Exotic mesons

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Conference on Flavor Physics and CP Violation

University of Victoria

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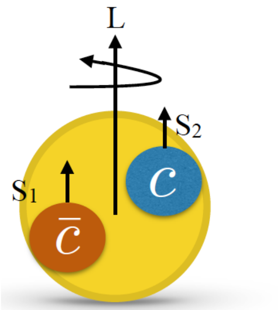
Quarkonium



- Quarkonium: $q\bar{q}$, the simplest hadronic system
- Quarkonium spectrum is similar to atomic spectra
- Below $D\bar{D}/B\bar{B}$ thresholds – both charmonium and bottomonium are success stories for QCD
- The potential model:

Example potential from Barnes, Godfrey, Swanson:

$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

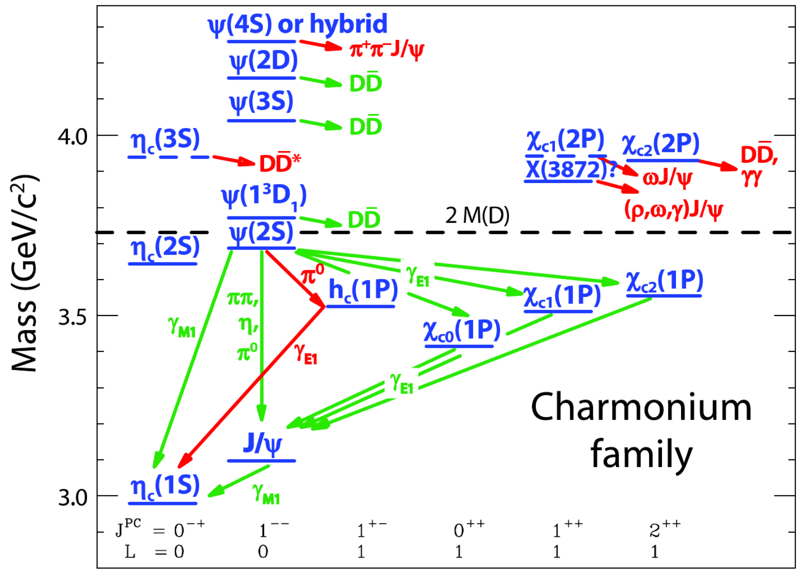
(Coulomb + Confinement + Contact)

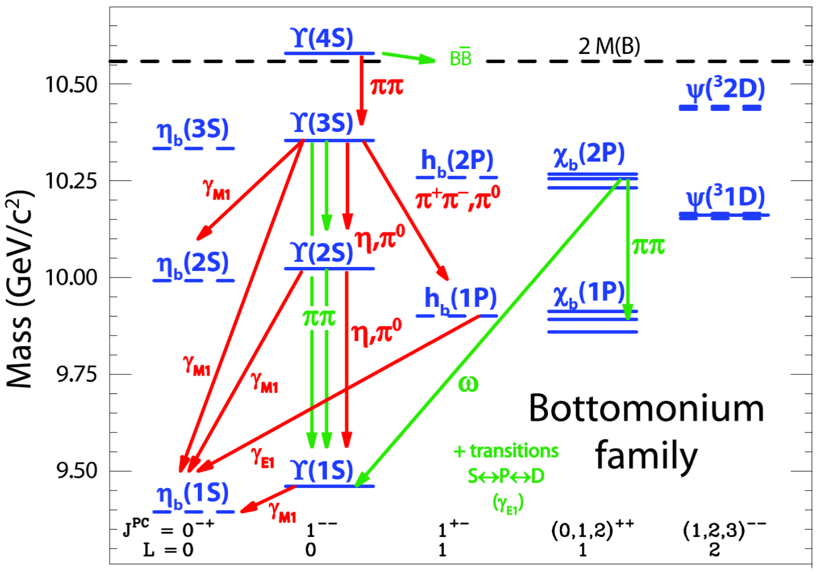
$$V_{\text{spin-dep}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

(Spin-Orbit + Tensor)

PRD72, 054026 (2005)

- But there are many “exotic” states observed in recent decades that are hard to fit into the two families

