北京航空航天大學
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Heavy quark spectroscopy

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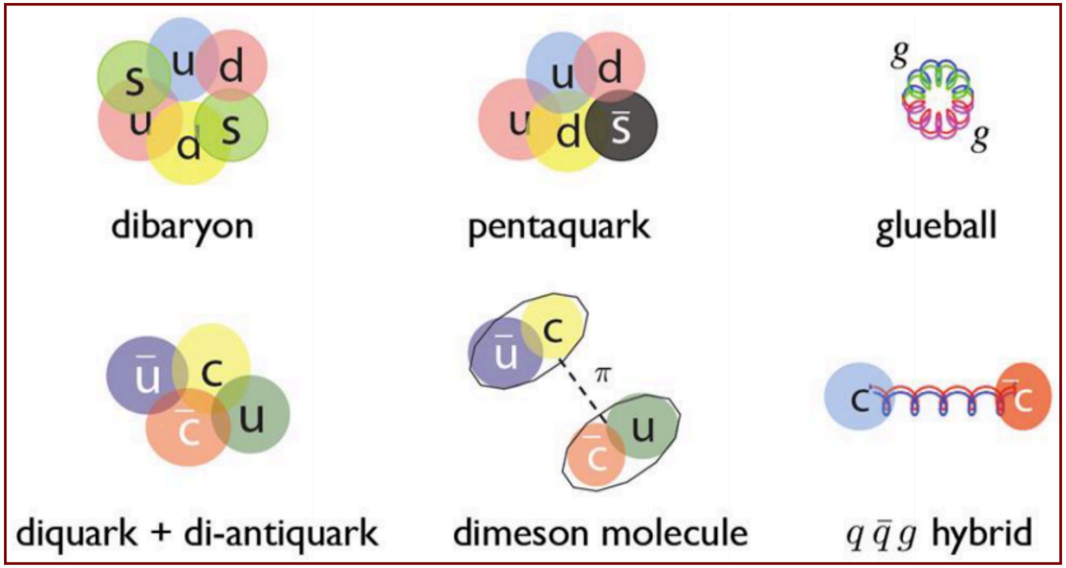
Outline

- Challenges in Hadron Spectroscopy
- XYZ states
  - The X states — whatever is leftover
  - The Y states — $J^{PC}=1^{--}$
  - The Z_c states — I=1 & decays into $\bar{c}c$
- Upgrade and prospects
- Summary

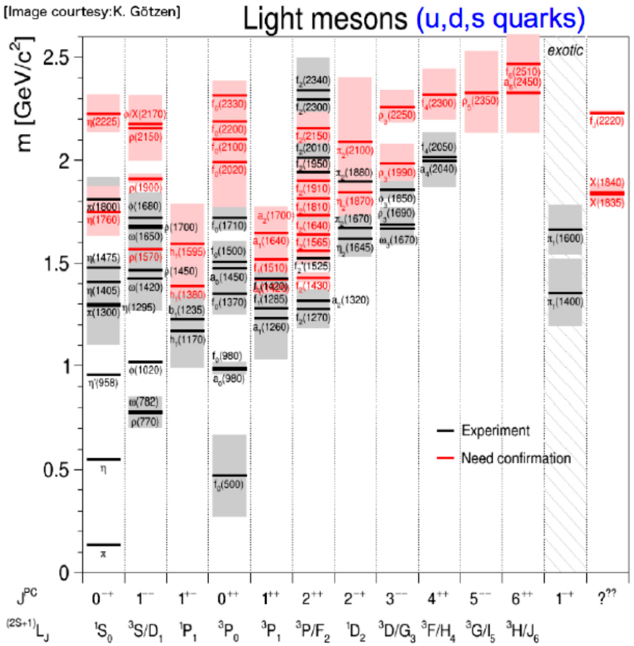
Hadrons: normal & exotic

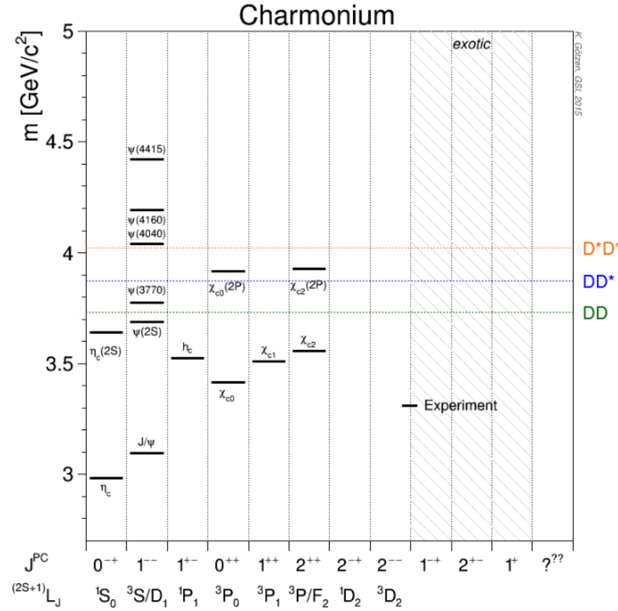
- Quark model: hadrons are composed from 2 (meson) quarks or 3 (baryon) quarks



- QCD does not forbid hadrons with $N_{quarks} \neq 2, 3$
  - Glueball : $N_{quarks} = 0$ (gg, ggg, …)
  - Hybrid : $N_{quarks} = 2$ (or more) + excited gluon
  - Multiquark state : $N_{quarks} > 3$
  - Molecule : bound state of more than 2 hadrons
  - …

Hadron spectra: normal





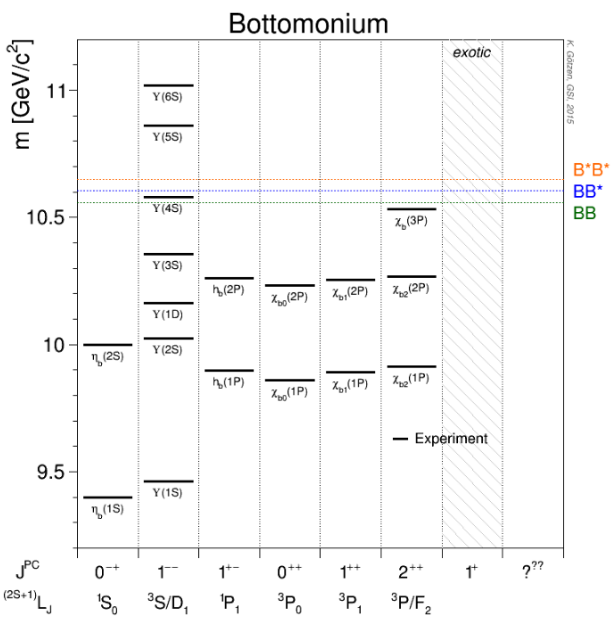
J^{PC} Quantum Numbers

- Parity = $(-1)^{L+1}$
- Charge Conjugation = $(-1)^{L+S}$
- Spin = $J = |L-S|, L, L+S$
- Vacuum = ${}^3P_0 \hat{=} 0^{++}$

Quark Degrees of Freedom **ONLY**

	0^{++}	0^{-+}	
1^{--}	1^{++}		1^{+-}
2^{--}	2^{++}	2^{-+}	
3^{--}	3^{++}		3^{+-}
4^{--}	4^{++}	4^{-+}	
5^{--}	5^{++}		5^{+-}

Experimental observation!!



- Light hadron spectroscopy is complicated
- Many broad and overlapping states discovered, some not yet – need complicated PWA technology
- Below open-charm/bottom threshold: good agreement between experiments and theoretical predictions
- Above open-charm/open-bottom threshold: some expected states not discovered yet

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

Multiquark states have been discussed since the 1st page of the quark model

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

M. Gell-Mann, Phys. Lett. 8, 214 (1964)

Where are they??

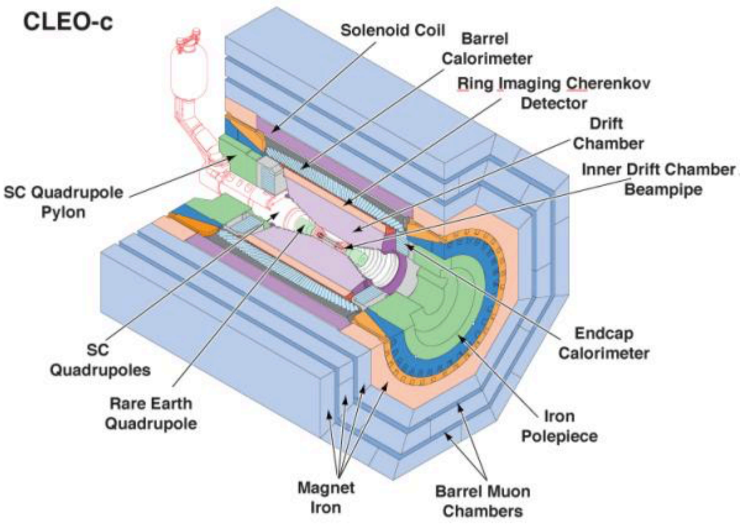
If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

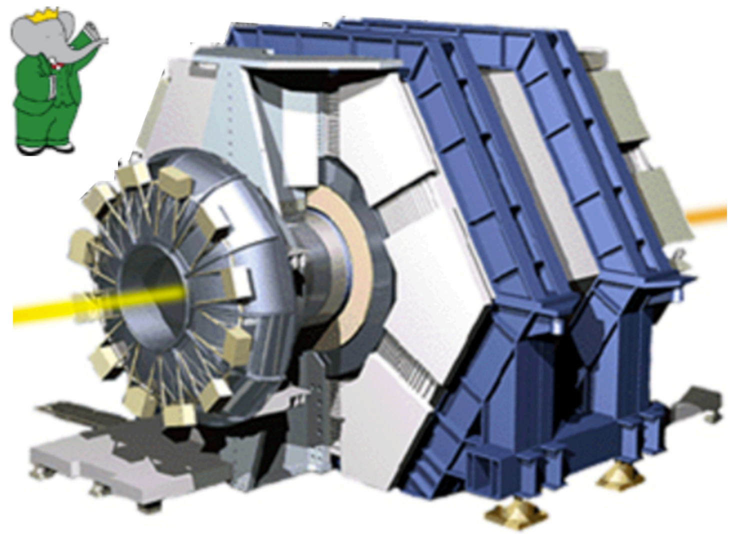
Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

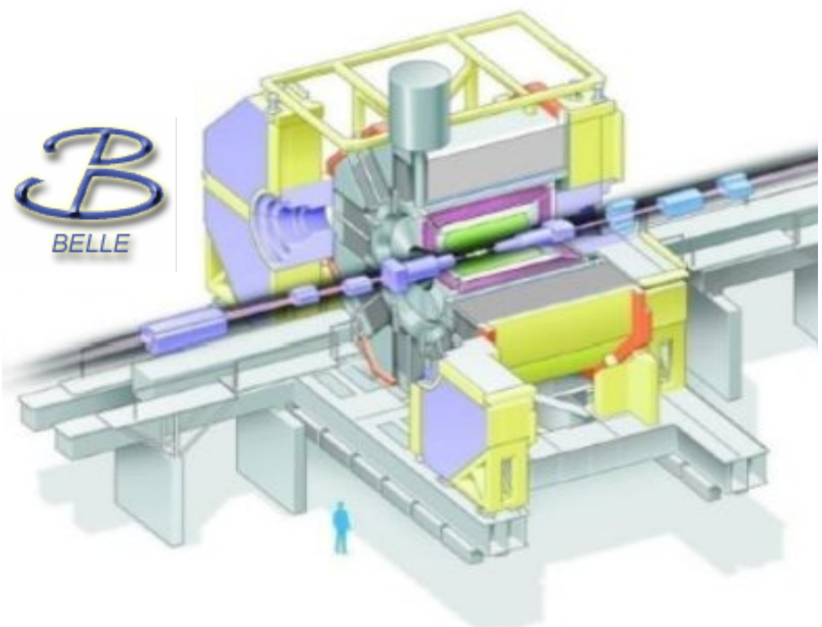
ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

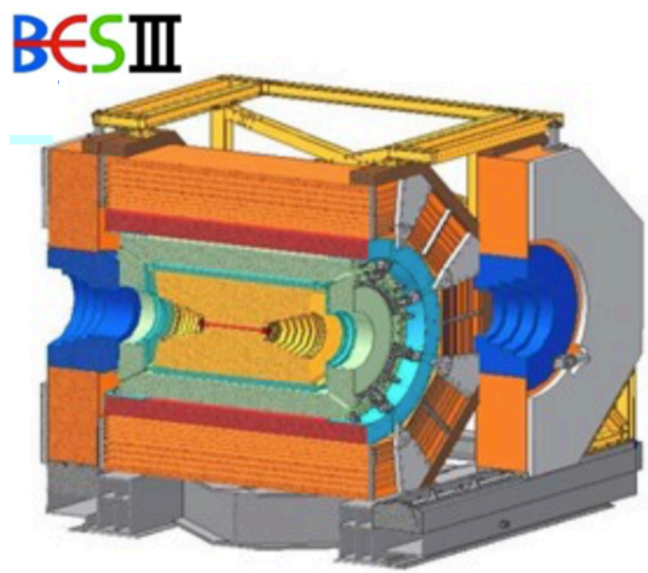
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

Main Suppliers of Exotics

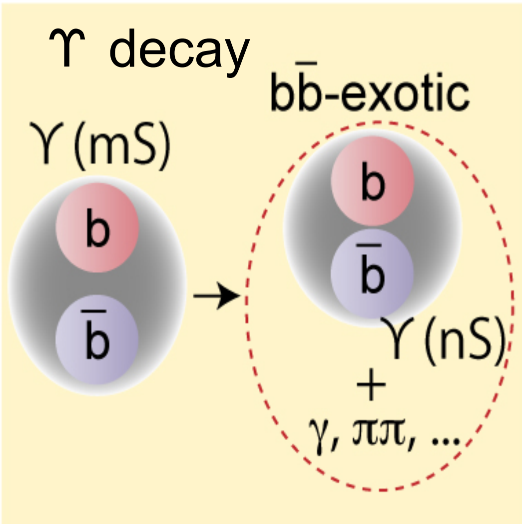


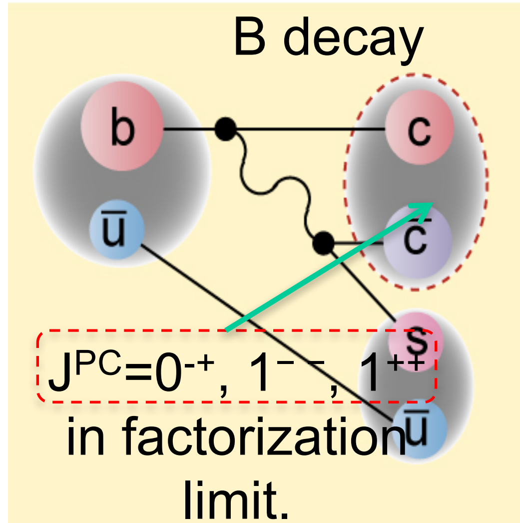


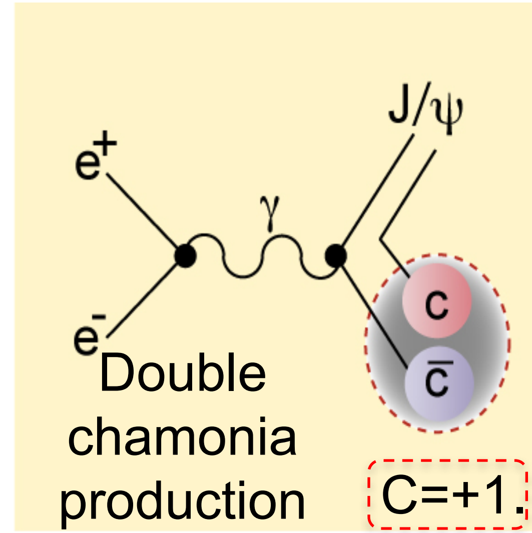


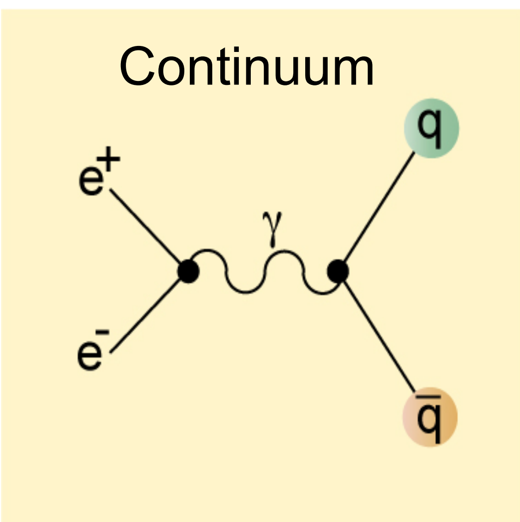


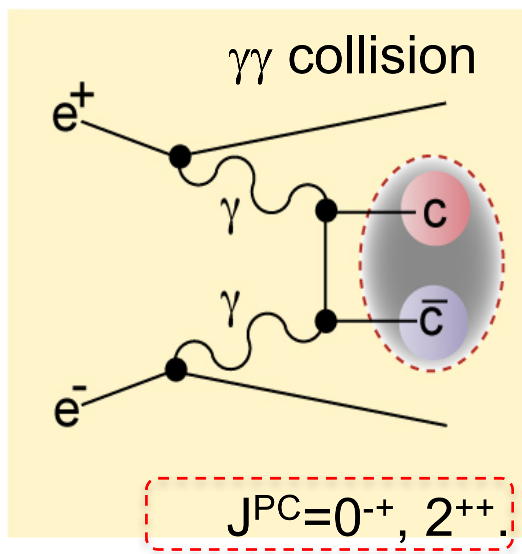
Variety of recorded reactions

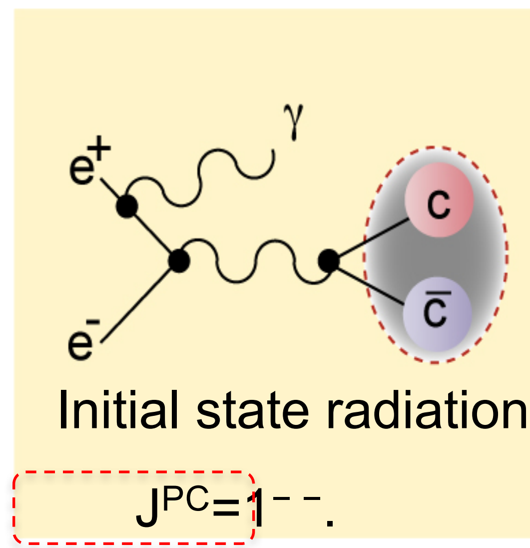




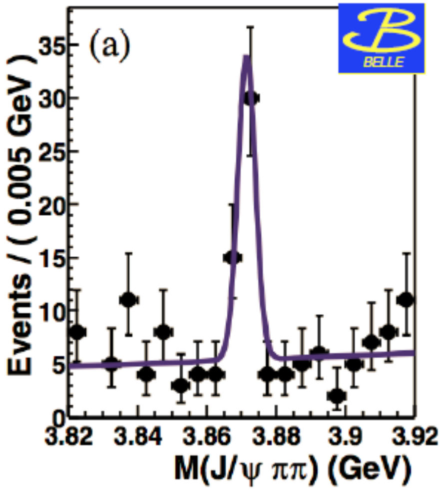








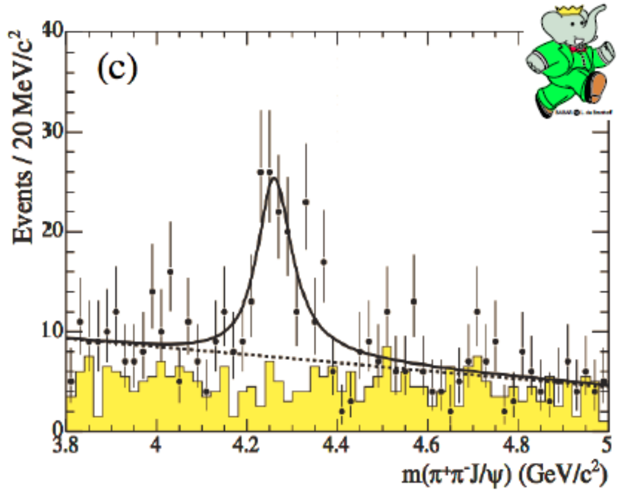
"X Y Z" – *the beginning*



$X(3872)$

PRL 91, 262001 (2003)

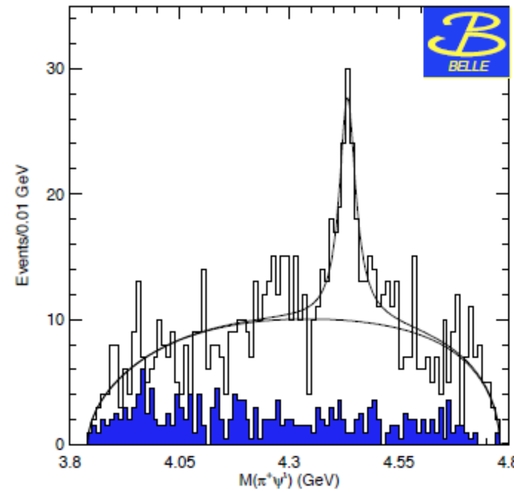
$B^{\pm} \to K^{\pm}[\pi^+\pi^- J/\psi]$



$Y(4260)$

PRL 95, 142001 (2005)

$e^+e^- \to \gamma[\pi^+\pi^- J/\psi]$



$Z_c(4430)^{\pm}$

PRL 100, 142001 (2008)

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

~20 multi-quark states are observed since 2003 with high significance

BES, Belle, Babar, CDF, D0, LHCb, Atlas, CMS

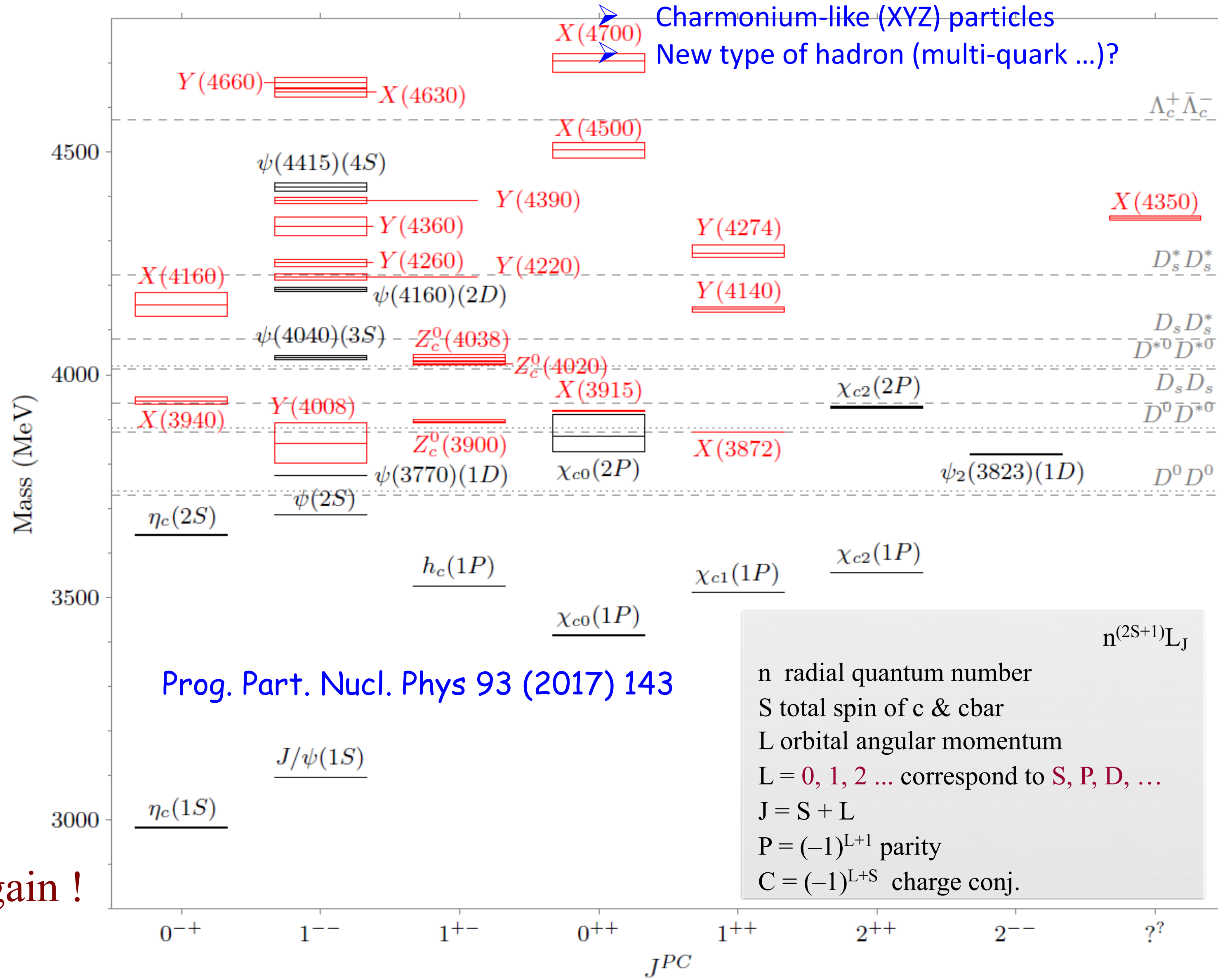
Some examples of multi-quark states

Tetraquarks candidates **X(3782)**$\to J/\psi\pi^+\pi^-$, **Z⁺(4430)**$\to \Psi'\pi^+$, **X(4140)**$\to J/\psi\phi$, **Z_b^+(10610)**$\to \Upsilon\pi^+$, **Z_b^+(10650)** $\to \Upsilon\pi^+$

Pentaquarks candidates **P_c^+(4450)** $\to J/\psi p$, **P_c^+(4380)** $\to J/\psi p$

XYZ particles

- Charmonium-like (XYZ) particles
- New type of hadron (multi-quark …)?



Prog. Part. Nucl. Phys 93 (2017) 143

$n^{(2S+1)}L_J$

n radial quantum number

S total spin of c & cbar

L orbital angular momentum

L = 0, 1, 2 ... correspond to S, P, D, …

J = S + L

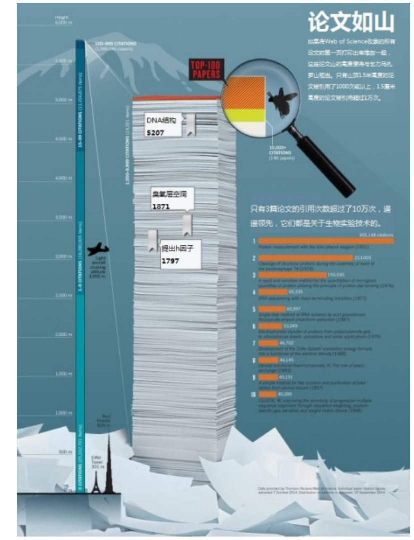
P = $(-1)^{L+1}$ parity

C = $(-1)^{L+S}$ charge conj.

