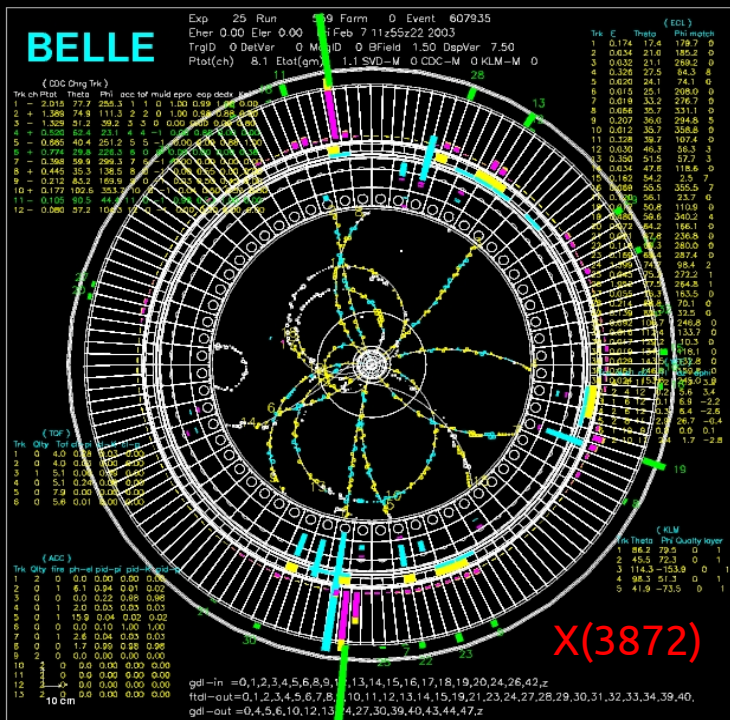




XYZ

Exotic states in the charmonium and bottomonium mass regions

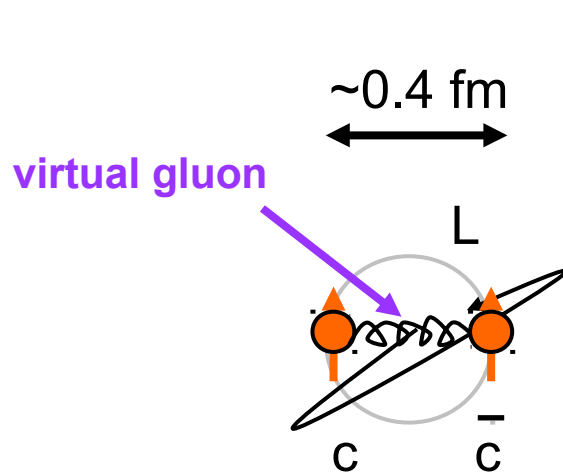
Jens Sören Lange
 Justus-Liebig-Universität Gießen

Dienstag Seminar, DESY Hamburg, 13.05.2014
 Colloquium, DESY Zeuthen, 14.05.2014

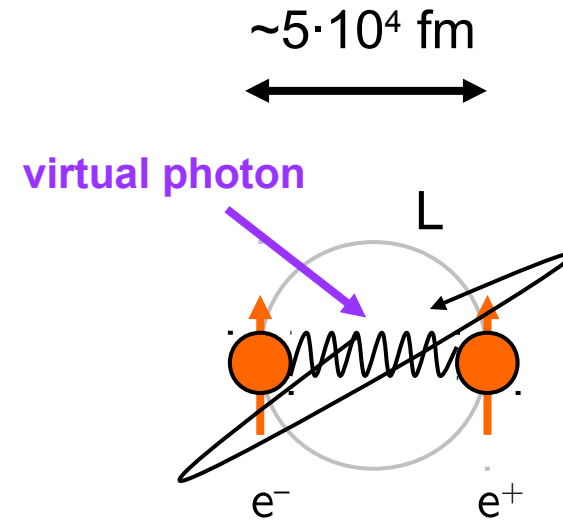
OUTLINE

- Potential model of charmonium and bottomonium
- Experiments: Belle, BaBar, BESIII
- Charmonium(-like) states
 - $X(3872)$
 - $Y(4260)$
 - $Z_c^\pm(3900)$
- Bottomonium(-like) states
 - Implications for potential model (→ **confinement**)
 - $Z_b^\pm$
- Future experiments: Belle II, $\overline{\text{PANDA}}$

Charmonium vs. Positronium



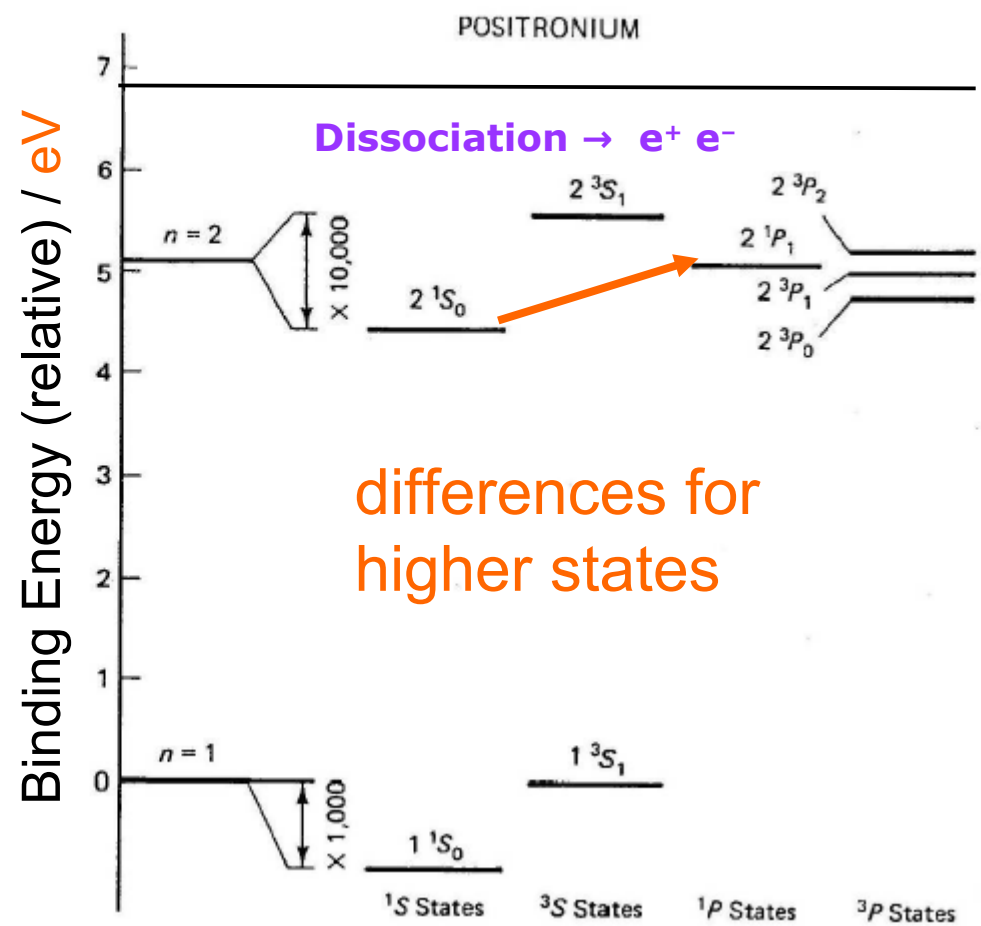
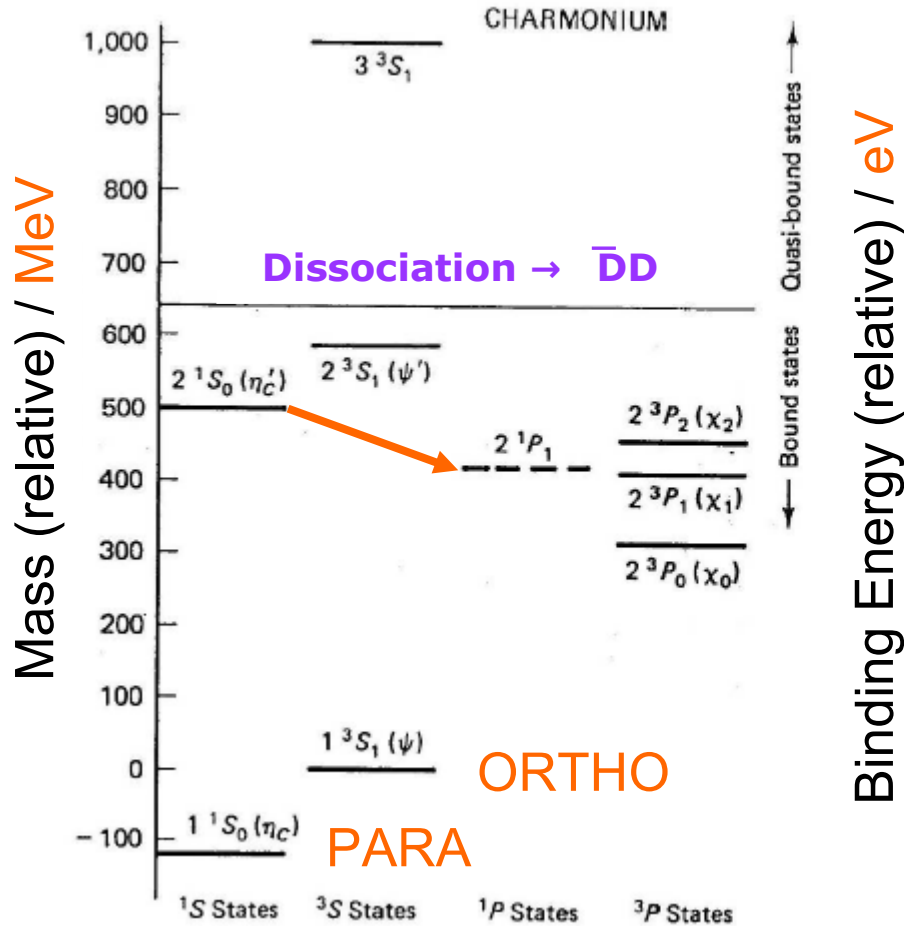
Charmonium



Positronium

Charmonium vs. Positronium

Decays to light quarks suppressed
→ narrow widths



differences for
higher states

Static Quark-Antiquark Potential

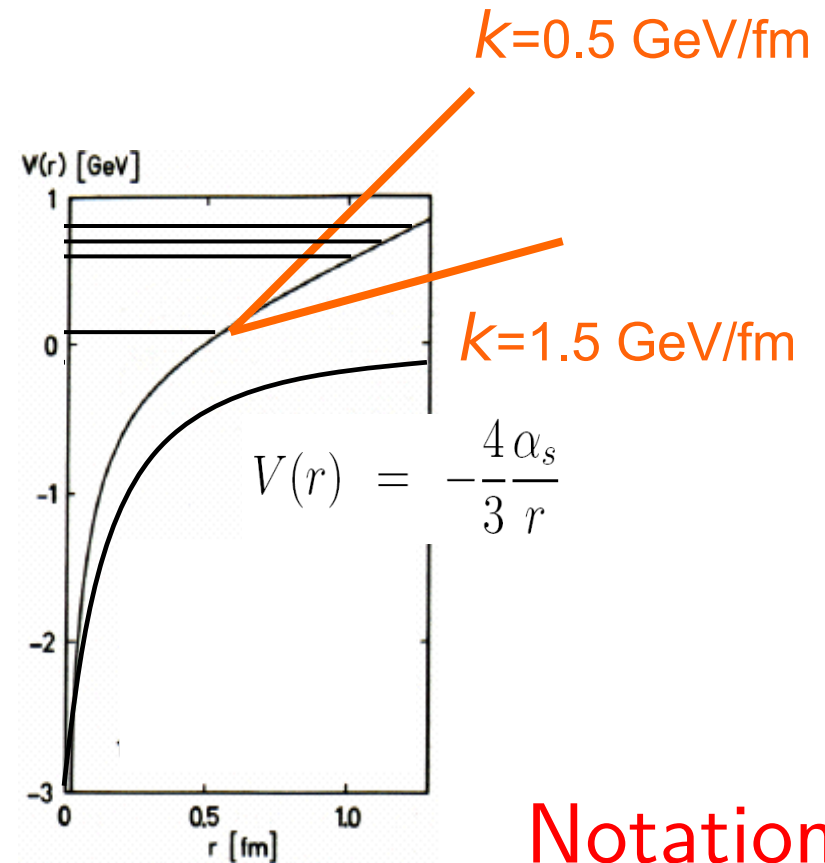
- Coulomb-Potential
+ Confinement-Term

$$\begin{aligned}
 V(r) = & -\frac{4\alpha_s}{3r} + \boxed{kr} \\
 \text{spin-spin} & + \frac{32\pi\alpha_s}{9m_c^2} \delta_r \vec{S}_c \vec{S}_{\bar{c}} \\
 \text{spin-orbit} & + \frac{1}{m_c^2} \left(\frac{2\alpha_s}{r^3} - \frac{k}{2r} \right) \vec{L} \vec{S} \\
 \text{tensor} & + \frac{1}{m_c^2} \frac{4\alpha_s}{r^3} \left(\frac{3\vec{S}_c \vec{r} \cdot \vec{S}_{\bar{c}} \vec{r}}{r^2} - \vec{S}_c \vec{S}_{\bar{c}} \right)
 \end{aligned}$$

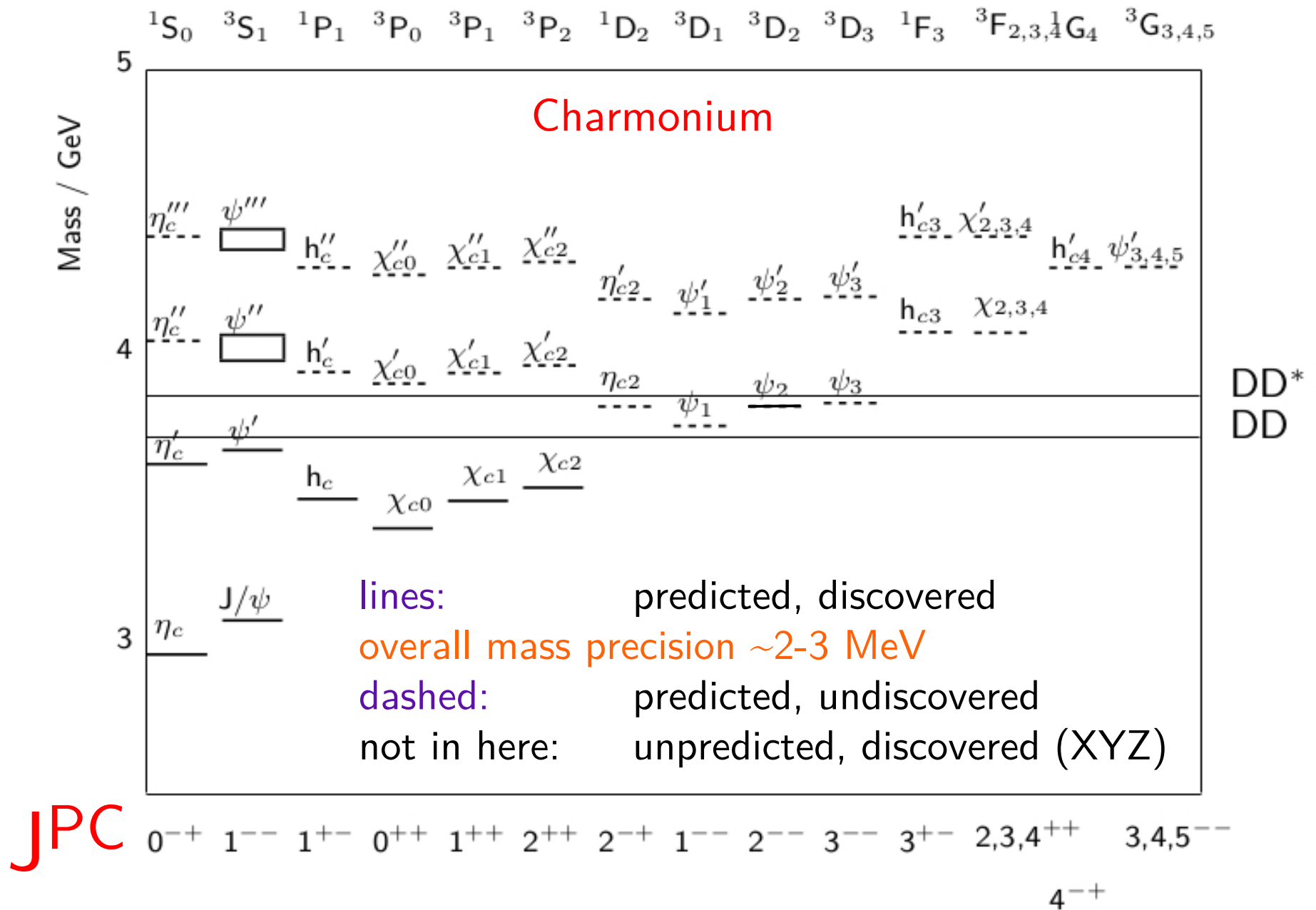
- solve Schrödinger equation
(quark mass heavy → non-relativistic)
→ states

