Highlights and perspectives of hadron spectroscopy at e+e- colliders

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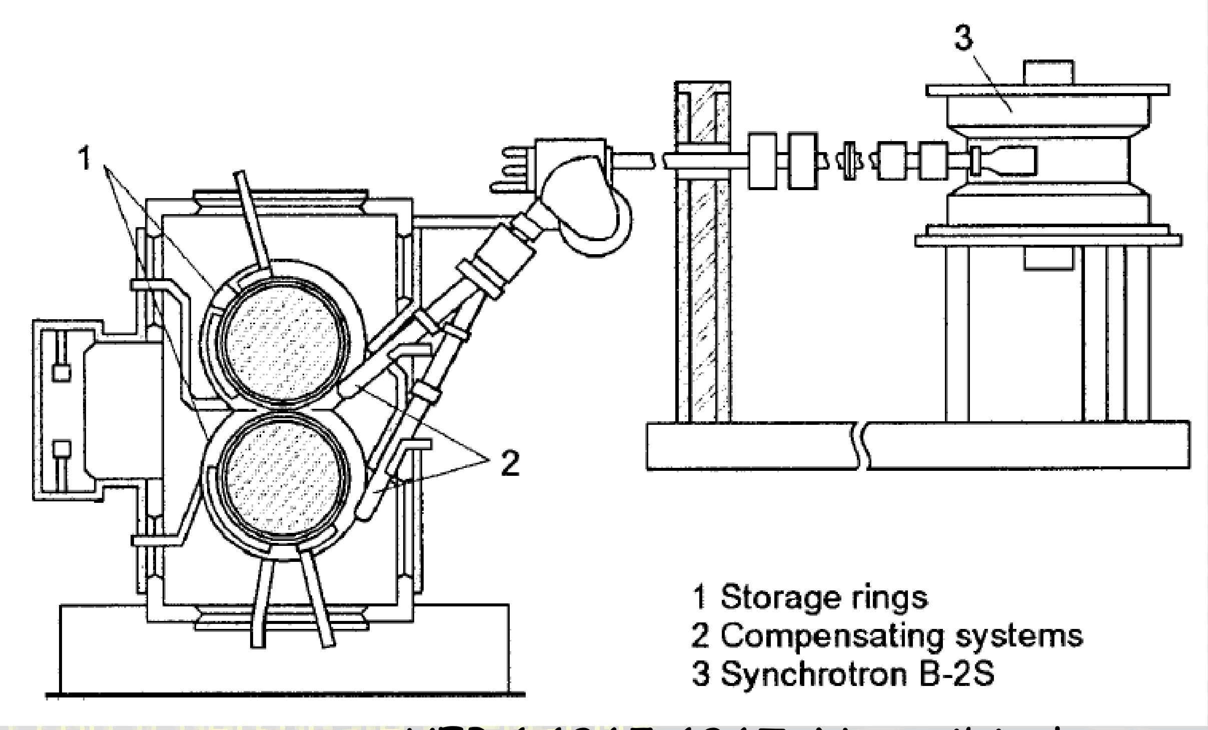
- Physics at e+e- colliders
- BESIII experiment
- Charmoniumlike XYZ states
- Decays J/Psi -> hyperon antihyperon

UPPSALA UNIVERSITET

Warszawa, 2017-05-22 NCBJ

e+e- colliders

AdA 1961, LNF Frascati



VEP-1 1965-1967, Novosibirsk

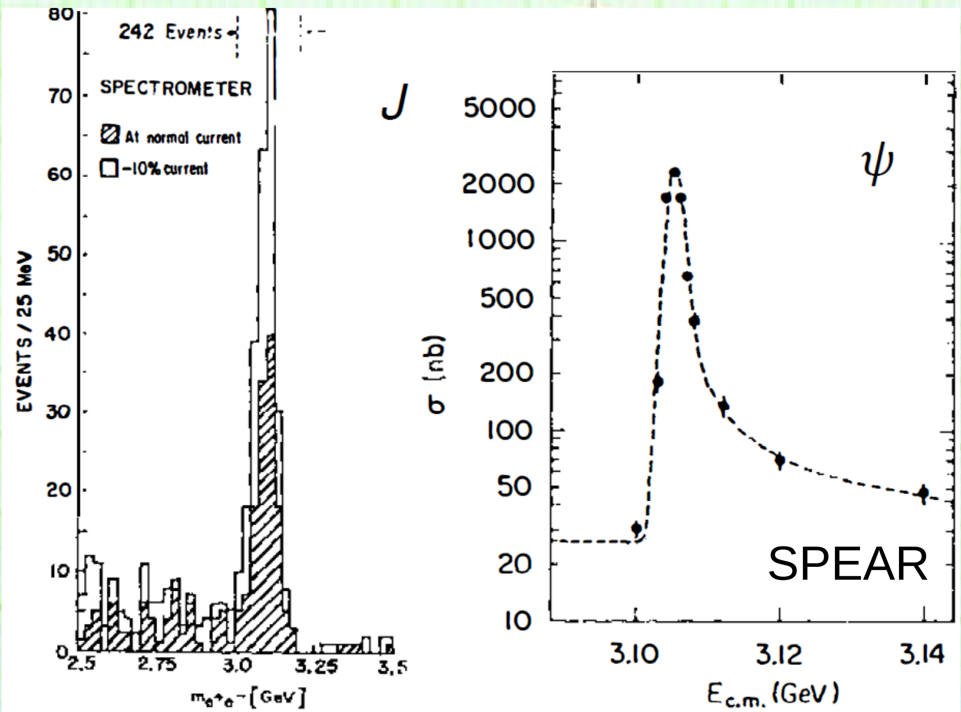
EPS Historic sites

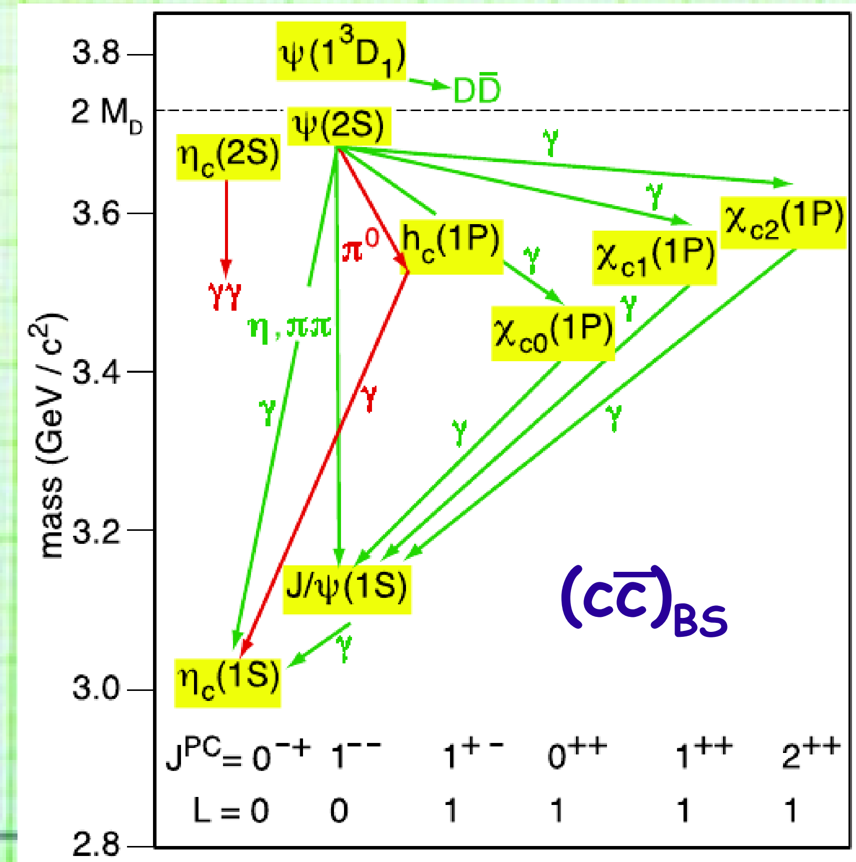
- AdA Storage Ring
- Berlin Institute of PTB
- Blackett Laboratory
- CERN Synchrocyclotron
- Fabra Observatory
- Fermi Fountain
- Georgi Nadjakov's Study
- "Hoza 69" building
- Hill of Arcetri
- Island of Hven
- JINR in Dubna
- Kleist Palais
- LAL-LURE Complex Accelerator
- MTA Atomki
- Niels Bohr Institute
- Refuge des Cosmiques
- Villa Griffone
- UK National Physical Laboratory

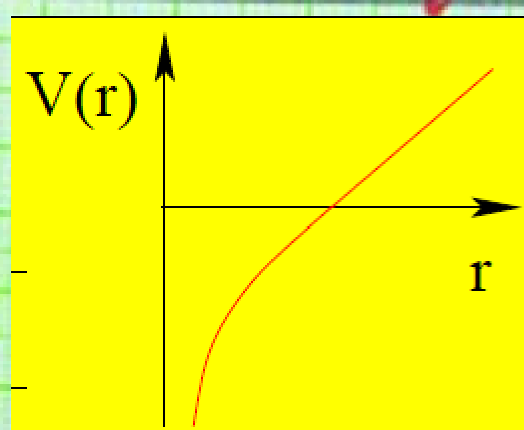
November revolution 1974

11/10/74

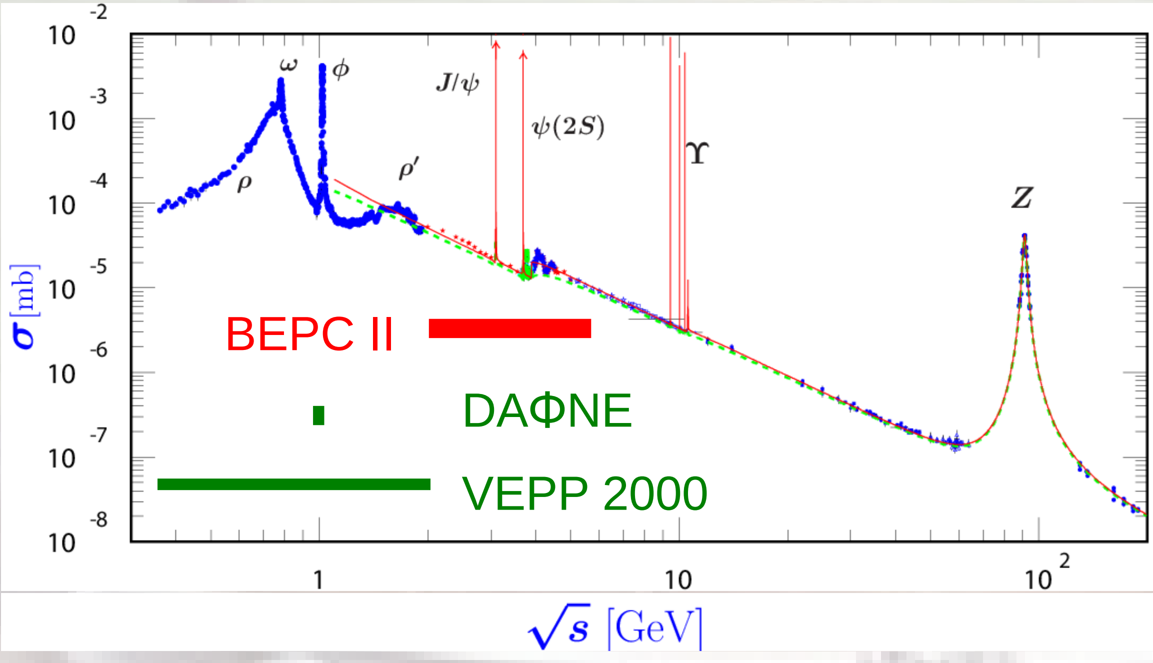
Charmonia

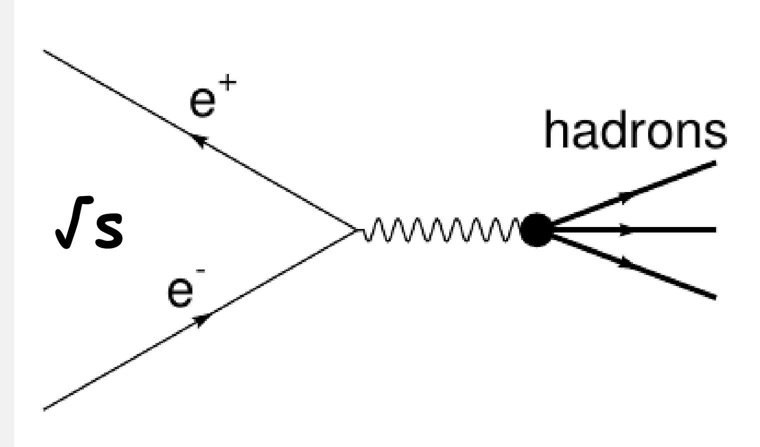


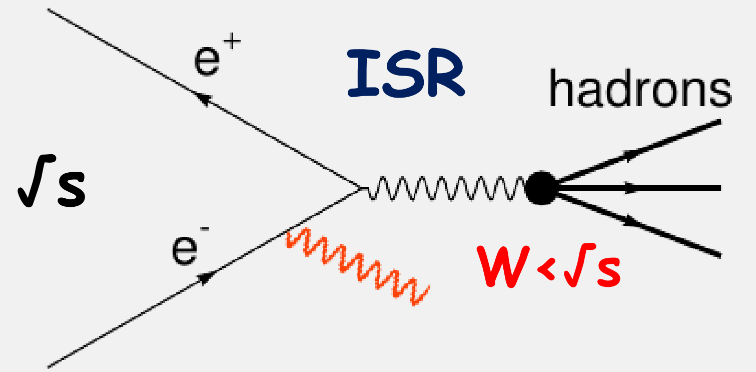


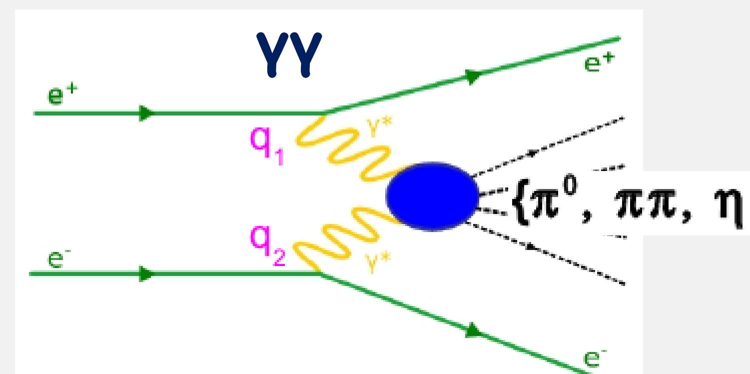


e+e- colliders







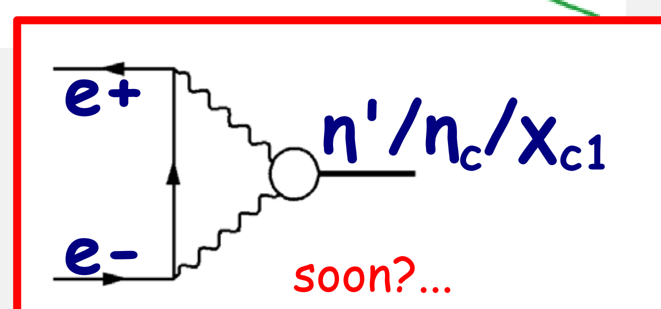


e+e- colliders in operation:

BEPCII L= 10^{33} $cm^{-2}s^{-1}$ at Ψ(3.77) **BESIII**

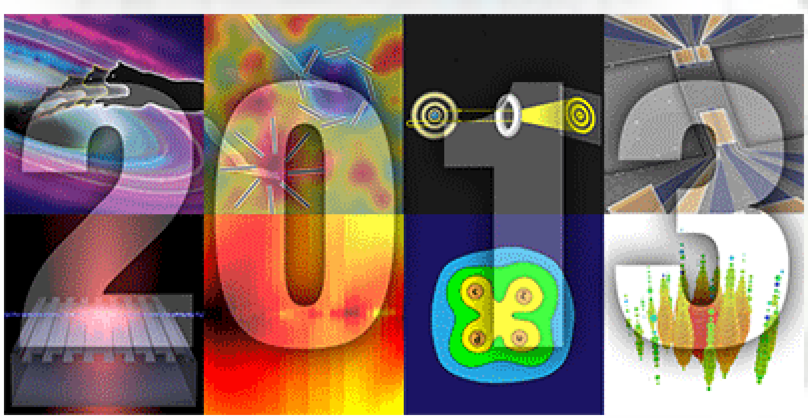
DAΦNE L= $2 \cdot 10^{32}$ $cm^{-2}s^{-1}$ at Φ **KLOE-2**

