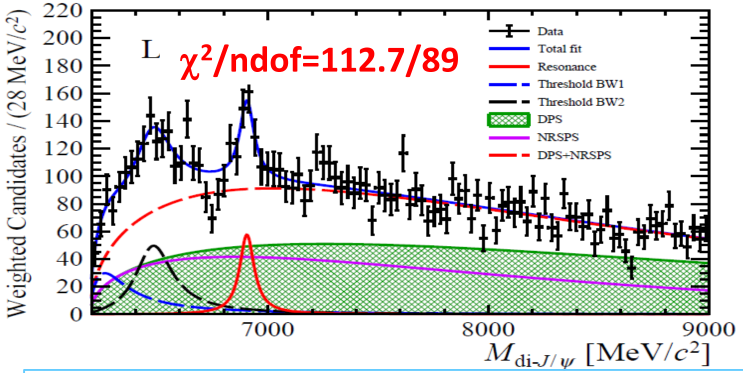
# Observation of structure in the J/ψ-pair mass spectrum

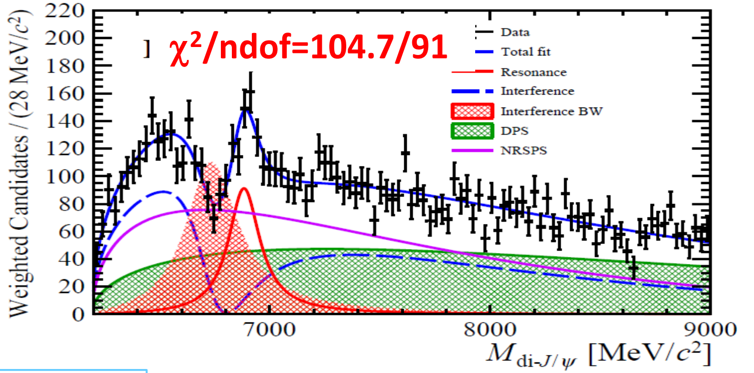
See talk by Daniel Johnson

LHCb: arXiv: 2006.16957

- **Theoretical predictions for the tetraquark states comprising only charm quarks $T_{cc\bar{c}\bar{c}}$ vary from 5.8 to 7.4 GeV/$c^2$ (lots of refs., see the list in arXiv:2006.16957)**
- **Search for $T_{cc\bar{c}\bar{c}}$ states in the di-J/ψ invariant mass spectrum @sqrt(s) = 7, 8 and 13 TeV, 9 fb$^{-1}$**




- Narrow structure ~ 6.9 GeV/$c^2$
- Broad structure near threshold
- Hint for another structure ~ 7.2 GeV/$c^2$
- No evidence for structures > 7.2 GeV/$c^2$

**Tetraquark candidate with $cc\bar{c}\bar{c}$.**

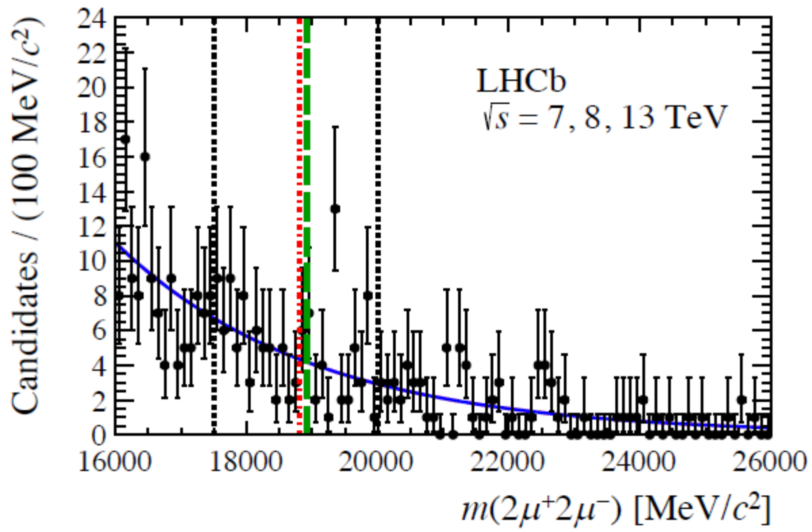
- S-wave BW for X(6900); 2 BWs for threshold enhancement; phase space
- No interference
- M=6905 ±11±7 MeV/$c^2$
  Γ=80 ±19 ±33 MeV/$c^2$
- Relative production cross-section R: (to that of all prompt J/ψ pairs)
  R=(2.6 ±0.6 ±0.8)% $p_T$>5.2 GeV/$c^2$
  R=(1.1 ±0.4 ±0.3)% full $p_T$ range

- S-wave BW for X(6900);
- a lower mass state;
- Interference considered
- M=6886 ±11±11 MeV/$c^2$
  Γ=168 ±33 ±69 MeV/$c^2$

# $T_{bb\bar{b}\bar{b}}$ searches at LHCb and CMS in the $\Upsilon\mu^+\mu^-$ decays

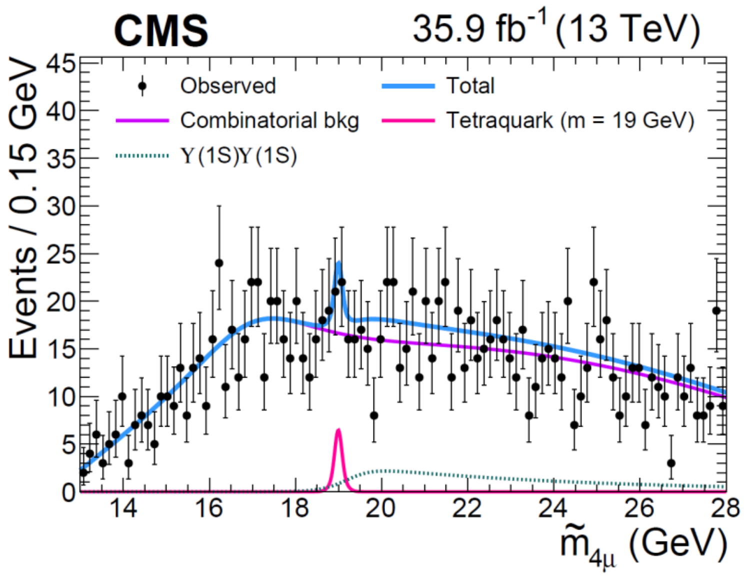
## $T_{bb\bar{b}\bar{b}}$ searches at LHCb (JHEP 10 (2018) 086)

- 6.3 $fb^{-1}$ at sqrt(s)=7, 8 and 13 TeV
- Explored the mass region 17.5 – 20.0 $GeV/c^2$
- No significant signal




## $T_{bb\bar{b}\bar{b}}$ searches at CMS (arXiv:2002.06393, accepted by PLB)

- 35.9 $fb^{-1}$ at sqrt(s)=13 TeV
- Explored the mass region 17.5 – 19.5 $GeV/c^2$
- No significant signal




**No tetraquark candidate with $bb\bar{b}\bar{b}$ is found.**

# X(3872) – named as $\chi_{c1}(3872)$ in PDG

## X(3872) properties

- Mass: $3871.69 \pm 0.17$ MeV/$c^2$, very close to $D^0\bar{D}^{*0}$ threshold
- Width: < 1.2 MeV
- $J^{PC}$: $1^{++}$ from angular correlation analysis in $B^+ \to K^+ X(3872) \to K^+ \rho J/\psi$ by LHCb

To understand X(3872) better:

- Find more production mechanisms of X(3872)
- Find more decay modes of X(3872)
- Measure the mass and width of X(3872) precisely

**In this talk**

# Production of X(3872)

- **From radiative decays of Y(4260): Y(4260) $\rightarrow \gamma$X(3872)**
  (BESIII: PRL 112, 092001(2014), PRL 122, 202001 (2019), see talk by Peirong LI in parallel session)
- **From $\Lambda_b^0$ decays: $\Lambda_b^0 \rightarrow pK^-$ X(3872)** (LHCb: JHEP 09, 028 (2019))
- **In two-photon process** (Belle: arXiv: 2007.05696 (2020). See talk by Sen JIA in parallel session.)
- **Production in heavy ion collision** (CMS preliminary ).
- **from $B_s$ decays: $B_s \rightarrow$ X(3872) $\phi$** (CMS: arXiv: 2005.04764)
- **From B decay: absolute rate** (Babar: PRL 124, 152001 (2020)), see talk by Fergus Wilson in parallel session

# Decay of X(3872)

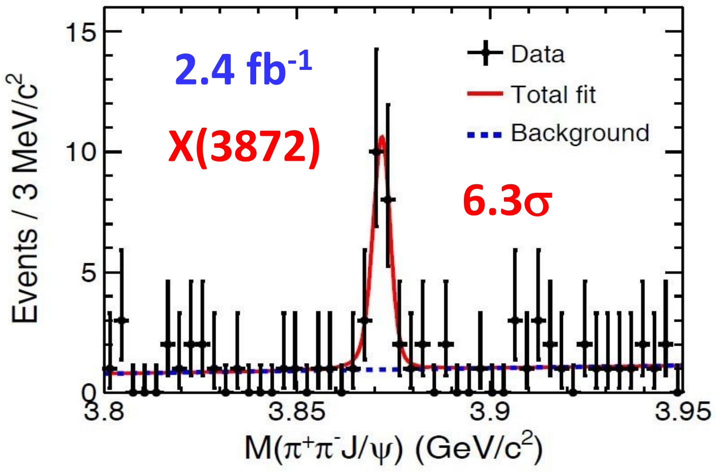
- **Radiative transition and open charm decay: X(3872) $\rightarrow \gamma$ J/$\psi$, $\gamma$ $\psi$(2S), $D^0\bar{D}^{*0}$, $\gamma D^+D^-$**
  (BESIII: arXiv: 2001.01156, see talk by Peirong LI in parallel session)
- **X(3872) $\rightarrow \omega$ J/$\psi$ and $\pi^0\chi_{c1}$** (BESIII: PRL122, 202001 (2019))

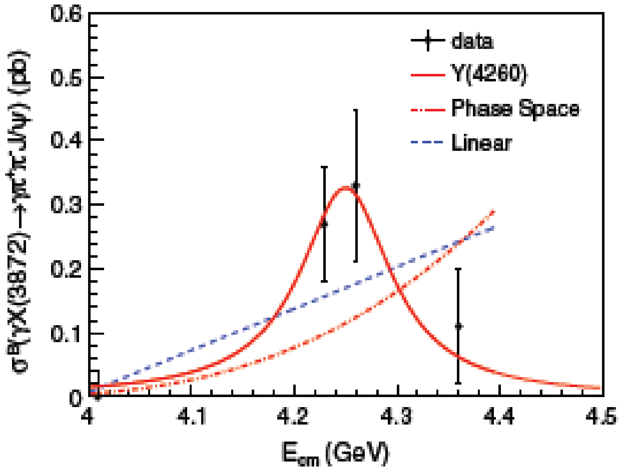
# Precise Measurement of M and $\Gamma$ from X(3872) lineshape

- **Inclusive b $\rightarrow$ X(3872) X decays** (LHCb: arXiv:2005.13419, see talk by Daniel Johnson in parallel session)
- **Exclusive B+ $\rightarrow$ X(3872) K+ decay** (LHCb: arXiv:2005.13422, See talk by Daniel Johnson in parallel session)

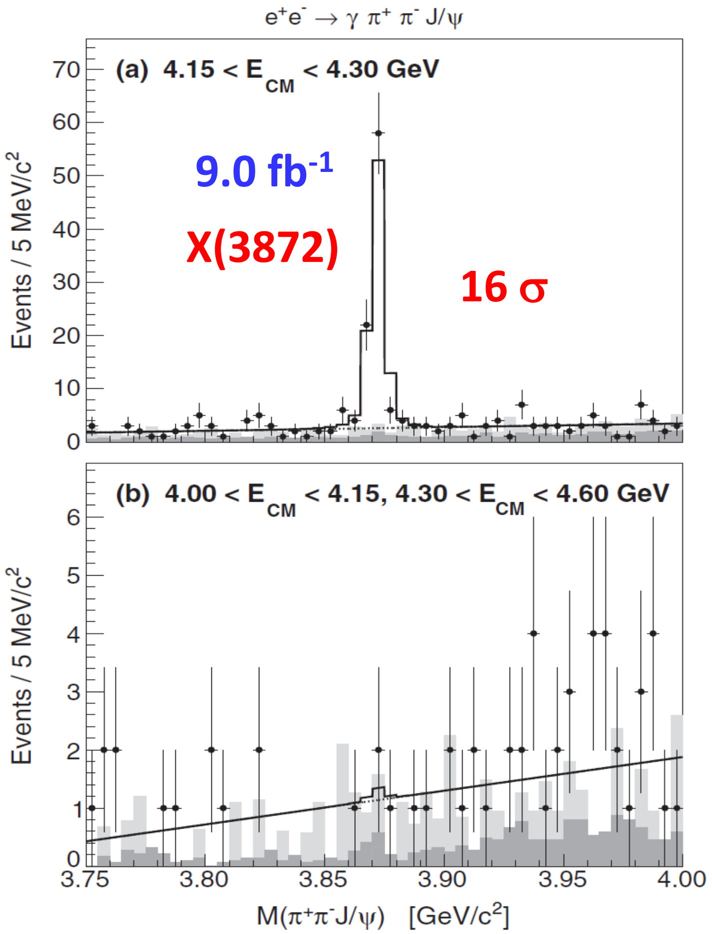
# Radiative production of X(3872) in $e^+e^- \to \gamma\, X(3872)$

BESIII: PRL 112. 092001 (2014)




BESIII: PRL 122, 202001 (2019)