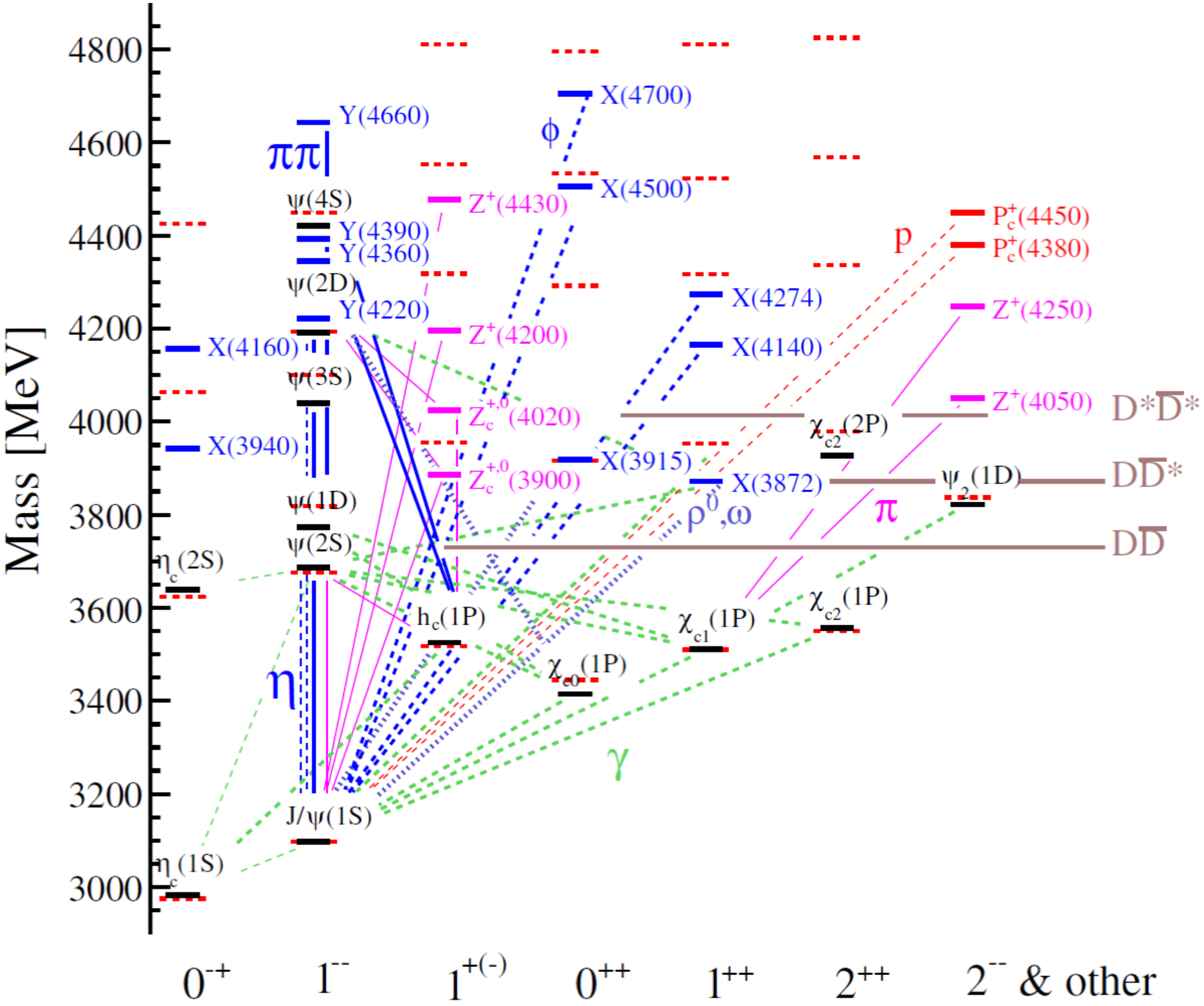


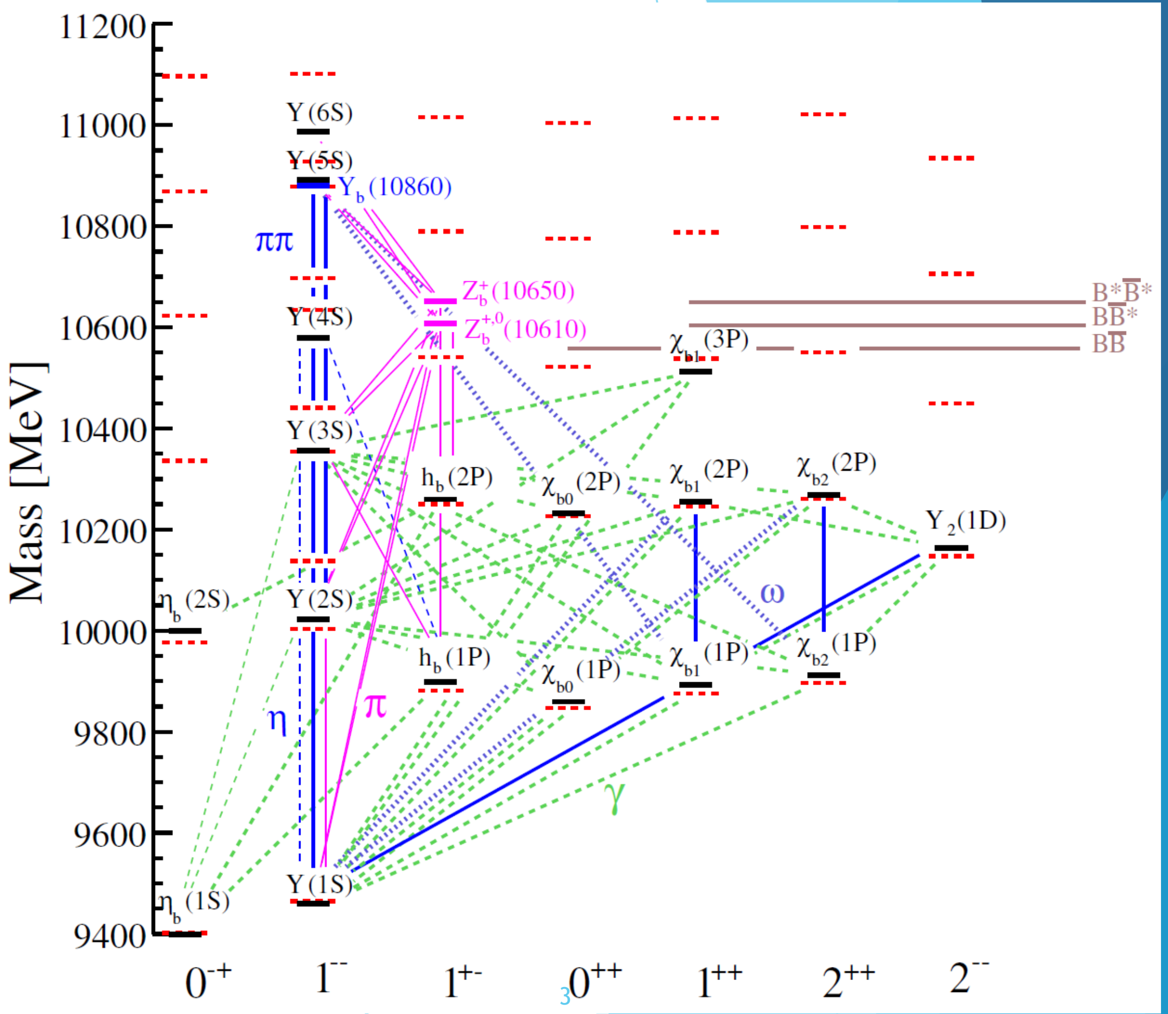


Eichten *et al.*, Rev. Mod. Phys.80,1161(2008)

Particle "Zoo"

Status of the spectra

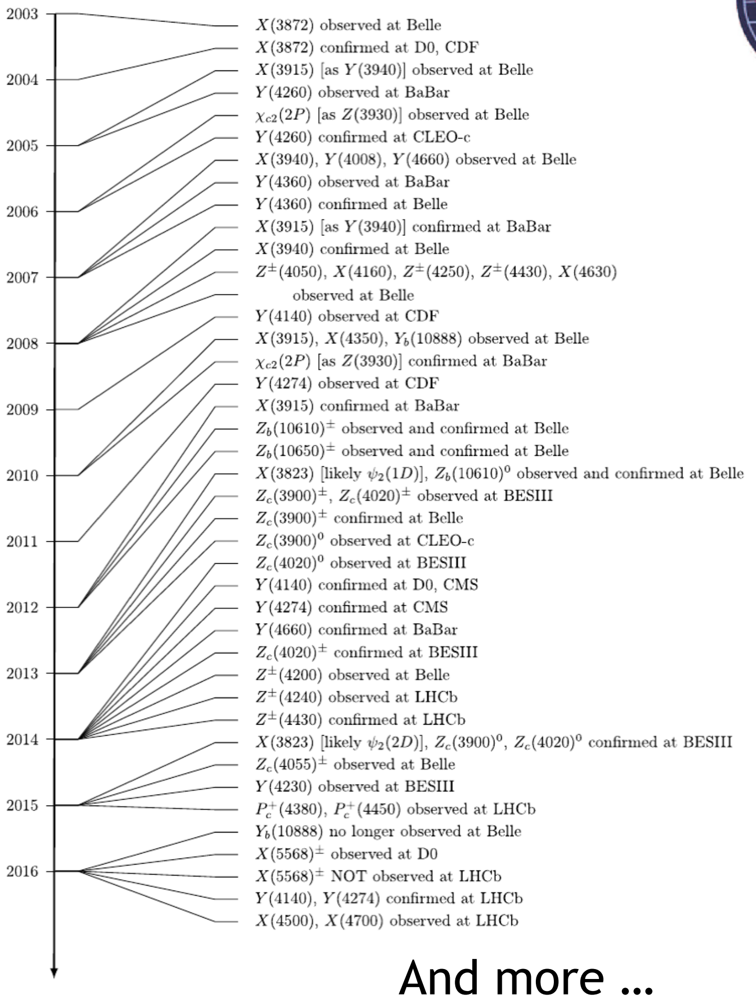




S. Olsen et al., Rev. Mod. Phys. 90, 015003(2018)

Particle "Zoo"

