XYZ

Exotic states in the charmonium and bottomonium mass regions

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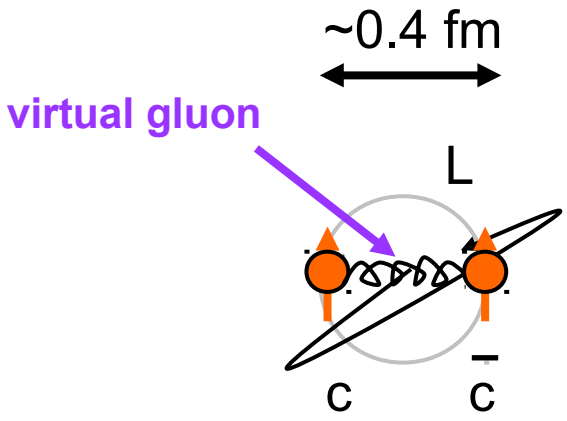
Justus-Liebig-Universität Gießen
Seminar, HISKP, Bonn, 19.12.2014

arXiv:1311.7594 [hep-ex]
arXiv:1208.6128 [hep-ex]
arXiv:1109.1699 [hep-ex]
arXiv:1010.2331 [hep-ex]

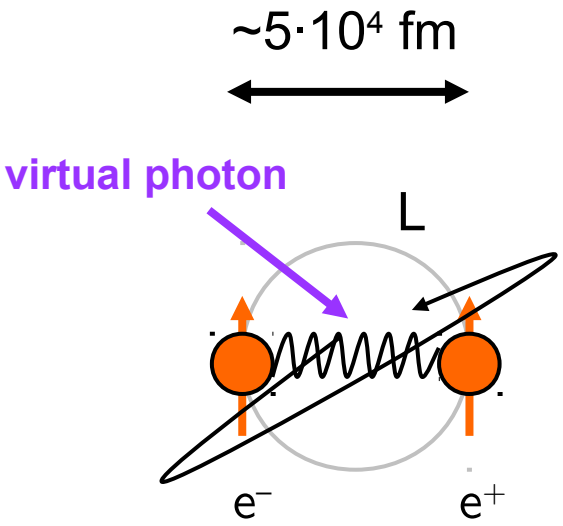
OUTLINE

- Potential model of charmonium and bottomonium
- Experiments: Belle, BaBar, BESIII
- Charmonium(-like) states
  - → X(3872)
  - → Y(4260)
  - → $Z_c^{\pm}$ (3900)
- Bottomonium(-like) states
  - → $Z_b^{\pm}$
- New 2014: neutral Z_b, Z_c
- Future experiments: Belle II, $\overline{\text{P}}$ANDA

Charmonium vs. Positronium



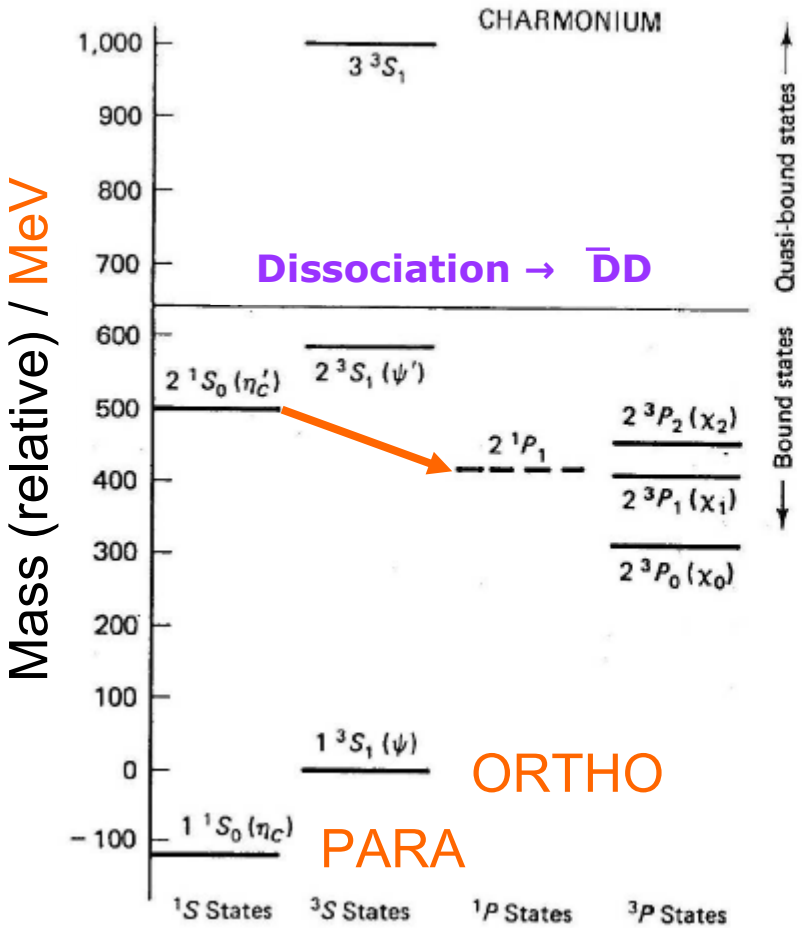
Charmonium

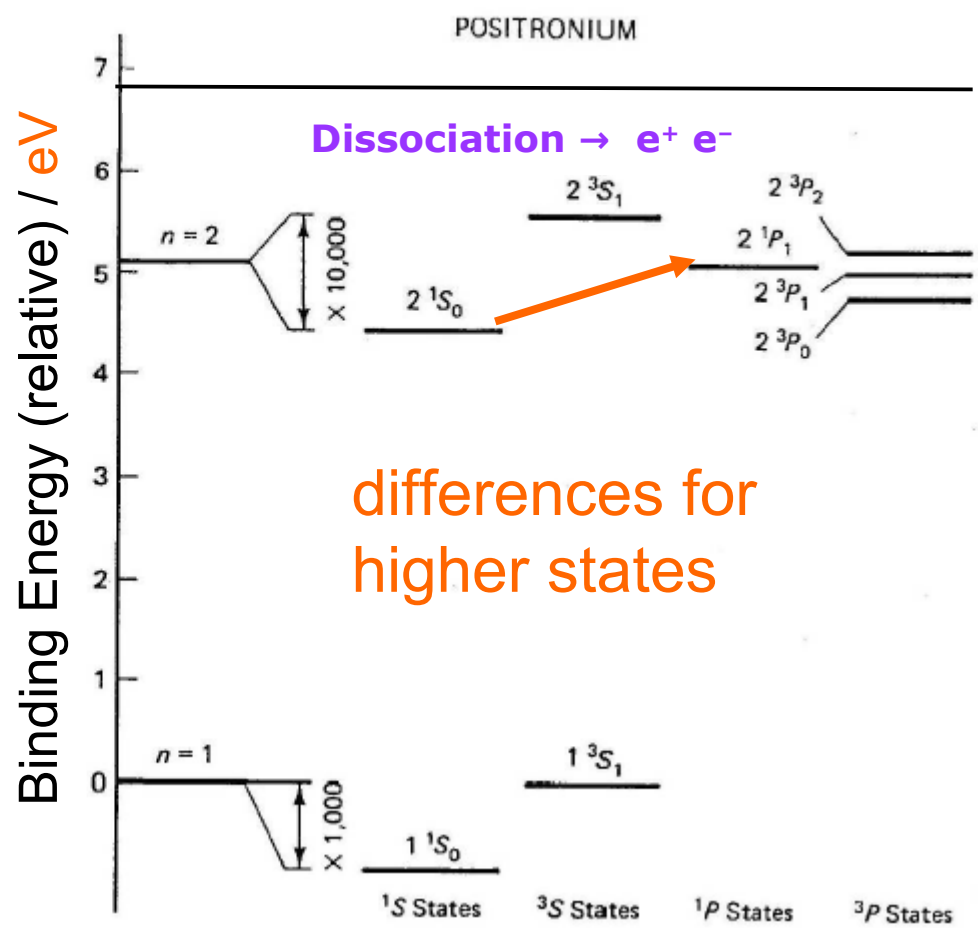


Positronium

Charmonium vs. Positronium

Decays to light quarks suppressed
→ narrow widths





Static Quark-Antiquark Potential

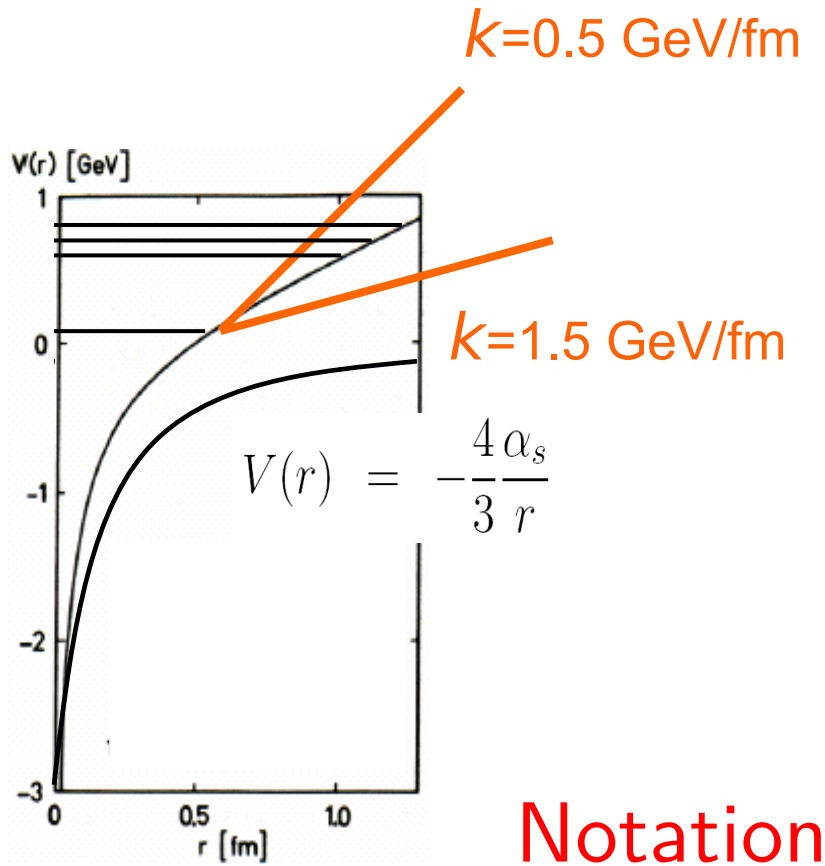
- Coulomb-Potential
  + Confinement-Term

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \boxed{kr}$$

spin-spin $$+\frac{32\pi\alpha_s}{9m_c^2}\delta_r\vec{S}_c\vec{S}_{\bar{c}}$$

spin-orbit $$+\frac{1}{m_c^2}\left(\frac{2\alpha_s}{r^3} - \frac{k}{2r}\right)\vec{L}\vec{S}$$

tensor $$+\frac{1}{m_c^2}\frac{4\alpha_s}{r^3}\left(\frac{3\vec{S}_c\vec{r}\cdot\vec{S}_{\bar{c}}\vec{r}}{r^2} - \vec{S}_c\vec{S}_{\bar{c}}\right)$$



- solve Schrödinger equation
  (quark mass heavy → non-relativistic)
  → states

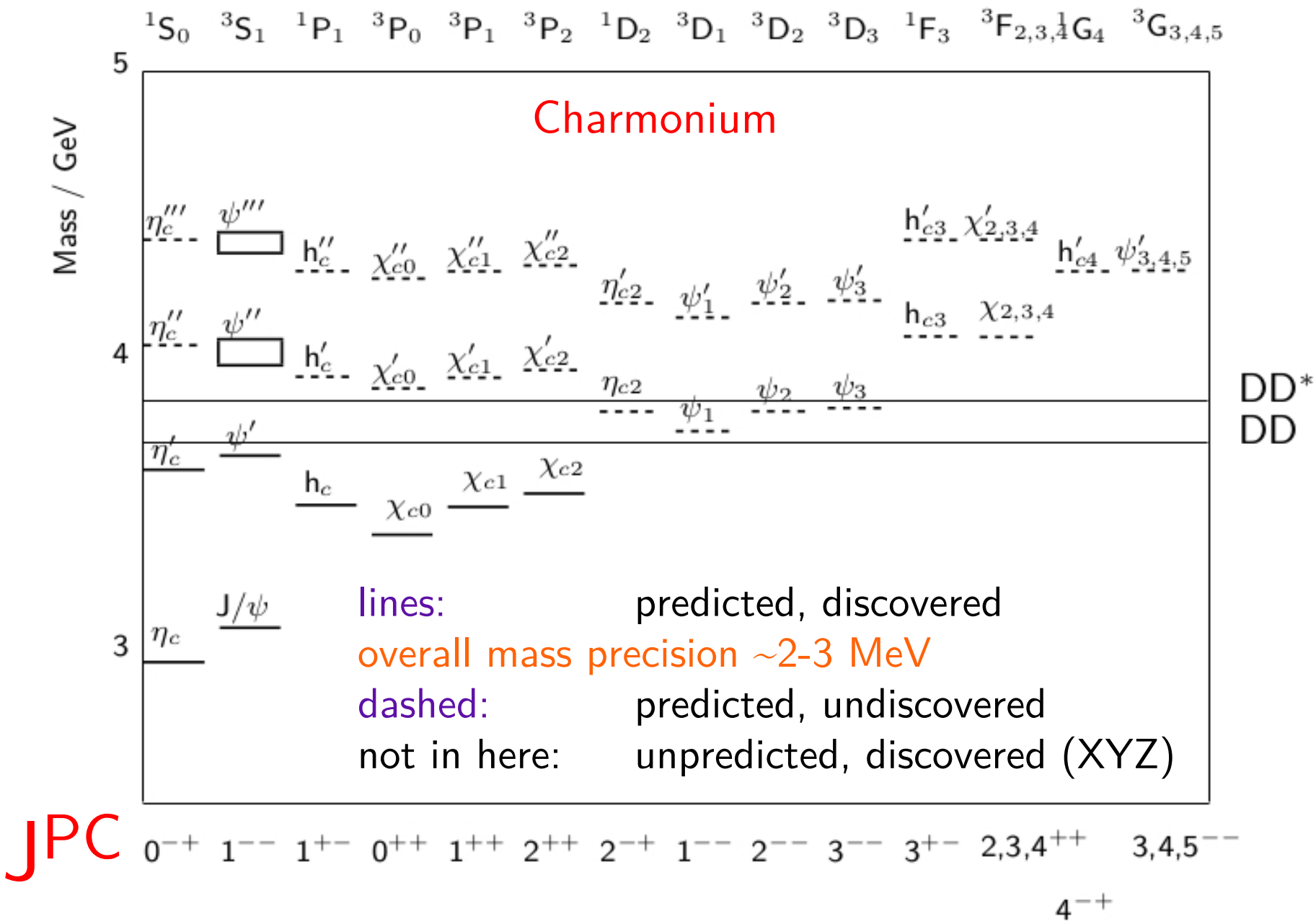
$$\Psi(r,\theta,\phi) = R_{nl}(r)Y_{lm}(\theta,\phi)$$

$$\left[-\frac{1}{m_q}\left(\frac{\partial^2}{\partial r^2} + \frac{2}{r}\frac{\partial}{\partial r} + \frac{l(l+1)}{m_q r^2} + V(r)\right)\right]R_{nl}(r) = E_{nl}R_{nl}(r)$$

Notation

$n^{2S+1}L_J$

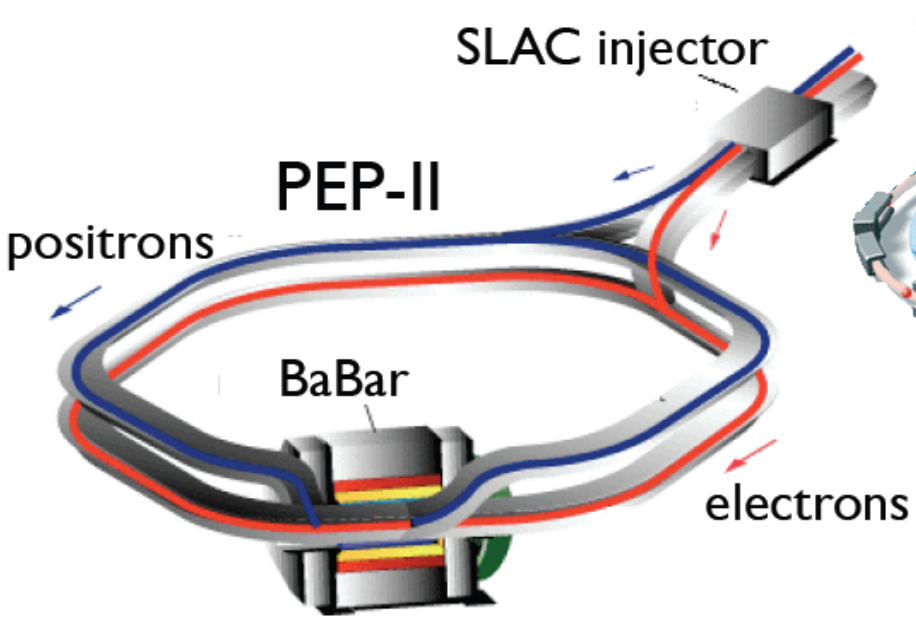
J^{PC}


Charmonium
Mass / GeV
5
4
3
$^1S_0$ $^3S_1$ $^1P_1$ $^3P_0$ $^3P_1$ $^3P_2$ $^1D_2$ $^3D_1$ $^3D_2$ $^3D_3$ $^1F_3$ $^3F_{2,3,4}$ $^1G_4$ $^3G_{3,4,5}$
η_c''' ψ''' h_c'' χ_{c0}'' χ_{c1}'' χ_{c2}'' η_{c2}' ψ_1' ψ_2' ψ_3' h_{c3}' $\chi_{2,3,4}'$ h_{c4}' $\psi_{3,4,5}'$
η_c'' ψ'' h_c' χ_{c0}' χ_{c1}' χ_{c2}' η_{c2} ψ_1 ψ_2 ψ_3 h_{c3} $\chi_{2,3,4}$
η_c' ψ' h_c χ_{c0} χ_{c1} χ_{c2}
η_c J/ψ
DD^*
DD
lines: predicted, discovered
overall mass precision ~2-3 MeV
dashed: predicted, undiscovered
not in here: unpredicted, discovered (XYZ)
JPC
0^{-+} 1^{--} 1^{+-} 0^{++} 1^{++} 2^{++} 2^{-+} 1^{--} 2^{--} 3^{--} 3^{+-} $2,3,4^{++}$ $3,4,5^{--}$
4^{-+}

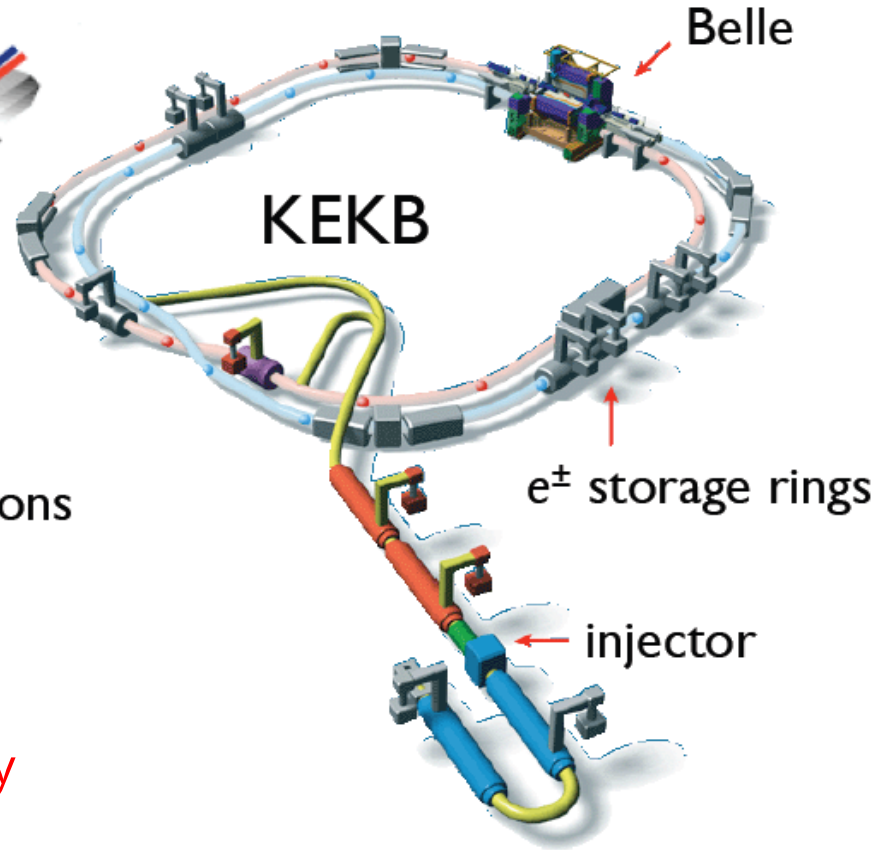
B Meson Factories

$$e^+e^- \to \Upsilon(4S) \to BB \ (\mathcal{B} \sim 99\%)$$

1999-2008

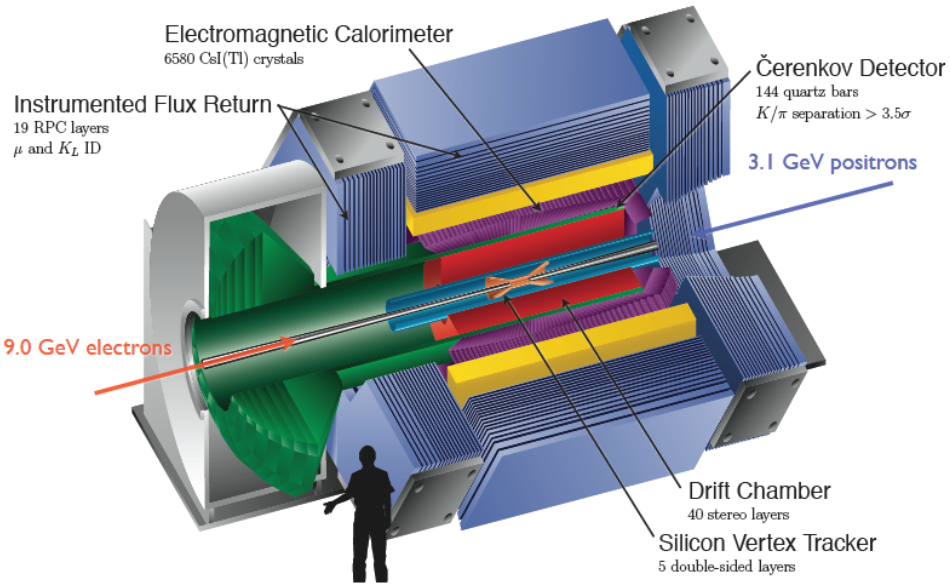


1999-2010



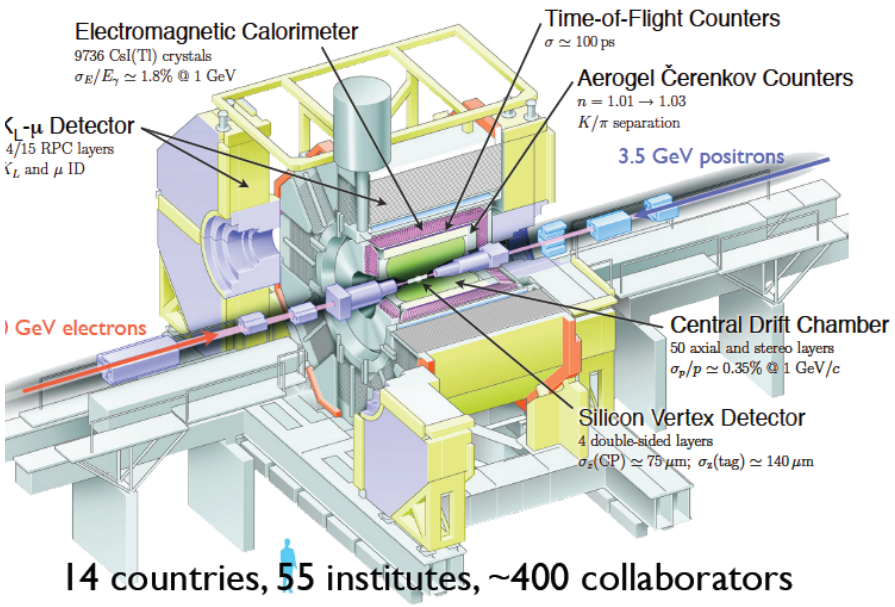
About 1 Million B mesons per day

BaBar at PEP-II



11 countries, 80 institutes, ~600 collaborators

Belle at KEKB



14 countries, 55 institutes, ~400 collaborators

~553 /fb
On-resonance samples:
Y(4S): 433 /fb
Y(3S): 30 /fb
Y(2S): 14 /fb
no Y(5S) data
Off-resonance: 54 /fb