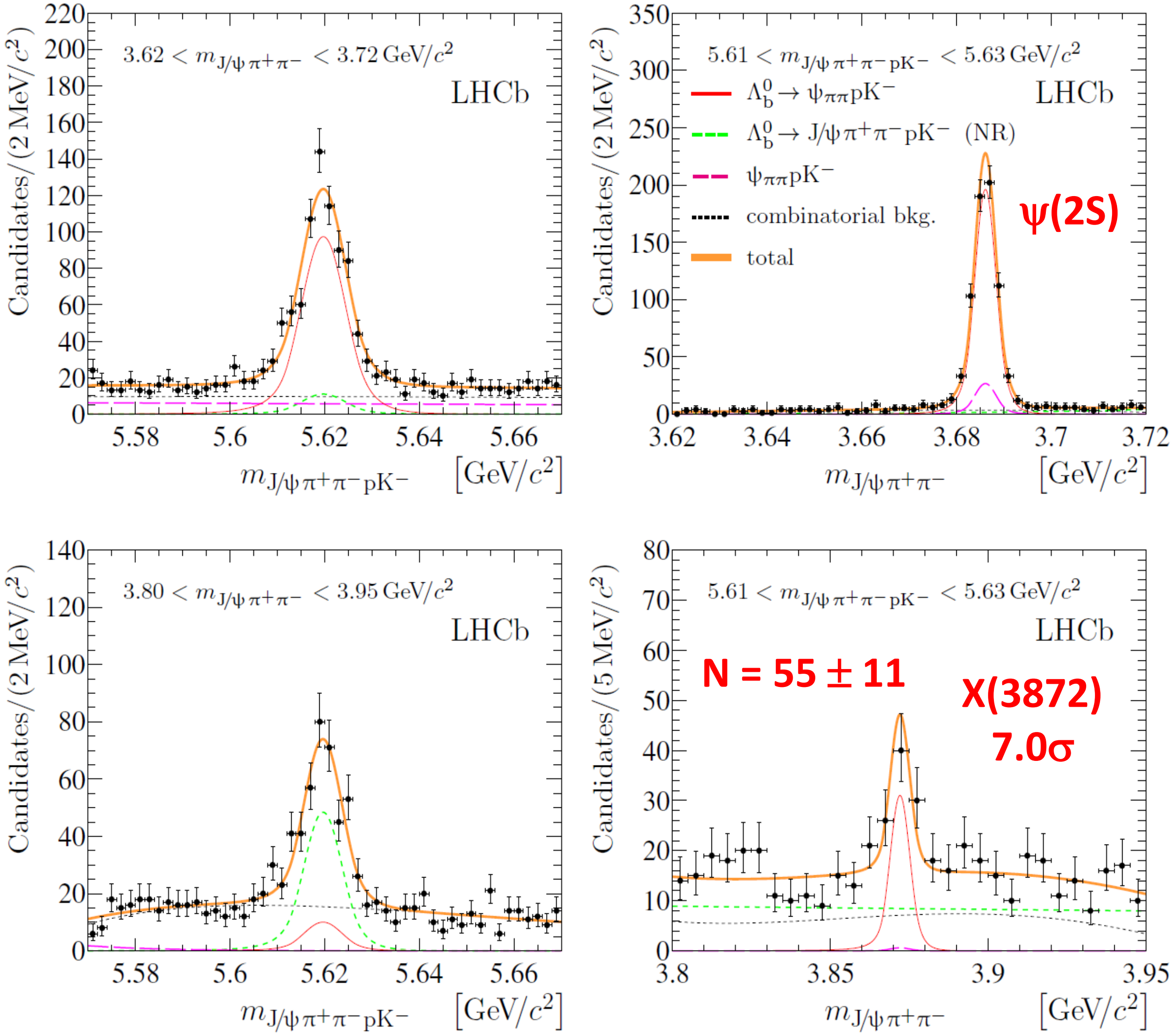



- Observed X(3872) @$E_{cm}$ = 4230, 4260, 4360MeV (2.4 $fb^{-1}$)
- Mass : 3871.9±0.7±0.2MeV
  [PDG : 3871.68±0.17MeV]
- Width : <2.4MeV at 90%C.L.
- Assuming $B(X(3872)\to\pi^+\pi^- J/\psi)$ = 5%

$$\frac{\sigma(Y(4260)\to\gamma X(3872))}{\sigma(Y(4260)\to\pi^+\pi^- J/\psi)} \sim 11\%, \text{ large ratio !}$$

# Observation of X(3872) from $\Lambda_b^0$ decays

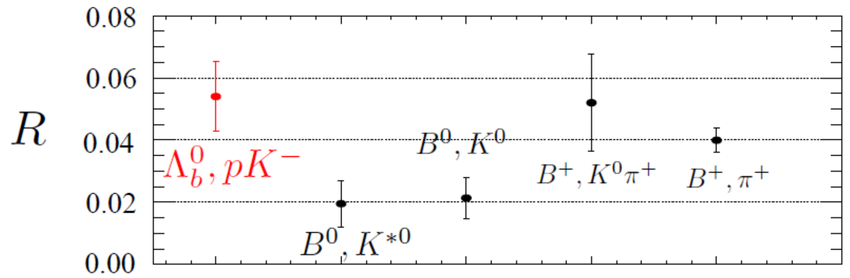
LHCb: JHEP 09, 028 (2019)




- **Data sets: 1.0, 2.0 and 1.9 fb$^{-1}$ for 7, 8, 13 TeV data**
- **$\Lambda_b^0 \to pK^-$ X(3872) observed with X(3872) $\to \pi^+\pi^- J/\psi$**
- **(58±15)% of the decays proceed via $\Lambda_b^0 \to \Lambda(1520)$ X(3872)**

$$R = \frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1}(3872) pK^-)}{\mathcal{B}(\Lambda_b^0 \to \psi(2S) pK^-)} \times \frac{\mathcal{B}(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)}$$

$$= (5.4 \pm 1.1 \pm 0.2) \times 10^{-2}$$



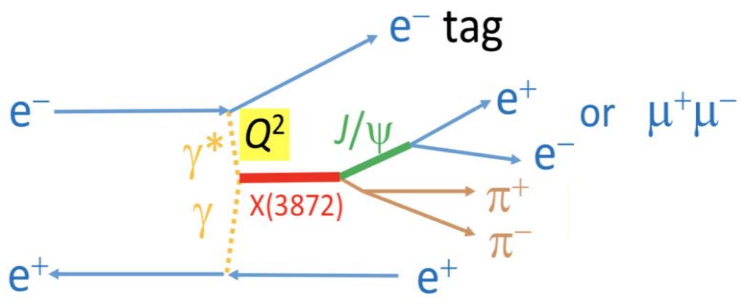
# First evidence for X(3872) in single tag two-photon ($\gamma\gamma^*$) interactions

See talk by Sen JIA in parallel session

Belle: arXiv: 2007.05696 (2020), submitted to PRL

**825 $fb^{-1}$@$\Upsilon$(nS) resonances (10.6GeV)**

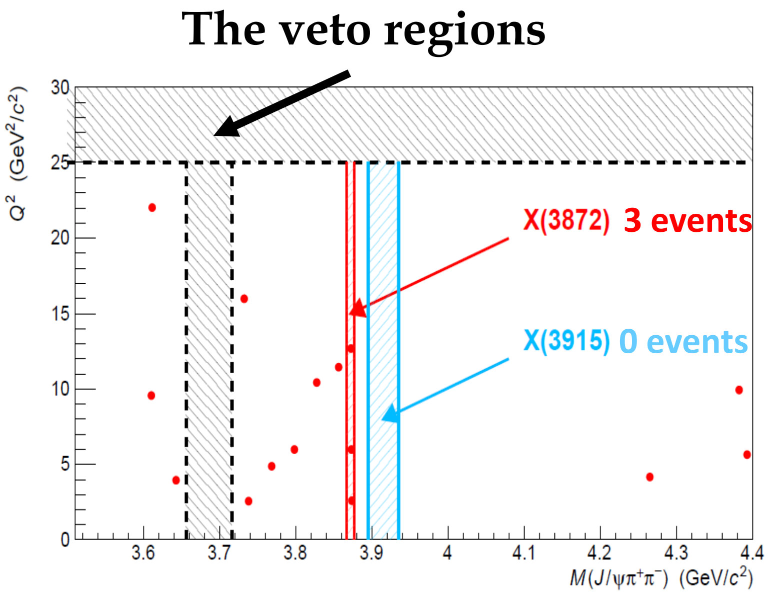
- **For $J^{PC} = 1^{++}$ X(3872), $\gamma\gamma \to$ X(3872) is forbidden.**
- **It is allowed if one or both photons are highly virtual** [Nucl. Phys. B 523, 423 (1998)].

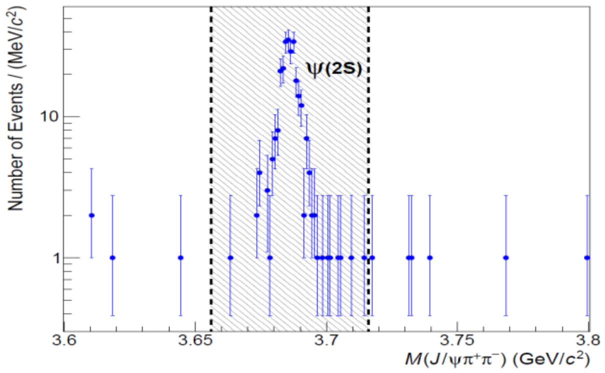



- **In $e^+e^- \to e^+e^-$ X(3872), tag $e^-$ in the final states, do not detect $e^+$ which scatters at an extremely forward (backward) angle.**
- **Three X(3872) candidates observed, expected background 0.11 ± 0.10, 3.2 σ ( $0.995 < N_{sig} < 7.315$ at the 90% C.L. )**

$$\tilde{\Gamma}_{\gamma\gamma}\mathcal{B}(X \to J/\psi\pi^+\pi^-) = 5.5^{+4.1}_{-3.8}\ (\text{stat.}) \pm 0.7\ (\text{syst.})\ \text{eV}.$$

(Using the $Q^2$ dependence from $c\bar{c}$ model)




**If take Br(X(3872) $\to \pi^+\pi^- J/\psi$) = (4.1±1.3) %**

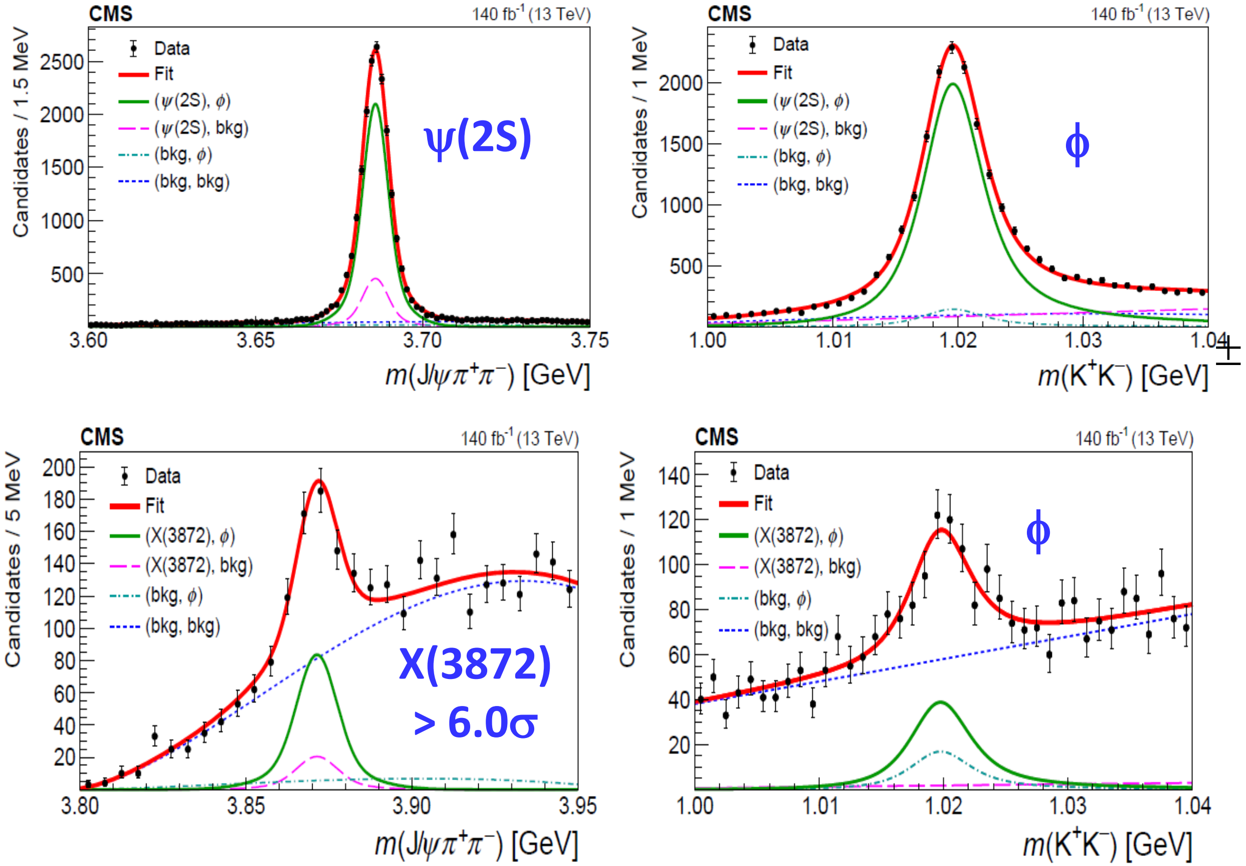
$\tilde{\Gamma}_{\gamma\gamma}$ **~ 75 eV**

**Calculation for non-$c\bar{c}$ model and high statistics data needed.**

# Observation of X(3872) from $B_s^0 \to X(3872)\,\phi$ decays

CMS: arXiv: 2005.04764

$140\ fb^{-1}$ @ 13 TeV




$$R = \frac{Br(B_s^0 \to X(3872)\phi) \times Br(X(3872) \to \pi^+\pi^- J/\psi)}{Br(B_s^0 \to \psi(2S)\phi) \times Br(\psi(2S) \to \pi^+\pi^- J/\psi)}$$

$$= (2.21 \pm 0.29 \pm 0.17)\ \%$$

$$Br(B_s^0 \to X(3872)\phi) \times Br(X(3872) \to \pi^+\pi^- J/\psi) =$$

$$= (4.14 \pm 0.54 \pm 0.32 \pm 0.46(Br)) \times 10^{-6}$$

$$\frac{Br(B_s^0 \to X(3872)\phi)}{Br(B^+ \to X(3872)K^+)} = 0.482 \pm 0.063 \pm 0.037 \pm 0.070\ (Br)$$

