北京航空航天大學
BEIHANG UNIVERSITY

Review on tetraquark states from experimental results

Chengping Shen

9th Workshop on Hadron physics in China and Opportunities Worldwide

2017年7月26日

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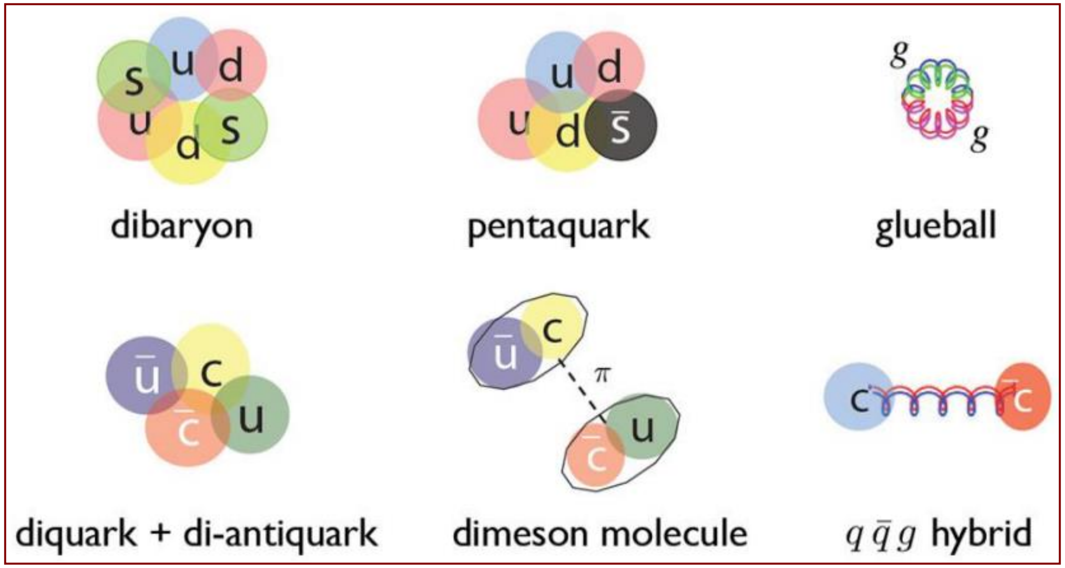
Outline

- Introduction
- Recent experimental results on X states
- Recent experimental results on Y states
- Recent experimental results on Z states
- The future plan
- 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
  - …

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??

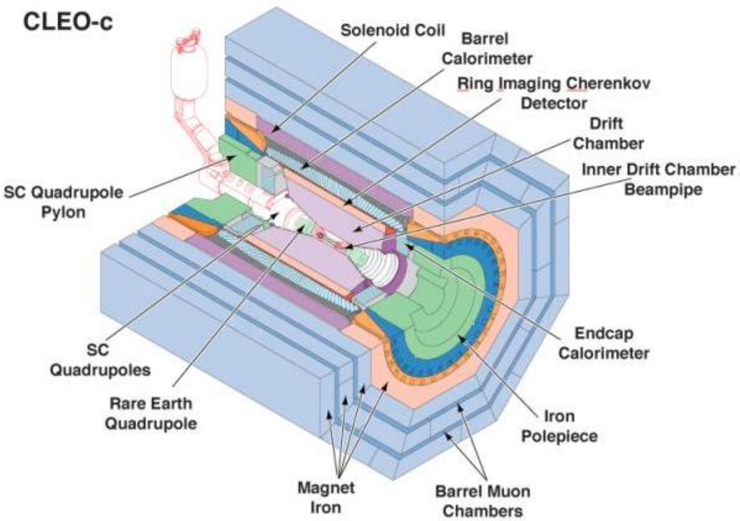
If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting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

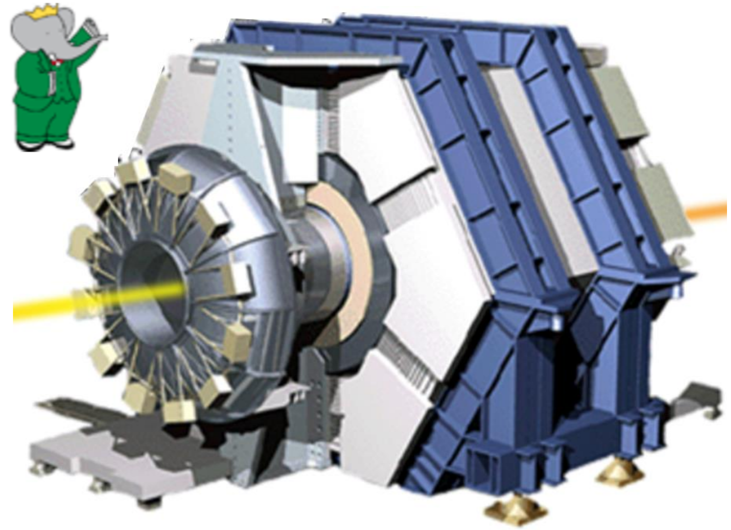
Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

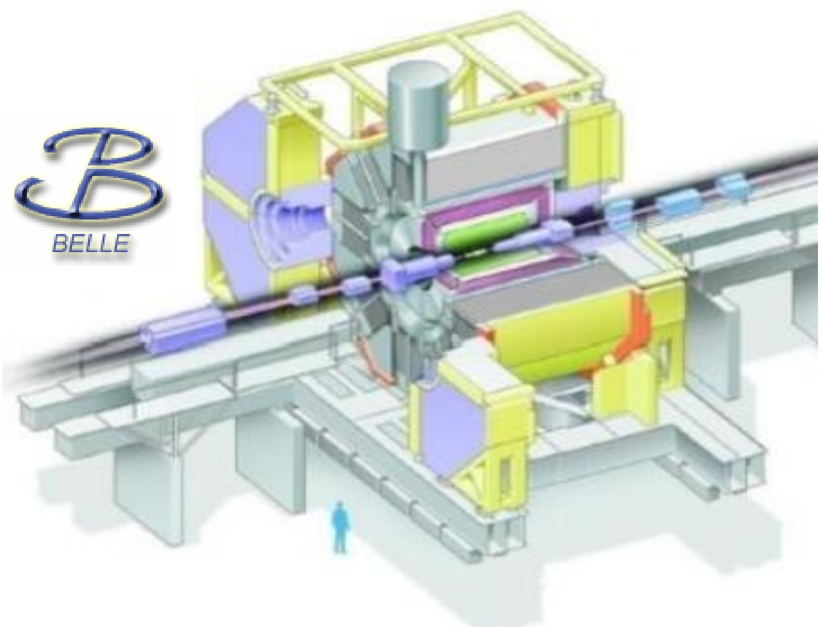
ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

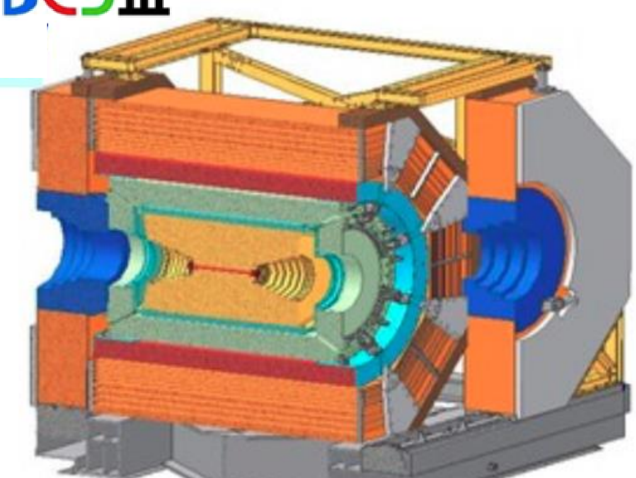
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the 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





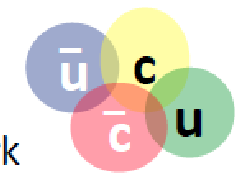




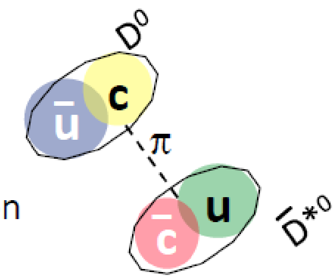
Possible non $q\bar{q}$ "white" combinations of quarks:

Tetraquark mesons

tightly bound
diquark-diantiquark



loosely bound
meson-antimeson
"molecule"



Particle "Zoo" again !

State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$Y(3915)$	3918.4 ± 1.9	20 ± 5	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [753] (8), BaBar [? ?] (19)	2004	Ok
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [754] (7.7), BaBar [755] (7.6)	2009	Ok
					756] (5.3), BaBar [757] (5.8)	2005	Ok
					Belle [758?] (6)	2005	NC!
					PDG [61]	1978	Ok
					II [?] (>10), Belle [?] (6.0)	2012	NC!
					[?] (5.0), BaBar [?] (1.1)	2008	NC!
$Y(4140)$	$4146.5^{+6.4}_{-5.3}$	83^{+30}_{-25}	1^{++}	$B^+ \to K^+(\phi J/\psi)$	CDF [759, 760] (5.0), Belle [761] (1.9)	2009	Ok
					LHCb [762] (1.4), CMS [763] (>5)		
					D0 [764] (3.1), BaBar [765] (1.6)		
					LHCb [766, 767] (8.4)		
$\psi(4160)$	4153 ± 3	103 ± 8	1^{--}	$e^+e^- \to$ (hadrons)	PDG [61]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [?] (6.5), BESIII [?] (>5)	2013	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi\,(D^*\bar{D}^*)$	Belle [?] (5.5)	2007	NC!
$Z(4200)^+$	4196^{+35}_{-32}	370^{+99}_{-149}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [?] (6.2)	2014	NC!
$Z(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [?] (5.0), BaBar [?] (2.0)	2008	NC!
$Y(4260)$	4221.1 ± 2.5	47.7 ± 4.0	1^{--}	$e^+e^- \to (\pi^+\pi^- J/\psi)$	BaBar [768, 769] (8), CLEO [770?] (11)	2005	Ok
					Belle [741, 771] (15), BESIII [740?] (np)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [?] (5.1), BESIII [?] (np)	2006	Ok
				$e^+e^- \to (K^+K^- J/\psi)$	CLEO [?] (3.7)	2006	NC!
				$e^+e^- \to (f_0(980) J/\psi)$	BaBar [769] (np), Belle [741] (np)	2012	Ok
				$e^+e^- \to (\pi^+\pi^- h_c)$	BESIII [742, 772] (10)	2013	NC!
				$e^+e^- \to (\pi^0\pi^0 h_c)$	BESIII [744] (np)	2014	NC!
				$e^+e^- \to (\omega\chi_{c0})$	BESIII [773] (>9)	2014	NC!
				$e^+e^- \to (\gamma\, X(3872))$	BESIII [774] (6.3)	2013	NC!
				$e^+e^- \to (\pi^- Z_c(3900)^+)$	BESIII [740?] (>8), Belle [741] (5.2)	2013	Ok
				$e^+e^- \to (\pi^0 Z_c(3900)^0)$	BESIII [? ?] (10.4)	2015	Ok
				$e^+e^- \to (\pi^{\mp,0} Z_c(4020)^{\pm,0})$	BESIII [742, 744? , 745] (>10)	2013	Ok
$Y(4274)$	$4273.3^{+19.1}_{-9.0}$	$56.2^{+13.8}_{-15.6}$	1^{++}	$B^+ \to K^+(\phi J/\psi)$	CDF [760] (3.1), LHCb [762] (1.0),	2011	NC!
					CMS [763] (>3), D0 [764] (np)		
					LHCb [766, 767] (6.0)		
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	13^{+18}_{-10}	$0/2^{?+}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [775] (3.2)	2009	NC!
$Y(4360)$	4341.2 ± 5.4	101.9 ± 9.3	1^{--}	$e^+e^- \to (\pi^+\pi^- \psi(2S))$	Belle [746, 776] (8), BaBar [777] (np)	2007	Ok
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	BESIII [?] (7.6)	2016	NC!
				$e^+e^- \to (\pi^+\pi^- \psi_2(3823))$	BESIII [778] (np)	2015	NC!
				$e^+e^- \to (\pi^0 Z_c(3900)^0)$	BESIII [?] (np)	2015	NC!
				$e^+e^- \to (\pi^- Z_c(4055)^+)$	Belle [746] (3.5)	2014	NC!
$Y(4390)$	4391.6 ± 6.4	139.5 ± 16.1	1^{--}	$e^+e^- \to (\pi^+\pi^- h_c)$	BESIII [772] (10)	2016	NC!
				$e^+e^- \to (\pi^{\mp,0} Z_c(4020)^{\pm,0})$	BESIII [742, 744] (np)	2013	NC!
$\psi(4415)$	4421 ± 4	62 ± 20	1^{--}	$e^+e^- \to$ (hadrons)	PDG [61]	1976	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [?] (np), BESIII [?] (>5)	2013	NC!
				$e^+e^- \to (\omega\chi_{c2})$	BESIII [?] (10.4)	2015	NC!
				$e^+e^- \to (D\bar{D}_2^*(2460))$	Belle [?] (10)	2007	NC!
$Z(4430)^+$	4478^{+15}_{-18}	181 ± 31	1^{+-}	$\bar{B}^0 \to K^-(\pi^+\psi(2S))$	Belle [779? , 780] (6.4), BaBar [?] (2.4),	2007	Ok
					LHCb [781?] (13.9)		
				$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [?] (4.0)	2014	NC!
$Y(4500)$	4506^{+16}_{-19}	92^{+30}_{-29}	0^{++}	$B^+ \to K^+(\phi J/\psi)$	LHCb [766, 767] (6.1)	2016	NC!
$Y(4660)$	4643 ± 9	72 ± 11	1^{--}	$e^+e^- \to (\pi^+\pi^- \psi(2S))$	Belle [746, 776] (5.8), BaBar [777] (5)	2007	Ok
				$e^+e^- \to (\Lambda_c^+\bar{\Lambda}_c^-)$	Belle [782] (8.2)	2007	NC!
$Y(4700)$	4704^{+17}_{-26}	120^{+52}_{-45}	0^{++}	$B^+ \to K^+(\phi J/\psi)$	LHCb [766, 767] (5.6)	2016	NC!

XYZ particles

- Charmonium-like (XYZ) particles
- New type of hadron (multi-quark …)?
- Too many vector states! Exotics?

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

n radial quantum number

S total spin of c & cbar

L orbital angular momentum

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

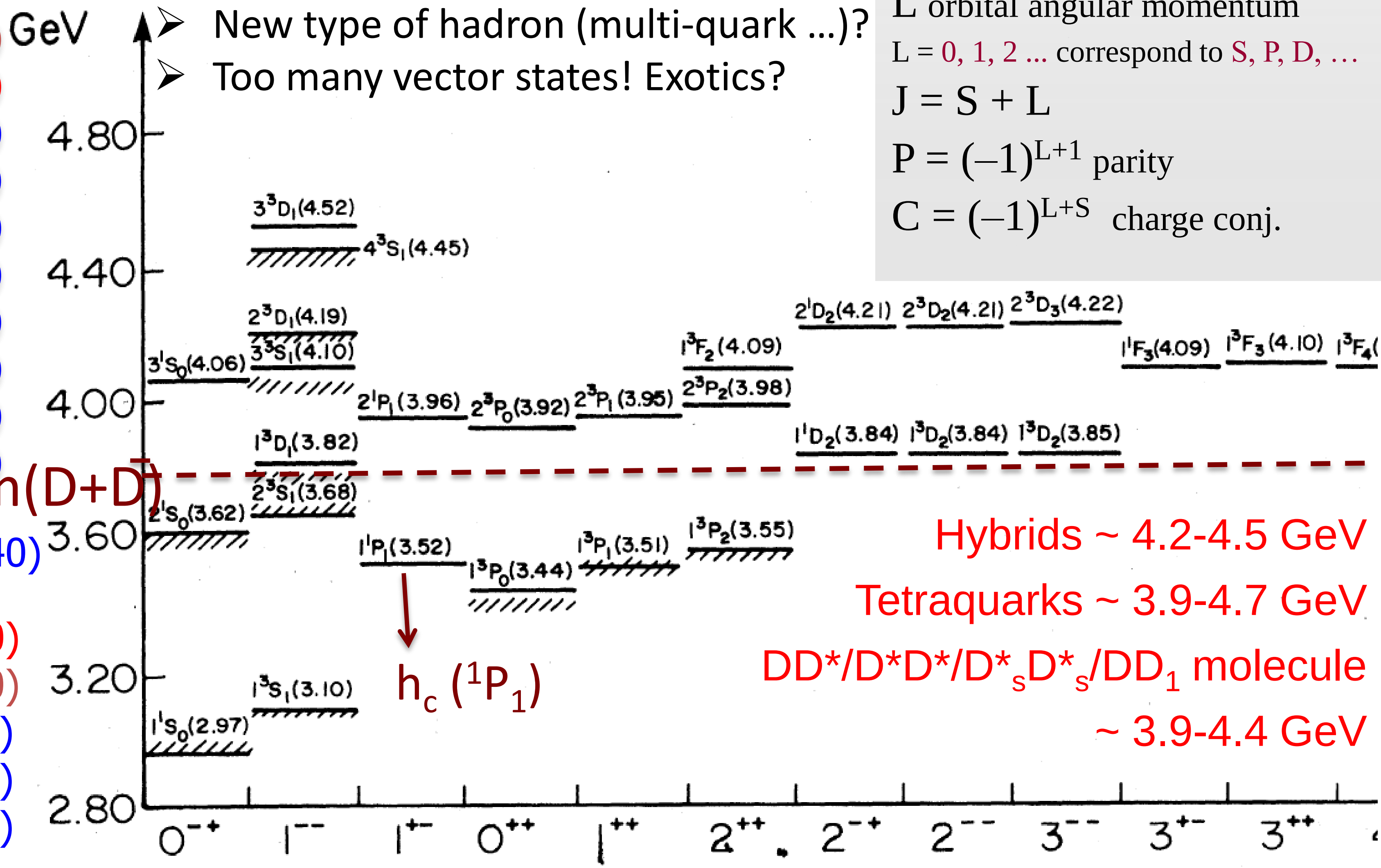
$J = S + L$

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

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

X(3823)
X(3872)
X(3915)
X(4350)
Y(4008)
Y(4260)
Y(4140)
Y(4360)
Y(4660)
Y(4630)
...
XYZ(3940)

$Z_c(3900)$
$Z_c(4020)$
Z(4430)
Z(4250)
Z(4050)
...



Hybrids ~ 4.2-4.5 GeV

Tetraquarks ~ 3.9-4.7 GeV

$DD^*/D^*D^*/D^*_sD^*_s/DD_1$ molecule ~ 3.9-4.4 GeV

Godfrey & Isgur, PRD32, 189 (1985)

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 …

QCD is another least understood part of the SM.

“The absence of exotics is one of the most obvious features of QCD” – R. L. Jaffe, 2005

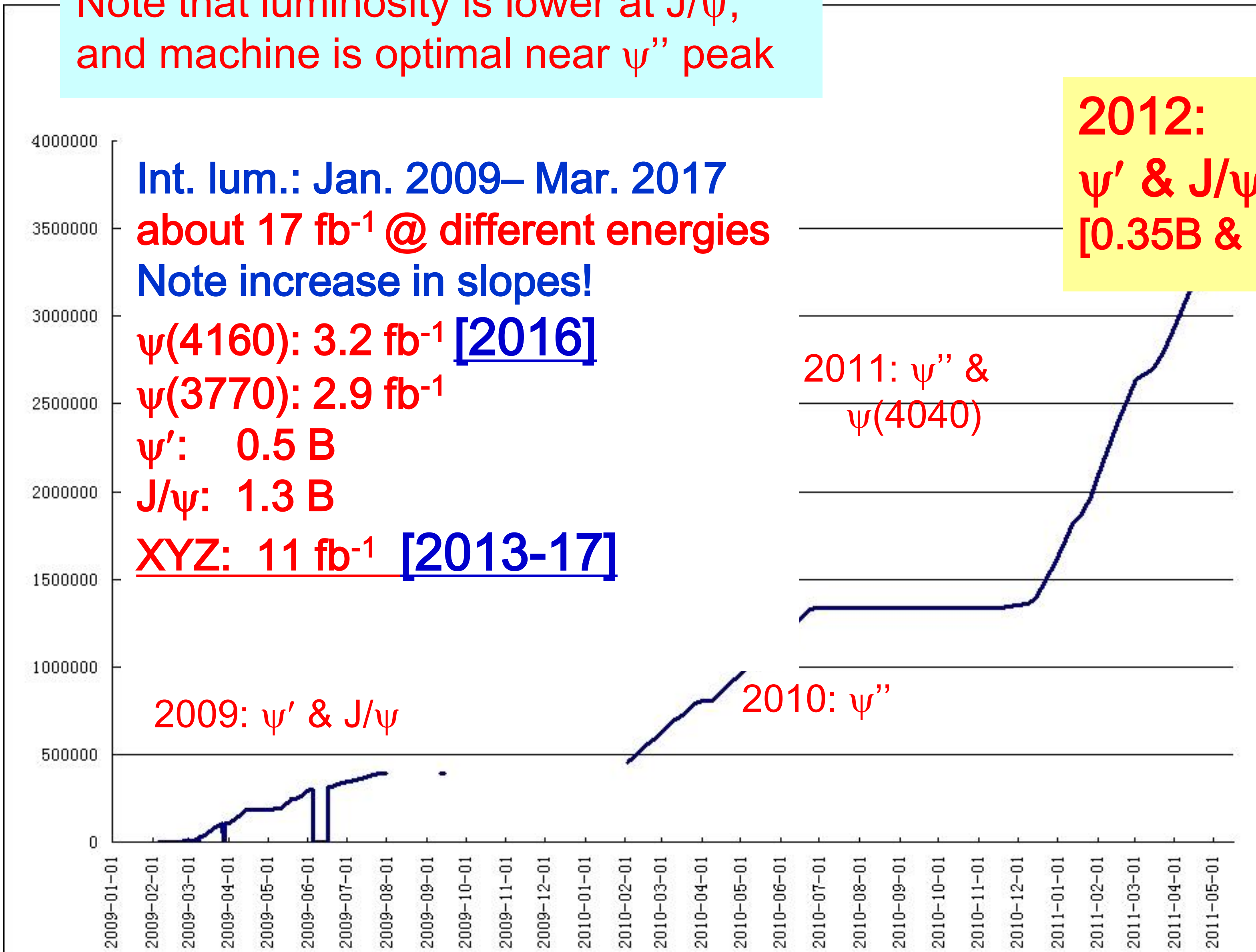
“The story of pentaquark shows how poorly we understand QCD” – F. Wilczek, 2005

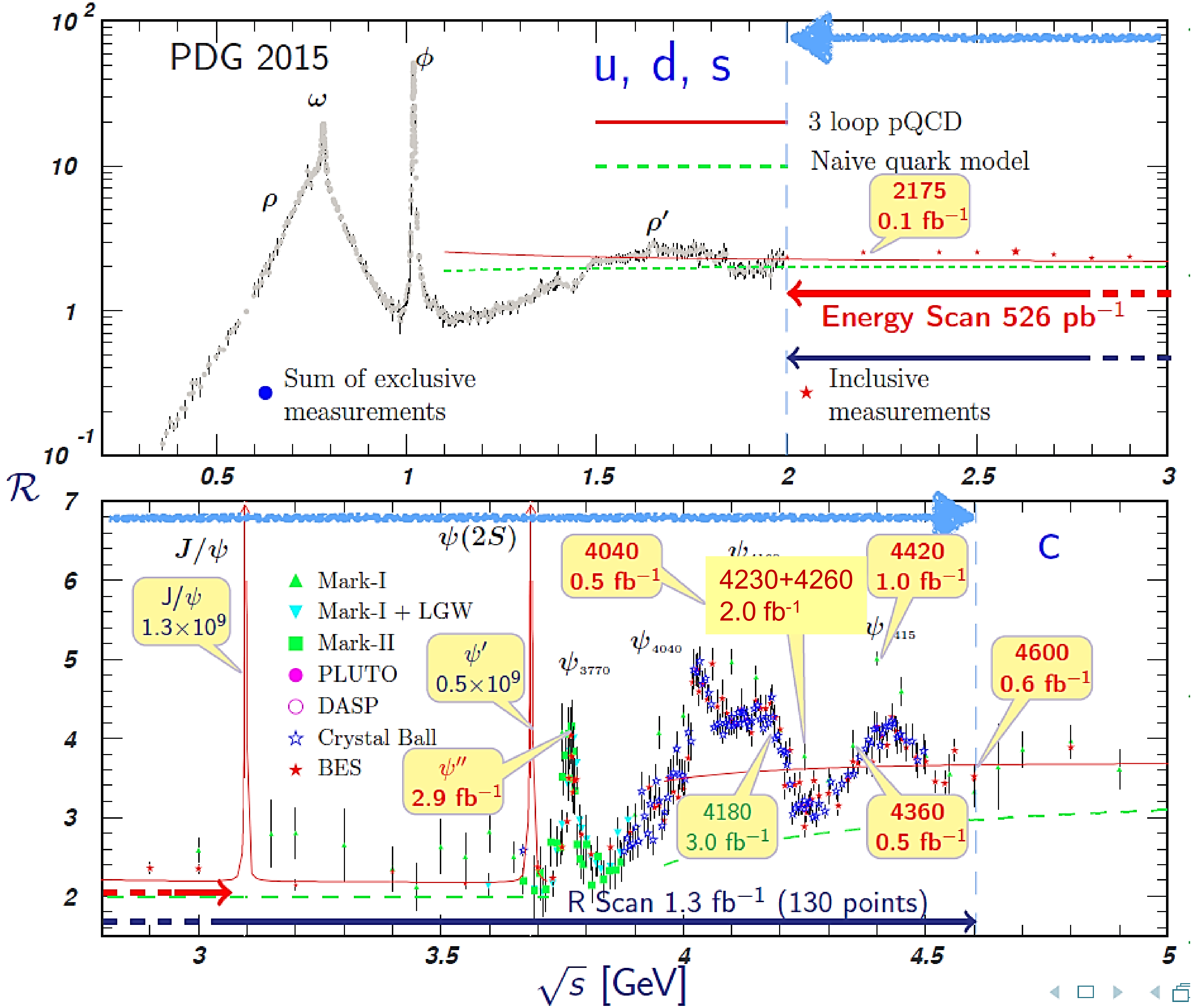
BESIII data samples

Note that luminosity is lower at J/ψ, and machine is optimal near ψ’’ peak

2012:
ψ′ & J/ψ
[0.35B & 1.1B]

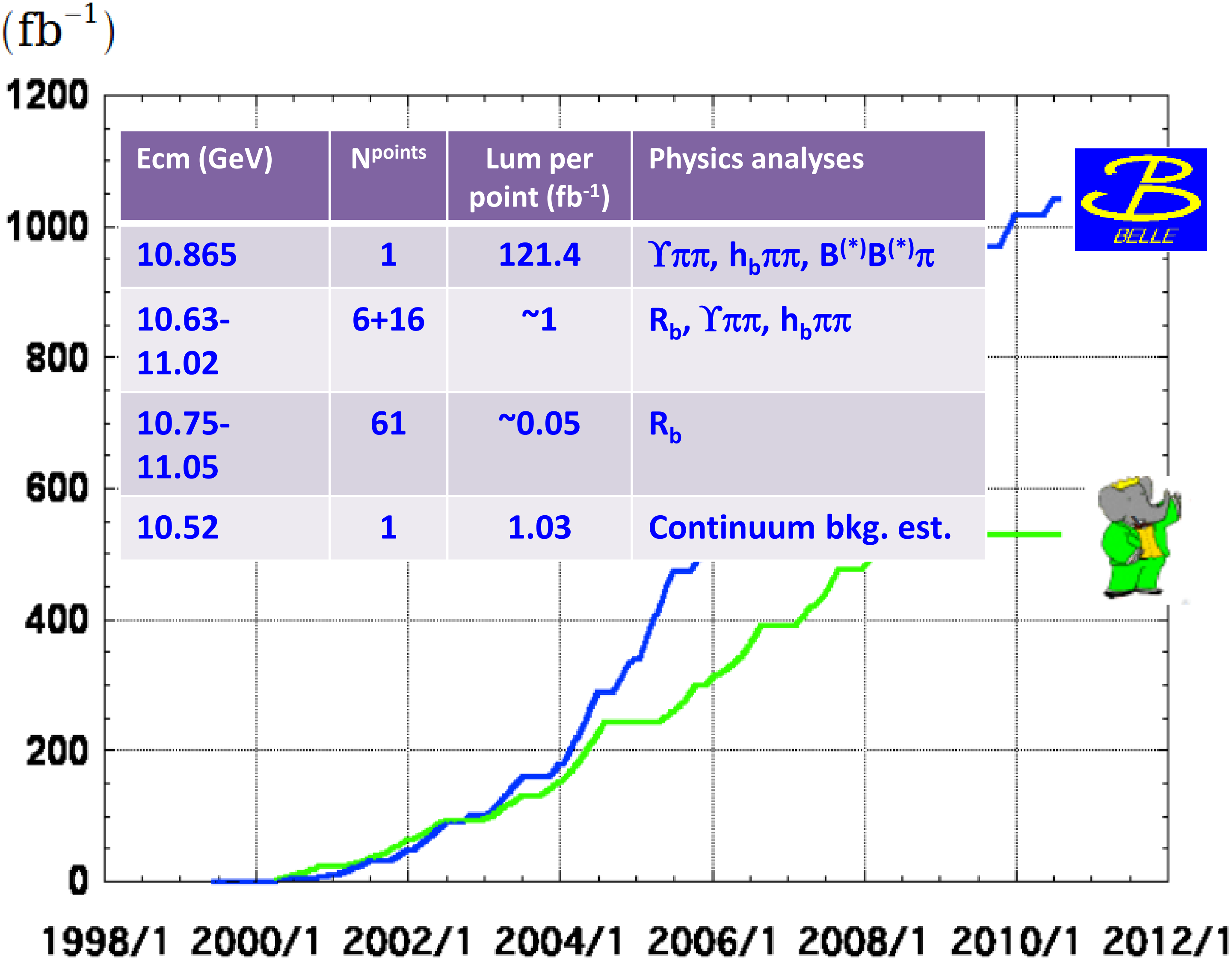
Int. lum.: Jan. 2009– Mar. 2017
about 17 fb^{-1} @ different energies
Note increase in slopes!
ψ(4160): 3.2 fb^{-1} [2016]
ψ(3770): 2.9 fb^{-1}
ψ′: 0.5 B
J/ψ: 1.3 B
XYZ: 11 fb^{-1} [2013-17]





PDG 2015
u, d, s
3 loop pQCD
Naive quark model
2175
0.1 fb^{-1}
Energy Scan 526 pb^{-1}
Sum of exclusive measurements
Inclusive measurements
ω
ϕ
ρ
ρ'
$\mathcal{R}$
J/ψ
$\psi(2S)$
J/ψ 1.3×10^9
ψ' 0.5×10^9
ψ'' 2.9 fb^{-1}
4040
0.5 fb^{-1}
4230+4260
2.0 fb^{-1}
4420
1.0 fb^{-1}
4600
0.6 fb^{-1}
4180
3.0 fb^{-1}
4360
0.5 fb^{-1}
ψ_{3770}
ψ_{4040}
ψ_{4415}
C
Mark-I
Mark-I + LGW
Mark-II
PLUTO
DASP
Crystal Ball
BES
R Scan 1.3 fb^{-1} (130 points)
$\sqrt{s}$ [GeV]

Integrated luminosity of B factories



Ecm (GeV)	N^{points}	Lum per point (fb^{-1})	Physics analyses
10.865	1	121.4	$\Upsilon\pi\pi$, $h_b\pi\pi$, $B^{(*)}B^{(*)}\pi$
10.63-11.02	6+16	~1	R_b, $\Upsilon\pi\pi$, $h_b\pi\pi$
10.75-11.05	61	~0.05	R_b
10.52	1	1.03	Continuum bkg. est.

BELLE

$> 1\ ab^{-1}$

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

$\sim 100\ fb^{-1}$

$\sim 550\ fb^{-1}$

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

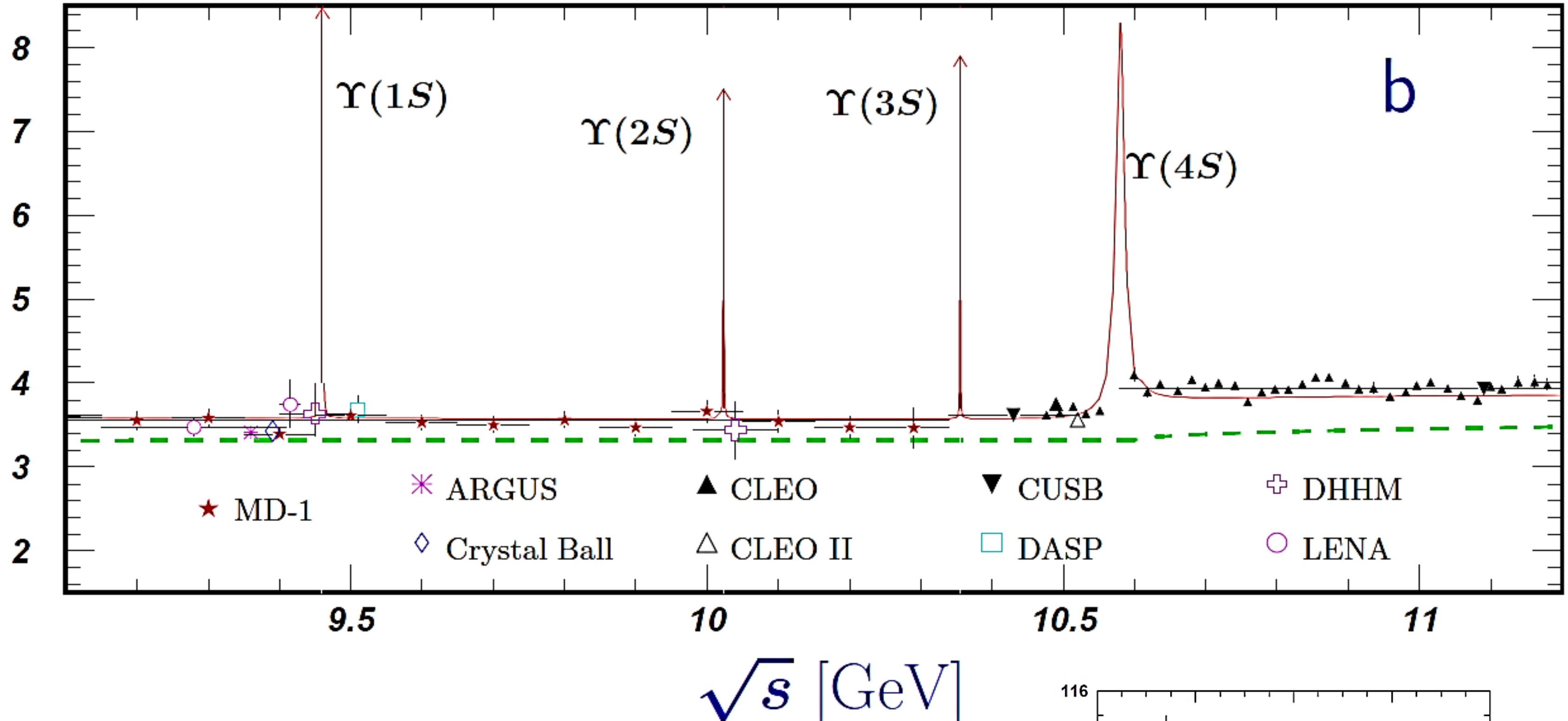
$\Upsilon(3S)$: 30 fb^{-1}

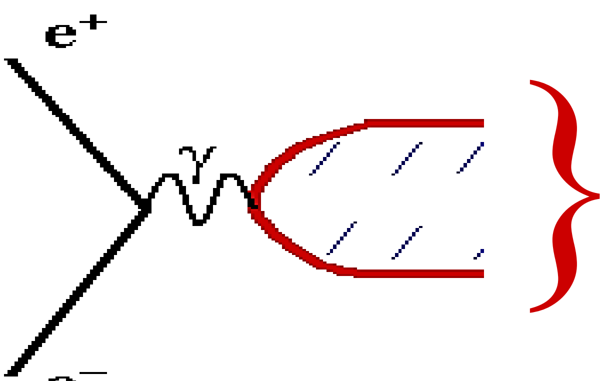
$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

$\sim 54\ fb^{-1}$

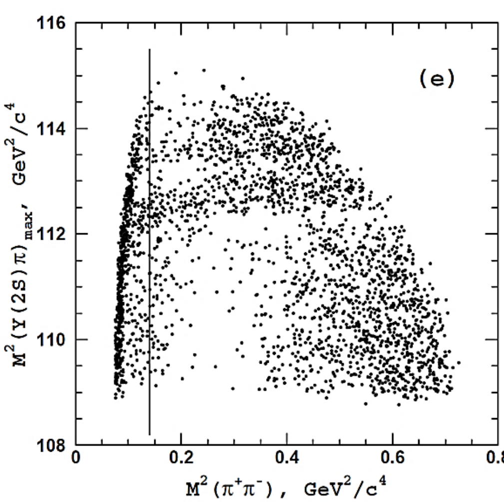
e^+e^- annihilation to vector bottomonia



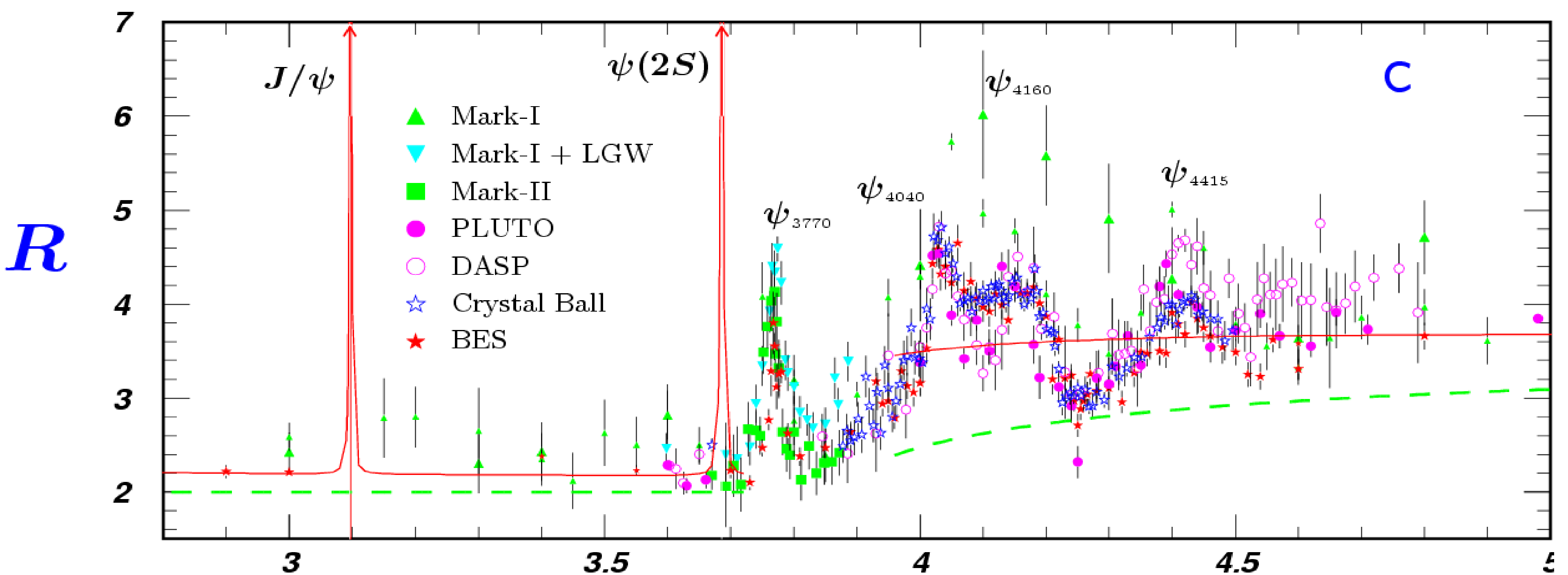


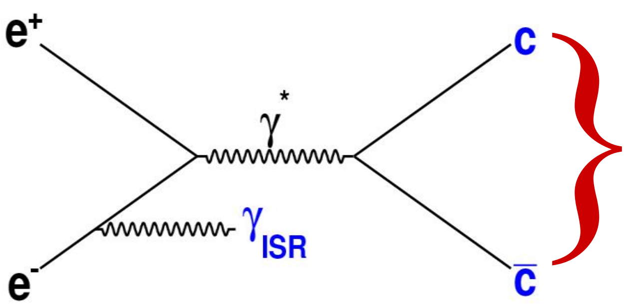
$J^{PC} = 1^{--}$

Υ(nS), Y_b…



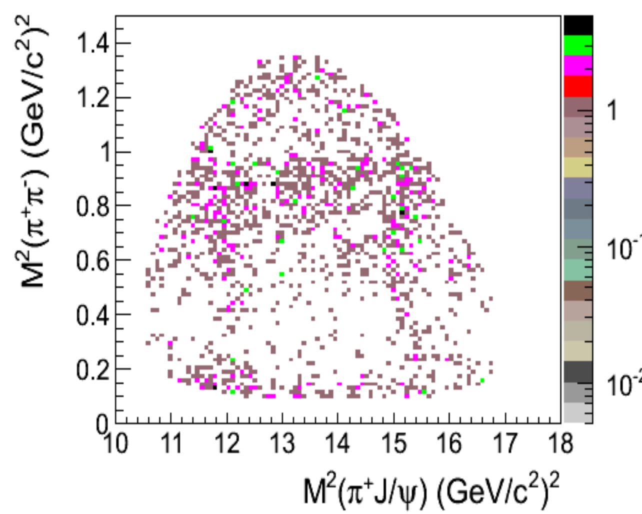
ISR production of vector charmonia





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

ψ', ψ'', Y…



X States

X(3872), X(5568), X_b …

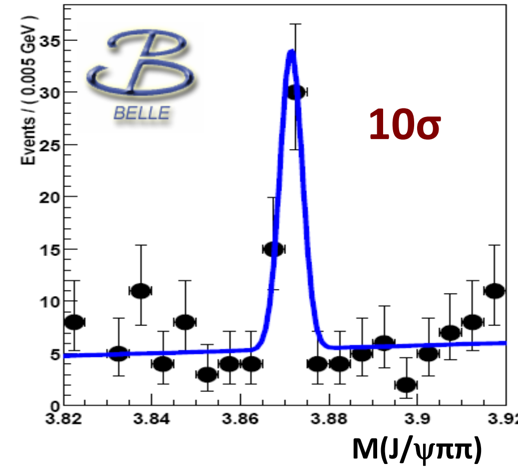
Observed in B decays and (suggestively) in decays of Y type states

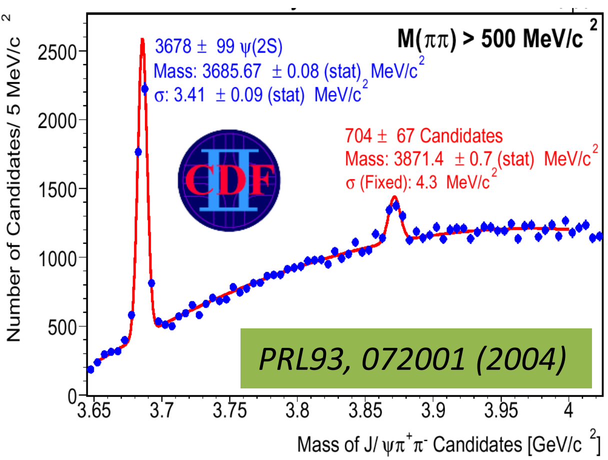
$X(3872) \to J/\psi\pi^+\pi^-$

Belle's most cited paper: 1200+

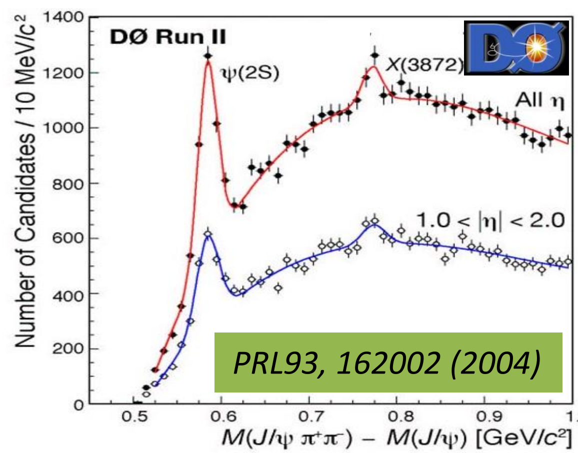
first observed by Belle in $B \to K\, J/\psi\pi^+\pi^-$ *PRL91, 262001 (2003)*

- 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

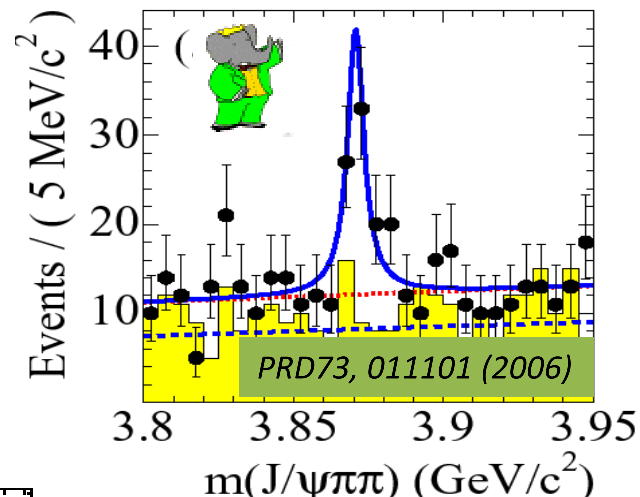




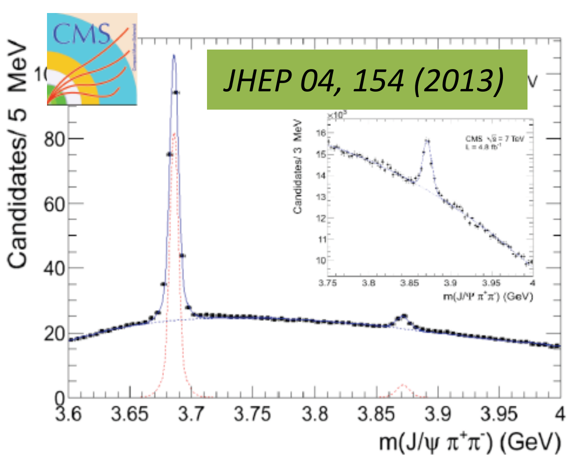
PRL93, 072001 (2004)



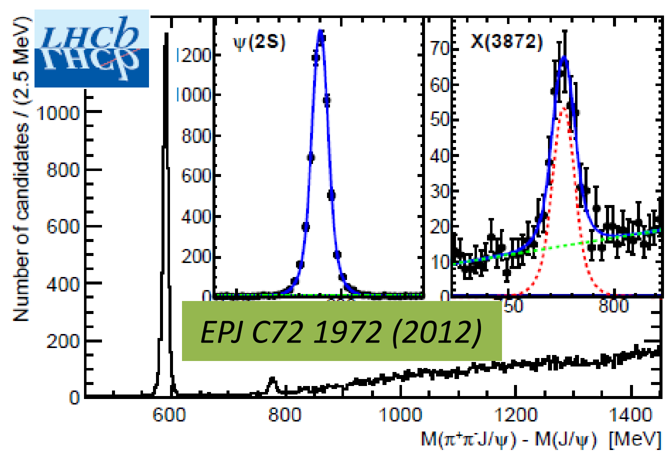
PRL93, 162002 (2004)



PRD73, 011101 (2006)



JHEP 04, 154 (2013)



EPJ C72 1972 (2012)

$X(3872) \to J/\psi\gamma$: 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): Other Decay Modes

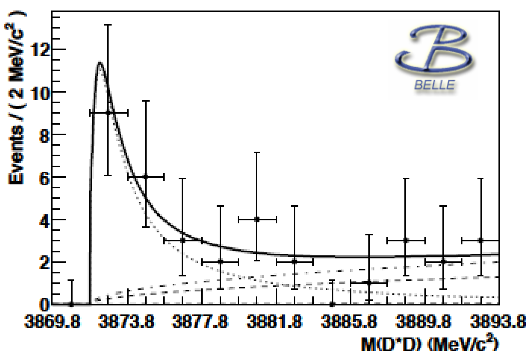
- **$\pi\pi = \rho$ means Isospin violation!**
- **X(3872) → $J/\psi\omega$ is seen: confirms isospin violation**

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

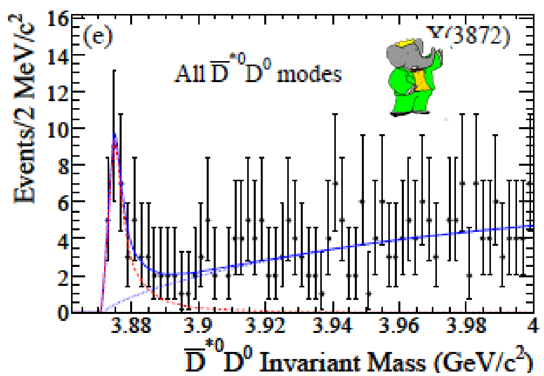
- Radiative decays: Belle&Babar good agreement for $X \to J/\psi\gamma$; not consistent for $X \to \psi(2S)\gamma$.

LHCb confirms BaBar's not vanishing $X \to \psi(2S)\gamma$.

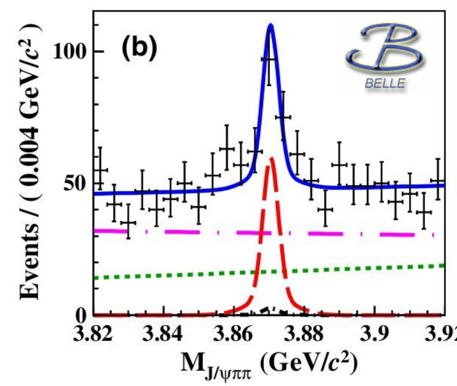
- X(3872) → DD* - dominant mode
- B→X(3872)Kπ non-resonant Kπ dominates!



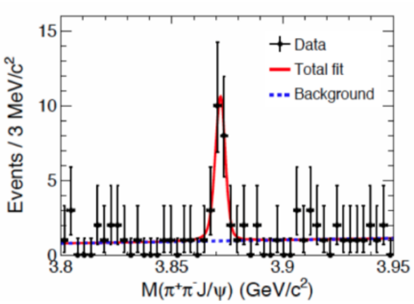
PRD 81, 031103 (2010)

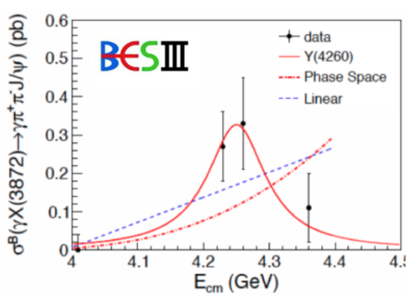


PRD 77, 011102 (2008)



PRD 91, 051101(R) (2015)

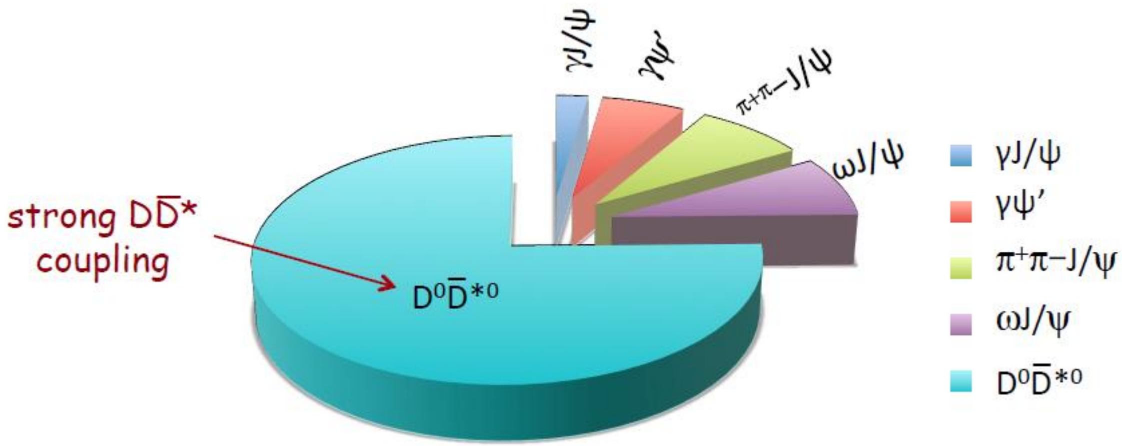




PRL 112, 092001 (2014)

- The first observation of $e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi$
- $M = 3871.9\pm0.7\pm0.2$ MeV/c², $\Gamma<2.4$ MeV, consistent with Belle's result
- Suggestive of $Y(4260) \to \gamma X(3872)$
- If $B(X(3872) \to \pi^+\pi^- J/\psi) = 5\%$, $\mathcal{R} = \dfrac{Br(e^+e^- \to \gamma X(3872))}{Br(e^+e^- \to \pi^+\pi^- J/\psi)} = 0.1$

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)

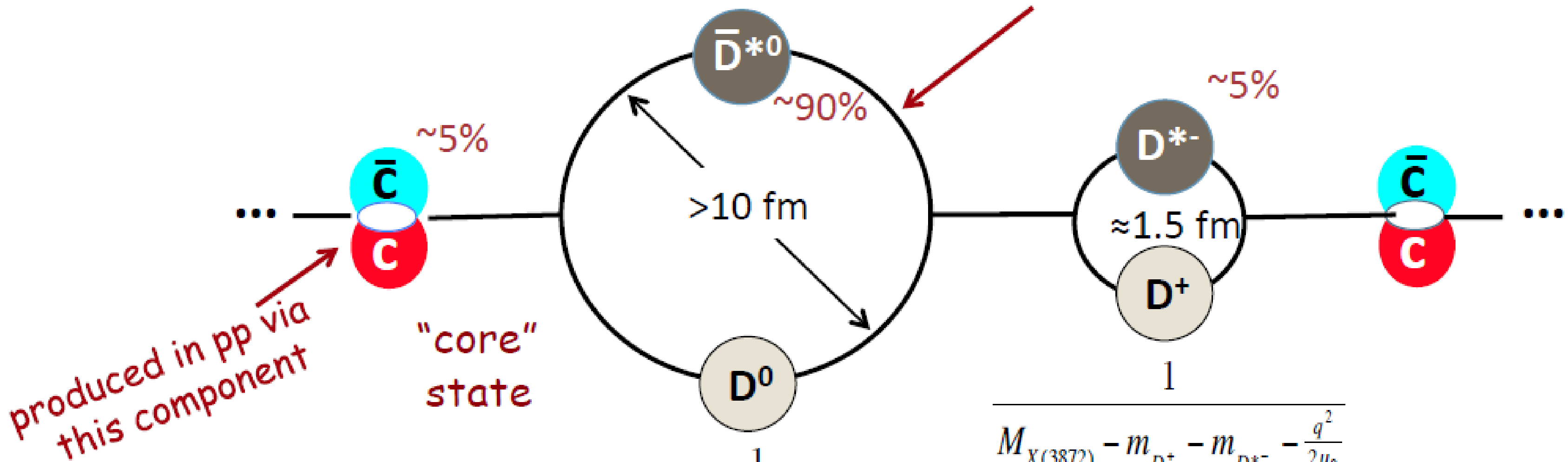
Predicts partner states (e.g., a nearby state with u→d) that have yet be seen.

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



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

$$|BE| < 0.2\ \text{MeV}$$

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

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

$$|BE| \approx 8\ \text{MeV}$$

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

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

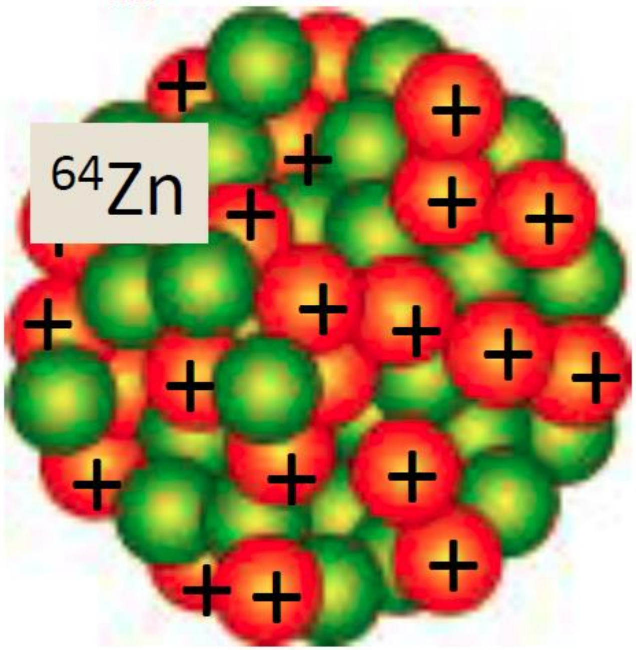
reduced mass

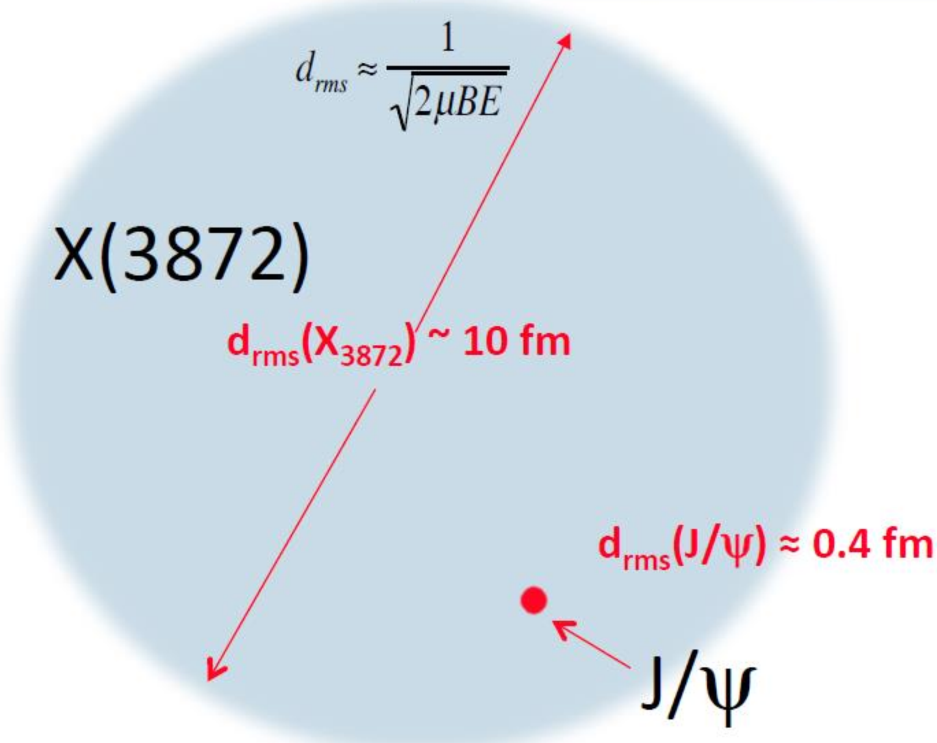
$|m_D + m_{D*} - m_{X3872}|$

X(3872)-J/ψ relative sizes

E. Braaten, J. Stapleton PRD81, 0140189

d_{rms}(^{64}Zn nucleus)≈8 fm





Volume(J/ψ) /Volume(X_{3872}) ≈ 10^{-4}

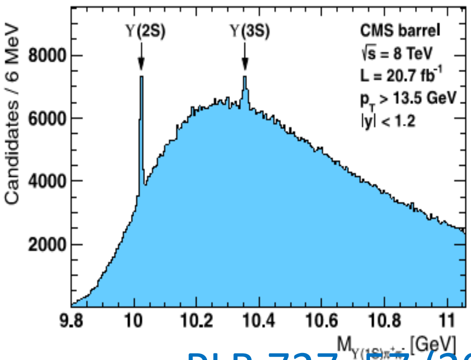
- How can such a fragile object be produced in H.E. pp collisions?

C. Bignamini *et al*, PRL 103, 162001: σ_{CDF}(meas)>3.1±0.7nb *vs* σ_{theory}(molecule)<0.11nb

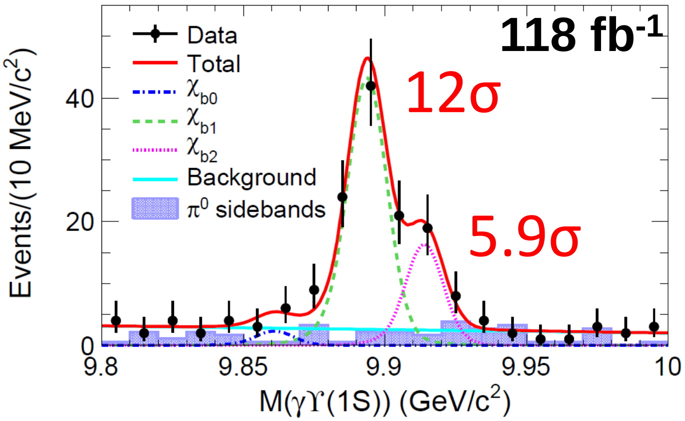
after 14 years, we still don't know

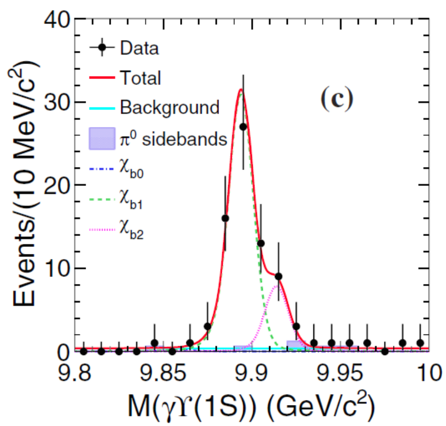
Search for X_b in $e^+e^- \to \gamma\pi^+\pi^-\pi^0\Upsilon(1S)$ at 10.867 GeV

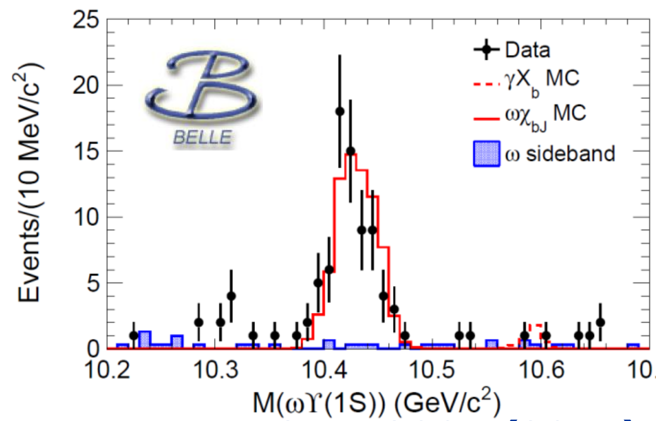
- The X(3872) counterpart in the bottomonium sector X_b, **NOT observed** decay channel $\pi^+\pi^-\Upsilon(1S)$.
- As X_b is above $\omega\Upsilon(1S)$ threshold, this Isospin-conserving process should be **a more promising decay mode**. [PRD88, 054007].



PLB 727, 57 (2013) .



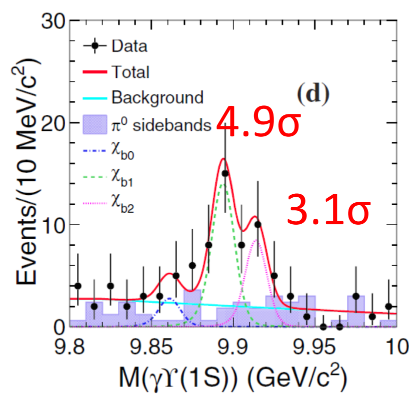




PRL 113, 142001 (2014)

- **Large Brs of Y(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 ?**

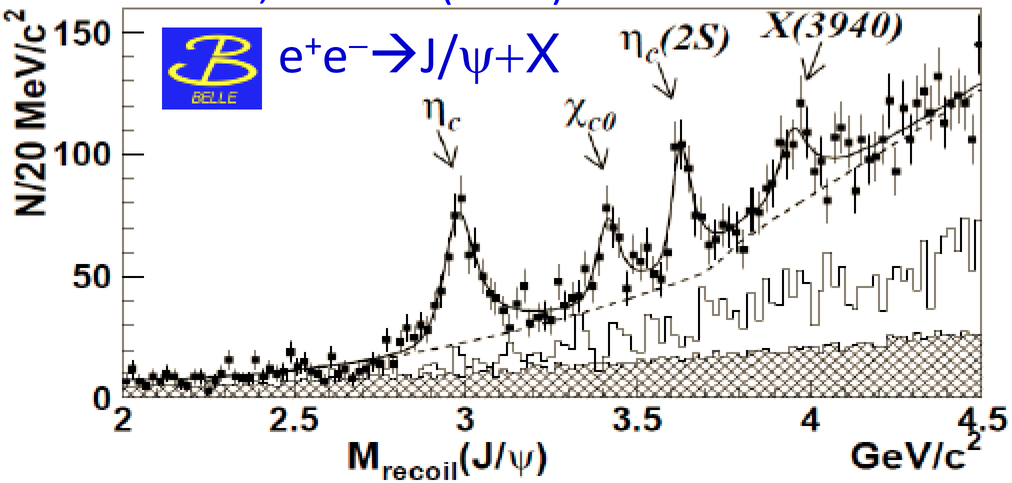
arXiv:1406.6763



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

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

PRL 98, 082001 (2007)



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

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

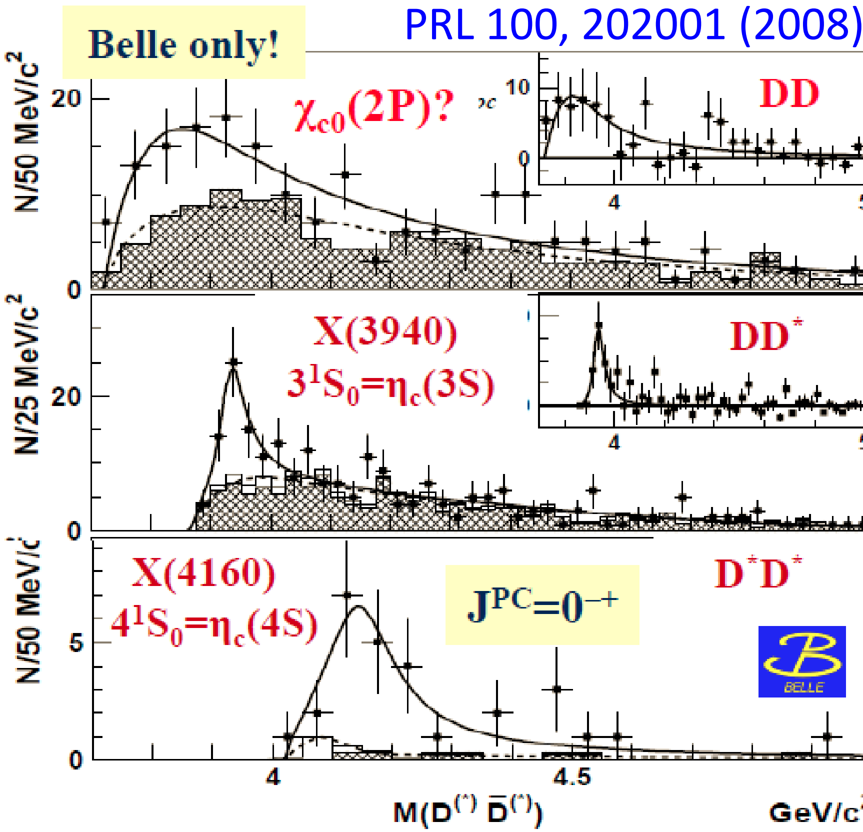
$X(4160) = 4^1S_0 = \eta_c(4S)$

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 $\eta_c(4S)$

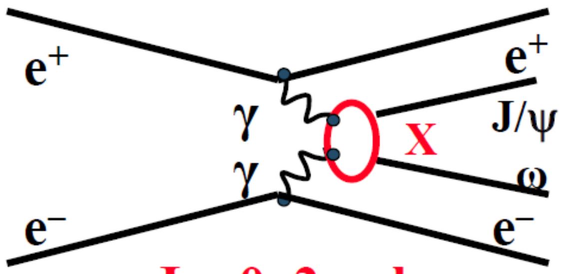
Theory probably needs more elaborate models to take into account charmonia couplings to meson pairs

PRL 100, 202001 (2008)

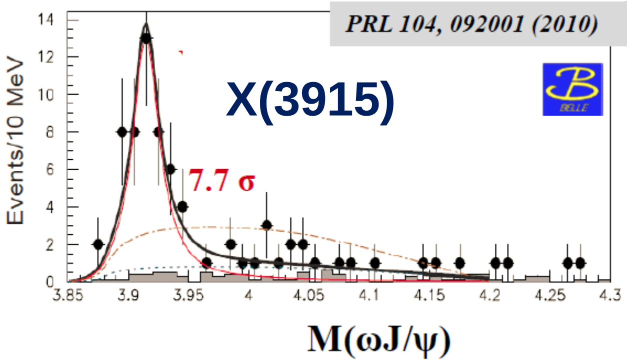


- Search for new states in $e^+e^- \to J/\psi D^{(*)}D^{(*)}\pi$ and in $e^+e^- \to \chi_{c1} D^{(*)}D^{(*)}$
- Production: reconstruction of the exclusive final states
- Production studies with other charmonium states (e.g. $\psi(2S)$, χ_{c1})

X*(3860) ($\chi_{c0}(2P)$)



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 $e^+e^- \to J/\psi DD$

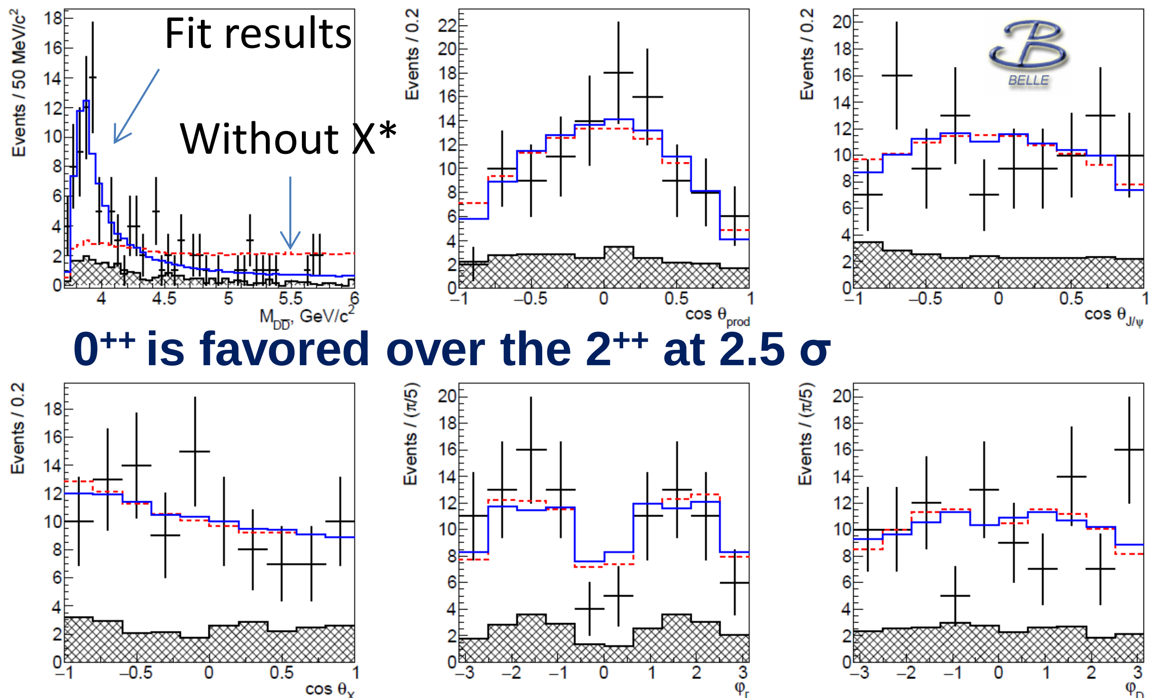
PDG 2016: X(3915)≠χ_{c0}(2P)

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
$\Gamma=201^{+154+88}_{-67-82}$ MeV
The parameters of X*(3915) are <2.7σ difference from the predicted χ_{c0}(2P)

23

If X(3915) ≠ χ'_{c0}, what is it?

It remains an intriguing puzzle

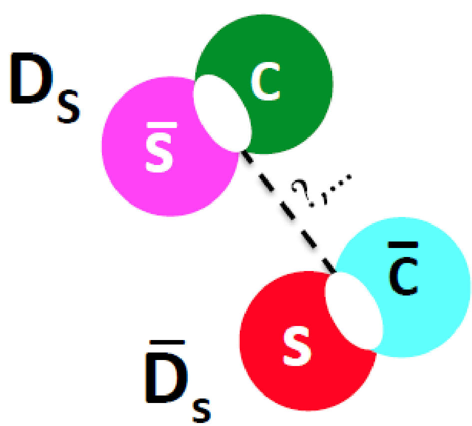
X(3915)→ωJ/ψ violates OZI-rule unless it's a 4-quark state

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

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

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

Li & Voloshin, PRD 91, 114014

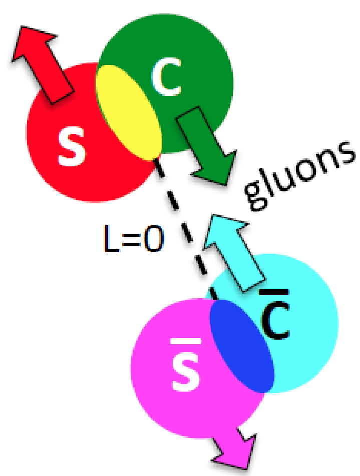


what binds it?

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

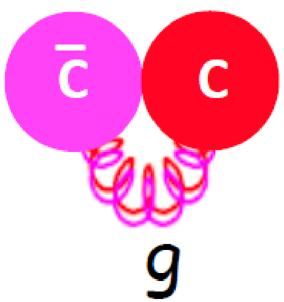
[$\bar{c}\bar{s}$][cs] tetraquark?

Lebed & Polosa, PRD 93, 094024



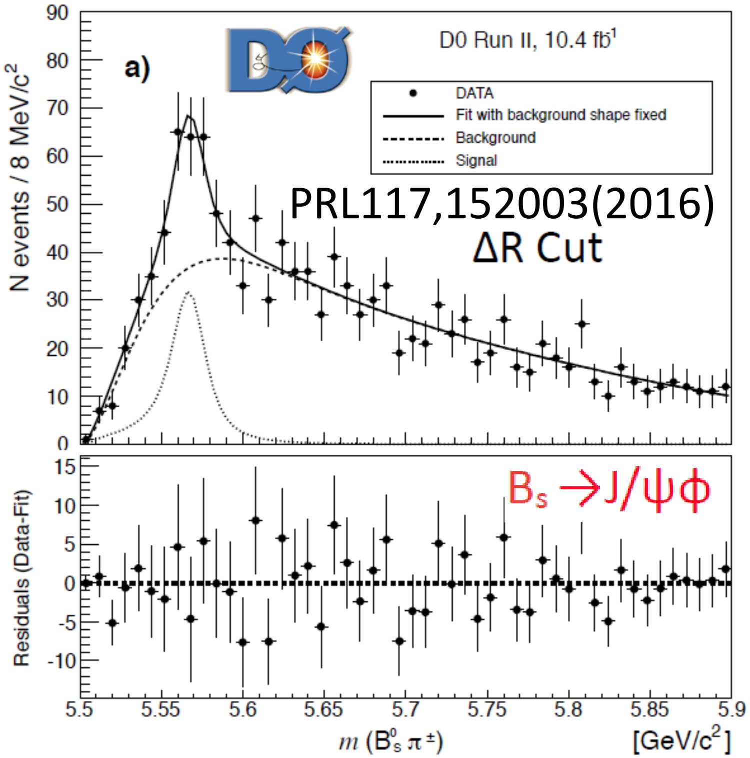
why not X→$\eta\eta_c$?

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



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

X(5568)



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

$$\underline{X(5568)}$$

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

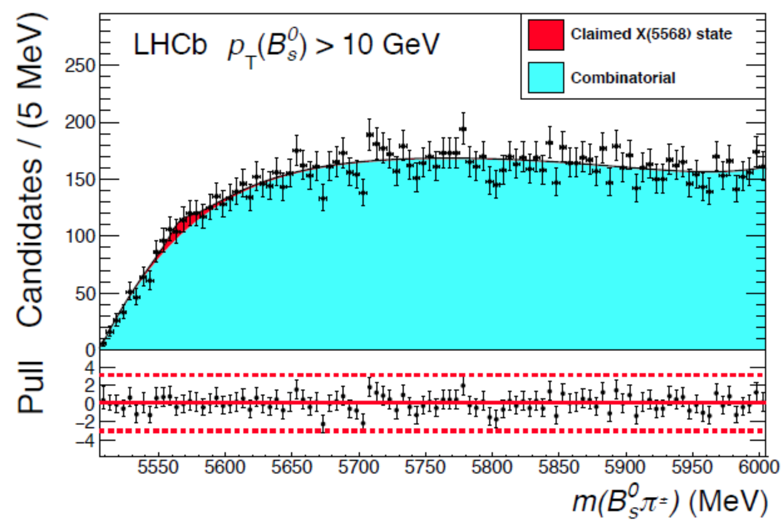
$$\Gamma_X = 21.9 \pm 6.4\,(\text{stat})^{+5.0}_{-2.5}\,(\text{syst})\,\text{MeV}/c^2$$

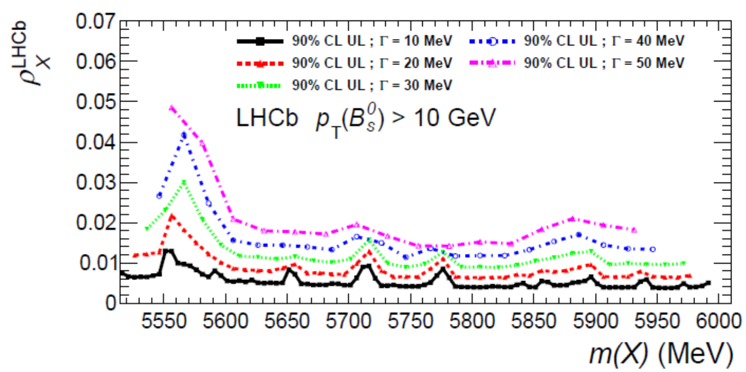
$$\rho = [8.6 \pm 1.9\,(\text{stat}) \pm 1.4\,(\text{syst})]\,\%$$

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

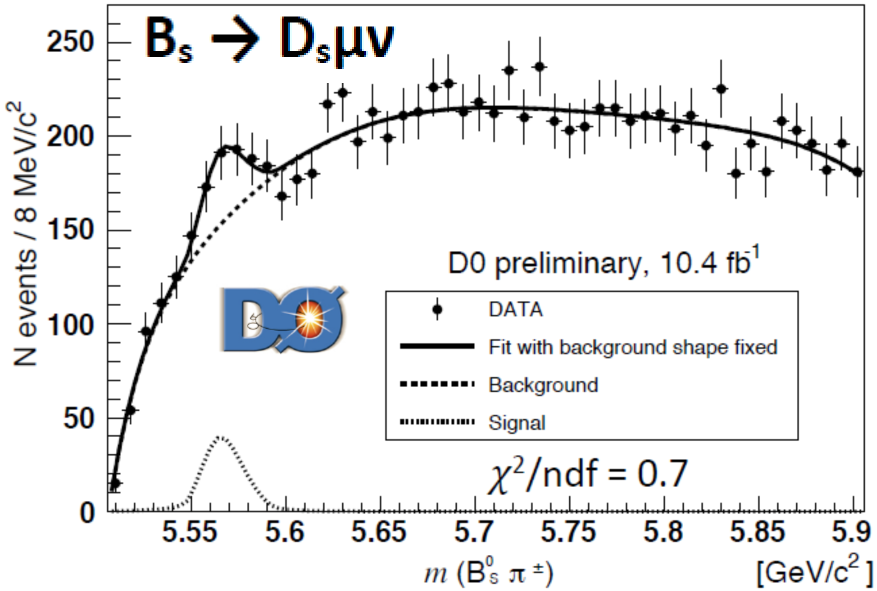
PRL117, 152003 (2016)

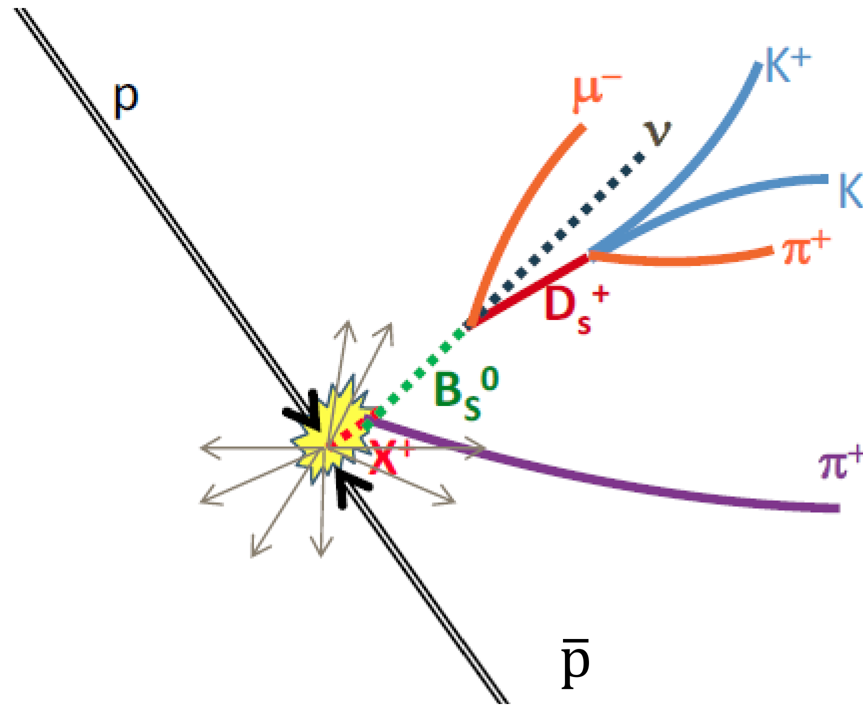




X(5568)

D0 Conference Note 6494





$$\underline{X(5568)}$$

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

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

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

Local Signficance

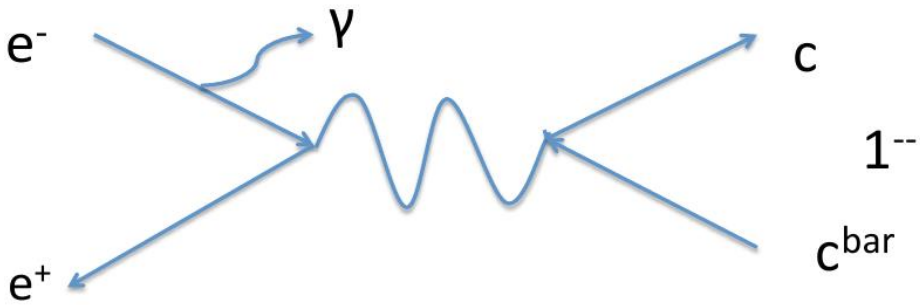
$$\sqrt{-2\ln\frac{\mathcal{L}_0}{\mathcal{L}_{\max}}}$$

Statistical Significance 4.5 σ.
Including Systematics 3.2 σ.

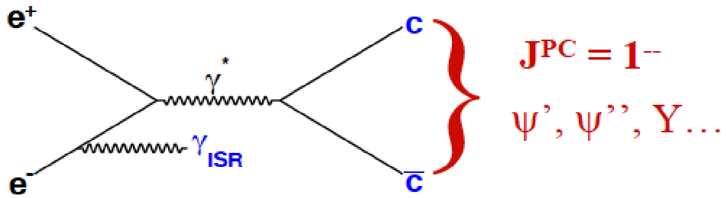
Y States

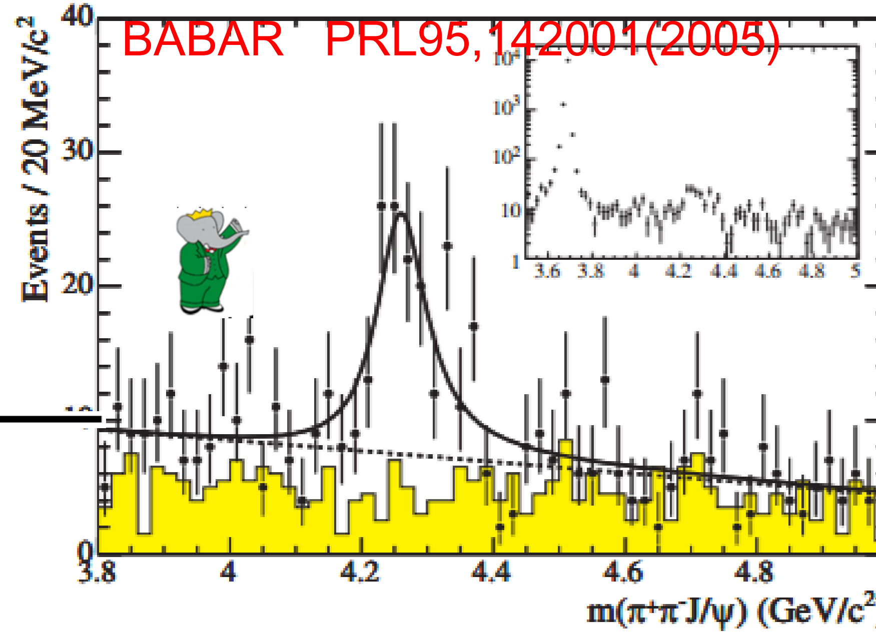
Y(4260), Y(4360), Y(4660)…

Observed in the e+e- annihilation (with ISR)



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

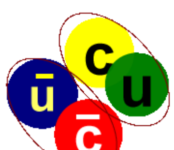




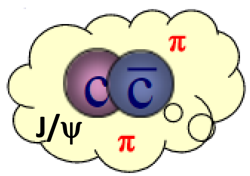
X(4260)

$I^G(J^{PC}) = ?^?(1^{--})$

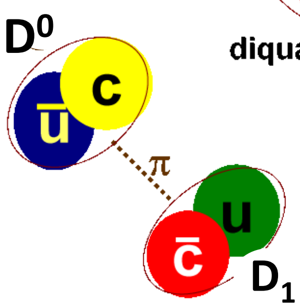
X(4260) MASS	4251 ± 9	PDG AVERAGE
X(4260) WIDTH	120 ±12	PDG AVERAGE



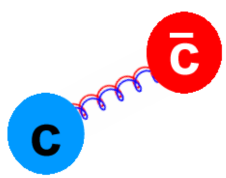
diquark-diantiquark



Hadro-charmonium



$D^0 - D_1$ “molecule”



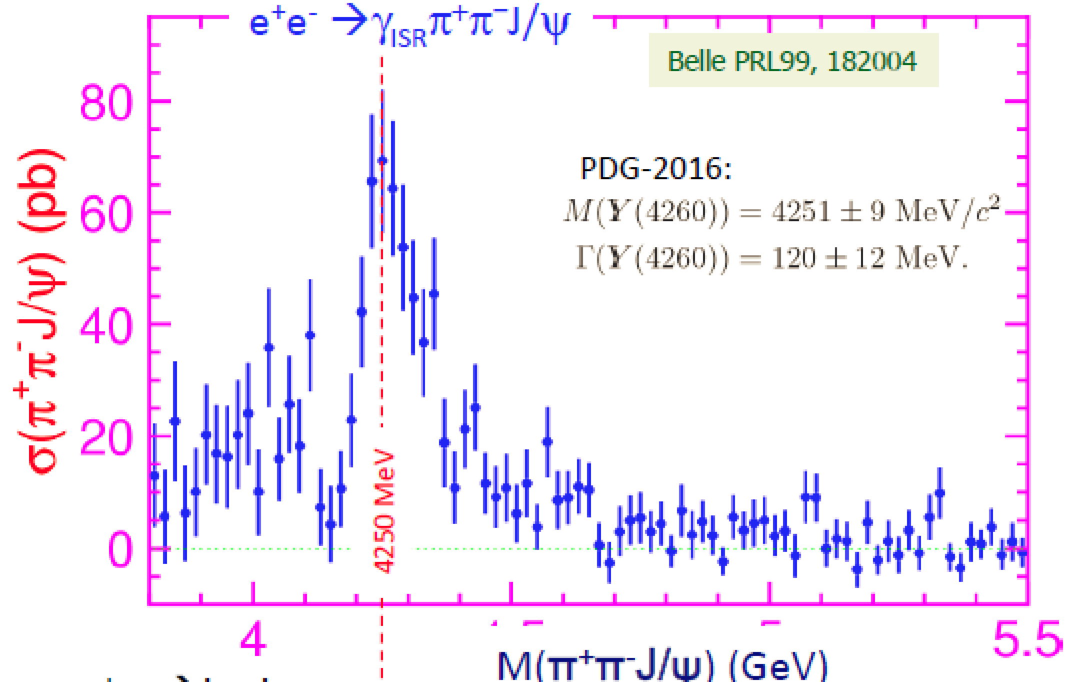
$q\bar{q}$-gluon“hybrid”

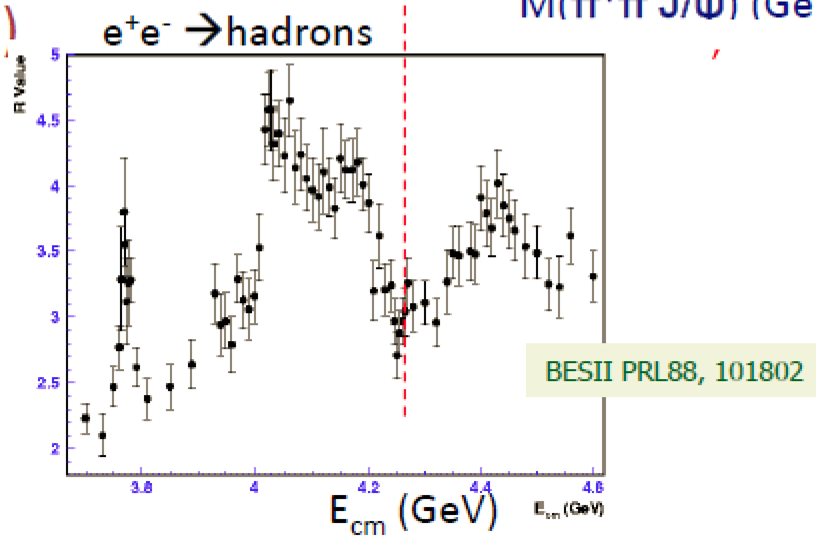
Y(4260) → $\pi^+\pi^- J/\psi$ confirmed by Belle

no sign of Y(4260) → $D^{(*)}\bar{D}^{(*)}$

Y(4260) peak in $\sigma(\pi^+\pi^- J/\psi)$ occurs at a dip in $\sigma(D^{(*)}\bar{D}^{(*)})$

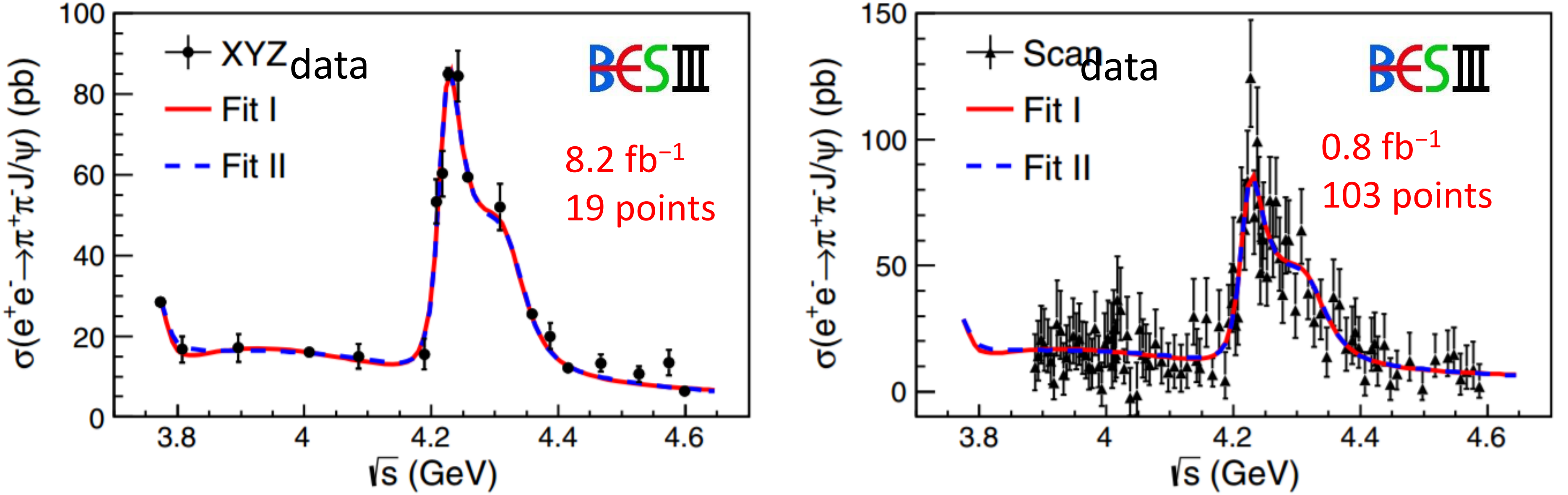
$\Gamma(\pi^+\pi^- J/\psi)$ is large, but should be OZI suppressed if $c\bar{c}$





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

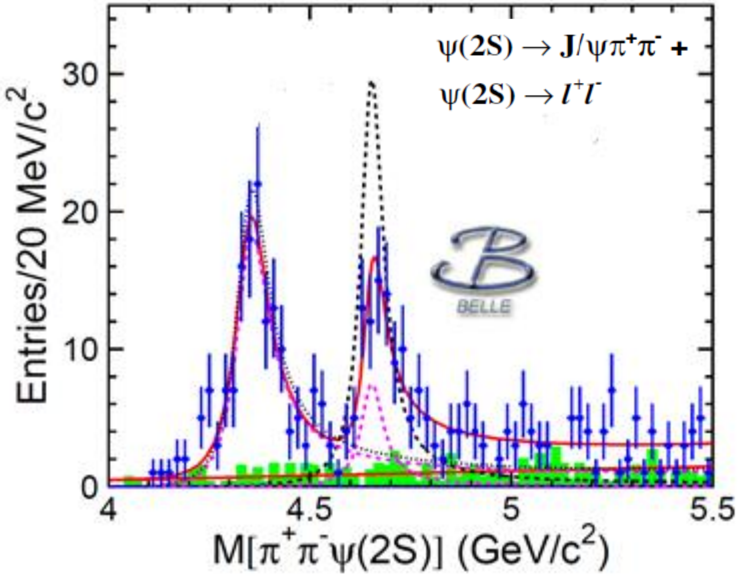
- A 2nd resonance Y_2 with M=4320.0±10.4±7.0 MeV/c^2
  $\Gamma=101.4^{+25.3}_{-19.7}\pm 10.2$ MeV
- Observed for the first time, significance > 7.6σ

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

PRD 91, 112007 (2015)

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

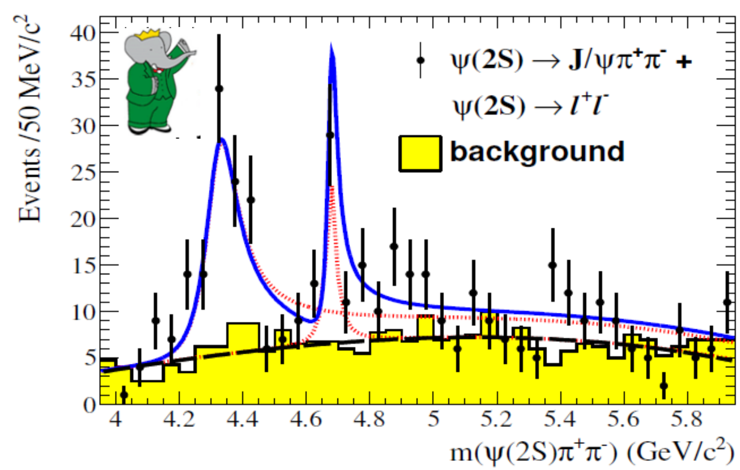
$Amp = BW_1 + e^{i\phi} \cdot BW_2$



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 (°)	$32 \pm 18 \pm 20$	$272 \pm 8 \pm 7$

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

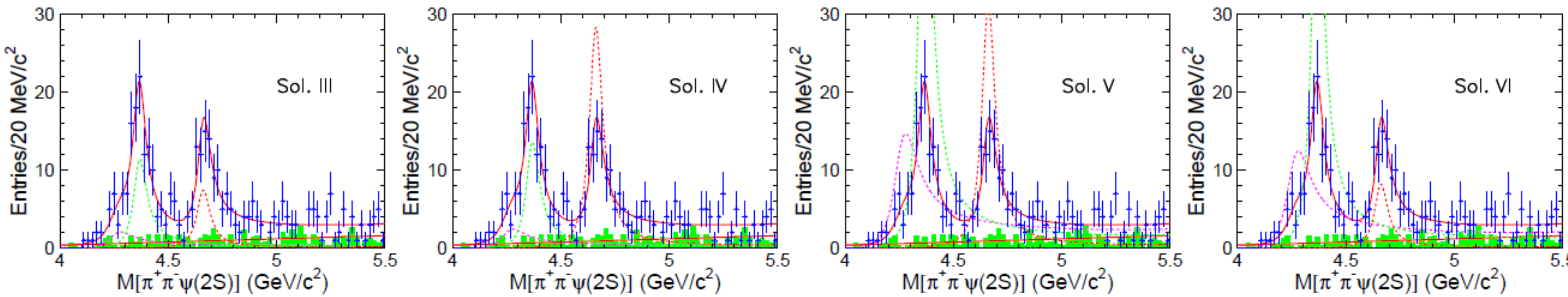
- Consistent with previous measurement
- No obvious signal above $Y(4660)$.
- Some events accumulate at $Y(4260)$, especially the $\pi^+\pi^- J/\psi$ mode.
- If $Y(4260)$ is included in the fit, ...



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 $\chi^2/ndf = 14.8/19$.

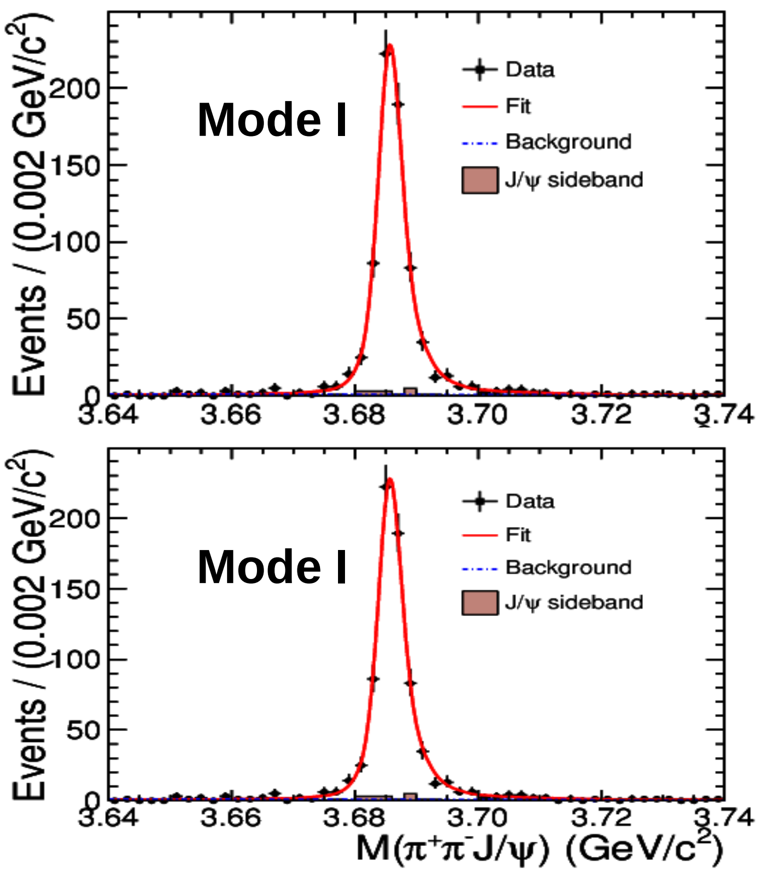
Comparsion of $e^+e^- \to \pi^+\pi^-\psi(2S)$ cross section

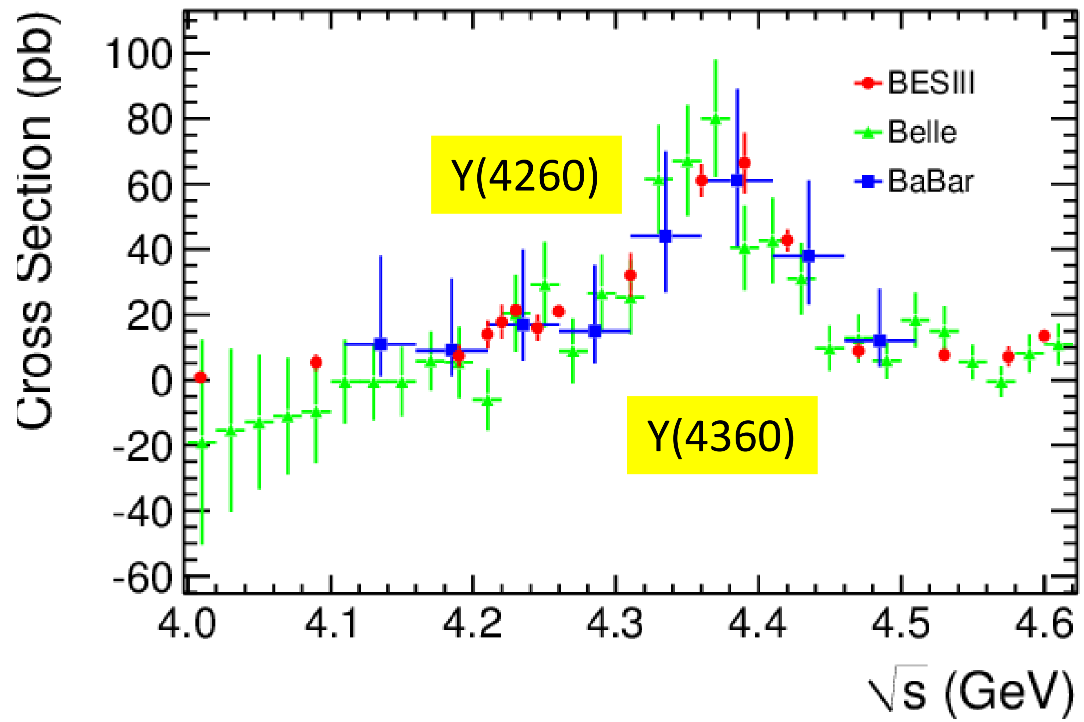
BESIII (16 energy points; L_{tot}=5.1fb^{-1})

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

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

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





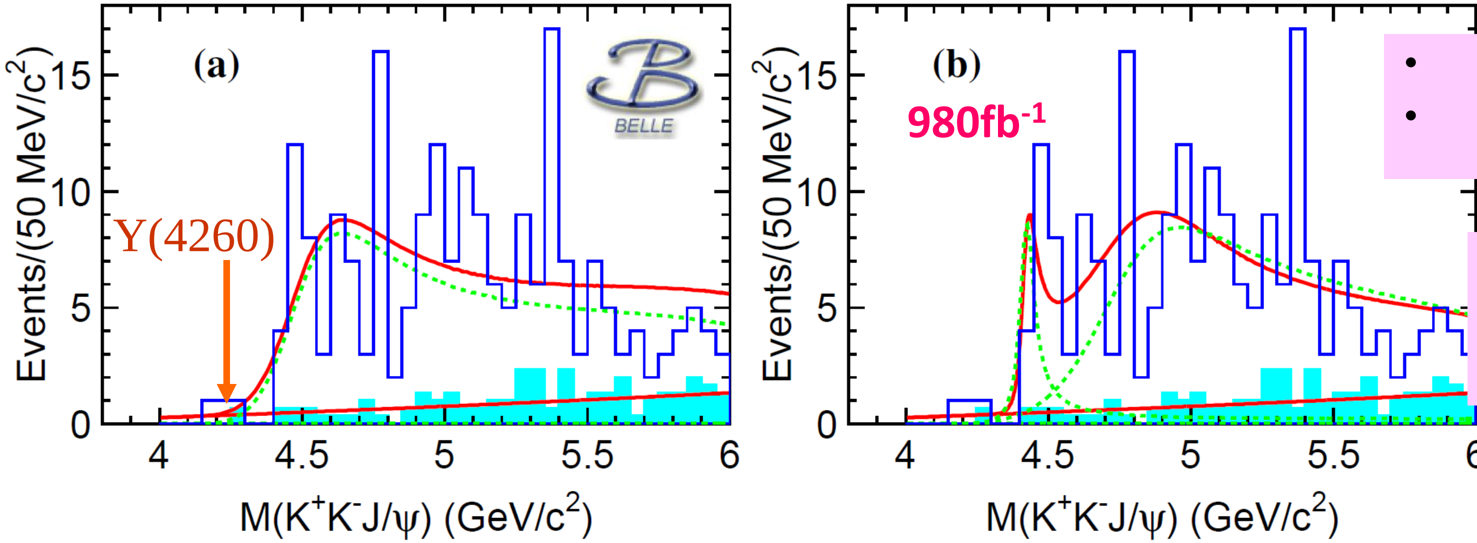
The measured Born cross sections of two modes are combined by considering the correlated and uncorrelated uncertainties.

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



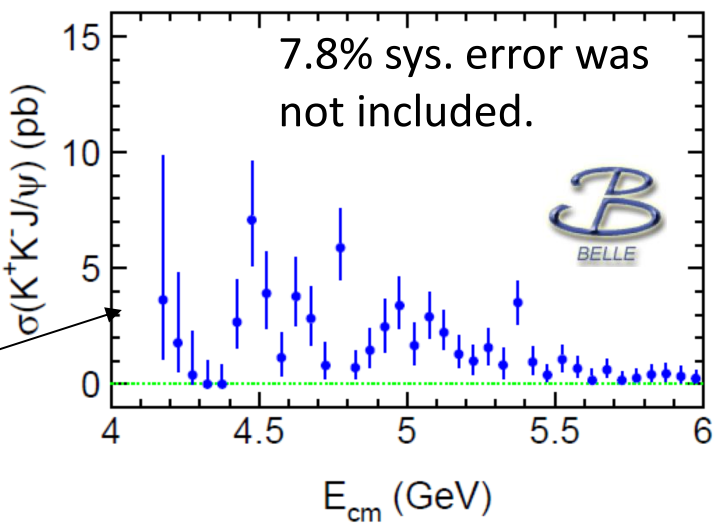
- +one resonance.
- Fit with $\psi(4415)$

$\chi^2/ndf=30/11$

- M=4747±117MeV
- Γ=671±86 MeV

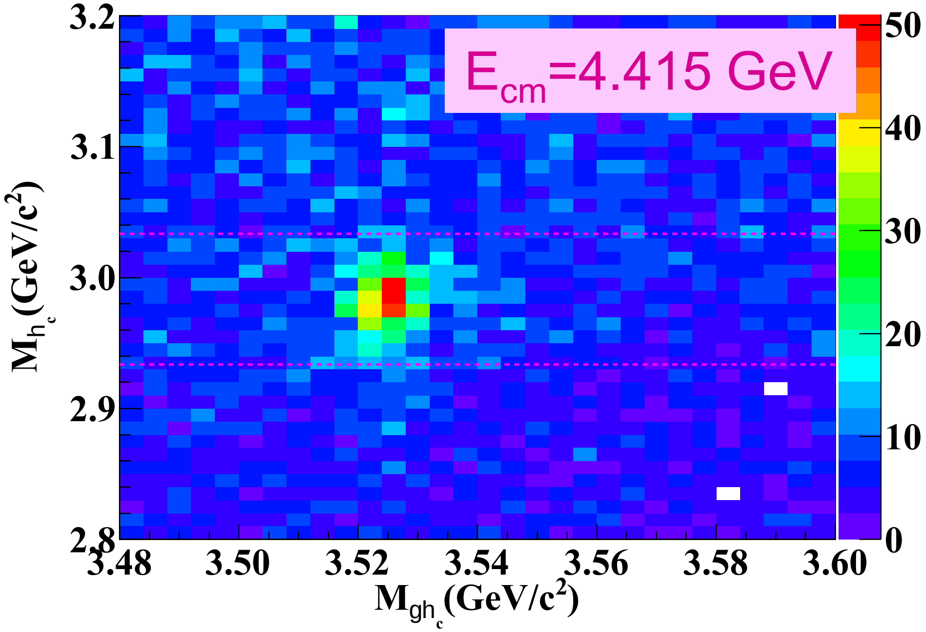
4-6 GeV: 213 events
35 bkg, 178±16 signal

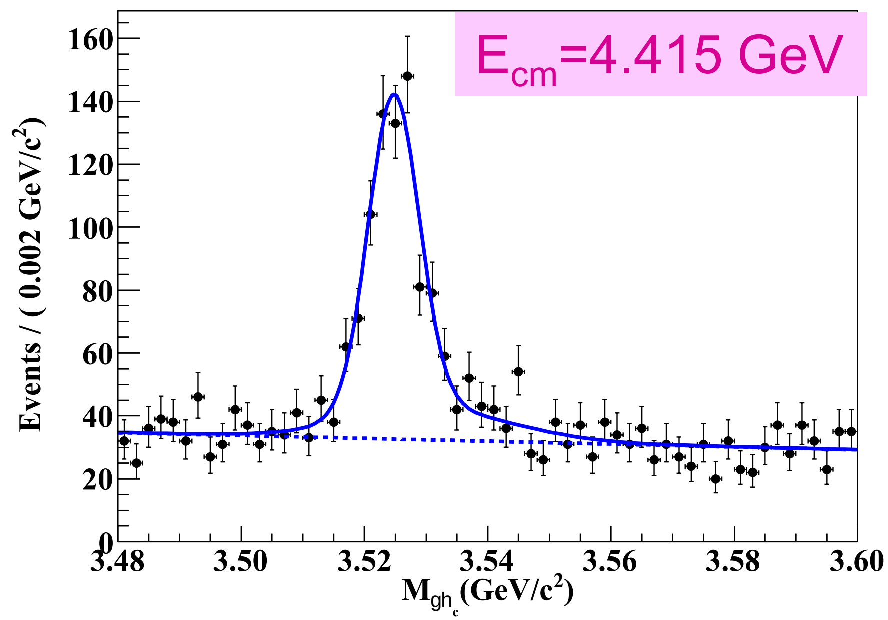
$$\sigma_i = \frac{n_i^{\mathrm{obs}} - f \times n_i^{\mathrm{bkg}}}{\mathcal{L}_i \cdot \epsilon_i \cdot \mathcal{B}(J/\psi \to \ell^+\ell^-)}$$



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

- $h_c \to \gamma\eta_c$, $\eta_c \to$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., $K^+K^-\pi^0$
  - $pp\pi^0$, $K^+K^-\eta$, $\pi^+\pi^-\eta$, $\pi^+\pi^-\pi^0\pi^0$, $2(\pi^+\pi^-)\eta$, $2(\pi^+\pi^-\pi^0)$

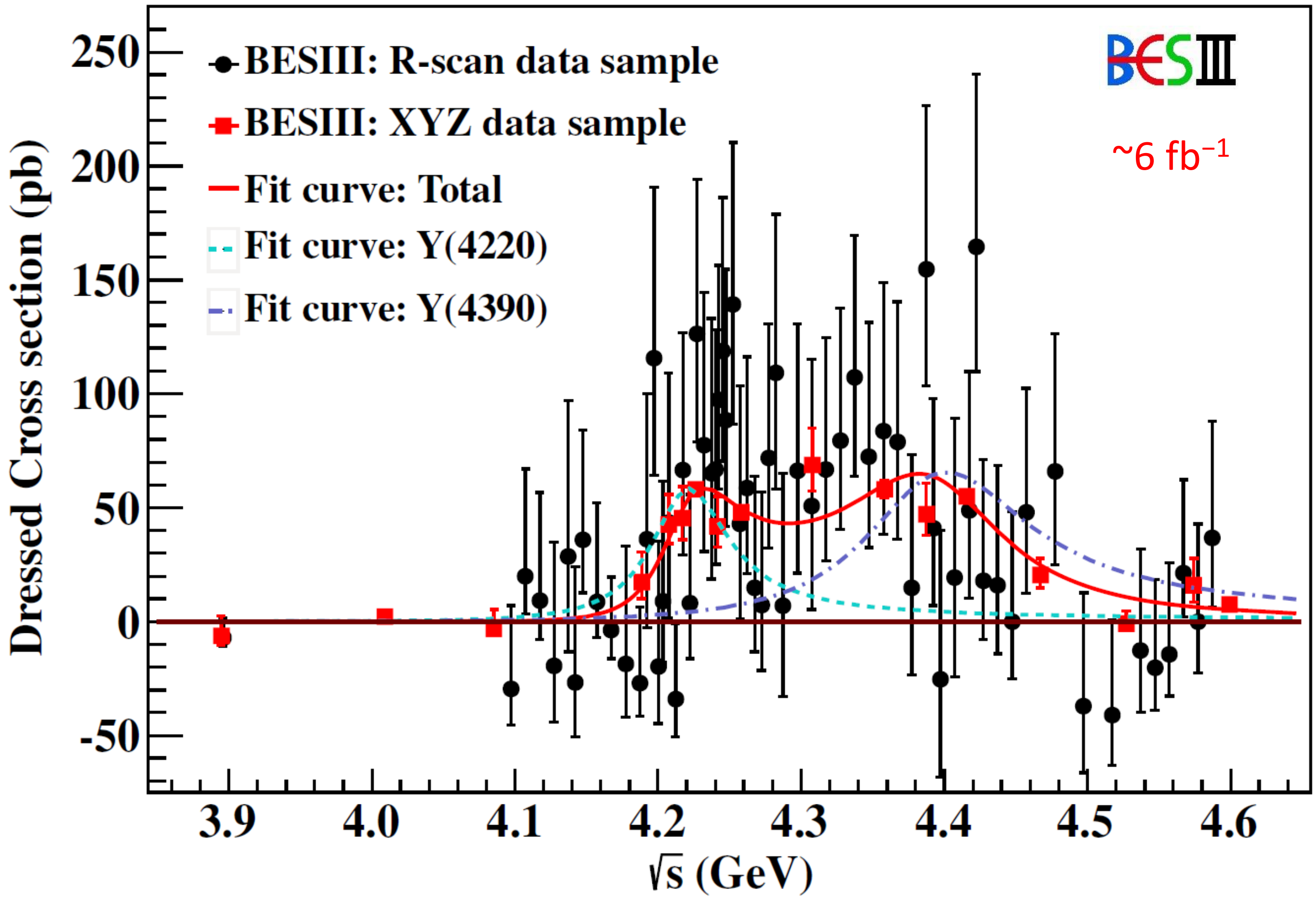




Method same as in PRL111, 242001 (2013)

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

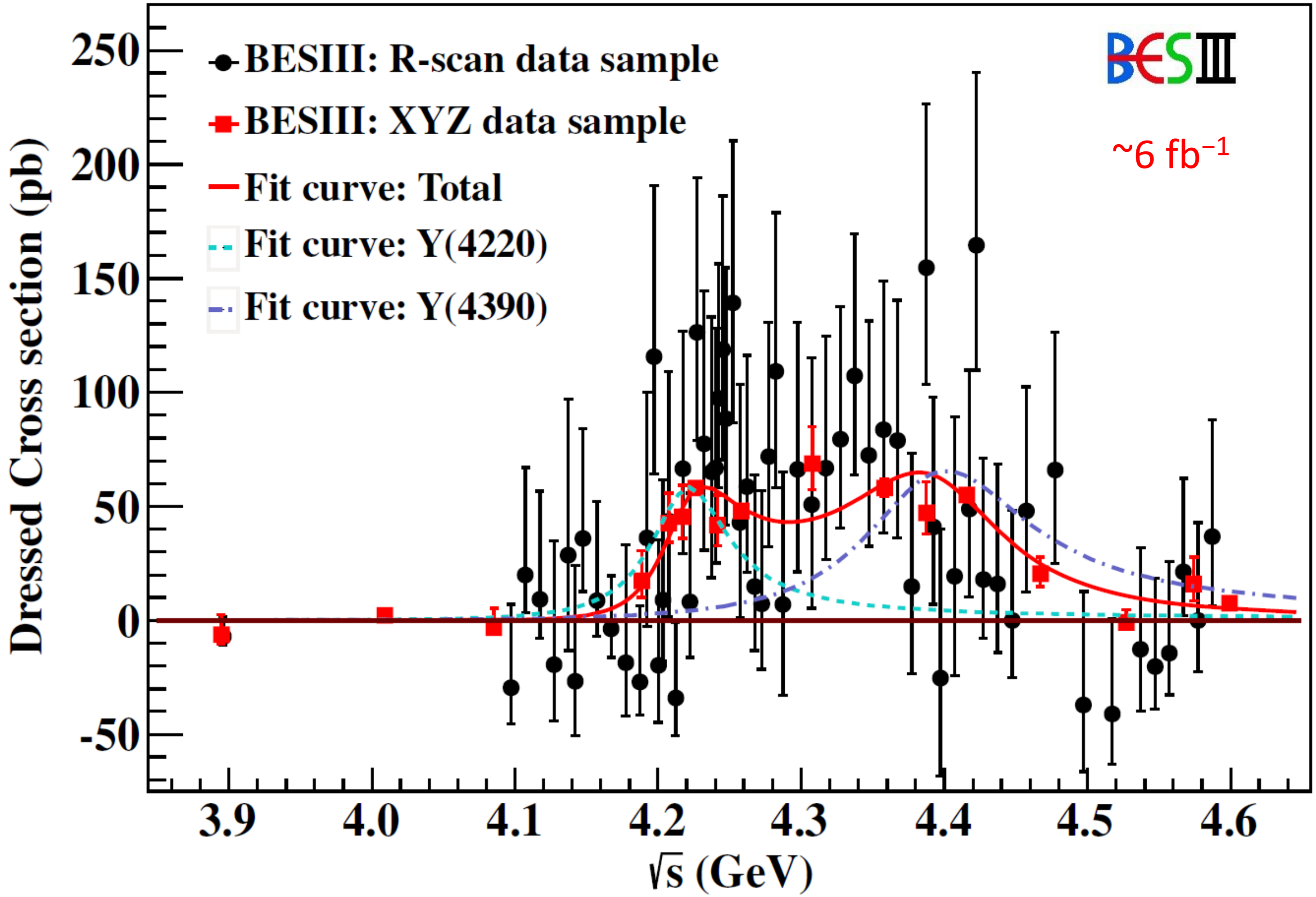
PRL118, 092002 (2017)



- 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

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

PRL118, 092002 (2017)

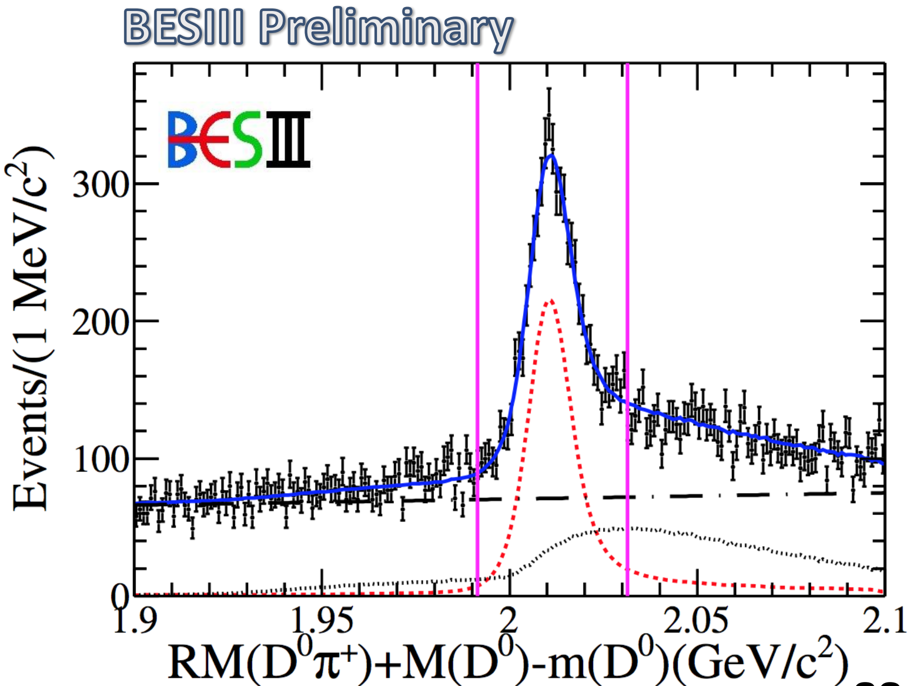


- $M_1 = 4218.4^{+5.5}_{-4.5} \pm 0.9$ MeV/c^2, $\Gamma_1 = 66.0^{+12.3}_{-8.3} \pm 0.4$ MeV → Y(4220)
- $M_2 = 4391.5^{+6.3}_{-6.8} \pm 1.0$ MeV/c^2, $\Gamma_2 = 139.5^{+16.2}_{-20.6} \pm 0.6$ MeV → Y(4390)

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

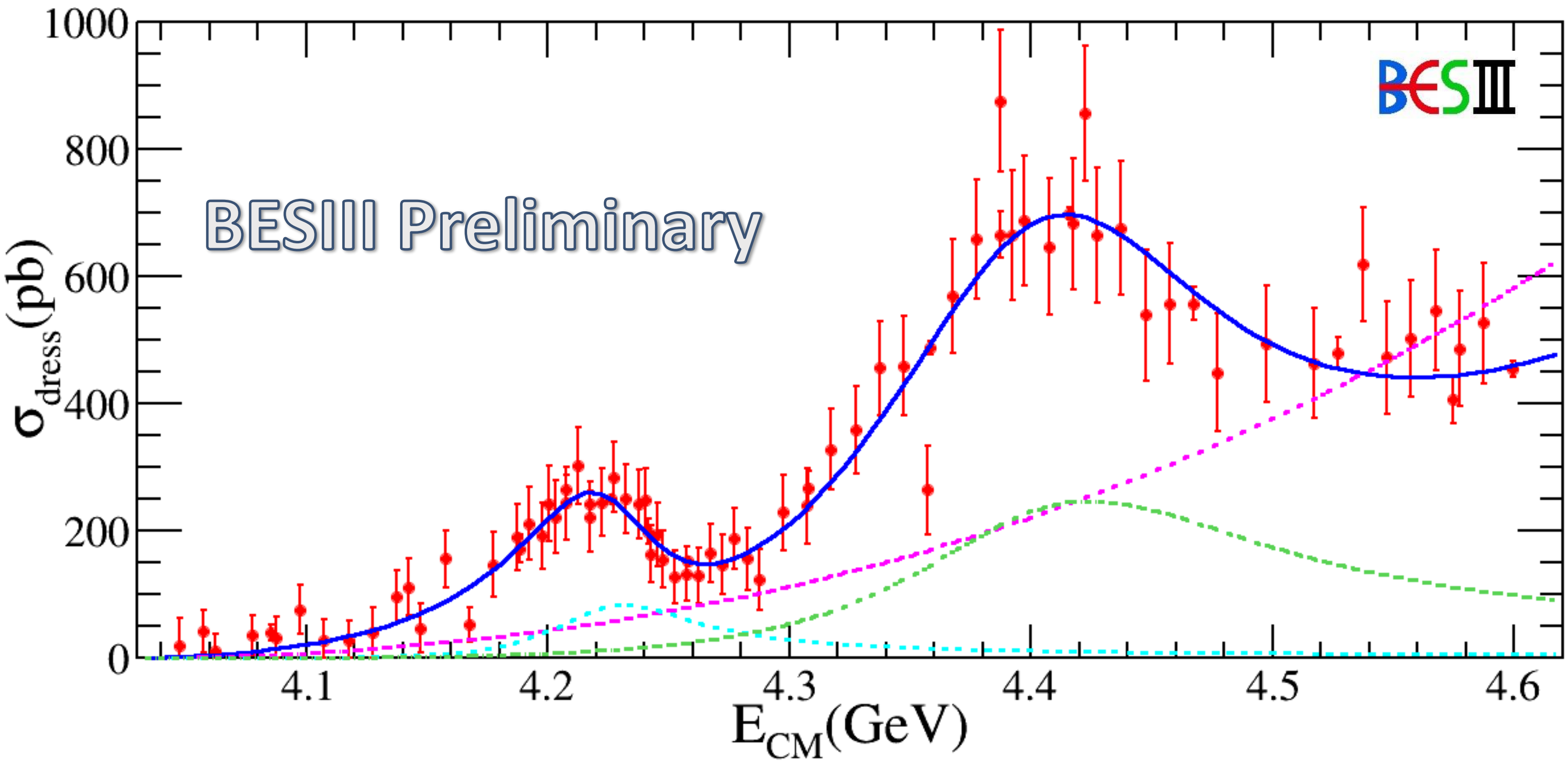
- An un-binned maximum likelihood fit
- Signal shape: MC convoluted with a Gaussian;
- The isospin partner background (dotted line) is parameterized with MC;
- A linear function for other bkg



Fit to the dressed cross section 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

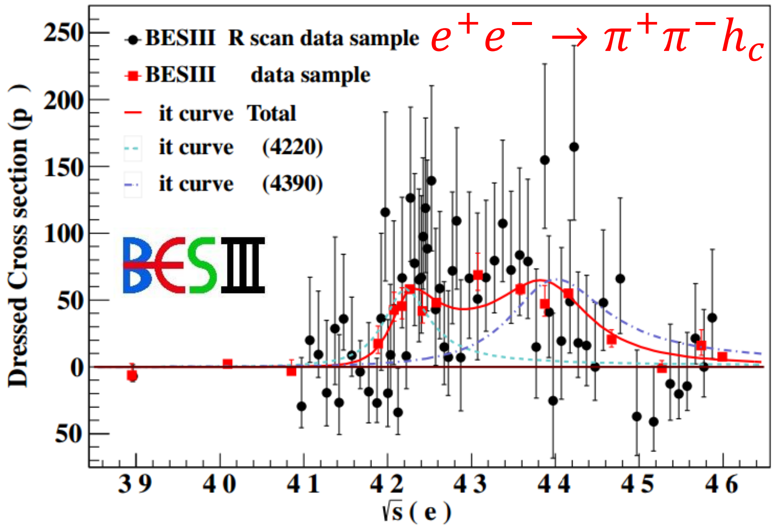
The error are statistical only.

BESIII Preliminary

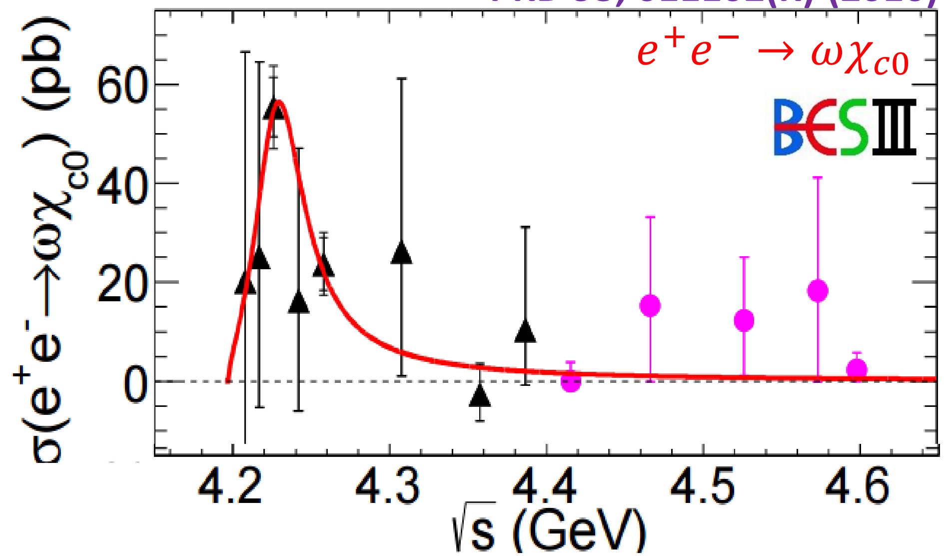
- Statistical significance is greater than 10σ.
- Consistent with those of Y(4220) and Y(4390) in $e^+e^- \to \pi^+\pi^-h_c$.

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

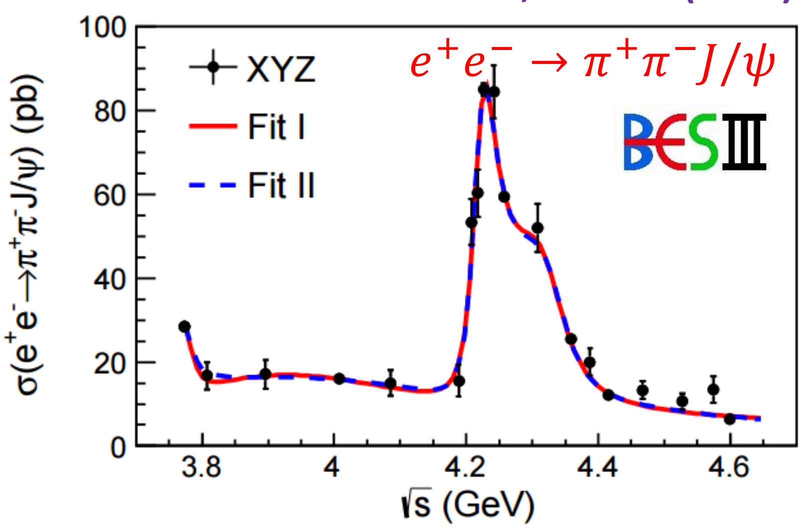
PRL 118, 092002 (2017)

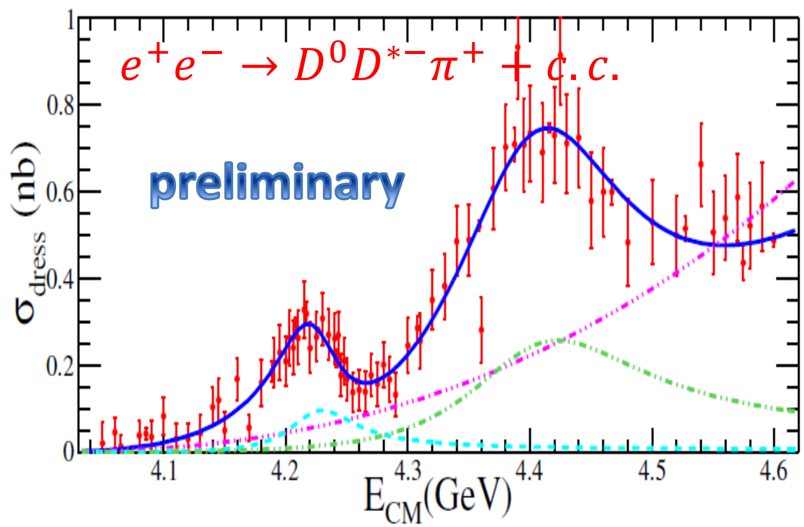


PRD 93, 011102(R) (2016)



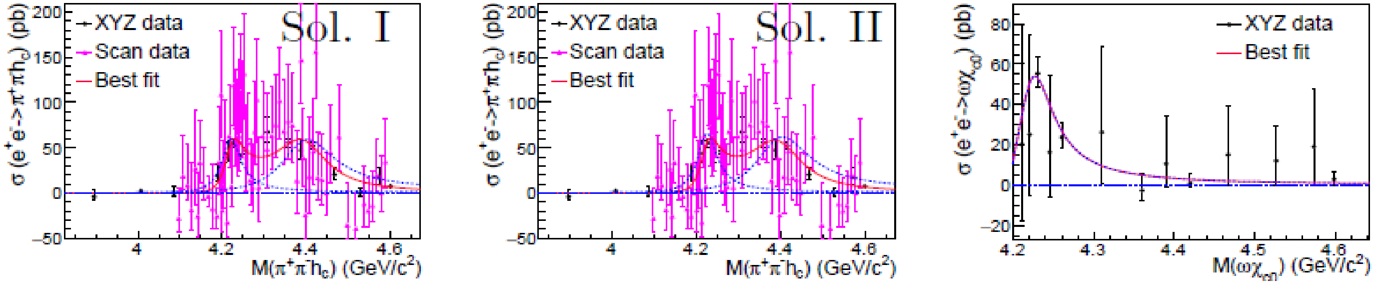
PRL118, 092001 (2017)



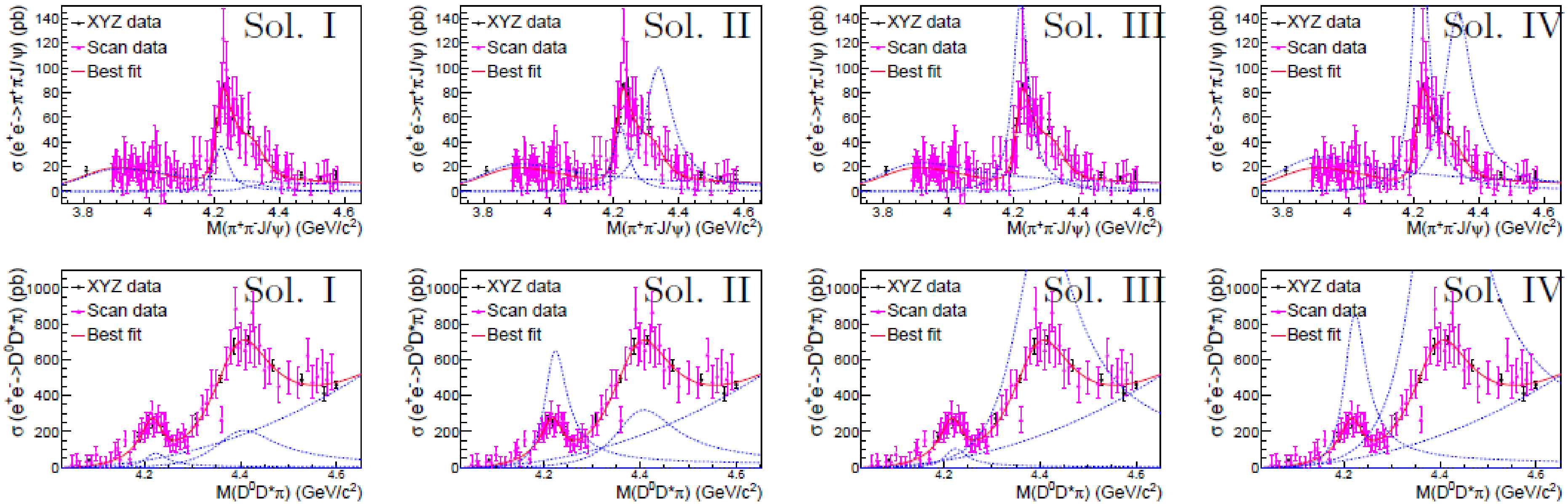


All above four channels show a structure at around 4.22 GeV/c^2.

Combined fit to understand the Y(4220) better



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



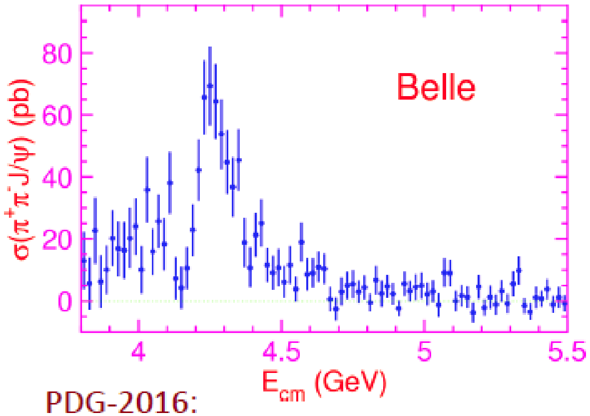
$M = 4219.6 \pm 3.3(stat) \pm 5.1(sys)$ MeV/c^2

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

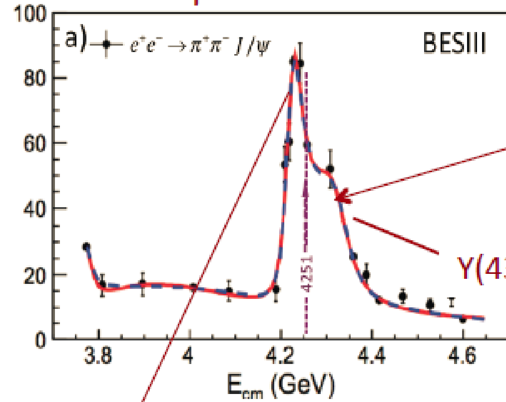
A combined fit is performed to extract the resonant parameters of the Y(4220) assuming it decays dominantly to the above four modes and their isospin symmetric modes

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

pre-2017

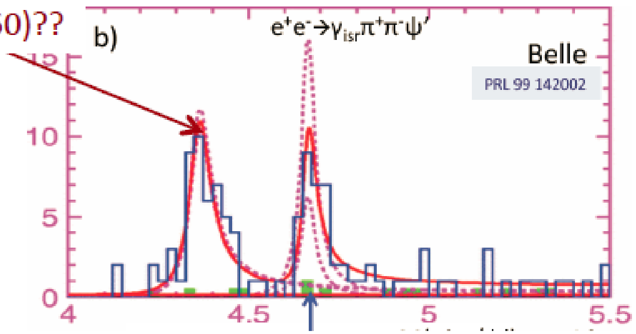


post-2017



what is the 2nd peak?

Y(4360)??



PDG-2016:

$M(Y(4260)) = 4251 \pm 9$ MeV$/c^2$ —(-31 MeV)→ $M_1 = 4220 \pm 4$ MeV$/c^2$

$\Gamma(Y(4260)) = 120 \pm 12$ MeV. —(×⅓)→ $\Gamma_1 = 44 \pm 5$ MeV

Y(4220) decay modes:

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

$M_2 = 4320 \pm 13$ MeV$/c^2$ —(δM≈-1.8σ)→ $M(Y(4360)) = 4346 \pm 6$ MeV$/c^2$

$\Gamma_2 = 101^{+27}_{-22}$ MeV —(spot on)→ $\Gamma(Y(4360)) = 102 \pm 12$ MeV.

Y(4320) decay modes:

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

What is the Y(4260)?

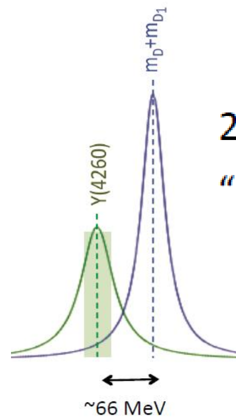
The Y(4260) mass is lower and width narrower than previously thought

"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

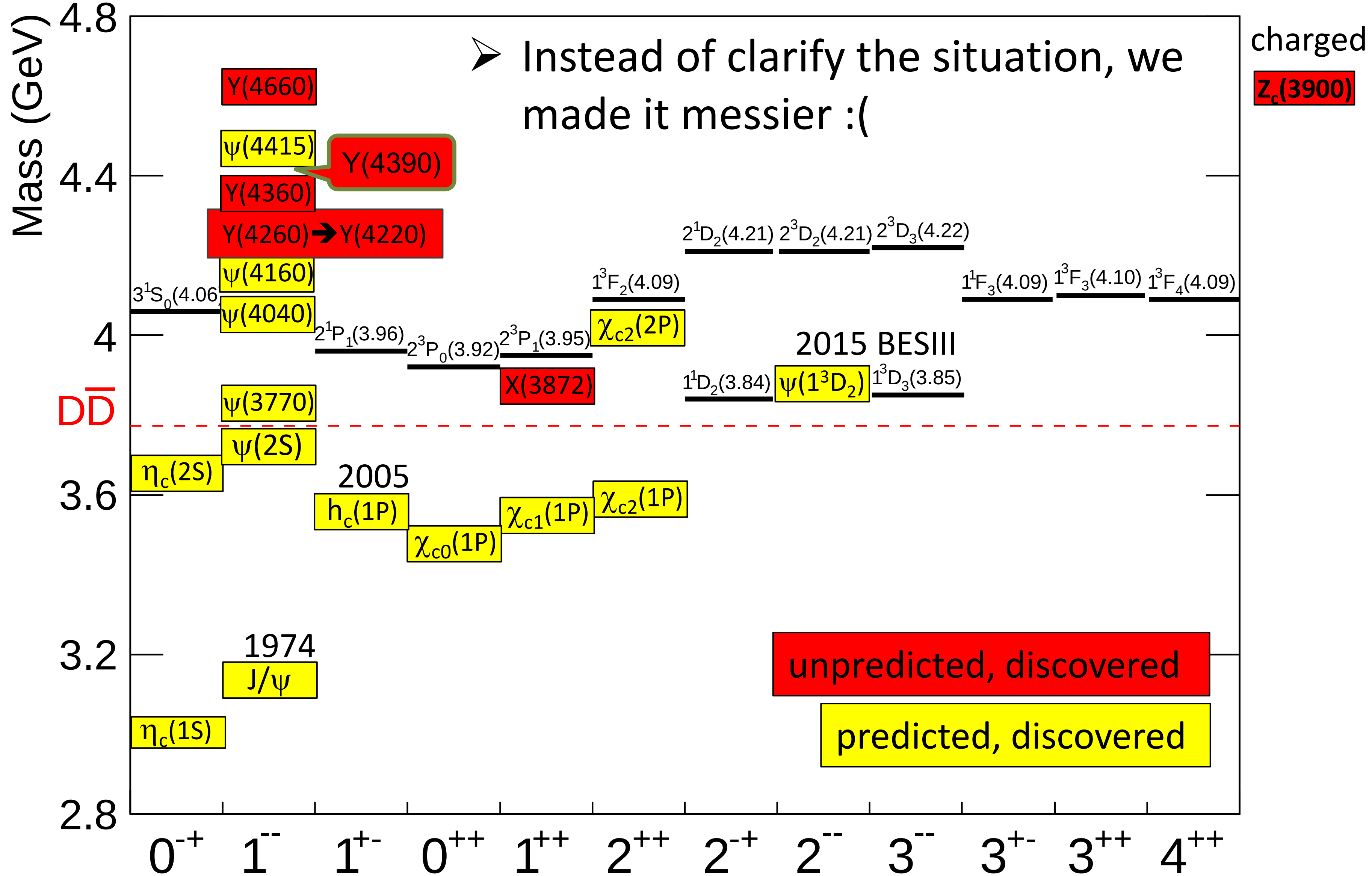
Dubynskiy & Voloshin, PLB 666, 344

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

Charmonium(like) spectroscopy



Godfrey & Isgur, PRD32, 189 (1985)

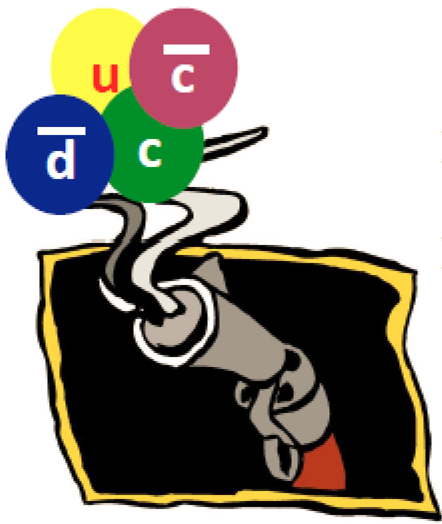
Z States

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

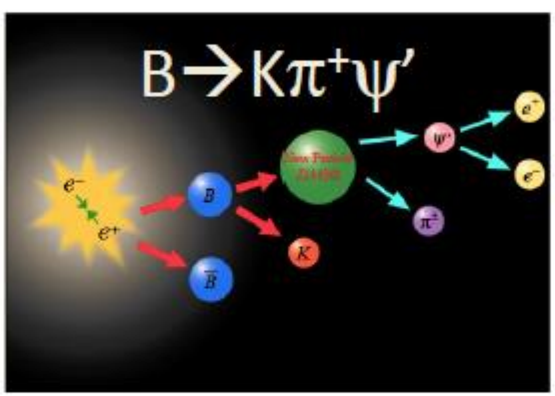
Observed in B decays and in decays of Y states

The $Z(4430)^+ \to \pi^+ \psi'$

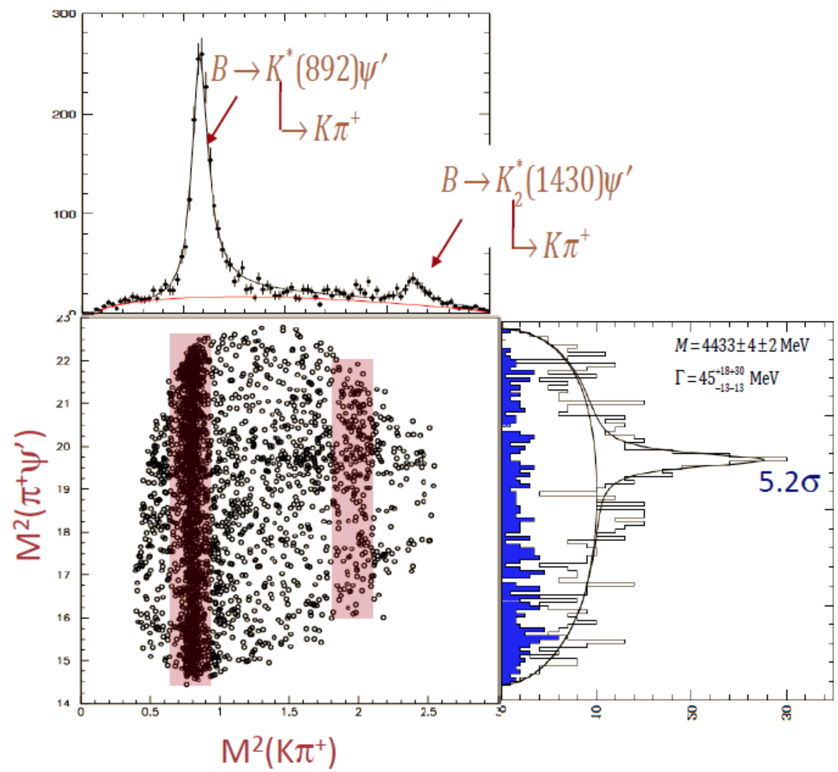
"smoking gun" evidence for a 4-quark meson



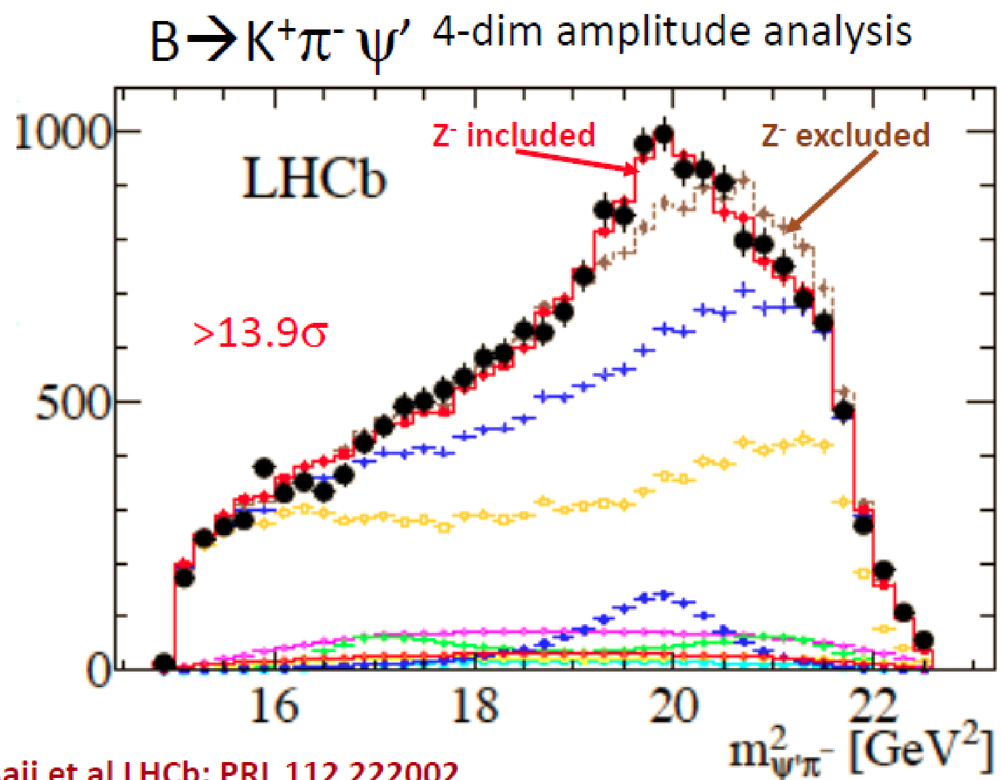
- decays to ψ′ ➔ must contain $c\bar{c}$ pair
- electrically charged ➔ must contain $u\bar{d}$ pair



S-K Choi et al Belle: PRL 100 142001



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



R. Aaij et al LHCb: PRL 112 222002

$$J^P = 1^+$$

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

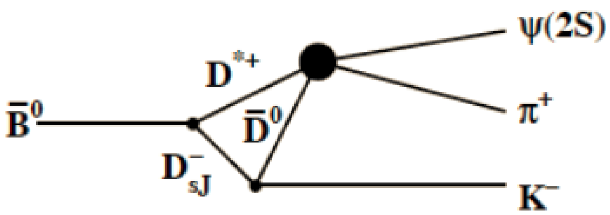
$$\Gamma = 172 \pm 13^{+37}_{-34}\ \text{MeV}$$

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)?

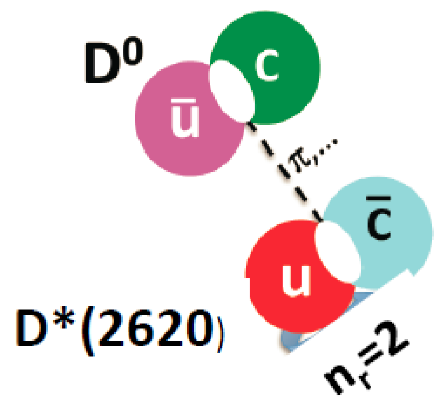
Kinematic effect due to $D^*\bar{D}$ rescattering?



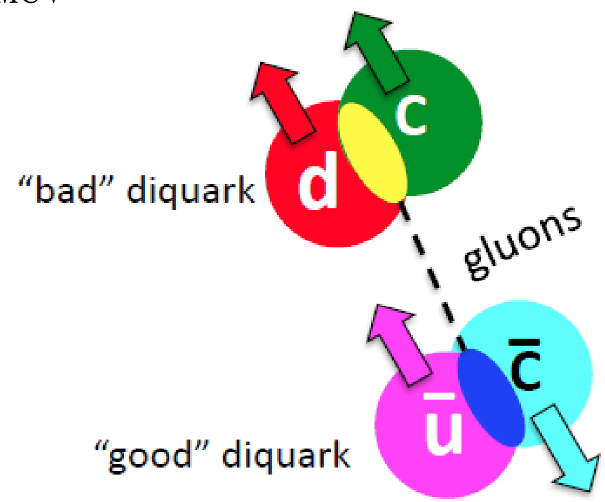
Pakhlov &Uglov, PLB 183 (2015)

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

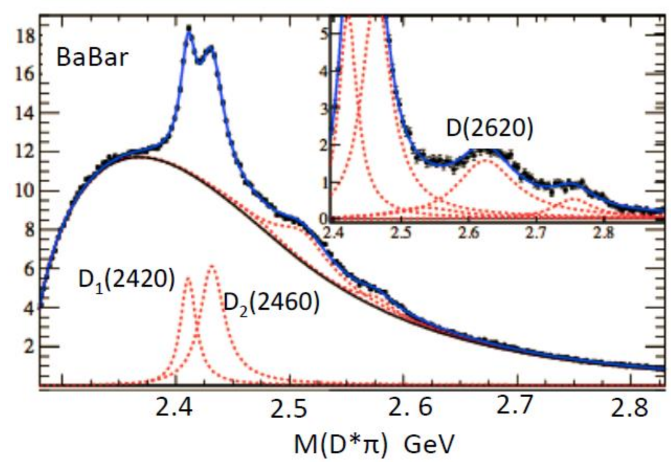
Bingding energy=20±30 MeV



tetraquark formed with a radially excited diquark



BaBar: Phys. Rev. D82, 111101

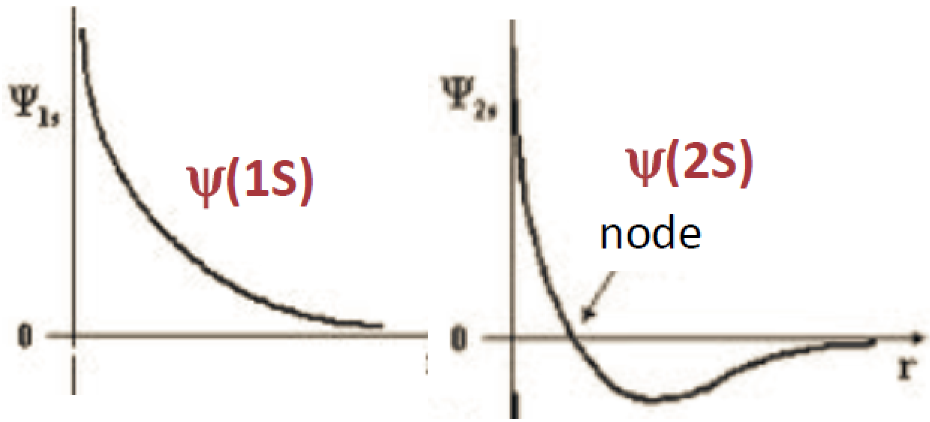


one of the diquarks is is in an n_r=2, radially excited state.

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

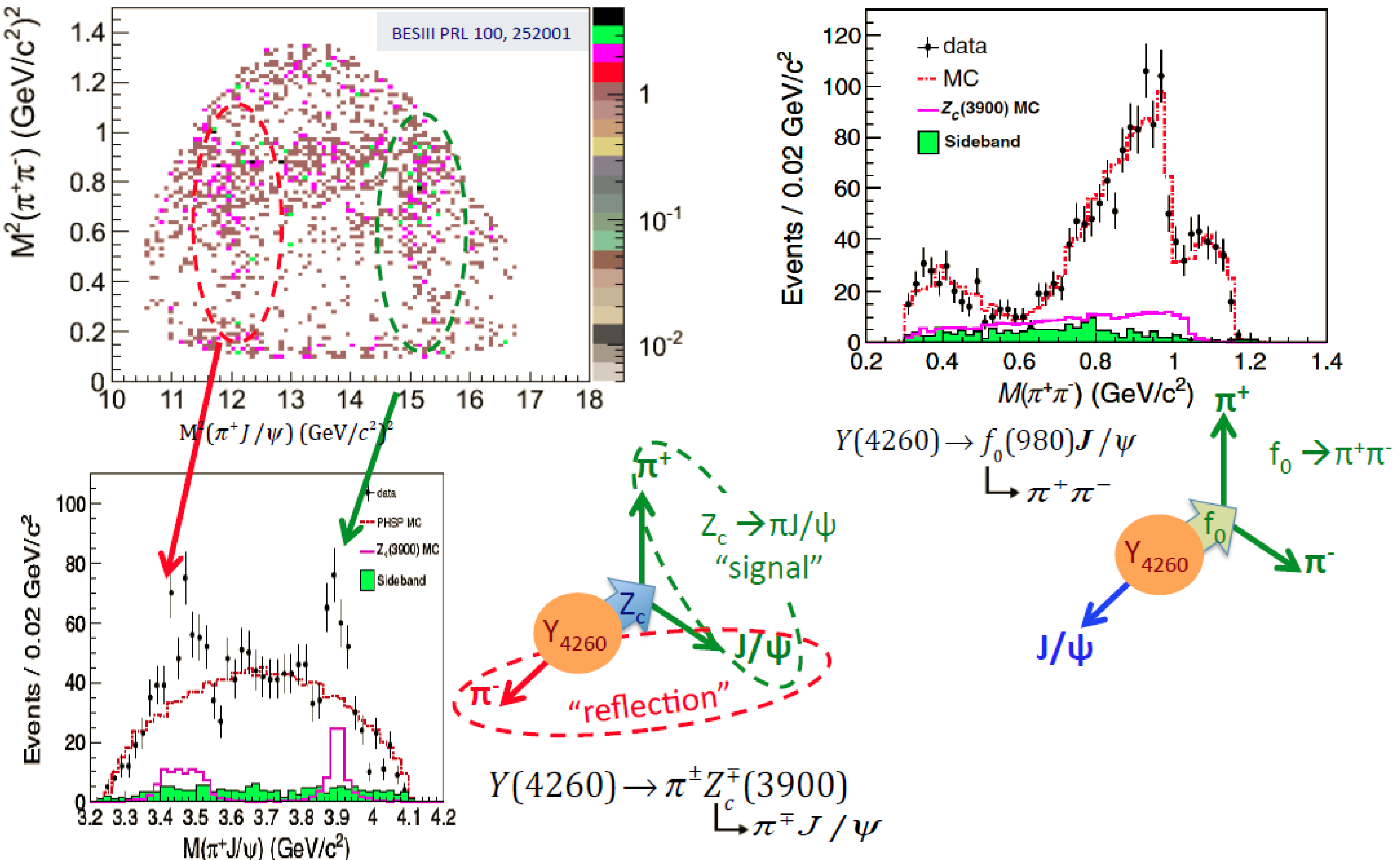


The $c\bar{c}$ part of the wave function of the Z(4430) likely has a node ➔ a radial excitation of the ground state: the $Z_c(3900)$?

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

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

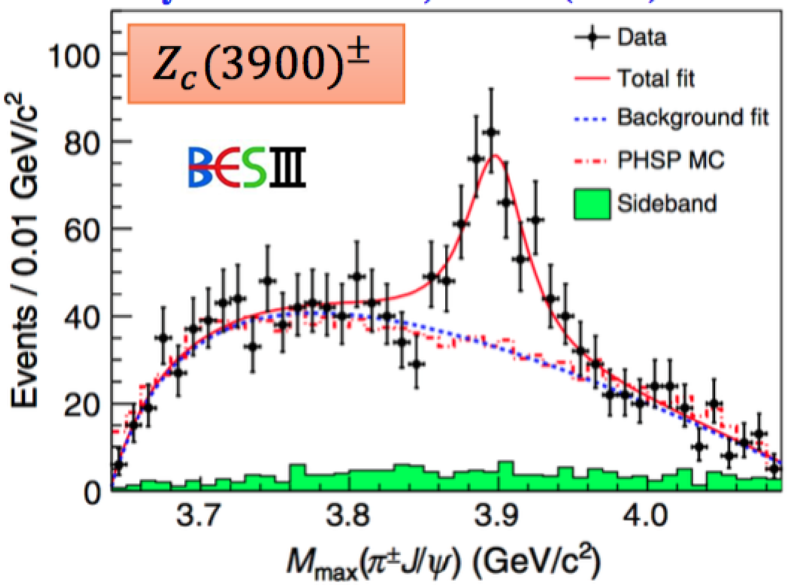
$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ "Dalitz plot"



$Z_c(3900)$ State

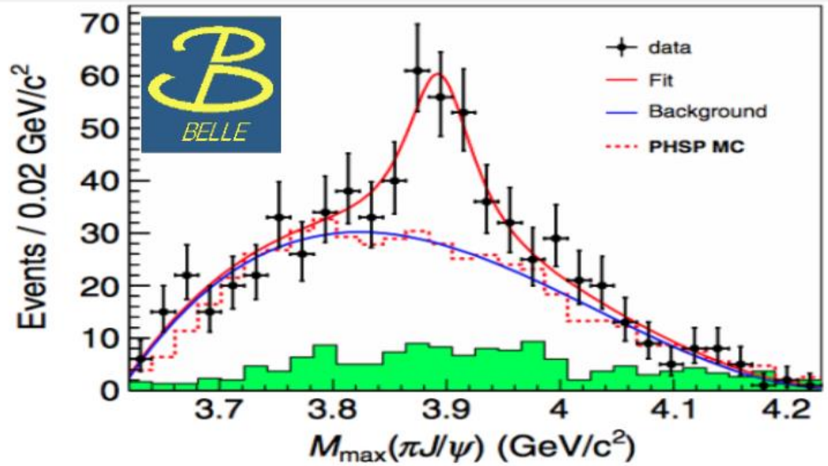
Observed in $e^+e^- \rightarrow (\gamma)Y(4260) \rightarrow J/\psi\pi^+\pi^-$

Phys. Rev. Lett 110, 252001 (2013)

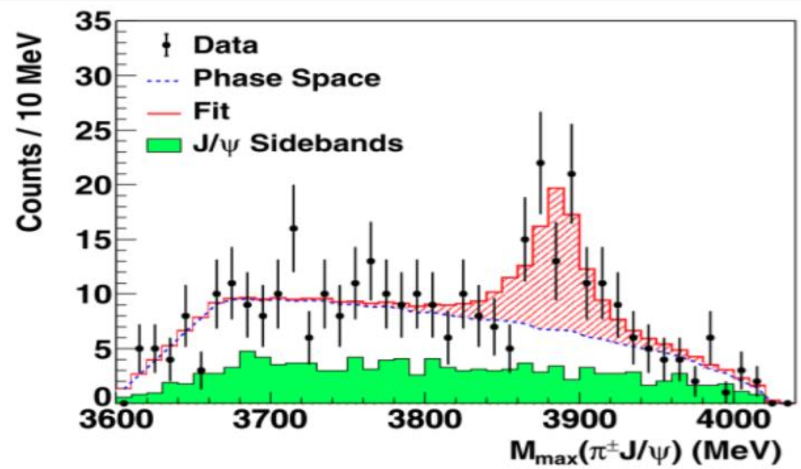


- ➢Charged charmonium-like structure (>10 σ)
- ➢Decay to J/ψ ($c\bar{c}$) and electric charge ($u\bar{d}$ or $d\bar{u}$)
- ➢$M = 3899.0 \pm 3.6 \pm 4.9$ MeV/c², $\Gamma = 46 \pm 10 \pm 20$ MeV
- ➢$\sigma(e^+e^- \rightarrow \pi^+\pi^- J/\psi) = 62.9 \pm 1.9 \pm 3.7$ pb at 4.26 GeV
- ➢$\frac{\sigma(e^+e^-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

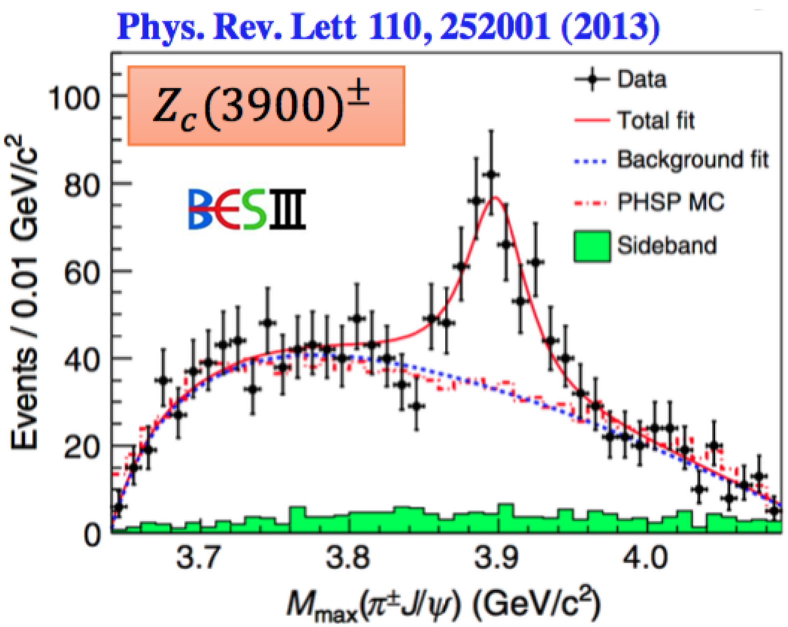
Belle with ISR data (PRL 110, 252002)



CLEOc data at 4.17 GeV (PLB 727, 366)



$Z_c(3900)$ State



- Charged charmonium-like structure (>10 σ)
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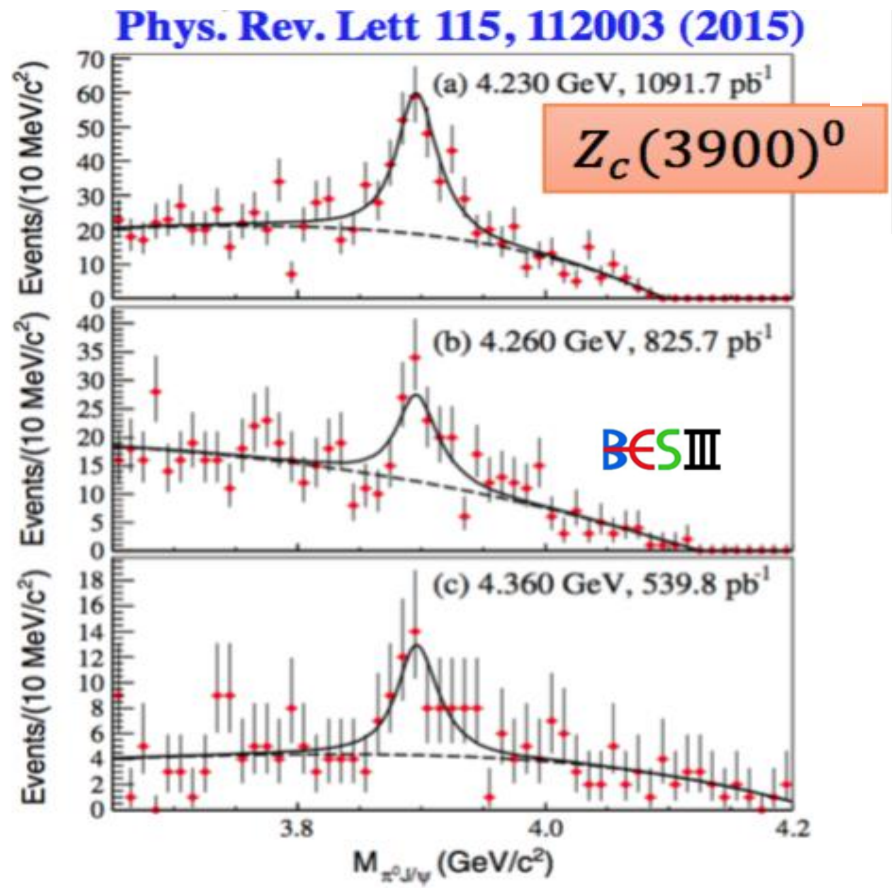
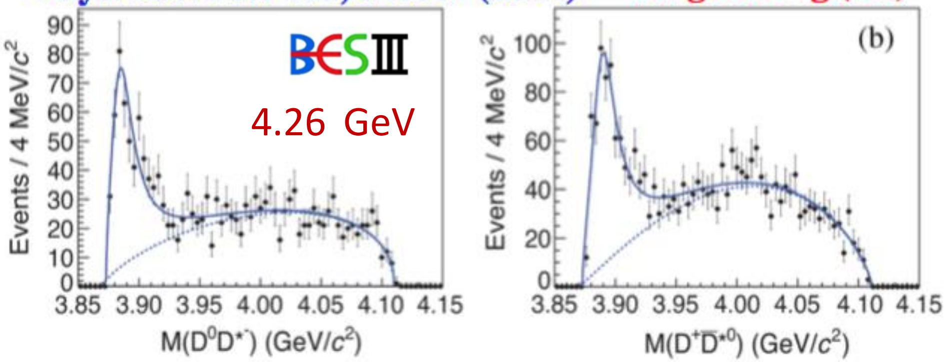
- The first Z_c state observed by more than one experiment (Belle and CLEO-c)!



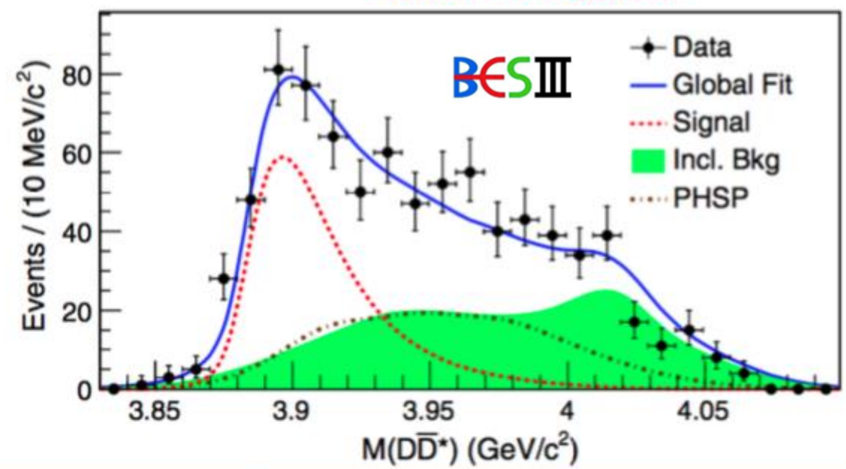
- Neutral charmonium-like structure (10.4 σ)
- Using 3 data samples (~2.5 fb⁻¹)
- Evidence with 3.7σ by using CLEO-c data
- $M = 3894.8 \pm 2.3 \pm 3.2$ MeV/c², $\Gamma = 29.6 \pm 8.2 \pm 8.2$ MeV
- An iso-spin triplet is established!

$Z_c(3900)$ State

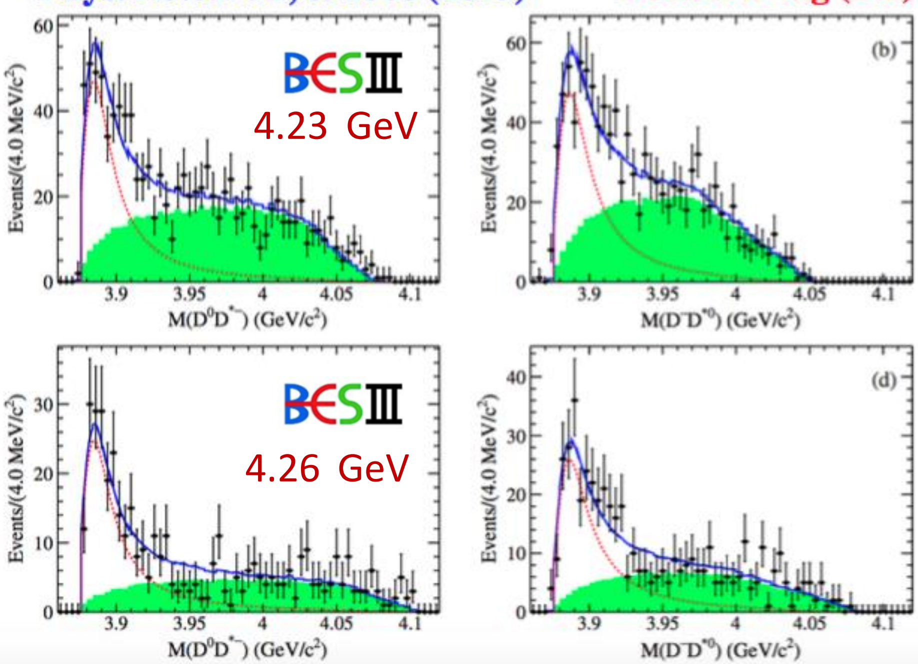
Phys. Rev. Lett 112, 022001 (2014) — Single D tag (ST)



Double D tag (DT)



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

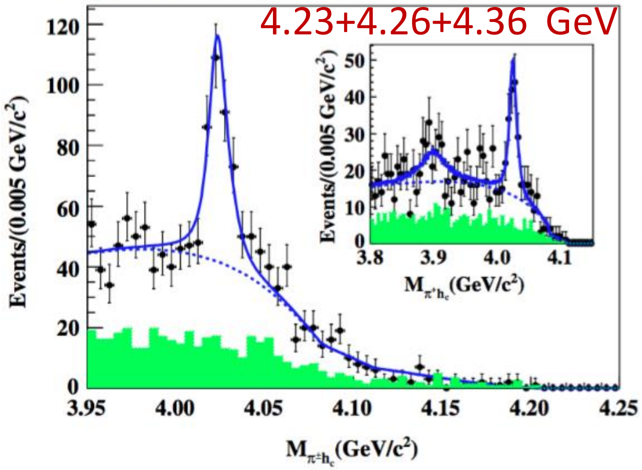


State	Mass (MeV/c²)	Width (MeV)
$Z_c(3885)^{\pm}$ (ST)	$3883.9 \pm 1.5 \pm 4.2$	$24.8 \pm 3.3 \pm 11.0$
$Z_c(3885)^{\pm}$ (DT)	$3881.7 \pm 1.6 \pm 1.6$	$26.6 \pm 2.0 \pm 2.1$
Weighted average	$3882.2 \pm 1.1 \pm 1.5$	$26.5 \pm 1.7 \pm 2.1$
$Z_c(3885)^0$ (DT)	$3885.7^{+4.3}_{-5.7} \pm 8.4$	$35^{+11}_{-12}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

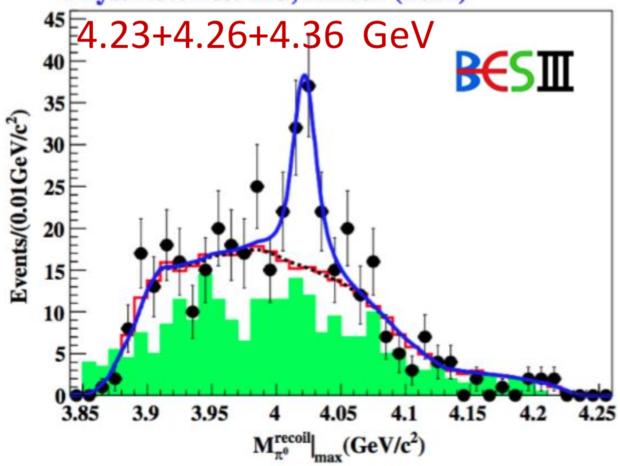
- Good agreement between ST and DT method
- Good agreement between charged state and neutral state
- Another iso-spin triplet is established!
- $Z_c(3885) = Z_c(3900)$?
- Tetraquark? Molecule state?

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

Phys. Rev. Lett 111, 242001 (2013)



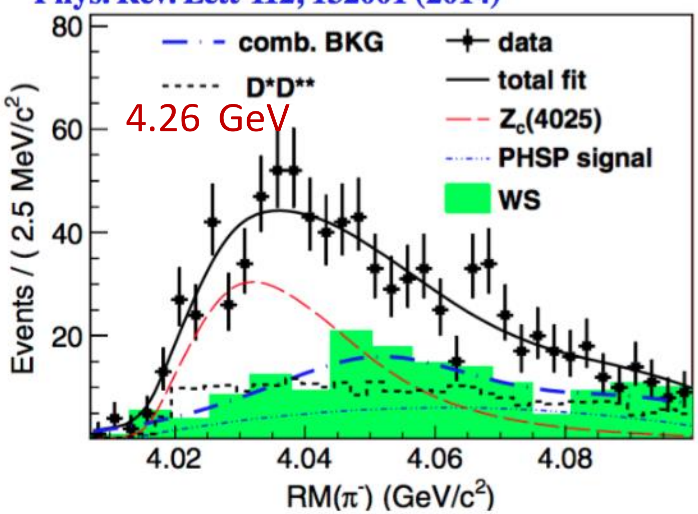
Phys. Rev. Lett 113, 212002 (2014)



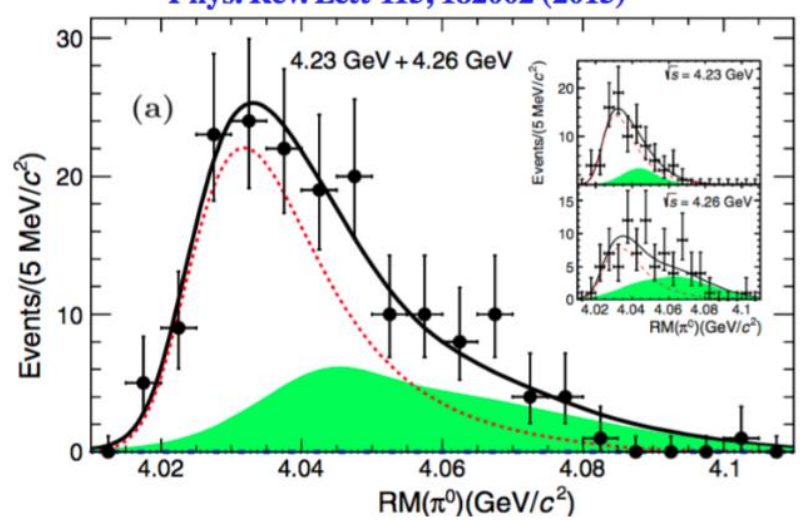
- ➢ $Z_c(4020)^{\pm/0}$ observed
- ➢ Another iso-spin triplet is established!
- ➢ No significant $Z_c(3900)^{\pm} \to \pi^{\pm} h_c$ is observed

State	Mass (MeV/c²)	Width (MeV)
$Z_c(4020)^{\pm}$	$4022.9\pm0.8\pm2.7$	$7.9\pm2.7\pm2.6$
$Z_c(4020)^0$	$4023.9\pm2.2\pm3.8$	7.9 (fixed)

Phys. Rev. Lett 112, 132001 (2014)



Phys. Rev. Lett 115, 182002 (2015)

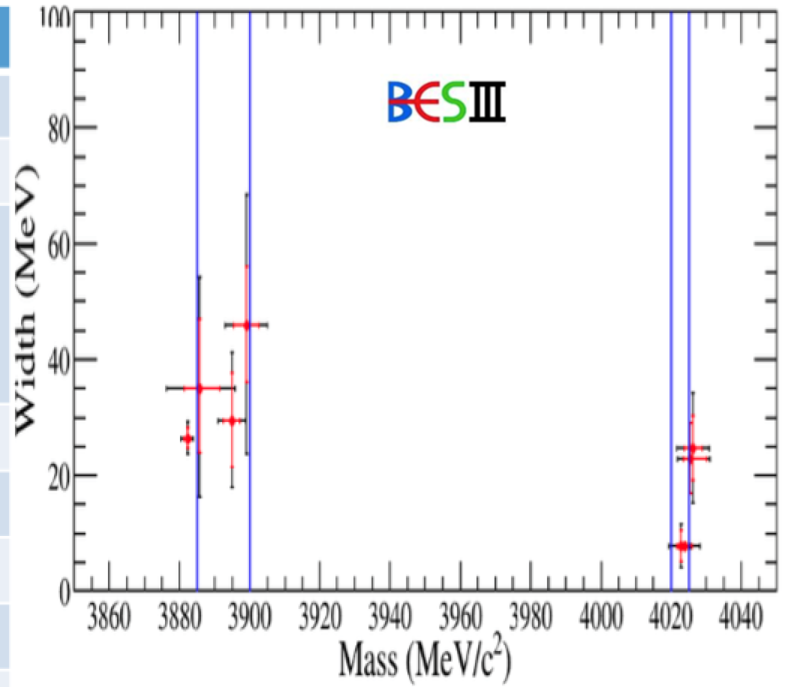


- ➢ $Z_c(4025)^{\pm/0}$ observed
- ➢ Another iso-spin triplet is established!

State	Mass (MeV/c²)	Width (MeV)
$Z_c(4025)^{\pm}$	$4026.3\pm2.6\pm3.7$	$24.8\pm5.6\pm7.7$
$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7}\pm3.1$	$23.0\pm6.0\pm1.0$

Summary on Z_c States by BESIII

State	Mass (MeV/c²)	Width (MeV)	Process
$Z_c(3900)^{\pm}$	$3899.0\pm3.6\pm4.9$	$46\pm10\pm20$	$e^+e^-\to\pi^+\pi^-J/\psi$
$Z_c(3900)^0$	$3894.8\pm2.3\pm3.2$	$29.6\pm8.2\pm8.2$	$e^+e^-\to\pi^0\pi^0J/\psi$
$Z_c(3885)^{\pm}$ (ST)	$3883.9\pm1.5\pm4.2$	$24.8\pm3.3\pm11.0$	$e^+e^-\to\pi^{\mp}(D\bar{D}^*)^{\pm}$
$Z_c(3885)^{\pm}$ (DT)	$3881.7\pm1.6\pm1.6$	$26.6\pm2.0\pm2.1$	
Weighted average	$3882.2\pm1.1\pm1.5$	$26.5\pm1.7\pm2.1$	
$Z_c(3885)^0$ (DT)	$3885.7^{+4.3}_{-5.7}\pm8.4$	$35^{+11}_{-12}\pm15$	$e^+e^-\to\pi^0(D\bar{D}^*)^0$
$Z_c(4020)^{\pm}$	$4022.9\pm0.8\pm2.7$	$7.9\pm2.7\pm2.6$	$e^+e^-\to\pi^+\pi^-h_c$
$Z_c(4020)^0$	$4023.9\pm2.2\pm3.8$	7.9 (fixed)	$e^+e^-\to\pi^0\pi^0h_c$
$Z_c(4025)^{\pm}$	$4026.3\pm2.6\pm3.7$	$24.8\pm5.6\pm7.7$	$e^+e^-\to\pi^{\mp}(D^*\bar{D}^*)^{\pm}$
$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7}\pm3.1$	$23.0\pm6.0\pm1.0$	$e^+e^-\to\pi^0(D^*\bar{D}^*)^0$

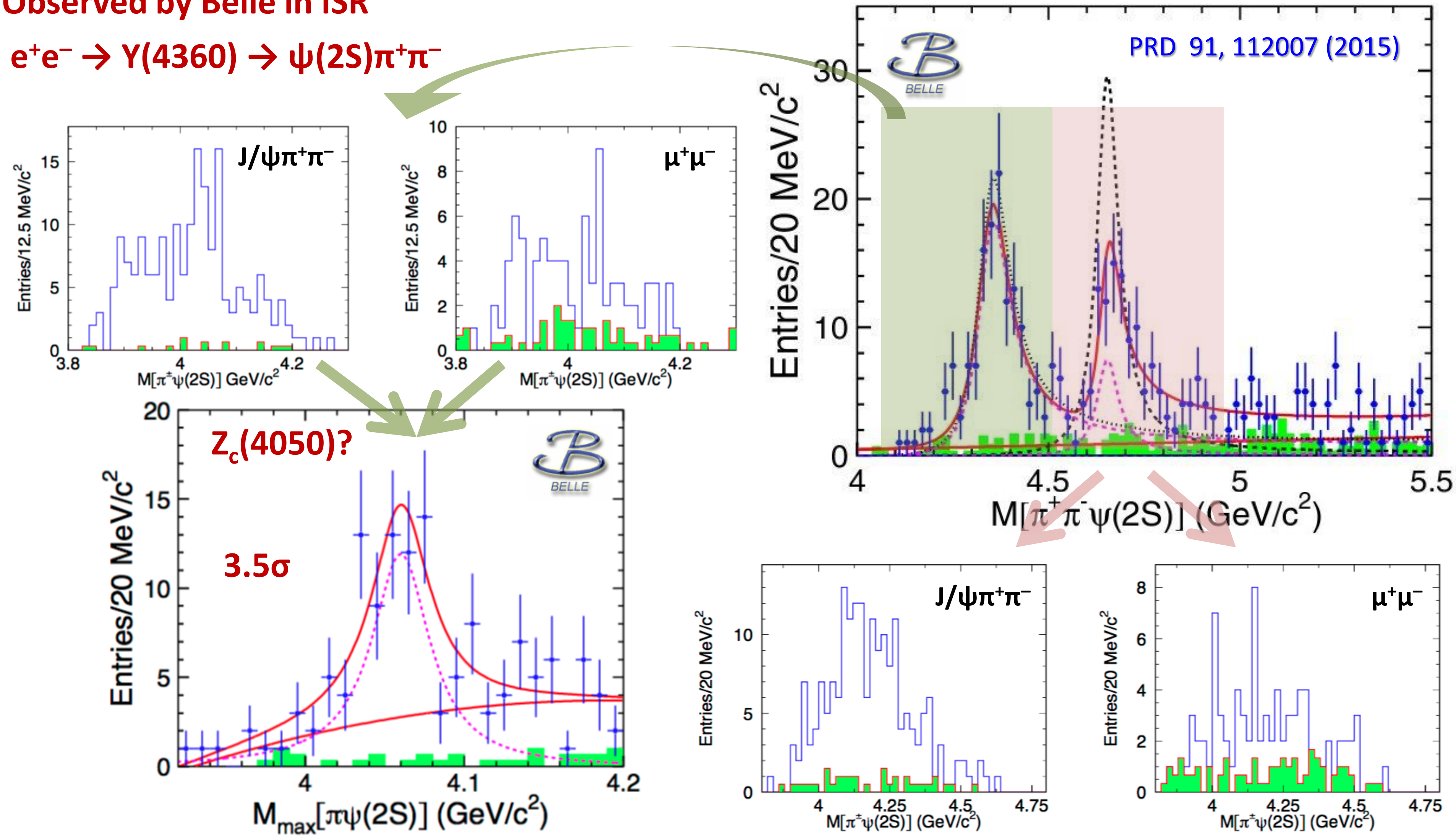


- $Z_c(3885)^{\pm}$ mass is about 2.6σ lower and the width 1.5σ lower than $Z_c(3900)^{\pm}$ value. If $Z_c(3885) = Z_c(3900)$, $\frac{\Gamma(Z_c(3885)^{\pm}\to(D\bar{D}^*)^{\pm})}{\Gamma(Z_c(3900)^{\pm}\to\pi^{\pm}J/\psi)} = 6.2\pm1.1\pm2.7$, coupling to $D\bar{D}^*$ is larger than to $\pi J/\psi$;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

$Z_c(4050)$

Observed by Belle in ISR

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



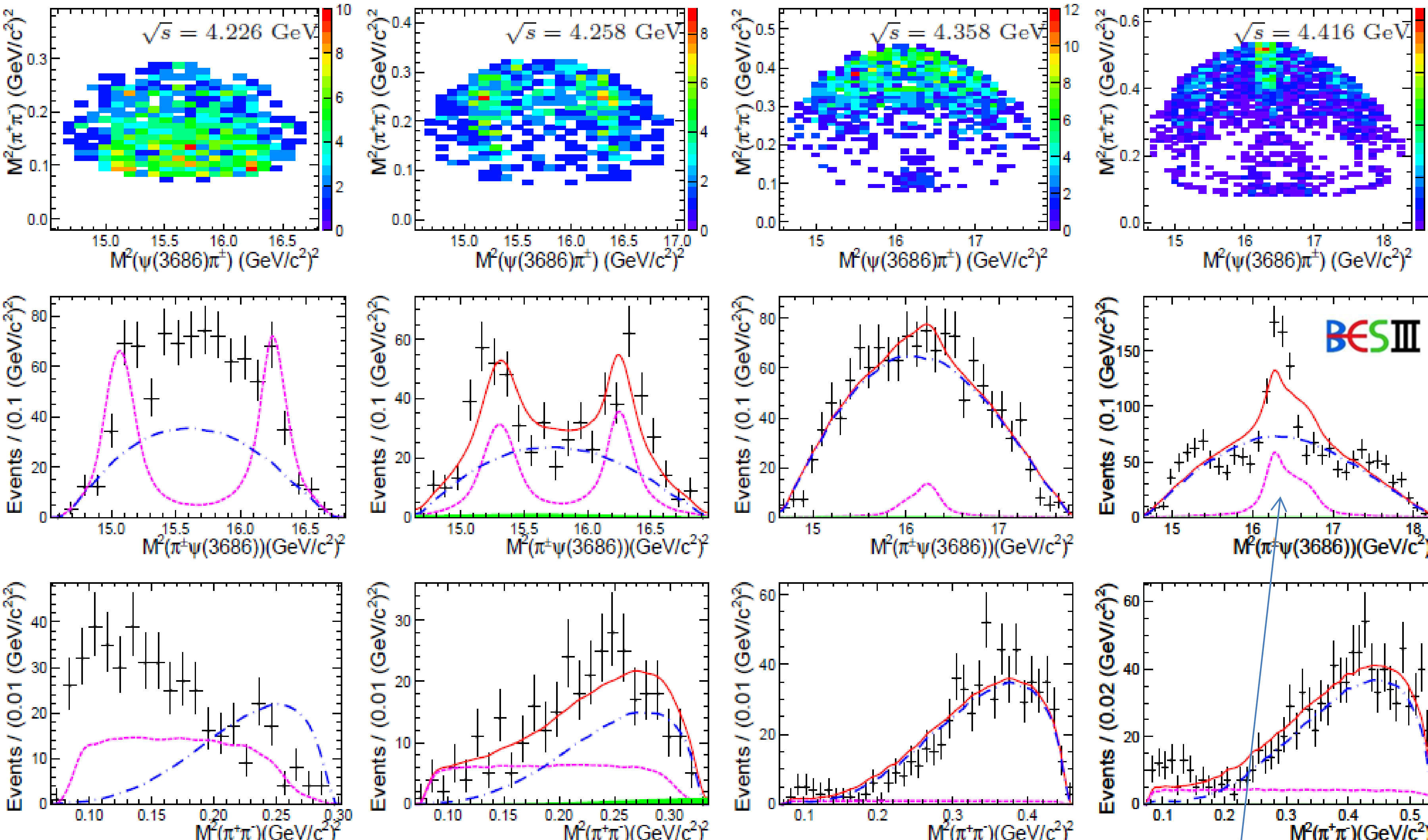
No clear signal found in the Y(4660) region

$M = 4054 \pm 3 \pm 1\ \mathrm{MeV}/c^2$

$\Gamma\ = 45 \pm 11 \pm 6\ \mathrm{MeV}$

Another Z_c state? Need confirmation

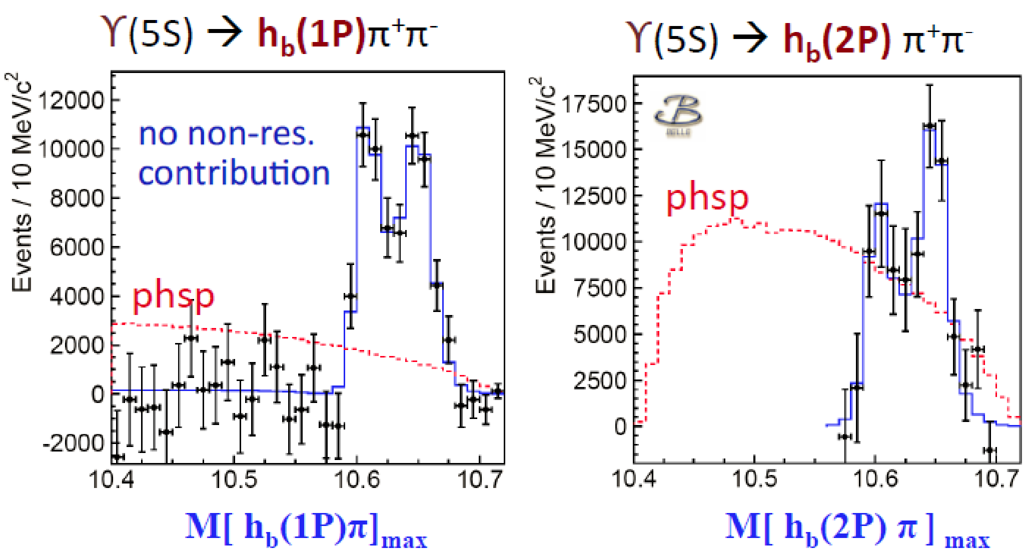
Search for $Z_c \rightarrow \pi\psi(2S)$ at BESIII



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**

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

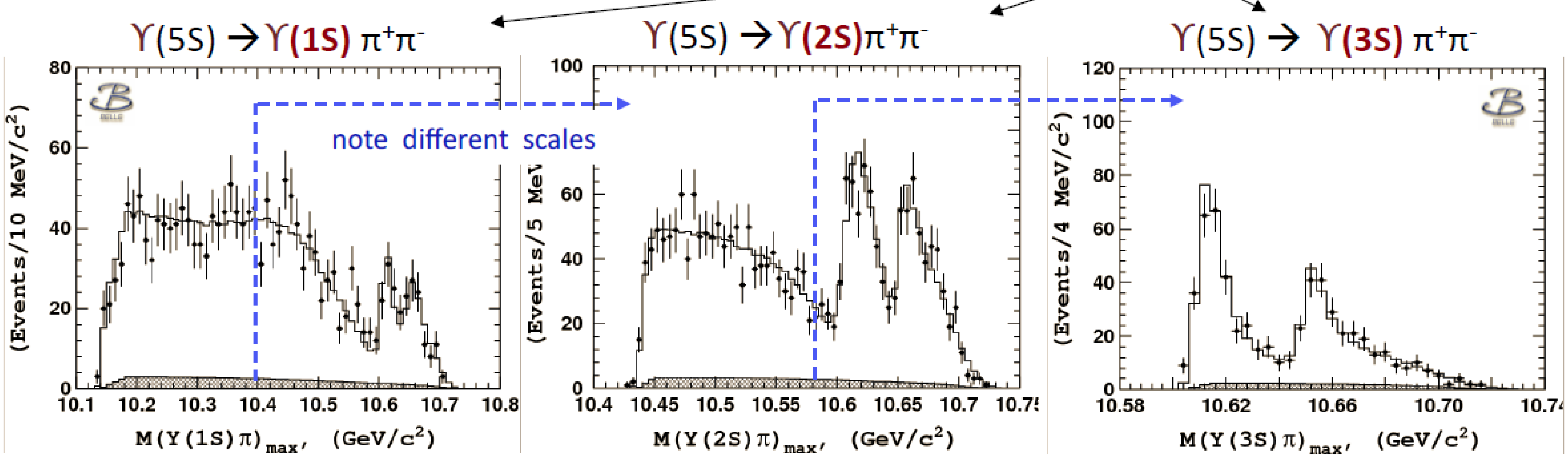


Two peaks are observed in all modes!

Belle: PRL108, 232001 (2012)

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

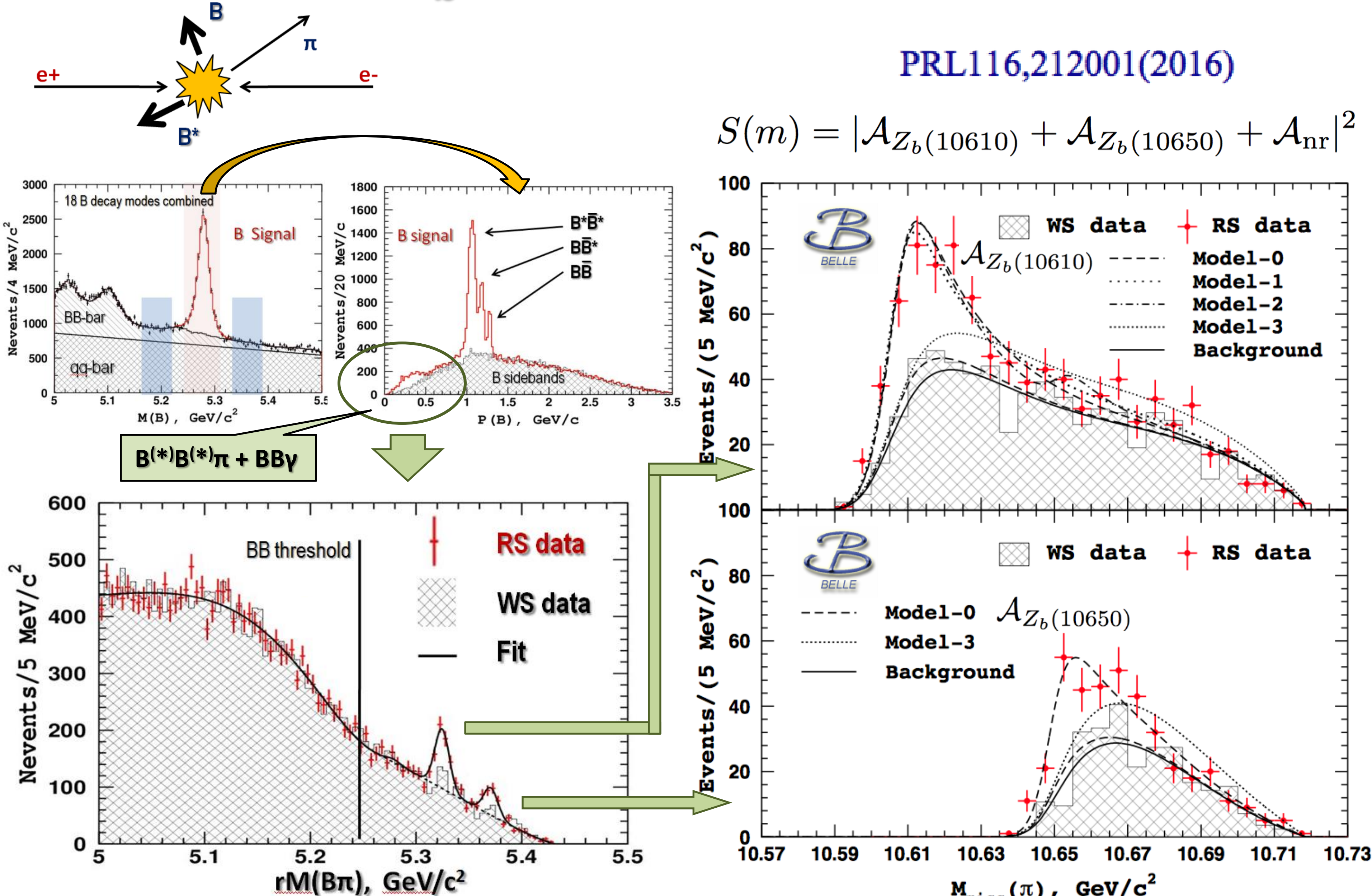
Dalitz plot analysis



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

PRL116,212001(2016)

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

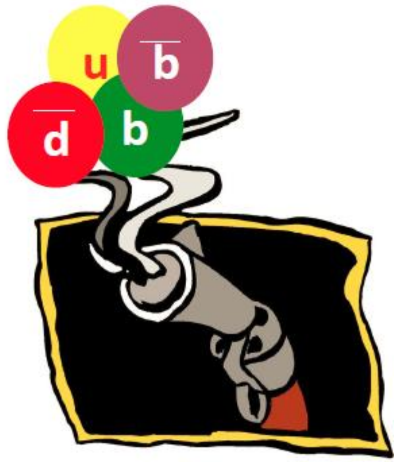


Summary on Z_b Decays by Belle

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



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

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

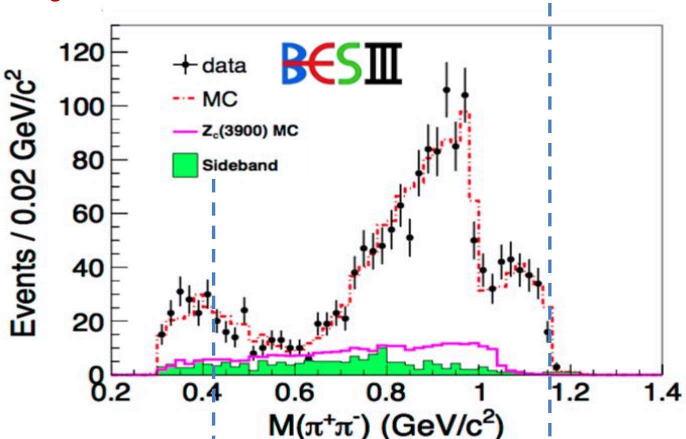
$B^{(*)}B^*$ channels dominate the Z_b decays

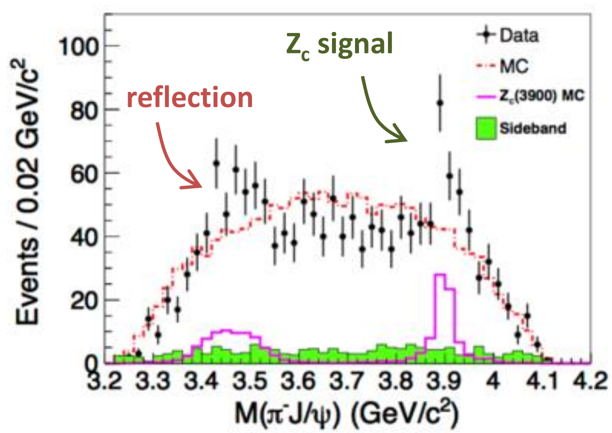
Charm vs. Beauty: I

What is in common?

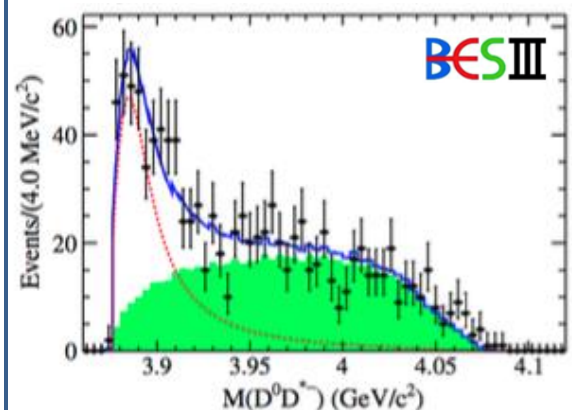
- $\Upsilon(10860)/Y(4260)$ demonstrates anomalously large coupling to $\Upsilon\pi^+\pi^-/\psi\pi^+\pi^-$ and $h_b\pi^+\pi^-/h_c\pi^+\pi^-$ final states.

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

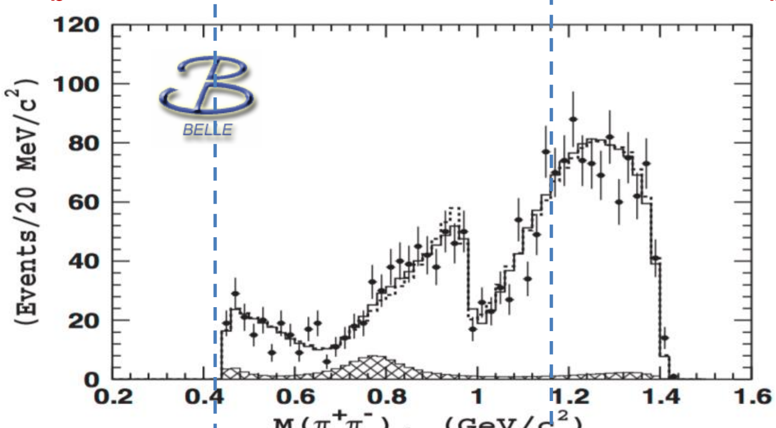




$\to Z_c\pi \to DD^*$

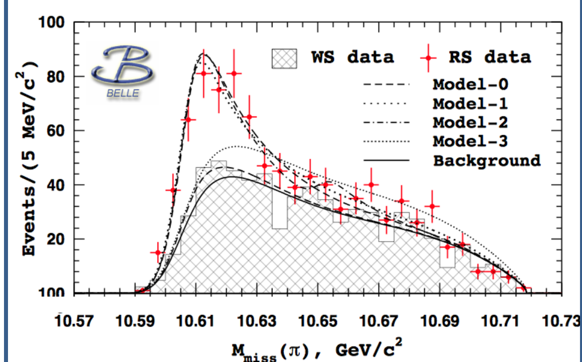


$Z_b(10610)$ is produced in $\Upsilon(10860) \to Z_b\pi \to \Upsilon(nS)\pi^+\pi^-$



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.

The plan for BESIII

— a fine scan with large statistics —

- Ecm=4.0 up to 4.6+ GeV
- 10 MeV step (slight adjust ~ thresholds, skip those points we have already collected large samples)
- 500 pb^{-1}/point

➔ total luminosity ~ 25 fb^{-1}

- With peak luminosity of $10^{33}/cm^2/s$
- Top-up injection at BEPCII !
- This plan can be finished in about 5 years!

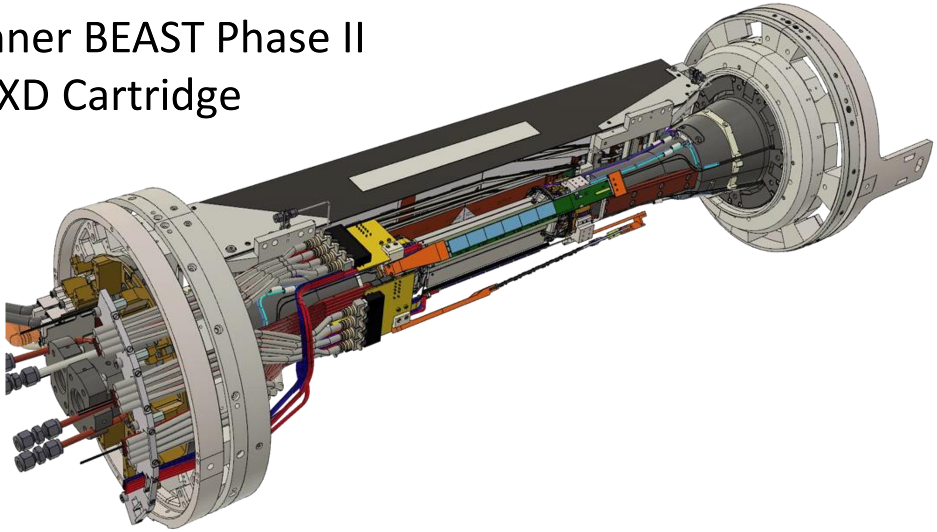
2016-17 running year: Ecm=4.19, 4.20, 4.21, …, 4.30 GeV

2017-18 running year: Ecm=4.31, 4.32, 4.33, …, 4.40 GeV?

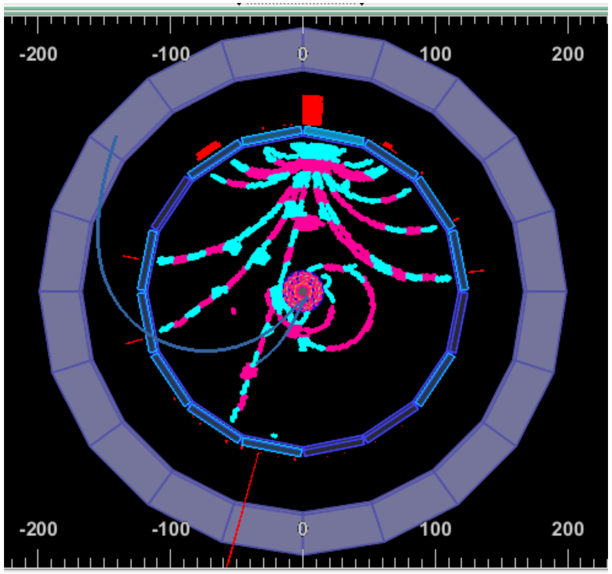
BelleII Status

BelleII Roll-In completed April 11, 2017

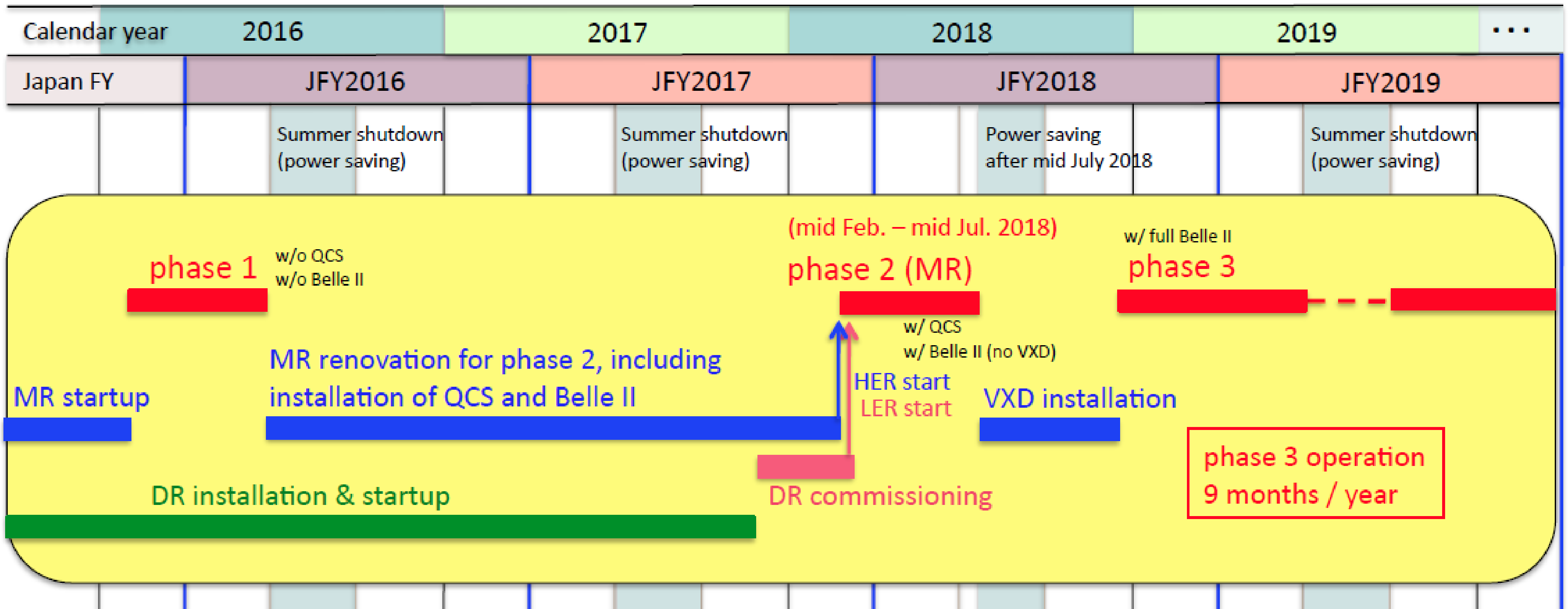
Inner BEAST Phase II VXD Cartridge



First Cosmics in a B field:

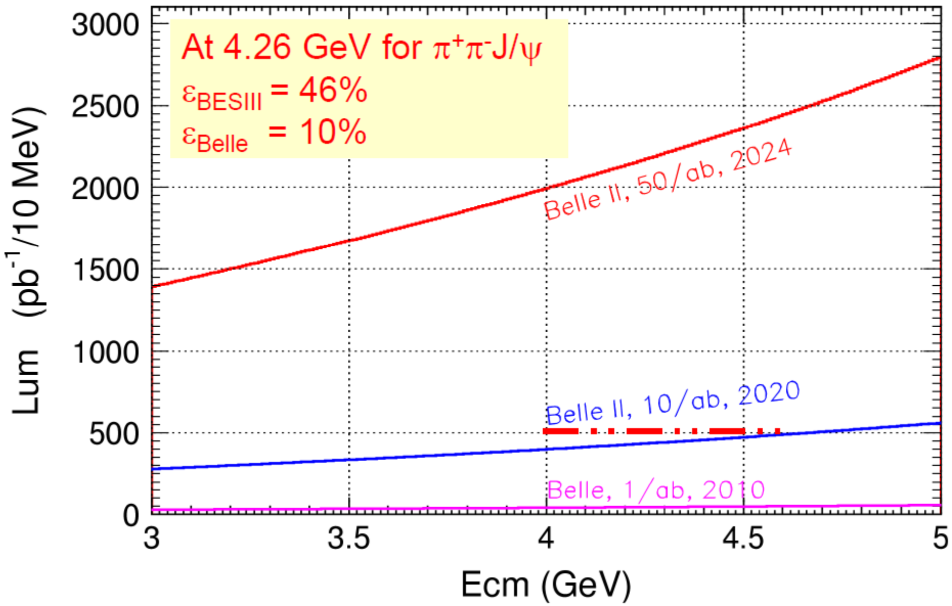


SuperKEKB / Belle II schedule



ISR at Belle II vs. BESIII

ISR produces events at all CM energies BESIII can reach



Direct scan

- (very) high luminosity at a few selected $\sqrt{s}$
- better resolution in $\sqrt{s}$ — relevant for direct production of 1^{--} states

ISR

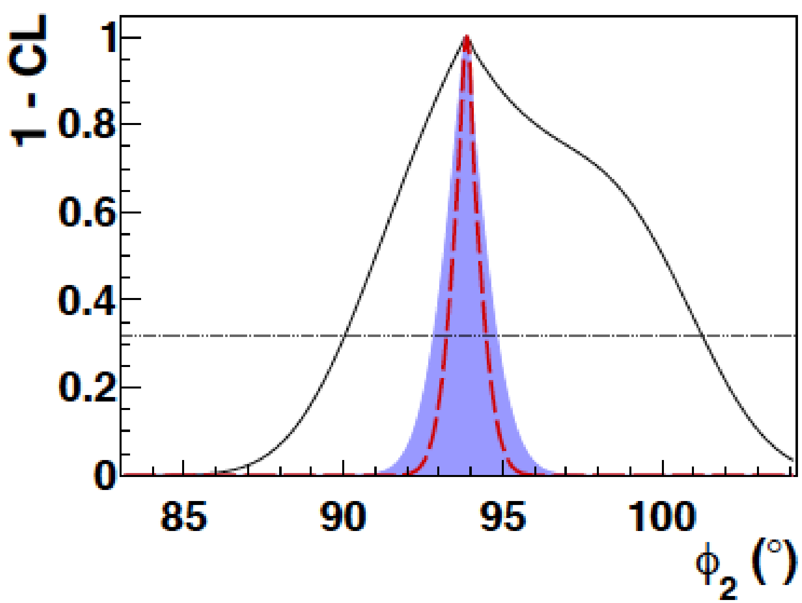
- ISR: many $\sqrt{s}$ simultaneously
- reduced point-to-point systematics
- mass resolution limited by detector res.
- boost of hadronic system vs. γ_{ISR} may actually help efficiency

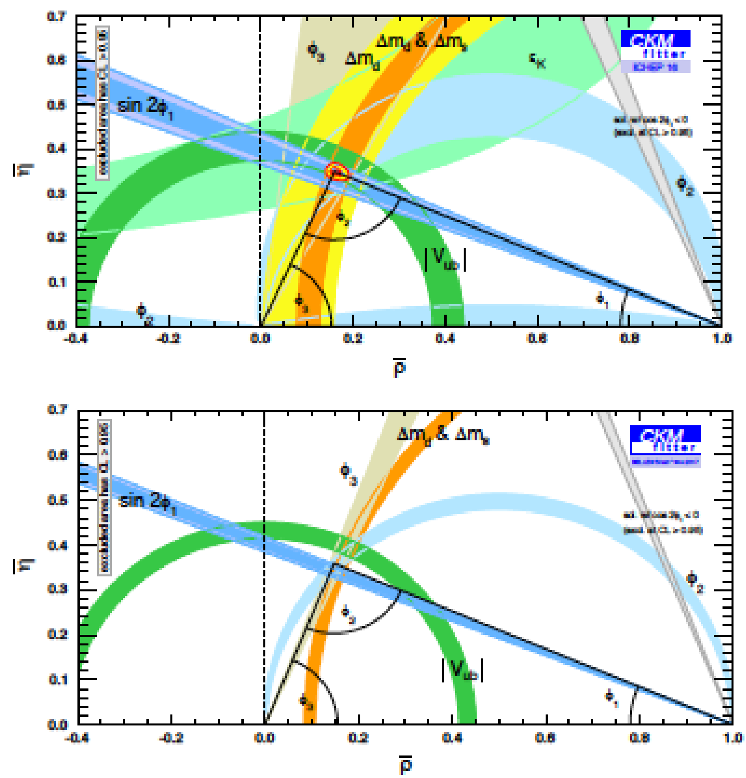
With > 5(10) ab^{-1} data sample, ISR $e^+e^- \to$ a charmonium+light hadrons[$\pi^+\pi^- J/\psi$, $\pi^+\pi^-\psi(2S)$, $K^+K^- J/\psi$, $K^+K^-\psi(2S)$, $\gamma X(3872)$, $\pi^+\pi^- X(3872)$, $\pi^+\pi^- hc$, $\pi^+\pi^- hc(2P)$, ωX_{cJ}, ϕX_{cJ}, $\eta J/\psi$, $\eta' J/\psi$, $\eta\psi(2S)$, η hc]; and charm meson pair+light hadrons [DD, DD*, DD*π, . . .]

Status of BelleII Physics Book

- Belle II physics book (630p), to be printed by PTEP / Oxford University Press
  https://confluence.desy.de/display/BI/B2TiP+ReportStatus
- A few small unfinished areas, but otherwise close to complete and ready for review to commence.
- Await formation of Belle II publication committee to conduct collaboration wide review and form full collaboration author list ASAP.

Recent highlight $S_{CP}(B \to \pi^0\pi^0)$ & Φ_2: F. Abudinen

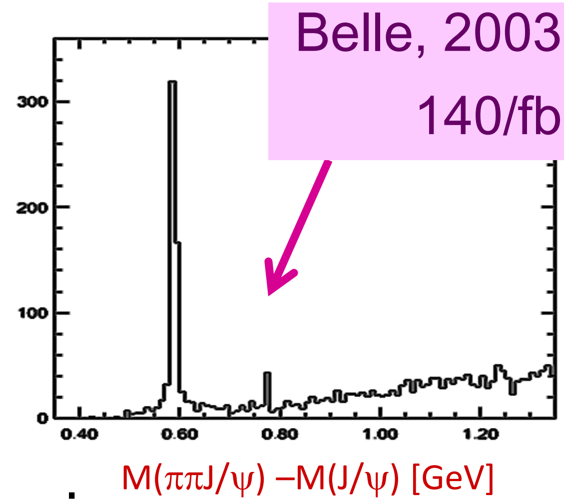




Summary

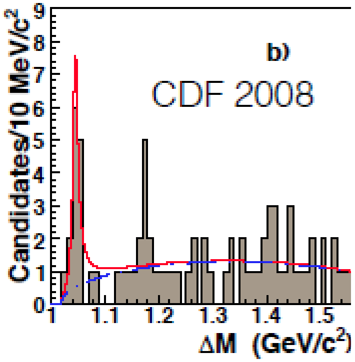
- A hole new field of exotic physics discovered in last decade; new information is still coming from both completed (Belle & BaBar) and currently ongoing (BESIII, D0, LHCb, CMS, …) experiments
- However (much) more data required for a better understanding (BelleII, BESIII, LHCb, …)
- BESIII is getting more data; start of the Belle II is approaching
- Input from Belle II is crucial to push exotic studies into bottomonium sector. Energy scan up to 11.24 GeV is accessible by the SuperKEKB.
- Common features between charmonium and bottomonium sectors is gradually emerging. No direct identity however.
- No clear understanding of the nature of new states yet. Theory needs to catch up with a flow of new data/puzzles from experiments.

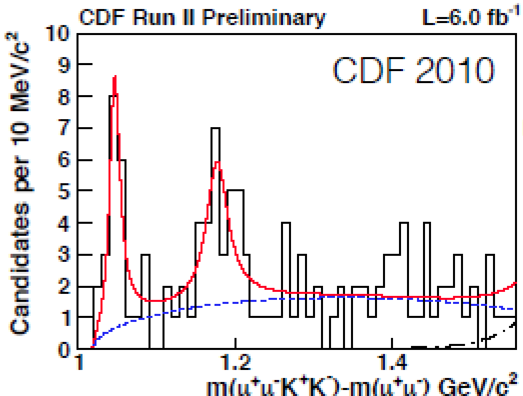
What is the X(3872)?

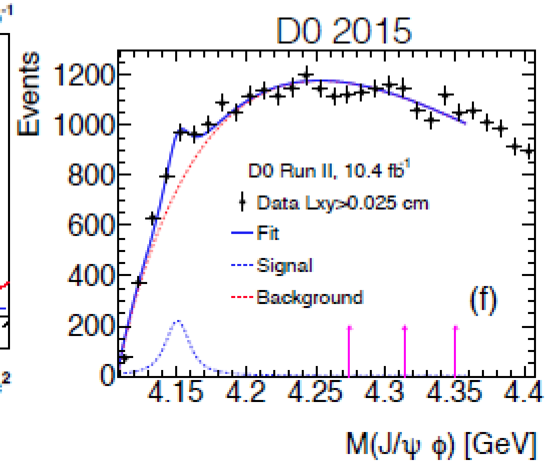


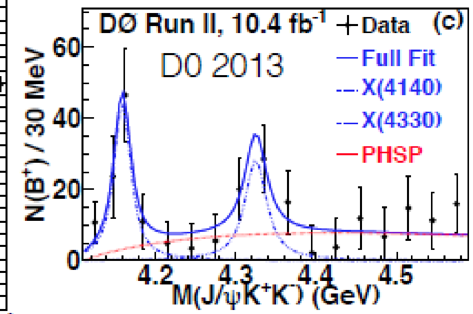
- Mass: Very close to $\bar{D}^0 D^{*0}$ threshold
- Width: Very narrow, < 1.2 MeV
- $J^{PC}=1^{++}$
- Production
  - in $\bar{p}p$/pp collison – rate similar to charmonia
  - In B decays – KX similar to $c\bar{c}$, K*X smaller than $c\bar{c}$
  - Y(4260)→γ+X(3872) (?)
- Decay BR: open charm ~ 50%, charmonium~O(%)
- 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?
  - Many other possibilities (if it is not χ'_{c1}, where is χ'_{c1}?)

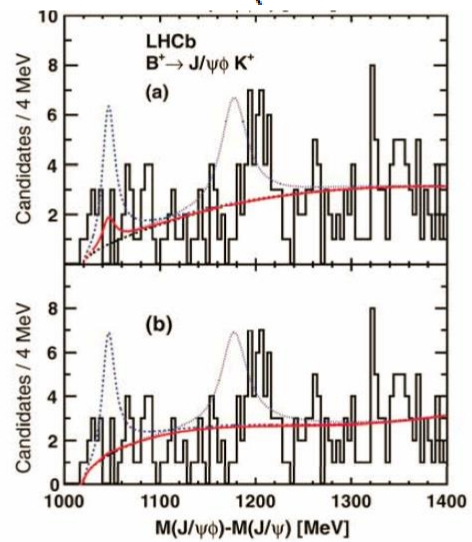
X(4140) and X(4270)

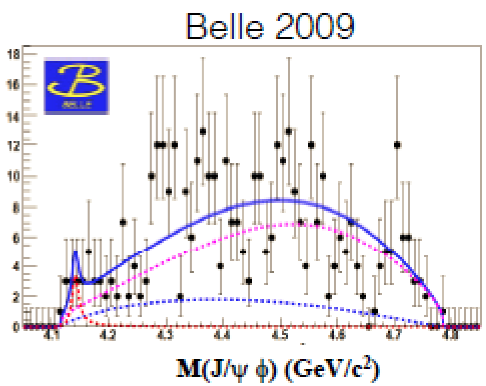


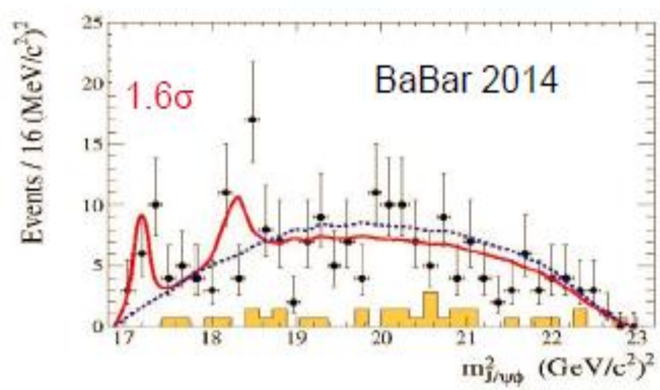


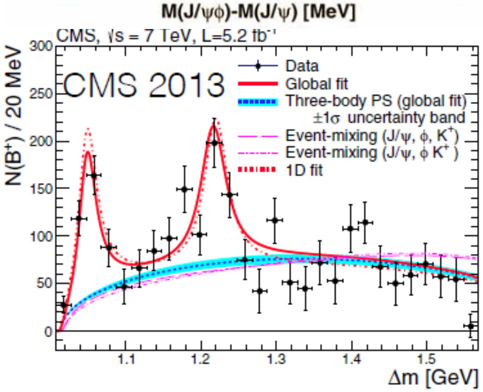










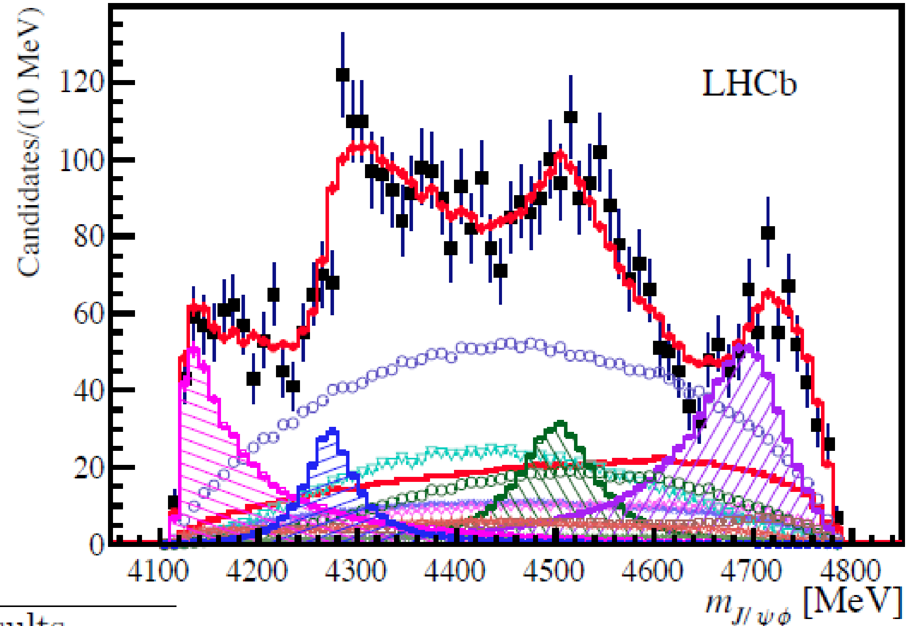


- X(4140)→J/ψφ claimed first by CDF in B⁺→J/ψφK
- Seen by some experiments, but not others
- Confusing situation

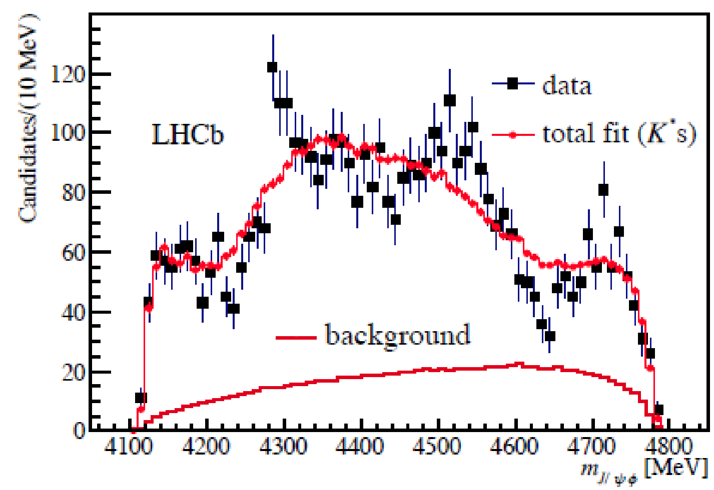
X(4140) at LHCb

PRD95, 012002(2017)

- Need 4 exotic contributions to describe data
- X(4140) possibly $D_s D_s^*$ cusp
- Some disagreement in parameters compared to previous experiments
  - Possibly due to missing interference effects in 1D fits

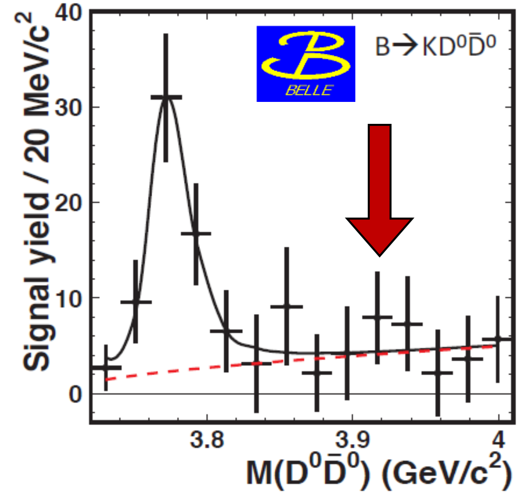


Contribution	sign. or Ref.	M_0 [MeV]	Γ_0 [MeV]	Fit results FF %
All $X(1^+)$				$16\pm3\ ^{+\ 6}_{-\ 2}$
$X(4140)$	8.4σ	$4146.5\pm4.5\ ^{+4.6}_{-2.8}$	$83\pm21\ ^{+21}_{-14}$	$13.0\pm3.2\ ^{+4.8}_{-2.0}$
ave.	Table 1	4147.1 ± 2.4	15.7 ± 6.3	
$X(4274)$	6.0σ	$4273.3\pm8.3\ ^{+17.2}_{-\ 3.6}$	$56\pm11\ ^{+\ 8}_{-11}$	$7.1\pm2.5\ ^{+3.5}_{-2.4}$
CDF	[29]	$4274.4\ ^{+8.4}_{-6.7}\pm1.9$	$32\ ^{+22}_{-15}\pm8$	
CMS	[25]	$4313.8\pm5.3\pm7.3$	$38\ ^{+30}_{-15}\pm16$	
All $X(0^+)$				$28\pm\ 5\pm\ 7$
$NR_{J/\psi\phi}$	6.4σ			$46\pm11\ ^{+11}_{-21}$
$X(4500)$	6.1σ	$4506\pm11\ ^{+12}_{-15}$	$92\pm21\ ^{+21}_{-20}$	$6.6\pm2.4\ ^{+3.5}_{-2.3}$
$X(4700)$	5.6σ	$4704\pm10\ ^{+14}_{-24}$	$120\pm31\ ^{+42}_{-33}$	$12\pm\ 5\ ^{+\ 9}_{-\ 5}$



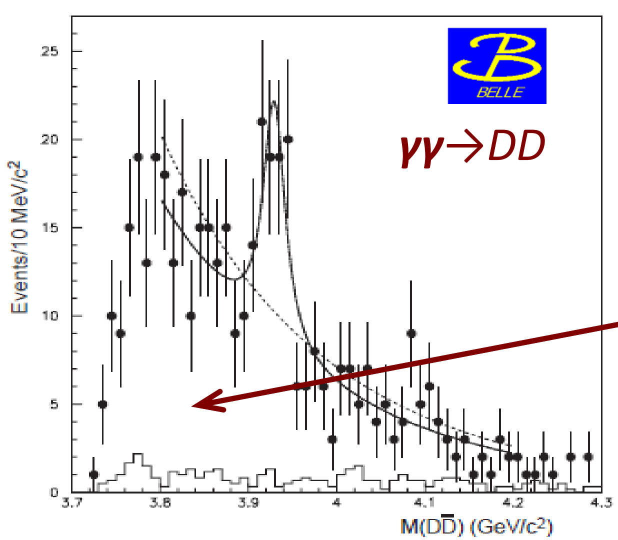
Is X(3915) = χ_{c0}'?

PDG ascribe Y(3915) to vacant χ_{c0}' state, based on BaBar's measurement of J=0 in $\gamma\gamma \to Y(3940) \to \omega J/\psi$

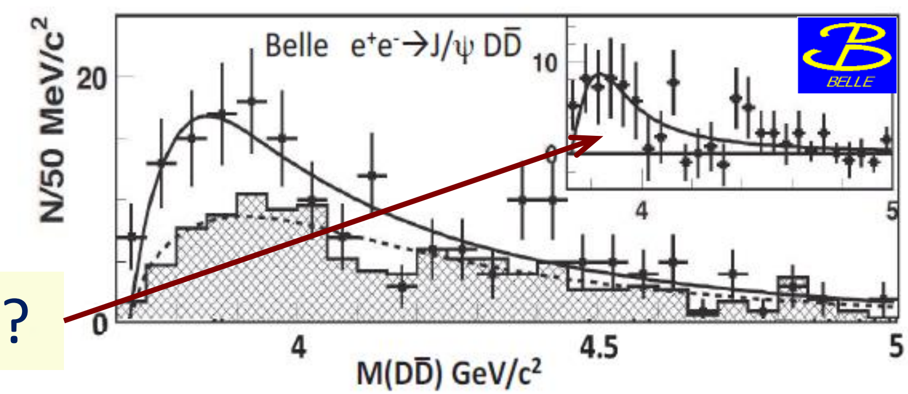


strongly criticized by theoreticians

- χ_{c0}' production in two body B decays suppressed
- $\chi_{c0}' \to DD$ should be dominant, but not seen in B decays and $\gamma\gamma$
- there is a better candidate for χ_{c0}'!



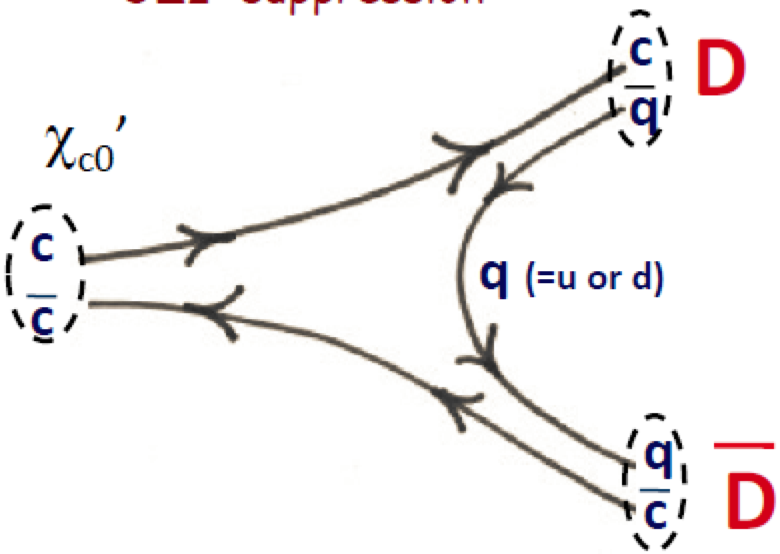
χ_{c0}'?



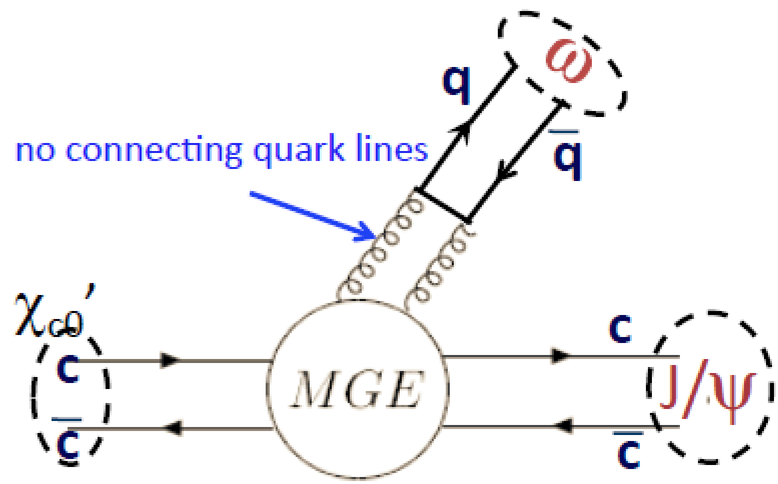
Theory does not like conventional interpretation, but suggests no good explanation for X(3915)…

$\chi_{c0}' \rightarrow D\overline{D}$ should be huge & $\chi_{c0}' \rightarrow \omega J/\psi$ tiny

Fall-apart mode, no "OZI" suppression



"OZI" suppressed



But: $Bf(X_{3915} \rightarrow D^0\overline{D}^0) < 1.2 \times Bf(X_{3915} \rightarrow \omega J/\psi)$

J. Brodzicka et al. (Belle) PRD 100, 092001

This strongly suggests that the X(3915) is a 4-quark state

Y(4220) leptonic width

Considering the isospin symmetry, we estimate the lower limit on the $\Gamma_{e^+e^-}(\mathrm{Y}(4220))$. For an isospin-zero charmoniumlike state, we expect

$$\begin{cases} \Gamma_{e^+e^-} = \sum_i \mathcal{B}_i \times \Gamma_{e^+e^-} \\ \mathcal{B}_{\pi\pi h_c} = \frac{3}{2} \times \mathcal{B}_{\pi^+\pi^- h_c}, \\ \mathcal{B}_{\pi\pi J/\psi} = \frac{3}{2} \times \mathcal{B}_{\pi^+\pi^- J/\psi}, \\ \mathcal{B}_{D\bar{D}^*\pi} = 3 \times \mathcal{B}_{D^0 D^{*-}\pi^+ + c.c.} \end{cases}$$

Taking Solutions with the smallest $B \times \Gamma_{e^+e^-}$,

$$\Gamma_{e^+e^-} > \left(29.1 \pm 2.5(stat)\ \pm 7.0(sys)\right) + \cdots \text{ eV}$$

Taking Solutions with the largest $B \times \Gamma_{e^+e^-}$,

$$\Gamma_{e^+e^-} > \left(202.2 \pm 12.9(stat)\ \pm 23.4(sys)\right) + \cdots \text{ eV}$$

For the most interesting mode $Y(4220) \to \pi\pi J/\psi$

For the case of highest $B \times \Gamma_{e^+e^-}$

$$B_{\pi\pi J/\psi} = (12.9 \pm 1.3 \pm 3.9)\%$$

For the case of smallest $B \times \Gamma_{e^+e^-}$

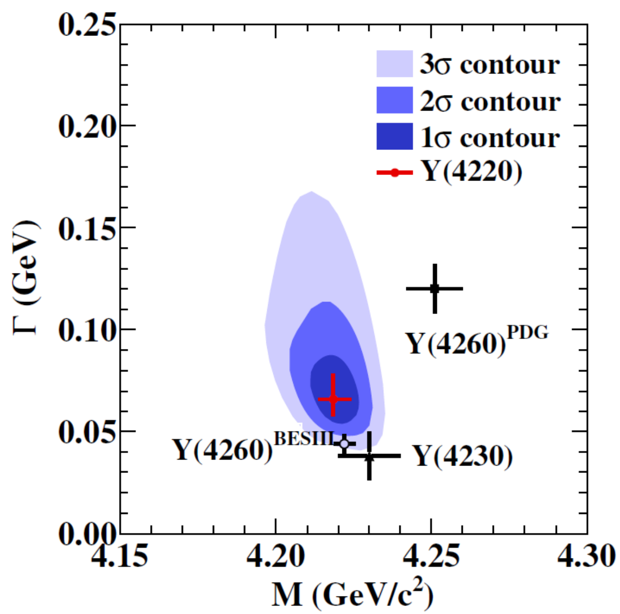
$$B_{\pi\pi J/\psi} = (11.2 \pm 1.1 \pm 1.9)\%$$

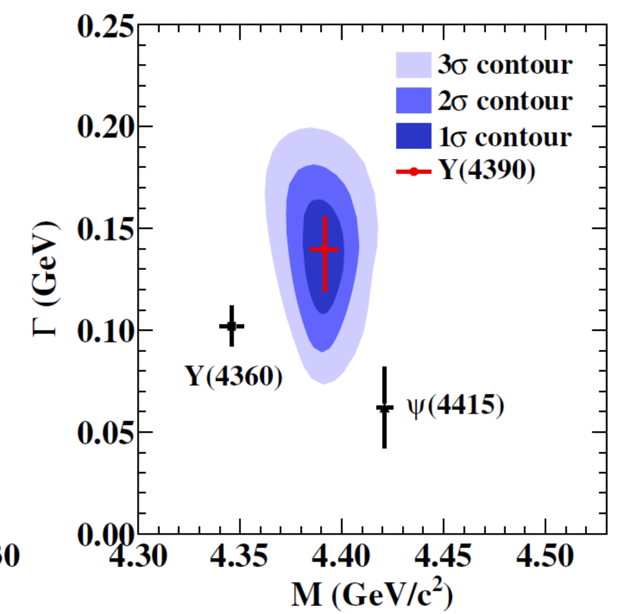
For the most extreme case, taking smallest $B \times \Gamma_{e^+e^-}$ for $\pi\pi J/\psi$ while largest $B \times \Gamma_{e^+e^-}$ for other mode

$$B_{\pi\pi J/\psi} = (2.1 \pm 0.3 \pm 0.7)\%$$

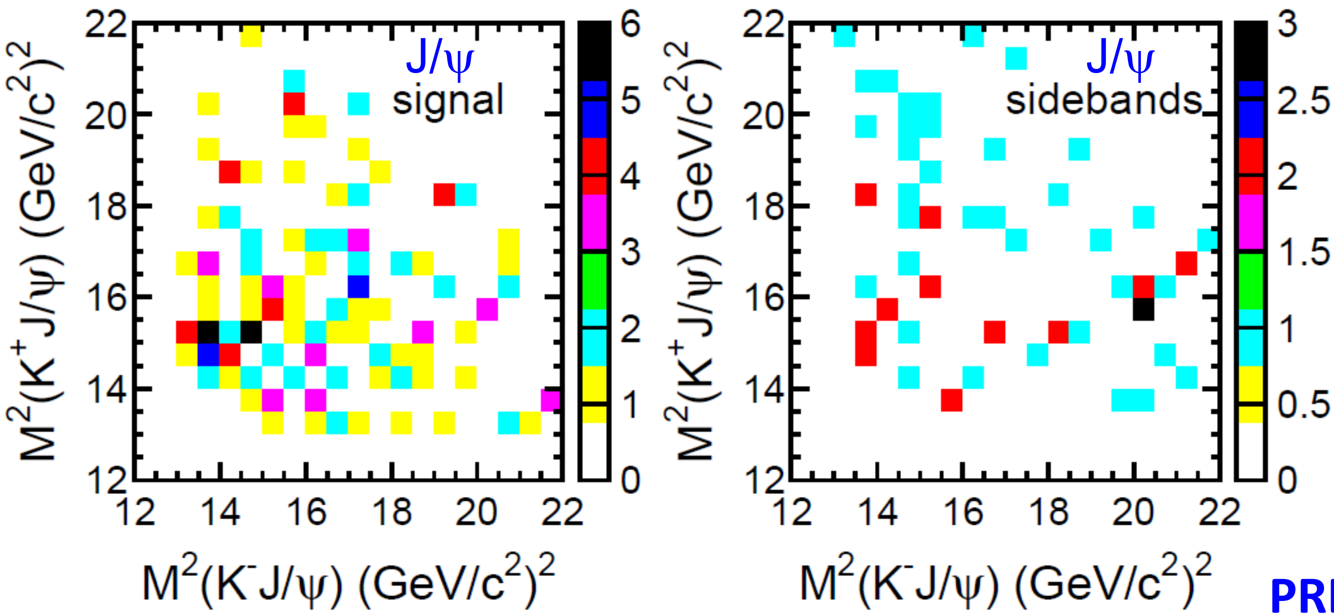
Y or ψ structures

Parameters	Y(4220) in $\pi^+\pi^-h_c$	Y(4260)	ψ(4160)	Structure in $\omega\chi_{c0}$
M (MeV)	4218.4±4.0±0.9	4251±9	4191±5	4226±8±6
Γ_{tot} (MeV)	66.0±9.0±0.4	120±12	70±10	39±12±2
Parameters	**Y(4390) in $\pi^+\pi^-h_c$**	**Y(4360)**	**ψ(4415)**	
M (MeV)	4391.6±6.3±1.0	4362±13	4421±4	
Γ_{tot} (MeV)	139.5±16.1±0.6	74±18	62±20	





Search for $Z_{cs} \to KJ/\psi$ states



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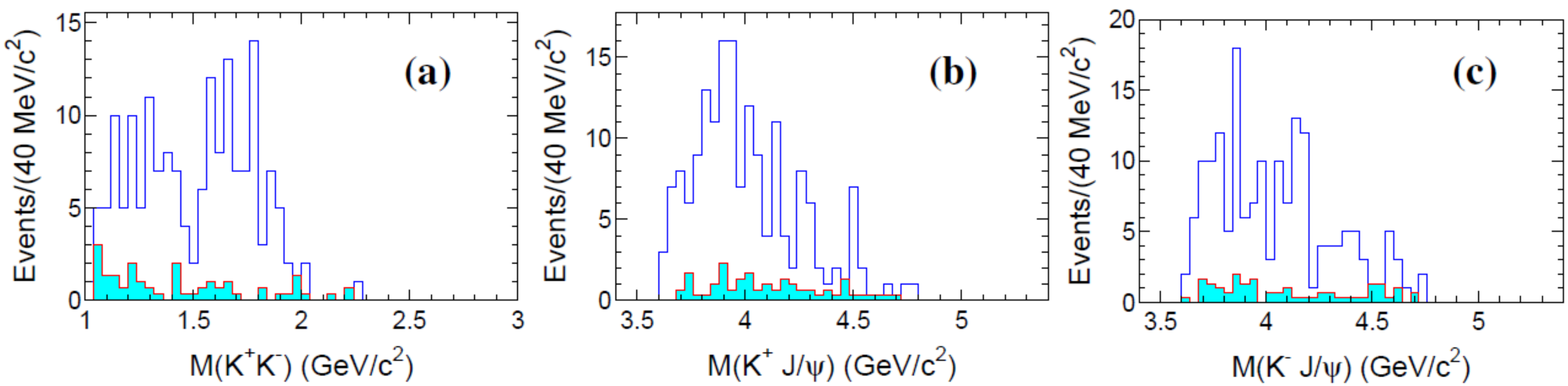
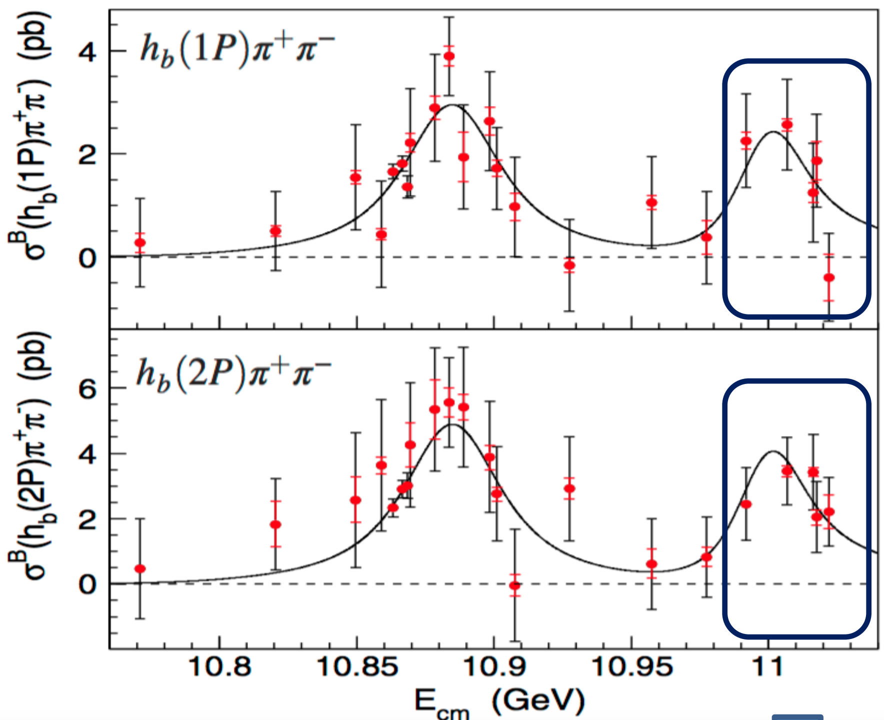
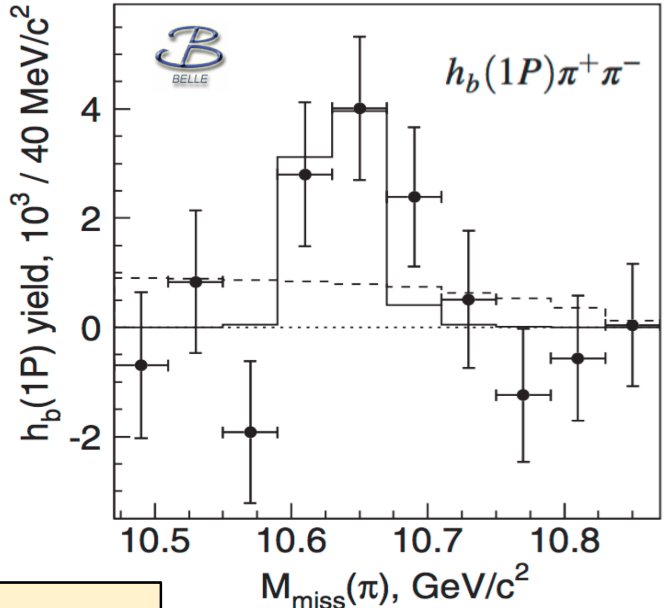


No evident structure in $K^{+-}J/\psi$ mass distribution under current statistics

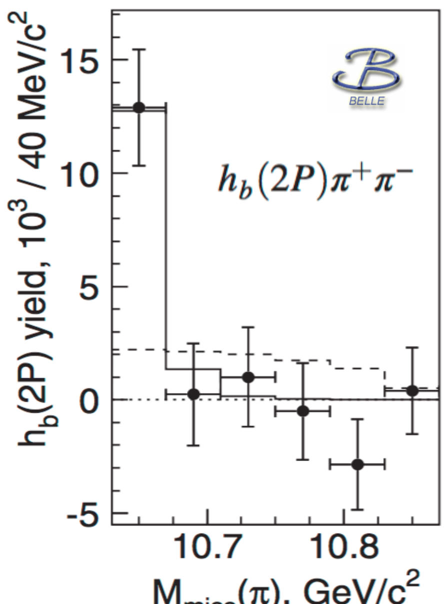
$Z_b^{\pm}$ Production at $\Upsilon(6S)$

PRL117,142001(2016)





$\Upsilon(6S)$ Data: 5 fb^{-1}



- 1st obs. of $\Upsilon(6S)\rightarrow\pi^+\pi^-h_b(nP)$
  3.5σ for 1P, 5.3σ for 2P.

The two Z_b states can not be separated with current statistics

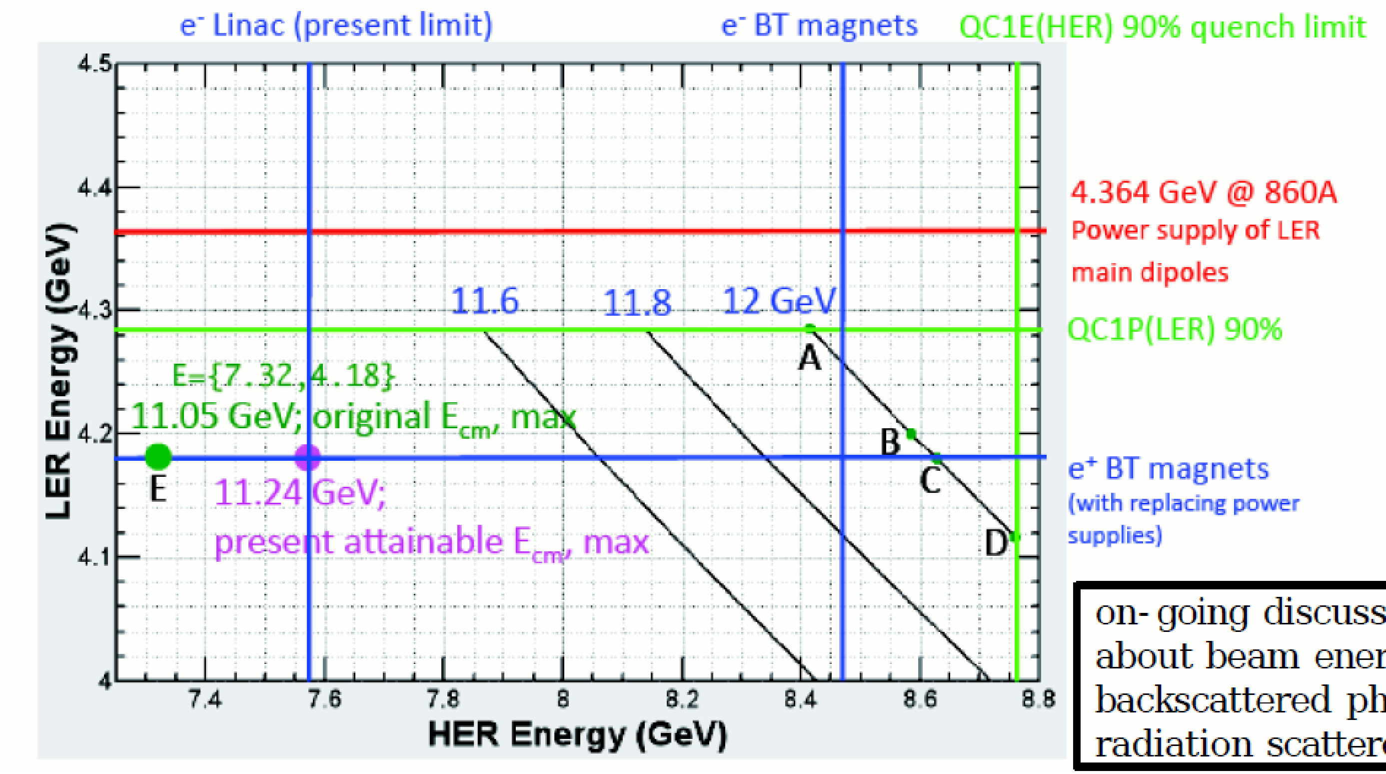
$\Upsilon(6S) \rightarrow h_b(mP)\pi^+\pi^-$ transition is dominated (saturated) by the intermediate $Z_b^{\pm}$ production. Two Z_b can be separated at Belle II !

Higher energy run

from K. Akai, BPAC Feb 2012

- Design: original design maximum energy is 11.05 GeV at $\Upsilon(6S)$
- Possible higher energy run (11.5 GeV – 12 GeV) ?
  - If any, higher energy run will be after several years running at $\Upsilon(4S) \sim \Upsilon(6S)$
  - **present max E_{cm} is 11.24 GeV**, limited by e^- Linac and e^+ BT magnets
  - In order to inject the electron beam to HER at the required energy for 12 GeV operation, there must be huge reinforcement of Linac (replacement of S-band with C-band, 7.571 → 8.6 GeV

11.24 GeV region: $\Lambda_b \bar{\Lambda}_b$ threshold

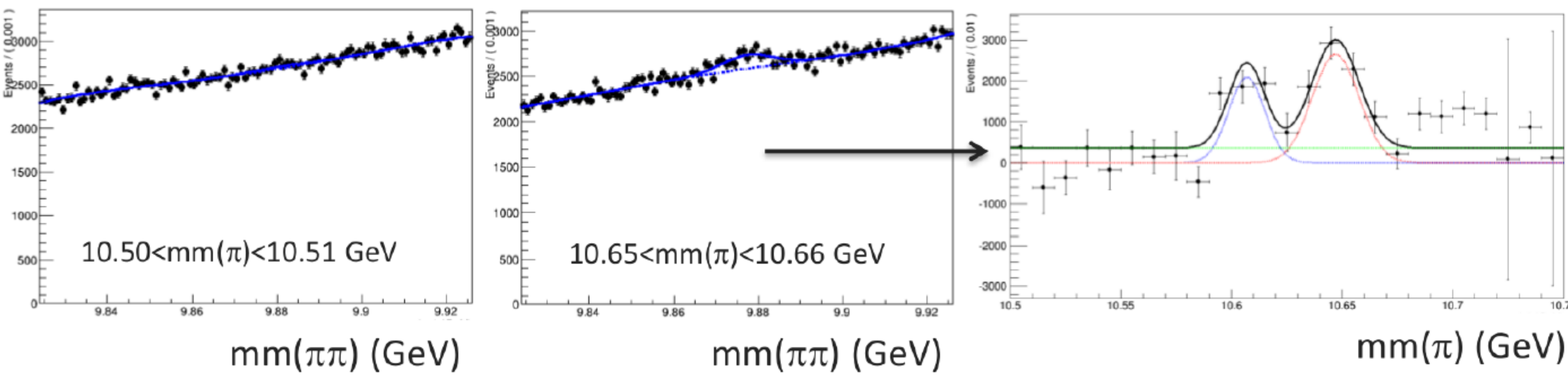


e.g. [arXiv:1211.0103]

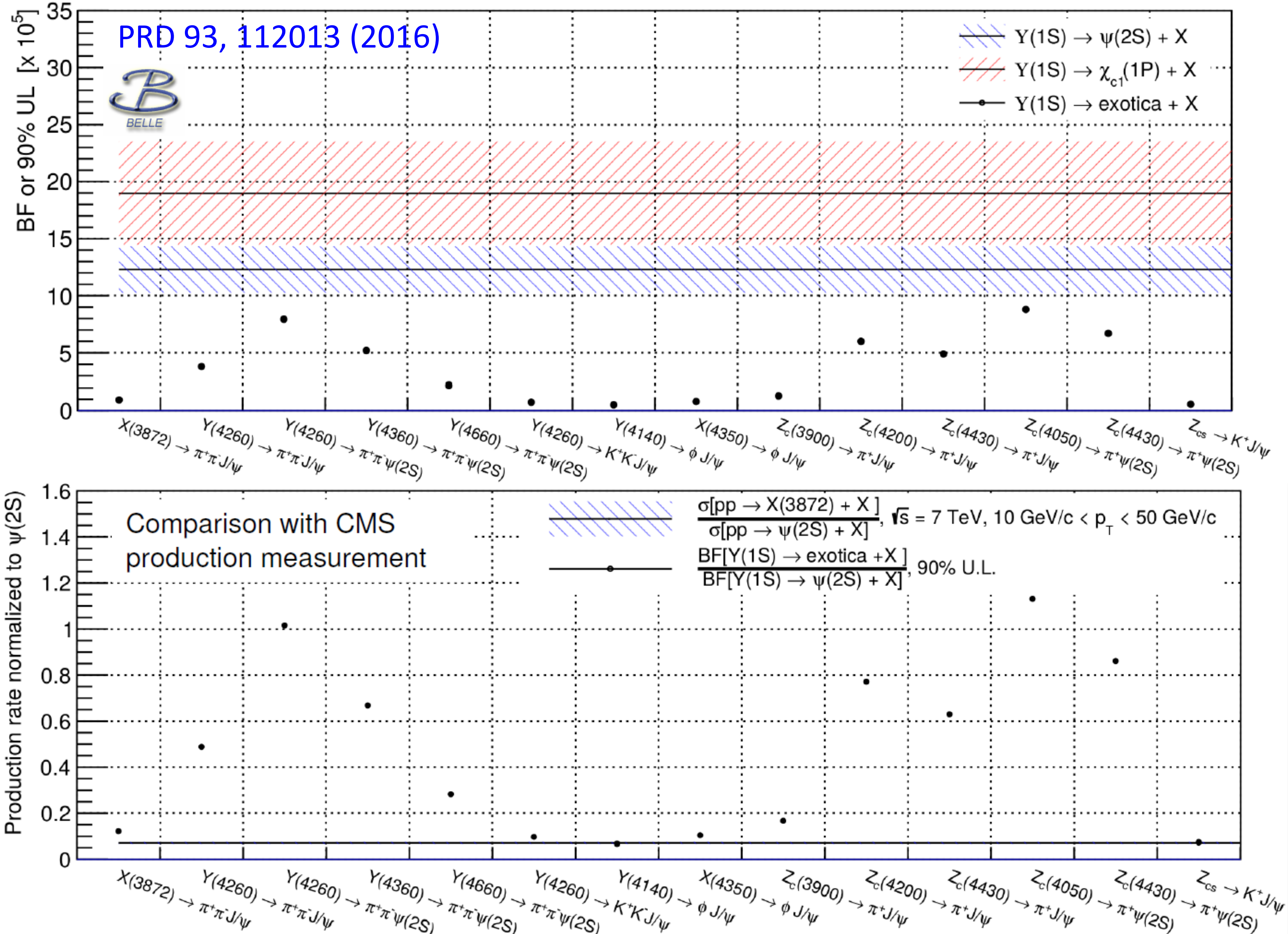
> on-going discussion with SuperKEKB people about beam energy measurement using backscattered photons produced by laser radiation scattered head-on the beams

Belle II's $\Upsilon(6S)$ measurements in Phase II

- May take $\sim 20-40\,\text{fb}^{-1}$ during the Phase II data taking and $\sim 10\,\text{fb}^{-1}$ at $\Upsilon(6S)$ resonance energy
- Using the Golden Modes:
  - $\Upsilon(6S) \to \pi Z_b(\pi h_b(nP))$
  - $\Upsilon(6S) \to \pi Z_b(\pi \Upsilon(pS)(l^+ l^-))$
- Monte-Carlo studies show that a good separation is possible with $10\,\text{fb}^{-1}$ of data



Υ(1S) to inclusive XYZ



PWA on Zc(3900) state

BESIII

preliminary

In the process $e^+e^- \to \gamma^* \to \pi^+\pi^- J/\psi$

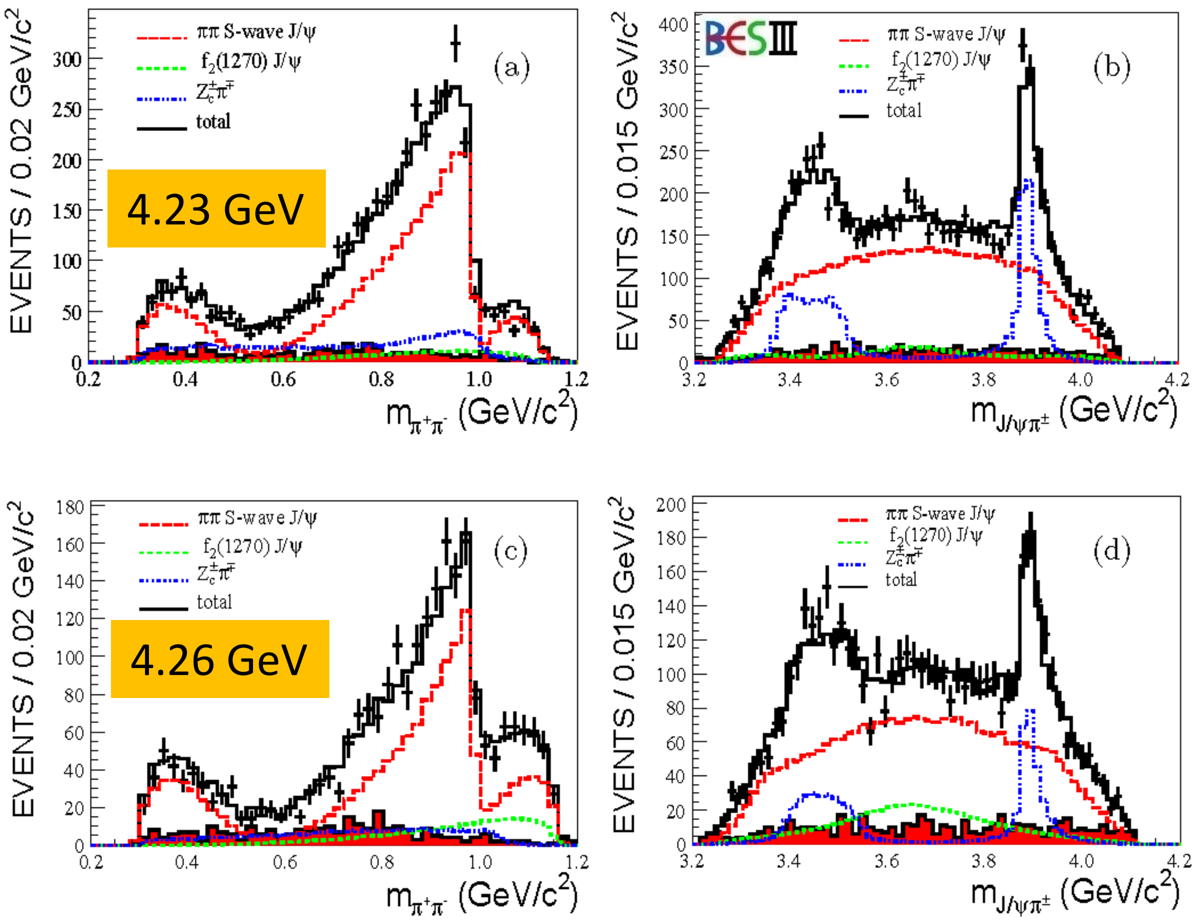
- The helicity value of γ^* is taken as $\lambda_0 = \pm 1$ due to from e+e- annihination
- $\gamma^* \to Z_c^\pm \pi^\mp$, $Z_c^\pm \to J/\psi \pi^\pm$, we try J^P for X: 0^-, $1^-, 1^+, 2^-, 2^+$, and 0^+ is not allowed
- Z_c^+ and Z_c^- states are assumed as isospin partner, share the same mass and coupling constants
- Six resonances are inclued in fitting to data:

$\sigma_0, f_0(980), f_2(1270), f_0(1370), Z_c^\pm$, and $\pi^+\pi^- J/\psi$

Z_c is taken as 1^+.

Resonance	σ	$f_0(980)$	$f_2(1270)$	$f_0(1370)$	Z_c^+	Z_c^-
Significanceσ	13	25	5	11	22	22

PWA on Zc(3900) state



- Zc line shape parameterized with Flatte-like formula

$$g_2'/g_1' = 27.1 \pm 13.1$$

$$\Gamma(Z_c^\pm \to (D\bar{D}^*)^\pm)/\Gamma(Z_c^\pm \to J/\psi\pi^\pm) = 6.2 \pm 2.9$$

The signal yields corresponding for each mode with the $Z_c^\pm$ assignment $J^P = 1^+$ **preliminary**

$\sqrt{s}$	σ	$f_0(980)$	$f_2(1270)$	$f_0(1370)$	$Z_c^+ + Z_c^-$	$\pi^+\pi^- J/\psi$
4.23 GeV	1576.9±431.2	1050.2±157.8	4356.2±549.4	273.2±85.1	875.2±84.8	6.2±7.6
4.26 GeV	1121.5±112.0	465.1 ± 53.2	2236.8±157.6	308.8±108.2	314.2±21.2	15.9±39.3

Comparison of fit results

- Mass, g_1' and Log-likelihood

preliminary

$Z_c : J^P$	M (MeV)	$g'_1(\mathrm{GeV}^2)$	g'_2/g'_1	$-\ln L$
0^-	3906.3 ± 2.3	0.079 ± 0.007	25.8 ± 2.9	-1528.8
1^-	3903.1 ± 1.9	0.063 ± 0.005	26.5 ± 2.6	-1457.7
1^+	3900.2 ± 1.5	0.075 ± 0.006	21.8 ± 1.7	-1569.8
2^-	3905.2 ± 2.1	0.060 ± 0.004	28.7 ± 2.7	-1516.5
2^+	3894.3 ± 1.9	0.051 ± 0.005	23.4 ± 3.3	-1316.2

- Zc favors the quantum number $J^P=1^+$

Significance to distinguish the quantum number 1^+ over other quantum numbers.

Hypothesis	$\Delta(-\ln L)$	$\Delta(ndf)$	significance
1^+ over 0^-	44.5	$4\times2+5$	7.3σ
1^+ over 1^-	107.0	$4\times2+5$	$> 8.0\sigma$
1^+ over 2^-	51.8	$4\times2+5$	$> 8.0\sigma$
1^+ over 2^+	193.5	$4\times2+5$	$> 8.0\sigma$