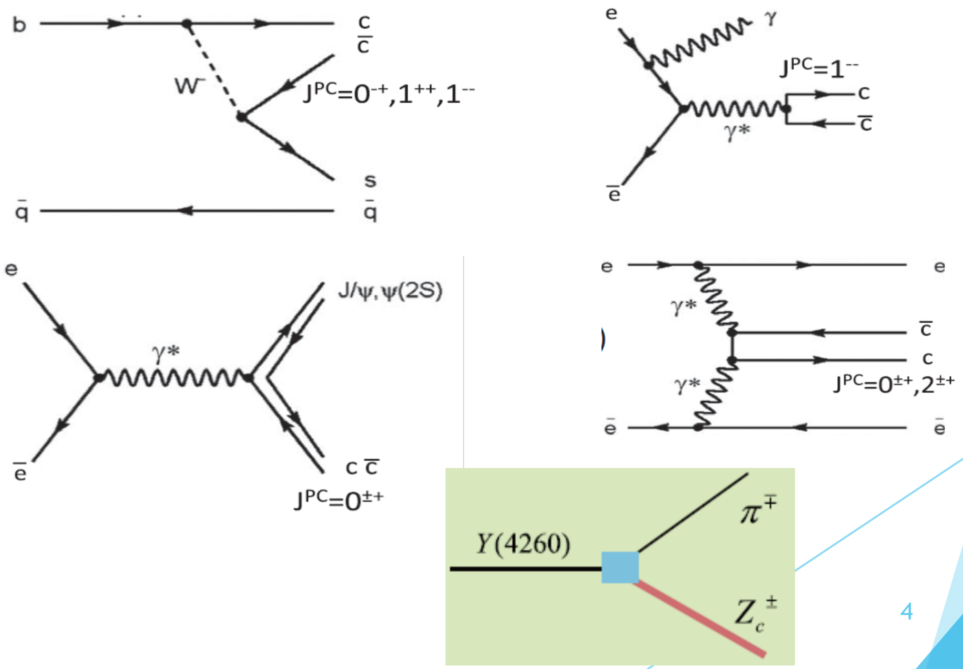
Status of the spectra



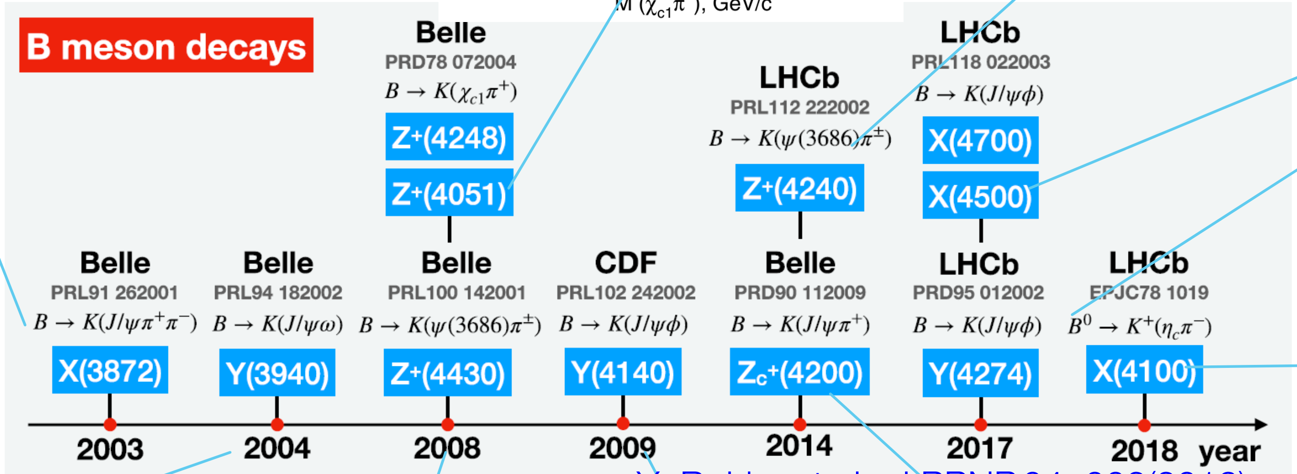
And more …

R. F. Lebed *et al.*, Prog. Part. Nucl. Phys 93, 143(2017)

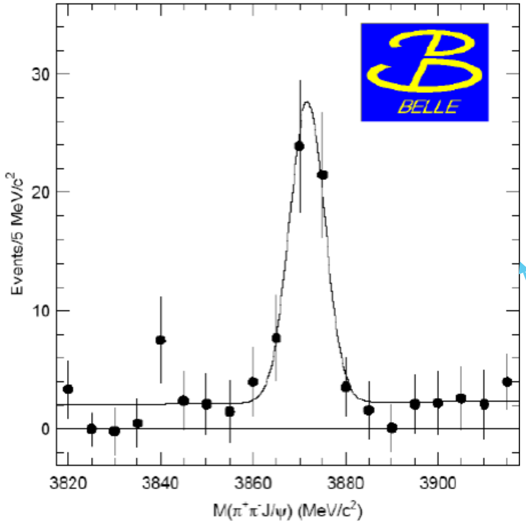
- Processes used in exotic discoveries

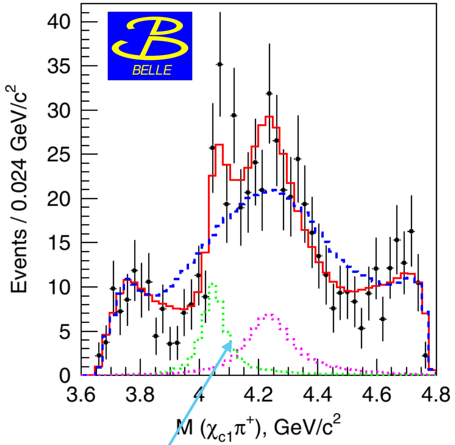


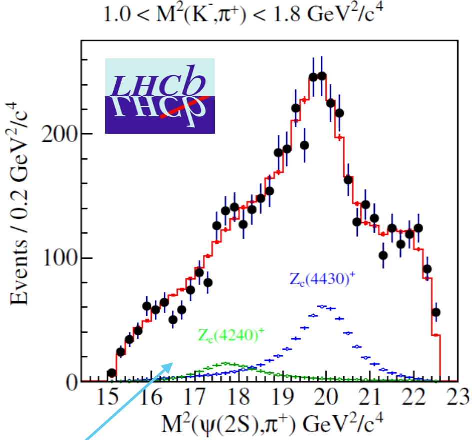
B meson decays

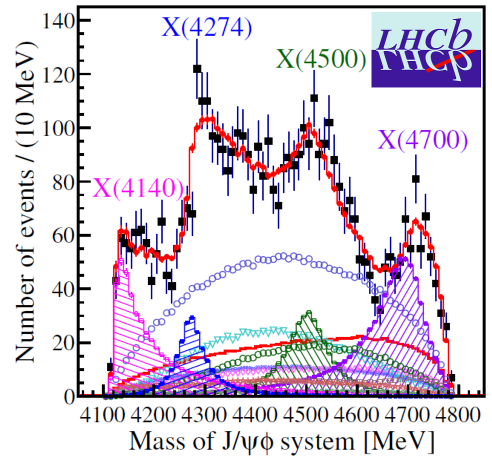


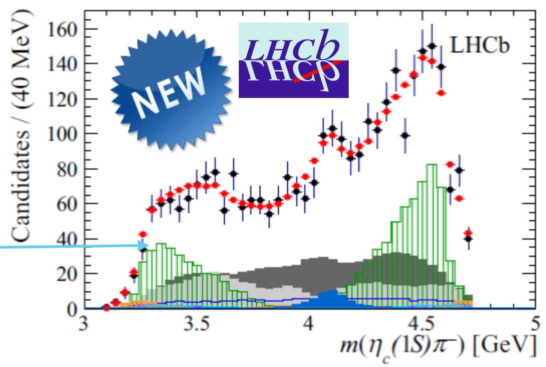
Y.-R. Liu, et al., J.PPNP.04, 003(2019)