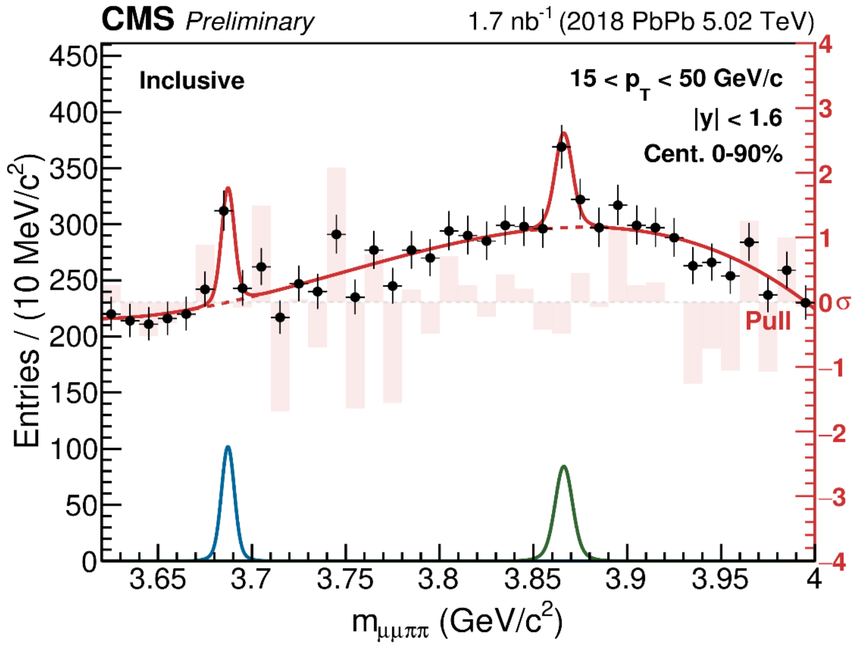
$$\frac{Br(B_s^0 \to \psi(2S)\phi)}{Br(B^+ \to \psi(2S)K^+)} = 0.87 \pm 0.10\ \ (PDG)$$

The X(3872) formation in B meson decays is different from ψ(2S) formation

Suggest X(3872) is not a pure charmonium state.

# Production of X(3872) in heavy ion collision

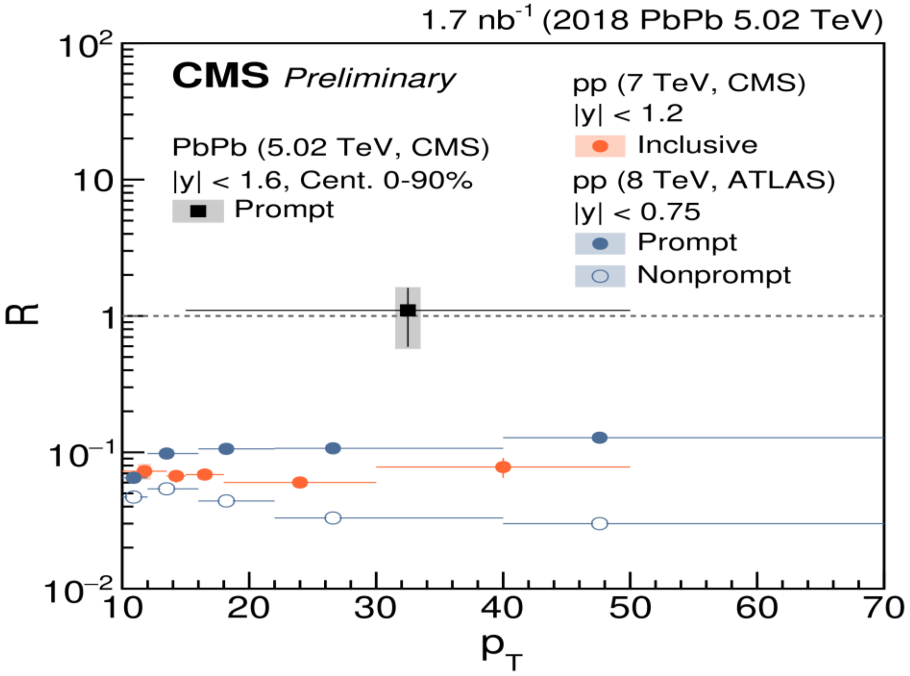
CMS preliminary




- $P_bP_b$ collision at C. M. energy of $\sqrt{s_{NN}}$ = 5.02 TeV per nucleon pair, 1.7 ± 0.1 $nb^{-1}$
- Decay chain $X(3872) \rightarrow \pi^+\pi^- J/\psi \rightarrow \pi^+\pi^-\mu^+\mu^-$
- The first evidence for X(3872) production in heavy ion collisions

$$R = \frac{\sigma(P_bP_b \rightarrow X(3872)+X) \times Br(X(3872) \rightarrow \pi^+\pi^- J/\psi)}{\sigma(P_bP_b \rightarrow \psi(2S)+X) \times Br(\psi(2S) \rightarrow \pi^+\pi^- J/\psi)}$$

$$= 1.10 \pm 0.51 \pm 0.48$$



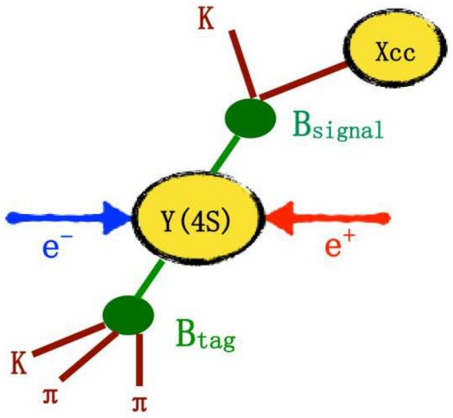

**An indication of large R in $P_bP_b$ collisions with respect to the pp collisions.**

# The absolute X(3872) rate for $B^{\pm} \to X(3872)K^{\pm}$

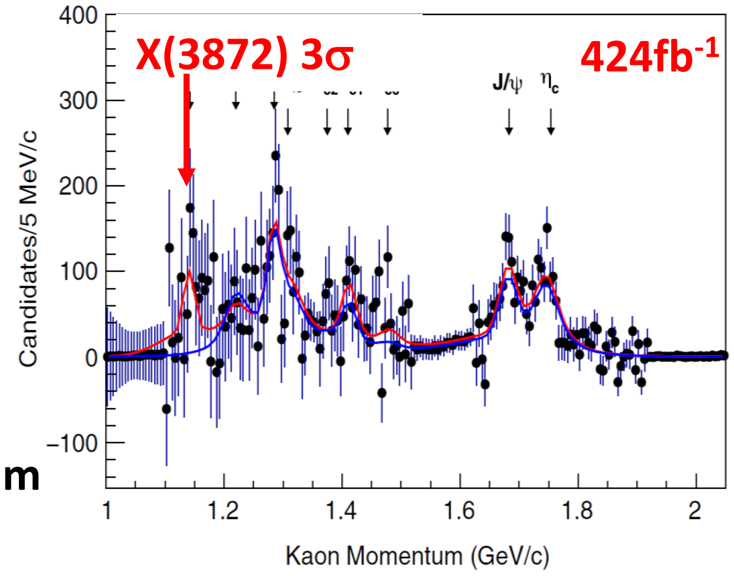
See talk by Fergus Wilson

BaBar: PRL 124, 152001 (2020)

- **Br(X(3872) $\to \pi^+\pi^- J/\psi$):**
  - **Tetraquark or Tetraquark+X: $\leq$ 50 %** (L. Maiani etc., PRD 71, 014028 (2005), PRL 99, 182003 (2007))
  - **Molecule: $\leq$ 10 %** (E. Braaten etc., PRD 72, 054022(2005); T. Barnes etc., PRD 69, 054008 (2004); P. G. Ortega etc., CPC 43, 124107 (2019))
- **The determination of the absolute branching fraction for $B^{\pm} \to X(3872)K^{\pm}$ leads to the absolute branching fraction of X(3872) $\to \pi^+\pi^- J/\psi$ ➔ nature of X(3872)**




**Measure K momentum spectrum in B rest frame.**




**Br($B^+ \to$ X(3872) $K^+$) =$(2.1 \pm 0.6 \pm 0.3) \times 10^{-4}$**

**By using the measured product BF:**

**$(8.6 \pm 0.8) \times 10^{-6}$ (from PDG)**

**➔ Br(X(3872) $\to \pi^+\pi^- J/\psi$) = $(4.1 \pm 1.3)$ %**

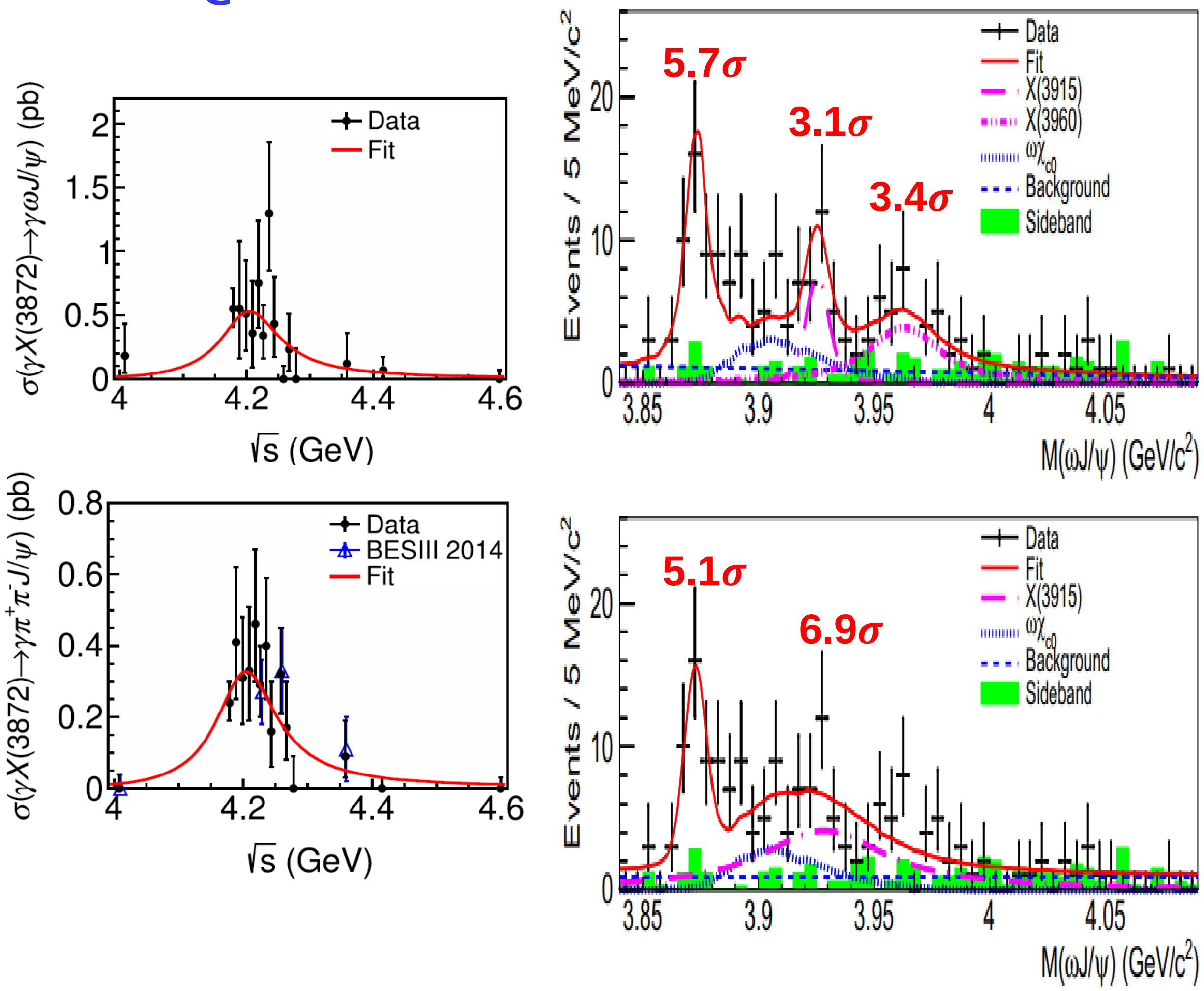
**Support X(3872) a molecular hypothesis.**

# Observation of X(3872) $\rightarrow \omega J/\psi$

BESIII: PRL 122, 232002 (2019)

$e^+e^- \rightarrow \gamma X \rightarrow \gamma\omega J/\psi$, with $\omega \rightarrow \pi^+\pi^-\pi^0$, $J/\psi \rightarrow l^+l^-$

$11.6\ fb^{-1}$ @ 4.008-4.600 GeV




**There were evidences at Belle (4.3σ) and BaBar (4σ) experiments.**

- ✓ Three: X(3872), X(3915) and X(3960))
  $N_{sig}(X(3872)) = 45 \pm 9 \pm 3$
- ✓ Two: (X(3872), X(3915))
  $N_{sig}(X(3872)) = 40 \pm 8 \pm 2$

| | Mass | Width |
|---|---|---|
| $X(3872)$ | $3873.3 \pm 1.1\ (3872.8 \pm 1.2)$ | $1.2\ (1.2)$ |
| $X(3915)$ | $3926.4 \pm 2.2\ (3932.6 \pm 8.7)$ | $3.8 \pm 7.5\ (59.7 \pm 15.5)$ |
| $X(3960)$ | $3963.7 \pm 5.5$ | $33.3 \pm 34.2$ |

$$R = \frac{Br(X(3872)\rightarrow\omega J/\psi)}{Br(X(3872)\rightarrow\pi^+\pi^- J/\psi)} = 1.6^{+0.4}_{-0.3} \pm 0.2$$

