Overview of experimental XYZ states and Tetraquarks

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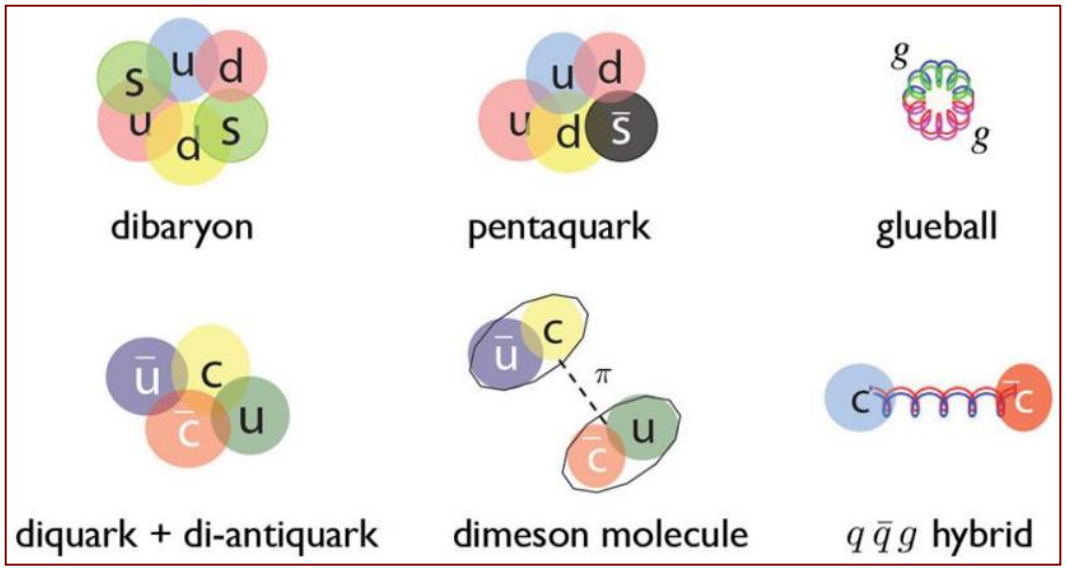
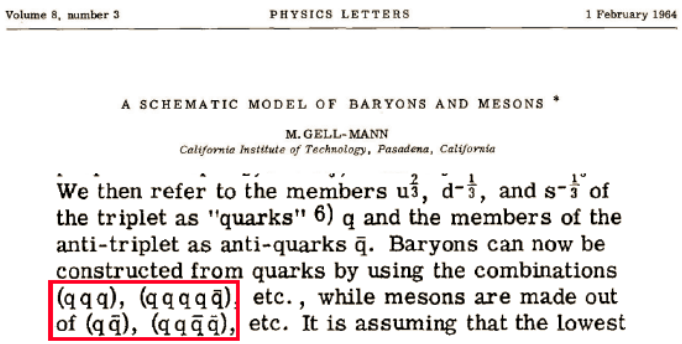
Outline

- 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





Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

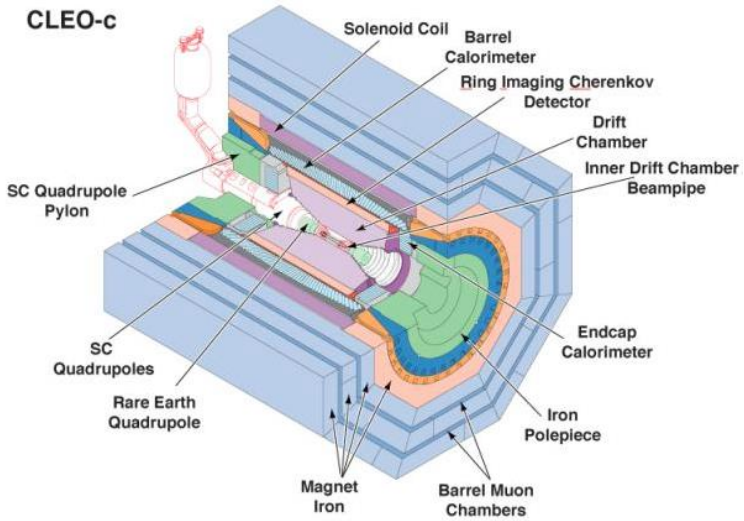
M. GELL-MANN
California Institute of Technology, Pasadena, California

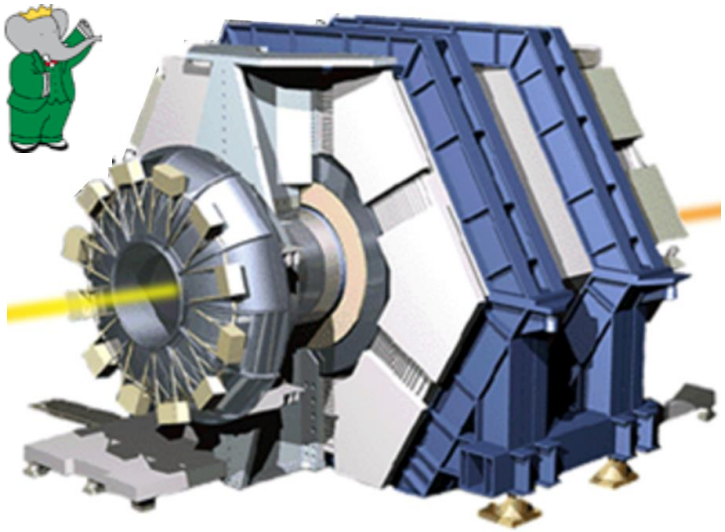
We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest

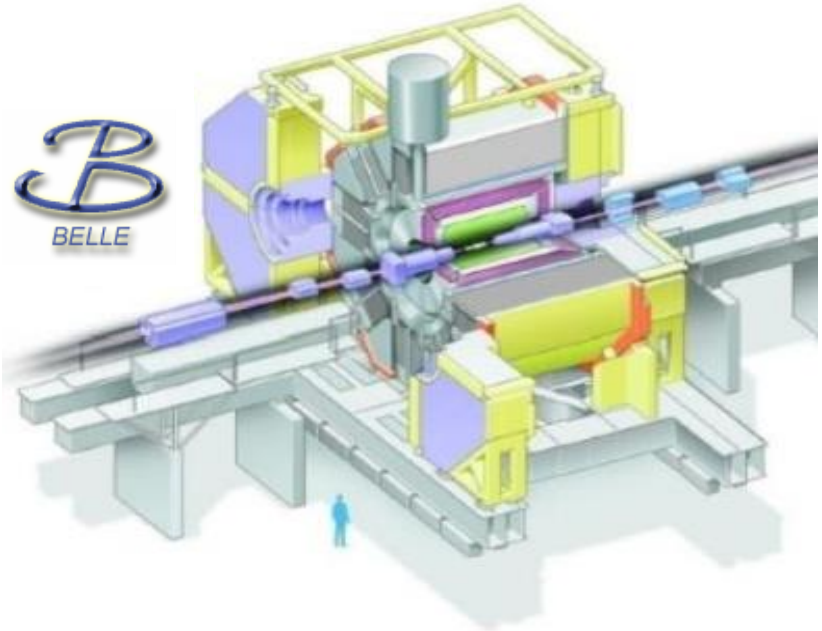
M. Gell-Mann, Phys. Lett. 8, 214 (1964)

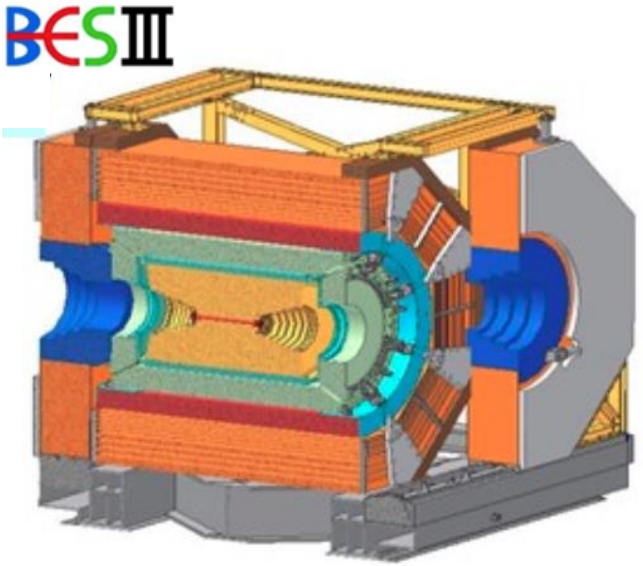
- QCD does not forbid hadrons with $N_{quarks} \neq 2, 3$
  - Glueball : $N_{quarks} = 0$ (gg, ggg, …)
  - Hybrid : $N_{quarks} = 2$ (or more) + excited gluon
  - Multiquark state : $N_{quarks} > 3$
  - Molecule : bound state of more than 2 hadrons
  - …

Main Suppliers of Exotics









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, …

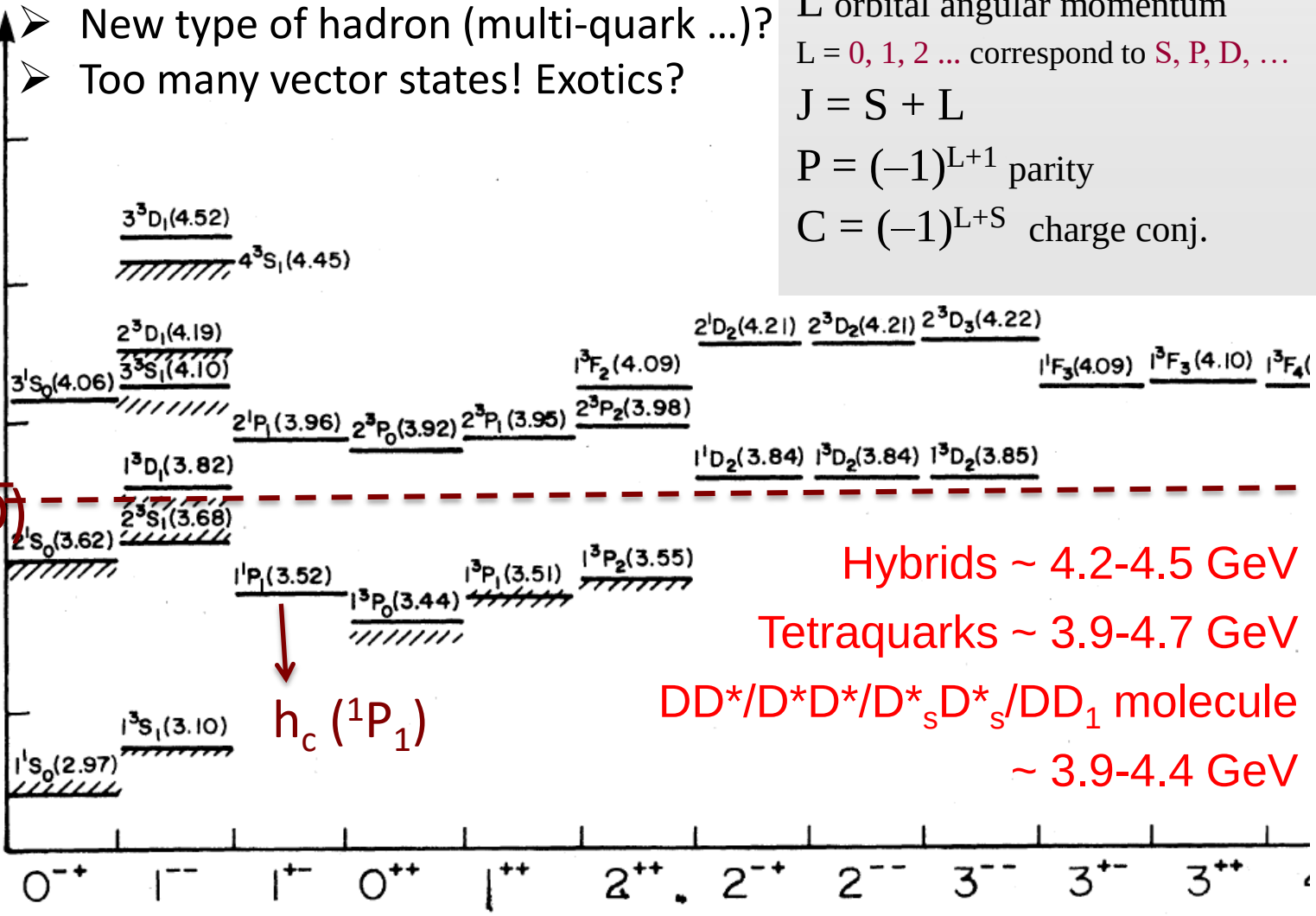
$J = S + L$

$P = (-1)^{L+1}$ 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)
…



m(D+D)

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 …

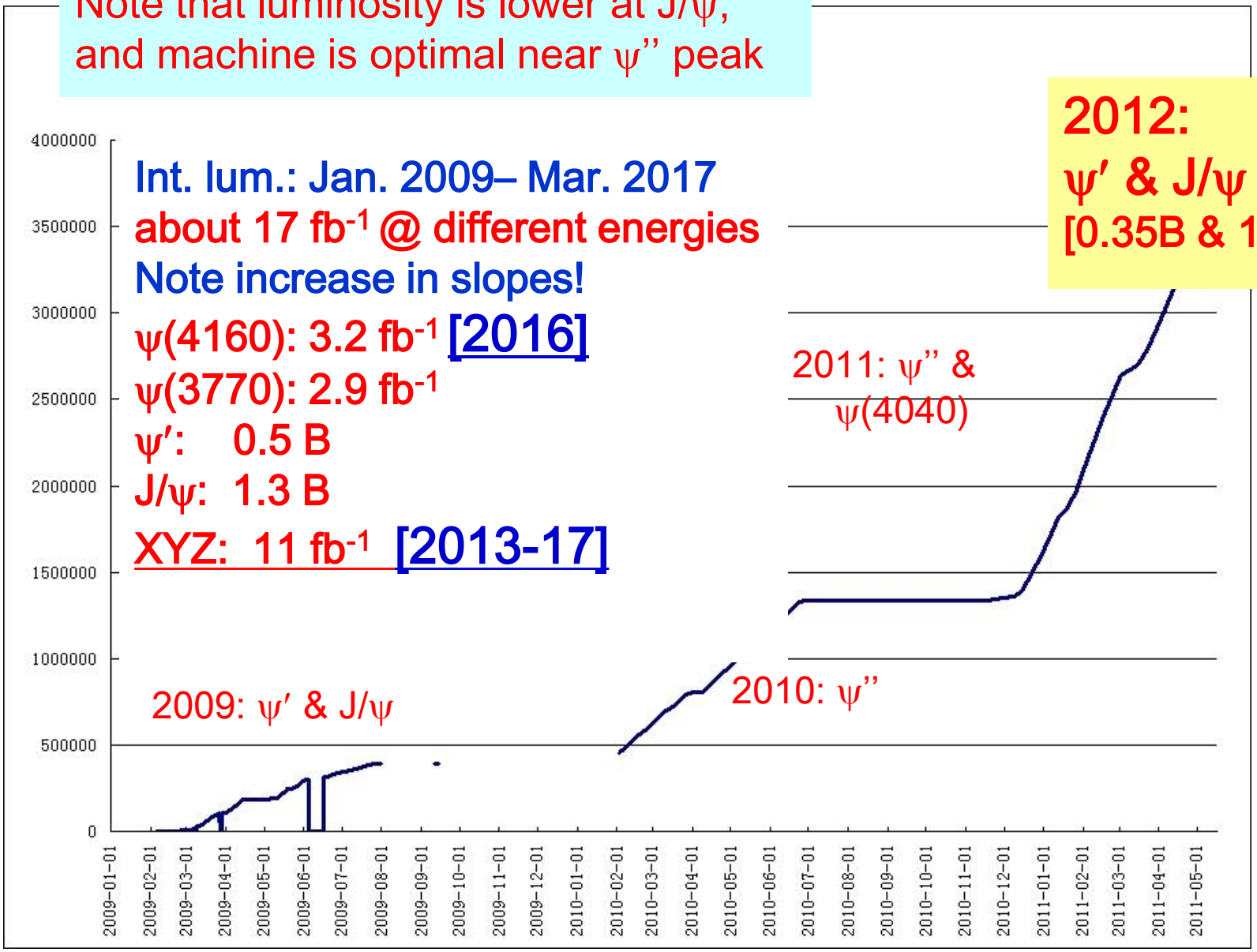
QCD is another least understood part of the SM.

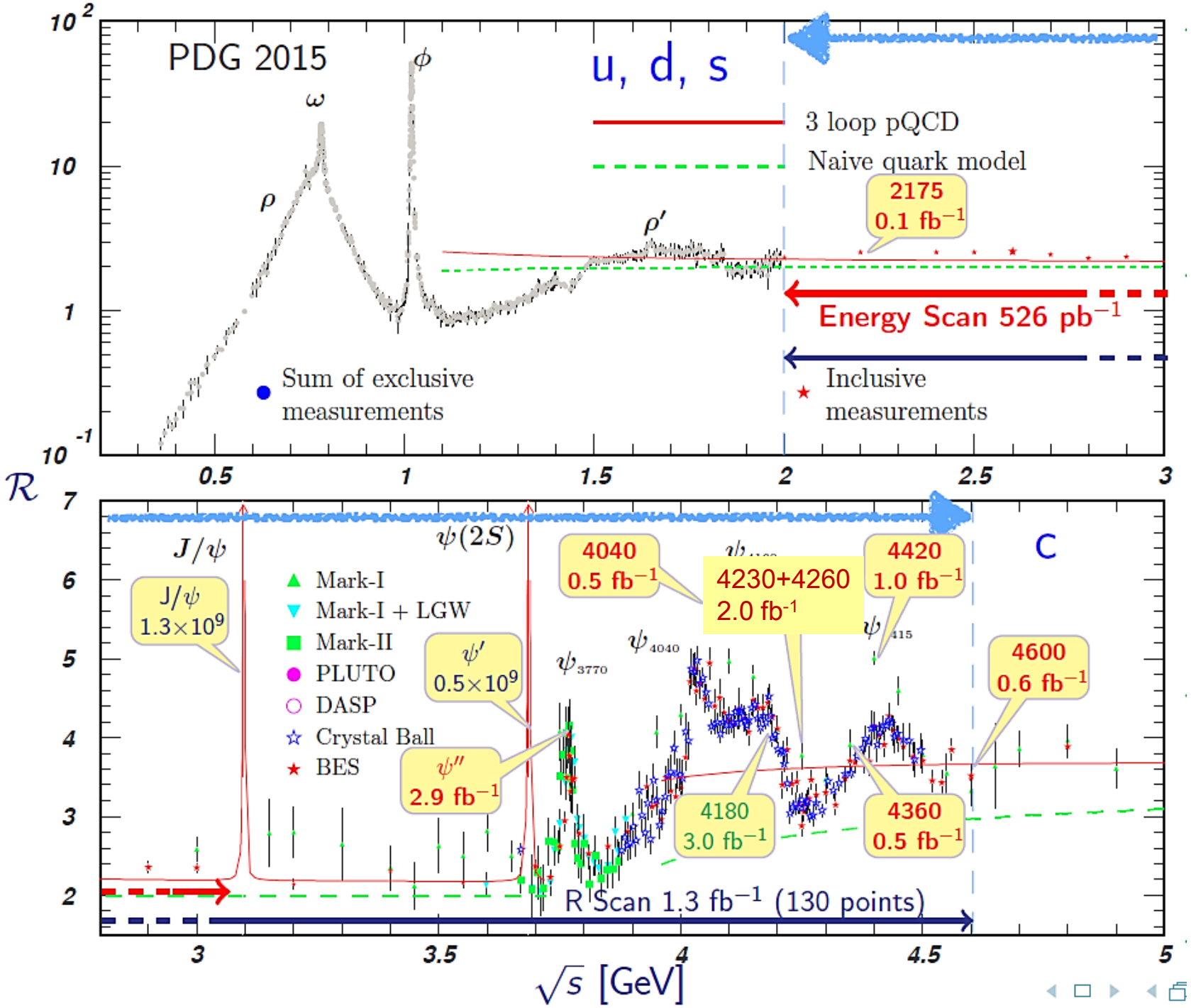
"The absence of exotics is one of the most obvious features of QCD" – R. L. Jaffe, 2005

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

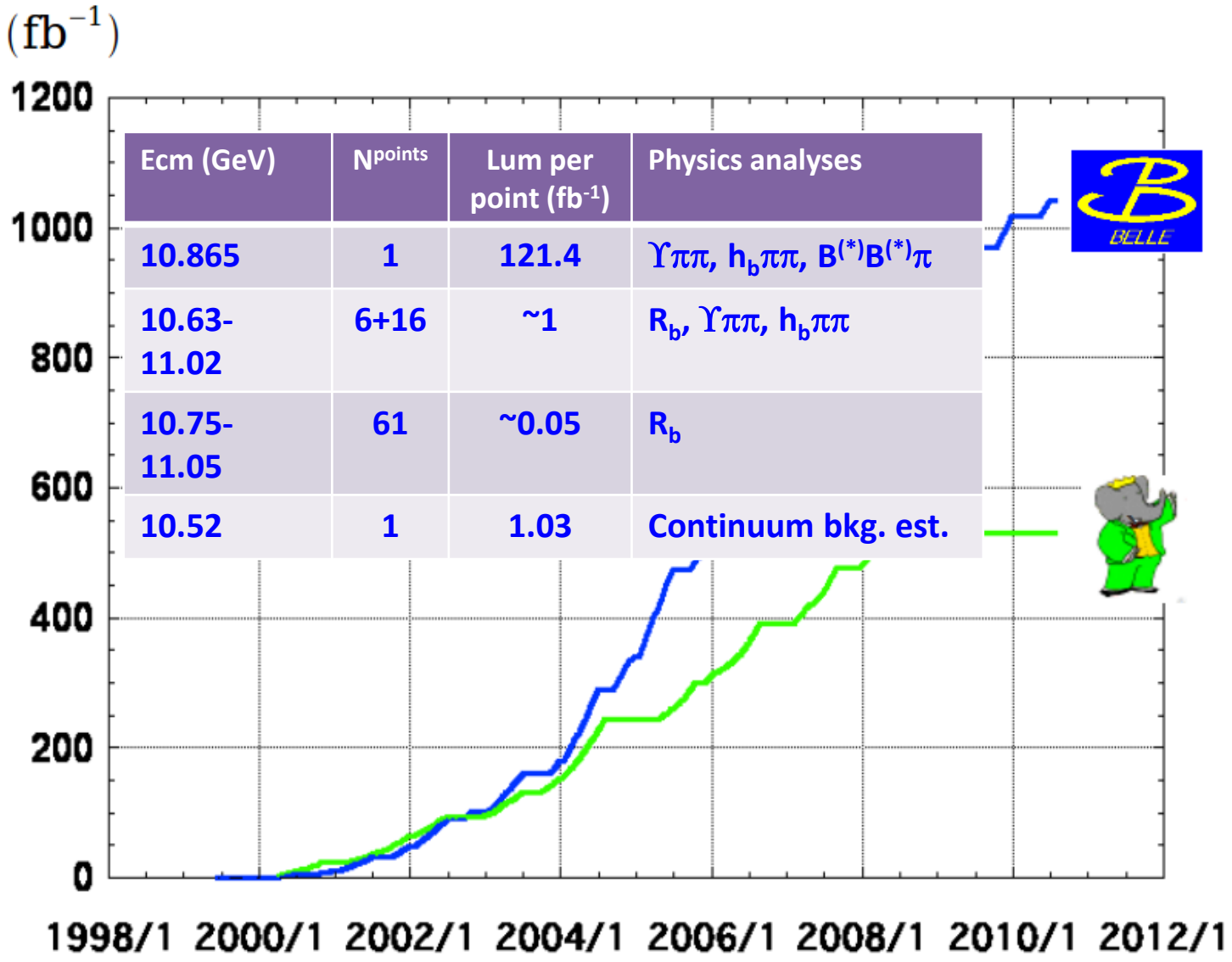
BESIII data samples

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




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}
Mark-I
Mark-I + LGW
Mark-II
PLUTO
DASP
Crystal Ball
BES
ψ_{3770}
ψ_{4040}
ψ_{4415}
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}
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.