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

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



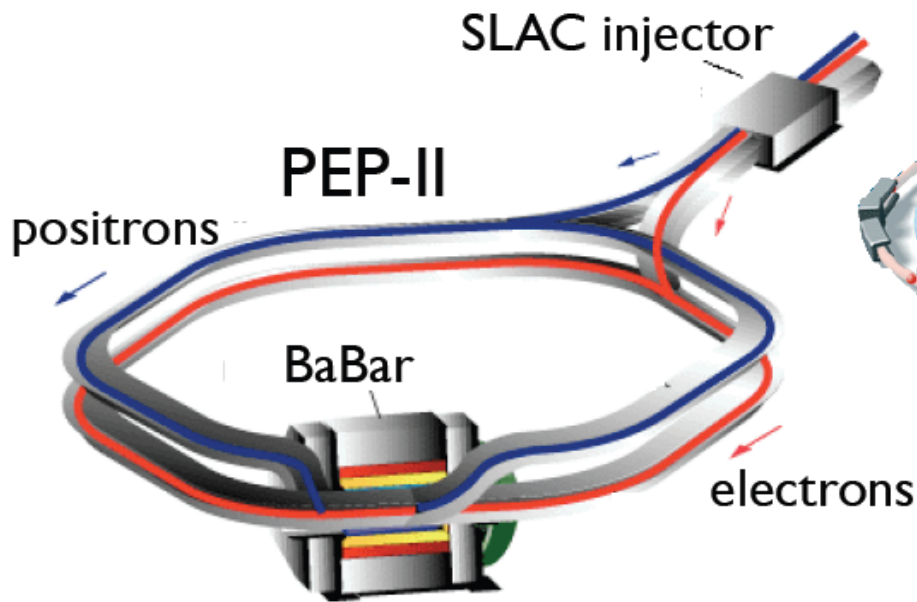
Notation
 $n^{2S+1}L_J$
 J^{PC}



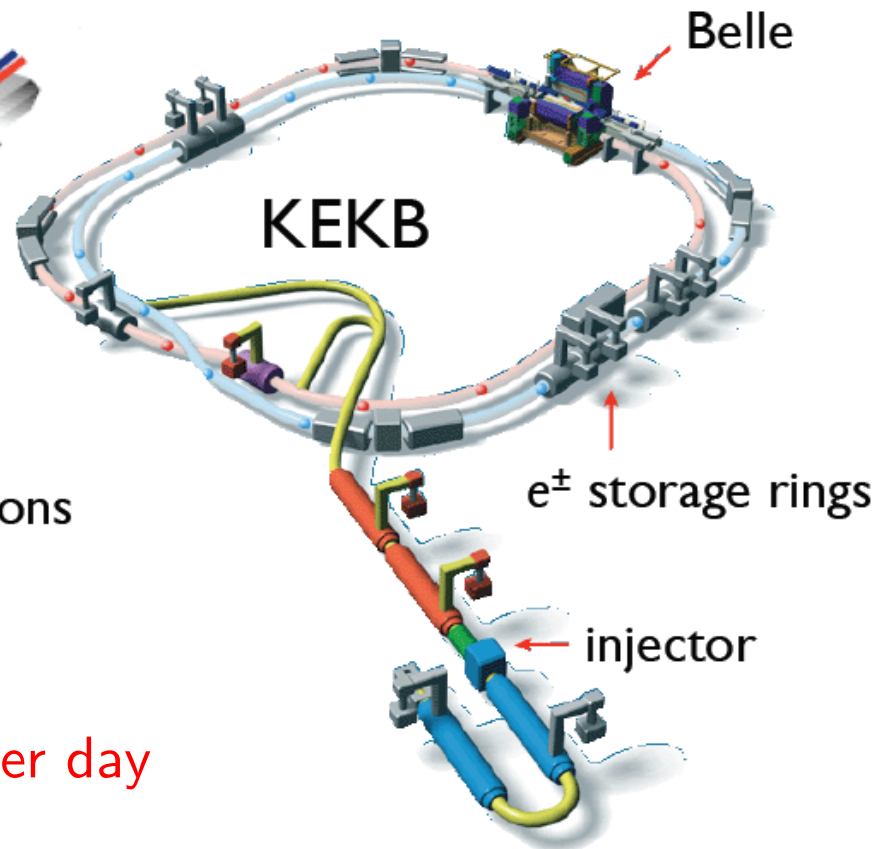
B Meson Factories

$$e^+e^- \rightarrow Y(4S) \rightarrow BB \quad (\mathcal{B} \sim 99\%)$$

1999-2008

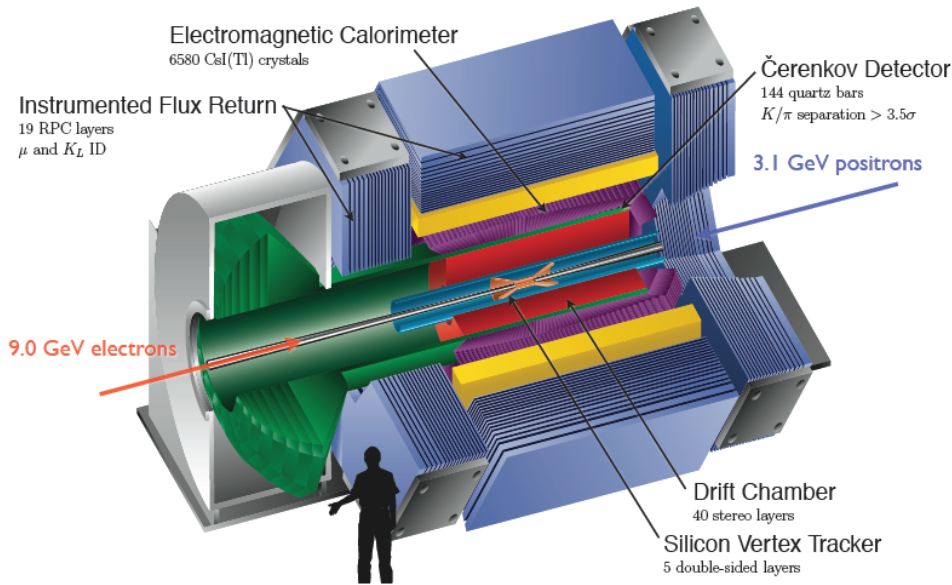


1999-2010



About 1 Million B mesons per day

BaBar at PEP-II



11 countries, 80 institutes, ~600 collaborators

~553 /fb

On-resonance samples:

Y(4S): 433 /fb

Y(3S): 30 /fb

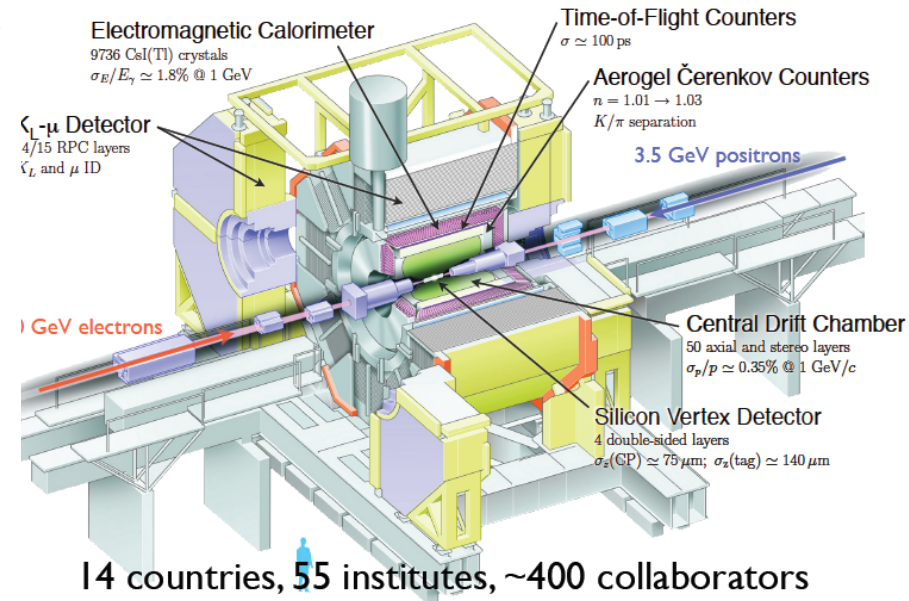
Y(2S): 14 /fb

no Y(5S) data

Off-resonance: 54 /fb

477M B meson decays

Belle at KEKB



14 countries, 55 institutes, ~400 collaborators

~952 /fb

On-resonance samples:

Y(4S): 711 /fb

Y(5S): 121 /fb

Y(3S): 3.0 /fb

Y(2S): 24 /fb

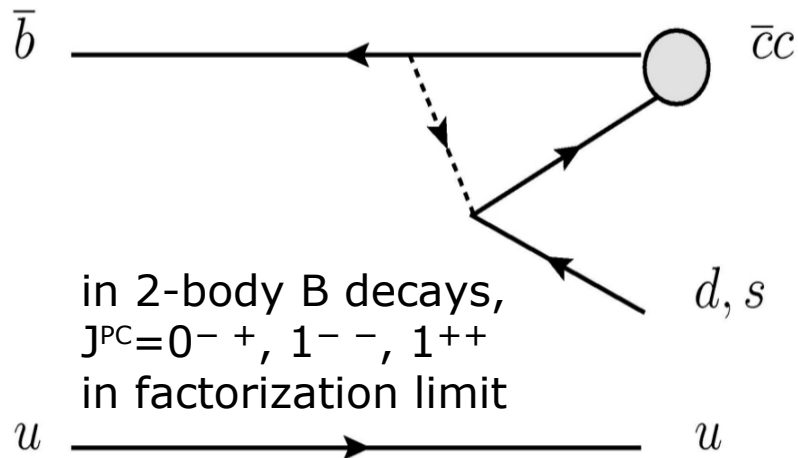
Y(1S): 5.7 /fb

Off-resonance: 87 /fb

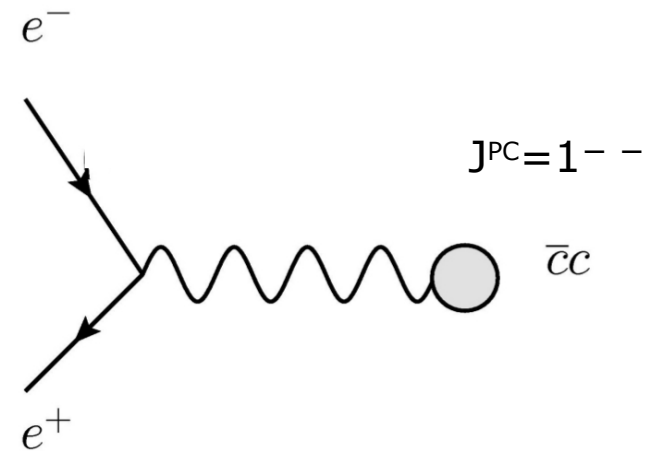
772M B meson decays

Charmonium Production

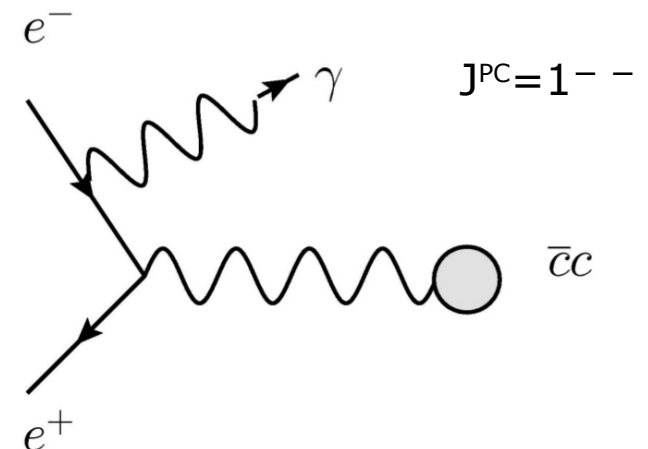
B Meson Decays



Direct Production

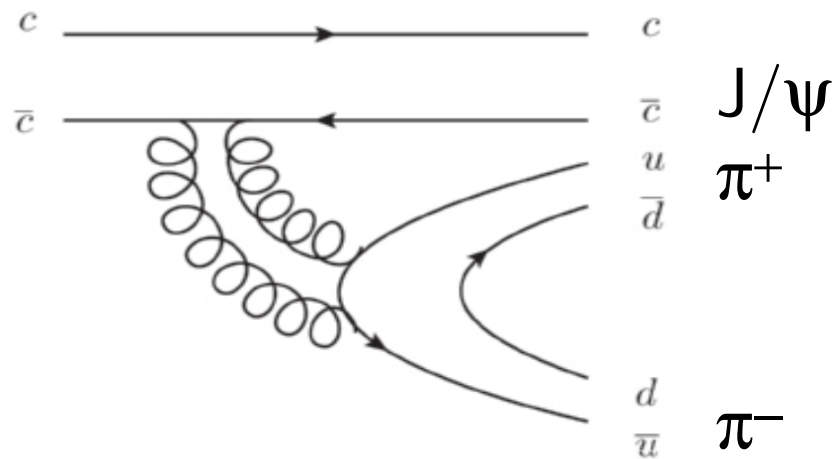


Initial State Radiation



X(3872)

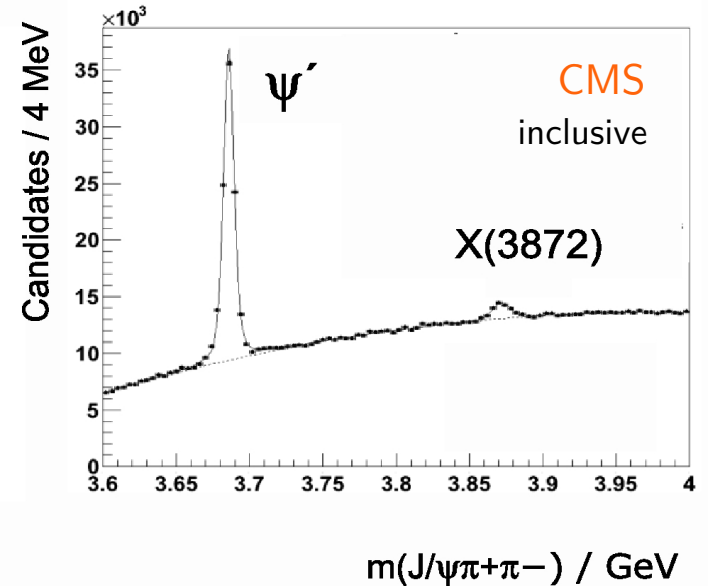
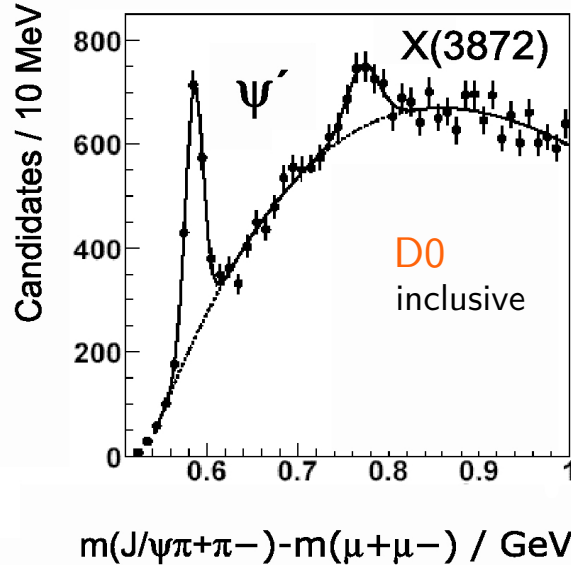
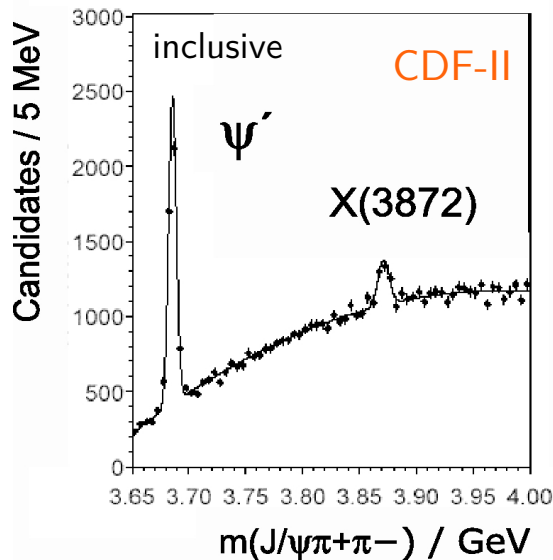
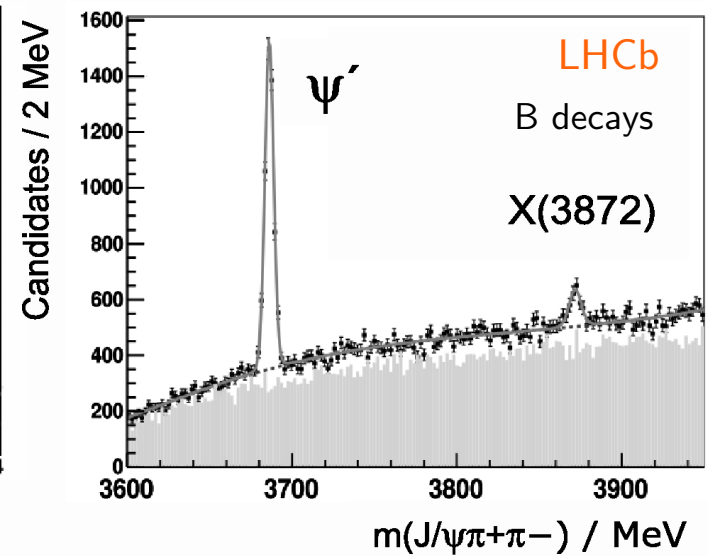
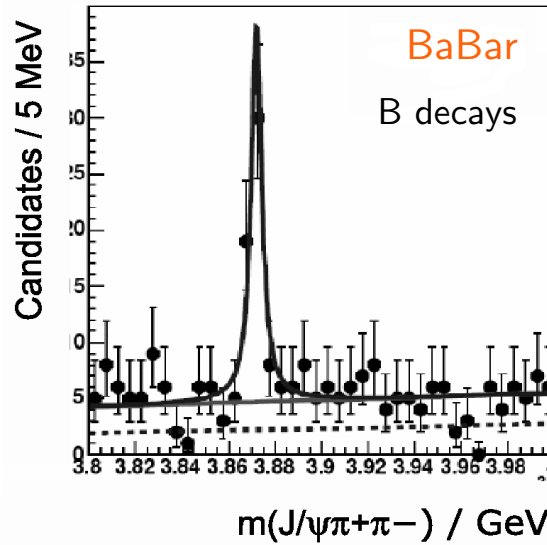
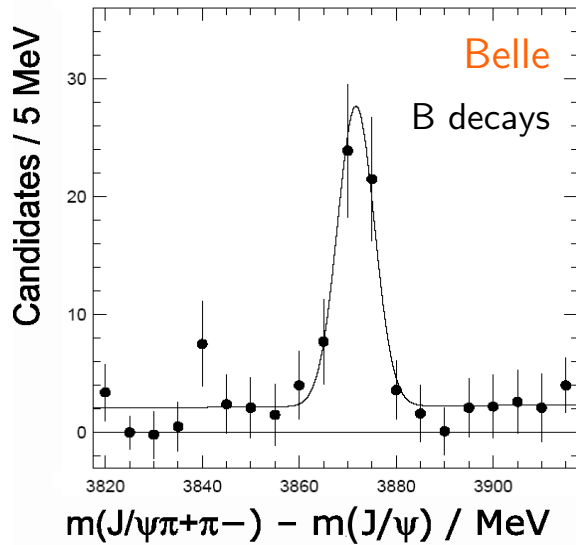
$$B^{\pm} \rightarrow K^{\pm} \underbrace{J/\psi \pi^+ \pi^-}_{\text{resonant state?}}$$