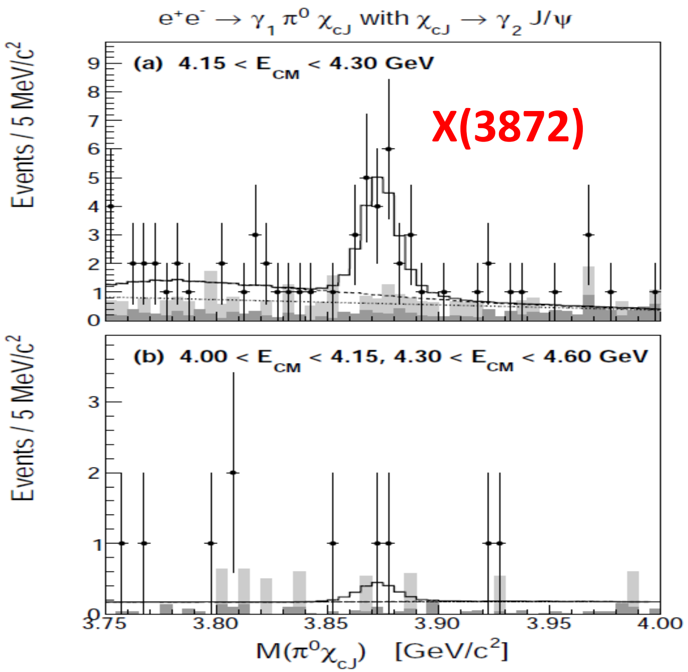
**Agree with BaBar's results** (PRD 82, 011101(R) (2010))

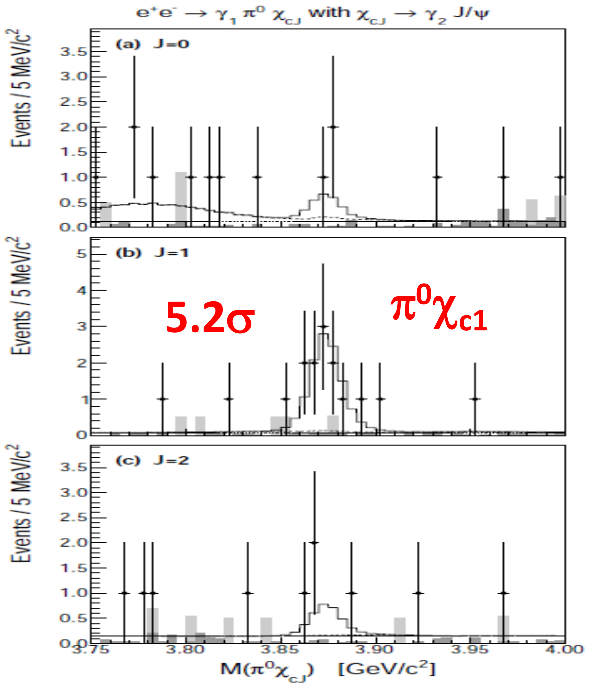
**Support X(3872) to be a molecular.**

(E. S. Swanson, PLB 588, 189 (2004); F. –K. Guo et. al., Rev. Mod. Phys., 90, 102002 (2006))

# Observation of $X(3872) \to \pi^0\chi_{c1}$

BESIII: PRL122, 202001 (2019)




**9.0 fb$^{-1}$ data**

- Br($X(3872) \to \pi^0\chi_{c1}$)/Br($X(3872) \to \pi\pi J/\psi$) ~ $0.88 \pm 0.34$
- Br($X(3872) \to \pi^0\chi_{c1}$) ~ 4% ( take BaBar's value of Br($X(3872) \to \pi\pi J/\psi$)=($4.1\pm1.3$) %)
- From S. Dubynskiy and M. B. Voloshin (PRD 77, 014013(2008)), if X(3872) were $\chi_{c1}(2P)$ charmonium state, $\Gamma(X(3872) \to \pi^0\chi_{c1})$ ~0.06 keV. Then the total width of X(3872) ~ 0.06/4% = 1.5 keV. Orders of magnitude smaller than any observed charmonium states.

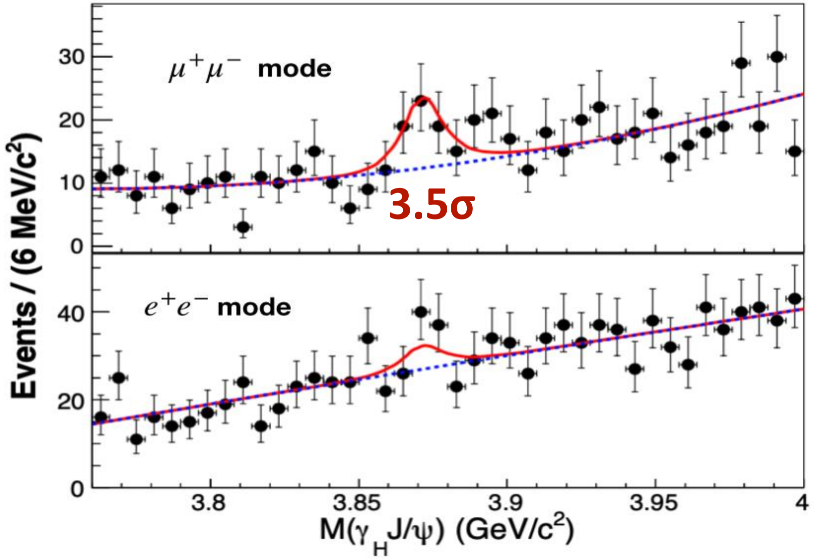
**This measurement disfavors the $c\bar{c}$ interpretation of X(3872).**

# Transition of $X(3872) \to \gamma J/\psi, \gamma\psi(2S)$

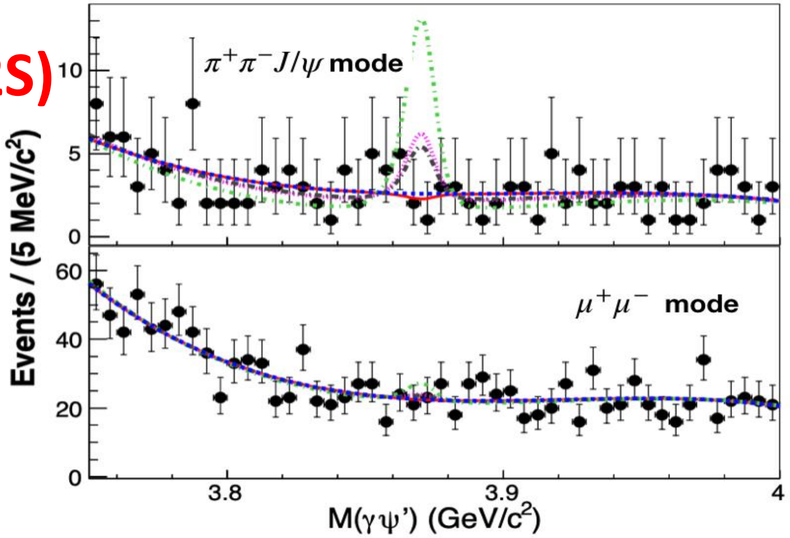
BESIII: arXiv:2001.01156
accepted by PRL

**9.0 fb$^{-1}$ @ e$^+$e$^-$ CM energies of 4.148 - 4.278 GeV**

γ J/ψ



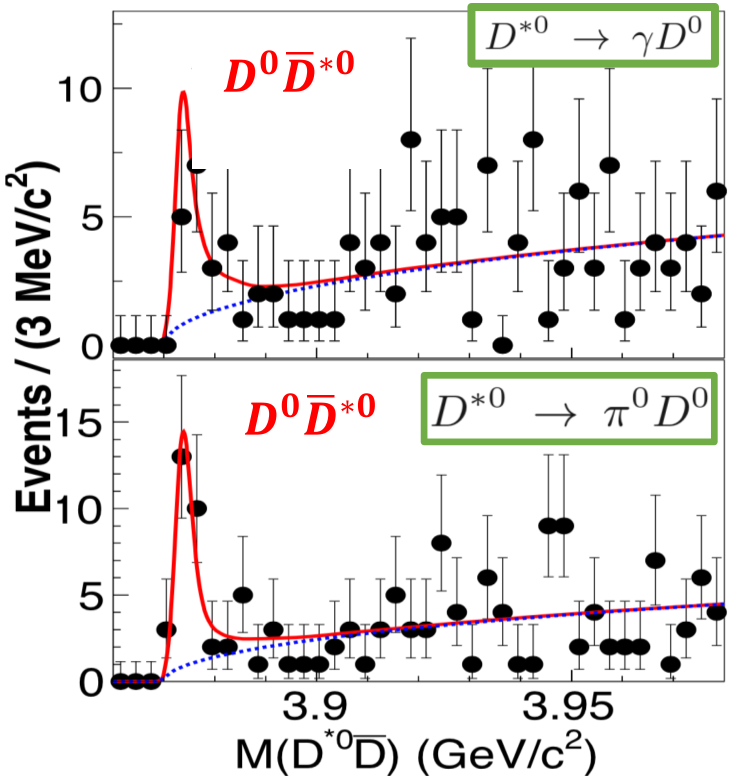

γ ψ(2S)




- Find the evidence of $X(3872) \to \gamma J/\psi$ with 3.5σ
- No evidence for $X(3872) \to \gamma\psi(2S)$.
- $R = \frac{\mathcal{B}(X(3872)\to\gamma\psi(2S))}{\mathcal{B}(X(3872)\to\gamma J/\psi)}$ <0.59 at 90% C.L. , agrees with Belle(<2.1)(PRL 107, 091803 (2011)) challenges Babar(3.4±1.1) and LHCb results (2.46± 0.70) (PRL 102, 132001 (2009); NPB 886, 665(2014))
- Not likely charmonium(1.2~15), but rather a molecule(3~4×10$^{-3}$) or a mixture(0.5~5).

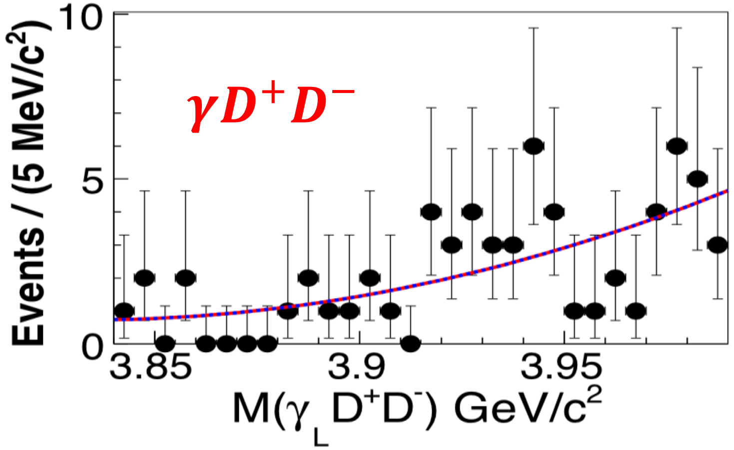
# Decays of $X(3872) \to D^0\bar{D}^{*0}$ and $\gamma D^+ D^-$

BESIII: arXiv:2001.01156
accepted by PRL




- Observed $X(3872) \to D^0\bar{D}^{*0}$ with stat. sig. of 7.4σ
- No evident signal in $\gamma D^+ D^-$.
- BF ratio to $\pi^+\pi^- J/\psi$ is measured.

| mode | ratio | UL |
|---|---|---|
| $\gamma J/\psi$ | $0.79 \pm 0.28$ | - |
| $\gamma\psi'$ | $-0.03 \pm 0.22$ | $< 0.42$ |
| $\gamma D^0\bar{D}^0$ | $0.54 \pm 0.48$ | $< 1.58$ |
| $\pi^0 D^0\bar{D}^0$ | $-0.13 \pm 0.47$ | $< 1.16$ |
| $D^{*0}\bar{D}^0 + c.c.$ | $11.77 \pm 3.09$ | - |
| $\gamma D^+ D^-$ | $0.00^{+0.48}_{-0.00}$ | $< 0.99$ |
| $\omega J/\psi$ | $1.6^{+0.4}_{-0.3} \pm 0.2$ [18] | - |
| $\pi^0\chi_{c1}$ | $0.88^{+0.33}_{-0.27} \pm 0.10$ [31] | - |




**Take Babar's result: Br(X(3872) → $\pi^+\pi^- J/\psi$) = (4.1±1.3) %**

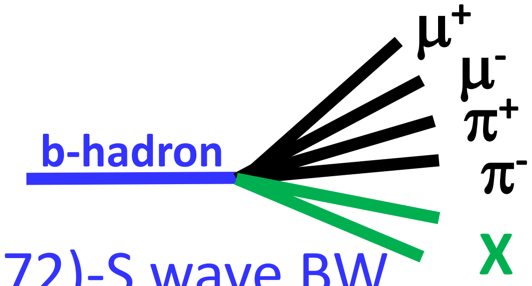
**Br(X(3872) → $D^0\bar{D}^{*0}$) ~ 48 %**

**Support X(3872) to be a $D^0\bar{D}^{*0}$ molecule**

**Very important to measure the mass of X(3872) precisely.**

# X(3872) lineshape study from b→X(3872) X

(LHCb: arXiv:2005.13419) See talk by Daniel Johnson




- **S-wave BW** (agree with PDG average, better precision)

✓$M(\chi_{c1}(3872)) - M(\psi(2S))$

$= 185.588 \pm 0.067 \pm 0.068\ \mathrm{MeV}/c^2$

✓$M_{\mathrm{BW}} = 3871.695 \pm 0.067 \pm 0.068 \pm 0.010\ \mathrm{MeV}/c^2$

✓$\Gamma_{\mathrm{BW}} = 1.39 \pm 0.24 \pm 0.10\ \mathrm{MeV}/c^2$

✓$\delta E = M(D^0) + M(\bar{D}^{*0}) - M(\chi_{c1}(3872))$

$= 0.01 \pm 0.14\ \mathrm{MeV}/c^2$ with

$M(D^0) + M(\bar{D}^{*0}) = 3871.70 \pm 0.11\ \mathrm{MeV}/c^2$

- **Flatte parametrization**

X(3872) is very close to $D^0\bar{D}^{*0}$ threshold. The opening up of $D^0\bar{D}^{*0}$ threshold distorts the lineshape from BW.

