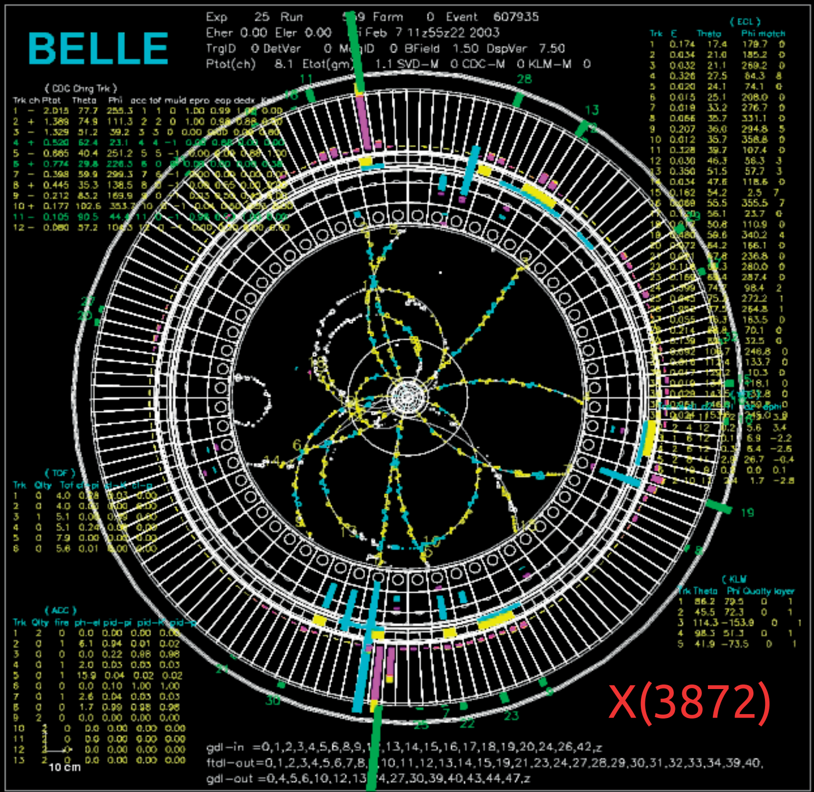


XYZ

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

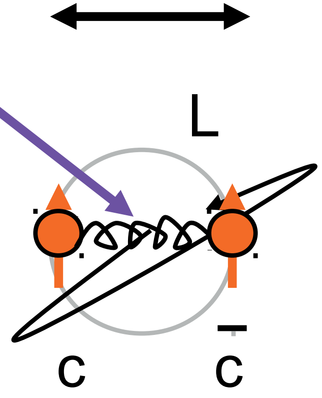
- Experiments: Belle, BaBar, BESIII

- Charmonium(-like) states
  → X(3872)
  → Y(4260)
  → $Z_c^{\pm}$ (3900)

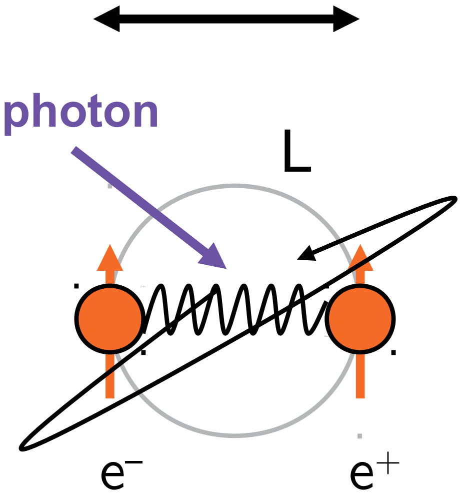
- Bottomonium(-like) states
  → Implications for potential model (→ confinement)
  → $Z_b^{\pm}$

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

Charmonium vs. Positronium



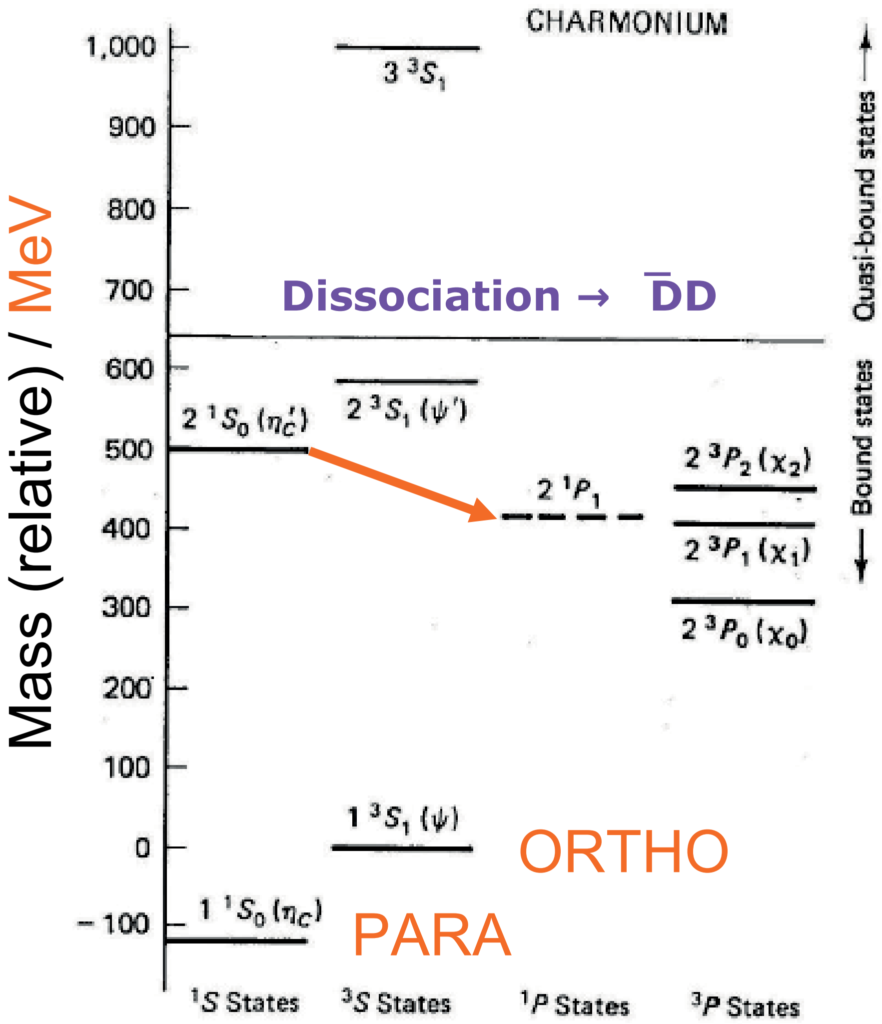
Charmonium

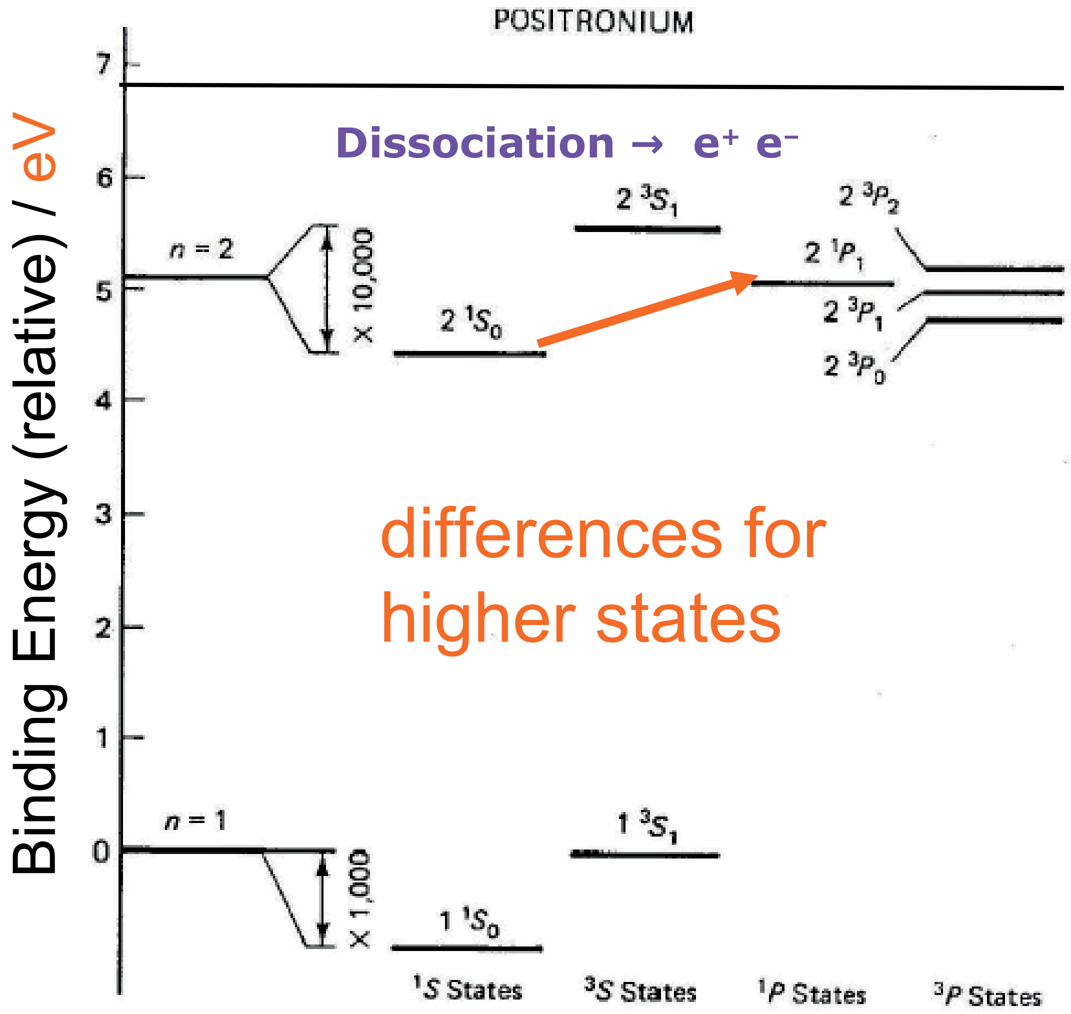


Positronium

Charmonium vs. Positronium

Decays to light quarks suppressed
→ narrow widths





Static Quark-Antiquark Potential

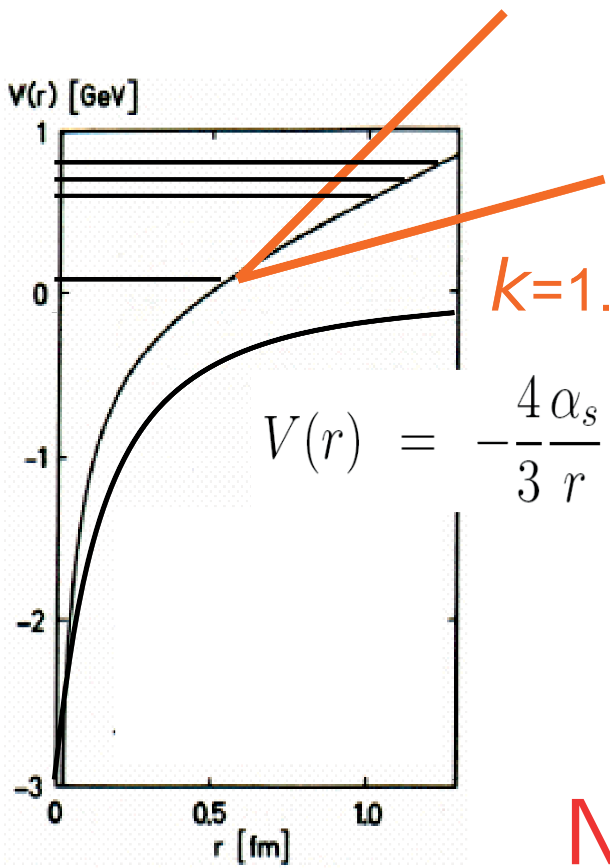
- Coulomb-Potential
  + Confinement-Term

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

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

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

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



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

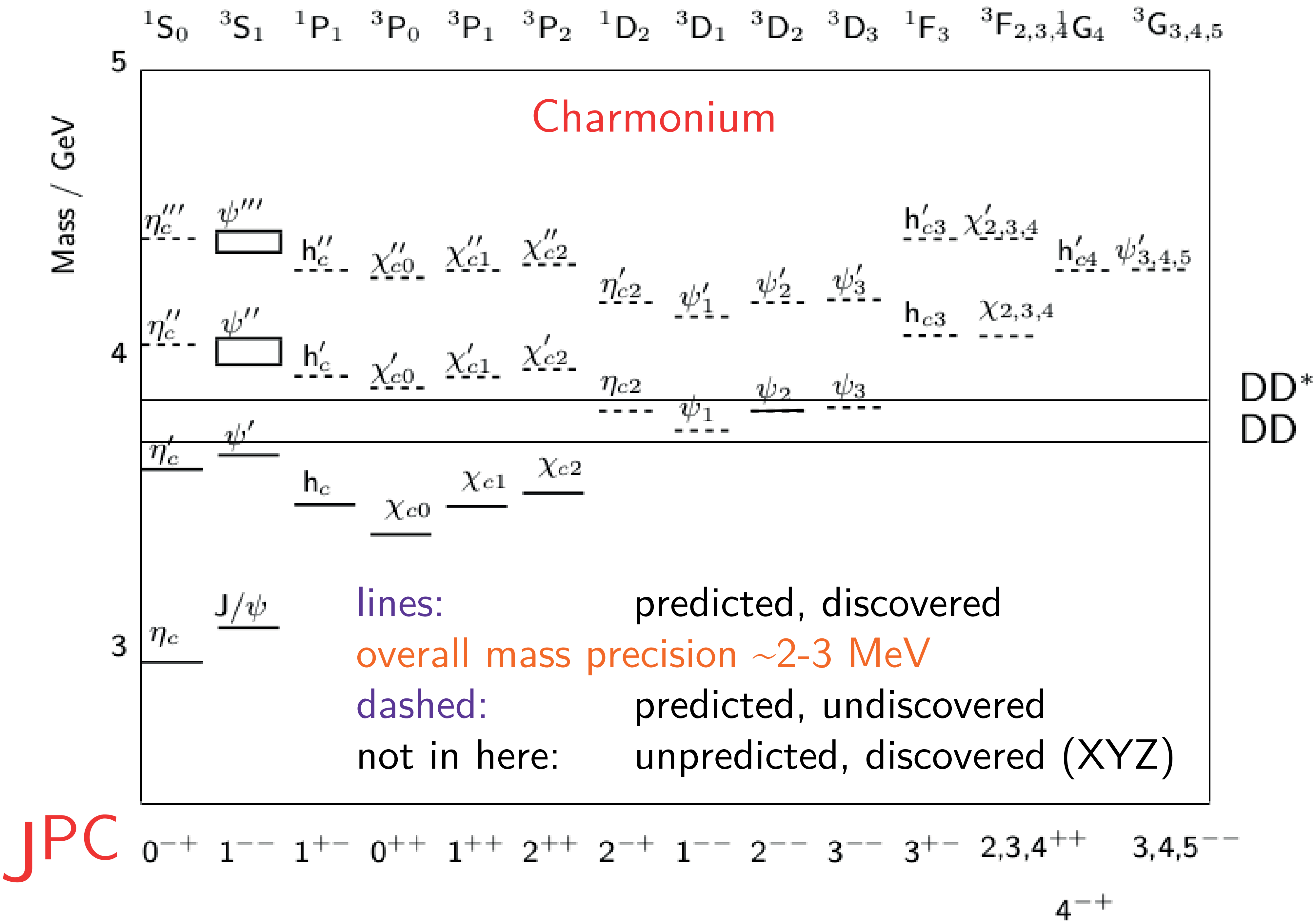
$$\Psi(r,\theta,\phi) = R_{nl}(r)Y_{lm}(\theta,\phi)$$

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

Notation

$n^{2S+1}L_J$

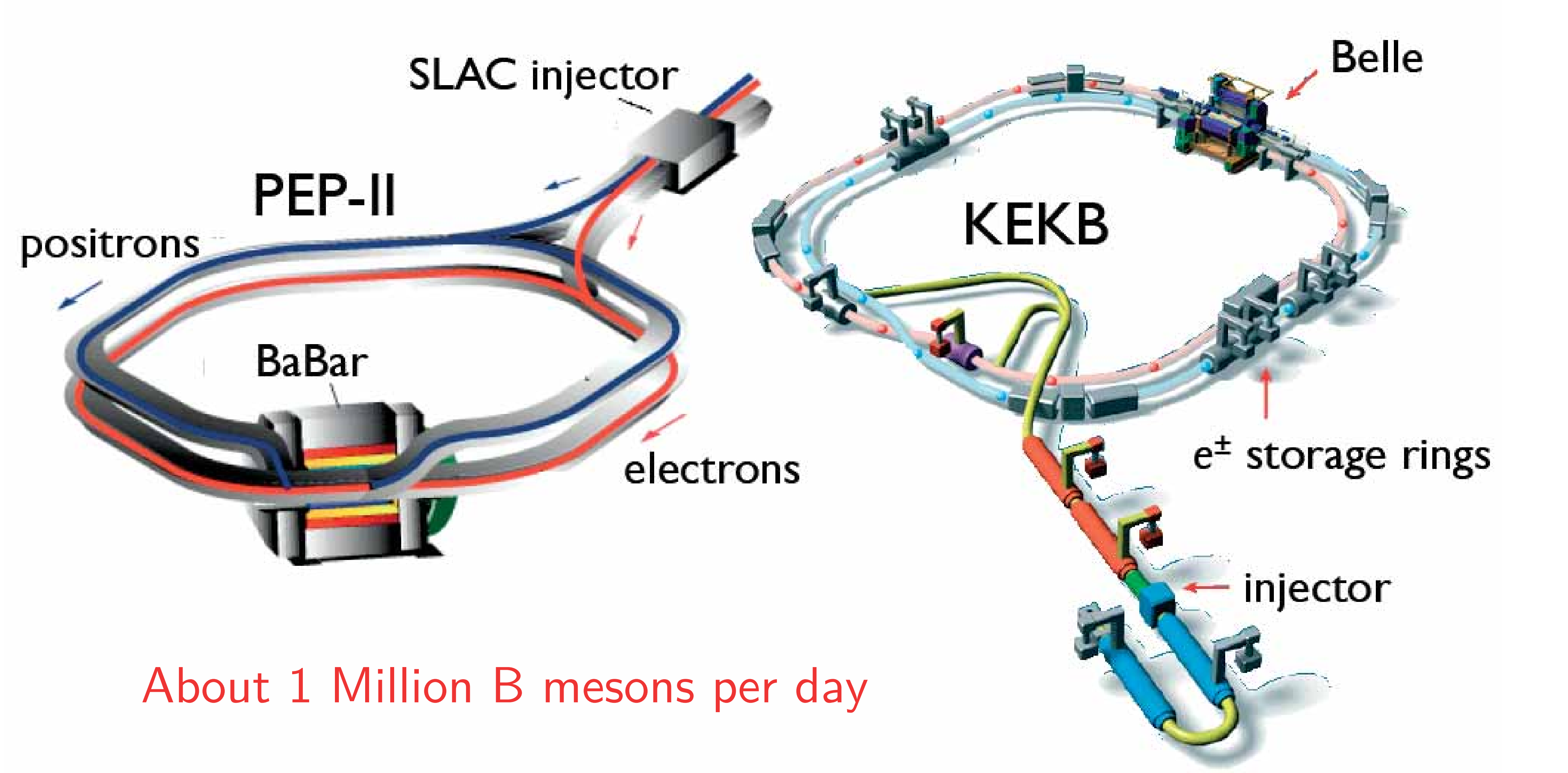
J^{PC}


Charmonium
Mass / GeV
5
4
3
¹S₀ ³S₁ ¹P₁ ³P₀ ³P₁ ³P₂ ¹D₂ ³D₁ ³D₂ ³D₃ ¹F₃ ³F₂,₃,₄ ¹G₄ ³G₃,₄,₅
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