VEPP2000 L= 10^{32} $cm^{-2}s^{-1}$ at 2GeV **CMD-3,SND**



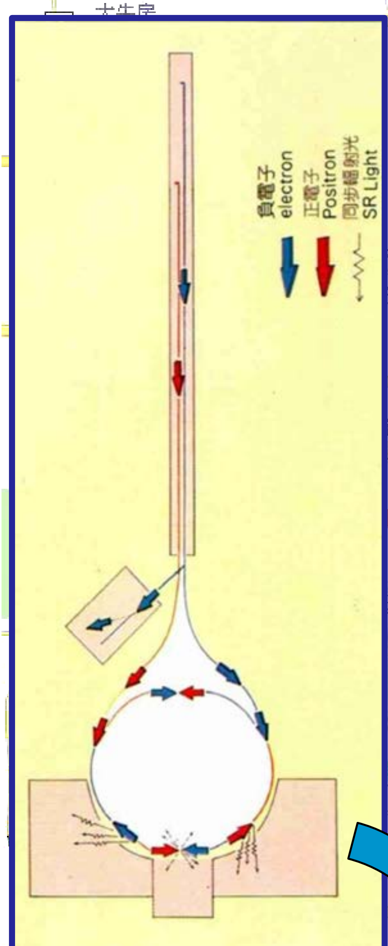
Beijing e+e- collider

1973 China decided to build a 50-GeV proton accelerator
1979 US-China Agreement on Cooperation in Science and Technology
1981 T.D. Lee and W.K.H. Panofsky suggest e+e- collider
1984 BEPC project approved
1988 First collisions in BEPC / BESI experiment
2003 BEPCII approved
2008 BEPCII/BESIII First hadron events recorded
2013 Charged charmoniumlike states

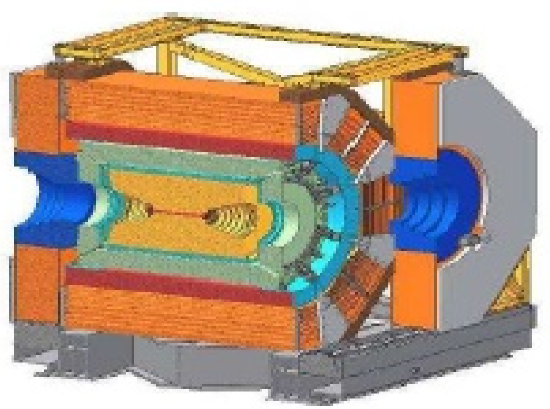


Annu. Rev. Nucl. Part. Sci. 2016. 66:143

Parameter	BEPC	Upgrade	BEPCII
Beam energy (GeV)	1.1–2.7	1.0–2.8	1.0–2.3
Design luminosity ($\times 10^{33}$) (cm^{-2} s^{-1})	0.0065	NA	1
at beam energy (GeV)	2.2	NA	1.89
Obtained luminosity ($\times 10^{33}$) (cm^{-2} s^{-1})	0.007	0.049	1.000
at beam energy (GeV)	2.2	1.55	1.89
No. bunches	1	1	93
Beam current (A)	0.03	0.045	0.91 (nominal)
at beam energy (GeV)	2.2	1.55	NA
Circumference (m)	240	240	237



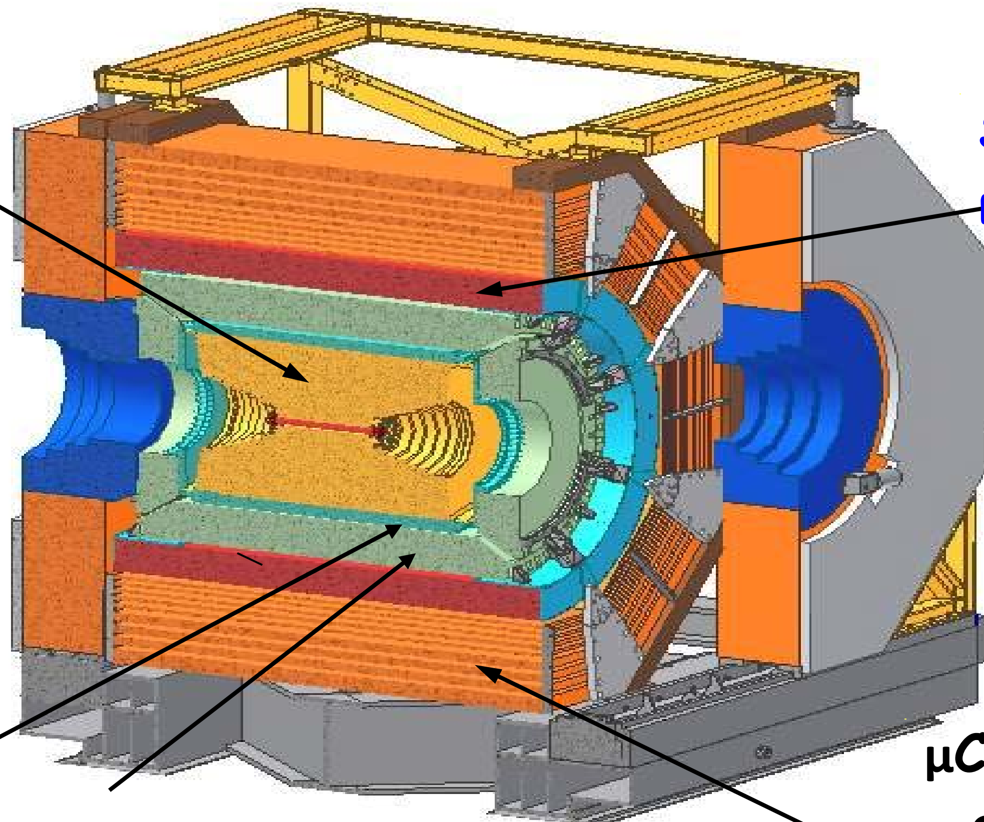
BEPCII (Beijing)



τ –charm factory $2<\sqrt{s}<4.6$ GeV:

- Charmonium spectroscopy/decays
- Light hadrons
- Charm
- τ physics
- R-scan

BESIII Detector



Drift Chamber (MDC)
$\sigma P/P$ = 0.5%(1GeV)
$\sigma(dE/dx)$ = 6%

Superconducting magnet (1.0 Tesla)

Time Of Flight (TOF)
$\sigma(t)$: 90 ps Barrel
110 ps endcap

EMC: $\sigma E/\sqrt{E}$ = 2.5 % (1 GeV)
(CsI) $\sigma_{z\varphi}$(cm) = 0.5 - 0.7 cm/$\sqrt{E}$

μCounter
8- 9 layers RPC
$\delta R\Phi$=1.4 – 1.7 cm

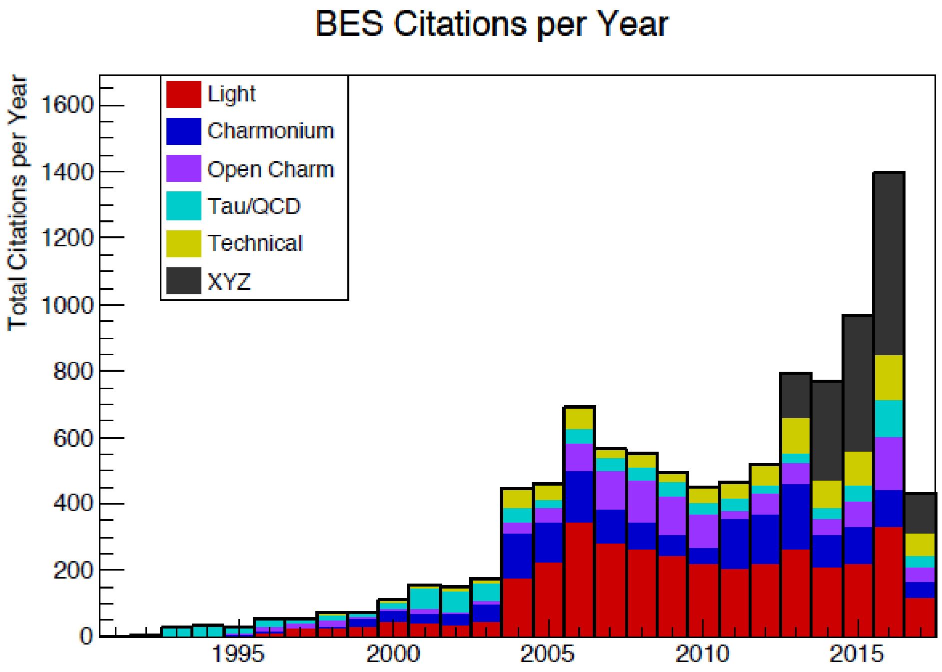
BESIII Collaboration

Groups from China (34 inst.), EU(13 inst.), US(5 inst.)
e.g.: Germany, Italy, US, Nederlands, Russia, Sweden

158 publications since 2010 (ca 20/year)

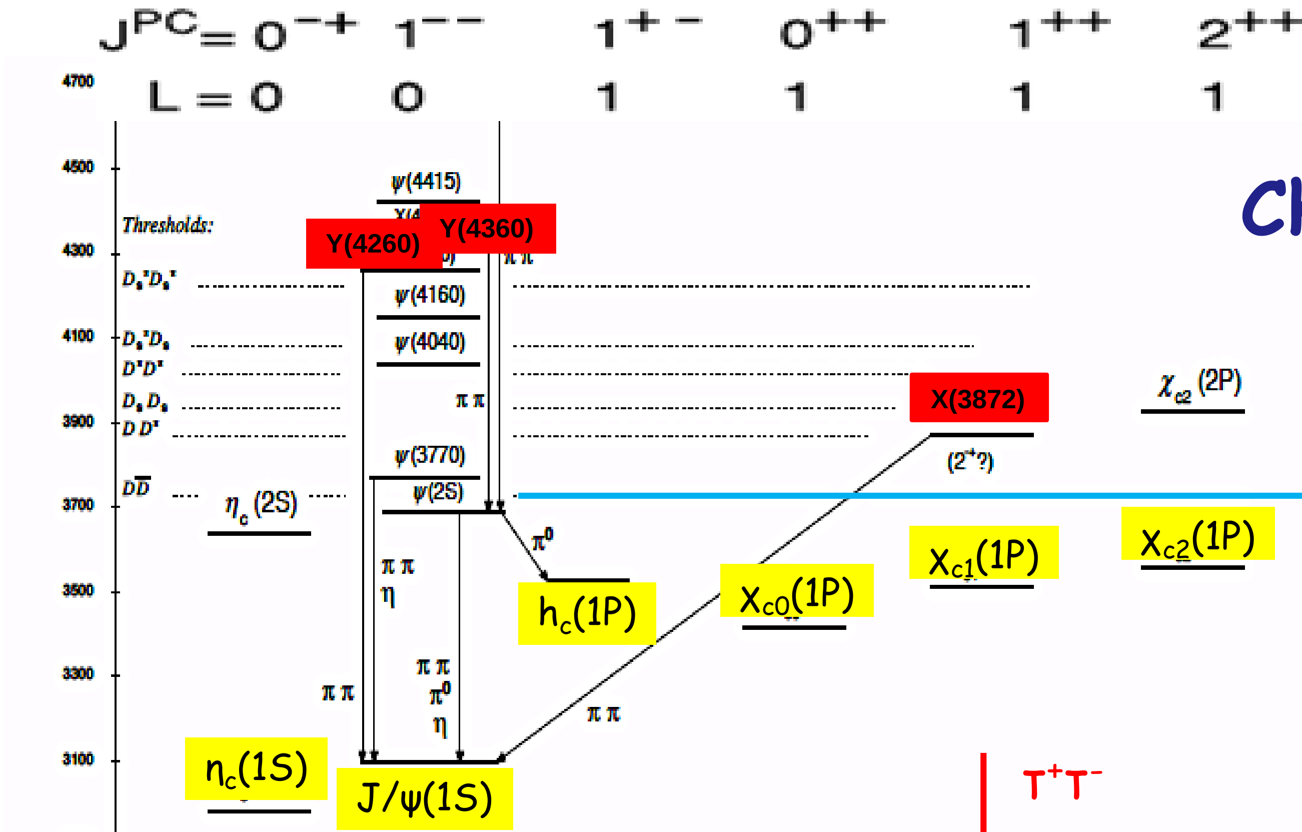
Uppsala University joined BESIII 2012:

- hyperon FF [K.Schönning, T. Johansson]
- η' decays (from J/ψ -- $6 \cdot 10^6$ η')
- e+e- -> η_c
- hyperon decay parameters in J/ψ decays (use spin correlations and polarization)



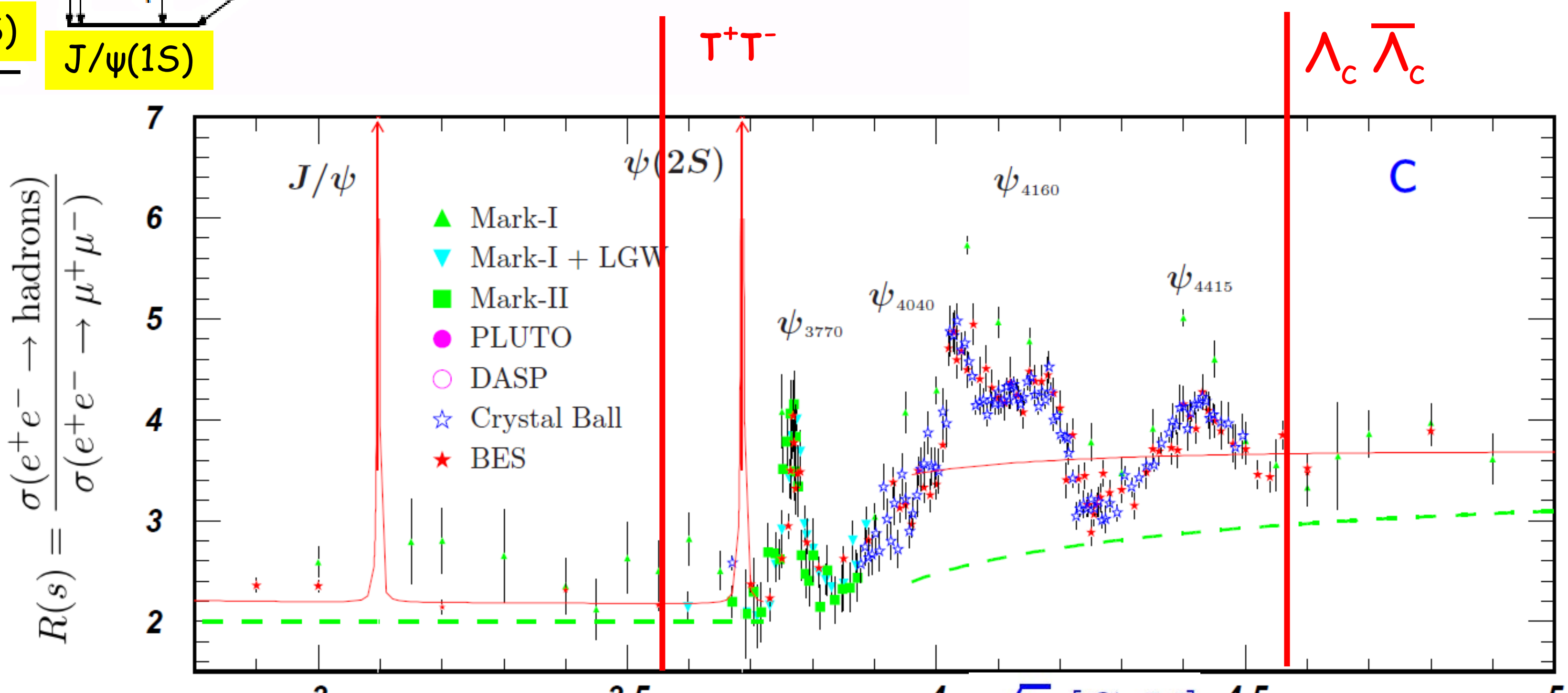
Charmonium system

PDG2014



$D\bar{D}$ threshold

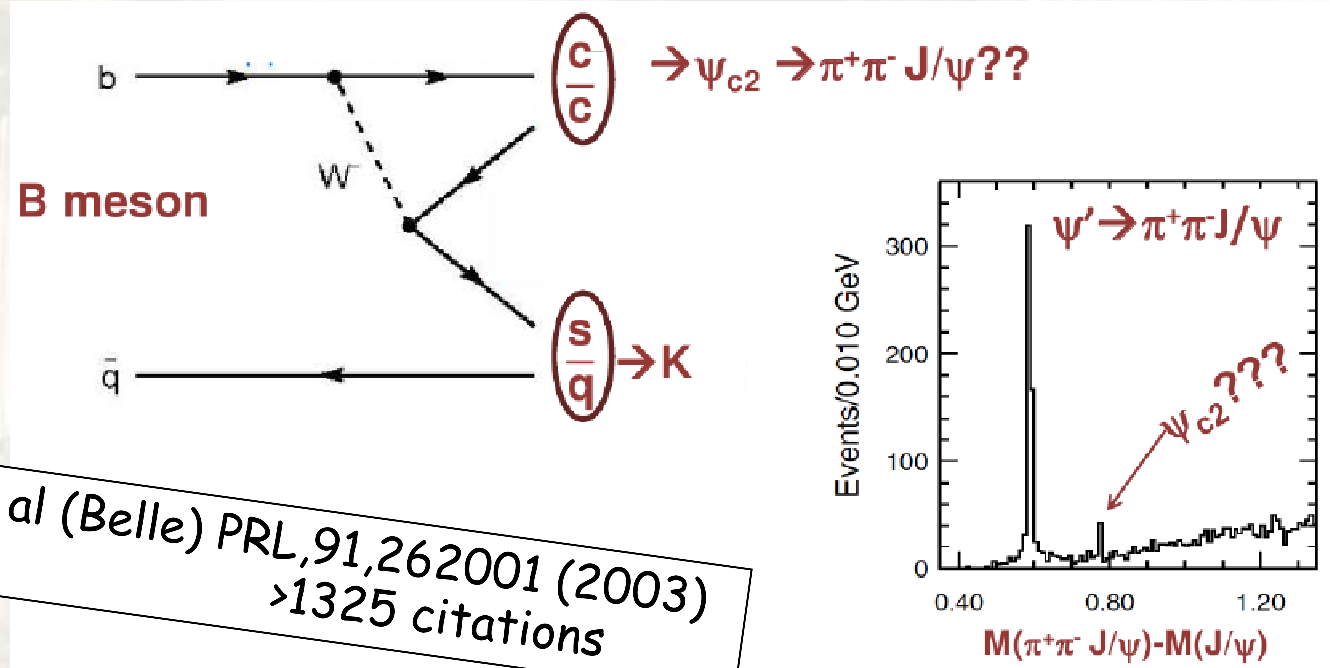
spectrum understood
(ρπ puzzle?)