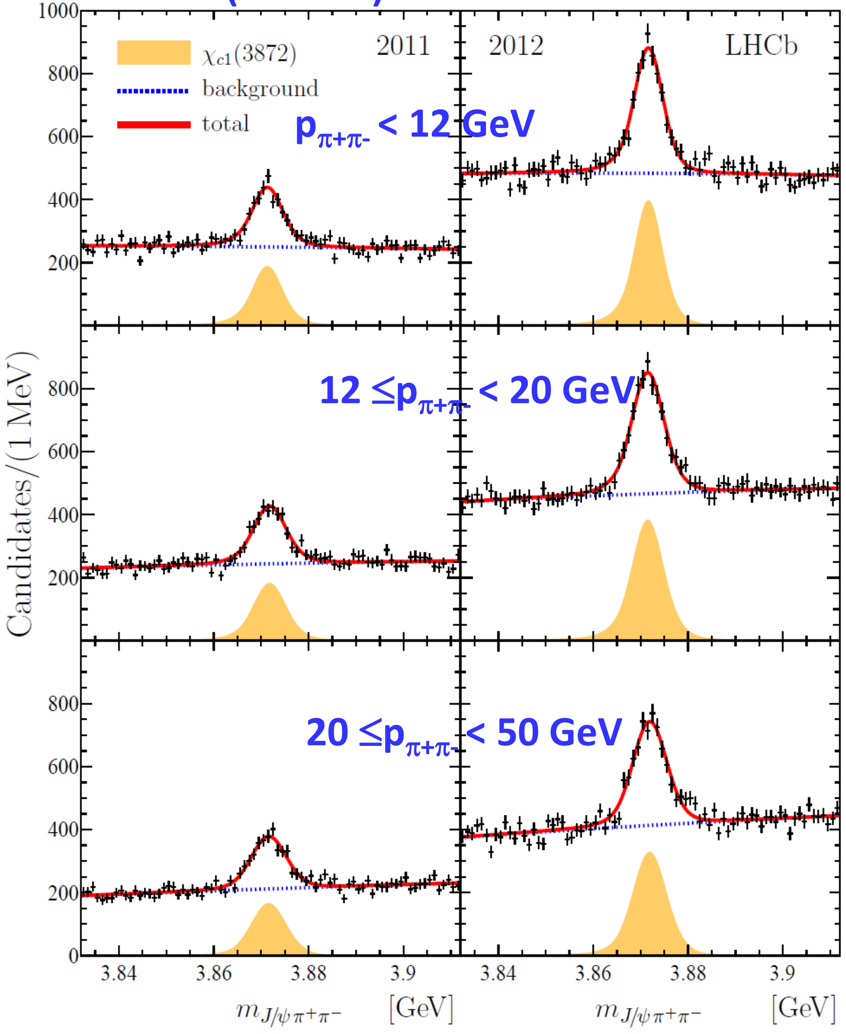
Pole: $3871.69^{+0.00+0.05}_{-0.04-0.13}\ \mathrm{MeV}/c^2$; FWHM: $0.22^{+0.06+0.25}_{-0.08-0.17}\ \mathrm{MeV}/c^2$

✓ Consistent with $D^0\bar{D}^{*0}$ quasi-bound state

✓ Quasi-virtual state cannot be excluded

**A better parametrization of the lineshape is needed.**

X(3872)-S wave BW



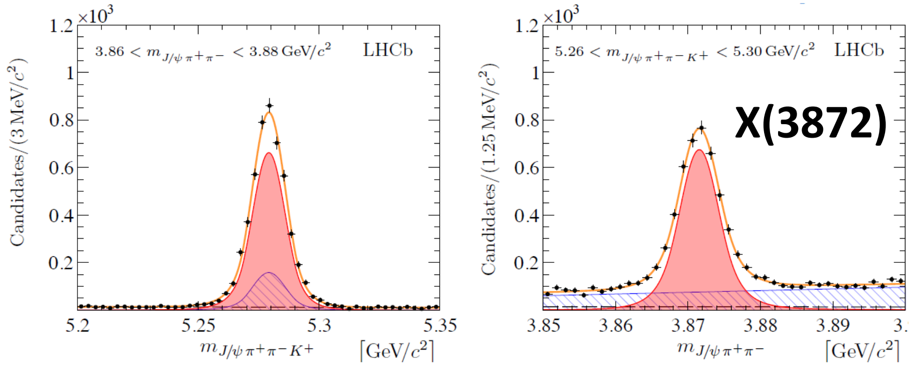

**3 fb$^{-1}$ @ 7 and 8 TeV**

# X(3872) from exclusive $B^+ \to Xcc(\to \pi^+\pi^- J/\psi)\, K^+$ decays

**$9\,fb^{-1}$ @ 7, 8, 13 TeV**

(See talk by Daniel Johnson)

(LHCb: arXiv:2005.13422)




✓ $M(\chi_{c1}(3872)) - M(\psi(2S)) = 185.49 \pm 0.06 \pm 0.03\ \mathrm{MeV}/c^2$

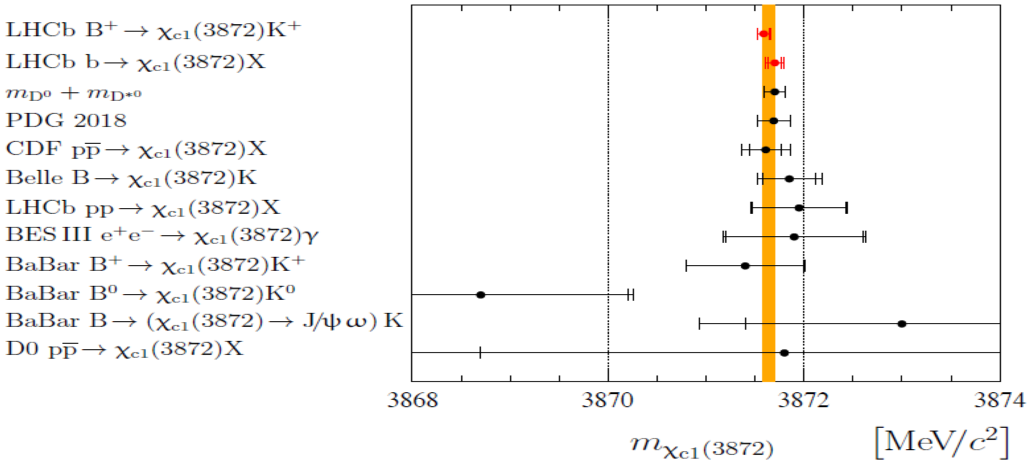
✓ $M_{\mathrm{BW}} = 3871.59 \pm 0.06 \pm 0.03 \pm 0.010\ \mathrm{MeV}/c^2$

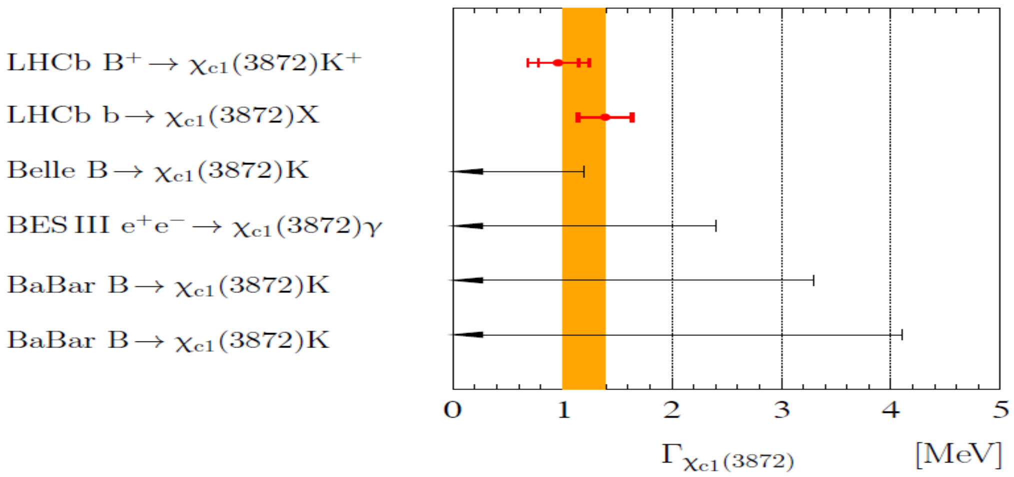
✓ $\Gamma_{\mathrm{BW}} = 0.96^{+0.19}_{-0.18} \pm 0.21\ \mathrm{MeV}/c^2$

✓ $\delta E = M(D^0) + M(\bar{D}^{*0}) - M(\chi_{c1}(3872)) = 0.12 \pm 0.13\ \mathrm{MeV}/c^2$

➢ $$\frac{\mathcal{B}(B^+ \to \chi_{c1}(3872)K^+)}{\mathcal{B}(B^+ \to \psi(2S)K^+)} \times \frac{\mathcal{B}(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} = (3.69 \pm 0.07 \pm 0.06)\times 10^{-2}$$

## X(3872) mass and width from BW( first measurement of $\Gamma$, most precise measurement of mass)




M(X(3872)) = 3871.64 ± 0.06 ± 0.01 MeV/$c^2$

LHCb average: $\Gamma$(X(3872)) = 1.19 ± 0.19 MeV/$c^2$

$\delta$E = M(X(3872)) – M($D^0\bar{D}^{*0}$) = 0.07 ± 0.12 MeV/$c^2$

# Y(4260) , Y(4360) and Y(4660)

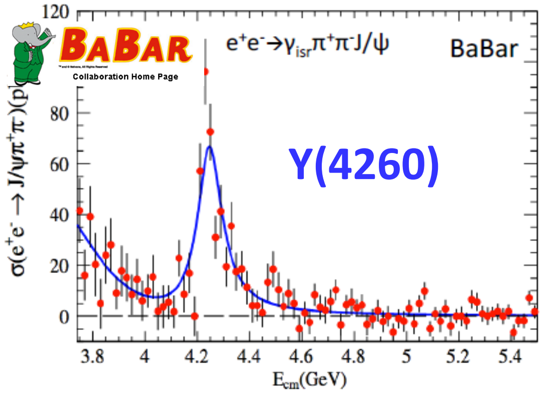
## (named as $\psi(4260)$ , $\psi(4360)$ and $\psi(4660)$ in PDG)

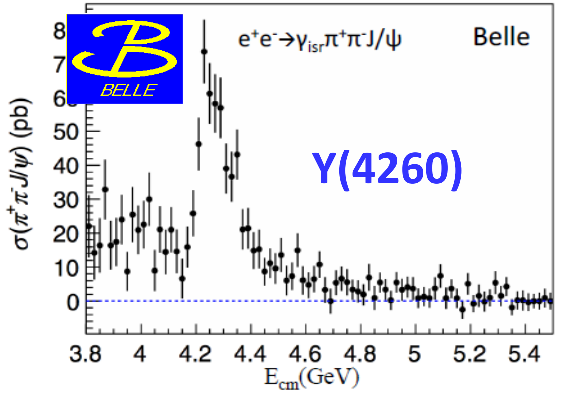
# Cross sections of $e^+e^- \to \pi^+\pi^- J/\psi$, $\pi^+\pi^-\psi(2S)$, $\pi^+\pi^- h_c$

## $\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$

Babar: PRD 86, 051102 (2012)

Belle: PRL 110, 242002 (2013)



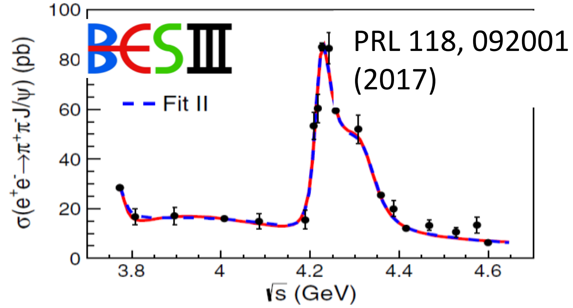



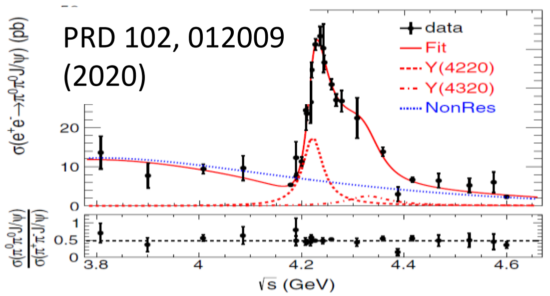

The weighted average of Babar, CLEO and Belle

From a single BW: M = 4251 ± 9 MeV

Γ = 120 ± 12 MeV

## $\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ $\sigma(e^+e^- \to \pi^0\pi^0 J/\psi)$




- Coherent sum of two BWs + one incoherent ψ(3770)

  M = 4222.0±3.1±1.4 MeV, Γ = 44.1±4.3±2.0 MeV

  Lower and narrower than Y(4260) PDG values

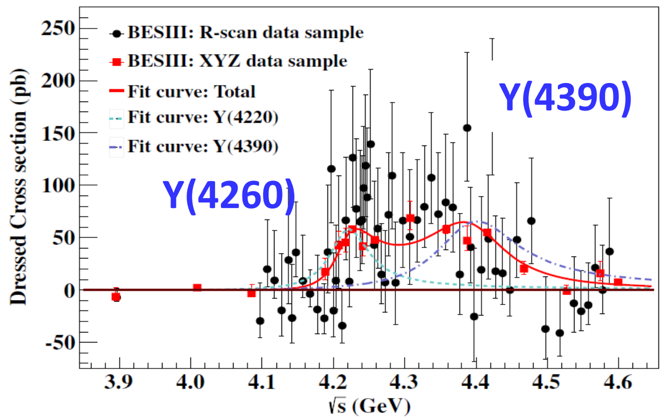
  M = 4320.0±10.4±7.0 MeV, Γ=101.4±25.3±10.2 MeV