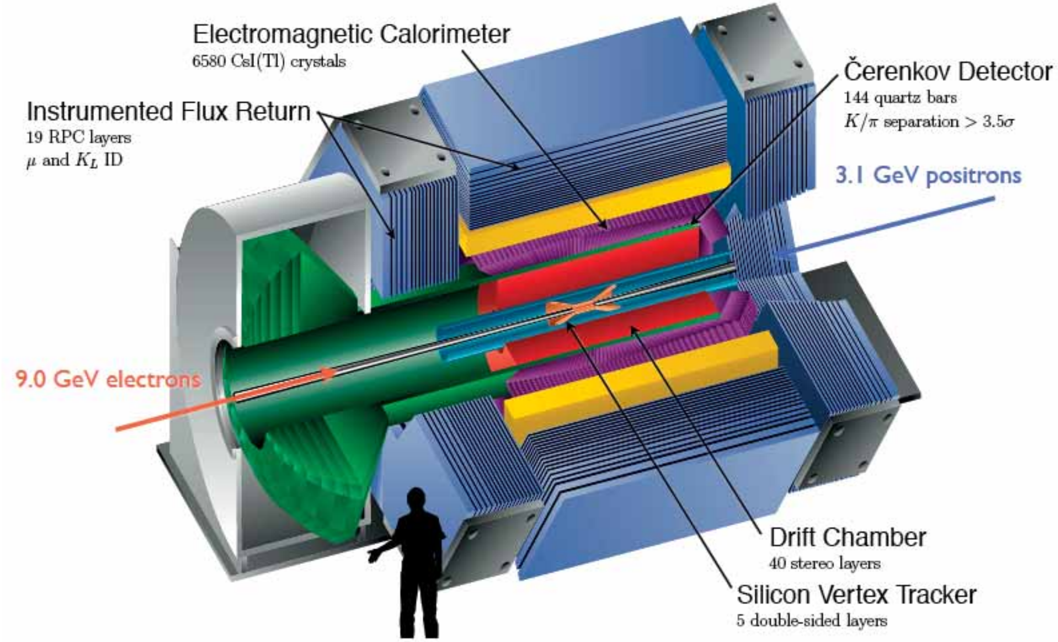
$e^+e^- \to \Upsilon(4S) \to B\bar{B}$ ($\mathcal{B} \sim 99\%$)

1999-2008 1999-2010



About 1 Million B mesons per day

BaBar at PEP-II

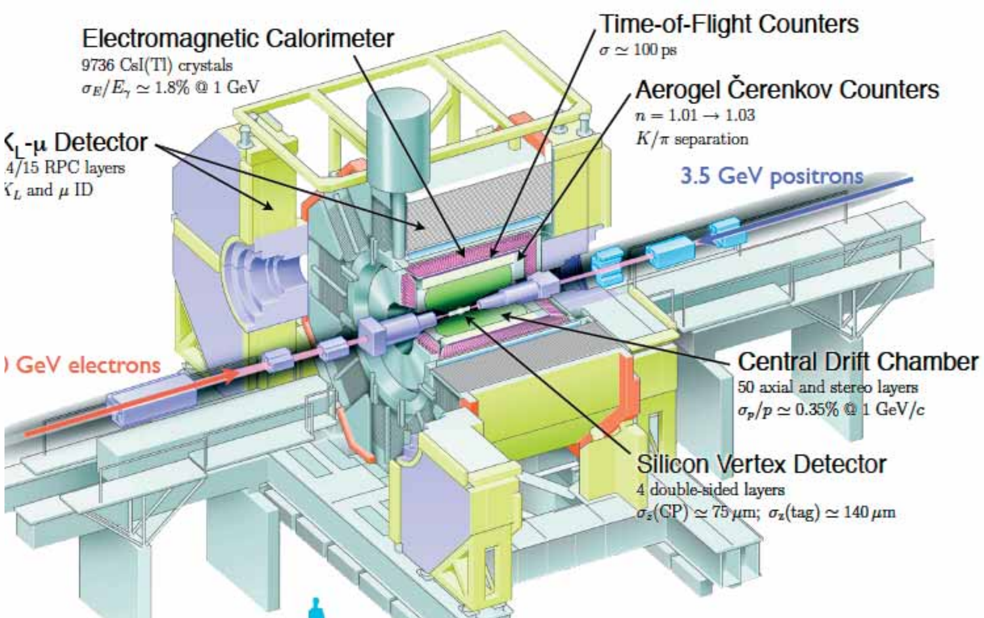


11 countries, 80 institutes, ~600 collaborators

~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



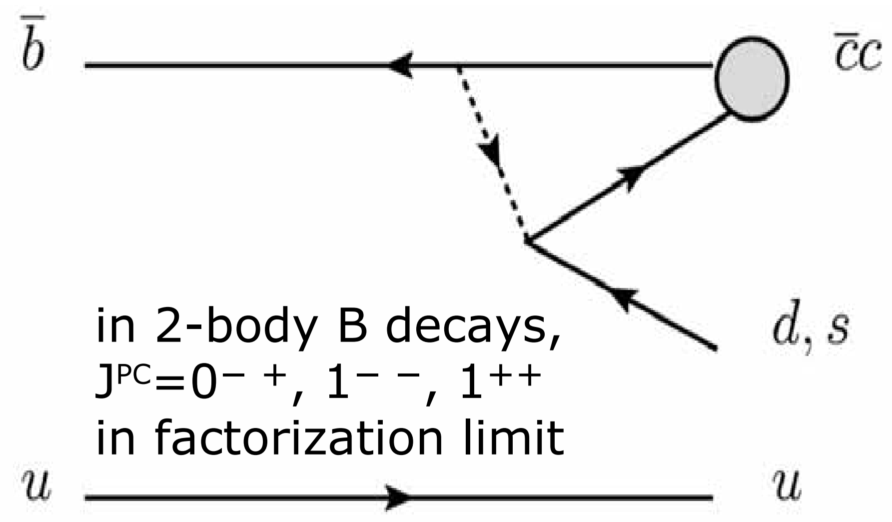
14 countries, 55 institutes, ~400 collaborators

~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

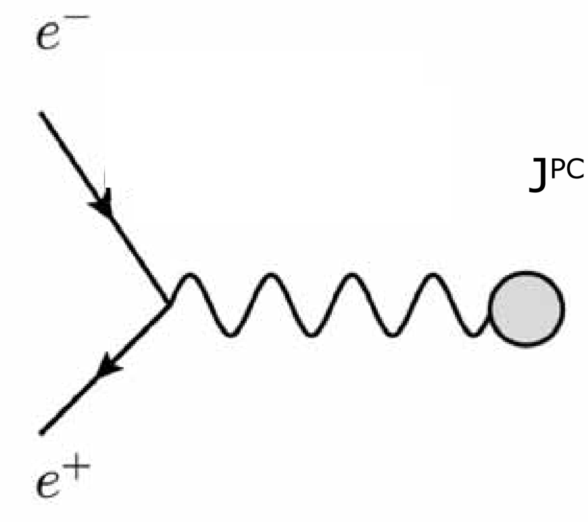
Charmonium Production

B Meson Decays



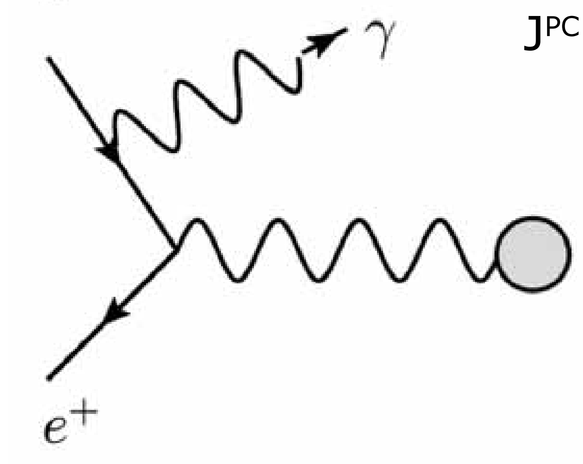
in 2-body B decays,
$J^{PC}=0^{-+}, 1^{--}, 1^{++}$
in factorization limit

Direct Production



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

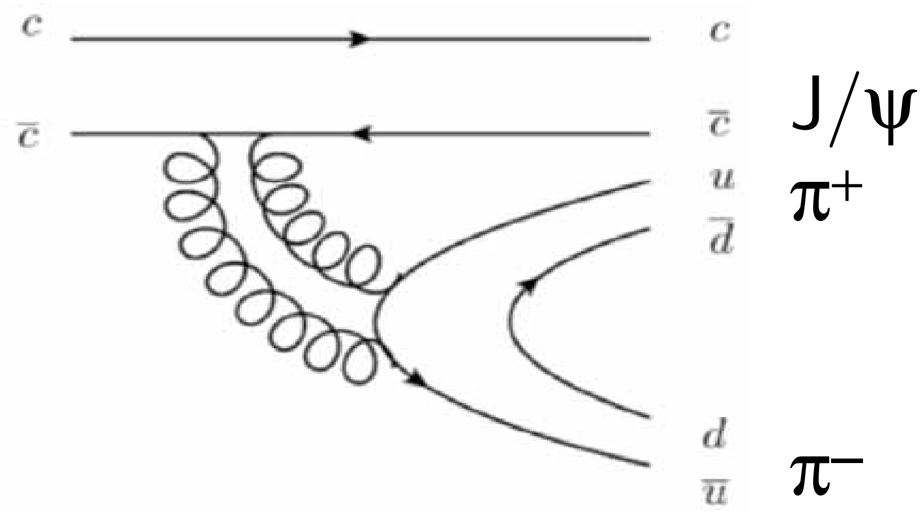
Initial State Radiation



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

X(3872)

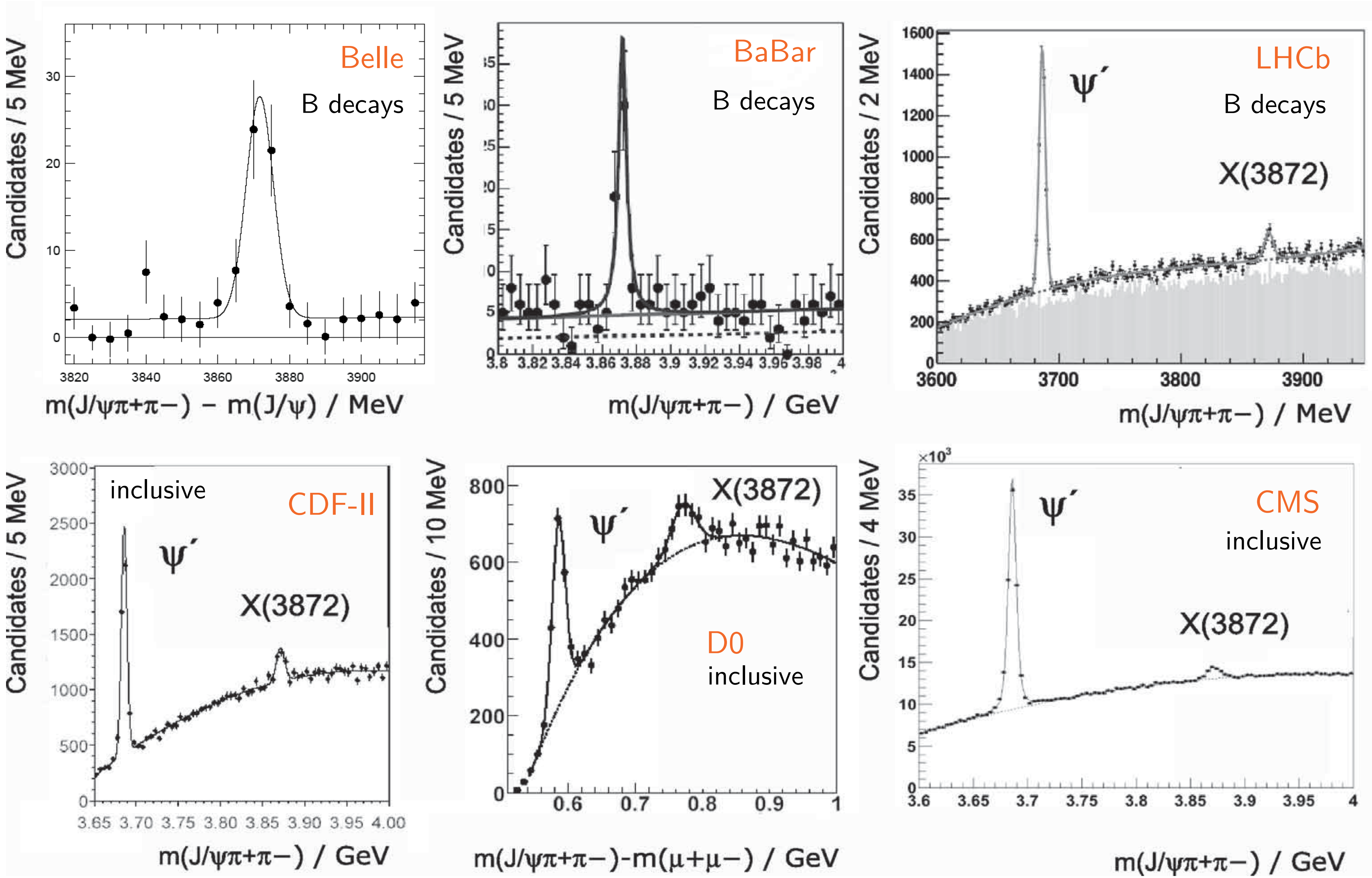
$$B^{\pm} \to K^{\pm} \underbrace{J/\psi\pi^{+}\pi^{-}}_{\text{resonant state?}}$$



Product branching fraction small

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

X(3872)

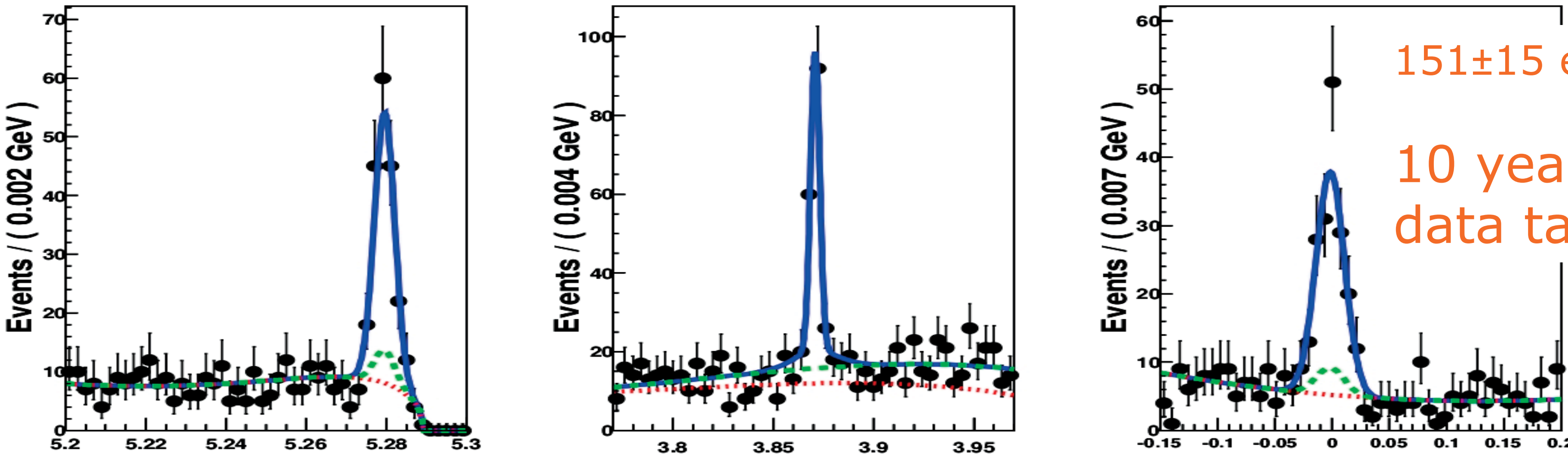


Belle
B decays
Candidates / 5 MeV
m(J/ψπ+π−) − m(J/ψ) / MeV
BaBar
B decays
Candidates / 5 MeV
m(J/ψπ+π−) / GeV
LHCb
B decays
ψ´
X(3872)
Candidates / 2 MeV
m(J/ψπ+π−) / MeV
inclusive
CDF-II
ψ´
X(3872)
Candidates / 5 MeV
m(J/ψπ+π−) / GeV
ψ´
X(3872)
D0
inclusive
Candidates / 10 MeV
m(J/ψπ+π−)-m(μ+μ−) / GeV
ψ´
CMS
inclusive
X(3872)
Candidates / 4 MeV
m(J/ψπ+π−) / GeV

X(3872) → J/ψ π+π−

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

Belle, Phys. Rev. D84(2011)052004



m_{BC} /GeV $M(J/\psi\ \pi^+\ \pi^-)$/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±0.28 MeV
  „binding energy“ −0.16±0.33 MeV
  → random coincidence or „grand design“ ?

- upper limit on width
  Γ < 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

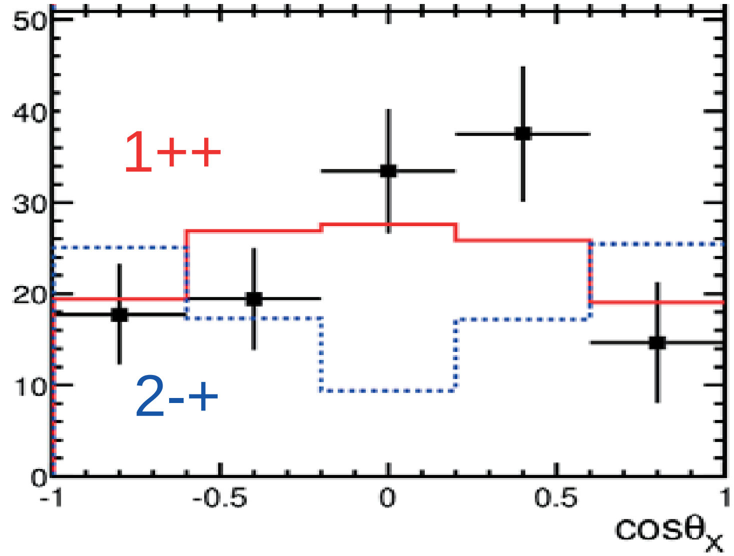
  $\rightarrow$ predicted width factor ≥100 larger
- Decay X(3872) $\rightarrow J/\psi\pi^+\pi^-$
  dominated by X(3872) $\rightarrow J/\psi\rho^0$(I=1)

  $\rightarrow$ violates isospin

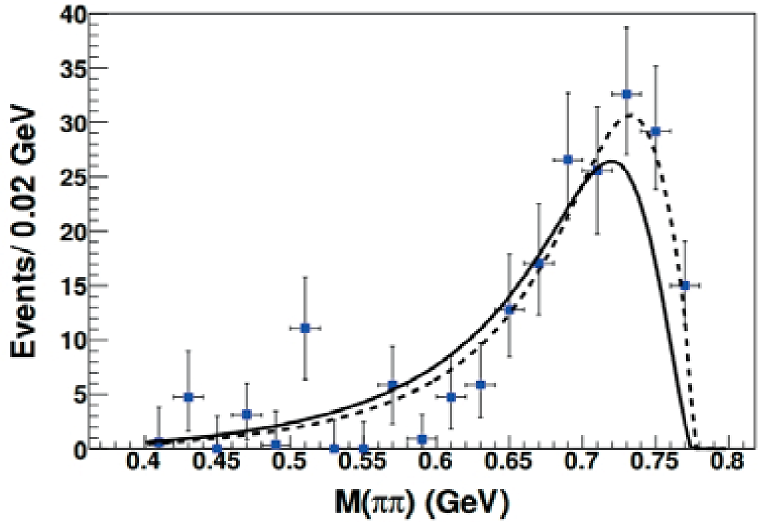
  (assume initial I=0)

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

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

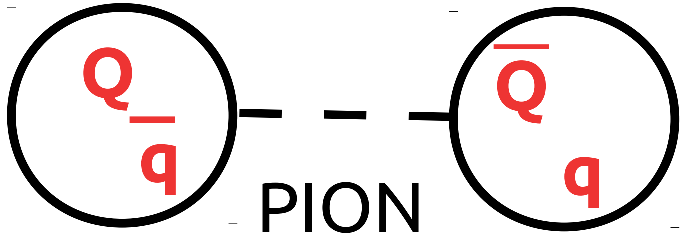


Belle, Phys. Rev. D84(2011)052004



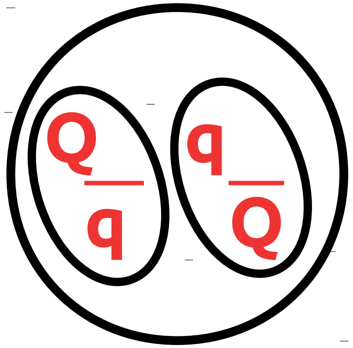
Is the X(3872) exotic ?