1.31×10^9 J/Ψ

X(3872)

Motivation: search for predicted missing narrow tensor charmonium state $\Psi_2(1^3D_2)$ $J^{PC} = 2^{--}$ PRL 89, 162002 (2002)



S.-K. Choi, S.L.Olsen et al (Belle) PRL,91,262001 (2003)
>1325 citations

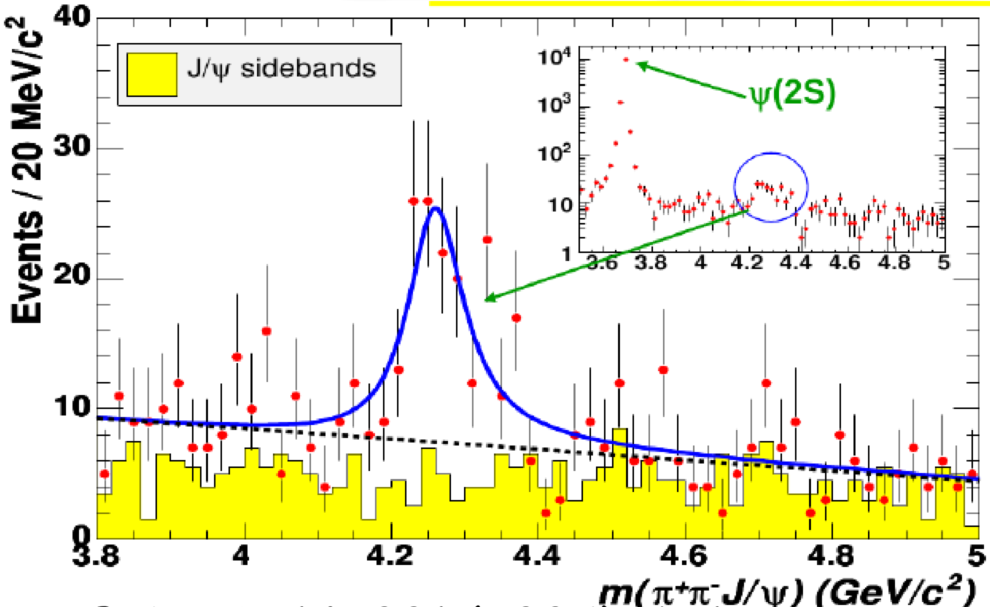
- very narrow (< 1.2 MeV)
- Mass 3871.69±0.17 MeV close to $D^*_0\bar{D}_0$ threshold (~3871.8 MeV)

- $J^{PC} = 1^{++}$ (LHCb) PRL110,222001 (2013)

a loosely bound $D\bar{D}*$ "molecular state," ?

Y(4260)

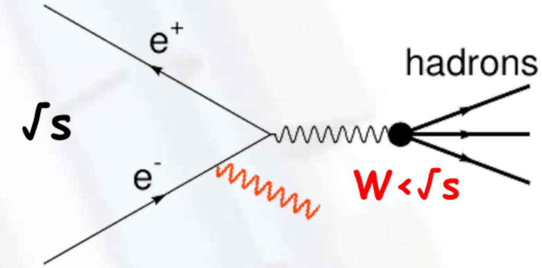
e+e− → π+π−J/Ψ (ISR) BaBar: (2005).



BaBar: 232 fb⁻¹

>8σ significance structure called Y(4260)

M(J/ψππ) of ψ(2S) with J/ψ constraint is well described by Cauchy shape funct.

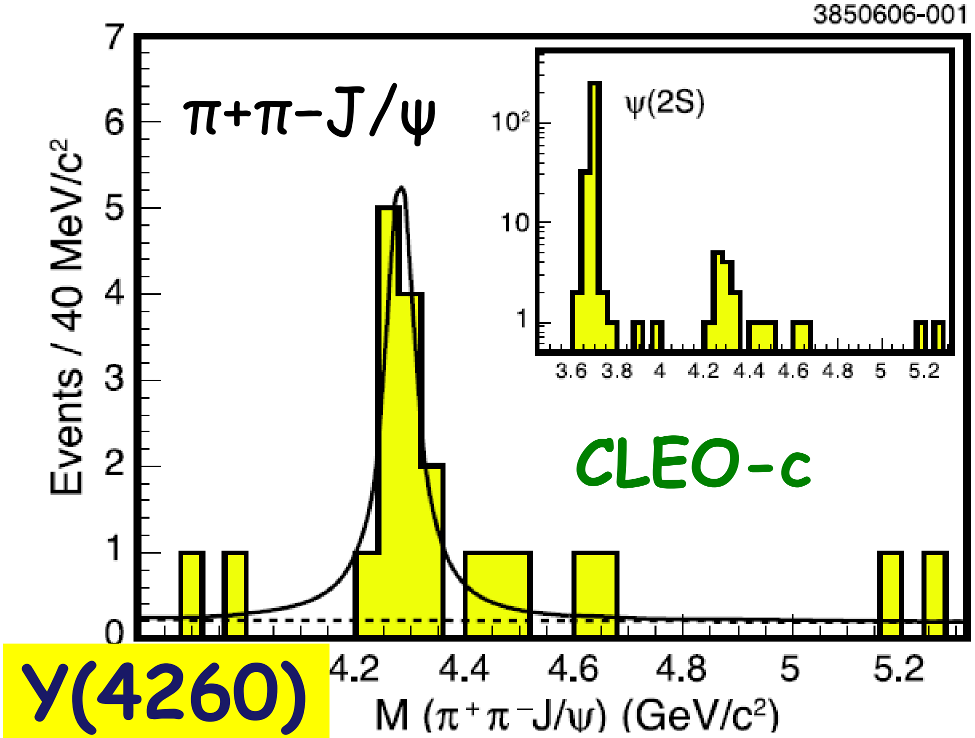


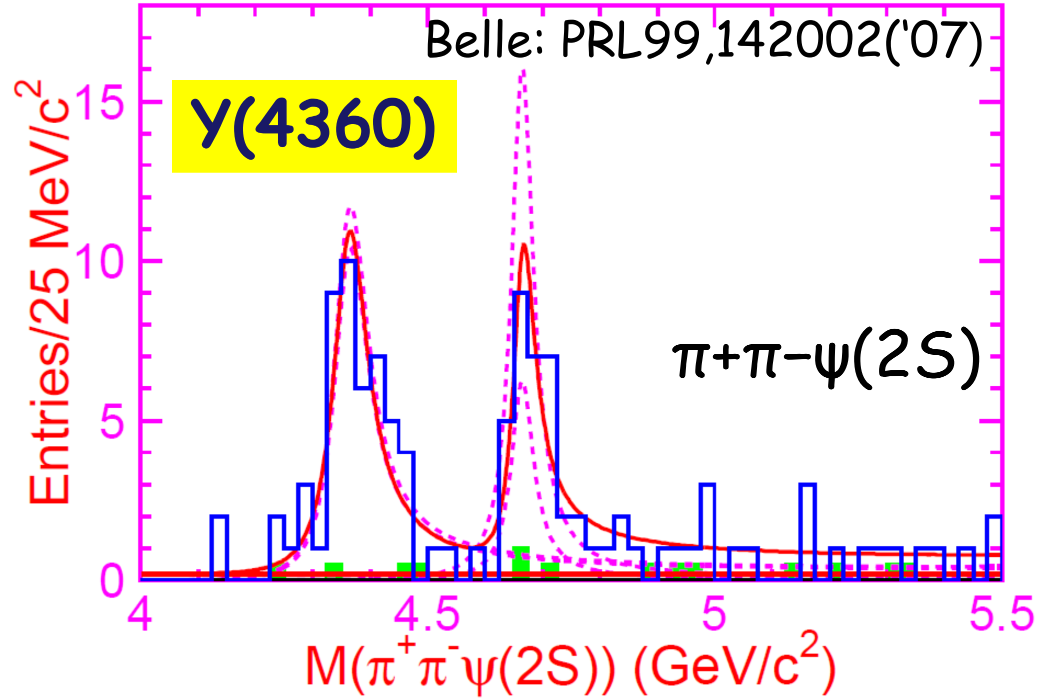
PRL **95**, 142001 (2005) 671 citations

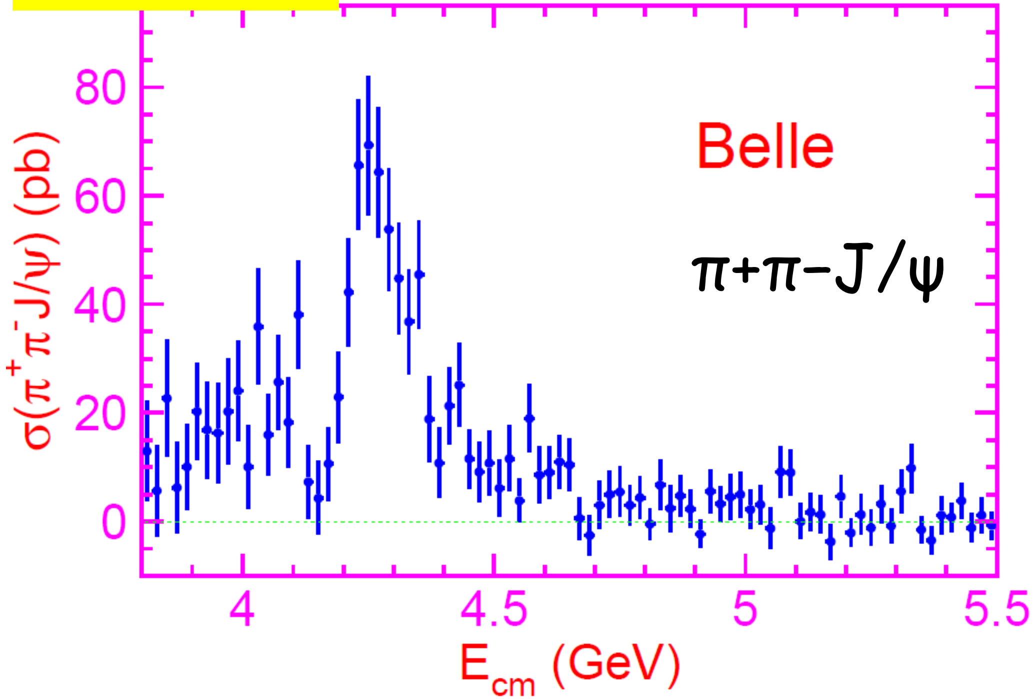
Y states: $J^{PC}=1^{--}$ (could be directly produced in e+e- colliders)
Y(4260) observed in π+π−J/ψ system (BaBar)
confirmed by CLEOc and Belle.

Exotic properties:

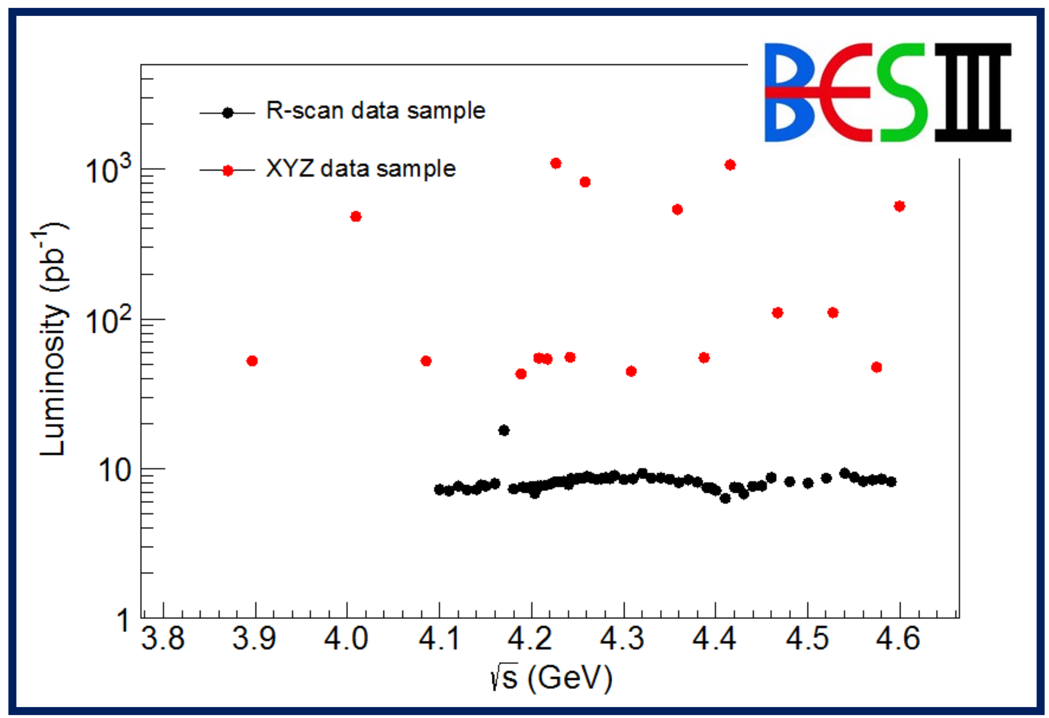
- Not expected $c\bar{c}$ state → already too many states
- Strongly coupled to ππJ/ψ
- Open charm decays suppressed





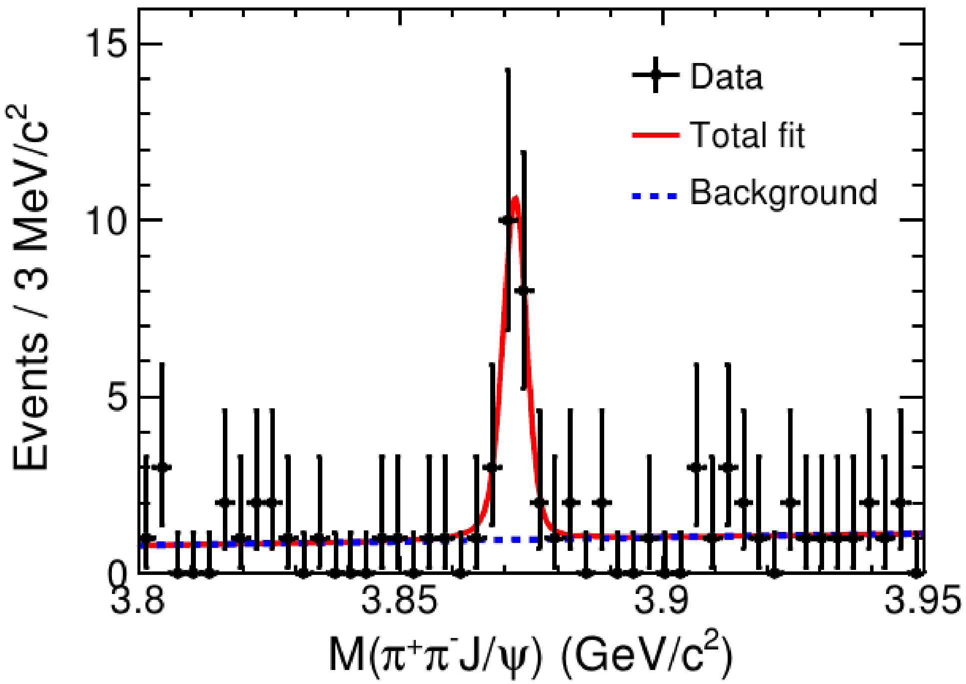


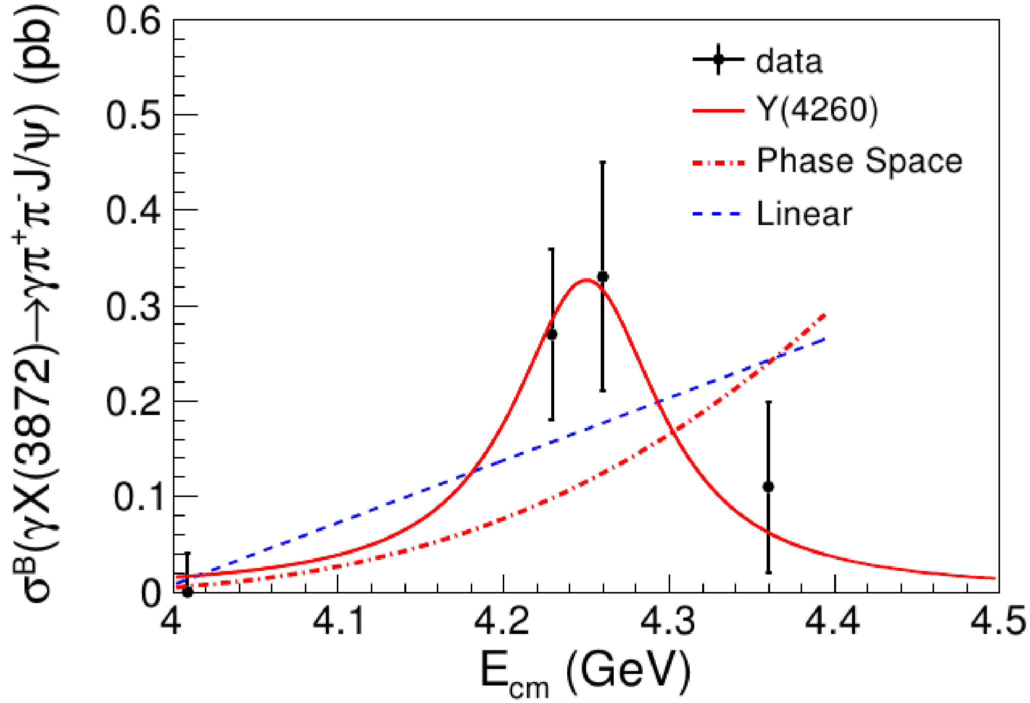
Belle: PRL99,182004('07)