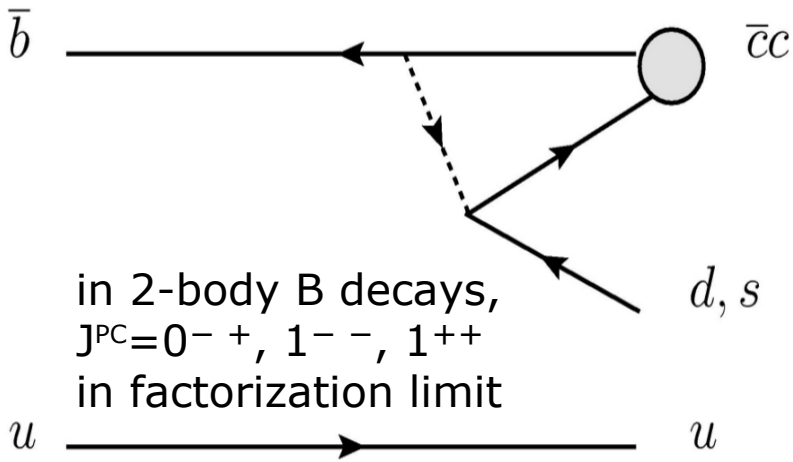
477M B meson decays

~952 /fb
On-resonance samples:
Y(4S): 711 /fb
Y(5S): 121 /fb
Y(3S): 3.0 /fb
Y(2S): 24 /fb
Y(1S): 5.7 /fb
Off-resonance: 87 /fb

772M B meson decays

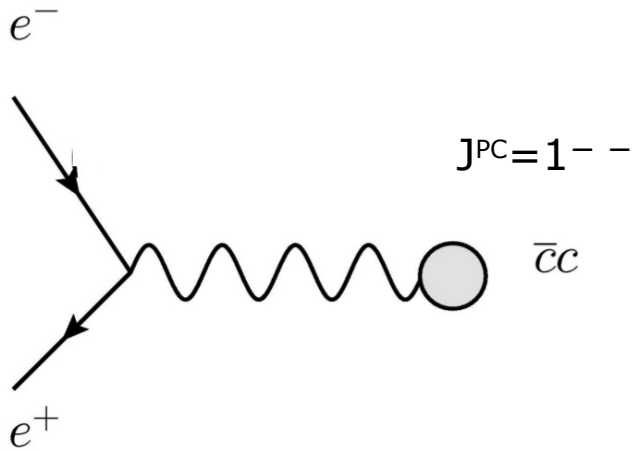
Charmonium Production

B Meson Decays

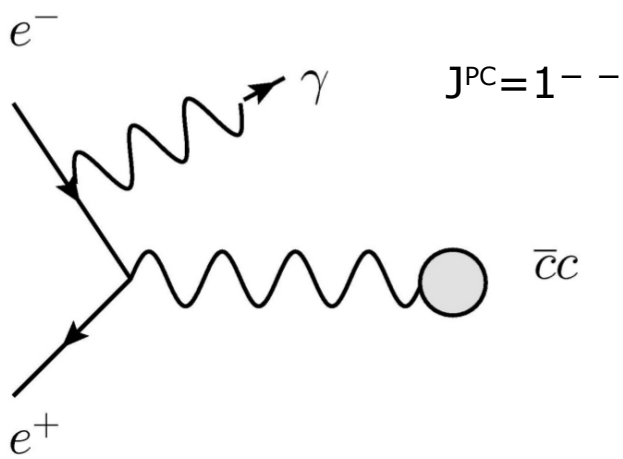


in 2-body B decays,
$J^{PC}=0^{-+}, 1^{--}, 1^{++}$
in factorization limit

Direct Production

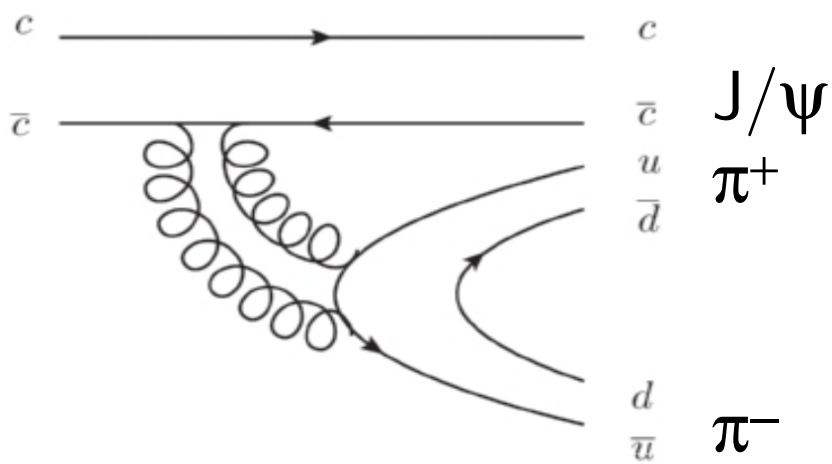


Initial State Radiation



X(3872)

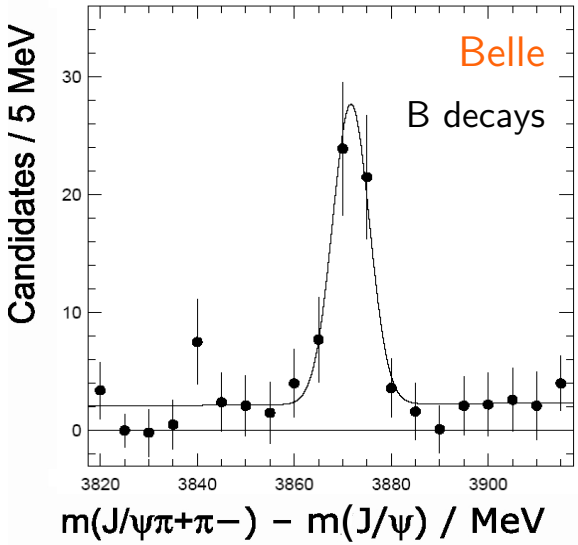
$$B^{\pm} \to K^{\pm} \underbrace{J/\psi\pi^{+}\pi^{-}}_{\text{resonant state?}}$$

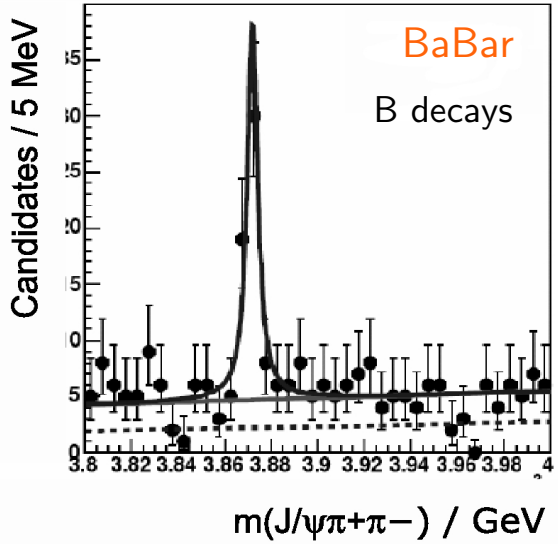


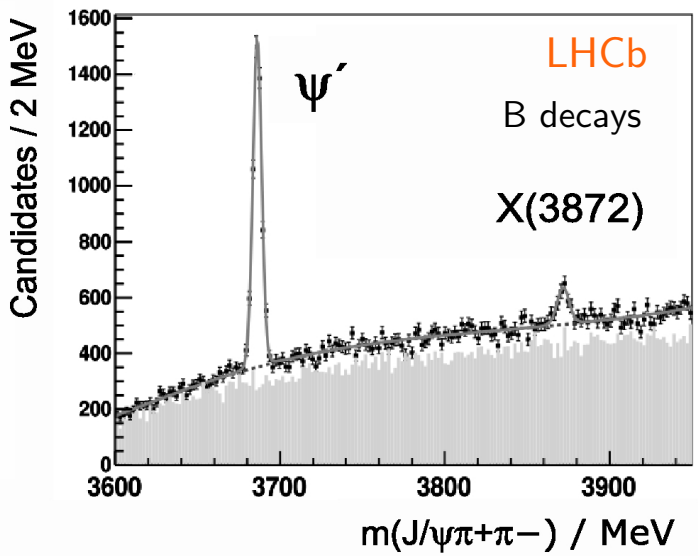
Product branching fraction small

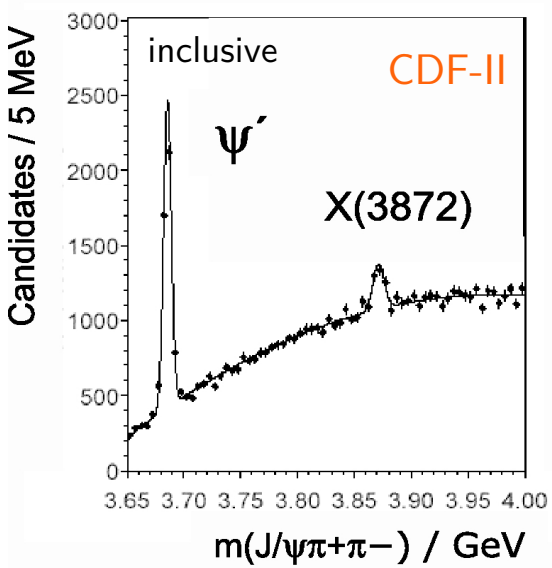
$\mathcal{B}(\text{B decay}) \times \mathcal{B}(\text{X decay}) = 10^{-5}$

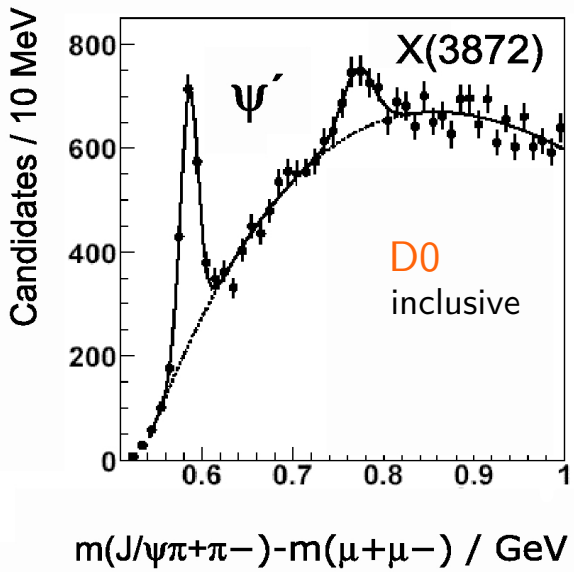
X(3872)

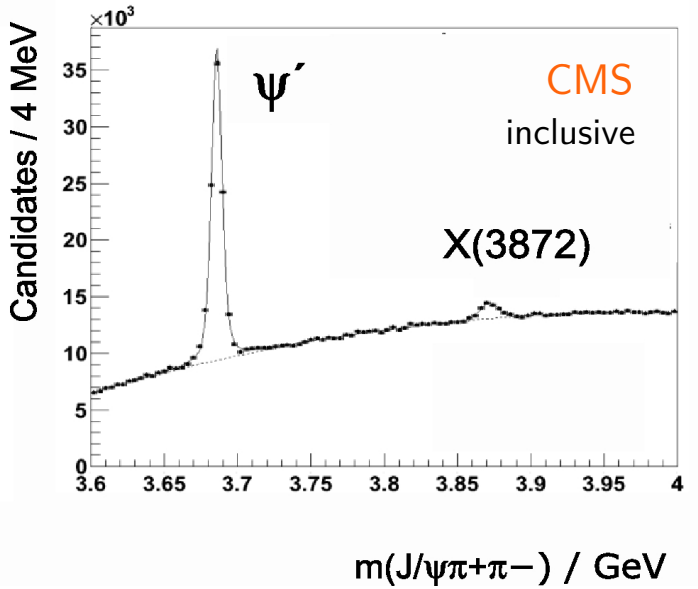

Belle
B decays
Candidates / 5 MeV
m(J/ψπ+π−) − m(J/ψ) / MeV


BaBar
B decays
Candidates / 5 MeV
m(J/ψπ+π−) / GeV


LHCb
B decays
ψ´
X(3872)
Candidates / 2 MeV
m(J/ψπ+π−) / MeV


inclusive
CDF-II
ψ´
X(3872)
Candidates / 5 MeV
m(J/ψπ+π−) / GeV


X(3872)
ψ´
D0
inclusive
Candidates / 10 MeV
m(J/ψπ+π−)-m(μ+μ−) / GeV

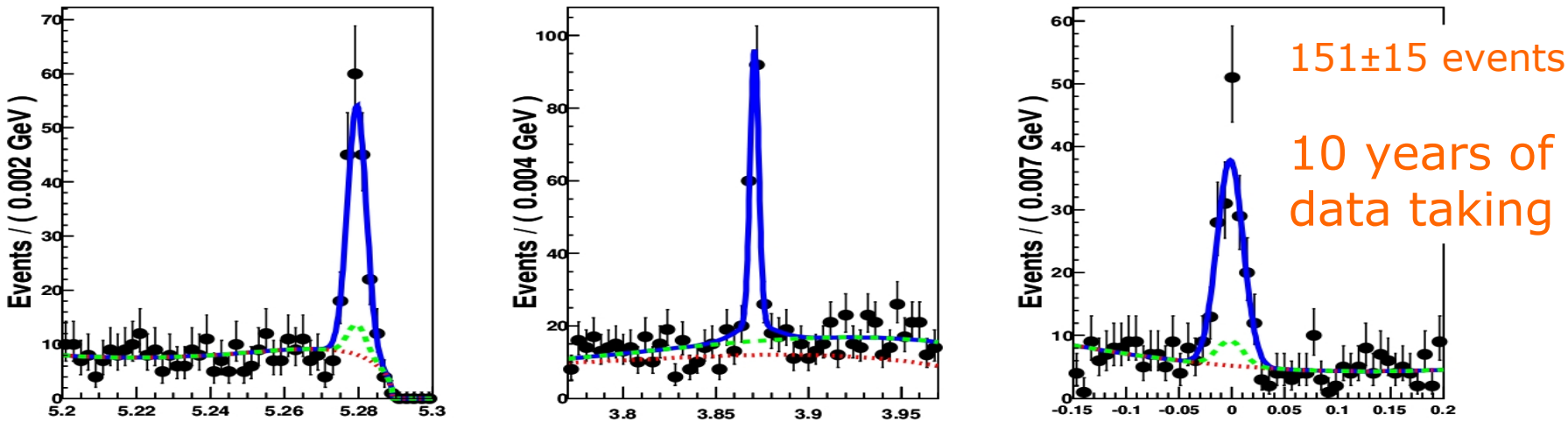

ψ´
CMS
inclusive
X(3872)
Candidates / 4 MeV
m(J/ψπ+π−) / GeV

X(3872) → J/ψ π+π−

$$m_{bc} = \sqrt{(\frac{E^{cms}_{beam}}{2})^2 - (p^{cms}_B)^2}$$

$$\Delta E = E^{cms}_B - \frac{E^{cms}_{beam}}{2}$$

Belle, Phys. Rev. D84(2011)052004



m_{BC} /GeV M(J/ψ $\pi^+ \pi^-$)/GeV ΔE/GeV

beam constraint and 3-dim fit (over-constraint)
→ fit resolution better than detector resolution

Precise Measurement of Mass and Width of X(3872)

Belle, Phys. Rev. Lett.91(2003)262001
CDF-II, Phys. Rev. Lett.93(2004)072001
D0, Phys. Rev. Lett.93(2004)162002
BaBar, Phys. Rev. D71(2005)071103
LHCb, Eur. Phys. J. C72(2012)1972
CMS, arXiv:1302.3968[hep-ex]

Experiment	Mass of X(3872)
CDF2	3871.61±0.16±0.19 MeV
BABAR (B^+)	3871.4±0.6±0.1 MeV
BABAR (B^0)	3868.7±1.5±0.4 MeV
D0	3871.8±3.1±3.0 MeV
Belle	3871.84±0.27±0.19 MeV
LHCb	3871.95±0.48±0.12 MeV
World Average	3871.68±0.17 MeV

- threshold $m(D^0)+m(D^{*0})=3871.84\pm0.28$ MeV
  „binding energy“ −0.16±0.33 MeV
  → random coincidence or „grand design“ ?

- upper limit on width
  $\Gamma < 1.2$ MeV (very narrow)

What do we know about the X(3872) ?

- Observed by 7 experiments
- Observed in 5 decay channels
- Quantum numbers are $J^{PC}=1^{++}$
  potential model: χ_{c1}'

  Barnes et al., Phys. Rev. D72(2005)054026

  $\rightarrow$ predicted mass ≥50 MeV higher

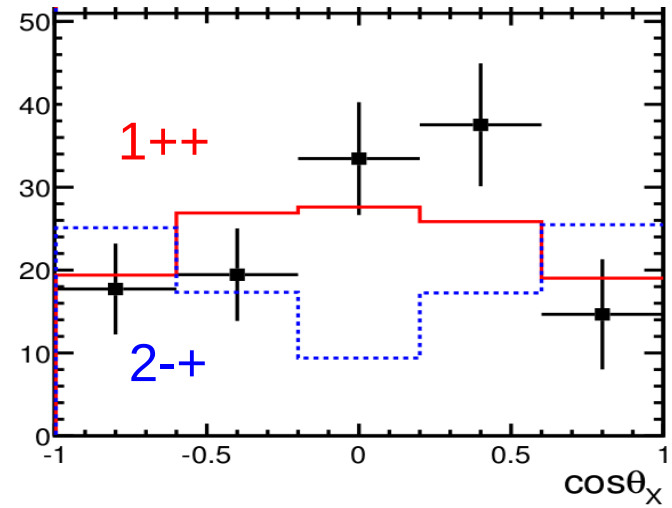
  $\rightarrow$ predicted width factor ≥100 larger
- Decay $X(3872) \rightarrow J/\psi\pi^+\pi^-$
  dominated by $X(3872) \rightarrow J/\psi\rho^0$(I=1)

  $\rightarrow$ violates isospin

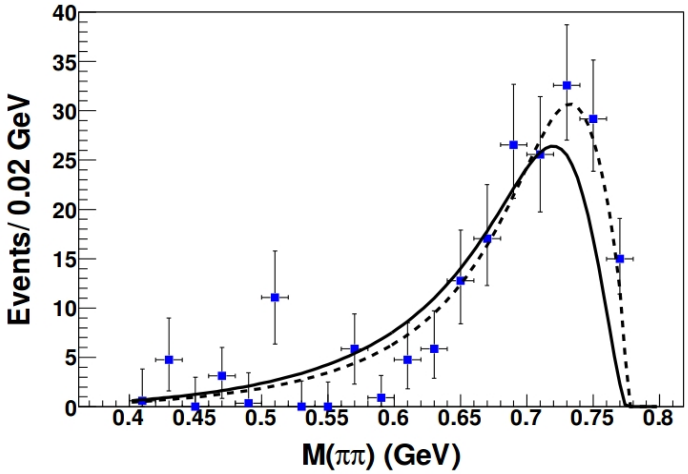
  (assume initial I=0)

  $\rightarrow$ $\mathcal{B}$ factor 10–100 too large

LHCb, Phys. Rev. Lett. 110(2013)222001

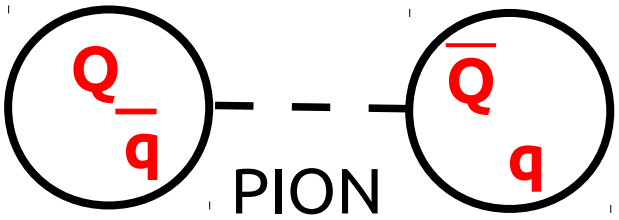


Belle, Phys. Rev. D84(2011)052004



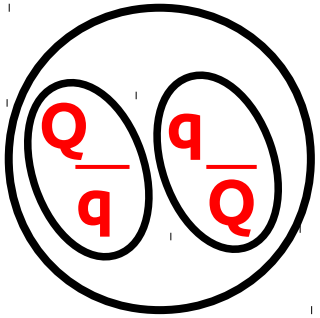
Is the X(3872) exotic ?

MOLECULE



Tornqvist; Swanson; Braaten, Kusonoki, Wong; Voloshin; Close, Page
Threshold CUSP: Bugg

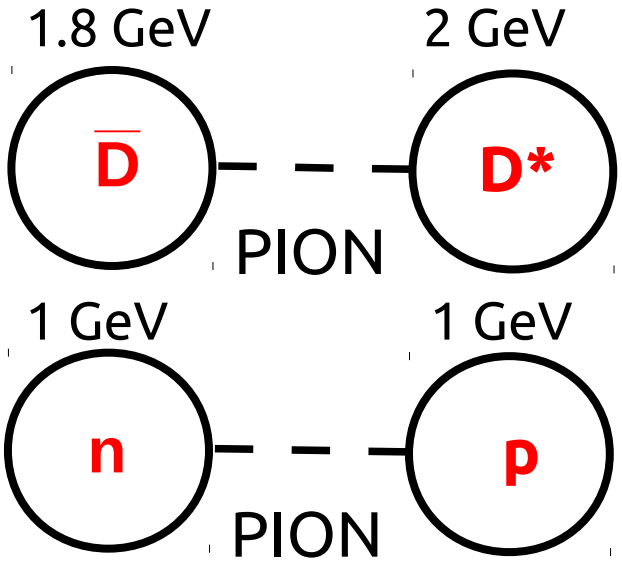
TETRAQUARK



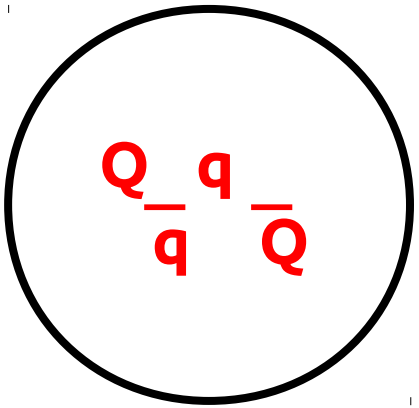
Diquarks can be colored

[Qq][$\overline{Qq}$] Maiani, Riquer, Piccinini, Polosa, Burns; Ebert, Paustov, Galkin; Chiu, Hsieh; Ali, Hambrock, Wang

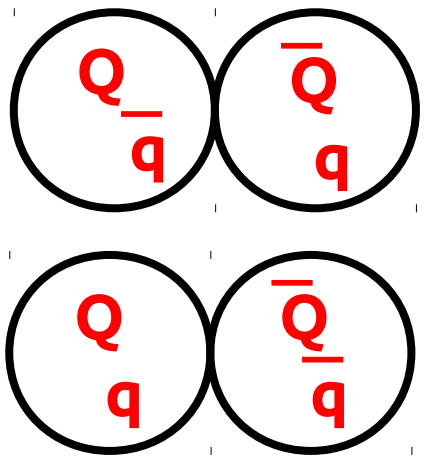
Intriguing Analogon



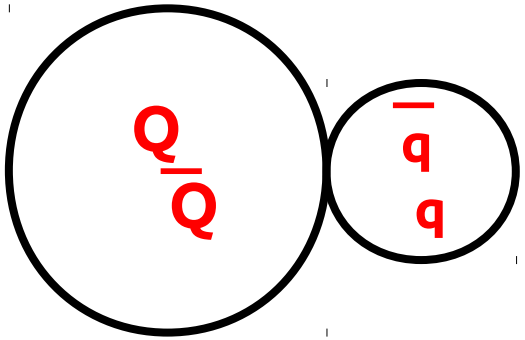
TETRAQUARK
(COMPACT)



TETRAQUARK
(DIQUARK- DIQUARK)



HADRO-QUARKONIUM



additional effects:
- thresholds
- final state interaction (rescattering)

Can the X(3872) be a mixture ?

$$|X(3872)>= c_1|c\bar{c}> + c_2|\overline{D}^0 D^{0*}>$$

χ_{c1}'
$J^{PC}=1^{++}$

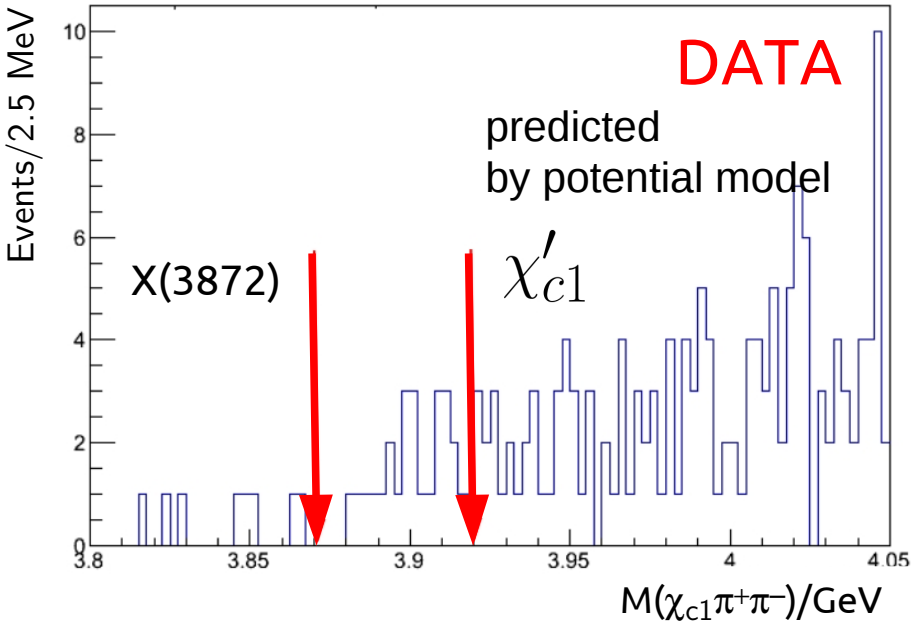
Is there $c\bar{c}$ admixture inside the X(3872) ?