> 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:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

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

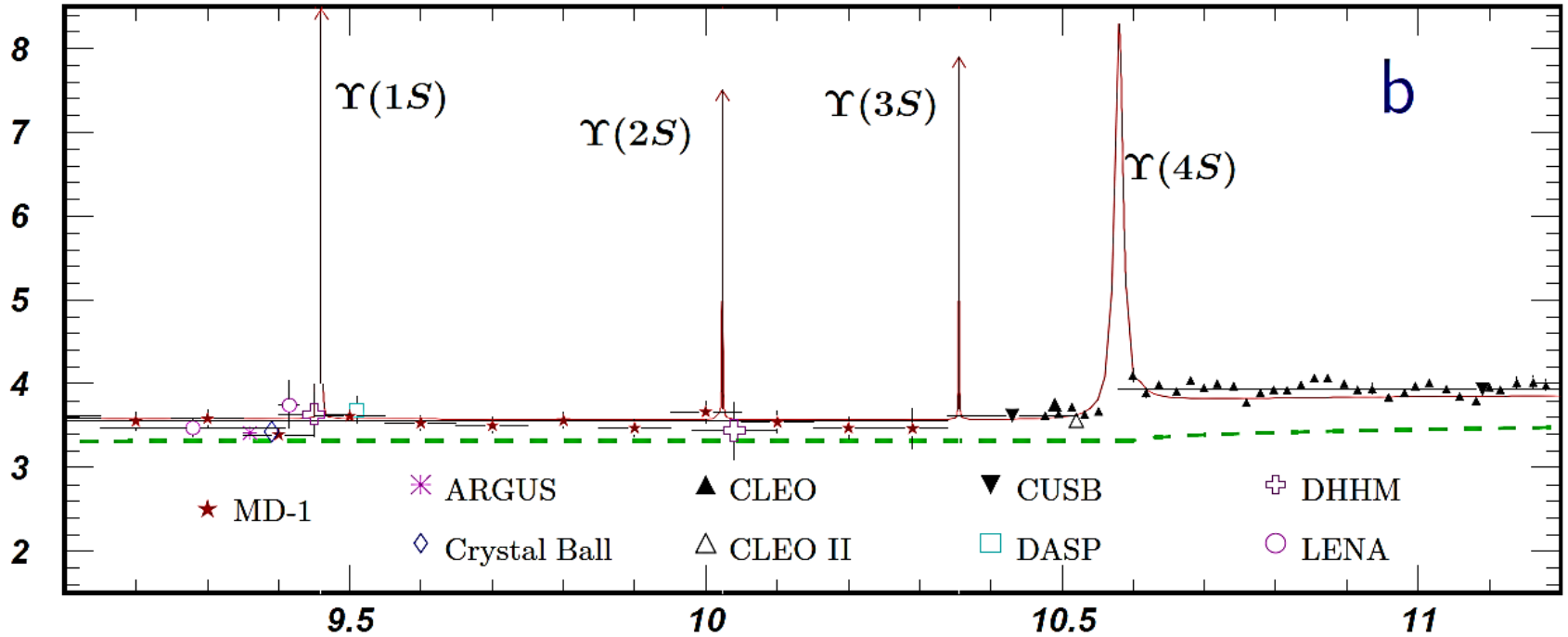
$\Upsilon(3S)$: 30 fb^{-1}

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

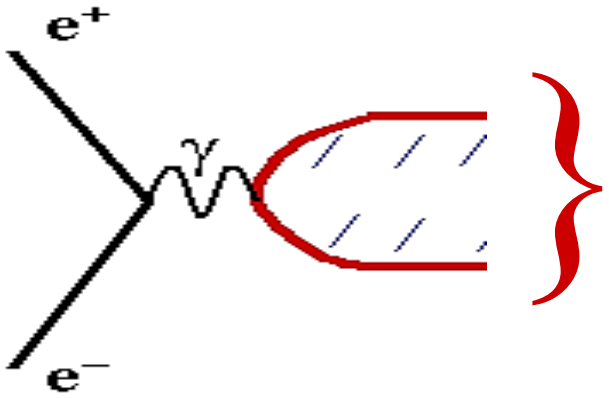
Off resonance:

~ 54 fb^{-1}

e^+e^- annihilation to vector bottomonia

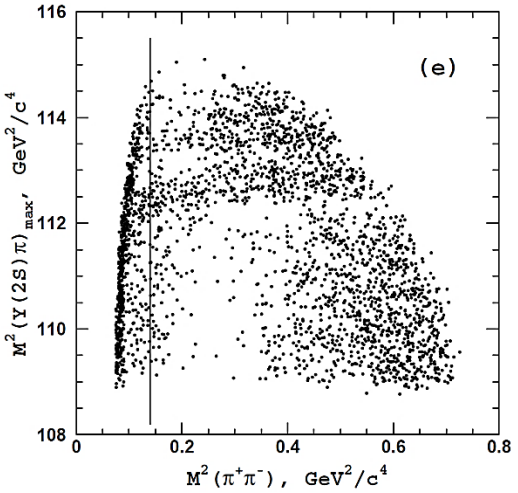


$\sqrt{s}$ [GeV]

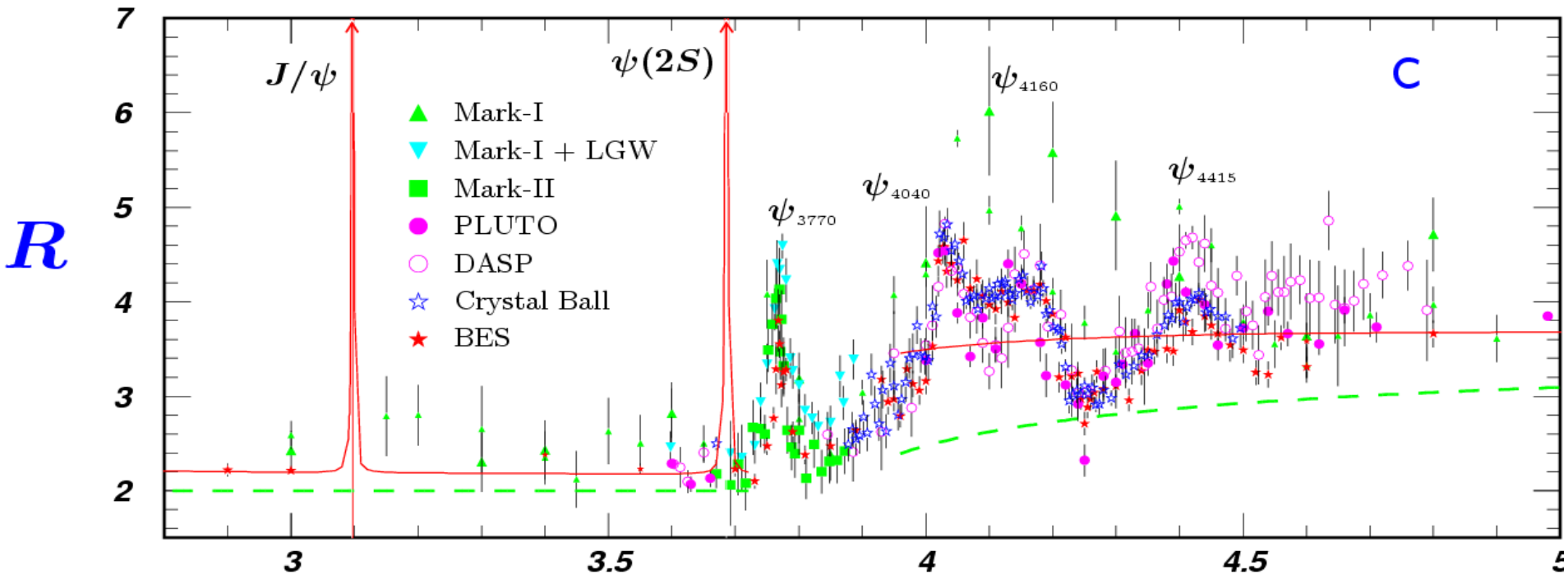


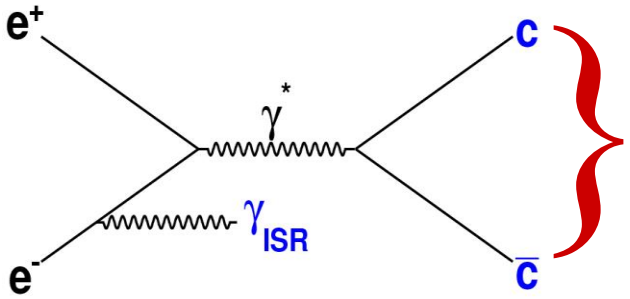
$J^{PC} = 1^{--}$

$\Upsilon(nS)$, Y_b…



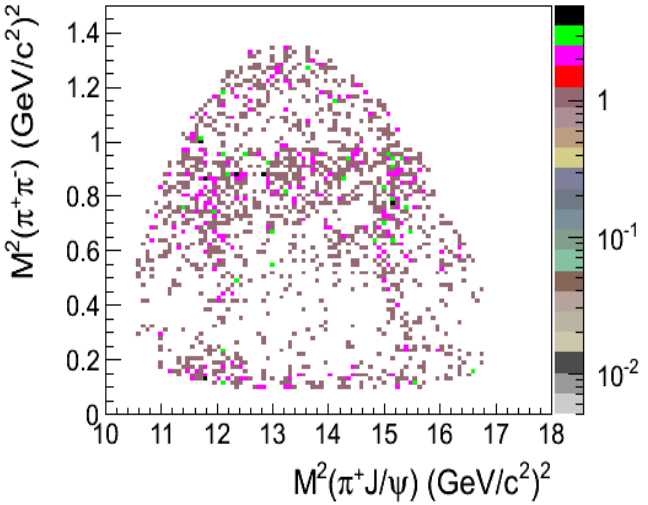
ISR production of vector charmonia





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

ψ', ψ'', Υ…



X States

X(3872), X(5568), X_b …

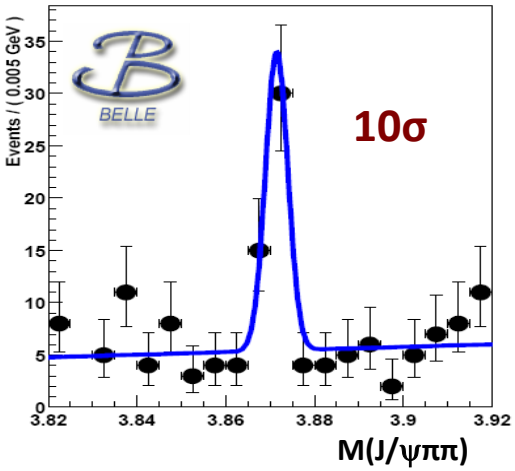
Observed in B decays and (suggestively) in decays of Y type states

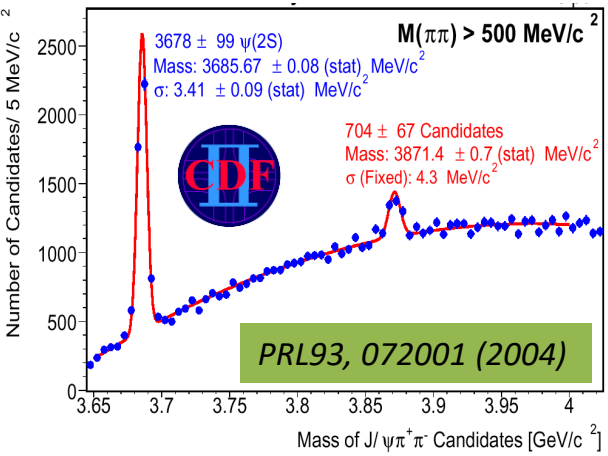
X(3872)→J/ψπ⁺π⁻

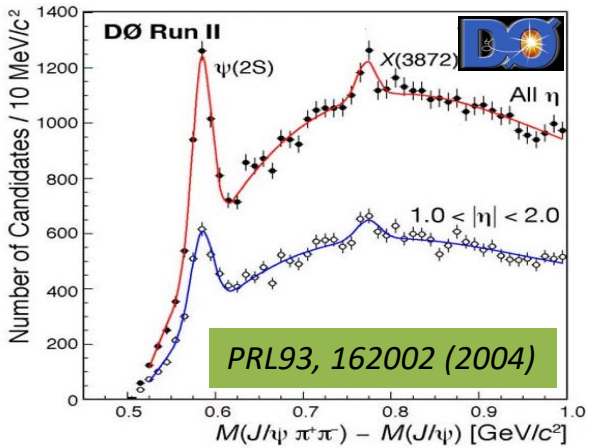
Belle's most cited paper: 1200+

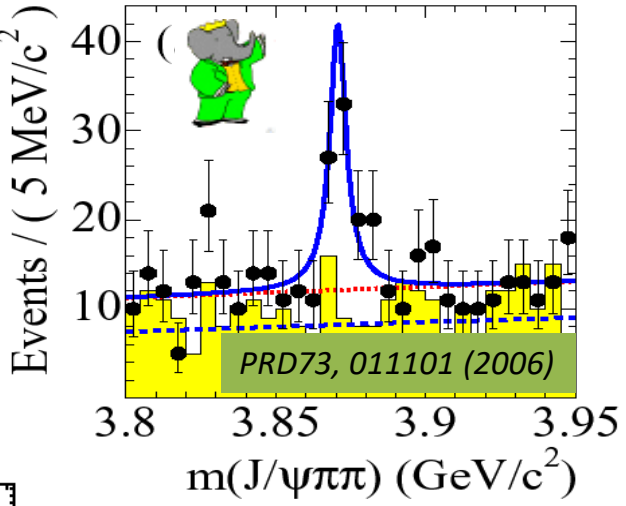
first observed by Belle in B→K J/ψπ⁺π⁻ ***PRL91, 262001 (2003)***

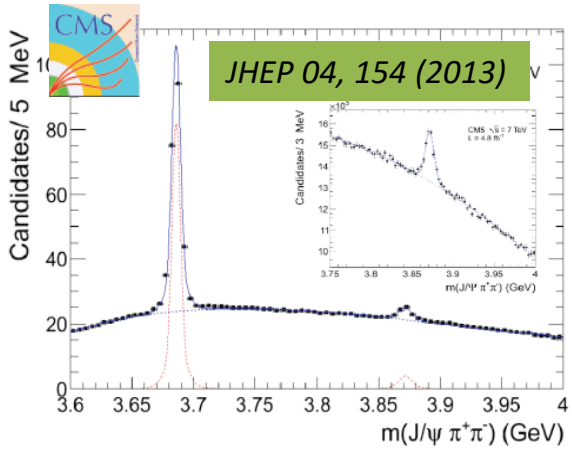
- **M_X close to D^0D^{*0} threshold M = 3871.68 ± 0.17 MeV (not clear below or above: Δm = – 0.16 ± 0.32 MeV)**
- **surprisingly narrow: Γ_{tot}< 1.2 MeV at 90% CL**

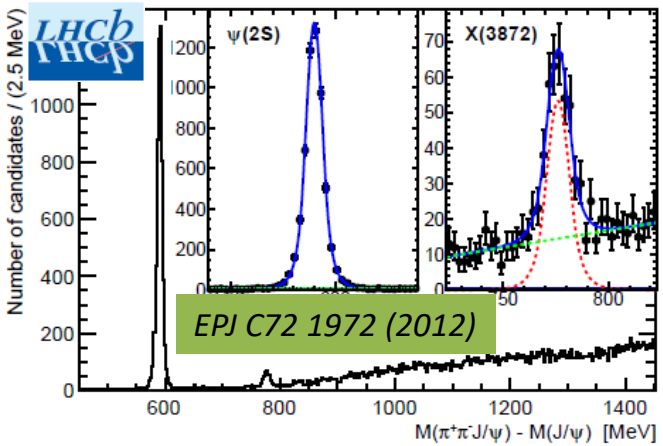












X(3872)→J/ψγ: C-even

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): Other Decay Modes

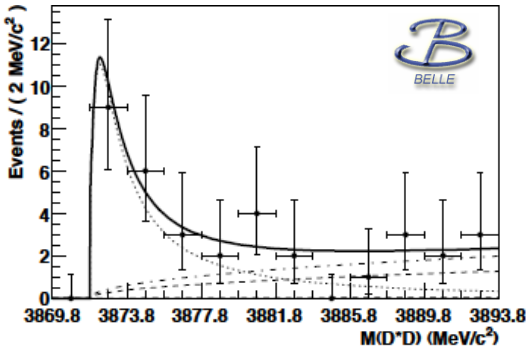
- **ππ = ρ means Isospin violation!**
- **X(3872) → J/ψω is seen: confirms isospin violation**

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

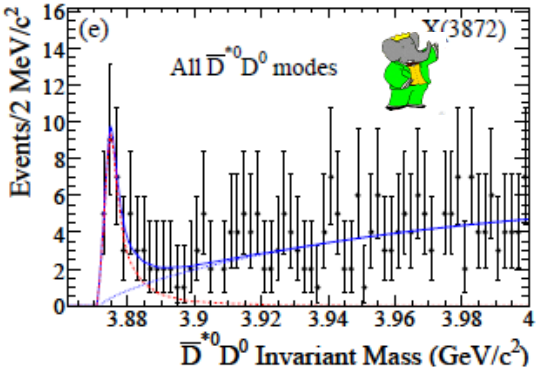
- Radiative decays: Belle&Babar good agreement for X →J/ψγ; not consistent for X →ψ(2S)γ.

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

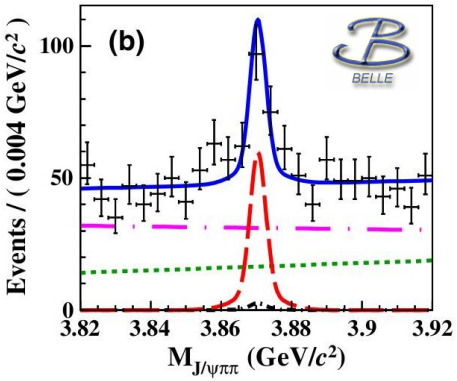
- X(3872) → DD* - dominant mode
- B→X(3872)Kπ non-resonant Kπ dominates!



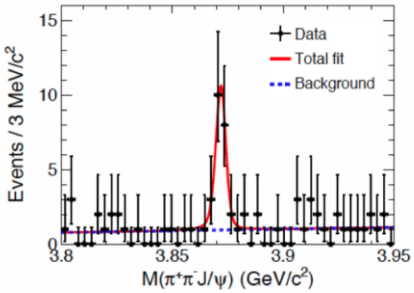
PRD 81, 031103 (2010)

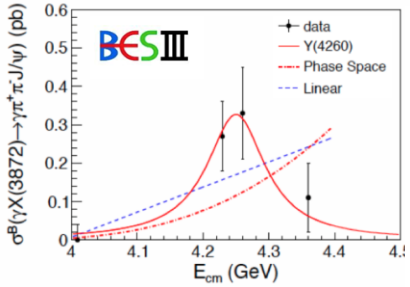


PRD 77, 011102 (2008)



PRD 91, 051101(R) (2015)





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 $B(X(3872) \to \pi^+\pi^- J/\psi) = 5\%$, $\mathcal{R} = \dfrac{Br(e^+e^- \to \gamma X(3872))}{Br(e^+e^- \to \pi^+\pi^- J/\psi)} = 0.1$

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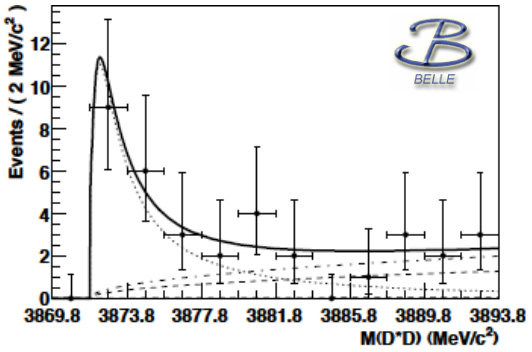
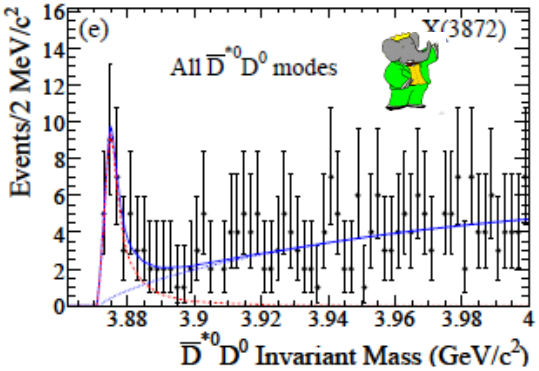
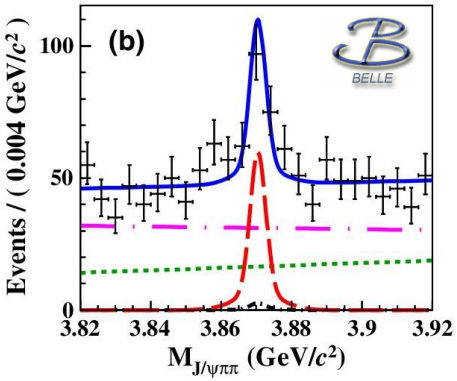


PRD 81, 031103 (2010)



PRD 77, 011102 (2008)



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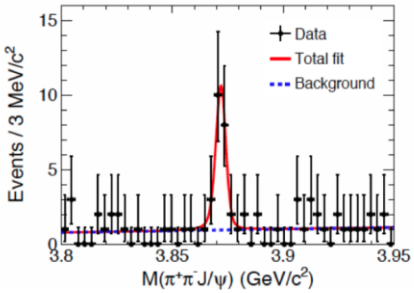

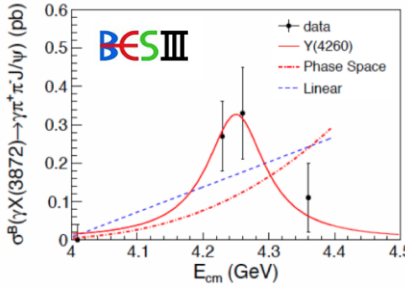

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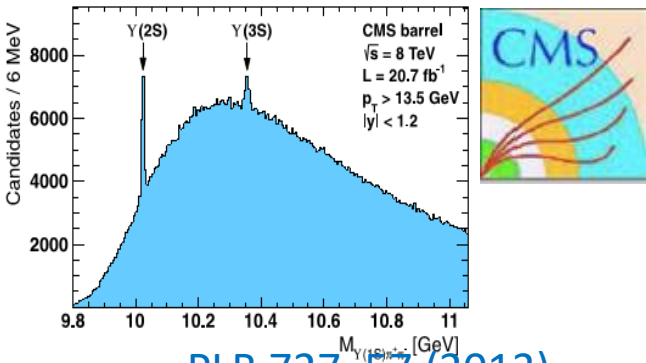
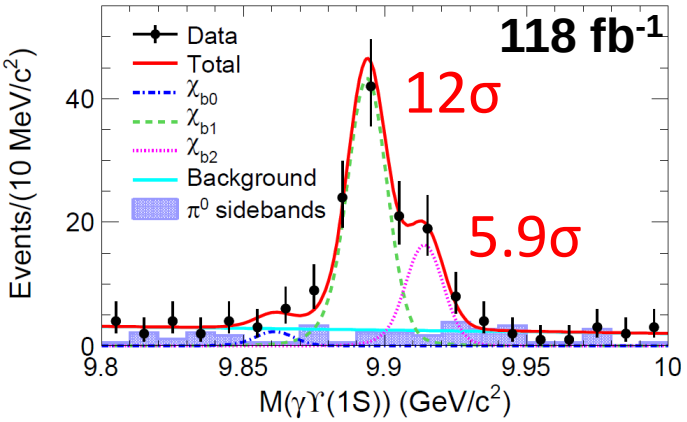
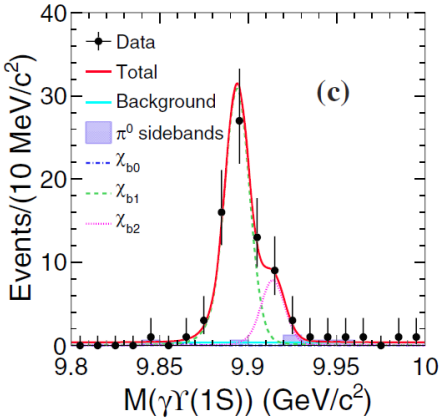
Search for X_b in $e^+e^- \to \gamma\pi^+\pi^-\pi^0\Upsilon(1S)$ at 10.867 GeV

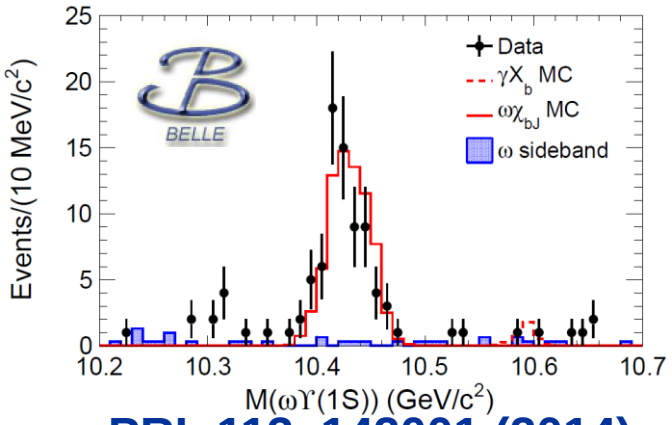
- **The X(3872) counterpart in the bottomonium sector X_b, NOT observed decay channel $\pi^+\pi^-\Upsilon(1S)$.**
- **As X_b is above $\omega\Upsilon(1S)$ threshold, this Isospin-conserving process should be a more promising decay mode.** [PRD88, 054007].



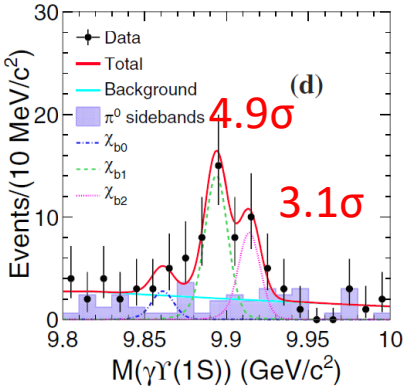
PLB 727, 57 (2013) .