MOLECULE



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

TETRAQUARK

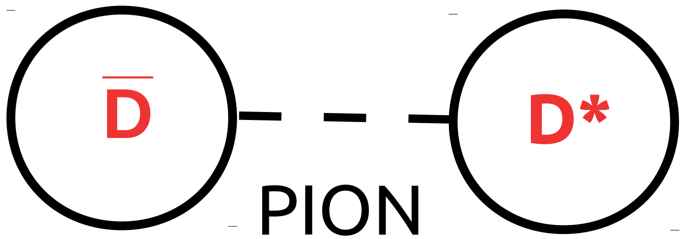


Diquarks can be colored

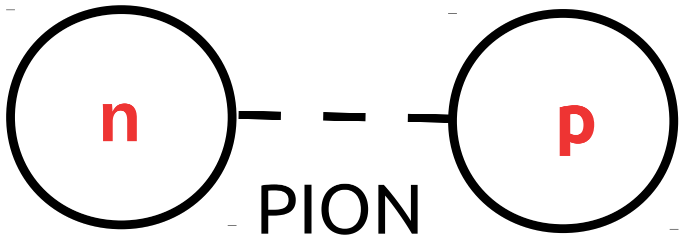
$[Qq][\overline{Qq}]$ Maiani, Riquer, Piccinini, Polosa, Burns; Ebert, Paustov, Galkin; Chiu, Hsieh; Ali, Hambrock, Wang

Intriguing Analogon

1.8 GeV 2 GeV



1 GeV 1 GeV



Can the X(3872) be a mixture ?

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

χ_{c1}'

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

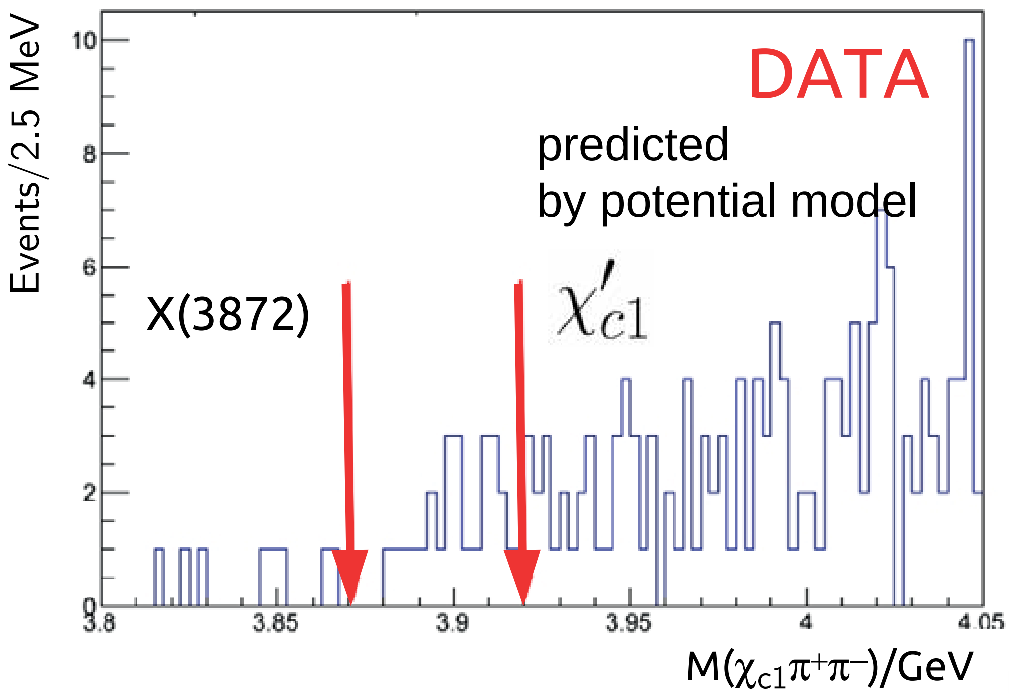
Is there $c\bar{c}$ admixture inside the X(3872) ?

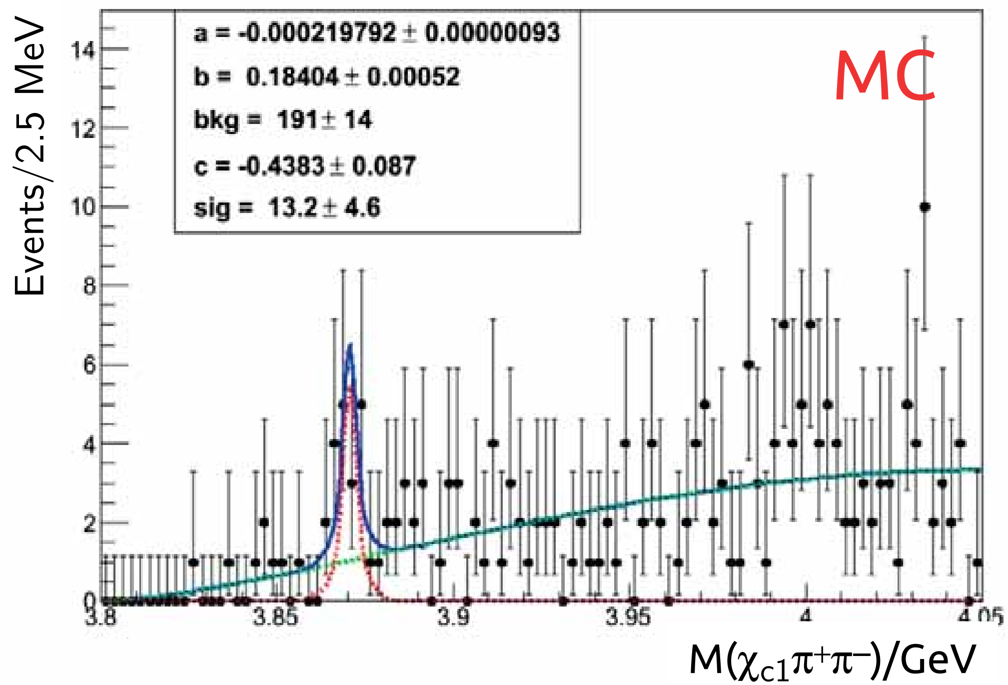
Search for $X(3872) \to \chi_{c1}\, \pi^+\pi^-$

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)

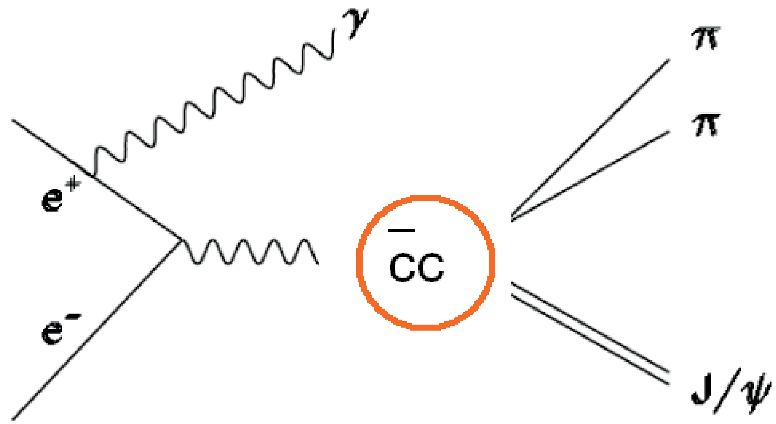
Note: recent notation
by PDG as X(4260)

Y(4260)

- Initial state radiation events

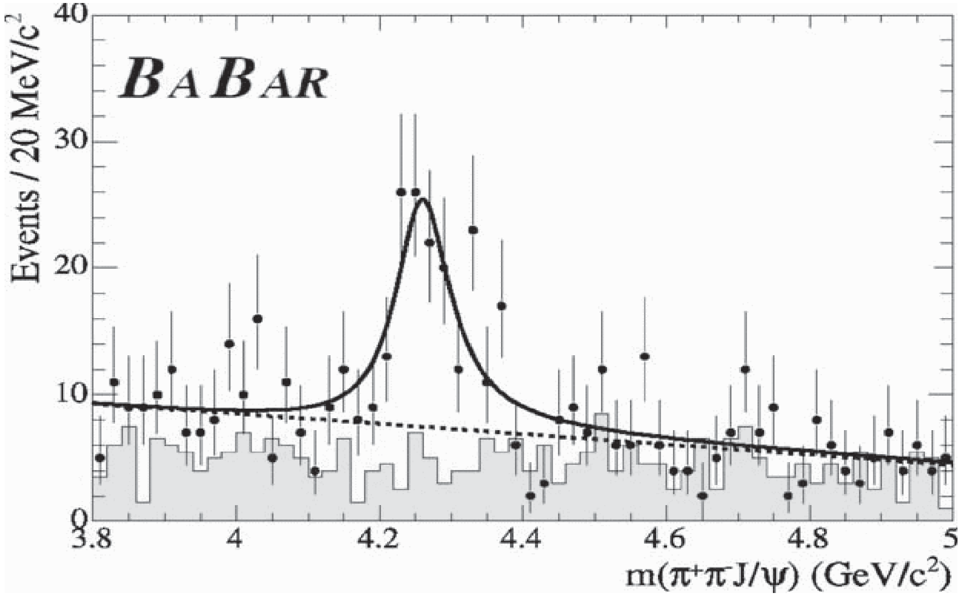
$$e^+e^- \rightarrow \gamma_{ISR} \underbrace{J/\psi\pi^+\pi^-}_{\text{resonant state?}}$$

initial state radiation



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

Phys. Rev. Lett. 95(2005)142001



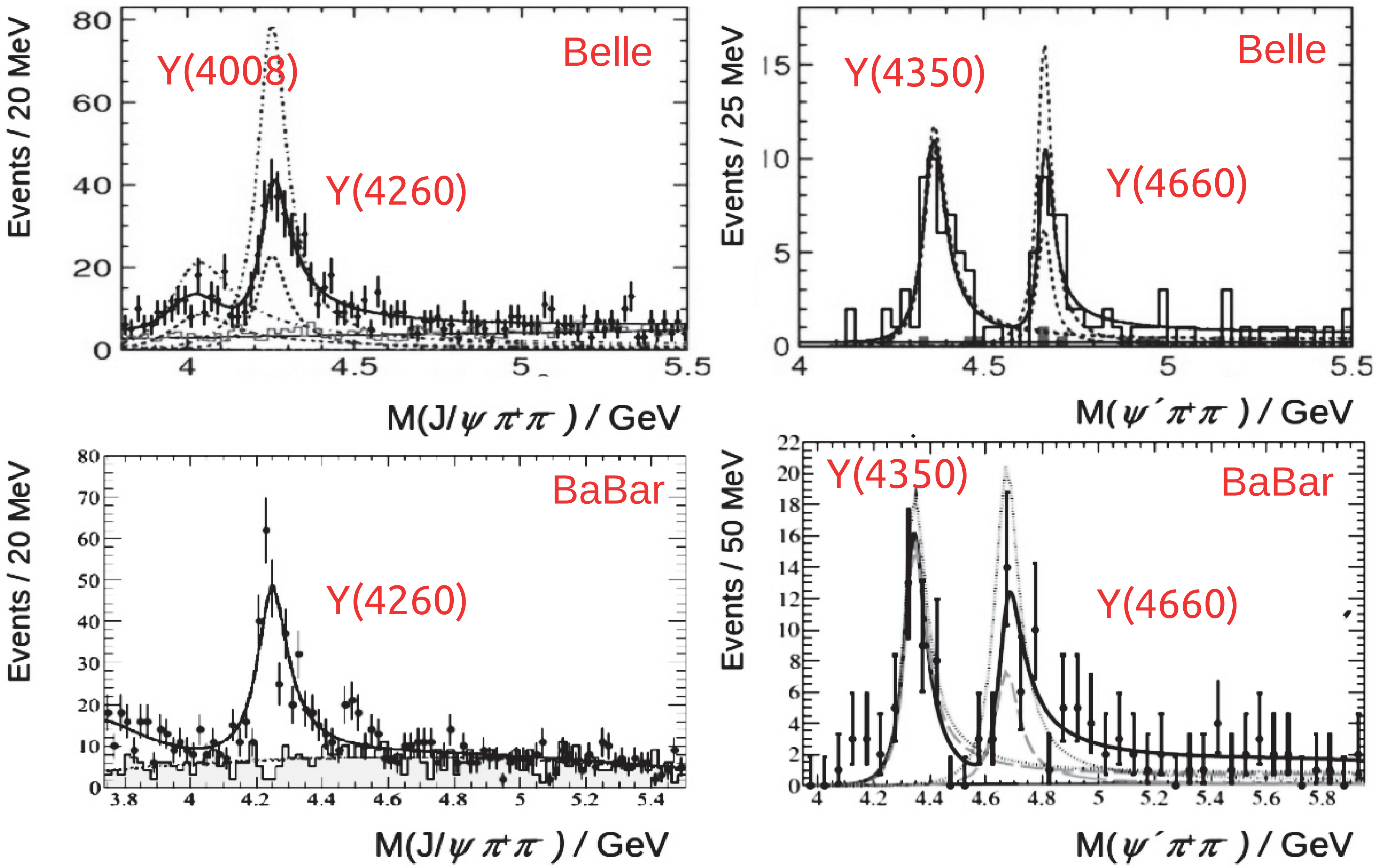
- Quantum numbers (based upon production mechanism)
  $J^{PC}=1^{--}$

Y(4260) Parameters

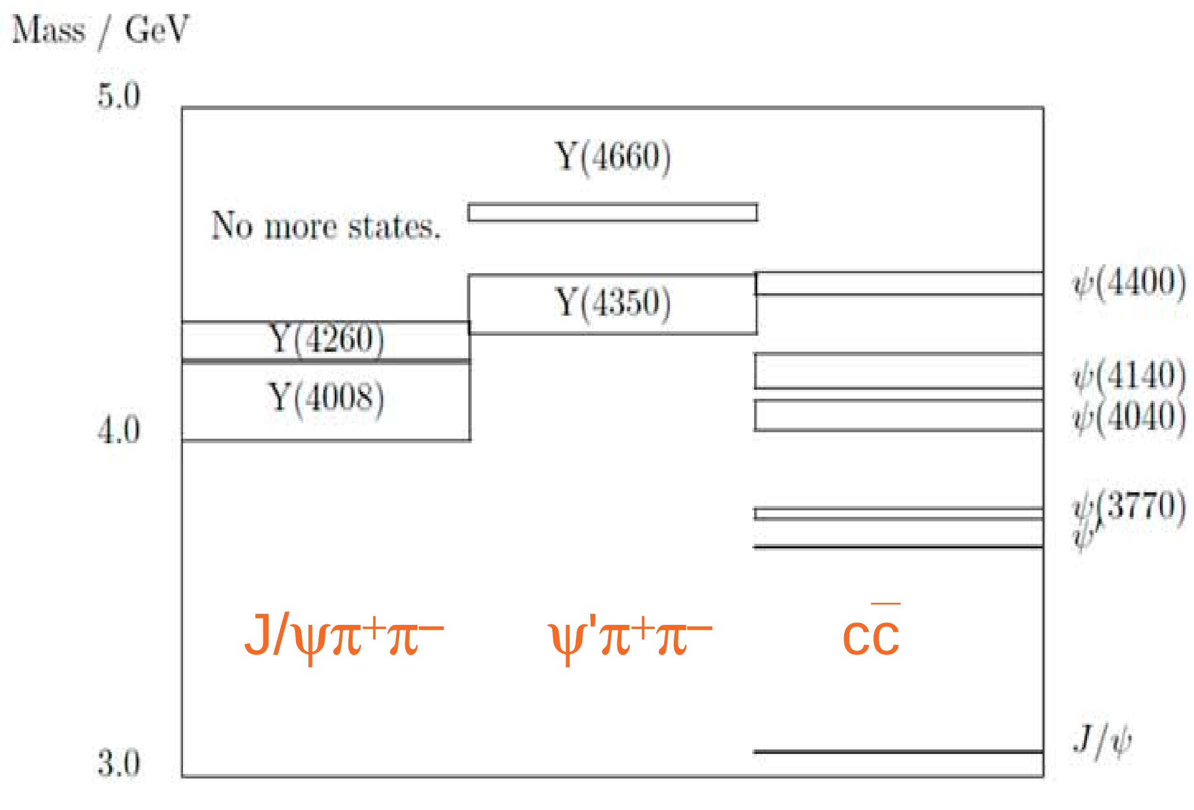
	BaBar [1]	CLEO-c [2]	Belle [3]	Belle [4]	BaBar [5]	BaBar [6]
$\mathcal{L}$	211 fb^{-1}	13.3 fb^{-1}	553 fb^{-1}	548 fb^{-1}	454 fb^{-1}	454 fb^{-1}
N	125 ± 23	$14.1^{+5.2}_{-4.2}$	165 ± 24	324 ± 21	344 ± 39	–
Significance	$\simeq 8\sigma$	$\simeq 4.9\sigma$	$\geq 7\sigma$	$\geq 15\sigma$	–	–
m / MeV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

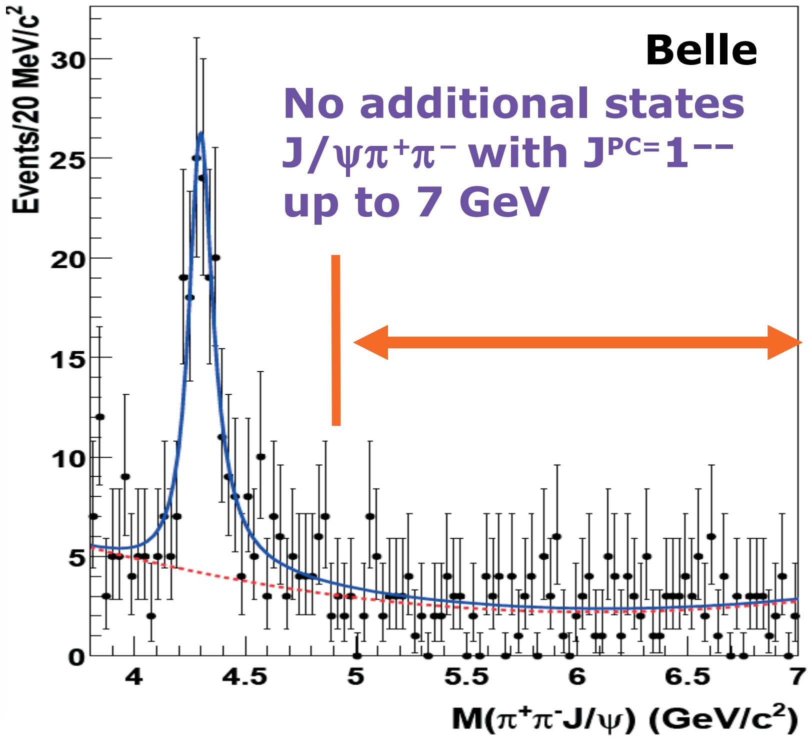
[1] BaBar Collaboration, arXiv:hep-ex/0506081, Phys. Rev. Lett. 95(2005)142001.
[2] CLEO-c Collaboration, arXiv:hep-ex/0611021, Phys. Rev. D74(2006)091104.
[3] Belle Collaboration, arXiv:hep-ex/0612006.
[4] Belle Collaboration, arXiv:0707.2541[hep-ex], Phys. Rev. Lett. 99(2007)182004.
[5] BaBar Collaboration,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



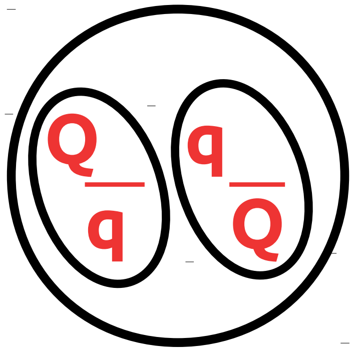


- Non-trivial pattern, not understood
- No mixing with conventional ψ states
- No mixing among them
  - → Y(4260) seems not to decay to $\psi'\pi^+\pi^-$
  - → Y(4350) seems not to decay to $J/\psi\pi^+\pi^-$

Is the Y(4260) exotic ?