Product branching fraction small

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

X(3872)

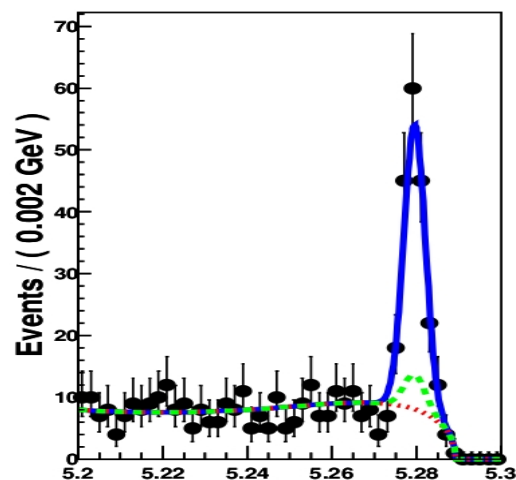


$X(3872) \rightarrow J/\psi \pi^+ \pi^-$

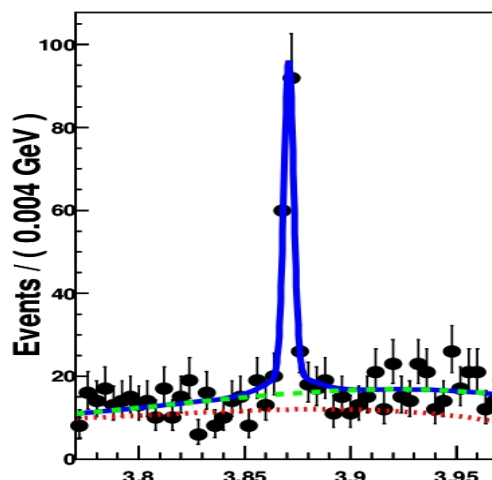
$$m_{bc} = \sqrt{\left(\frac{E_{beam}^{cms}}{2}\right)^2 - (p_B^{cms})^2}$$

$$\Delta E = E_B^{cms} - \frac{E_{beam}^{cms}}{2}$$

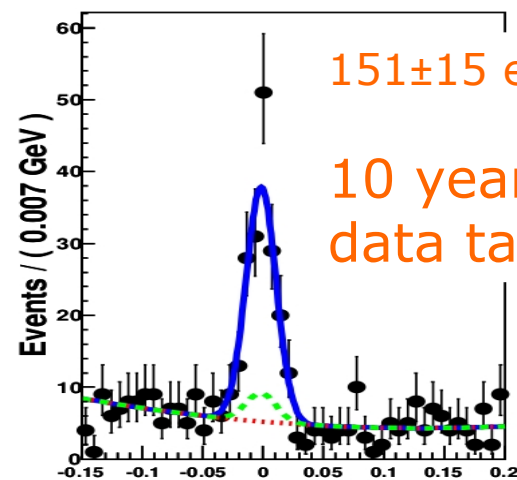
Belle, Phys. Rev. D84(2011)052004



m_{BC} / GeV



$M(J/\psi \pi^+ \pi^-) / \text{GeV}$



151±15 events
10 years of
data taking

$\Delta E / \text{GeV}$

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	$3871.61 \pm 0.16 \pm 0.19$ MeV
<i>BABAR</i> (B^+)	$3871.4 \pm 0.6 \pm 0.1$ MeV
<i>BABAR</i> (B^0)	$3868.7 \pm 1.5 \pm 0.4$ MeV
D0	$3871.8 \pm 3.1 \pm 3.0$ MeV
Belle	$3871.84 \pm 0.27 \pm 0.19$ MeV
LHCb	$3871.95 \pm 0.48 \pm 0.12$ MeV
World Average	3871.68 ± 0.17 MeV

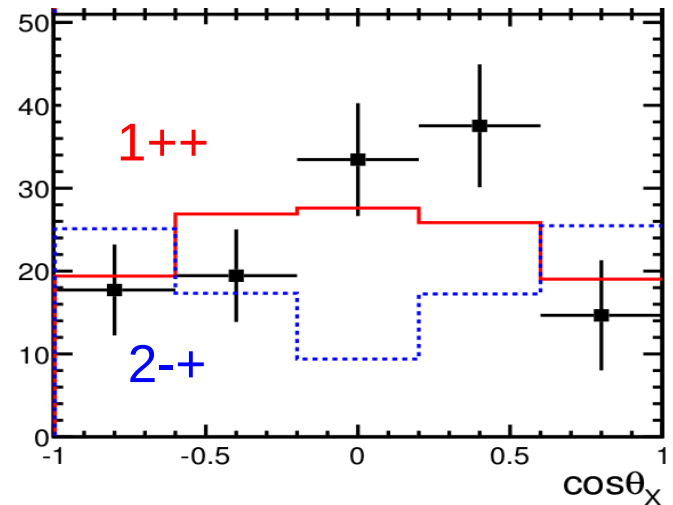


- threshold $m(D^0) + m(D^{*0}) = 3871.84 \pm 0.28$ MeV
 „binding energy“ -0.16 ± 0.33 MeV
 → random coincidence or „grand design“ ?
- upper limit on width
 $\Gamma < 1.2$ MeV (very narrow)

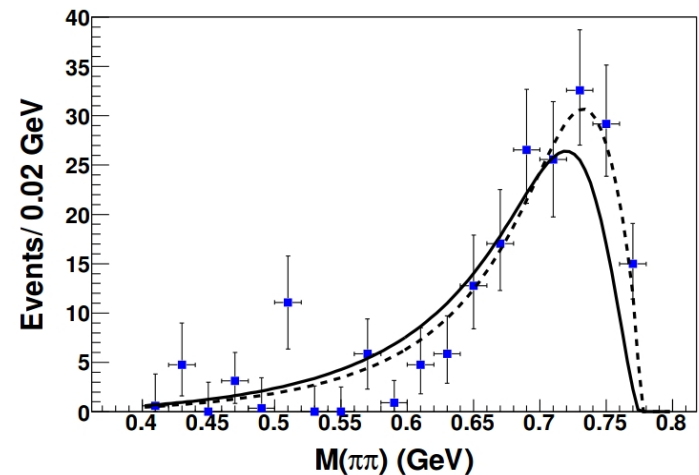
What do we know about the X(3872) ?

- 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
→ predicted mass ≥ 50 MeV higher
→ predicted width factor ≥ 100 larger
- Decay $X(3872) \rightarrow J/\psi \pi^+ \pi^-$
dominated by $X(3872) \rightarrow J/\psi \rho^0 (I=1)$
→ violates isospin
(assume initial $I=0$)
→ $\mathcal{B}$ factor 10–100 too large

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

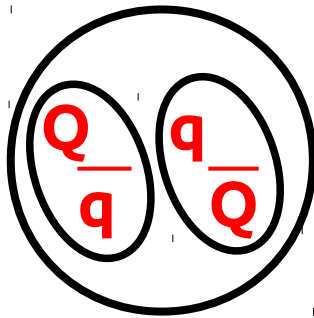


Belle, Phys. Rev. D84(2011)052004



Is the X(3872) exotic ?

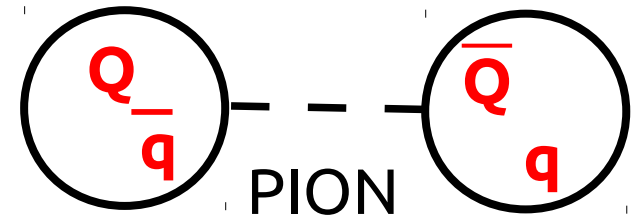
TETRAQUARK



Diquarks
can be
colored

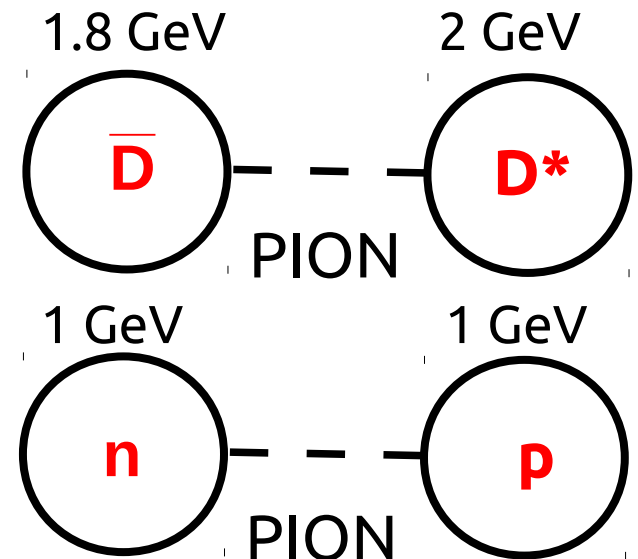
[Qq][$\bar{Q}\bar{q}$] Maiani, Riquer, Piccinini, Polosa,
Burns; Ebert, Paustov, Galkin; Chiu, Hsieh;
Ali, Hambrock, Wang

MOLECULE



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

Intriguing Analogon



Can the X(3872) be a mixture ?

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

$$\chi_{c1}'$$
$$J^{PC}=1^{++}$$

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

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

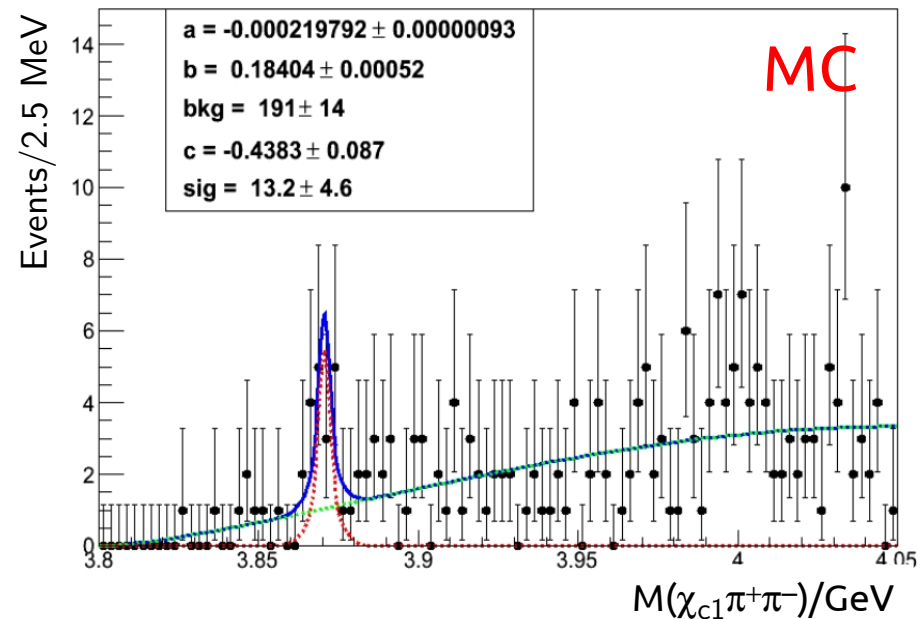
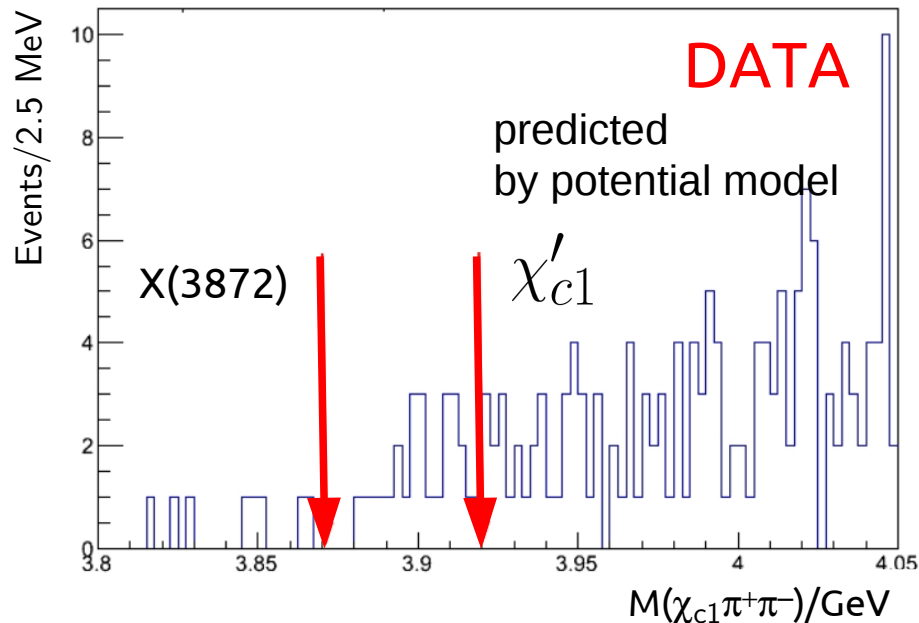
NEW, Belle, 711 fb⁻¹

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)

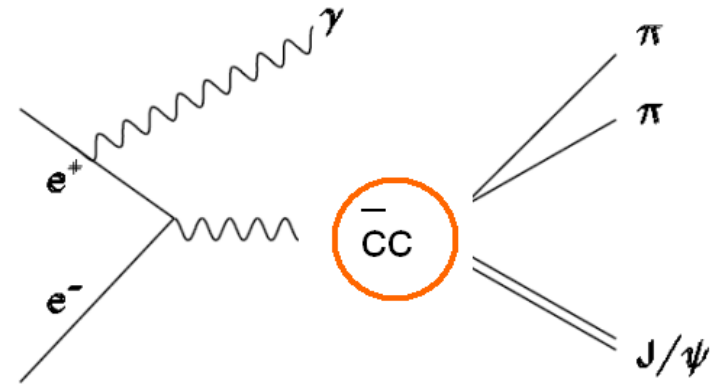
- Initial state radiation events

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

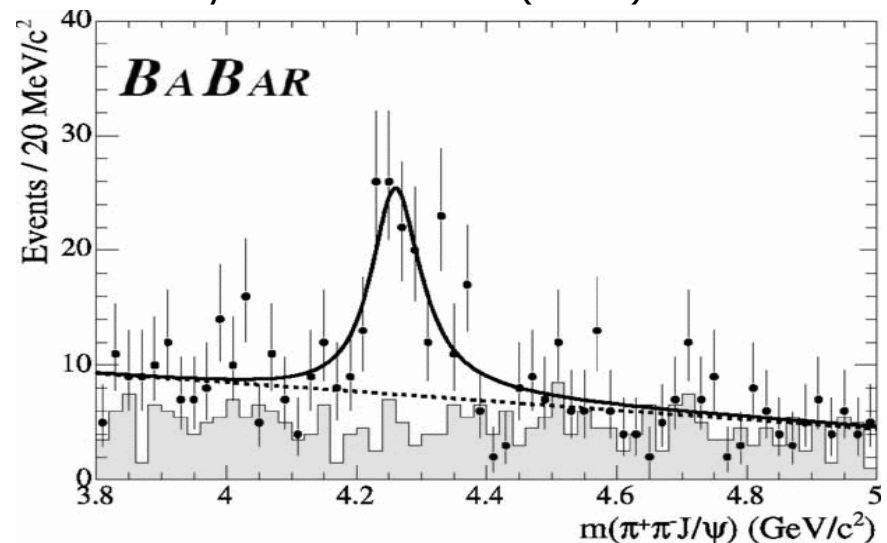
- $m > 4 \text{ GeV}$
 $\rightarrow$ far above $D^{(*)}D^{(*)}$ threshold,
but decay to open charm
not observed