Particle "Zoo" again !

If I could remember the names of all these particles, I'd be a botanist. - E. Fermi

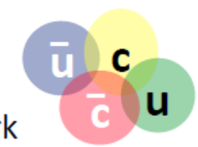
Too many models !



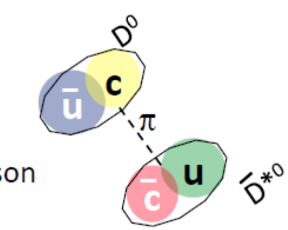
- Theory 1: screened potential
- Theory 2: hybrids with excited gluons
- Theory 3: tetraquark states
- Theory 4: meson molecules
- Theory 5: cusps effect
- Theory 6: final state interaction
- Theory 7: coupled-channel effect
- Theory 8: mixing of normal quarkonium and exotics
- Theory 9: mixture of all these effects
- Theories …

Tetraquark mesons

tightly bound
diquark-diantiquark



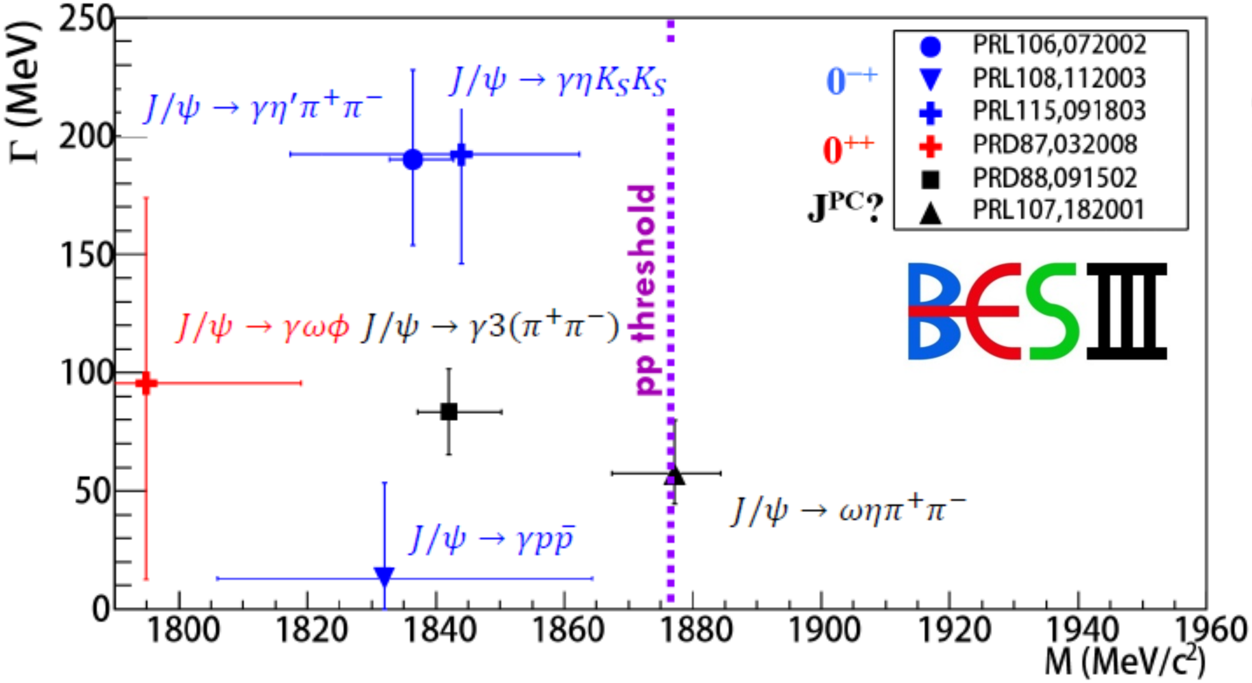
loosely bound
meson-antimeson
“molecule”

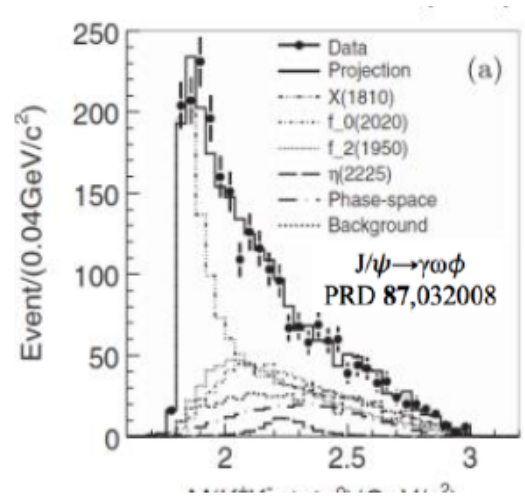


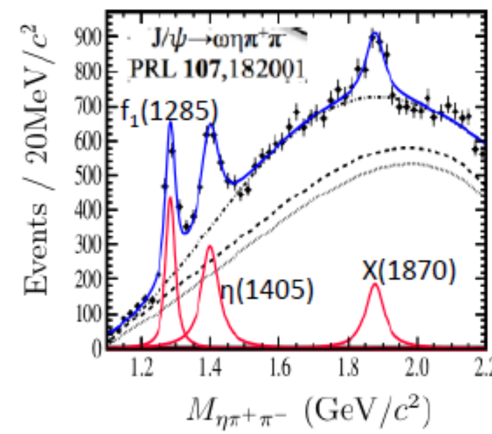
We need clear features to identify exotic hadronic states !

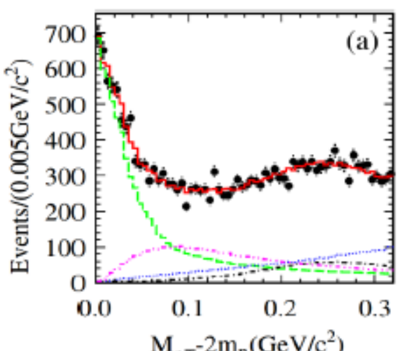
The X state

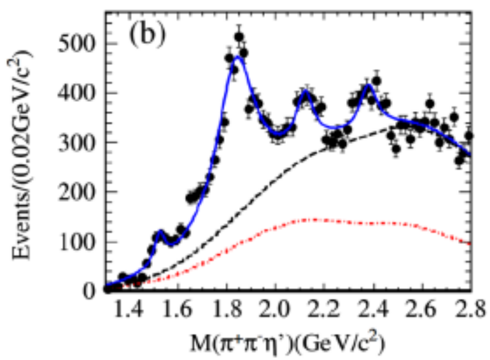
X(18??) at BESIII

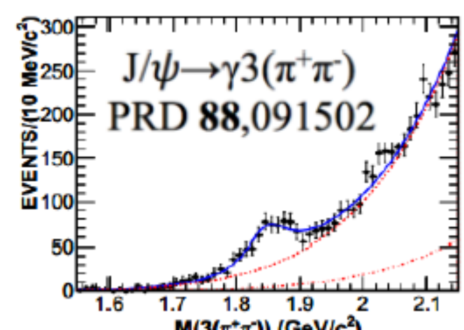








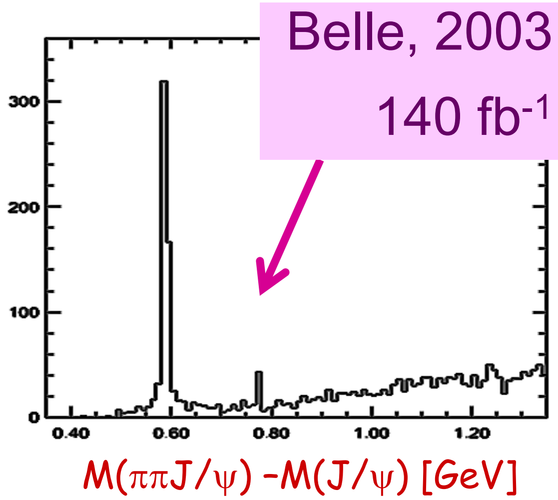




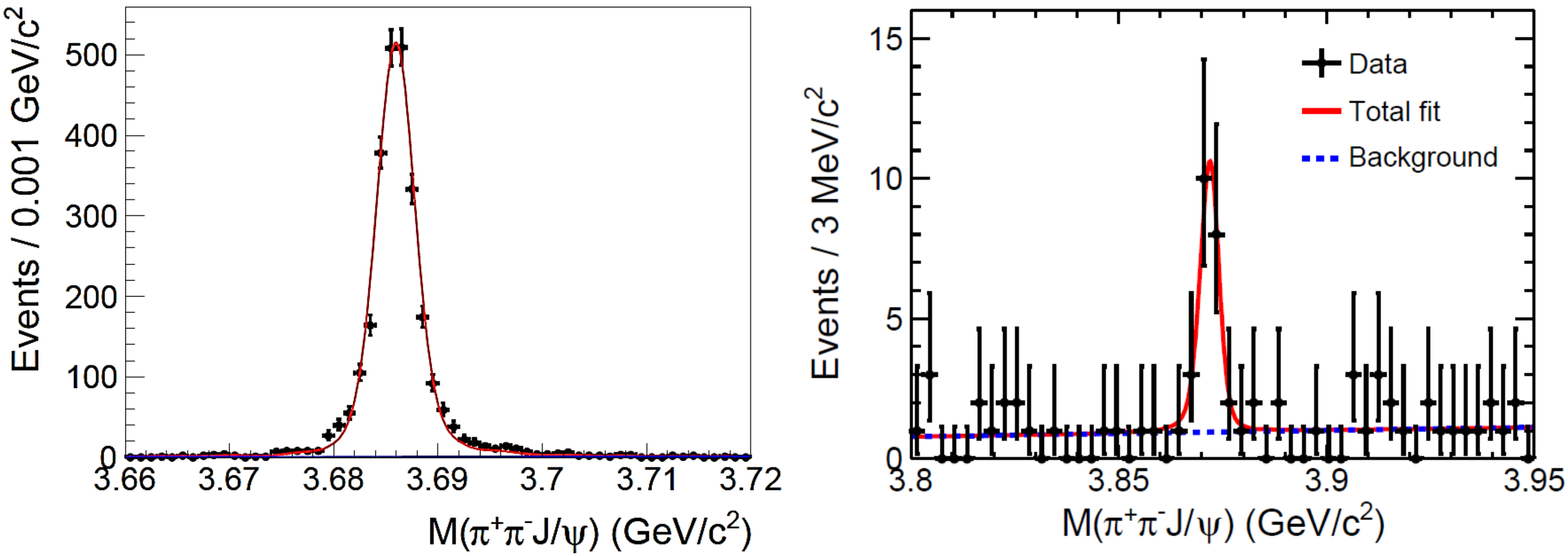
- Any relations?
- What is the role of the ppbar threshold (and other thresholds)?
- Patterns in the production and decay modes

What is the X(3872)?

- Mass: Very close to $\bar{D}^0 D^{*0}$ threshold
- Width: Very narrow, < 1.2 MeV
- $J^{PC}=1^{++}$
- Production
  - in $\bar{p}p$/pp collision – rate similar to charmonia
  - In B decays – KX similar to $c\bar{c}$, K*X smaller than $c\bar{c}$
  - $Y(4260) \rightarrow \gamma + X(3872)$
- Decay BR: open charm ~ 50%, charmonium~O(%)
- Nature (very likely exotic)
  - Loosely $\bar{D}^0 D^{*0}$ bound state (like deuteron)?
  - Mixture of excited χ_{c1} and $\bar{D}^0 D^{*0}$ bound state?



Observation of $e^+e^- \rightarrow \gamma X(3872)$



ISR ψ' signal is used for mass, and mass resolution calibration.

N=1818; ΔM=0.34±0.04 MeV; $\Delta\sigma_M$=1.14 ±0.07 MeV

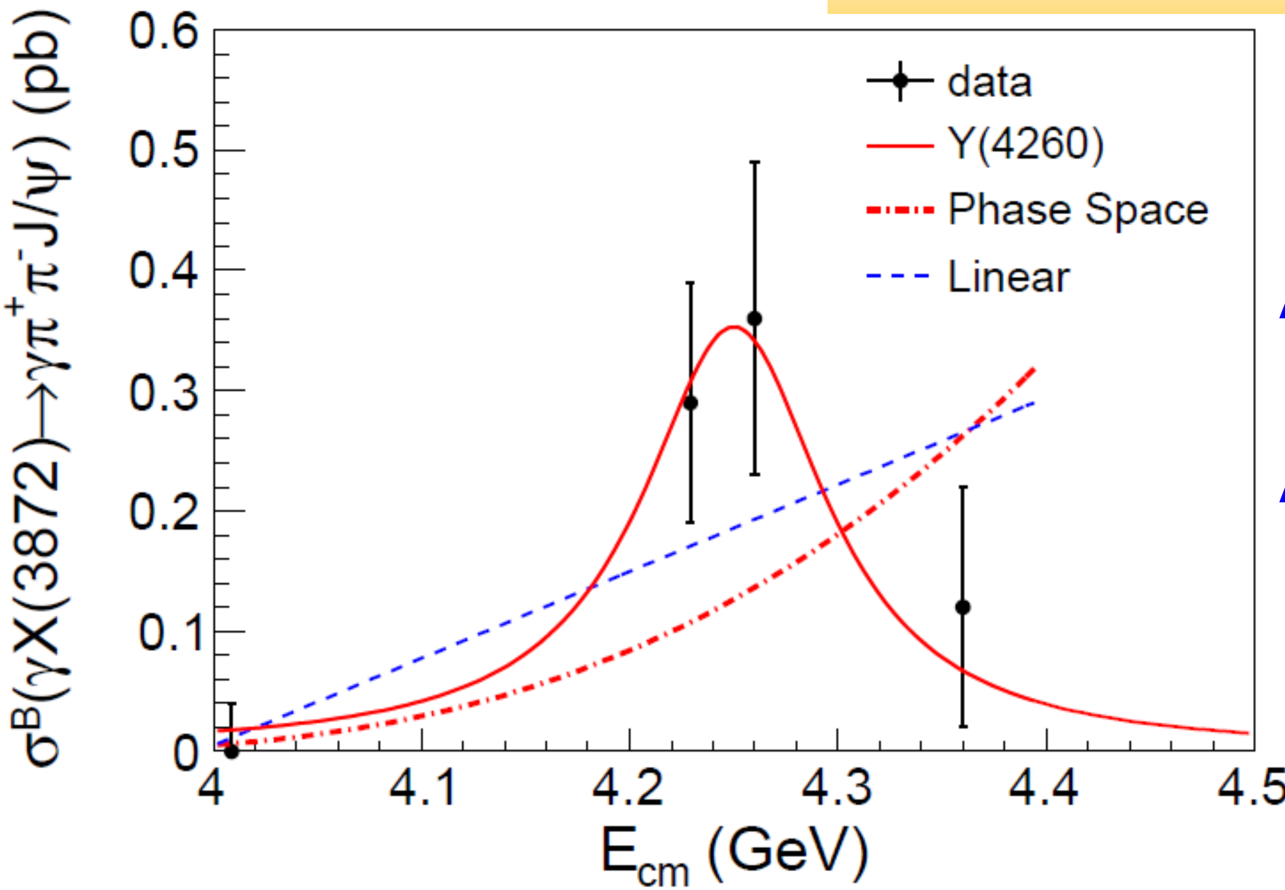
PRL 112, 092001 (2014)

N(X(3872)) = 20.1±4.5 **6.3σ**

M(X(3872)) = 3871.9±0.7±0.2 MeV [PDG: 3871.68 ±0.17 MeV]

Observation of **Y(4260)**→γX(3872)

PRL 112, 092001 (2014)



A new Y(4260) decay mode

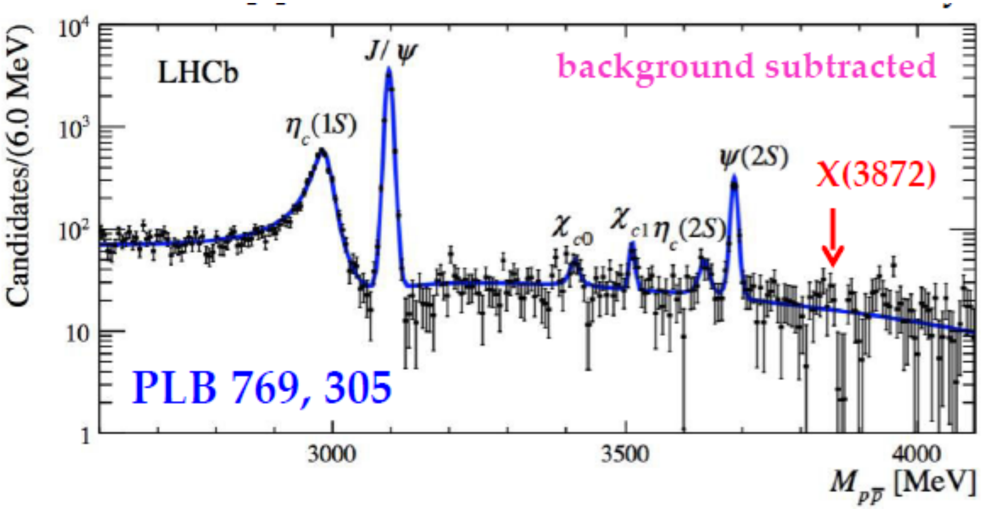
A new X(3872) production mode

If we take $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) \sim 5\%$, (>2.6% in PDG)

$\frac{\sigma(e^+e^-\to\gamma X(3872))}{\sigma(e^+e^-\to\pi^+\pi^- J/\psi)} \sim$ 10%   Large transition ratio !

Search for X(3872)→$p\bar{p}$ and $\varphi\varphi$

- $B^+ \to p\bar{p}K^+$: clean environment to study $(c\bar{c}) \to p\bar{p}$

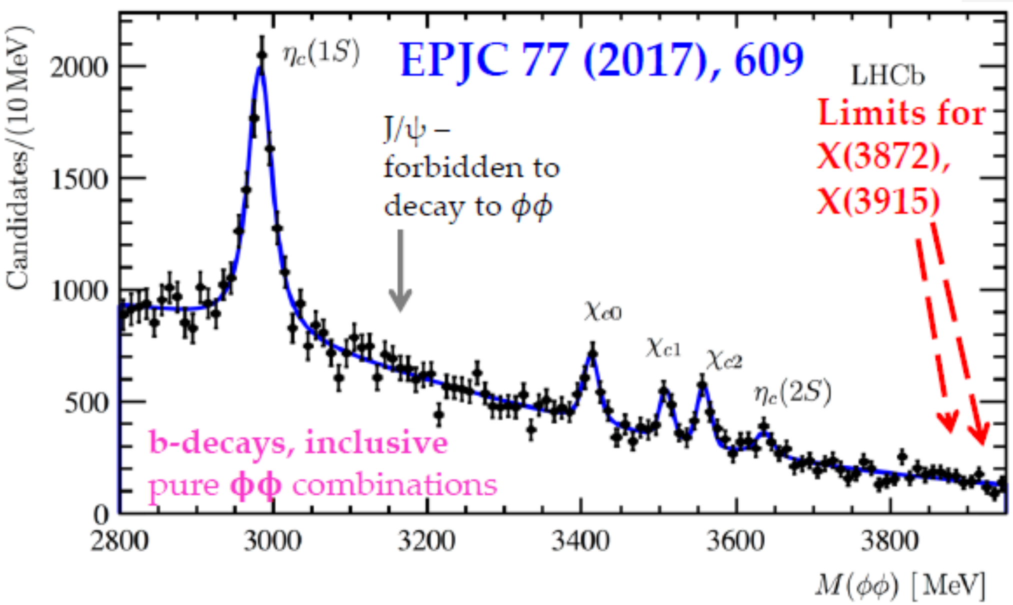


Upper limits at 95%(90%) C.L.

$$\mathcal{B}(b \to X(3872)X) \times \mathcal{B}(X(3872) \to \phi\phi) < 4.5(3.9) \times 10^{-7}$$

$$\mathcal{B}(b \to X(3915)X) \times \mathcal{B}(X(3915) \to \phi\phi) < 3.1(2.7) \times 10^{-7}$$

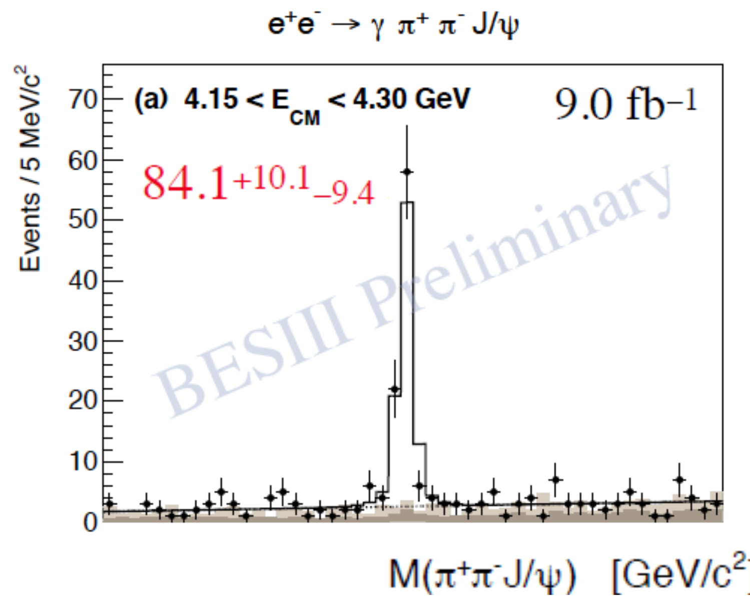
- ϕϕ spectrum from inclusive b-hadron decays

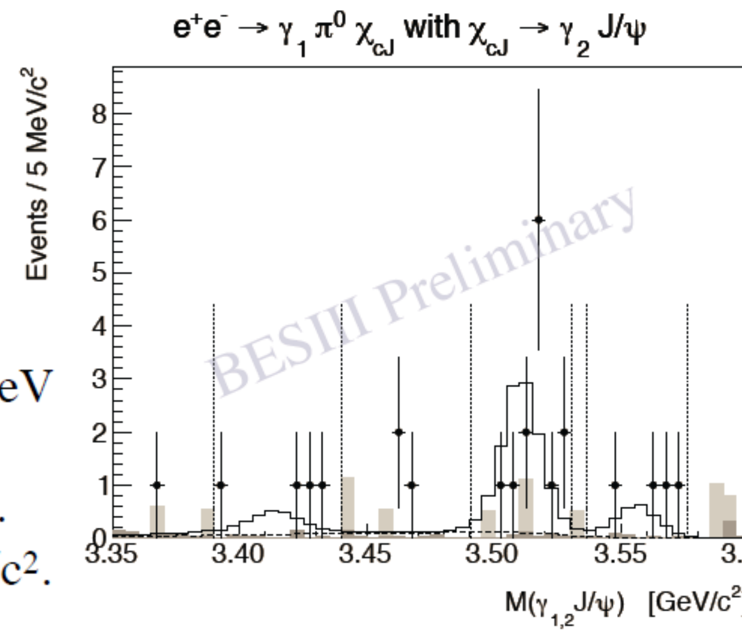


$$\frac{\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})}$$

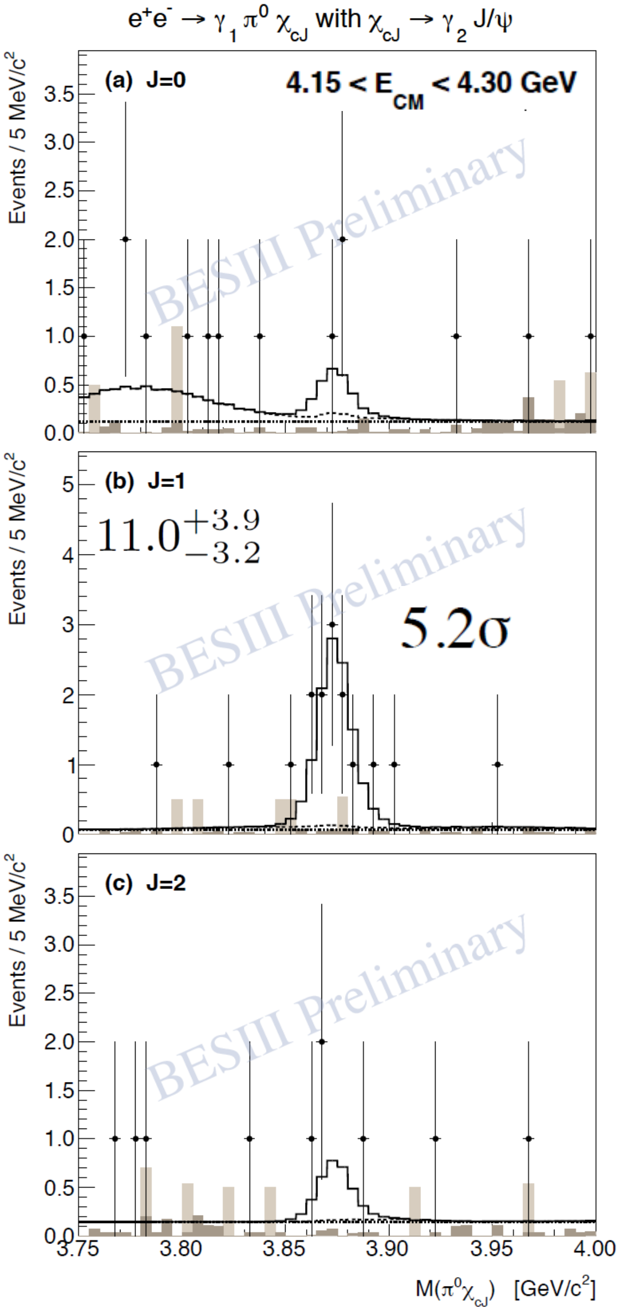
Observation of X(3872)→$\pi^0\chi_{c1}$

- If the X(3872) were the $\chi_{c1}(2P)$ state of charmonium:
  $\Gamma(X(3872) \to \pi^0\chi_{c1}(1P)) \sim 0.06$ keV *(i.e. very small)*
  If the X(3872) were a tetraquark state:
  $\Gamma(X(3872) \to \pi^0\chi_{c1}(1P))$ should be enhanced.
  [Dubynskiy, Voloshin, PRD 77, 014013 (2008)]
- The **X(3872) → $\pi^0\chi_{cJ}$** decays are sensitive to the internal structure of the X(3872).
- For normalization, first reconstruct:
  $e^+e^- \to \gamma X(3872)$ with $X(3872) \to \pi^+\pi^- J/\psi$
  using $J/\psi \to e^+e^-/\mu^+\mu^-$.
- Next search for:
  $e^+e^- \to \gamma_1 X(3872)$ with $X(3872) \to \pi^0\chi_{cJ}$
  using $\chi_{cJ} \to \gamma_2 J/\psi$ and $J/\psi \to e^+e^-/\mu^+\mu^-$.
- Finally, take the distribution for $4.15 < E_{CM} < 4.30$ GeV and separate the χ_{cJ} for J = 0, 1, and 2 by choosing the γ_2 that minimizes $\Delta M_J \equiv |M(\gamma_2 J/\psi) - M_{PDG}(\chi_{cJ})|$. Also require $\Delta M_0 < 25$ MeV/c^2 and $\Delta M_{1,2} < 20$ MeV/c^2.





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



- Find a clear X(3872) signal (5.2σ) for $\pi^0\chi_{c1}$, and no signal for J = 0 or 2.

  $R_J = B(X \to \pi^0\chi_{cJ}) / B(X \to \pi^+\pi^- J/\psi)$:

  $R_0 < 19$ (90% U.L.)

  $R_1 = 0.88^{+0.31}_{-0.26} \pm 0.14$

  $R_2 < 1.0$ (90% U.L.)

3.2%[PDG]< $B(X(3872) \to \pi^+\pi^- J/\psi) < 6.4\%$

Then we have:

$B(X(3872) \to \pi^0\chi_{c1})$~(3-6)%

- **The large value for R_1 disfavors the $\chi_{c1}(2P)$ interpretation of the X(3872).**

[Dubynskiy, Voloshin, PRD 77, 014013 (2008)]

Loosely $\bar{D}^0D^{*0}$ bound state ?

Mixture of excited χ_{c1} and $\bar{D}^0D^{*0}$ bound state?

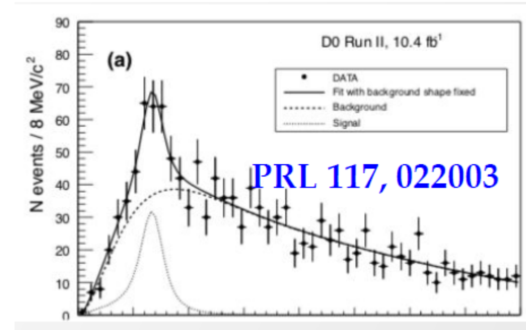
Tetraquark state ?

X(5568) – puzzle ?

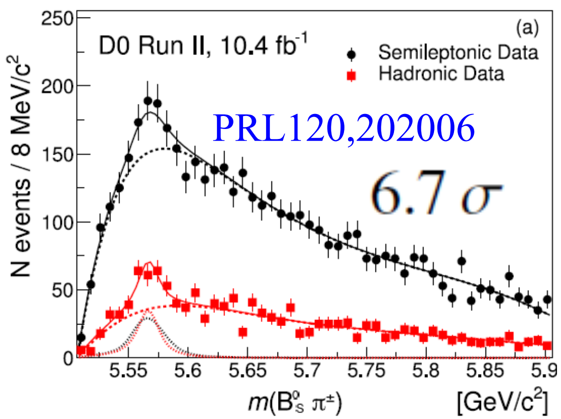
- Possible tetraquark candidate of four different quarks
- Seen by D0 with **4.8 σ** significance

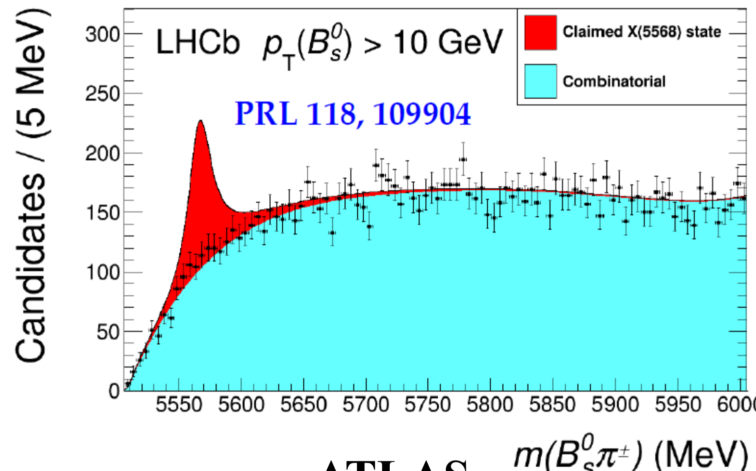
$$m = 5567.8 \pm 2.9\,(\text{stat})^{+0.9}_{-1.9}\,(\text{syst})\ \text{MeV}/c^2$$

$$\Gamma = 21.9 \pm 6.4\,(\text{stat})^{+5.0}_{-2.5}\,(\text{syst})\ \text{MeV}/c^2$$

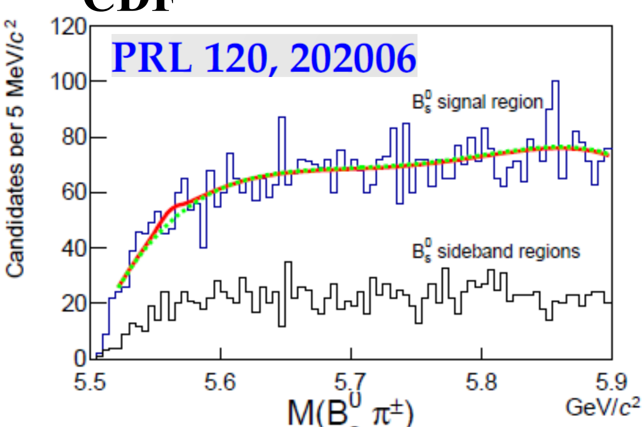


If confirmed, would be unique with 4 different flavors

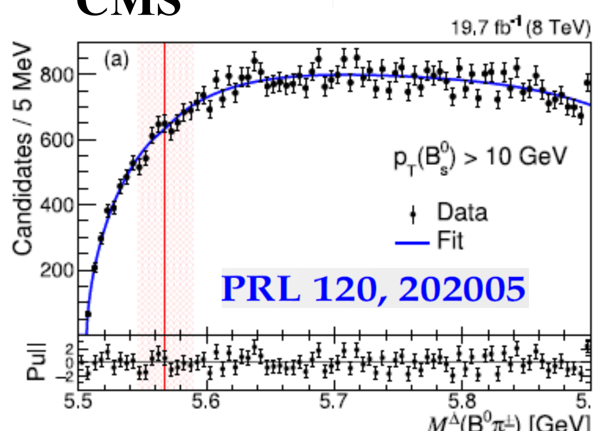




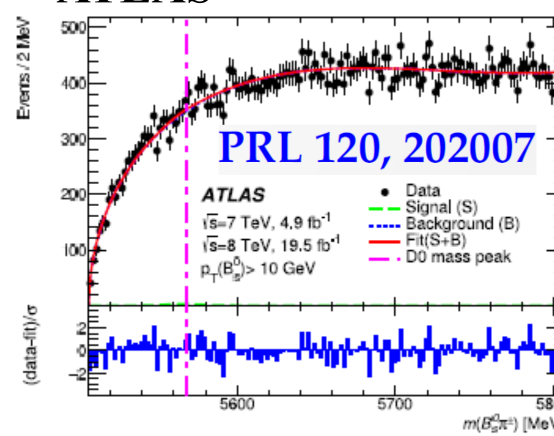
CDF



CMS

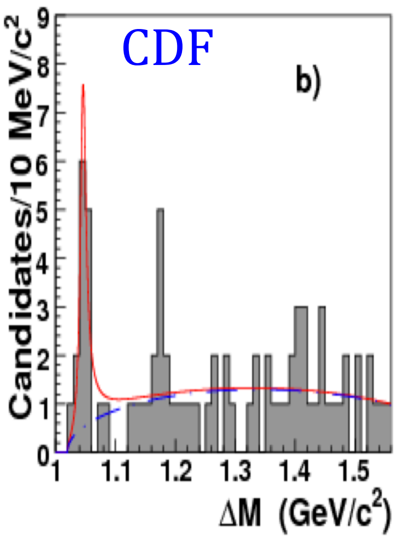


ATLAS

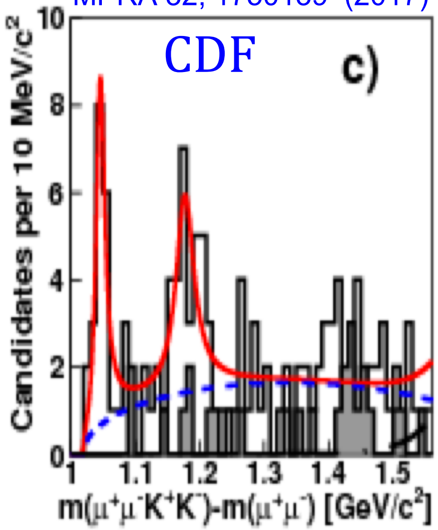


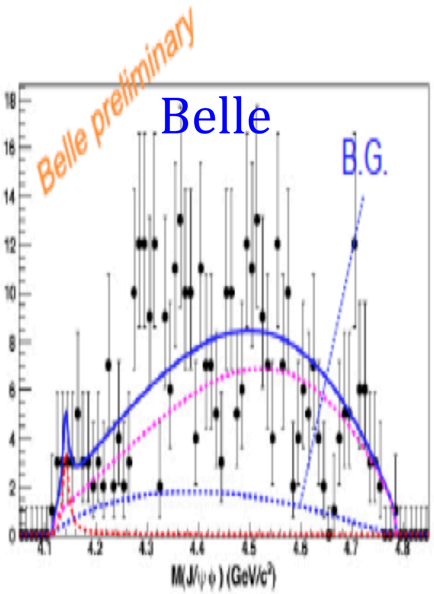
The Story of X(4140)—(2009-2011)

PRL102, 242002 (2009)

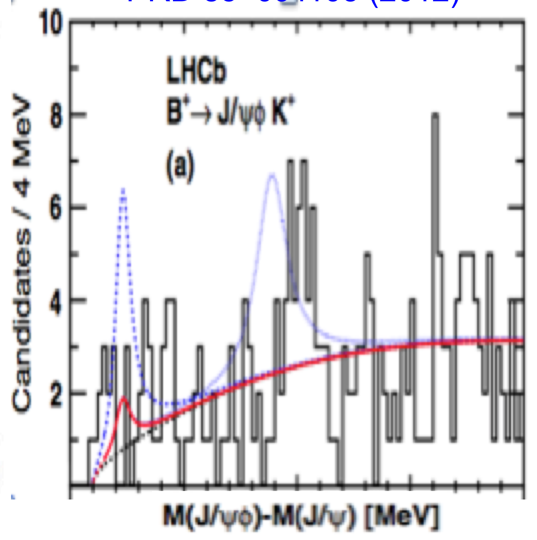


MPRA 32, 1750139 (2017)

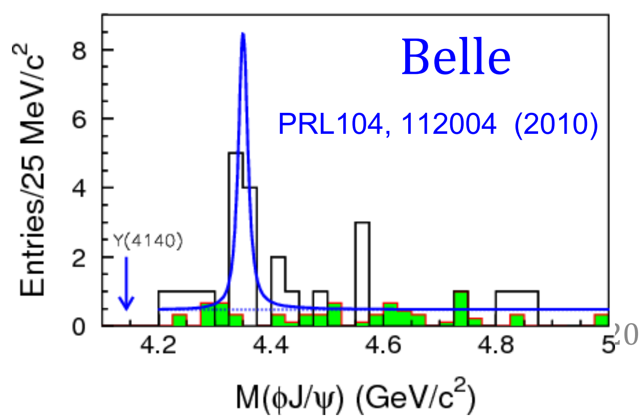




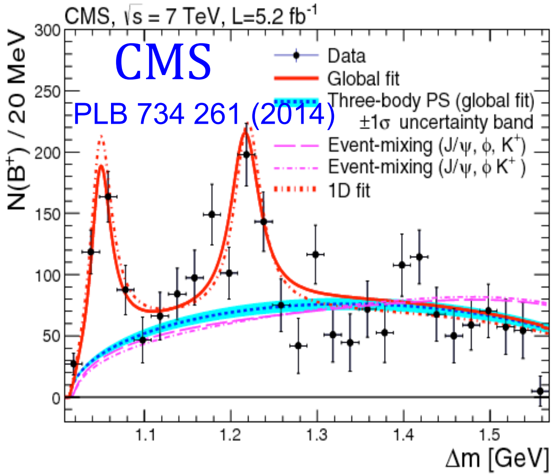
PRD 85 091103 (2012)

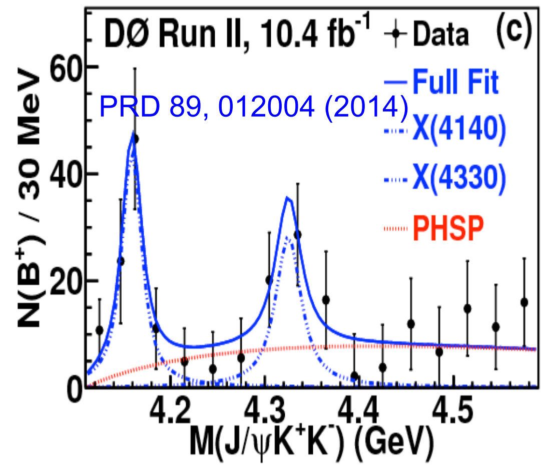


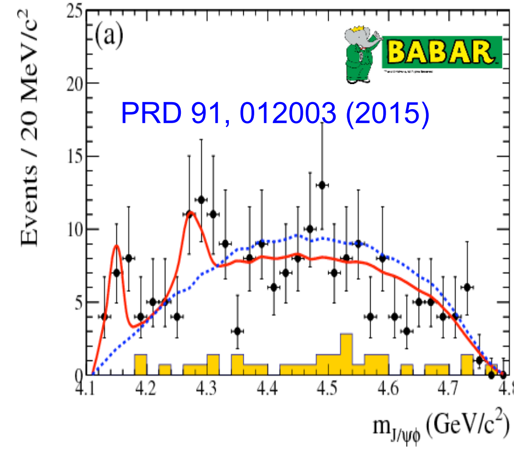
- CDF (2009) found evidence of Y(4140), now called X(4140)
- Belle (2010) cannot confirm or deny the existence of X(4140)
- LHCb(2011) confirms neither of the structures, 2.4sigma disagreement with CDF
- Belle found evidence of X(4350) in γγ process

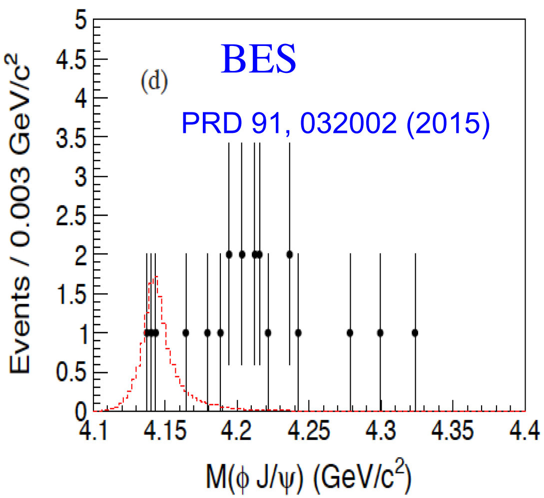


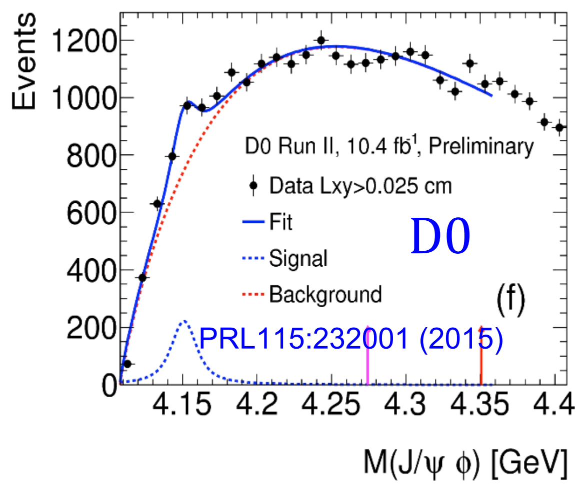
The Story of X(4140)—(2012-2016)

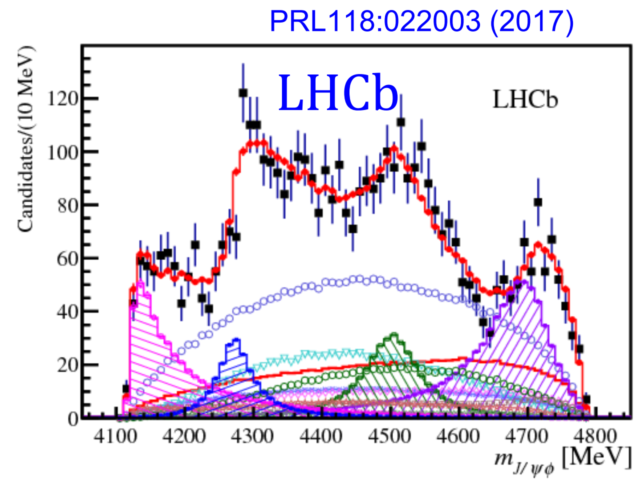












- CMS, D0, LHCb finally confirm the existence of X(4140) with >5sigma significance
- LHCb also confirms the existence of Y(4274) with >5sigma significance
- LHCb found two more structures: X(4500) & X(4700)

Search for $X_{bb\bar{b}\bar{b}}$

Motivation:

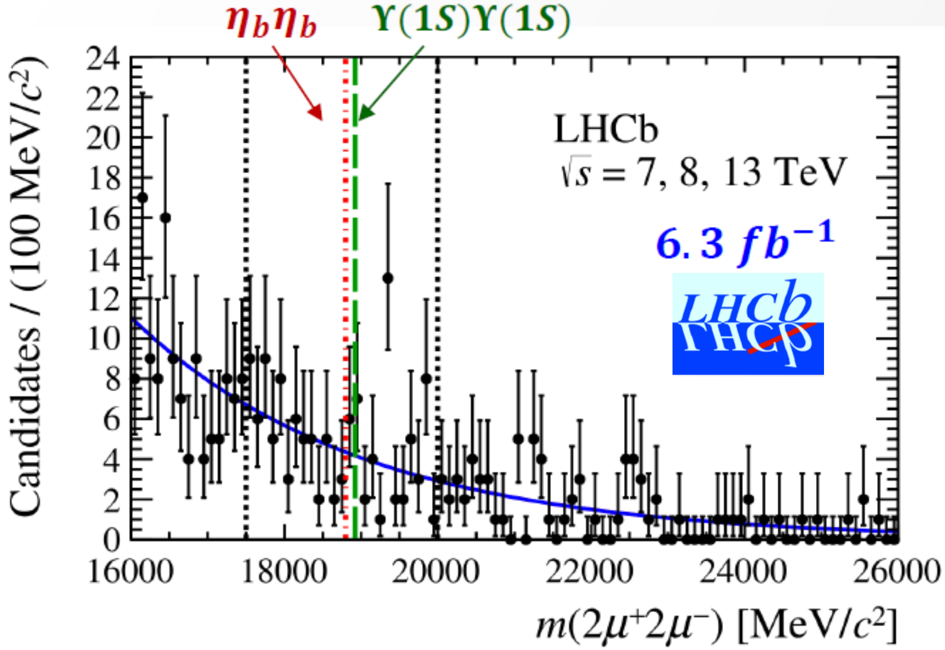
- ***$bb\bar{b}\bar{b}$* tetraquark below the $\eta_b\eta_b$ threshold ($18.8\ GeV/c^2$) may be found decaying to $\Upsilon\mu^+\mu^-$**
- Predictions: **(Karliner et al., PRD 95 034011)**
- (cross section × BR) expected at the level $\sim$**4 *fb***, width $\sim 1.2\ MeV$

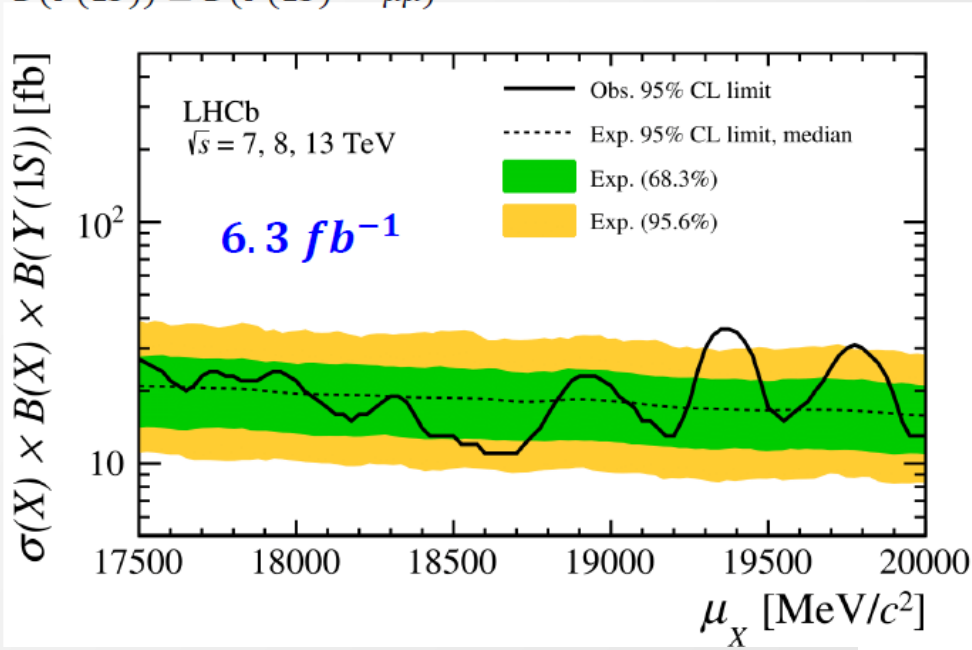
Analysis:

- Data sample: $6\ fb^{-1}$, **2011-2017(!)** data
- $\Upsilon(1S) \to \mu^+\mu^-$ used as normalization
- Resolution extracted from MC, **$\sim$ 65 *MeV***
- **Upper limits as a function of inv. mass**

CMS has observed double upsilons
(JHEP 1705 013 (2017)
should check mass spectrum?

$\sigma(X) \equiv \sigma(pp \to X_{bb\bar{b}\bar{b}})$
$B(X) \equiv \sigma(X_{bb\bar{b}\bar{b}} \to \Upsilon(1S)\mu\mu)$
$B(\Upsilon(1S)) \equiv B(\Upsilon(1S) \to \mu\mu)$



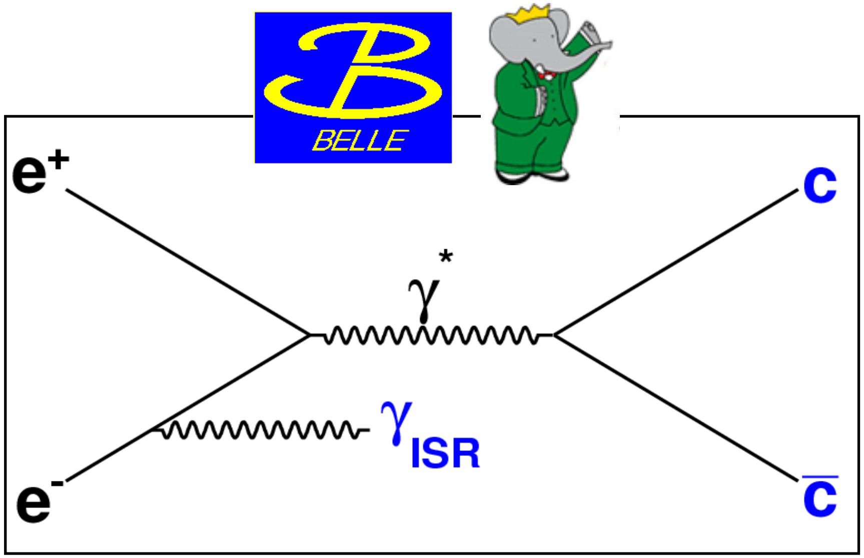


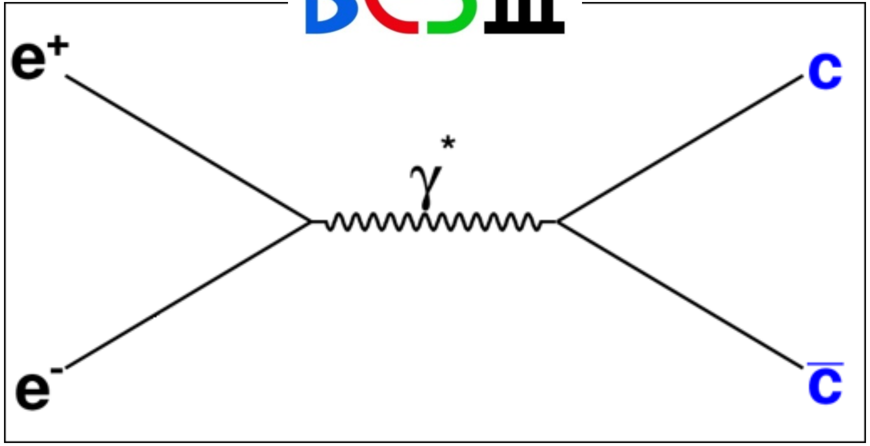
No significant signal, upper limit for mass range 17.5–20.0 GeV/c^2

The Y states

measurements of more final states for the

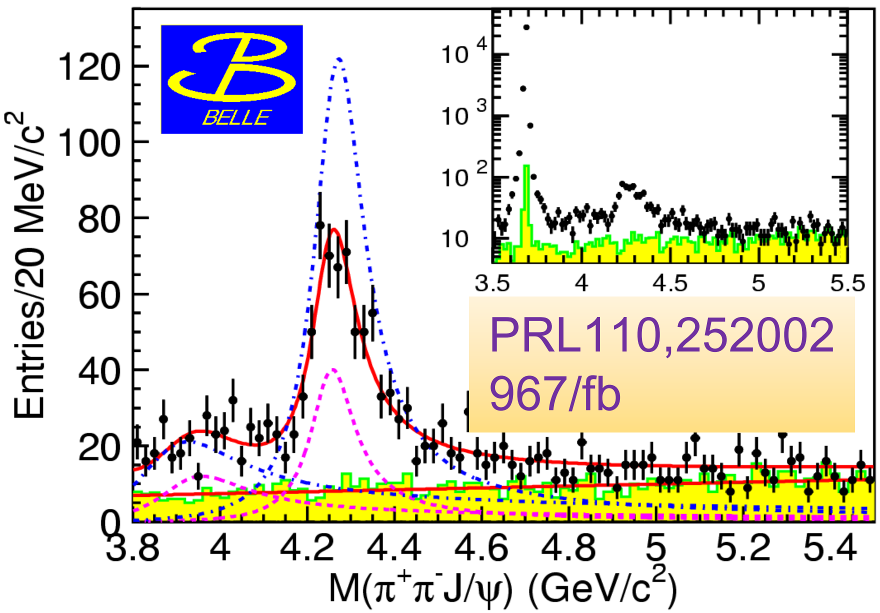
Y and ψ states



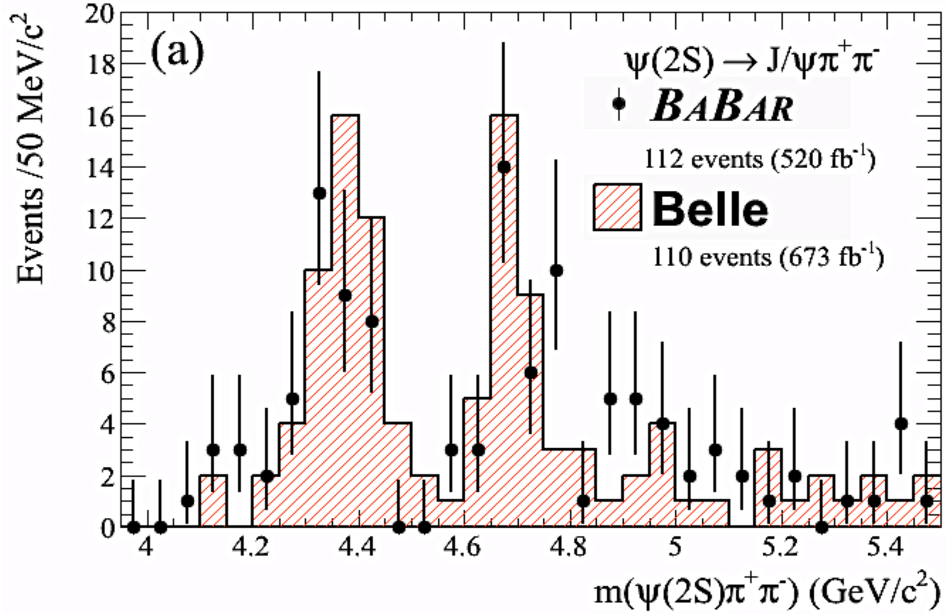


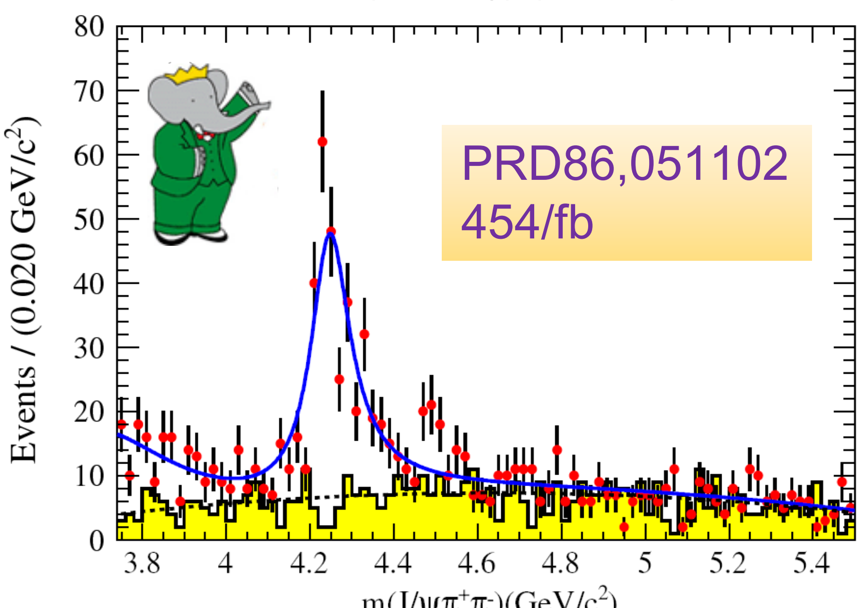
The Y states

Belle: PRL99,142002, 670/fb
BaBar: PRD89, 111103, 520/fb

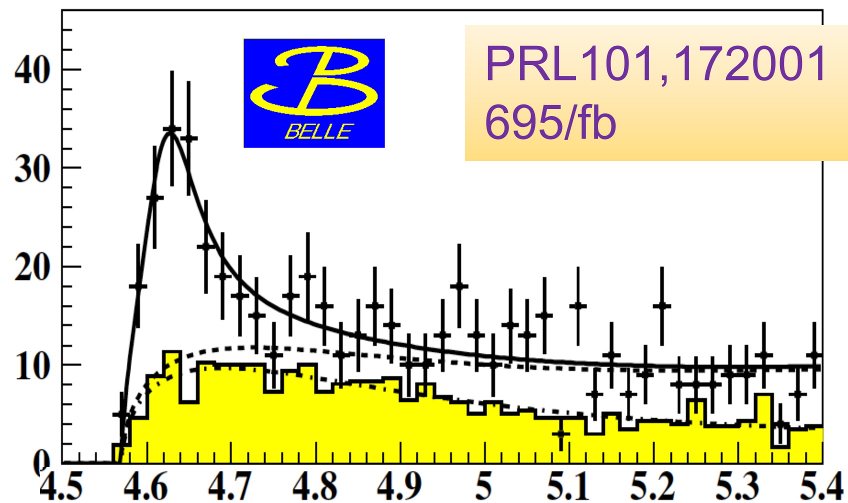


PRL110,252002
967/fb





PRD86,051102
454/fb



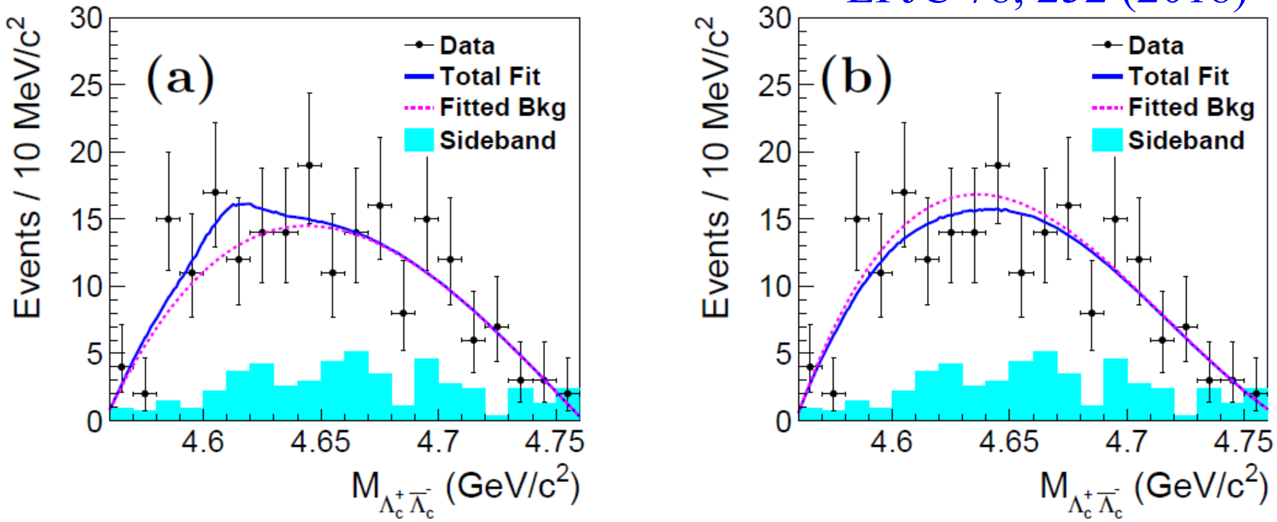
PRL101,172001
695/fb

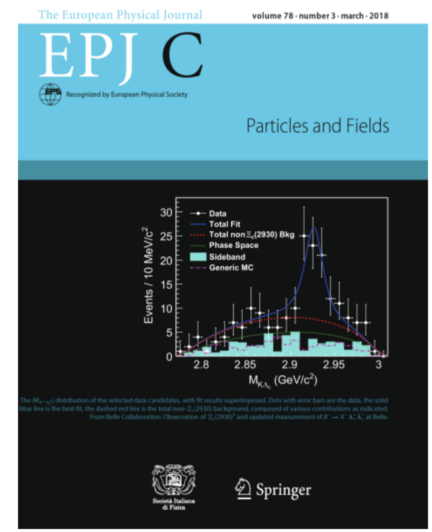
$M(\Lambda_c^+\Lambda_c^-)$

Search for Y(4660) and its spin part in $B^+ \to K^+ \Lambda_c^+ \overline{\Lambda}_c^-$ at Belle

- Belle reported a structure, called X(4630), in the $\Lambda_c^+\overline{\Lambda}_c^-$ invariant mass distribution in $e^+e^- \to \gamma_{ISR}\Lambda_c^+\overline{\Lambda}_c^-$ PRL 101, 172001
- Also, some theory explained that Y(4660) has a large partial decay width to $\Lambda_c^+\overline{\Lambda}_c^-$ and it's spin partner Y(4616) is predicted. PRD 82, 094008; PRL102, 242004

EPJC 78, 252 (2018)

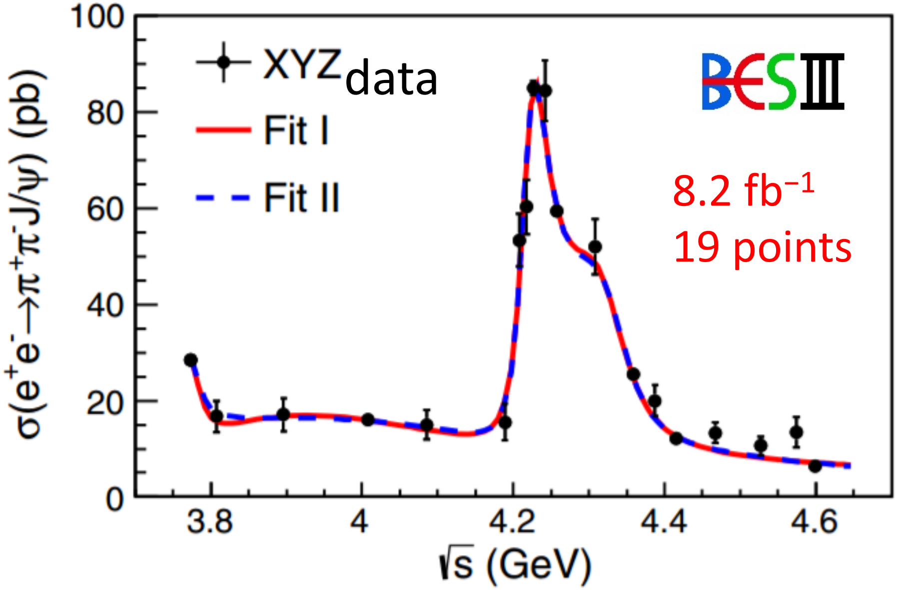


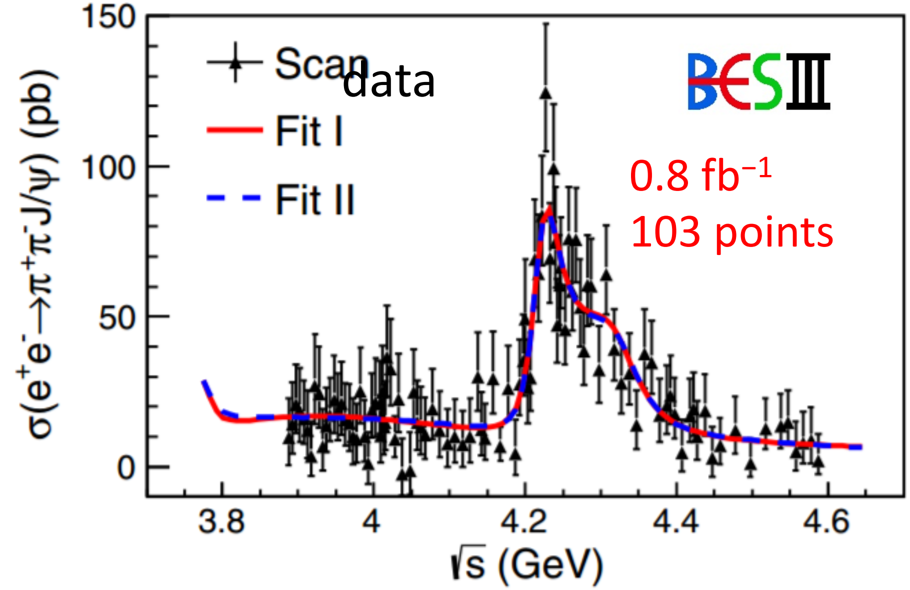


- No Y(4660) and its spin partner Y_η were observed. in the $\Lambda_c^+\overline{\Lambda}_c^-$ invariant mass distribution
- 90% C.L. upper limits of $B^+ \to K^+Y(4660) \to K^+\Lambda_c^+\overline{\Lambda}_c^-$ and $B^+ \to K^+Y_\eta \to K^+\Lambda_c^+\overline{\Lambda}_c^-$ are 1.2×10^{-4} and 2.0×10^{-4}.

$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ cross section

PRL118, 092001 (2017)

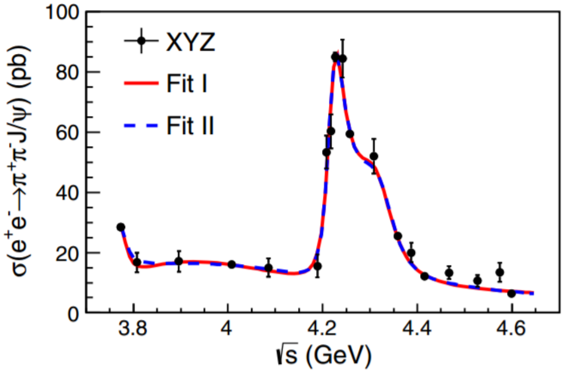


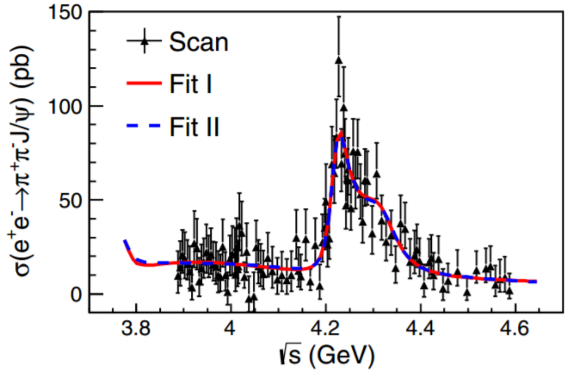


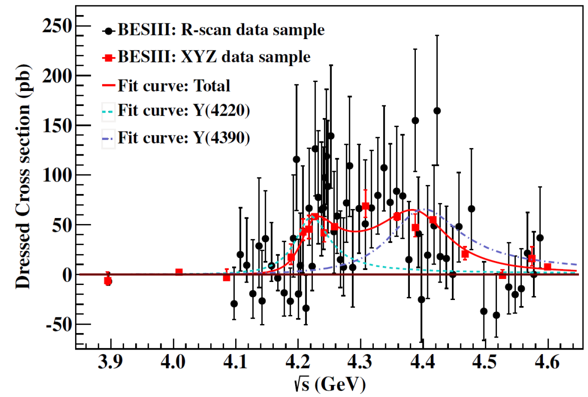
- Most precise cross section measurment to date from BESIII
- Fit I = $|BW_1+BW_2{*}e^{i\phi 2}+BW_3{*}e^{i\phi 3}|^2$ or Fit II = $|\exp+BW_2{*}e^{i\phi 2}+BW_3{*}e^{i\phi 3}|^2$ (other fits ruled out)
- M = 4222.0 $\pm$ 3.1 $\pm$ 1.4 MeV (lower)
- Γ = 44.1 $\pm$ 4.3 $\pm$ 2.0 MeV (narrower)

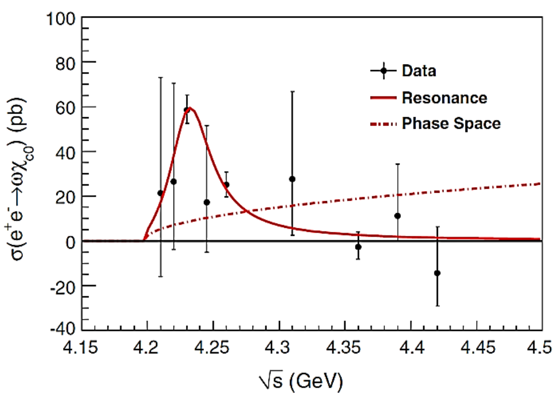
- A 2nd resonance Y_2 with M=4320.0 $\pm$ 10.4 $\pm$ 7.0 MeV/c^2
  Γ=$101.4^{+25.3}_{-19.7}$ $\pm$ 10.2 MeV
- Observed for the first time, significance > 7.6σ

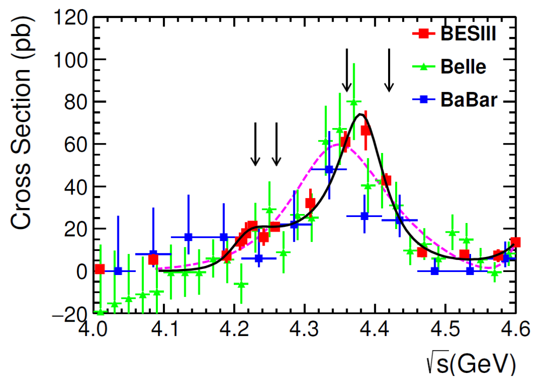
Y(4260)➔Y(4220): what is it?

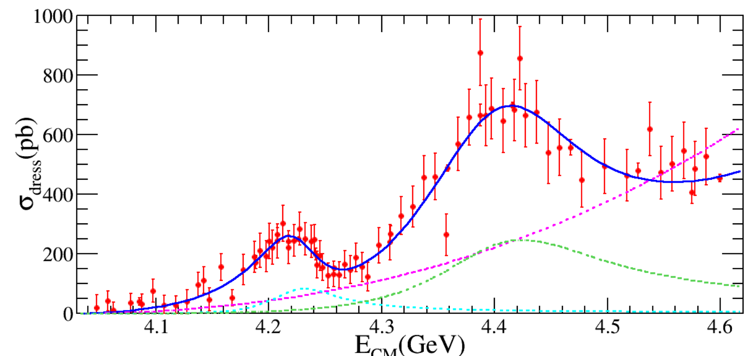












Y(4220) appeared in $\omega\chi_{c0}$, $\pi^+\pi^- J/\psi$, $\pi^+\pi^-\psi'$, $\pi^+\pi^- h_c$, $D^0 D^{*-}\pi^+$

Mass~4220 MeV, Width~ 60 MeV!

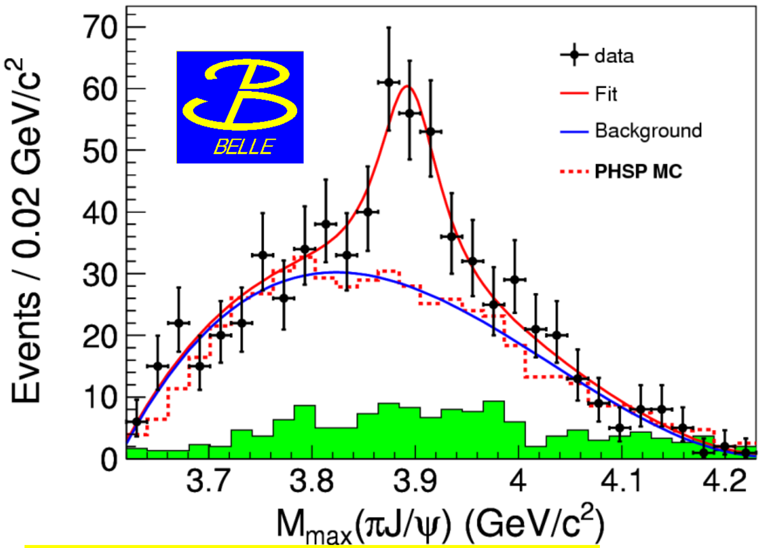
- ✓ Hybrid?
- ✓ $\bar{D}_1 D$ molecule?
- ✓ $\psi(4S)$ state?
- ✓ $D_s^* D_s^*$ molecule?
- ✓ $\omega\chi_{c0}$ molecule?

➔More data and more theoretical work needed

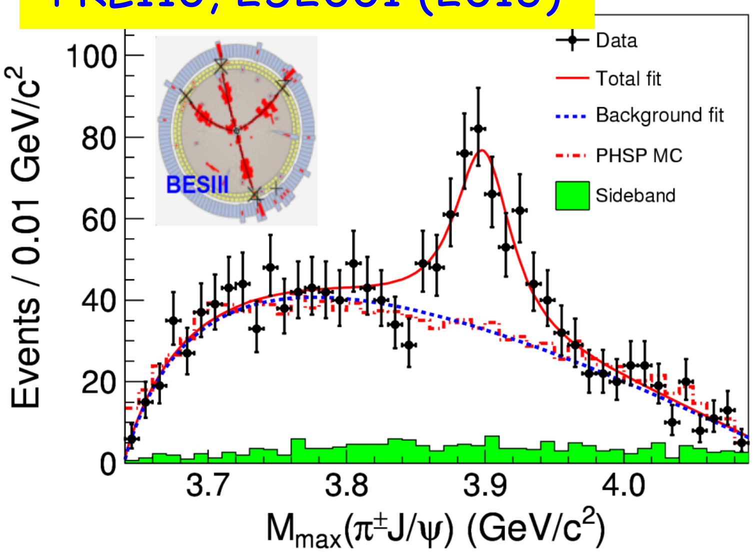
The Z_c states

Observation of Zc(3900)

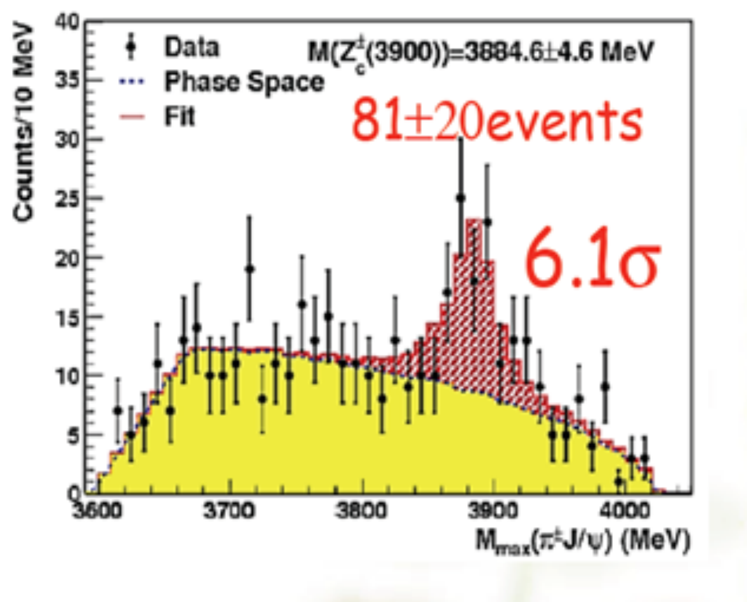
PRL110, 252002 (2013)



PRL110, 252001 (2013)



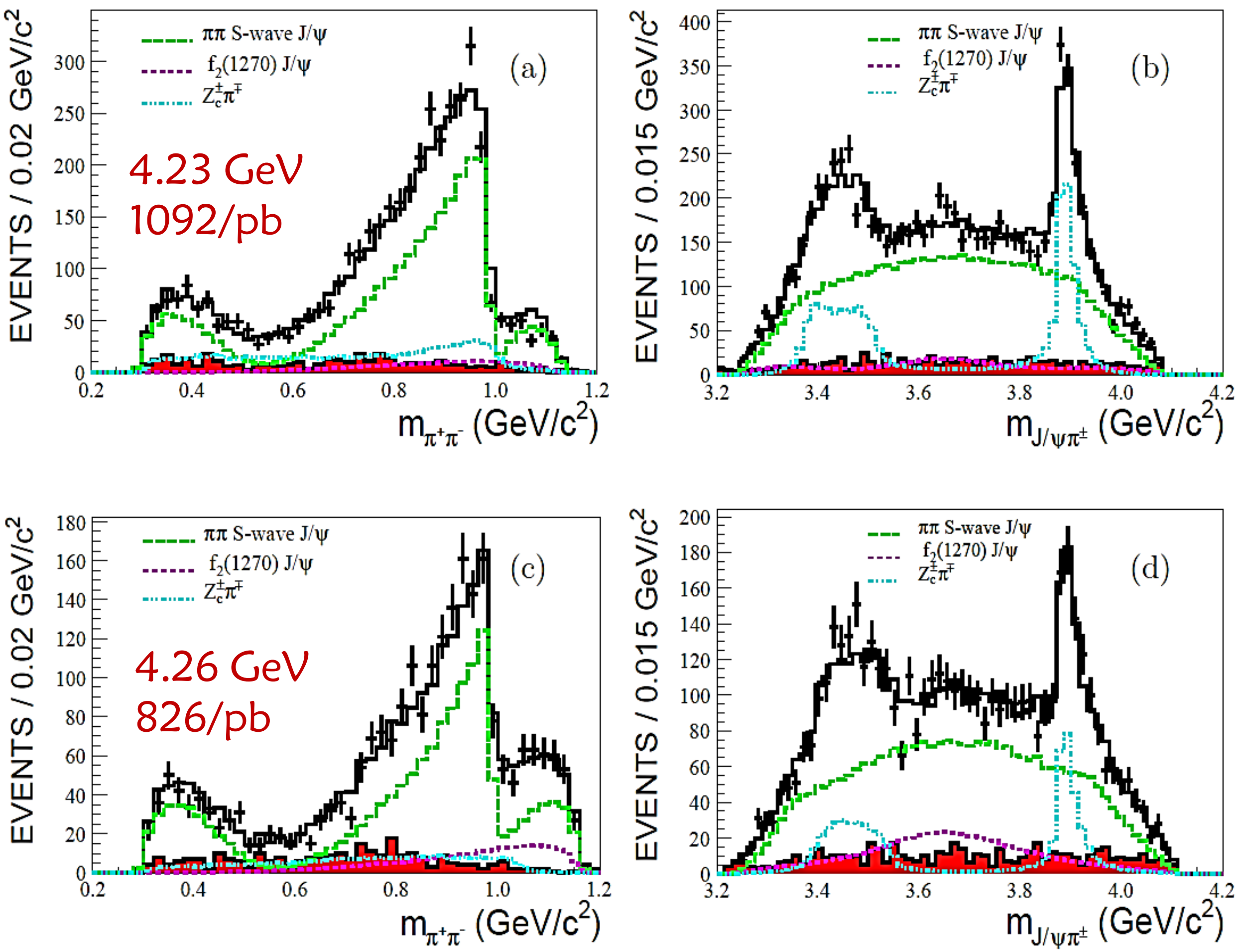
CLEOc data at 4.17 GeV: PLB 727, 366 (2013)



- $M = 3899.0 \pm 3.6 \pm 4.9$ MeV
- $\Gamma = 46 \pm 10 \pm 20$ MeV
- 307 ± 48 events
- $>8\sigma$

Spin-parity of $Z_c(3900)$

PRL 119, 072001 (2017)



- Asymmetric line shape
- JP=1+ preferred over 0-, 1-, 2-, 2+ by at least 7σ.
- Significant $f_0(980)$ contribution
- ππ D-wave fraction increases as E_{cm} increases

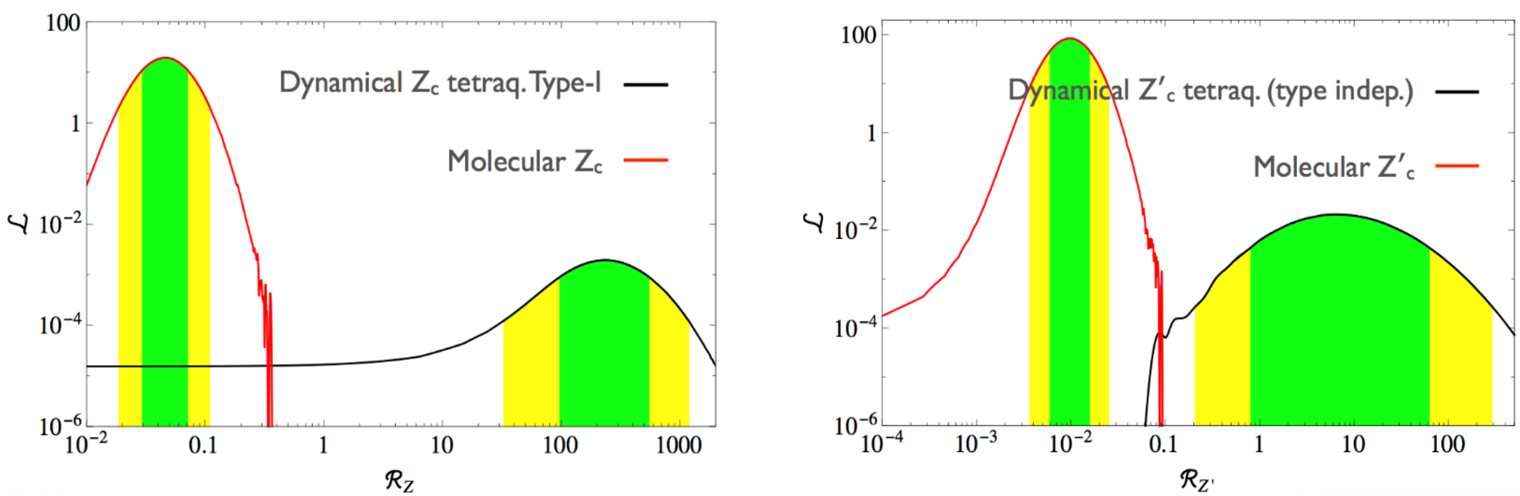
May any model calculate the s-dependent Dalitz plot?

[large data samples at 4.18-4.28 every 0.01 GeV, 4.36, and 4.42 GeV]

Search for $Z_c \to \rho\eta_c$

New

- Search for new decay mode of $Z_c(3900)$ and $Z_c(4020)$
- The ratios of $Z_c^{(\prime)} \to \rho\eta_c$ to $Z_c^{(\prime)} \to \pi J/\psi(\pi h_c)$ may discriminate **the tetra-quark** and **molecule** models.



$$R_z = \frac{B(Z_c \to \rho\eta_c)}{B(Z_c \to \pi J/\psi)} \qquad R_{z\prime} = \frac{B(Z_c' \to \rho\eta_c)}{B(Z_c' \to \pi h_c)}$$

A.Esposito, A.L.Guerrieri, A.Pilloni, Phys. Lett. B 746, 194 (2015)

Type II tetraquark model:
neglect the spin-spin interaction outside the diquarks

Evidence for $Z_c \to \rho\eta_c$

New

preliminary

- $e^+e^- \to \pi^+\pi^-\pi^0\eta_c$
- $\eta_c \to 9$ hadronic decays

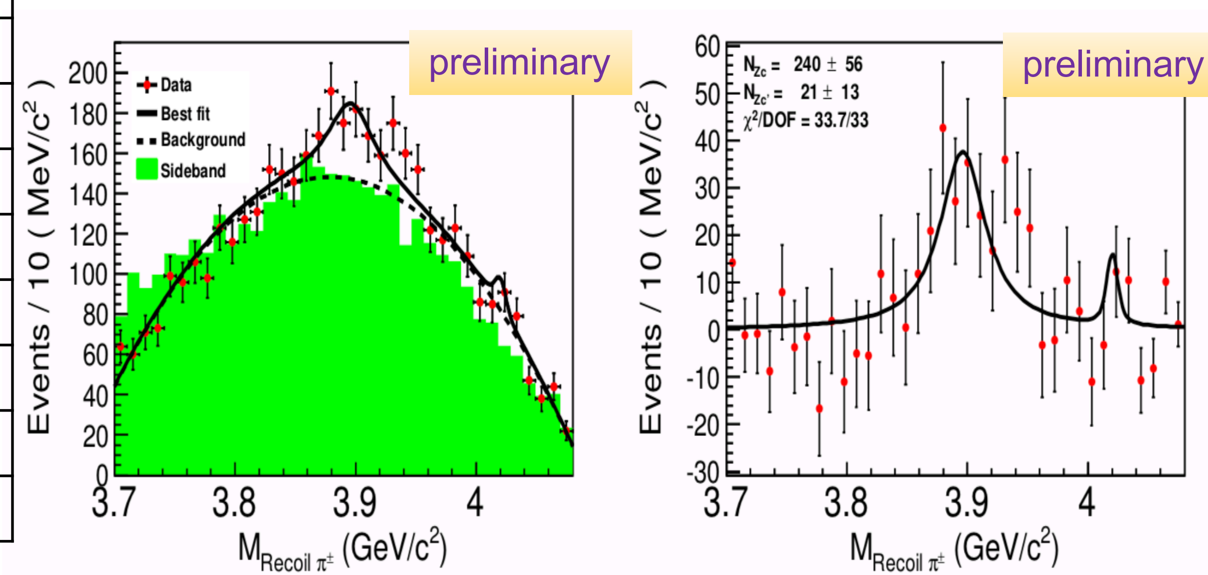
Decay mode	BR
$\eta_c \to p\bar{p}$	~0.13%
$\eta_c \to 2(K^+K^-)$	~0.15%
$\eta_c \to \pi^+\pi^-K^+K^-$	~1.50%
$\eta_c \to K^+K^-\pi^0$	~1.20%
$\eta_c \to p\bar{p}\pi^0$	~0.18%
$\eta_c \to K_SK\pi$	~1.80%
$\eta_c \to \pi^+\pi^-\eta$	~1.60%
$\eta_c \to K^+K^-\eta$	~0.57%
$\eta_c \to \pi^+\pi^-\pi^0\pi^0$	~2.40%

- Strong evidence for $e^+e^- \to \pi Z_c$, $Z_c \to \rho\,\eta_c$ at $\sqrt{s} = 4.23$,

  240±56 events

  statistical significance is 4.3σ.
- $e^+e^- \to \pi Z_c', Z_c' \to \rho\,\eta_c$ not seen

  21±13 events (1σ)



$e^+e^- \to \pi Z_c, Z_c \to \rho\,\eta_c$ @ 4.23 GeV

Evidence for $Z_c \to \rho\eta_c$

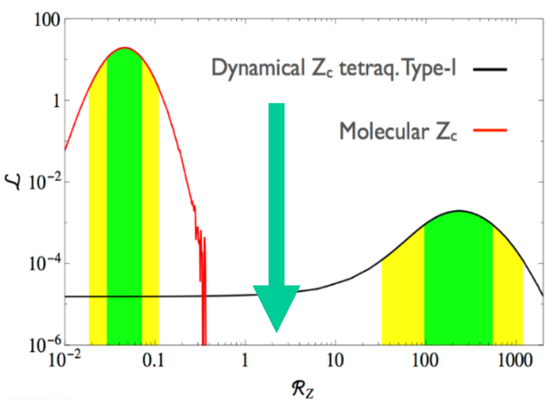
preliminary

New

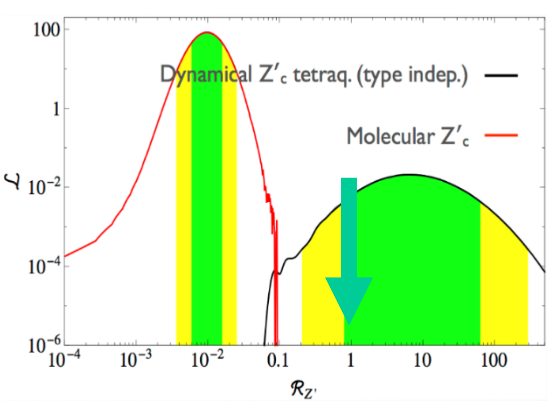
- **Measure Born cross section at 4.23 GeV:**

$$\sigma^B(e^+e^- \to \pi^+\pi^-\pi^0\eta_c) = (46 \pm 12 \pm 10)\ \text{pb}$$
$$\sigma^B(e^+e^- \to \pi Z_c, Z_c \to \rho\,\eta_c) = (47 \pm 11 \pm 11)\ \text{pb}$$

	$\sqrt{s} = 4.23\,\mathrm{GeV}$	$\sqrt{s} = 4.26\,\mathrm{GeV}$	$\sqrt{s} = 4.36\,\mathrm{GeV}$	Tetra-quarks-I	Tetra-quarks-II	Molecule
$R_{Z_c(3900)}$	2.1 ± 0.8	< 6.4	$\ldots$	230^{+330}_{-140}	$0.27^{+0.40}_{-0.17}$	$0.046^{+0.025}_{-0.017}$
$R_{Z_c(4020)}$	< 1.9	< 1.2	< 1.0	$6.6^{+56.8}_{-5.8}$		$0.010^{+0.006}_{-0.004}$



$$R_z = \frac{B(Z_c \to \rho\eta_c)}{B(Z_c \to \pi J/\psi)}$$



$$R_{Z'} = \frac{B(Z'_c \to \rho\eta_c)}{B(Z'_c \to \pi h_c)}$$

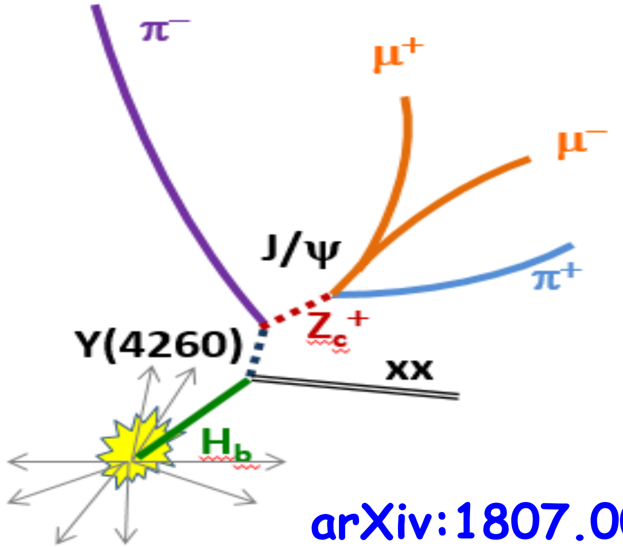
A.Esposito et al, Phys. Lett. B 746, 194 (2015)

Also calculations predict very different values:

$R_z = 10^{-3} \sim 10^2$!

arXiv:1806.05651
arXiv:1512.01938
PRD 91, 034032 (2015)
PRD 90, 054006 (2014)
EPJC 73, 2561 (2013)

Production of $Z_c^{\pm}(3900)$ in b-hadron Decays

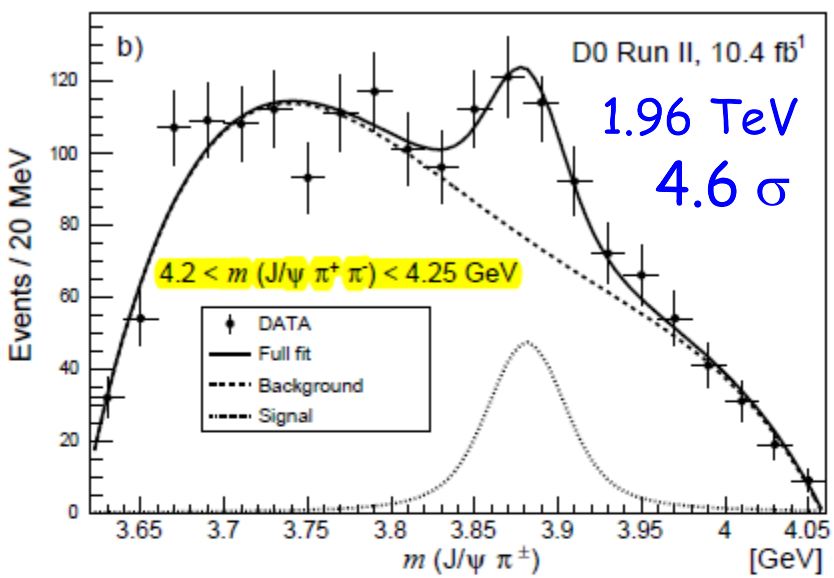


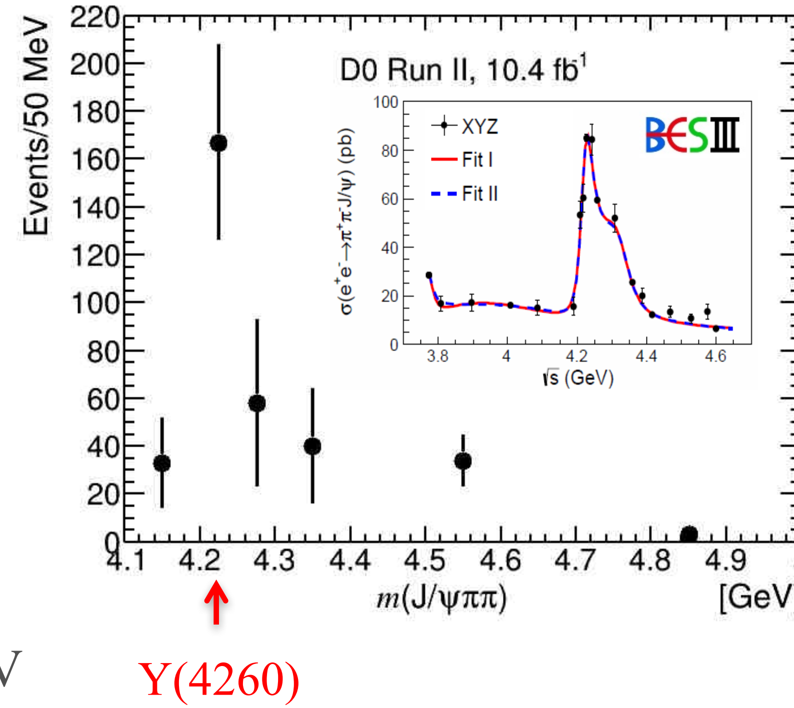
- Search for the $Z_c^{+}(3900)$ production in H_b decays via the following decays:

$$H_b \rightarrow Y(4260) + \text{anything}$$
$$Y(4260) \rightarrow Z_c^{\pm}(3900)\pi^{\mp}$$
$$Z_c^{\pm}(3900) \rightarrow J/\psi\pi^{\pm}$$

where H_b is any b-flavored hadron

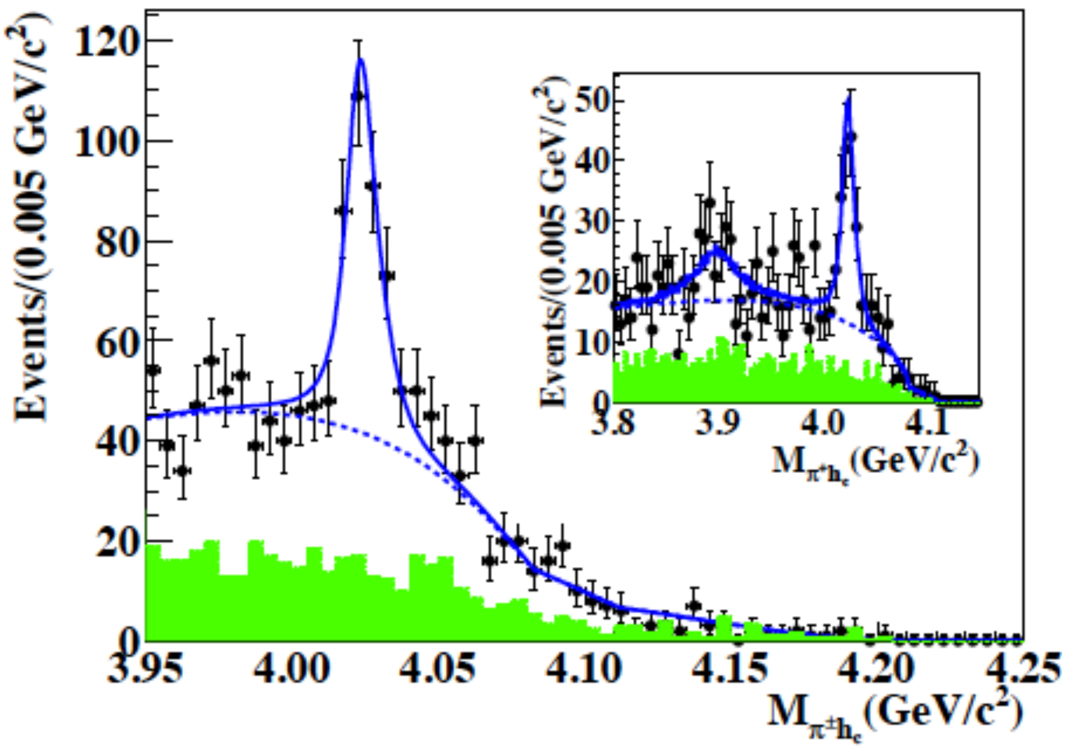
arXiv:1807.00183





- $M = 3895.0 \pm 5.2\ (\text{stat})^{+4.0}_{-2.7}\ (\text{syst})$ MeV

Observation of $Z_c(4020)^+$



BESIII: PRL111, 242001

Simultaneous fit to 4.23/4.26/4.36 GeV data, 16 η_c decay modes. 8.9σ

$M(Z_c(4020))$ = 4022.9±0.8±2.7 MeV;

$\Gamma(Z_c(4020))$ = 7.9±2.7±2.6 MeV

Close to $\bar{D}^*D^*$ threshold

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

8.7±1.9±2.8±1.4 pb @ 4.230 GeV

7.4±1.7±2.1±1.2 pb @ 4.260 GeV

10.3±2.3±3.1±1.6 pb @ 4.360 GeV

Significance: 8.9σ [$Z_c(4020)$]

No significant $Z_c(3900)$ (2.1σ)

Z_c in $e^+e^- \to \pi^+\pi^-\psi'$?

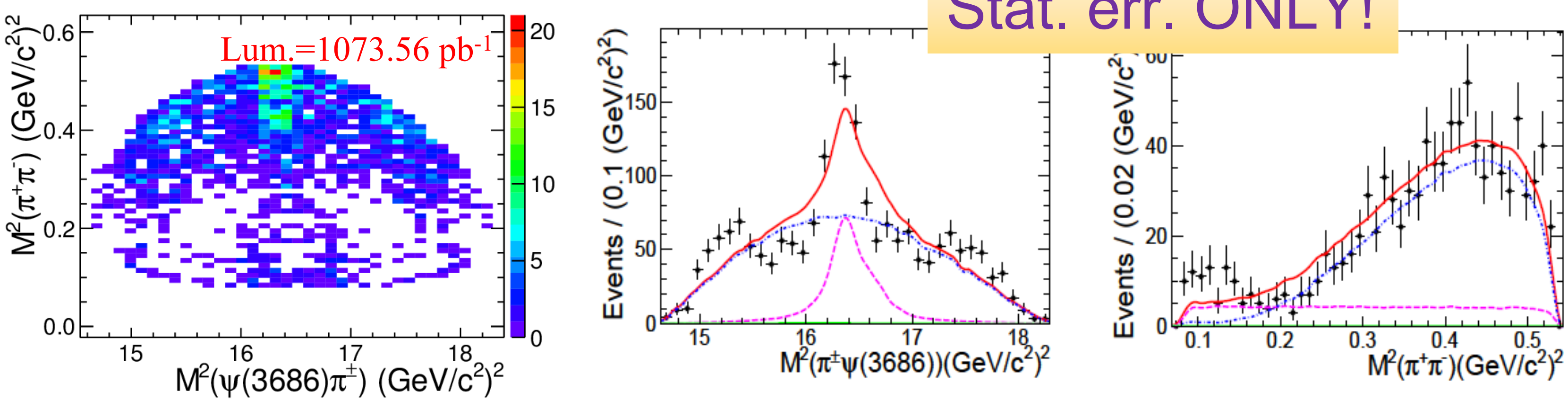
PRD 96, 032004 (2017)

- A prominent narrow structure is observed in $\pi\psi(3686)$ mass spectrum for data at $\sqrt{s} = 4.416$ GeV.
- An S-wave Breit-Wigner fit function is performed on the Dalitz plot of $M^2(\pi^+\psi(3686))$ versus $M^2(\pi^-\psi(3686))$

$$\boxed{\frac{p\cdot q/c^2}{(M_R^2 - x)^2 + M_R^2\cdot\Gamma^2/c^4} + \frac{p\cdot q/c^2}{(M_R^2 - y) + M_R^2\cdot\Gamma^2/c^4}}$$

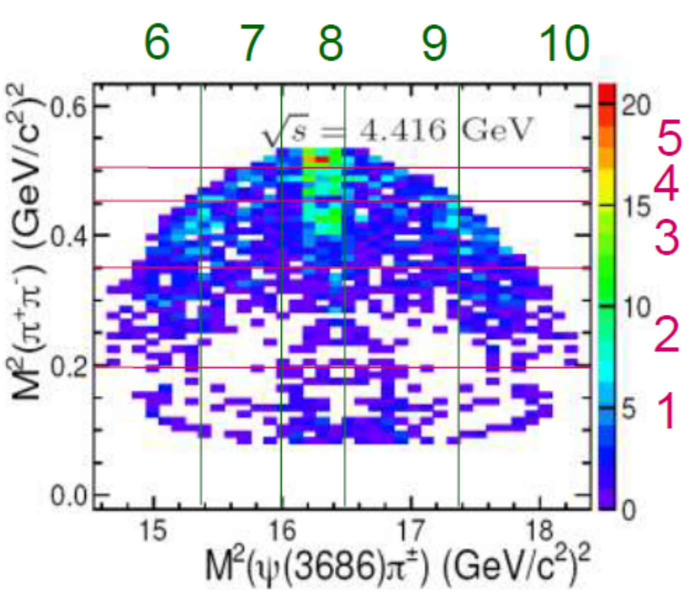
- The fit yields a mass of $M=4032.1\pm2.4$ MeV/c^2 and a width of $\Gamma=26.1\pm5.3$ MeV, with a significance of 9.2σ

Stat. err. ONLY!

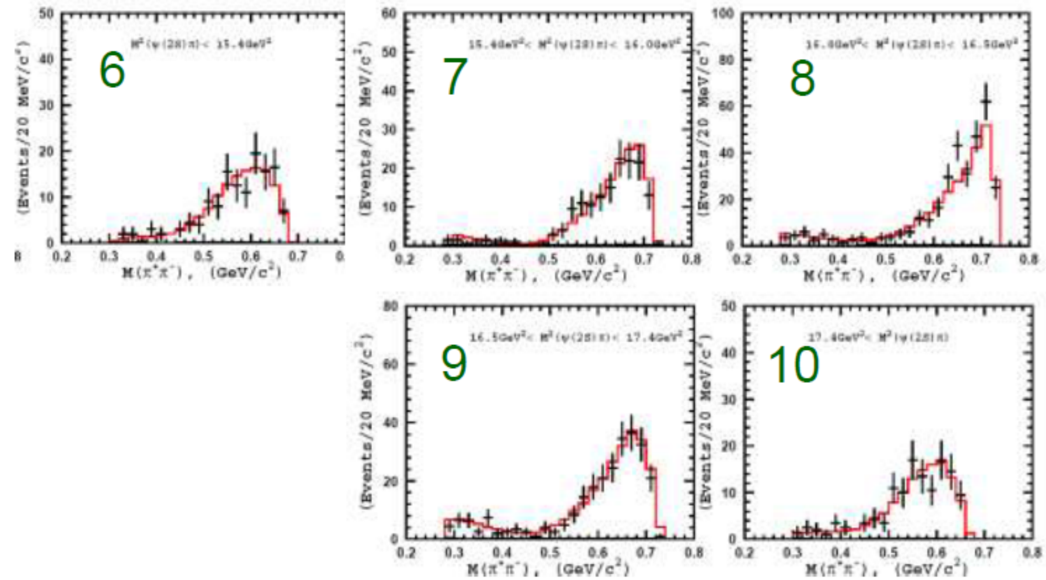


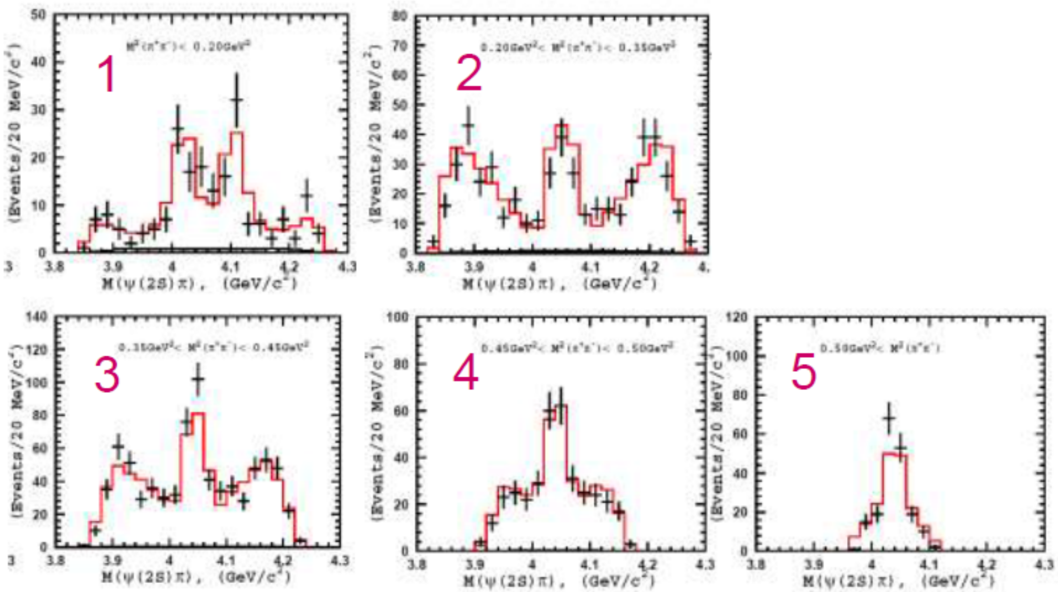
Different behavior between high and low $M^2(\pi^+\pi^-)$!

A toy fit by Alex Bondar @ Charm2018



Toy Fit of BESIII data at 4.416 GeV





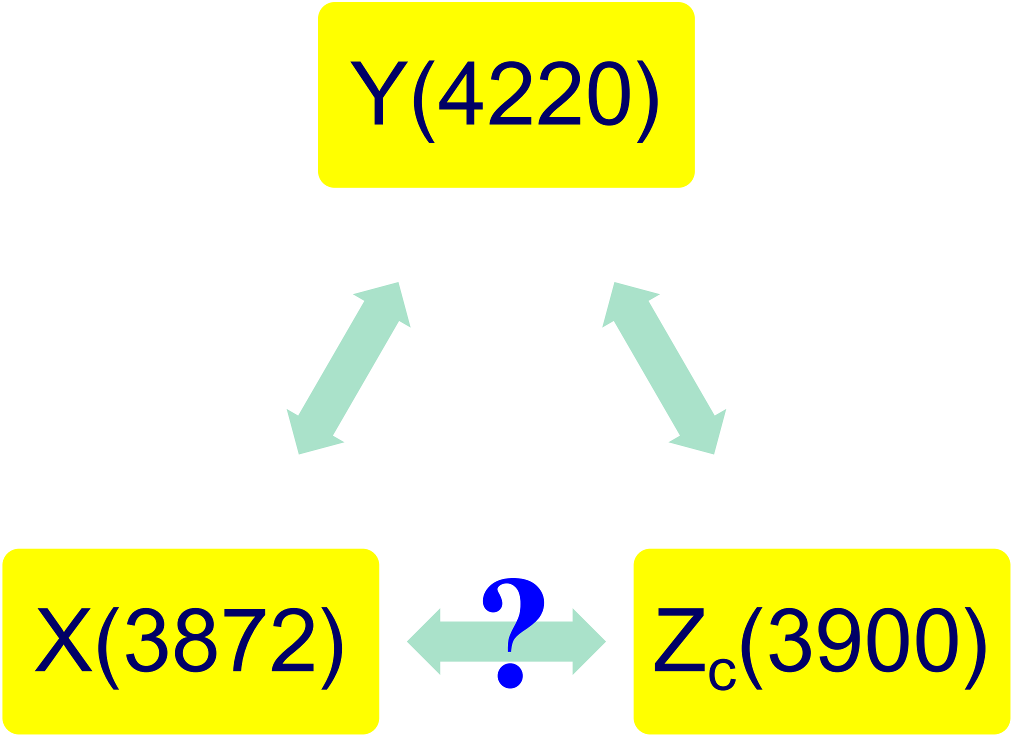
Toy Fit Results:
M_Z = 4019 ± 1.9 MeV/c^2
Γ_Z = 29 ± 4 MeV
Fit Fraction 12 ± 3.7%

Probably this is a new Zc(4020) decay mode.

X, Y, Z particles are correlated

Whatever they are, they are very similar.

Molecule? Compact tetraquark? Kinematic effect?



Upgrade and Prospects

BEPCII Upgrade

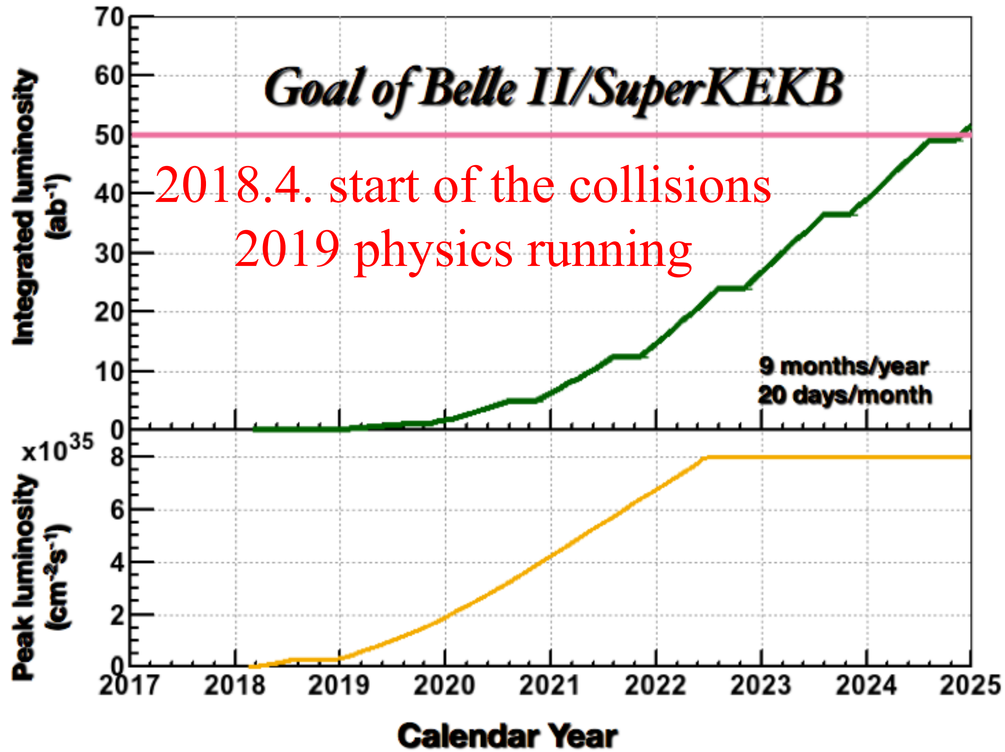
- Increase of beam energy
  - E_{beam}=2.30→2.35→2.45 GeV
  - Plan:
    - Get to 2.35 GeV in 2019
    - Get to 2.45 GeV in 2020-21, change ISPB (Interaction region SePtum Bending) magnet, big challenge
- Top-up injection
  - Data taking efficiency increases by 20~30%

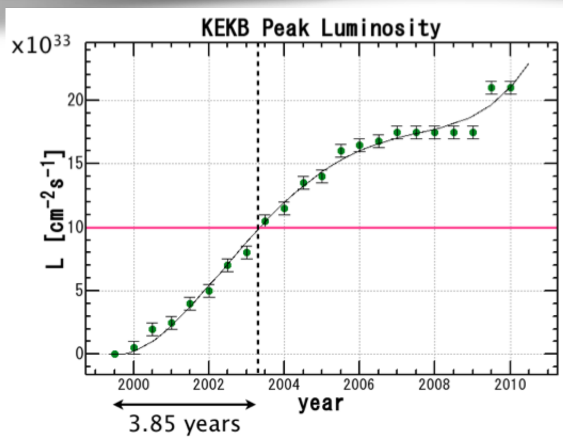
SuperKEKB

Expected data sample @ full luminosity

Channel	Belle	BaBar	Belle II (per year)
$B\bar{B}$	7.7×10^8	4.8×10^8	1.1×10^{10}
$B_s^{(*)}\bar{B}_s^{(*)}$	7.0×10^6	–	6.0×10^8
$\Upsilon(1S)$	1.0×10^8		1.8×10^{11}
$\Upsilon(2S)$	1.7×10^8	0.9×10^7	7.0×10^{10}
$\Upsilon(3S)$	1.0×10^7	1.0×10^8	3.7×10^{10}
$\Upsilon(5S)$	3.6×10^7	–	3.0×10^9
$\tau\tau$	1.0×10^9	0.6×10^9	1.0×10^{10}

* assuming 100% running at each energy

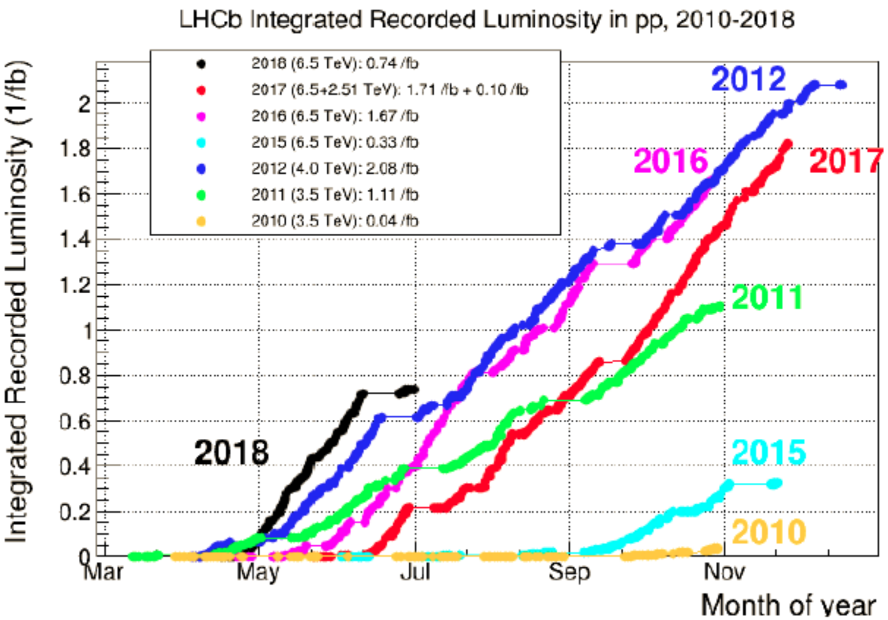


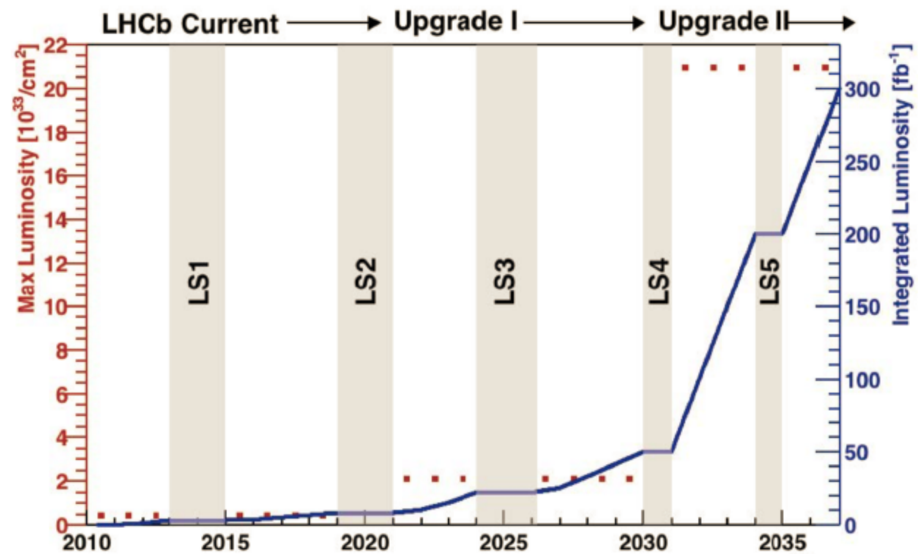


- Assumptions:
  - same commission time to reach design lum. as KEKB
  - 9 months/year running
  - 20 days/month

The target integrated luminosity will be 50-100 ab^{-1}

LHCb upgrade





LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
3 fb^{-1}	6 fb^{-1}	23 fb^{-1}	46 fb^{-1}	>300 fb^{-1} ??
		Phase-1 Upgrade!!	Phase-1b Upgrade!?	Phase-2 Upgrade??

Now.....End of Upgrade Ia (23 fb^{-1}).....End of Upgrade II (300 fb^{-1})

Summary

- Lots of progress in the study of exotic states at experiments
- Some new (charm-)baryons were found recently （see backup）
- More experimental and theoretical efforts are needed to understand heavy flavor spectroscopy
- BESIII, Belle II, LHC, … will take more data and continue the study

Thanks a lot!

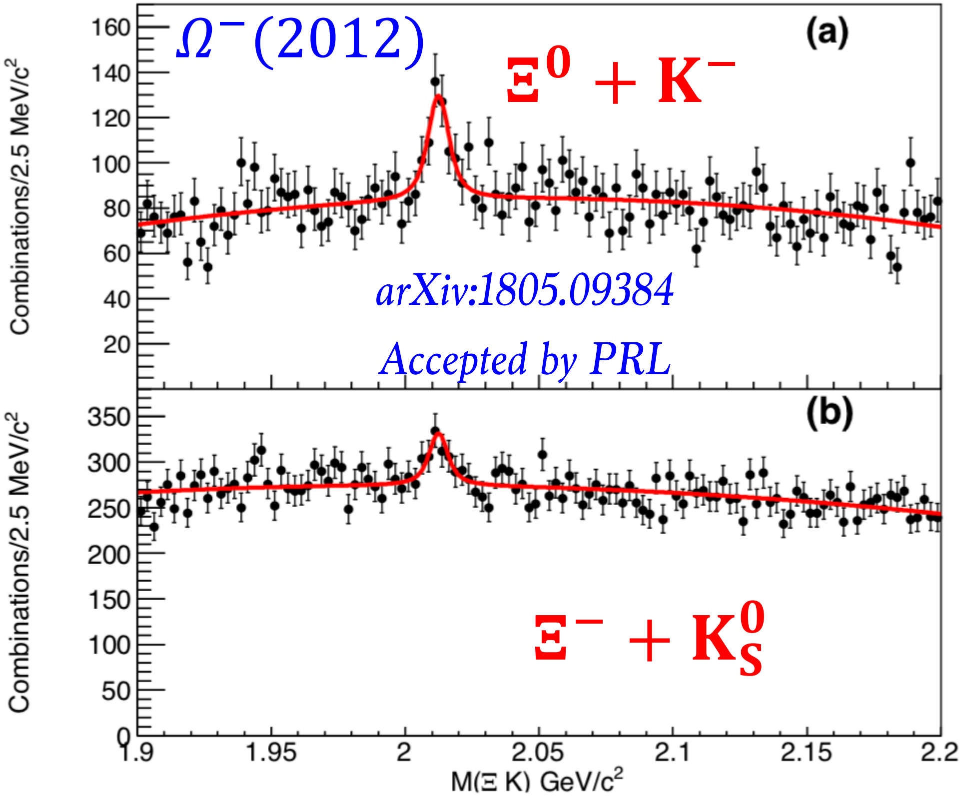
Baryon Spectroscopy

Observation of an excited Ω^- baryon

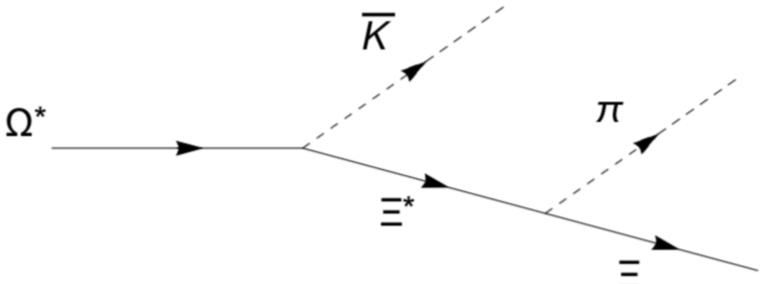
- Only one excited Ω^- states, $\Omega(2250)$, was confirmed until now.
- The evidence for two other states of Ω^- were reported.

- Observation $\Omega^-(2012)$ with a significance of 8.3σ in $\Upsilon(1,2,3S)$ data

  - $M = (2012.4 \pm 0.7 \pm 0.6)\ \mathrm{MeV}/c^2$ & $\Gamma = (6.4^{+2.5}_{-2.0} \pm 1.6)\mathrm{MeV}$



A measurement of the three-body decay, e.g., $\Omega(2012) \to \Xi\pi K$, is crucial to identify the nature of this hyperon.



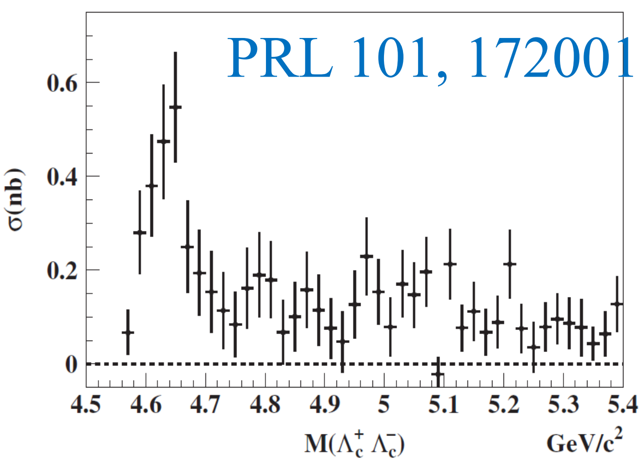
Y. H. Lin and B. S. Zou, arXiv:1807.00997

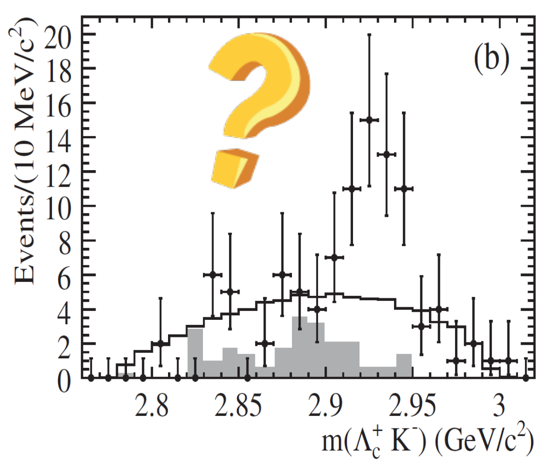
M. V. Polyakov, arXiv:1806.04427

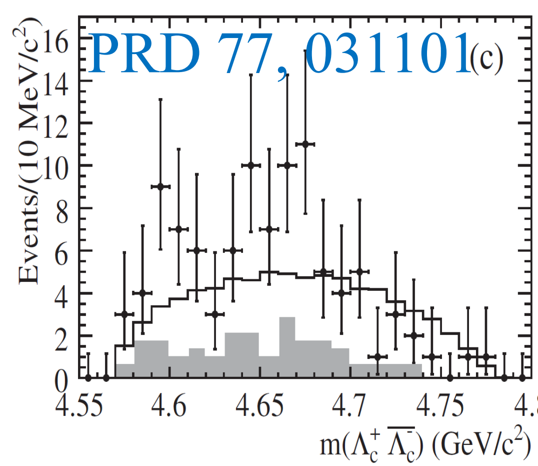
M. P. Valderrama, arXiv:1807.00718

$\Xi_c(2930)^0$ in $B^+ \to K^+\Lambda_c^+\bar{\Lambda}_c^-$

- Belle reported a structure, called X(4630), in the $\Lambda_c^+\bar{\Lambda}_c^-$ invariant mass distribution in $e^+e^- \to \gamma_{ISR}\Lambda_c^+\bar{\Lambda}_c^-$ PRL 101, 172001
- BarBar once studied $B^+ \to K^+\Lambda_c^+\bar{\Lambda}_c^-$ and found two small peaks in $M_{\Lambda_c^+\bar{\Lambda}_c^-}$ spectrum and a vague structure named $\Xi_c(2930)$ is seen in the distribution of $M_{K\,\Lambda_c}$. Larger data is needed to verify them. PRD 77, 031101
- Also, some theory explained that Y(4660) has a large partial decay width to $\Lambda_c^+\bar{\Lambda}_c^-$ and it's isospin partner Y(4616) is predicted. PRD 82, 094008; PRL102, 242004



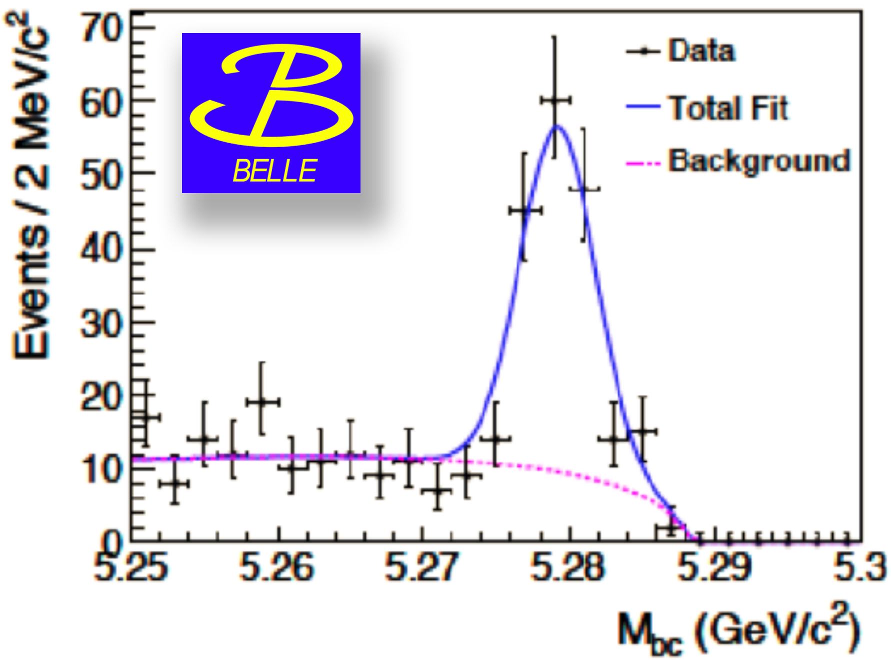




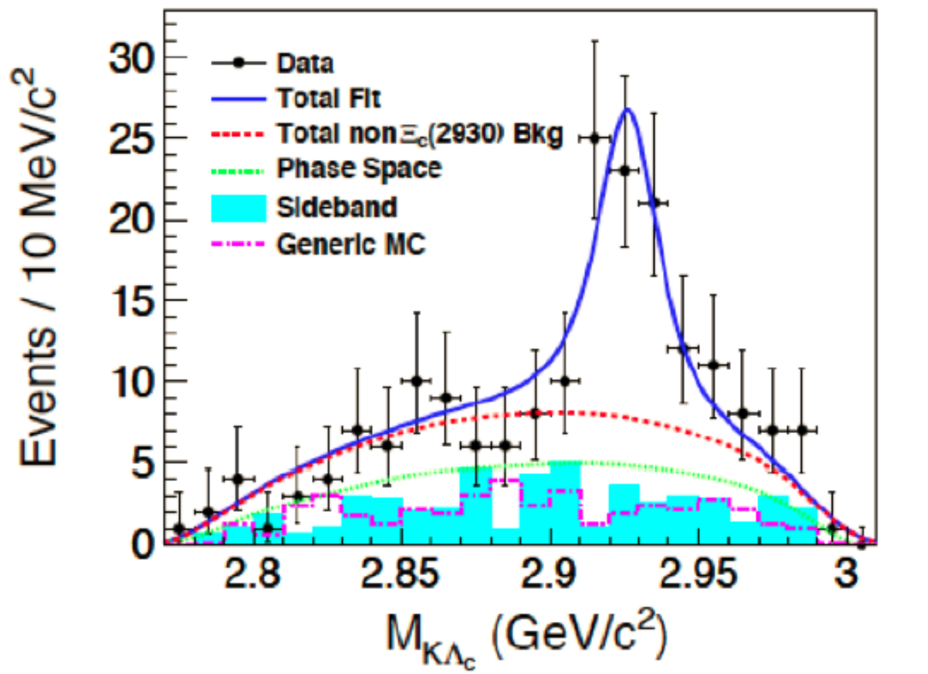
Observation of $\Xi_c(2930)^0$ in $B^+ \to K^+ \Lambda_c^+ \overline{\Lambda}_c^-$ at Belle

Eur. Phys. J. C78, 252 (2018)

$M_{\rm bc} = \sqrt{E_{\rm beam}^2 - \vec{p}^{\,2}}$ — beam-constrained mass



153±14 B decay signal events.
$\mathrm{Br}(B^+ \to \Lambda_c^+ \Lambda_c^- K^+) = (4.80 \pm 0.43 \pm 0.68) \times 10^{-4}$



$\Xi_c(2930)^0 \to \Lambda_c^+ K^-$ 61±16 events
5.1σ significance

Clear confirmation for the BaBar claim, PRD77,031101(2008) and much more precise M=2928.9±3.0 +0.8/-12.0 MeV, Γ=19.5±8.4 +5.4/-7.9 MeV

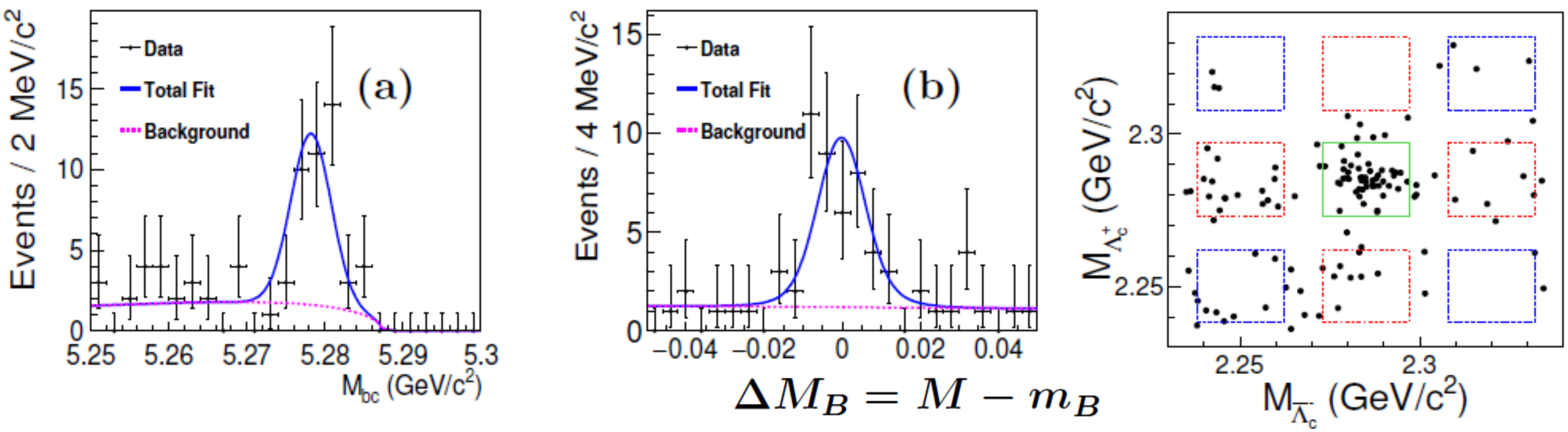
- $\Xi_c(2930)^0 = csd$ is the first charmed-strange baryon established in B decay.