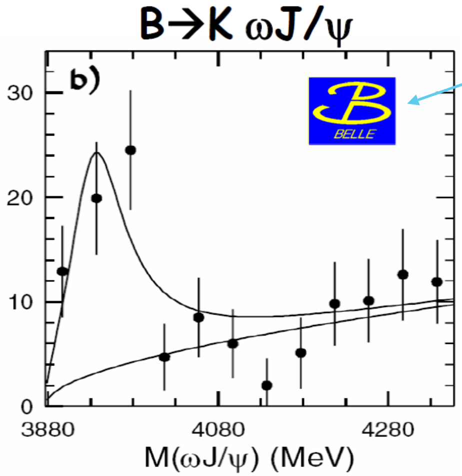


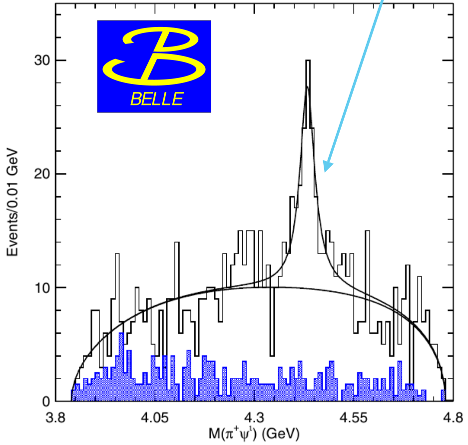


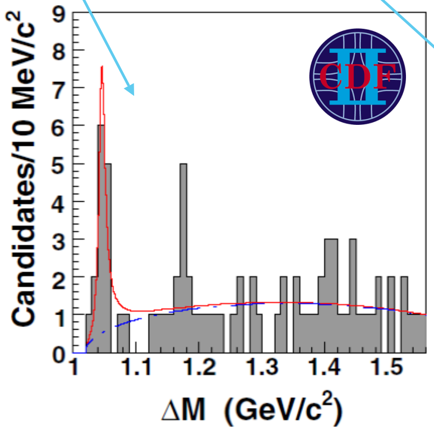


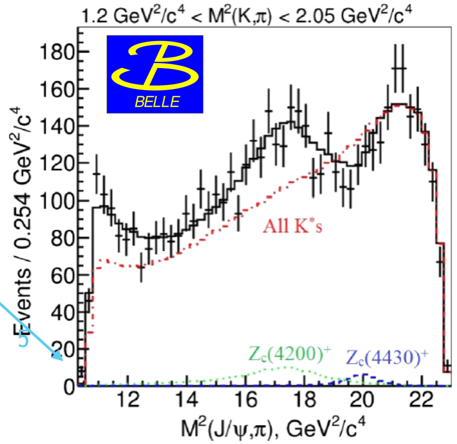




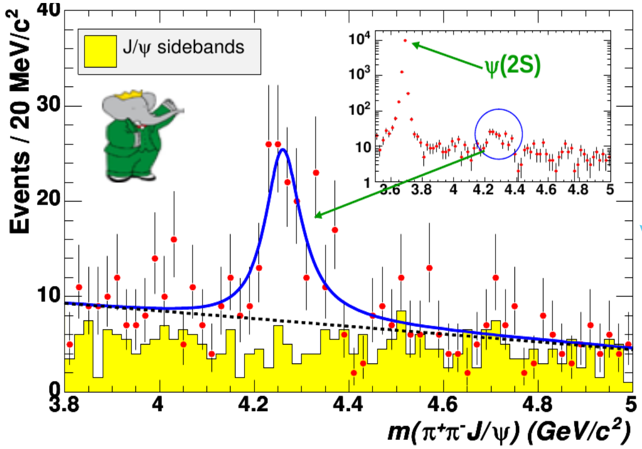


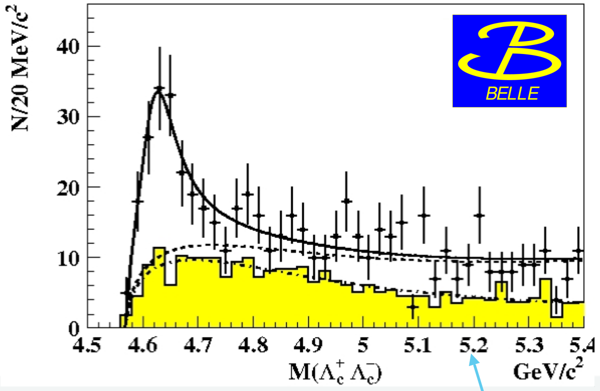


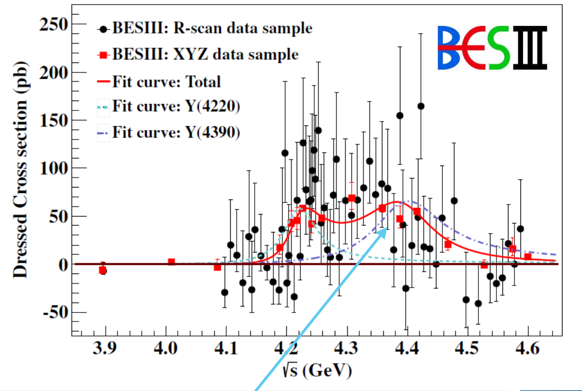


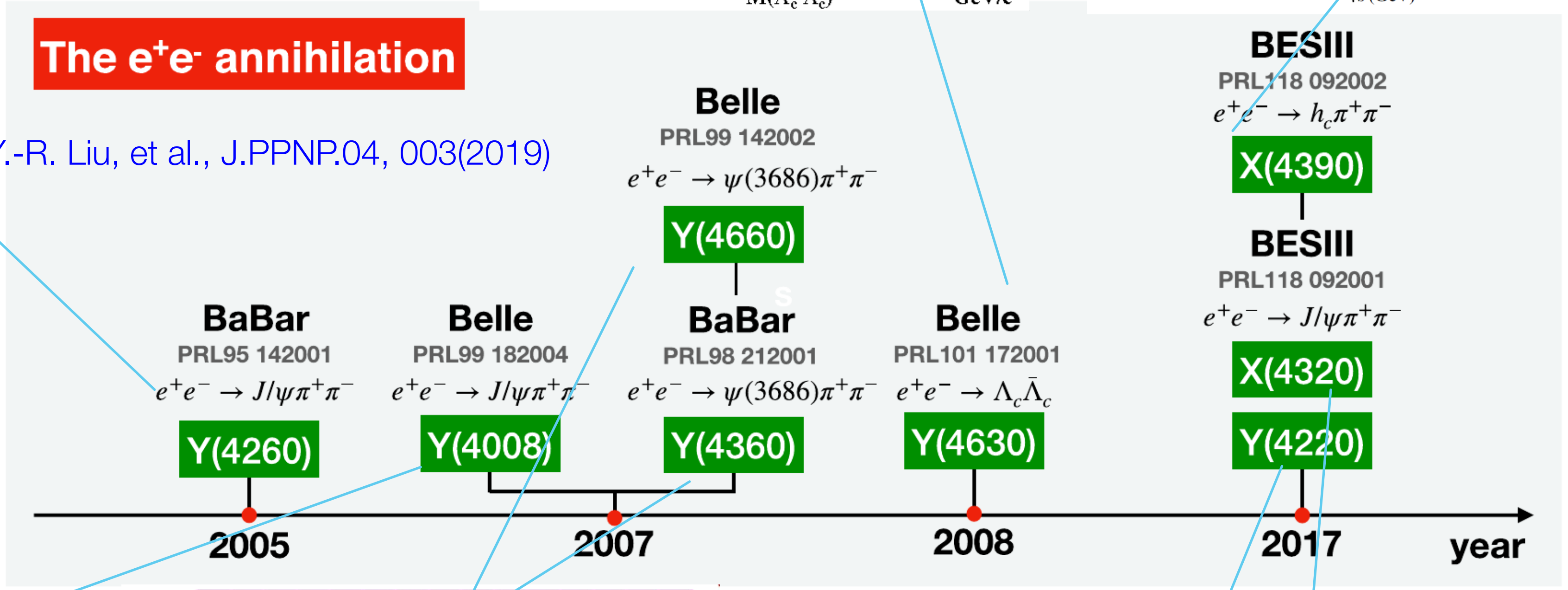


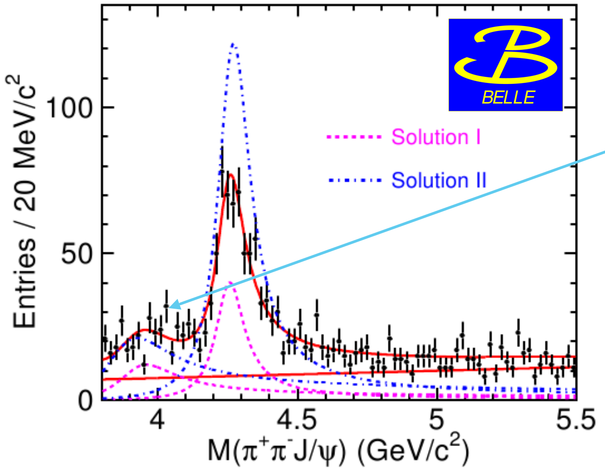
ISR and e+e- collision

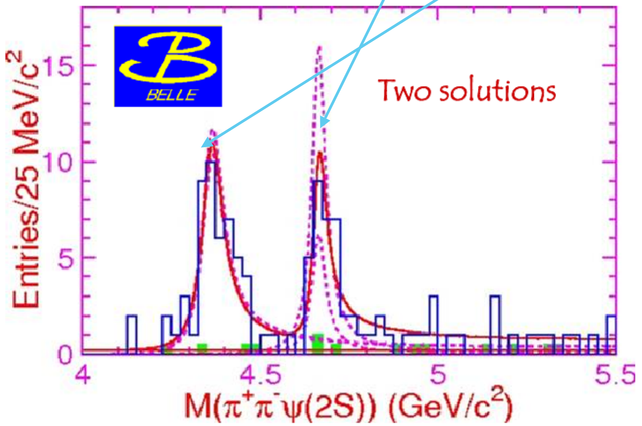


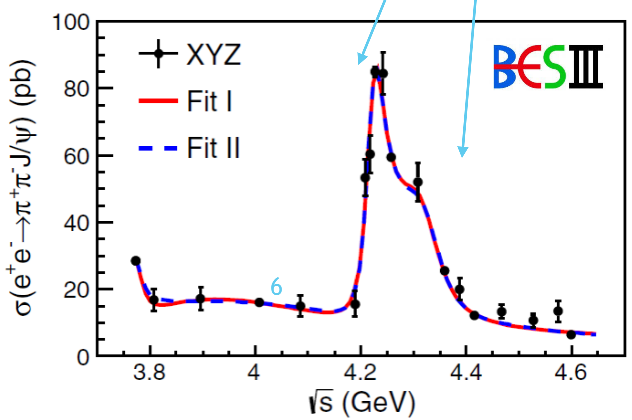






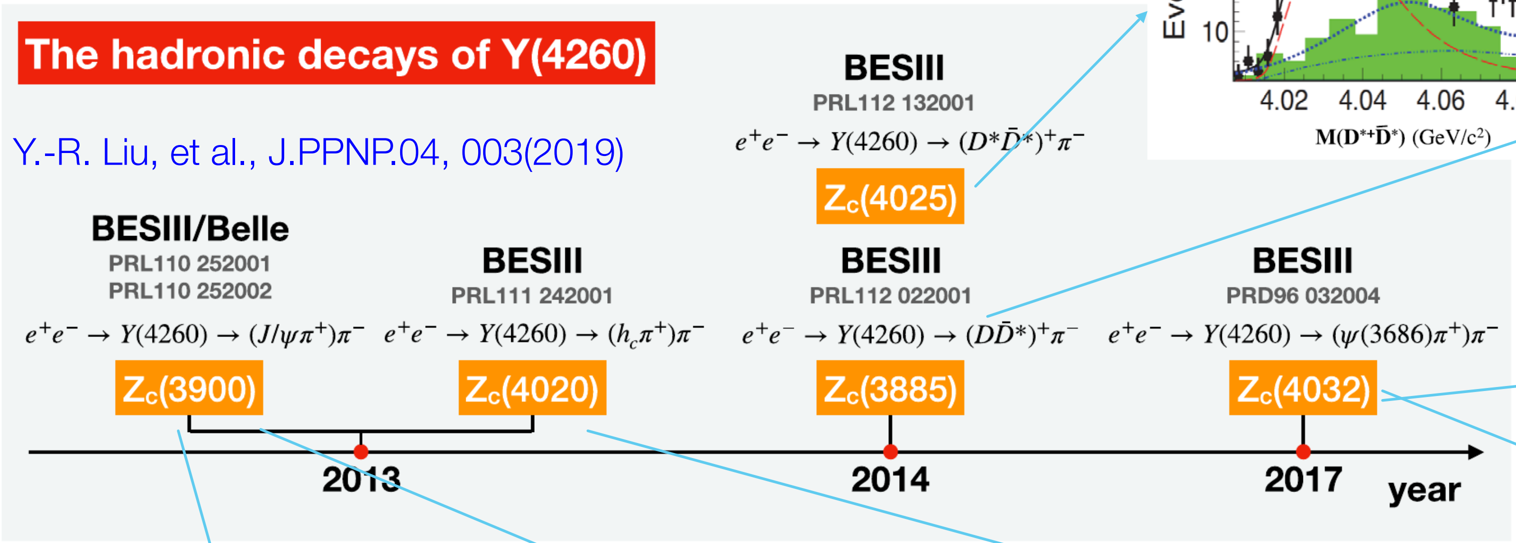


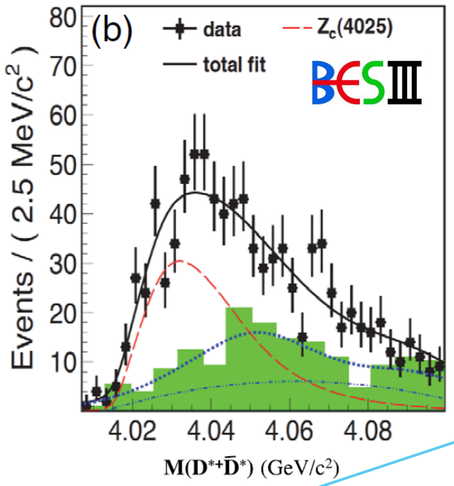