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

initial state radiation



Phys. Rev. Lett. 95(2005)142001

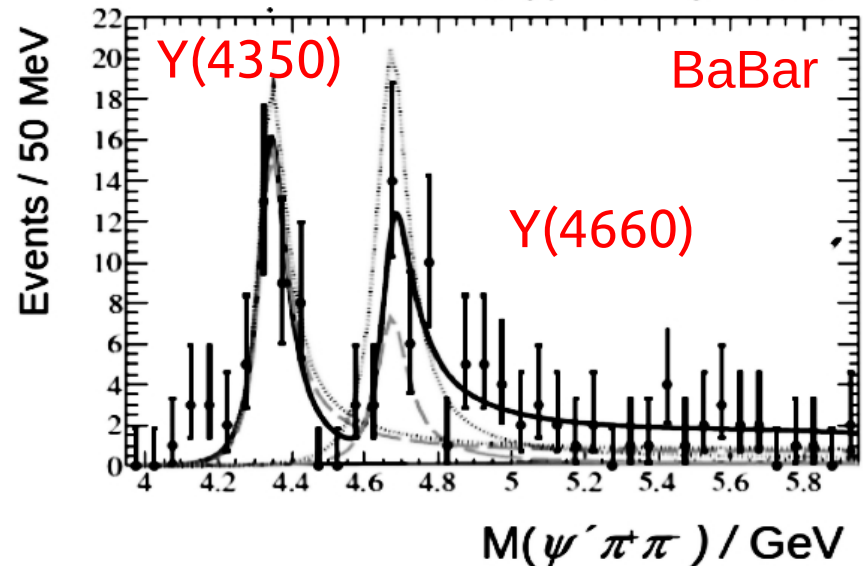
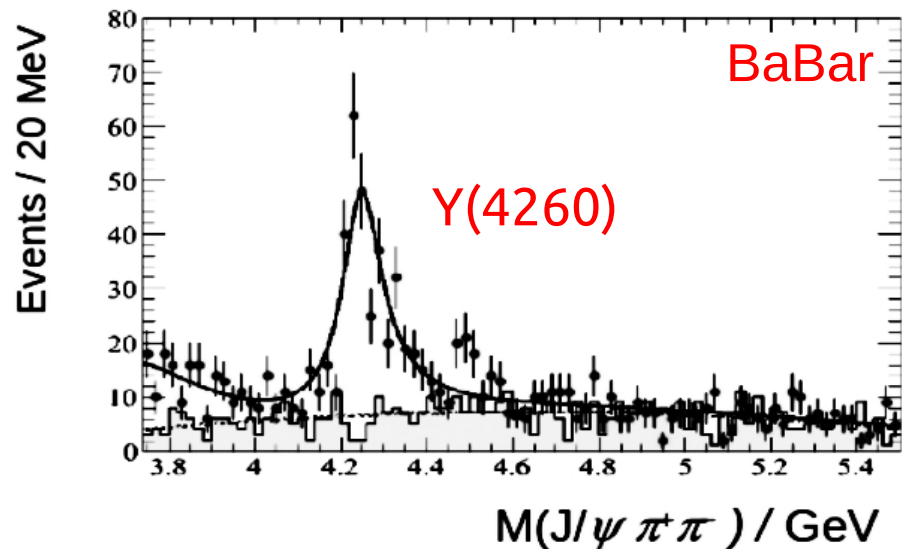
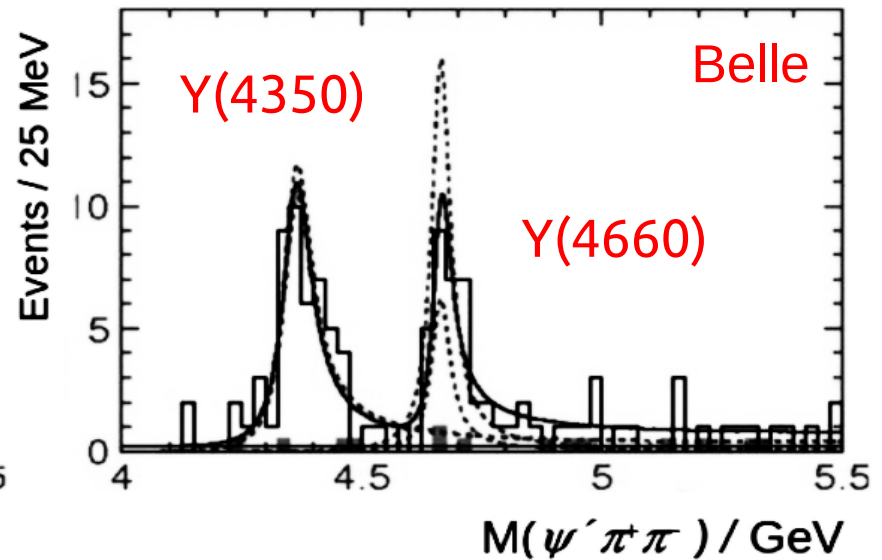
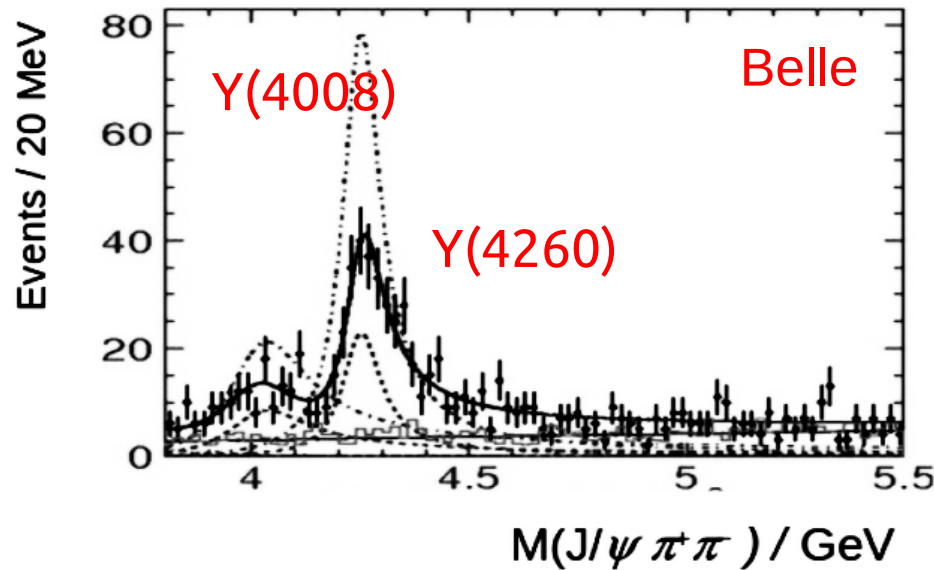


Y(4260) Parameters

	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	≃8σ	≃4.9σ	≥7σ	≥15σ	—	—
m / MeV	4259±8 ⁺² ₋₆	4283 ⁺¹⁷ ₋₁₆ ±4	4295±10 ⁺¹⁰ ₋₃	4247±12 ⁺¹⁷ ₋₃₂	4252±6 ⁺² ₋₃	4244±5±4
Γ / MeV	88±23 ⁺⁶ ₋₄	70 ⁺⁴⁰ ₋₂₅	133±26 ⁺¹³ ₋₆	108±19±10	105±18 ⁺⁴ ₋₆	114 ⁺¹⁶ ₋₁₅ ±7

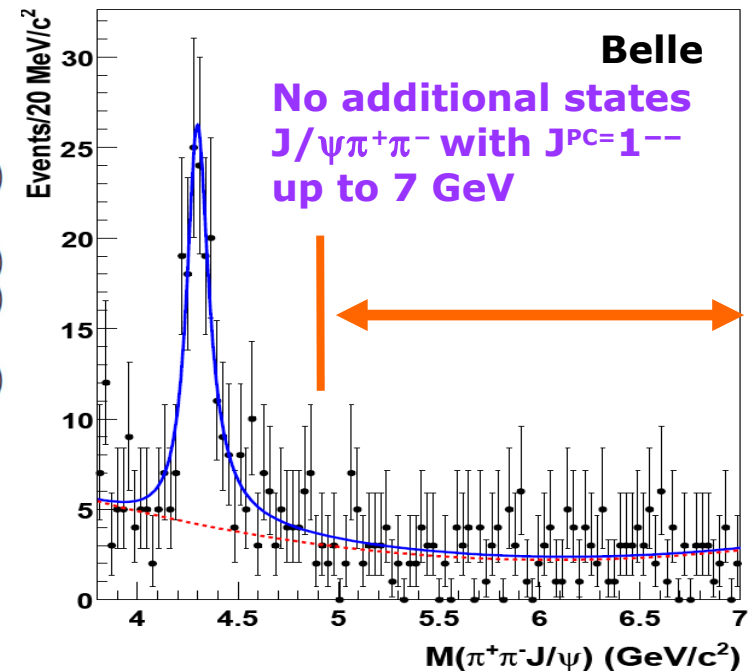
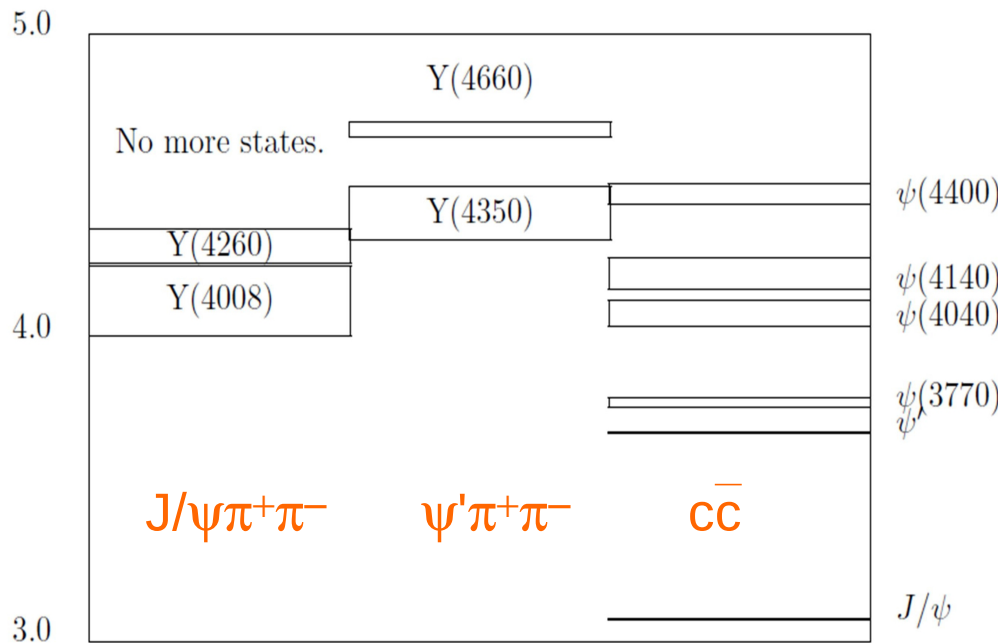
- [1] BaBar Collaboration, arXiv:hep-ex/0506081, Phys. Rev. Lett. 95(2005)142001.
- [2] CLEO-c Collaboration, arXiv:hep-ex/0611021, Phys. Rev. D74(2006)091104.
- [3] Belle Collaboration, arXiv:hep-ex/0612006.
- [4] Belle Collaboration, arXiv:0707.2541[hep-ex], Phys. Rev. Lett. 99(2007)182004.
- [5] BaBar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

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



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

Mass / GeV

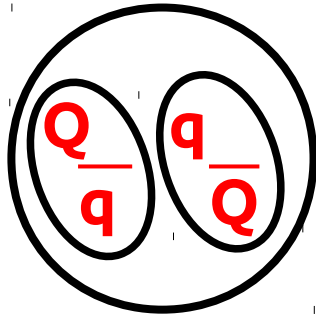


- Non-trivial pattern, not understood
- No mixing with conventional ψ states
- No mixing among them
 - $Y(4260)$ seems not to decay to $\psi'\pi^+\pi^-$
 - $Y(4350)$ seems not to decay to $J/\psi\pi^+\pi^-$

Is the $Y(4260)$ exotic ?

TETRAQUARK

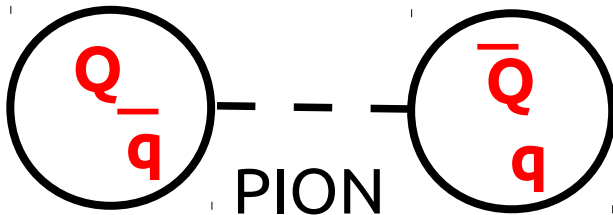
higher excitation ?



$[Qq][\bar{Q}\bar{q}]$ Maiani, Riquer, Piccinini, Polosa, Burns

MOLECULE

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



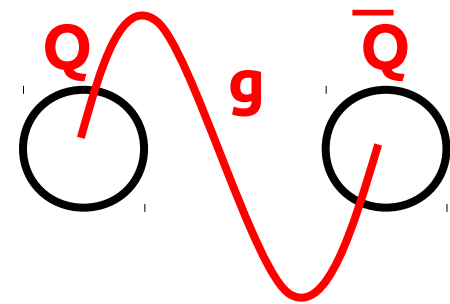
PION

$[Qq][\bar{Q}\bar{q}]$ Swanson, Rosner, Close

$[Q\bar{Q}][q\bar{q}]$ „Hadro-Charmonium“

Guo, Hanhart, Krewald, Meissner

HYBRID



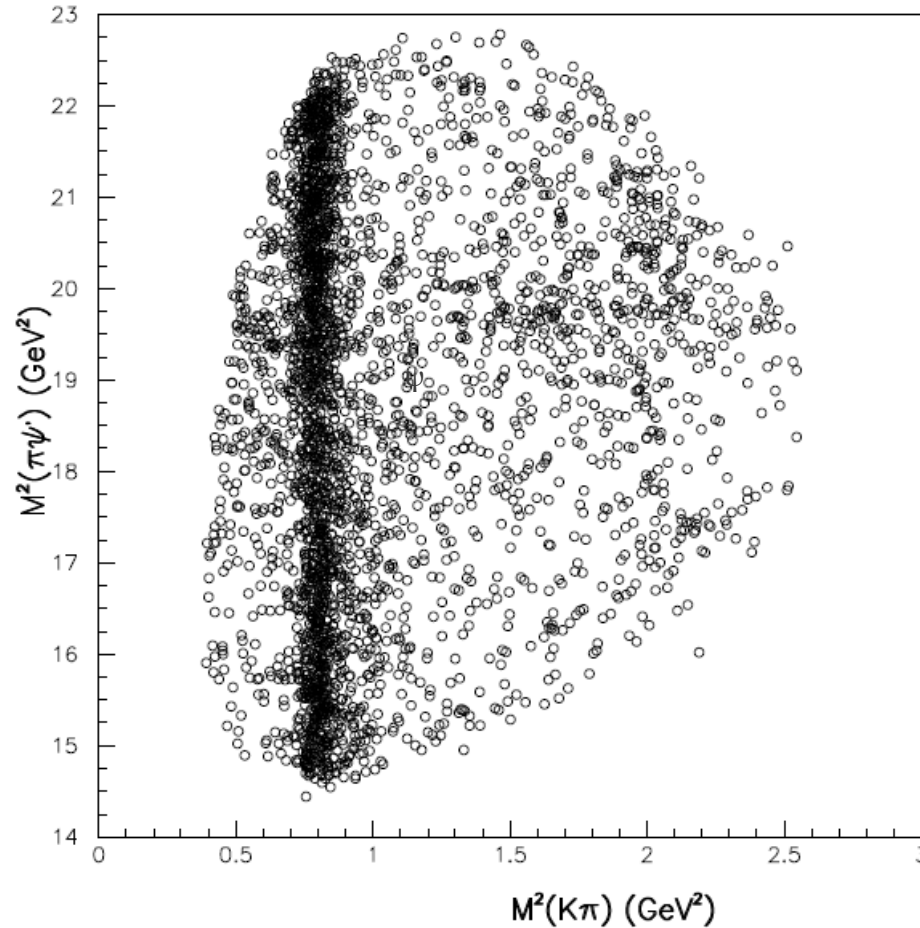
Zhu; Kou, Pene; Close, Page;
Lattice QCD, Bernard et al.; Mei, Luo

Z_c^+ States

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

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

$$B^0 \rightarrow K^+ \psi' \pi^-$$
$$\psi' \rightarrow J/\psi \pi^+ \pi^-$$

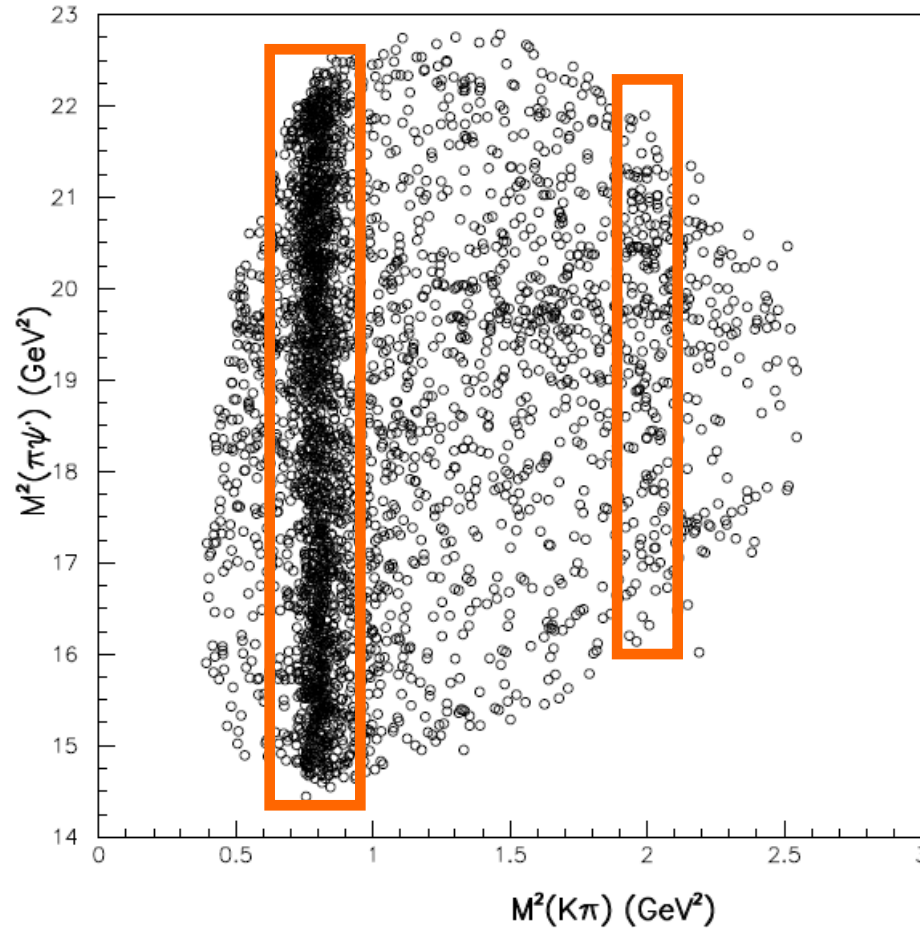


$$B^0 \rightarrow K^+ \psi' \pi^-$$

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

K*(892)

K*(1430)