PRL 113, 142001 (2014)



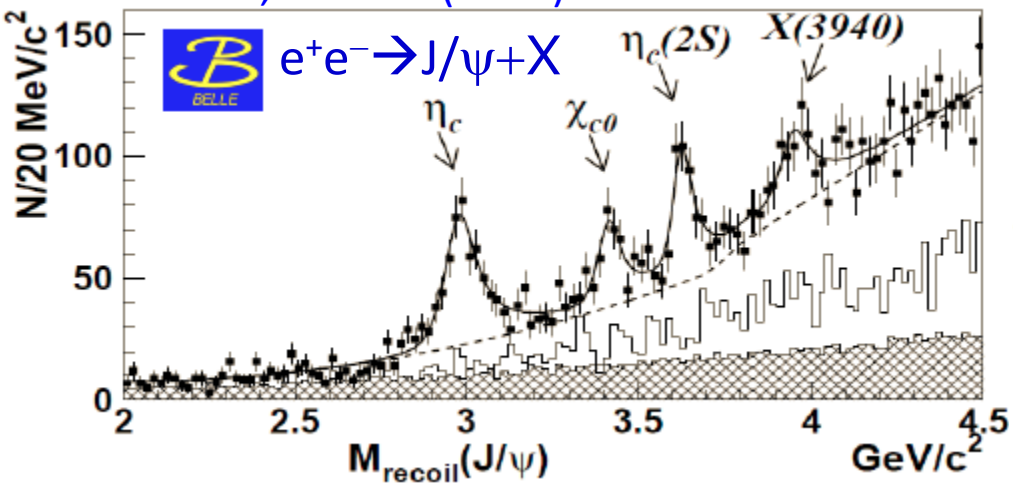
- **Large Brs of Y(5S) to $\pi^+\pi^-\pi^0\chi_{b1/b2}$, $\omega\chi_{b1/b2}$ are observed for the first time and their ratios are measured: hadronic loop effect ?**

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)



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

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

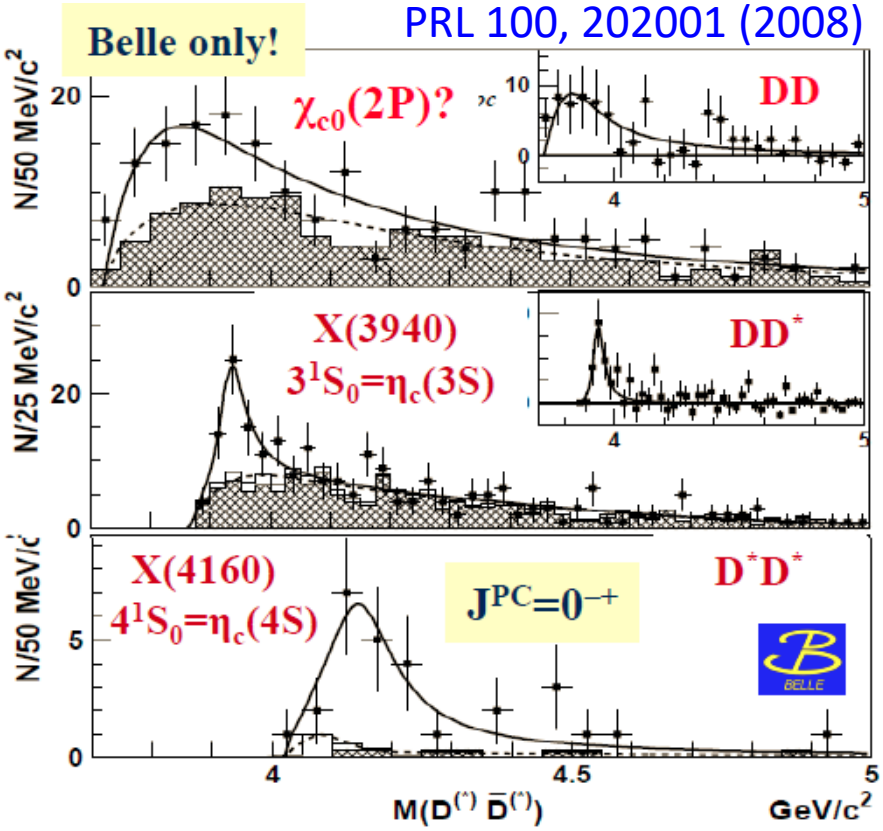
$X(4160) = 4^1S_0 = \eta_c(4S)$

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 $\eta_c(4S)$

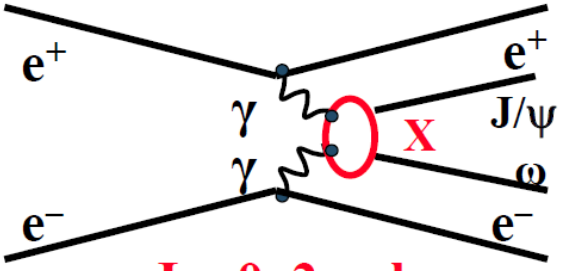
Theory probably needs more elaborate models to take into account charmonia couplings to meson pairs

PRL 100, 202001 (2008)

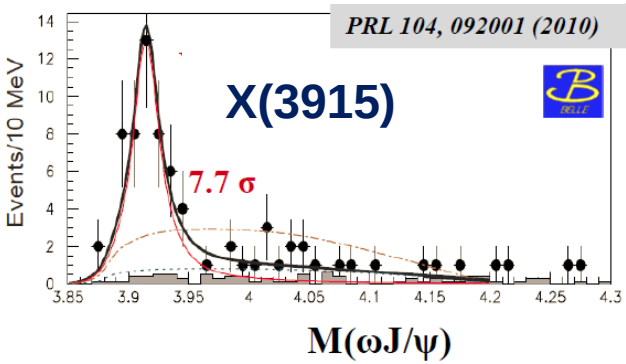


- Search for new states in $e^+e^- \to J/\psi D^{(*)}D^{(*)}\pi$ and in $e^+e^- \to \chi_{c1} D^{(*)}D^{(*)}$
- Production: reconstruction of the exclusive final states
- Production studies with other charmonium states (e.g. $\psi(2S)$, χ_{c1})

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



J = 0, 2 only



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

PDG: Y(3940)=X(3915)=$\chi_{c0}(2P)$

Theory ☹

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

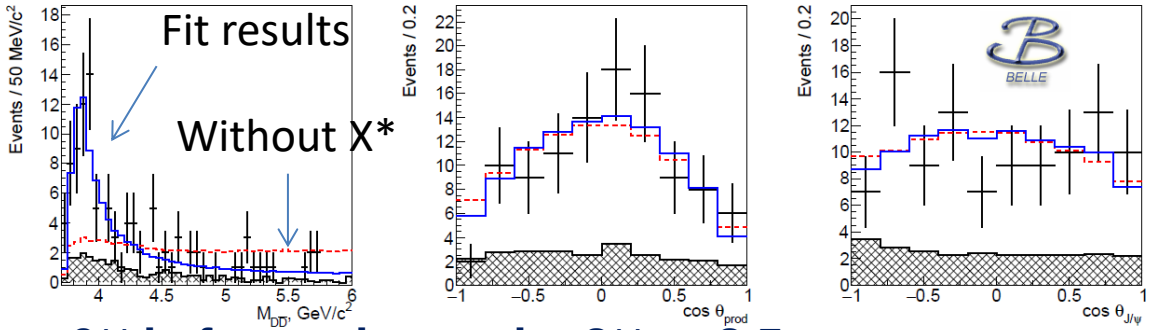
PDG 2016: X(3915)≠$\chi_{c0}(2P)$

arXiv:1704.01872(accepted by PRD)

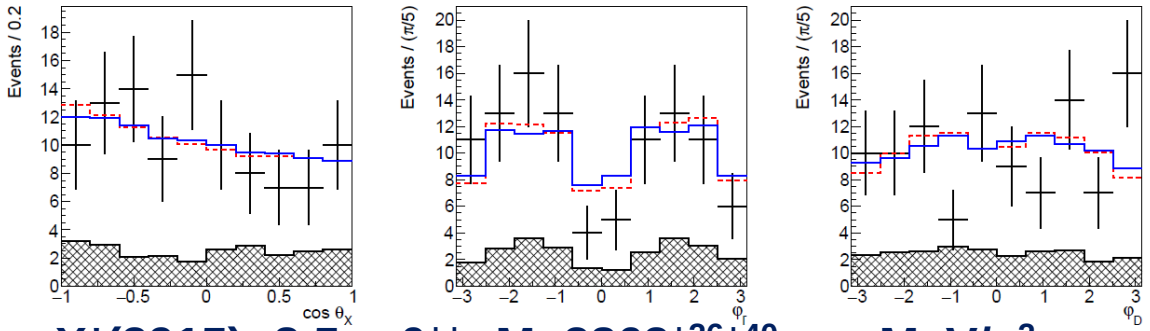
A 6D amplitude analysis was done to $e^+e^- \rightarrow J/\psi D\bar{D}$

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

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/c^2

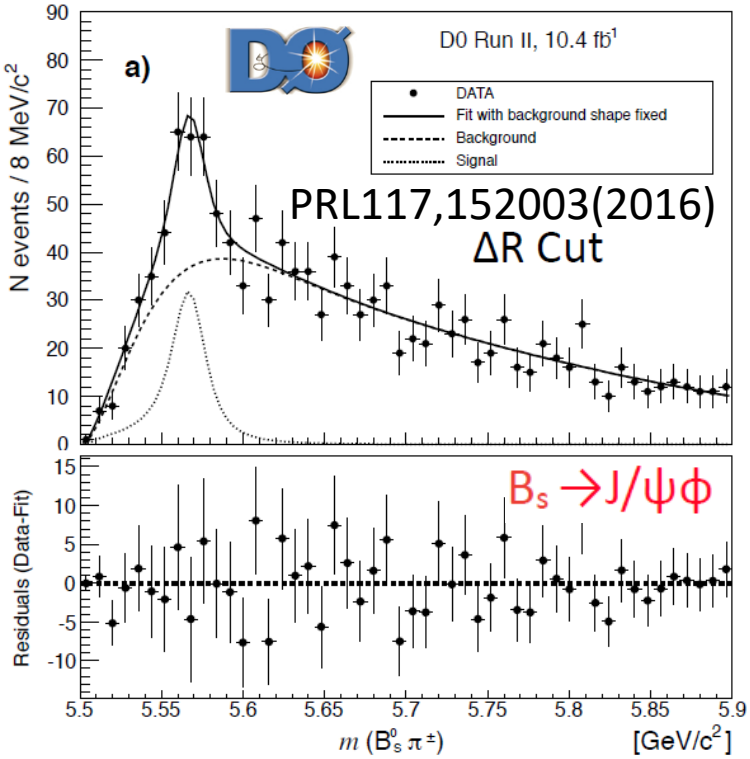
$\Gamma=201^{+154+88}_{-67-82}$ MeV

The parameters of X*(3915) are <2.7σ difference from the predicted $\chi_{c0}(2P)$

X(5568)

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



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

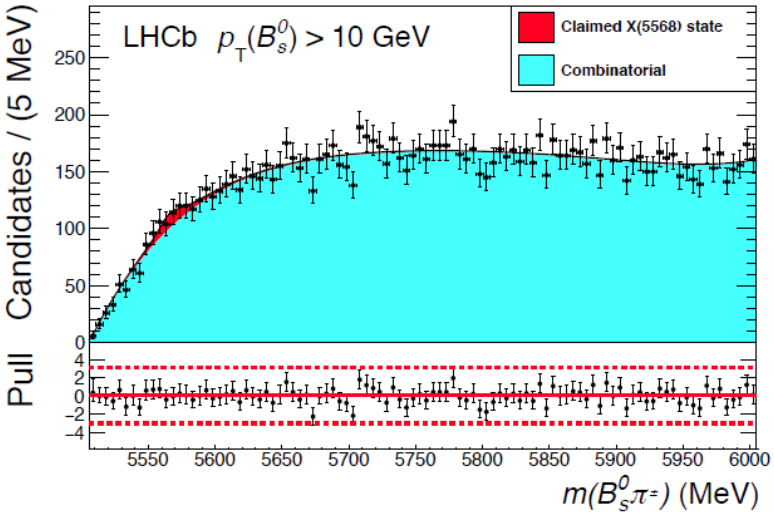
$$X(5568)$$

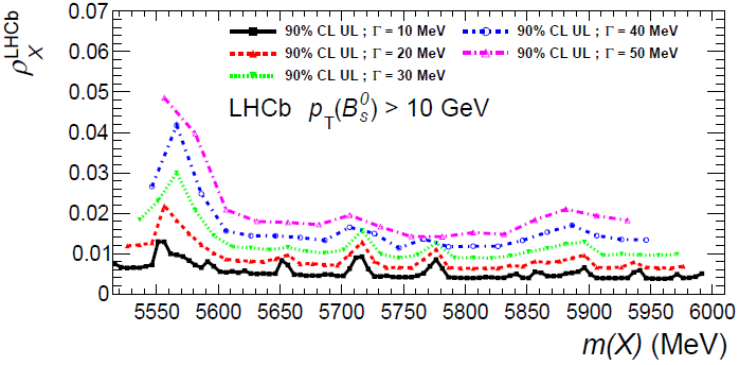
$$M_X = 5567.8 \pm 2.9\,(\text{stat})^{+0.9}_{-1.9}\,(\text{syst})\,\text{MeV/c}^2$$

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

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

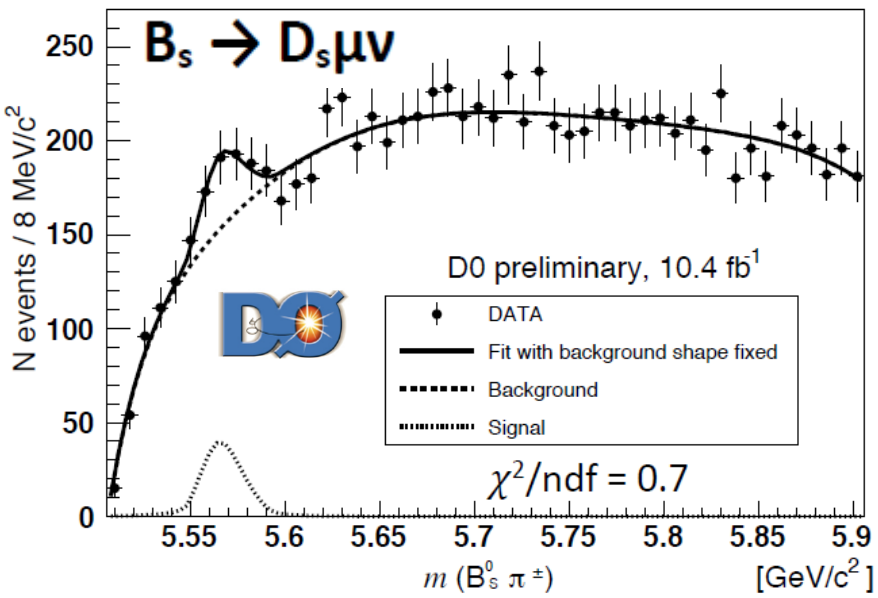
PRL117, 152003 (2016)

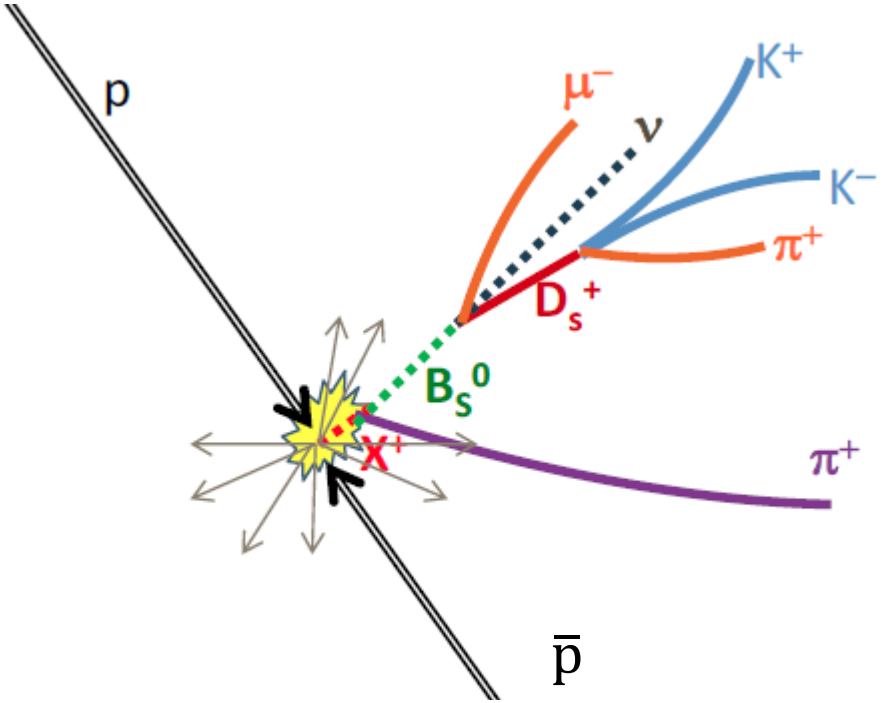




X(5568)

D0 Conference Note 6494





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

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

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

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

$$\underline{\text{Local Signficance}}$$

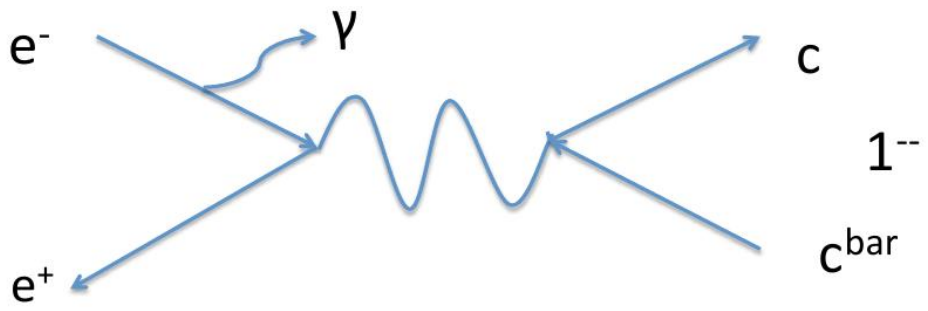
$$\sqrt{-2\ln\frac{\mathcal{L}_0}{\mathcal{L}_{\max}}}$$

Statistical Significance $4.5\,\sigma$.
Including Systematics $3.2\,\sigma$.

Y States

Y(4260), Y(4360), Y(4660)…

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

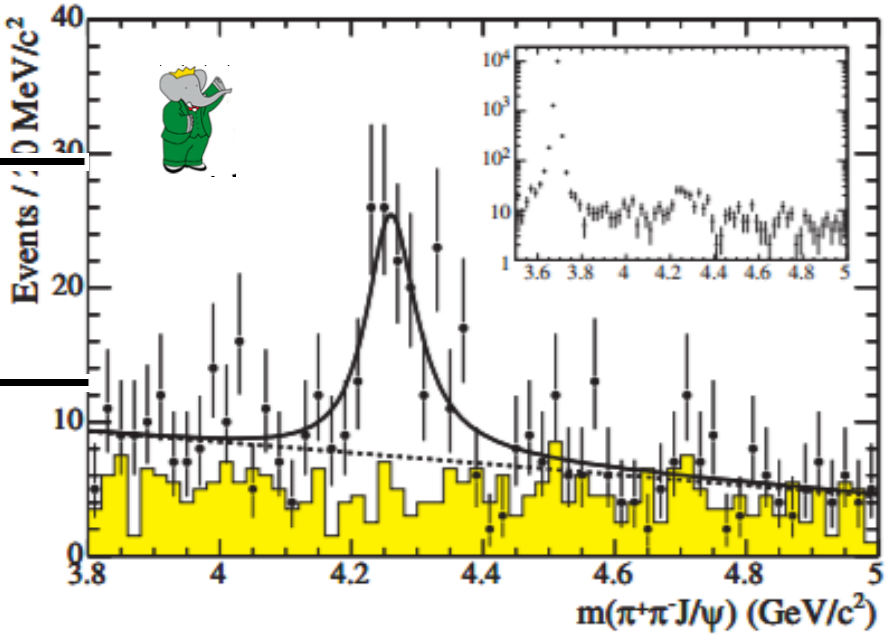


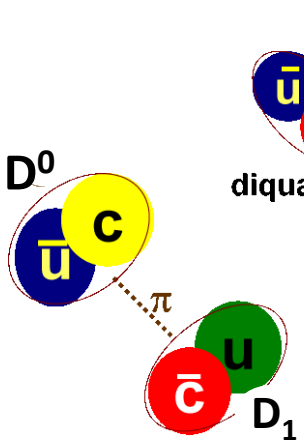
$e^+e^- \to \pi^+\pi^- J/\psi$ cross section

BABAR PRL95,142001(2005)

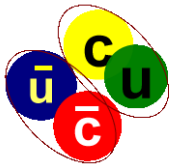
X(4260) $\quad I^G(J^{PC}) = ?^?(1^{--})$

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

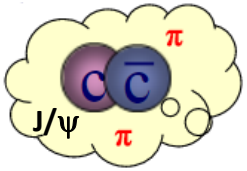




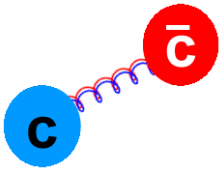
$D^0 - D_1$ "molecule"



diquark-diantiquark

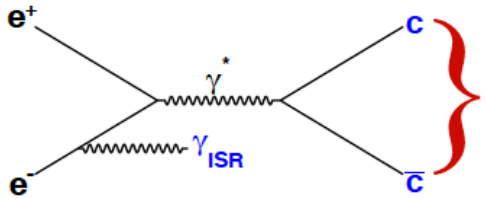


Hadro-charmonium



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

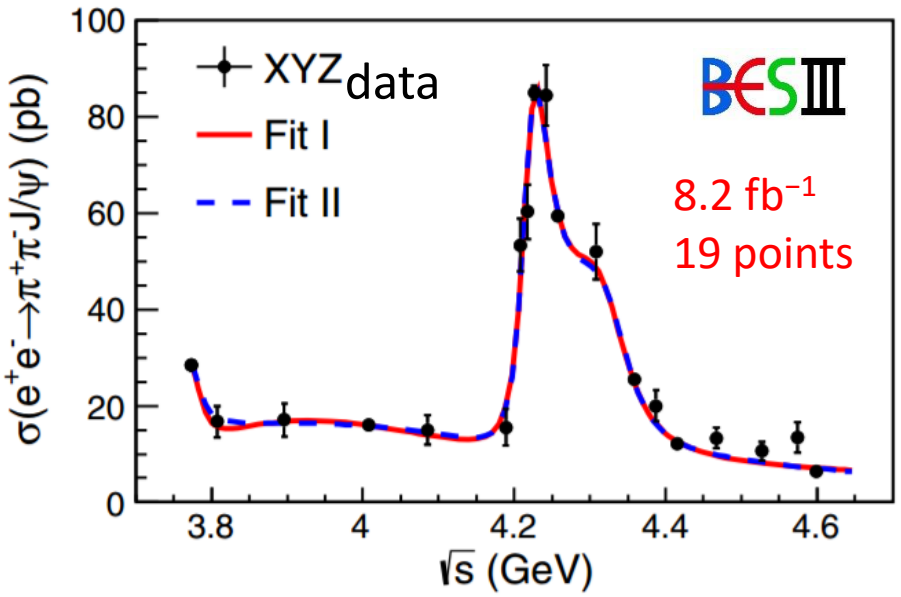
Y(4260)/X(4260)

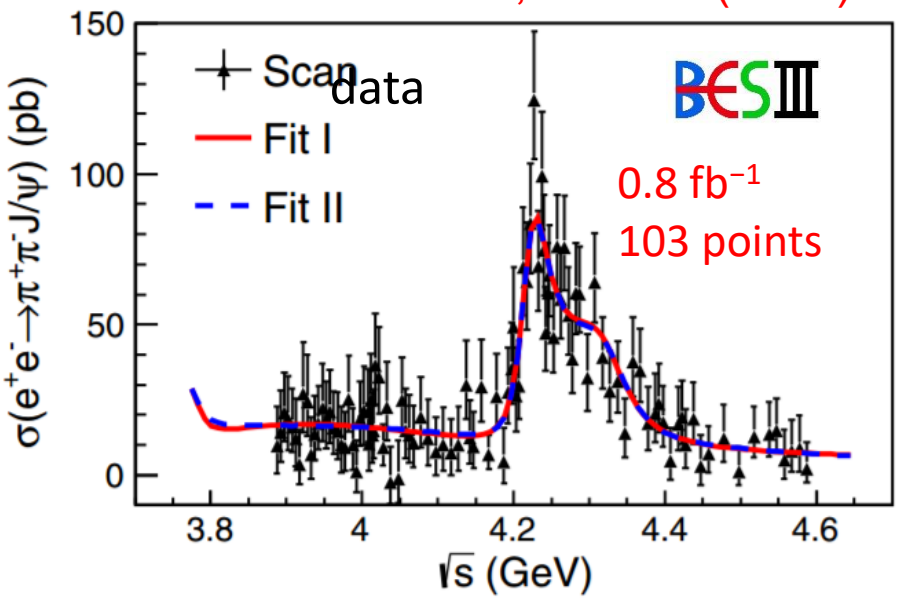


Confirmed by Belle, CLEO, BESIII

$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ 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=$4320.0 \pm 10.4 \pm 7.0$ MeV/c^2

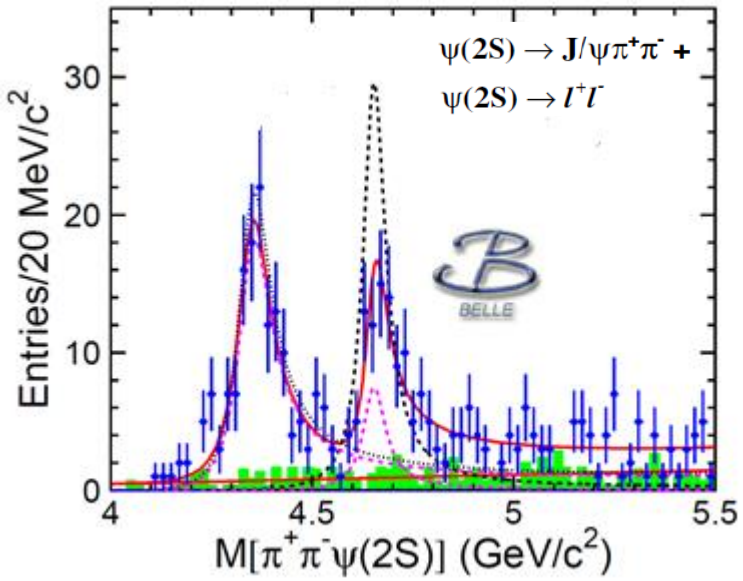
  $\Gamma = 101.4^{+25.3}_{-19.7} \pm 10.2$ MeV
- Observed for the first time, significance > 7.6σ

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

PRD 91, 112007 (2015)

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

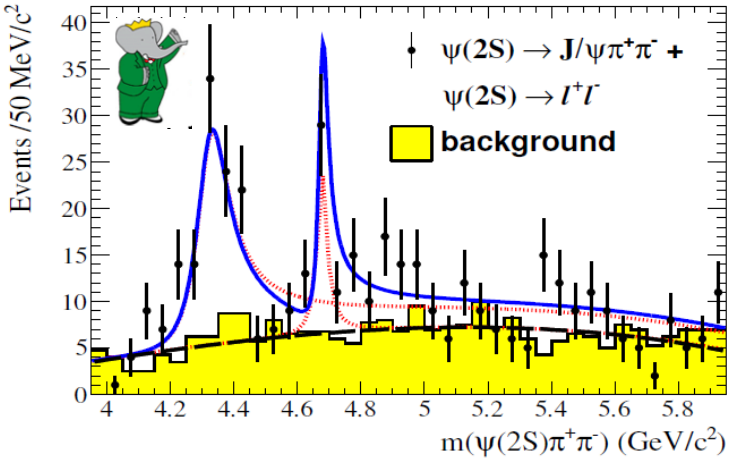
$$Amp = BW_1 + e^{i\phi} \cdot BW_2$$



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

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

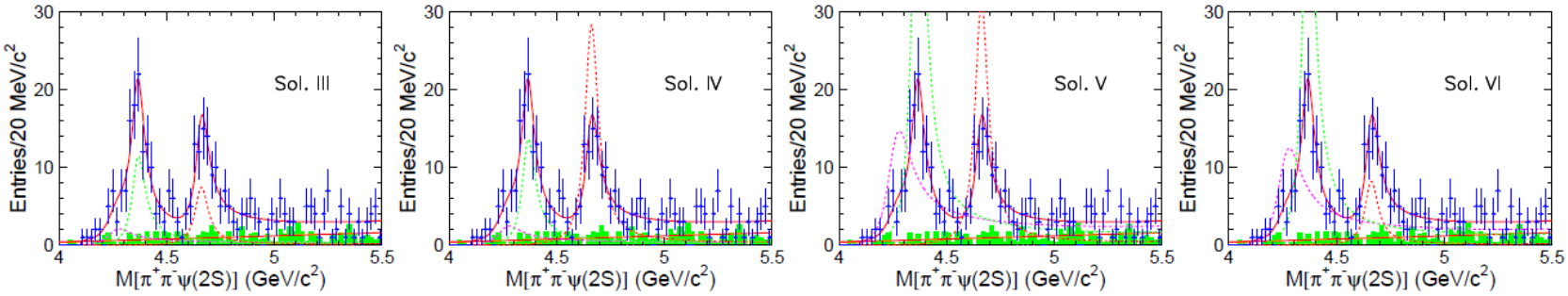
- Consistent with previous measurement
- No obvious signal above $Y(4660)$.
- Some events accumulate at $Y(4260)$, especially the $\pi^+\pi^- J/\psi$ mode.
- If $Y(4260)$ is included in the fit, ...