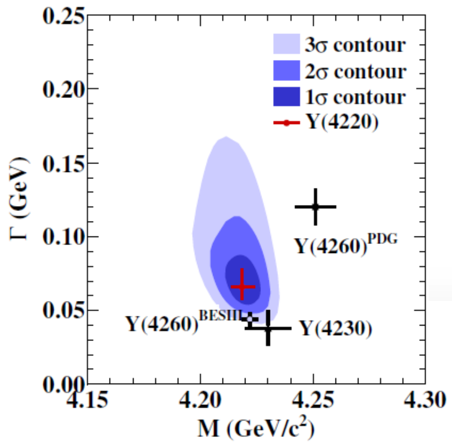
  Lower than Y(4360) PDG value

- The sig. of the second BW is 7.6σ

## $\sigma(e^+e^- \to \pi^+\pi^- h_c)$

BESIII: PRL 118, 092002 (2017)

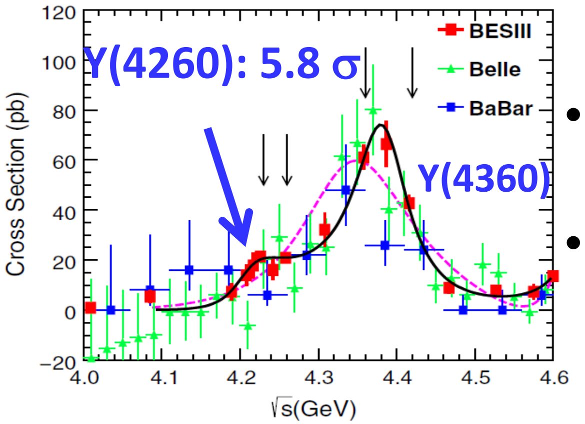



- ❑ Fitted with coherent sum of two BW-like structures
- ➢ $M_1=4218.4^{+5.5}_{-4.5}\pm0.9$ MeV/c², $\Gamma_1= 66.0^{+12.3}_{-8.3}\pm0.4$ MeV → Y(4220)
- ➢ $M_2=4391.5^{+6.3}_{-6.8}\pm1.0$ MeV/c², $\Gamma_2=139.5^{+16.2}_{-20.6}\pm0.6$ MeV → Y(4390)
- ❑ The Y(4220) here is consistent with the state observed in $\pi^+\pi^- J/\psi$ around 4220MeV

# Cross sections of $e^+e^- \to \pi^+\pi^- \psi(2S)$, $\eta J/\psi$, $\omega\chi_{c0}$, $\pi^+D^0\bar{D}^{*-}$

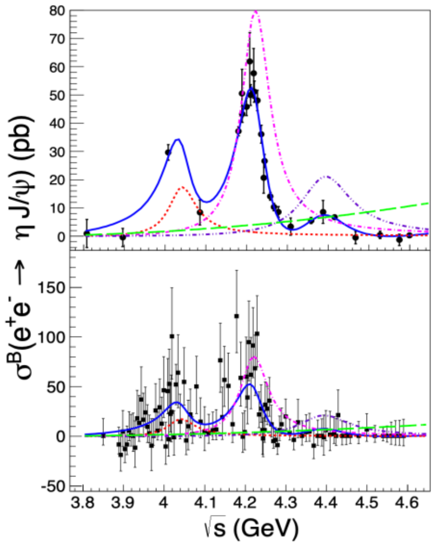
## $\sigma(e^+e^- \to \pi^+\pi^- \psi(2S))$




BESIII: PRD96, 032004 (2017)

- Solid curve: 3 coherent BWs Y(4260), Y(4360) and Y(4660)
- Dashed curve: 2 coherent BWs Y(4260) and Y(4360)

## $\sigma(e^+e^- \to \eta J/\psi)$



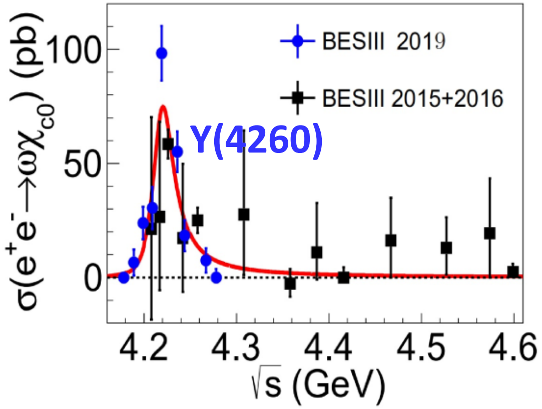

BESIII: arXiv:2003.03705, submitted to PRL

3 BWs: ψ(4040), Y(4260) and Y(4360)

$M_1$= (4218.7±4.0±2.5) MeV/$c^2$
$\Gamma_1$=(82.5 ± 5.9 ± 0.5) MeV/$c^2$
$M_2$= (4380.4±14.2±1.8) MeV/$c^2$
$\Gamma_2$=(147.0 ± 63.0 ± 25.8) MeV/$c^2$

## $\sigma(e^+e^- \to \omega\chi_{c0})$

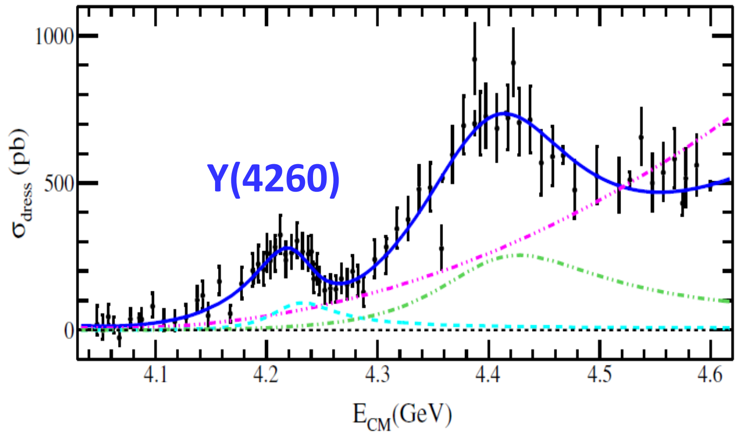
BESIII: PRD99, 091103(R) (2019)




M= (4218.5 ±1.6±4.0) MeV/$c^2$
Γ=(28.2±3.9±1.6) MeV/$c^2$

## $\sigma(e^+e^- \to \pi^+D^0\bar{D}^{*-})$

BESIII: PRL 122, 102002 (2019)



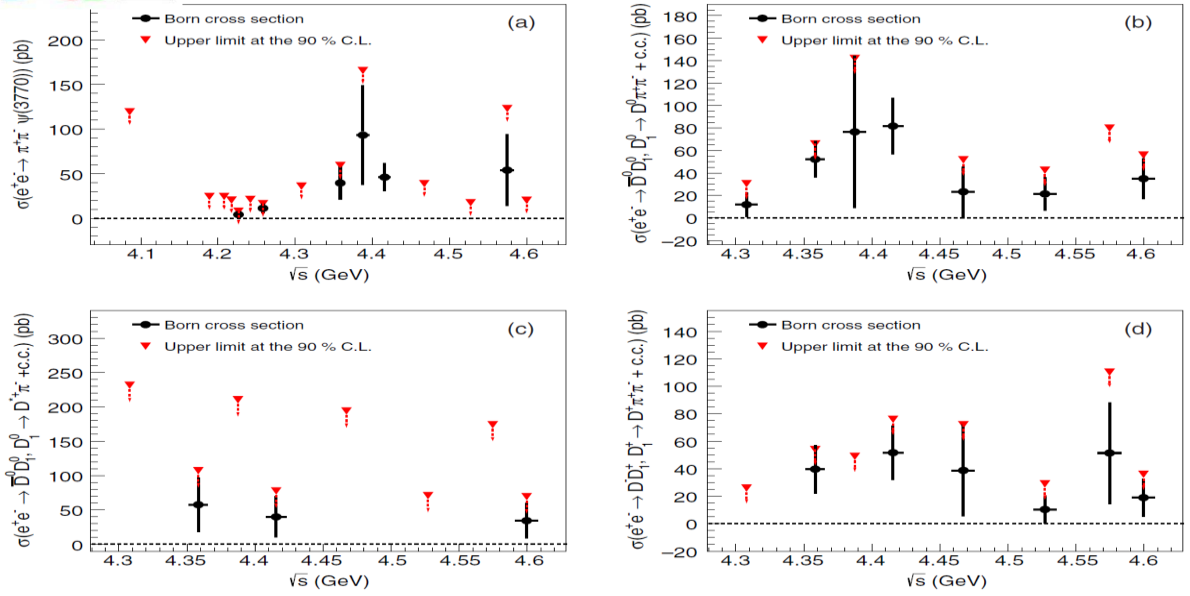

The total amplitude: coherent sum of a direct 3-body PS + 2 relativistic BWs

$$\sigma_{\rm dress}(m) = \left| c\sqrt{P(m)} + e^{i\phi_1} B_1(m)\sqrt{P(m)/P(M_1)} + e^{i\phi_2} B_2(m)\sqrt{P(m)/P(M_2)} \right|^2,$$

M= (4228.6 ± 4.1 ± 6.3) MeV/$c^2$
Γ=(77.0 ± 6.8 ± 6.3) MeV/$c^2$

# cross sections of $e^+e^- \to \pi^+\pi^-\psi(3770)$, $\pi^+\pi^- D^0\bar{D}^0$, $\pi^+\pi^- D^+D^-$

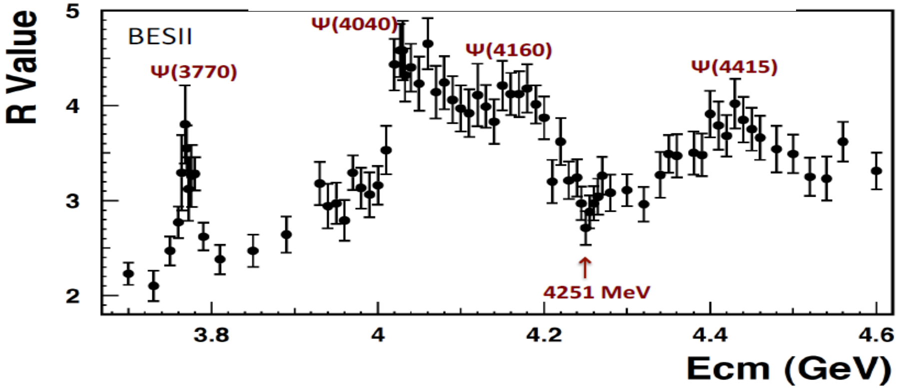
BESIII: PRD 100, 032005 (2019)




**No significant Y(4260) observed**

# cross sections of $e^+e^- \to$ hadrons

BESII: PRL 88, 101802 (2002)

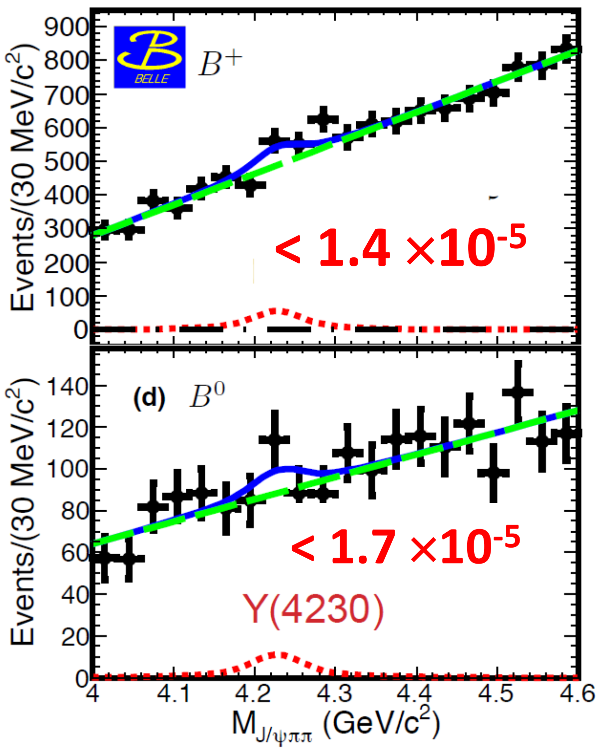



**No significant Y(4260) observed**

# Y(4260) in b-flavored decays

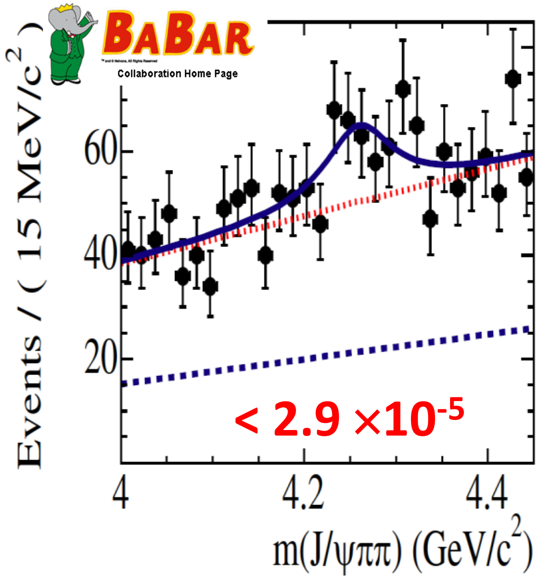
Belle: PRD 99, 071102 (2019)

$B^{\pm,0} \to K^{\pm,0}\pi^+\pi^- J/\psi$

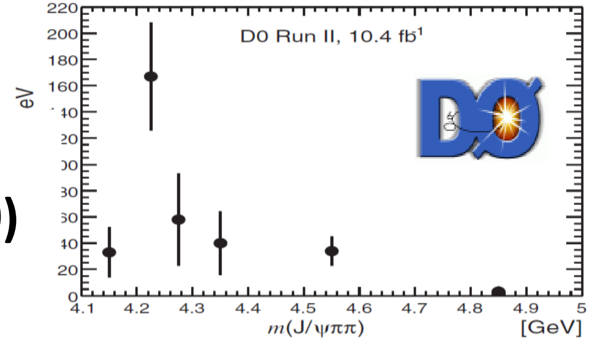



BaBar: PRD 73, 011101(R) (2006)