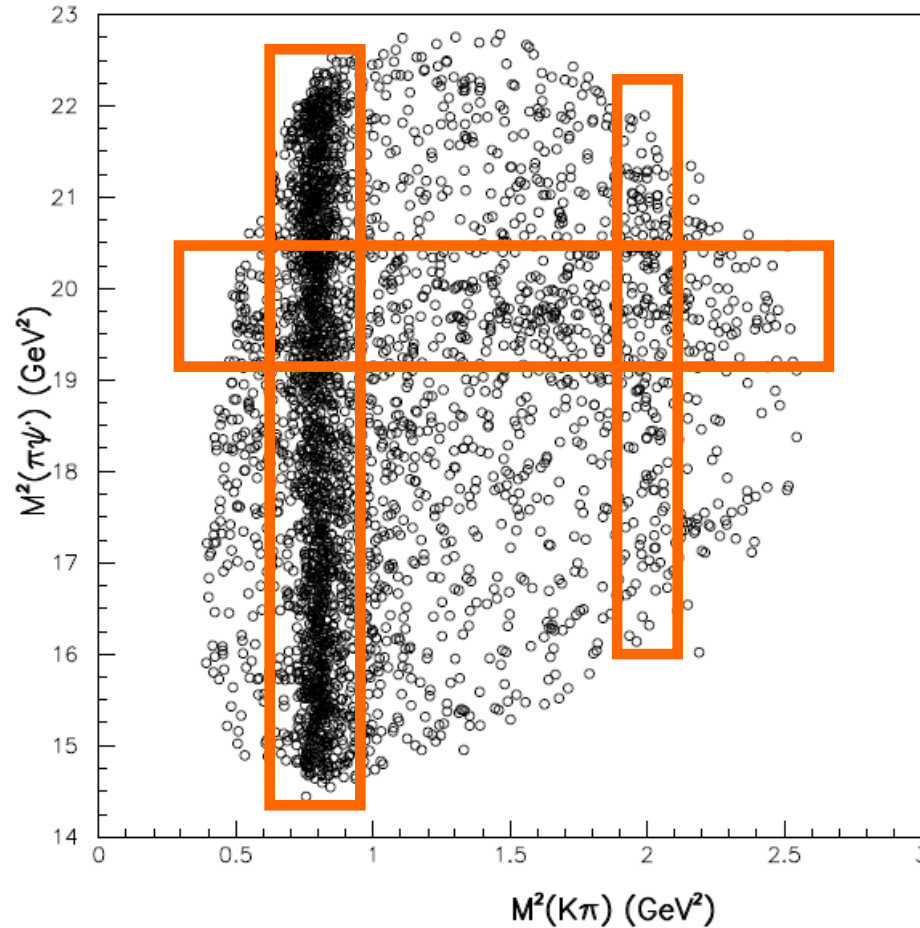


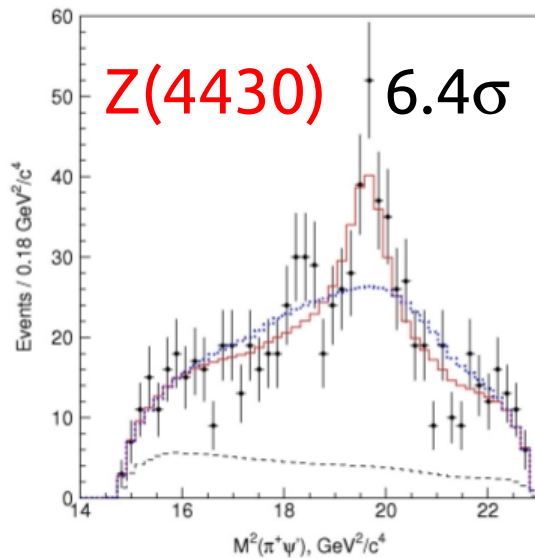
$$B^0 \rightarrow K^+ \psi' \pi^-$$

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

K*(892)

K*(1430)



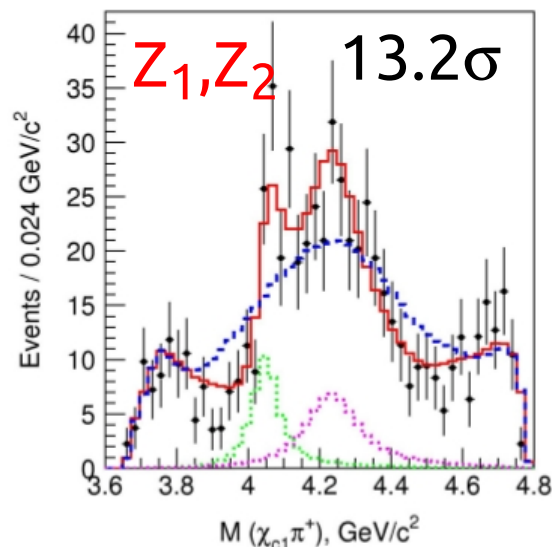


$$B^0 \rightarrow K^\pm \underbrace{\psi' \pi^\mp}_{\text{resonant state?}}$$

not
confirmed
by BaBar
Phys. Rev D79
(2009)112001

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

Belle, Phys. Rev D80(2009)031104



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

not
confirmed
by BaBar

$$m(Z_1) = 4051 \pm 14^{+20}_{-41} \text{ MeV}, \Gamma(Z_1) = 82^{+21+47}_{-17-22} \text{ MeV}$$

$$m(Z_2) = 4248^{+44+180}_{-29-35} \text{ MeV}, \Gamma(Z_2) = 177^{+54+316}_{-39-61} \text{ MeV}$$

Belle, Phys. Rev D78(2008)072004

Problem: understanding of 3-body decay dynamics

Beijing Electron Positron Collider II

Satellite view of BEPCII / BESIII

LINAC

**BESIII
detector**

**2004: started BEPCII upgrade,
BESIII construction**

2008: test run

2009 - now: BESIII physics run

Beijing Electron Positron Collider II

Satellite view of BEPCII / BESIII

BESIII Experiment (IHEP Beijing)
Beam energy 1.0–2.3 GeV ($\rightarrow \sqrt{s}=2.0\text{--}4.6\text{ GeV}$)

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

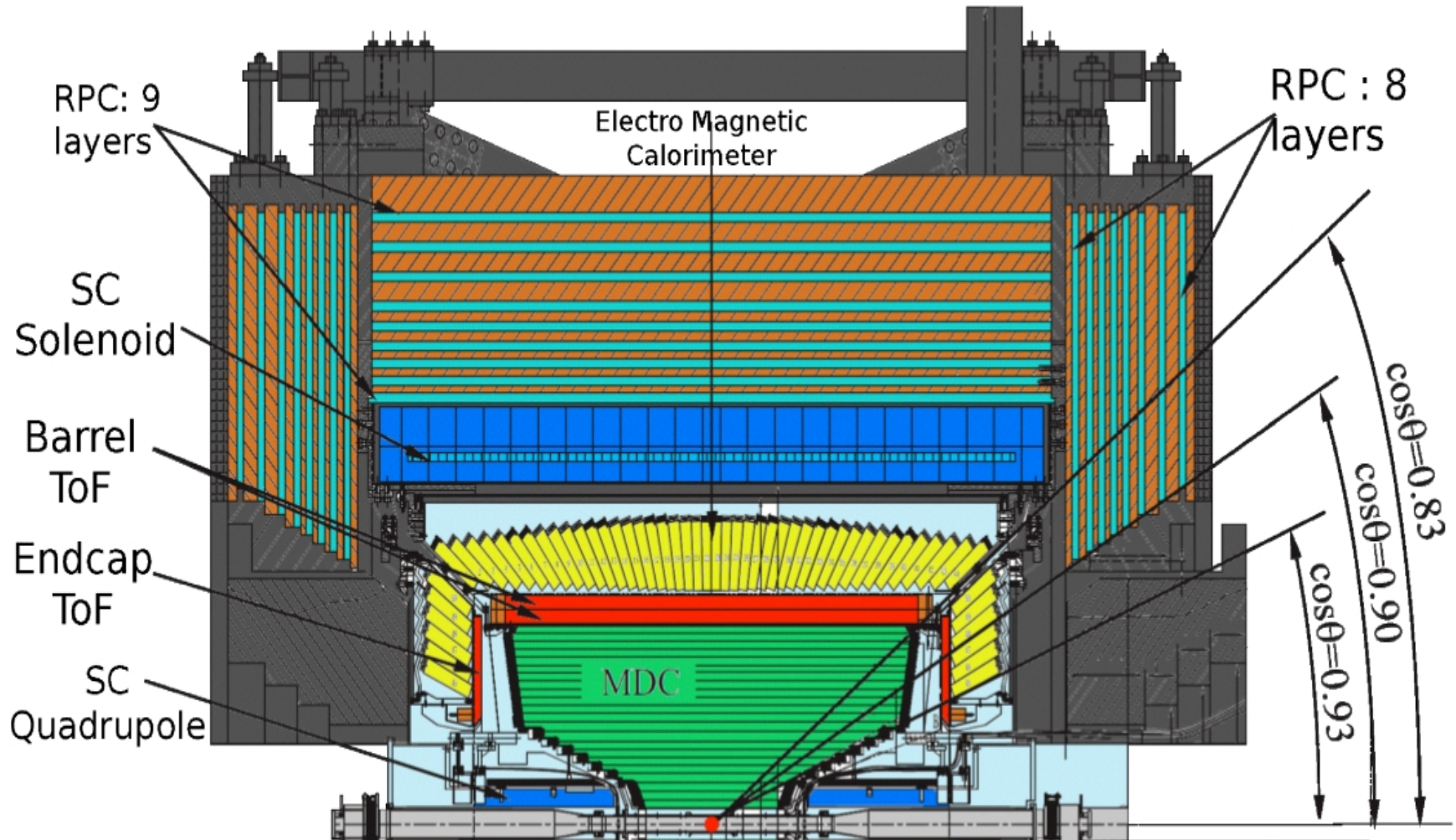
**BESIII
detector**

**2004: started BEPCII upgrade,
BESIII construction**

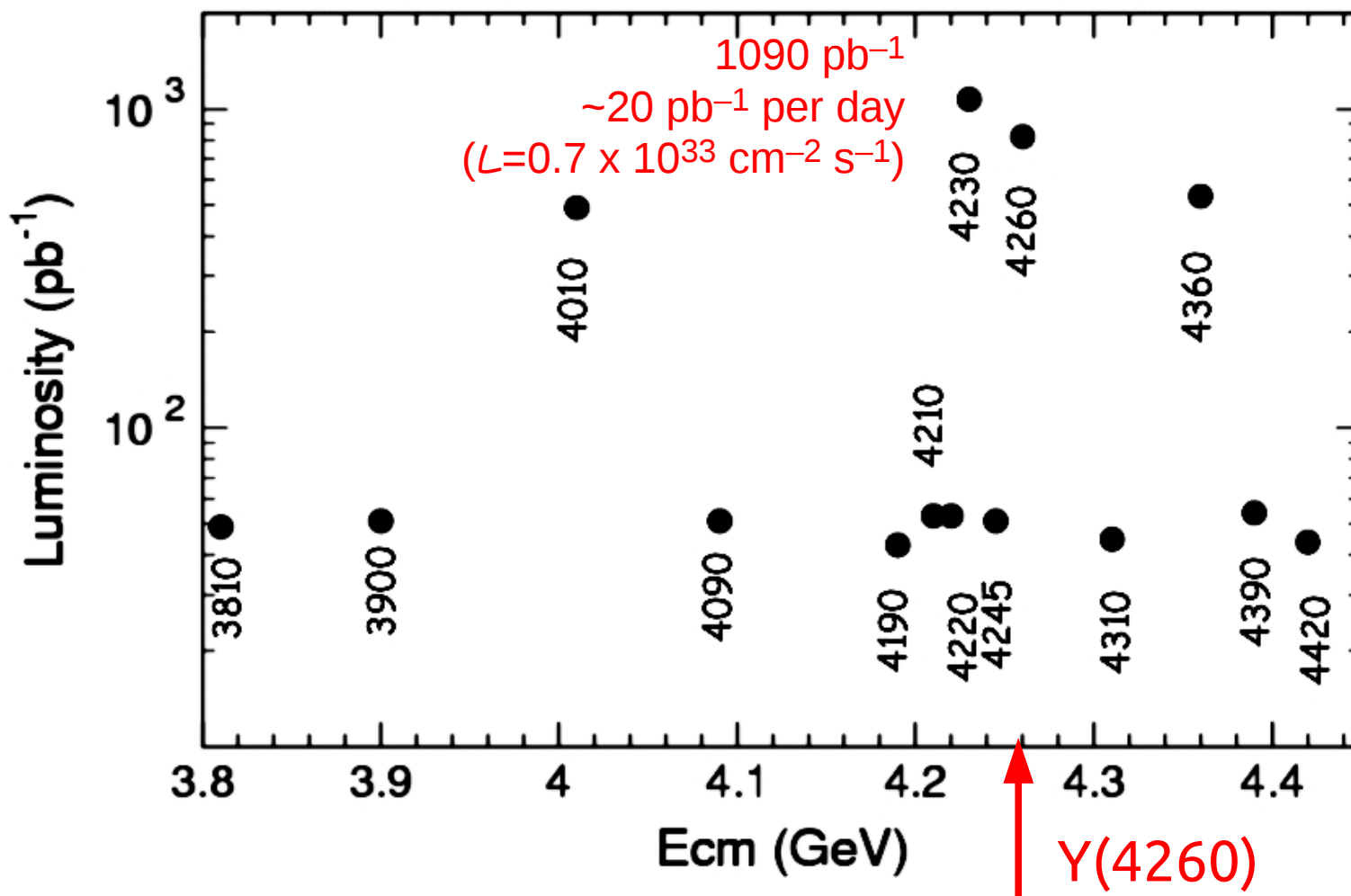
2008: test run

2009 - now: BESIII physics run

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



BESIII Data Taking at different $\sqrt{s}$ (e.g. adjust Beam Energies to $Y(4260)$)

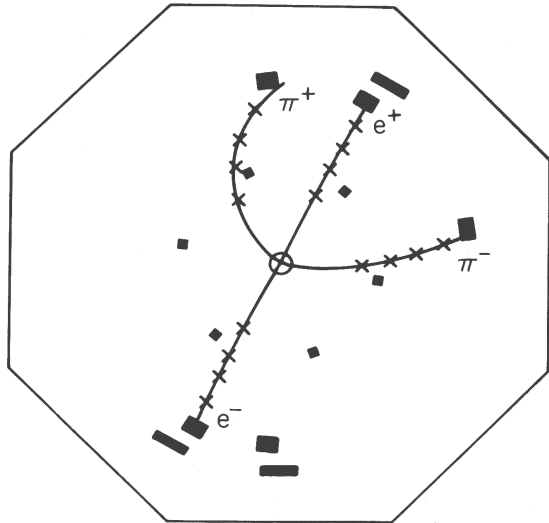


$$e^+e^- \rightarrow J/\psi \pi^+ \pi^-$$

MARK I, 1977

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

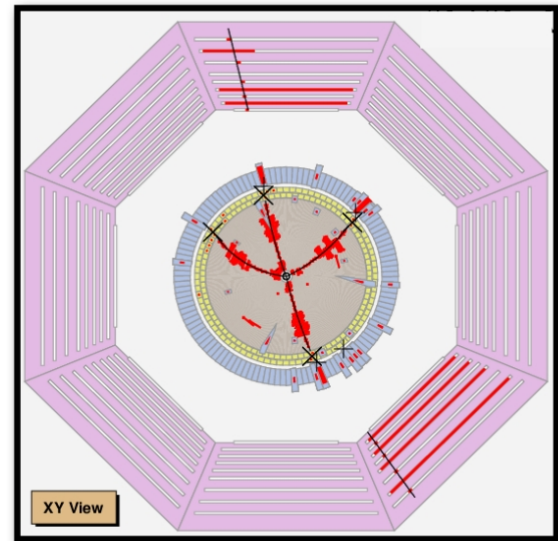
$\sqrt{s}=3868 \text{ MeV}$



BESIII, 2013

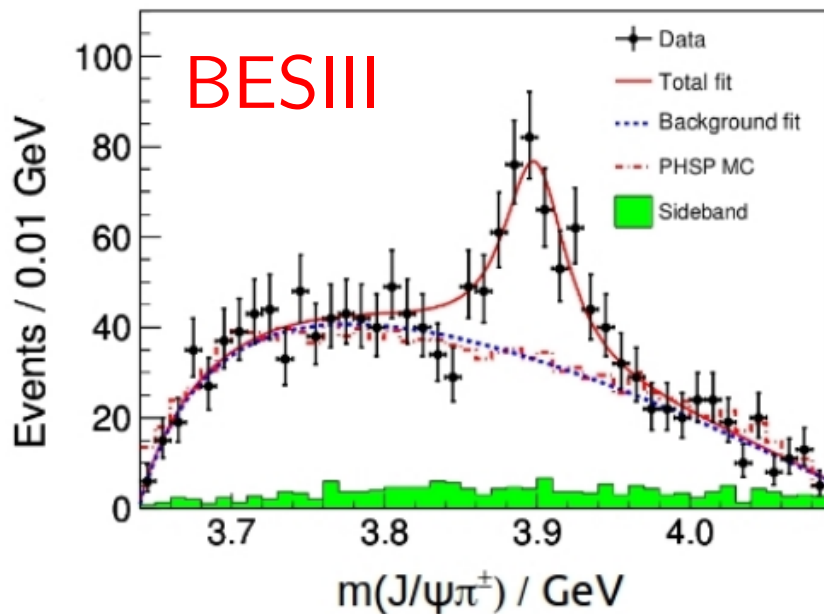
$$e^+e^- \rightarrow Y(4260) \rightarrow J/\psi \pi^+ \pi^-$$