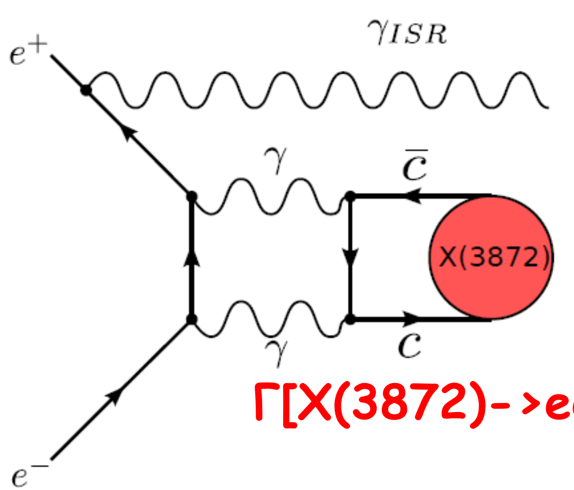
e+e- → γX(3872) → γπ+π−J/ψ

BESIII





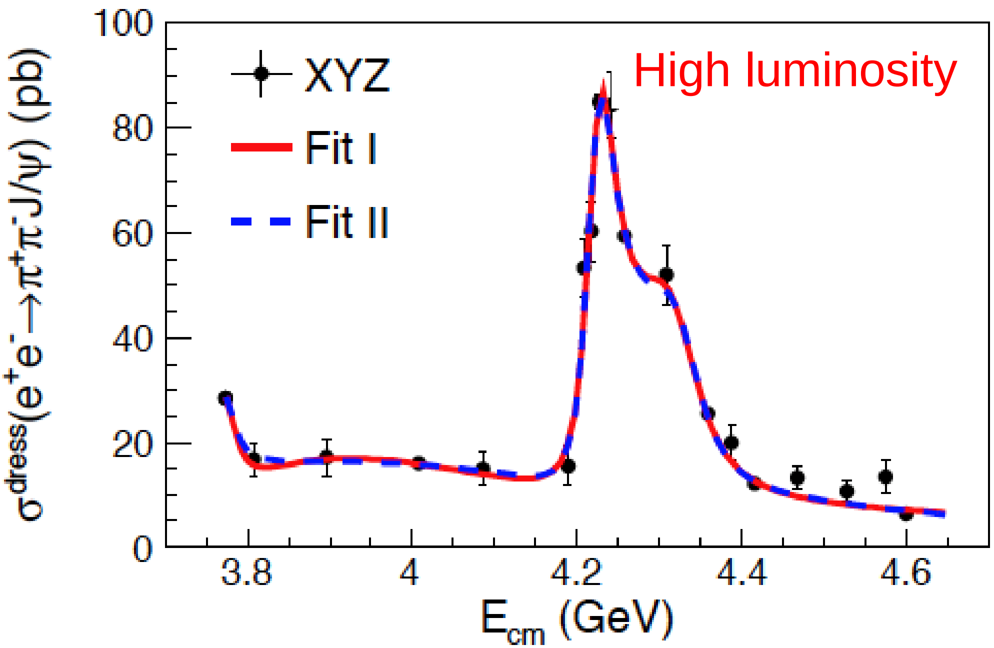
PRL 112 092001 ('14) M = (3871.9±0.7±0.2) MeV, Γ<2.4 MeV,
=> Y(4260) -> X(3872)γ transition

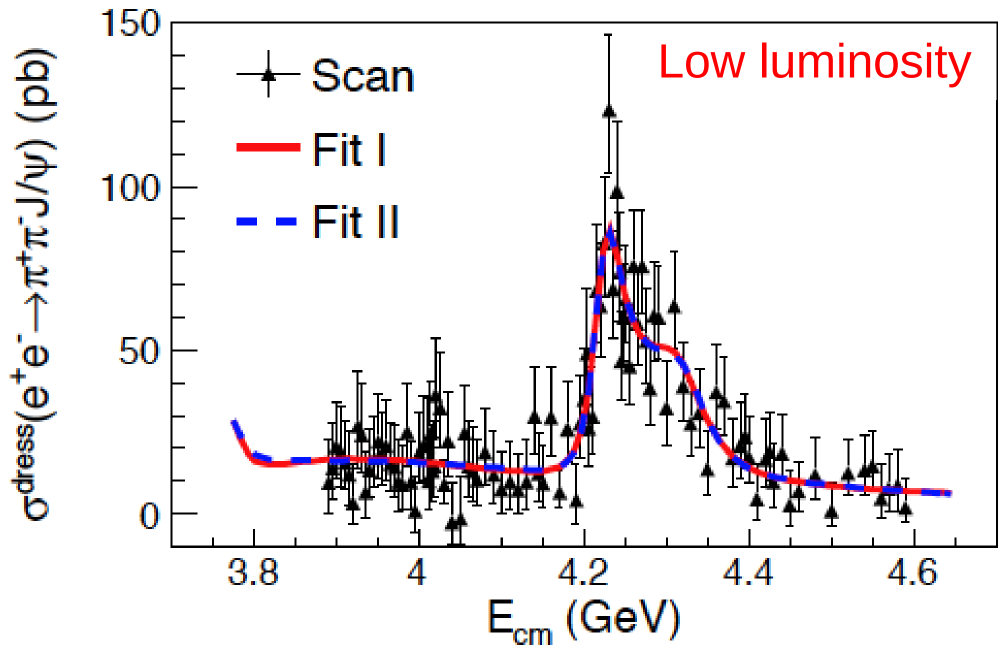


Γ[X(3872)->ee] 0.03 eV VMD
quarkonium 0.044 eV- 0.46 eV

BESIII PLB749 ('15) 414:
Γ[X(3872)->ee]·B(X(3872)-> π+π-J/ψ) < 0.13 eV 90% CL

$e^+e^- \to \pi^+\pi^- J/\psi$ at BESIII



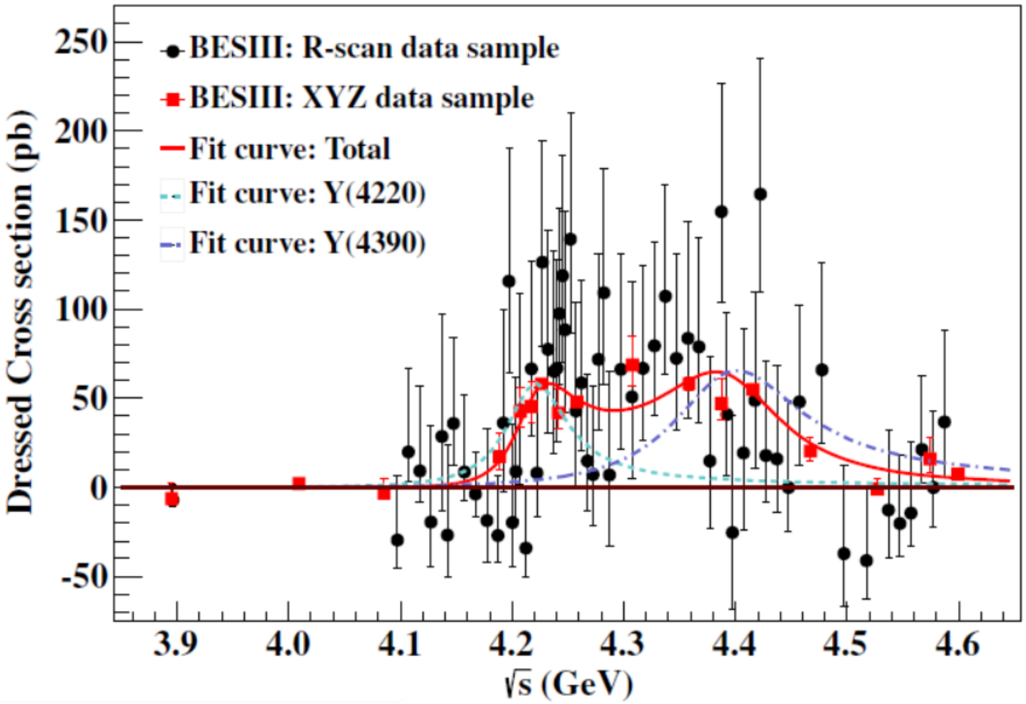


Three coherent BW Fit I vs
an exponential and two BW (Fit II)

Parameters	Fit result
$M(R_1)$	$3812.6^{+61.9}_{-96.6}$ $(\cdots)$
$\Gamma_{tot}(R_1)$	$476.9^{+78.4}_{-64.8}$ $(\cdots)$
$M(R_2)$	4222.0 ± 3.1 (4220.9 ± 2.9)
$\Gamma_{tot}(R_2)$	44.1 ± 4.3 (44.1 ± 3.8)
$M(R_3)$	4320.0 ± 10.4 (4326.8 ± 10.0)
$\Gamma_{tot}(R_3)$	$101.4^{+25.3}_{-19.7}$ $(98.2^{+25.4}_{-19.6})$

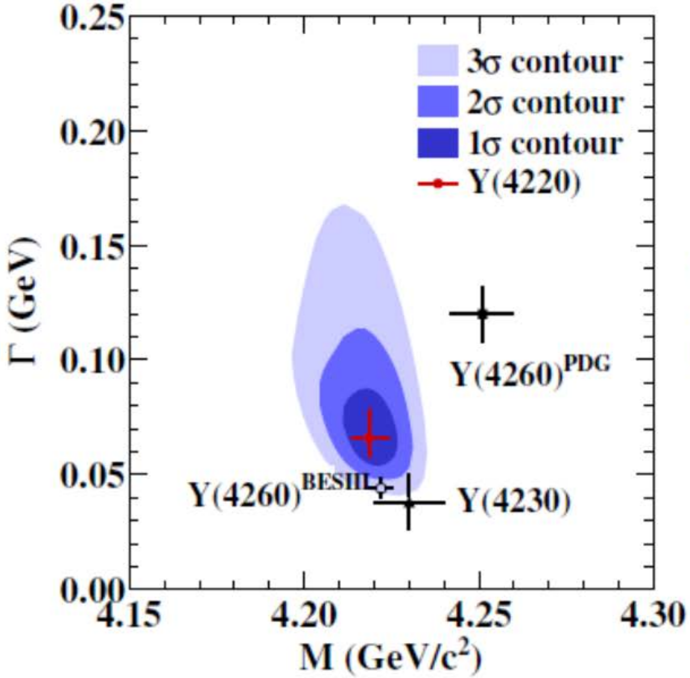
PRL 118, 092001 (2017)

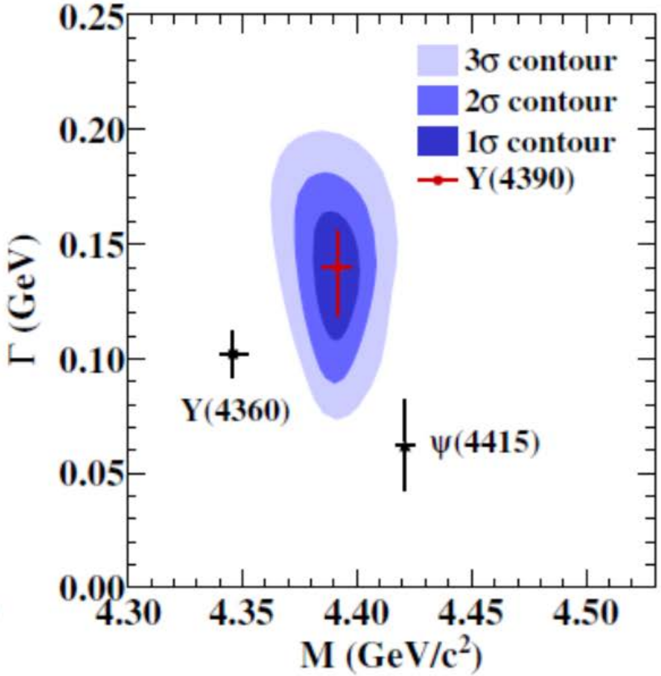
$e^+e^- \to \pi^+\pi^- h_c(1P)$ at BESIII



- Resonant structures
- Significance two vs one BW >10σ
- Parameters different from

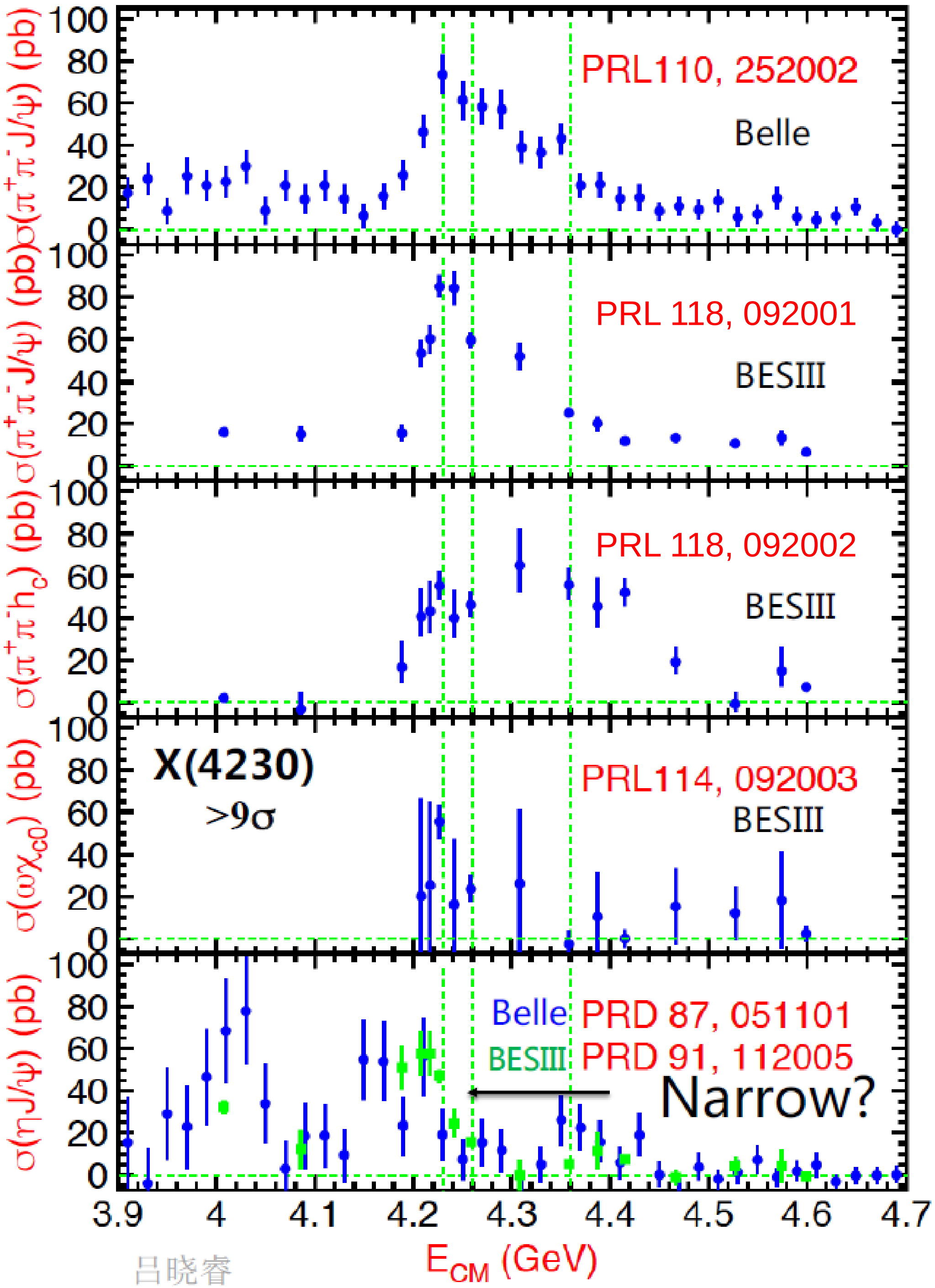
Y(4260), Y(4360), and ψ(4415)