TETRAQUARK

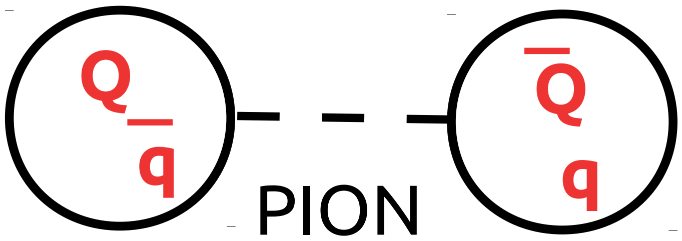
higher excitation ?



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

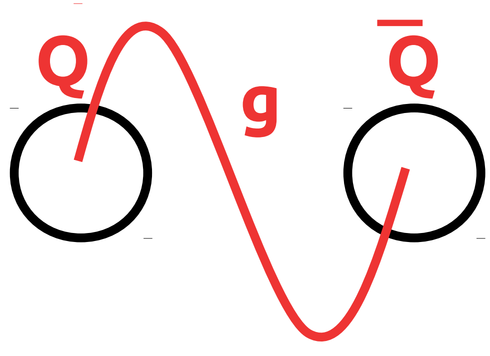
MOLECULE

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



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

HYBRID



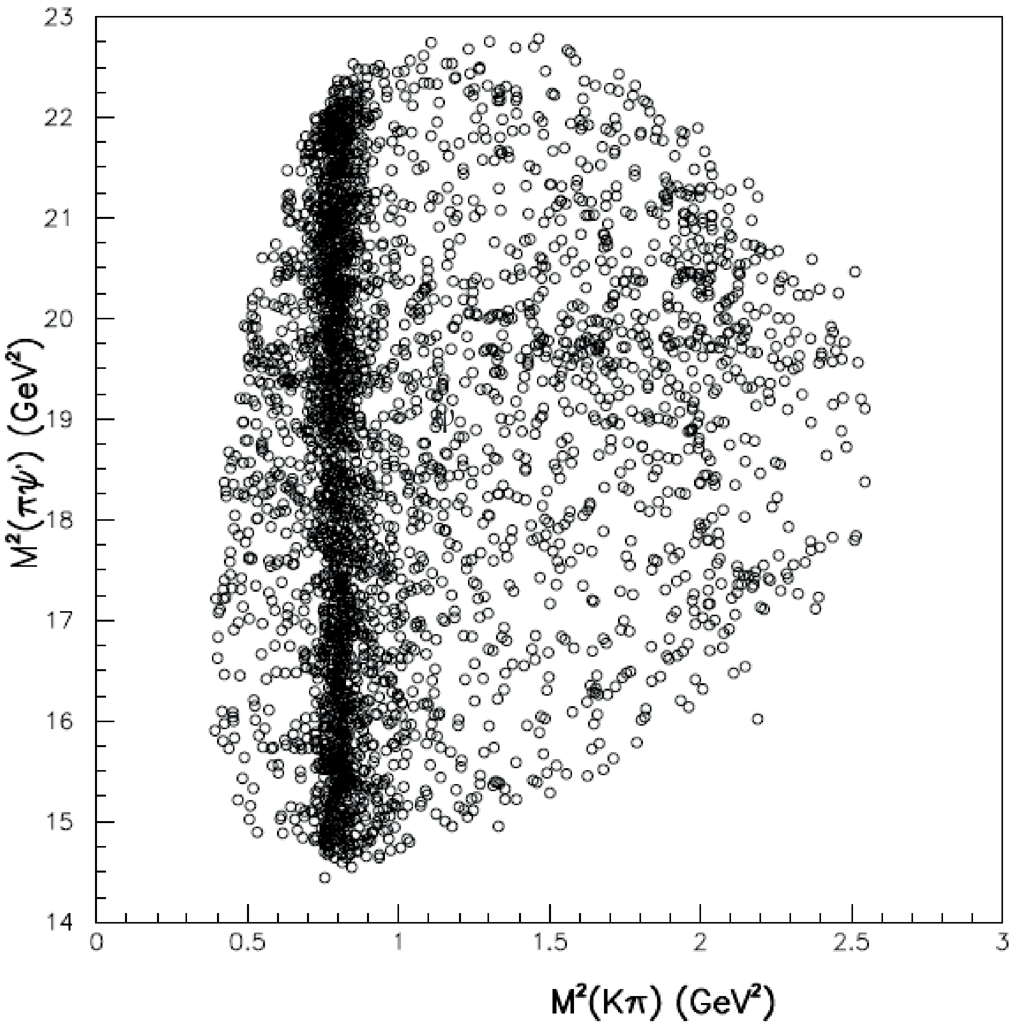
Zhu; Kou, Pene; Close, Page;
Lattice QCD, Bernard et al.; Mei, Luo

Z_c^+ States

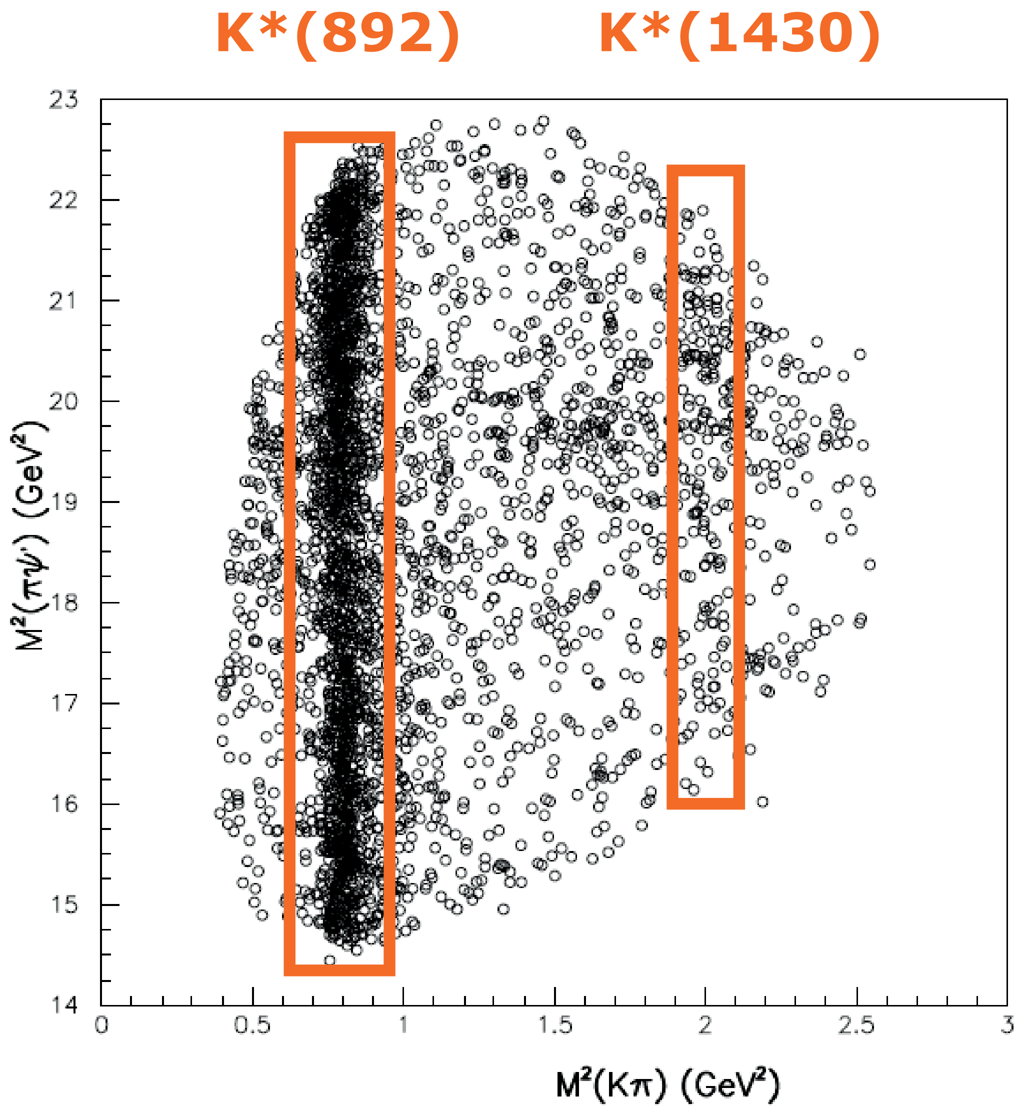
If there are exotic neutral states,
are there also exotic charged states ?
(→ cannot be charmonium!)

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

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

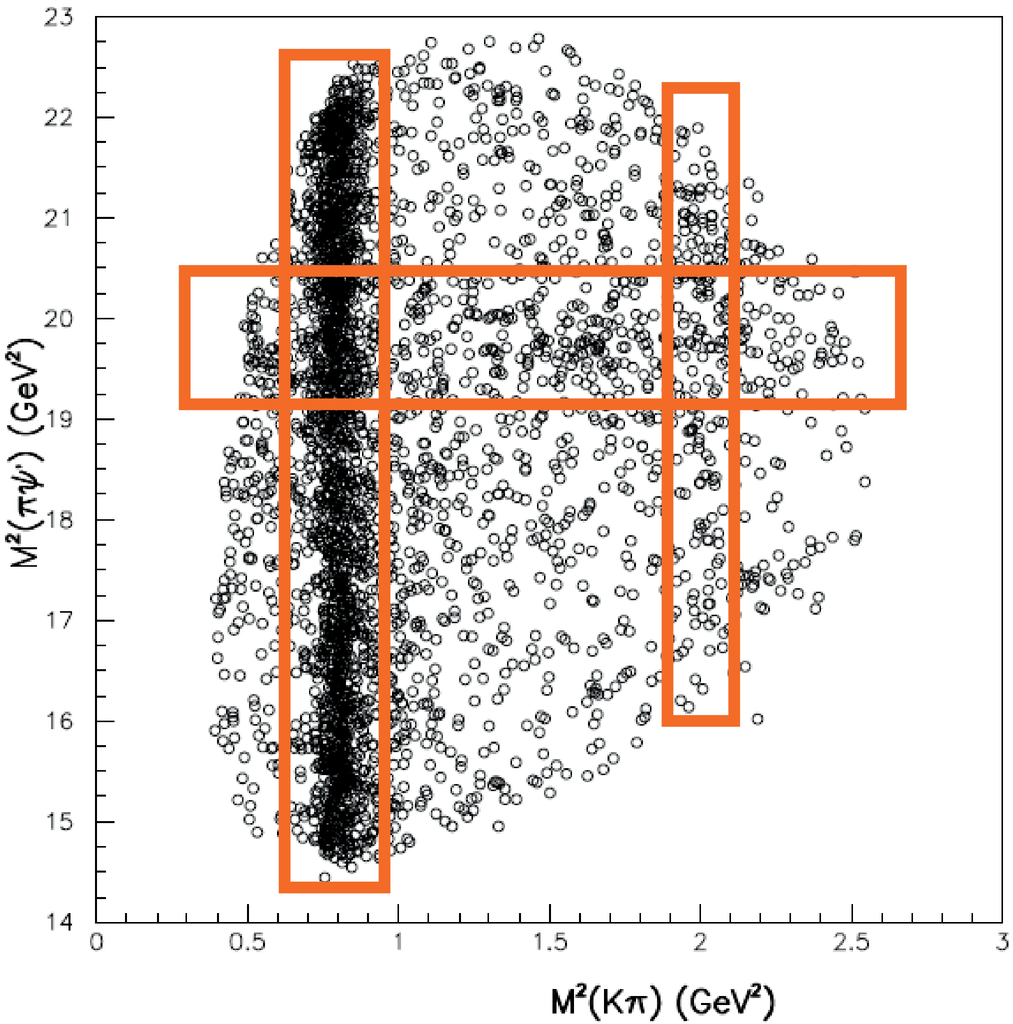


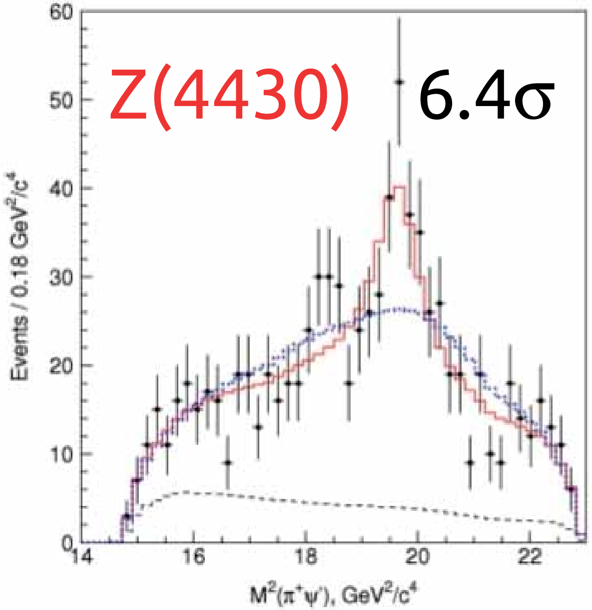
$B^0 \rightarrow K^+ \psi' \pi^-$
$\psi' \rightarrow J/\psi \, \pi^+ \pi^-$



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

K*(892) **K*(1430)**



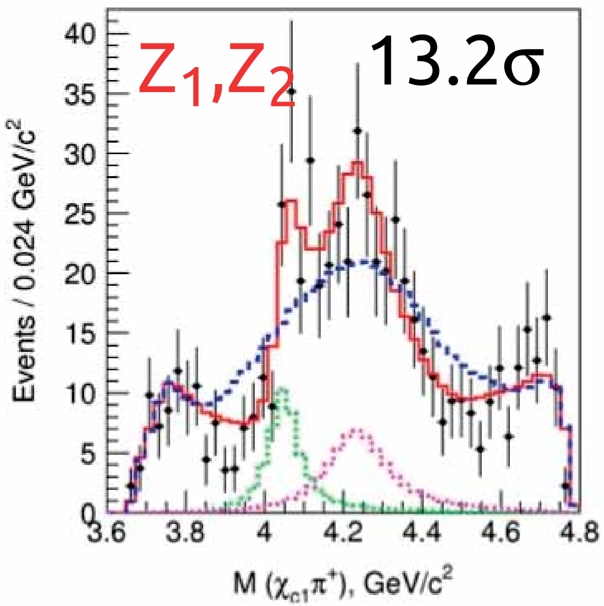


$$B^0 \to K^\pm \underbrace{\psi'\pi^\mp}_{\text{resonant state?}}$$

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

$$m=4433\pm4\pm2\ \mathrm{MeV},\ \Gamma=45^{+18+30}_{-13-13}\ \mathrm{MeV}$$

Belle, Phys. Rev D80(2009)031104



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

not confirmed by BaBar

$$m(\mathrm{Z}_1)=4051\pm14^{+20}_{-41}\ \mathrm{MeV},\ \Gamma(\mathrm{Z}_1)=82^{+21+47}_{-17-22}\ \mathrm{MeV}$$

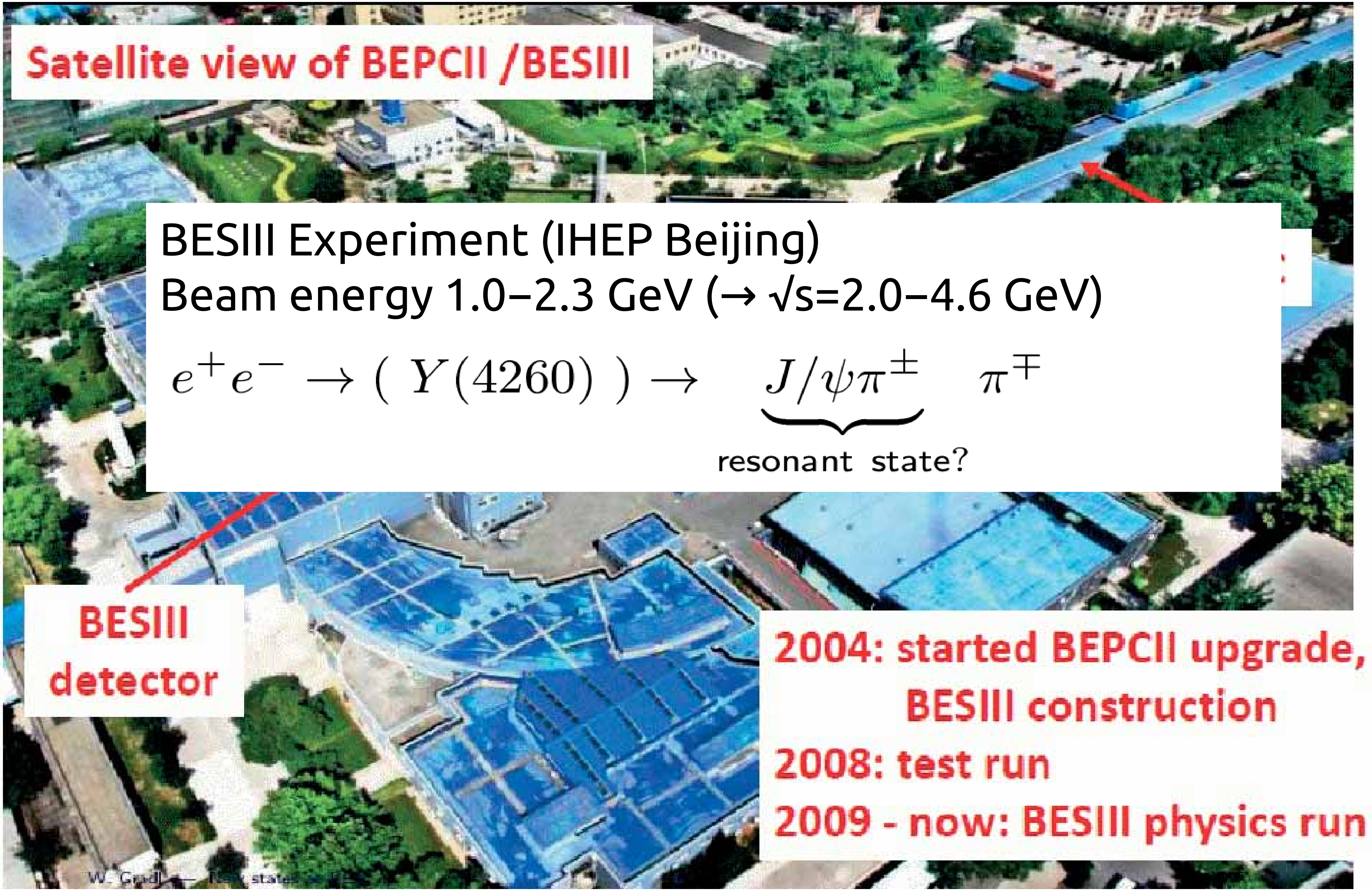
$$m(\mathrm{Z}_2)=4248^{+44+180}_{-29-35}\ \mathrm{MeV},\ \Gamma(\mathrm{Z}_2)=177^{+54+316}_{-39-61}\ \mathrm{MeV}$$