$B^- \to \pi^+\pi^- J/\psi K^-$




$H_b \to \pi^+\pi^- J/\psi$ + anything

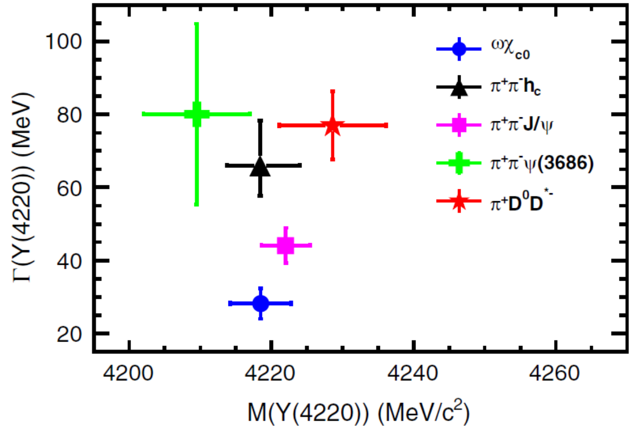



**D0: PRD 98, 052010 (2018)**

**Y(4260) is correlated with $Z_c(3900)$**

# Y(4260) summary and explanations

- M= 4220 $\pm$15 MeV, Full width $\Gamma$= 20 to 100 MeV (PDG 2020)
- $I^G(J^{PC})=0^-(1^{--})$
- Y(4260) appears in $\eta J/\psi$, $\omega\chi_{c0}$, $\pi^+\pi^-J/\psi$, $\pi^+\pi^-\psi(2S)$, $\pi^+\pi^-h_c$, $D^0D^{*-}\pi^+$+c.c.
- Y(4260) has strong transition to X(3872) and $Z_c(3900)$
- Y(4260) is not observed in $e^+e^-\rightarrow$inclusive hadron cross section
- Y(4260) is not observed in $e^+e^-\rightarrow$ open charm pair cross section




- For charmonium states above open charm threshold, they mostly decay to open charm pair – OZI rule
- Absence of Y(4260) decaying to charmed meson pair + strong coupling to $J/\psi\ \pi^+\pi^-$ and hidden charm final states
  ➔Y(4260) might not be a charmonium state

**Theoretical explanations:**

- Bound state of $D\bar{D}_1(2420)$ (binding energy is too large);
- $c\bar{c}g$ hybrid state (mass lower than LQCD calculation, large radiative width is odds);
- …

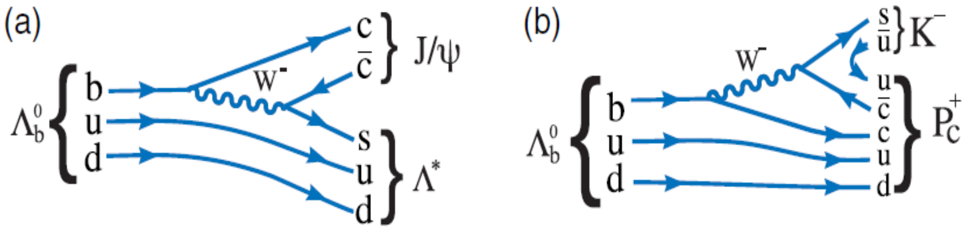
} (lots of references…)

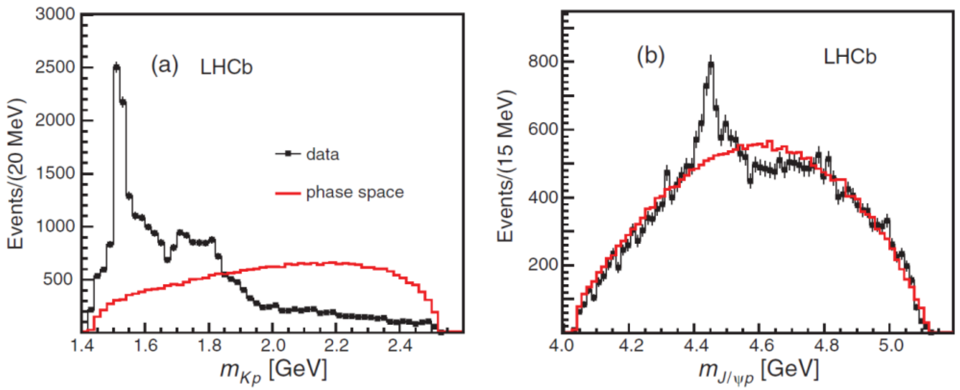
# Pentaquark states

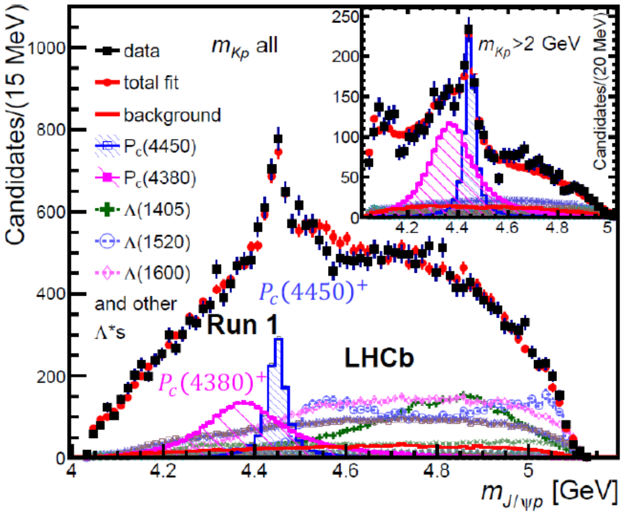
LHCb: PRL 115, 072001 (2015)

- Two J/ψ p resonant structures observed in $\Lambda_b^0 \rightarrow J/\psi K^- p$ from a full amplitude analysis

**3 fb$^{-1}$ @ 7 and 8 TeV**




- $P_c(4450)^+$ : the nominal peak, 12σ

  $M = 4449.8 \pm 1.7 \pm 2.5$ MeV/c$^2$, $\Gamma = 39 \pm 5 \pm 19$ MeV

  Fit fraction: $(4.1 \pm 0.5 \pm 1.1)\%$

  Phase change in amplitude consistent with that of a resonance

- $P_c(4380)^+$: required to have a good fit, 9σ

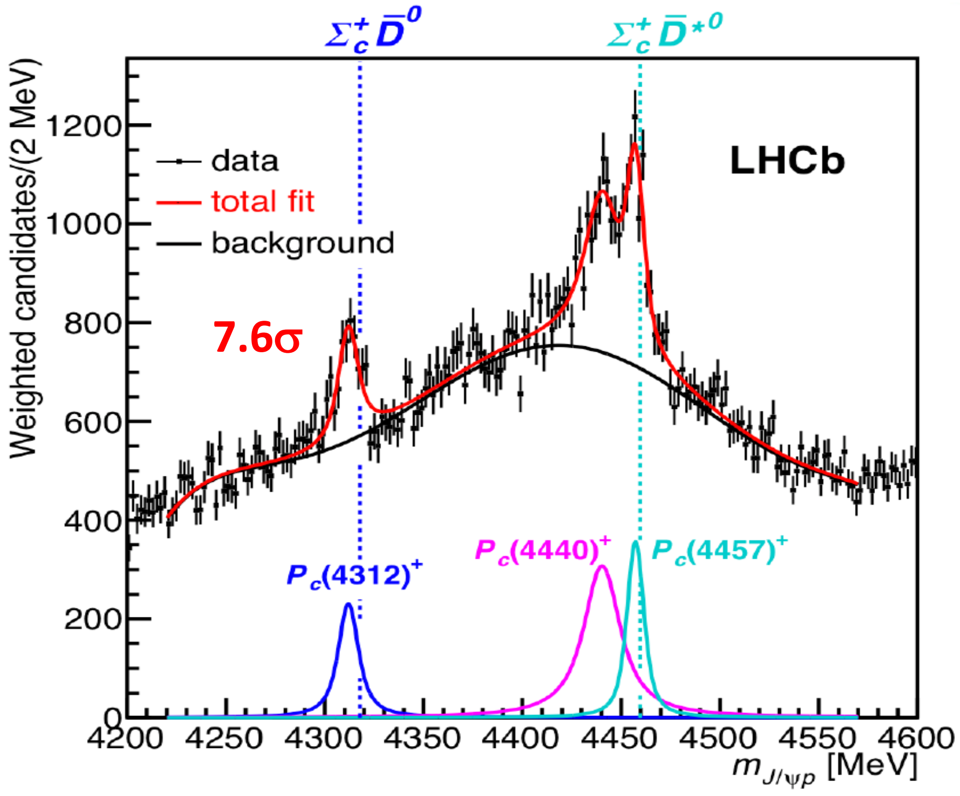
  $M = 4380 \pm 8 \pm 29$ MeV/c$^2$, $\Gamma = 205 \pm 18 \pm 86$ MeV

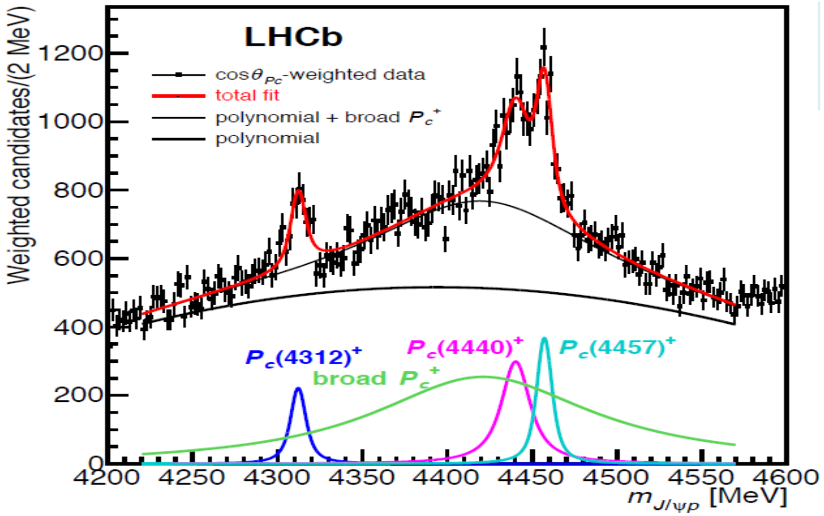
  Fit fraction: $(8.4 \pm 0.7 \pm 4.2)\%$

# Observe a narrow new $P_c$ state and two-peak structure of $P_c(4450)$ in $\Lambda_b^0 \rightarrow J/\psi K^- p$

LHCb: PRL 122, 222001 (2019)

**Run 1 and Run 2 data, ~an order of magnitude larger statistics**



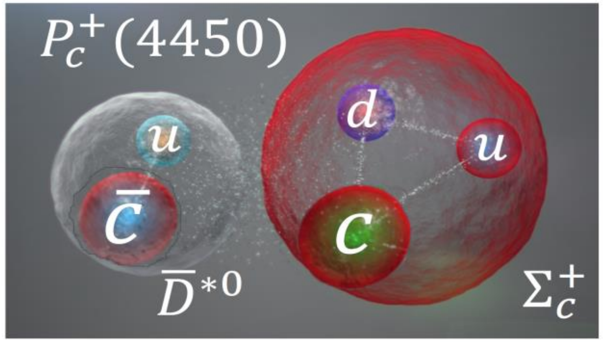

$$\mathcal{R} = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow P_c^+ K^-)\mathcal{B}(P_c^+ \rightarrow J/\psi p)}{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi p K^-)}$$

| State | $M$ [ MeV ] | $\Gamma$ [ MeV ] (95% CL) | $\mathcal{R}$ [%] |
|---|---|---|---|
| $P_c(4312)^+$ | $4311.9 \pm 0.7^{+6.8}_{-0.6}$ | $9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$ ($<$ 27) | $0.30 \pm 0.07^{+0.34}_{-0.09}$ |
| $P_c(4440)^+$ | $4440.3 \pm 1.3^{+4.1}_{-4.7}$ | $20.6 \pm 4.9^{+\ 8.7}_{-10.1}$ ($<$ 49) | $1.11 \pm 0.33^{+0.22}_{-0.10}$ |
| $P_c(4457)^+$ | $4457.3 \pm 0.6^{+4.1}_{-1.7}$ | $6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$ ($<$ 20) | $0.53 \pm 0.16^{+0.15}_{-0.13}$ |

The fit is not sensitive to the broad structures, like $P_c(4380)^+$

# Interpretations of $P_c$ states

## Loosely-bound pentaquark (Molecule)




- Theoretical predictions for $\Sigma_c^+ \bar{D}^{(*)0}$ made before LHCb's observation. Good agreement.

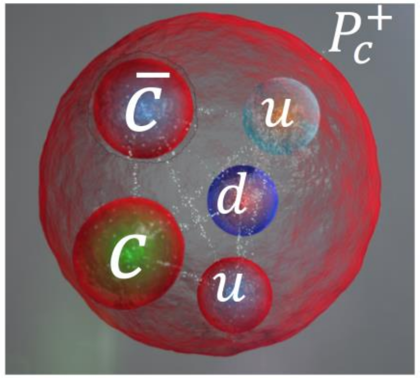
  J. J. Wu et al., PRL 105, 232001(2010)
  W. L. Wang, PRC 84, 015203 (2011)
  Z. C. Yang et al., Chin. Phys. C 36, 6 (2012)
  J. J. Wu, et al., PRC 85, 044002(2012)D0
  M. Karliner eta al., PRL 115, 122001(2015)
  .........

- $J^P$ and more predictions at $\Sigma_c^* \bar{D}^{(*)0}$ threshold

  M. Z. Liu et al., PRL 122, 242001(2019)

- The mass coincidence of $P_c(4312)^+$ and $P_c(4457)^+$ with two related thresholds, $\Sigma_c^+ \bar{D}^0$ and $\Sigma_c^+ \bar{D}^{*0}$, provides strong evidence in favor of a loosely bound charmed baryon- anti-charmed meson molecular interpretation.

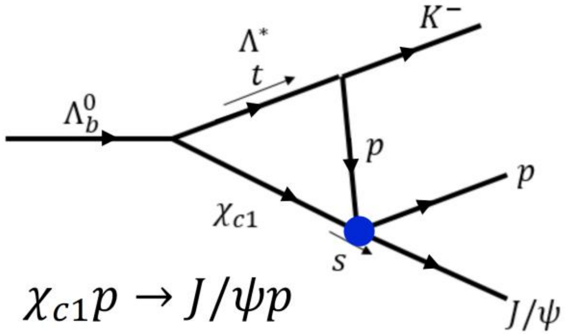
## Tightly-bound pentaquark (hadro-charmonium)




L. Maiani et al., PLB 749, 289 (2015)
R. F. Lebed, PLB 749, 454 (2015)
V. V. Anisovich eta al., arXiv:1507.07652
M. I. Eides et al., arXiv:1904.11616
.........

- The binding energy
- Predicted width of $P_C$ too big
- $J^P$ of $P_c(4440)^+$ $1/2^-$
  $J^P$ of $P_c(4457)^+$ $3/2^-$
  (hyperfine hadro-charmonium doublet)

## Kinematic effects (Rescattering via triangle diagrams)




F. K. Guo eta. At., PRD 92, 071502(2015)
A. P. Szczepaniak, PLB 757, 61 (2016)
X. H. Liu eta al., PLB 757, 231 (2016)
Mikhasenko, arXiv:1507.06552
......

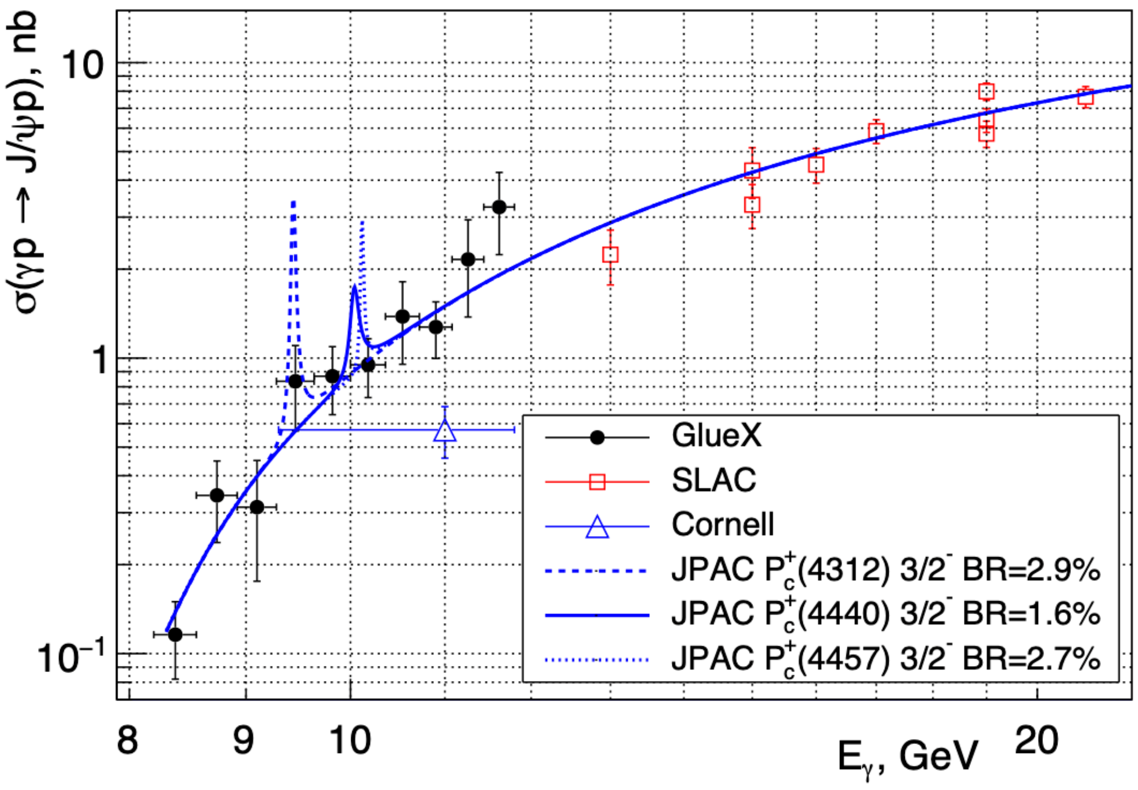
- $P_c(4312)^+$ and $P_c(4440)^+$ are too far from any rescattering threshold
- $P_c(4457)^+$ is right at $\Lambda_c(2595)^+\bar{D}^0$ threshold, cannot be ruled out as a triangle effect. (Supplemental material for PRL 122,222001)

**Determination of $J^P$ and study of more decay modes and production mechanisms will be crucial.**

# Search for pentaquarks in photo-production process at JLAB

GlueX: arXiv:1905.10811, PRL 123, 072001 (2019)

- The $P_c$ states observed at LHCb can be produced in the s-channel $\gamma p \to P_c^+ \to J/\psi\ p$, which is free from the three-body re-scattering effects.
- The $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$ produced in the s-channel process would appear as structures at $E_\gamma$ = 9.44, 10.04 and 10.12 GeV in the cross-section results.




- No evidence for such structures.
- The upper limits are set assuming $J^P=3/2^-$ at 90% C.L. (systematic uncertainties incl.) (if $J^P=5/2$, the upper limits are a factor of 5 smaller)

✓ JPAC model: (PRD 94, 034002 (2016))

$B(P_c(4312)^+ \to J/\psi\ p) < 4.6\%$

$B(P_c(4440)^+ \to J/\psi\ p) < 2.3\%$

$B(P_c(4457)^+ \to J/\psi\ p) < 3.8\%$

✓ Incoherent sum of BW and non-resonant

$\sigma(\gamma p \to P_c(4312)^+) \times B(P_c(4312)^+ \to J/\psi\ p) < 4.6\text{nb}$

$\sigma(\gamma p \to P_c(4440)^+) \times B(P_c(4440)^+ \to J/\psi\ p) < 1.8\text{nb}$

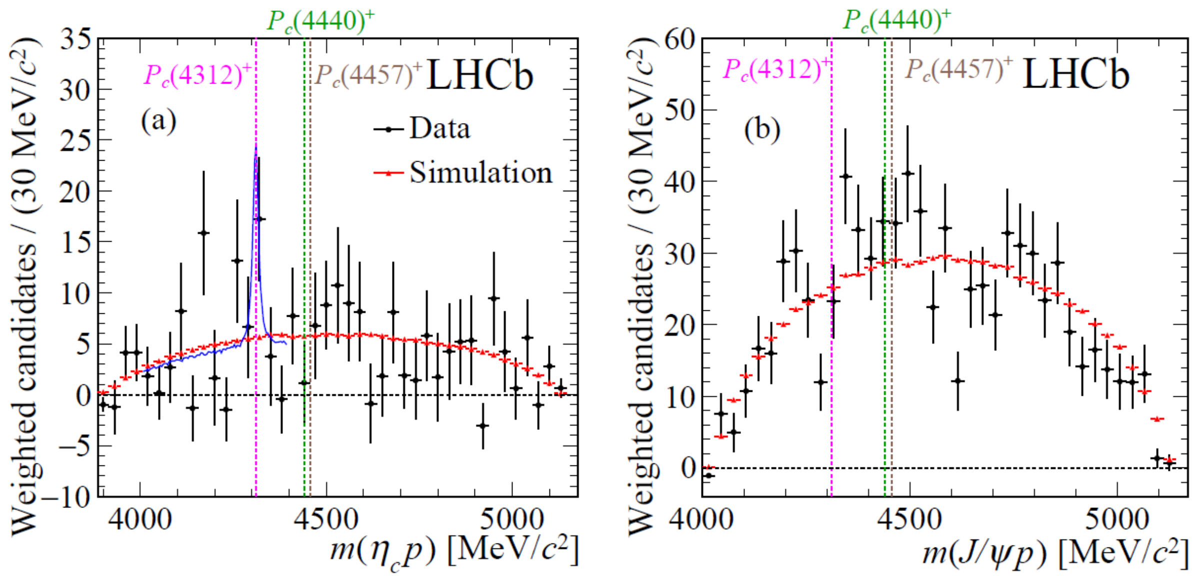
$\sigma(\gamma p \to P_c(4457)^+) \times B(P_c(4457)^+ \to J/\psi\ p) < 3.9\text{nb}$

# Search for $P_c(4312)^+$ in $\Lambda_b^0 \to \eta_c(1S) K^- p$

LHCb: arXiv:2007.11292

See talk by Daniel Johnson

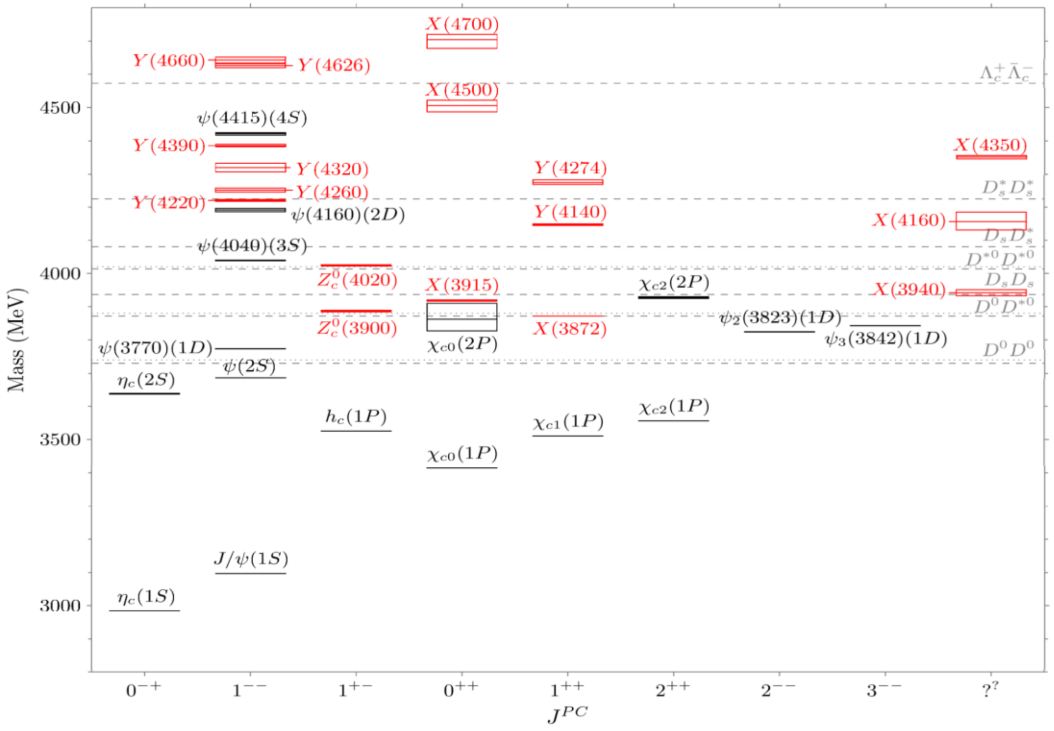
- The decay $\Lambda_b^0 \to \eta_c(1S) K^- p$ is observed for the first time at 7.7 $\sigma$(5.5 $fb^{-1}$ @ 13 TeV)
- No significant pentaquark contributions observed.

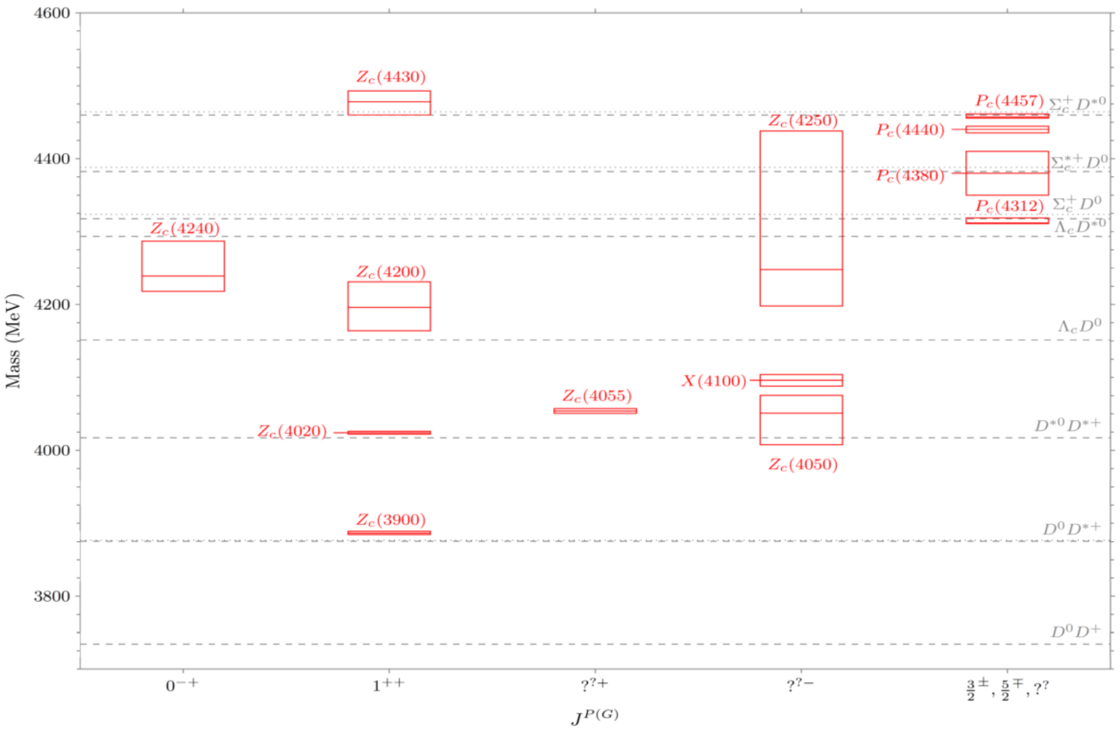



$Br(\Lambda_b^0 \to P_c(4312)^+ K^-) \times Br(P_c(4312)^+ \to \eta_c p) / Br(\Lambda_b^0 \to \eta_c(1S) K^- p) < 24\%$ (at 95% C.L.)

# Before close my talk…….

From Richard Lebed, Snowmass talk (2020)




Most of these charmoniumlike states are related to the open-charm thresholds.

- Do we have a single picture to understand them?
- More data are needed to build more relations among the exotic hadrons.

# Thanks for your attention