PRL 118, 092002 (2017)

More channels



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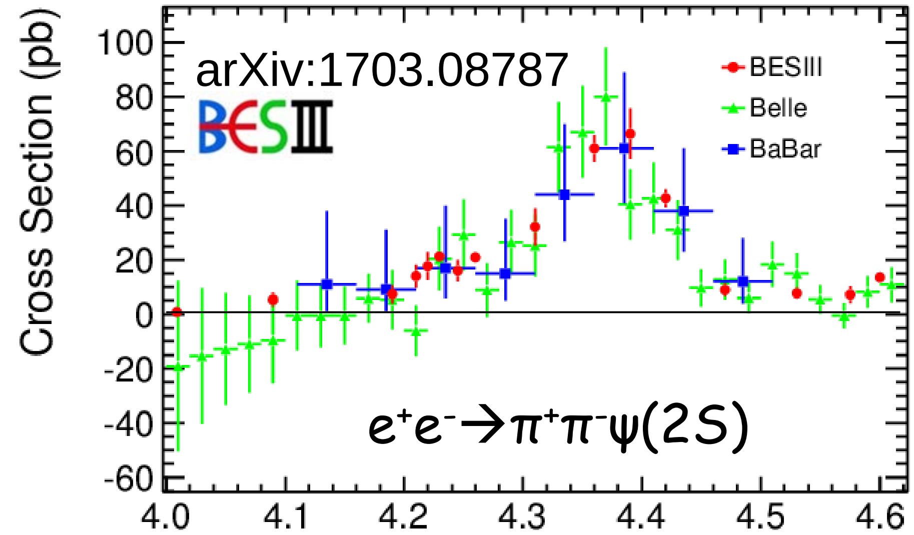
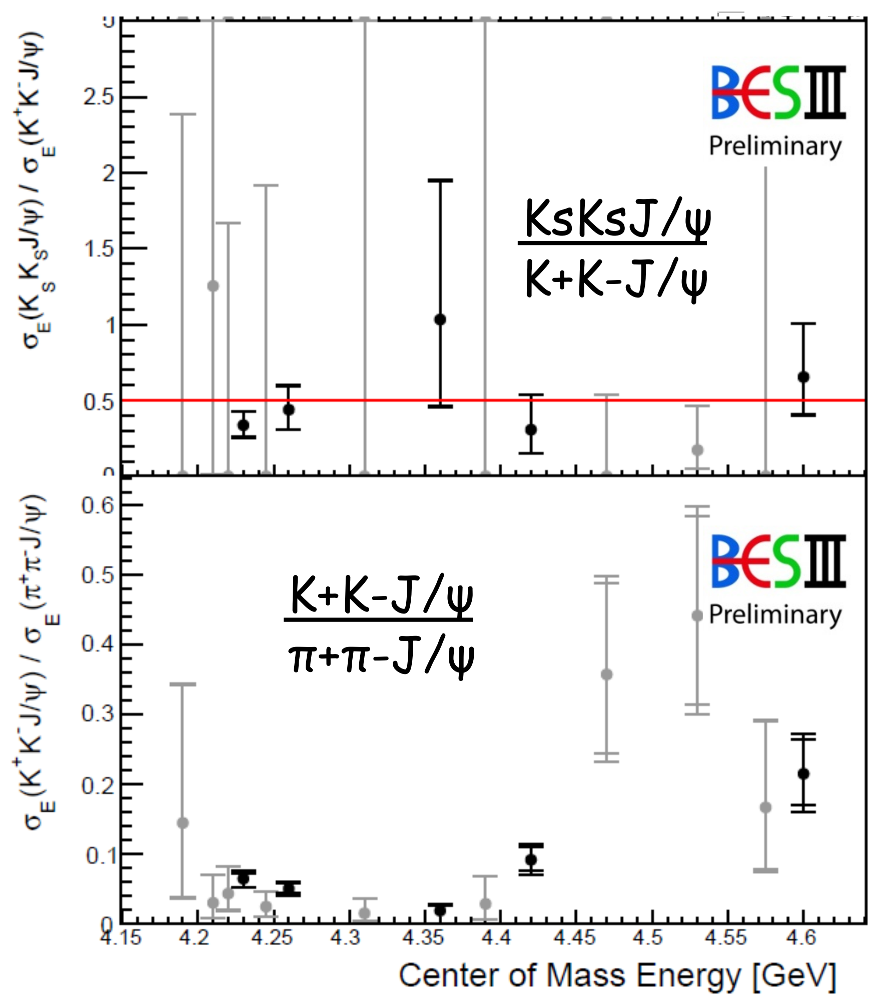
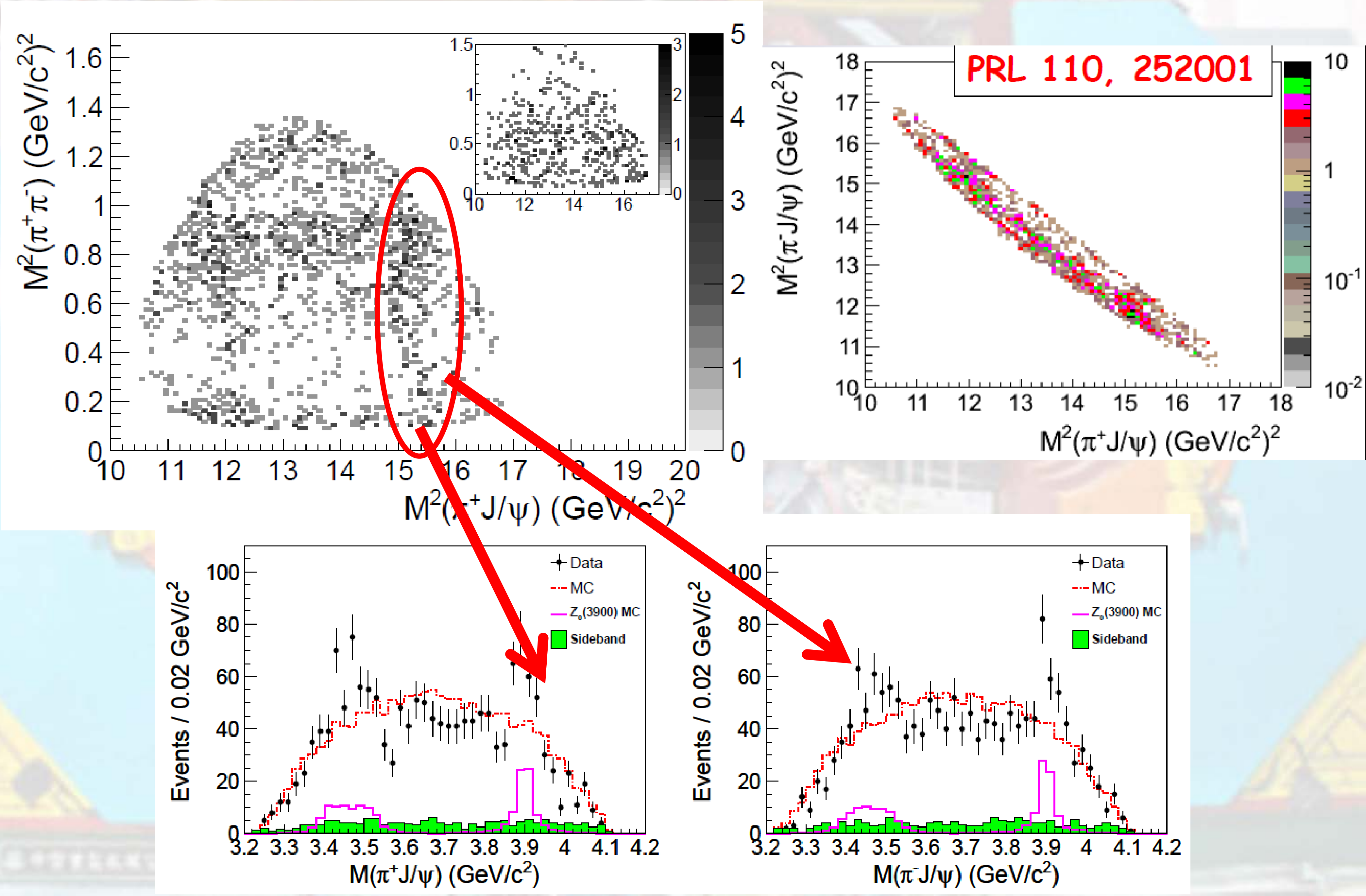




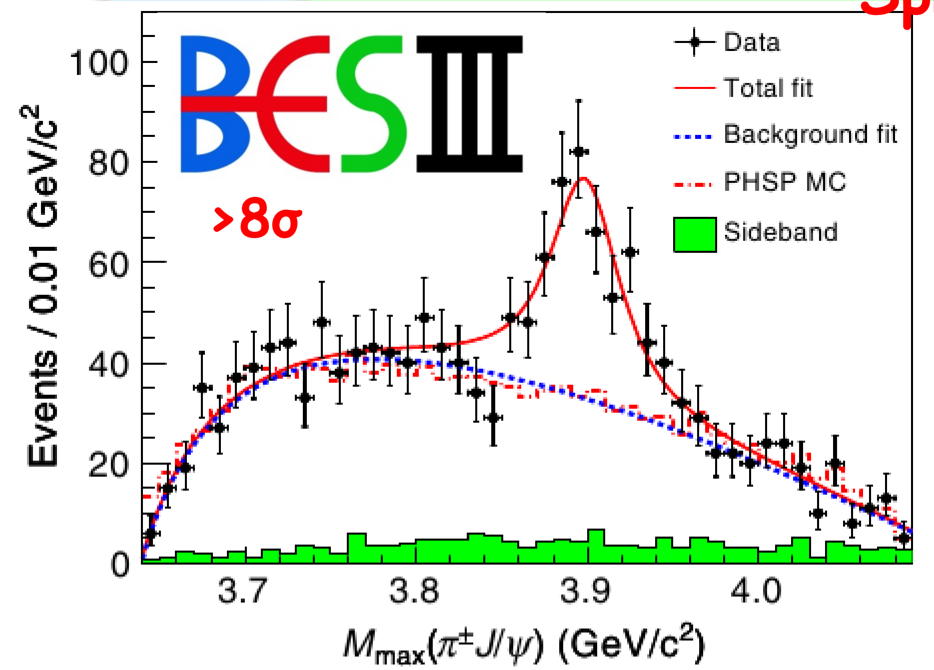
$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at Y(4260) peak

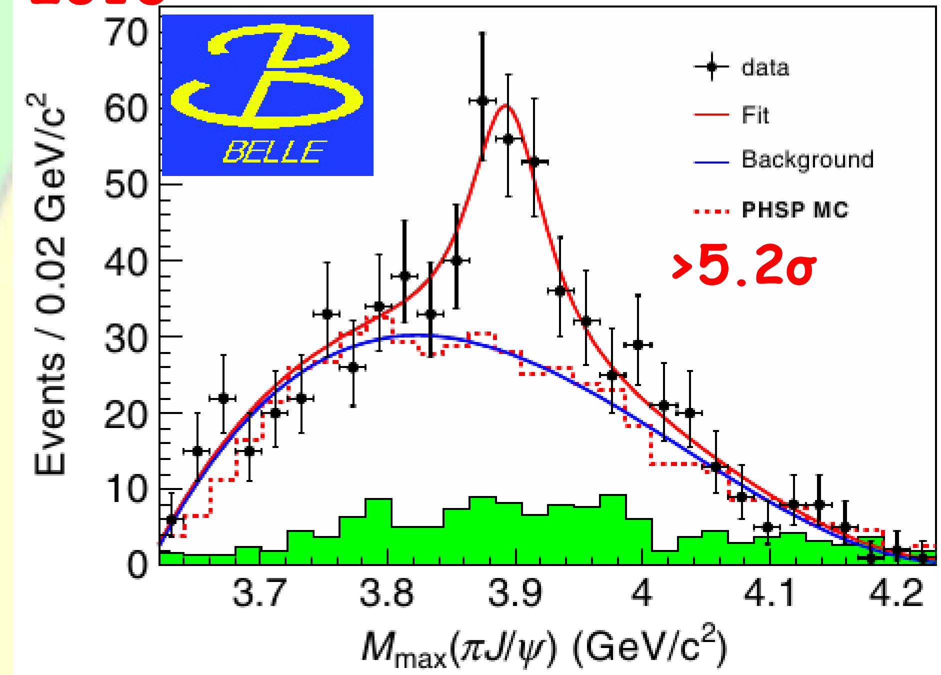
$0.5 fb^{-1}$ @4.26 GeV Collected winter 2012/2013

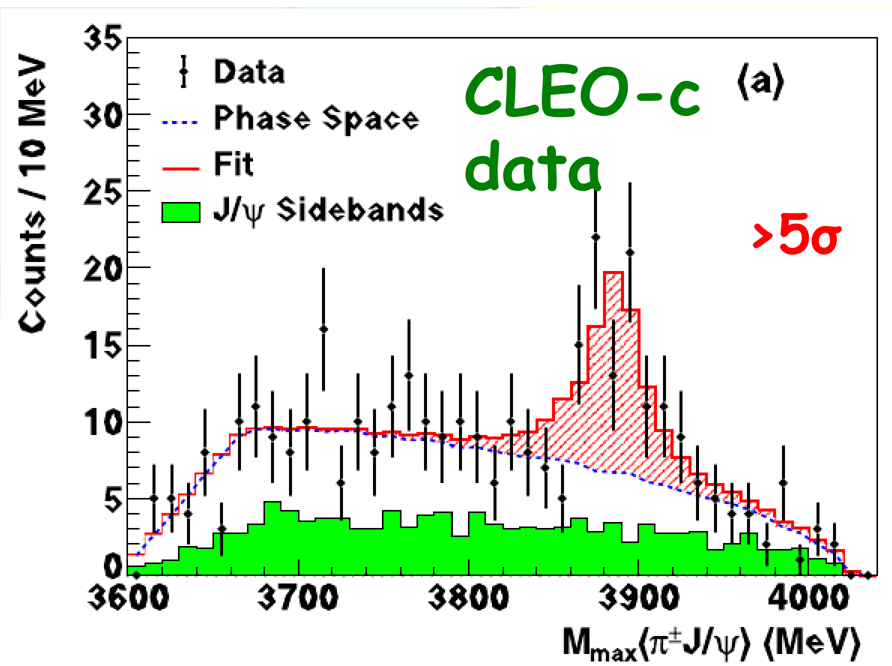


Observation of $Z_c^{\pm}(3900)$ in $e+e- \to \pi+\pi- J/\psi$

Spring 2013







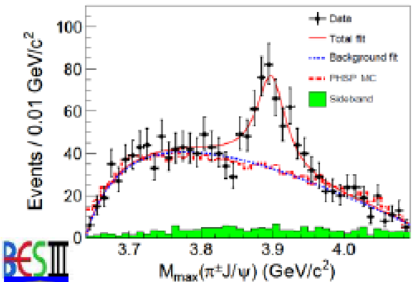
- Couples to $c\bar{c}$
- Has electric charge

=> At least 4-quarks

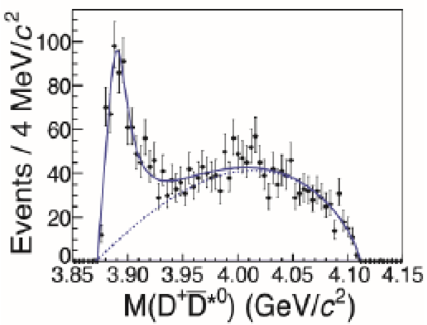
BESIII: PRL 110 252001 (474)
BELLE: PRL 110 252002
CLEO-c data: PLB 727, 366

$Z_c^{\pm,0}$ states at BESIII

PRL110 ('13) 252001



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



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

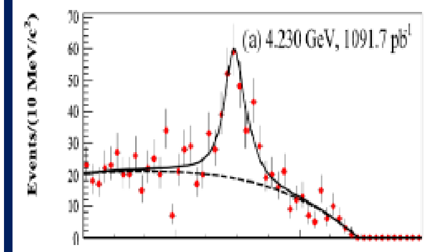
$Z_c(3900)^{\pm}$?