Belle, Phys. Rev D78(2008)072004

Problem: understanding of 3-body decay dynamics

Beijing Electron Positron Collider II

Beijing Electron Positron Collider II



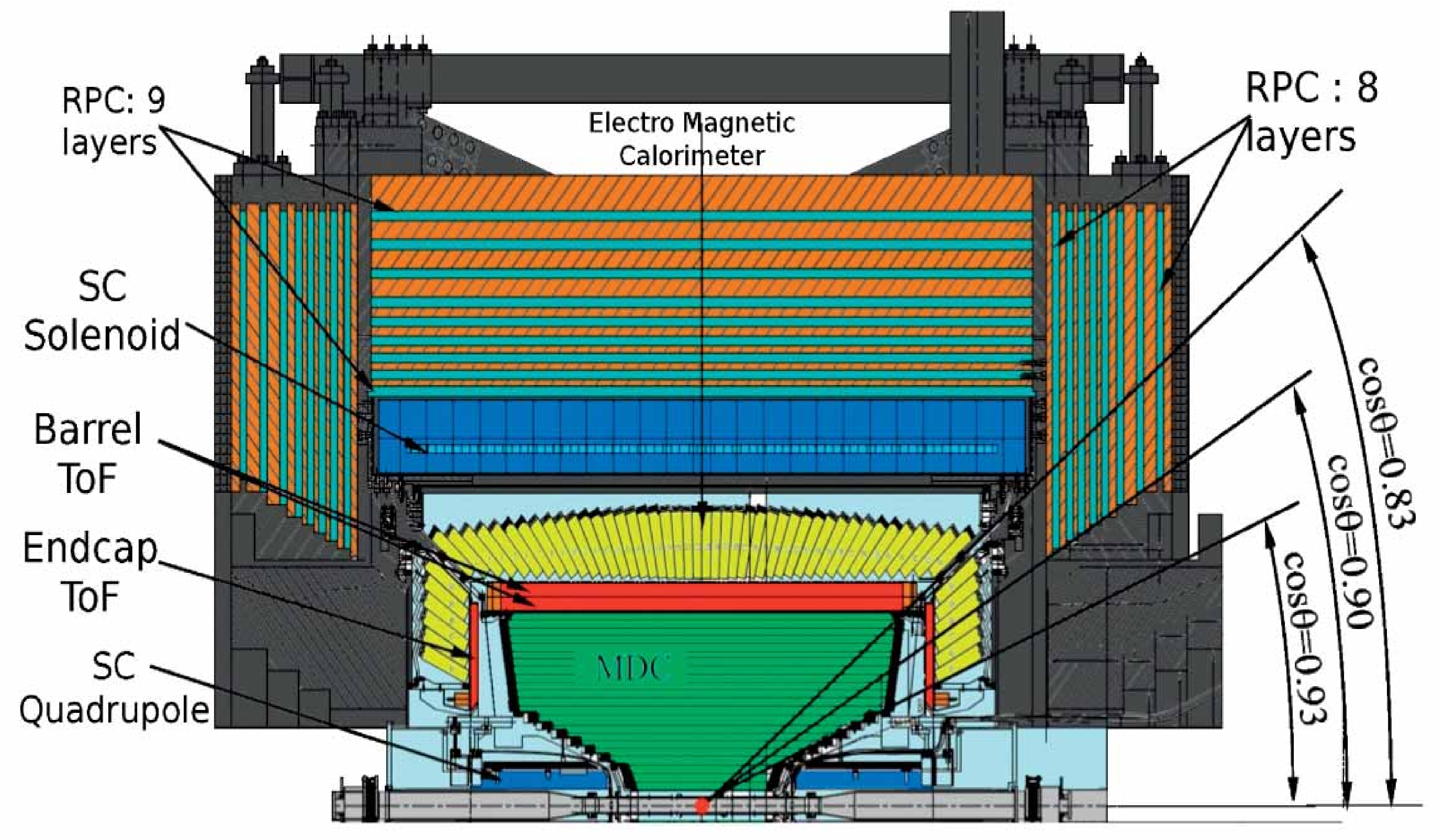
BESIII Experiment (IHEP Beijing)

Beam energy 1.0–2.3 GeV (→ $\sqrt{s}$=2.0–4.6 GeV)

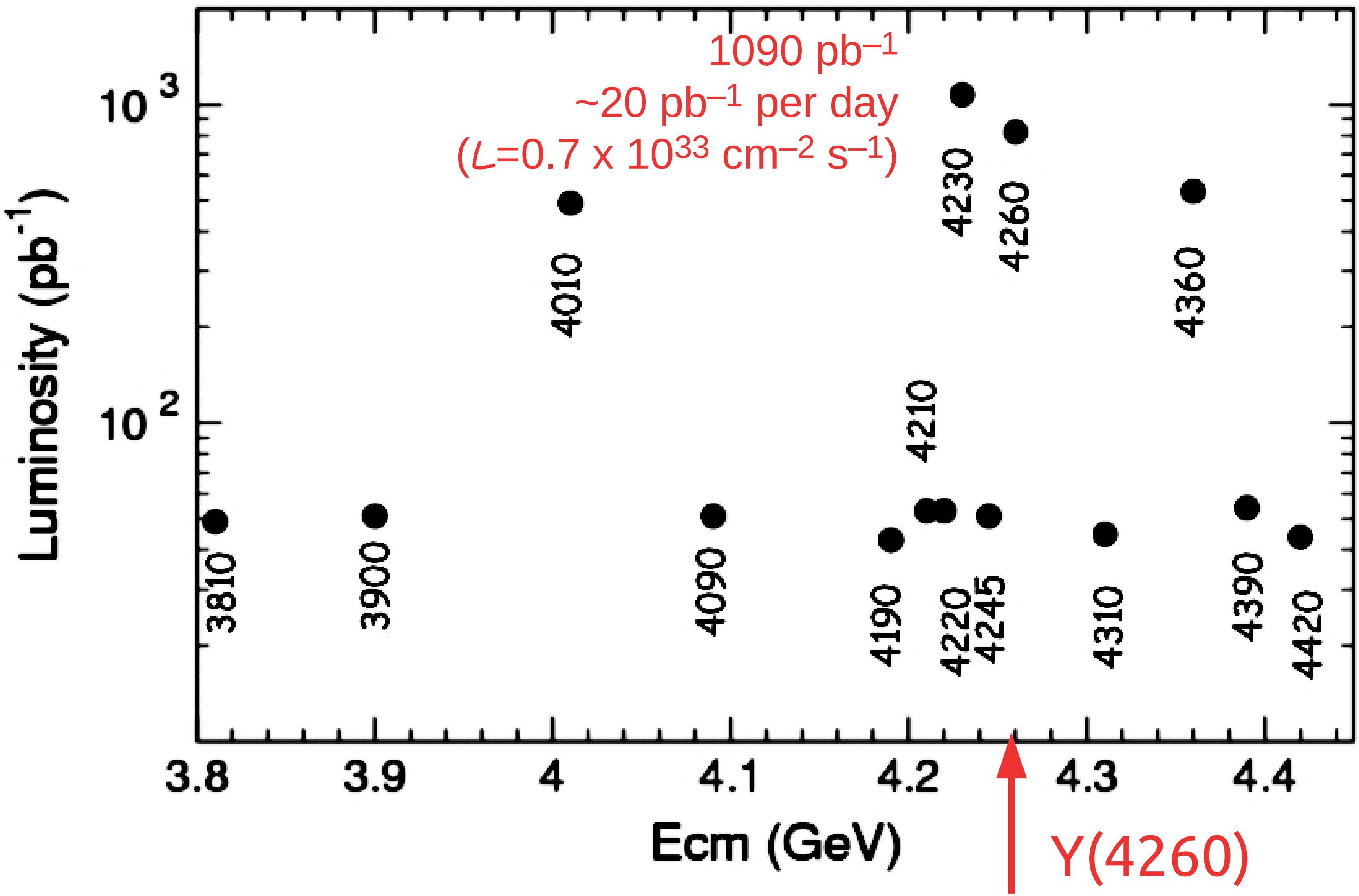
$$e^+e^- \rightarrow (\ Y(4260)\ ) \rightarrow \underbrace{J/\psi\pi^\pm}_{\text{resonant state?}} \quad \pi^\mp$$

BESIII Experiment

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

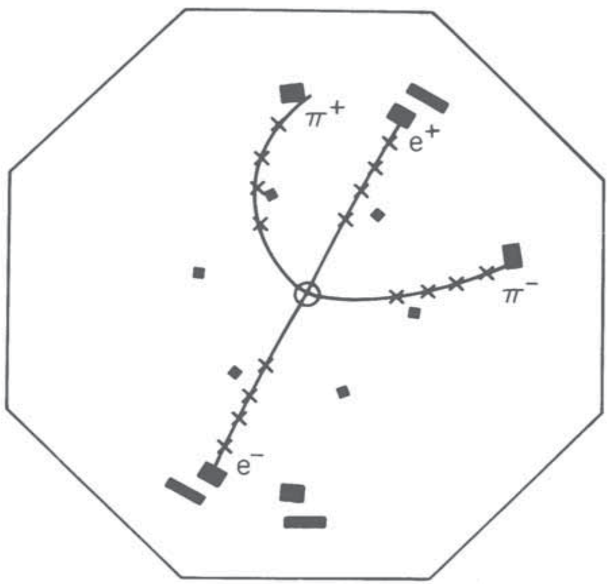


BESIII Data Taking at different √s
(e.g. adjust Beam Energies to Y(4260))

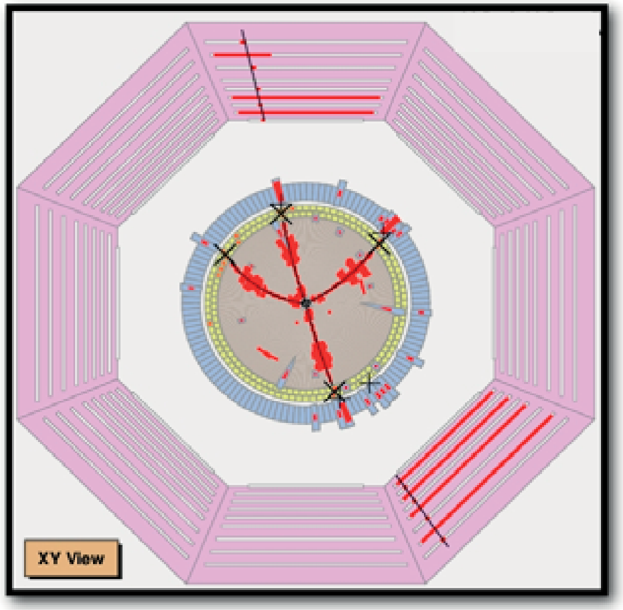


$e^+e^- \rightarrow J/\psi\,\pi^+\pi^-$

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

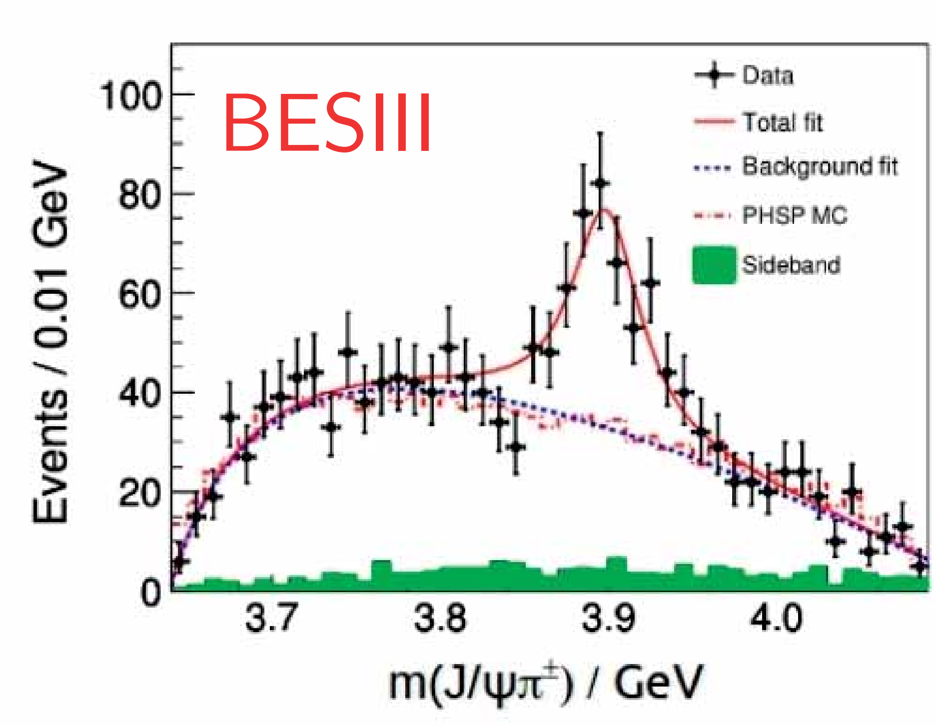


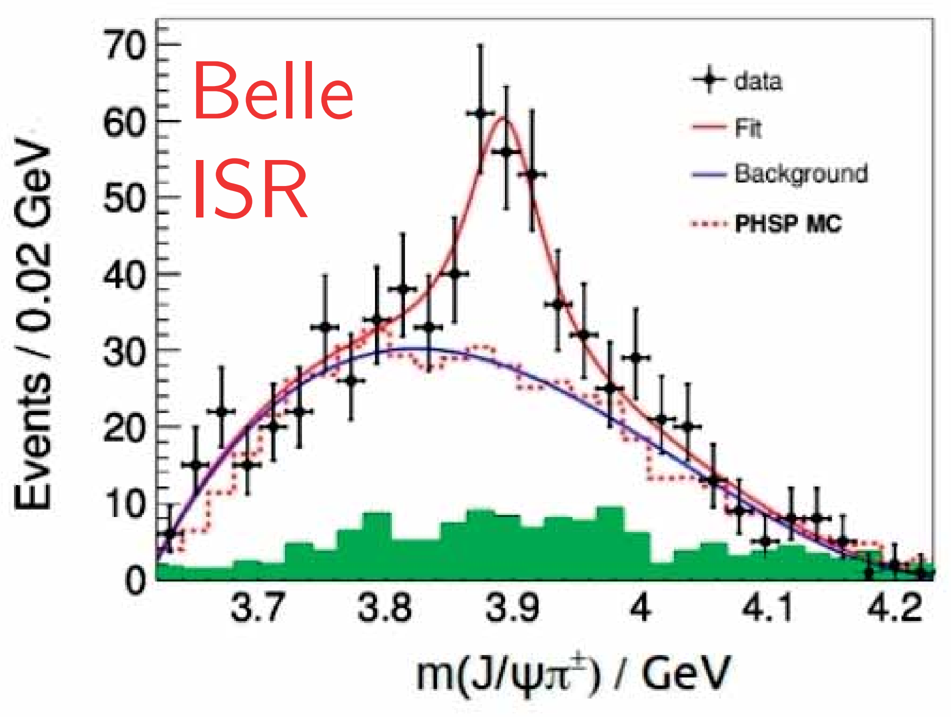
BESIII, 2013
$e^+e^- \rightarrow Y(4260) \rightarrow J/\psi\,\pi^+\pi^-$
$\sqrt{s}$=4260 MeV



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

$Z_c(3900)$





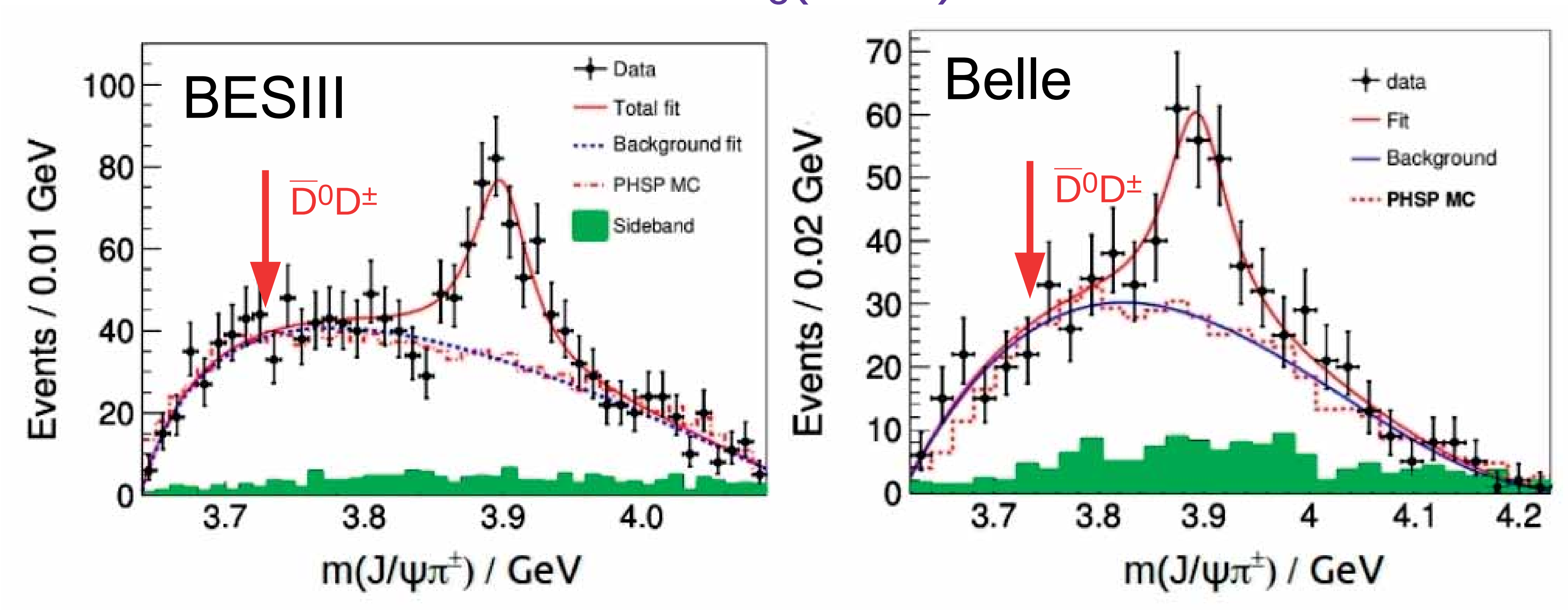
m = 3899.0±3.6±4.9 MeV
Γ = 46±10±20 MeV
307±48 events, >8 σ
arXiv:1303.5949, PRL 110(2013)252001