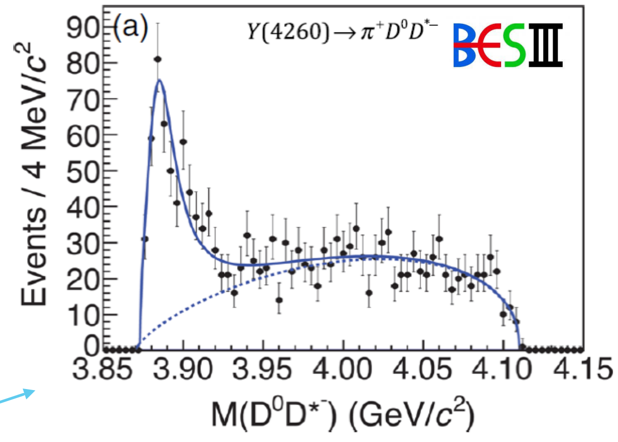


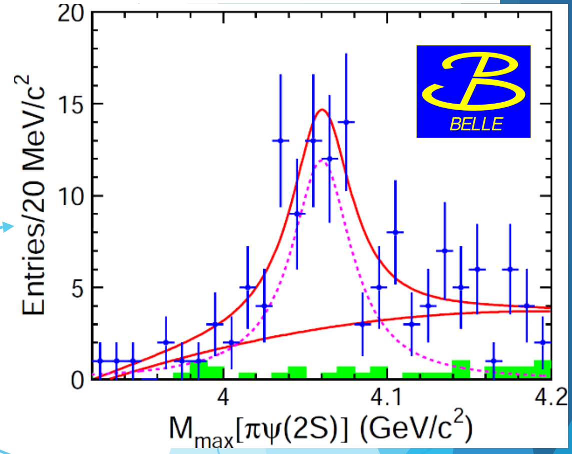
Y decays

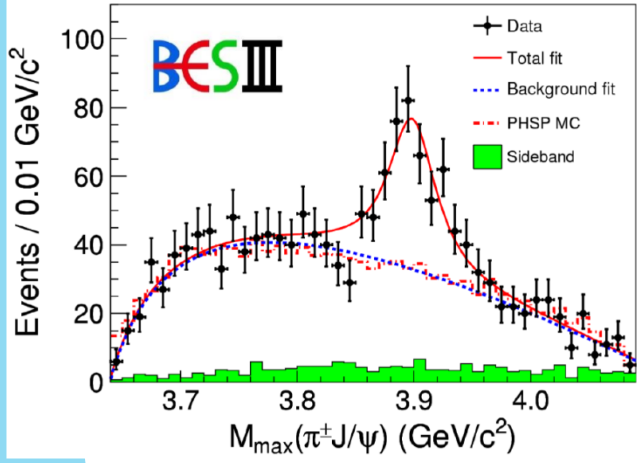
Many charged Z_c particles

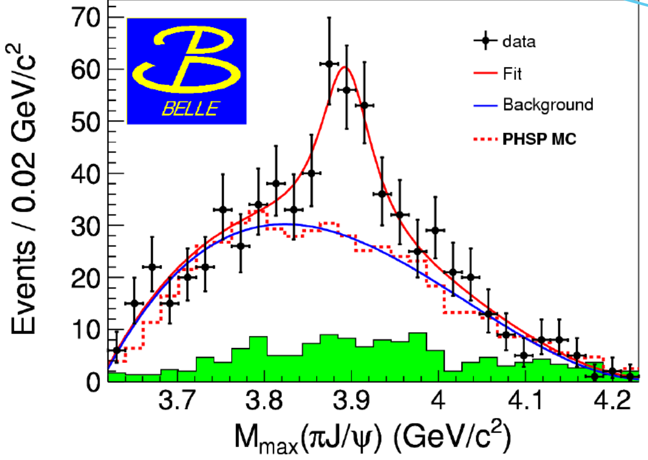


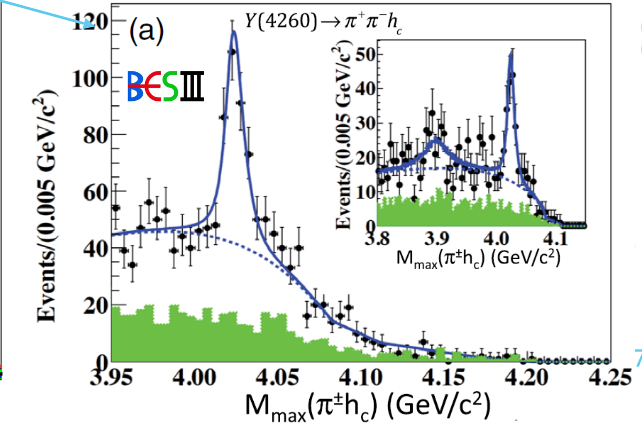


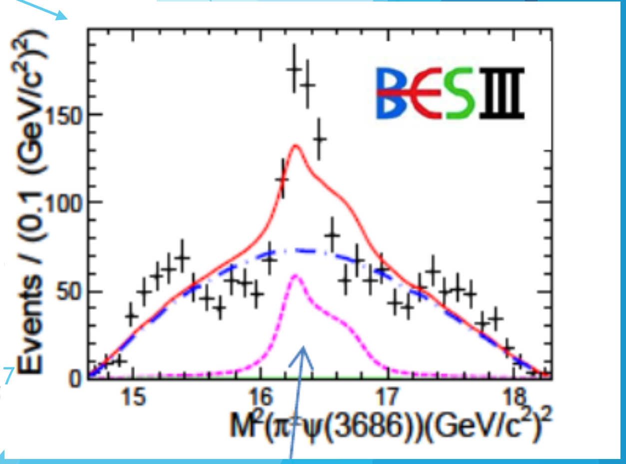




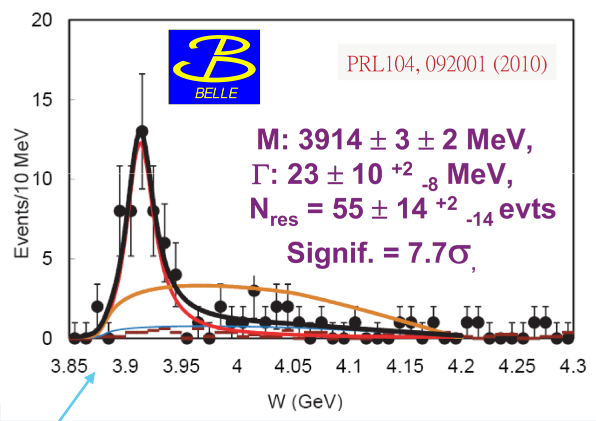








Double charmonium production and γγ collision



The double charmonium production process

Belle	Belle	Belle
PRL98 082001	PRL100 202001	PRD95 112003
$e^+e^- \to J/\psi(\bar{D}D^*)$	$e^+e^- \to J/\psi(D^{*+}D^{*-})$	$e^+e^- \to J/\psi(D\bar{D})$
X(3940)	Y(4160)	X*(3860)
2007	2008	2017