PRL 112 ('14)022001

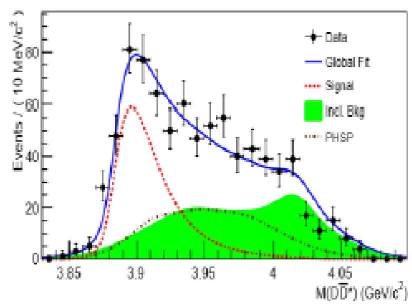
PRD92 ('15) 092006

$J^P = 1^+$

PRL 115 ('15)112003



$e^+e^- \to \pi^0 \pi^0 J/\psi$

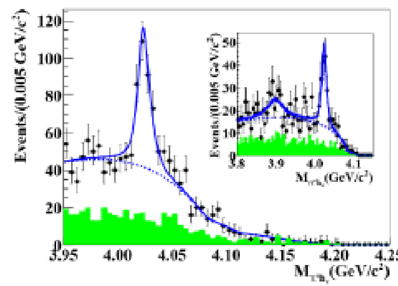


$e^+e^- \to \pi^0 (D\bar{D}^*)^0$

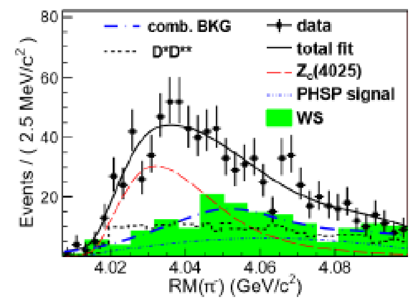
$Z_c(3900)^0$?

PRL115 ('15) 222002

PRL111 ('13)242001



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

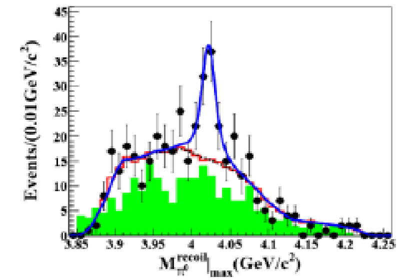


$e^+e^- \to \pi^+ (D^*\bar{D}^*)^-$

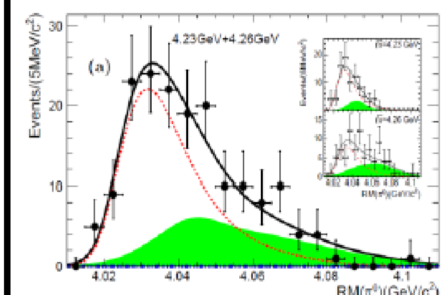
$Z_c(4020)^{\pm}$?

PRL112 ('14)132001

PRL 113 ('14)212002



$e^+e^- \to \pi^0 \pi^0 h_c$



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

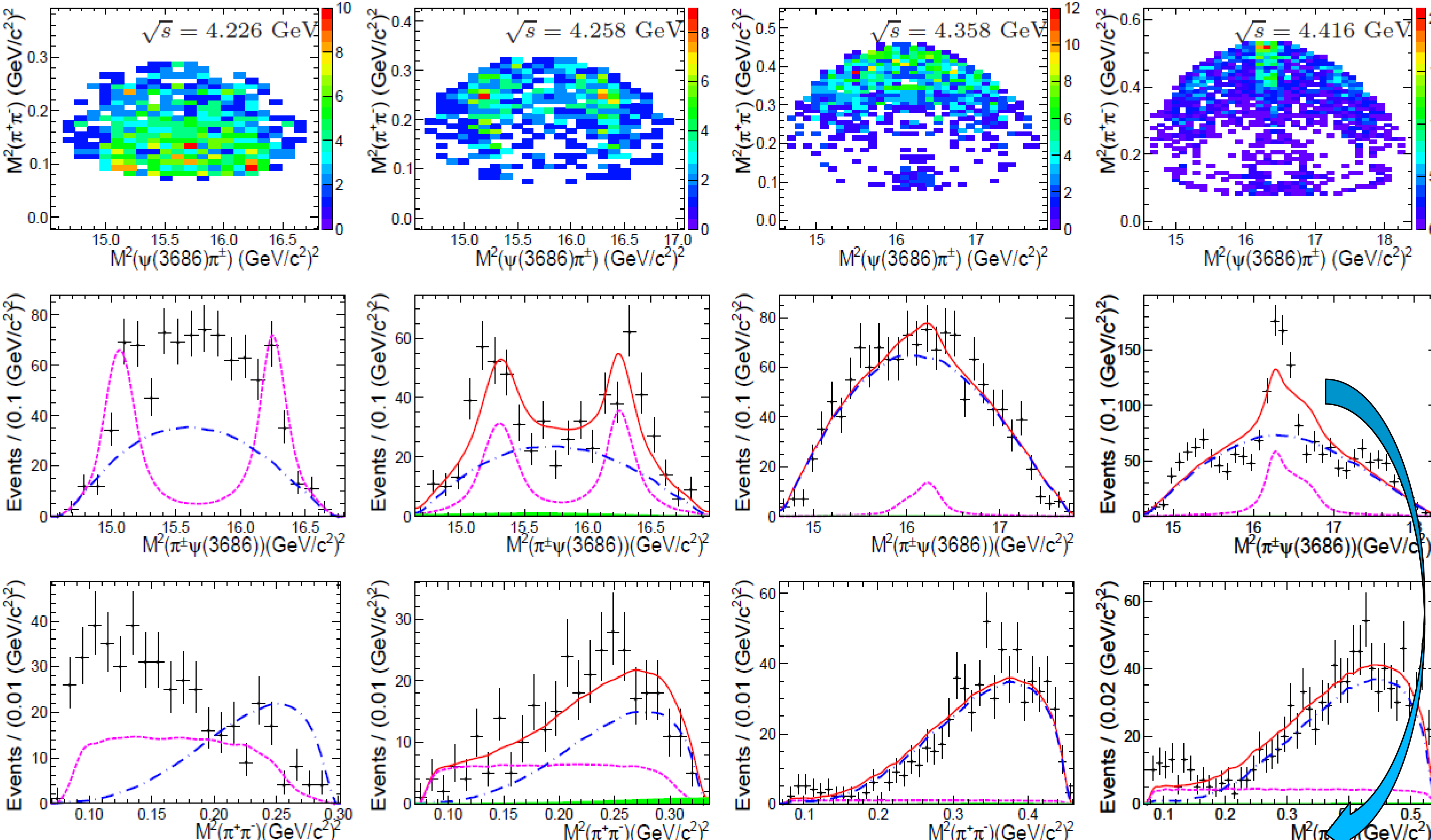
$Z_c(4020)^0$?

PRL115 (2015)182002

Search for $Zc(3900)^{\pm} \to \omega\pi^{\pm}$ PRD92 ('15) 032009

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

arXiv:1703.08787



Zc? $M=4032.1\pm2.4$ MeV/c^2
$\Gamma=26.1\pm5.3$ MeV

Summary XYZ

New structures:
Zc
Yc

Transitions:

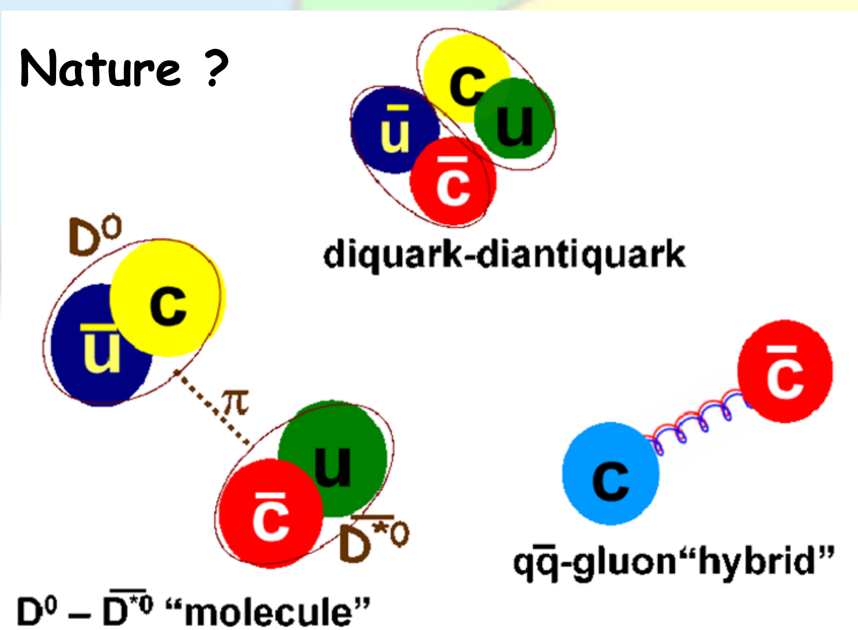
Y(4260)

$\pi^{\mp}$ → $Z_c^{\pm}(3900)$

γ → X(3872)

Perspectives: BESIII more data
BelleII

Bottomonium-like structures ->
BelleII,LHCb

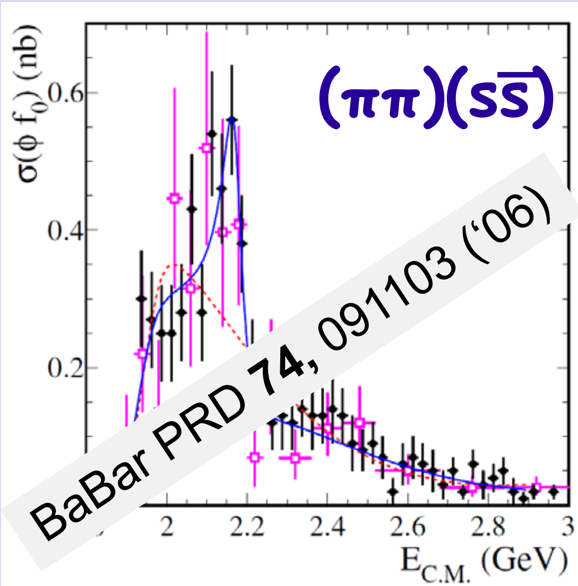


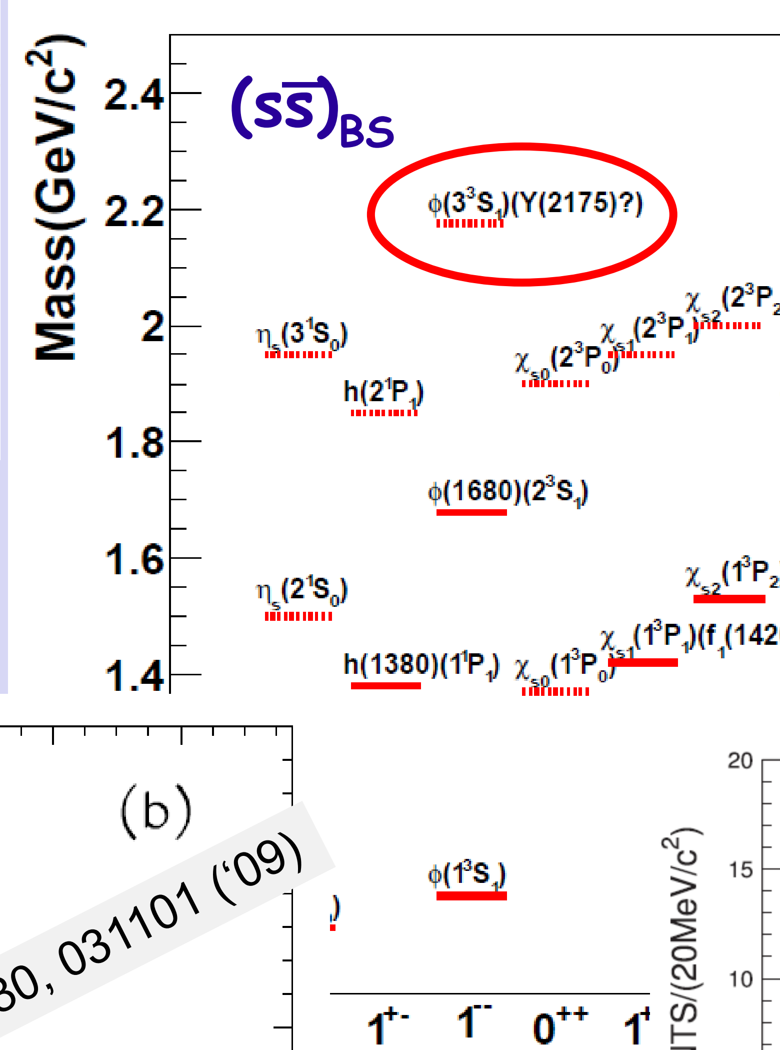
Picture: S.Godfrey, S.L.Olsen Ann.Rev.Part.Sci. 58,51

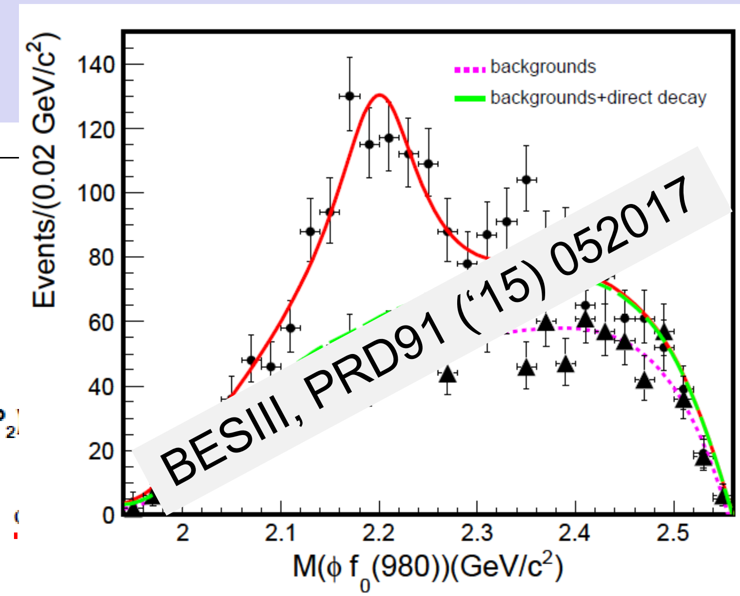
http://www.wired.com/2014/09/tetraquark-quantum-feud/

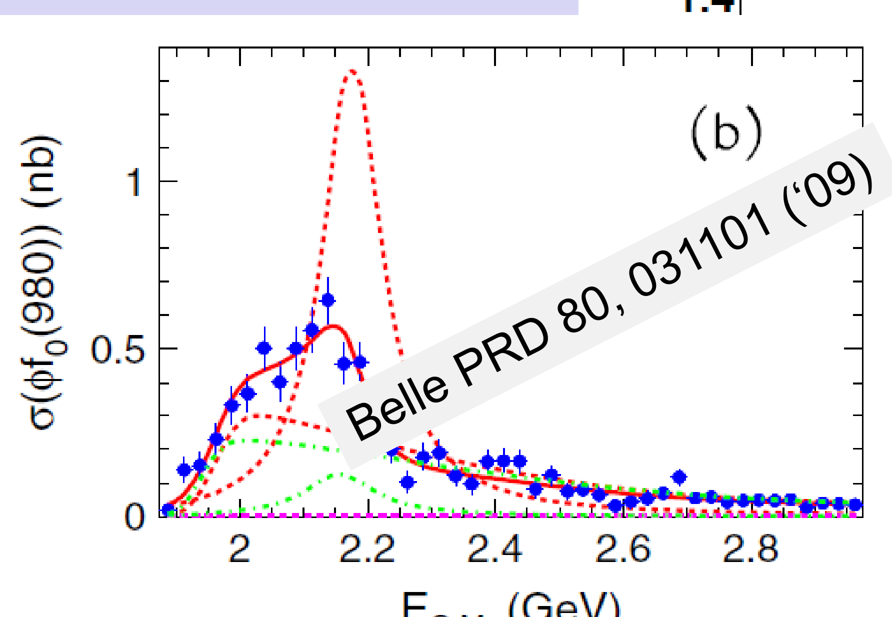
What about strangeonium system?...

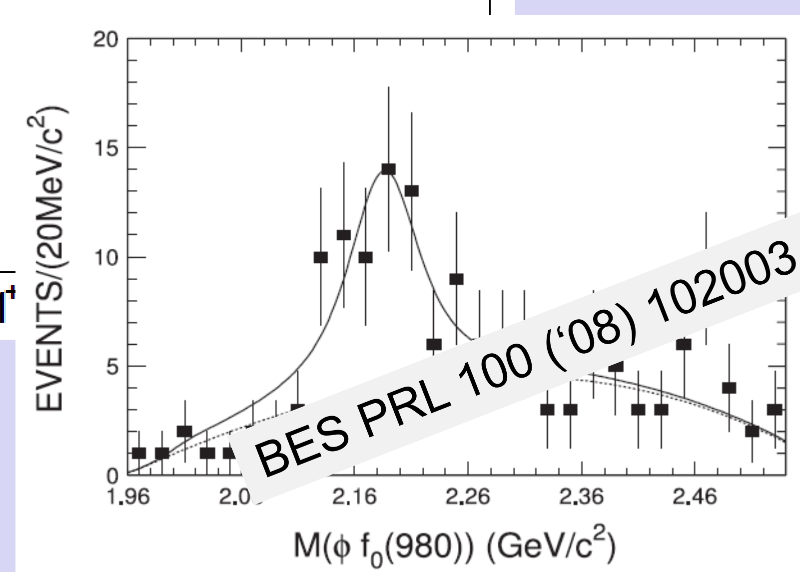
Y(2175) / φ(2170)









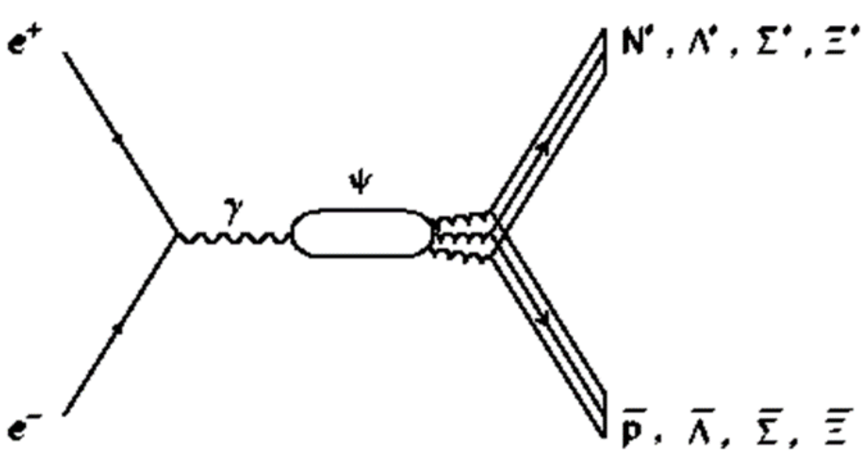


e+e- ->J/ψ-> hyperon anti-hyperon

Use spin entanglement and polarization to extract hyperon decay parameters and test CP for baryons

Revise assumption that hyperons from decays are unpolarized

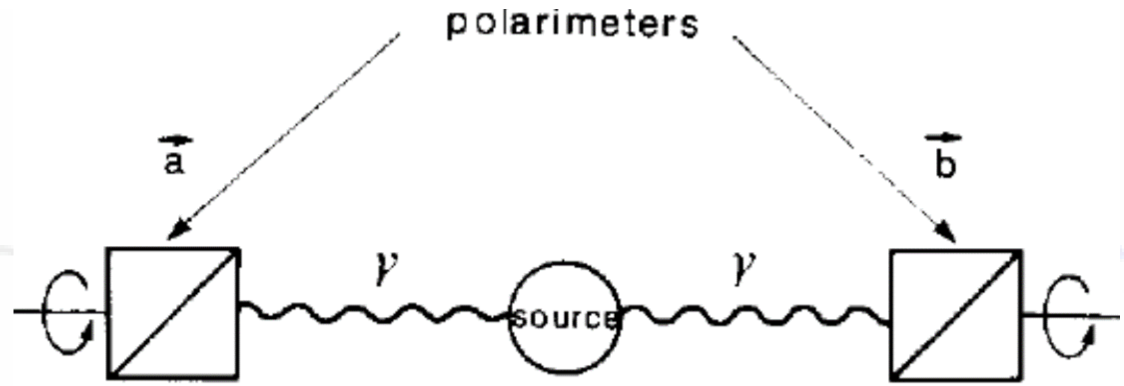
Göran Fäldt, AK arXiv:1702.07288

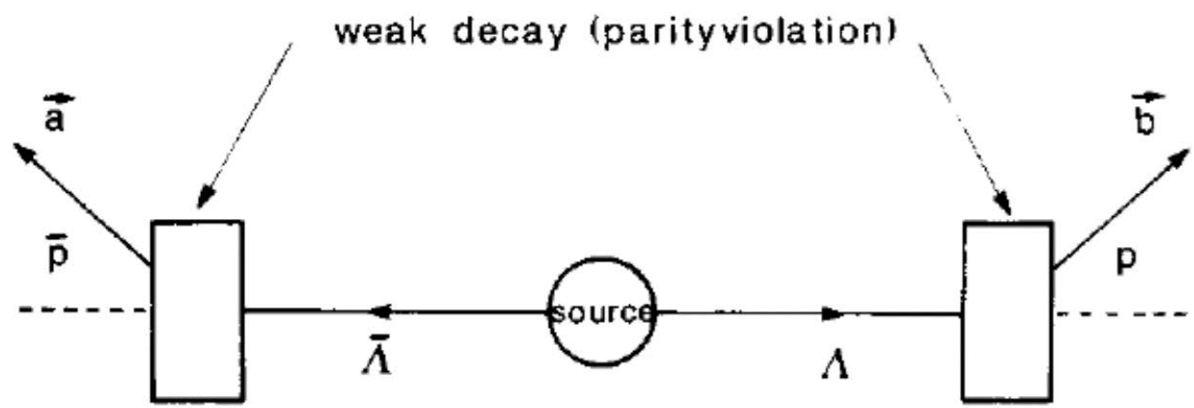


Foundations of Physics, Vol. 11, Nos. 1/2, 1981

Suggestion for Einstein–Podolsky–Rosen Experiments Using Reactions Like $e^+e^- \to \Lambda\bar{\Lambda} \to \pi^- p \pi^+ \bar{p}$

Nils A. Törnqvist[1]





THE DECAY $J/\psi \to \Lambda\bar{\Lambda} \to \pi^- p \pi^+ \bar{p}$ AS AN EINSTEIN–PODOLSKY–ROSEN EXPERIMENT

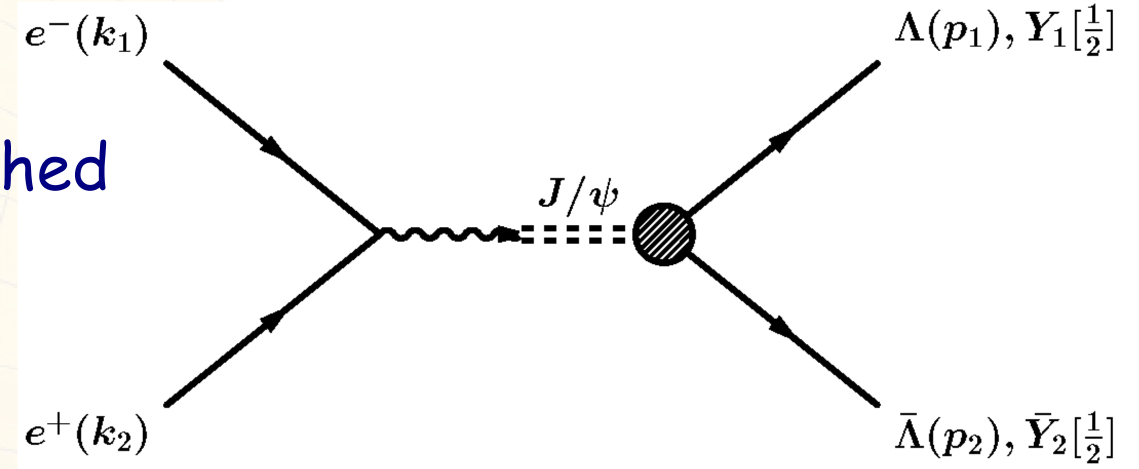
Nils A. TÖRNQVIST

Physics Letters A117(1986)1

Background picture: R. Bertlmann

Formalism for $e^+e^- \to \gamma^* \to J/\psi \to Y\bar{Y}$

Special case of a well established formalism for baryon FFs



Göran Fäldt (Uppsala U.),
EPJ A51 (2015) 74; EPJ A52 (2016)141
Göran Fäldt, AK arXiv:1702.07288

$$\Gamma_\mu^\Lambda(p_1, p_2) = -ie_g\left[G_M^\psi \gamma_\mu - \frac{2M}{Q^2}(G_M^\psi - G_E^\psi)Q_\mu\right]$$

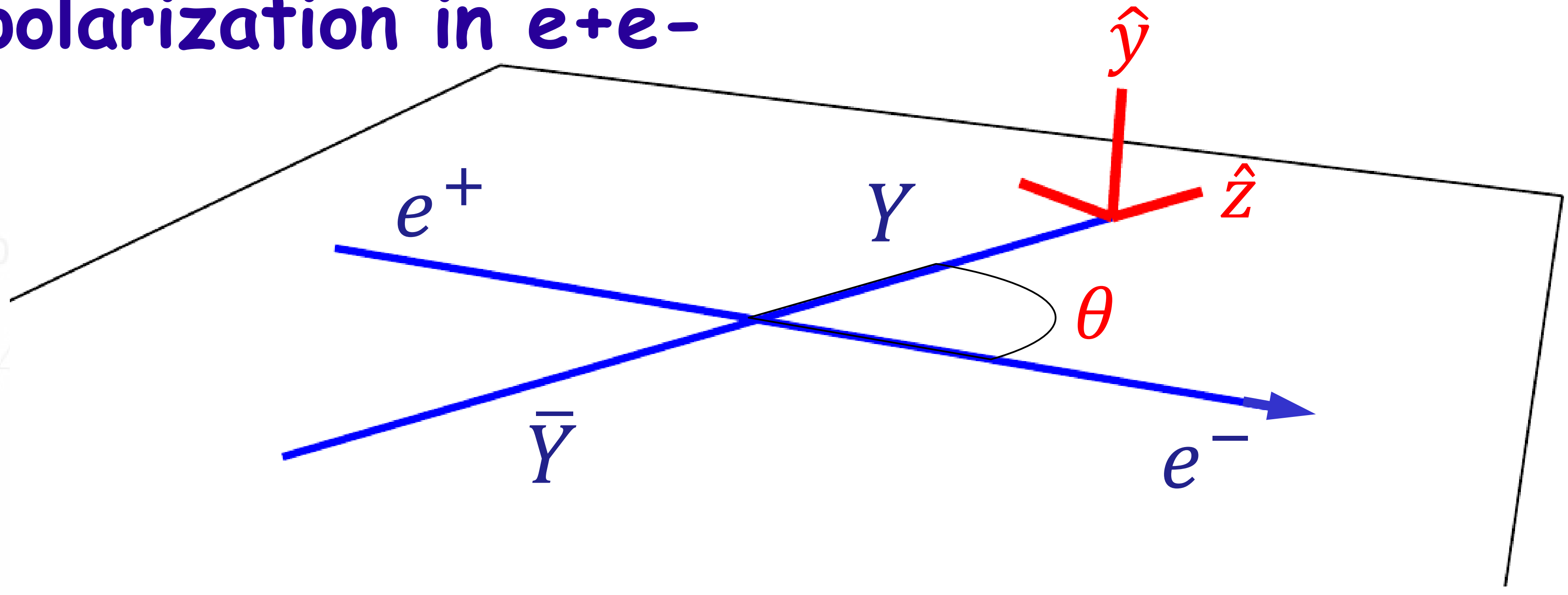
$$Q = p_1 - p_2$$

form factors: G_M^ψ and G_E^ψ

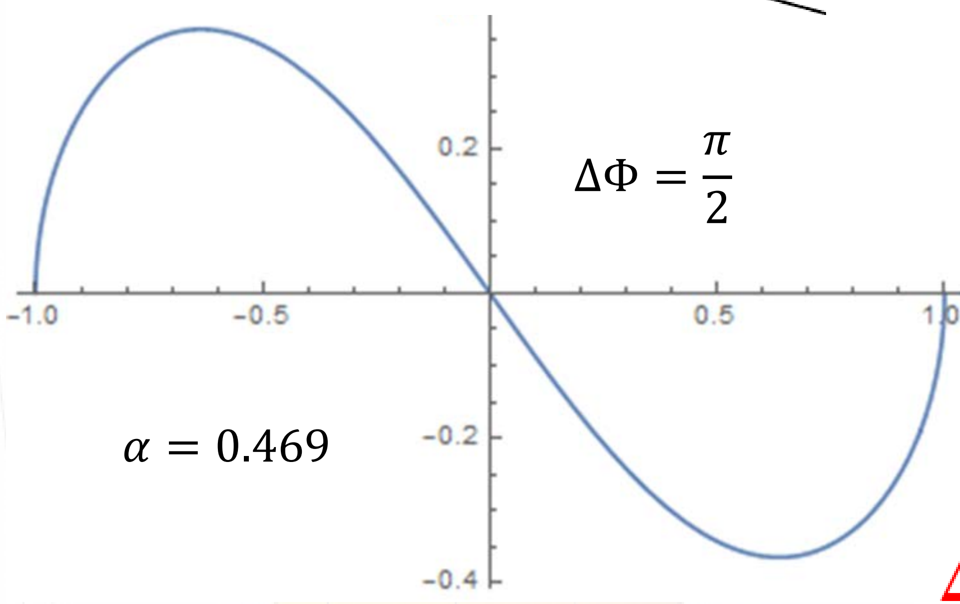
$$G_E^\psi = \frac{\sqrt{s}}{2M_\Lambda}\sqrt{\frac{1-\alpha_\psi}{1+\alpha_\psi}}\, e^{i\Delta\Phi}\, G_M^\psi$$

$$\frac{d\Gamma}{d\Omega} \propto 1 + \alpha_\psi \cos^2\theta \qquad -1 < \alpha_\psi < 1$$

Y polarization in e+e-



$$\mathbf{P}_Y(\theta) = \frac{\sqrt{1-\alpha_\psi{}^2}\cos\theta\sin\theta}{1+\alpha_\psi\cos^2\theta}\sin(\Delta\Phi)\,\hat{\mathbf{y}}$$



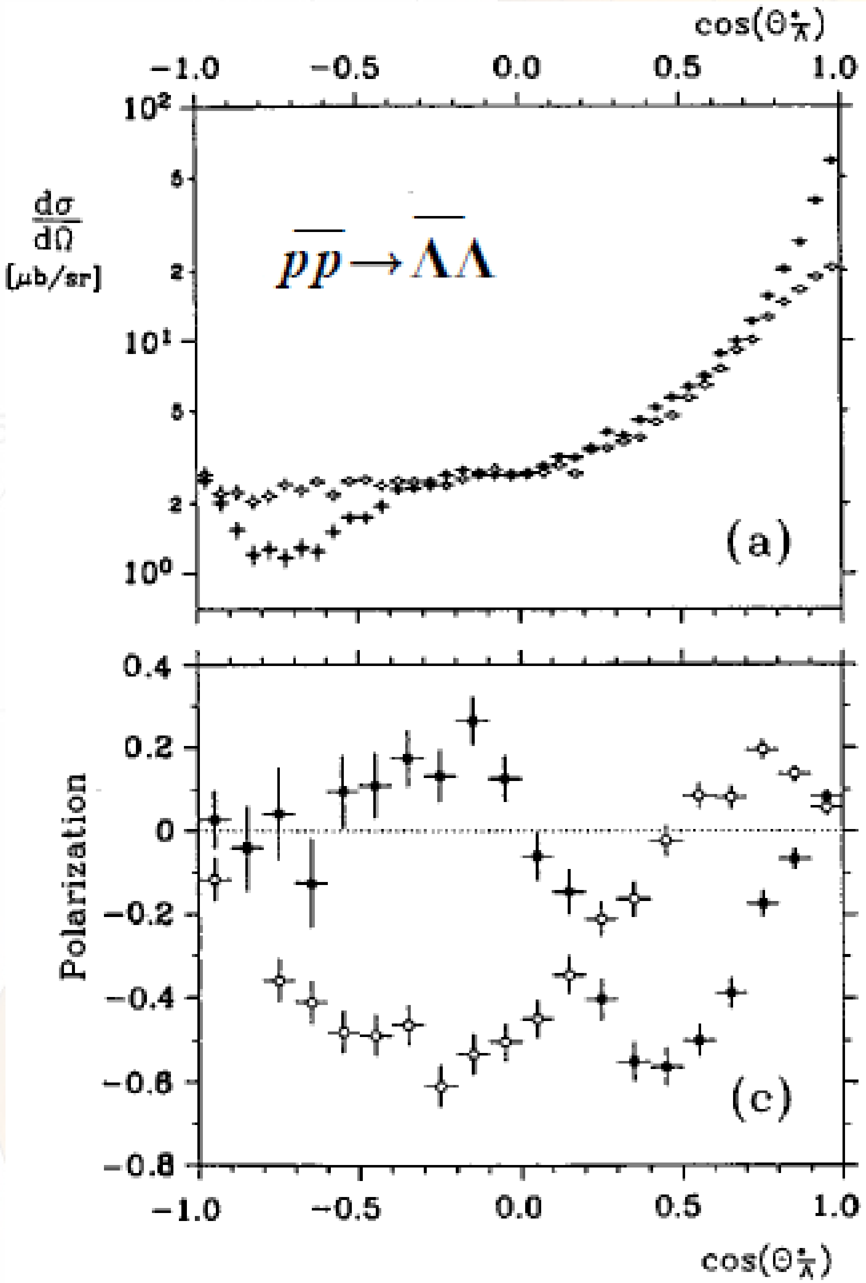
$$\boldsymbol{P}_Y(\theta) = -\boldsymbol{P}_Y(\pi-\theta) = -\boldsymbol{P}_{\bar{Y}}(\theta)$$

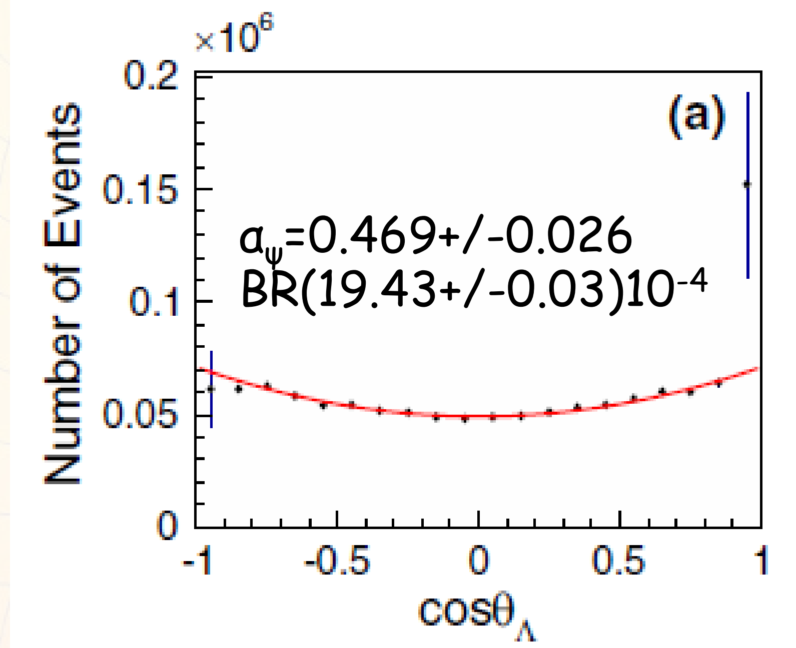
$$\boldsymbol{P}_Y(0) = \boldsymbol{P}_Y(\pi/2) = \boldsymbol{P}_Y(\pi) = \mathbf{0}$$

$$\langle \boldsymbol{P}_Y(\theta) \rangle = \mathbf{0}$$

$$\Delta\Phi \neq 0 \;\Rightarrow\; \boldsymbol{P}_Y(\theta) \neq 0\;!$$

$$e^+e^- \rightarrow \gamma^* \rightarrow J/\psi \rightarrow \Lambda\bar{\Lambda}$$





$J/\psi \rightarrow \Lambda\bar{\Lambda}$ $\quad 440,675 \pm 670$

PS185, PRC54 (1996) 1877

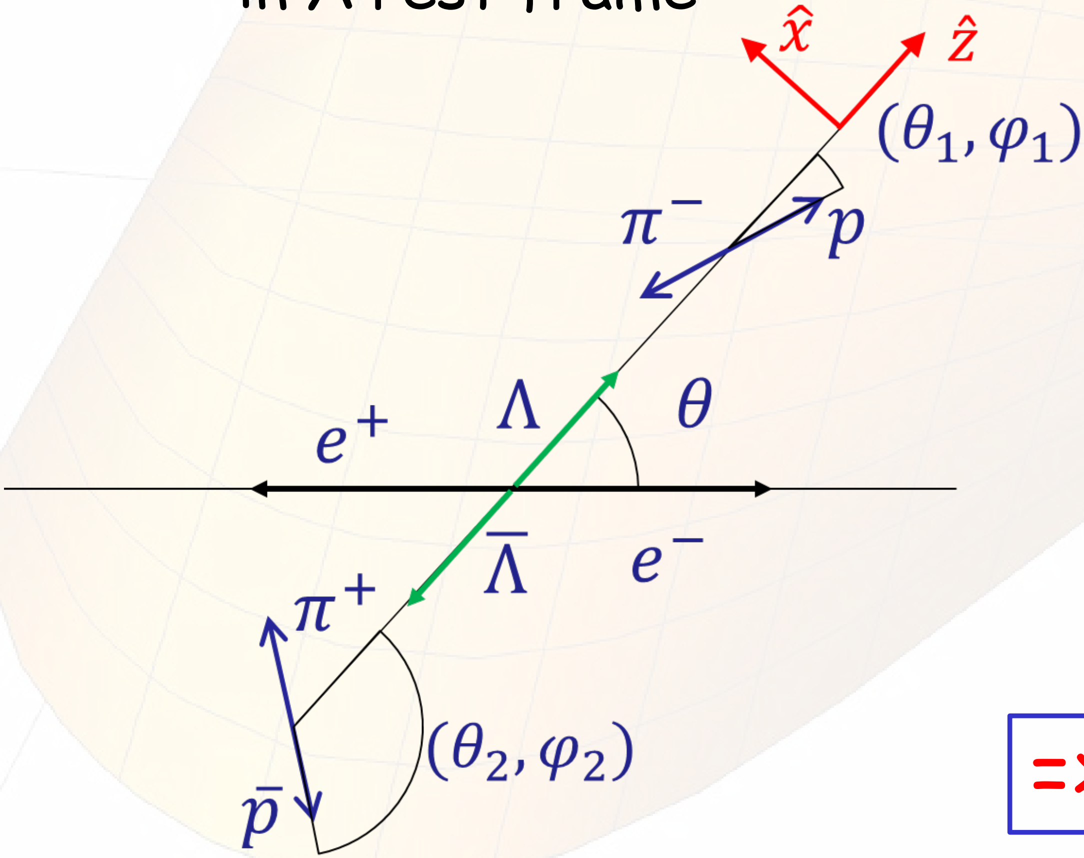
BESIII,Phys. Rev. D 95, 052003 (2017)

Single tag decay distributions

$$\frac{d\Gamma}{d\cos\theta d\Omega_1} \propto \left(1 + \alpha_\psi \cos^2\theta\right) \{1 + \alpha_1 P_\Lambda(\theta) \sin\theta_1 \sin\phi_1\}$$

$\Lambda \to p\pi^-$: $\Omega_1 = (\cos\theta_1, \phi_1)$ $\alpha_\Lambda = \alpha_1$

proton direction: spherical coord
in Λ rest frame



Use max log likelihood
to fit $\Gamma(\theta, \theta_1, \phi_1)$

=> α_ψ $\alpha_1 \sin(\Delta\Phi)$

Double tag decay distribution

$$e^+e^- \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+)$$

EPJ A52 (2016)141
arXiv:1702.07288

$$d\sigma \propto \mathcal{W}(\boldsymbol{\xi})\ d\cos\theta\ d\Omega_1 d\Omega_2$$

$\Lambda \to p\pi^-$: $\Omega_1 = (\cos\theta_1, \phi_1)$ $\qquad \alpha_\Lambda = \alpha_1$

$\bar{\Lambda} \to \bar{p}\pi^+$: $\Omega_2 = (\cos\theta_2, \phi_2)$ $\qquad \alpha_{\bar{\Lambda}} = \alpha_2$

ξ : $(\cos\theta, \Omega_1, \Omega_2)$

Spin correlations

$$\begin{aligned}\mathcal{W}(\boldsymbol{\xi}) = & 1 + \boldsymbol{\alpha_\psi} \cos^2\theta \\ & + \boldsymbol{\alpha_1\alpha_2}\left(\mathcal{T}_1(\boldsymbol{\xi}) + \sqrt{1-\boldsymbol{\alpha_\psi}^2}\cos(\boldsymbol{\Delta\Phi})\mathcal{T}_2(\boldsymbol{\xi}) + \boldsymbol{\alpha_\psi}\mathcal{T}_6(\boldsymbol{\xi})\right) \\ & + \sqrt{1-\boldsymbol{\alpha_\psi}^2}\sin(\boldsymbol{\Delta\Phi})\ \sin\theta\cos\theta\,(\boldsymbol{\alpha_1}\sin\theta_1\sin\phi_1 + \boldsymbol{\alpha_2}\sin\theta_2\sin\phi_2)\end{aligned}$$

Background picture: R. Bertlmann

LOOKING AT *CP* INVARIANCE AND QUANTUM MECHANICS IN $J/\psi \to \Lambda\bar{\Lambda}$ DECAY

DM2 Coll. (1988) Phys. Lett. B 212, 523

$$\mathcal{W}^{\mathcal{B}}(\xi) = 1 + \alpha_\psi \mathcal{G}_1(\xi) + \alpha_1\alpha_2\, \mathcal{G}_2(\xi) + \alpha_\psi\alpha_1\alpha_2\, \mathcal{G}_3(\xi)$$

BES, Phys.Rev. D81 (2010) 012003

$$A = \frac{\alpha_1 + \alpha_2}{\alpha_1 - \alpha_2}\left[= \frac{\alpha_\Lambda + \alpha_{\bar{\Lambda}}}{\alpha_\Lambda - \alpha_{\bar{\Lambda}}}\right]$$

	$\alpha_{\bar{\Lambda}}(\bar{\Lambda} \to \bar{p}\pi^+)$	A
DM2	-0.63 ± 0.13	0.01 ± 0.10
BES	$-0.755 \pm 0.083 \pm 0.063$	$-0.081 \pm 0.055 \pm 0.059$

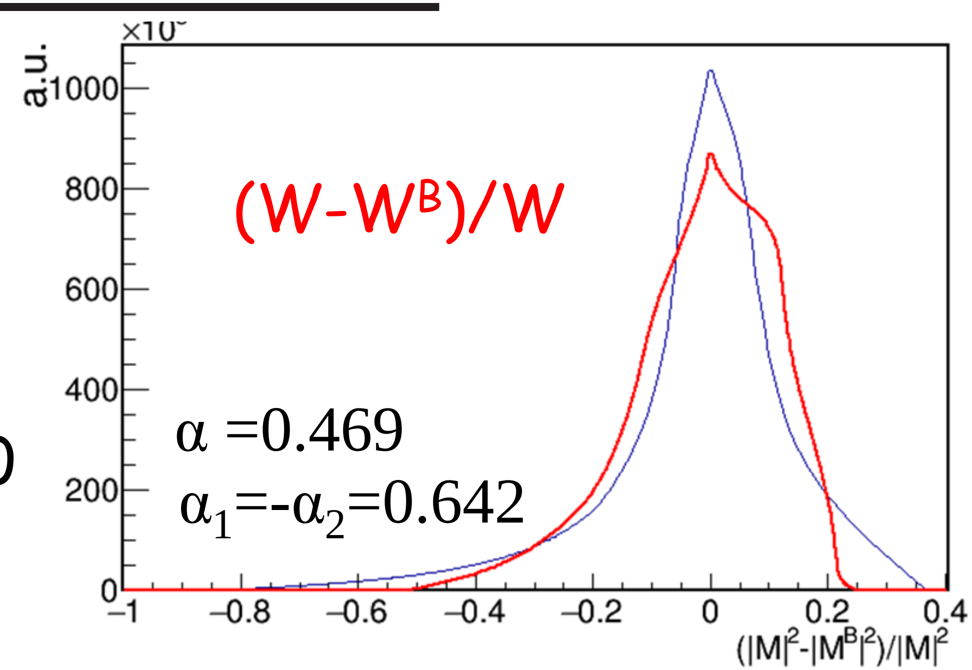
1847 $\Lambda\bar{\Lambda}$

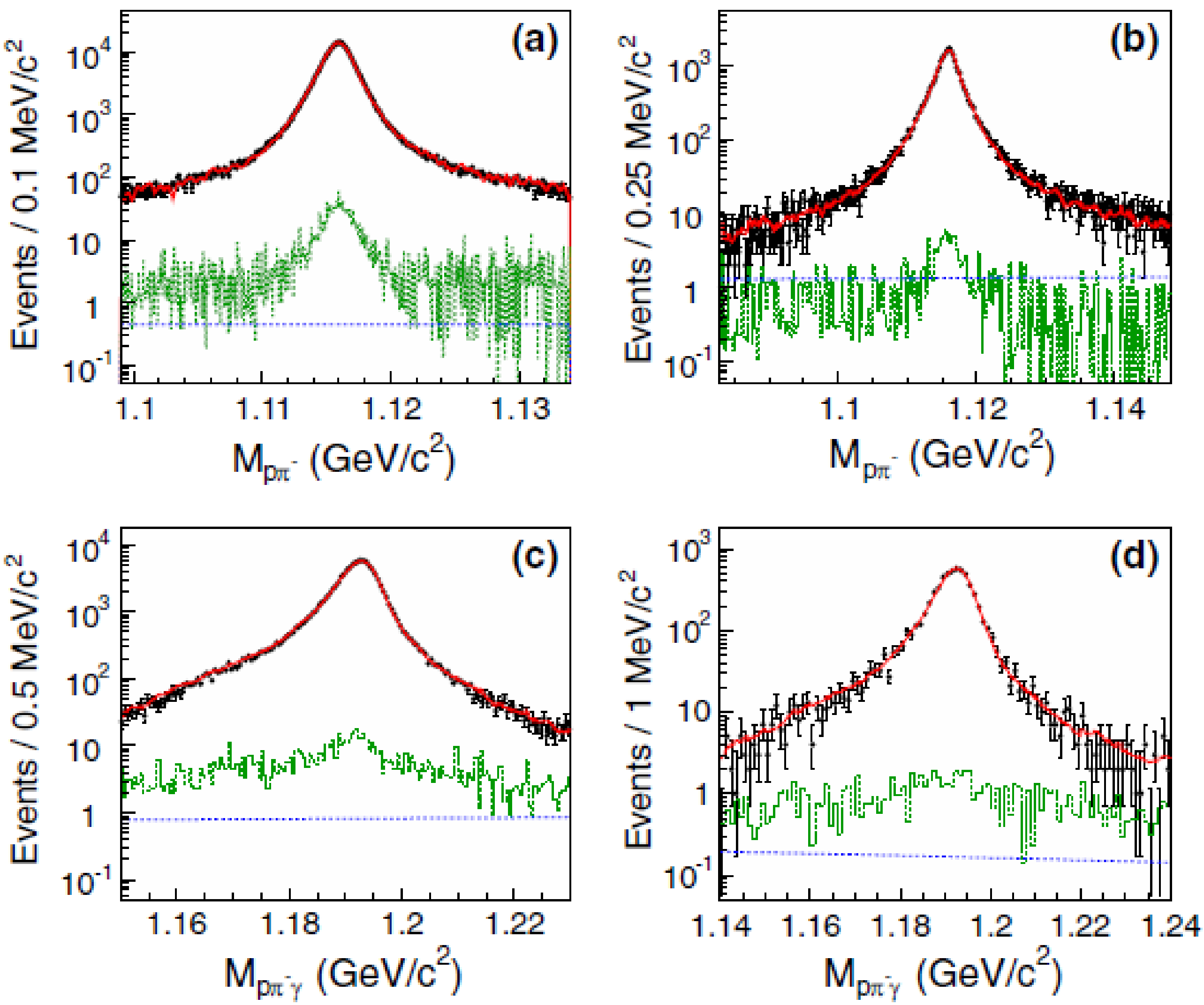
8997 events

$$\alpha_\Lambda = 0.642 \pm 0.013$$ PDG

- Only two parameters:

  $\alpha_\psi \quad \alpha_1 \cdot \alpha_2$
- Λ unpolarized
- W^B and W differs even for $\Delta\Phi$=0





Channel	N_{obs}
$J/\psi \to \Lambda\bar{\Lambda}$	$440,675 \pm 670$
$J/\psi \to \Sigma^0\bar{\Sigma}^0$	$111,026 \pm 335$
$\psi(3686) \to \Lambda\bar{\Lambda}$	$31,119 \pm 187$
$\psi(3686) \to \Sigma^0\bar{\Sigma}^0$	$6,612 \pm 82$

Determine $\Delta\Phi$ for each decay

for Σ^0

Λ polarized longitunally

$P_\Lambda = (P_\Sigma) \cos\theta_{\Sigma\Lambda}$

Phys. Rev. D 95, 052003 (2017)
arXiv:1701.07191

Conclusions/outlook (hyperon decays)

Well established general formulas for
$e^+e^- \to \gamma^* \to B_{1/2}\ \bar{B}_{1/2}$ are applied to J/ψ and ψ(2S)

Access to decay parameters even using single tag mode
if corresponding ΔΦ≠0.

Charmonia: determine ΔΦ for J/ψ and ψ(2S) $Y\bar{Y}$ decays

Charm: Single tag mode for Λc decay parameters (if ΔΦ≠0...)

- Λc decays $N(e^+e^- \to \Lambda_c \bar{\Lambda}_c) = (105.9 \pm 4.8 \pm 0.5) \times 10^3$

Summary

- BESIII: best place to study charmonium like XYZ states:
  Zc(3900,4020) isospin triplets
  complicated spectrum of Yc states, transitions
  … more questions than answers (->XYZ scan at BESIII)

- Light hadron spectroscopy (high statistics and low background), complementary to hadro- and photoproduction experiments $1.3 \cdot 10^9$ J/ψ -> 10^{10} J/ψ

- Many unexplored, interesting topics …