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 $\sqrt{s} \rightarrow$ not Y(4260)
S. Dobbs et al., Phys. Lett. B727(2013)366

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

$Z_c(3900)$



- $Y(4260) \to [J/\psi\pi^+]\,\pi^-$
  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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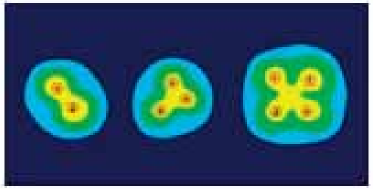
Notes from the Editors: Highlights of the Year

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

PHYSICS VIEWPOINT



New Particle Hints at Four-Quark Matter

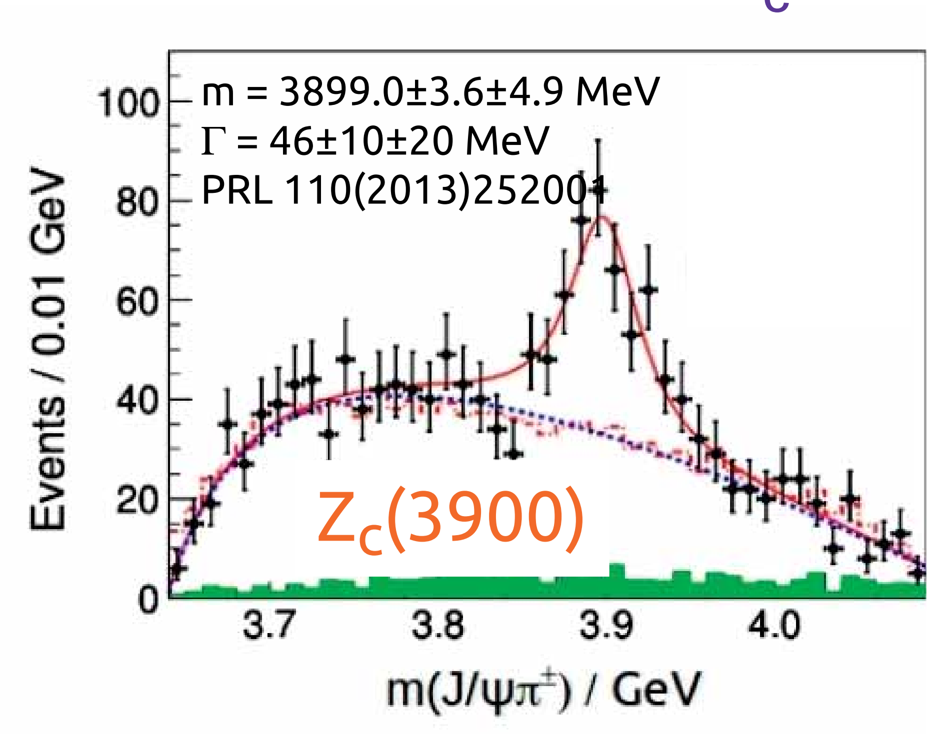
Published 17 June 2013

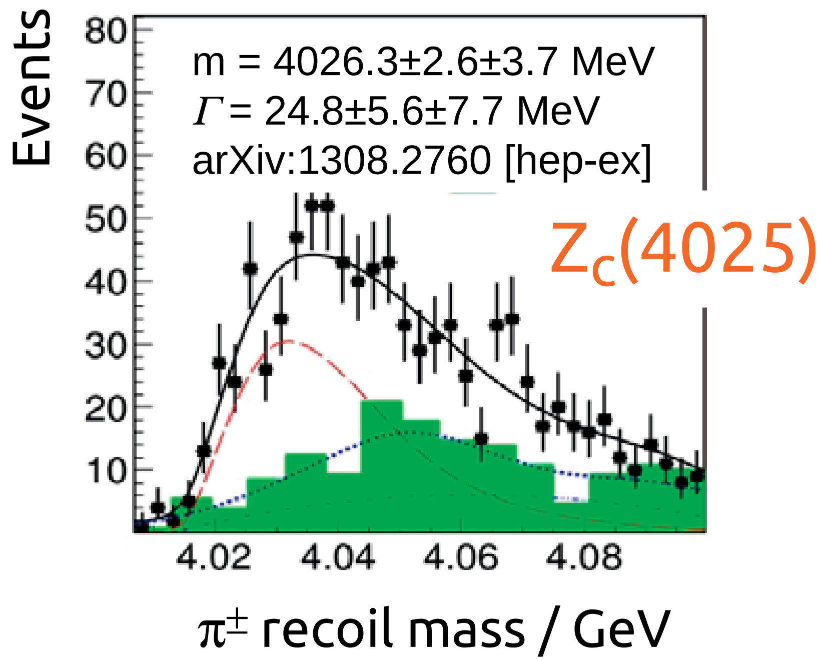
Two experiments have detected the signature of a new particle, which may combine quarks in a way not seen before.

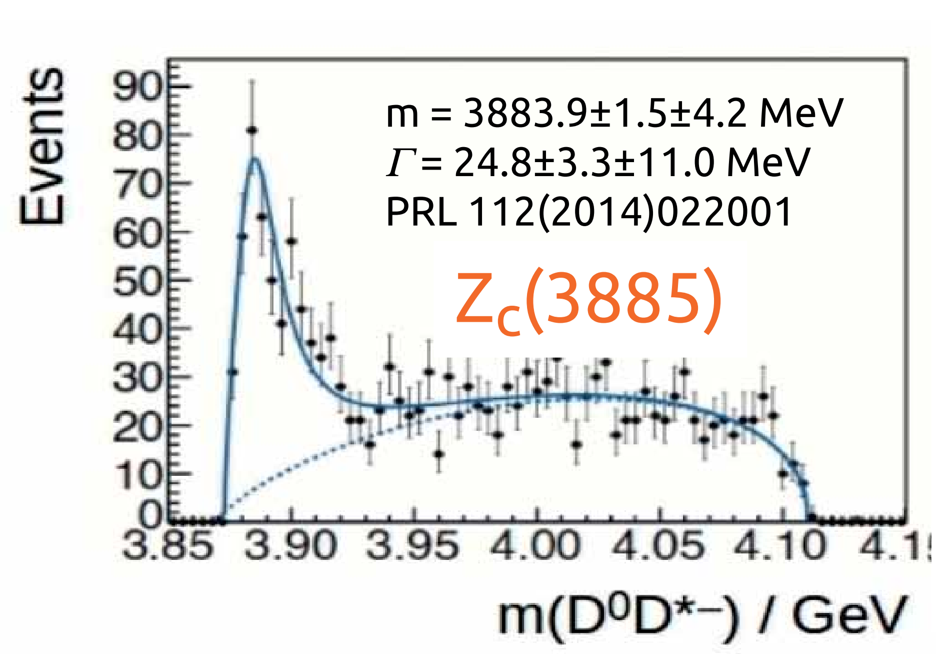
This is the first charged Z state observed by 2 experiments!

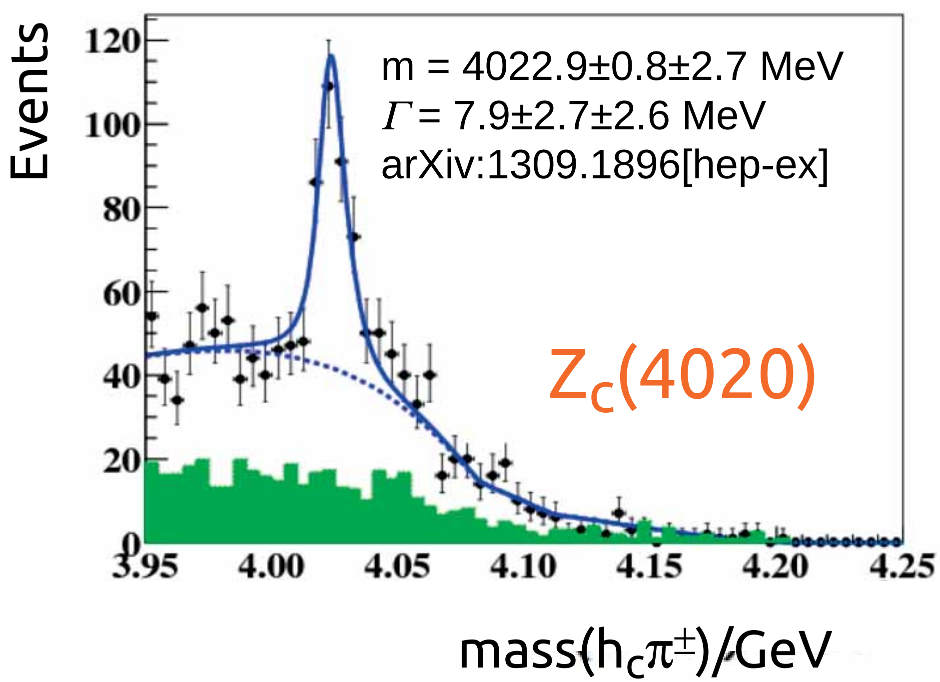
named „APS Highlight of the year 2013“
among others, e.g. extra-solar neutrinos by IceCube

Z_c^+ states at BESIII



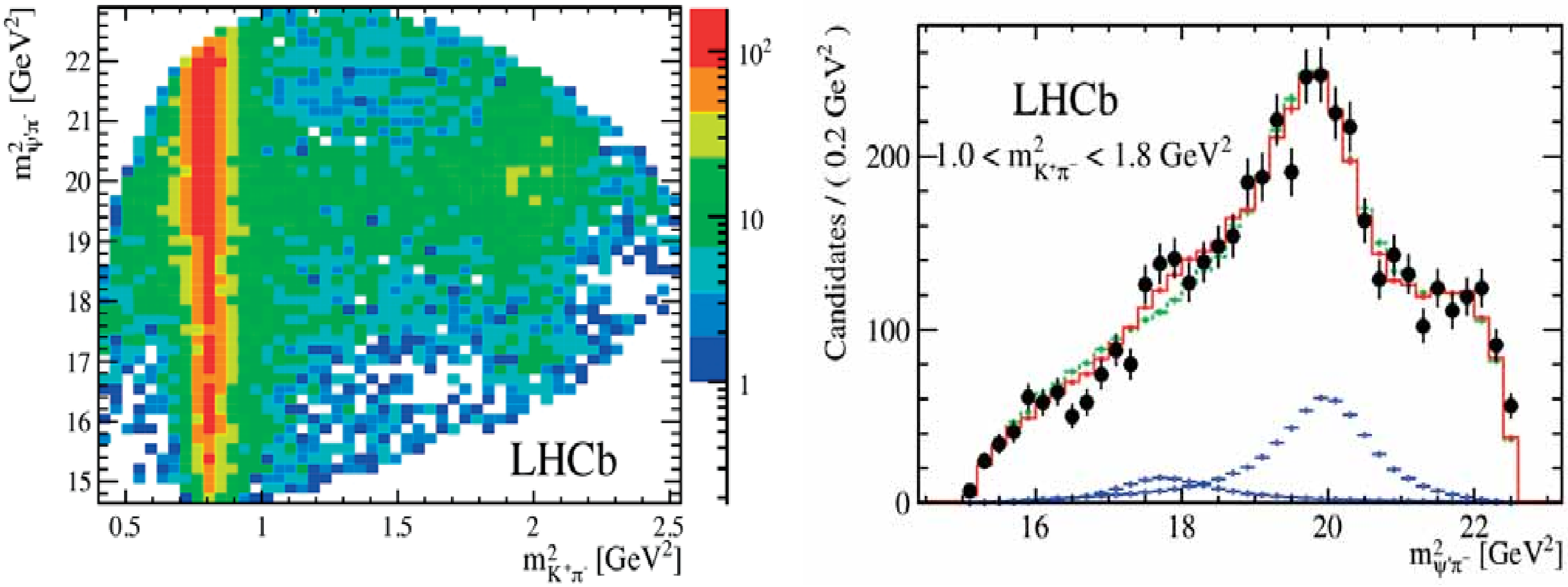






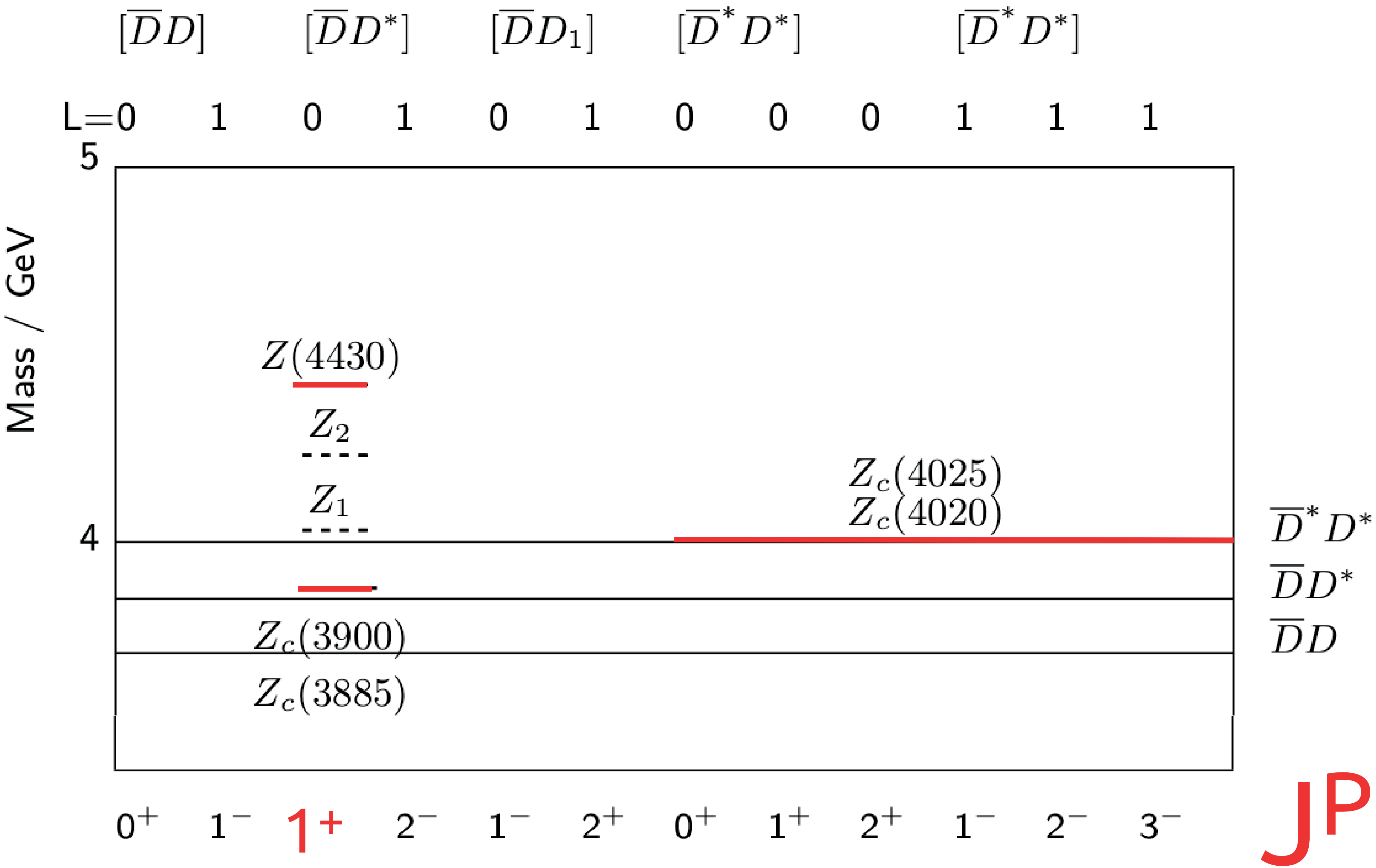
Confirmation of the Z(4430) in $B^0 \to K^+ \psi' \pi^-$

LHCb, arXiv:1404.1903[hep-ex]



- data set 3 fb^{-1}, $\sqrt{s}$=7 and 8 TeV
- significance >13.9σ
- $J^P=1^+$ unambigously 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 $D^{(*)}\overline{D}^{(*)}$ 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

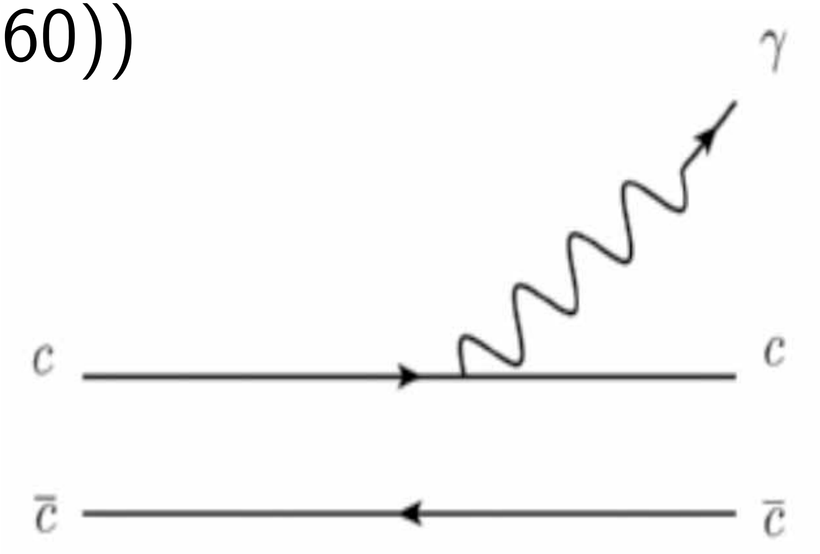
Is there a decay from an XYZ to another XYZ?

$Y \rightarrow Z$

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

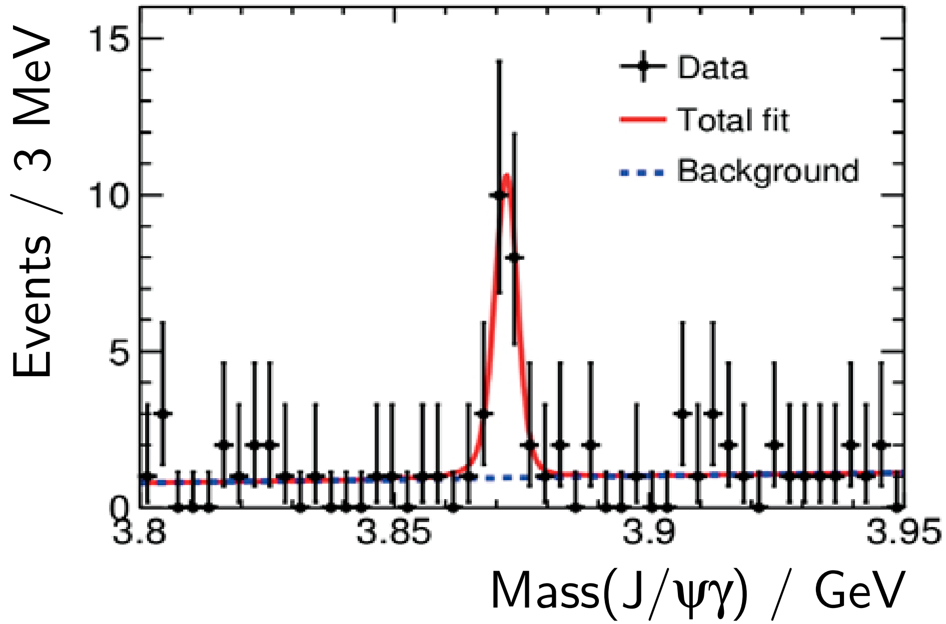
$Y \rightarrow X$

$\rightarrow$ X(3872) in Y(4260) decay ?
$1^{--} \rightarrow 1^{++}$, parity flip, $\Delta L=1$
$\rightarrow$ search for radiative decay



e+e– → Y(4260) → X(3872) γ

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

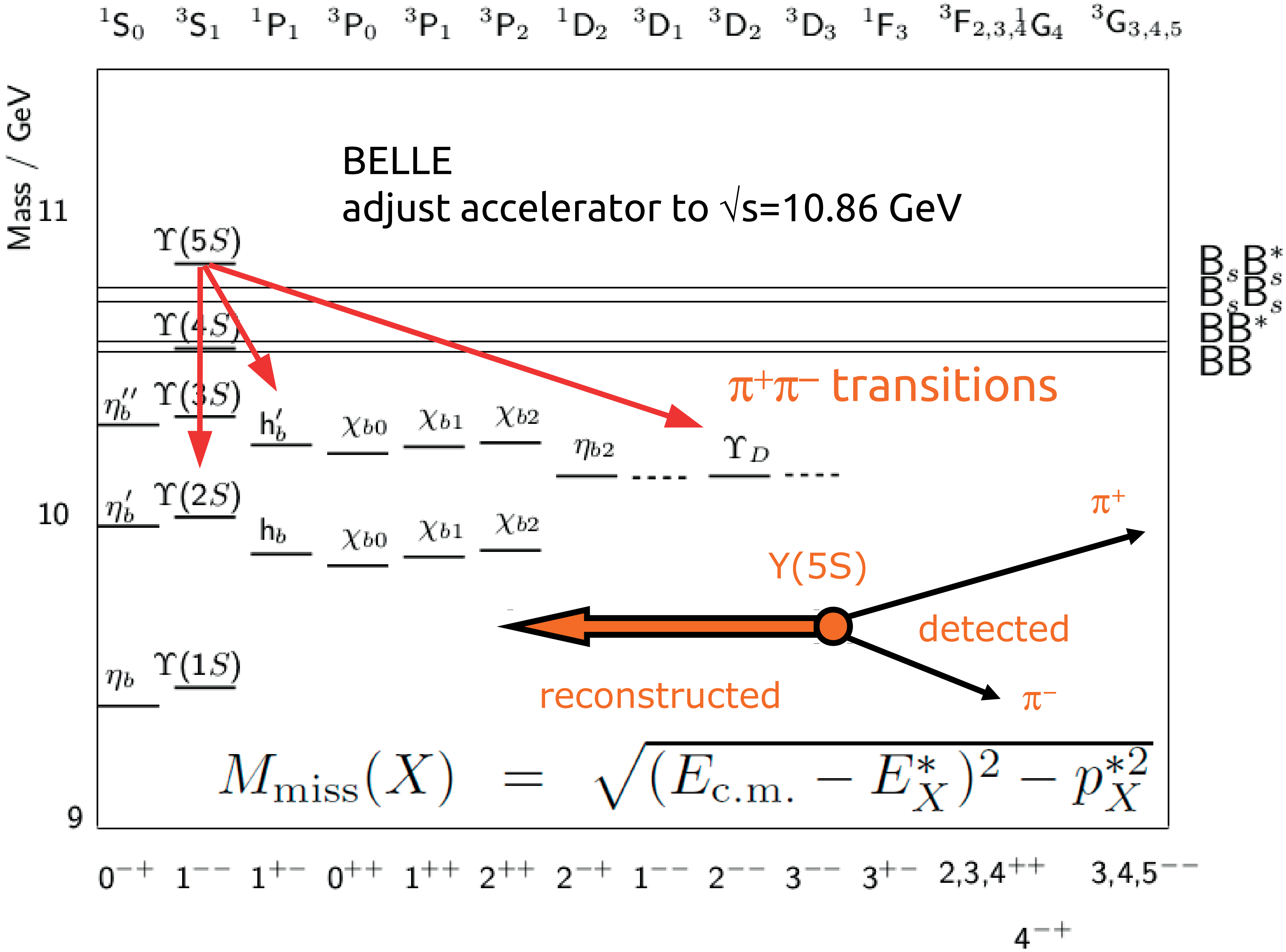


Confirmation of X(3872)
20.0 ± 4.6 events
m = (3871.9 ± 0.7 ± 0.2) MeV
6.3σ

Cross section peaks at Y(4260)

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

Bottomonium



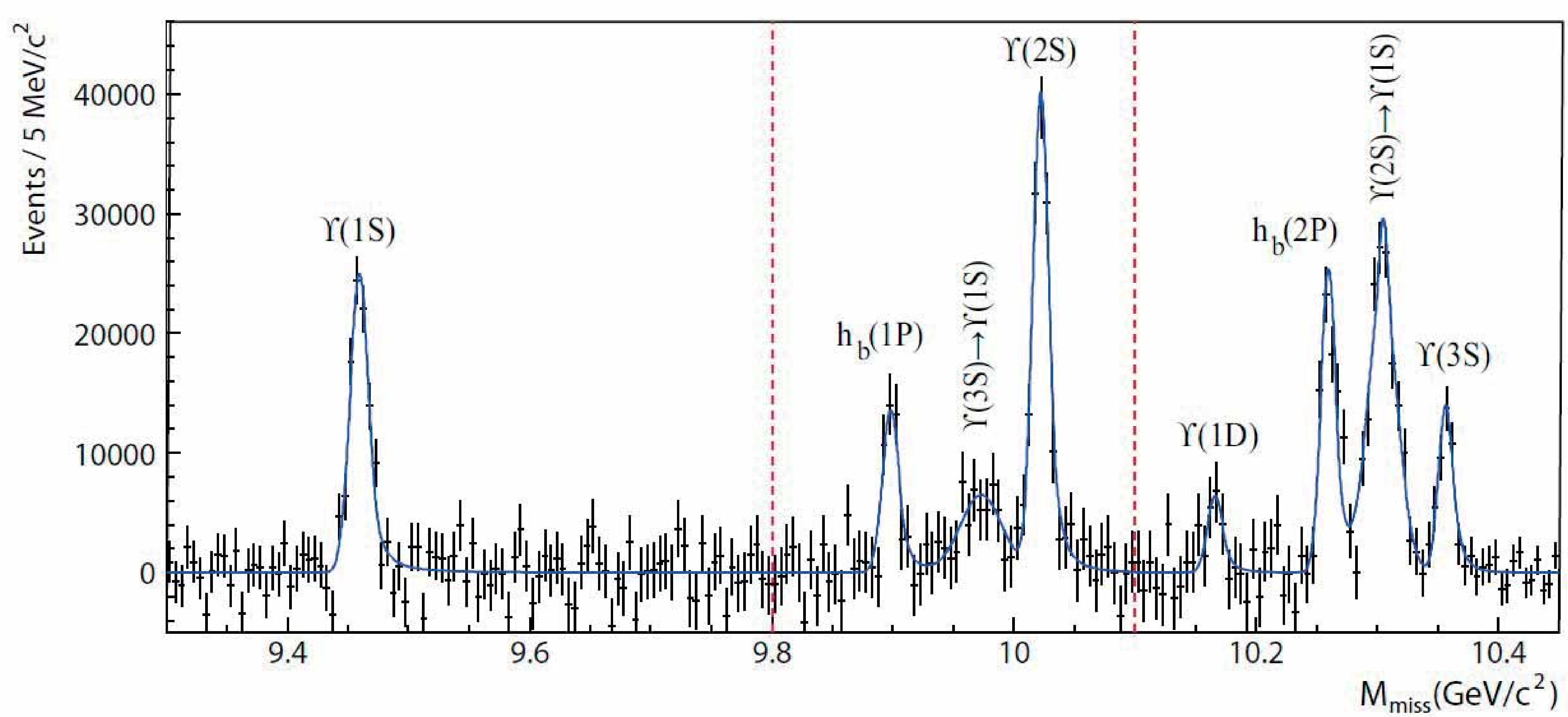
$$M_{\mathrm{miss}}(X) = \sqrt{(E_{\mathrm{c.m.}} - E_X^*)^2 - p_X^{*2}}$$

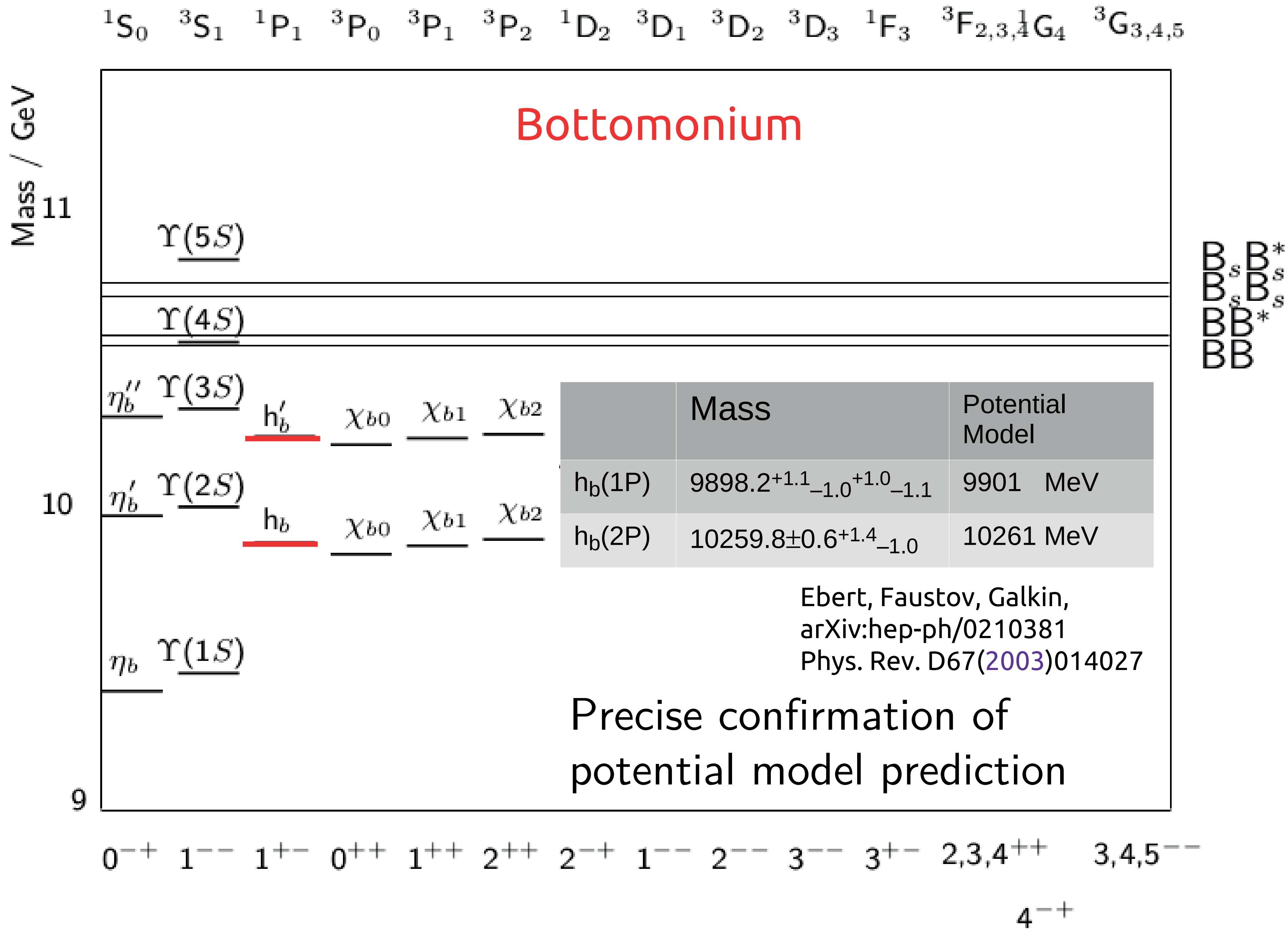
Υ(5S) Decays

$\pi^+ \pi^-$ 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





	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

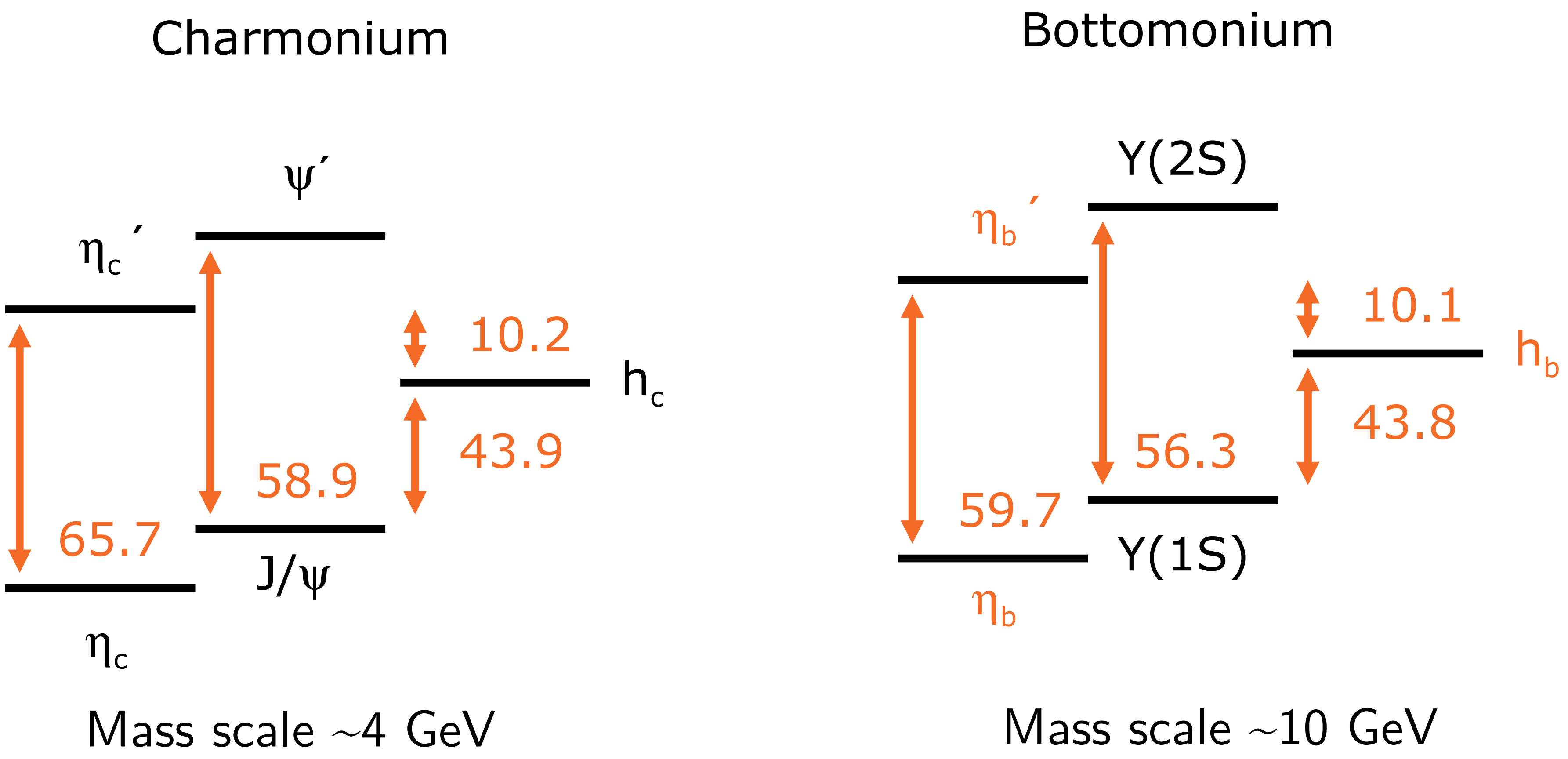
Precise confirmation of potential model prediction

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?



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

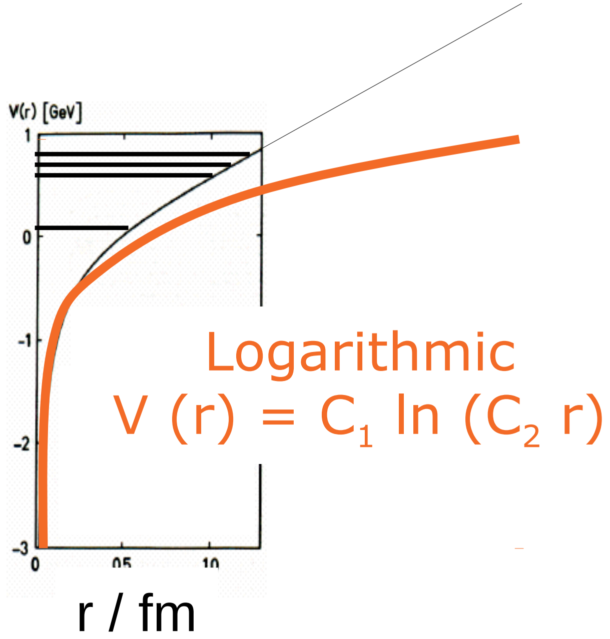
Experimental observation of

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

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

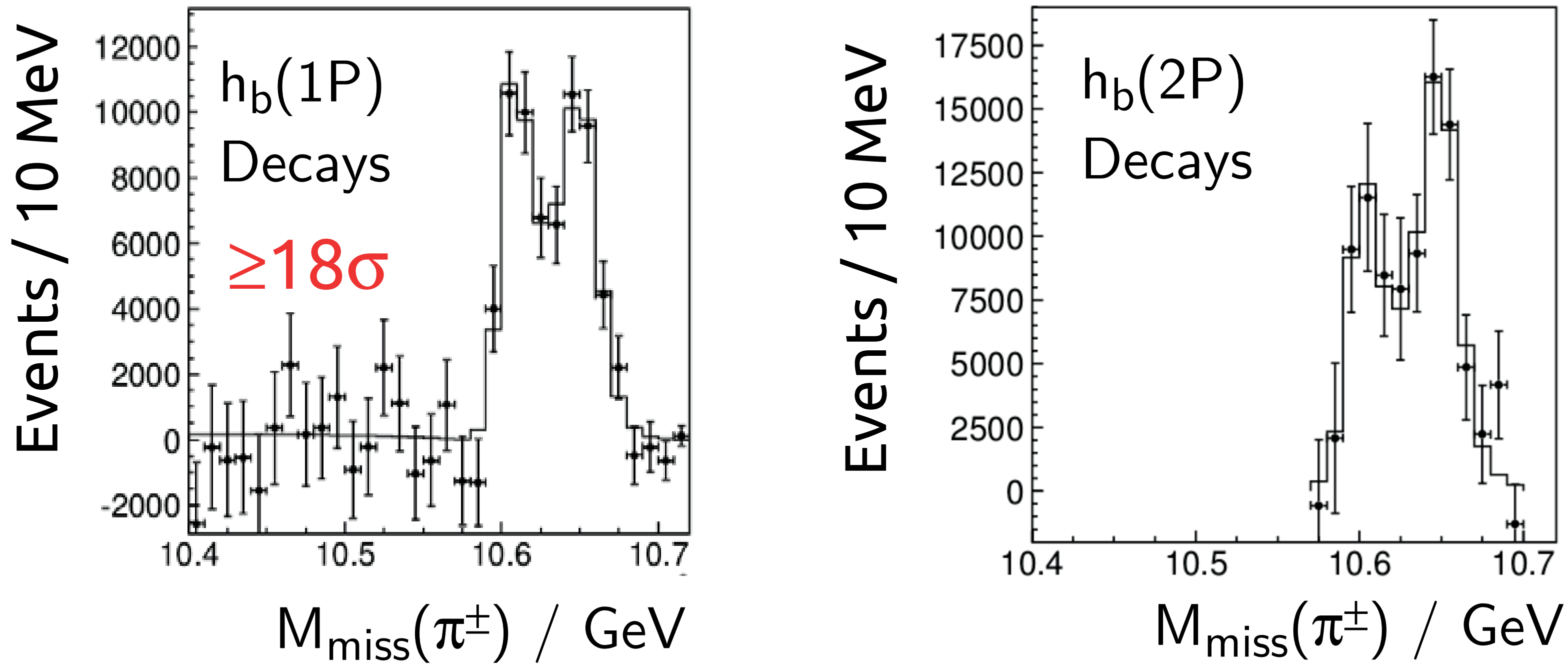
is inconsistent with potential model

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



Explicit quark mass dependence (except for logarithmic potentials).

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



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

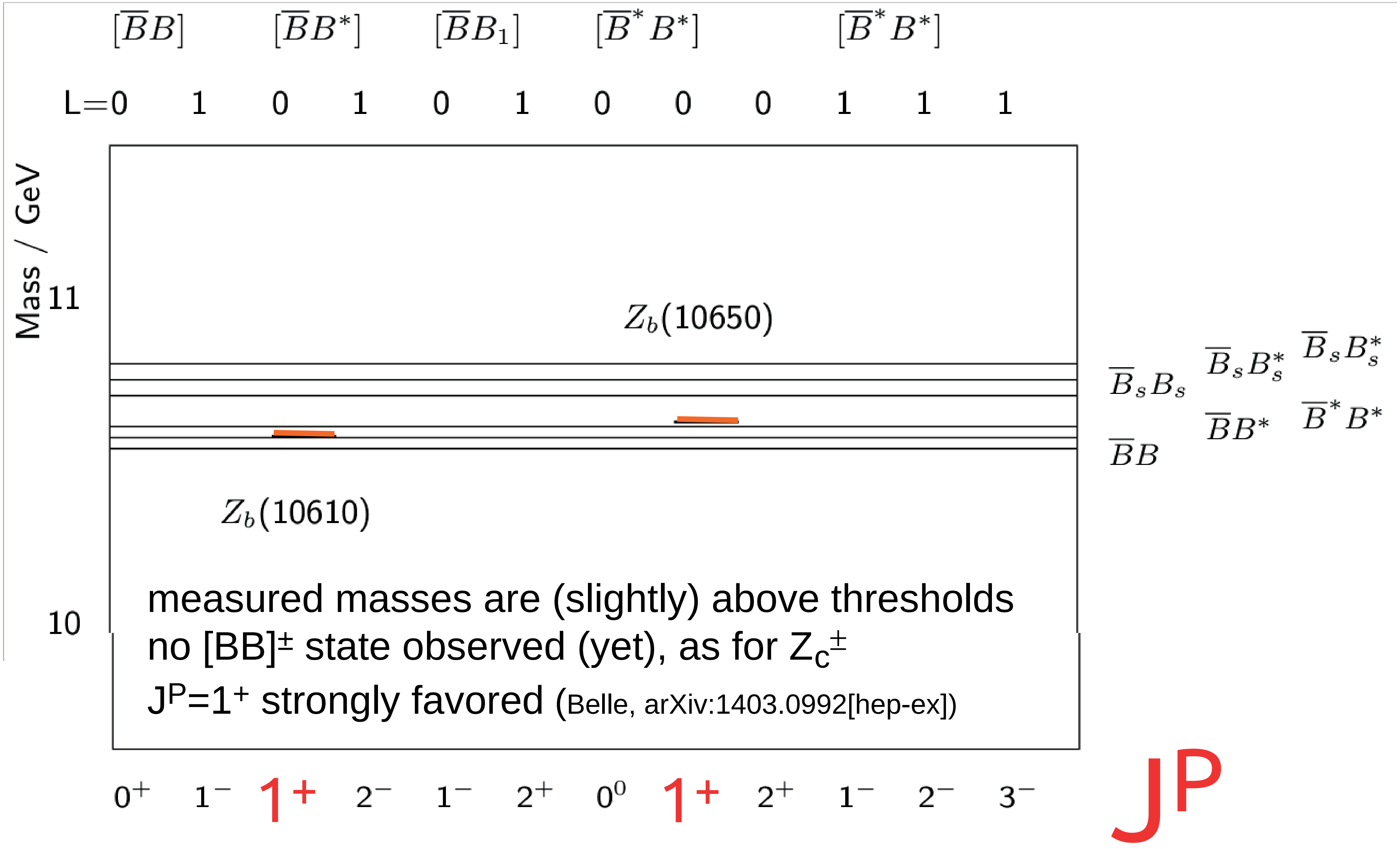
2.6 MeV above $\bar{B}B^*$ threshold

$Z_b'(10650)^\pm$ 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



measured masses are (slightly) above thresholds

no $[BB]^{\pm}$ state observed (yet), as for $Z_c^{\pm}$

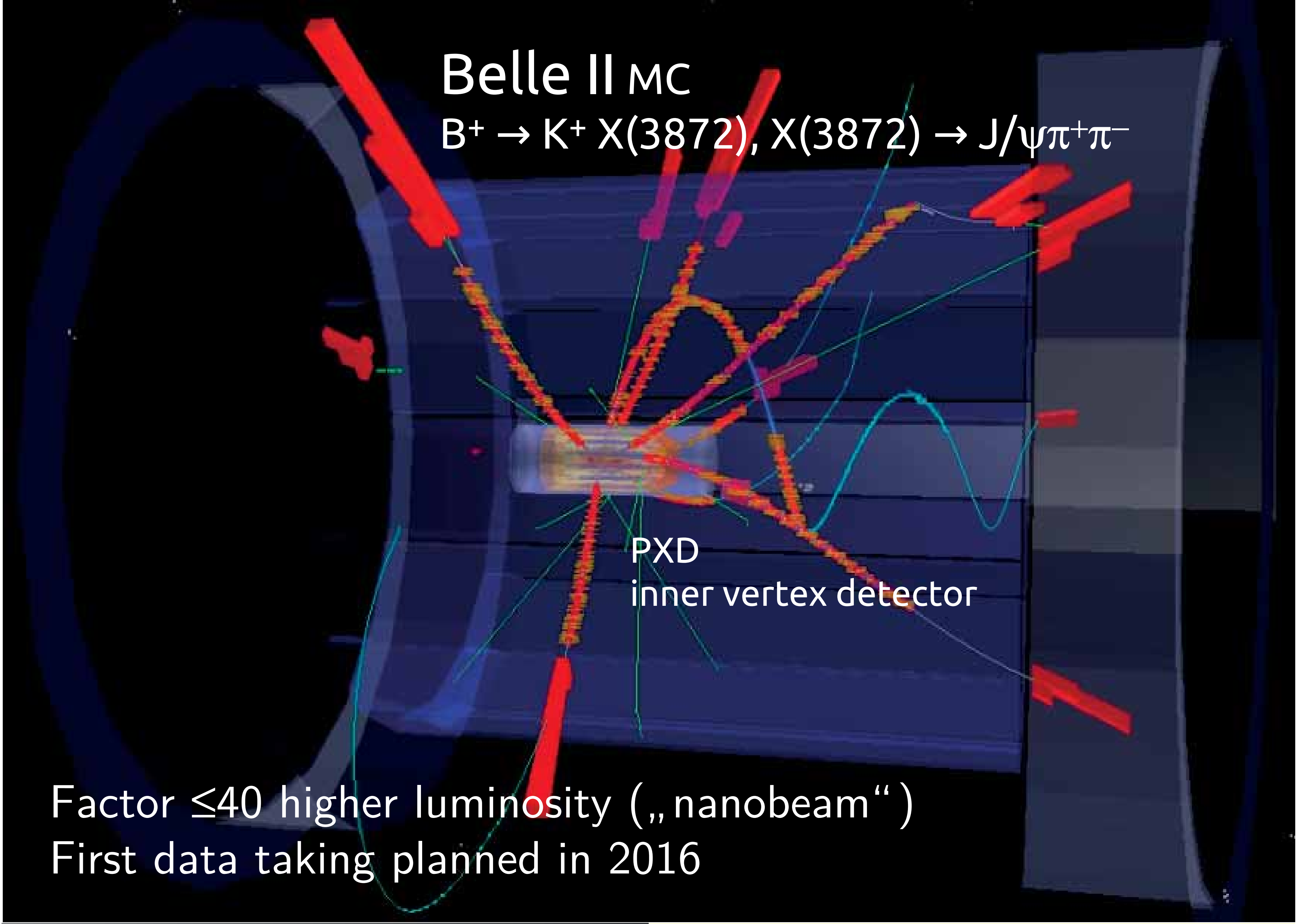
$J^P=1^+$ strongly favored (Belle, arXiv:1403.0992[hep-ex])

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

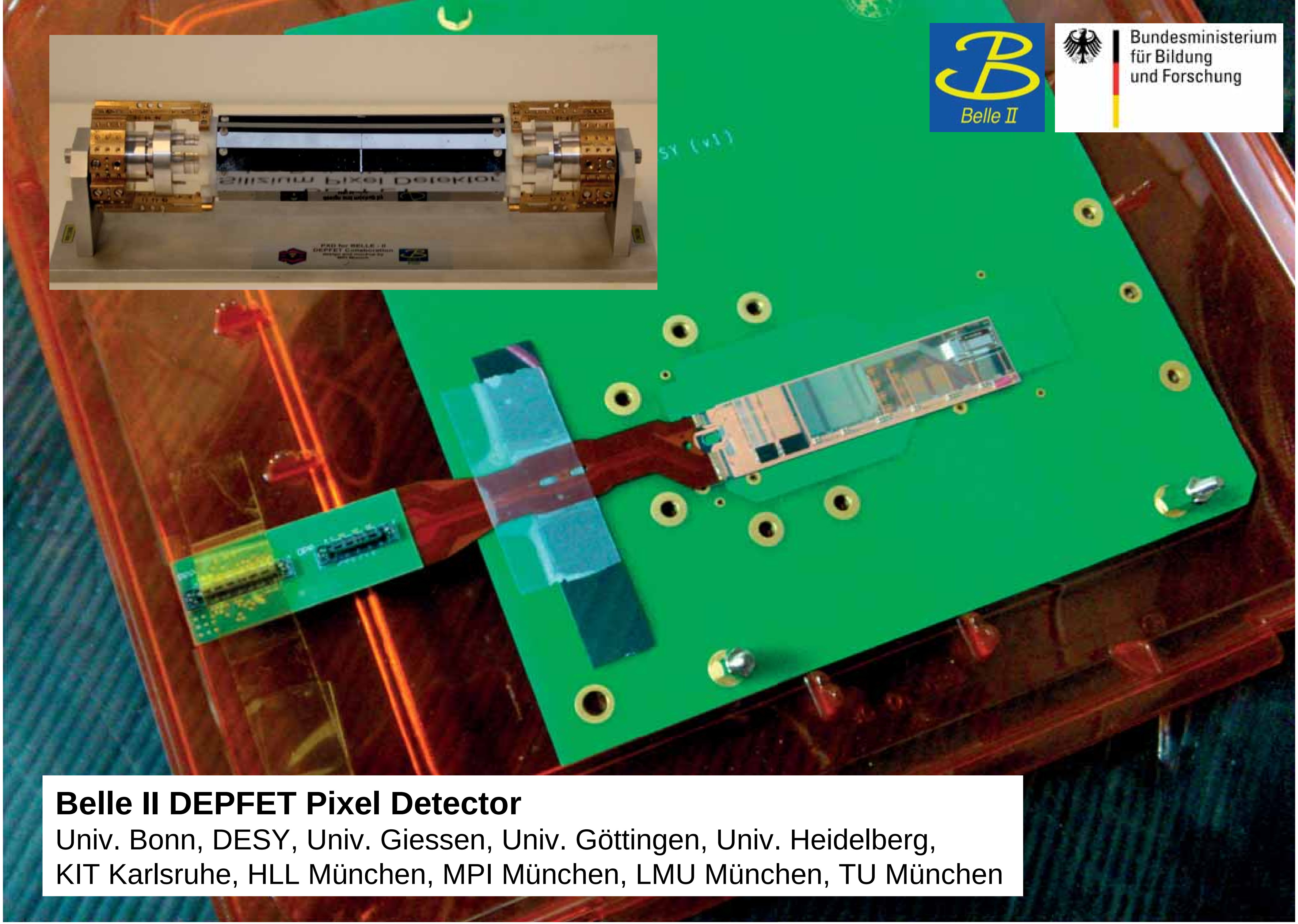
Belle in Service Position for Upgrade to Belle II

Belle II MC

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



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



Belle II

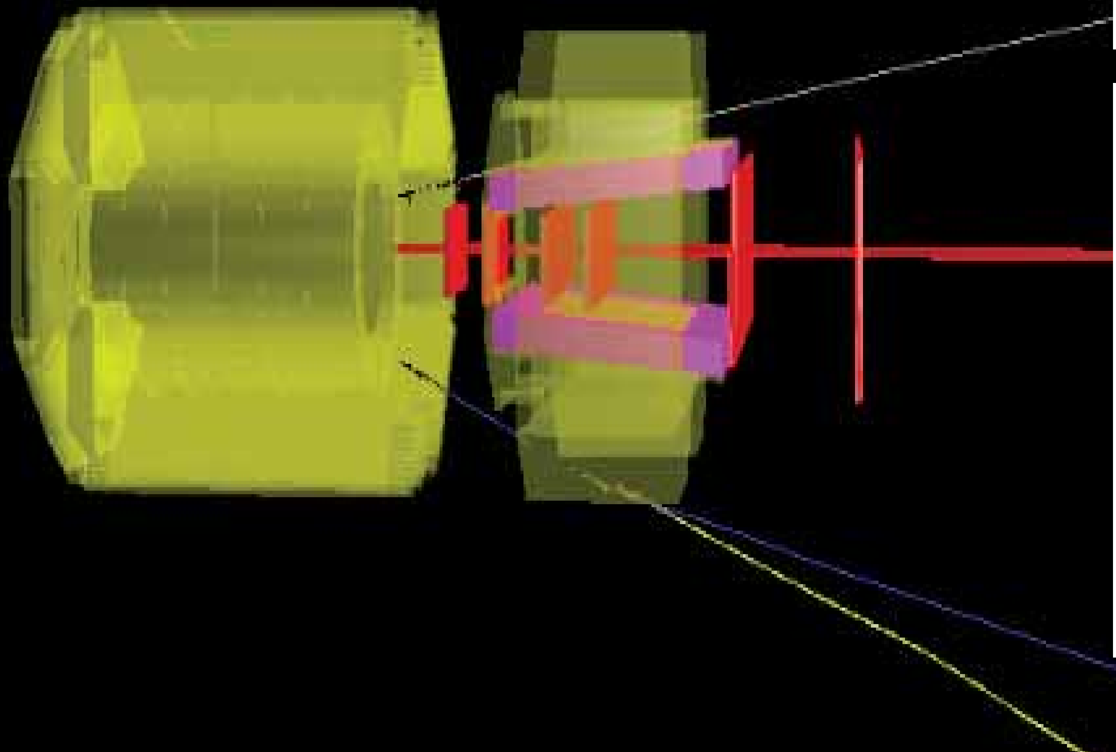
Bundesministerium für Bildung und Forschung

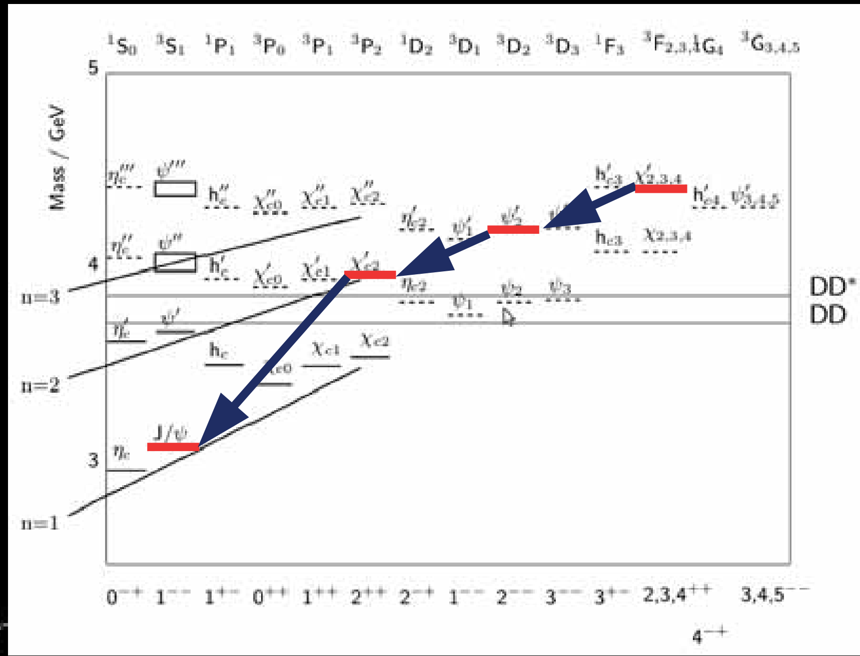
Belle II DEPFET Pixel Detector

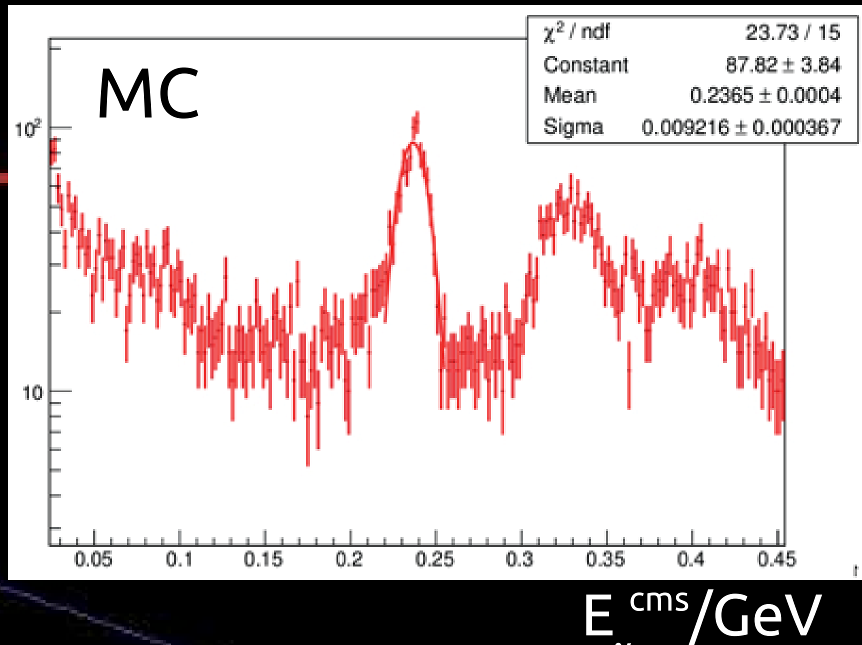
Univ. Bonn, DESY, Univ. Giessen, Univ. Göttingen, Univ. Heidelberg, KIT Karlsruhe, HLL München, MPI München, LMU München, TU München

$\overline{\text{P}}$ANDA @ FAIR

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







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	$J/\psi\rho$, $J/\psi\omega$ $J/\psi\gamma$, $D^0\bar{D}^{0*}$	Belle, *BABAR* , CDF D0, LHCb, CMS	4-quark, $(D^0\bar{D}^{*0})$ molecule?
X(3940)	$e^+e^- \to c\bar{c}X$	$0^{?+}$	$\simeq$3942	$\simeq$37	$D\bar{D}^*$ (not $D\bar{D}$, $J/\psi\omega$)	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 ? $(D\bar{D}^*)^\pm$ 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	$?^{?+}$	$\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	$D^*\bar{D}^*$ (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)	$\gamma\gamma$	$?^{?+}$	$\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 ($\mathcal{B}\sim10^{-5}$)
  $\rightarrow$ 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]