PRD89, 111103 (2014)

$M(\pi^+\pi^-\psi(2S))$ with $\Upsilon(4260,4360,4660)$

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

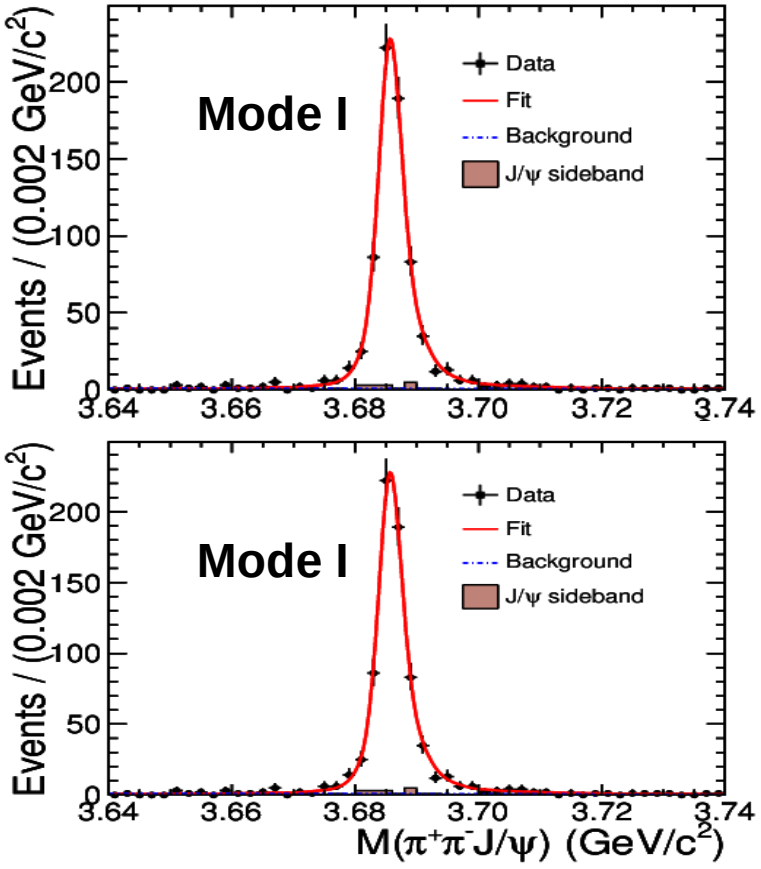
Comparsion of $e^+e^-\rightarrow\pi^+\pi^-\psi(2S)$ cross section

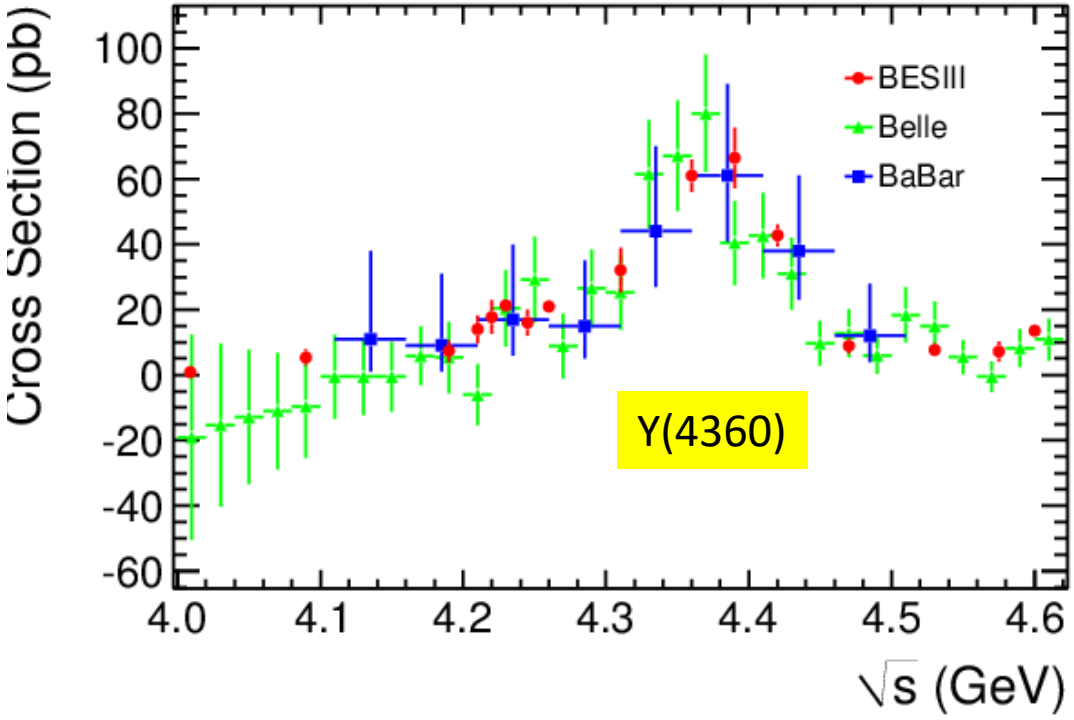
BESIII (16 energy points; L_{tot}=5.1fb^{-1})

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

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

Mode II: $\Psi(3686)\rightarrow$*neutrals*$+J/\psi$, *neutrals*=($\pi^0\pi^0$, π^0, η and γγ) $J/\psi\rightarrow l^+l^-$ (l=e/μ)





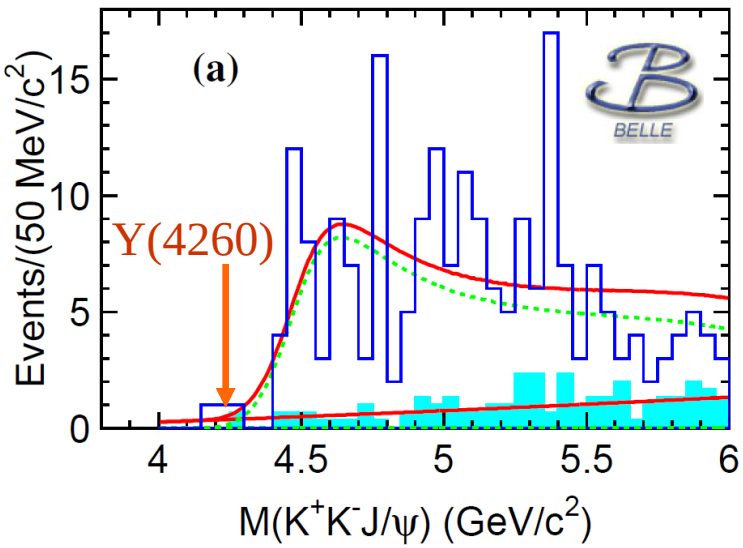
The measured Born cross sections of two modes are combined by considering the correlated and uncorrelated uncertainties.

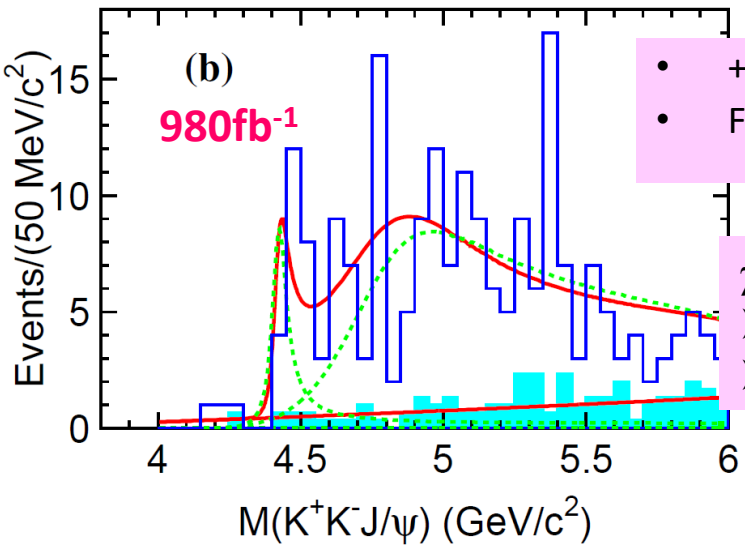
Updated $e^+e^- \to K^+K^-J/\psi$

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



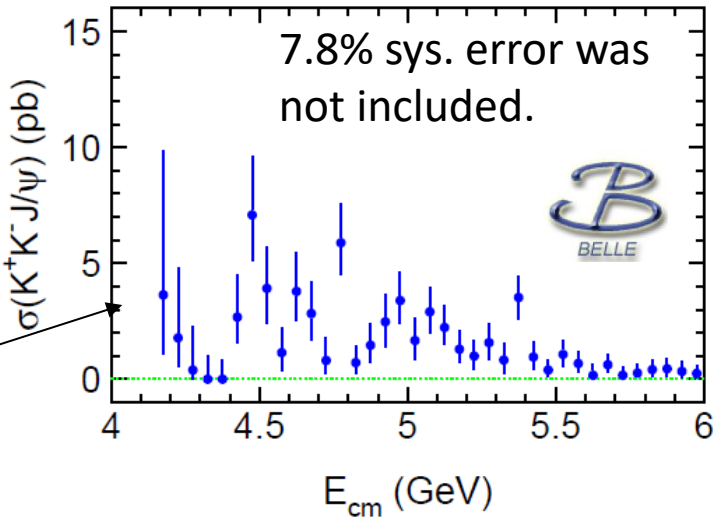


- +one resonance.
- Fit with ψ(4415)

χ^2/ndf=30/11
- M=4747±117MeV
- Γ=671±86 MeV

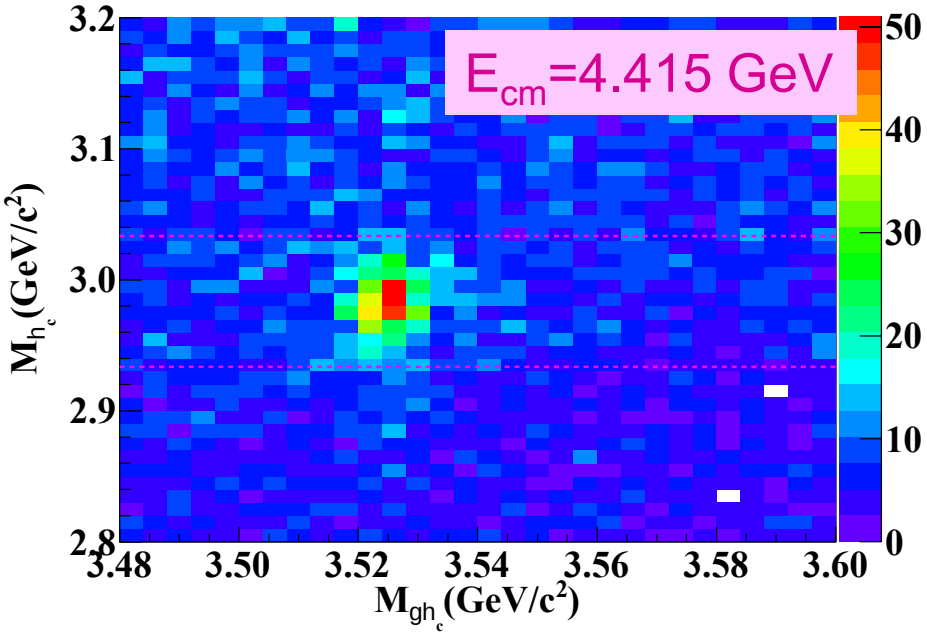
4-6 GeV: 213 events
35 bkg, 178±16 signal

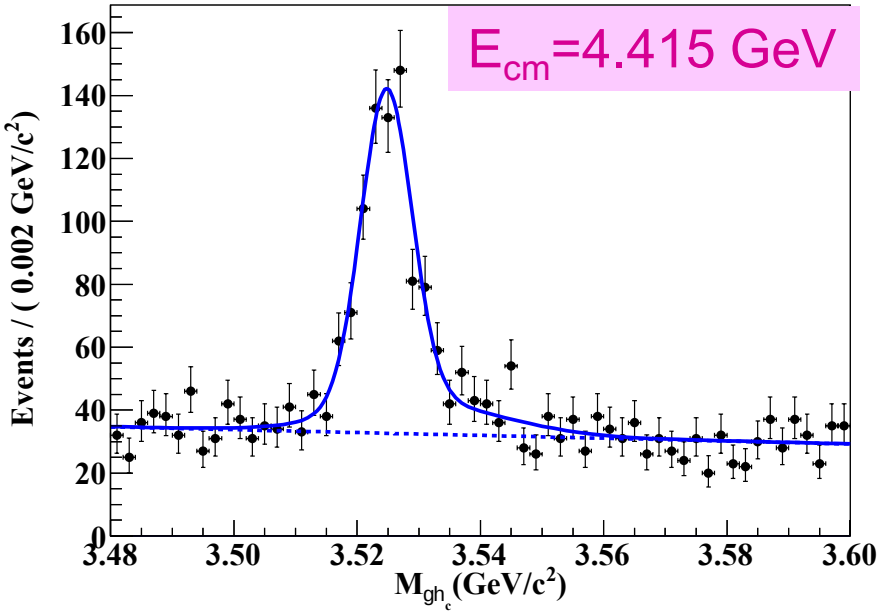
$$\sigma_i = \frac{n_i^{\rm obs} - f \times n_i^{\rm bkg}}{\mathcal{L}_i \cdot \epsilon_i \cdot \mathcal{B}(J/\psi \to \ell^+\ell^-)}$$



$e^+e^- \to \pi^+\pi^- h_c(1P)$ 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., $K^+K^-\pi^0$
  - $pp\pi^0$, $K^+K^-\eta$, $\pi^+\pi^-\eta$, $\pi^+\pi^-\pi^0\pi^0$, $2(\pi^+\pi^-)\eta$, $2(\pi^+\pi^-\pi^0)$

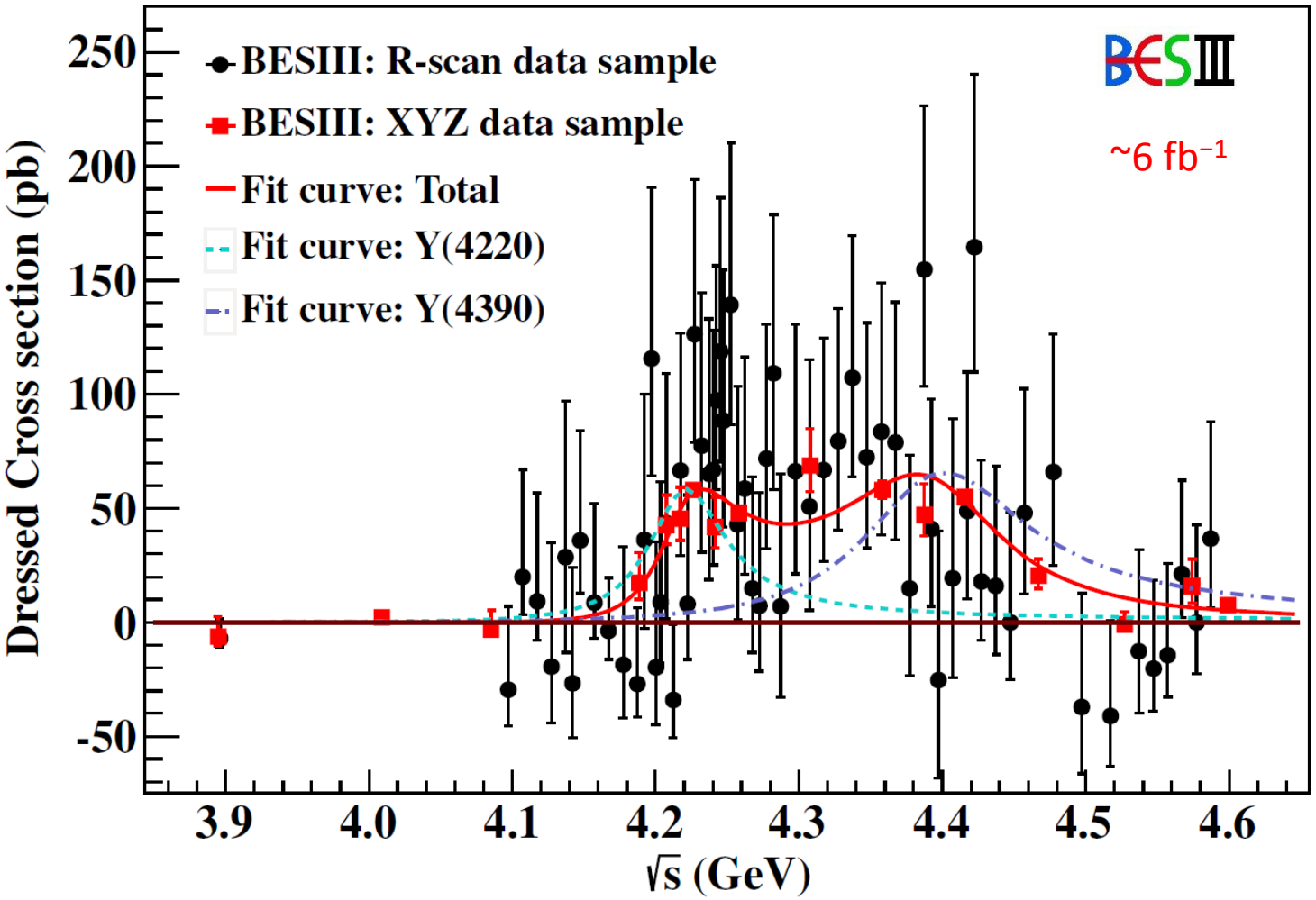




Method same as in arXiv:1309.1896, PRL111, 242001

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

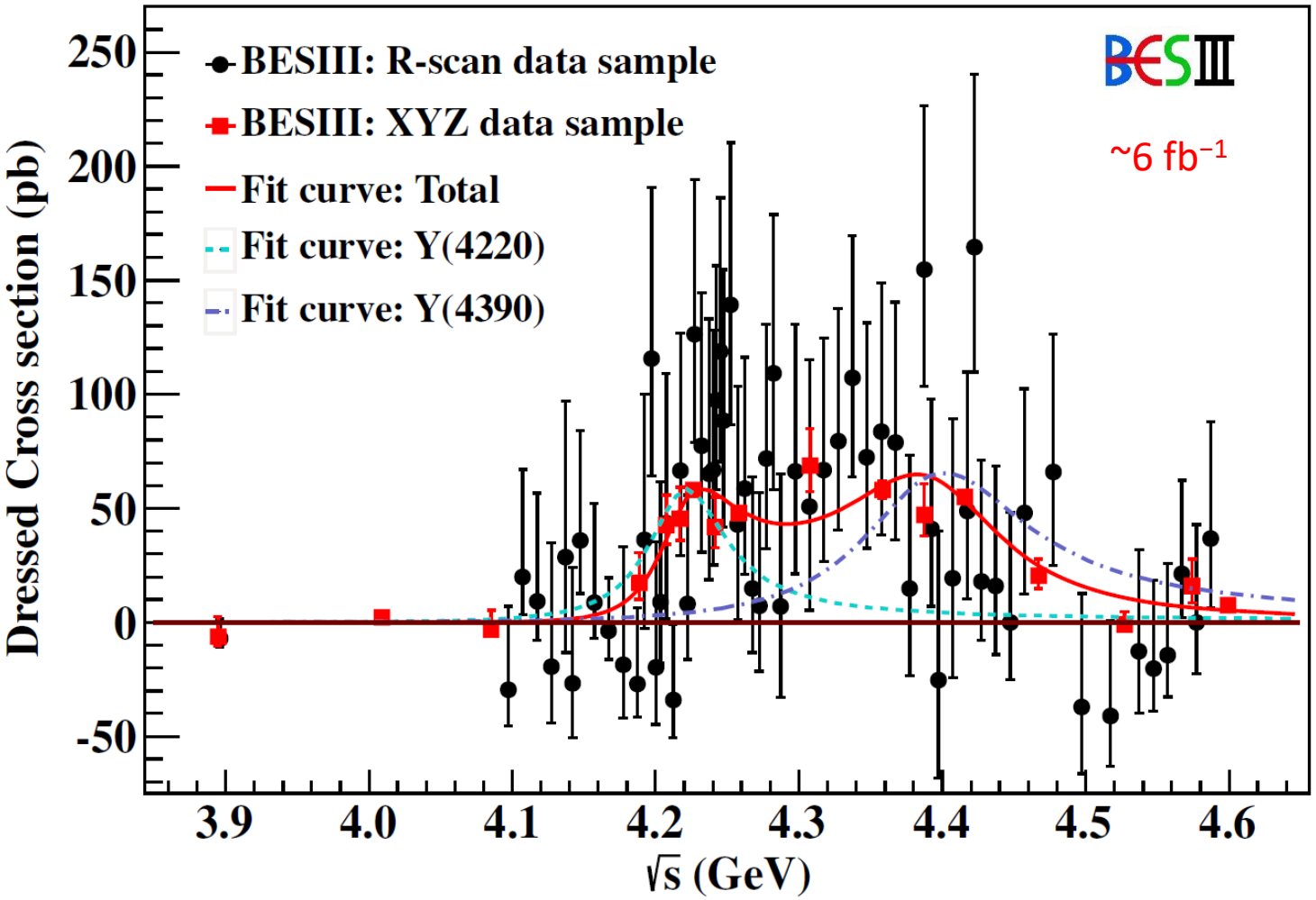
PRL118, 092002 (2017)



- 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

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

PRL118, 092002 (2017)

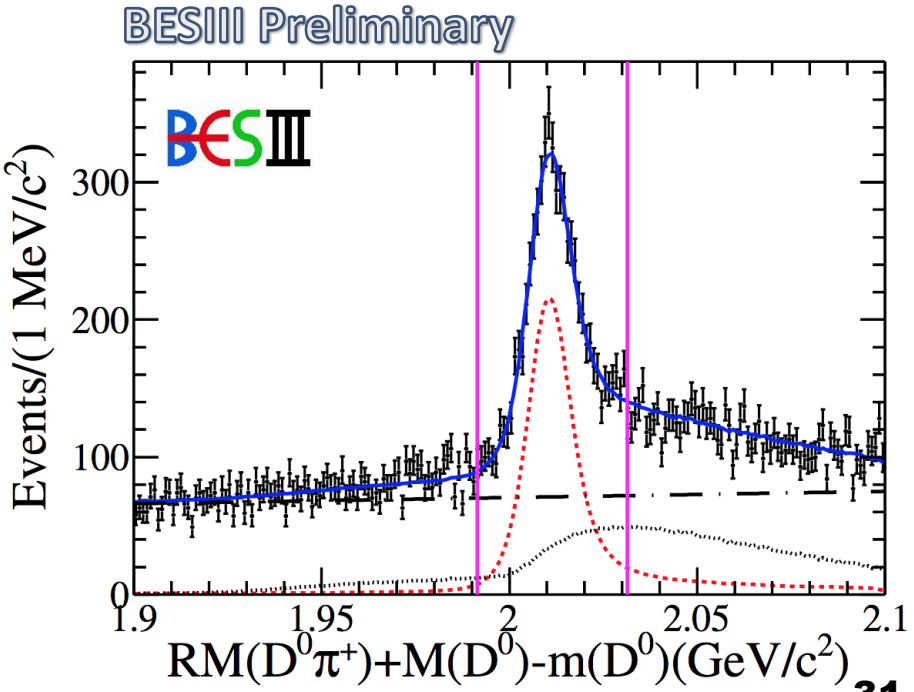


- $M_1=4218.4^{+5.5}_{-4.5}\pm0.9$ MeV/c^2, $\Gamma_1=66.0^{+12.3}_{-8.3}\pm0.4$ MeV → Y(4220)
- $M_2=4391.5^{+6.3}_{-6.8}\pm1.0$ MeV/c^2, $\Gamma_2=139.5^{+16.2}_{-20.6}\pm0.6$ MeV → Y(4390)

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

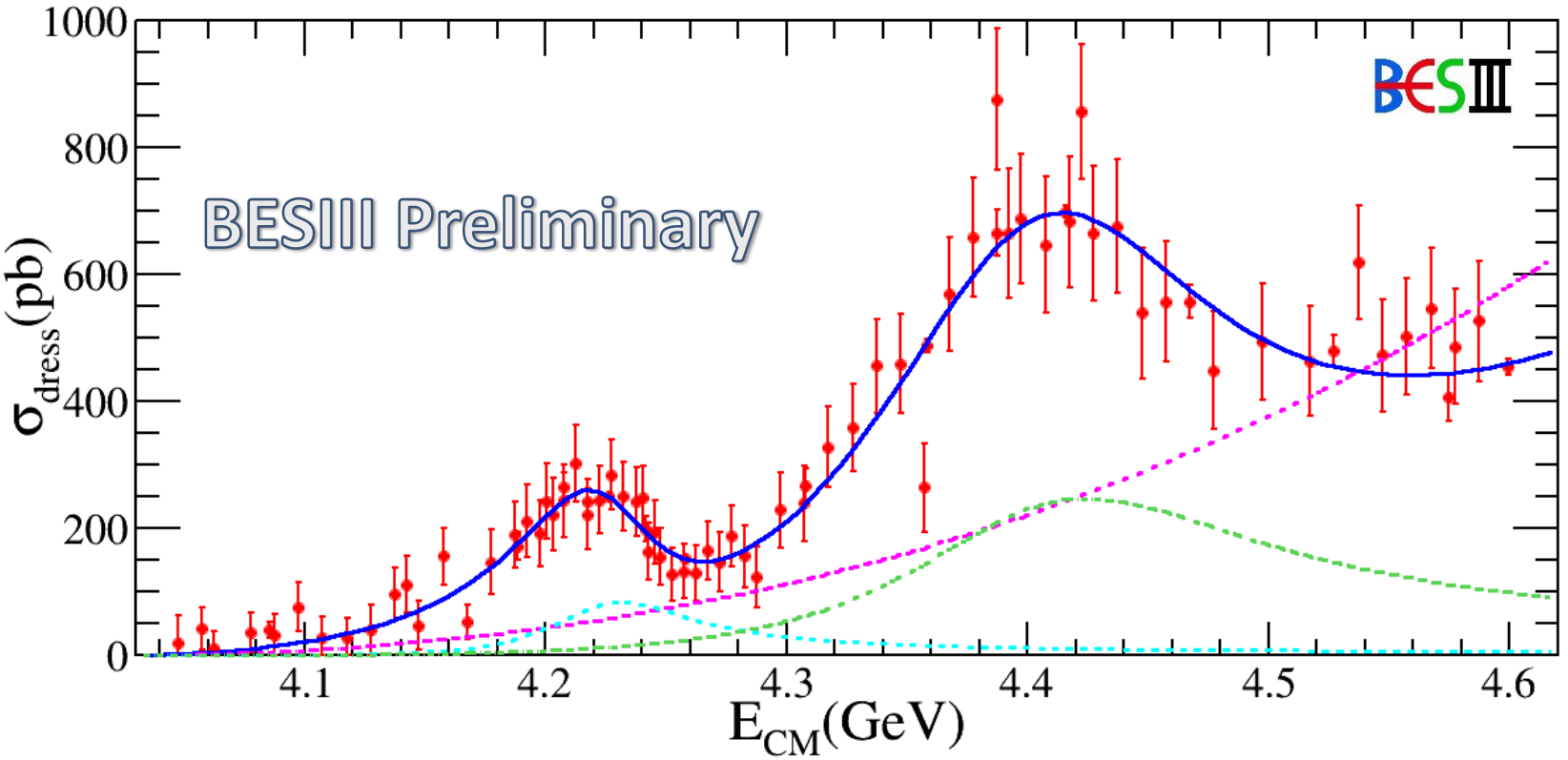
- An un-binned maximum likelihood fit
- Signal shape: MC convoluted with a Gaussian;
- The isospin partner background (dotted line) is parameterized with MC;
- A linear function for other bkg



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.