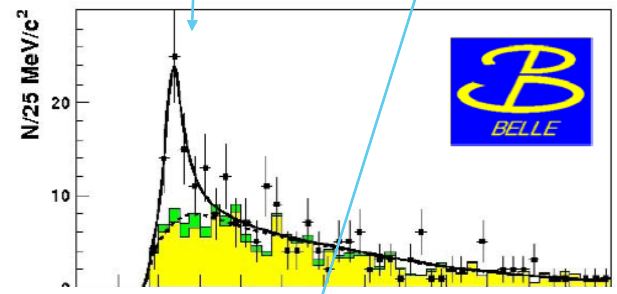
year

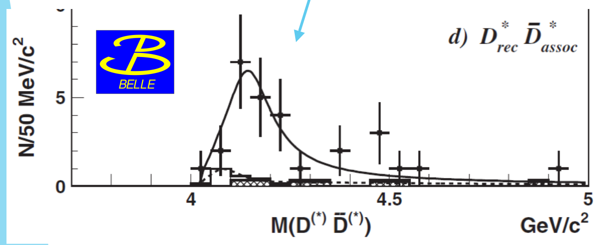
The γγ fusion process

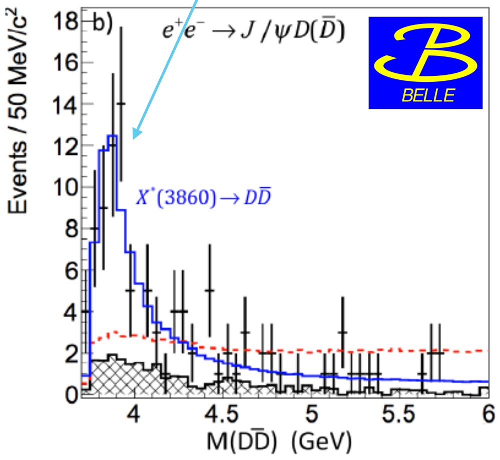
Belle	Belle	Belle
PRL96 082003	PRL104 092001	PRL104 112004
$\gamma\gamma \to (D\bar{D})$	$\gamma\gamma \to (J/\psi\omega)$	$\gamma\gamma \to (J/\psi\phi)$
Z(3930)	X(3915)	X(4350)
2005	2010	2010

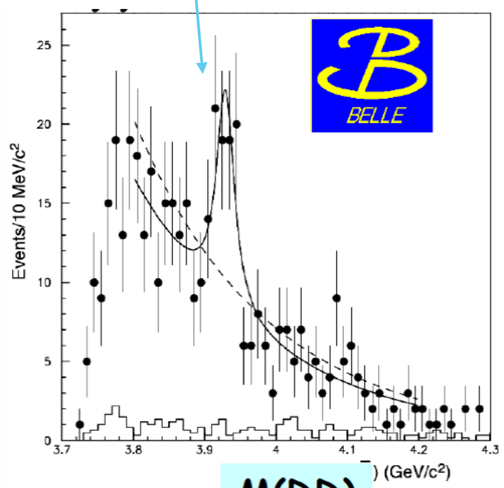
year

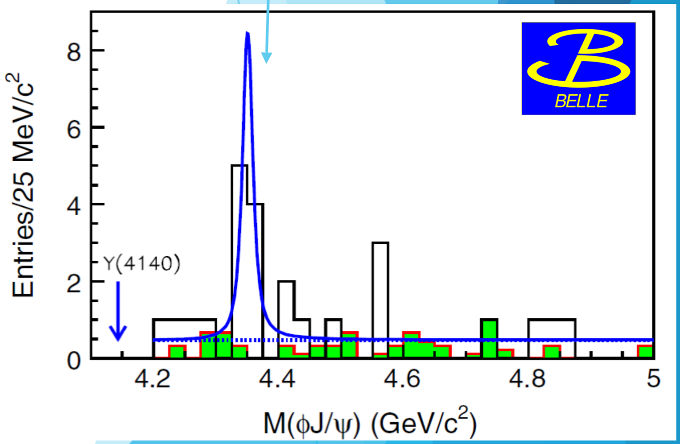
Y.-R. Liu, et al., J.PPNP.04, 003(2019)





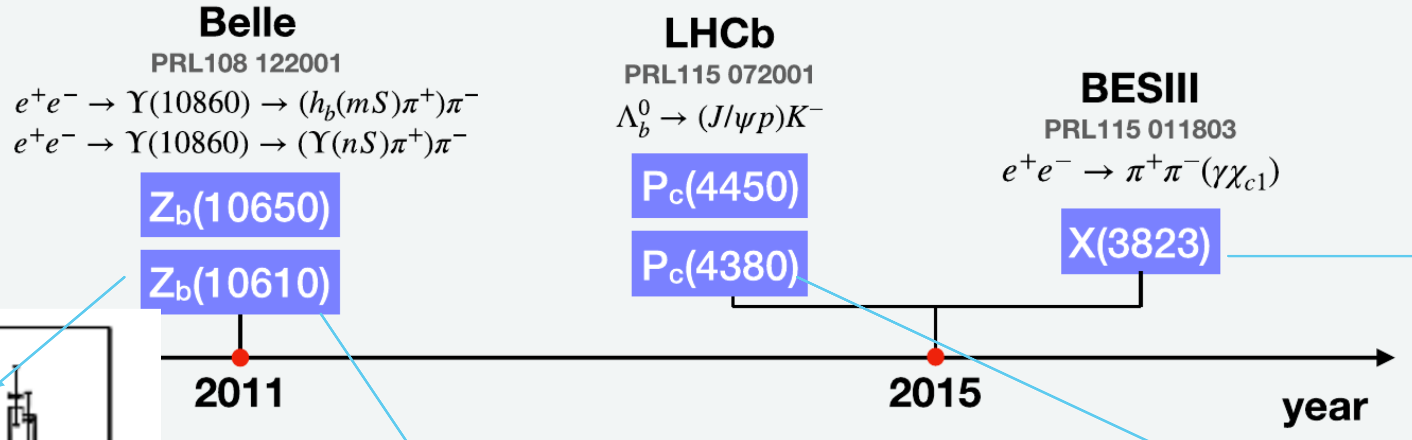


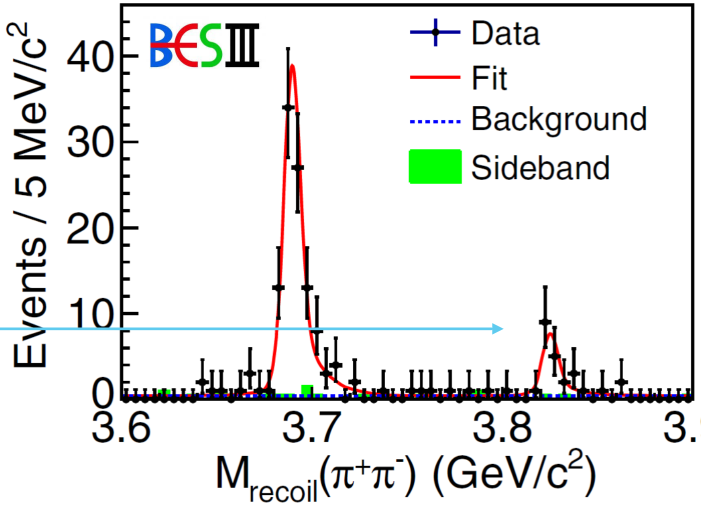


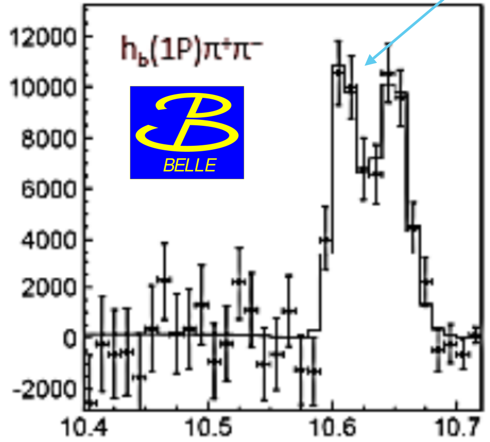


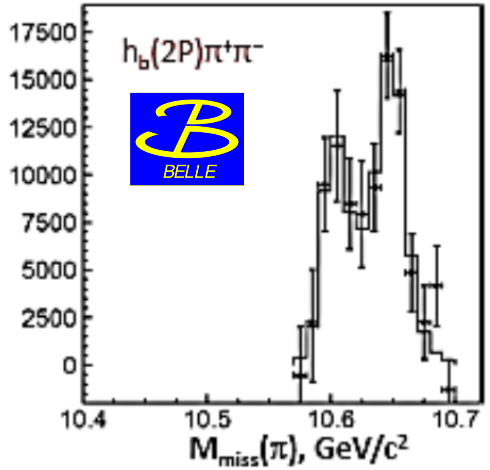
Other processes

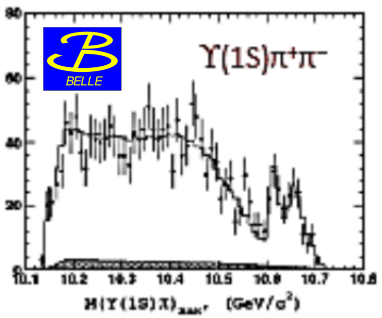
Y.-R. Liu, et al., J.PPNP.04, 003(2019)