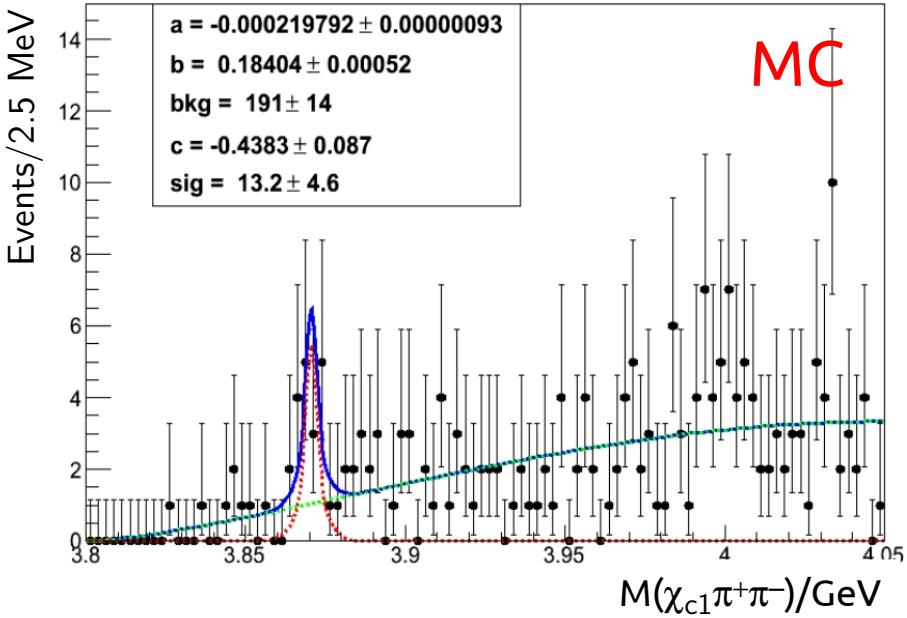
Search for X(3872) → $\chi_{c1}\,\pi^+\pi^-$

NEW, Belle, 711 fb^{-1}
E. Panzenboeck (Göttingen/Nara)
Hadron 2013. LLWI 2014

No signal observed
(no indication of admixture)

MC simulation, assuming
$\mathcal{B}(\chi_{c1}\,\pi^+\pi^-) = \mathcal{B}(J/\psi\,\pi^+\pi^-)$





Y(4260)

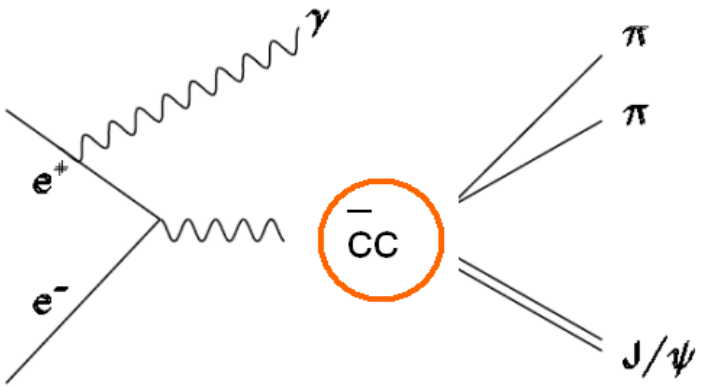
Note: recent notation
by PDG as X(4260)

Y(4260)

- Initial state radiation events

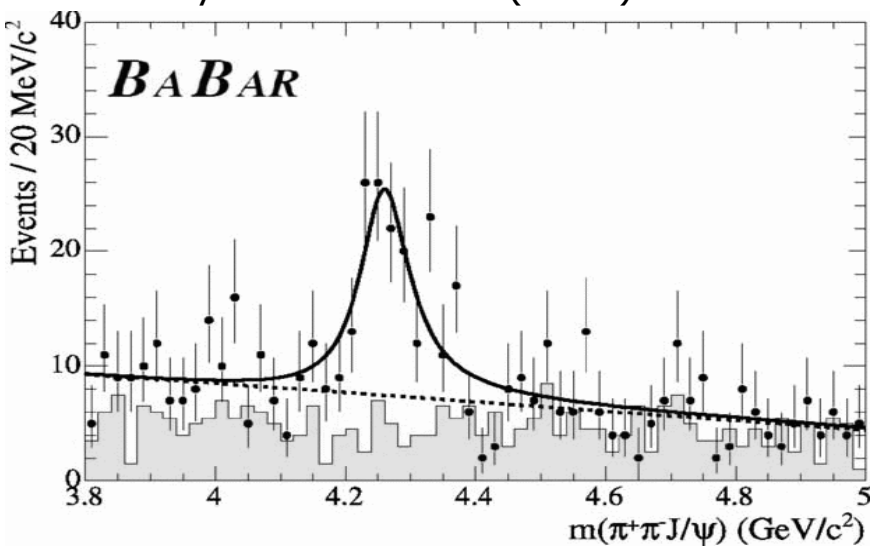
$$e^+e^- \to \gamma_{ISR} \underbrace{J/\psi\pi^+\pi^-}_{\text{resonant state?}}$$

initial state radiation



- m > 4 GeV
  → far above $D^{(*)}D^{(*)}$ threshold, but decay to open charm not observed

Phys. Rev. Lett. 95(2005)142001



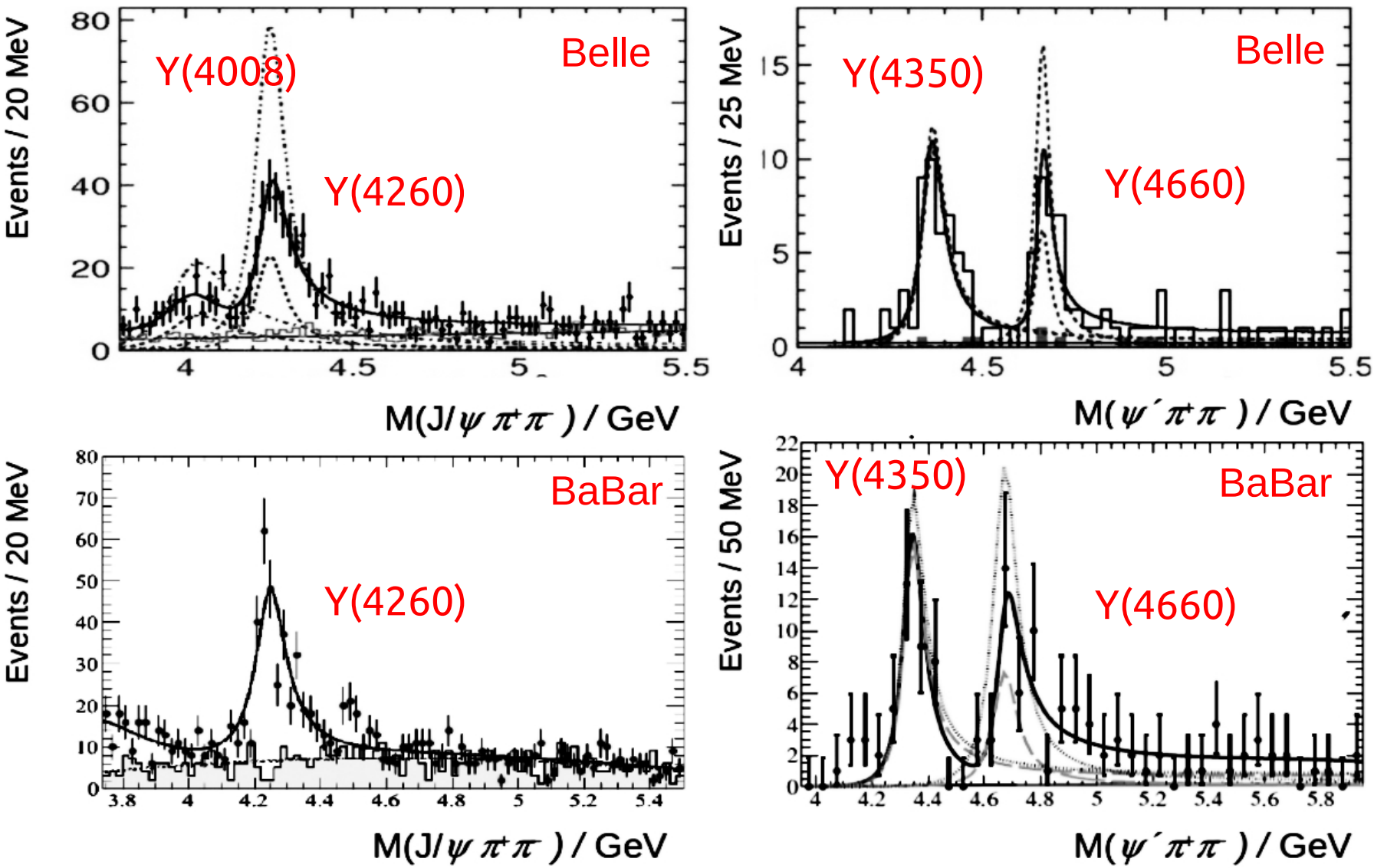
- Quantum numbers (based upon production mechanism)
  $J^{PC}=1^{--}$

Y(4260) Parameters

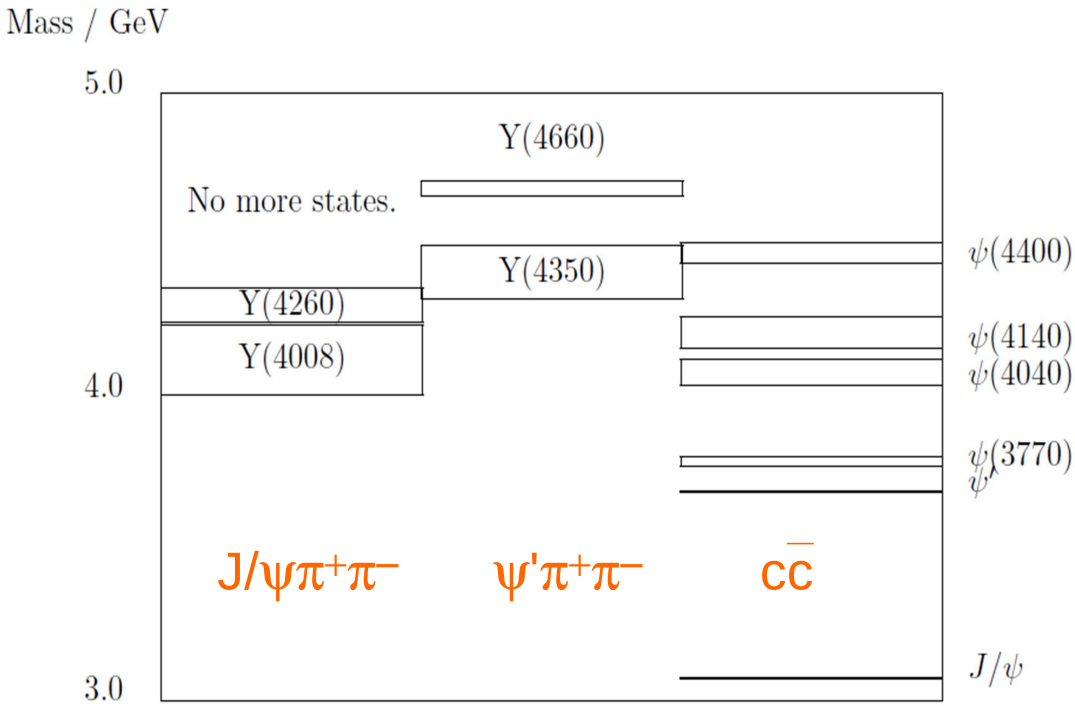
	BaBar [1]	CLEO-c [2]	Belle [3]	Belle [4]	BaBar [5]	BaBar [6]
$\mathcal{L}$	211 fb^{-1}	13.3 fb^{-1}	553 fb^{-1}	548 fb^{-1}	454 fb^{-1}	454 fb^{-1}
N	125 ± 23	$14.1^{+5.2}_{-4.2}$	165 ± 24	324 ± 21	344 ± 39	–
Significance	$\simeq 8\sigma$	$\simeq 4.9\sigma$	$\geq 7\sigma$	$\geq 15\sigma$	–	–
m / MeV	$4259\pm8^{+2}_{-6}$	$4283^{+17}_{-16}\pm4$	$4295\pm10^{+10}_{-3}$	$4247\pm12^{+17}_{-32}$	$4252\pm6^{+2}_{-3}$	$4244\pm5\pm4$
Γ / MeV	$88\pm23^{+6}_{-4}$	70^{+40}_{-25}	$133\pm26^{+13}_{-6}$	$108\pm19\pm10$	$105\pm18^{+4}_{-6}$	$114^{+16}_{-15}\pm7$

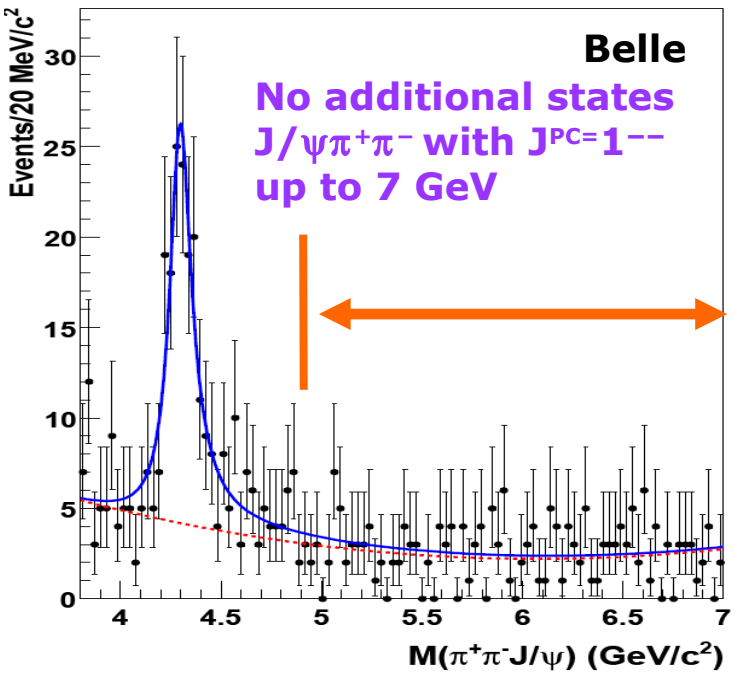
[1] BaBar Collaboration, arXiv:hep-ex/0506081, Phys. Rev. Lett. 95(2005)142001.
[2] CLEO-c Collaboration, arXiv:hep-ex/0611021, Phys. Rev. D74(2006)091104.
[3] Belle Collaboration, arXiv:hep-ex/0612006.
[4] Belle Collaboration, arXiv:0707.2541[hep-ex], Phys. Rev. Lett. 99(2007)182004.
[5] BaBar Collaboration, arXiv:0808.1543[hep-ex].
[6] BaBar Collaboration, arXiv:1204.2158[hep-ex], Phys. Rev. D86(2012)051102.

$e^+e^- \to \gamma_{ISR}\, J/\psi\ (\psi')\ \pi^+\pi^-$: Y States



Overpopulation of $J^{PC}=1^{--}$ States



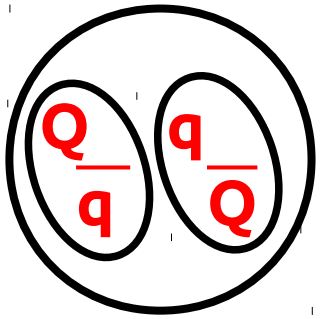


- Non-trivial pattern, not understood
- No mixing with conventional ψ states
- No mixing among them
  → Y(4260) seems not to decay to $\psi'\pi^+\pi^-$
  → Y(4350) seems not to decay to $J/\psi\pi^+\pi^-$

Is the Y(4260) exotic ?

TETRAQUARK

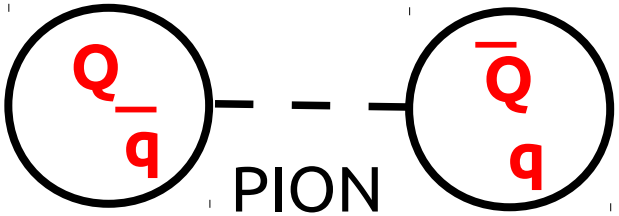
higher excitation ?



[Qq][$\overline{Qq}$] Maiani, Riquer, Piccinini, Polosa, Burns

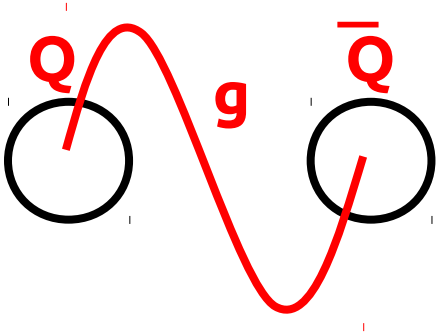
MOLECULE

heavier mesons ($\overline{D}D_1(2460)$) ?



[Qq][$\overline{Qq}$] Swanson, Rosner, Close
[$Q\overline{Q}$][$q\overline{q}$] „Hadro-Charmonium“
Guo, Hanhart, Krewald, Meissner

HYBRID

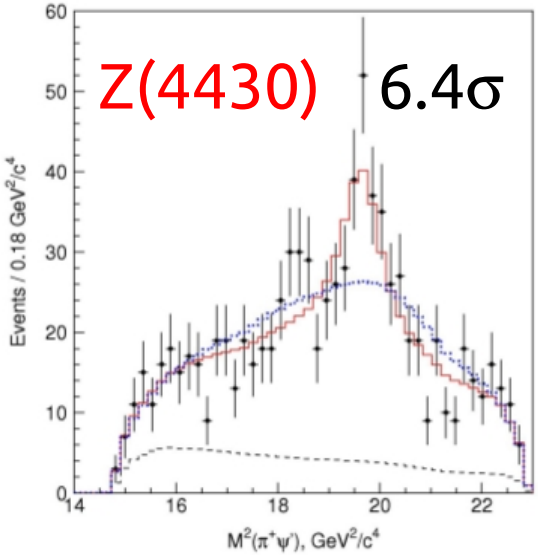


Zhu; Kou, Pene; Close, Page;
Lattice QCD, Bernard et al.; Mei, Luo

Z_c^+ States

If there are exotic neutral states,
are there also exotic charged states ?
(→ cannot be charmonium!)

Example: $[c\,\bar{c}\,u\,\bar{d}]^+$

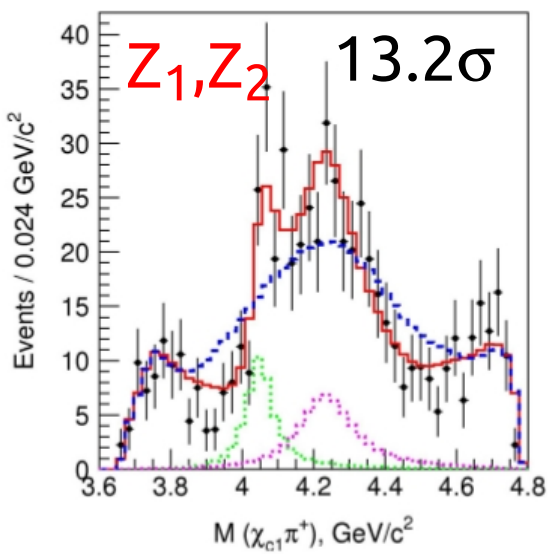


$$B^0 \to K^\pm \underbrace{\psi' \pi^\mp}_{\text{resonant state?}}$$

not confirmed by BaBar

$$m = 4433 \pm 4 \pm 2 \text{ MeV}, \; \Gamma = 45^{+18+30}_{-13-13} \text{ MeV}$$

Belle, Phys. Rev D80(2009)031104



$$B^0 \to K^\pm \underbrace{\chi_{c1} \pi^\mp}_{\text{resonant state?}}$$

not confirmed by BaBar

$$m(\mathrm{Z}_1) = 4051 \pm 14^{+20}_{-41} \text{ MeV}, \; \Gamma(\mathrm{Z}_1) = 82^{+21+47}_{-17-22} \text{ MeV}$$

$$m(\mathrm{Z}_2) = 4248^{+44+180}_{-29-35} \text{ MeV}, \; \Gamma(\mathrm{Z}_2) = 177^{+54+316}_{-39-61} \text{ MeV}$$

Belle, Phys. Rev D78(2008)072004

Problem: understanding of 3-body decay dynamics

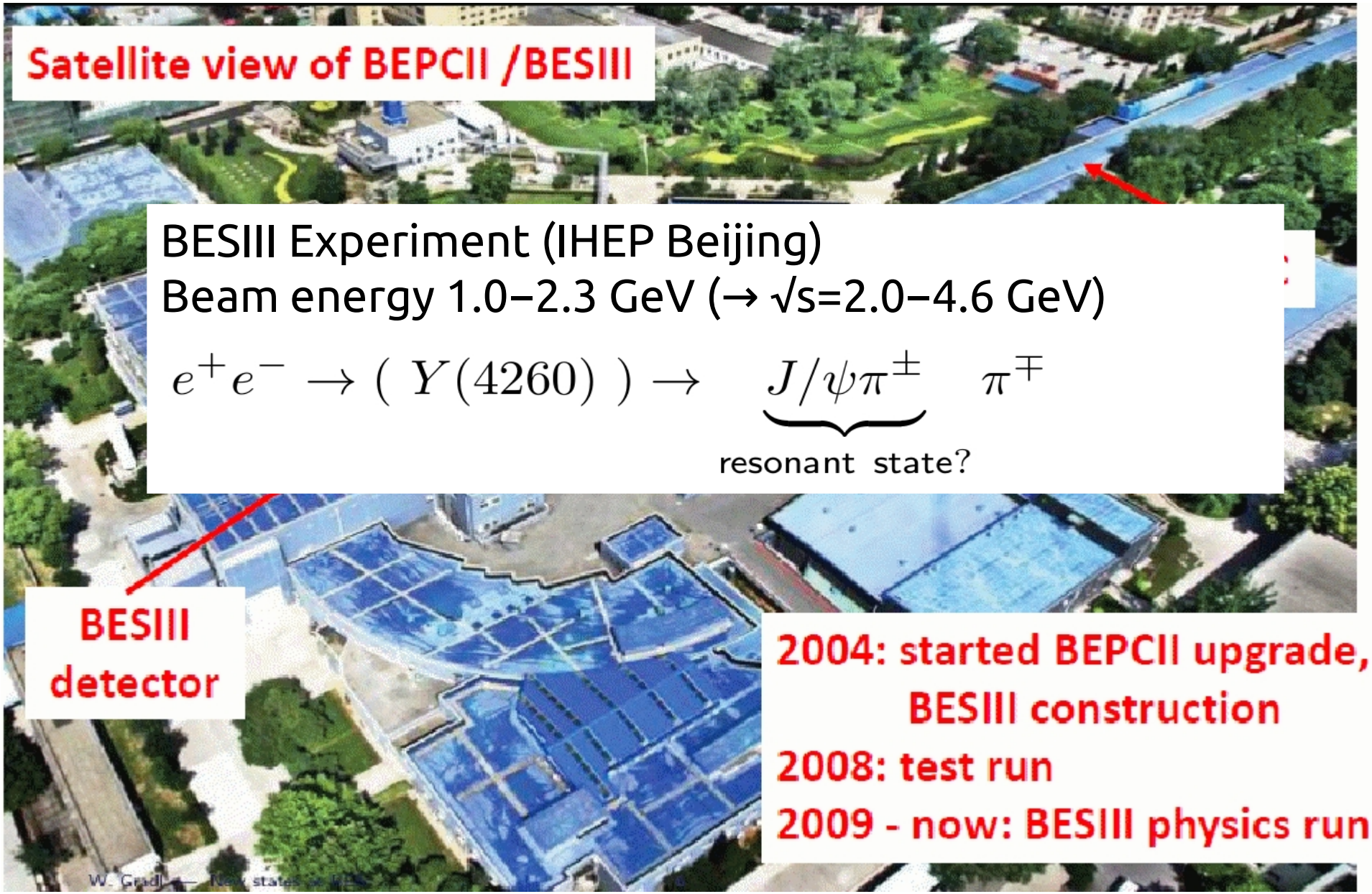
Beijing Electron Positron Collider II

2004: started BEPCII upgrade, BESIII construction

2008: test run

2009 - now: BESIII physics run

Beijing Electron Positron Collider II



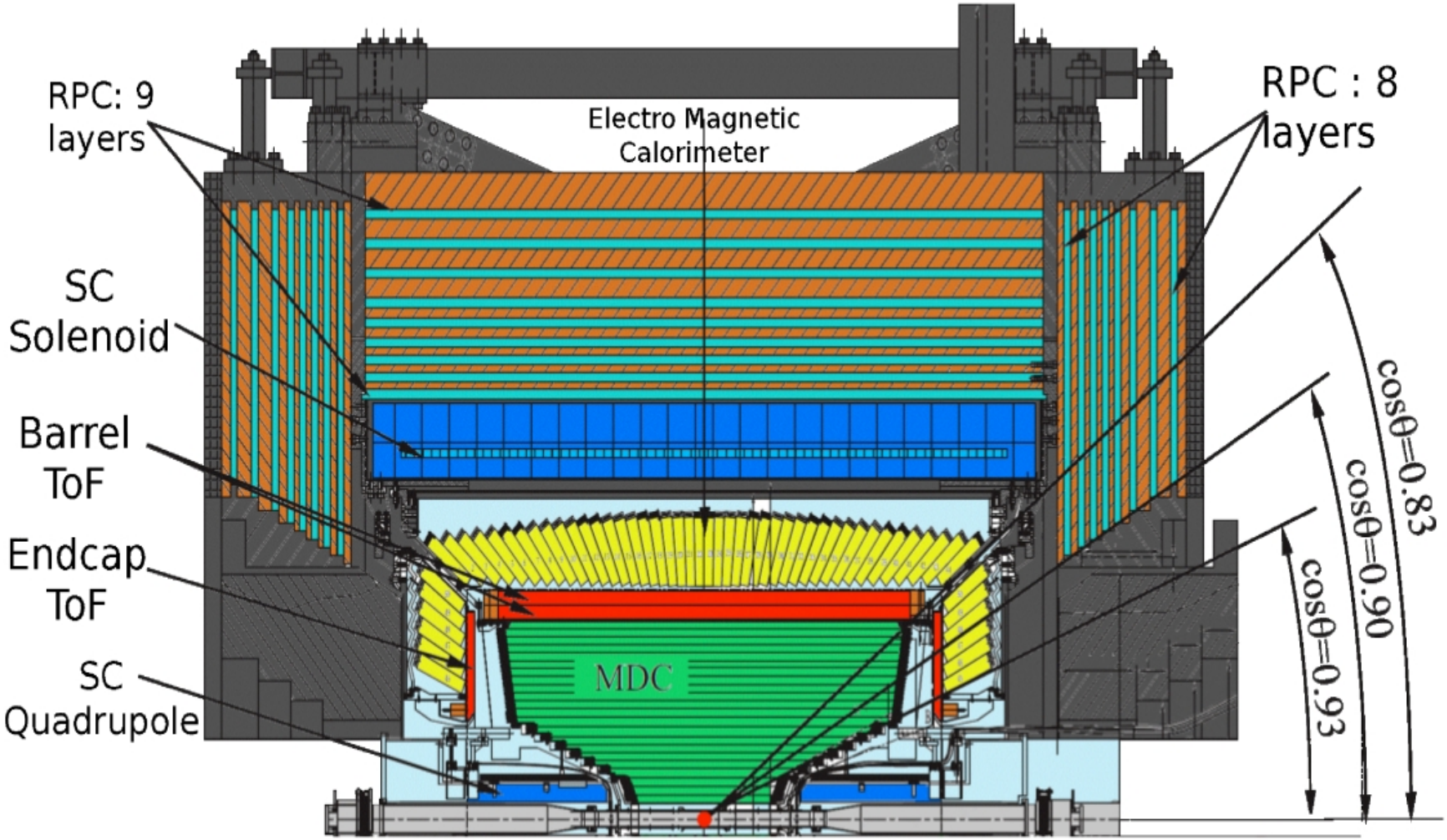
BESIII Experiment (IHEP Beijing)
Beam energy 1.0–2.3 GeV (→ √s=2.0–4.6 GeV)

$$e^+e^- \to (\ Y(4260)\ ) \to \underbrace{J/\psi\pi^\pm}_{\text{resonant state?}} \quad \pi^\mp$$

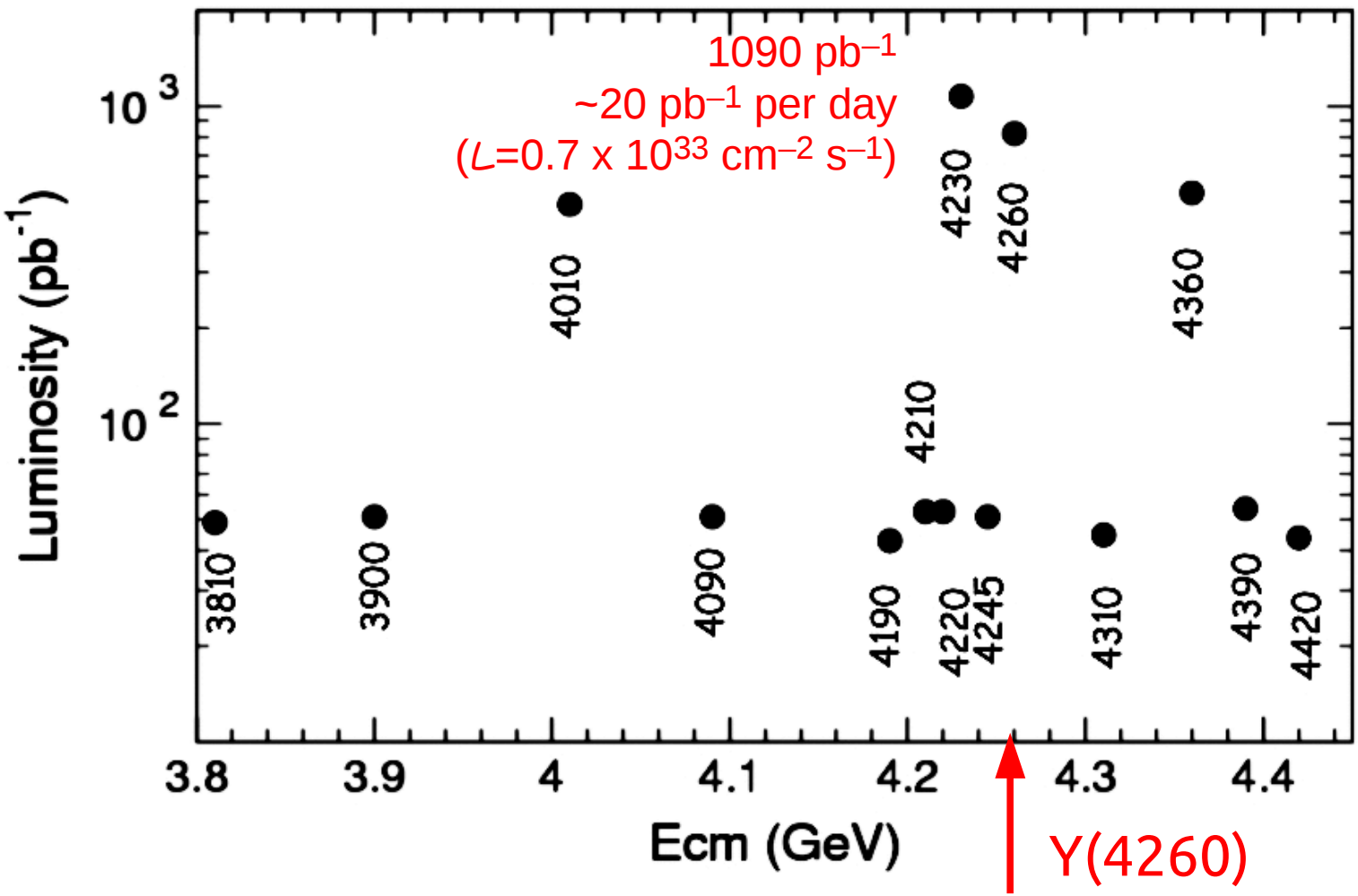
2004: started BEPCII upgrade, BESIII construction
2008: test run
2009 - now: BESIII physics run

BESIII Experiment

360 members, 52 institutions, 11 countries
Germany: Univ. Bochum, GSI Darmstadt, Univ. Giessen, Univ. Mainz



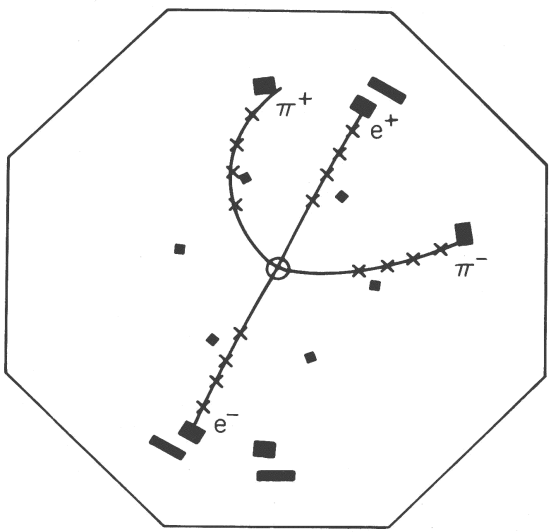
BESIII Data Taking at different √s
(e.g. adjust Beam Energies to Y(4260))

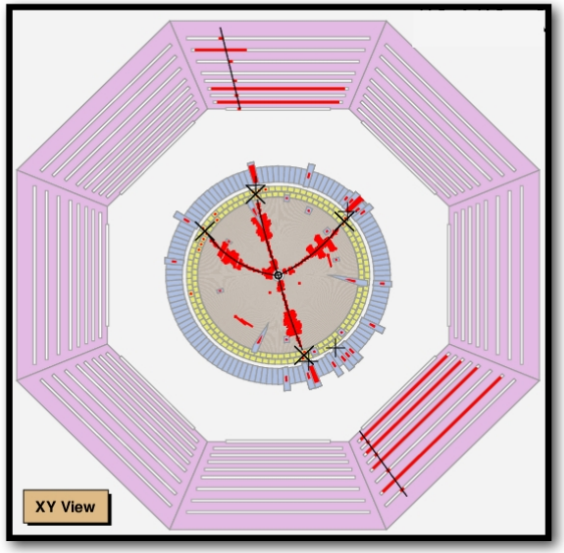


$e^+e^- \to J/\psi\, \pi^+ \pi^-$

MARK I, 1977
$e^+e^- \to \psi' \to J/\psi\, \pi^+ \pi^-$
$\sqrt{s}$=3868 MeV

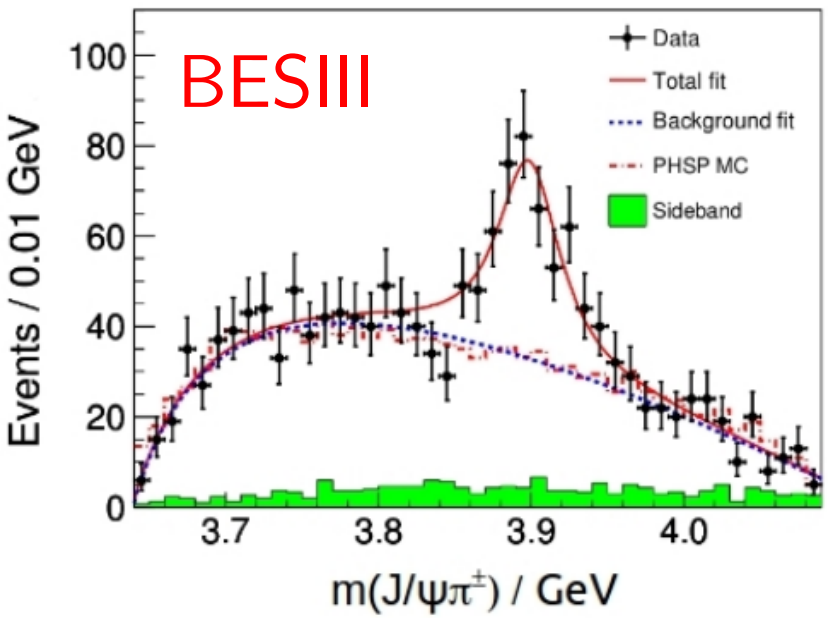
BESIII, 2013
$e^+e^- \to Y(4260) \to J/\psi\, \pi^+ \pi^-$
$\sqrt{s}$=4260 MeV

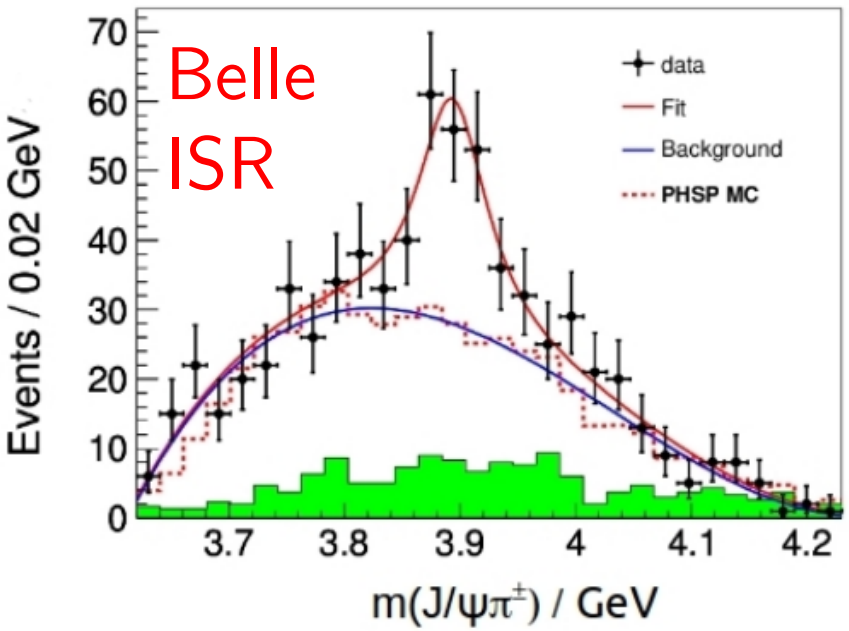




$$e^+e^- \to (\ Y(4260)\ ) \to \underbrace{J/\psi\pi^\pm}_{\text{resonant state?}} \quad \pi^\mp$$

$Z_c(3900)$



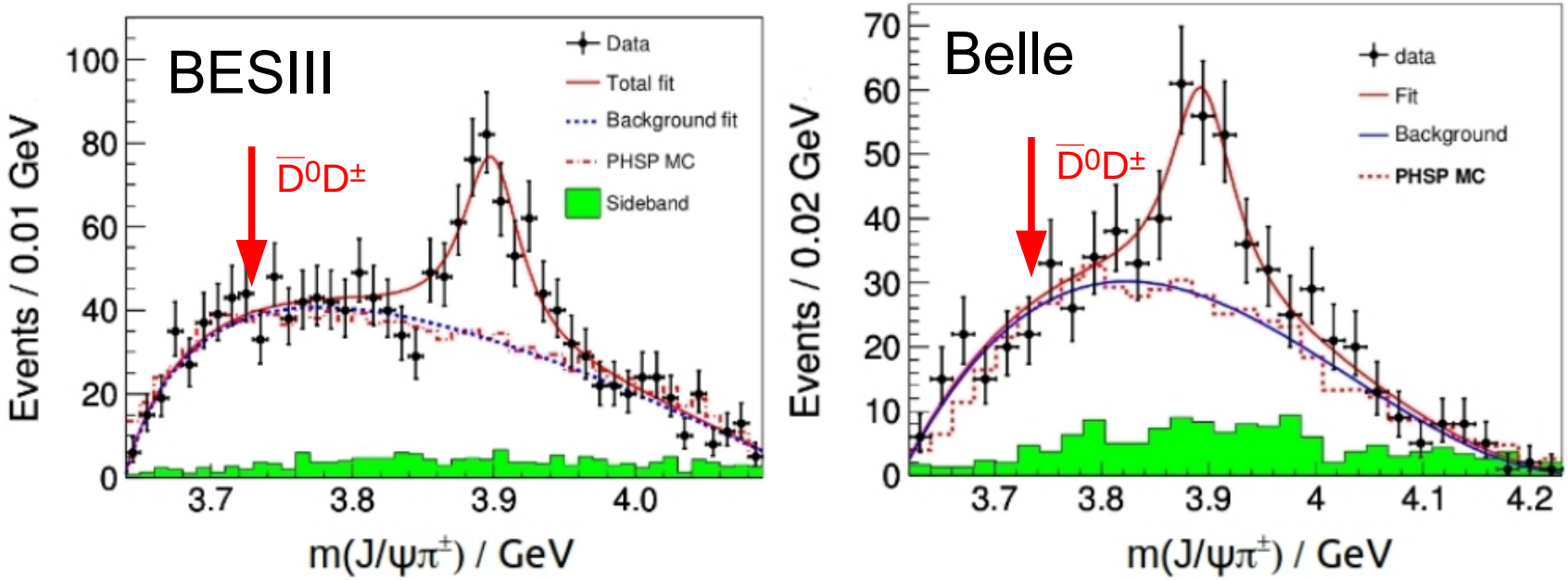


m = 3899.0±3.6±4.9 MeV
Γ = 46±10±20 MeV
307±48 events, >8 σ
arXiv:1303.5949, PRL 110(2013)252001

m = 3894.5±6.6±4.5 MeV
Γ = 63±24±26 MeV
159±49 events, >5.2 σ
arXiv:1304.0121, PRL 110(2013)252002

Confirmed with CLEO-c data, but different √s → not Y(4260)
S. Dobbs et al., Phys. Lett. B727(2013)366

$Z_c(3900)$



- $Y(4260) \rightarrow [J/\psi\pi^+]\,\pi^-$
  charged → no C-parity
  1^- 0^- and assume L=0 → $J^P=1^+$, similar to X(3872)
- D^+D^{*0} threshold 3877 MeV
  measured: 3899 MeV (BESIII), 3894 MeV (Belle)
  → higher than threshold
  → no binding energy („virtual state“)
- There is no state at $[\bar{D}^0D^\pm]$ threshold !

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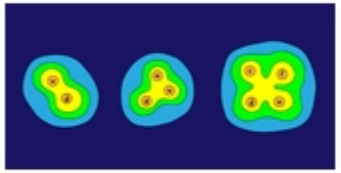
Notes from the Editors: Highlights of the Year

Published December 30, 2013 | Physics **6**, 139 (2013) | DOI: 10.1103/Physics.6.139

PHYSICS VIEWPOINT



New Particle Hints at Four-Quark Matter

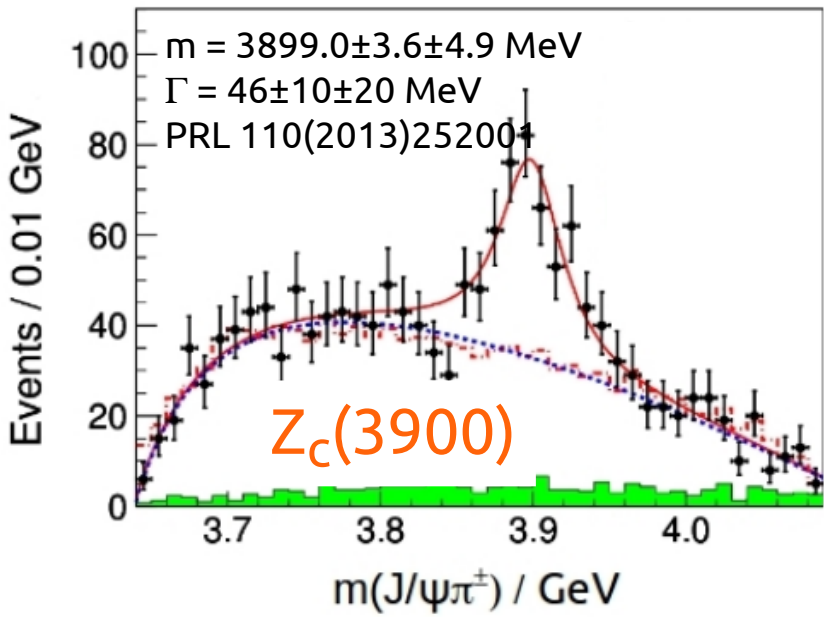
Published 17 June 2013

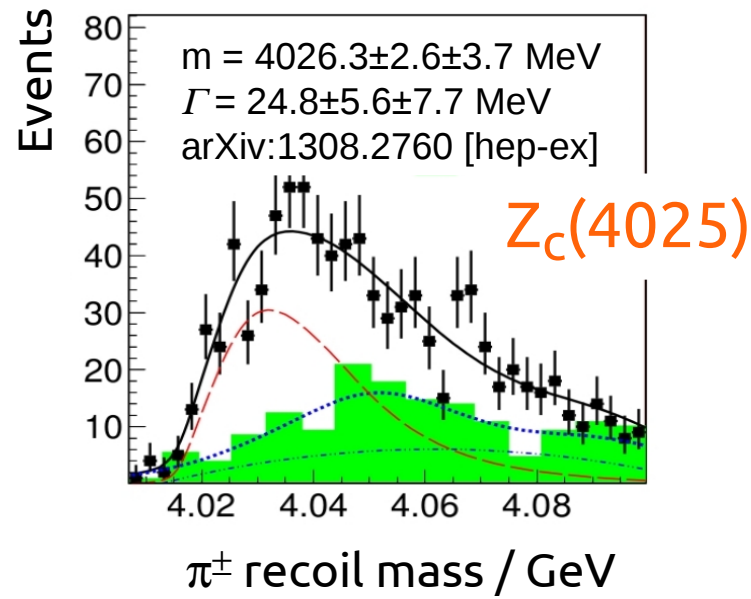
Two experiments have detected the signature of a new particle, which may combine quarks in a way not seen before.

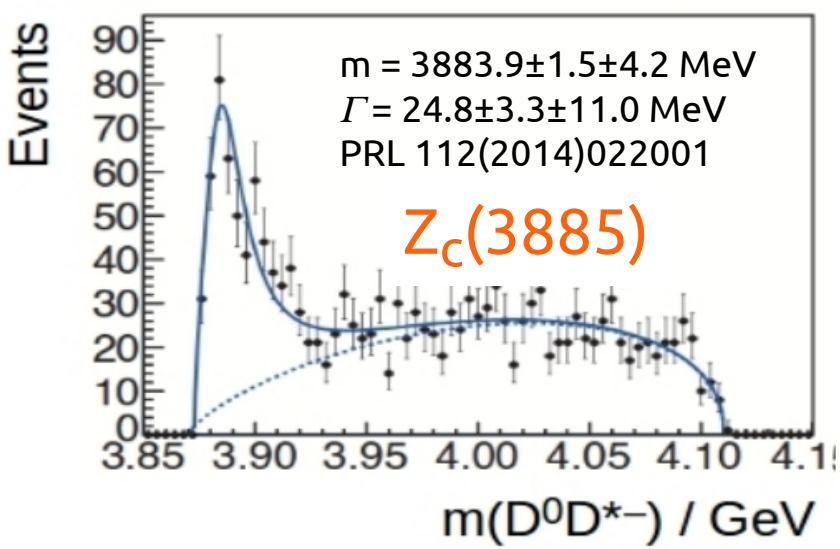
This is the first charged Z state observed by 2 experiments!

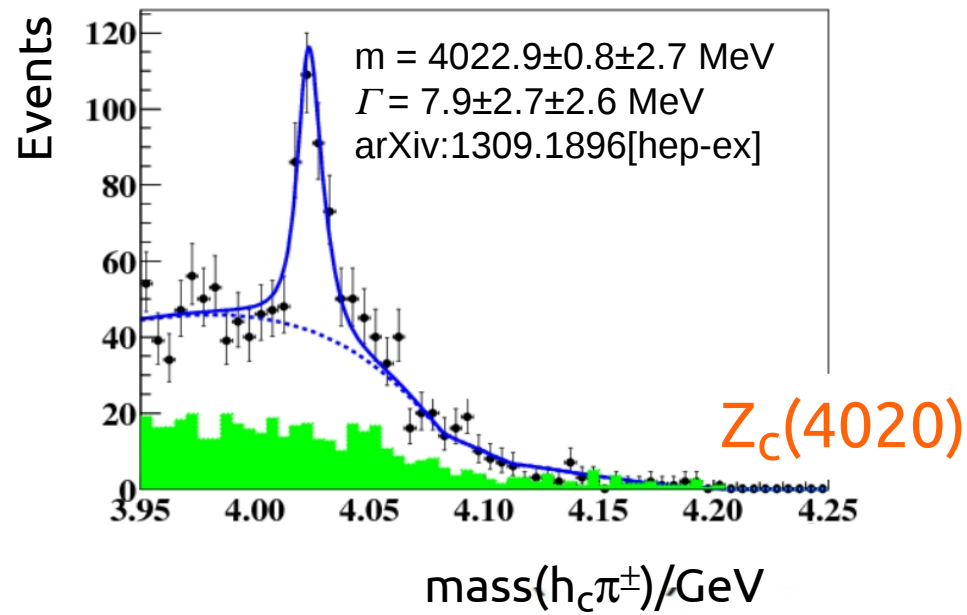
named „APS Highlight of the year 2013“
among others, e.g. extra-solar neutrinos by IceCube

Z_c^+ states at BESIII









Are these identical or different Z states?

$\rightarrow$ maybe different quantum numbers

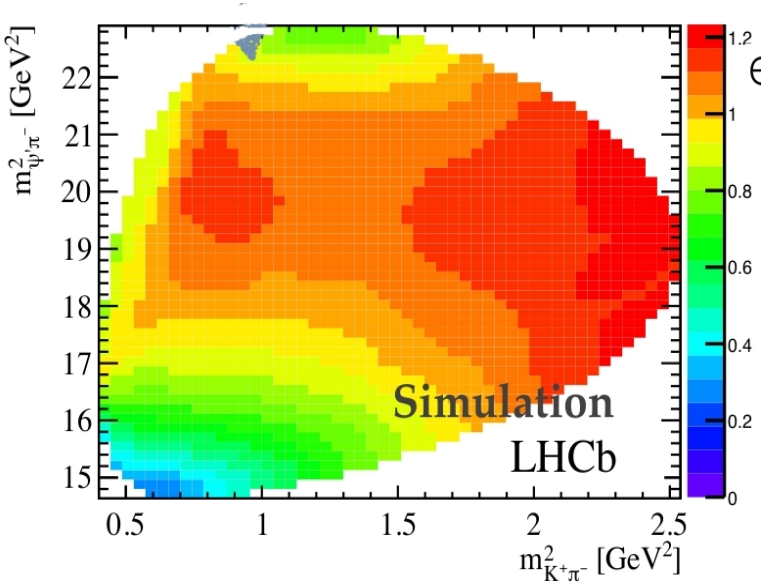
close to threshold ($\rightarrow$ S-wave, L=0)

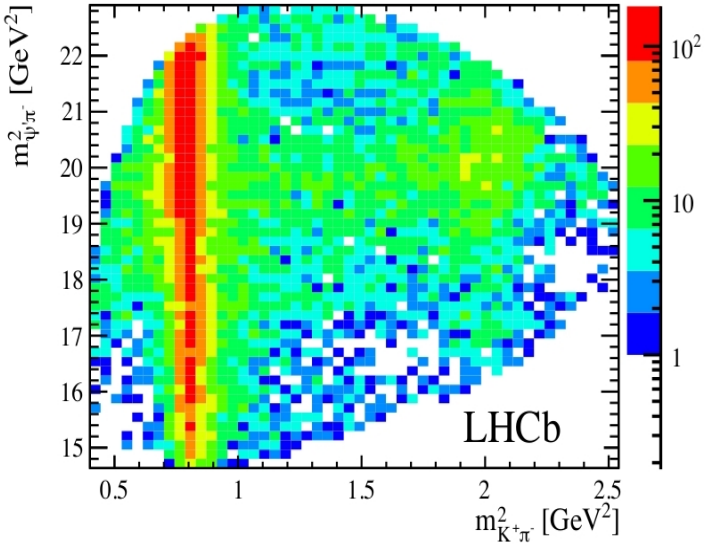
$J/\psi\ \pi^{\pm} \quad \rightarrow 1^{-}\ 0^{-} \quad \rightarrow 1^{+}$

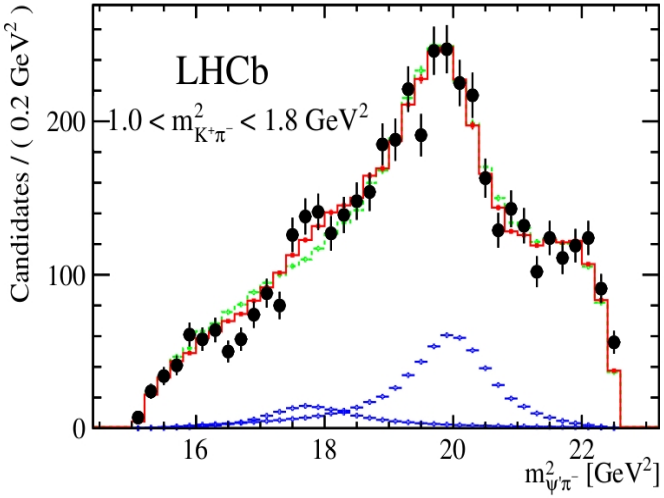
$h_c\ \pi^{\pm} \quad \rightarrow 1^{+}\ 0^{-} \quad \rightarrow 1^{-}$

Confirmation of the $Z(4430)^+$ in $B^0 \to K^+ \psi' \pi^-$

LHCb, arXiv:1404.1903[hep-ex], Phys. Rev. Lett. 112(2014)222002



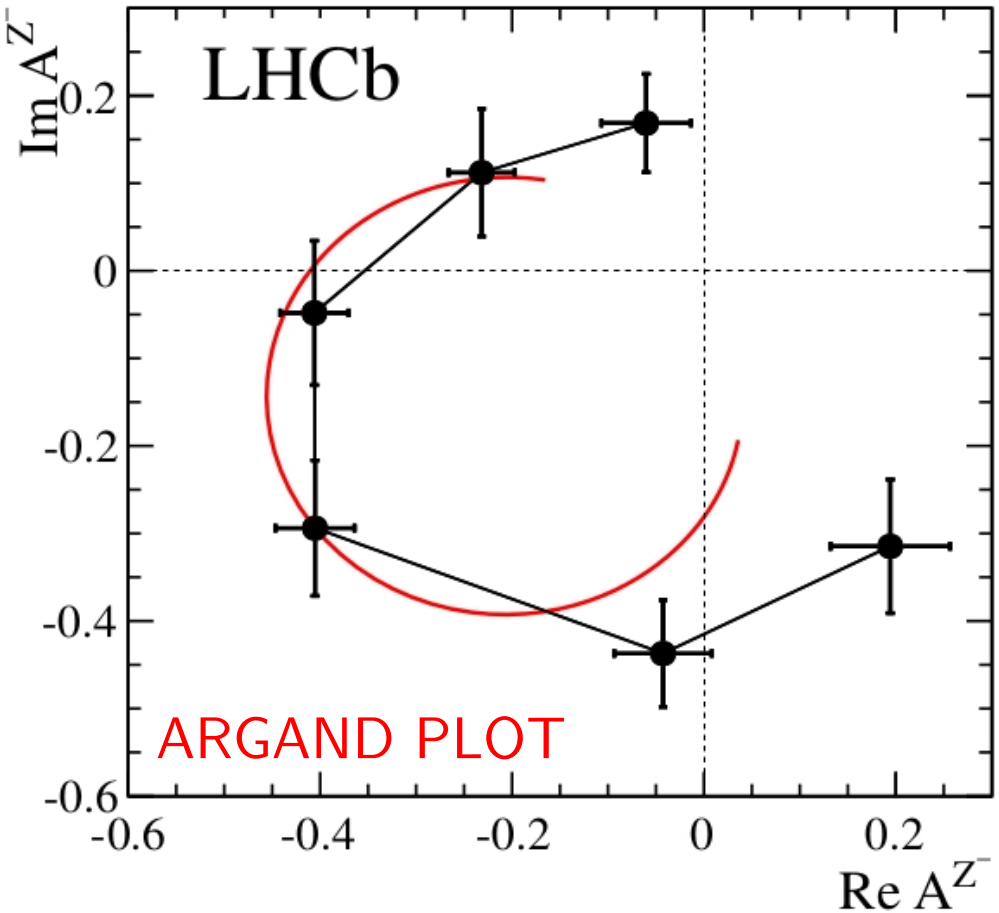




- data set 3 fb^{-1}, $\sqrt{s}$=7 and 8 TeV
- significance >13.9σ
- $J^P=1^+$ unambigously established (exclusion of 0−, 1−, 2+, 2− by 9.7σ, 15.8σ, 16.1σ and 14.6σ)
- mass and width consistent with Belle

Resonant character of the $Z_c(4430)^+$

LHCb, arXiv:1404.1903[hep-ex], Phys. Rev. Lett. 112(2014)222002



2nd $Z(J^P=0^-)$ in LHCb data (significance 6σ)

0– preferred over 1–,2–,2+ by $8\,\sigma$

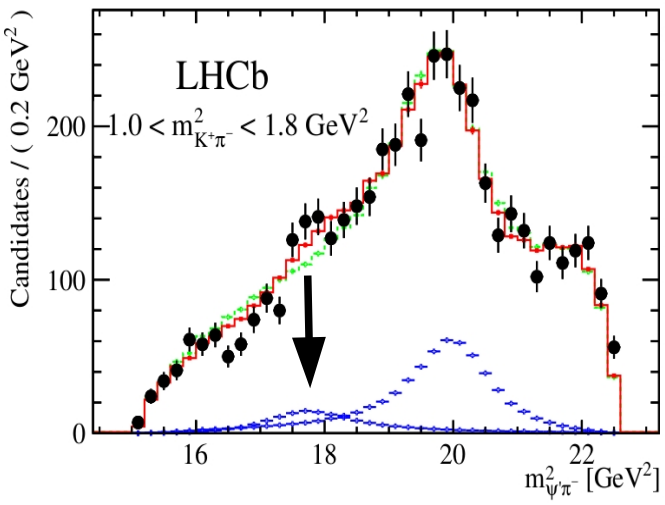
0– preferred over 1+ by 1σ, but width Z(4430) $\rightarrow$ 660 MeV has same mass as one of the $[\chi_{c1}\pi^{\pm}]$ states from Belle

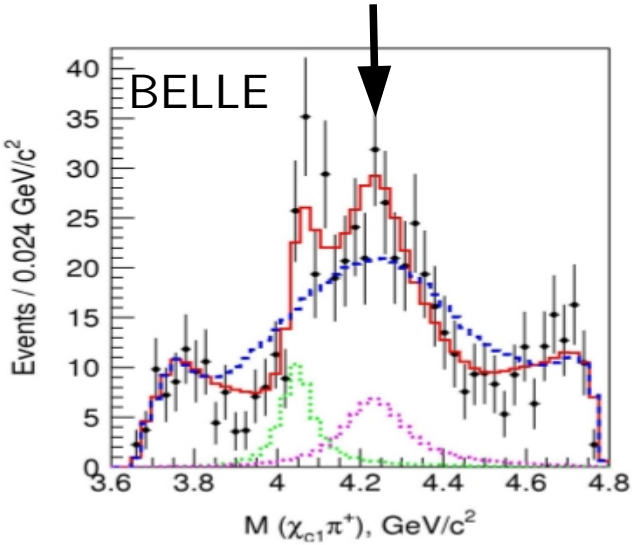
$m=4239\pm18^{+45}_{-10}$ MeV, $\Gamma=220\pm47^{+108}_{-74}$ MeV

$m=4248^{+44}_{-29}{}^{+180}_{-35}$ MeV, $\Gamma=177^{+54}_{-39}{}^{+316}_{-61}$ MeV

but: strong decay 0– $\rightarrow$ 1+ 0– not allowed (violates parity)

$\rightarrow$ 2 different Z states at same mass!





What about $[J/\psi\pi^{\pm}]$ in B decays ?
(instead of $[\psi'\pi^{\pm}]$)

Is there any indication of the $Z_c(3900)$?

New 2014: $Z_c(4020)^+$ in $[J/\psi\pi^\pm]$

Belle, arXiv:1408.6457[hep-ex], Phys. Rev. D 90, 112009 (2014)

4-dimensional amplitude analysis

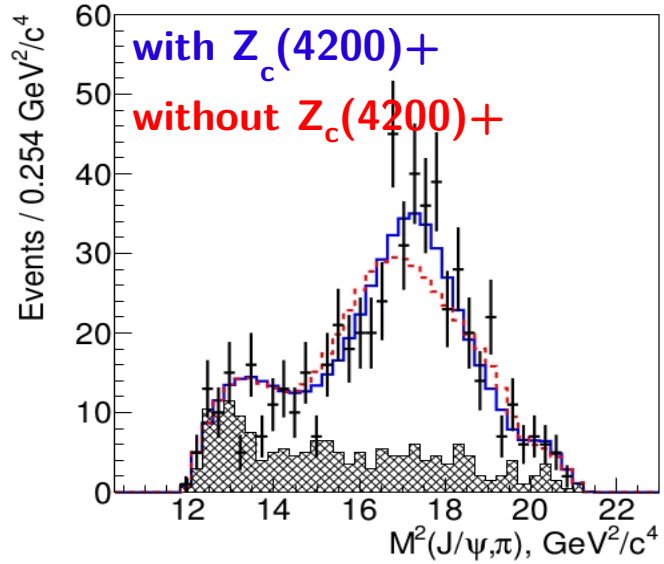
(similar to $Z_c(4430)^+$)

significance 6.2σ

$J^P = 1^+$ preferred

exclusion level (J^P=0^-, 1^-, 2^-, 2^+):

6.1σ, 7.4σ, 4.4σ, 7.0σ



$$M = 4196^{+31+17}_{-29-13}\ \mathrm{MeV}/c^2, \quad \Gamma = 370^{+70+70}_{-70-132}\ \mathrm{MeV}$$

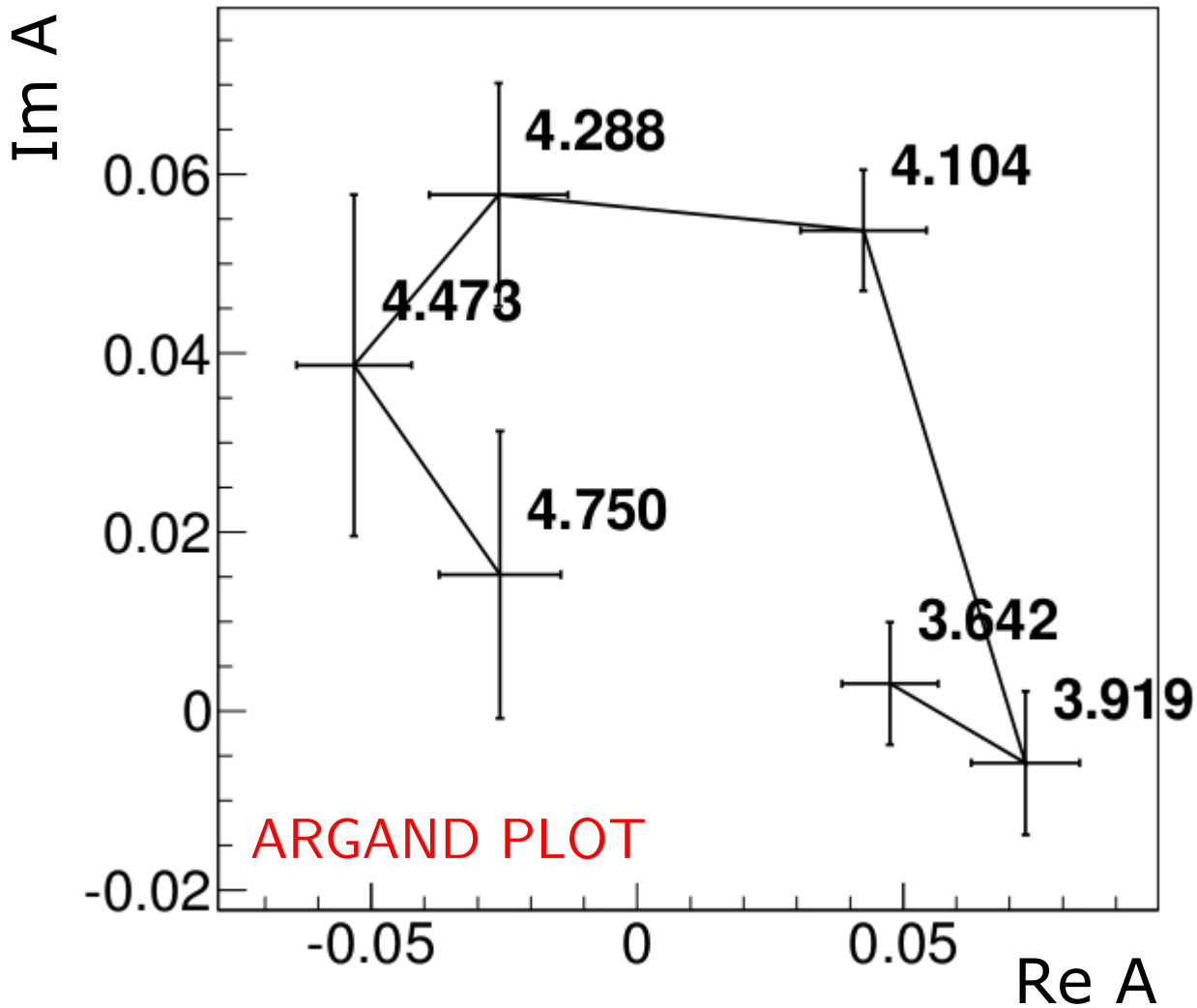
$Z_c(4200)^+$

TABLE I. Fit results in the default model. Errors are statistical only.

J^P	0^-	1^-	1^+	2^-	2^+
Mass, MeV/c^2	4318 ± 48	4315 ± 40	4196^{+31}_{-29}	4209 ± 14	4203 ± 24
Width, MeV	720 ± 254	220 ± 80	370 ± 70	64 ± 18	121 ± 53
Significance (Wilks)	3.9σ	2.3σ	8.2σ	3.9σ	1.9σ

Resonant character of the $Z_c(4200)^+$

Belle, arXiv:1408.6457[hep-ex], Phys. Rev. D90(2014)112009



Search for $Z_c(3900)^+$ and $Z_c(4430)^+$

Belle, arXiv:1408.6457[hep-ex], Phys. Rev. D90(2014)112009

- $Z_c(4430)^+ \to J/\psi\pi^+$

  2nd decay mode !

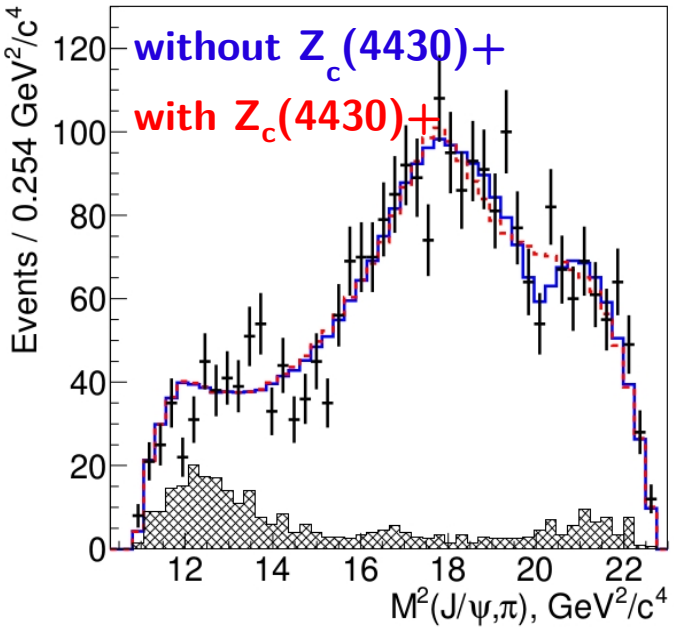
  4.0σ

  mass and width are FIXED in the fit

  suppressed by factor ~4
  (smaller phasespace)

- no evidence for $Z_c(3900)^+$

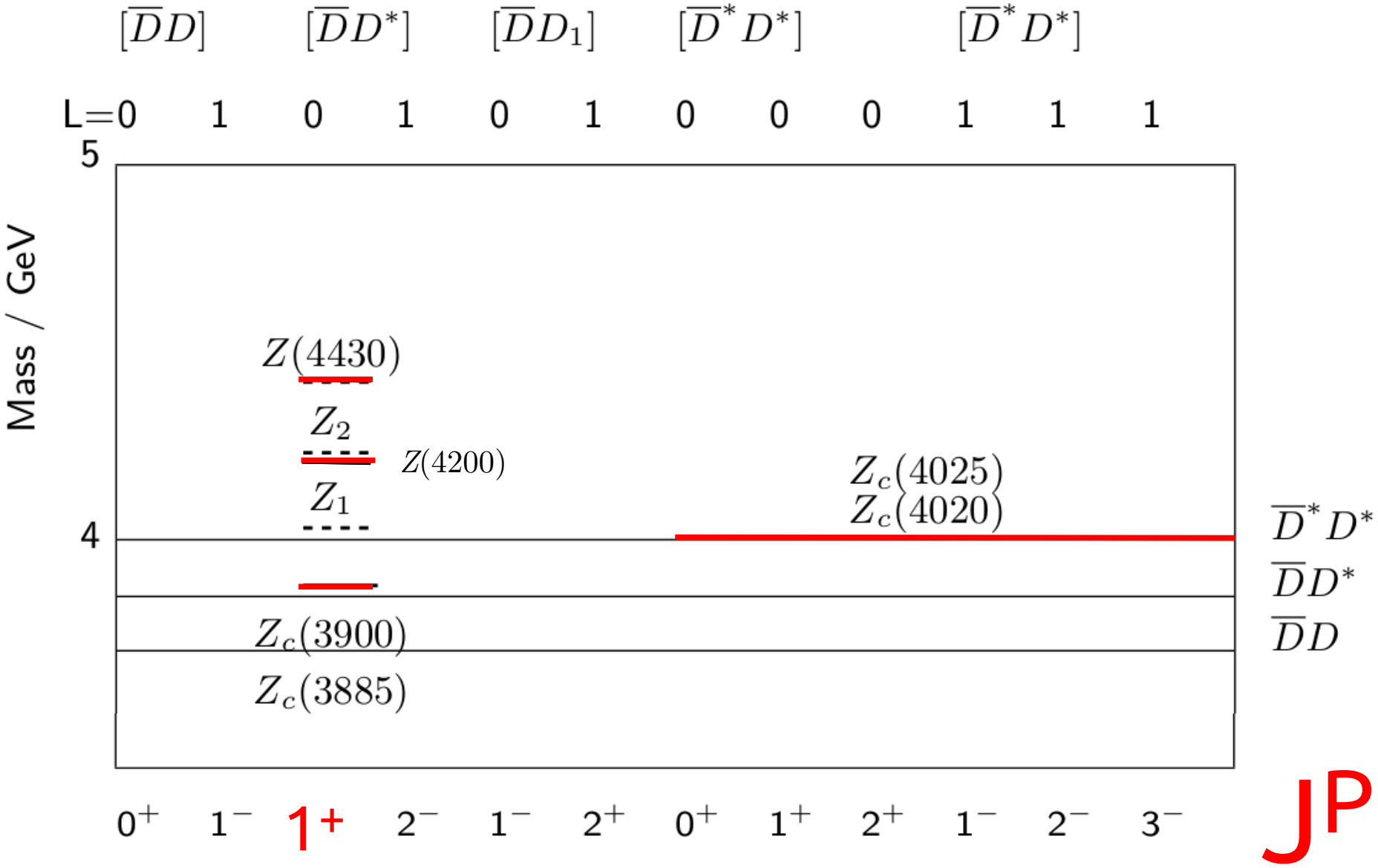
  $<0.1\sigma$ (if $J^P=1^+$)



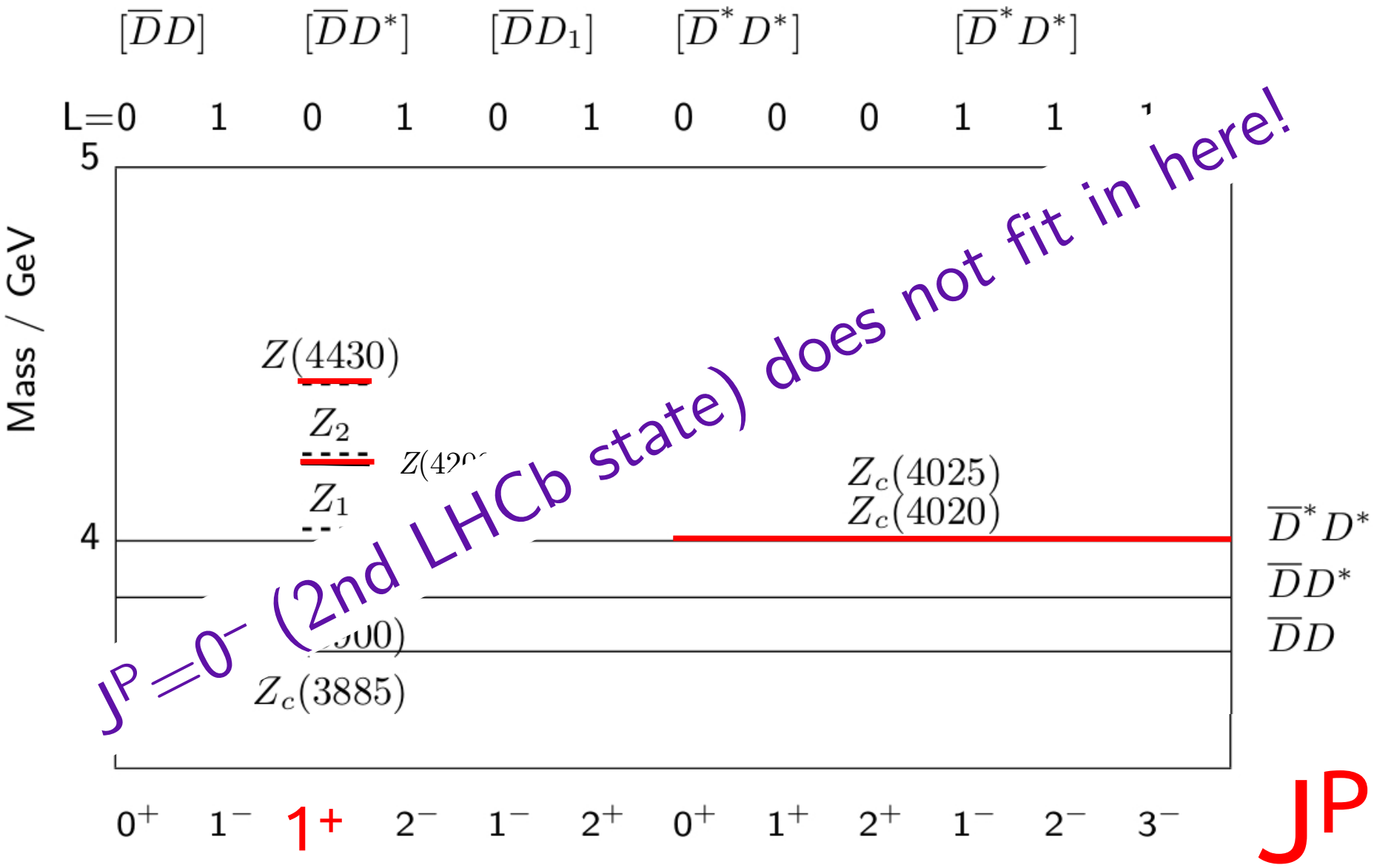
$$\mathcal{B}(\bar{B}^0 \to Z_c(4430)^+ K^-) \times \mathcal{B}(Z_c(4430)^+ \to J/\psi\pi^+) = (5.4^{+4.0+1.1}_{-1.0-0.9}) \times 10^{-6},$$

$$\mathcal{B}(\bar{B}^0 \to Z_c(4200)^+ K^-) \times \mathcal{B}(Z_c(4200)^+ \to J/\psi\pi^+) = (2.2^{+0.7+1.1}_{-0.5-0.6}) \times 10^{-5},$$

Spectrum of Z_c+ States



Spectrum of Z_c+ States



$J^P = 0^-$ (2nd LHCb state) does not fit in here!

Note:

so far, no connection found between Z_c states in ISR and Z_c states in B decays

$\rightarrow$ 2 different types ?

note: only Z_c states in ISR are close to $D^*D^{(*)\pm}$ thresholds

All measured $Z_c^{\pm}$ masses are above $D^{(*)}\overline{D}^{(*)}$ thresholds.

State	m/MeV	Threshold	Δm/MeV
$Z_c(3900)$	$3899.0 \pm 3.6 \pm 4.9$	$D^+\overline{D}^{0*}$	$+22.4$
$Z_c(3900)$	$3899.0 \pm 3.6 \pm 4.9$	$D^0\overline{D}^{+*}$	$+23.9$
$Z_c(3900)$	$3894.5 \pm 6.6 \pm 4.5$	$D^+\overline{D}^{0*}$	$+17.9$
$Z_c(3900)$	$3894.5 \pm 6.6 \pm 4.5$	$D^0\overline{D}^{+*}$	$+19.4$
$Z_c(3900)$	$3885 \pm 5 \pm 1$	$D^+\overline{D}^{0*}$	$+8.4$
$Z_c(3900)$	$3885 \pm 5 \pm 1$ MeV	$D^0\overline{D}^{+*}$	$+9.9$
$Z_c(3885)$	$3883.9 \pm 1.5 \pm 4.2$	$D^+\overline{D}^{0*}$	$+7.4$
$Z_c(3885)$	$3883.9 \pm 1.5 \pm 4.2$	$D^0\overline{D}^{+*}$	$+8.8$
$Z_c(4020)$	$4022.9 \pm 0.8 \pm 2.7$	$D^{0*}\overline{D}^{\pm *}$	$+5.6$
$Z_c(4025)$	$4026.3 \pm 2.6 \pm 3.7$	$D^{0*}\overline{D}^{\pm *}$	$+9.0$

→ not explained yet

Is there a decay from an XYZ to another XYZ?

$Y \to Z$

Z_c^+ are observed in Y(4260) decay

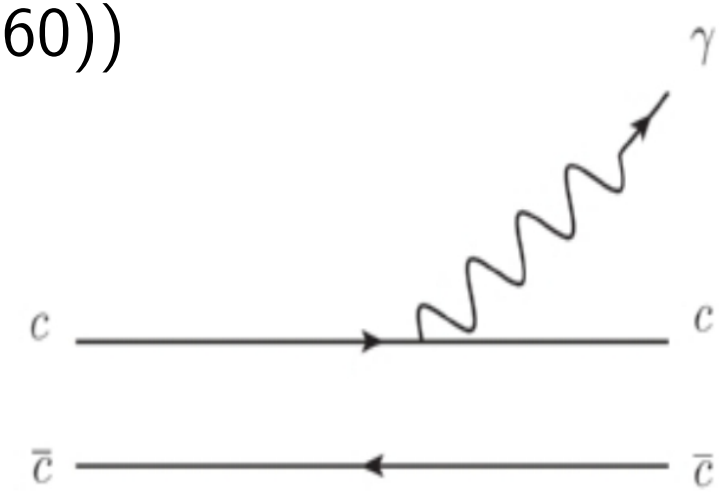
(cross section vs. $\sqrt{s}$ peaks at Y(4260))

$Y \to X$

$\to$ X(3872) in Y(4260) decay ?

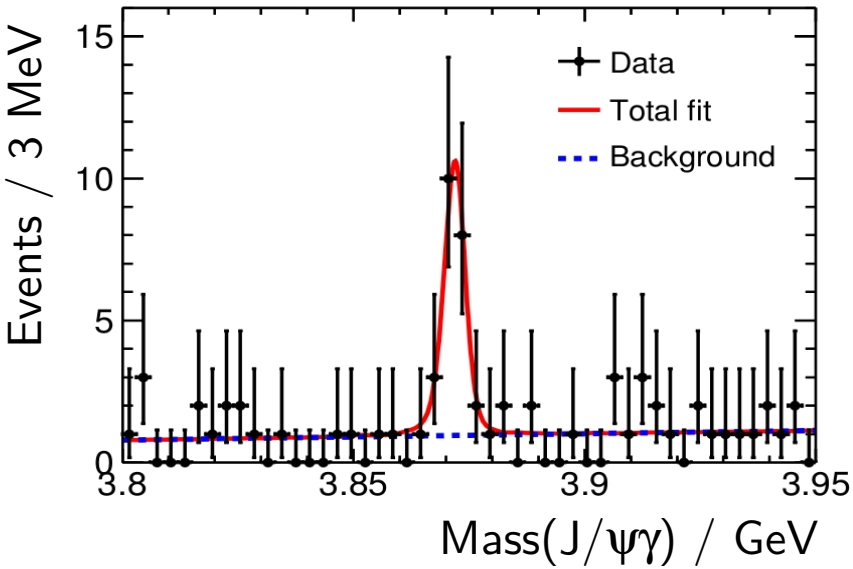
$1^{--} \to 1^{++}$, parity flip, $\Delta L=1$

$\to$ search for radiative decay



e+e− → Y(4260) → X(3872) γ

BESIII, Phys. Rev. Lett. 112(2014)092001

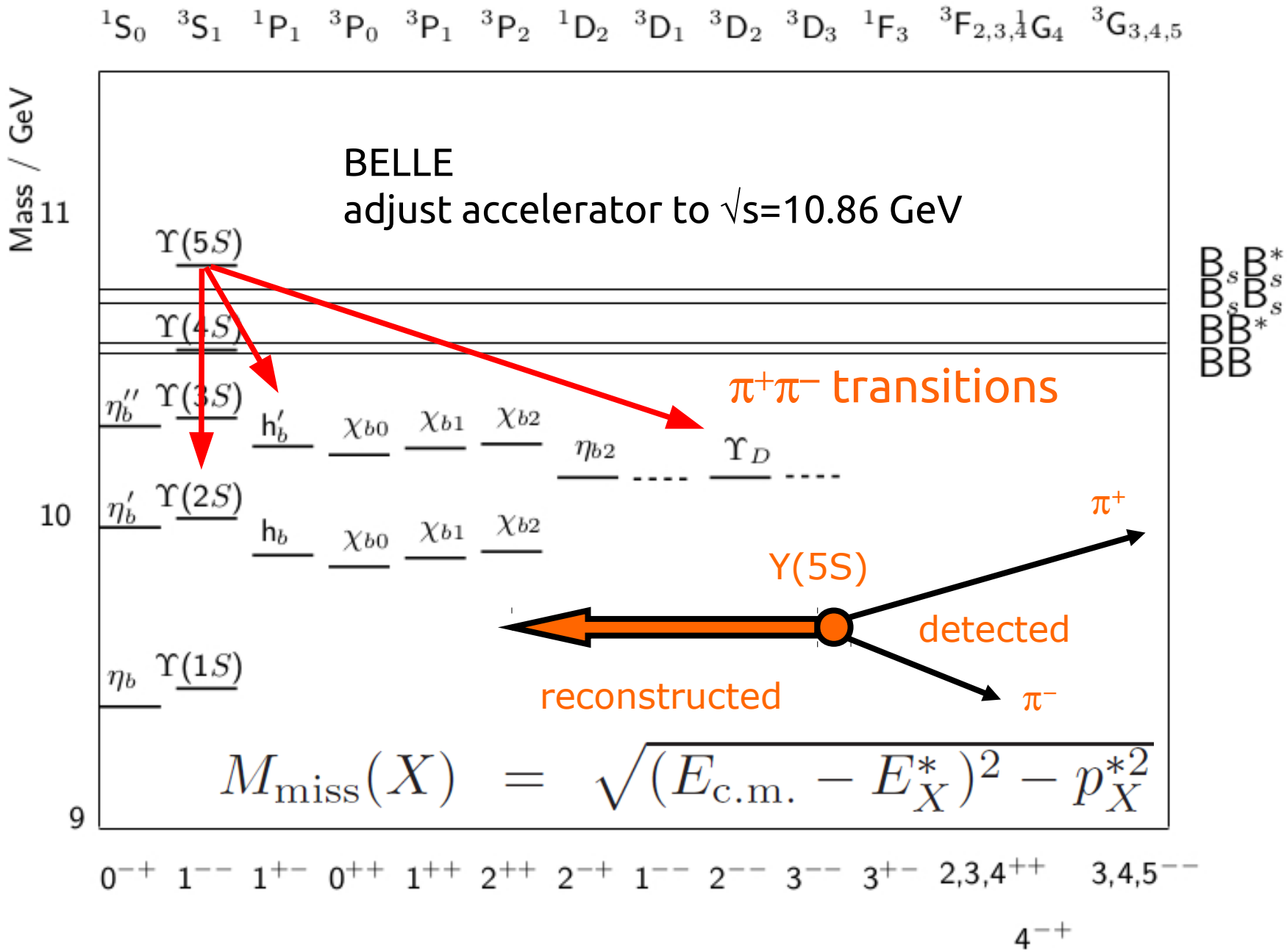


Confirmation of X(3872)
20.0 ± 4.6 events
m = (3871.9 ± 0.7 ± 0.2) MeV
6.3σ

Cross section peaks at Y(4260)

$\mathcal{B}(Y \to \gamma X)$ is factor ≤50 higher
than for E1 charmonium transition with same quantum numbers
(assume: no additional Y decay and $\mathcal{B}(X \to J/\psi\pi\pi)$=5%))

Bottomonium

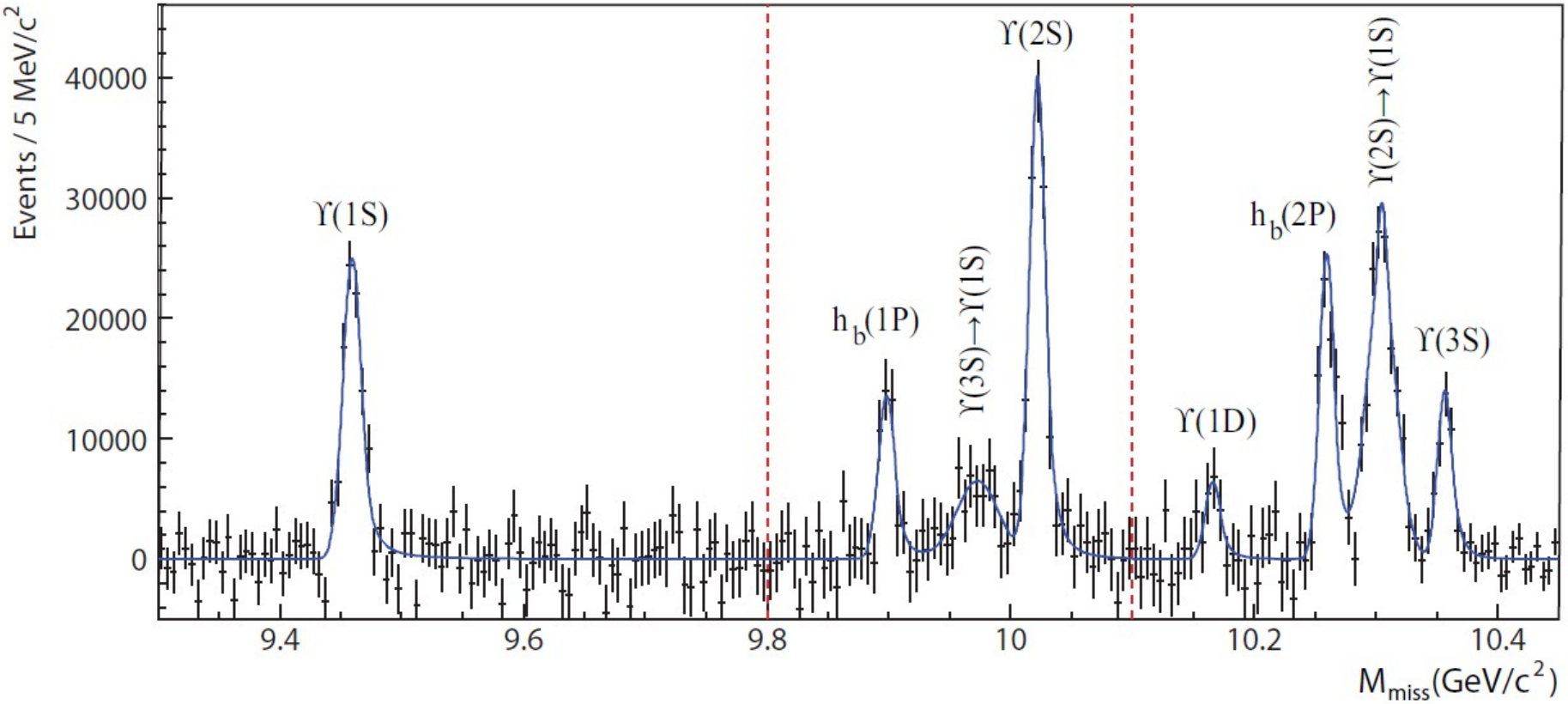

BELLE
adjust accelerator to √s=10.86 GeV
Mass / GeV
11
10
9
Υ(5S)
Υ(4S)
Υ(3S)
Υ(2S)
Υ(1S)
π+π− transitions
Υ(5S)
detected
reconstructed
π+
π−
$M_{\mathrm{miss}}(X) = \sqrt{(E_{\mathrm{c.m.}} - E^*_X)^2 - p^{*2}_X}$

Υ(5S) Decays

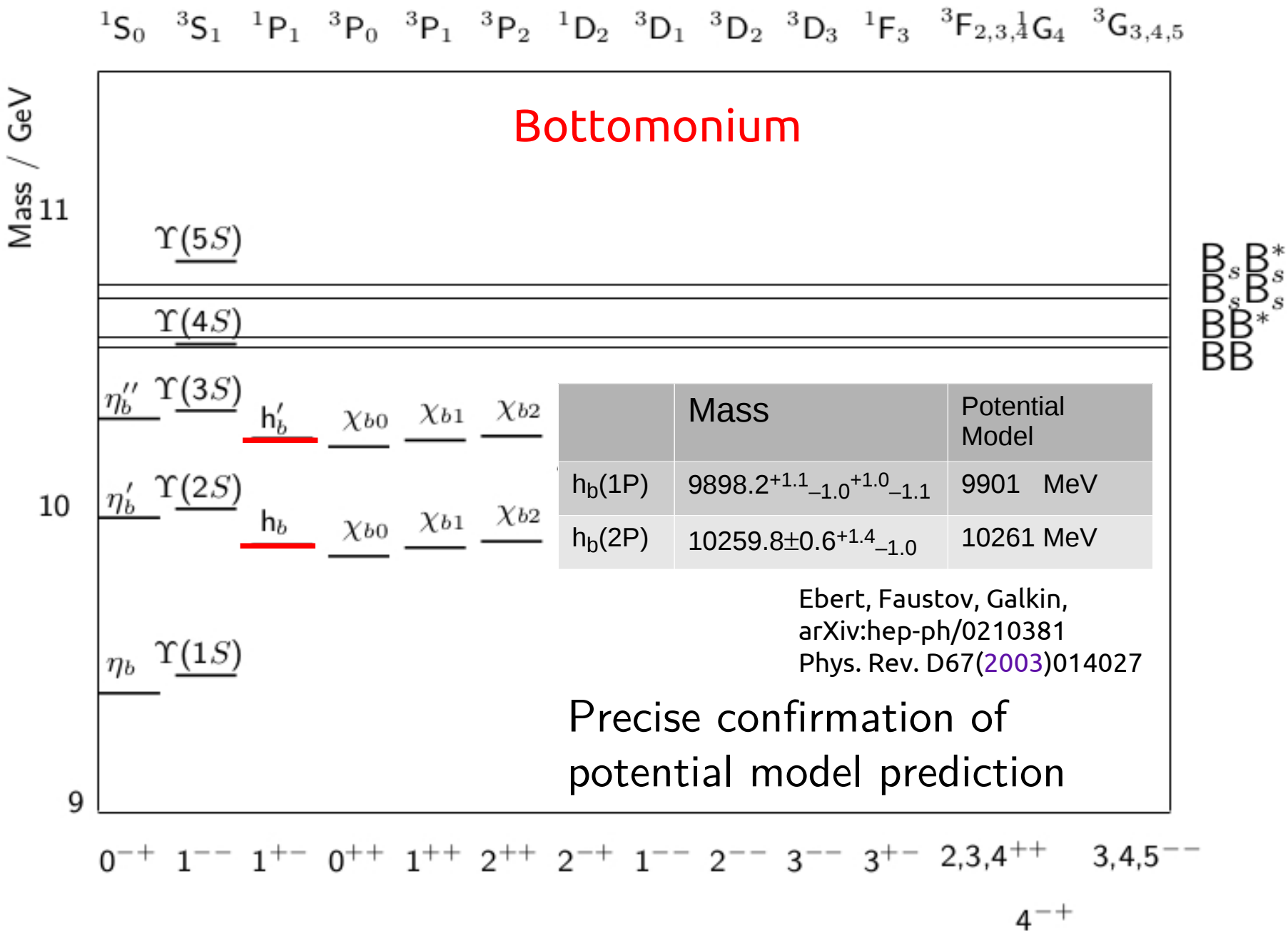
$\pi^+ \pi^-$ missing mass

First observation of $h_b(1P)$ and $h_b(2P)$

Belle, 121.4 fb^{-1}
Phys. Rev. Lett 108(2011)032001
arXiv:1103.3419



Bottomonium

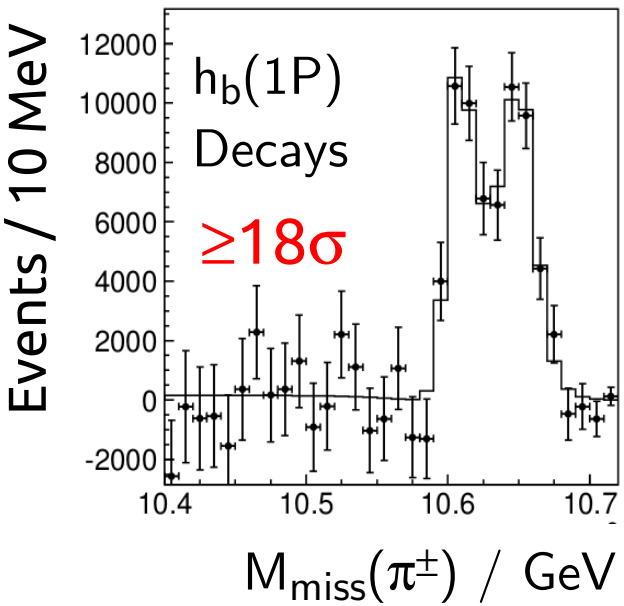


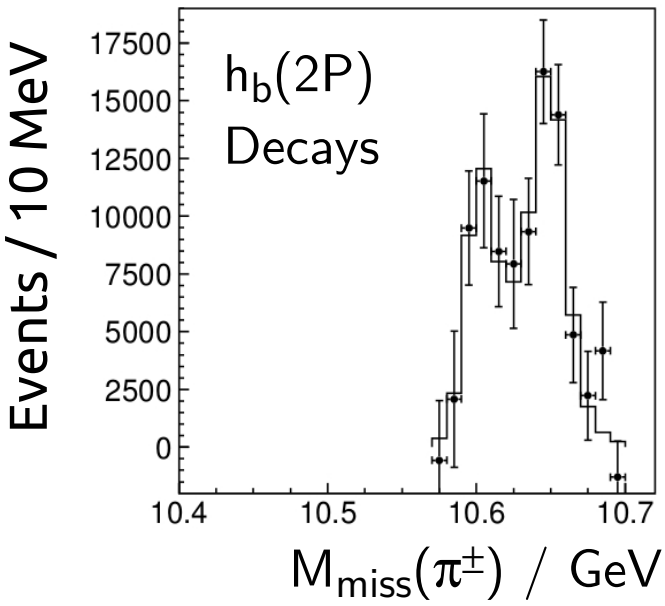
	Mass	Potential Model
$h_b(1P)$	$9898.2^{+1.1}_{-1.0}{}^{+1.0}_{-1.1}$	9901 MeV
$h_b(2P)$	$10259.8\pm0.6^{+1.4}_{-1.0}$	10261 MeV

Ebert, Faustov, Galkin,
arXiv:hep-ph/0210381
Phys. Rev. D67(2003)014027

Precise confirmation of potential model prediction

$$e^+e^- \to \Upsilon(5S) \to \underbrace{h_b(mP)\pi^\pm}_{\text{resonant state?}} \pi^\mp$$





$Z_b(10610)^\pm$ m=10607.2±2.0 MeV , Γ=18.4±2.4 MeV

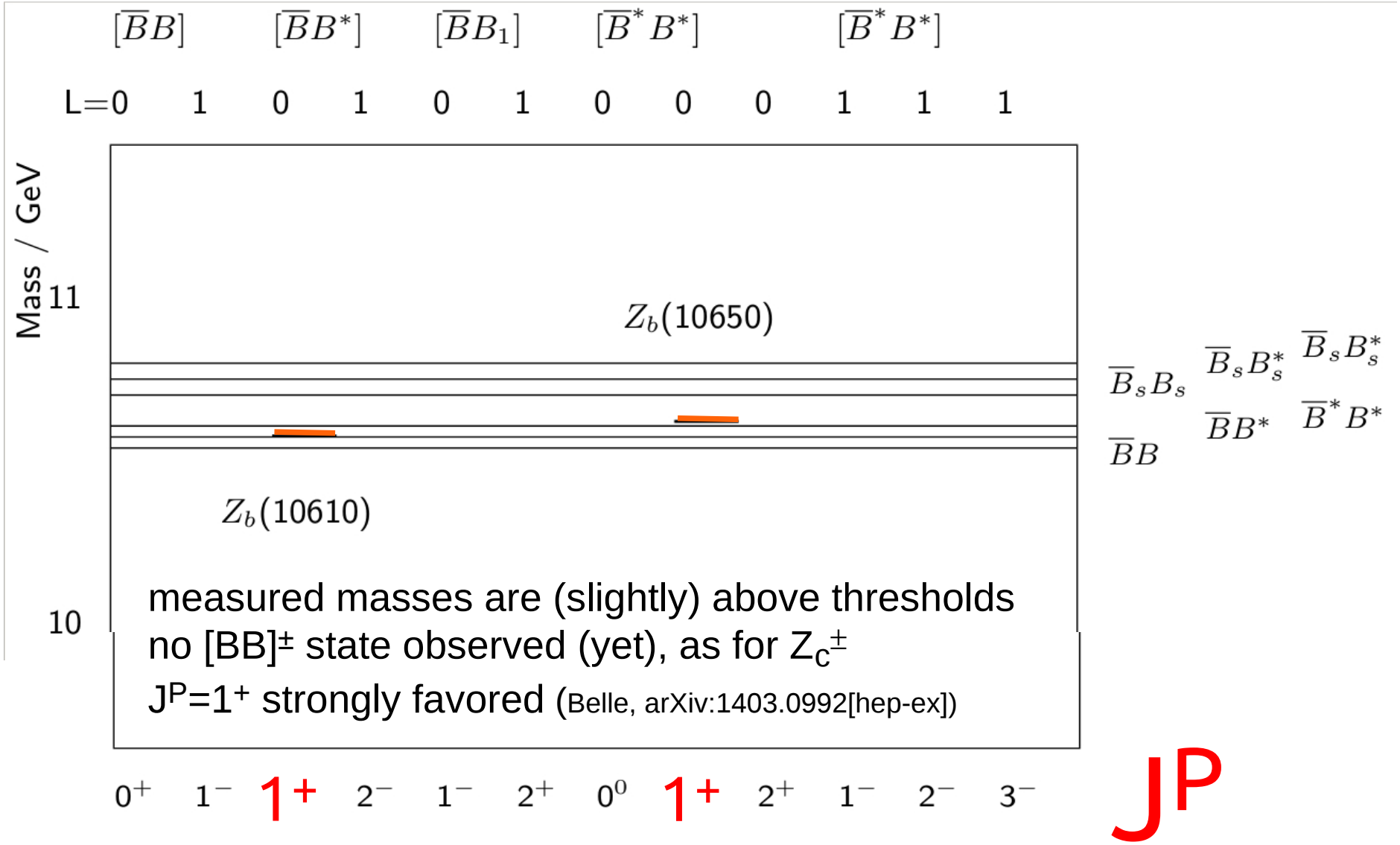
2.6 MeV above $\bar{B}B^*$ threshold

$Z_b'(10650)^\pm$ m=10652.2±1.5 MeV , Γ=11.5±2.2 MeV

2.0 MeV above $\bar{B}^*B^*$ threshold

confirmed in 3 additional decay modes

Spectrum of Z_b^+ states



NEW 2014

Neutral Z states

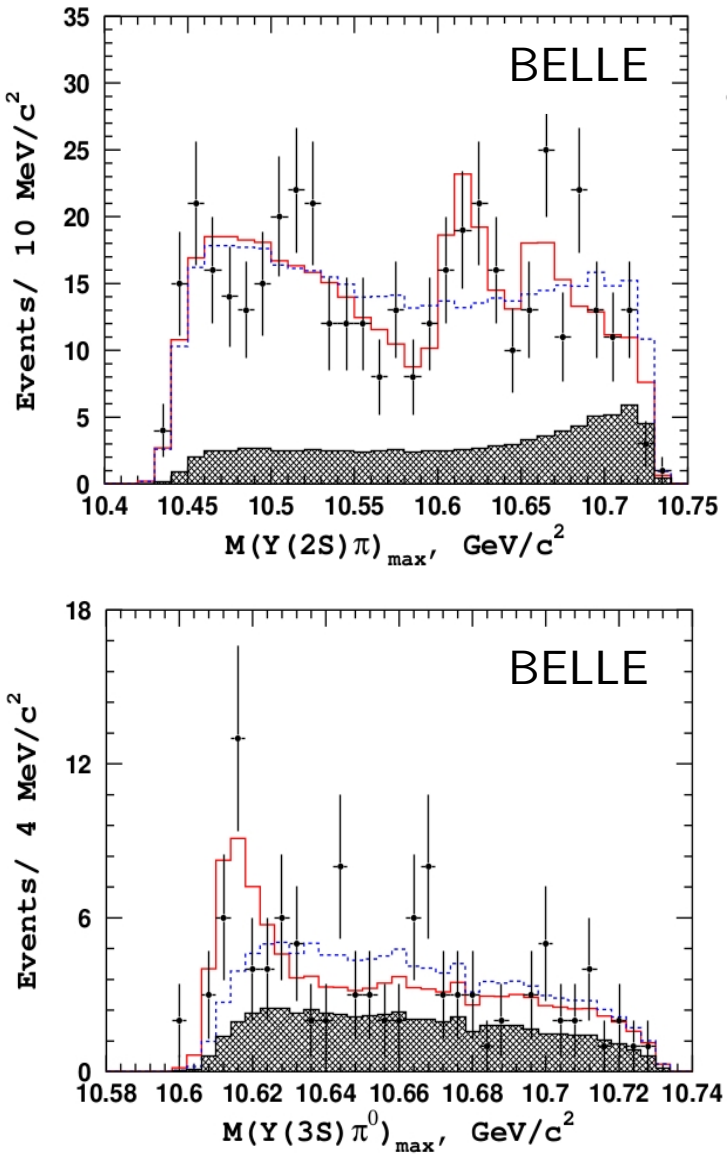
Neutral Z_b

Belle, 1308.2646[hep-ex]
Phys. Rev. D88(2013)052016

121.4 fb−1 Υ(5S) decays
$Z_b(10610)^0$
decaying to $\Upsilon(2S)\pi^0$, $\Upsilon(3S)\pi^0$
significance 6.5σ

$$\sigma(e^+e^- \to \Upsilon(1S)\pi^0\pi^0) = (1.16 \pm 0.06 \pm 0.10)\,\mathrm{pb}$$
$$\sigma(e^+e^- \to \Upsilon(2S)\pi^0\pi^0) = (1.87 \pm 0.11 \pm 0.23)\,\mathrm{pb}$$
$$\sigma(e^+e^- \to \Upsilon(3S)\pi^0\pi^0) = (0.98 \pm 0.24 \pm 0.19)\,\mathrm{pb}$$

cross sections are about factor ½ of p+p− → consistent with isospin scaling



Neutral Z_b

first evidence in CLE0c data at $\sqrt{s}$=4.17 GeV (Phys. Lett. B727(2013)366)

BESIII preliminary, QWG2014

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

m=3894.8±2.3±2.7 MeV

Γ=29.6±8.2±8.2 MeV

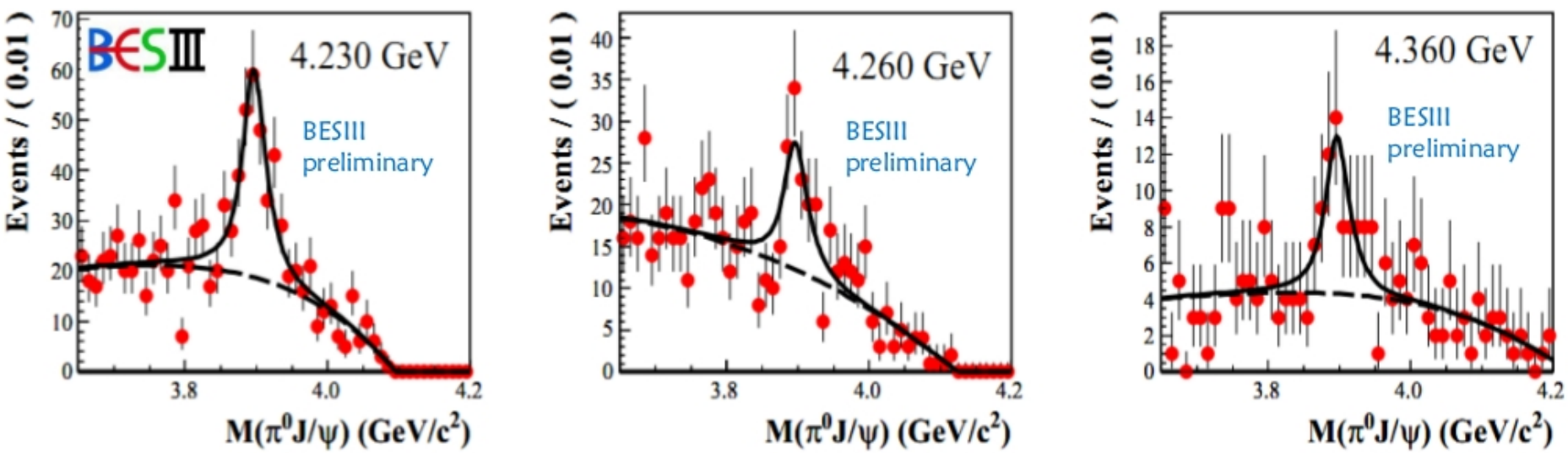
significance 10.4σ

Reminder: charged Zc(3900)+

m = 3899.0±3.6±4.9 MeV

Γ = 46±10±20 MeV

arXiv:1303.5949, PRL 110(2013)252001



Notes:

- Isospin Triplet
  $\rightarrow$ these Z States are I=1

- Remember the connection
  decay Y $\rightarrow$ X, decay Y $\rightarrow$ Z

  but there is
  a neutral Z(3900) and a neutral X(3872),
  and they are different
  (width $>$20 MeV vs. width $<$1 MeV)

2nd neutral Z_c, near $D^*\bar{D}^*$ threshold

BESIII 1409.6577[hep-ex], Phys. Rev. Lett. 113, 212002 (2014)

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

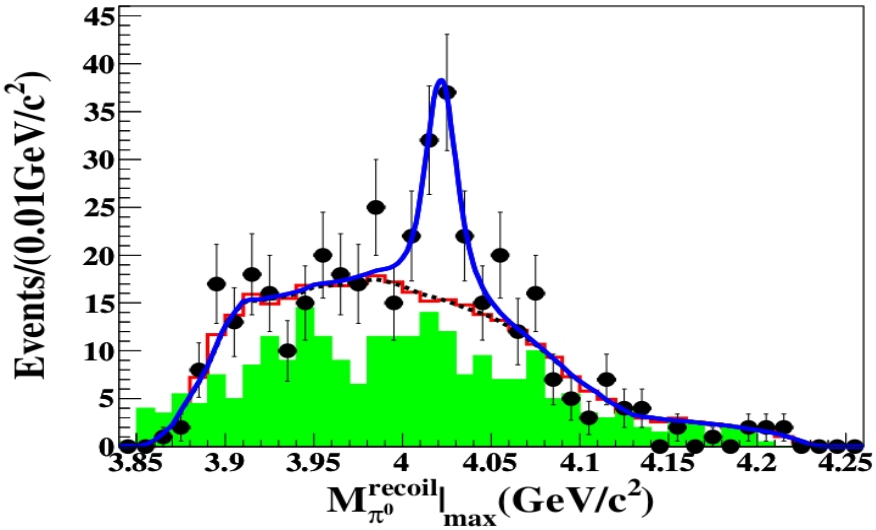
$hc \rightarrow \gamma\,\eta_c$ with 16 reconstructed η_c decay channels

$Z_c(4020)^0$

$>5\sigma$

m=4023.9±2.2±3.8 MeV

no width measurement
width is fixed to charged Z



Isospin in $Z_c(4020)^0$ production

BESIII, 1409.6577[hep-ex], Phys. Rev. Lett. 113(2014)212002

$$\frac{\sigma(e^+e^- \to \pi^0\pi^0 h_c)}{\sigma(e^+e^- \to \pi^+\pi^- h_c)}$$

→ ratio ½, as expected from isospin scaling (similar to Υ(nS) transitions)

$\sqrt{s}$ (GeV)	$\mathcal{R}_{\pi\pi h_c}$
4.230	$0.54 \pm 0.11 \pm 0.06$
4.260	$0.63 \pm 0.14 \pm 0.10$
4.360	$0.73 \pm 0.14 \pm 0.10$

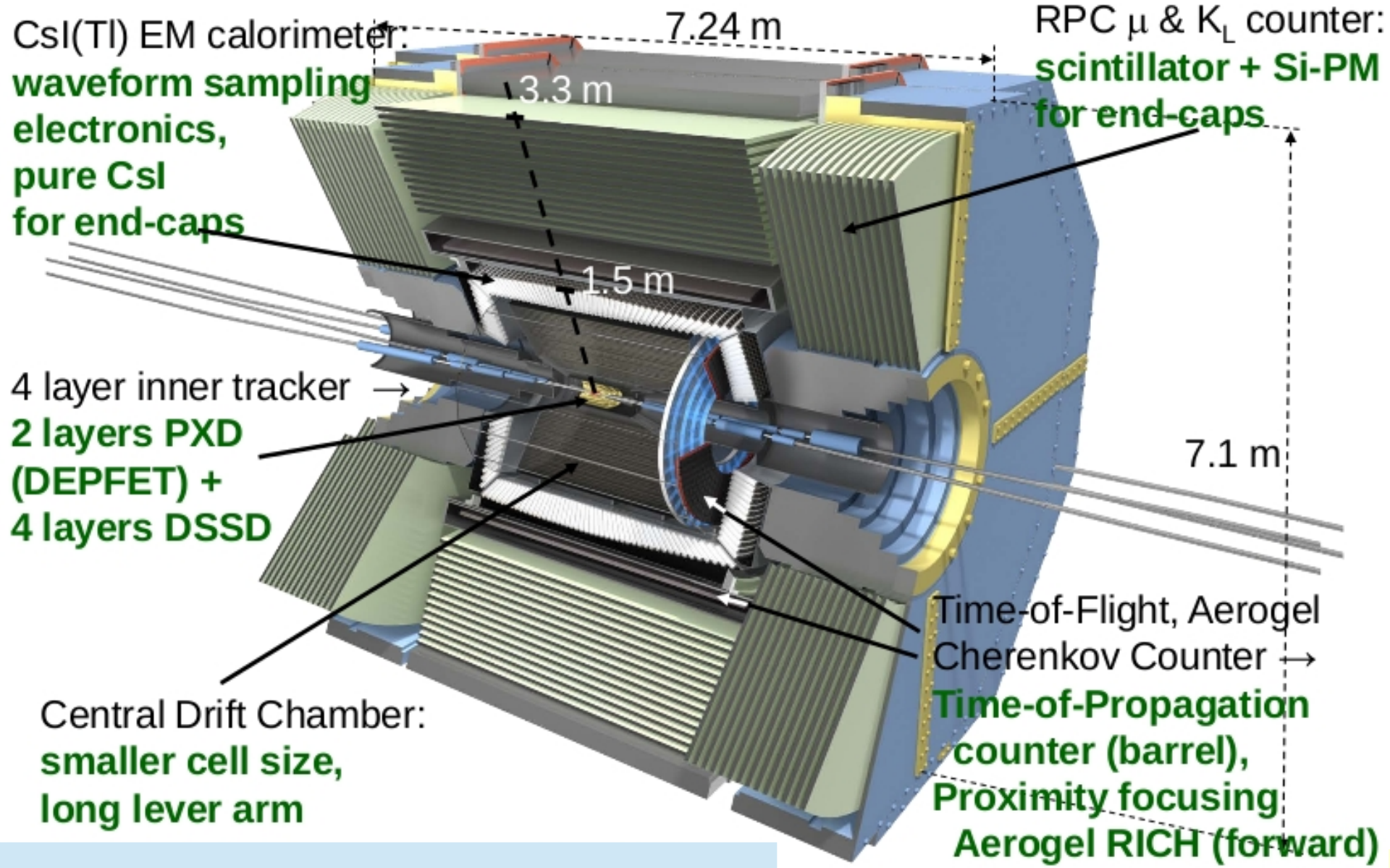
$$\frac{\sigma(e^+e^- \to \pi^0 Z_c(4020)^0 \to \pi^0\pi^0 h_c)}{\sigma(e^+e^- \to \pi^\pm Z_c(4020)^\mp \to \pi^\pm\pi^\mp h_c)}$$

→ ratio closer to ~1 (?) (but ½ not excluded)

$\sqrt{s}$ (GeV)	$R_{\pi Z_c(4020)}$
4.230	$0.77 \pm 0.31 \pm 0.25$
4.260	$1.21 \pm 0.50 \pm 0.38$
4.360	$1.00 \pm 0.48 \pm 0.32$

Future Experiments: Belle II, $\overline{\text{P}}$ANDA

The Belle II Detector



Belle II in service position for upgrade

Foto 04.11.2014

Super KEKB

BELLE

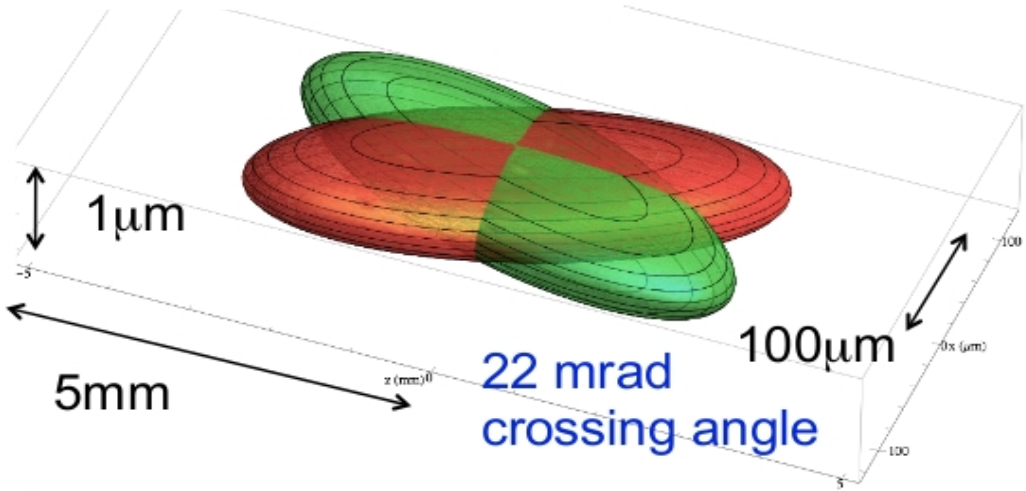
Belle II

Bundesministerium für Bildung und Forschung

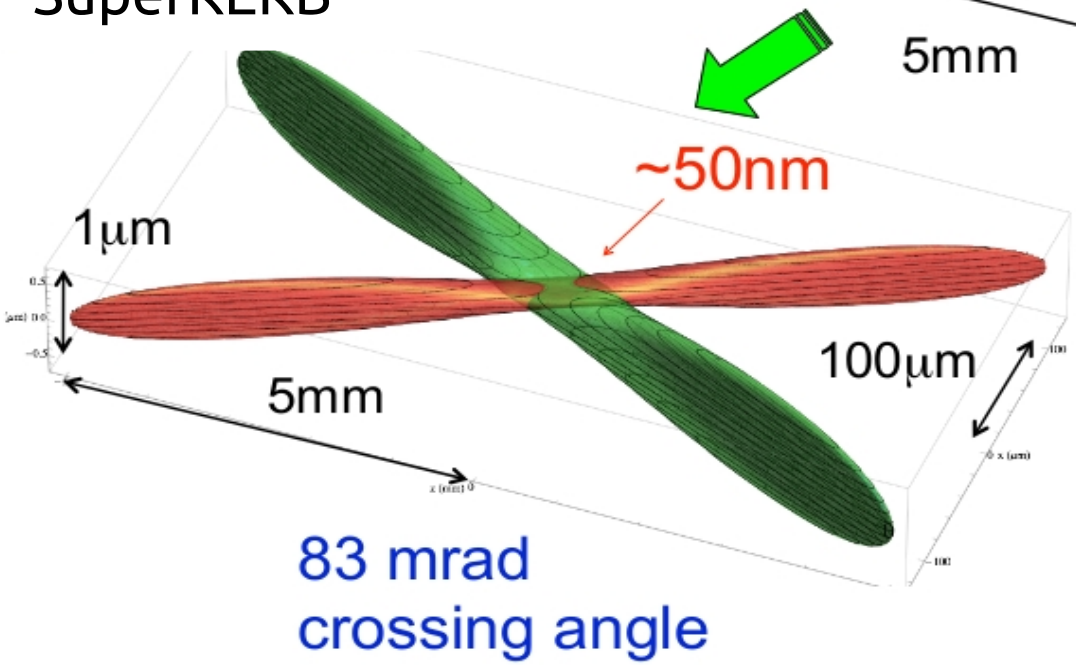
Nano-Beam Scheme

Belle → Belle II
Luminosity x 40
$\mathcal{L} \leq 0.8 \times 10^{36}\ cm^{-2}\ s^{-1}$

KEKB (without crab)

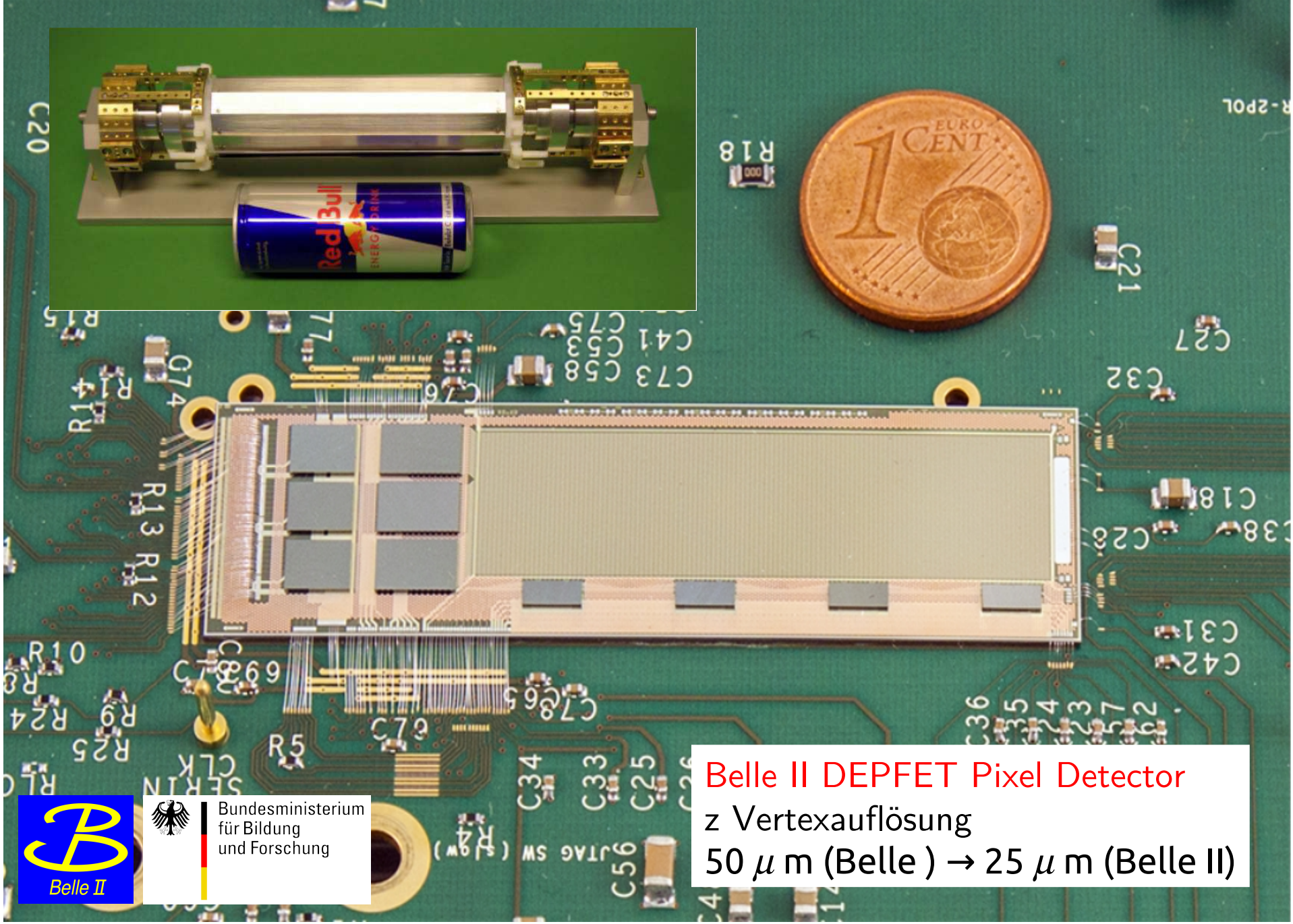


SuperKEKB



originally proposed for SuperB
by P. Raimondi (INFN)

graphics E. Paoloni (Pisa)



Belle II DEPFET Pixel Detector

z Vertexauflösung

50 μ m (Belle) → 25 μ m (Belle II)

Belle II

Bundesministerium
für Bildung
und Forschung

Installation of 100 new LER Dipole Magnets

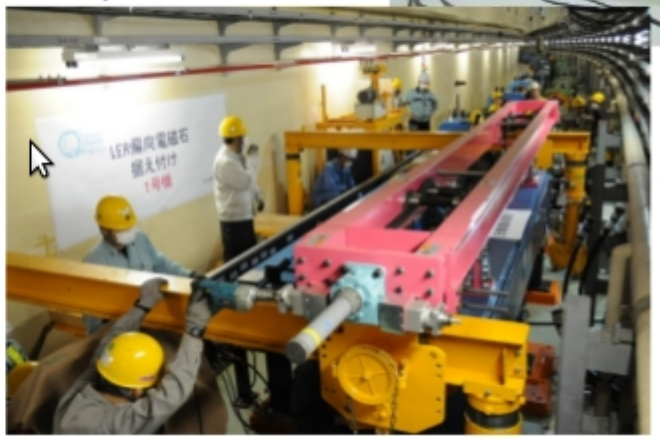
field measurement

move into tunnel

Installation of 100 new LER bending magnets done

carry on an air-pallet

Install over HER magnets



~3 magnets per day

SuperKEKB Status, 7th BPAC, Mar. 11, 2013, K. Akai

19

B-KLM Installation

2013

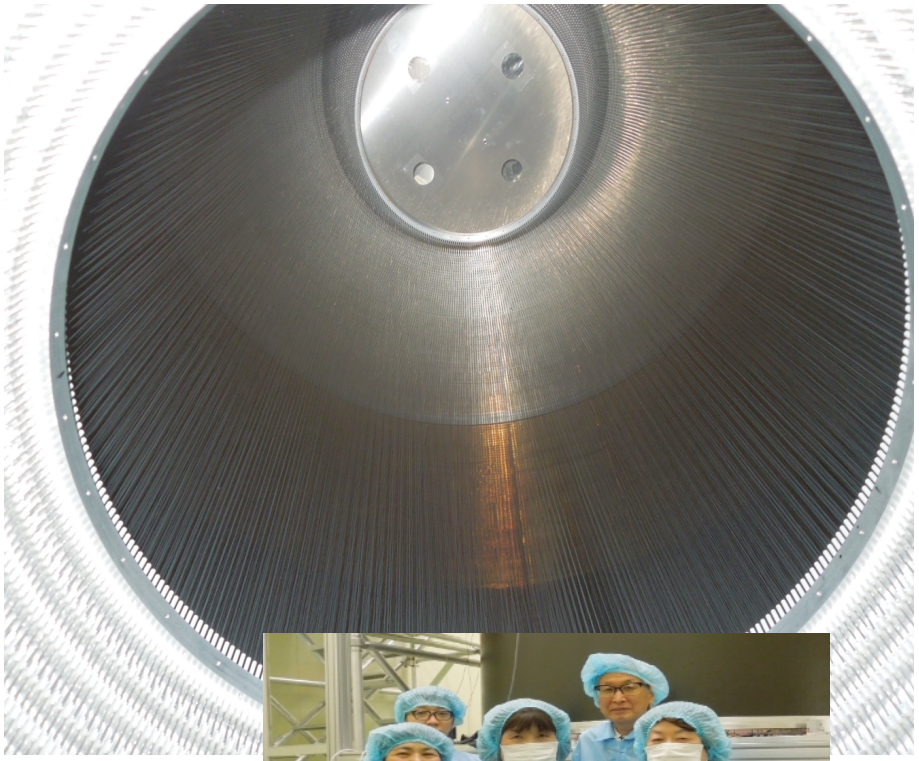
Completed on November 16th

~2 months delay

During installation, modules have been checked, found to be healthy.

The 1st New Detector Installed !!

CDC wire stringing finished (01/2014)
51456 wires



FWD side: ground cabling finished (11/2014)
white: axial super layers
green: stereo super layers

TOP Assembly of 1st Module

Mirror

Glue joint between two bars

Optics done, need to integrate with bar box

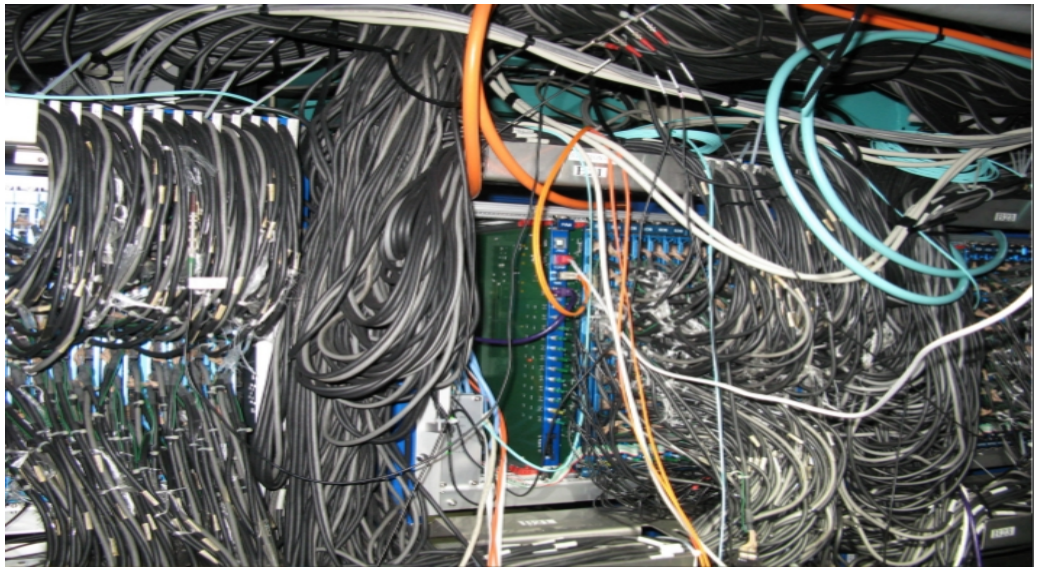
Lifting jig with vacuum chucks

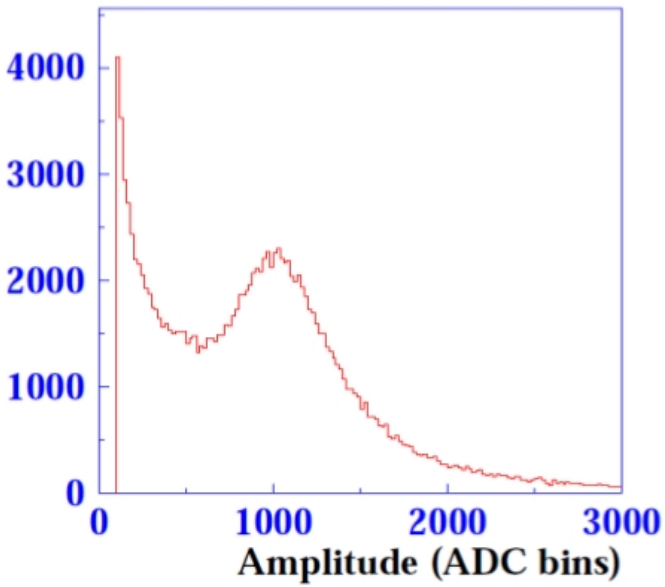
"Expansion block" or prism

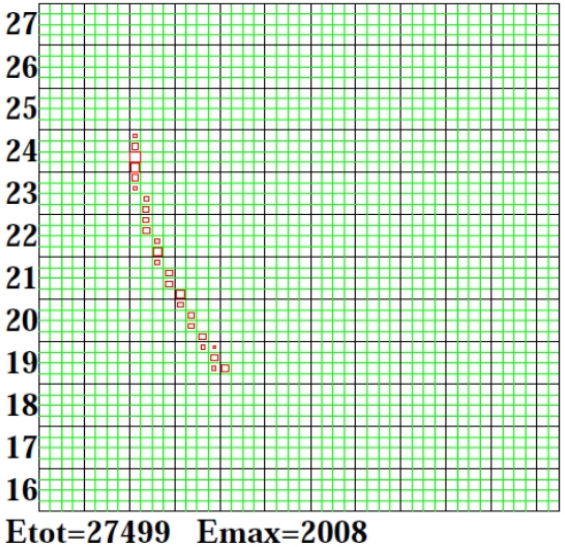
Scene at the Fuji Hall clean room just before Halloween 2014

ECL cosmic data taking w/ ~4000 crystals

31.10.2014, w/ new electronics:
- shaping time 1 us (before) $\rightarrow$ 0.5 us (Belle II)
- waveform digitization 2 MSamples/s

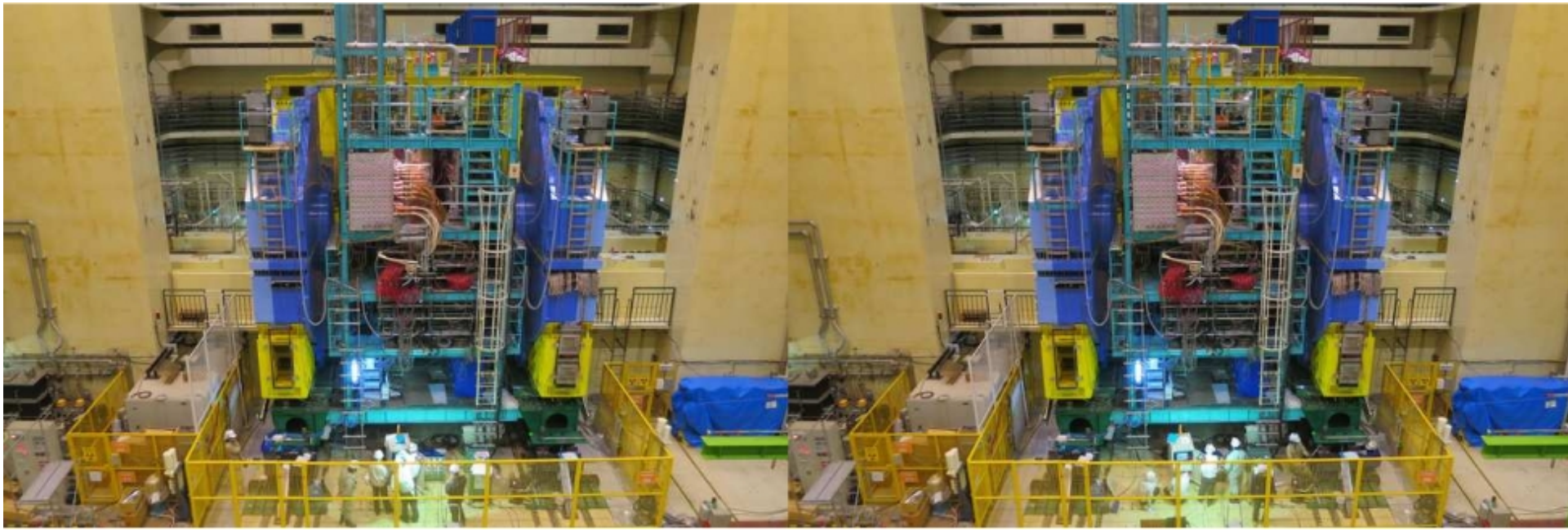






Belle Rotation 03/2013

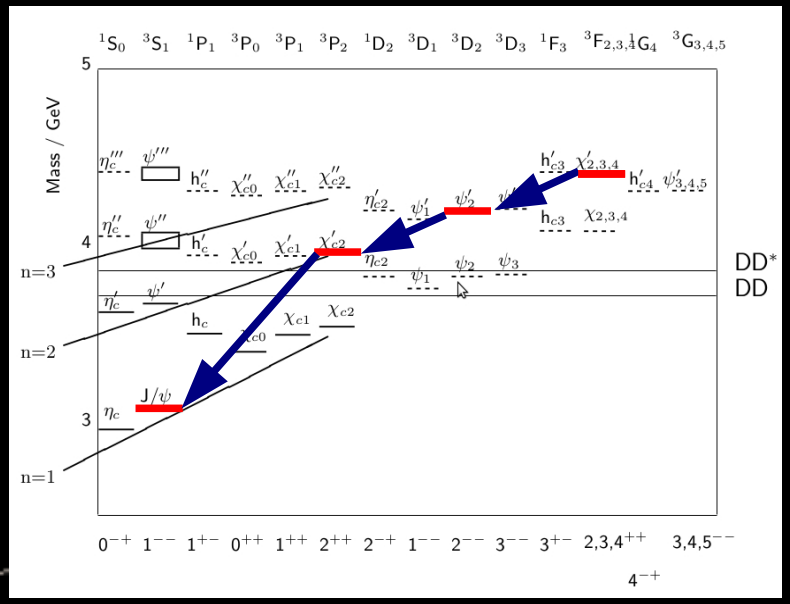
for larger crossing angle 22 mrad $\rightarrow$ 83 mrad (nanobeam)

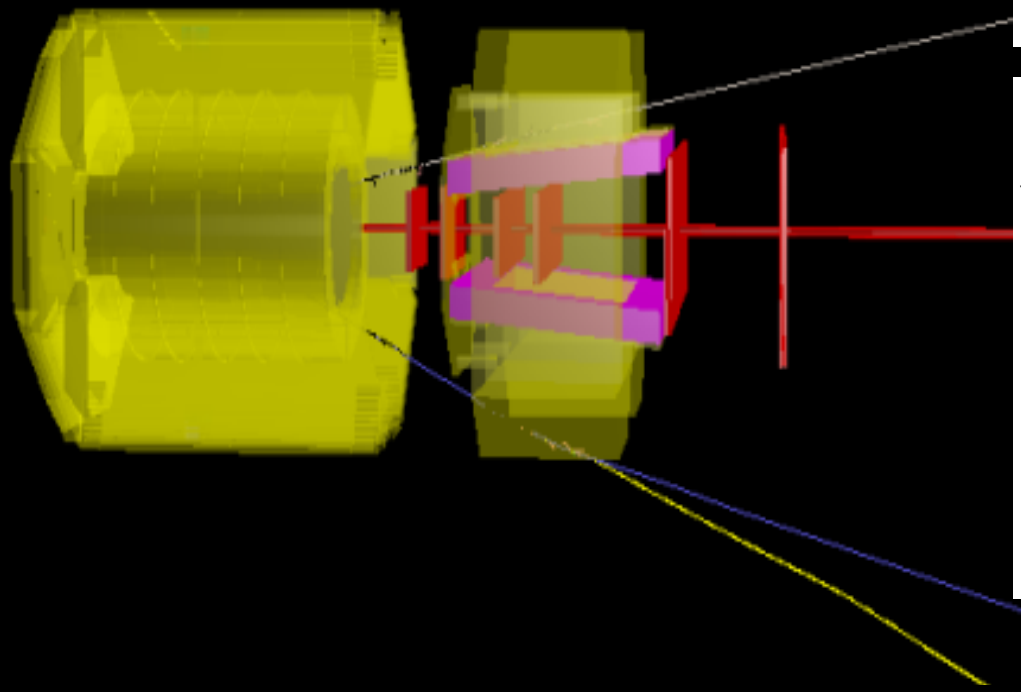


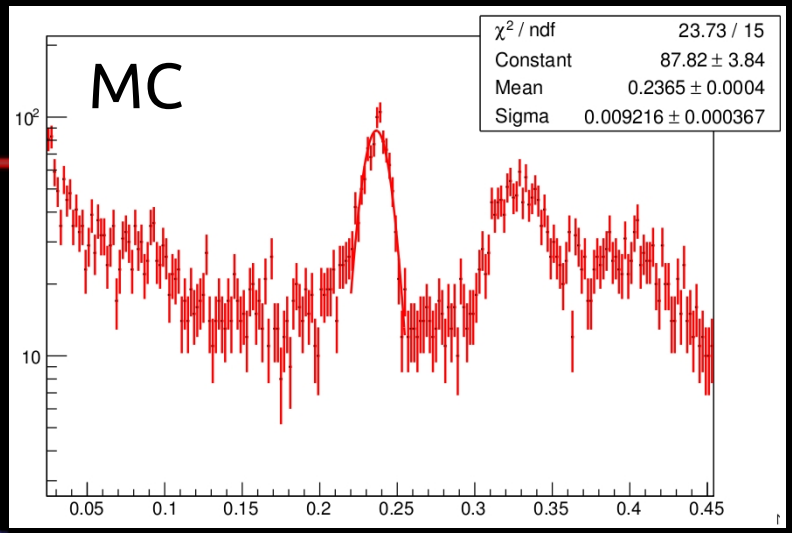
18.6 cm @ end of platform (accuracy 0.5 mm)

$\bar{P}$ANDA @ FAIR

$\bar{p}p \rightarrow$ formation of
any (non-exotic) quantum number
e.g. high F-wave state (L=3, $J^{PC}=4^{++}$)
suppressed in B decays
suppressed in radiative decays of 1^{--}







E_γ^{cms}/GeV

M. Galuska, S. Reiter, E. Prencipe, S. Spataro, S.L.
arXiv:1311.7597[hep-ex]

Many states not covered today

State	Production	J^{PC}	Mass (MeV)	Width (MeV)	Decay	Experiment	Interpretation
X(3872)	B decays, $p\bar{p}$	1^{++}	$\simeq$3872	<1.2	$J/\psi\rho$, $J/\psi\omega$ $J/\psi\gamma$, $D^0\overline{D}^{0*}$	Belle, *BABAR* , CDF D0, LHCb, CMS	4-quark, $(D^0\overline{D}^{*0})$ molecule?
X(3940)	$e^+e^-\to c\bar{c}X$	$0^{?+}$	$\simeq$3942	$\simeq$37	$D\overline{D}^*$ (not $D\overline{D}$, $J/\psi\omega$)	Belle	shifted η_c''?
Y(3940)	B decays	$?^{?+}$	$\simeq$3943	$\simeq$20	$J/\psi\omega$ (not DD^*)	Belle, *BABAR*	shifted χ_{c0}'?
$Z_c(3900)$	Y(4260) decays	1^+	$\simeq$3899	$\simeq$46	$J/\psi\pi^\pm$	BESIII, Belle	4-quark ? $(D\overline{D}^*)^\pm$ molecule?
$Z_c(3885)$	Y(4260) decays	$?^?$	$\simeq$3884	$\simeq$25	$(D\overline{D}^*)^\pm$	BESIII	4-quark ? $(D\overline{D}^*)^\pm$ molecule?
$Z_c(4020)$	Y(4260) decays	$?^?$	$\simeq$4023	$\simeq$8	$h_c\pi^\pm$	BESIII	4-quark ? $(D^*\overline{D}^*)^\pm$ molecule?
$Z_c(4025)$	Y(4260) decays	$?^?$	$\simeq$4026	$\simeq$25	$(D^*D^*)^\pm$	BESIII	4-quark ? $(D^*\overline{D}^*)^\pm$ molecule?
Y(4140)	B decays	$?^{?+}$	$\simeq$4143	$\simeq$15	$J/\psi\phi$	CDF	$c\bar{c}s\bar{s}$
X(4160)	$e^+e^-\to c\bar{c}X$	$0^{?+}$	$\simeq$4156	$\simeq$139	$D^*\overline{D}^*$ (not $D\overline{D}$, $D\overline{D}^*$)	Belle	η_c''?
Y(4008)	ISR	1^{--}	$\simeq$4008	$\simeq$226	$J/\psi\pi^+\pi^-$	Belle (not *BABAR*)	$c\bar{c}g$ hybrid?
Y(4260)	ISR	1^{--}	$\simeq$4264	$\simeq$83	$J/\psi\pi^+\pi^-$, $J/\psi\pi^0\pi^0$, $J/\psi K^+K^-$	*BABAR* , CLEO, Belle	$c\bar{c}g$ hybrid?
X(4350)	$\gamma\gamma$	$?^{?+}$	$\simeq$4351	$\simeq$13	$J/\psi\phi$	Belle	$c\bar{c}s\bar{s}$
Y(4350)	ISR	1^{--}	$\simeq$4361	$\simeq$74	$\psi'\pi^+\pi^-$	*BABAR* , Belle	$c\bar{c}g$ hybrid?
Y(4660)	ISR	1^{--}	$\simeq$4664	$\simeq$48	$\psi'\pi^+\pi^-$	Belle	$c\bar{c}g$ hybrid?
X(4630)	ISR	1^{--}	$\simeq$4634	$\simeq$92	$\Lambda_c\overline{\Lambda_c}$	Belle	$\Lambda_c\overline{\Lambda_c}$ molecule?
$Z^\pm(4050)$	B decays	$?^?$	$\simeq$4051	$\simeq$82	$\chi_{c1}\pi^\pm$	Belle	4-quark?
$Z^\pm(4250)$	B decays	$?^?$	$\simeq$4248	$\simeq$177	$\chi_{c1}\pi^\pm$	Belle	4-quark?
$Z^\pm(4430)$	B decays	$?^?$	$\simeq$4433	$\simeq$45	$\psi'\pi^\pm$	Belle (not *BABAR*)	4-quark?
$Z_b^\pm(10610)$	$\Upsilon(5S)$ decays	1^+	$\simeq$10607	$\simeq$18	$\Upsilon(1S)\pi^\pm$ $\Upsilon(2S)\pi^\pm$ $\Upsilon(3S)\pi^\pm$ $h_b(1P)\pi^\pm$ $h_b(2P)\pi^\pm$	Belle	4-quark? $(B\overline{B}^*)^\pm$ molecule?
$Z_b^\pm(10650)$	$\Upsilon(5S)$ decays	1^+	$\simeq$10652	$\simeq$11	$\Upsilon(1S)$ $\Upsilon(2S)\pi^\pm$ $\Upsilon(3S)\pi^\pm$ $h_b(1P)\pi^\pm$ $h_b(2P)\pi^\pm$	Belle	4-quark? $(B^*\overline{B}^*)^\pm$ molecule?
$Y_b(10889)$	e^+e^-	1^{--}	$\simeq$10890	$\simeq$100	$\psi'\pi^\pm$ $\Upsilon(1S)\pi^+\pi^-$ $\Upsilon(2S)\pi^+\pi^-$ $\Upsilon(3S)\pi^+\pi^-$	Belle (not *BABAR*) Belle	4-quark? 4-quark, $[b\bar{b}]_8g$ hybrid? rescattering?

SUMMARY

- Experiments at e^+e^- colliders re-defined our understanding of hadrons
- Many unexplained states have $J^{P(C)}=1^{+(+)}$
- Probably 1st transitions between X and Y and Z observed
- Product branching fractions of XYZ states are small ($\mathcal{B}\sim10^{-5}$)
  $\rightarrow$ next-generation high luminosity experiments are required
  Belle II, PANDA, LHCb (upgrade), more BESIII running ...

THANK YOU.