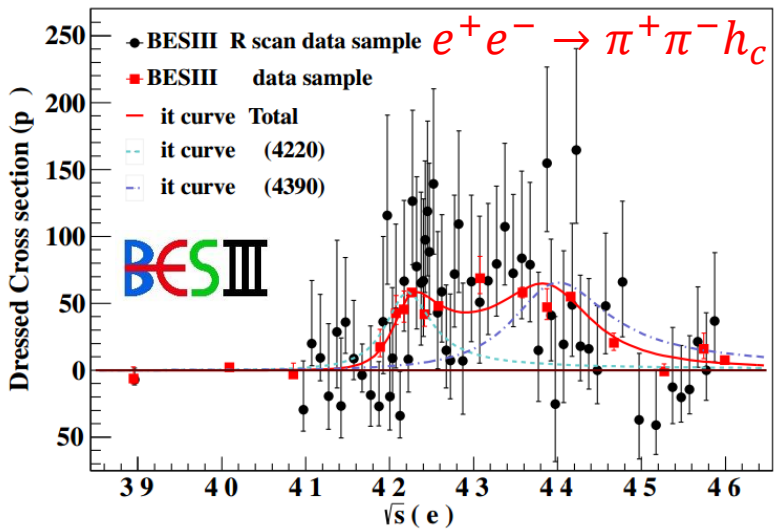
BESIII Preliminary

BESIII

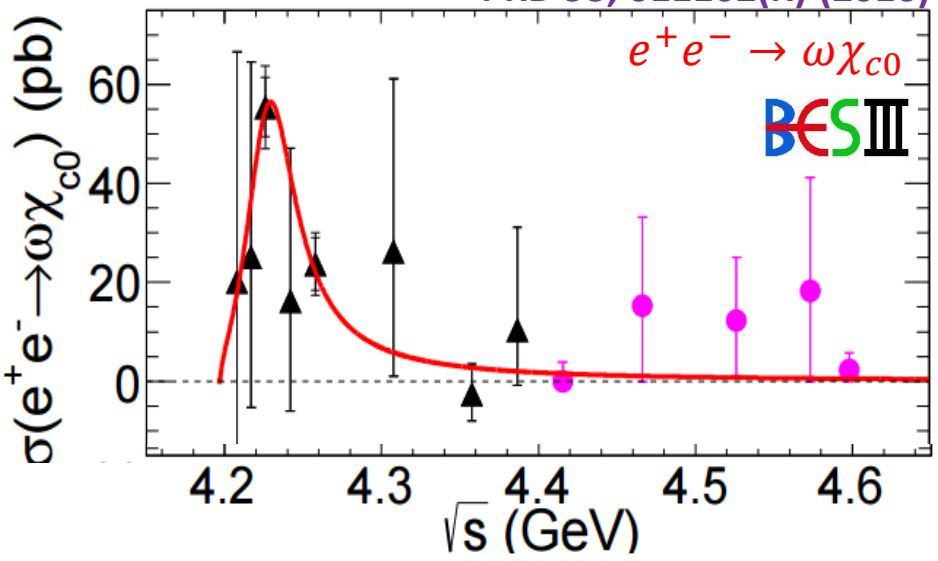
- Statistical significance is greater than 10σ.
- Consistent with those of Y(4220) and Y(4390) in $e^+e^- \to \pi^+\pi^- h_c$.

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

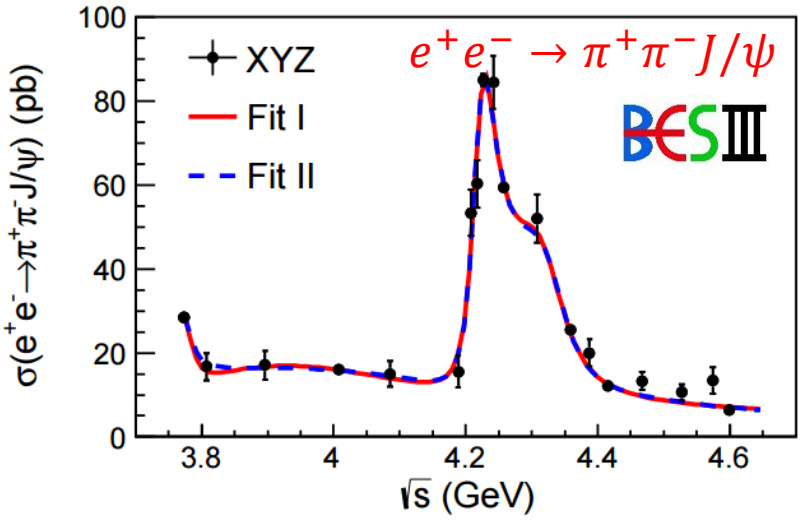
PRL 118, 092002 (2017)

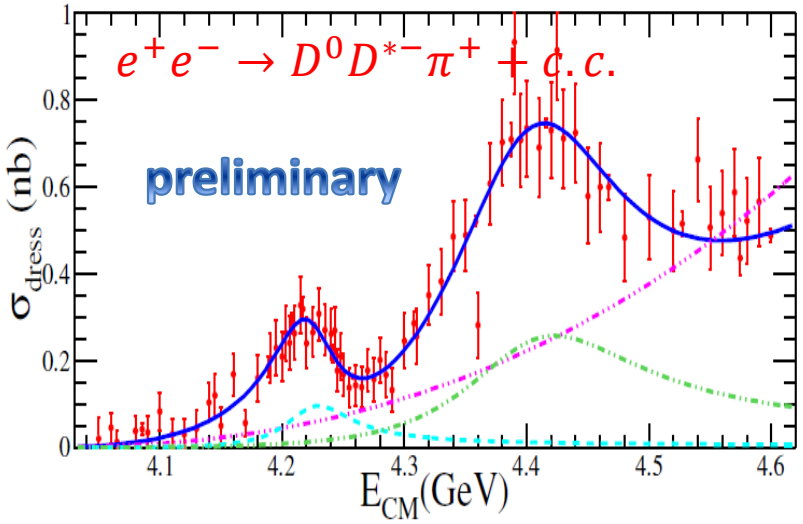


PRD 93, 011102(R) (2016)



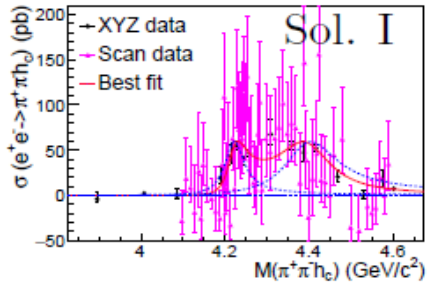
PRL118, 092001 (2017)

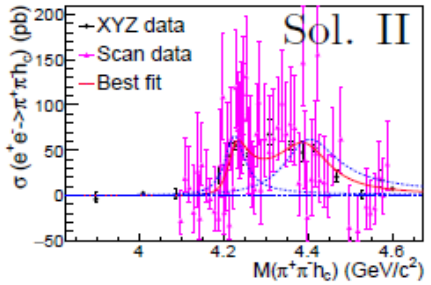


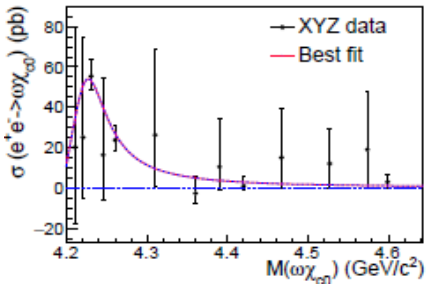


All above four channels show a structure at around 4.22 GeV/c^2.

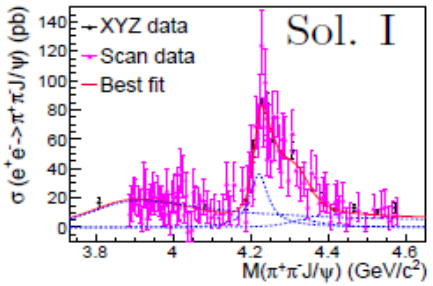
Combined fit to understand the Y(4220) better

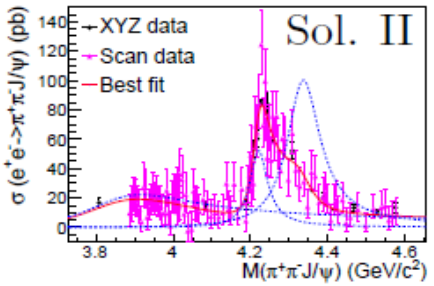


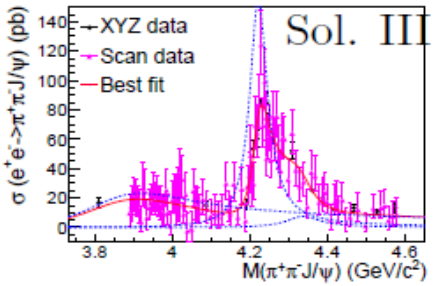


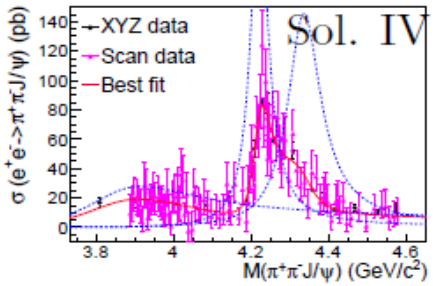


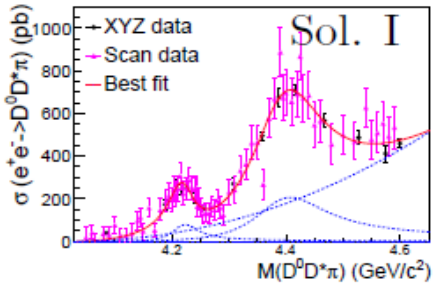
PRD95,092007(2017)
X.Y.Gao, C.P.Shen, C.Z.Yuan

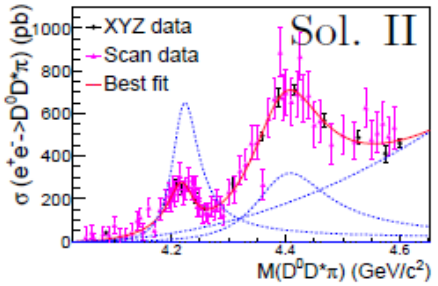


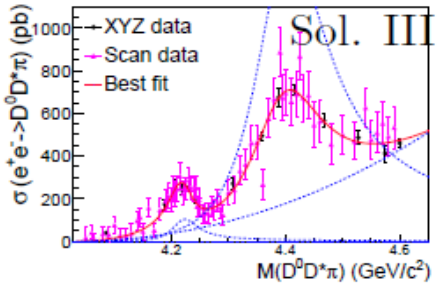


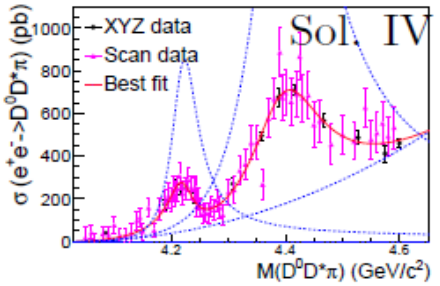










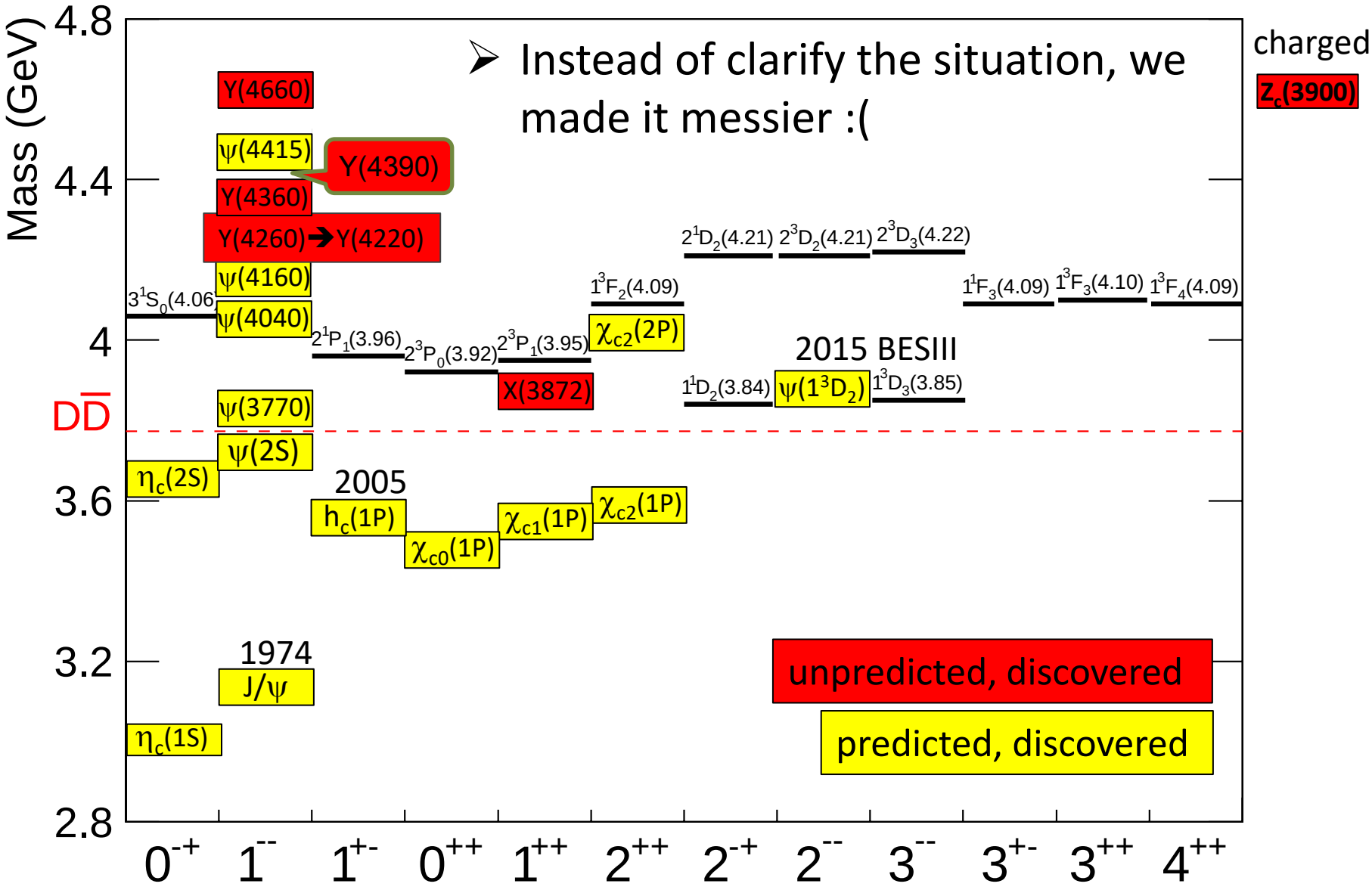


$M = 4219.6 \pm 3.3(stat) \pm 5.1(sys)$ MeV/c^2

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

Charmonium(like) spectroscopy



Godfrey & Isgur, PRD32, 189 (1985)

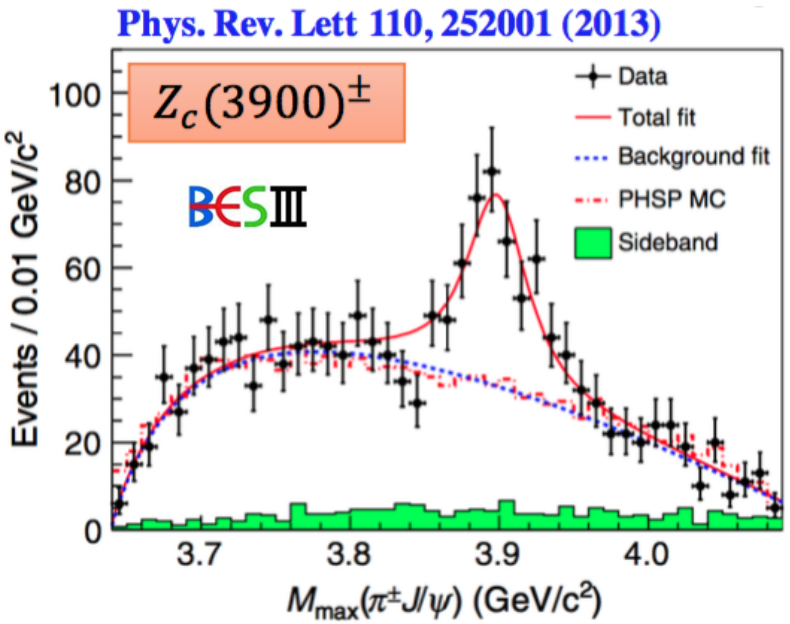
Z States

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

Observed in B decays and in decays of Y states

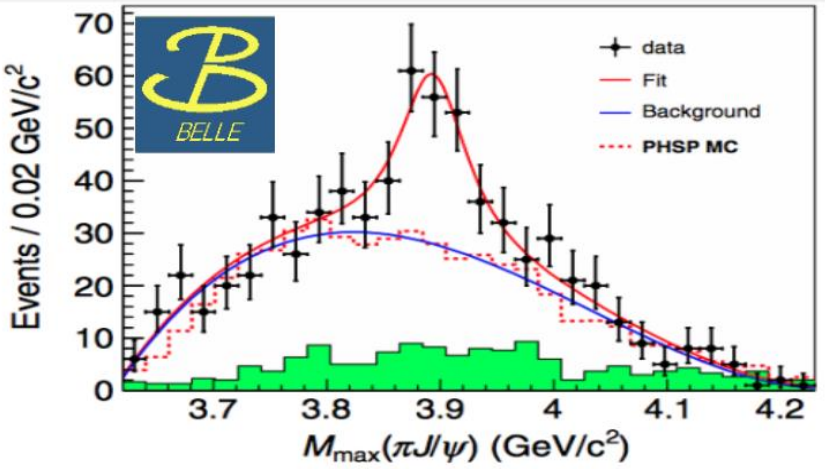
$Z_c(3900)$ State

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

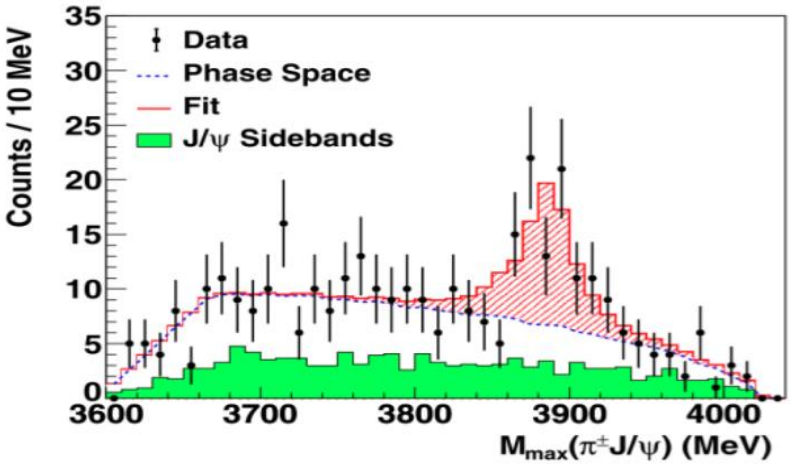


- Charged charmonium-like structure (>10 σ)
- Decay to J/ψ ($c\bar{c}$) and electric charge ($u\bar{d}$ or $d\bar{u}$)
- $M = 3899.0 \pm 3.6 \pm 4.9$ MeV/c², $\Gamma = 46 \pm 10 \pm 20$ MeV
- $\sigma(e^+e^- \to \pi^+\pi^- J/\psi) = 62.9 \pm 1.9 \pm 3.7$ pb at 4.26 GeV
- $\dfrac{\sigma(e^+e^- \to \pi^{\mp}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

Belle with ISR data (PRL 110, 252002)

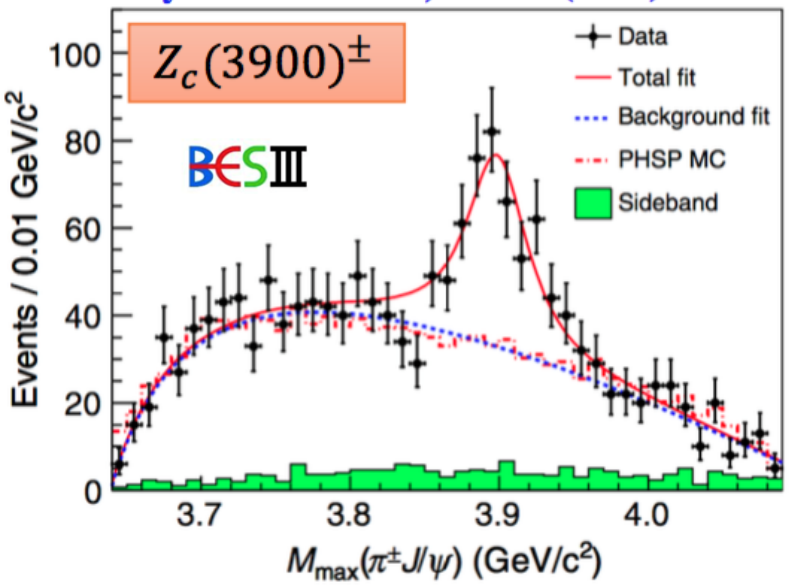


CLEOc data at 4.17 GeV (PLB 727, 366)



$Z_c(3900)$ State

Phys. Rev. Lett 110, 252001 (2013)



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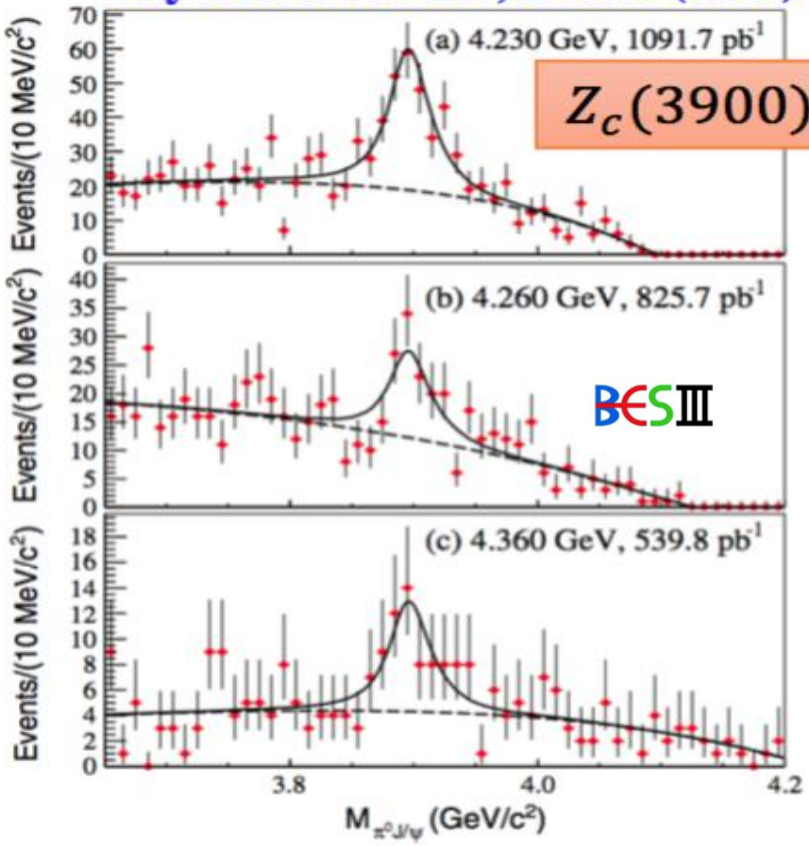
- $\dfrac{\sigma(e^+e^- \to \pi^{\mp} Z_c(3900)^{\pm} \to \pi^+\pi^- J/\psi)}{\sigma(e^+e^- \to \pi^+\pi^- J/\psi)} = 21.5 \pm 3.3 \pm 7.5$ %
- The first Z_c state observed by more than one experiment (Belle and CLEO-c)!

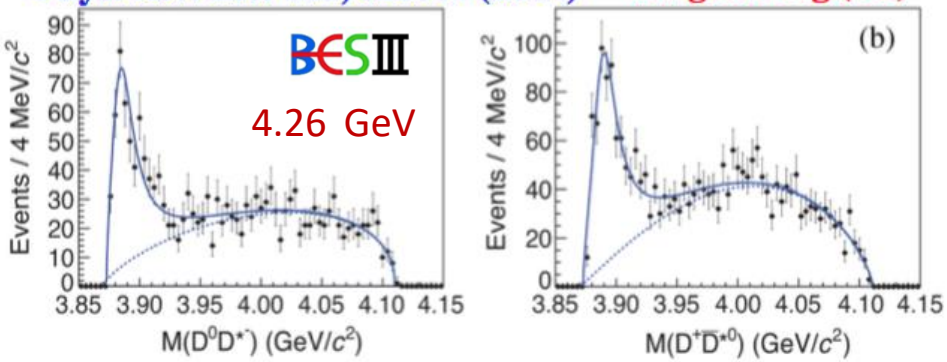
Phys. Rev. Lett 115, 112003 (2015)



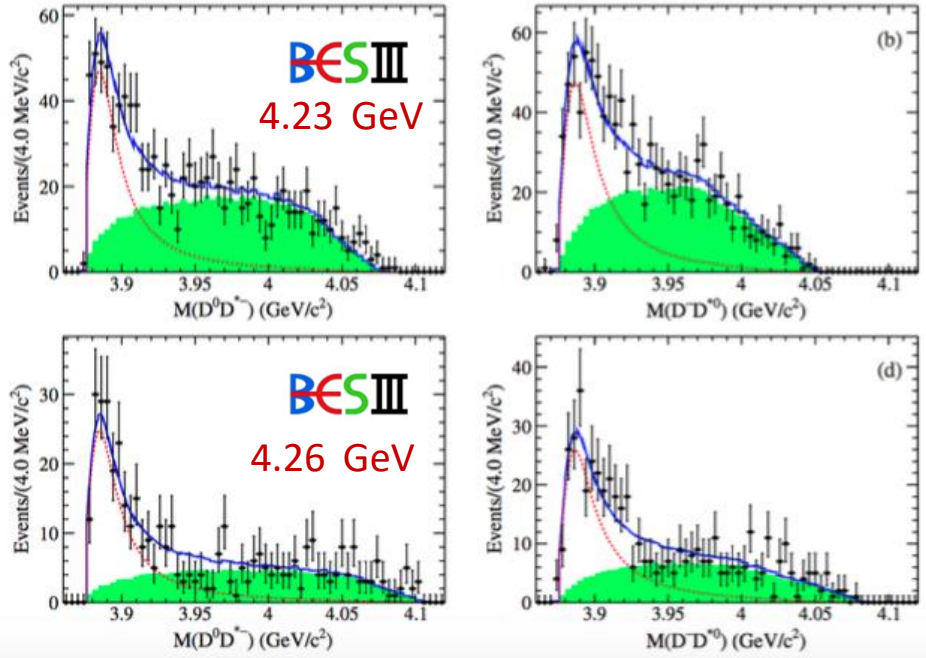
- Neutral charmonium-like structure (10.4 σ)
- Using 3 data samples (~2.5 fb⁻¹)
- Evidence with 3.7σ by using CLEO-c data
- $M = 3894.8 \pm 2.3 \pm 3.2$ MeV/c², $\Gamma = 29.6 \pm 8.2 \pm 8.2$ MeV
- An iso-spin triplet is established!

$Z_c(3900)$ State

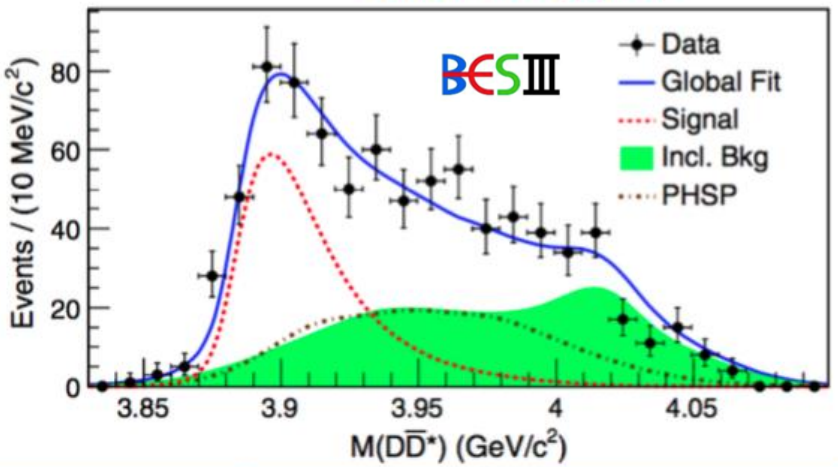
Phys. Rev. Lett 112, 022001 (2014) **Single D tag (ST)**



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



Double D tag (DT)



State	Mass (MeV/c^2)	Width (MeV)
$Z_c(3885)^{\pm}$ (ST)	$3883.9\pm1.5\pm4.2$	$24.8\pm3.3\pm11.0$
$Z_c(3885)^{\pm}$ (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)	$3885.7^{+4.3}_{-5.7}\pm8.4$	$35^{+11}_{-12}\pm15$

- 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?

PWA on Zc(3900) state

BESIII

preliminary

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

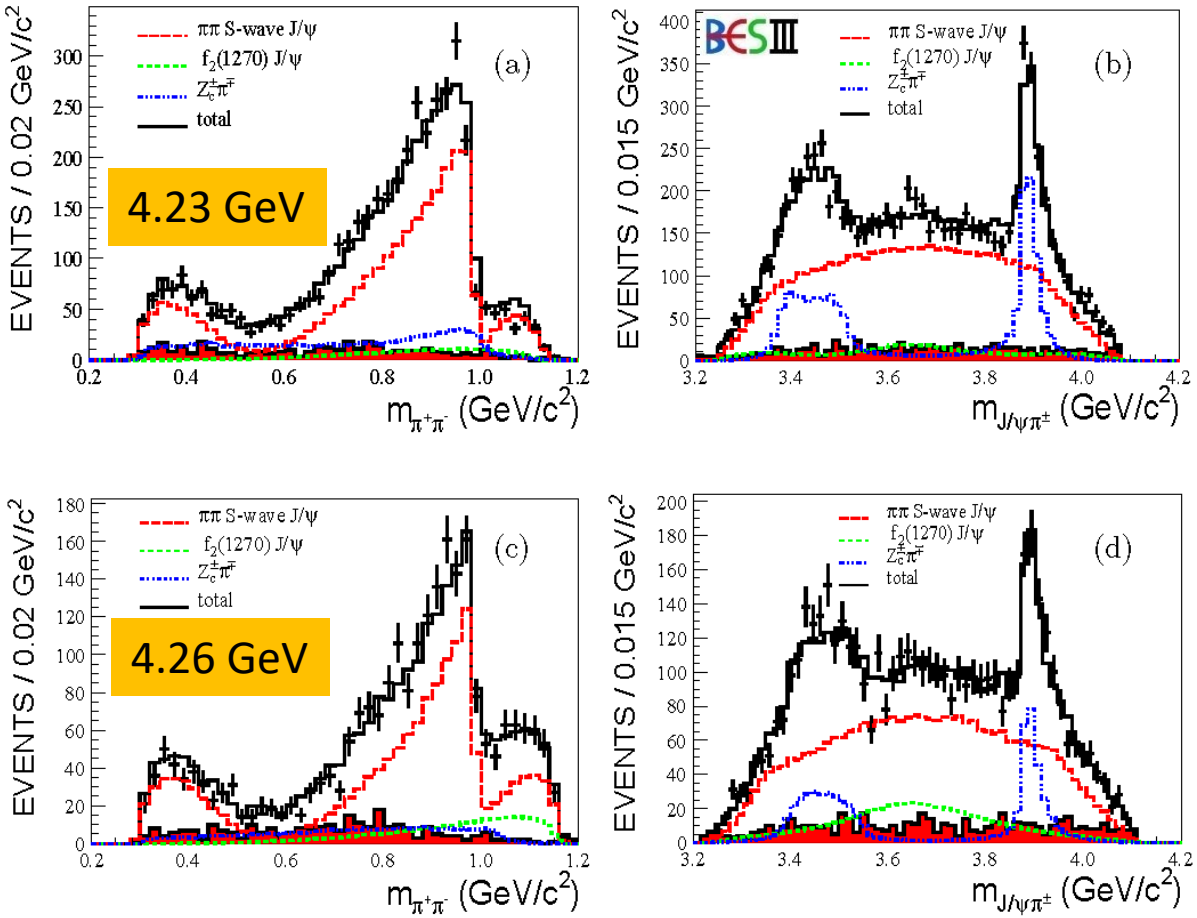
- **The helicity value of γ^* is taken as $\lambda_0 = \pm 1$ due to from e+e- annihination**
- **$\gamma^* \to Z_c^{\pm}\pi^{\mp}$, $Z_c^{\pm} \to J/\psi\pi^{\pm}$, we try J^P for X: 0^-, 1^-,1^+,2^-,2^+, and 0^+ is not allowed**
- **Z_c^+ and Z_c^- states are assumed as isospin partner, share the same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

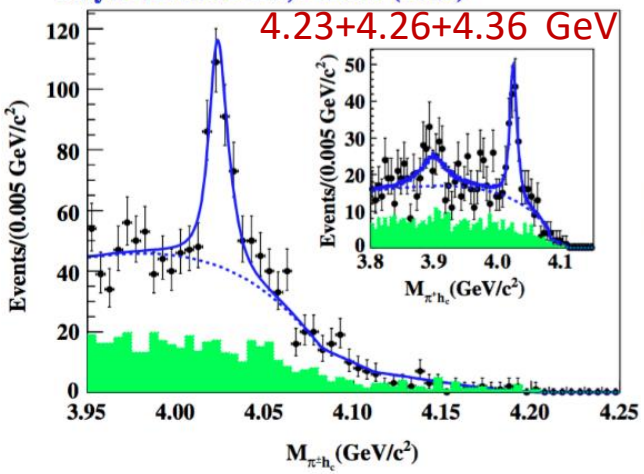
- Zc favors the quantum number $J^P=1^+$

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

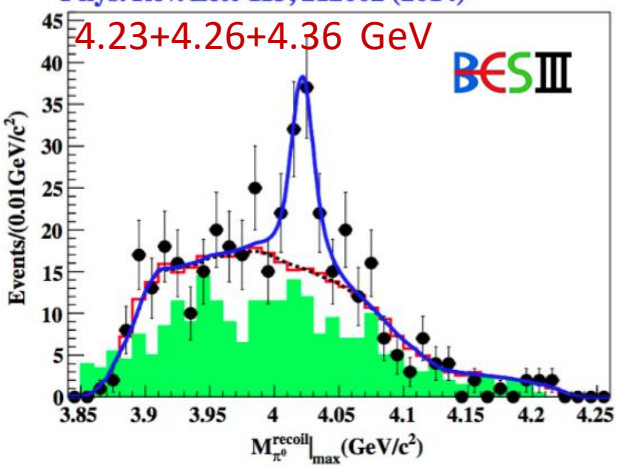
Hypothesis	$\Delta(-\ln L)$	$\Delta(ndf)$	significance
1^+ over 0^-	44.5	$4\times2+5$	7.3σ
1^+ over 1^-	107.0	$4\times2+5$	$> 8.0\sigma$
1^+ over 2^-	51.8	$4\times2+5$	$> 8.0\sigma$
1^+ over 2^+	193.5	$4\times2+5$	$> 8.0\sigma$

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

Phys. Rev. Lett 111, 242001 (2013)



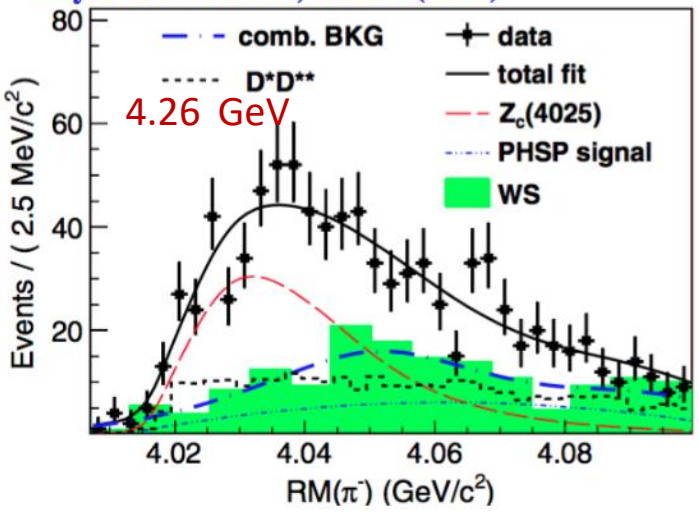
Phys. Rev. Lett 113, 212002 (2014)



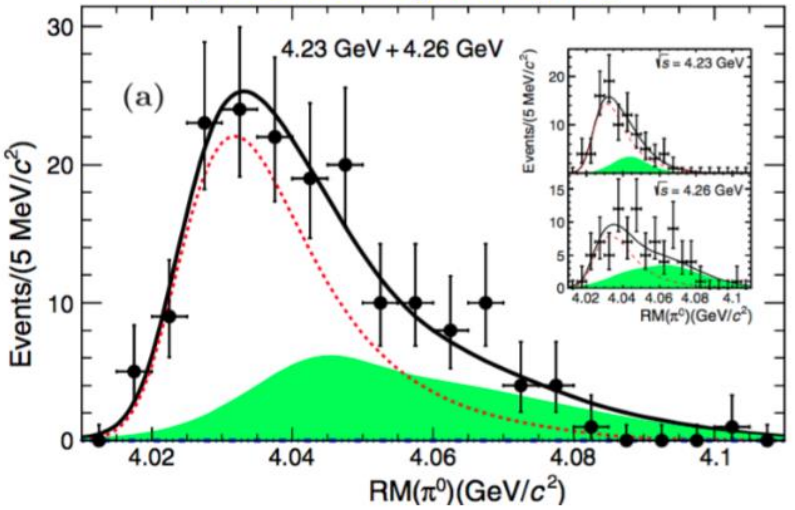
- $Z_c(4020)^{\pm/0}$ observed
- Another iso-spin triplet is established!
- No significant $Z_c(3900)^{\pm} \to \pi^{\pm} h_c$ is observed

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

Phys. Rev. Lett 112, 132001 (2014)



Phys. Rev. Lett 115, 182002 (2015)

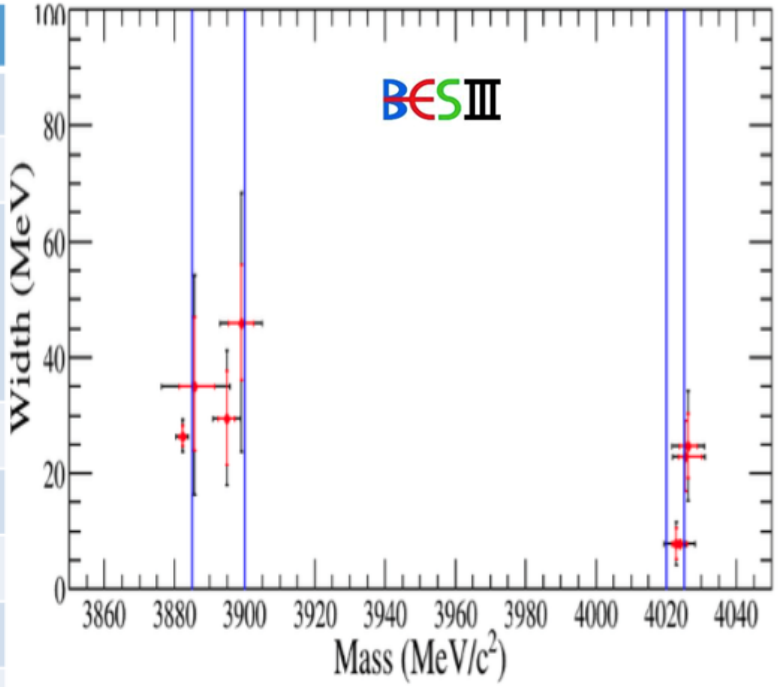


- $Z_c(4025)^{\pm/0}$ observed
- Another iso-spin triplet is established!

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

Summary on Z_c States by BESIII

State	Mass (MeV/c^2)	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	$e^+e^-\to\pi^0(D^*\bar{D}^*)^0$

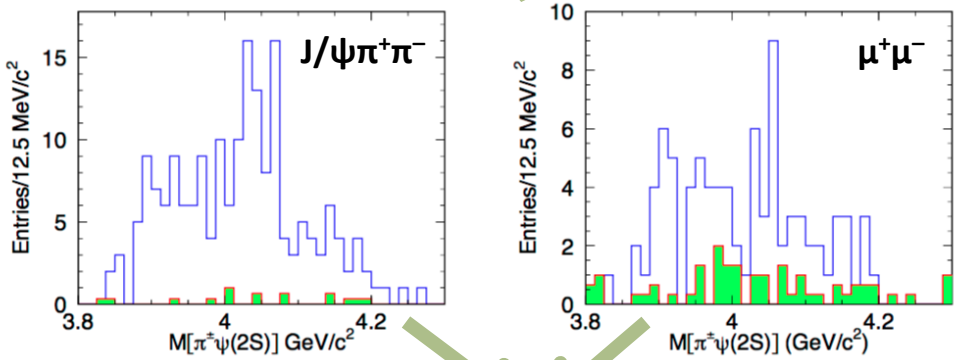


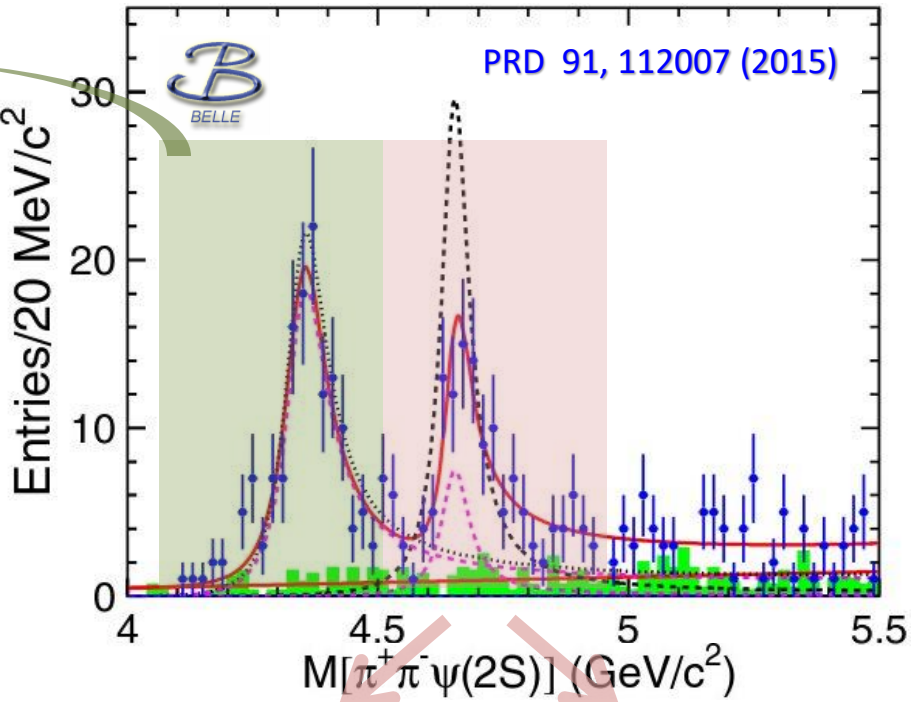
- $Z_c(3885)^{\pm}$ mass is about 2.6σ lower and the width 1.5σ lower than $Z_c(3900)^{\pm}$ value. If $Z_c(3885) = Z_c(3900)$, $\frac{\Gamma(Z_c(3885)^{\pm}\to(D\bar{D}^*)^{\pm})}{\Gamma(Z_c(3900)^{\pm}\to\pi^{\pm}J/\psi)} = 6.2\pm1.1\pm2.7$, coupling to $D\bar{D}^*$ is larger than to πJ/ψ;
- $Z_c(4020)^{\pm}$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

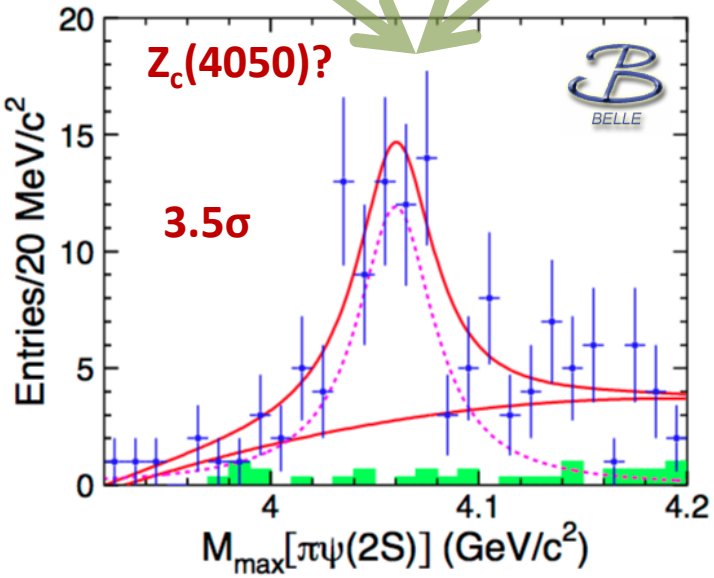
$Z_c(4050)$

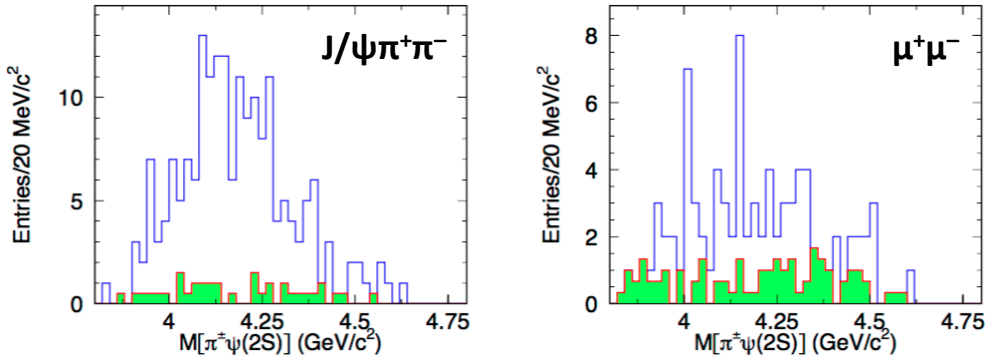
Observed by Belle in ISR

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









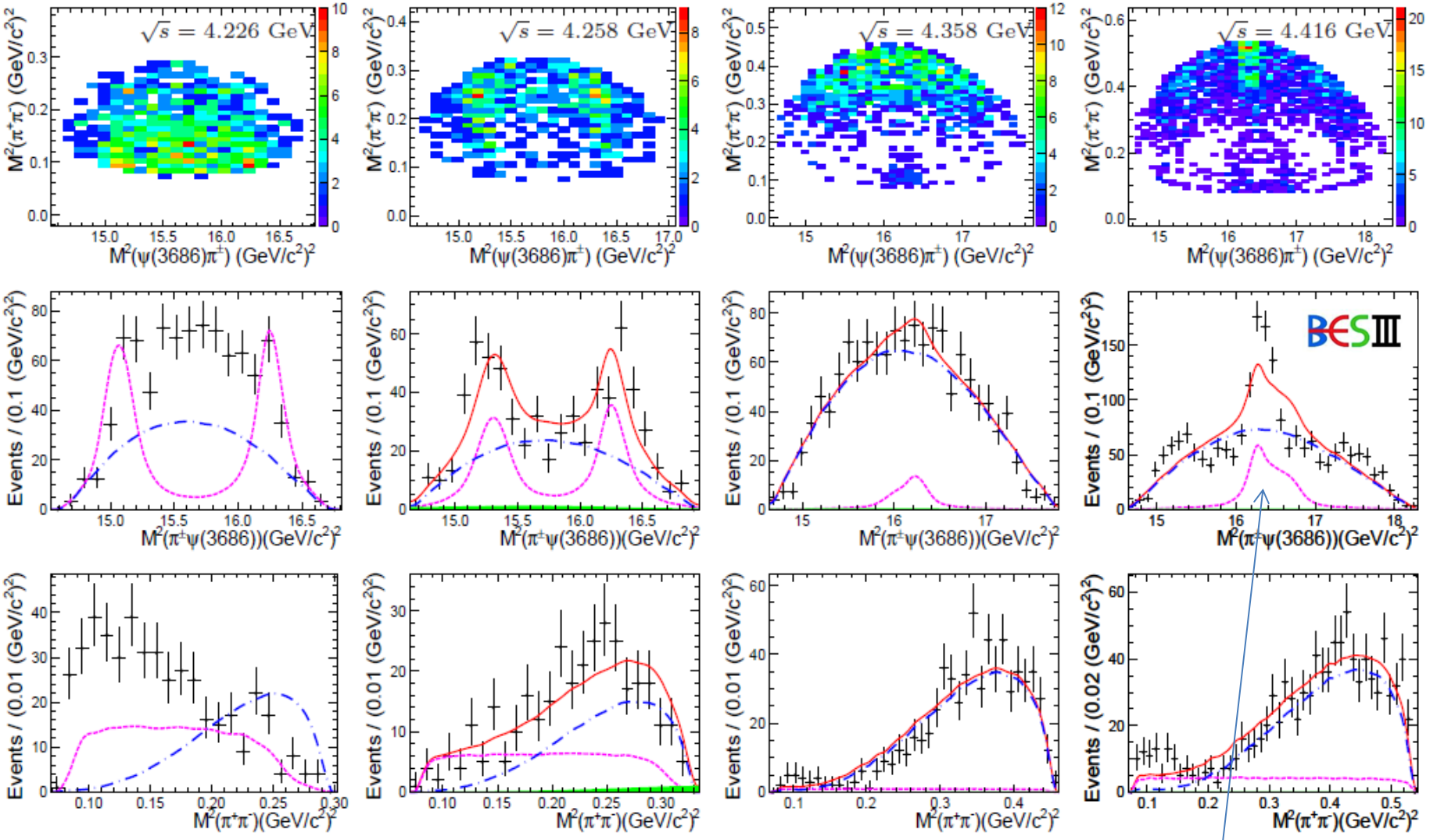
No clear signal found in the Y(4660) region

$M = 4054 \pm 3 \pm 1$ MeV/c²

$\Gamma = 45 \pm 11 \pm 6$ MeV

Another Z_c state? Need confirmation

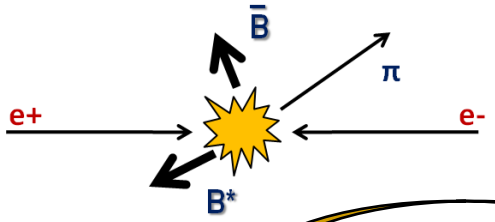
Search for $Z_c \rightarrow \pi\psi(2S)$ at BESIII



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

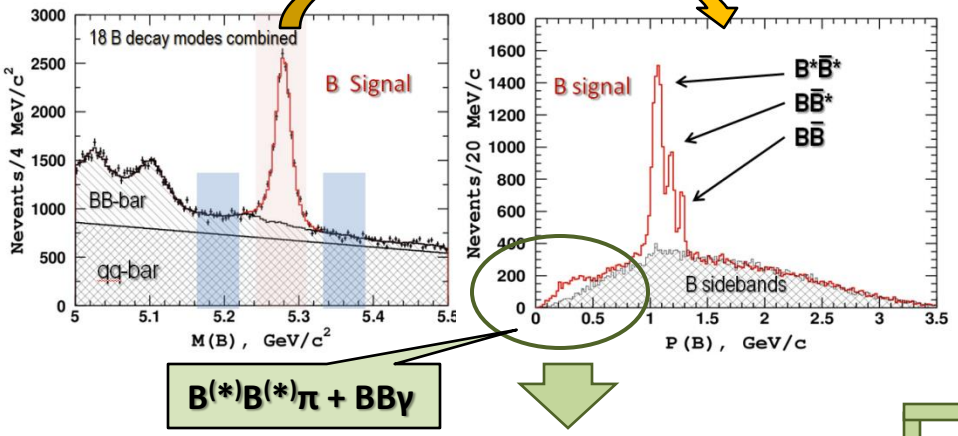
- M = (4032.1 ± 2.4) MeV/c^2
- Γ = (26.1 ± 5.3) MeV

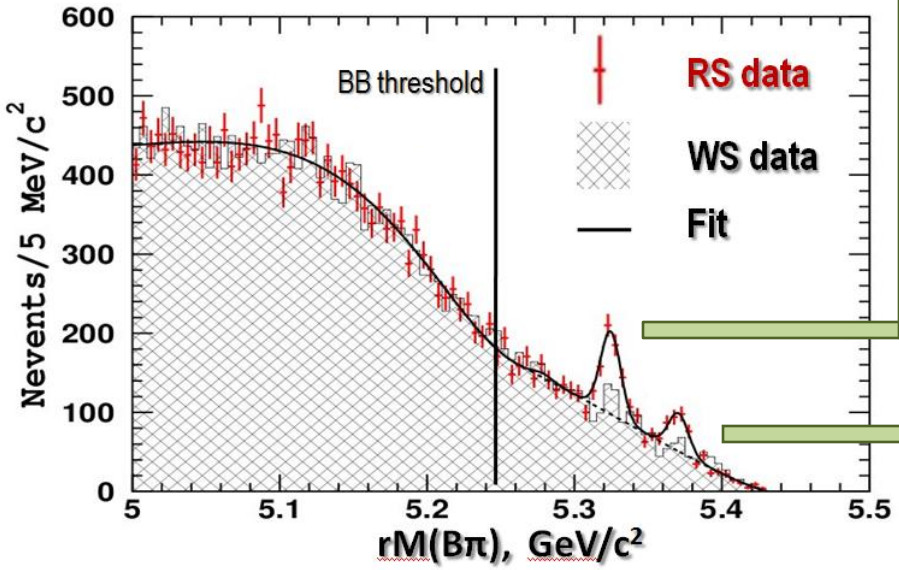
$Z_b^{\pm} \rightarrow$ Open Beauty

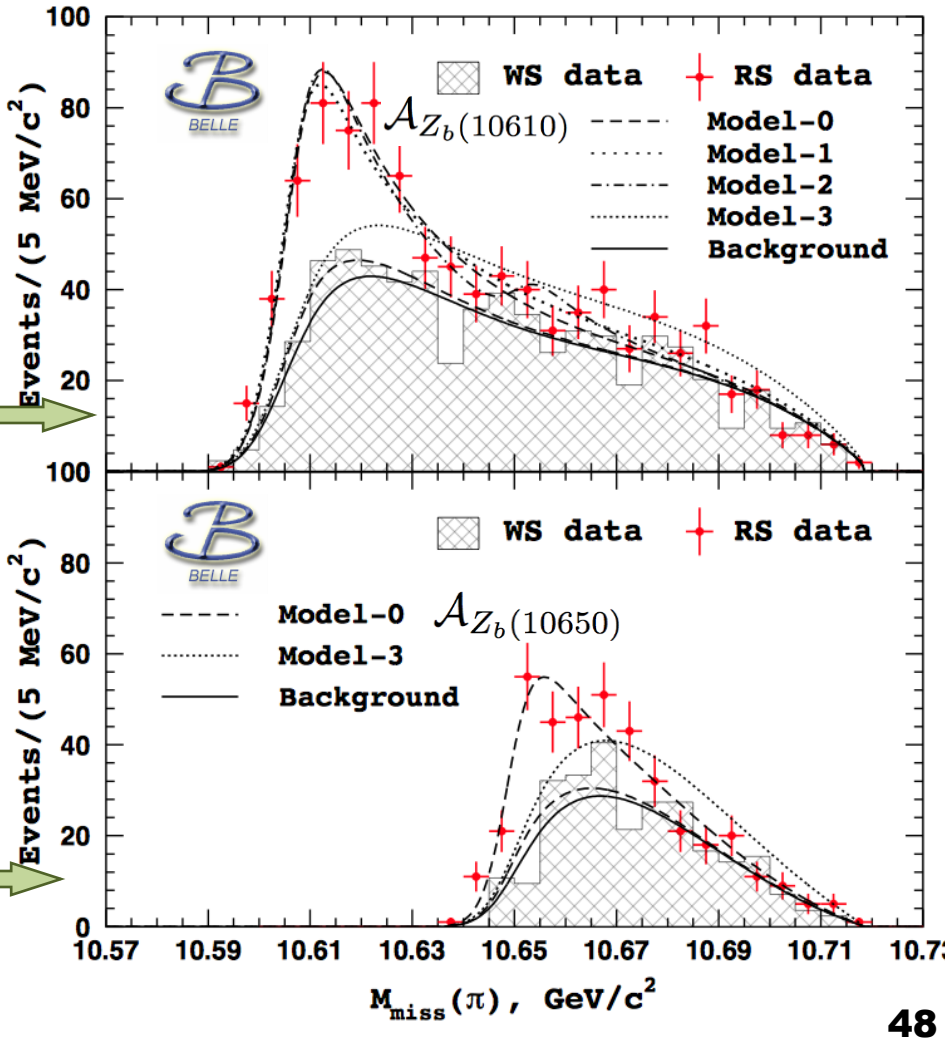


PRL116,212001(2016)

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







Summary on Z_b Decays by Belle

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

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

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

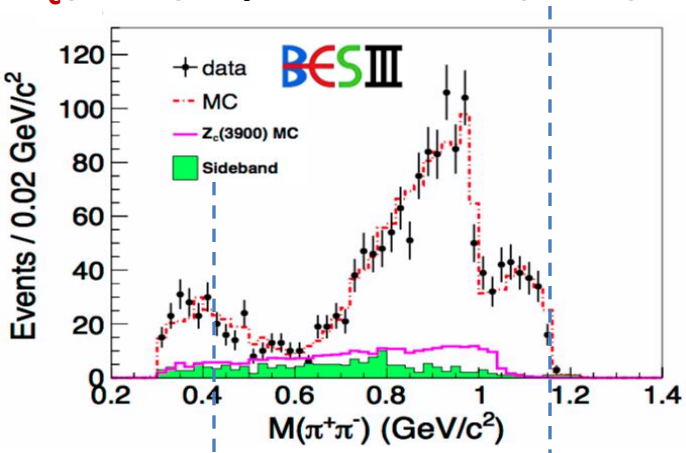
$B^{(*)}B^*$ channels dominate the Z_b decays

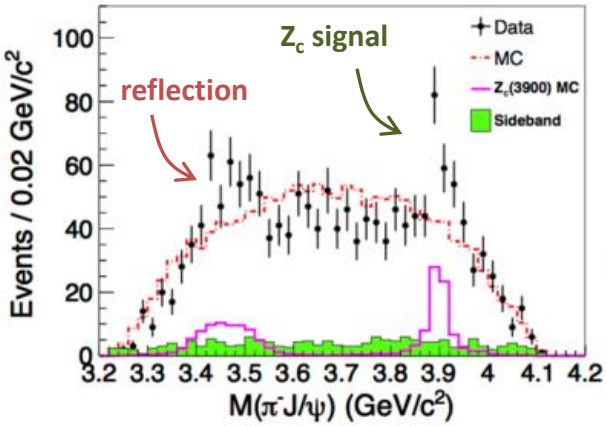
Charm vs. Beauty: I

What is in common?

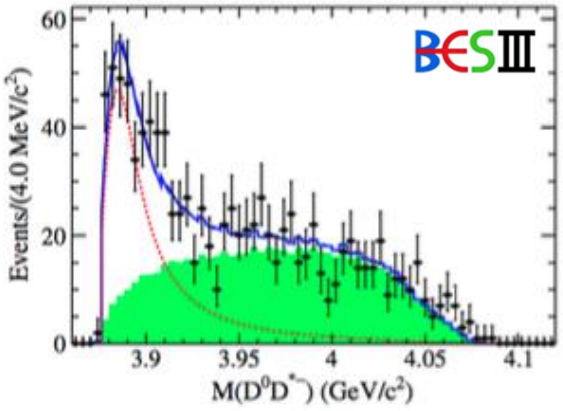
- $\Upsilon(10860)$/Y(4260) demonstrates anomalously large coupling to $\Upsilon\pi^+\pi^-$/$\psi\pi^+\pi^-$ and $h_b\pi^+\pi^-$/$h_c\pi^+\pi^-$ final states.

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

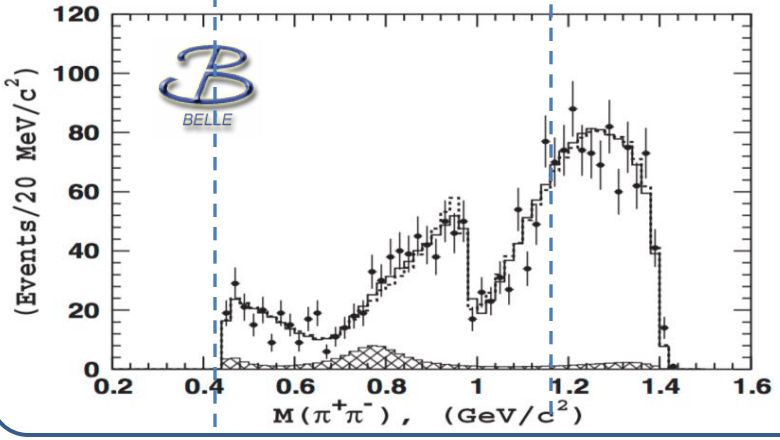




$\to Z_c\pi\to DD^*$

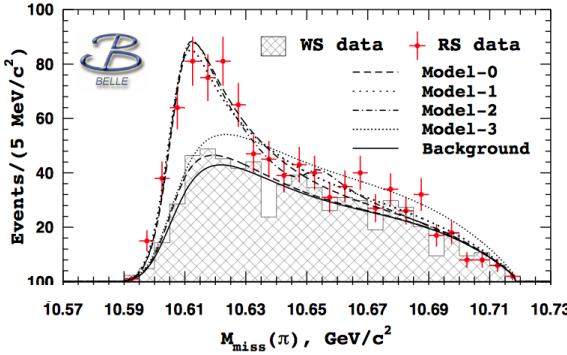


$Z_b(10610)$ is produced in $\Upsilon(10860)\to Z_b\pi\to \Upsilon(nS)\pi^+\pi^-$



MISSING PLOT

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



Charm vs. Beauty: II

What is different?

- 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!

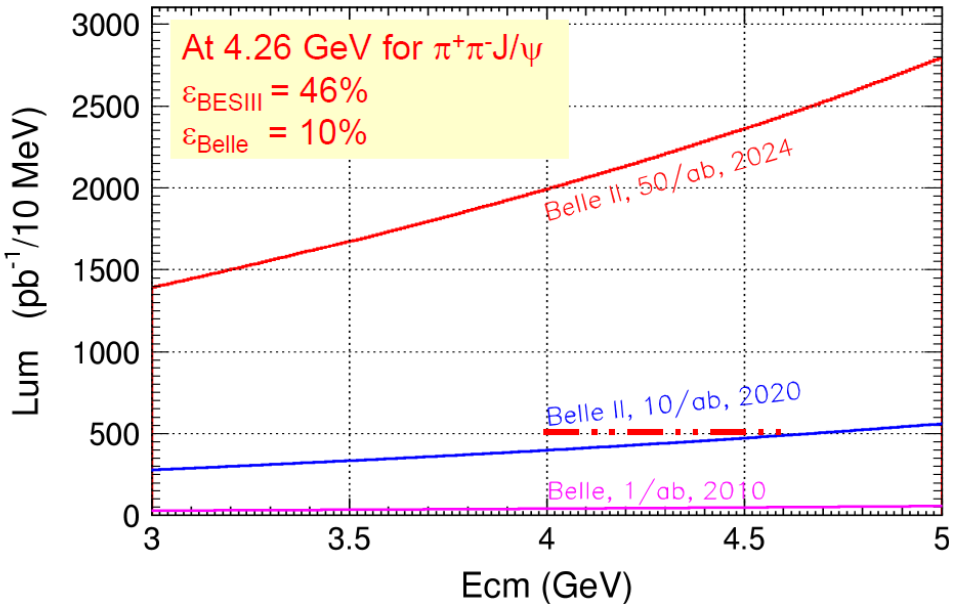
2016-17 running year: Ecm=4.19, 4.20, 4.21, …, 4.30 GeV

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

ISR at Belle II vs. BESIII

For SuperKEKB / Belle II status,
Please see *Sangro's report on Friday*

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

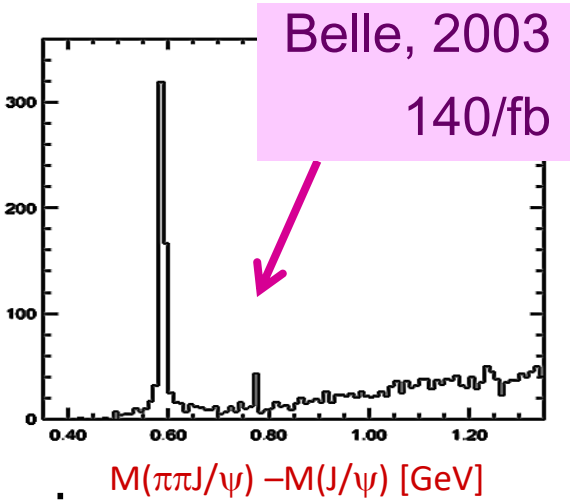
With > 5(10) ab^{-1} data sample, ISR $e^+e^- \rightarrow$ a charmonium+light hadrons[$\pi^+\pi^- J/\psi$, $\pi^+\pi^-\psi(2S)$, $K^+K^- J/\psi$, $K^+K^-\psi(2S)$, $\gamma X(3872)$, $\pi^+\pi^- X(3872)$, $\pi^+\pi^- hc$, $\pi^+\pi^- hc(2P)$, ωX_{cJ}, ϕX_{cJ}, $\eta J/\psi$, $\eta' J/\psi$, $\eta\psi(2S)$,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

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.

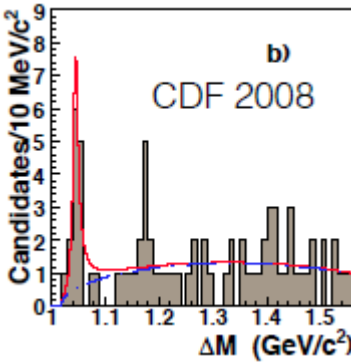
thank you!

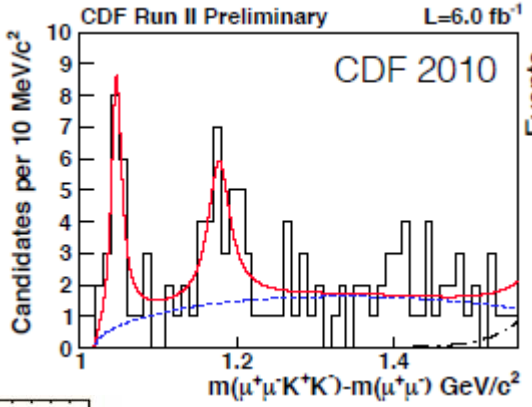
What is the X(3872)?

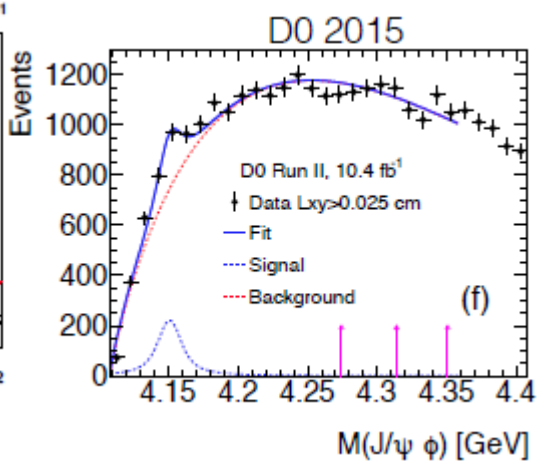


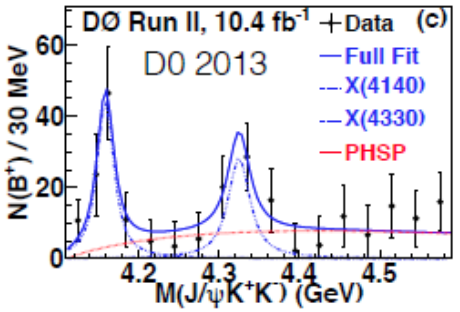
- Mass: Very close to $\bar{D}^0D^{*0}$ threshold
- Width: Very narrow, < 1.2 MeV
- $J^{PC}=1^{++}$
- Production
  - in $\bar{p}p$/pp collison – rate similar to charmonia
  - In B decays – KX similar to $c\bar{c}$, K*X smaller than $c\bar{c}$
  - Y(4260)→γ+X(3872) (?)
- Decay BR: open charm ~ 50%, charmonium~O(%)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

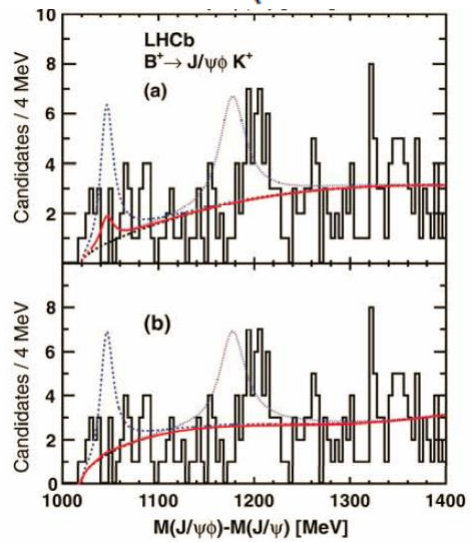
X(4140) and X(4270)

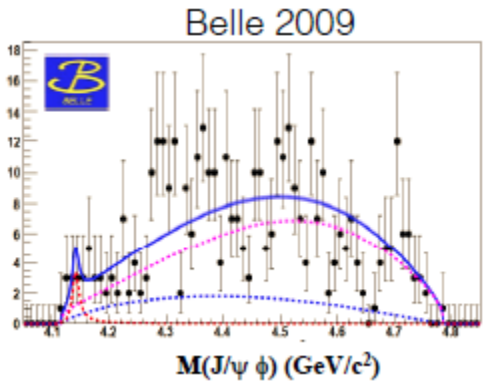


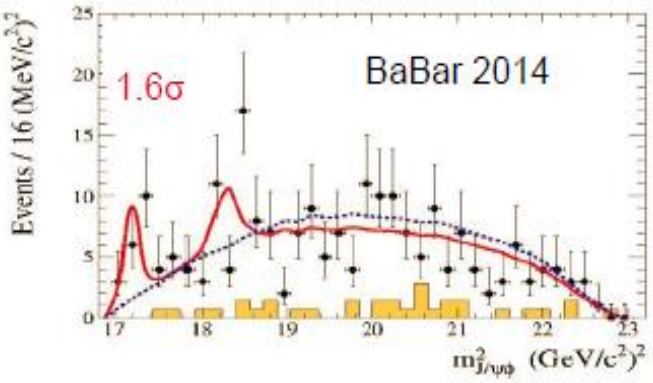


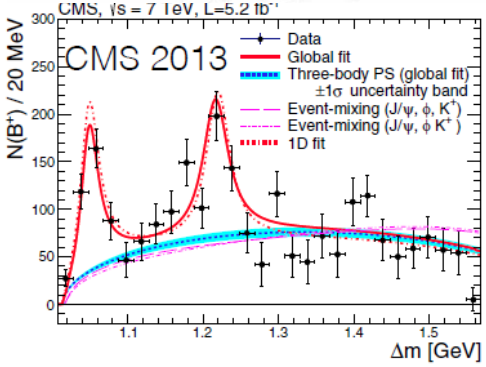










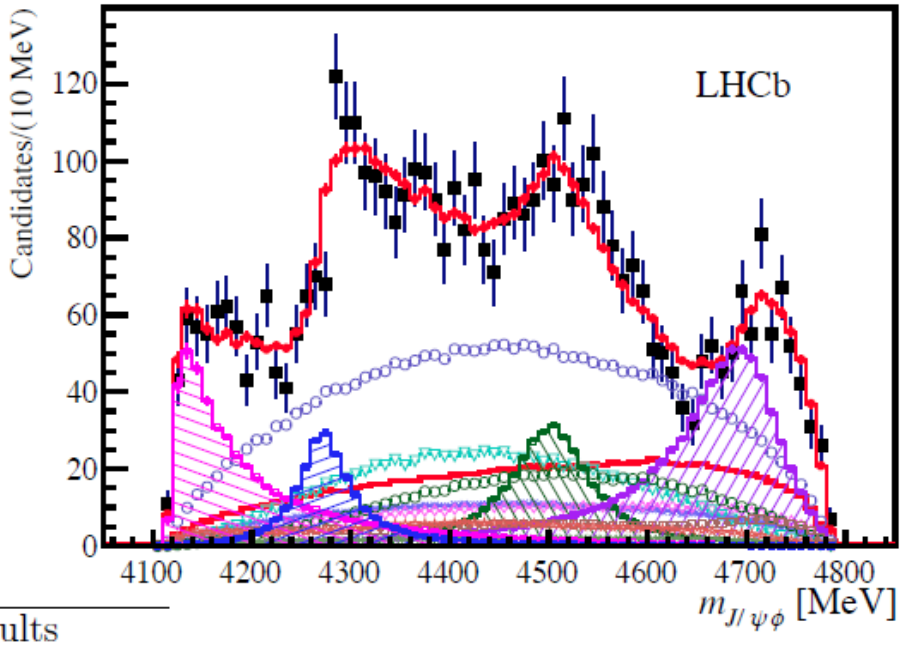


- X(4140)→J/ψφ claimed first by CDF in B⁺→J/ψφK
- Seen by some experiments, but not others
- Confusing situation

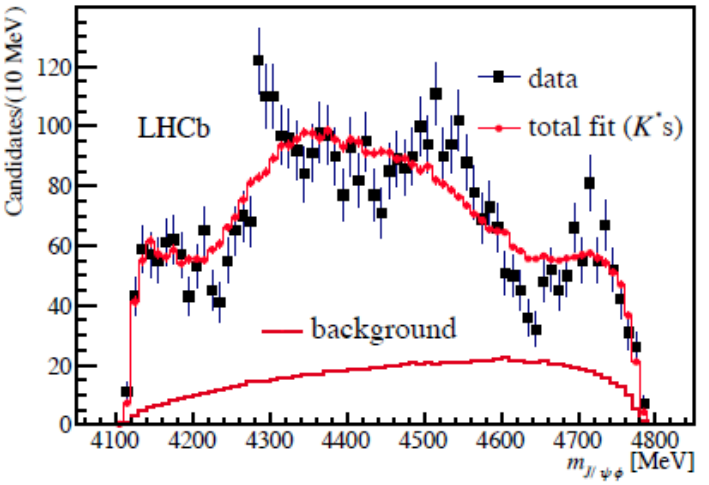
X(4140) at LHCb

PRD95, 012002(2017)

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



Contri-bution	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	$4704\pm10\ ^{+14}_{-24}$	$120\pm31\ ^{+42}_{-33}$	$12\pm\ 5\ ^{+\ 9}_{-\ 5}$

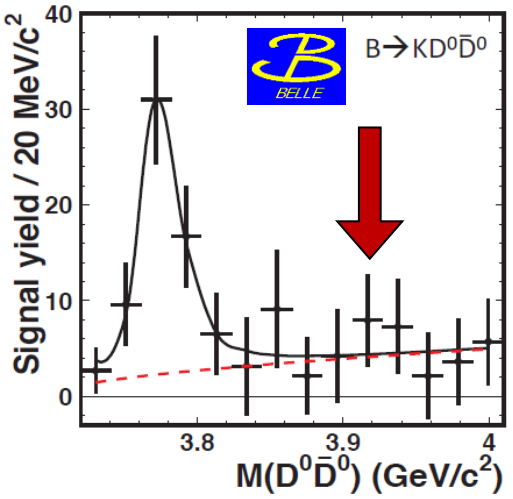


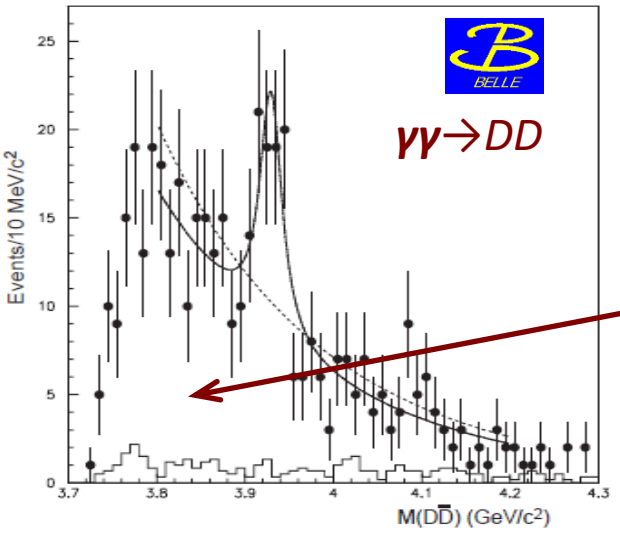
Is X(3915) = χ_{c0}'?

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

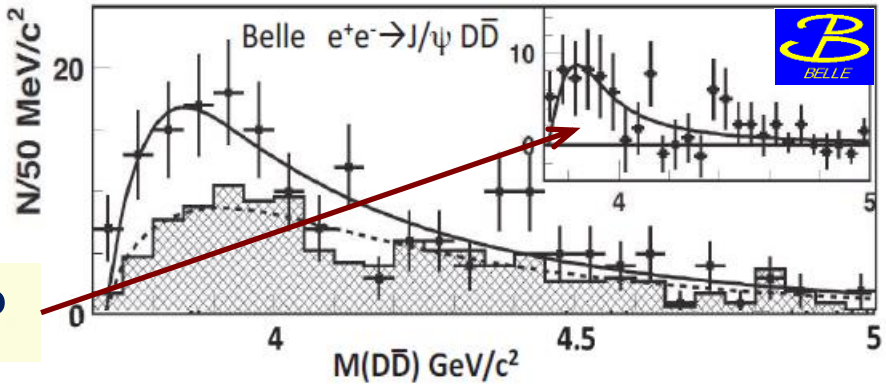
strongly criticized by theoreticians

- χ_{c0}' production in two body B decays suppressed
- χ_{c0}' → 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)…

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

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 $B \times \Gamma_{e^+e^-}$,

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

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

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 $B \times \Gamma_{e^+e^-}$

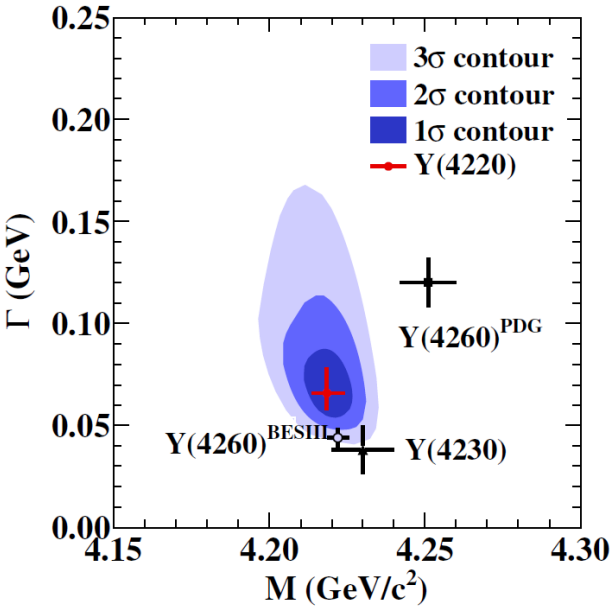
$$B_{\pi\pi J/\psi} = (11.2 \pm 1.1 \pm 1.9)\%$$

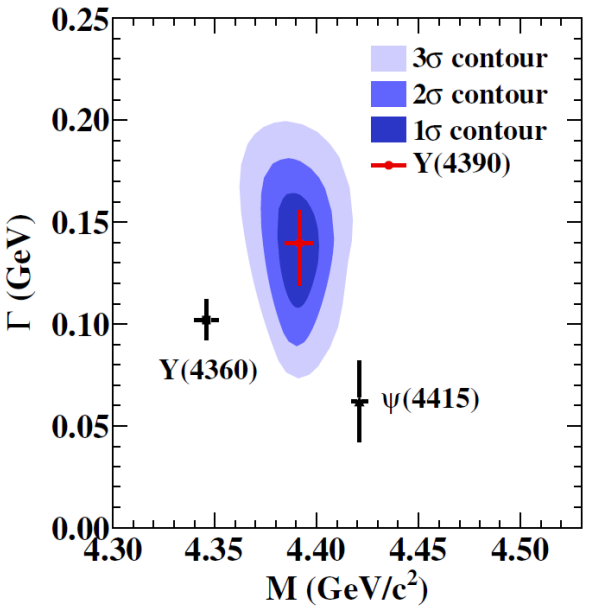
For the most extreme case, taking smallest $B \times \Gamma_{e^+e^-}$ for $\pi\pi J/\psi$ while largest $B \times \Gamma_{e^+e^-}$ for other mode

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

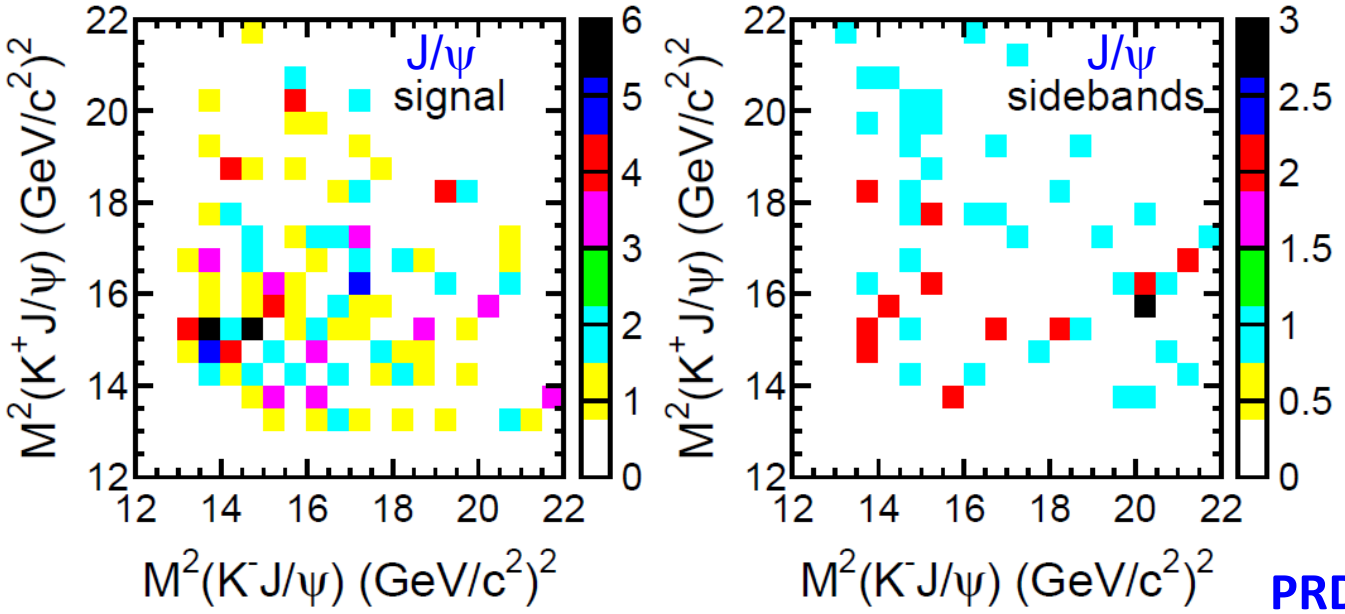
Y or ψ structures

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	

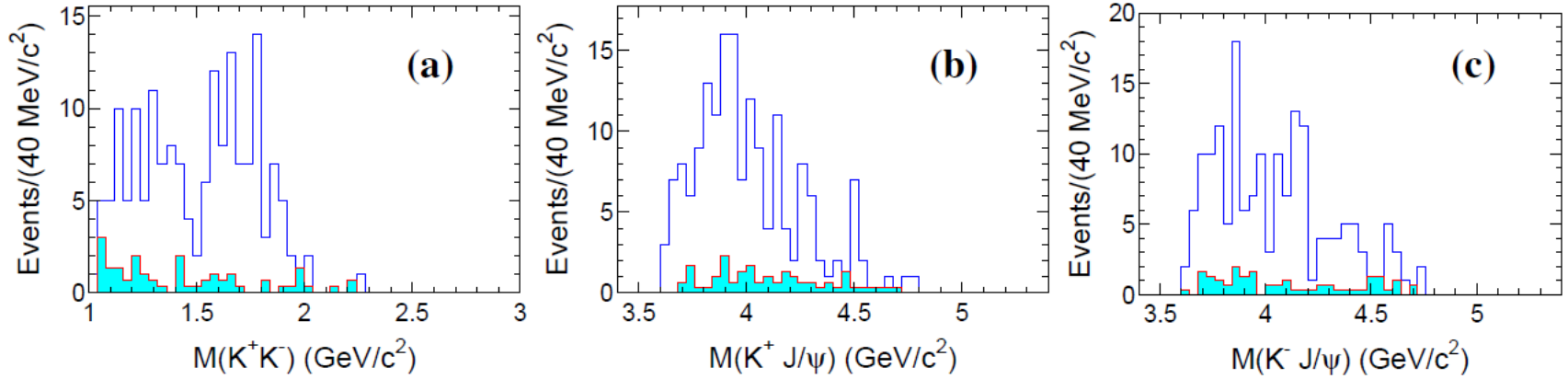




Search for Z_{cs}→KJ/ψ states



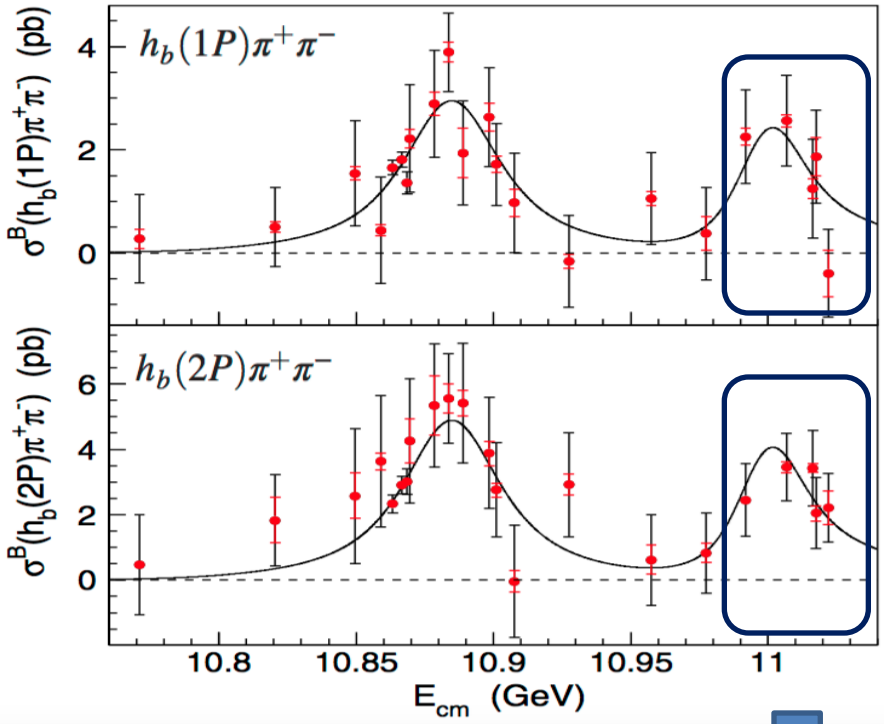
PRD 89,072015(2014)

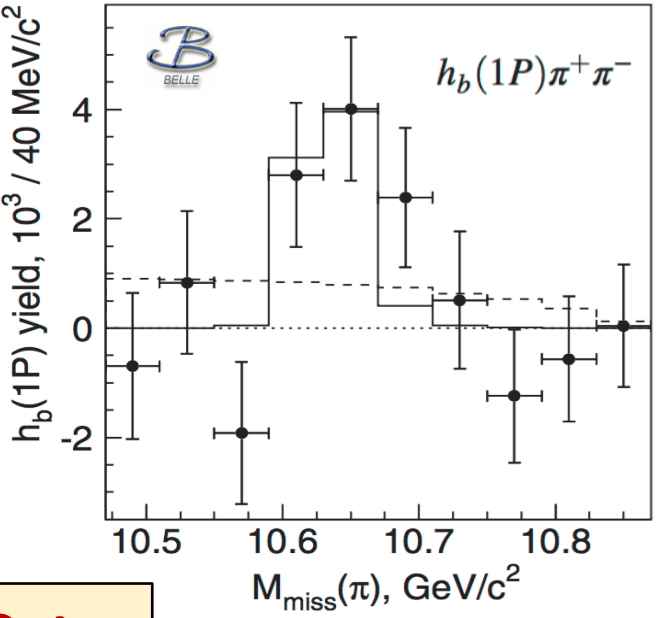


No evident structure in $K^{+-}J/\psi$ mass distribution under current statistics

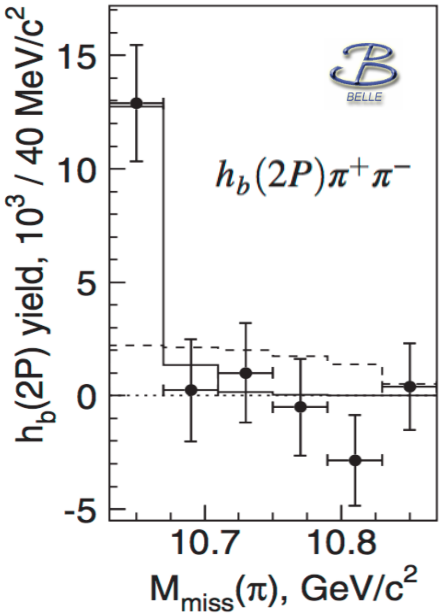
$Z_b^{\pm}$ Production at $\Upsilon(6S)$

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

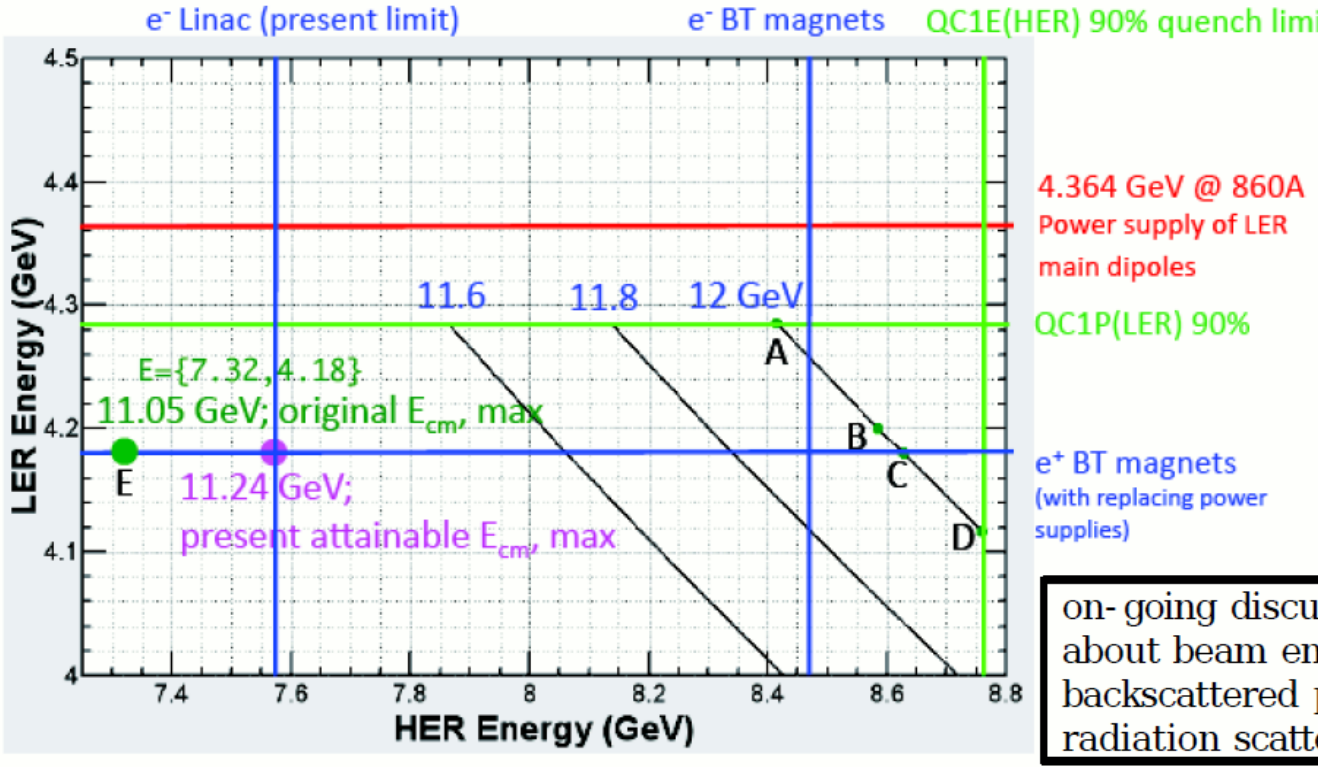
$\Upsilon(6S) \rightarrow h_b(mP)\pi^+\pi^-$ transition is dominated (saturated) by the intermediate $Z_b^{\pm}$ production. Two Z_b can be separated at Belle II !

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: $\Lambda_b \overline{\Lambda}_b$ threshold

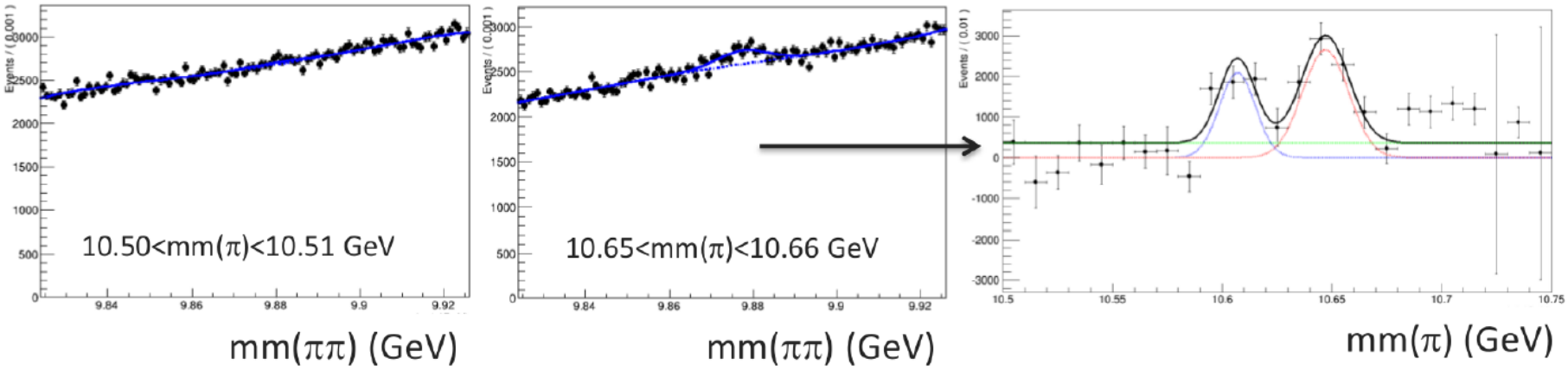
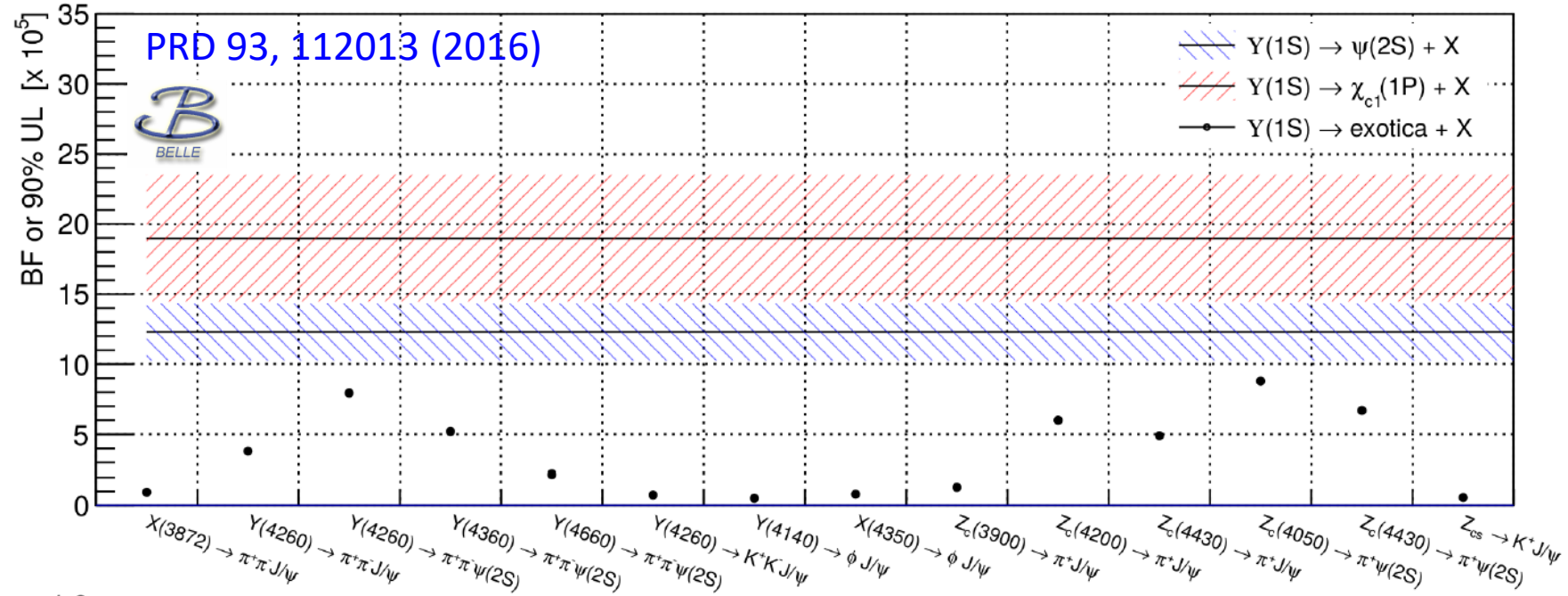
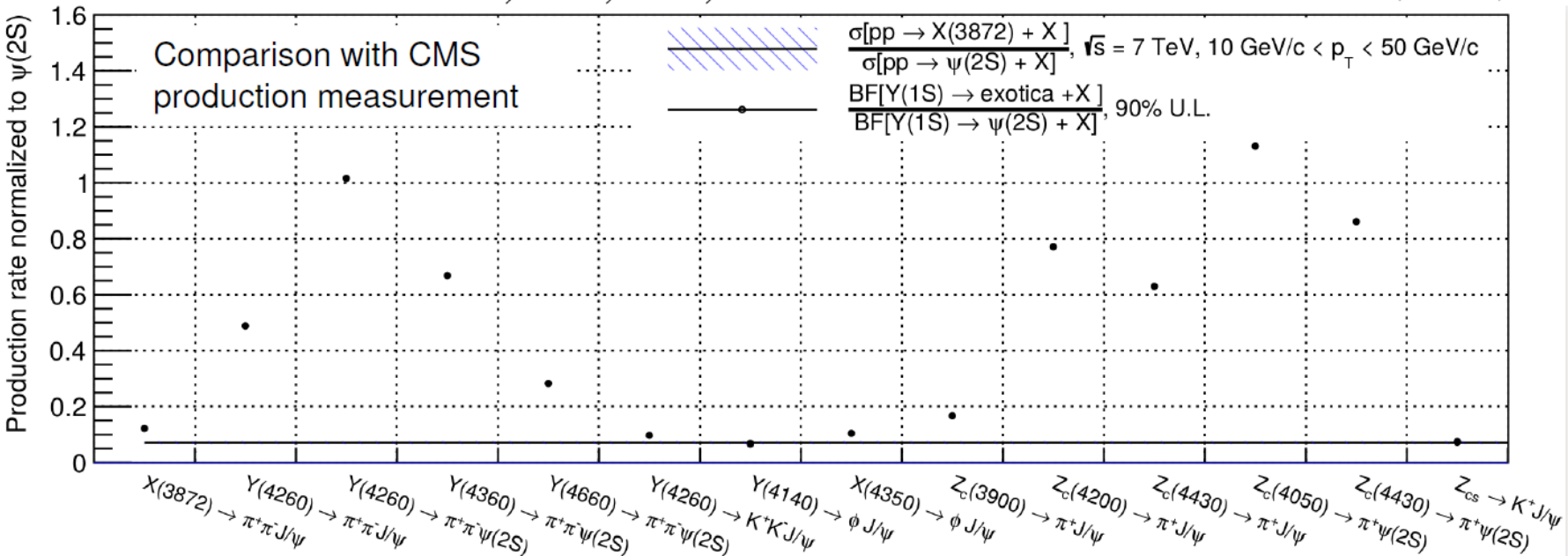


e.g. [arXiv:1211.0103]

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



Y(1S) to inclusive XYZ