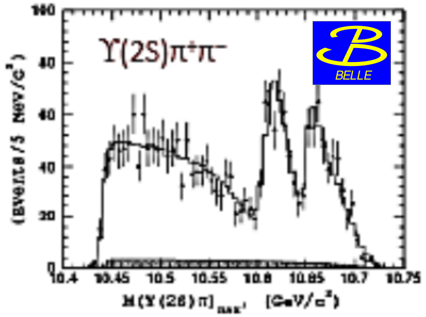




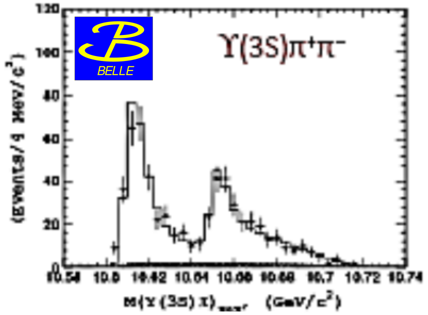


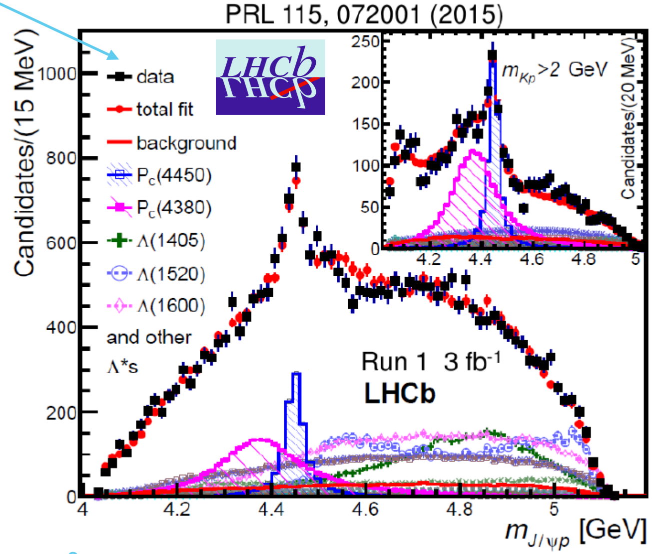


Zb(10610)



Zb(10650)





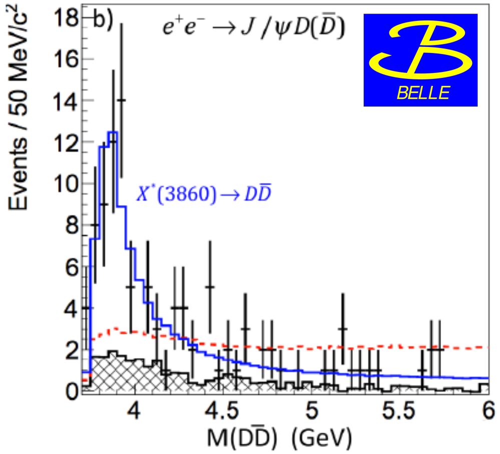
NEW

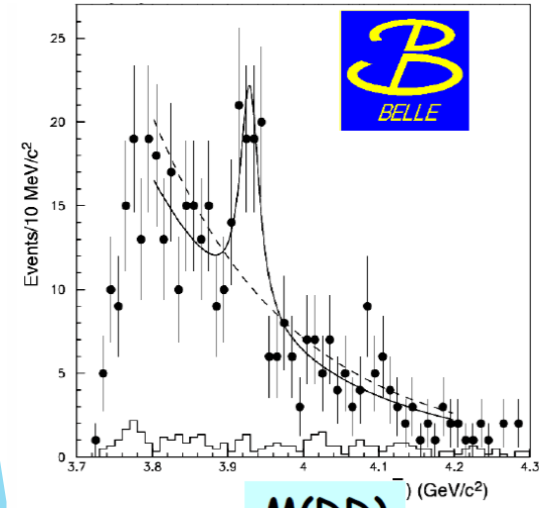
Update:

- ➢ Pc(4450) → Pc(4440)+Pc(4457)
- ➢ Pc(4380) → Pc(4312)

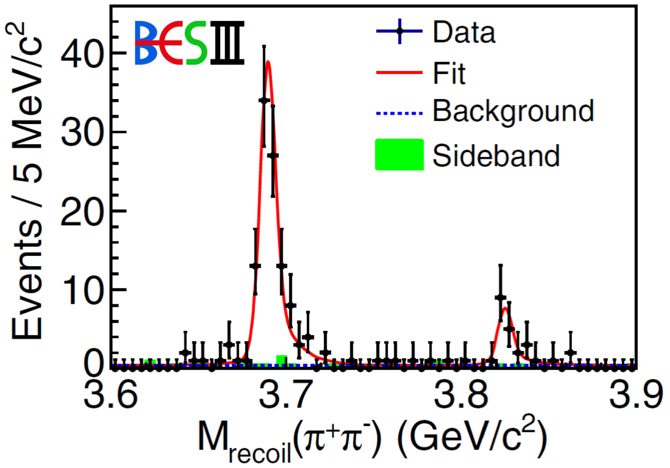
Some candidates for conventional quarkonium states

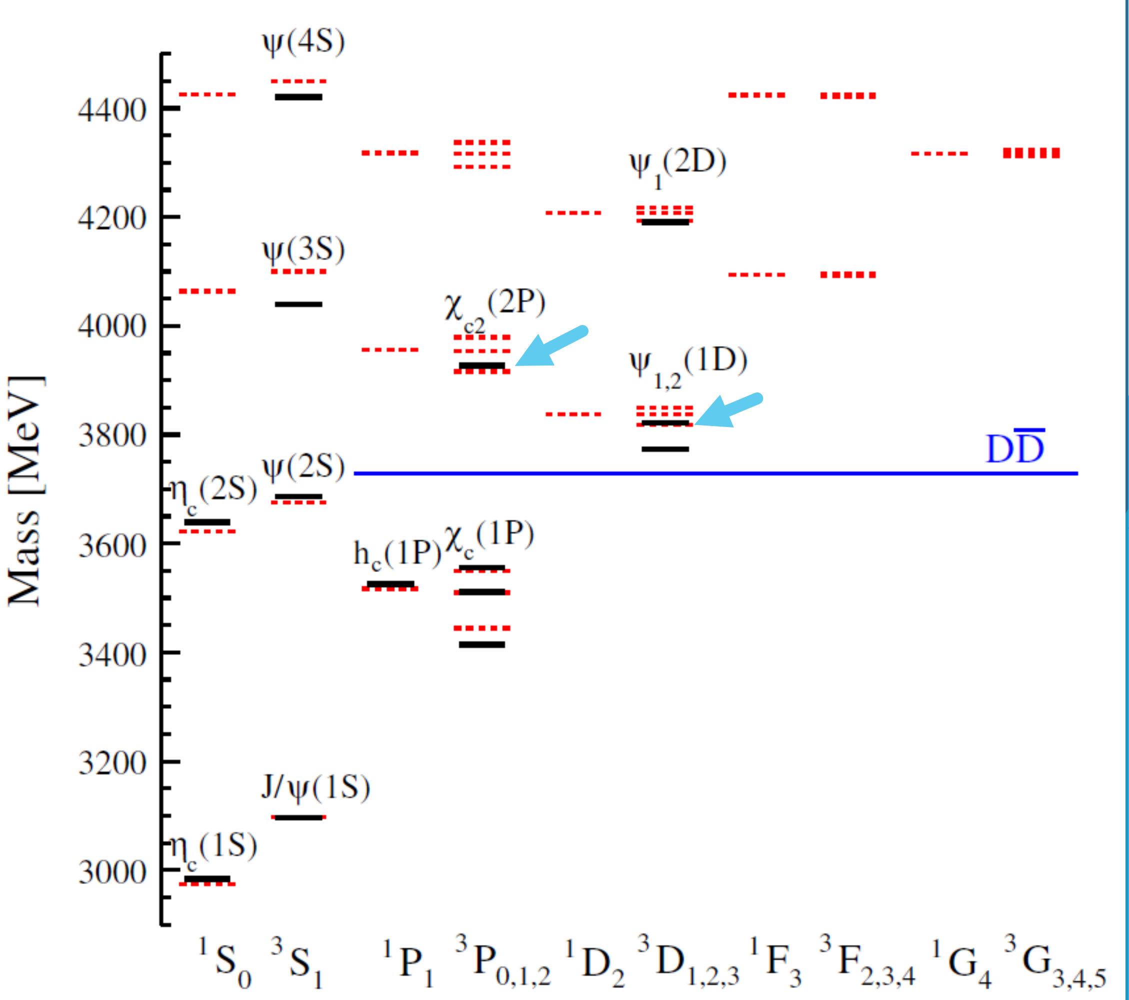
- X*(3860) → $\chi_{c0}(2P)$
- Z(3930) → $\chi_{c2}(2P)$?
- X(3823) → $\psi(1^3D_2)$