$\sqrt{s}=4260 \text{ MeV}$



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

$Z_c(3900)$

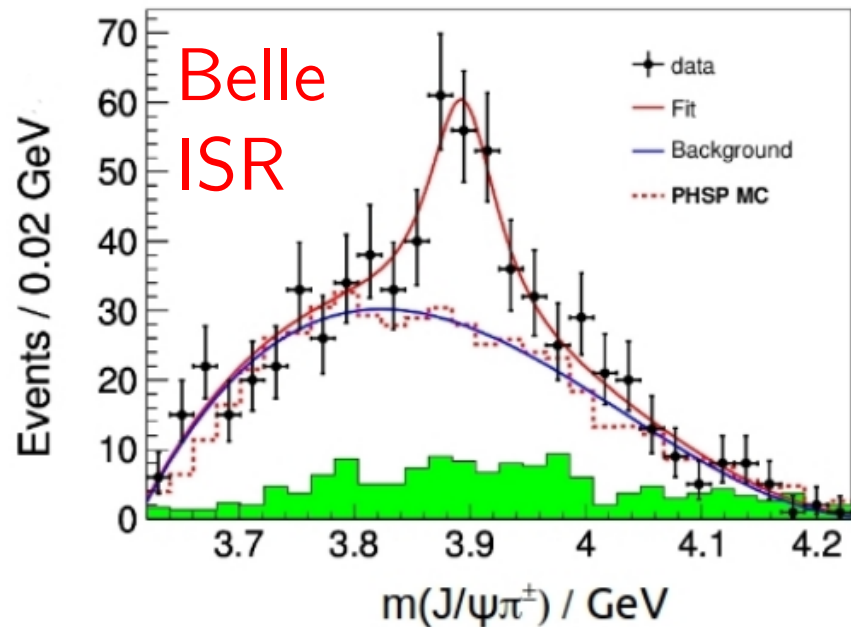


$m = 3899.0 \pm 3.6 \pm 4.9 \text{ MeV}$

$\Gamma = 46 \pm 10 \pm 20 \text{ MeV}$

$307 \pm 48 \text{ events}, >8 \sigma$

arXiv:1303.5949, PRL 110(2013)252001



$m = 3894.5 \pm 6.6 \pm 4.5 \text{ MeV}$

$\Gamma = 63 \pm 24 \pm 26 \text{ MeV}$

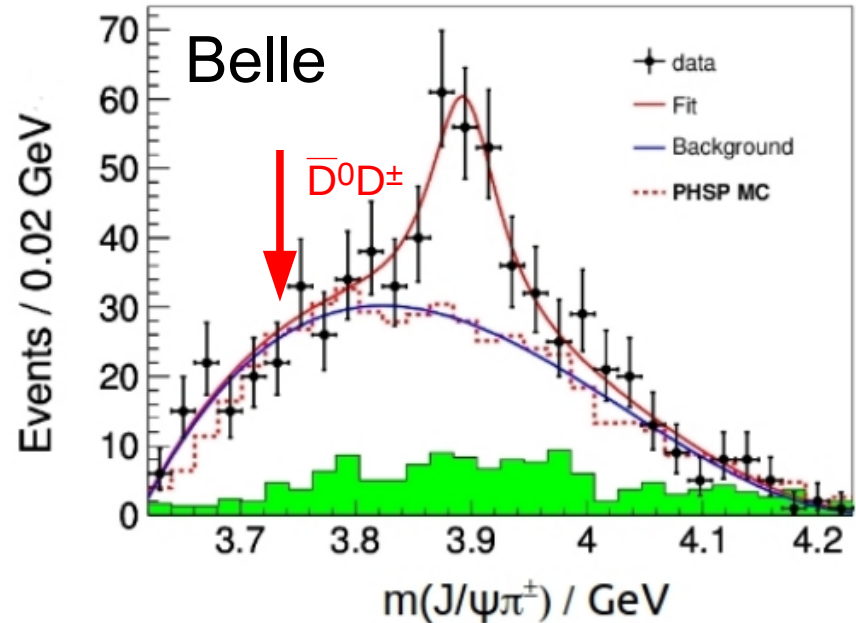
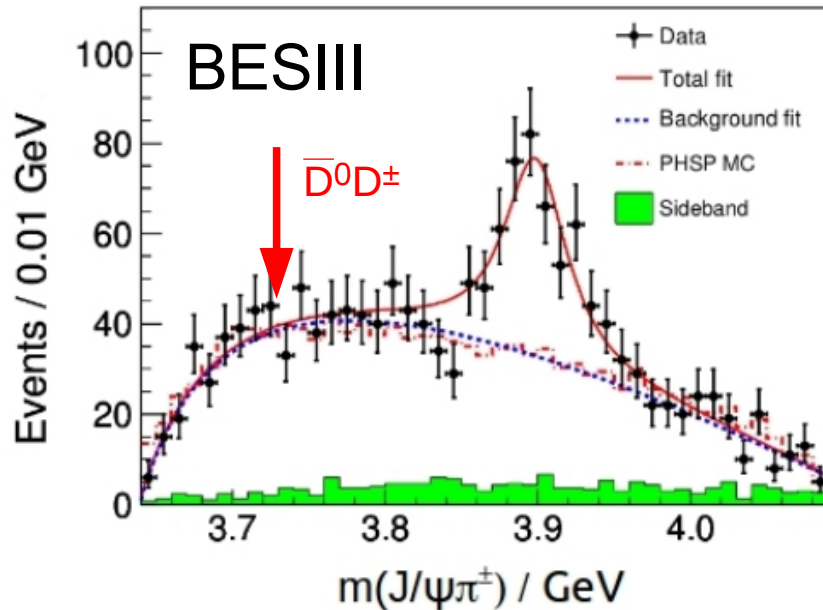
$159 \pm 49 \text{ events}, >5.2 \sigma$

arXiv:1304.0121, PRL 110(2013)252002

Confirmed with CLEO-c data, but different $\sqrt{s} \rightarrow$ not $Y(4260)$
S. Dobbs et al., Phys. Lett. B727(2013)366

Tetraquark state predicted at $m=3.882 \text{ GeV}$
Ali, Hambrock, Wang, Phys. Rev. D85(2012)054011

$Z_c(3900)$

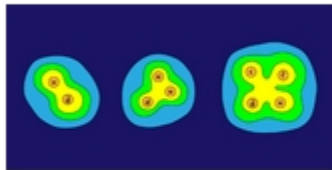


- $Y(4260) \rightarrow [J/\psi\pi^+] \pi^-$
charged $\rightarrow$ no C-parity
 $1^- 0^-$ and assume $L=0 \rightarrow J^P=1^+$, similar to $X(3872)$
- $D^+ D^{*0}$ threshold 3877 MeV
measured: 3899 MeV (BESIII), 3894 MeV (Belle)
 $\rightarrow$ higher than threshold
 $\rightarrow$ no binding energy („virtual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

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

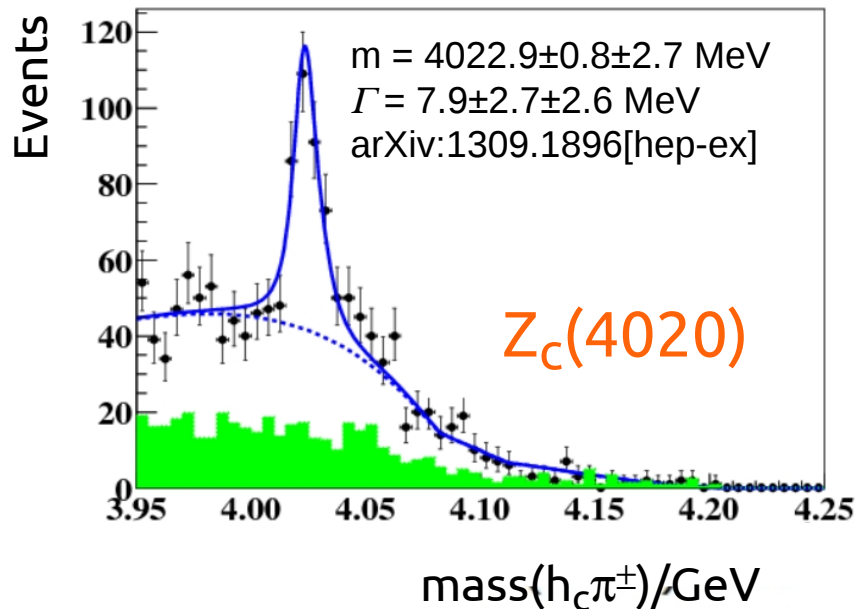
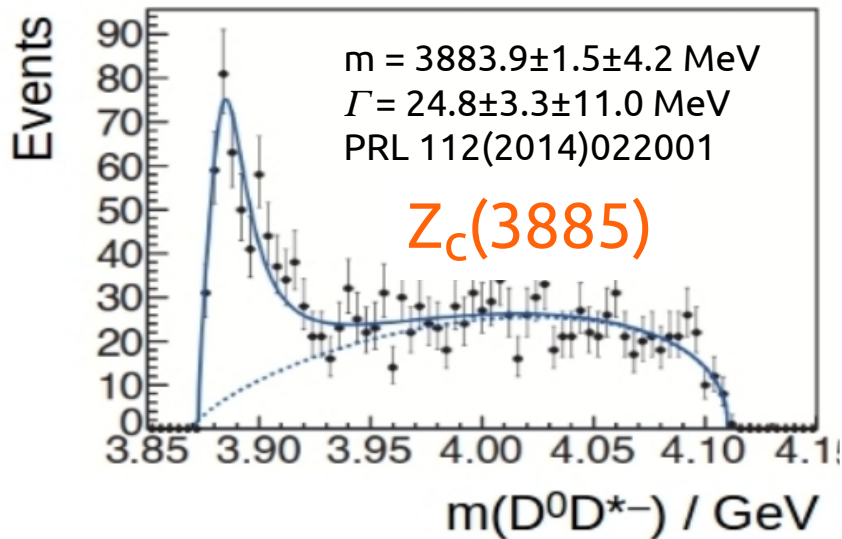
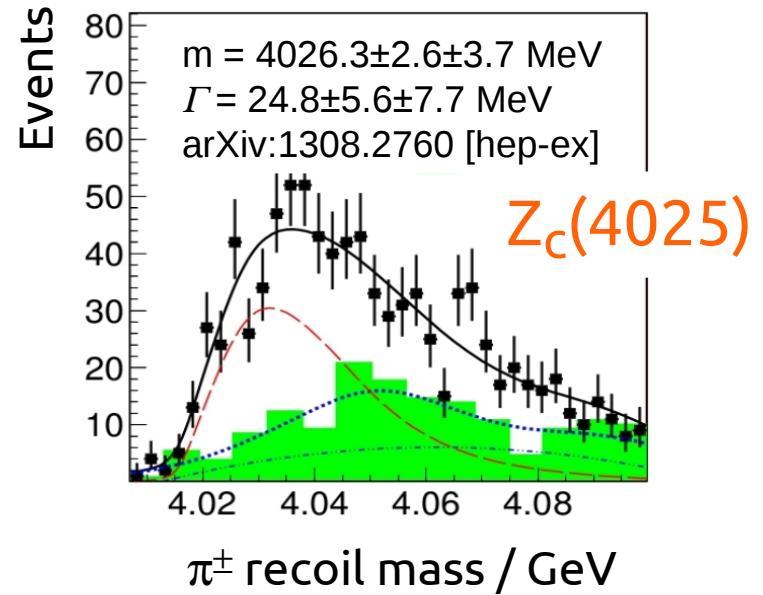
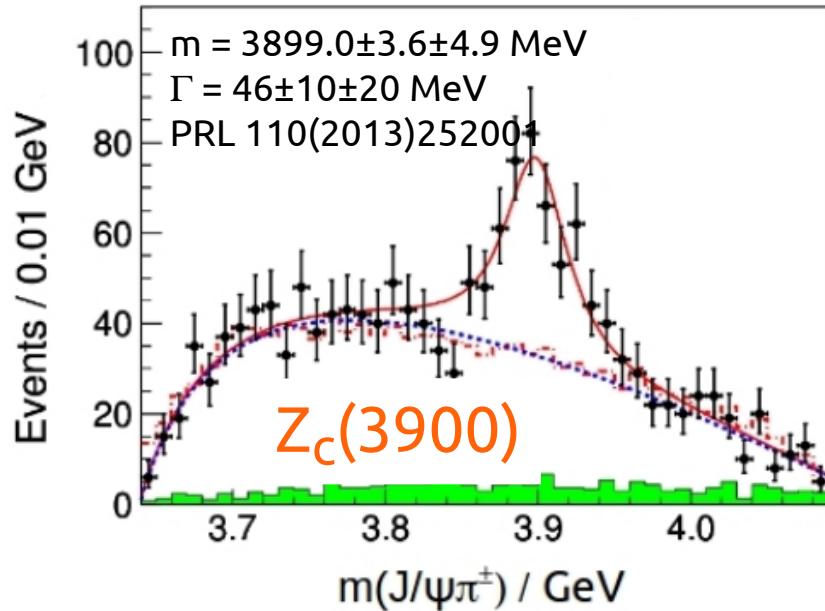
Published 17 June 2013

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!

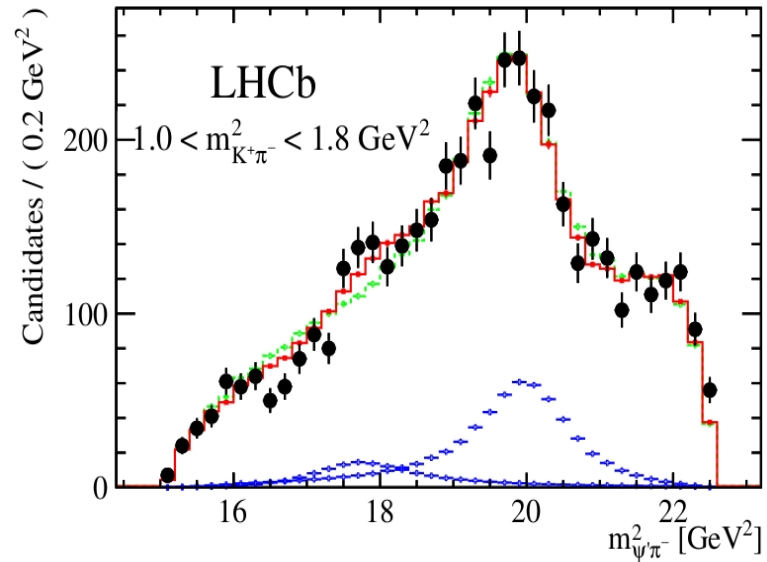
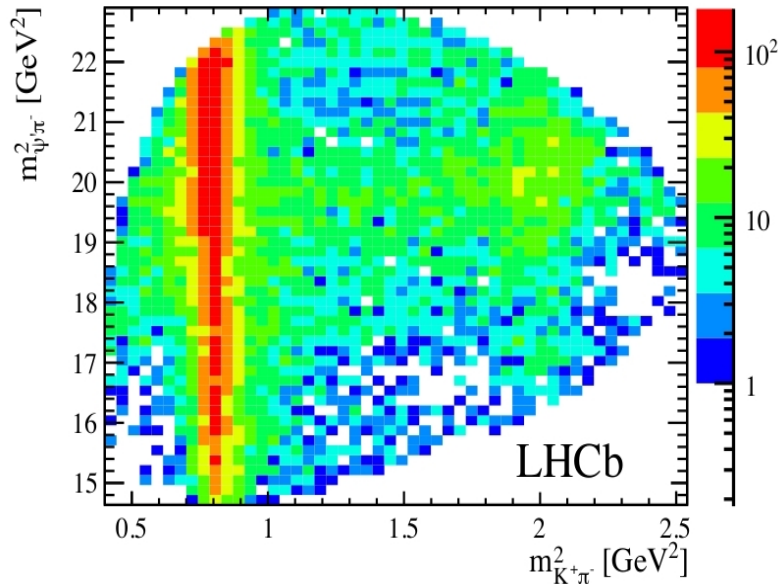
named „APS Highlight of the year 2013“
among others, e.g. extra-solar neutrinos by IceCube

Z_c^+ states at BESIII



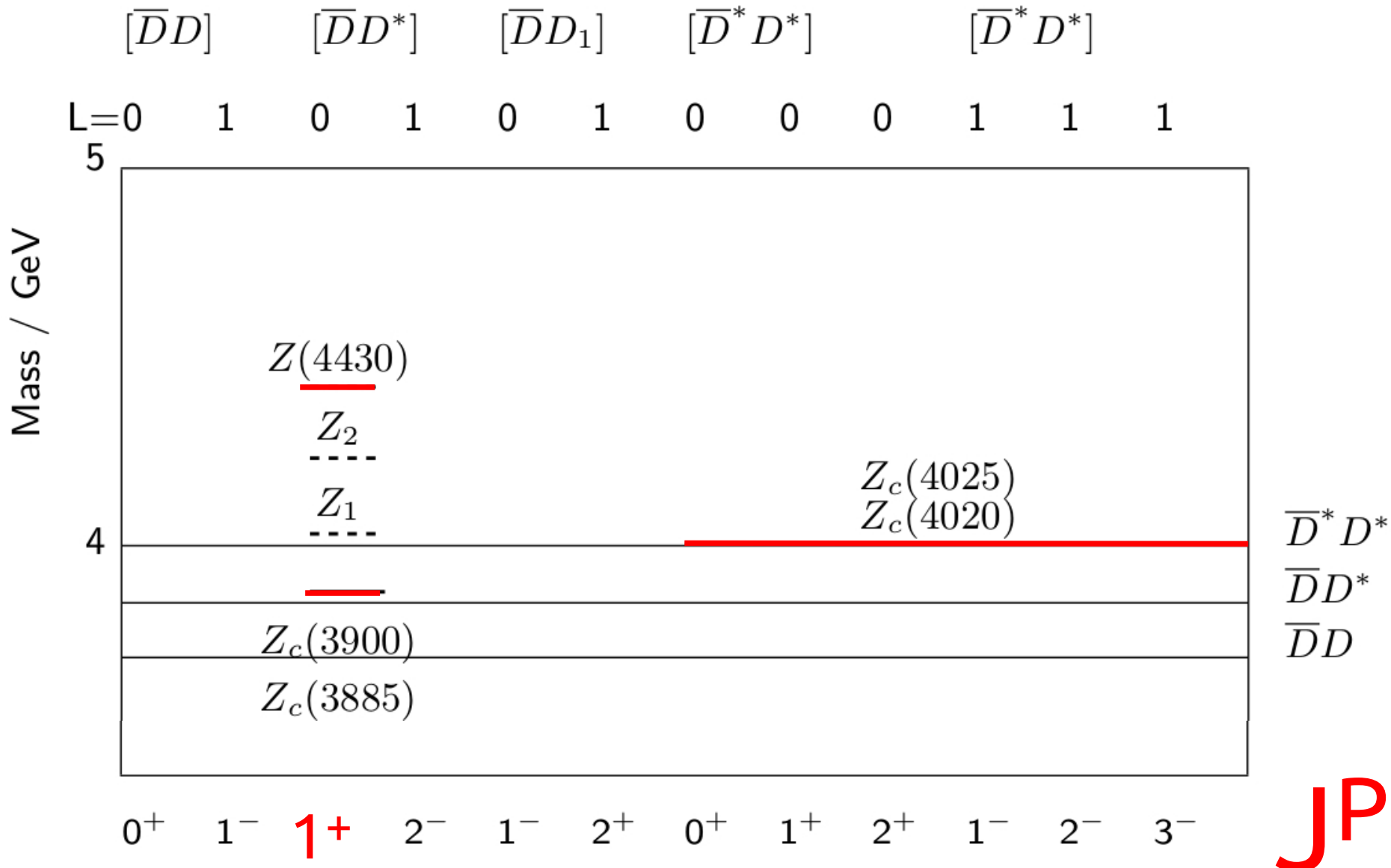
Confirmation of the $Z(4430)$ in $B^0 \rightarrow K^+ \psi' \pi^-$

LHCb, arXiv:1404.1903[hep-ex]



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

Spectrum of Z_c^+ States



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

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

→ not explained yet

Is there a decay from an XYZ to another XYZ?

$Y \rightarrow Z$

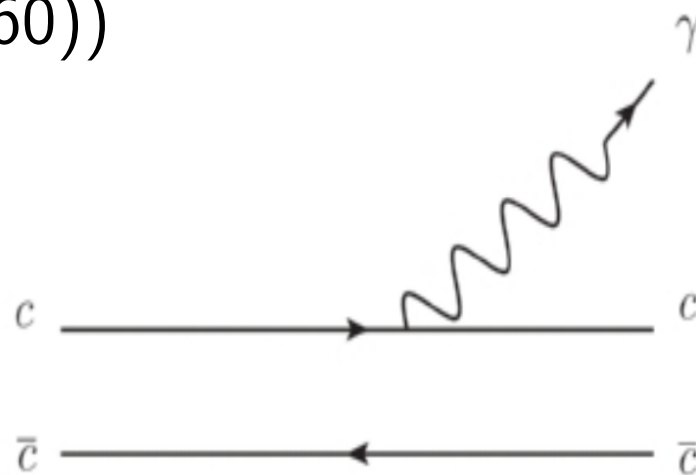
Z_c^+ are observed in $Y(4260)$ decay
(cross section vs. $\sqrt{s}$ peaks at $Y(4260)$)

$Y \rightarrow X$

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

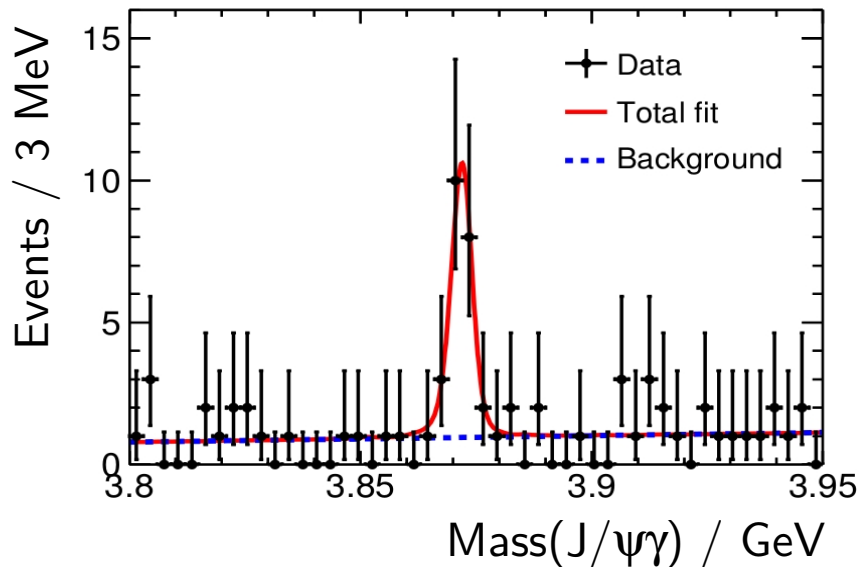
$1^- \rightarrow 1^{++}$, parity flip, $\Delta L=1$

$\rightarrow$ search for radiative decay



$$e+e- \rightarrow Y(4260) \rightarrow X(3872) \gamma$$

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



Confirmation of $X(3872)$

20.0 ± 4.6 events

$m = (3871.9 \pm 0.7 \pm 0.2) \text{ MeV}$

6.3σ

Cross section peaks at $Y(4260)$

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

Bottomonium

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 $^3G_{3,4,5}$

Mass / GeV

11

BELLE

adjust accelerator to $\sqrt{s}=10.86$ GeV

$\Upsilon(5S)$

$\Upsilon(4S)$

η_b'' $\Upsilon(3S)$

h_b'

χ_{b0}

χ_{b1}

χ_{b2}

η_{b2}

$\pi^+\pi^-$ transitions

Υ_D

10

η_b' $\Upsilon(2S)$

h_b

χ_{b0}

χ_{b1}

χ_{b2}

π^+

$\Upsilon(5S)$

detected

η_b $\Upsilon(1S)$

reconstructed

π^-

$$M_{\text{miss}}(X) = \sqrt{(E_{\text{c.m.}} - E_X^*)^2 - p_X^{*2}}$$

$B_s B_s^*$
 $B_s B_s^*$
 $B B$

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

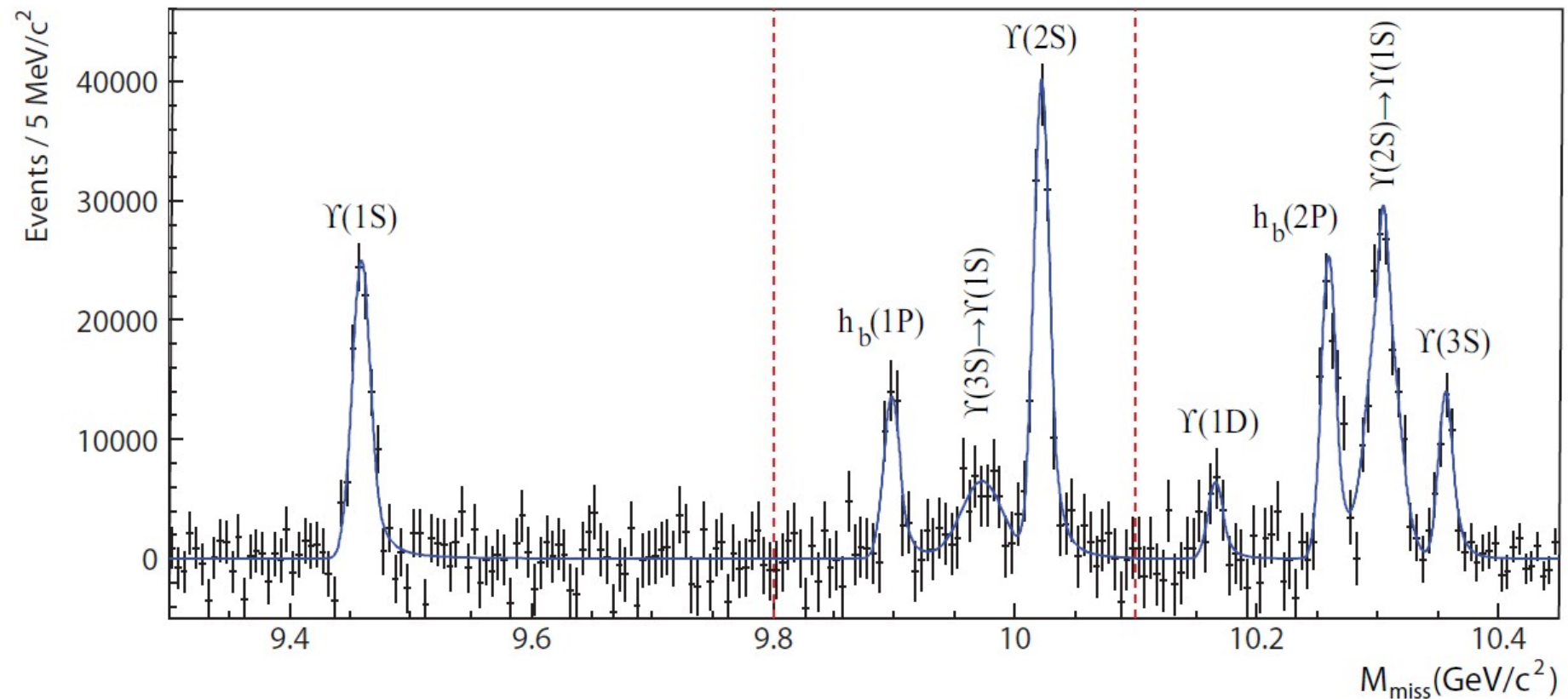
4^{-+}

Y(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



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 $^3G_{3,4,5}$

Mass / GeV

Bottomonium

$\Upsilon(5S)$

$\Upsilon(4S)$

$\eta_b'' \Upsilon(3S)$

h_b' χ_{b0} χ_{b1} χ_{b2}

$\eta_b' \Upsilon(2S)$

h_b χ_{b0} χ_{b1} χ_{b2}

$\eta_b \Upsilon(1S)$

	Mass	Potential Model
$h_b(1P)$	$9898.2^{+1.1}_{-1.0} {}^{+1.0}_{-1.1}$	9901 MeV
$h_b(2P)$	$10259.8 \pm 0.6 {}^{+1.4}_{-1.0}$	10261 MeV

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

Precise confirmation of
potential model prediction

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

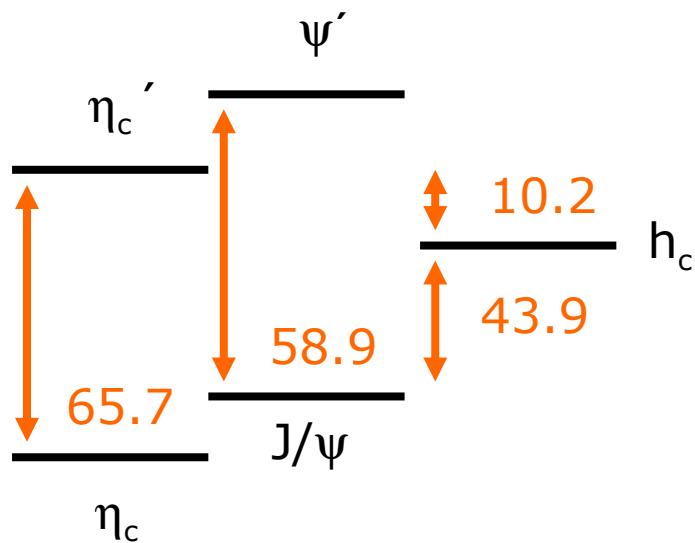
4^{-+}

$B_s B_s^*$
 $B B^*$

Implications
of newly observed, expected bottomonium states
for potential model (confinement) ?

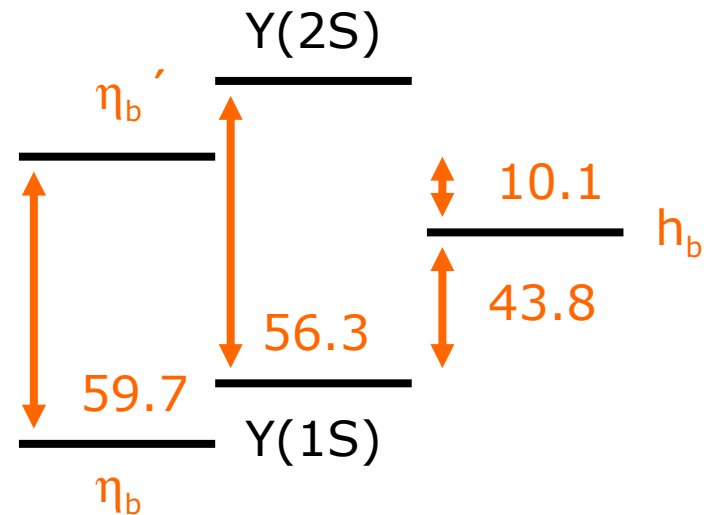
Precision Test of Flavor Independence of $Q\bar{Q}$ Potential → Are the level spacings identical?

Charmonium



Mass scale ~ 4 GeV

Bottomonium



Mass scale ~ 10 GeV

Agreement to $10^{-3} - 10^{-4}$ level

Experimental observation of

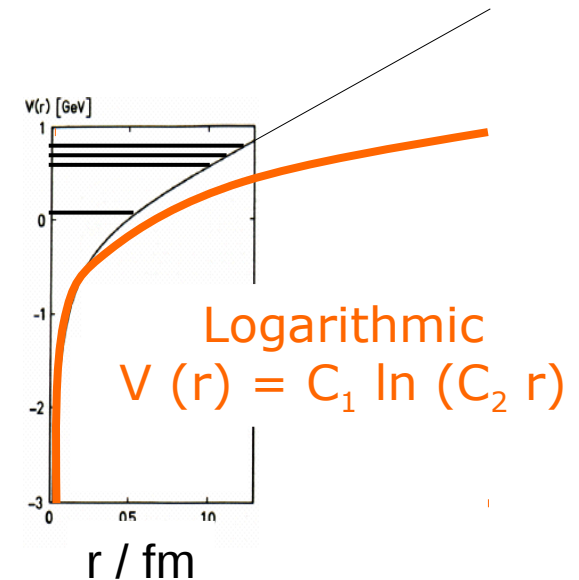
$$|\Delta m|_{c\bar{c}} = |\Delta m|_{b\bar{b}}$$

is inconsistent with potential model

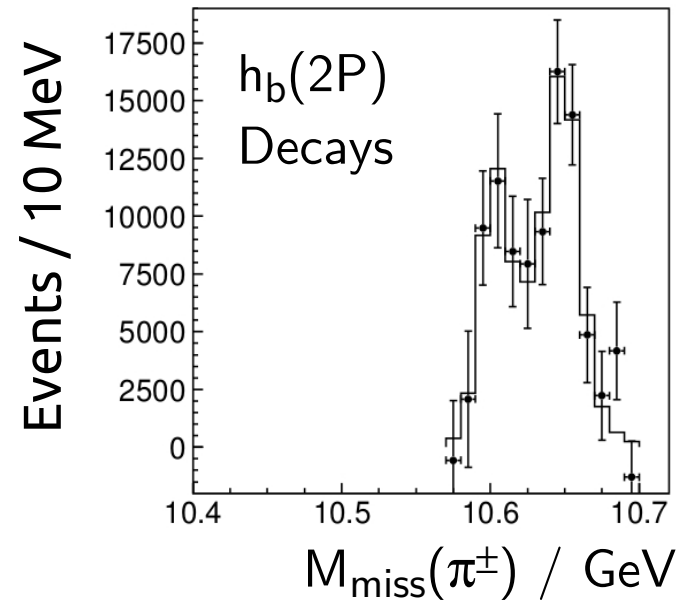
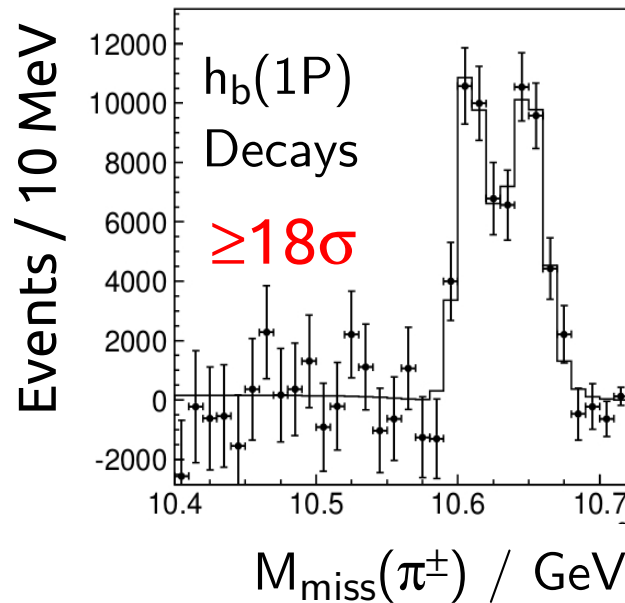
		$ \Delta m $ Scaling
<i>Coulomb</i>	$V(r) = k/r$	$m_Q k ^2$
<i>Linear</i>	$V(r) = kr$	$m_Q^{-1/3} k ^{2/3}$
<i>Logarithmic</i>	$V(r) = k \ln r$	$ k $

Explicit quark mass dependence
(except for logarithmic potentials).

C. Quigg, arXiv:hep-ph/9707493
C. Quigg, J. L. Rosner,
Phys. Lett. B71(1977)153
C. Quigg, J. L. Rosner, H. B. Thacker,
Phys. Rev. D21(1980) 234
C. Quigg, J. L. Rosner,
Phys. Rev. D23(1981)2625



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



$Z_b(10610)^\pm$ $\underline{m}=10607.2 \pm 2.0$ MeV , $\Gamma=18.4 \pm 2.4$ MeV

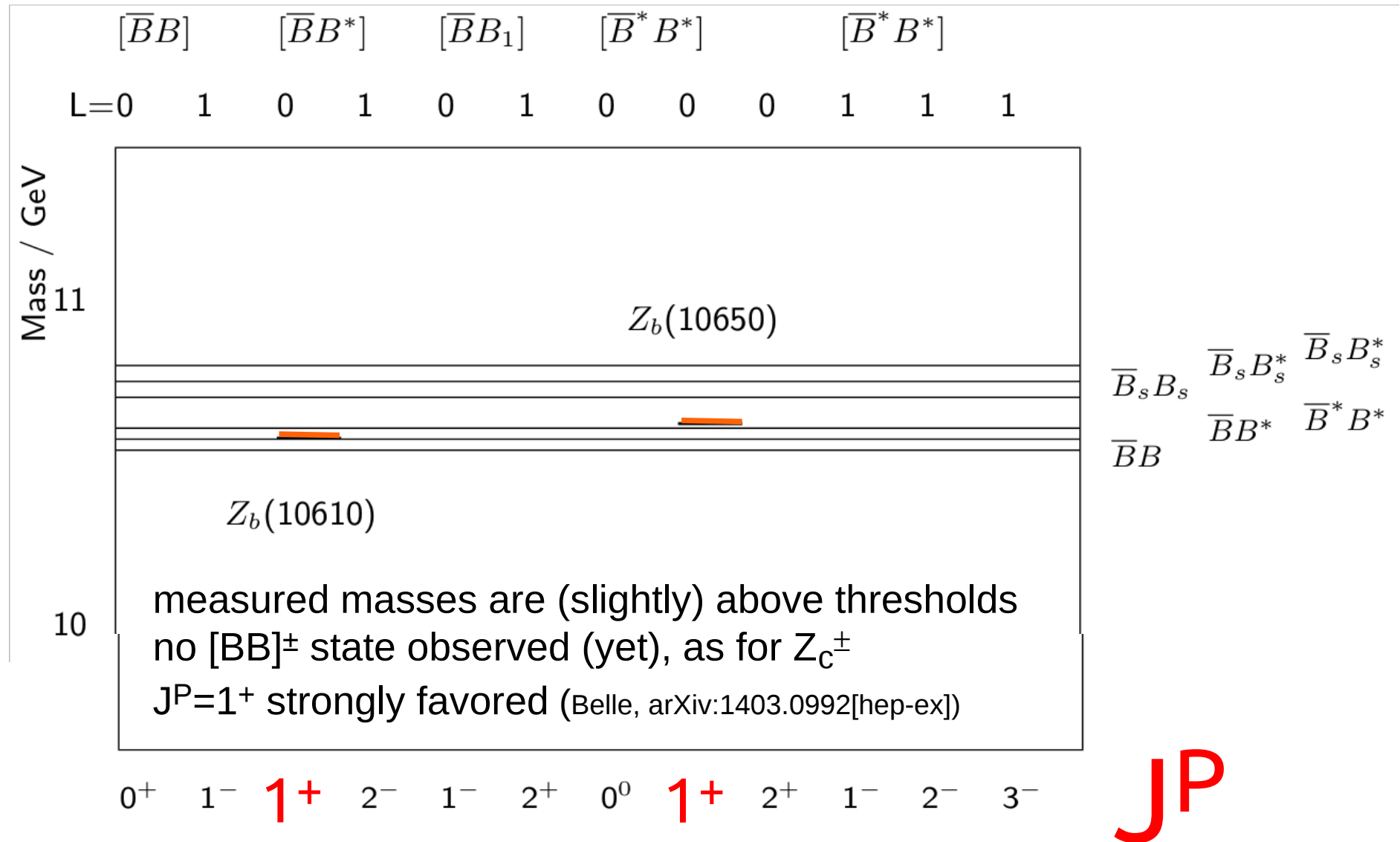
2.6 MeV above $\bar{B}B^*$ threshold

$Z_b'(10650)^\pm$ $\underline{m}=10652.2 \pm 1.5$ MeV , $\Gamma=11.5 \pm 2.2$ MeV

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

confirmed in 3 additional decay modes

Spectrum of Z_b^+ states



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

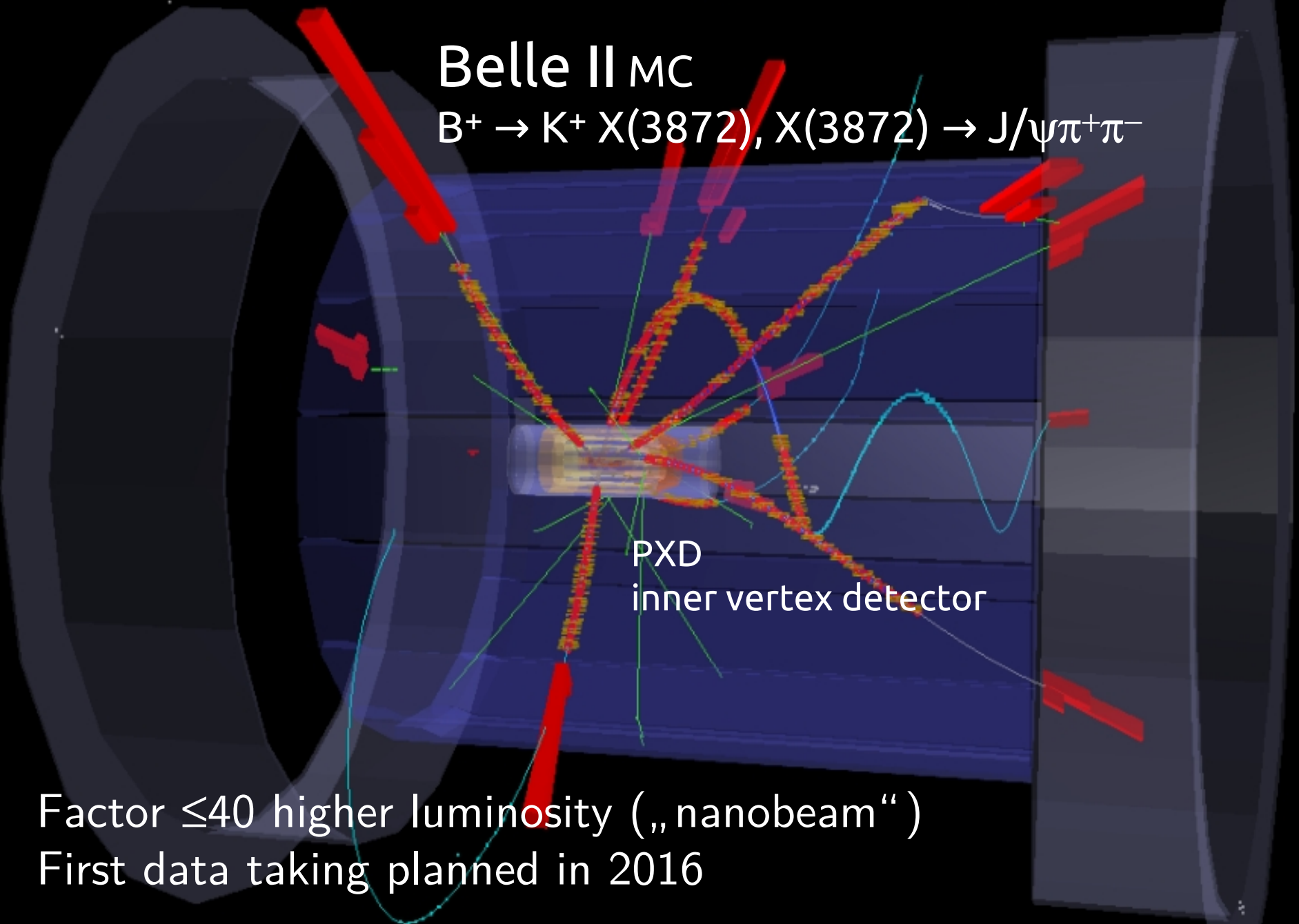
Belle in Service Position for Upgrade to Belle II



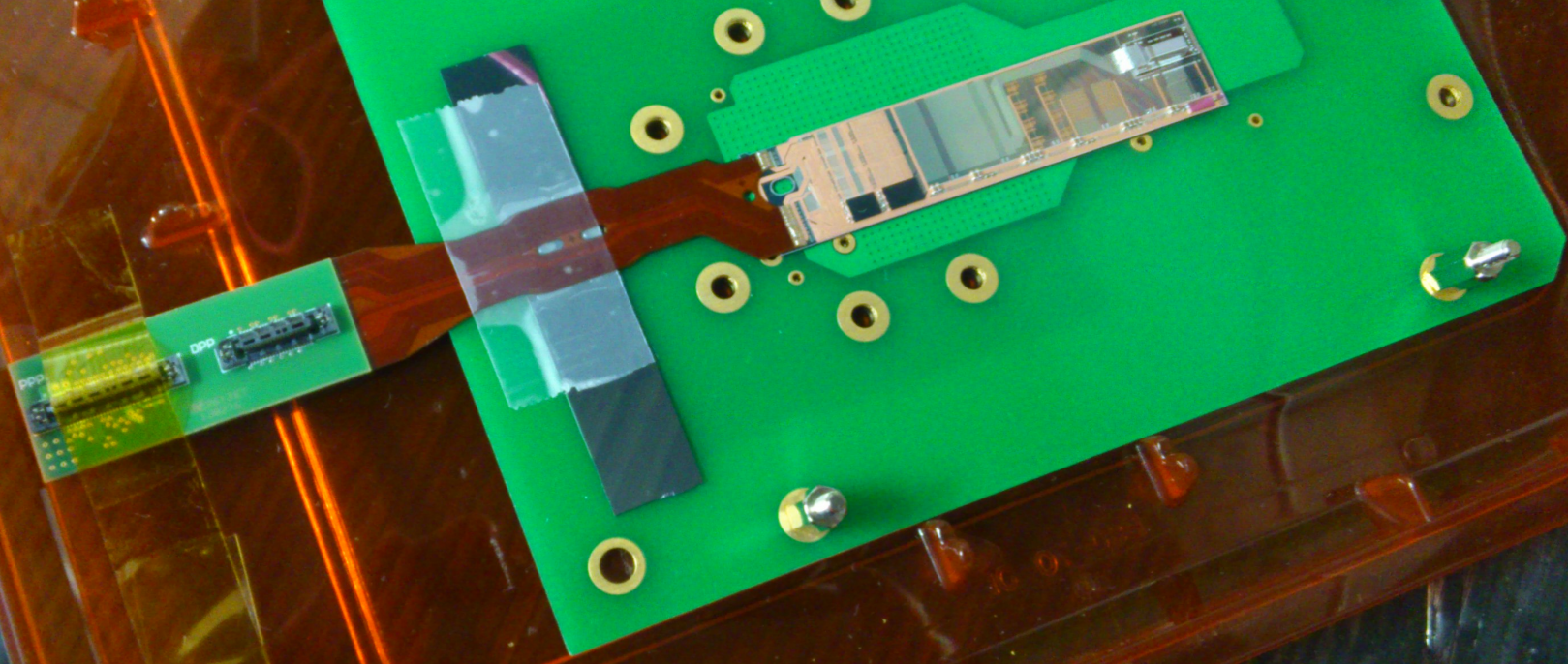
Belle II MC

$$B^+ \rightarrow K^+ X(3872), X(3872) \rightarrow J/\psi \pi^+ \pi^-$$

PXD
inner vertex detector



Factor ≤ 40 higher luminosity („nanobeam“)
First data taking planned in 2016

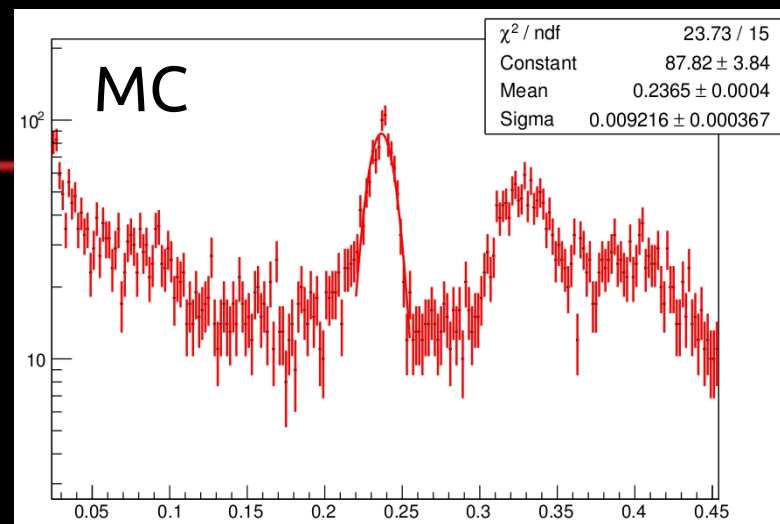
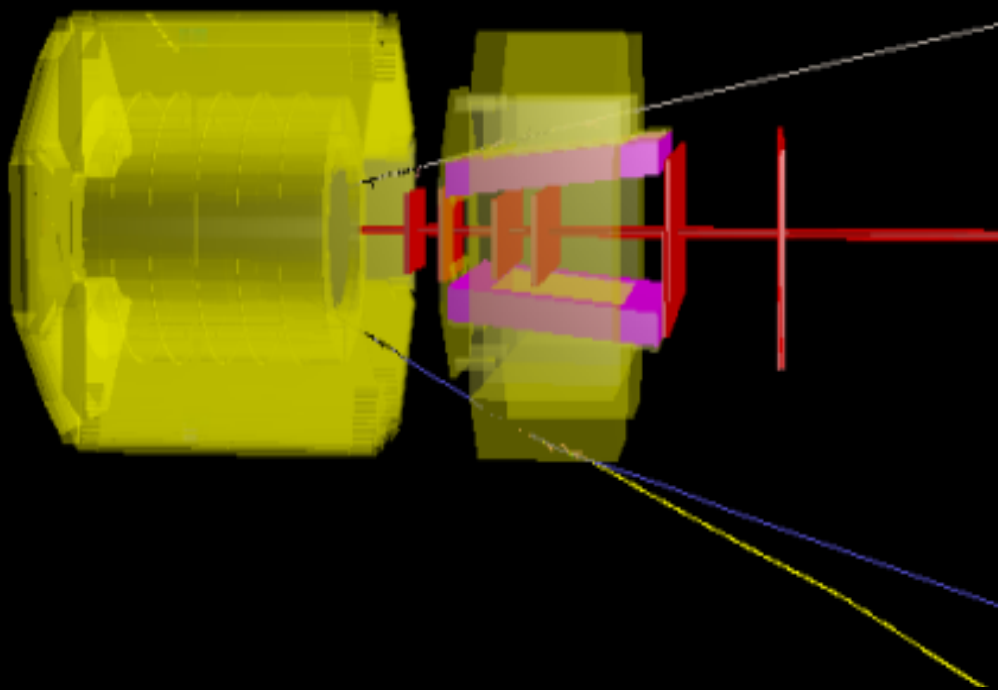
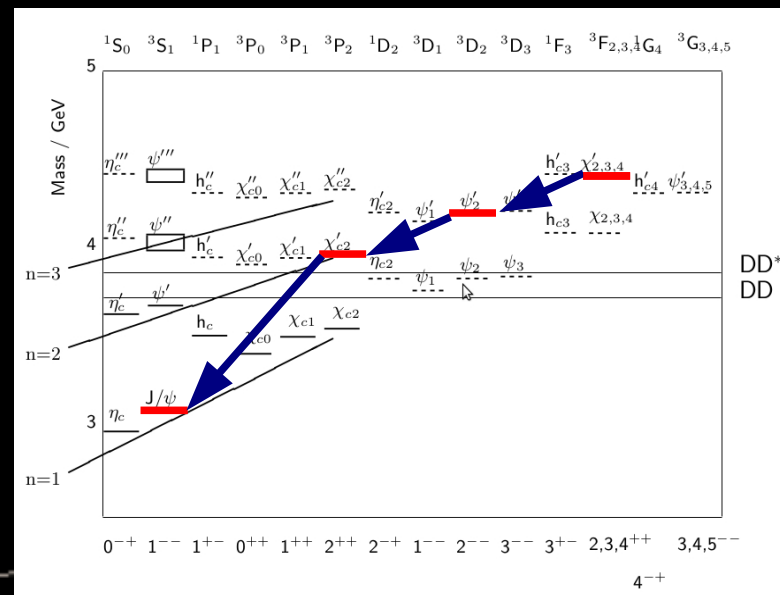


Belle II DEPFET Pixel Detector

Univ. Bonn, DESY, Univ. Giessen, Univ. Göttingen, Univ. Heidelberg,
KIT Karlsruhe, HLL München, MPI München, LMU München, TU München

PANDA @ FAIR

pp → formation of
any (non-exotic) quantum number
e.g. high F-wave state ($L=3, J^{PC}=4^{++}$)
3-step radiative cascade



$E_{\gamma}^{cms}/\text{GeV}$
M. Galuska, S. Reiter, E. Prencipe, S. Spataro, S.L.
arXiv:1311.7597[hep-ex]

State	Production	J^{PC}	Mass (MeV)	Width (MeV)	Decay	Experiment	Interpretation
X(3872)	B decays, $p\bar{p}$	1^{++}	$\simeq 3872$	< 1.2	$J/\psi \rho$, $J/\psi \omega$ $J/\psi \gamma$, $D^0 \bar{D}^{*0}$	Belle, BABAR, CDF D0, LHCb, CMS	4-quark, $(D^0 \bar{D}^{*0})$ molecule?
X(3940)	$e^+e^- \rightarrow c\bar{c}X$	0^{7+}	$\simeq 3942$	$\simeq 37$	$D\bar{D}^*$ (not $D\bar{D}$, $J/\psi \omega$)	Belle	shifted η_c'' ?
Y(3940)	B decays	$?^{7+}$	$\simeq 3943$	$\simeq 20$	$J/\psi \omega$ (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 ? $(D\bar{D}^*)^\pm$ molecule?
Z _c (3885)	Y(4260) decays	$?^?$	$\simeq 3884$	$\simeq 25$	$(D\bar{D}^*)^\pm$	BESIII	4-quark ? $(D\bar{D}^*)^\pm$ molecule?
Z _c (4020)	Y(4260) decays	$?^?$	$\simeq 4023$	$\simeq 8$	$h_c \pi^\pm$	BESIII	4-quark ? $(D^* \bar{D}^*)^\pm$ molecule?
Z _c (4025)	Y(4260) decays	$?^?$	$\simeq 4026$	$\simeq 25$	$(D^* D^*)^\pm$	BESIII	4-quark ? $(D^* \bar{D}^*)^\pm$ molecule?
Y(4140)	B decays	$?^{7+}$	$\simeq 4143$	$\simeq 15$	$J/\psi \phi$	CDF	$c\bar{c}s\bar{s}$
X(4160)	$e^+e^- \rightarrow c\bar{c}X$	0^{7+}	$\simeq 4156$	$\simeq 139$	$D^* \bar{D}^*$ (not $D\bar{D}$, $D\bar{D}^*$)	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)	$\gamma\gamma$	$?^{7+}$	$\simeq 4351$	$\simeq 13$	$J/\psi \phi$	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^{--}	$\simeq 4634$	$\simeq 92$	$\Lambda_c \bar{\Lambda}_c$	Belle	$\Lambda_c \bar{\Lambda}_c$ 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? $(B\bar{B}^*)^\pm$ 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? $(B^* \bar{B}^*)^\pm$ 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, $[b\bar{b}]_{sg}$ 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 ($\mathcal{B} \sim 10^{-5}$)
→ next-generation high luminosity experiments are required
Belle II, PANDA, LHCb (upgrade), more BESIII running ...

THANK YOU.

Review Articles:

arXiv:1311.7594 [hep-ex]

arXiv:1208.6128 [hep-ex]

arXiv:1109.1699 [hep-ex]

arXiv:1010.2331 [hep-ex]