Evidence of charged $\Xi_c(2930)$ in $B^0 \to K^0 \Lambda_c^+ \bar{\Lambda}_c^-$

arXiv:1806.09182

- Based on full $\Upsilon(4S)$ data set (772 M $B\bar{B}$ pairs) at Belle
- Three Λ_c decay channels:

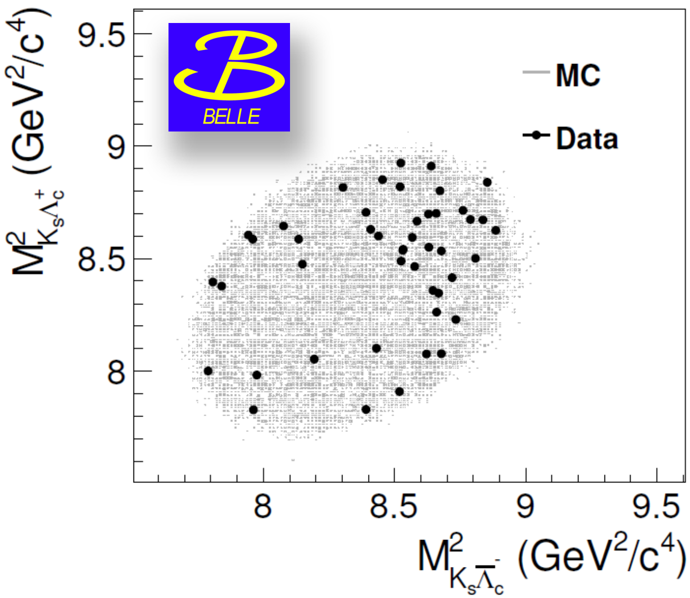
  $\Lambda_c^+ \to pK^-\pi^+$, $\Lambda_c^+ \to pK_s(\pi^+\pi^-)$ and $\Lambda_c^+ \to \Lambda(p\pi^-)\pi^+$.
- B candidates extracted via 2D fit to M_{bc} and ΔM_B

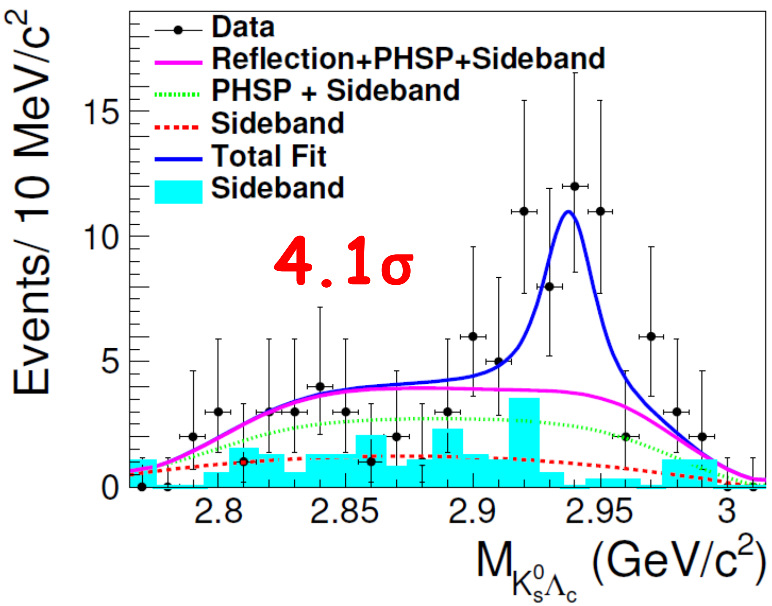


- Quite clear $\Lambda_c^+\bar{\Lambda}_c^-$ signals and B^0 signals.
  - $N^{\rm sig} = 34.9 \pm 6.6$ with a statistical signal significance above 8.3σ
  - $\mathcal{B}(B^0 \to K^0\Lambda_c^+\bar{\Lambda}_c^-) = (3.84 \pm 0.73 \pm 0.48) \times 10^{-4}$

Evidence of charged $\Xi_c(2930)$ in $B^0 \to K^0 \Lambda_c^+ \bar{\Lambda}_c^-$

- Charged $\Xi_c(2930)$ extracted by fitting $M_{K_S^0 \Lambda_c}$

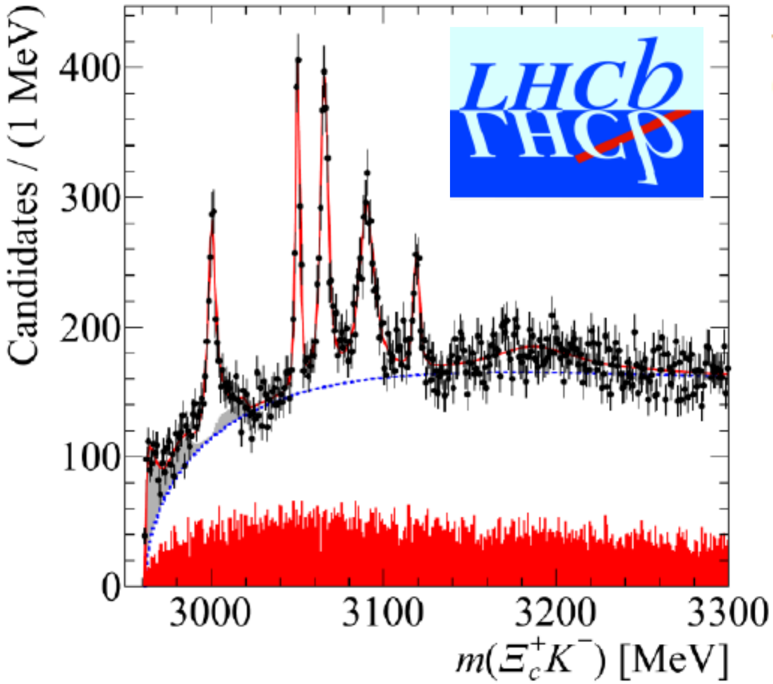




- $N_{\Xi_c^\pm} = 21.2 \pm 4.6$, stat. significance 4.1σ
- $M_{\Xi_c^\pm(2930)} = 2942.3 \pm 4.4 \pm 1.6$ MeV$/c^2$
- $\Gamma_{\Xi_c^\pm(2930)} = 14.8 \pm 8.8 \pm 7.1$ MeV

Exicted Ω_c at LHCb and Belle

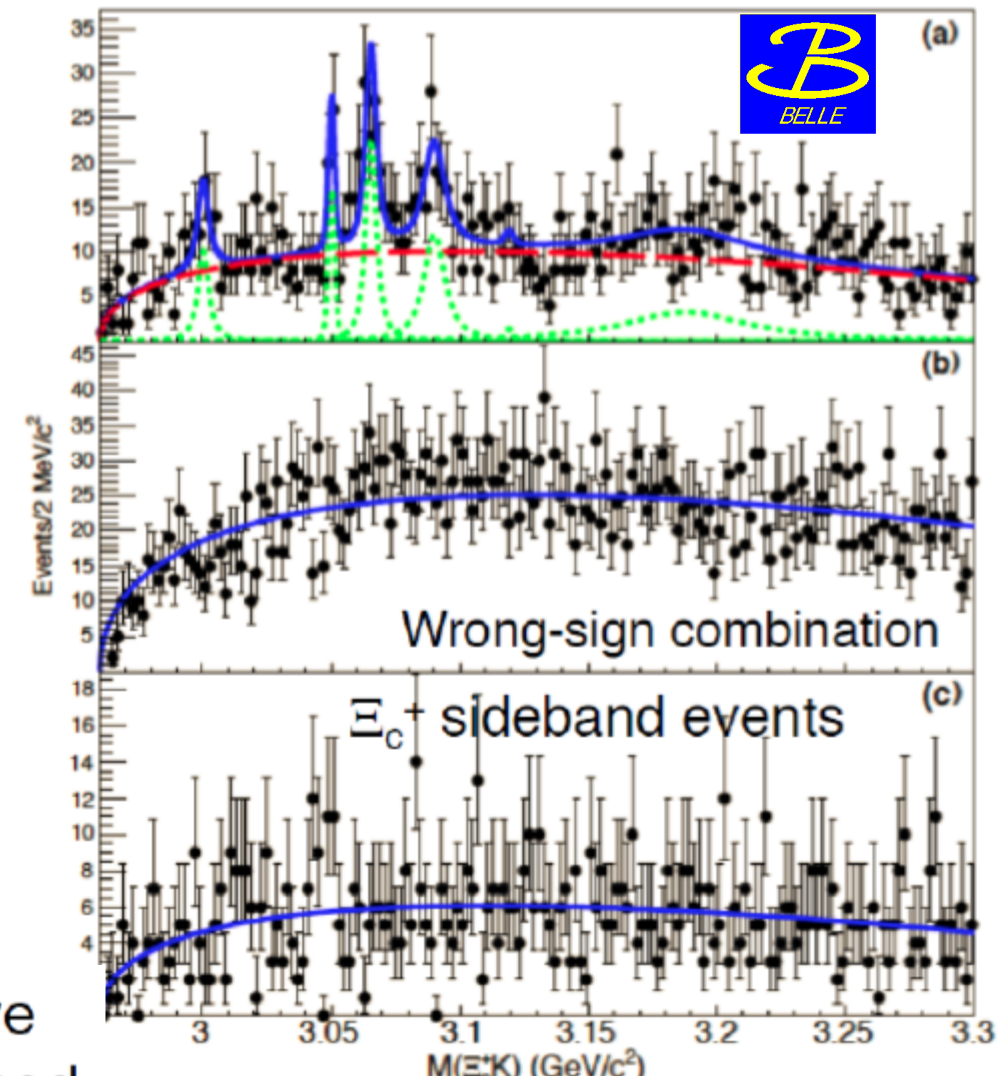
PRL118, 182001(2017)



5 Narrow states
(+ possibly one wide one)

Four narrow states out of five reported from LHCb confirmed.

PRD97, 051102 (2018)



Observation of a new Ξ_b^{**-} state

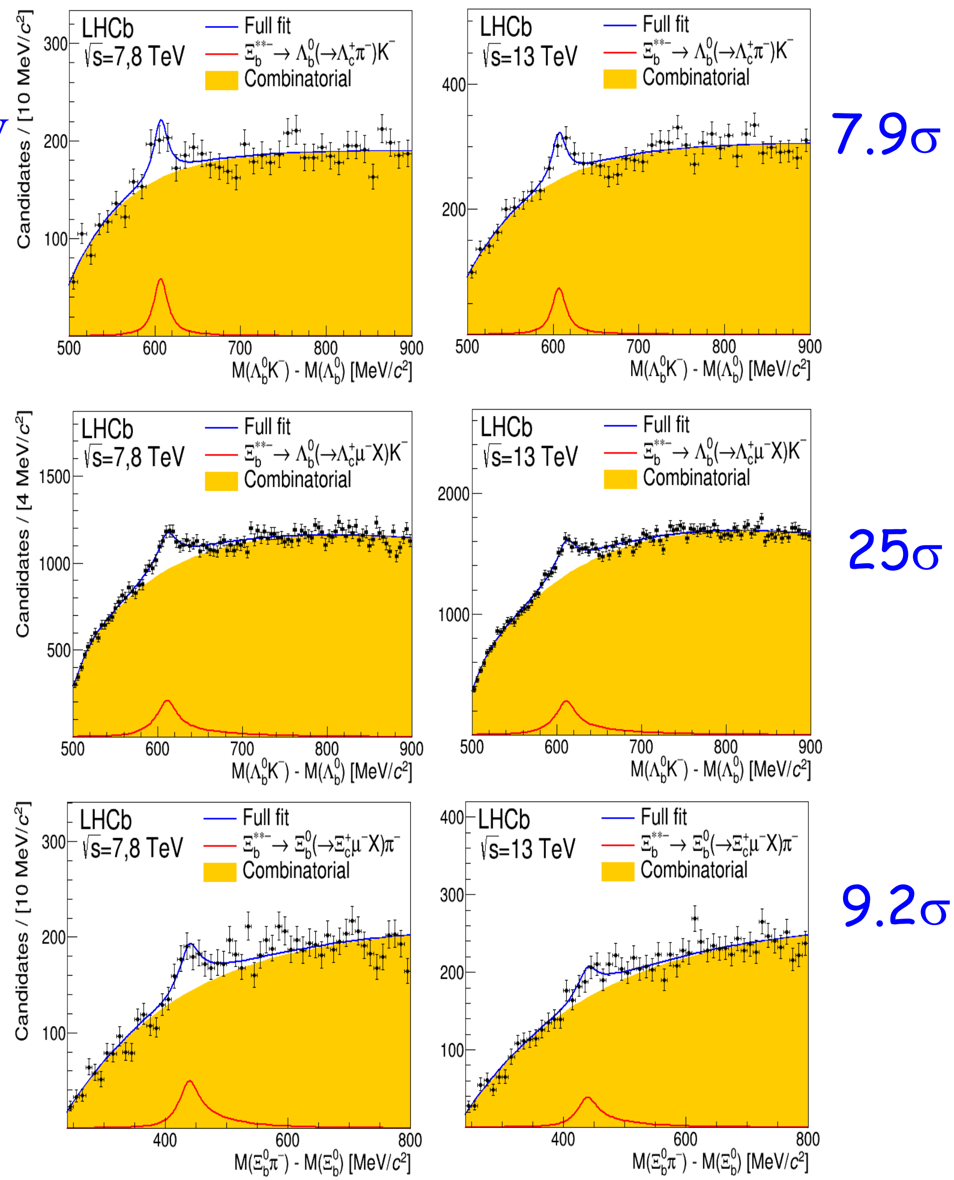
arXiv:1805.09418, submitted to PRL

- Hadronic $\Lambda_b^0 \to \Lambda_c^+ \pi^-$:
  - Resolution: 2 MeV
  - M=6226.9±2.0 ± 0.3 ± 0.2 MeV
  - Γ = 18.1 ± 5.4 ± 1.8 MeV

- Semileptonic (SL) $\Lambda_b^0 \to \Lambda_c^+ \mu^- X \bar{\nu}_\mu$
  - Resolution: ~18 MeV
  - Yields ~15 larger

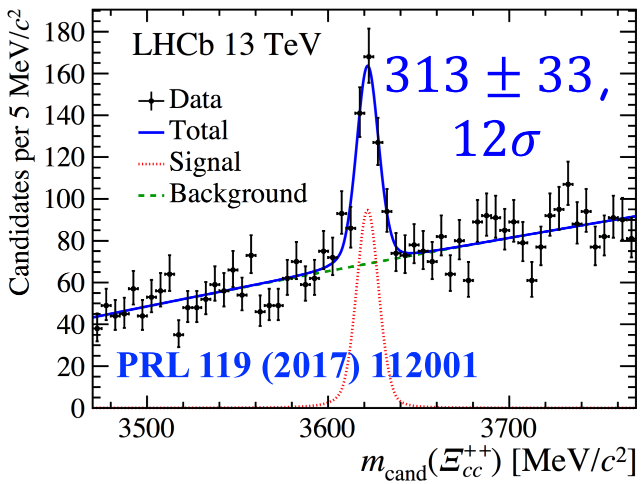
- Semileptonic (SL) $\Xi_b^0 \to \Xi_c^+ \mu^- X \bar{\nu}_\mu$

Many states are predicted at ~6230 MeV To distinguish them further information needed (e.g. J^P, $\mathcal{B}$)

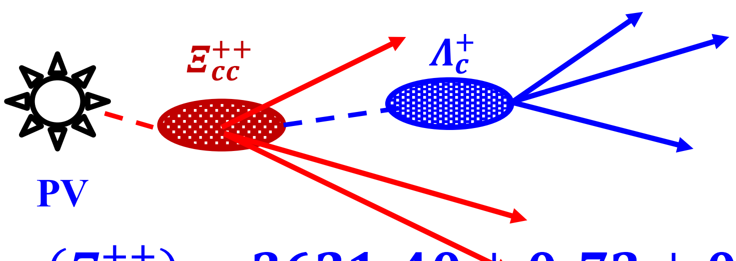


Observation of Ξ_{cc}^{++} at LHCb

- Decay: $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$, $\mathcal{B}$ could be as large as 10% [Yu et al., CPC **42** (2018) 051001]
- LHCb run II at $\sqrt{s} = 13$ TeV, ~1.7 fb^{-1}



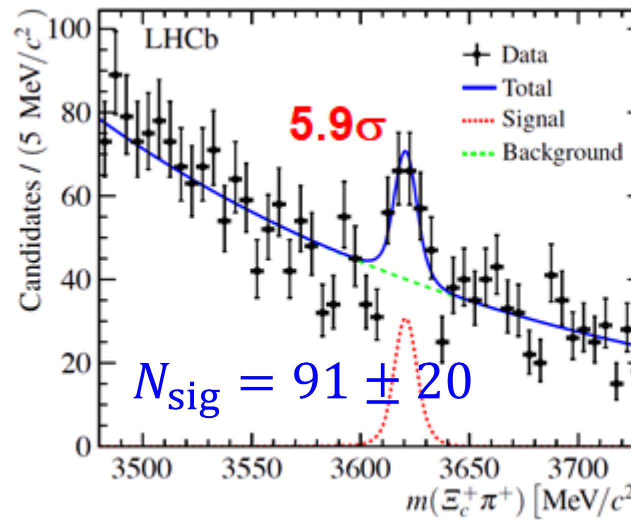
$\Xi_{cc}^{++} \to K^- \pi^+ \pi^+ \Lambda_c^+ (\to pK^-\pi^+)$



$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72 \pm 0.27$

$\pm 0.14(\Lambda_c^+)$ MeV/c^2

arXiv:1807.01919, submitted to PRL



new decay mode $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

$\Xi_c^+ (\to pK^+\pi^-)\pi^+$

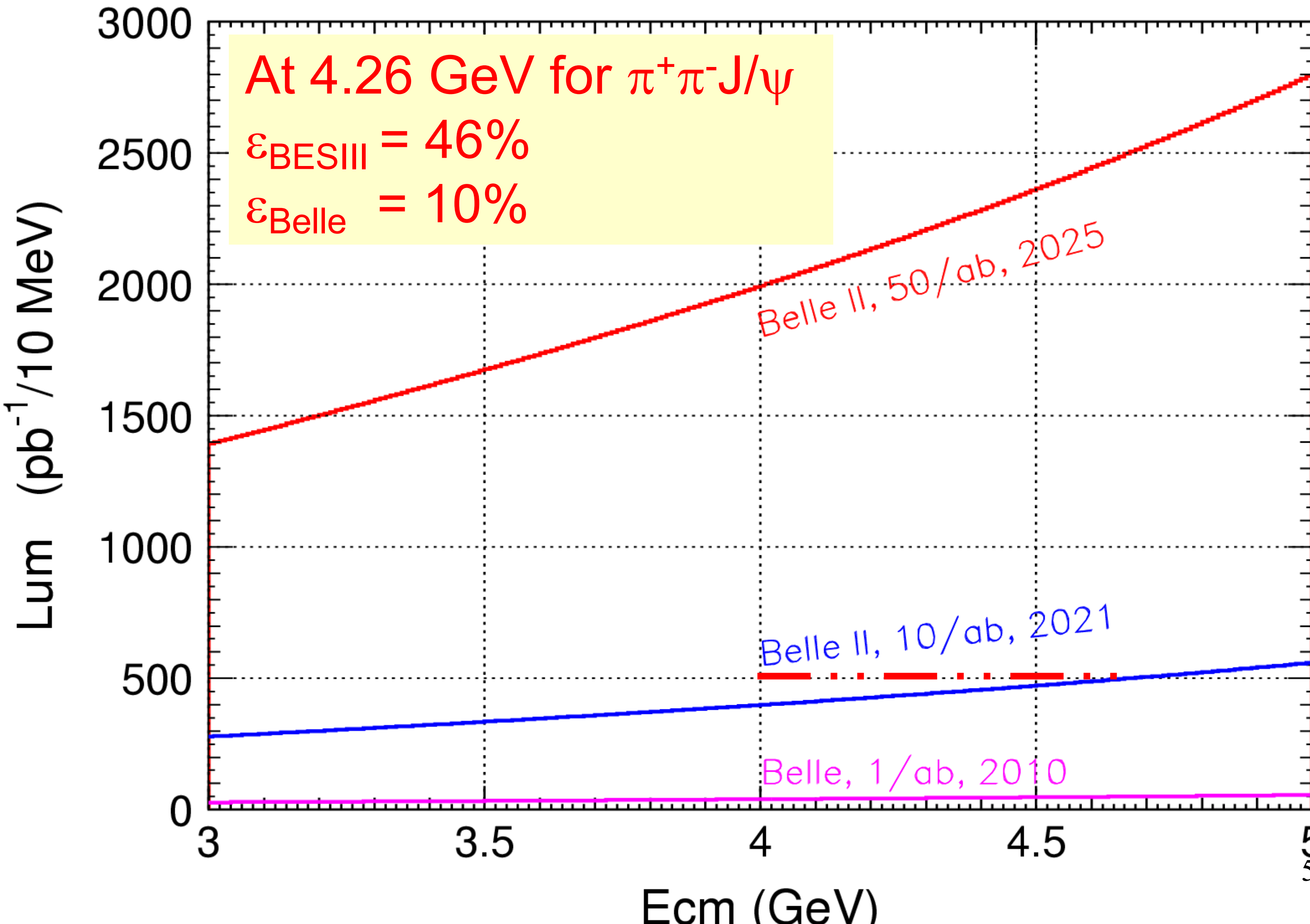
$3620.56 \pm 1.5 \pm 0.4 \pm 0.3(\Xi_c^+)$ MeV/c^2

$\tau_{\Xi_{cc}^{++}} = 256^{+24}_{-22} \pm 14$ fs

arXiv:1806.02744, accepted by PRL

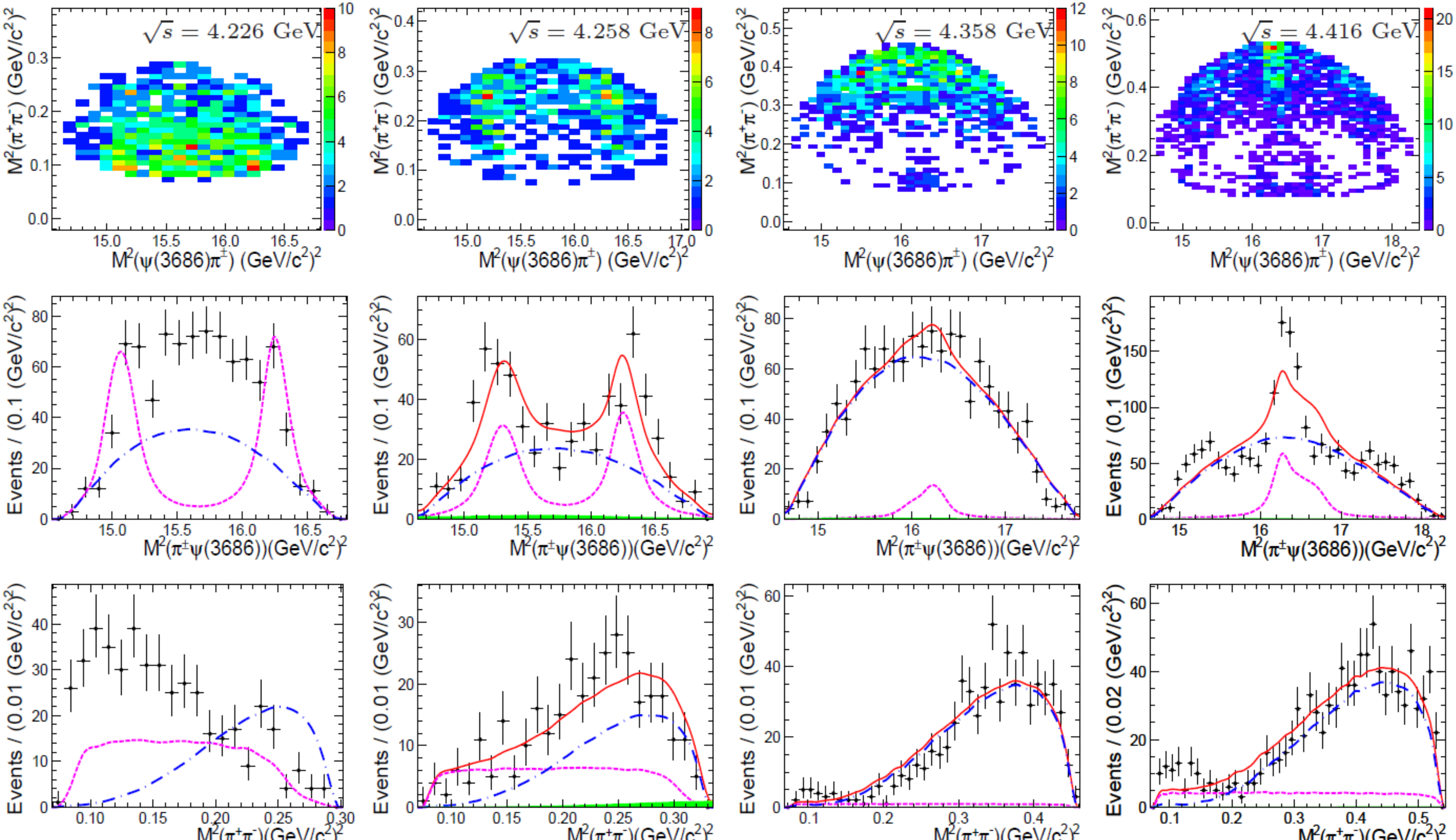
Belle II vs. BESIII

ISR produces events at all CM energies BESIII can reach



Fit of intermediate state

Interference not considered & fits cannot describe data well!

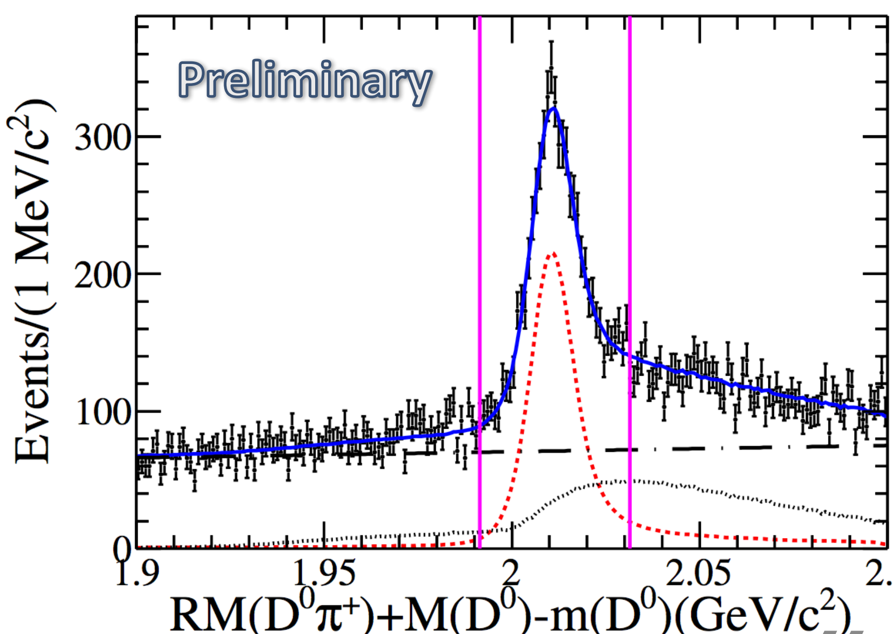


PRD 96, 032004 (2017)

BESIII $e^+e^- \to \pi^+ D^0 D^{*-}$+c.c.