M(DD)



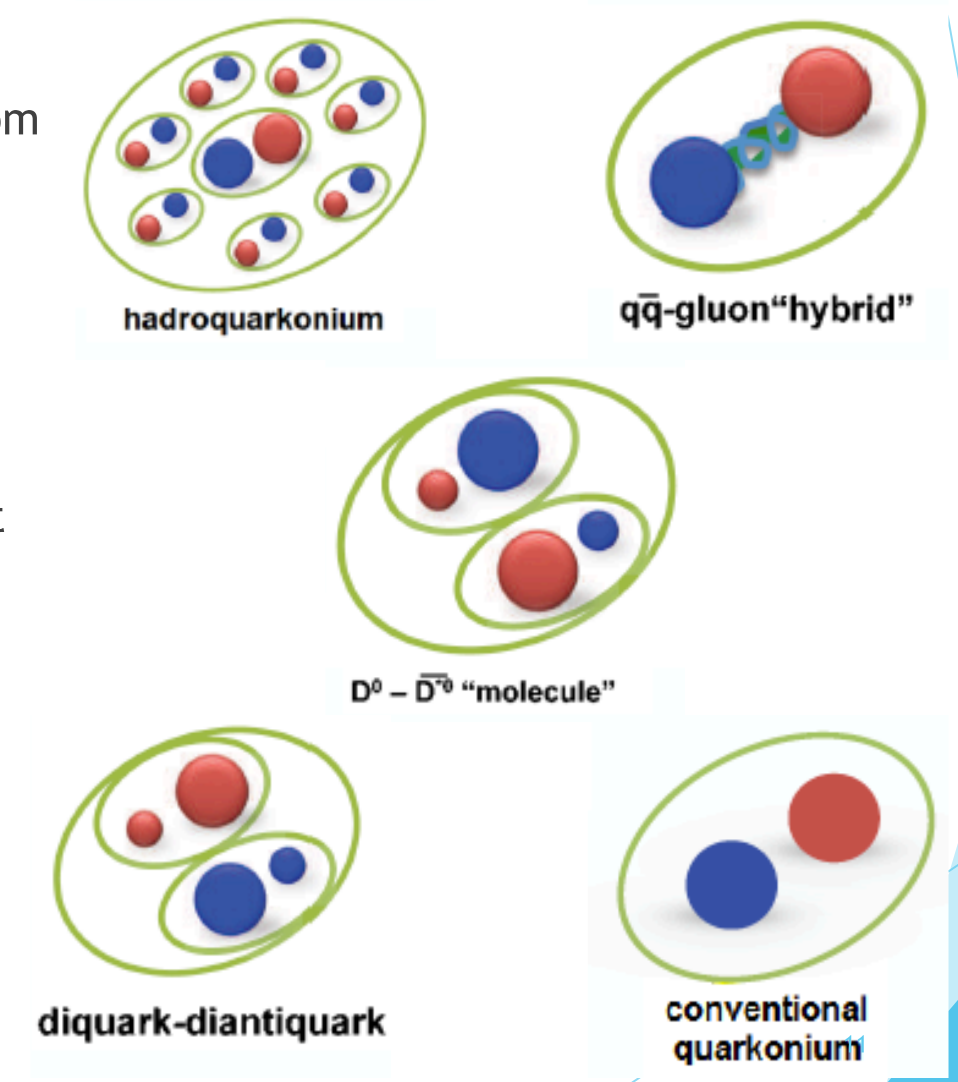


Still many slots to be filled!

Most of the observed quarkonium-like states remain exotic candidate states!

Theoretical Interpretations of exotic states

- Most models can be classified according to quark clustering and degrees of freedom
  - **Hadroquarkonium**: compact quarkonium-like core surrounded by light quarks
  - **Tetraquarks**: compact diquark and anti-diquark substructures
  - **Hadronic molecules**: heavy and light quarks and anti-quarks combine to form a hadron pair
  - **Hybrids**: both quarks and gluons act as active degrees of freedom (contribute to quantum numbers)
  - **Kinematical effects**
  - All of the above…



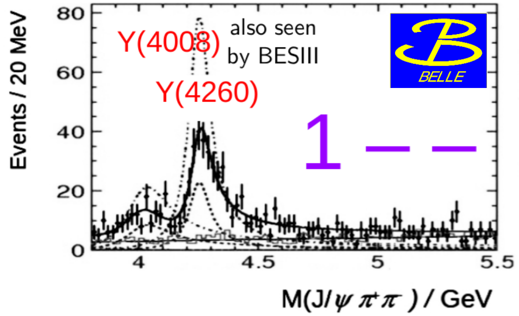
More details from M. Voloshin, later this session

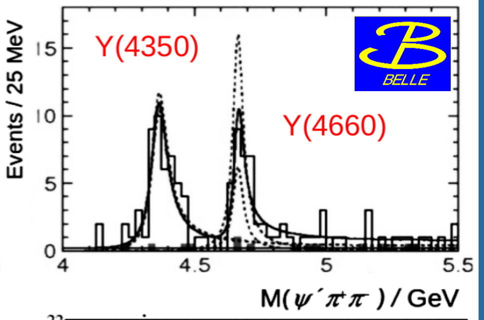
Recent results on candidate exotic hadrons

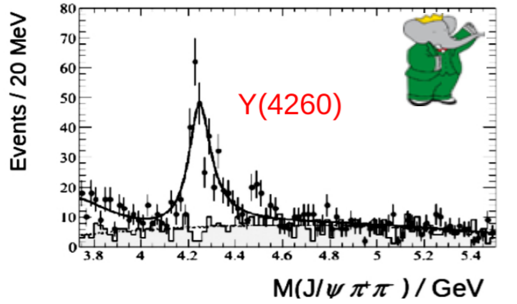
- Belle:
  - Y(4260) in B decays
  - Search for spin partner state of Y(4630)
  - Inclusive $B \to X_{cc}K$ and absolute production of X(3872) in B decays
  - Search for double Z_c production at Belle
- LHCb:
  - $\eta_c\pi^-$ resonance in $B^0 \to \eta_c\pi^-K^+$ decays
  - Search for beautiful tetraquarks
  - Exotic contributions to $B^0 \to J/\psi\pi^-K^+$
- D0: Evidence for $Z_c(3900)$ in semi-inclusive decays of b-flavored hadrons
- BESIII: (*see review by G. Mezzadri later)
  - $e^+e^- \to \gamma\omega J/\psi$
  - $X(3872) \to \pi^0\chi_{c1}$
  - $e^+e^- \to \omega\chi_{c0}$
  - $e^+e^- \to DD\pi\pi$
  - …

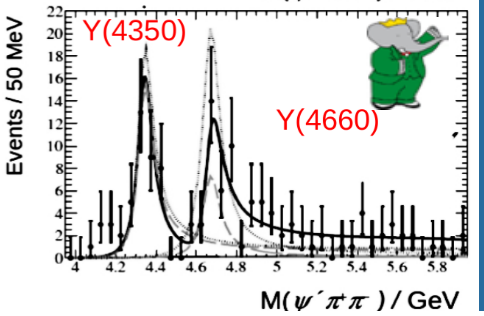
Y(4260) in B decays

- Y states observed in ISR by BaBar, Belle, CLEO
- Y(4260) → Y(4220)+Y(4320) in e^+e^- direct production at BESIII
- Y(4008), