北京航空航天大學
BEIHANG UNIVERSITY

Hadron Spectroscopy: Experiment

Chengping Shen

Particles and Nuclei International Conference 2017

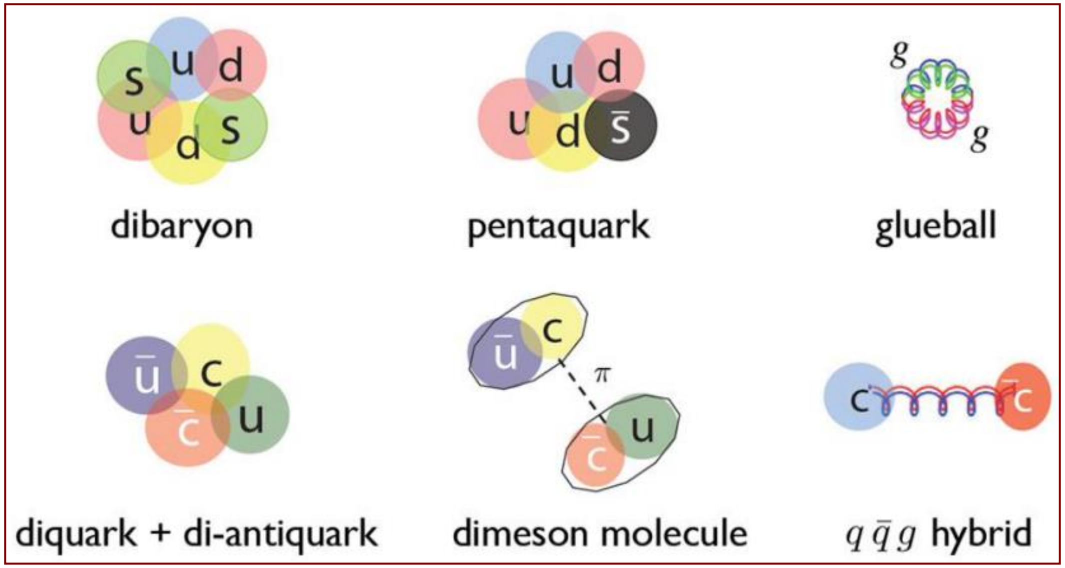
2017年9月3日

Outline

- Introduction
- Light hadron spectroscopy
- Recent experimental results on X states
- Recent experimental results on Y states
- Recent experimental results on Z states
- Others (pentaquark, glueball, …)
- Summary

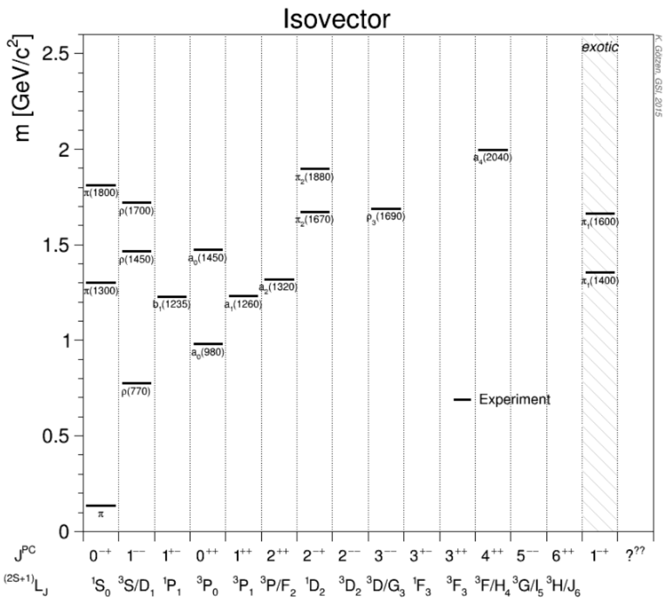
Hadrons: normal & exotic

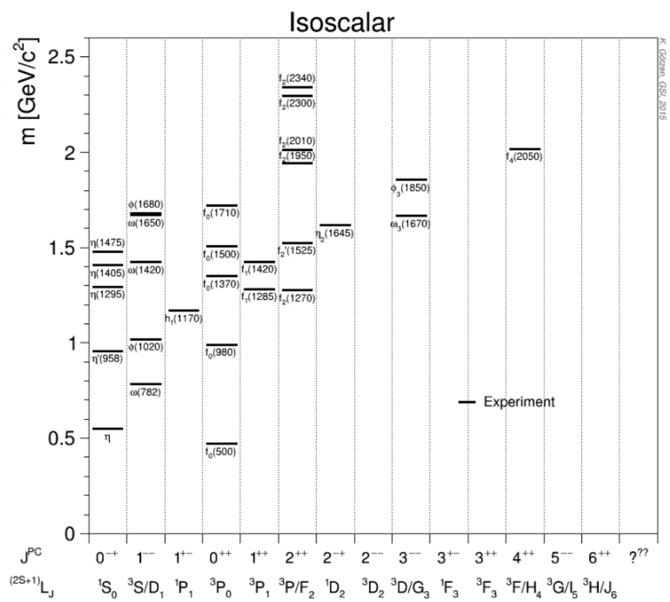
- Quark model: hadrons are composed from 2 (meson) quarks or 3 (baryon) quarks

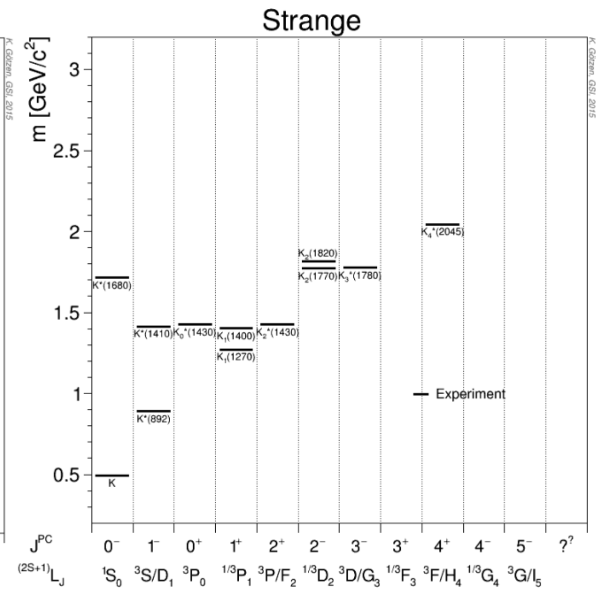


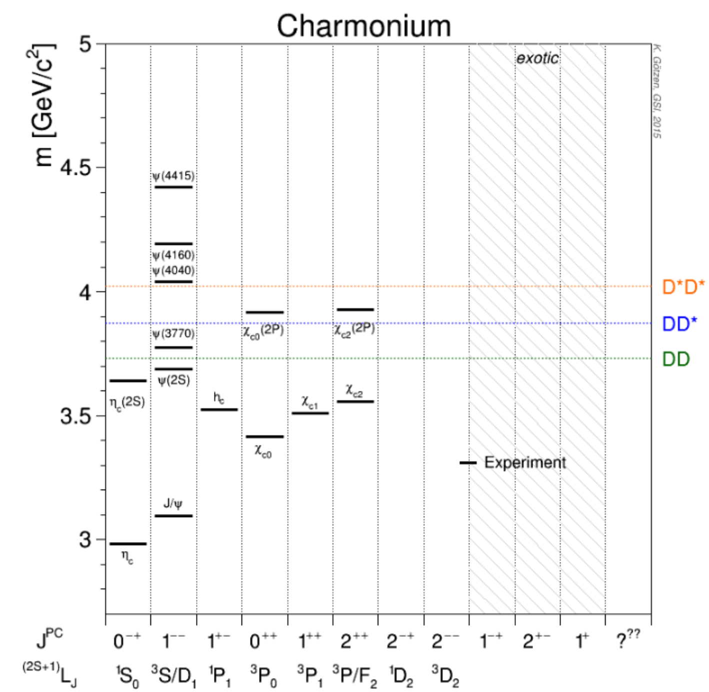
- QCD does not forbid hadrons with $N_{quarks} \neq 2, 3$
  - Glueball : $N_{quarks} = 0$ (gg, ggg, …)
  - Hybrid : $N_{quarks} = 2$ (or more) + excited gluon
  - Multiquark state : $N_{quarks} > 3$
  - Molecule : bound state of more than 2 hadrons
  - …

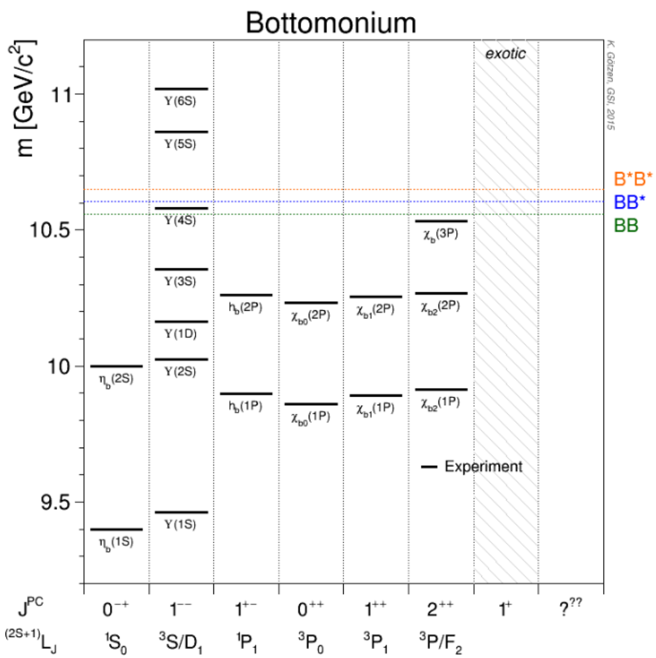
Hadron spectra: normal











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!!

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??

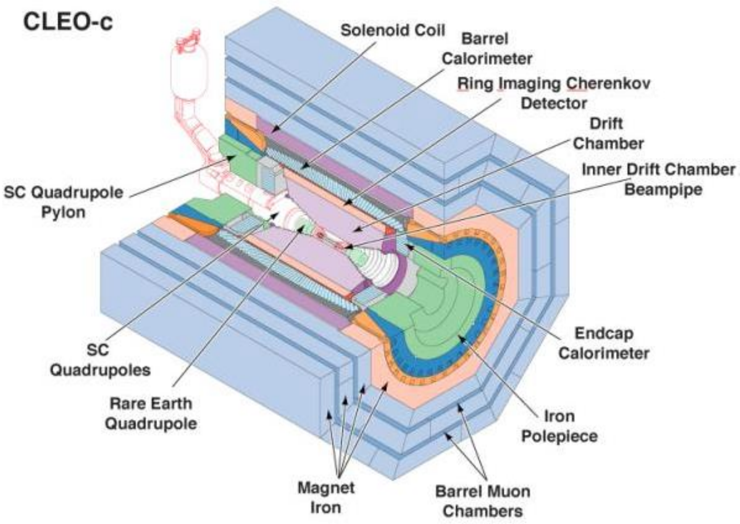
If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting 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.

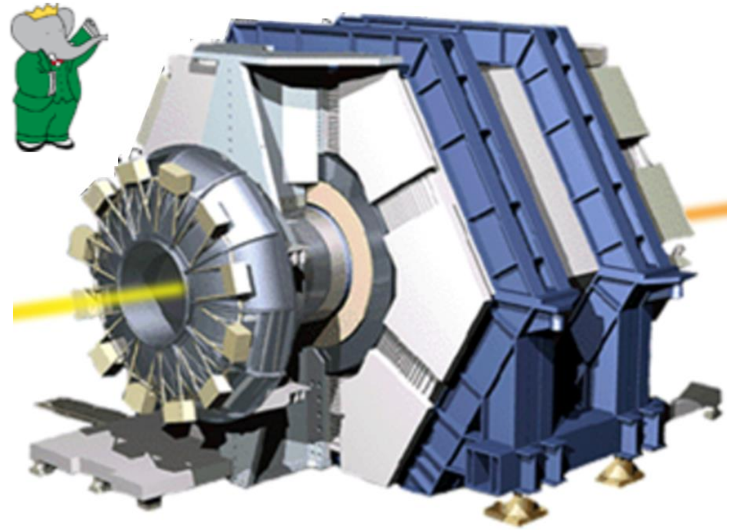
Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

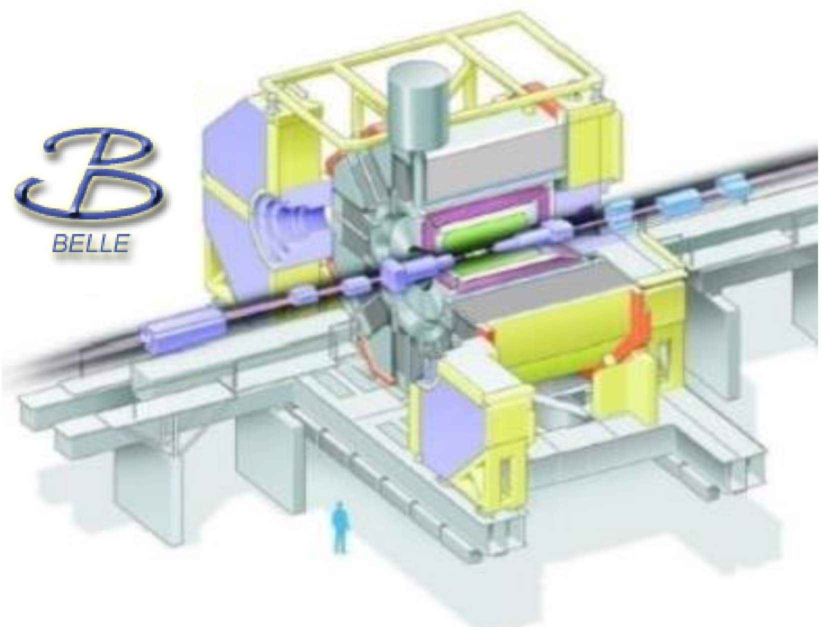
ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

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 (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) 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**.

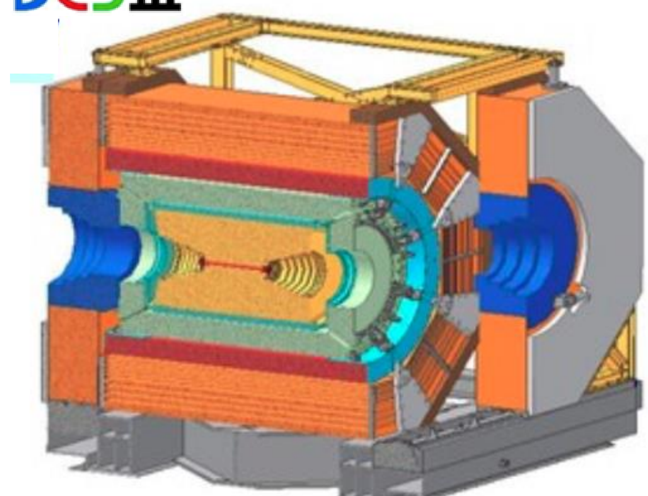
Main Suppliers of Exotics





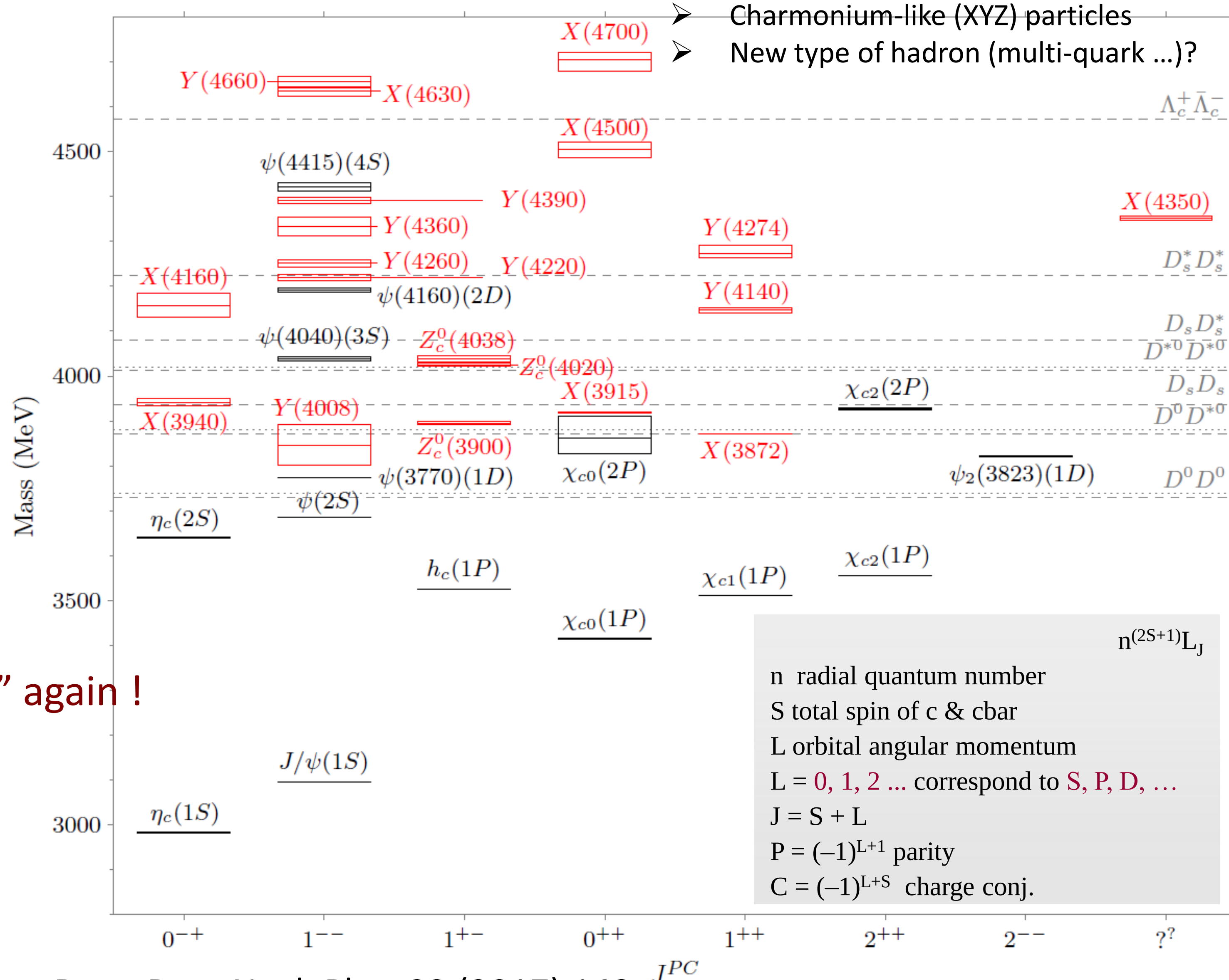


BESIII



XYZ particles

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

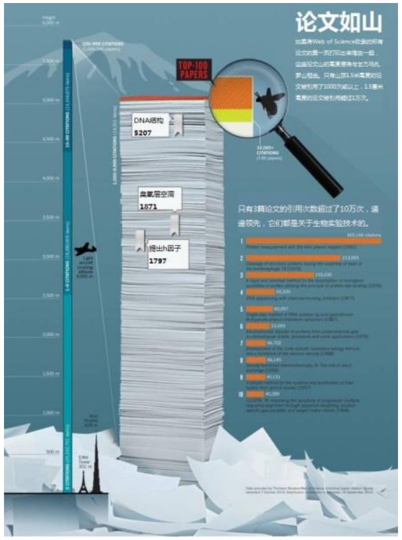


Particle “Zoo” again !

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

Too many models !

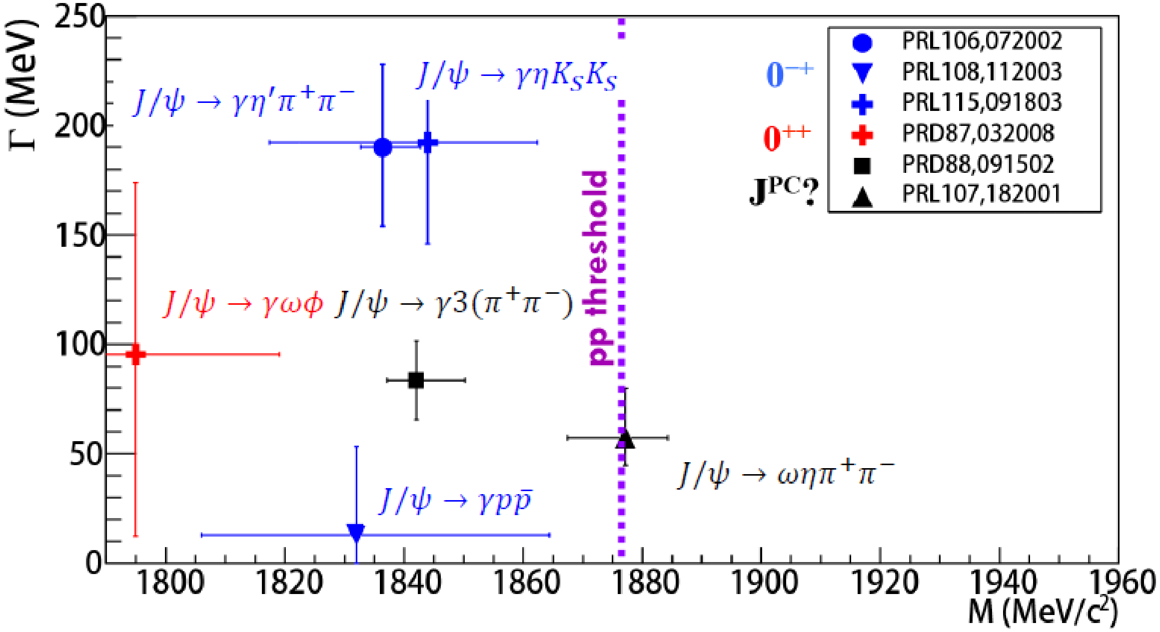
– Theory 1: screened potential
– Theory 2: hybrids with excited gluons
– Theory 3: tetraquark states
– Theory 4: meson molecules
– Theory 5: cusps effect
– Theory 6: final state interaction
– Theory 7: coupled-channel effect
– Theory 8: mixing of normal quarkonium and exotics
– Theory 9: mixture of all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

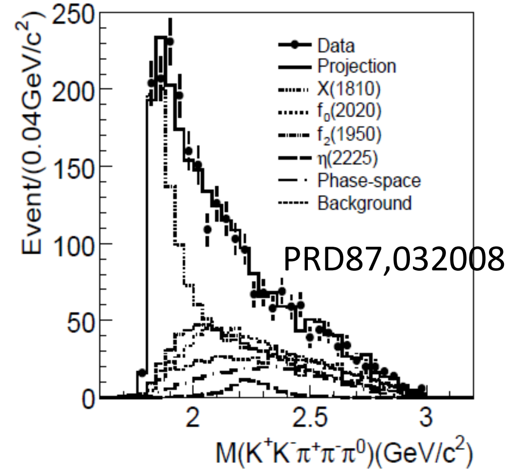


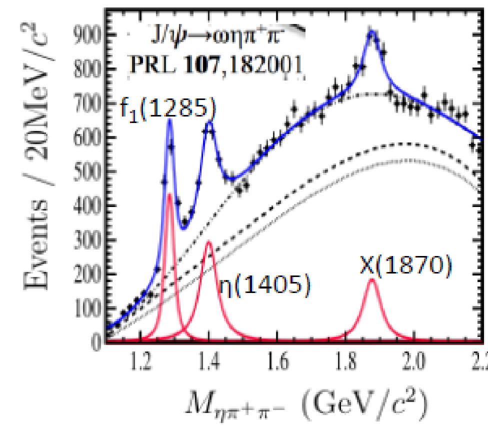
Light hadron spectroscopy

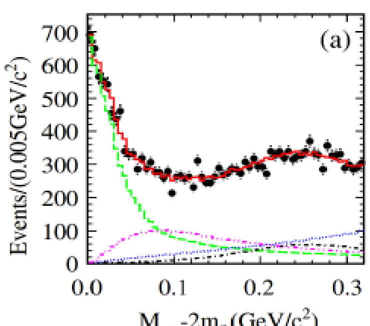
X(18??), Y(2175), …

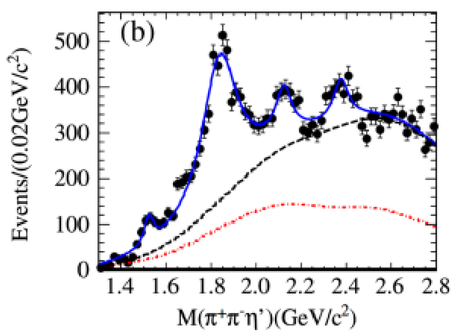
X(18??) at BESIII

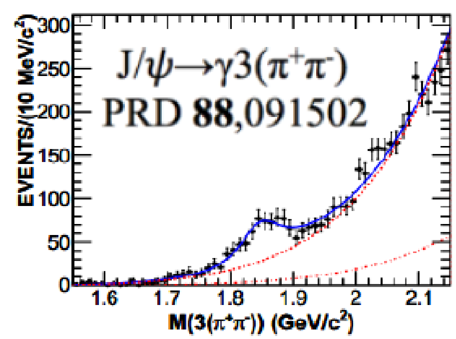








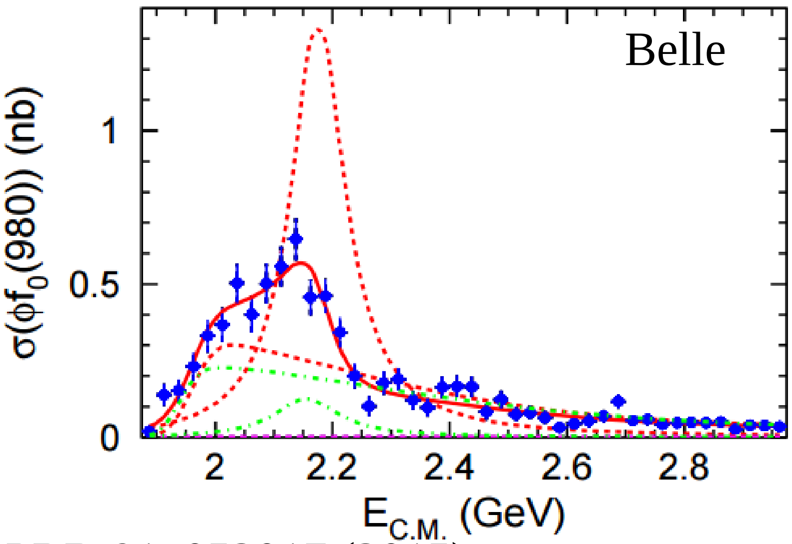




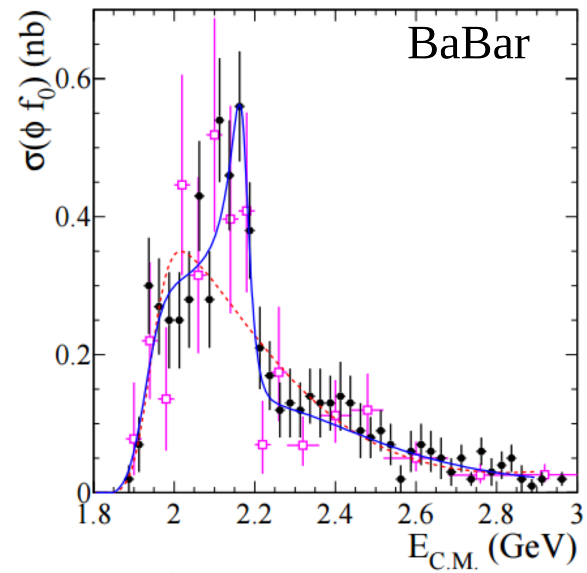
- Any relations?
- What is the role of the ppbar threshold (and other thresholds)?
- Patterns in the production and decay modes

Y(2175)

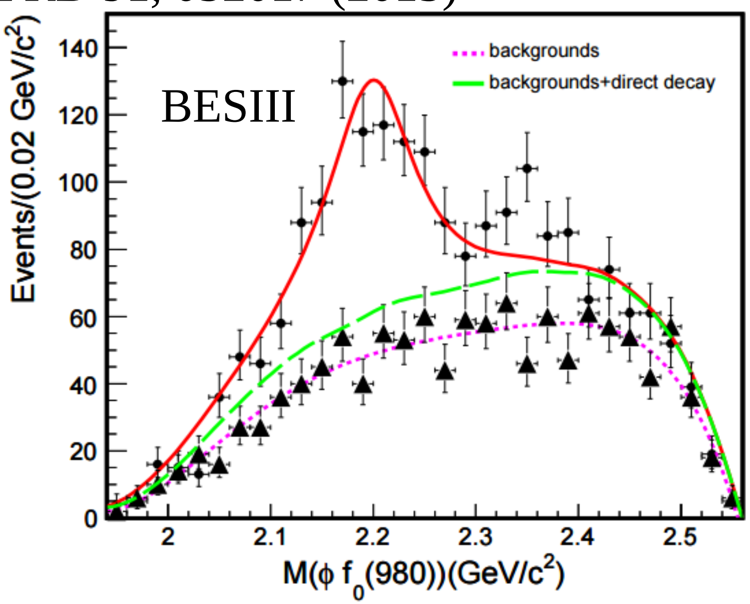
PRD 80, 031101 (2009)



PRD 74, 091103 (2006)



PRD 91, 052017 (2015)



BaBar: $\Gamma=58\pm16\pm20$ MeV

Belle: $\Gamma=211\pm14\pm19$ MeV

BESIII: $\Gamma=104\pm15\pm15$ MeV

- A strangeonium analogue of the Y(4260)?
- More strangeonium states ?

X States

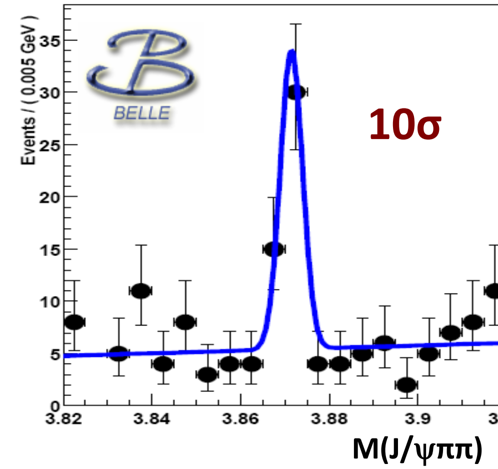
X(3872), X(5568), X_b …

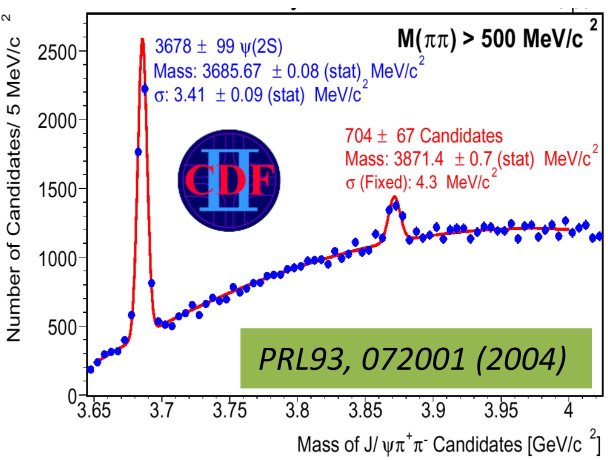
X(3872)→J/ψπ⁺π⁻

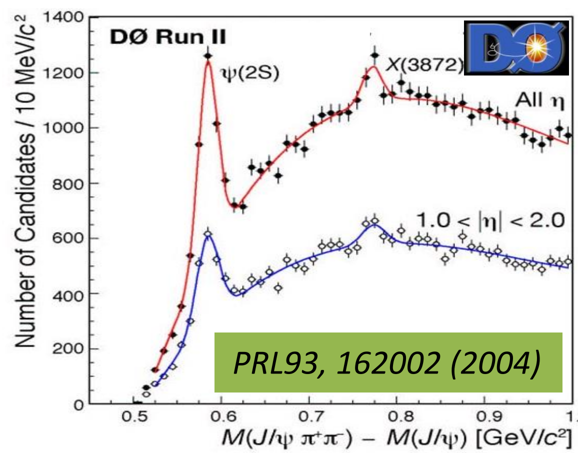
Belle's most cited paper: 1200+

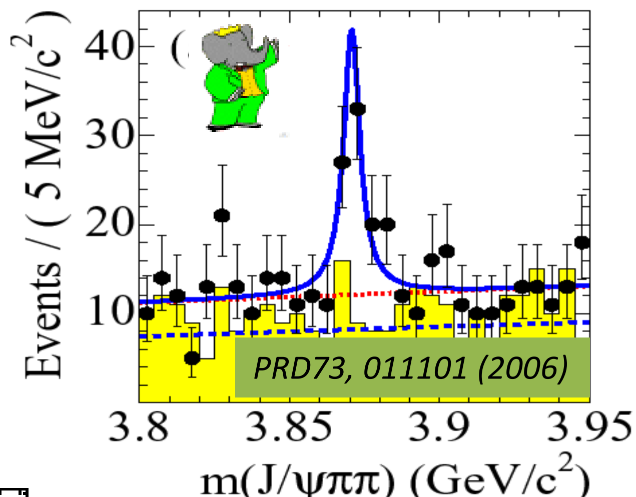
first observed by Belle in B→K J/ψπ⁺π⁻ *PRL91, 262001 (2003)*

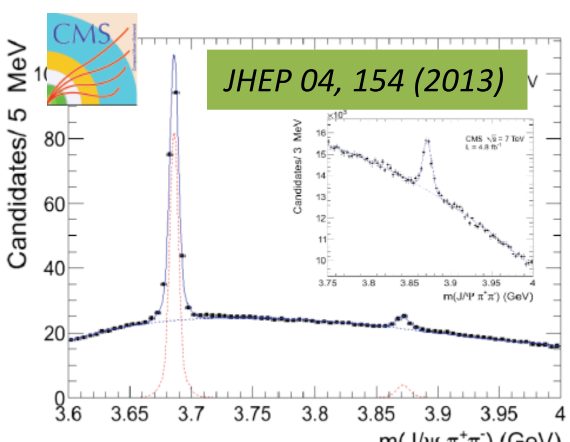
- M_X close to D^0D^{*0} threshold M = 3871.68 ± 0.17 MeV
  (not clear below or above: Δm = – 0.16 ± 0.32 MeV)
- surprisingly narrow: Γ_{tot}< 1.2 MeV at 90% CL

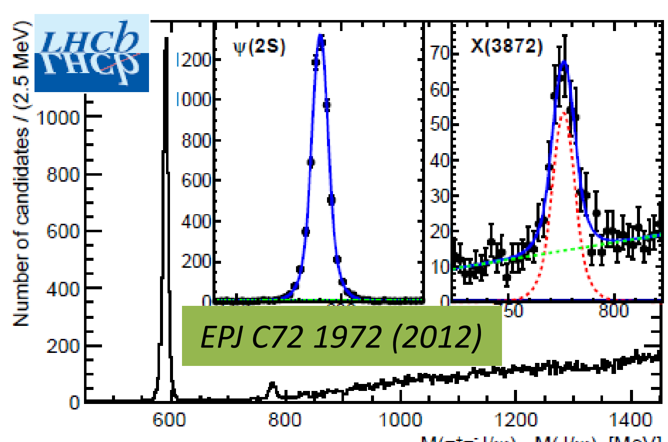












X(3872)→J/ψγ: C-even

Angular analysis:

Belle 2006: J^{PC} = 1⁺⁺ or ≥2
CDF 2008: J^{PC} = 1⁺⁺ or 2⁻⁺
Belle 2011: J^{PC} = 1⁺⁺ or 2⁻⁺

***LHCb 2013**:* J^{PC} = 1⁺⁺

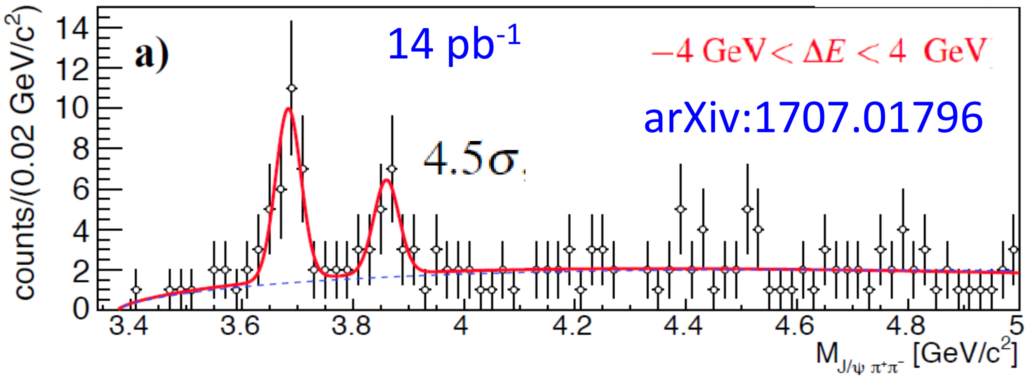
$X(3872) \to J/\psi\pi^+\pi^-$ at COMPASS

- various targets, „exclusive“ reaction $\mu^+ N \to \mu^+ X^0 \pi^\pm N' \to \mu^+ (J/\psi\pi^+\pi^-)\pi^\pm N'$
- significance > 6 σ for large missing masses (M_{miss} > 3 GeV/c²)
- ππ spectrum differs from previous observations

160 or 200 GeV/c μ

^{6}LiD or NH_3 targets

$$M^2_{\text{miss}} = (P_\mu + P_N - P_{\mu'} - P_{X^0})^2$$



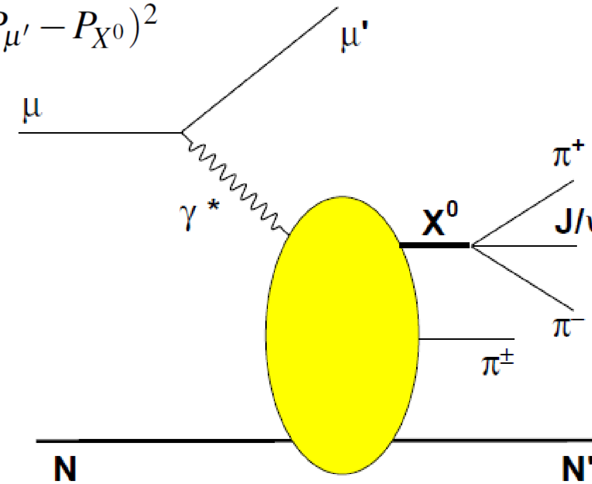
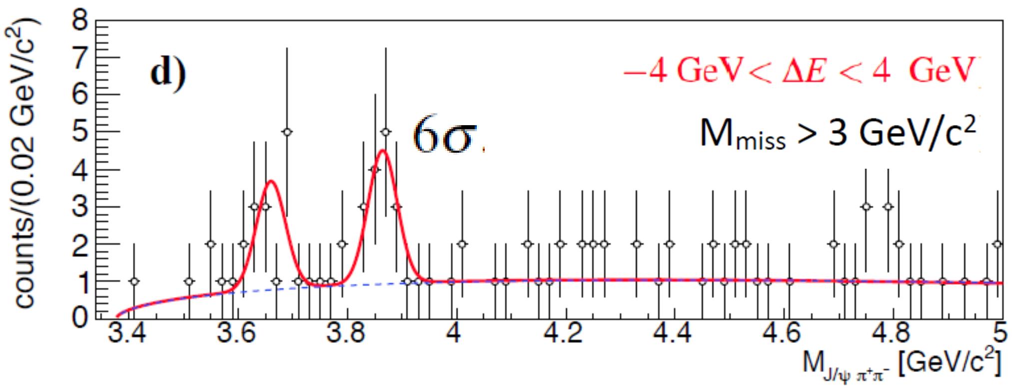
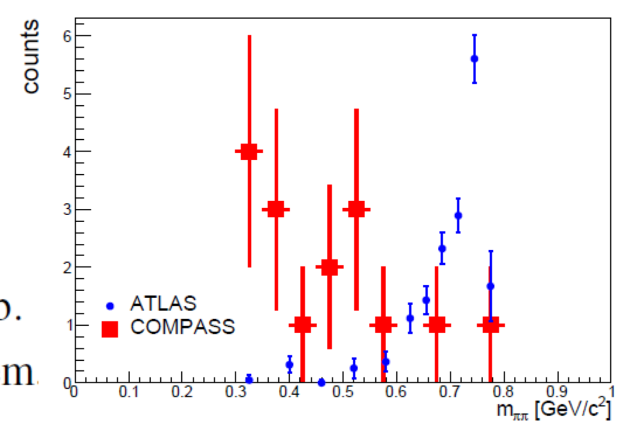


Diagram for exclusive muoproduction of $X^0\pi^\pm$





$$\sigma_{\gamma N \to X(3872)\pi N'} \times \mathcal{B}_{X(3872)\to J/\psi\pi\pi} = 71 \pm 28(\text{stat}) \pm 39(\text{syst})\ \text{pb}.$$

N denotes the target nucleon and N' the unobserved recoil system

X(3872): Other Decay Modes

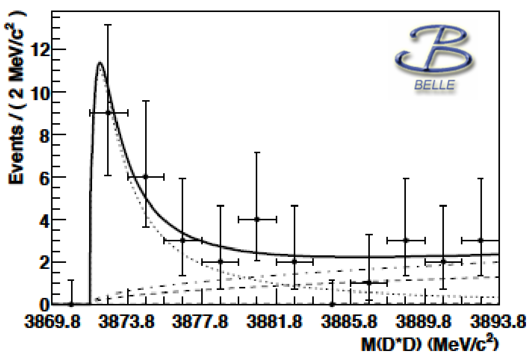
- **$\pi\pi = \rho$ means Isospin violation!**
- **X(3872) → J/ψω is seen: confirms isospin violation**

$$B(X(3872) \to J/\psi\omega)/B(X(3872) \to J/\psi\pi\pi)=0.8\pm0.3$$

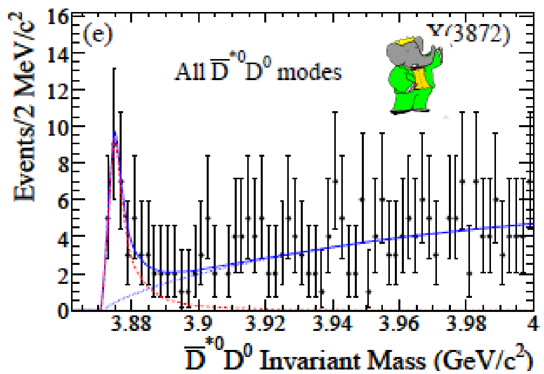
- Radiative decays: Belle&Babar good agreement for X →J/ψγ; not consistent for X →ψ(2S)γ.

LHCb confirms BaBar's not vanishing X →ψ(2S)γ.

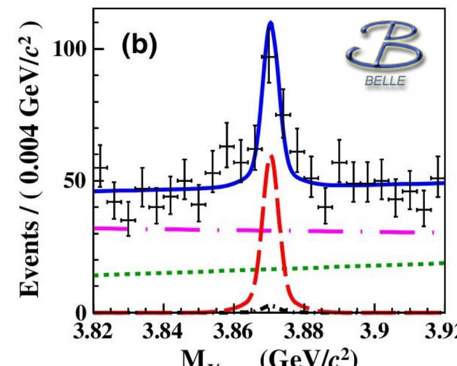
- X(3872) → DD* - dominant mode
- B→X(3872)Kπ non-resonant Kπ dominates!



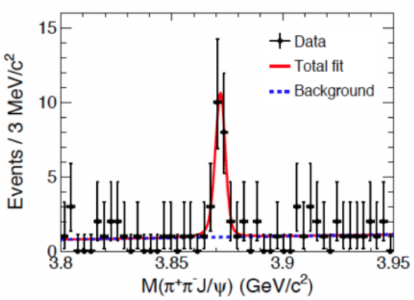
PRD 81, 031103 (2010)

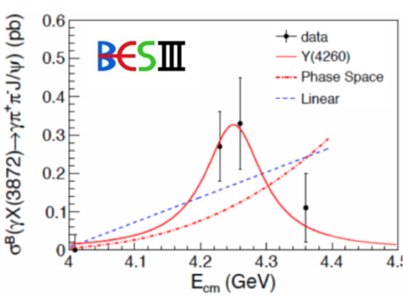


PRD 77, 011102 (2008)



PRD 91, 051101(R) (2015)

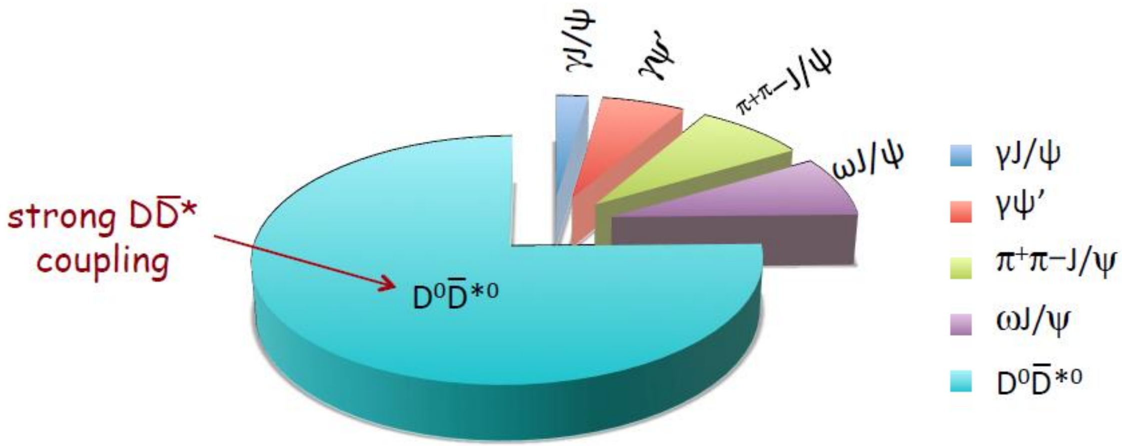




- The first observation of $e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi$
- M = 3871.9±0.7±0.2 MeV/c², Γ<2.4 MeV, consistent with Belle's result
- Suggestive of Y(4260)→γX(3872)
- If $B(X(3872)\to\pi^+\pi^- J/\psi) = 5\%$, $\mathcal{R} = \dfrac{Br(e^+e^-\to\gamma X(3872))}{Br(e^+e^-\to\pi^+\pi^- J/\psi)} = 0.1$

PRL 112, 092001 (2014)

X(3872) decay channels



$\Gamma_{\text{"tot"}} \approx 15\ \Gamma(X(3872) \rightarrow \pi^+\pi^- J/\psi)$

$\Gamma(X(3872) \rightarrow \pi^+\pi^- J/\psi) < 80$ keV

D^0-$\bar{D}^{*0}$ molecule?

Lots of literature about this

Impossible to produce such an fragile extended object in prompt high energy hadron colliders at the rates reported by CDF & CMS

QCD diquark-diantiquark?

Maiani et al. PRD 71, 014028 (2005)

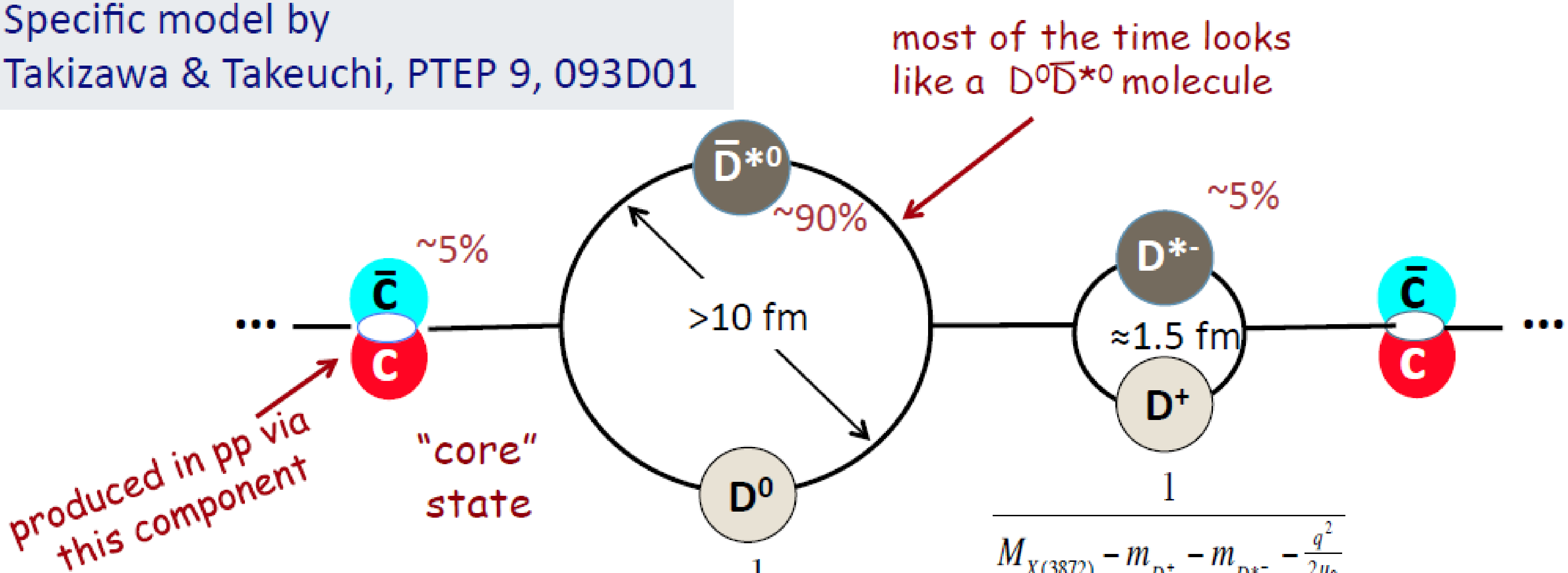
Predicts partner states (e.g., a nearby state with u→d) that have yet be seen.

no charged partners of the X(3872)

no nearby neutral X(3872) partners

Probably a mixture of $D\bar{D}^*$ & a $c\bar{c}$ "core"

Specific model by
Takizawa & Takeuchi, PTEP 9, 093D01



$$\frac{1}{M_{X(3872)} - m_{D^0} - m_{D^{*0}} - \frac{q^2}{2\mu_0}}$$

$|BE| < 0.2$ MeV

$d_{\text{rms}}^{D^0\bar{D}^{*0}} > 10$ fm

$$\frac{1}{M_{X(3872)} - m_{D^+} - m_{D^{*-}} - \frac{q^2}{2\mu_0}}$$

$|BE| \approx 8$ MeV

$d_{\text{rms}}^{D^+D^{*-}} \simeq 1.5$ fm

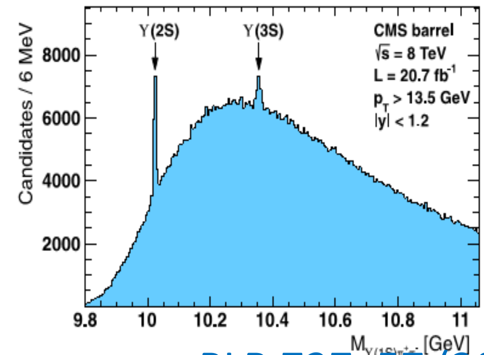
$$d_{\text{rms}} \approx \frac{1}{\sqrt{2\mu_D |BE|}}:$$

reduced mass

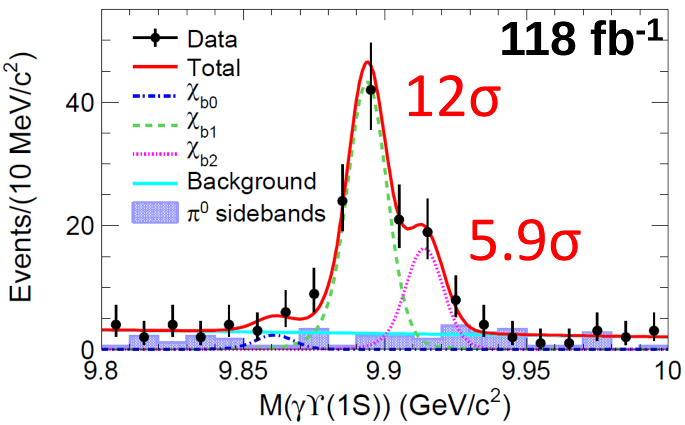
$|m_D + m_{D^*} - m_{X3872}|$

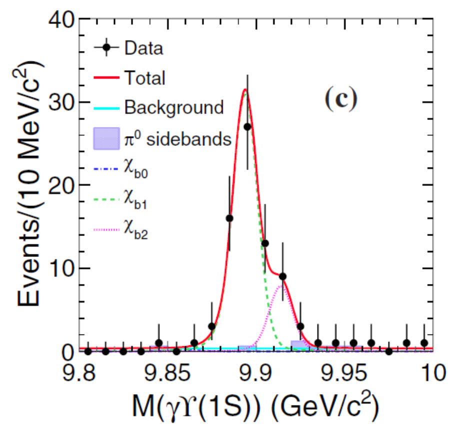
Search for X_b in $e^+e^- \to \gamma\pi^+\pi^-\pi^0\Upsilon(1S)$ at 10.867 GeV

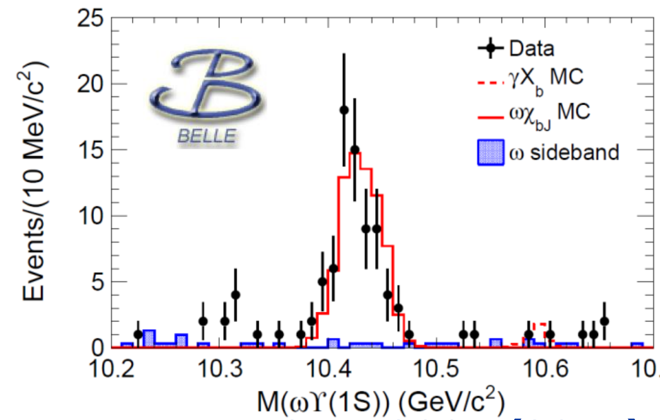
- The X(3872) counterpart in the bottomonium sector X_b, **NOT observed** decay channel $\pi^+\pi^-\Upsilon(1S)$.
- As X_b is above $\omega\Upsilon(1S)$ threshold, this Isospin-conserving process should be **a more promising decay mode**. [PRD88, 054007].



PLB 727, 57 (2013) .



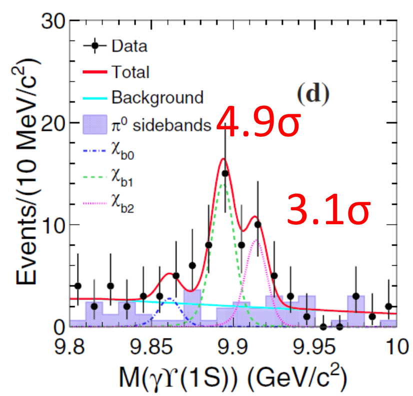




PRL 113, 142001 (2014)

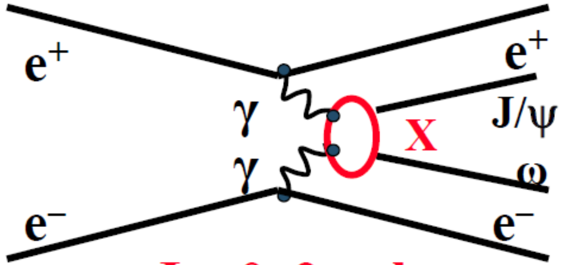
•Large Brs of Υ(5S) to $\pi^+\pi^-\pi^0\chi_{b1/b2}$, $\omega\chi_{b1/b2}$ are observed for the first time and their ratios are measured: hadronic loop effect ?

arXiv:1406.6763

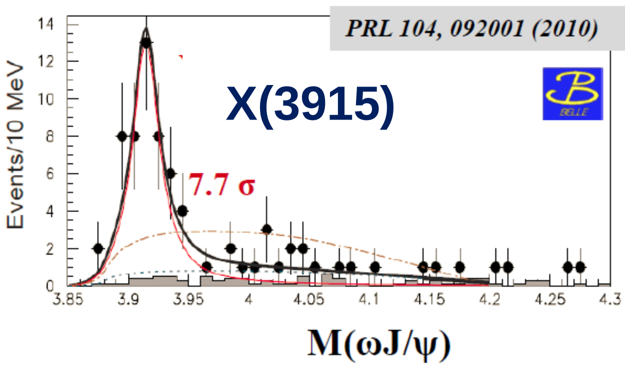


Assuming X_b is narrow, the upper limit on the product branching fraction was given.

X*(3860) (χ_{c0}(2P))



J = 0, 2 only



Confirmed by BaBar, prefer $J^P=0^+$

PDG: Y(3940)=X(3915)=χ_{c0}(2P)

Theory ☹

- χ_{c0}(2P) production in two body B decays is suppressed
- χ_{c0}(2P) → DD should be dominant, but not seen
- a better candidate for χ_{c0}(2P) seen in $e^+e^- \to J/\psi DD$

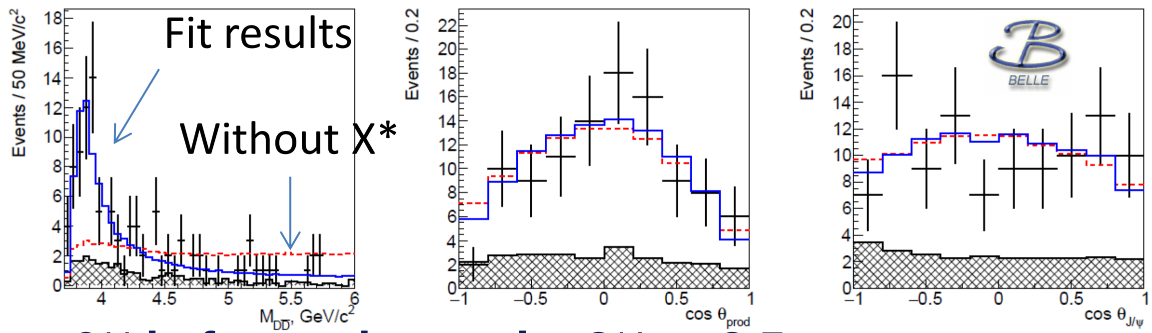
PDG 2016: X(3915)≠χ_{c0}(2P)

PRD 95， 112003 (2017)

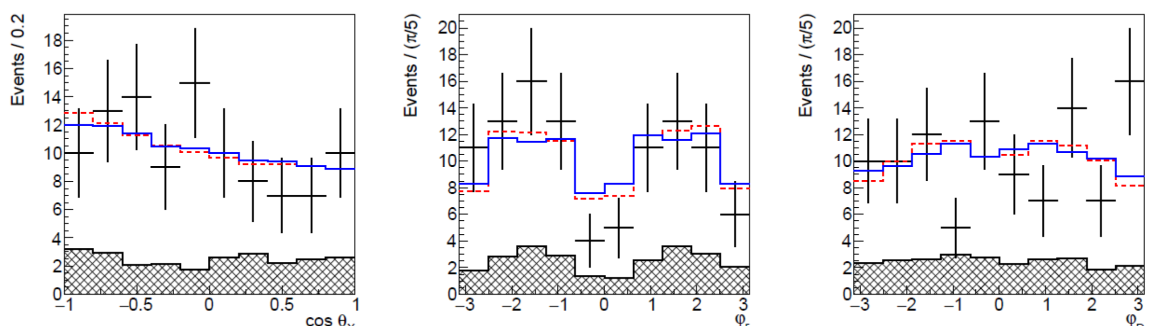
A 6D amplitude analysis was done to $e^+e^- \to J/\psi D\bar{D}$

$$\Phi = (M_{D\bar{D}}, \theta_{\rm prod}, \theta_{J/\psi}, \theta_{X^*}, \varphi_{\ell^-}, \varphi_D),$$

where $\theta_{\rm prod}$ is the production angle, $\theta_{J/\psi}$ and θ_{X^*} are the J/ψ and X^* helicity angles, respectively, and φ_{ℓ^-} and φ_D are the ℓ^- and D azimuthal angles, respectively.



0^{++} is favored over the 2^{++} at 2.5 σ



X*(3915): 8.5σ, 0^{++}, M=3862^{+26+40}_{-32-13} MeV/c²
Γ=$201^{+154+88}_{-67-82}$ MeV
The parameters of X*(3915) are <2.7σ difference from the predicted χ_{c0}(2P)

If X(3915) ≠ χ'_{c0}, what is it?

It remains an intriguing puzzle

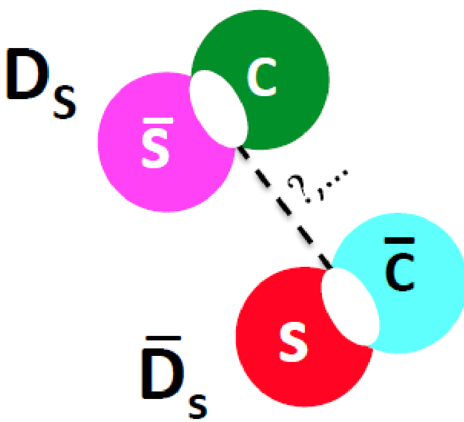
$X(3915) \rightarrow \omega J/\psi$ violates OZI-rule unless it's a 4-quark state

Mass is near $2m_{D_s}$ threshold: $M(X(3915)) = 2m_{D_s}$ -18 MeV

$X(3915) \rightarrow D\bar{D}$ decays are suppressed: $\Gamma(X(3915) \rightarrow D\bar{D}) < 1$ MeV

D_s-$\bar{D}_s$ molecule?

Li & Voloshin, PRD 91, 114014

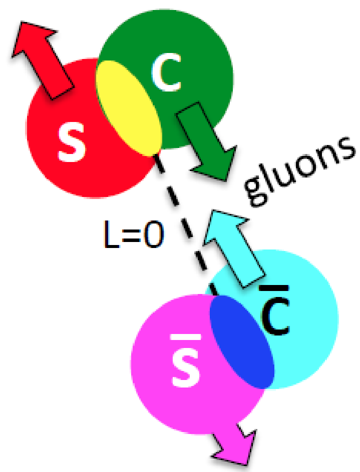


what binds it?

no plausible nuclear-physics-type force can bind $D_s\bar{D}_s$ into a "molecule"

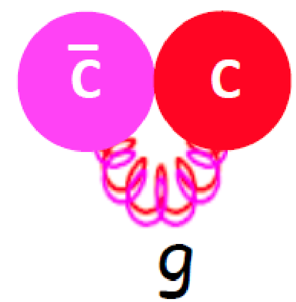
$[\bar{c}\bar{s}][cs]$ tetraquark?

Lebed & Polosa, PRD 93, 094024



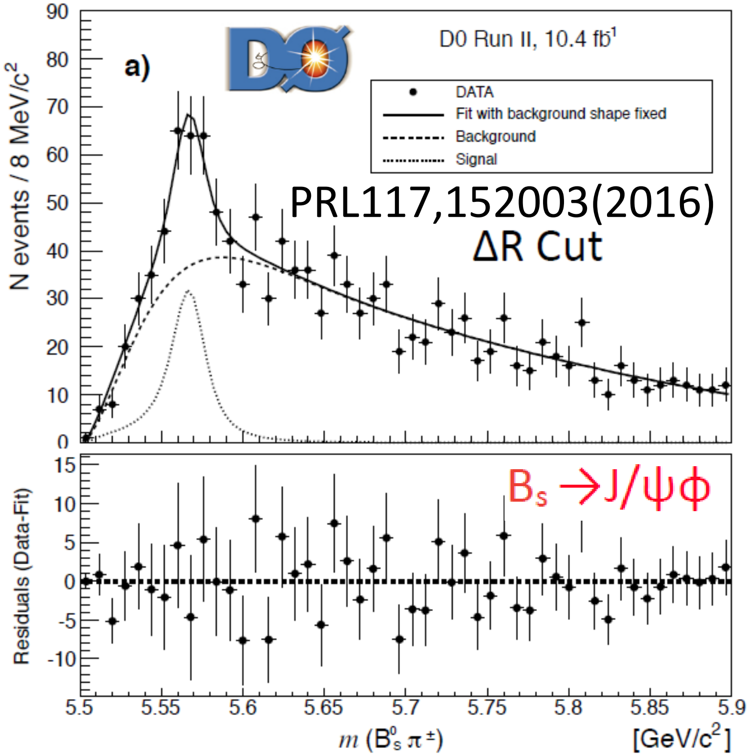
why not $X \rightarrow \eta\eta_c$?

$c\bar{c}$-gluon hybrid?



too light for 0^{++} cc-hybrid

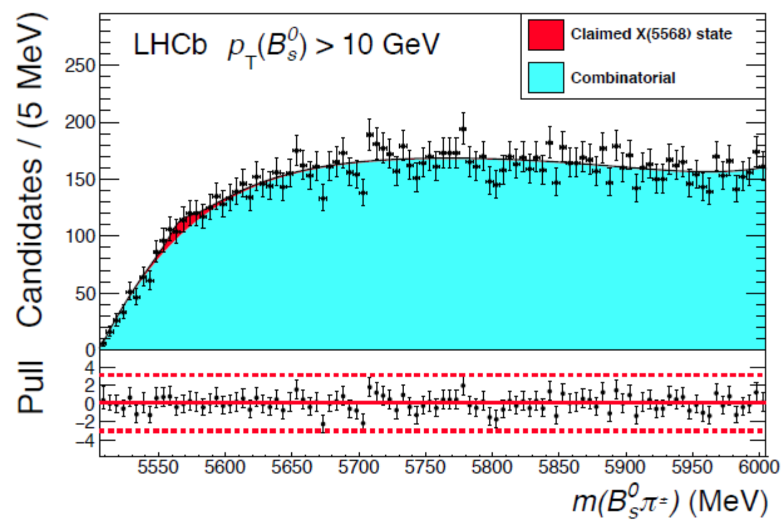
X(5568) at D0

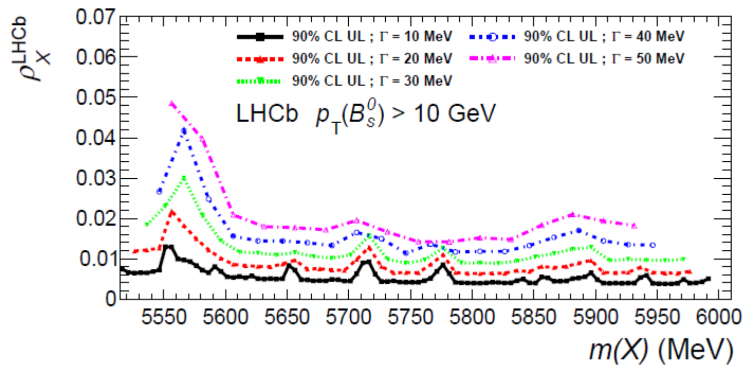


Structure in $B_s\pi$ spectrum?

- D0 collaboration claimed state decaying to $B_s\pi^+$
- LHCb has large data sample to check it
  - 112600 B_s events (LHCb) vs. 5582 (D0)
- No state seen in place of D0 state

PRL117, 152003 (2016)





Statistical significance of signal (including systematics and LEE)

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.3$$

With ΔR Cut: 5.1 σ, Without ΔR Cut: 3.9 σ

Not seen at LHCb and CMS

$\underline{X(5568)}$

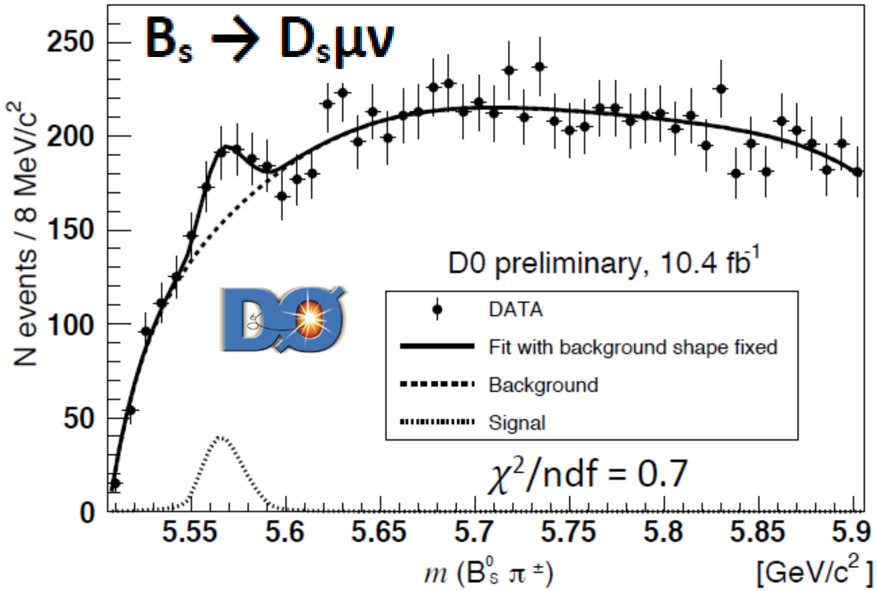
$$M_X = 5567.8 \pm 2.9\,(\text{stat})^{+0.9}_{-1.9}\,(\text{syst})\,\text{MeV}/c^2$$

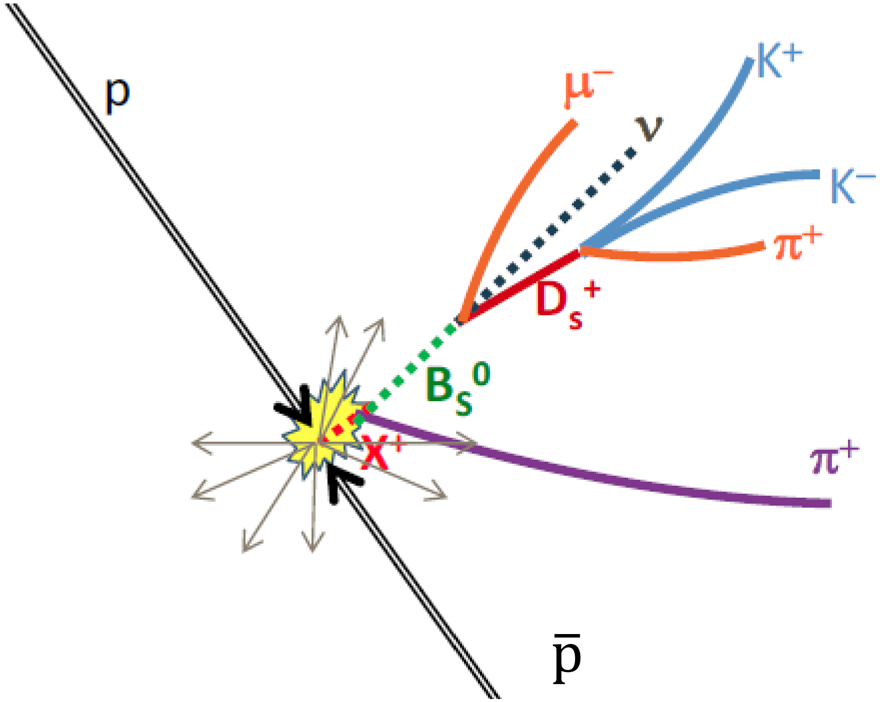
$$\Gamma_X = 21.9 \pm 6.4\,(\text{stat})^{+5.0}_{-2.5}\,(\text{syst})\,\text{MeV}/c^2$$

$$\rho = [8.6 \pm 1.9\,(\text{stat}) \pm 1.4\,(\text{syst})]\,\%$$

X(5568) at D0

D0 Conference Note 6494





X(5568)

$$N_X = 139^{+51}_{-63}$$

$$M_X = 5566.7^{+3.6}_{-3.4}\ \mathrm{MeV/c^2}$$

$$\Gamma_X = 6.0^{+9.5}_{-6.0}\ \mathrm{MeV/c^2}$$

Local Signficance

$$\sqrt{-2\ln\frac{\mathcal{L}_0}{\mathcal{L}_{\max}}}$$

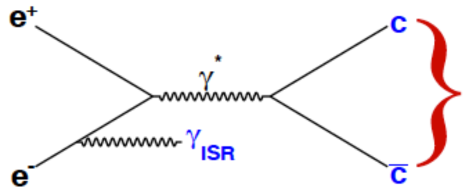
Statistical Significance 4.5 σ.

Including Systematics 3.2 σ.

Y States

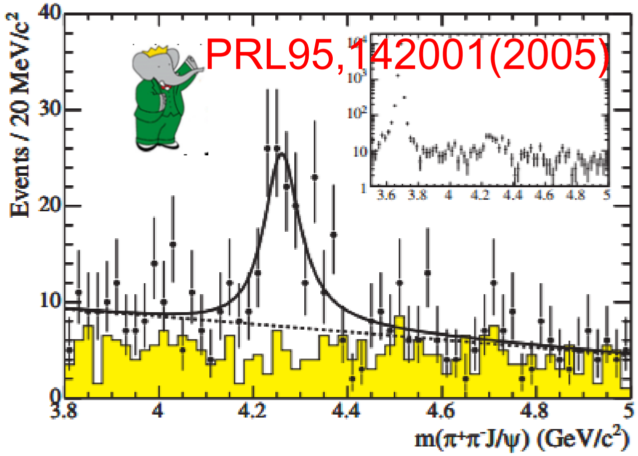
Y(4260), Y(4360), Y(4660)…

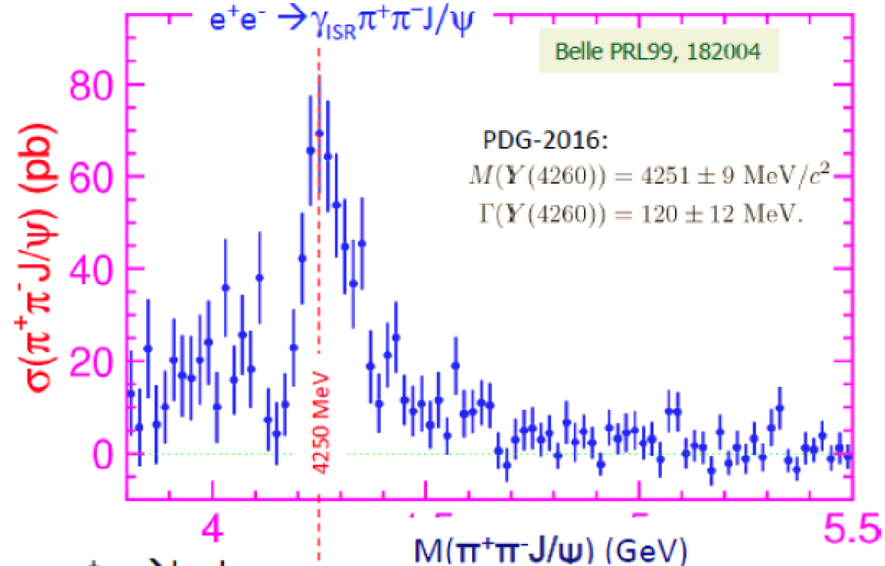
Y(4260) in $e^+e^- \rightarrow \pi^+\pi^- J/\psi$

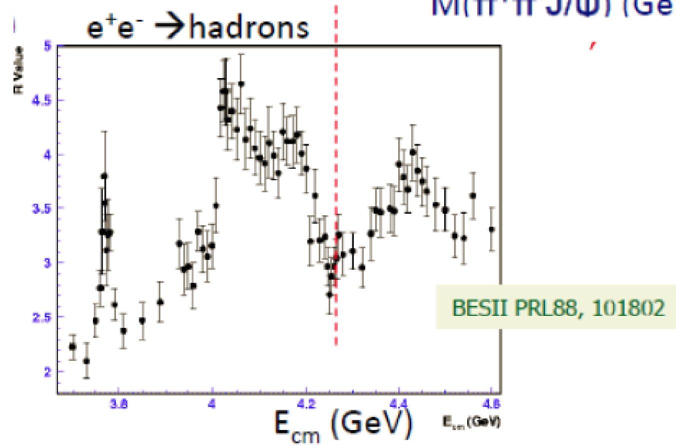


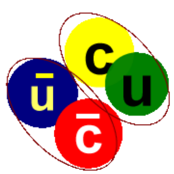
$J^{PC} = 1^{--}$

ψ', ψ'', Y…

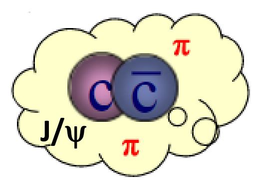




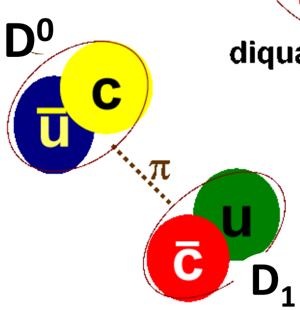




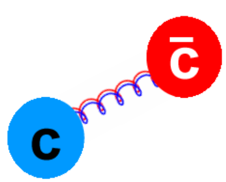
diquark-diantiquark



Hadro-charmonium



$D^0 - D_1$ "molecule"

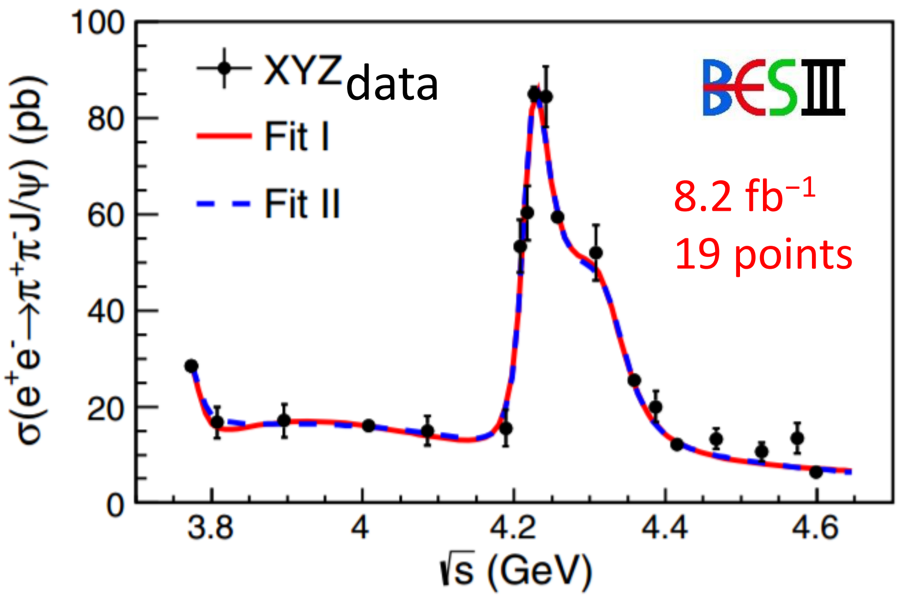


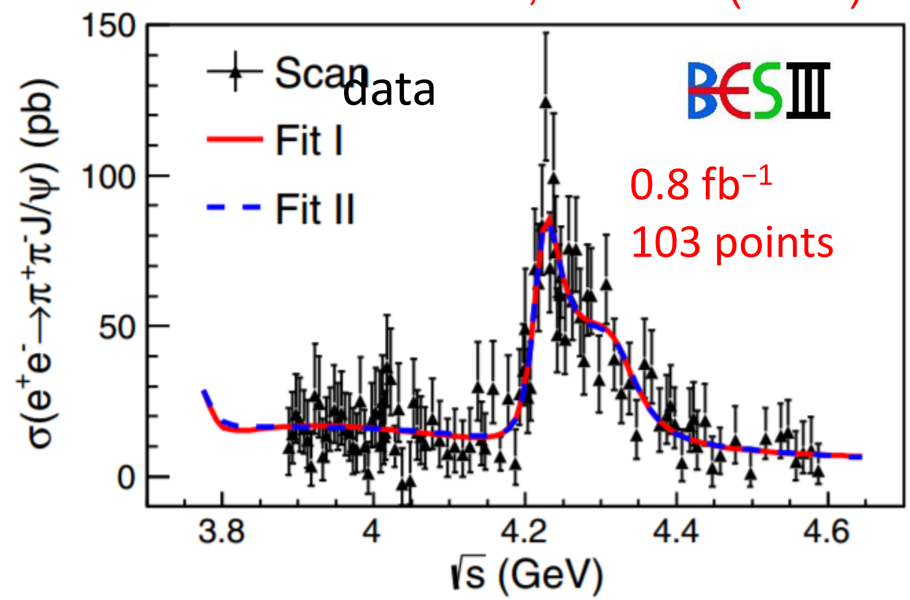
$q\bar{q}$-gluon"hybrid"

- No Y(4260) to $D^{(*)}\overline{D}^{(*)}$
- If Y(4260) is $c\bar{c}$, the Γ to $\pi^+\pi^- J/\psi$ should be small

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

PRL118, 092001 (2017)





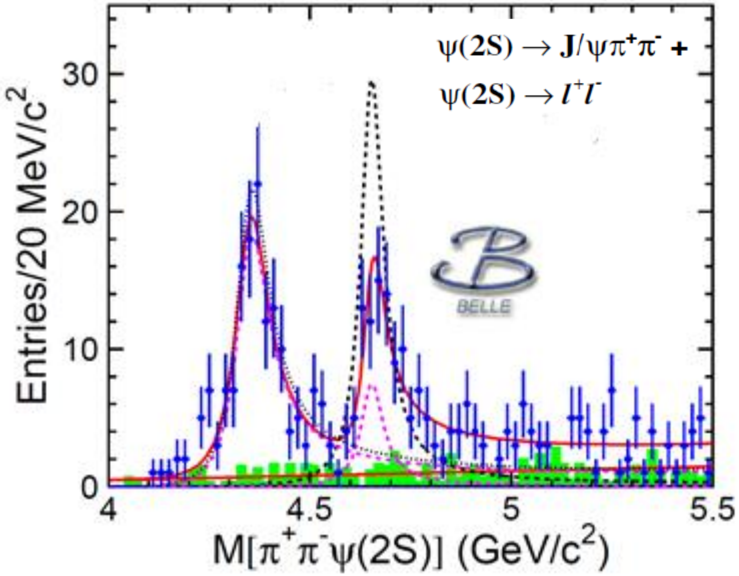
- Most precise cross section measurment to date from BESIII
- Fit I = $|BW_1+BW_2*e^{i\phi 2}+BW_3*e^{i\phi 3}|^2$ or Fit II = $|\exp+BW_2*e^{i\phi 2}+BW_3*e^{i\phi 3}|^2$ (other fits ruled out)
- M = 4222.0±3.1±1.4 MeV (lower)
- Γ = 44.1±4.3±2.0 MeV (narrower)
- A 2nd resonance Y_2 with M=4320.0±10.4±7.0 MeV/c^2
  Γ=$101.4^{+25.3}_{-19.7}$±10.2 MeV
- Observed for the first time, significance > 7.6σ

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

PRD 91, 112007 (2015)

Unbinned simultaneous maximum likelihood fit for $Y(4360)$ and $Y(4660)$.

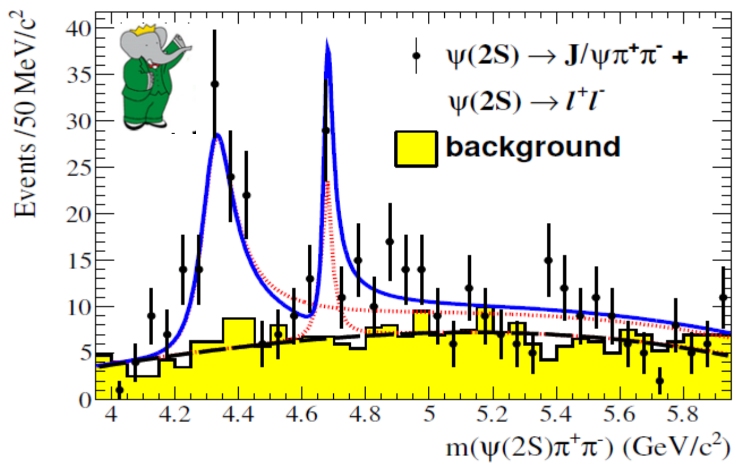
$Amp = BW_1 + e^{i\phi} \cdot BW_2$



Parameters	Solution I	Solution II
$M_{Y(4360)}$ (MeV$/c^2$)	$4347 \pm 6 \pm 3$	
$\Gamma_{Y(4360)}$ (MeV)	$103 \pm 9 \pm 5$	
$\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4360)}$ (eV)	$9.2 \pm 0.6 \pm 0.6$	$10.9 \pm 0.6 \pm 0.7$
$M_{Y(4660)}$ (MeV$/c^2$)	$4652 \pm 10 \pm 11$	
$\Gamma_{Y(4660)}$ (MeV)	$68 \pm 11 \pm 5$	
$\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4660)}$ (eV)	$2.0 \pm 0.3 \pm 0.2$	$8.1 \pm 1.1 \pm 1.0$
ϕ ($^\circ$)	$32 \pm 18 \pm 20$	$272 \pm 8 \pm 7$

$\chi^2/ndf = 18.7/21$.

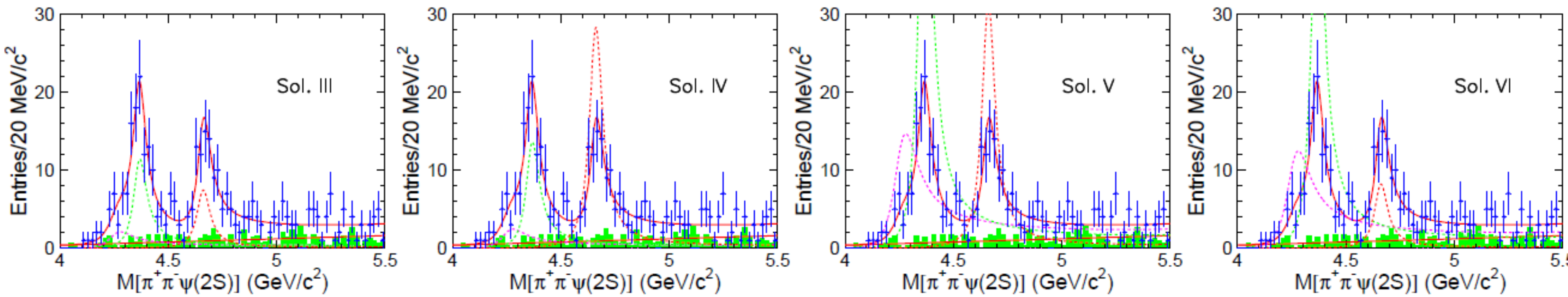
- Consistent with previous measurement
- No obvious signal above $Y(4660)$.
- Some events accumulate at $Y(4260)$, especially the $\pi^+\pi^- J/\psi$ mode.
- If $Y(4260)$ is included in the fit, ...



PRD89, 111103 (2014)

M(π⁺π⁻ ψ(2S)) with Y(4260,4360,4660)

Unbinned simultaneous maximum likelihood fit for $Y(4260)$, $Y(4360)$ and $Y(4660)$. $Amp = BW_1 + e^{i\phi_1} \cdot BW_2 + e^{i\phi_2} \cdot BW_3$.



Parameters	Solution I	Solution II	Solution III	Solution IV
$\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4260)}$ (eV)	$1.5 \pm 0.6 \pm 0.4$	$1.7 \pm 0.7 \pm 0.5$	$10.4 \pm 1.3 \pm 0.8$	$8.9 \pm 1.2 \pm 0.8$
$M_{Y(4360)}$ (MeV/c^2)		$4365 \pm 7 \pm 4$		
$\Gamma_{Y(4360)}$ (MeV)		$74 \pm 14 \pm 4$		
$\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4360)}$ (eV)	$4.1 \pm 1.0 \pm 0.6$	$4.9 \pm 1.3 \pm 0.6$	$21.1 \pm 3.5 \pm 1.4$	$17.7 \pm 2.6 \pm 1.5$
$M_{Y(4660)}$ (MeV/c^2)		$4660 \pm 9 \pm 12$		
$\Gamma_{Y(4660)}$ (MeV)		$74 \pm 12 \pm 4$		
$\mathcal{B} \cdot \Gamma^{e^+e^-}_{Y(4660)}$ (eV)	$2.2 \pm 0.4 \pm 0.2$	$8.4 \pm 0.9 \pm 0.9$	$9.3 \pm 1.2 \pm 1.0$	$2.4 \pm 0.5 \pm 0.3$
ϕ_1 (°)	$304 \pm 24 \pm 21$	$294 \pm 25 \pm 23$	$130 \pm 4 \pm 2$	$141 \pm 5 \pm 4$
ϕ_2 (°)	$26 \pm 19 \pm 10$	$238 \pm 14 \pm 21$	$329 \pm 8 \pm 5$	$117 \pm 23 \pm 25$

Significance of $Y(4260)$ is 2.4σ—low, but affects $Y(4360)$ and $Y(4660)$ masses and widths.

FOUR solutions with equally good fit quality, which is $\chi^2/ndf = 14.8/19$.

Comparsion of $e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ cross section

BESIII (16 energy points; L_{tot}=5.1fb^{-1})

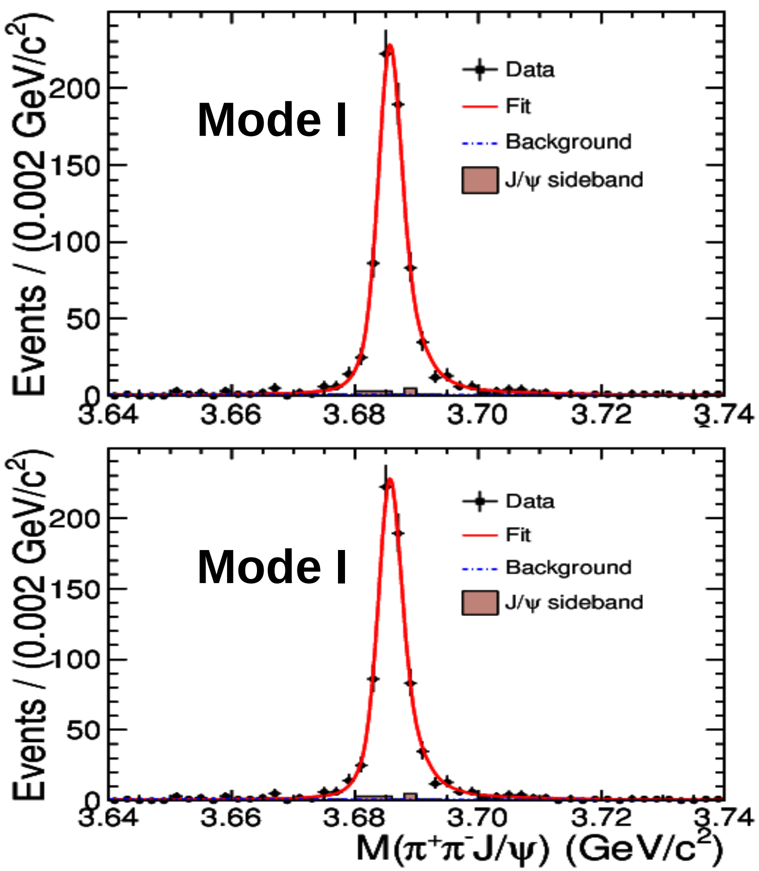
$\psi(2S)$ **Reconstructed modes:**

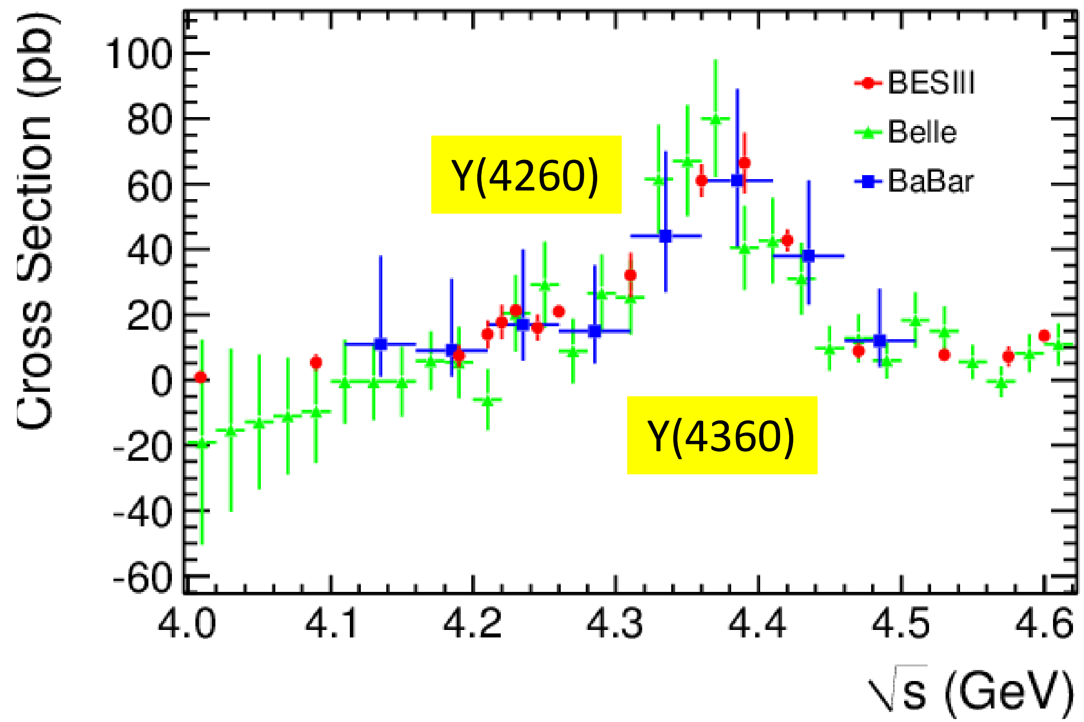
Mode I: $\Psi(3686)\rightarrow\pi^+\pi^- J/\psi$, $J/\psi\rightarrow l^+l^-$ ($l=e/\mu$)

Mode II: $\Psi(3686)\rightarrow$*neutrals*$+J/\psi$, *neutrals*$=(\pi^0\pi^0, \pi^0, \eta$ and $\gamma\gamma)$ $J/\psi\rightarrow l^+l^-$ ($l=e/\mu$)

arXiv:1703.08787

Accepted by PRD





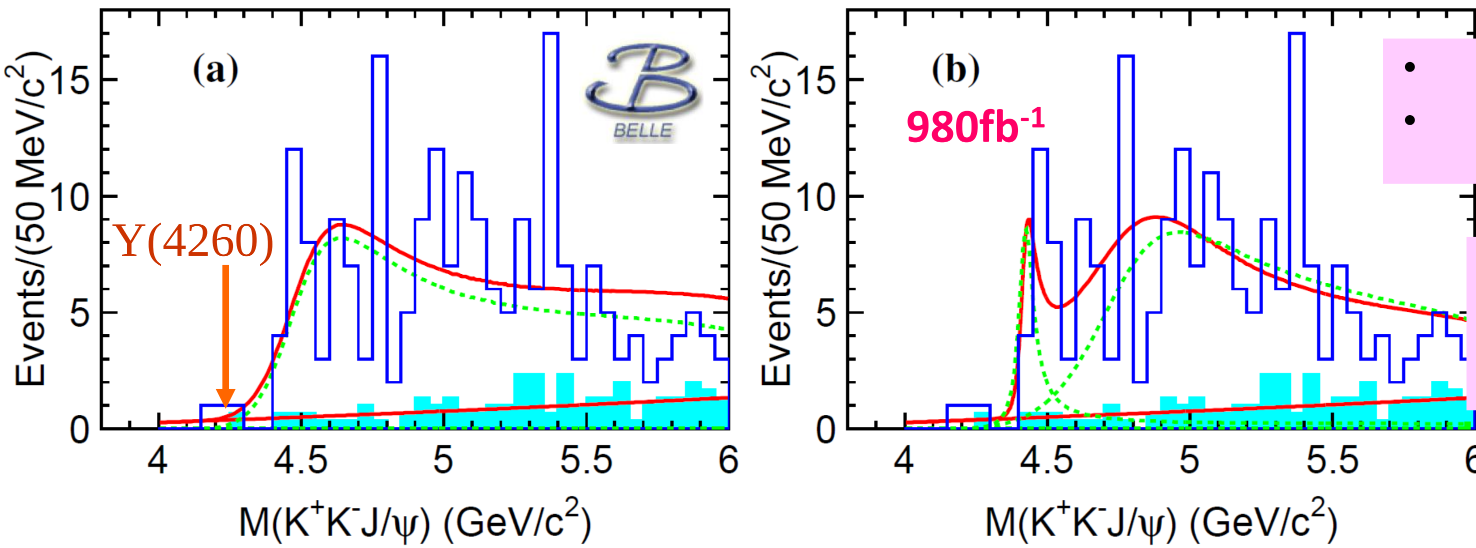
The measured Born cross sections of two modes are combined by considering the correlated and uncorrelated uncertainties.

Updated $e^+e^- \to K^+K^-J/\psi$

PRD 89,072015(2014)

Event selections are almost the same as in Phys. Rev. D 77, 011105(R) (2008)

Shaded hist.: J/ψ mass sidebands



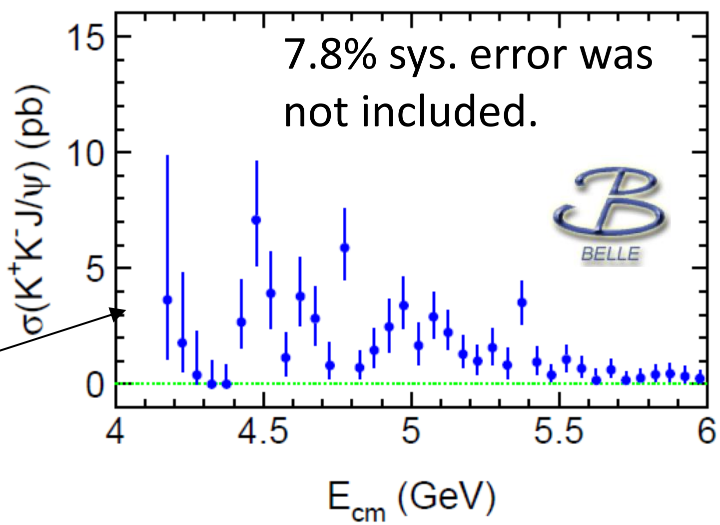
- +one resonance.
- Fit with $\psi(4415)$

χ^2/ndf=30/11

- M=4747±117MeV
- Γ=671±86 MeV

4-6 GeV: 213 events
35 bkg, 178±16 signal

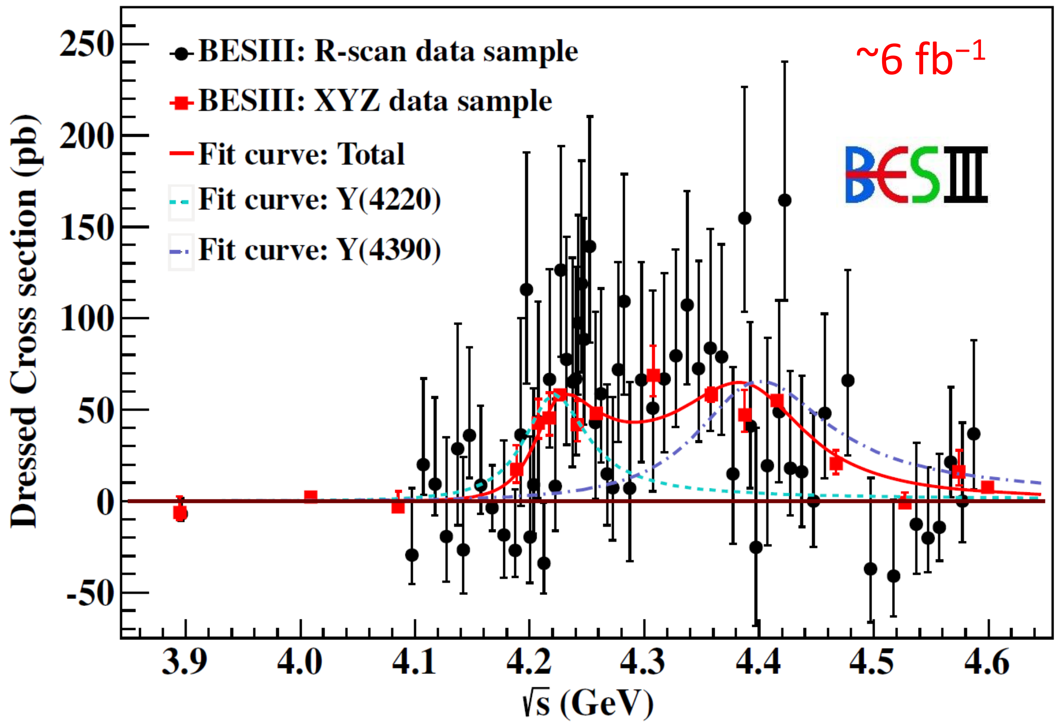
$$\sigma_i = \frac{n_i^{\rm obs} - f \times n_i^{\rm bkg}}{\mathcal{L}_i \cdot \epsilon_i \cdot \mathcal{B}(J/\psi \to \ell^+\ell^-)}$$



$e^+e^- \rightarrow \pi^+\pi^- h_c$ cross section at BESIII

PRL118, 092002 (2017)

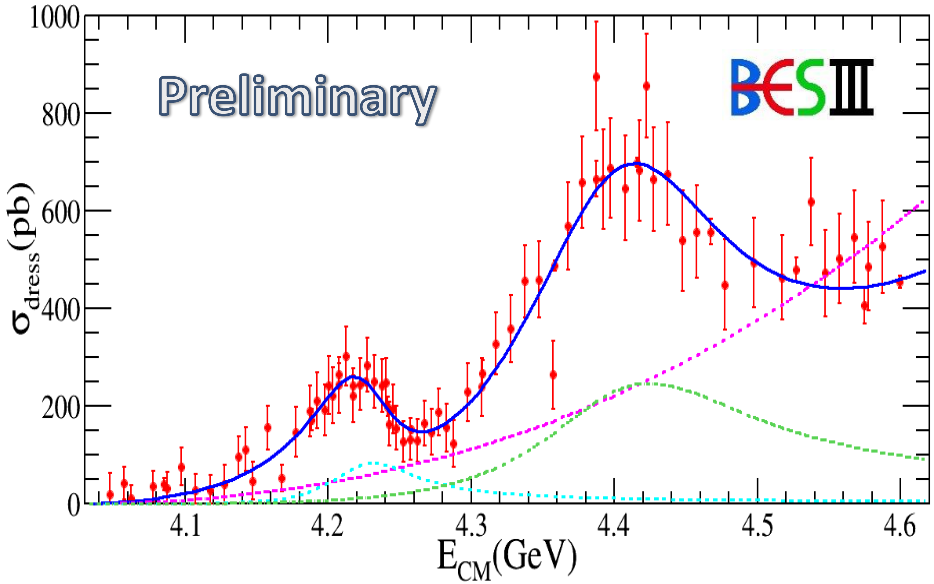
- $h_c \rightarrow \gamma\eta_c$, $\eta_c \rightarrow$hadrons [16 exclusive decay modes]



- M_1=4218.4$^{+5.5}_{-4.5}$±0.9 MeV/c^2,
  Γ_1= 66.0$^{+12.3}_{-8.3}$±0.4 MeV
  → Y(4220)
- M_2=4391.5$^{+6.3}_{-6.8}$±1.0 MeV/c^2,
  Γ_2=139.5$^{+16.2}_{-20.6}$±0.6 MeV
  → Y(4390)

- 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

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



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

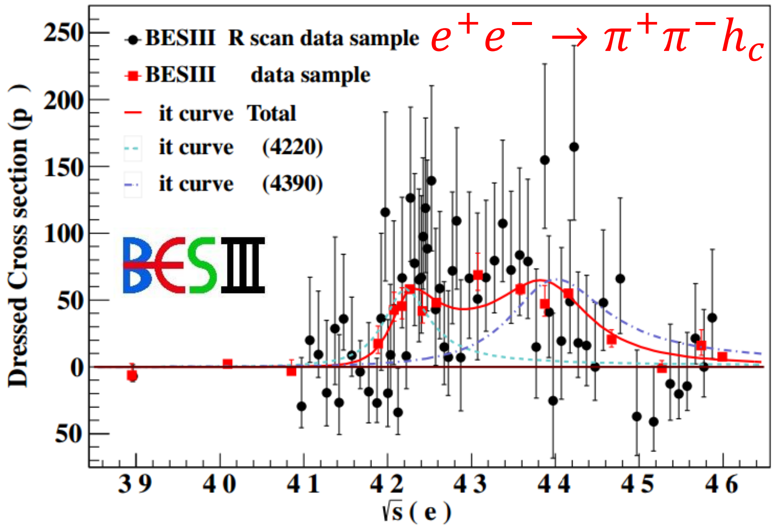
- Fit with a constant and two BW functions with interference
- Statistical significance is greater than 10σ.
- Consistent with those of Y(4220) and Y(4390) in $e^+e^- \to \pi^+\pi^-h_c$.

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

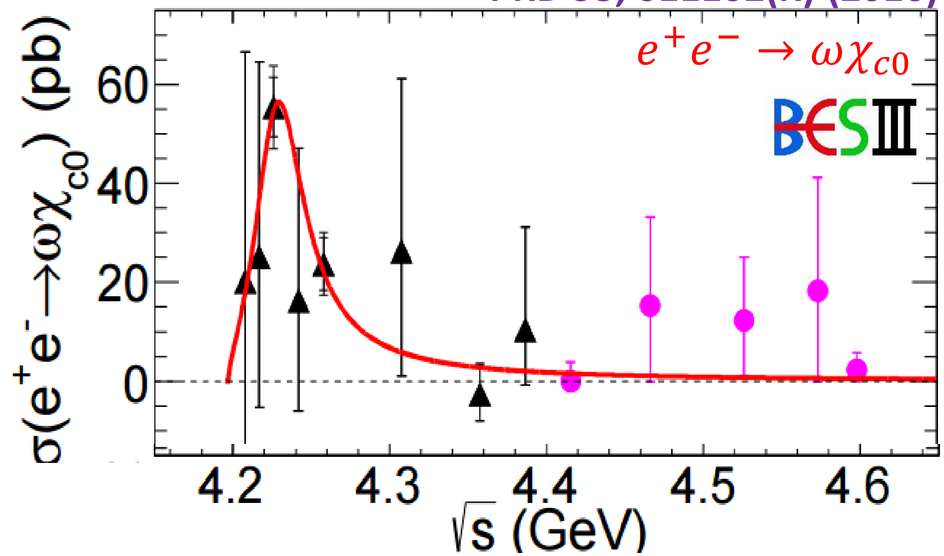
The error are statistical only.

More precise measurements are helpful !
"Y(4260)" in different channels?

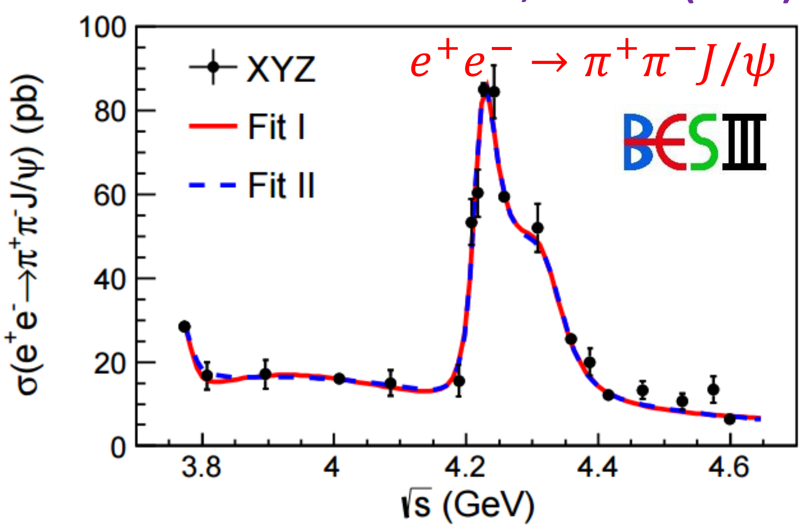
PRL 118, 092002 (2017)

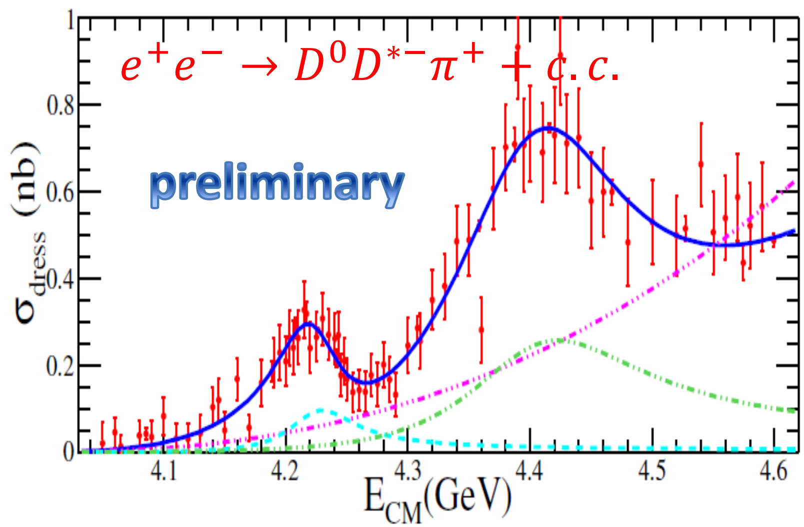


PRD 93, 011102(R) (2016)



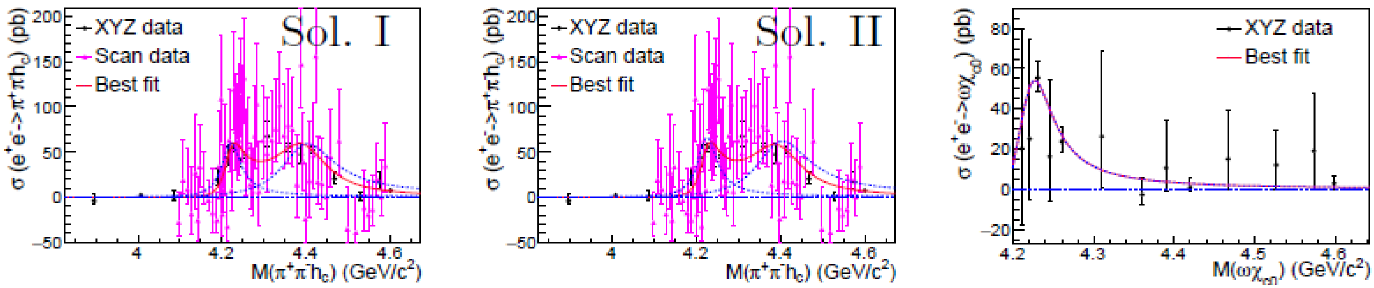
PRL118, 092001 (2017)



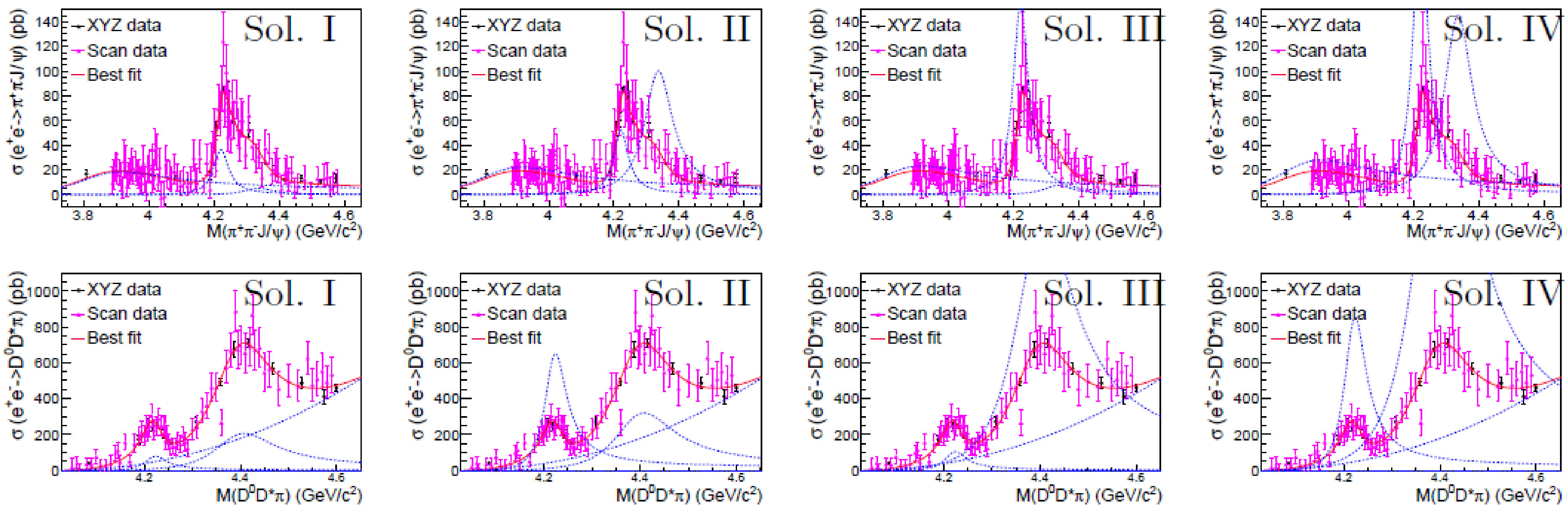


All above four channels show a structure at around 4.22 GeV/c^2.

Combined fit to understand the Y(4220) better



PRD95,092007(2017)
X.Y.Gao, *C.P.Shen, C.Z.Yuan



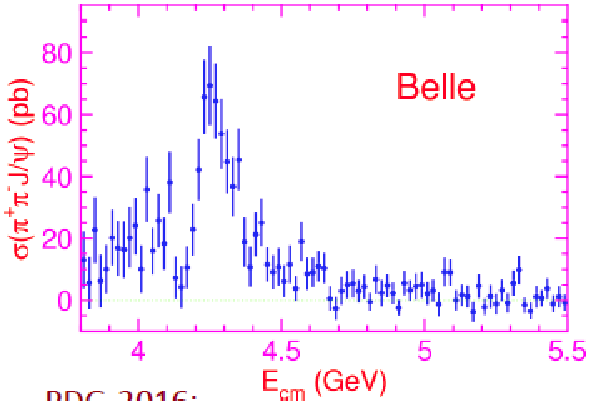
$M = 4219.6 \pm 3.3(\mathrm{stat}) \pm 5.1(\mathrm{sys})\ \mathrm{MeV}/c^2$

$\Gamma = 56.0 \pm 3.6(\mathrm{stat}) \pm 6.9(\mathrm{sys})\ \mathrm{MeV}$

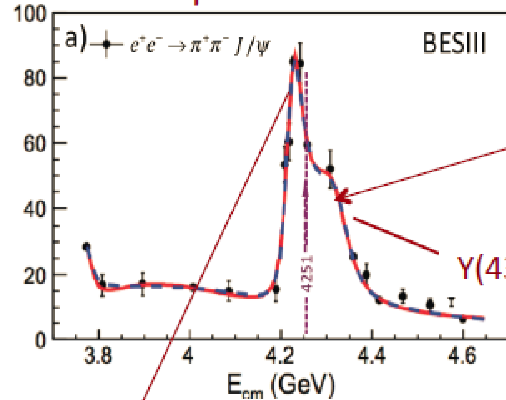
A combined fit is performed to extract the resonant parameters of the Y(4220) assuming it decays dominantly to the above four modes and their isospin symmetric modes

Y(4260): mass → lower & width → narrower

pre-2017

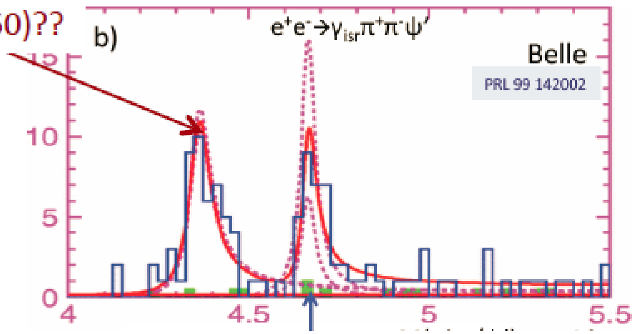


post-2017



what is the 2[nd] peak?

Y(4360)??



PDG-2016:

$M(Y(4260)) = 4251 \pm 9\ \mathrm{MeV}/c^2 \xrightarrow{-31\ \mathrm{MeV}} M_1 = 4220 \pm 4\ \mathrm{MeV}/c^2$

$\Gamma(Y(4260)) = 120 \pm 12\ \mathrm{MeV}. \xrightarrow{\times 1/3} \Gamma_1 = 44 \pm 5\ \mathrm{MeV}$

Y(4220) decay modes:

- $\pi^+\pi^- J/\psi$
  - $\pi Z_c(3900)$
  - $f_0(980)\, J/\psi$
- $\pi^+\pi^- h_c$
- $\omega\chi_{c0}$
- $\eta J/\psi$
- $\gamma X(3872)$
- $\pi D\bar{D}^*$

$M_2 = 4320 \pm 13\ \mathrm{MeV}/c^2 \xrightarrow{\delta M \approx -1.8\sigma} M(Y(4360)) = 4346 \pm 6\ \mathrm{MeV}/c^2$

$\Gamma_2 = 101^{+27}_{-22}\ \mathrm{MeV} \xrightarrow[\text{spot on}]{} \Gamma(Y(4360)) = 102 \pm 12\ \mathrm{MeV}.$

Y(4320) decay modes:

- $\pi^+\pi^- J/\psi$
- $\pi^+\pi^- \psi'$

What is the Y(4260)?

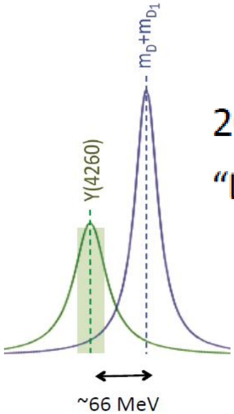
The Y(4260) mass is lower and width narrower than previously thought

"Y(4260)" → Y(4220)?

If it is a $D\bar{D}_1(2420)$ molecule:

B.E. ≈ 66 MeV ←too large??

"affinity" to $D\bar{D}_1(2420)$ should be high



2012 LQCD calc. (m_π≈400 MeV):

"Lowest 1^{--} $c\bar{c}$-gluon hybrid: M=4285 ± 14 MeV"

pre-2017: too high by ~35 MeV
post-2017: too high by ~65 MeV

Had. Spectr. Collab. JHEP07, 126

If it is a $c\bar{c}$-gluon hybrid:

its mass is ~65 MeV below current (m_π≈400 MeV) LQCD predictions ← not so bad?

"affinity" to $D\bar{D}_0(2400)$ should be high

If it is a QCD diquark–diantiquark tetraquark: Maiani et al. PRD89,114010

it should have Isospin- & $SU_F(3)$-multiplet partner states ← not seen

Dubynskiy & Voloshin, PLB 666, 344

If it is hadrocharmonium: Li & Voloshin, Mod. Phys. Lett. A29, 1450060

decays to non-J/ψ(h_c) charmonium states should be suppressed ← they aren't

BESIII is well suited to further investigate this intriguing puzzle ← a "Y(4260)" factory

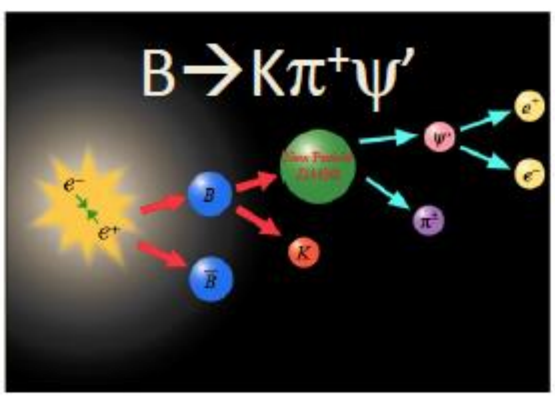
Z States

Zc(3900), Zc(4020), Zb(10610), Zb(10650), …

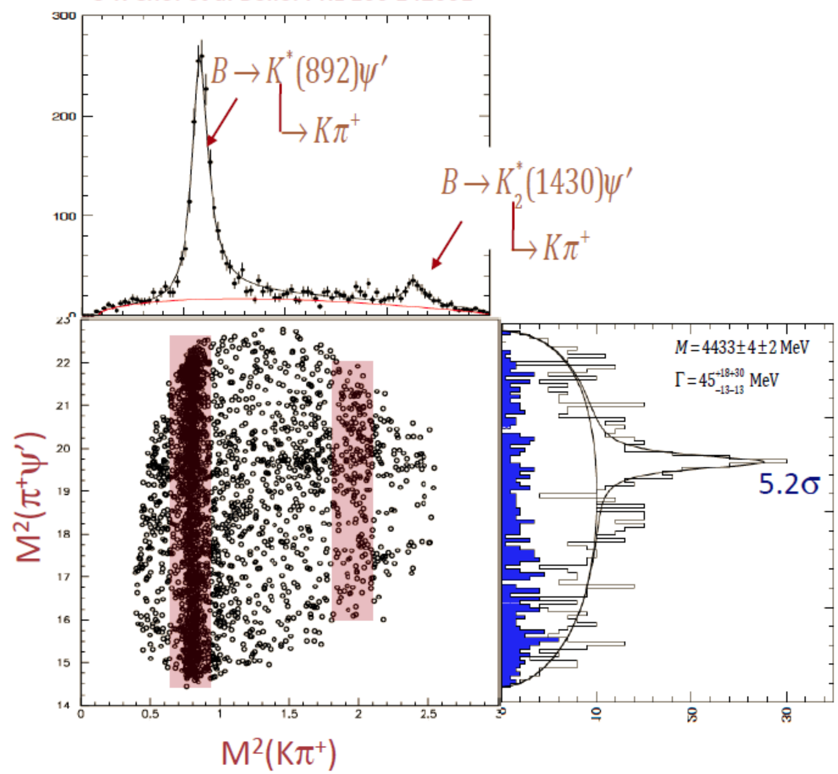
The Z(4430)$^+$ → π^+ ψ'

"smoking gun" evidence for a 4-quark meson

- decays to ψ' → must contain $c\bar{c}$ pair
- electrically charged → must contain $u\bar{d}$ pair

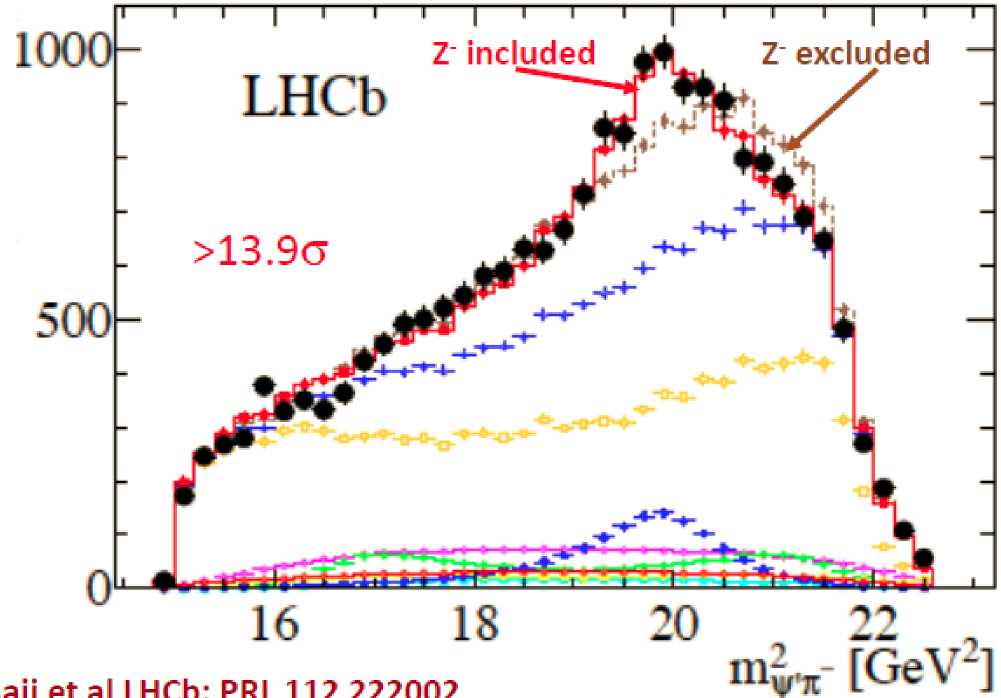


S-K Choi et al Belle: PRL 100 142001



LHCb 4-dim analysis of B→K$^+\pi^-\psi'$

B→K$^+\pi^-\psi'$ 4-dim amplitude analysis



R. Aaij et al LHCb: PRL 112 222002

$J^P = 1^+$

$M = 4475 \pm 7^{+15}_{-25}$ MeV

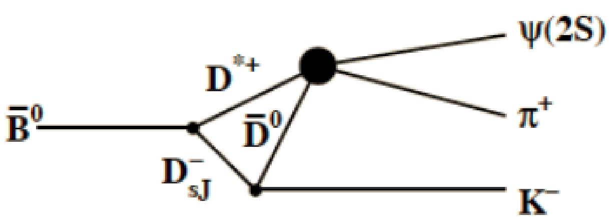
$\Gamma = 172 \pm 13^{+37}_{-34}$ MeV

Good agreement with Belle,
(with smaller errors)

$$Bf(B^0 \to Z(4430)^- K^+) \times Bf(Z(4430)^- \to \pi^- \psi') \approx (3.4^{-1.1}_{-2.3}) \times 10^{-5}$$

What is the Z(4430)?

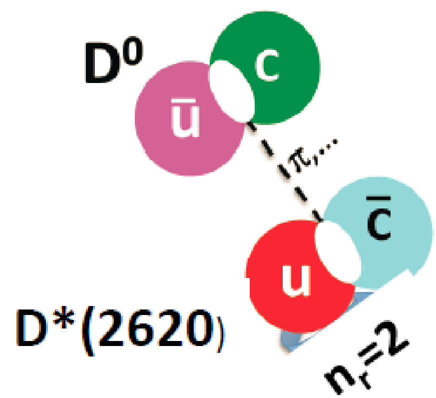
Kinematic effect due to $D^*\bar{D}$ rescattering?



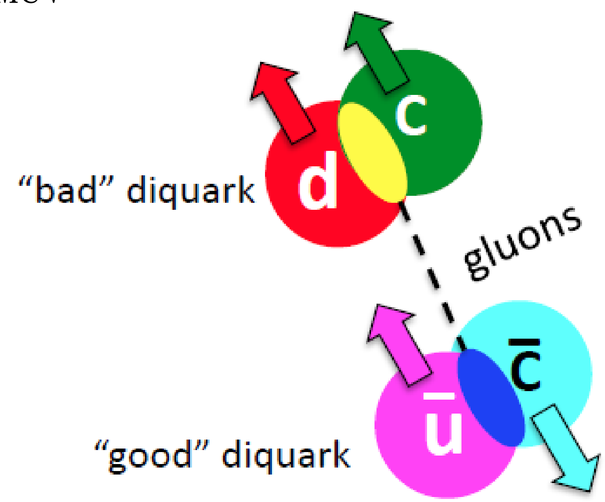
Pakhlov &Uglov, PLB 183 (2015)

$D^*(2S)\bar{D}$ molecule?

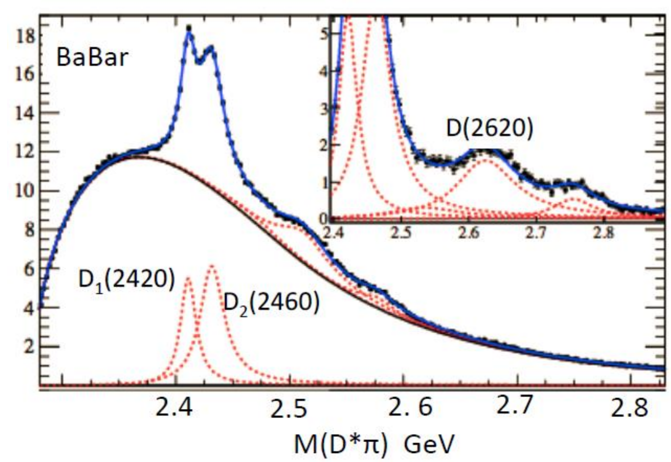
Bingding energy=20$\pm$30 MeV



tetraquark formed with a radially excited diquark

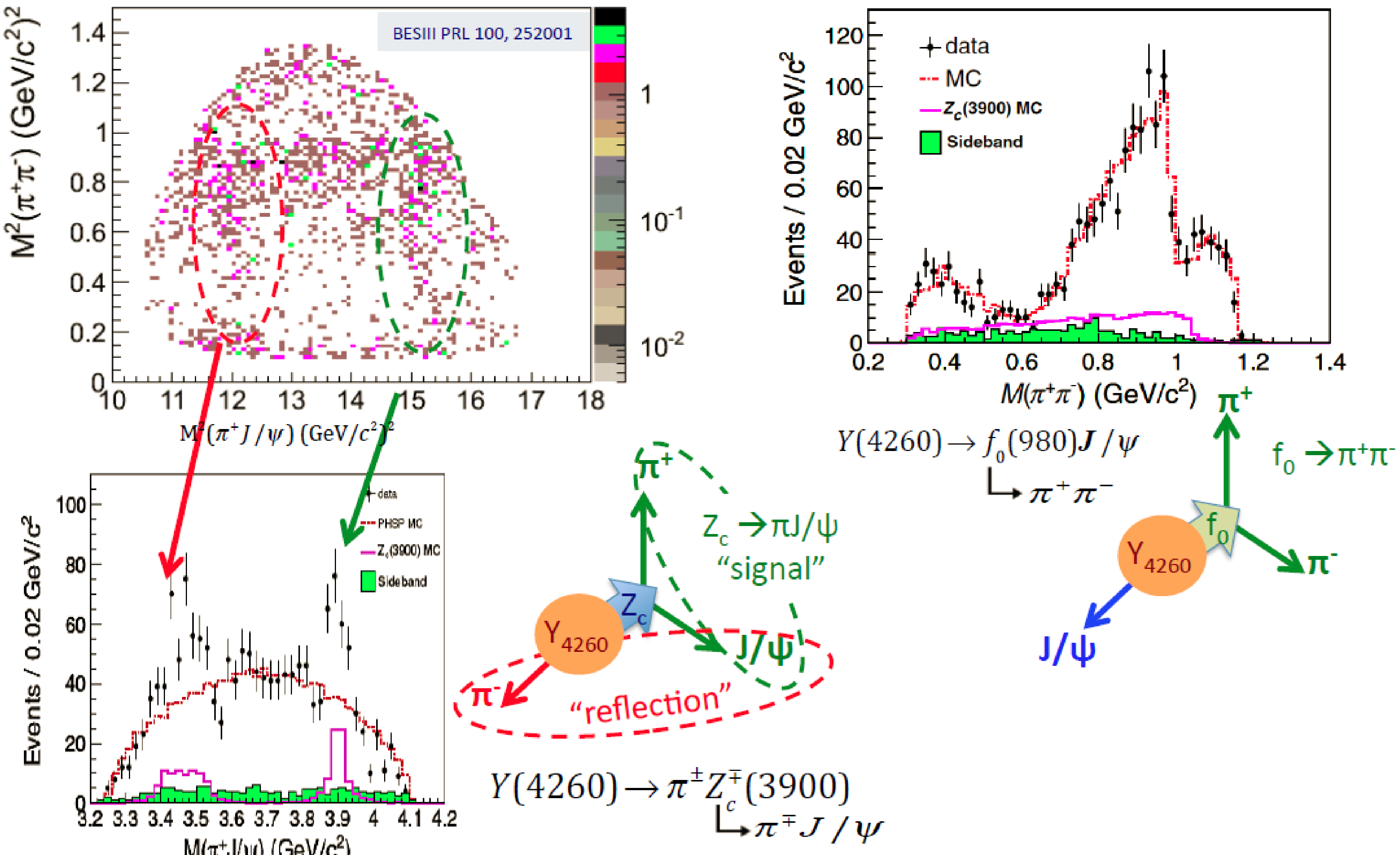


BaBar: Phys. Rev. D82, 111101



one of the diquarks is is in an n_r=2, radially excited state.

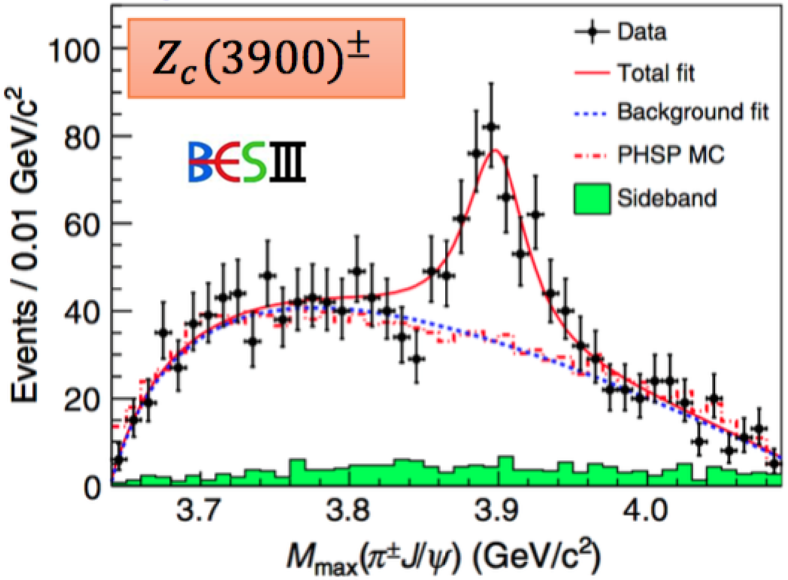
$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ “Dalitz plot”



$Z_c(3900)$ State

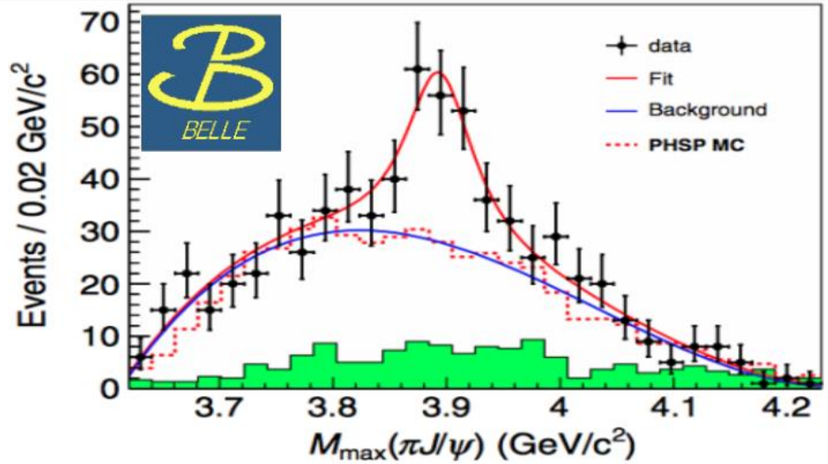
Observed in $e^+e^- \rightarrow (\gamma)Y(4260) \rightarrow J/\psi\pi^+\pi^-$

Phys. Rev. Lett 110, 252001 (2013)

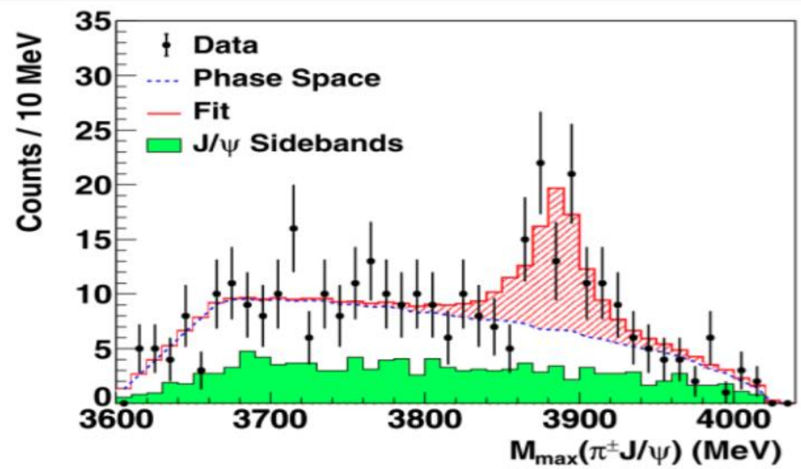


- Charged charmonium-like structure (>10 σ)
- Decay to J/ψ ($c\bar{c}$) and electric charge ($u\bar{d}$ or $d\bar{u}$)
- $M = 3899.0 \pm 3.6 \pm 4.9$ MeV/c^2, $\Gamma = 46 \pm 10 \pm 20$ MeV
- $\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi) = 62.9 \pm 1.9 \pm 3.7$ pb at 4.26 GeV
- $\dfrac{\sigma(e^+e^- \rightarrow \pi^{\mp} Z_c(3900)^{\pm} \rightarrow \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi)} = 21.5 \pm 3.3 \pm 7.5$ %
- The first Z_c state observed by more than one experiment (Belle and CLEO-c)!

Belle with ISR data (PRL 110, 252002)

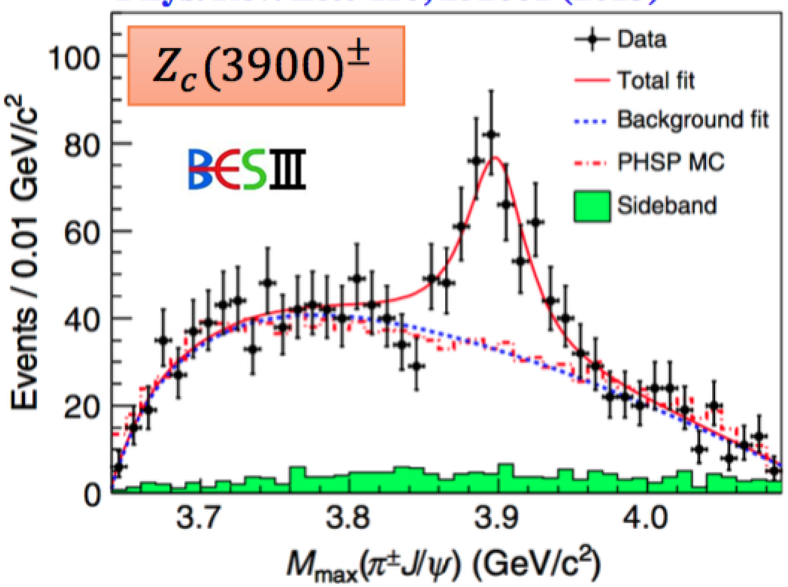


CLEOc data at 4.17 GeV (PLB 727, 366)



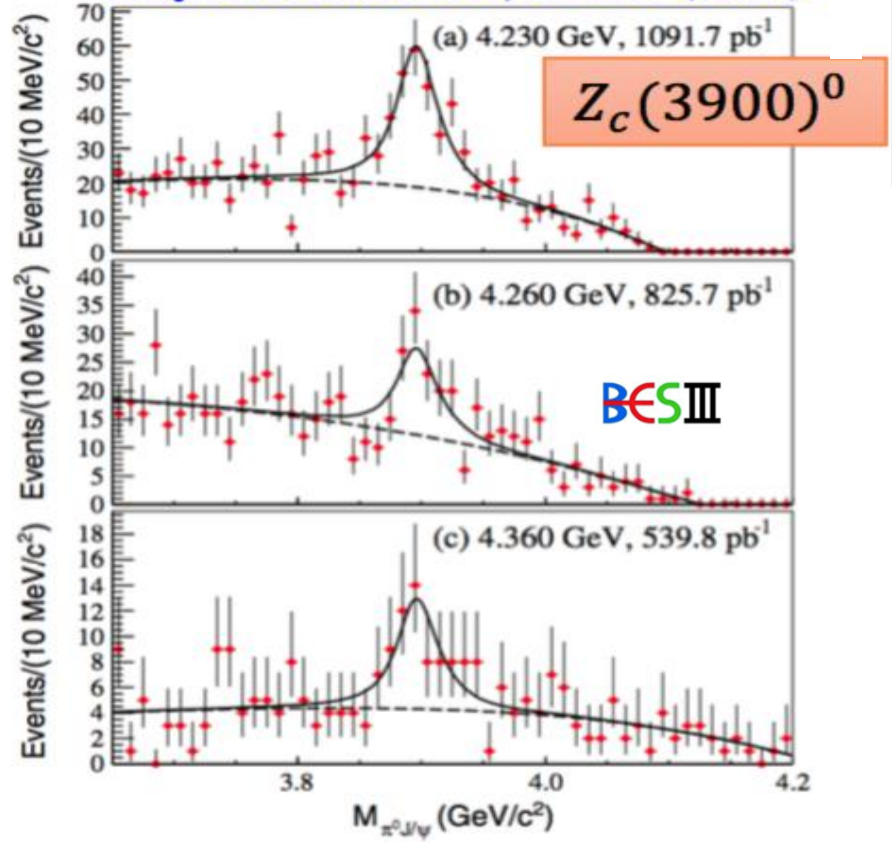
$Z_c(3900)$ State

Phys. Rev. Lett 110, 252001 (2013)



- Charged charmonium-like structure (>10 σ)
- Decay to J/ψ ($c\bar{c}$) and electric charge ($u\bar{d}$ or $d\bar{u}$)
- $M = 3899.0 \pm 3.6 \pm 4.9$ MeV/c², $\Gamma = 46 \pm 10 \pm 20$ MeV
- $\sigma(e^+e^- \to \pi^+\pi^- J/\psi) = 62.9 \pm 1.9 \pm 3.7$ pb at 4.26 GeV
- $\dfrac{\sigma(e^+e^- \to \pi^{\mp} Z_c(3900)^{\pm} \to \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} = 21.5 \pm 3.3 \pm 7.5$ %
- The first Z_c state observed by more than one experiment (Belle and CLEO-c)!

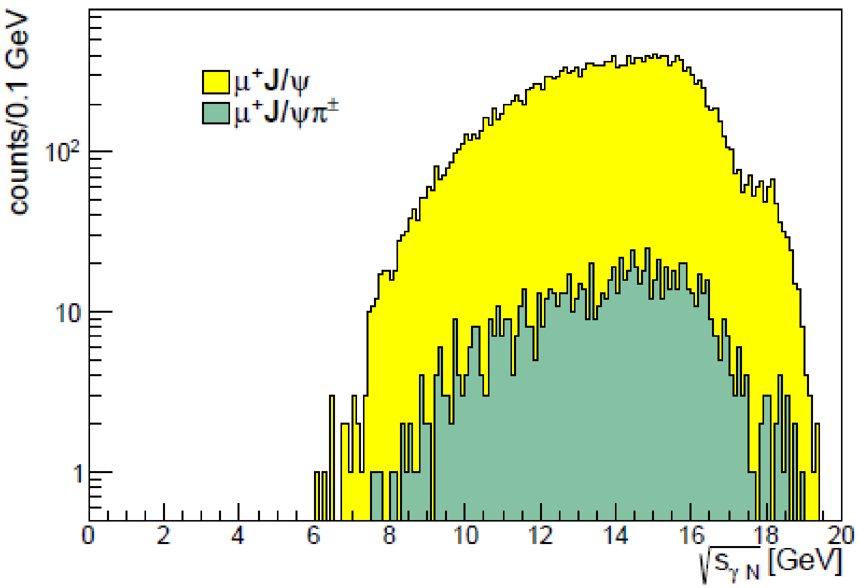
Phys. Rev. Lett 115, 112003 (2015)

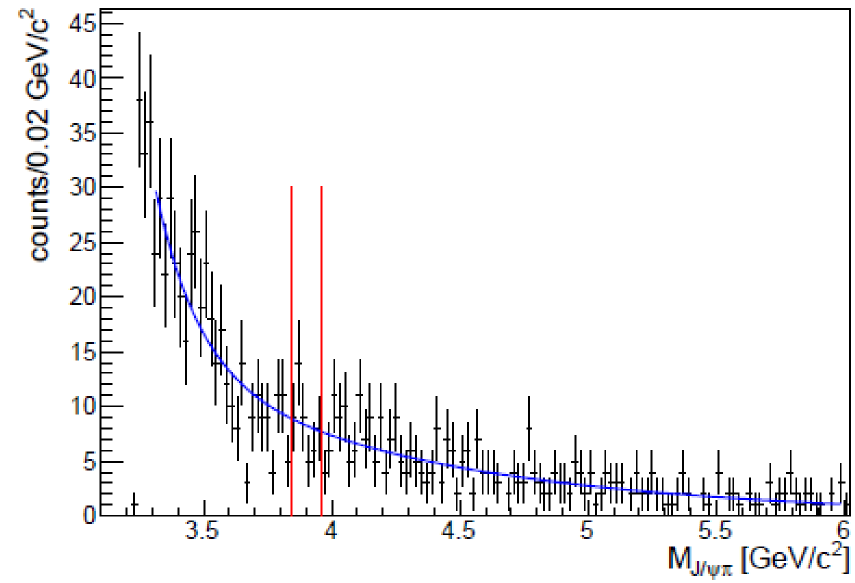


- Neutral charmonium-like structure (10.4 σ)
- Using 3 data samples (~2.5 fb⁻¹)
- Evidence with 3.7σ by using CLEO-c data
- $M = 3894.8 \pm 2.3 \pm 3.2$ MeV/c², $\Gamma = 29.6 \pm 8.2 \pm 8.2$ MeV
- An iso-spin triplet is established!

Search for exclusive photoproduction of $Z_c^{\pm}(3900)$ at COMPASS

PLB742, 330 (2015)

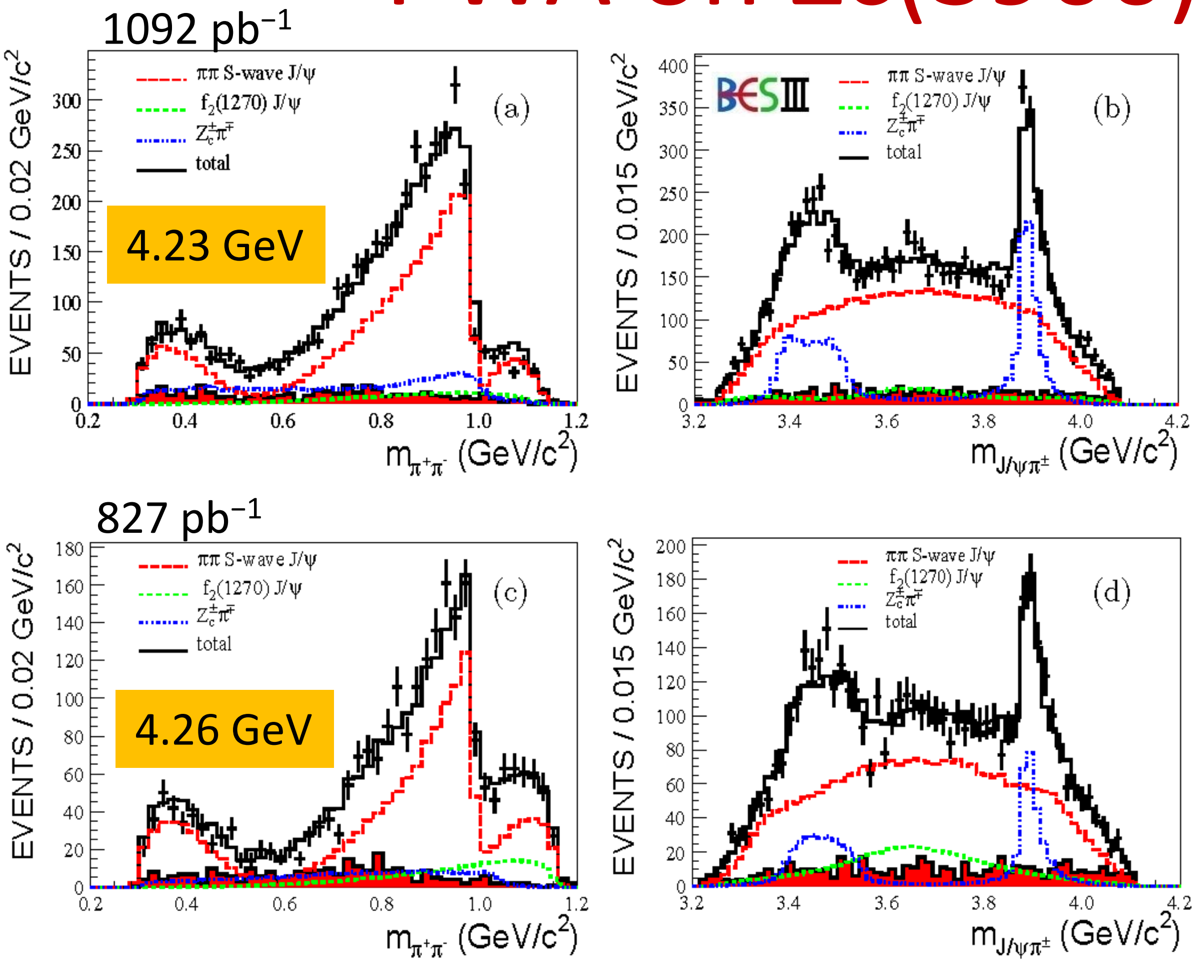




$$BR(Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}) \times \sigma_{\gamma\ N \to Z_c^{\pm}(3900)\ N}\Big|_{\langle\sqrt{s_{\gamma N}}\rangle = 13.8\ \mathrm{GeV}} < 52\ \mathrm{pb}.$$

Assuming $\Gamma_{\mathrm{tot}} = 46\ \mathrm{MeV}/c^2$, we obtain an upper limit $\Gamma_{J/\psi\pi} < 2.4\ \mathrm{MeV/c}^2$.

PWA on Zc(3900) state



PRL**119**, 072001 (2017)

- Amplitude analysis with helicity formalism
- Zc line shape parameterized with Flatte-like formula
- $\pi^+\pi^-$ spectrum is described by σ, $f_0(980)$, $f_2(1270)$ and $f_0(1370)$
- J^P of Zc favors 1^+ with Significance larger than 7.3σ over other quantum numbers

Born cross sections: σ ($e^+e^- \to \pi^+ Zc^-$ + c.c.)=(21.8 ±1.0± 4.4) pb @4.23 GeV

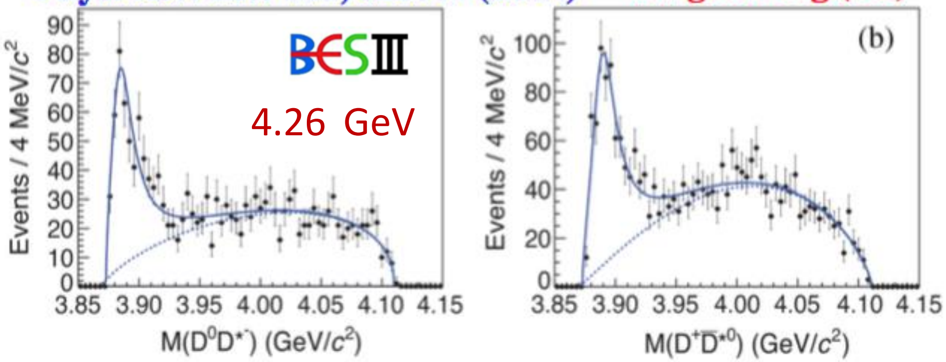
(11.0 ±1.2± 5.4) pb @4.26 GeV.

No significant Zc(4020) signals; σ ($e^+e^- \to \pi^+ Zc(4020)^-$ + c.c.)<0.9 pb @4.23 GeV

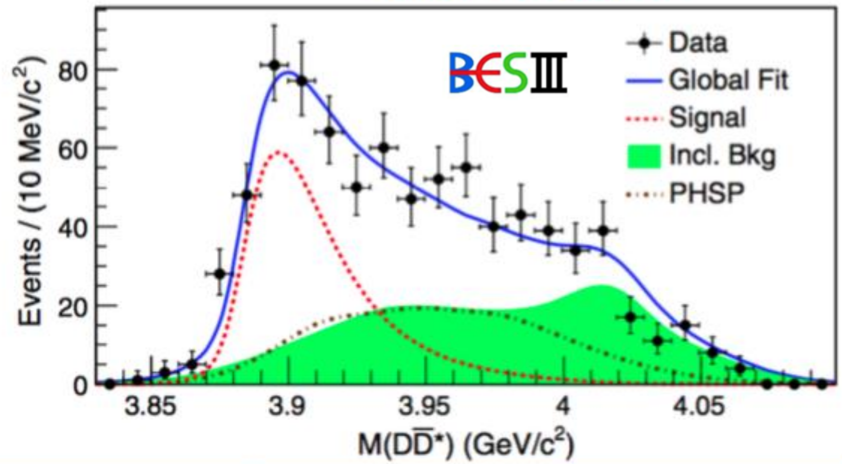
< 1.4 pb@4.26 GeV

$Z_c(3900)$ State

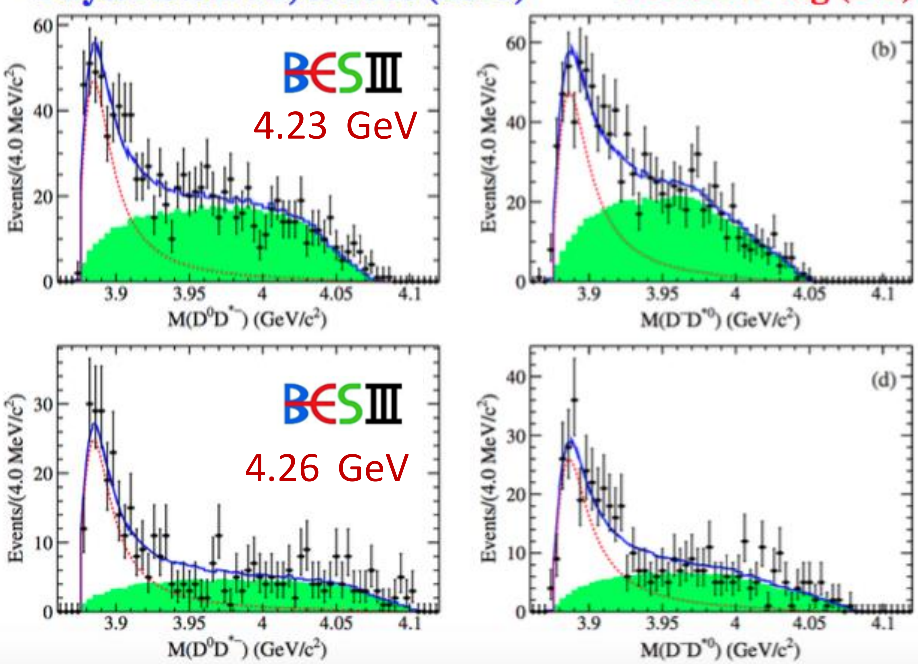
Phys. Rev. Lett 112, 022001 (2014) Single D tag (ST)



Double D tag (DT)



Phys. Rev. D 92, 092006 (2015) Double D tag (DT)

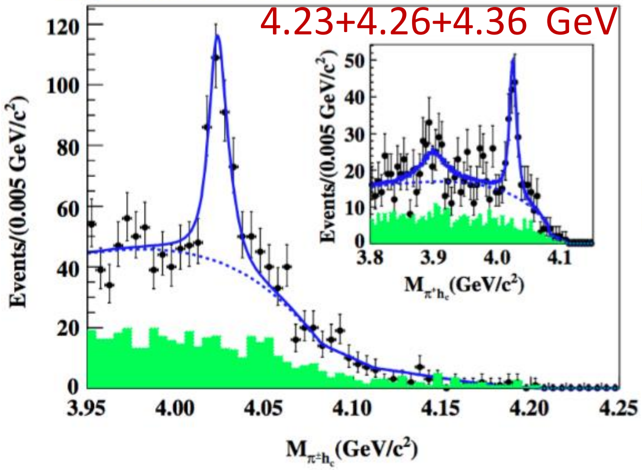


State	Mass (MeV/c²)	Width (MeV)
$Z_c(3885)^{\pm}$ (ST)	$3883.9 \pm 1.5 \pm 4.2$	$24.8 \pm 3.3 \pm 11.0$
$Z_c(3885)^{\pm}$ (DT)	$3881.7 \pm 1.6 \pm 1.6$	$26.6 \pm 2.0 \pm 2.1$
Weighted average	$3882.2 \pm 1.1 \pm 1.5$	$26.5 \pm 1.7 \pm 2.1$
$Z_c(3885)^0$ (DT)	$3885.7^{+4.3}_{-5.7} \pm 8.4$	$35^{+11}_{-12} \pm 15$

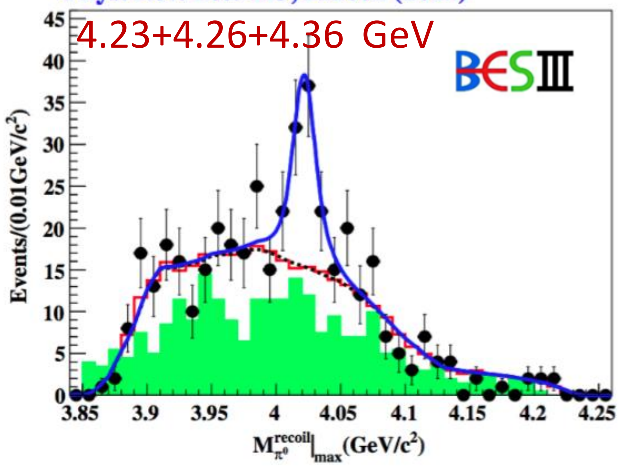
- Good agreement between ST and DT method
- Good agreement between charged state and neutral state
- Another iso-spin triplet is established!
- $Z_c(3885) = Z_c(3900)$?
- Tetraquark? Molecule state?

$Z_c(4020)$ & $Z_c(4025)$ States

Phys. Rev. Lett 111, 242001 (2013)



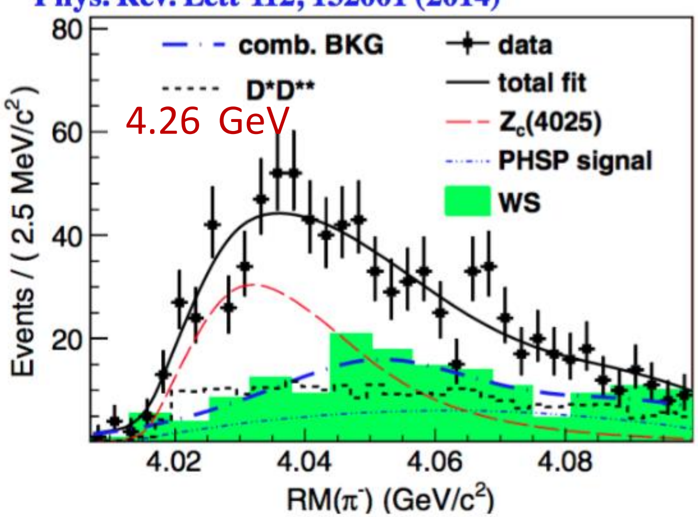
Phys. Rev. Lett 113, 212002 (2014)



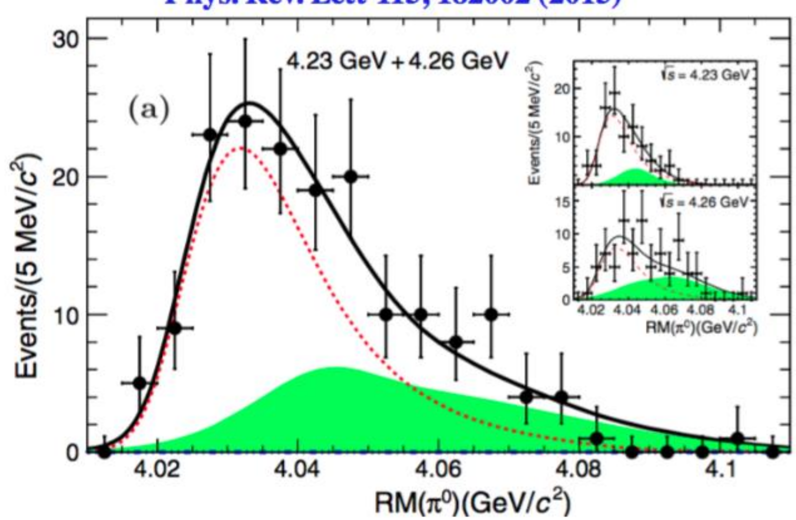
- ➢$Z_c(4020)^{\pm/0}$ observed
- ➢Another iso-spin triplet is established!
- ➢No significant $Z_c(3900)^{\pm} \rightarrow \pi^{\pm}h_c$ is observed

State	Mass (MeV/c²)	Width (MeV)
$Z_c(4020)^{\pm}$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$
$Z_c(4020)^0$	$4023.9 \pm 2.2 \pm 3.8$	7.9 (fixed)

Phys. Rev. Lett 112, 132001 (2014)



Phys. Rev. Lett 115, 182002 (2015)

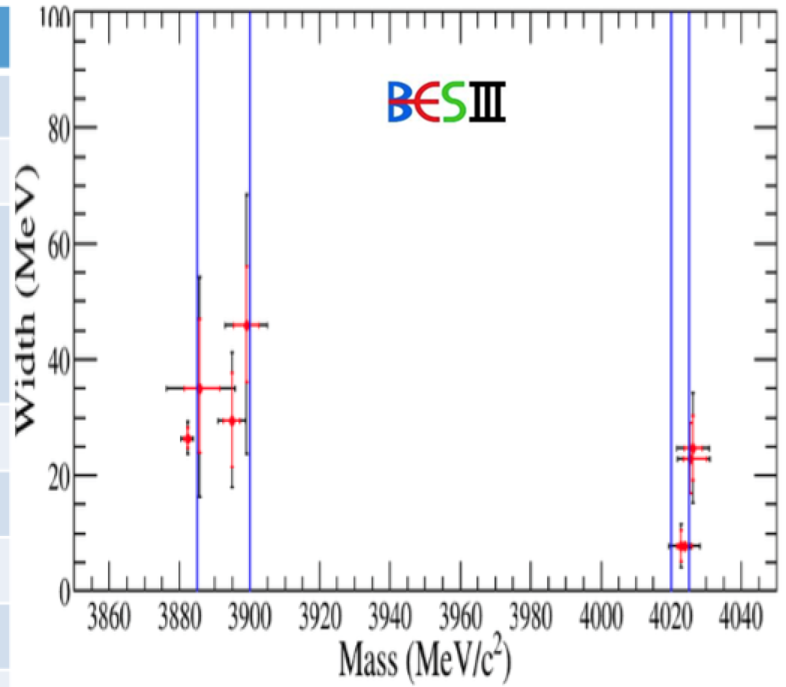


- ➢$Z_c(4025)^{\pm/0}$ observed
- ➢Another iso-spin triplet is established!

State	Mass (MeV/c²)	Width (MeV)
$Z_c(4025)^{\pm}$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$
$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7} \pm 3.1$	$23.0 \pm 6.0 \pm 1.0$

Summary on Z_c States by BESIII

State	Mass (MeV/c²)	Width (MeV)	Process
$Z_c(3900)^{\pm}$	3899.0±3.6±4.9	46±10±20	$e^+e^- \to \pi^+\pi^- J/\psi$
$Z_c(3900)^0$	3894.8±2.3±3.2	29.6±8.2±8.2	$e^+e^- \to \pi^0\pi^0 J/\psi$
$Z_c(3885)^{\pm}$ (ST)	3883.9±1.5±4.2	24.8±3.3±11.0	$e^+e^- \to \pi^{\mp}(D\bar{D}^*)^{\pm}$
$Z_c(3885)^{\pm}$ (DT)	3881.7±1.6±1.6	26.6±2.0±2.1	
Weighted average	3882.2±1.1±1.5	26.5±1.7±2.1	
$Z_c(3885)^0$ (DT)	$3885.7^{+4.3}_{-5.7}\pm 8.4$	$35^{+11}_{-12}\pm 15$	$e^+e^- \to \pi^0(D\bar{D}^*)^0$
$Z_c(4020)^{\pm}$	4022.9±0.8±2.7	7.9±2.7±2.6	$e^+e^- \to \pi^+\pi^- h_c$
$Z_c(4020)^0$	4023.9±2.2±3.8	7.9 (fixed)	$e^+e^- \to \pi^0\pi^0 h_c$
$Z_c(4025)^{\pm}$	4026.3±2.6±3.7	24.8±5.6±7.7	$e^+e^- \to \pi^{\mp}(D^*\bar{D}^*)^{\pm}$
$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7}\pm 3.1$	23.0±6.0±1.0	$e^+e^- \to \pi^0(D^*\bar{D}^*)^0$

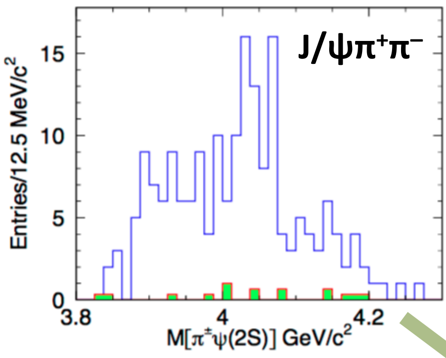


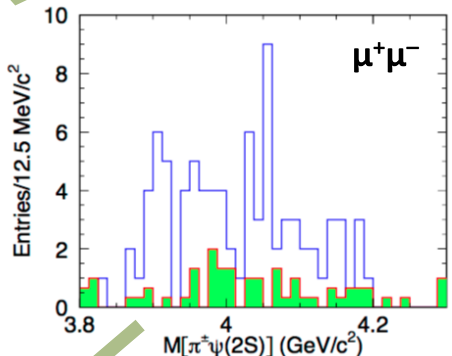
- $Z_c(3885)^{\pm}$ mass is about 2.6σ lower and the width 1.5σ lower than $Z_c(3900)^{\pm}$ value. If $Z_c(3885) = Z_c(3900)$, $\frac{\Gamma(Z_c(3885)^{\pm}\to (D\bar{D}^*)^{\pm})}{\Gamma(Z_c(3900)^{\pm}\to\pi^{\pm}J/\psi)} = 6.2\pm1.1\pm2.7$, coupling to $D\bar{D}^*$ is larger than to $\pi J/\psi$;
- $Z_c(4020)^{\pm}$ and $Z_c(4025)^{\pm}$ mass and width are consistent within 1.5σ. If $Z_c(4020) = Z_c(4025)$, $\frac{\Gamma(Z_c(4025)^{\pm}\to (D^*\bar{D}^*)^{\pm})}{\Gamma(Z_c(4020)^{\pm}\to\pi^{\pm}h_c)} = 12\pm5$, coupling to $D^*\bar{D}^*$ is larger than to πh_c.

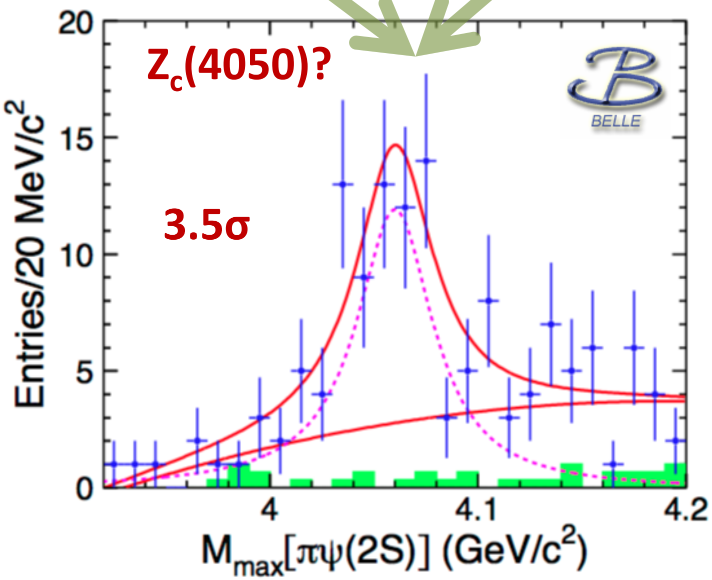
$Z_c(4050)$ at Belle

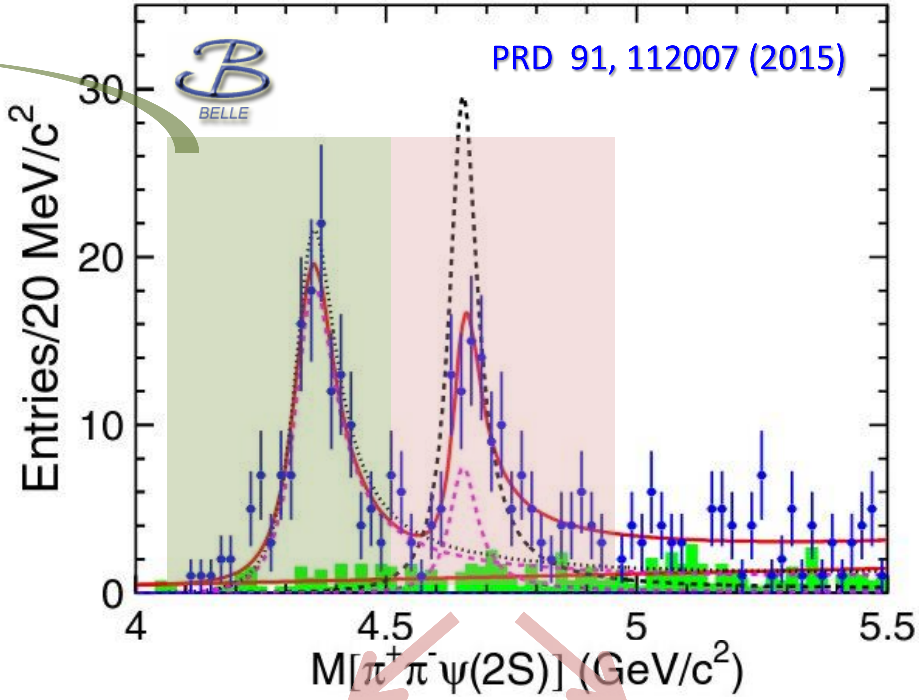
Observed by Belle in ISR

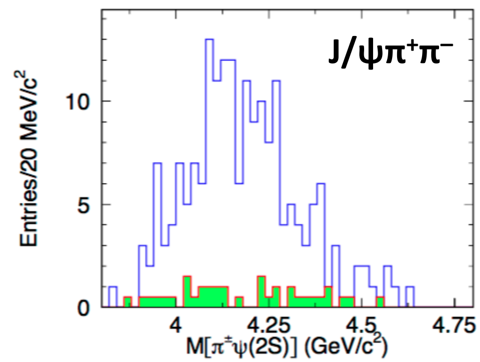
$e^+e^- \rightarrow Y(4360) \rightarrow \psi(2S)\pi^+\pi^-$

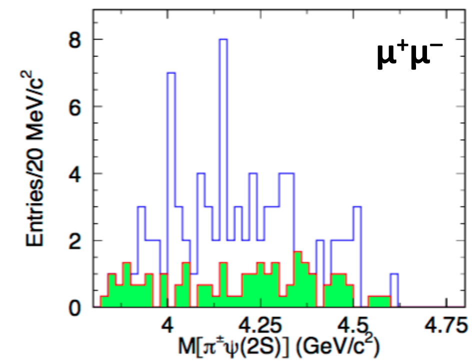










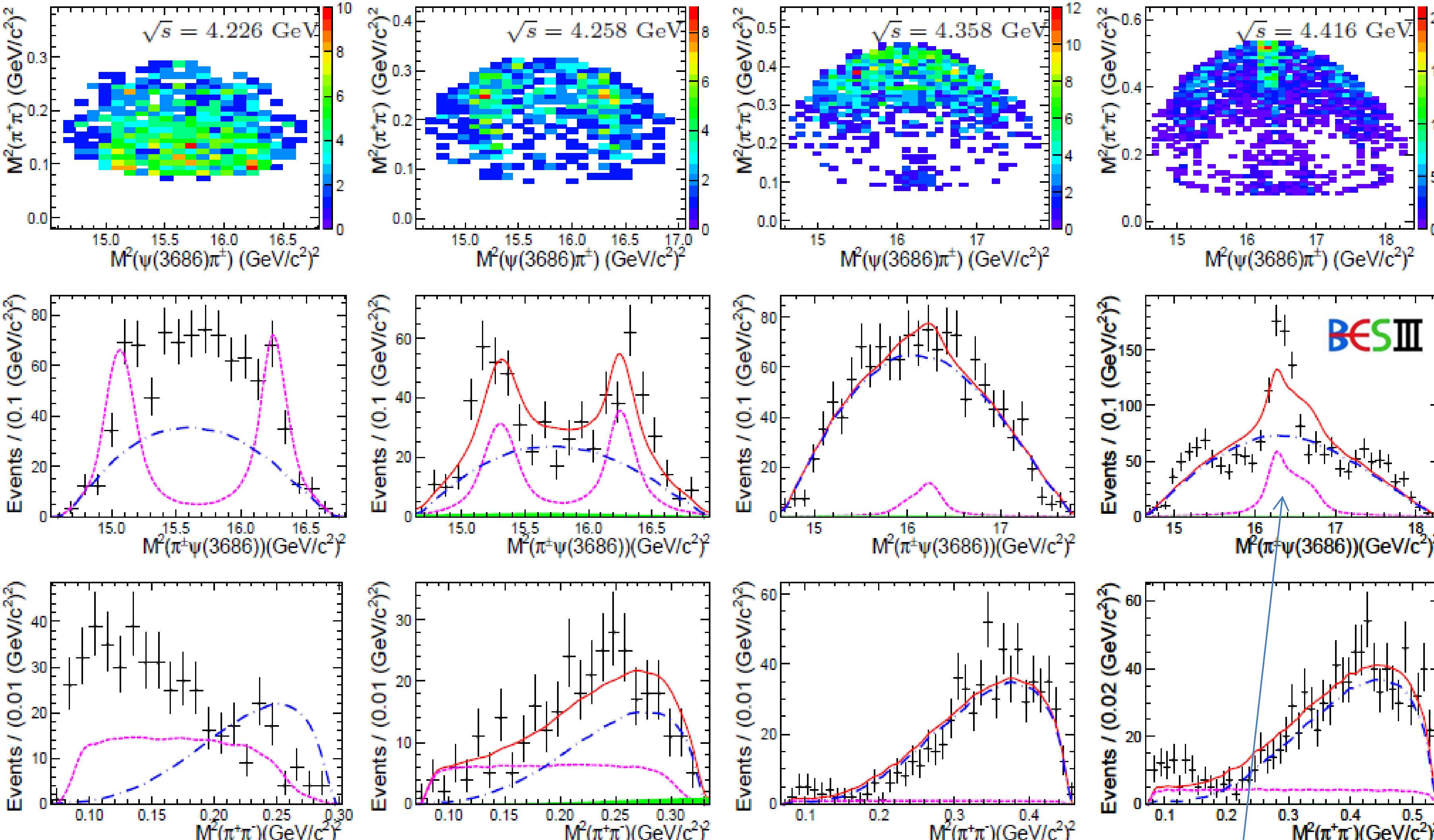


No clear signal found in the Y(4660) region

$M = 4054 \pm 3 \pm 1$ MeV/c^2
$\Gamma \ = 45 \pm 11 \pm 6$ MeV

Another Z_c state? Need confirmation

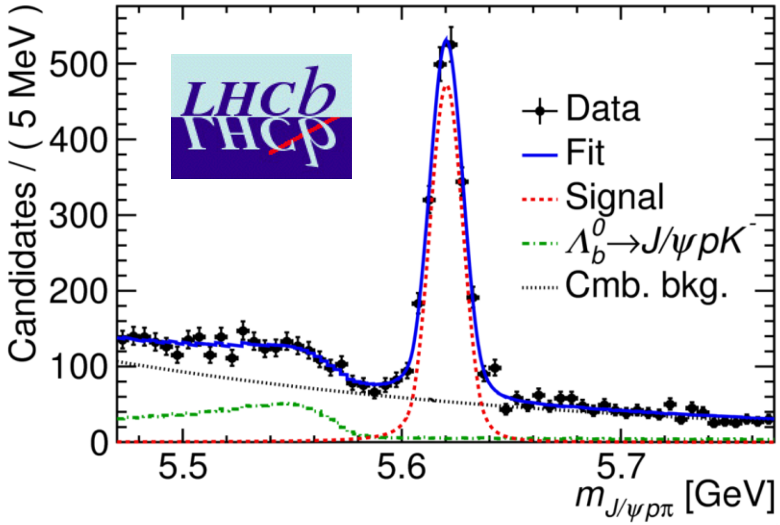
Search for $Z_c \rightarrow \pi\psi(2S)$ at BESIII



Not like π J/ψ, the structures in π ψ(2S) vs. Ecm are much more complicated !

- **M = (4032.1 ± 2.4) MeV/c^2**
- **Γ = (26.1 ± 5.3) MeV**

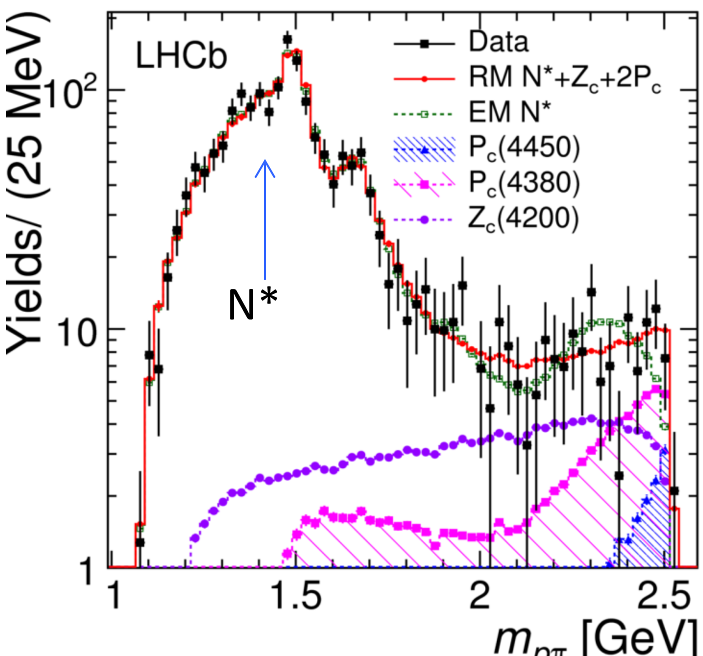
$Z_c^{\pm}(4200)$ in $\Lambda^0_b \to J/\psi p \pi^-$ at LHCb



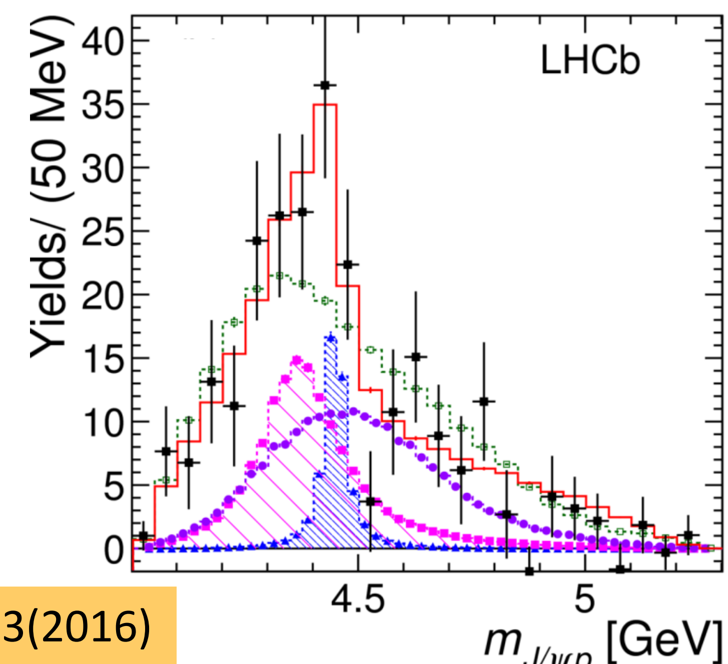
Cabibbo suppressed mode (less statistics)

Can be exotic Z contributions in J/ψ p

Fit with 2 pentaquarks + $Z_c(4200)$ favoured by 3σ compared to no exotic contributions

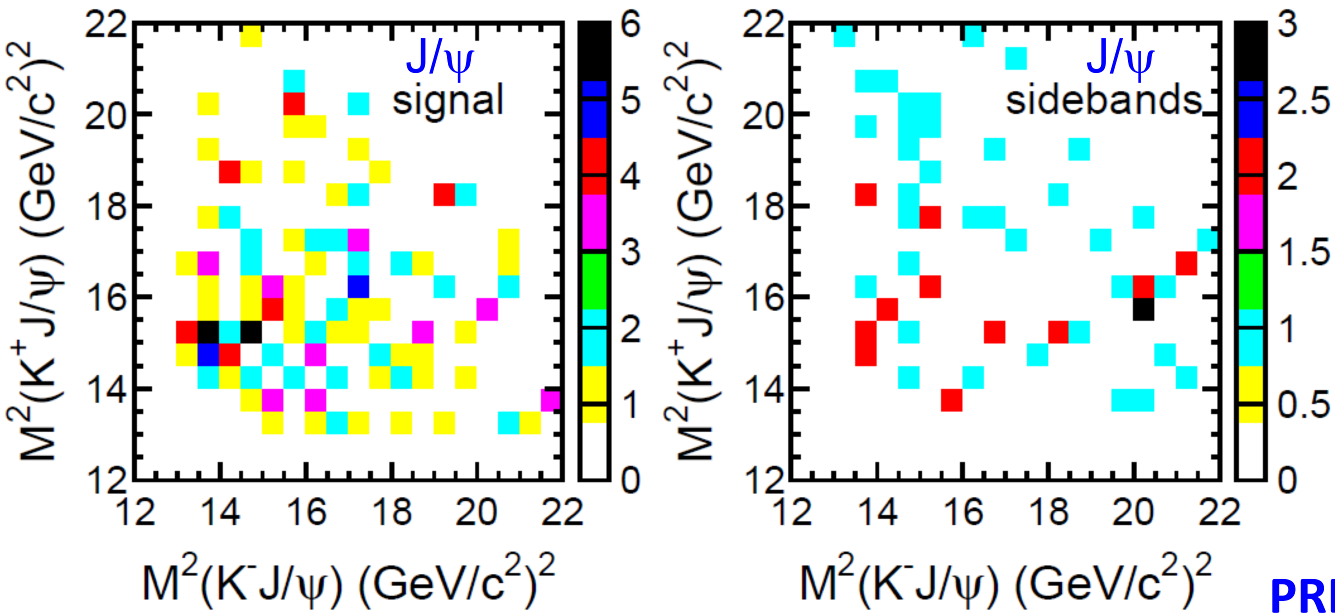


$m_{p\pi} > 1.8\,\mathrm{GeV}$

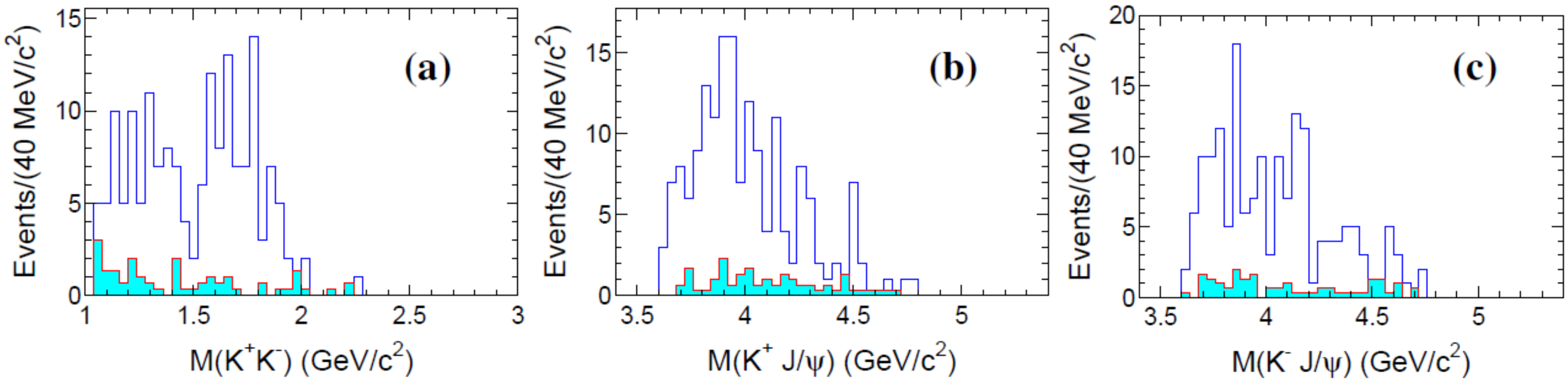


PRL 117, 082003(2016)

Search for Z_{cs} states at Belle



PRD 89,072015(2014)



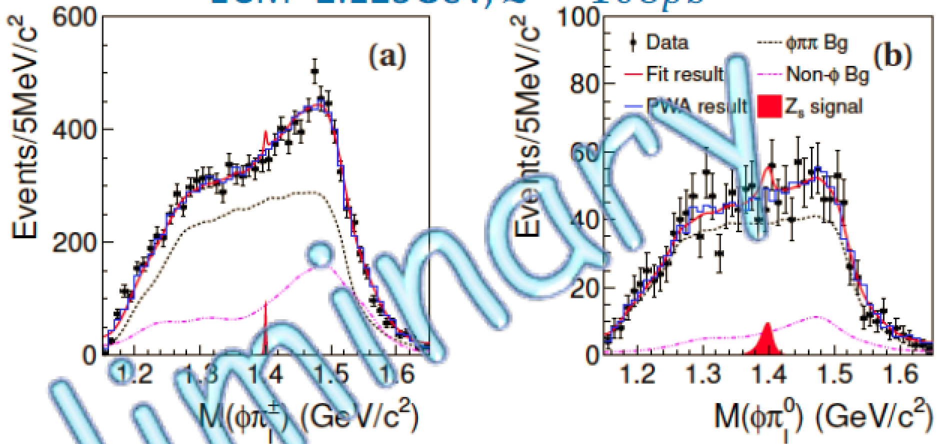
No evident structure in $K^{+-}J/\psi$ mass distribution under current statistics

Search for Z_s states at BESIII

- ISPE predicts two Z_s structrues near the $K^*\bar{K}$ (narrow width) and $K^*\bar{K}^*$ (broad width), respectively, in $\phi(2170) \to \phi\pi^+\pi^-$ decay.
- The ϕ paired with low-momentum π is expected to be sensitive to Z_s around 1.4 GeV/c^2.

ECM=2.125GeV, $\mathcal{L} = 108pb^{-1}$

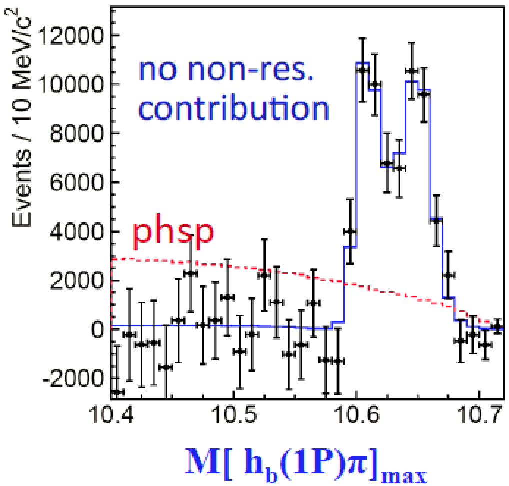
- PWA is applied on $\phi\pi\pi$ candidates, no Z_s observed.
- The upper limit of Z_s production is obtained with different width hypothesis.



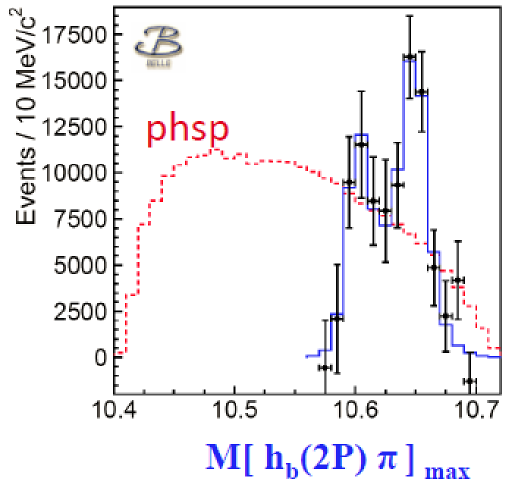
	Mass (GeV/c^2)	1.380			1.400			1.420		
	Width (MeV)	N^{UL}	ε(%)	$\sigma^{UL}_{Z_s}$(pb)	N^{UL}	ε(%)	$\sigma^{UL}_{Z_s}$(pb)	N^{UL}	ε(%)	$\sigma^{UL}_{Z_s}$(pb)
$\phi\pi^+\pi^-$	0	22.2	47.3	0.90	16.6	46.9	0.68	44.4	46.8	1.82
	5	37.8	47.5	1.53	29.8	46.9	1.22	54.6	47.2	2.22
	10	49.6	47.5	2.01	40.2	47.4	1.63	60.8	47.3	2.47
$\phi\pi^0\pi^0$	0	25.6	13.8	3.75	25.2	13.7	3.72	27.2	13.5	4.07
	5	28.0	13.8	4.10	28.6	13.7	4.22	30.2	13.5	4.52
	10	31.2	13.8	4.57	32.4	13.7	4.78	33.6	13.6	4.99

Resonant structure of $\Upsilon(5S) \rightarrow (b\bar{b})\pi^+\pi^-$

$\Upsilon(5S) \rightarrow h_b(1P)\pi^+\pi^-$



$\Upsilon(5S) \rightarrow h_b(2P)\pi^+\pi^-$



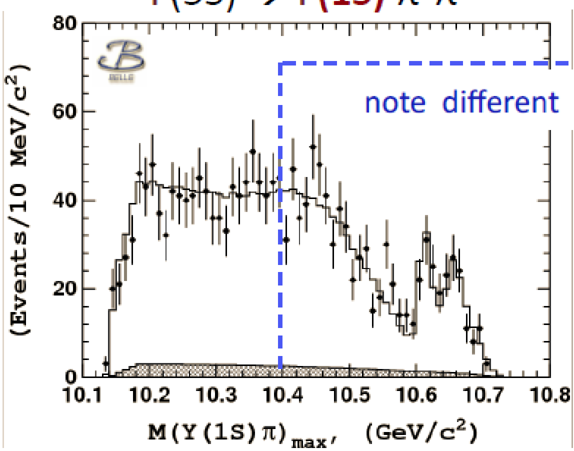
Two peaks are observed in all modes!

Belle: PRL108, 232001 (2012)

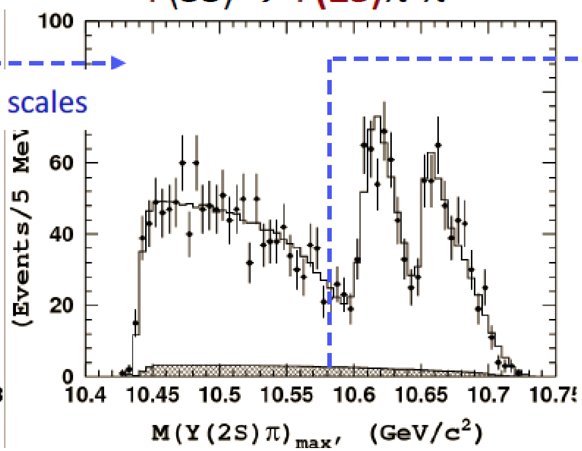
$Z_b(10610)$ and $Z_b(10650)$ should be multiquark states

Dalitz plot analysis

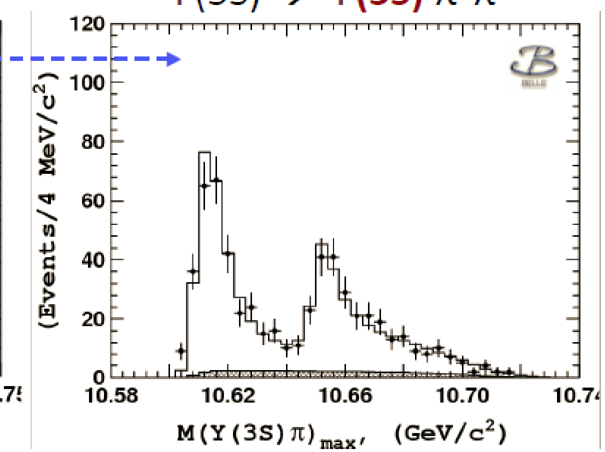
$\Upsilon(5S) \rightarrow \Upsilon(1S)\pi^+\pi^-$



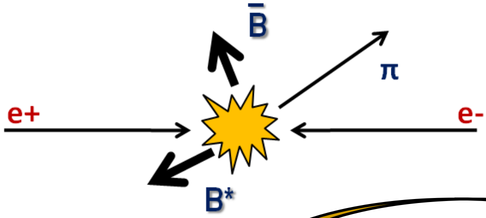
$\Upsilon(5S) \rightarrow \Upsilon(2S)\pi^+\pi^-$



$\Upsilon(5S) \rightarrow \Upsilon(3S)\pi^+\pi^-$

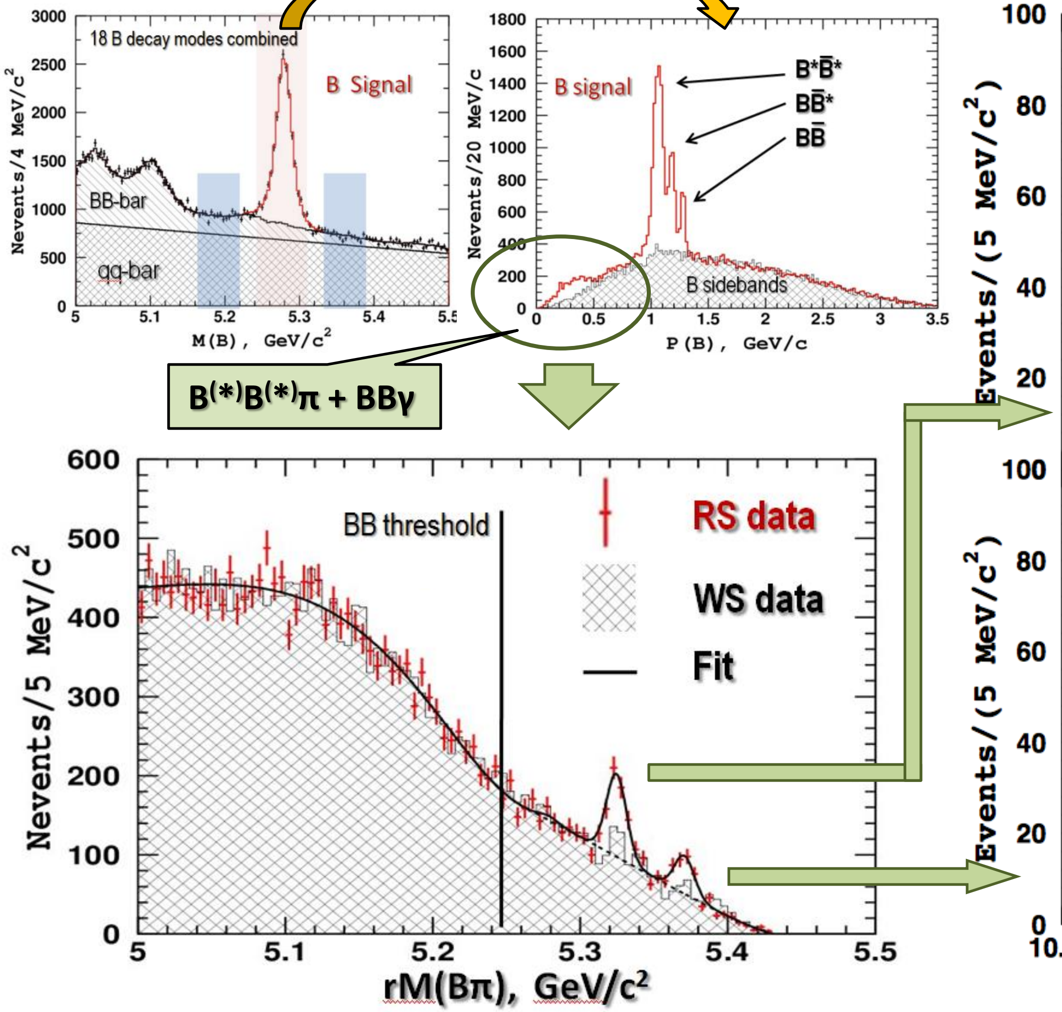


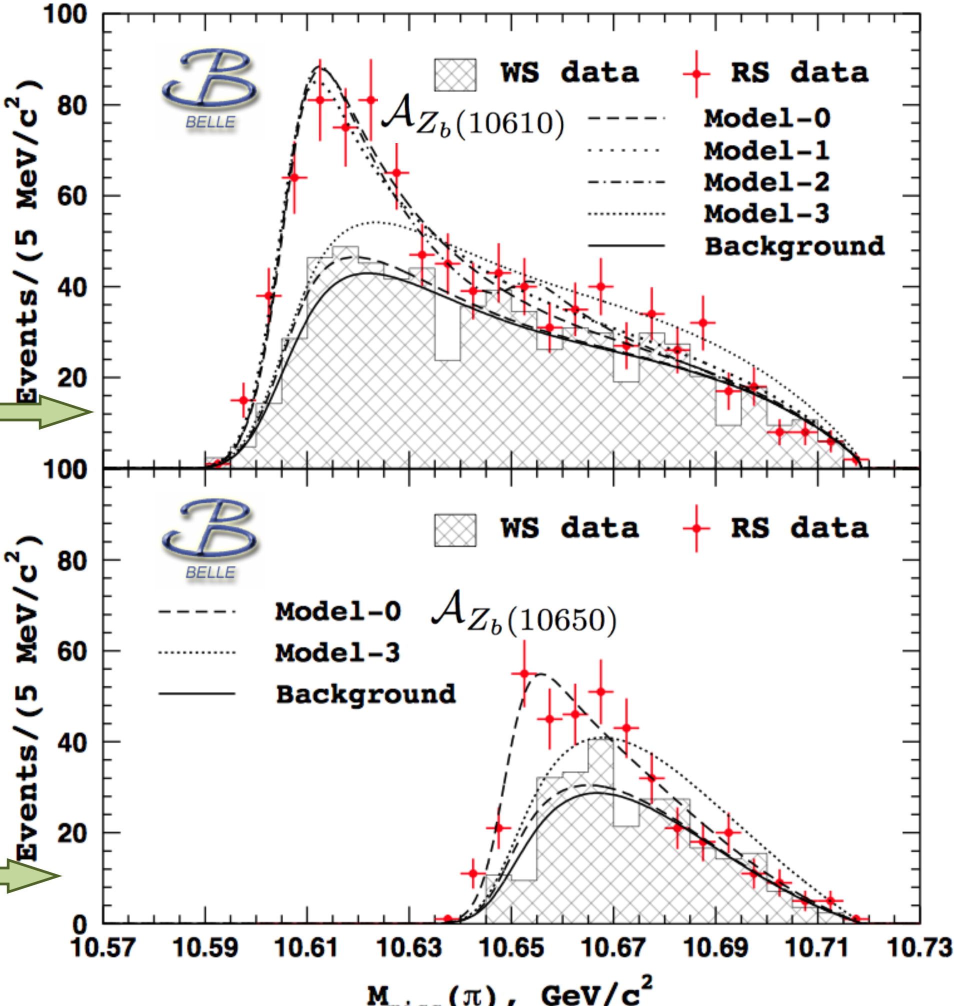
$Z_b^{\pm} \rightarrow$ Open Beauty



PRL116,212001(2016)

$$S(m) = |\mathcal{A}_{Z_b(10610)} + \mathcal{A}_{Z_b(10650)} + \mathcal{A}_{\rm nr}|^2$$



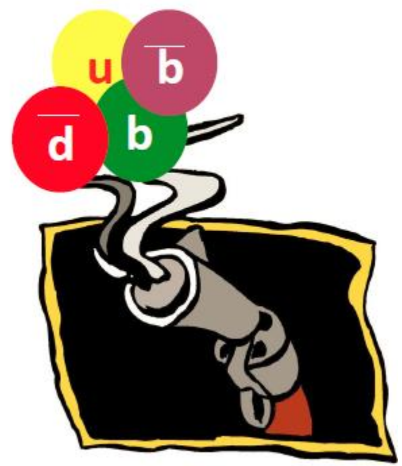


Summary on Z_b Decays by Belle

- decays to $\Upsilon(nS)$ & $h_b(nP)$ ➔ must contain $b\bar{b}$ pair
- electrically charged ➔ must contain $u\bar{d}$ pair

Assuming that Z_b decays are saturated by the $\Upsilon(nS)\pi$, $h_b(mP)\pi$ and $B^{(*)}B^*$ channels, one can calculate a table of relative branching fractions:

Channel	Fraction, % $Z_b(10610)$	Fraction, % $Z_b(10650)$
$\Upsilon(1S)\pi^+$	$0.60 \pm 0.17 \pm 0.07$	$0.17 \pm 0.06 \pm 0.02$
$\Upsilon(2S)\pi^+$	$4.05 \pm 0.81 \pm 0.58$	$1.38 \pm 0.45 \pm 0.21$
$\Upsilon(3S)\pi^+$	$2.40 \pm 0.58 \pm 0.36$	$1.62 \pm 0.50 \pm 0.24$
$h_b(1P)\pi^+$	$4.26 \pm 1.28 \pm 1.10$	$9.23 \pm 2.88 \pm 2.28$
$h_b(2P)\pi^+$	$6.08 \pm 2.15 \pm 1.63$	$17.0 \pm 3.74 \pm 4.1$
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	$82.6 \pm 2.9 \pm 2.3$	–
$B^{*+}\bar{B}^{*0}$	–	$70.6 \pm 4.9 \pm 4.4$

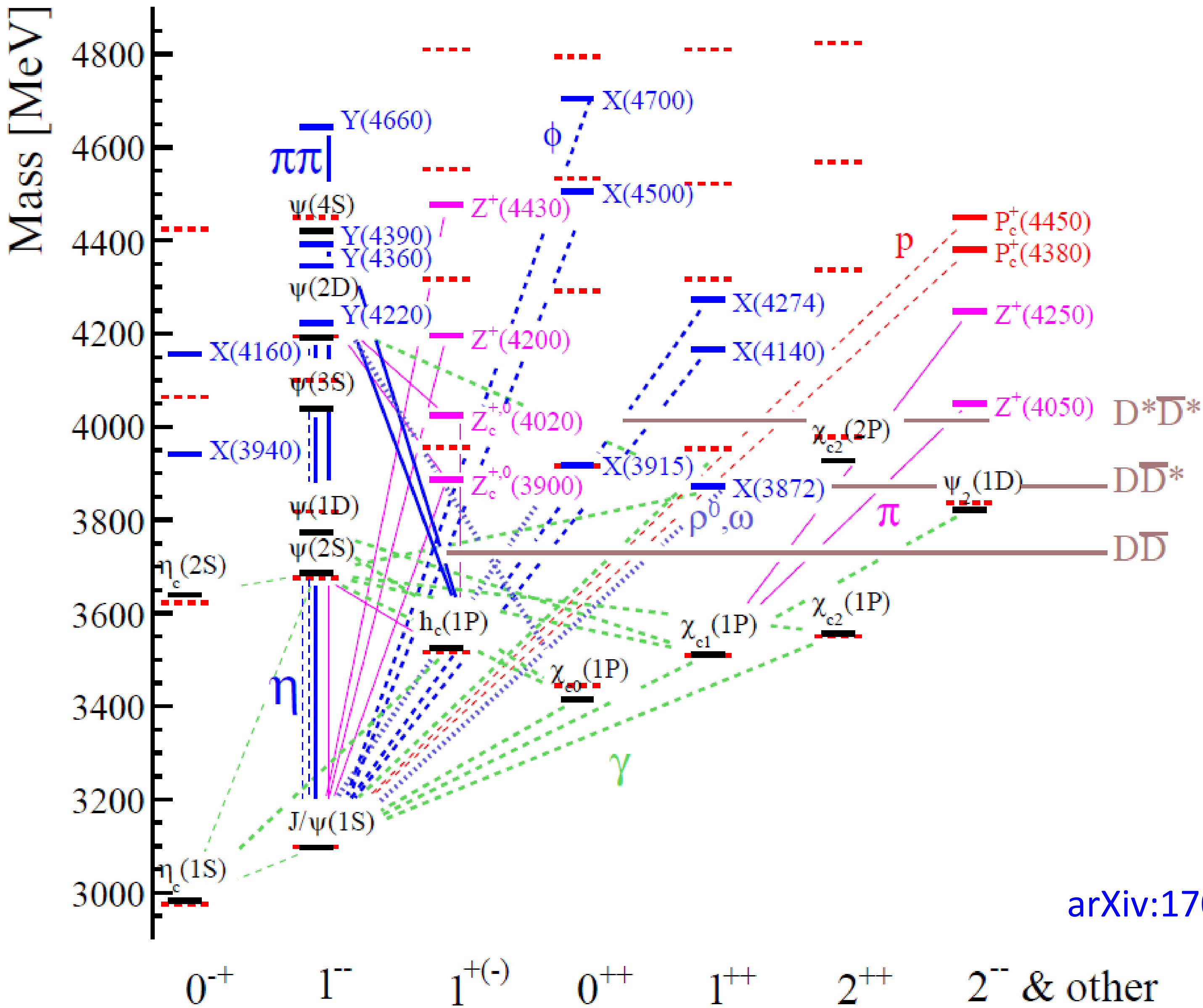


$$\frac{Br(Z_b(10610)^+ \to B\bar{B}^*)}{Br(Z_b(10610)^+ \to b\bar{b})} = 5.93 {+0.99/-0.59} {+1.01/-0.73}$$

$$\frac{Br(Z_b(10650)^+ \to B^*\bar{B}^*)}{Br(Z_b(10650)^+ \to b\bar{b})} = 2.80 {+0.69/-0.40} {+0.54/-0.36}$$

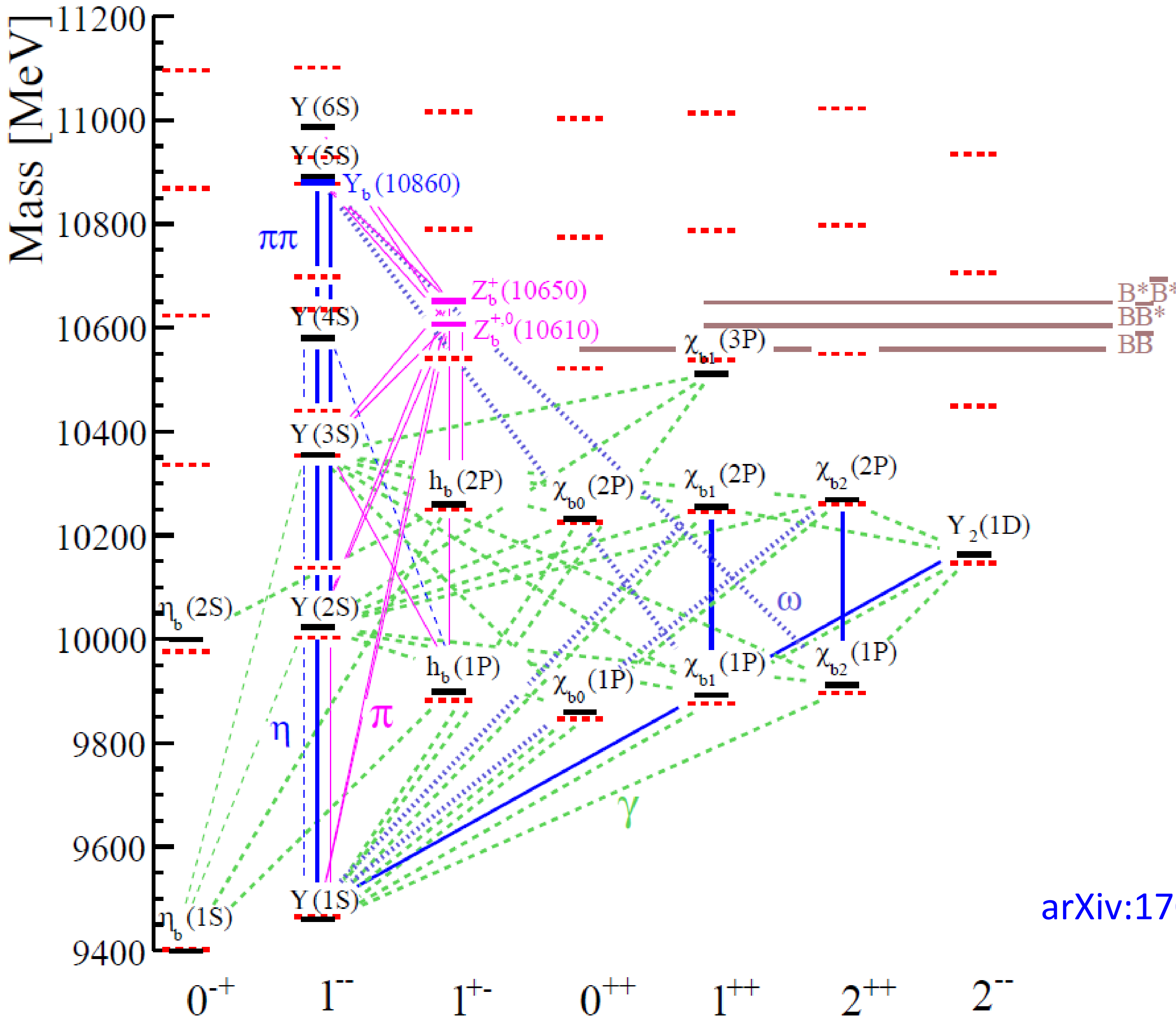
$B^{(*)}B^*$ channels dominate the Z_b decays

Charmonium(like) spectroscopy



arXiv:1708.04012

Bottomonium(like) spectroscopy



arXiv:1708.04012

Others …

Pentaquarks, Glueballs, …

Observation of Pc states at LHCb

LHCb: PRL115, 072001 (2015)

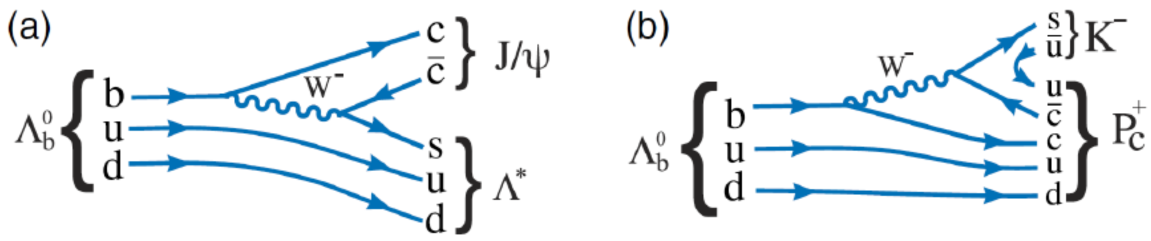
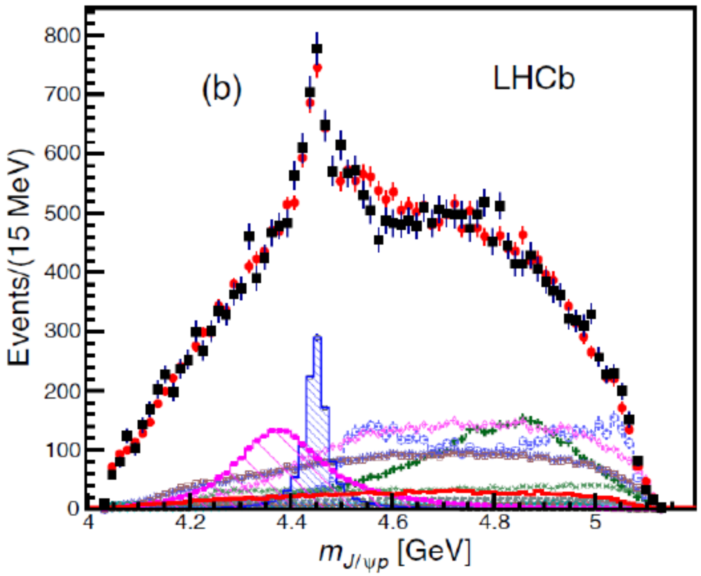
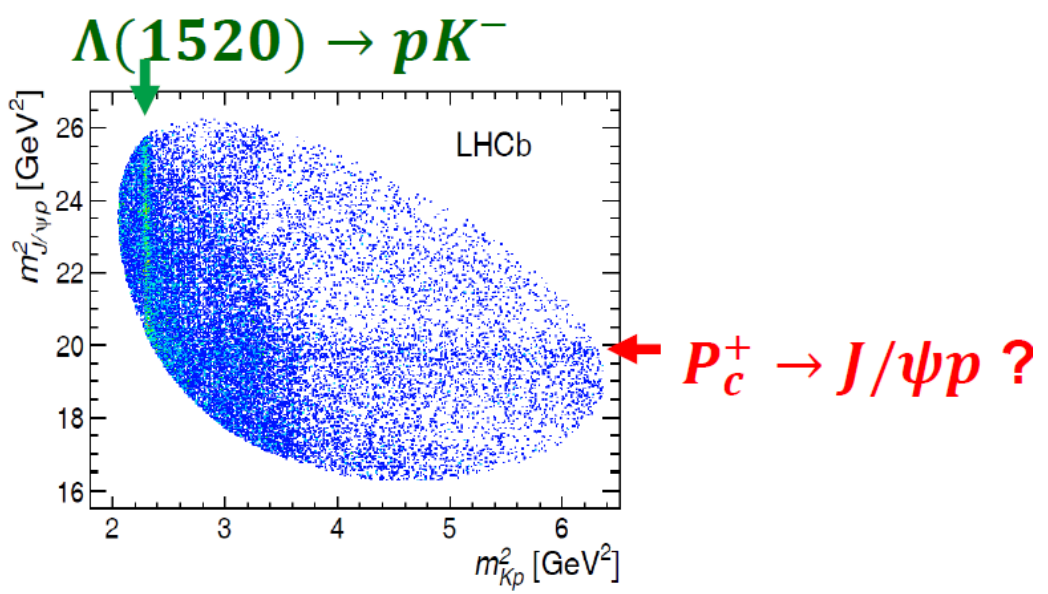


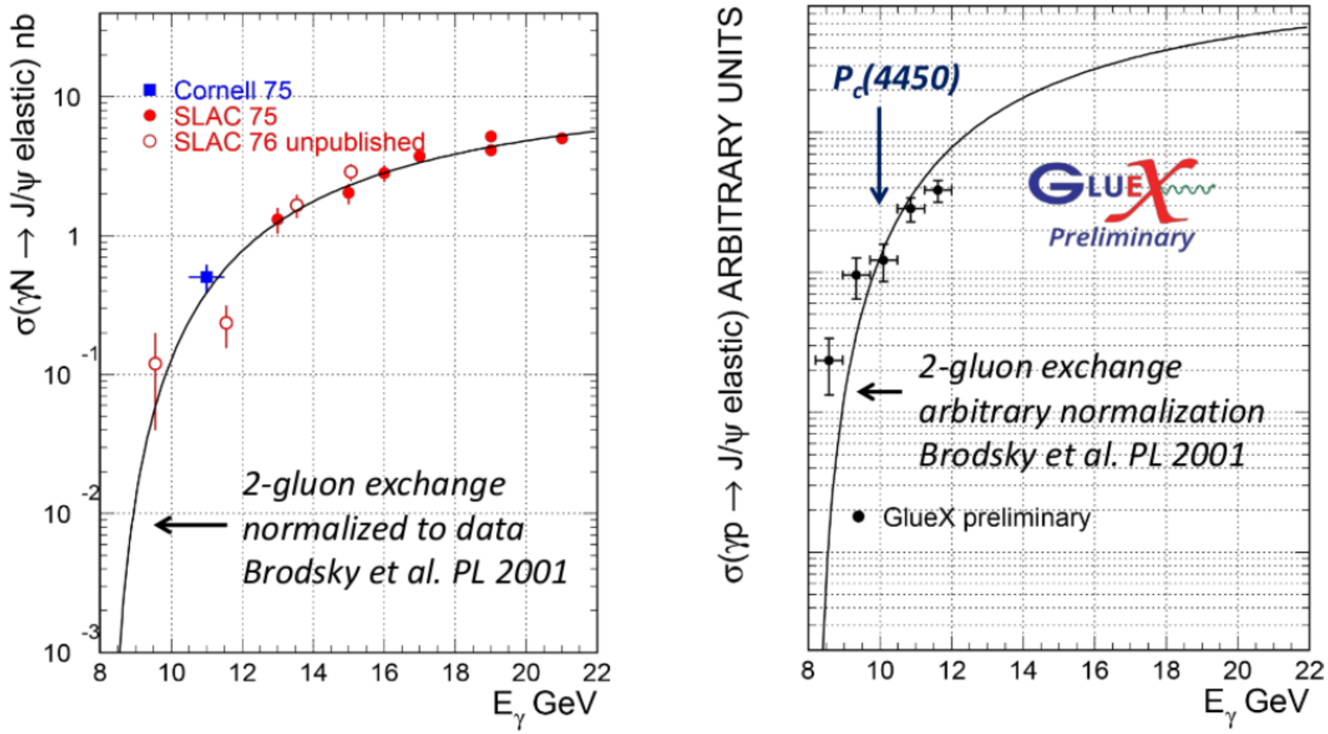
FIG. 1 (color online). Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.





Search for Pc states at GlueX

J/ψ cross section as function of $E_{\gamma_{beam}}$



Spring 2016: 12 GeV Engineering run

- Electron Beam Energy: 12.05 GeV
- Commissioning complete: Detector, Beamline, DAQ
- Data taken for early physics results: $\sim$26 billion events, $\sim$7 billion with good quality

Search for Ps states at Belle

Belle: arXiv: 1707.00089, PRD (in press) 915 fb^{-1} data

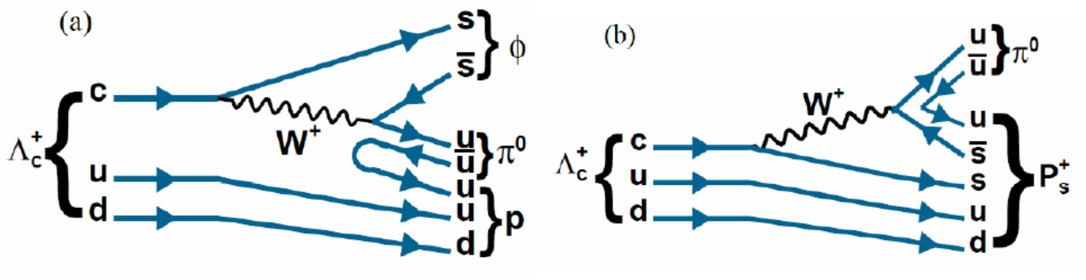
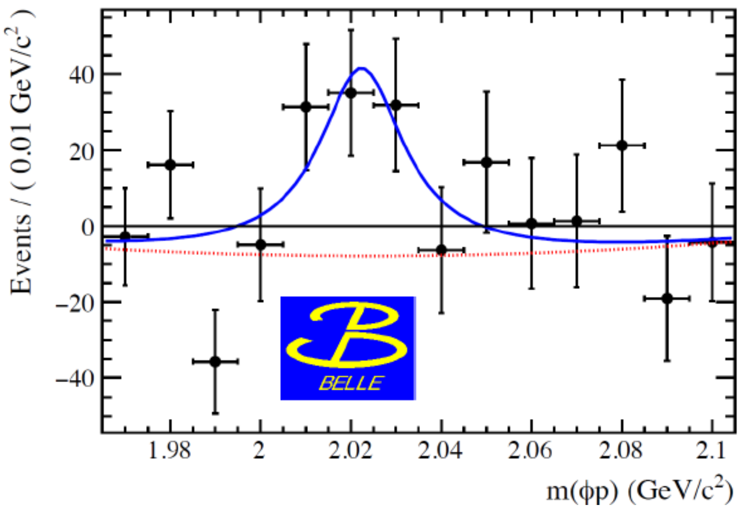


FIG. 1. Feynman diagram for the decay (a) $\Lambda_c^+ \to \phi p \pi^0$ and (b) $\Lambda_c^+ \to P_s^+ \pi^0$.



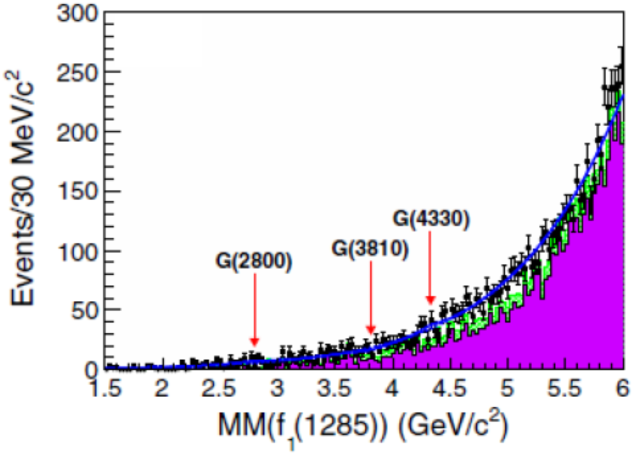
$\Sigma^+ \to p\pi^0$ vetoed

- **No significant Ps signal**
- **Best fit yields a peak at M=(2025±5) MeV/c² and Γ=(22±12) MeV**

Number of candidate $\Lambda_c \to P_s\pi^0 \to \phi p\pi^0$ events: 77.6±28.1

$B(\Lambda_c \to P_s\pi^0) \times B(P_s \to \phi p) < 8.3 \times 10^{-5}$ @90% C.L.

Exotic Glueball



- Glueballs are allowed by QCD
- The predicted 0^{--} glueballs masses are 2.80, 3.81 and 4.33GeV/c^2. [PRL113, 221601 (2014)]、[JHEP 1510 (2015) 137]
- No signals in Y(1S,2S) and χ_{b1} decays: $\chi_{b1} \to J/\psi$+Glueball, Y(1S,2S) $\to \boldsymbol{\chi_{c1}}$+ G_0^{--}, Y(1S,2S) $\to f_1(1285)$+ G_0^{--} and $\boldsymbol{\chi_{b1}} \to \omega$+ G_0^{--} at Belle [PRD 95, 012001 (2017)]

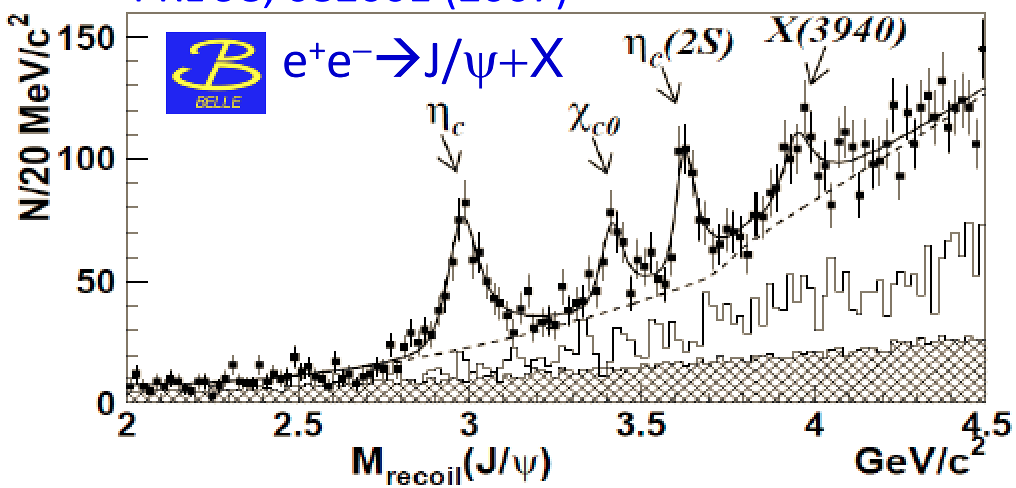
- Some multi-quark states with exotic quantum numbers are predicted in low mass region, for example, 0^{--} tetraquark with m=1.66 ± 0.14 GeV/c^2 and 1^{+-} with m=[1.18, 1.43] GeV/c^2 [PRD 95, 076017 (2017)].

Summary

- A hole new field of exotic physics was discovered in last decade; new information is still coming from both completed (Belle & BaBar) and currently ongoing (BESIII, D0, LHCb, CMS, …) experiments
- However (much) more data is required for a better understanding (BelleII, BESIII, LHCb, …)
- BESIII, LHCb …are getting more data; start of the Belle II is approaching. Inputs from them are important to understand quarkonium(-like) spectra
- Common features between charmonium and bottomonium sectors is gradually emerging. No direct identity however.
- Bottomonium spectra are less well studied compared to charmoniua. Input from Belle II is crucial to push exotic studies into bottomonium sector.
- No clear understanding of the nature of new states yet. Let’s work harder.

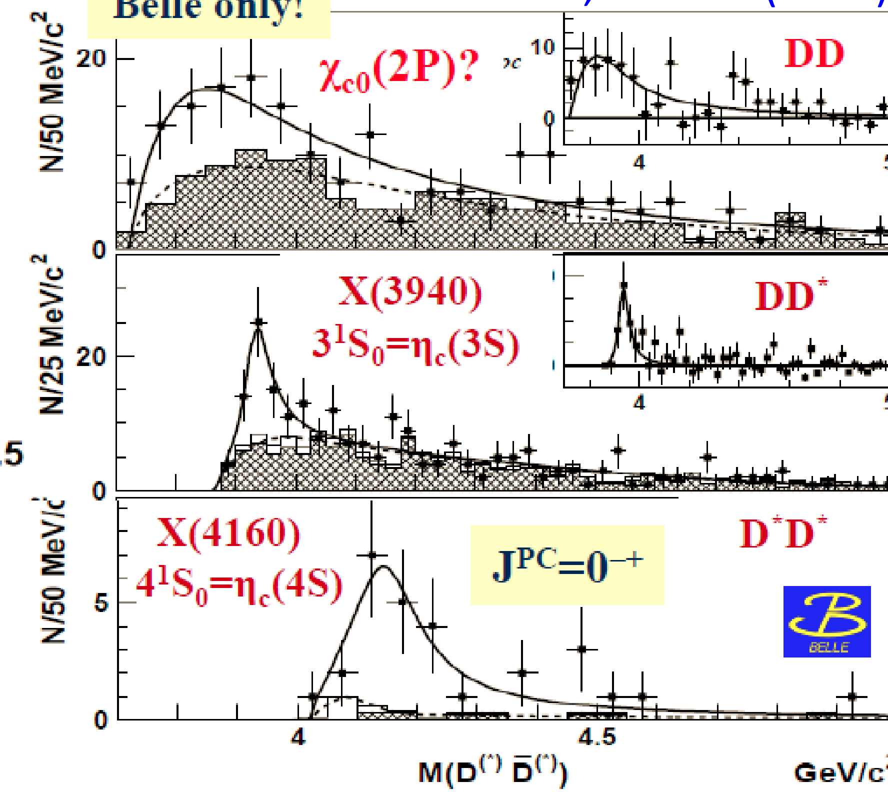
X(3940) and X(4160) (Exotic ? Standard ?)

PRL 98, 082001 (2007)



Belle only!

PRL 100, 202001 (2008)



$J^{PC}=0^{-+}$

$X(3940) = 3^1S_0 = \eta_c(3S)$

$X(4160) = 4^1S_0 = \eta_c(4S)$

Decays to open charm like standard charmonium

Mass of X(3940) &X(4160) are ~100-150 (250-300) MeV lower than the masses predicted by the potential models for $\eta_c(3S)$ and $\eta_c(4S)$

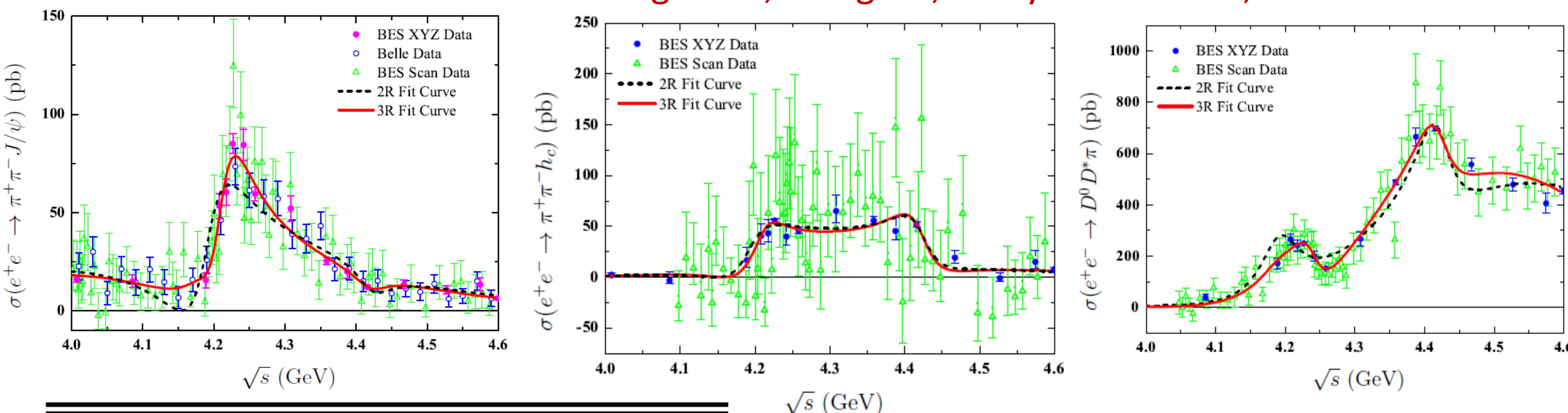
Theory probably needs more elaborate models to take into account charmonia couplings to meson pairs

- Search for new states in $e^+e^- \rightarrow J/\psi D^{(*)}D^{(*)}\pi$ and in $e^+e^- \rightarrow \chi_{c1} D^{(*)}D^{(*)}$
- Production: reconstruction of the exclusive final states
- Production studies with other charmonium states (e.g. $\psi(2S)$, χ_{c1})

Not all Y states are new ?

- Opinion: Y(4320) and Y(4390) are not needed, not genuine resonances
- Fit method: ψ(4160), ψ(4415), Y(4220) with interference
- Conclusions: ψ(4160) and ψ(4415) can replace Y(4320) and Y(4390) ; Y(4220) is possible ψ(4S) state

Dian-Yong Chen, Xiang Liu, Takayuki Matsuki , arXiv:1708.01954



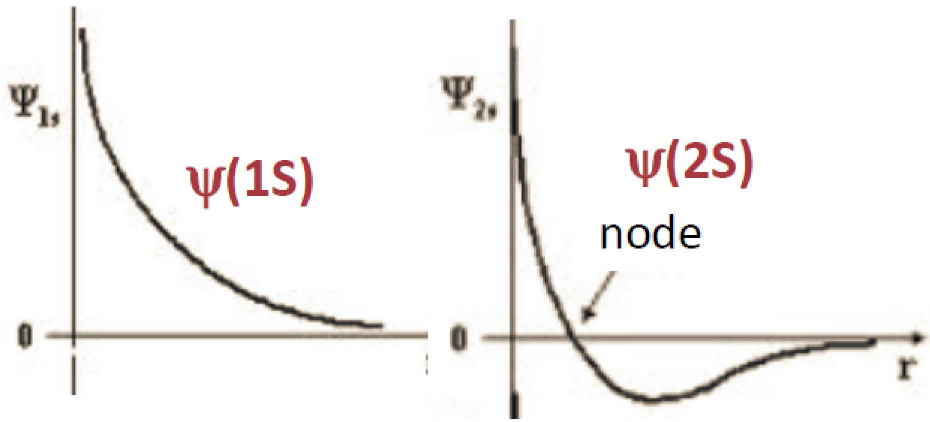
Parameters	$e^+e^- \to \pi^+\pi^- J/\psi$ 2R Fit	$e^+e^- \to \pi^+\pi^- J/\psi$ 3R Fit	$e^+e^- \to \pi^+\pi^- h_c$ 2R Fit	$e^+e^- \to \pi^+\pi^- h_c$ 3R Fit
g (GeV^{-1})	49.93 ± 6.51	49.86 ± 5.89	78.02 ± 1.90	64.84 ± 4.75
a (GeV^{-2})	2.00 ± 0.17	2.11 ± 0.16	3.91 ± 0.83	3.41 ± 0.21
$\mathcal{R}_{\psi(4160)}$ (eV)	5.59 ± 0.25	2.38 ± 1.37	3.62 ± 0.29	1.32 ± 1.01
ϕ_1 (rad)	5.70 ± 0.23	1.59 ± 0.76	5.59 ± 0.40	5.31 ± 0.35
$\mathcal{R}_{\psi(4415)}$ (eV)	5.14 ± 1.82	5.05 ± 2.54	1.54 ± 0.15	2.11 ± 0.54
ϕ_2 (rad)	4.41 ± 0.21	4.62 ± 0.46	2.93 ± 0.62	3.11 ± 0.15
$m_{Y(4220)}$	–	4207 ± 12	–	4211 ± 6
$\Gamma_{Y(4220)}$	–	58 ± 38	–	47 ± 13
$R_{Y(4220)}$	–	6.59 ± 4.88	–	0.51 ± 0.33
ϕ_3	–	5.75 ± 0.93	–	0.15 ± 0.84
χ^2/n.d.f	205/157	118/153	20/73	18/69

The authors' suggestion: In study of XYZ, we should also focus on on-resonance mechanism, which may provide a unique perspective beyond XYZ

Z(4430) = radial excitation of $Z_c(3900)$?

$$\frac{\mathcal{B}(Z_c(4430)^+ \to \psi(2S)\pi^+)}{\mathcal{B}(Z_c(4430)^+ \to J/\psi\pi^+)} \sim 10$$

Radial Wave Functions



The $c\bar{c}$ part of the wave function of the Z(4430) likely has a node ➔ a radial excitation of the ground state: the $Z_c(3900)$?

$M(Z_c(4430))-M(Z_c(3900)) = 589 \pm 30$ MeV

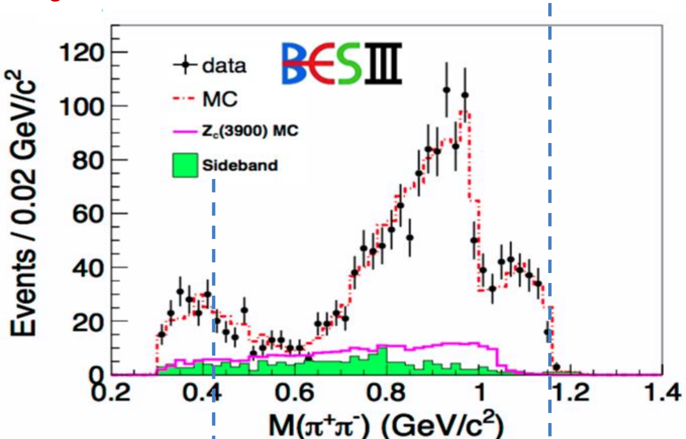
$M(\psi') - M(J/\psi) = 589$ MeV

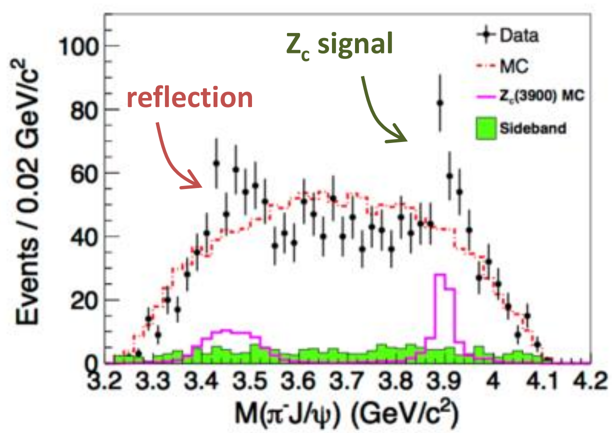
Charm vs. Beauty: I

What is in common?

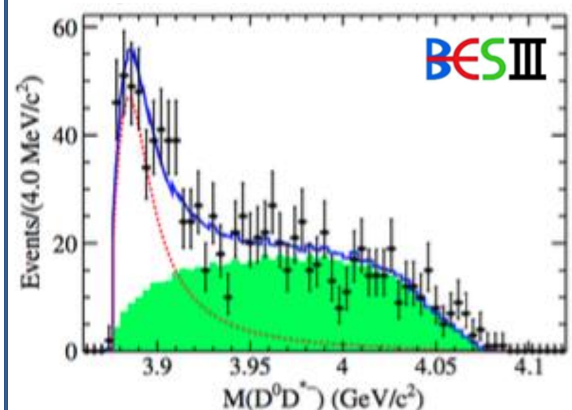
- $\Upsilon(10860)$/$Y(4260)$ demonstrates anomalously large coupling to $\Upsilon\pi^+\pi^-$/$\psi\pi^+\pi^-$ and $h_b\pi^+\pi^-$/$h_c\pi^+\pi^-$ final states.

$Z_c(3900)$ is produced in $Y(4260) \to Z_c\pi \to \psi\pi^+\pi^-$

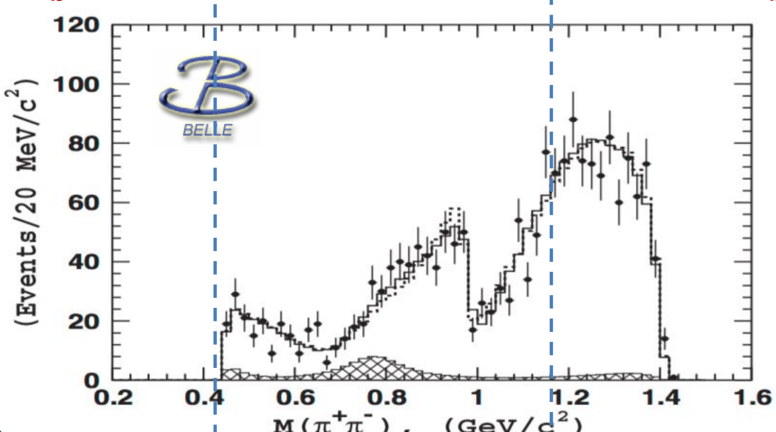




$\to Z_c\pi \to DD^*$

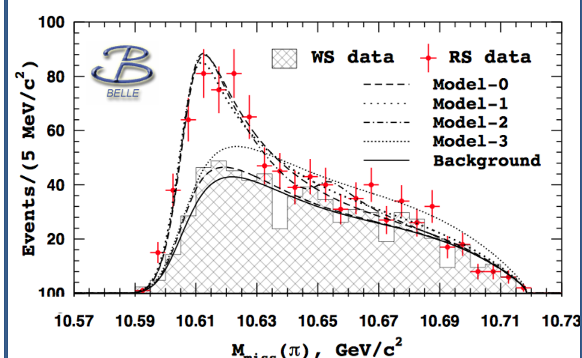


$Z_b(10610)$ is produced in $\Upsilon(10860) \to Z_b\pi \to \Upsilon(nS)\pi^+\pi^-$



MISSING PLOT

$\to Z_b\pi \to BB^*$



Charm vs. Beauty: II

What is difference?

- Both $Z_b(10610)$ and $Z_b(10650)$ isotriplets are observed in the $\Upsilon(nS)\pi$, (n=1,2,3) and $h_b\pi$ final states.

- $\Upsilon(10860)\to h_b\pi^+\pi^-$ is saturated by the intermediate two-body $Z_b\pi$ production.

- Only $Z_c(3900)$ is observed in the $J/\psi\pi$ while both $Z_c(3900)$ and $Z_c(4020)$ are observed in the $h_c\pi$ final state. None of them is observed in the $\psi(2S)\pi$ final state (instead, another $Z_c(4430)$ is found).

- Large non $Z_c\pi$ component is observed in the $Y(4260)\to h_c\pi^+\pi^-$ amplitude.

Exotic mesons

Masses (lattice QCD)

- $1^{-+} \sim 2.0 - 2.4$ GeV
- $0^{+-} \sim 2.3 - 2.5$ GeV
- $2^{+-} \sim 2.4 - 2.6$ GeV

Decay widths (from Models)

- $\Gamma \sim 0.1 - 0.5$ GeV

$$
\begin{array}{lll}
1^{-+} & \pi_1 & \rightarrow \rho\pi,\ b_1\pi,\ f_1\pi,\ \eta'\pi,\ a_1\eta \\
 & \eta_1 & \rightarrow f_2\pi,\ a_2\pi,\ f_1\eta,\ \eta'\eta,\ \pi(1300)\pi,\ a_1\pi \\
 & \eta_1' & \rightarrow K^*\overline{K},\ K_1(1270)\overline{K},\ K^*(1410)\overline{K},\ \eta'\eta \\
2^{+-} & b_2 & \rightarrow \omega\pi,\ a_2\pi,\ \rho\eta,\ f_1\rho,\ a_1\pi \\
 & h_2 & \rightarrow \rho\pi,\ b_1\pi,\ \omega\eta,\ f_1\omega \\
 & h_2' & \rightarrow K_1(1270)\overline{K},\ K^*(1410)\overline{K},\ K_2\overline{K},\ \phi\eta \\
0^{+-} & b_o & \rightarrow \pi(1300)\pi,\ h_1\pi,\ f_1\rho,\ b_1\eta \\
 & h_o & \rightarrow b_1\pi,\ h_1\eta \\
 & h_o' & \rightarrow K_1(1270)\overline{K},\ K^*(1410)\overline{K},\ h_1\eta
\end{array}
$$

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**

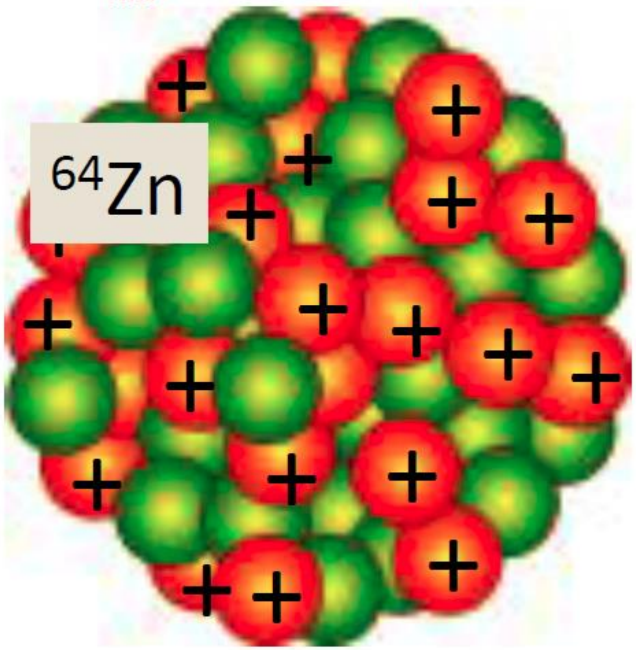
0^{--}	0^{++}	0^{-+}	0^{+-}
1^{--}	1^{++}	1^{-+}	1^{+-}
2^{--}	2^{++}	2^{-+}	2^{+-}
3^{--}	3^{++}	3^{-+}	3^{+-}
4^{--}	4^{++}	4^{-+}	4^{+-}
5^{--}	5^{++}	5^{-+}	5^{+-}

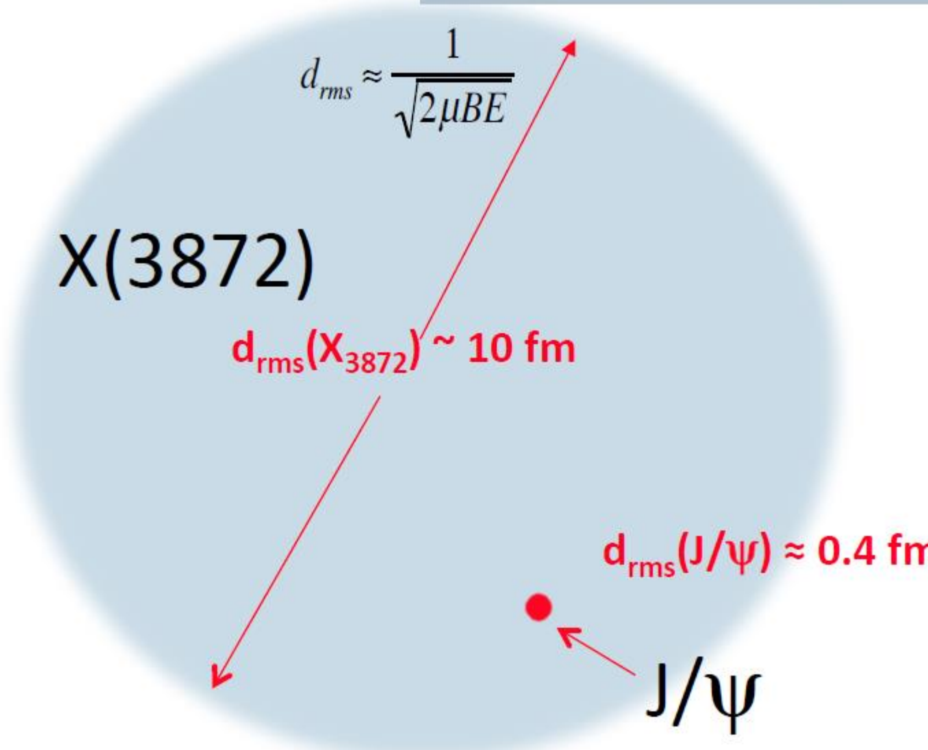
J^{PC} Exotic quantum numbers

X(3872)-J/ψ relative sizes

E. Braaten, J. Stapleton PRD81, 0140189

$d_{rms}(^{64}Zn \text{ nucleus}) \approx 8$ fm





$\text{Volume}(J/\psi)/\text{Volume}(X_{3872}) \approx 10^{-4}$

- How can such a fragile object be produced in H.E. pp collisions?

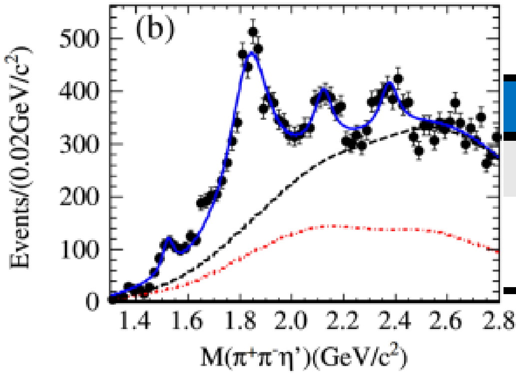
C. Bignamini *et al*, PRL 103, 162001: $\sigma_{CDF}(\text{meas}) > 3.1 \pm 0.7$nb *vs* $\sigma_{theory}(\text{molecule}) < 0.11$nb

after 14 years, we still don't know

Anomalous line shape of $\eta'\pi^+\pi^-$ near $p\bar{p}$ mass threshold: connection between X(1835) and X($p\bar{p}$)

X(1835) observed in $J/\psi \to \gamma\eta'\pi^+\pi^-$

Phys. Rev. Lett. 106, 072002 (2011)



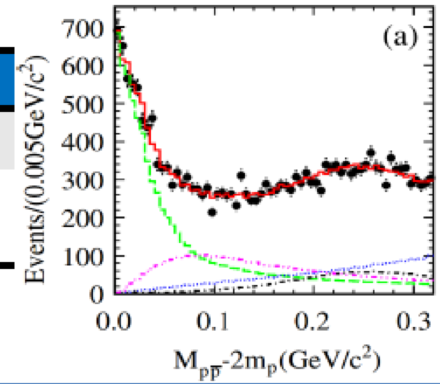
X(1835) $J^{PC}=0^{-+}$
$M = 1844 \pm 9^{+16}_{-25}$ MeV/c^2
$\Gamma = 192^{+20+62}_{-17-43}$ MeV/c^2

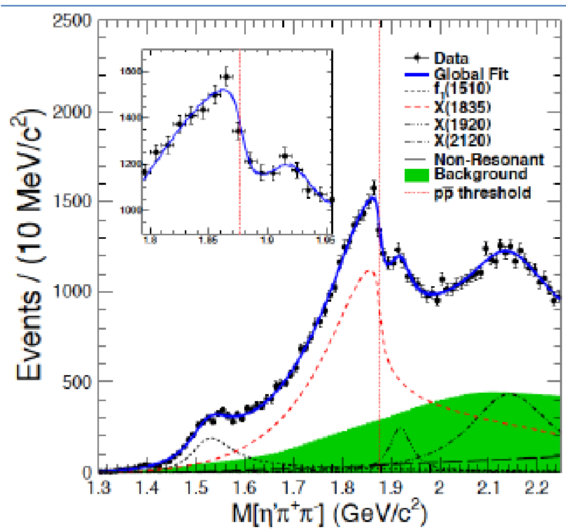
X($p\bar{p}$) observed in $J/\psi \to \gamma p\bar{p}$

PRL 108, 112003 (2012)

PRL 115, 091803 (2015)

X($p\bar{p}$) $J^{PC}=0^{-+}$
$M = 1832^{+19}_{-5}{}^{+18}_{-17} \pm 19$ MeV/c^2
$\Gamma = 13 \pm 19$ MeV/c^2 (< 76 MeV/c^2 @ 90% C.L.)



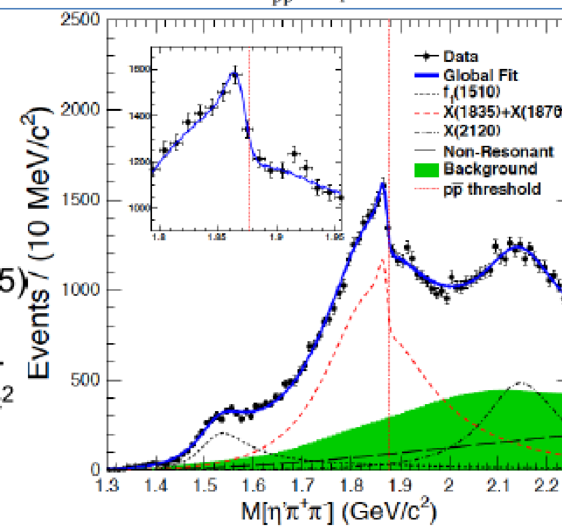


Connection is emerging

PRL 117, 042002 (2016)

Model 1:
Flatte lineshape with strong coupling to $p\bar{p}$ and one additional, narrow Breit-Wigner at ~1920 MeV/c^2

Model 2:
Coherent sum of X(1835) Breit-Wigner and one additional, narrow Breit-Wigner at ~1870 MeV/c^2



- Suggest the existence of a state, either a broad one with strong couplings to $p\bar{p}$, or a narrow state just below the $p\bar{p}$ mass thresh.
- Support the existence of a $p\bar{p}$ molecule-like state or bound state