- Reconstruct $D^0 \to K^-\pi^+$
- Select the combination closest to D^0 mass ($m(D^0)$)
- Find an additional π^+;
- 1.9 < $M(D^{*-})$ ($RM(D^0\pi^+) + M(D^0) - m(D^0)$) < 2.1 GeV/$c^2$
- select the candidate closest to D^{*-} mass

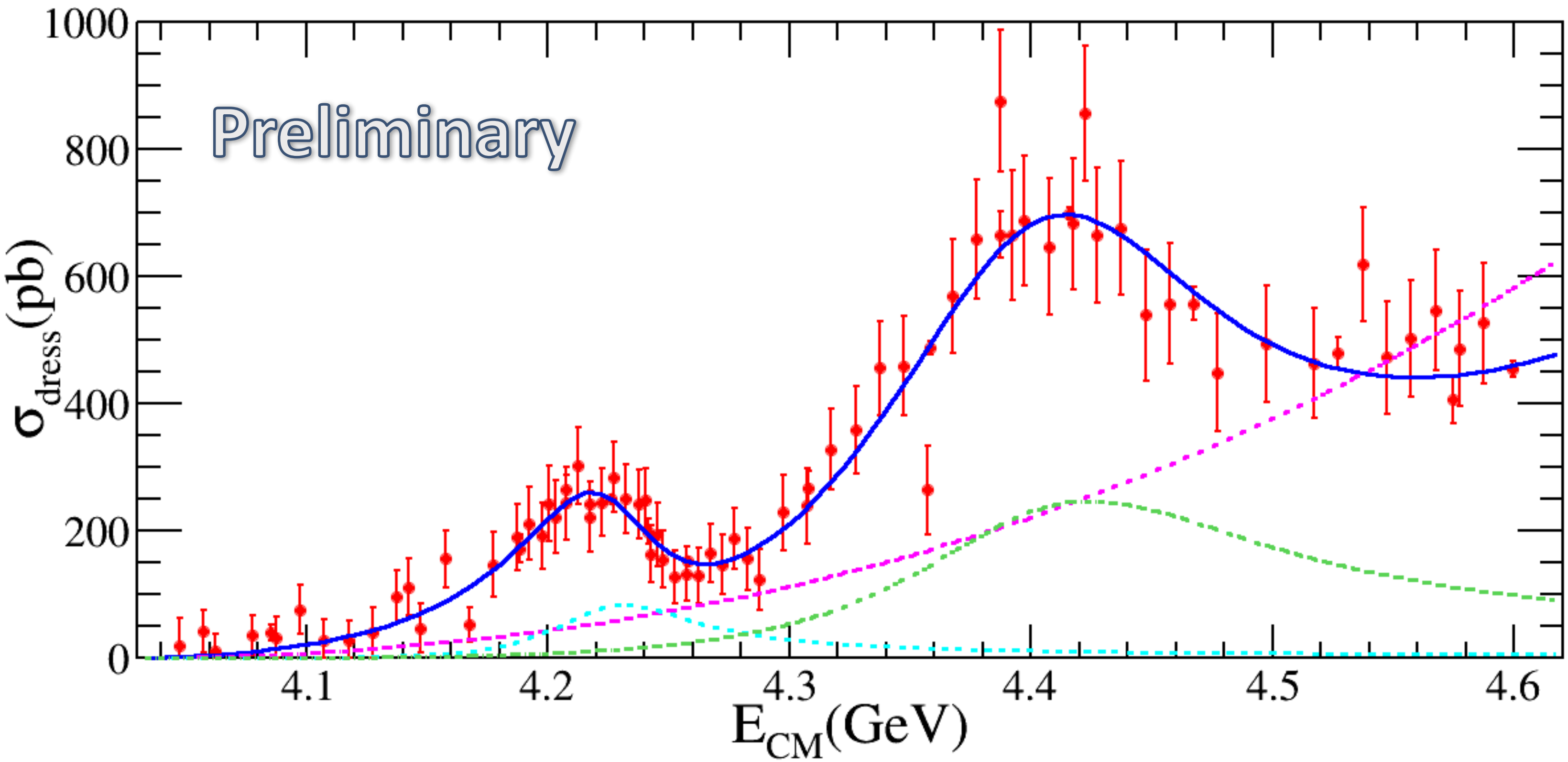
- An un-binned maximum likelihood fit
- Signal shape: MC convolved with a Gaussian;
- The isospin partner background (dotted line) is parameterized with MC;
- A linear function for other bkg



Fit to the dressed Xsection of $e^+e^- \to \pi^+ D^0 D^{*-}$+c.c.

$$\sigma_{dress} = \frac{N^{obs}}{\mathcal{L}(1+\delta^r)B(D^0 \to K^-\pi^+)\varepsilon}$$

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



Fit with a constant (pink dashed triple-dot line) and two constant width relativistic BW functions (green dashed double-dot line and aqua dashed line).

Resonant parameters

Parameters	SolutionI	SolutionII	SolutionIII	SolutionIV
c (10^{-4})		5.5 ± 0.6		
M_1 (MeV/c^2)		4224.8 ± 5.6		
Γ_1 (MeV)		72.3 ± 9.1		
M_2 (MeV/c^2)		4400.1 ± 9.3		
Γ_2 (MeV)		181.7 ± 16.9		
Γ_1^{el} (eV)	62.9 ± 11.5	7.2 ± 1.8	81.6 ± 15.9	9.3 ± 2.7
Γ_2^{el} (eV)	88.5 ± 15.8	55.3 ± 8.7	551.9 ± 85.3	344.9 ± 70.6
ϕ_1	-2.1 ± 0.1	2.8 ± 0.3	-0.9 ± 0.1	-2.3 ± 0.2
ϕ_2	1.9 ± 0.3	2.3 ± 0.2	2.3 ± 0.1	-1.9 ± 0.1

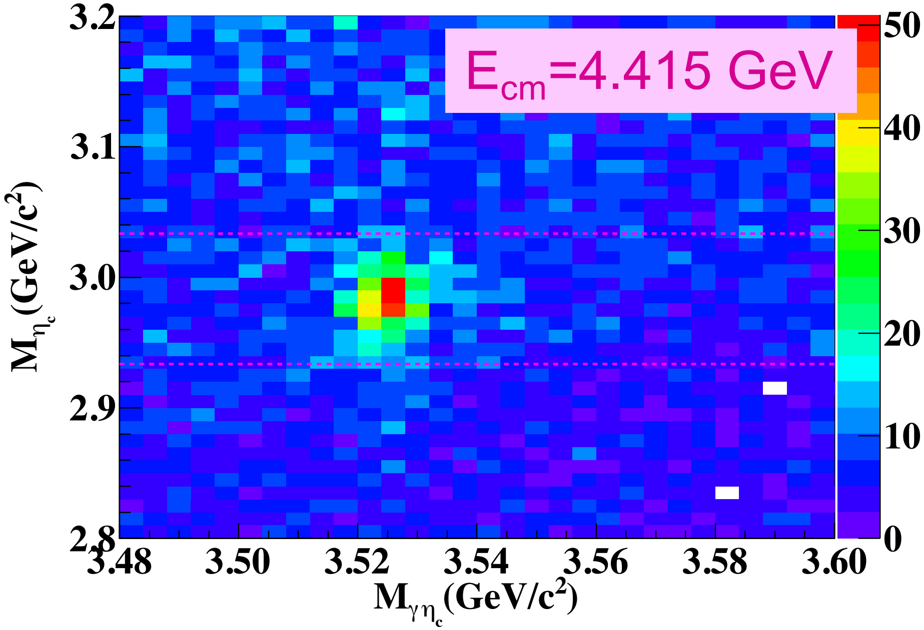
The error are statistical only.

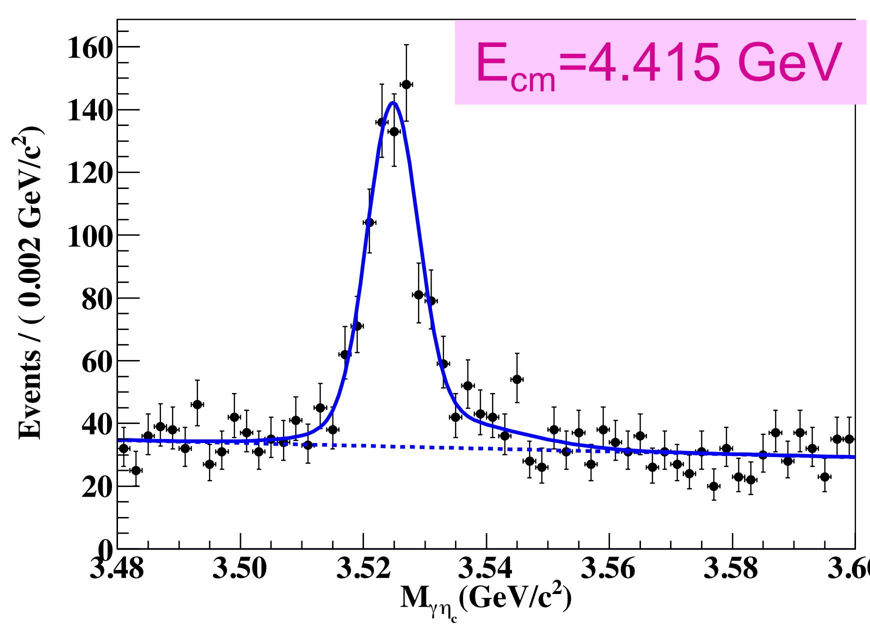
Preliminary

- Statistical significance is greater than 10σ.
- Consistent with those of Y(4220) and Y(4390) in $e^+e^- \to \pi^+\pi^- h_c$.

$e^+e^- \to \pi^+\pi^- h_c(1P)$

- $h_c \to \gamma\eta_c$, $\eta_c \to$ hadrons [16 exclusive decay modes]
  - pp, $\pi^+\pi^-K^+K^-$, $\pi^+\pi^-pp$, $2(K^+K^-)$, $2(\pi^+\pi^-)$, $3(\pi^+\pi^-)$
  - $2(\pi^+\pi^-)K^+K^-$, $K_S^0K^+\pi^-$+c.c., $K_S^0K^+\pi^-\pi^+\pi^-$+c.c., $K^+K^-\pi^0$
  - $pp\pi^0$, $K^+K^-\eta$, $\pi^+\pi^-\eta$, $\pi^+\pi^-\pi^0\pi^0$, $2(\pi^+\pi^-)\eta$, $2(\pi^+\pi^-\pi^0)$

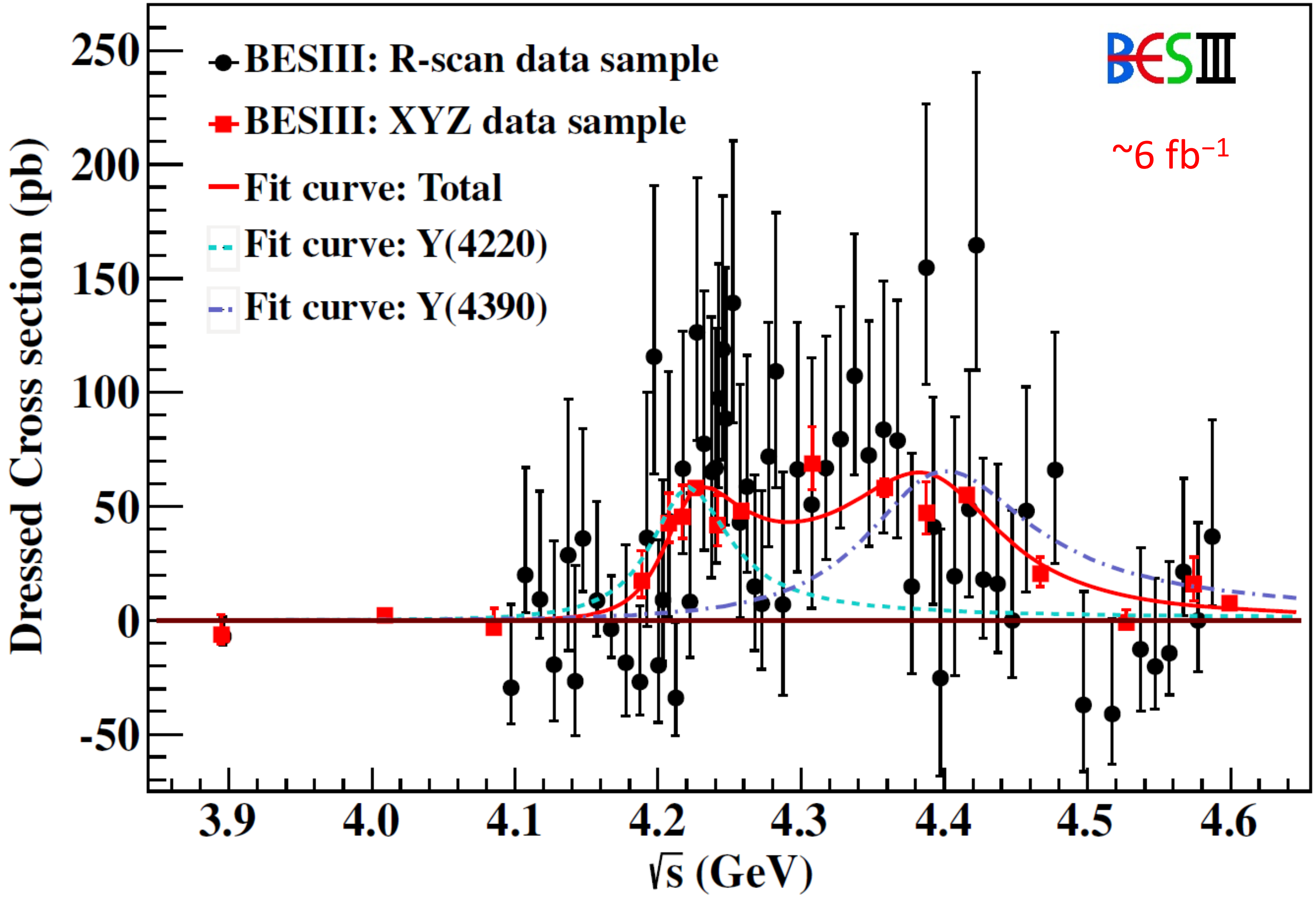




Method same as in PRL111, 242001 (2013)

$e^+e^- \to \pi^+\pi^- h_c$ cross section

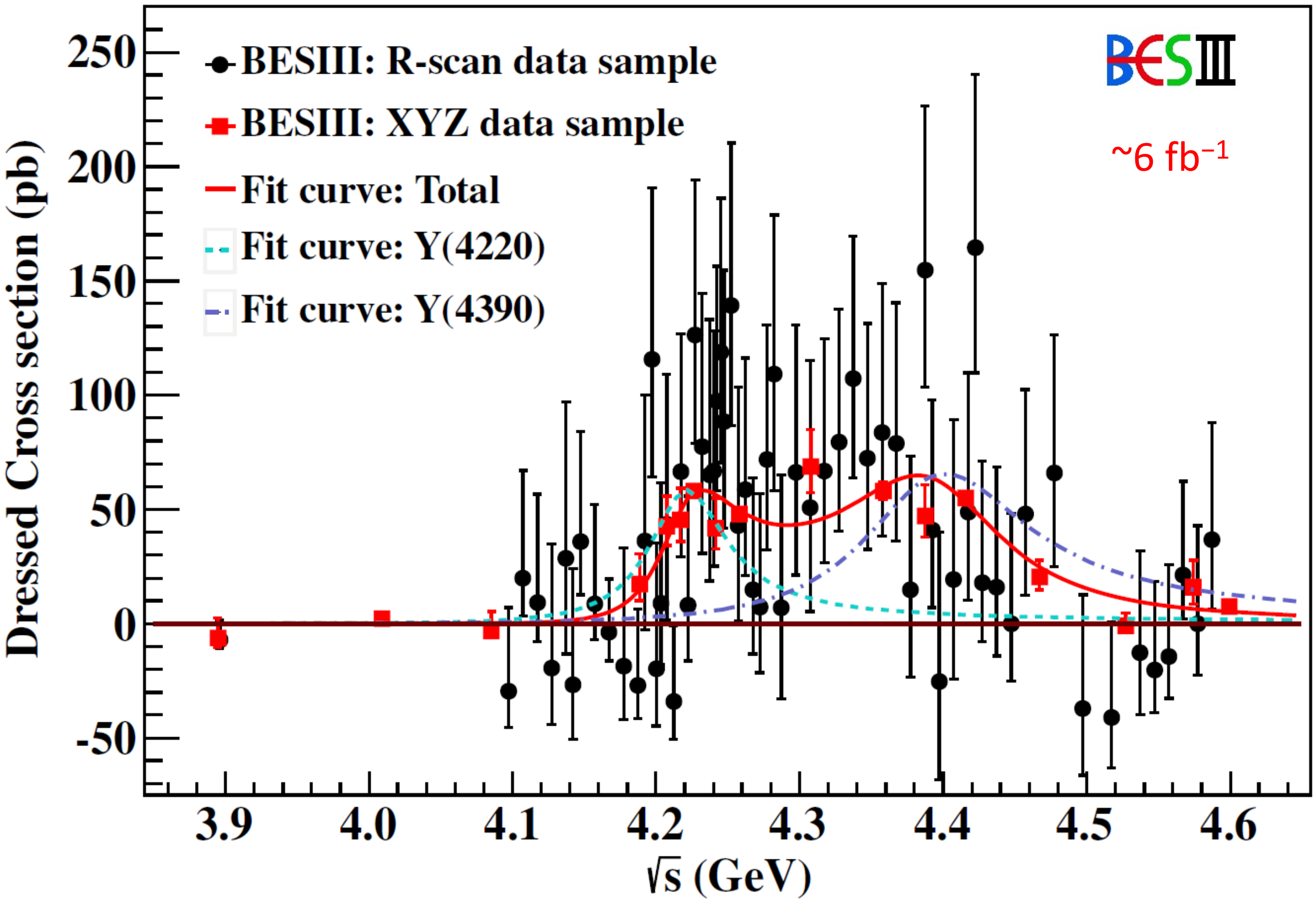
PRL118, 092002 (2017)



- First precise cross section measurement from threshold to 4.6 GeV
- Fit with $|BW_1+BW_2*e^{i\phi 2}|^2$, two resonant structures are evident

$e^+e^- \to \pi^+\pi^- h_c$ cross section

PRL118, 092002 (2017)



- $M_1=4218.4^{+5.5}_{-4.5}\pm0.9$ MeV/c^2, $\Gamma_1= 66.0^{+12.3}_{-8.3}\pm0.4$ MeV → Y(4220)
- $M_2=4391.5^{+6.3}_{-6.8}\pm1.0$ MeV/c^2, $\Gamma_2=139.5^{+16.2}_{-20.6}\pm0.6$ MeV → Y(4390)

Improvement of $e^+e^- \to \pi^+\pi^-\psi'$

PRD 96, 032004 (2017)

- **Data samples:**
  - 16 energy points from $\sqrt{s}$=4.008 to 4.600 GeV.
  - The total integrated luminosity (L_{int}) is 5.1 fb^{-1}.

- **Reconstructed modes:**

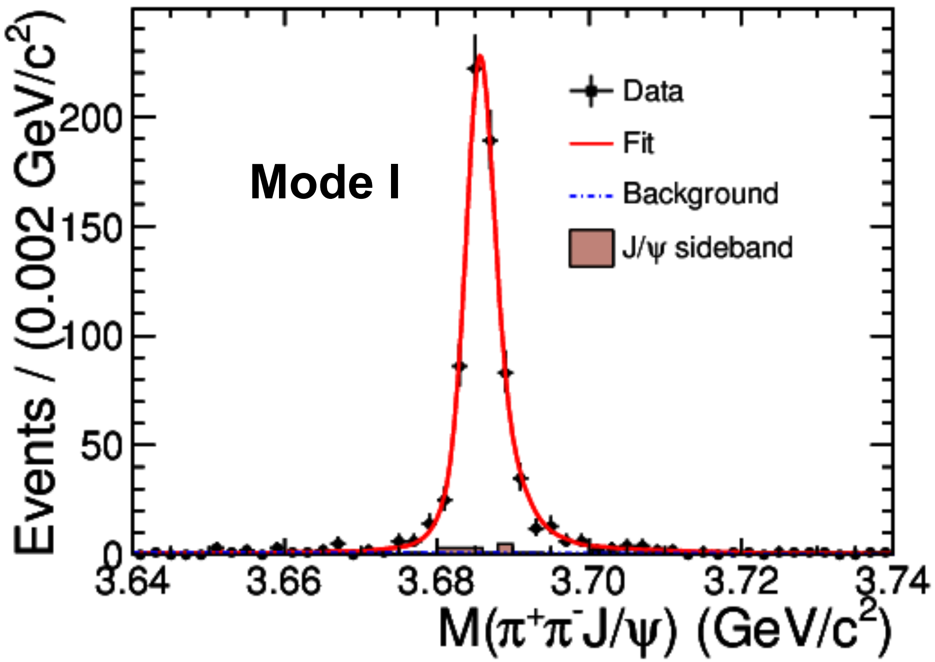
Mode I: $\Psi(3686)\to\pi^+\pi^- J/\psi$, $J/\psi\to l^+l^-$ ($l=e/\mu$)

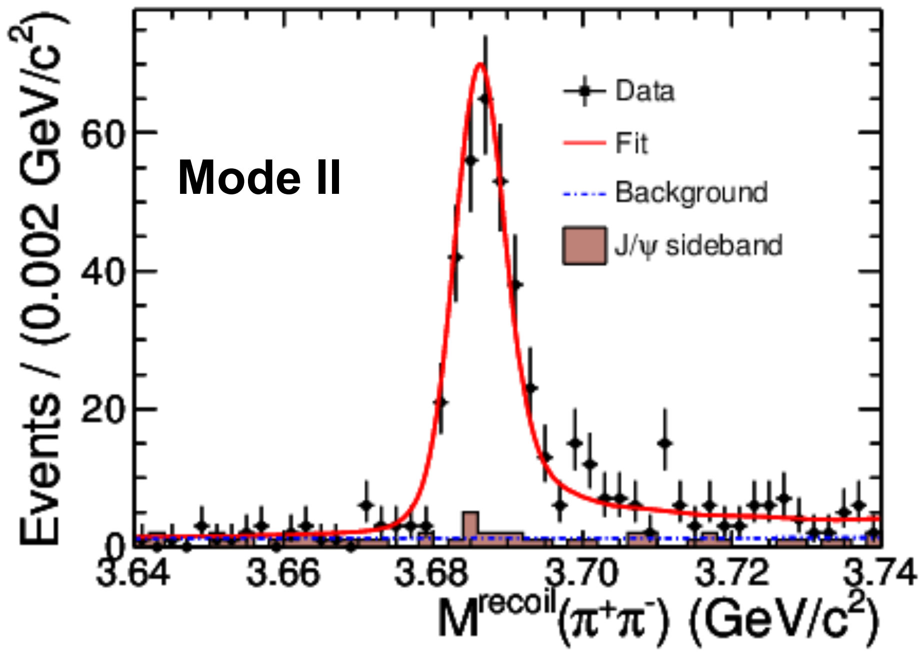
Mode II: $\Psi(3686)\to \mathit{neutrals}+J/\psi$,

$\mathit{neutrals}=(\pi^0\pi^0, \pi^0, \eta$ and $\gamma\gamma)$ $J/\psi\to l^+l^-$ ($l=e/\mu$)

Signals at Ecm=4.416 GeV

PRD 96, 032004 (2017)

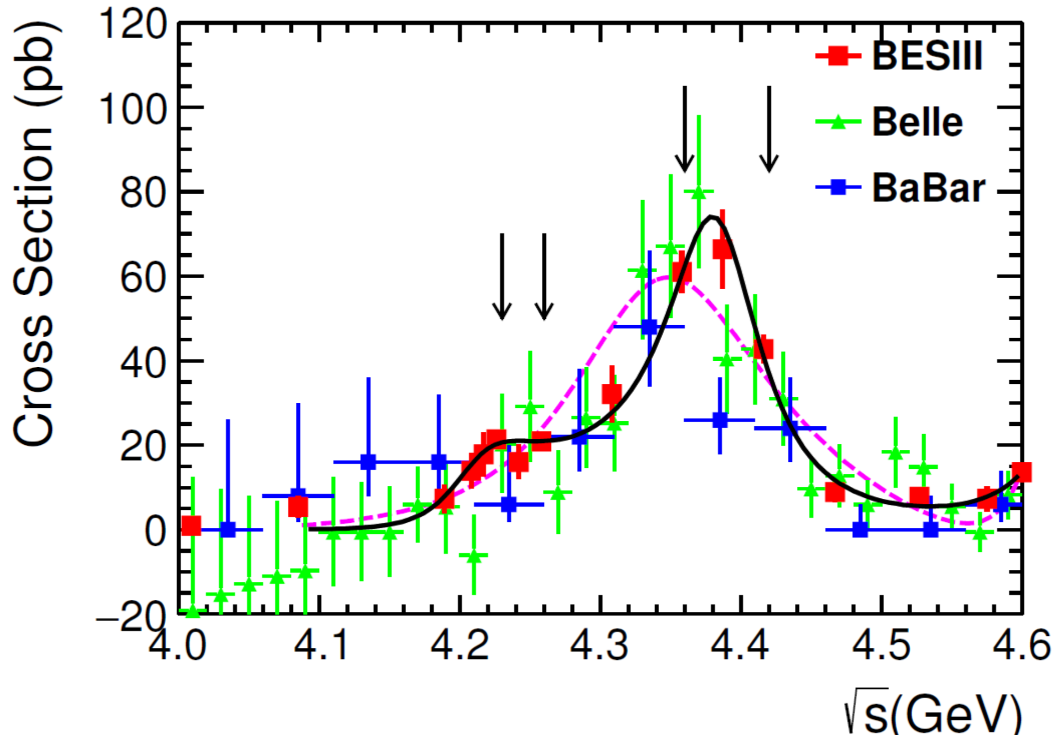




- Number of signals are extracted from $\pi^+\pi^- J/\psi$ invariant mass (mode I) and $\pi^+\pi^-$ recoiled mass spectrum (mode II).
- Signals are described with MC simulated shape convolved with a Gaussian function.

The Ys in $e^+e^- \to \pi^+\pi^-\psi'$

arXiv:1703.08787,
PRD 96, 032004 (2017)



The Y(4220) is necessary

(significance = 5.8σ)

Fix parameters of the Y(4660) to Belle results

Parameters	Solution I	Solution II
$M(Y4220)$ (MeV/c^2)	4209.5 ± 7.4	
$\Gamma(Y(4220))$ (MeV)	80.1 ± 24.6	
$\mathcal{B}\Gamma^{e^+e^-}(Y(4220))$ (eV)	0.8 ± 0.7	0.4 ± 0.3
$M(Y4390)$ (MeV/c^2)	4383.8 ± 4.2	
$\Gamma(Y(4390))$ (MeV)	84.2 ± 12.5	
$\mathcal{B}\Gamma^{e^+e^-}(Y(4390))$ (eV)	3.6 ± 1.5	2.7 ± 1.0
ϕ_1 (rad)	3.3 ± 1.0	2.8 ± 0.4
ϕ_2 (rad)	0.8 ± 0.9	4.7 ± 0.1

Summary of the Z_c states at BESIII

Decay Modes	$Z_c(3900)$	$Z_c(4020)$
$I^G(J^{PC})$	$1^+(1^{+-})$	$1^+(?^{?-})$
$\pi J/\psi$	Discovery mode	No
πh_c	2.1σ	Discovery mode
$\bar{D}^*D$	Yes	No
$\bar{D}^*D^*$	No	Yes
$\pi\psi'$	No	Yes?
$\rho\eta_c$	4.3σ	No

Results from Five Collider Experiments on X(5568)

Analysis	Production ratio (B_s / X(5568))	Reference
D0 ($J/\psi\ \phi$)	$8.6 \pm 1.9 \pm 1.4\%$	PRL 117,022003(2016)
D0 ($\mu\ D_s$)	$7.3^{+2.8}_{-2.4}\,^{+0.6}_{-1.7}\%$	PRD 97, 092004 (2018)
LHCb	$< 2.4\%$ ($p_T(B_s^0) > 10$ GeV)	PRL 117,152003 (2016)
CMS	$< 1.1\%$ ($p_T(B_s^0) > 10$ GeV)	PRL 120, 202005 (2018)
ATLAS	$< 1.5\%$ ($p_T(B_s^0) > 10$ GeV)	PRL 120, 202007 (2018)
CDF	$< 6.7\%$ ($2.3 \pm 1.9 \pm 0.9\%$)	PRL 120, 202006 (2018)

- LHC experiments do not observe X(5568) at higher collisions energy
- CDF result is in ~2σ tension with DØ studies in hadronic decay channel
  - Kinematic selections vary substantially
  - Ratio to B_s^0 production might not be the best metric
- Without theoretical model of X(5568) production and decays it is hard to compare various experiments quantitively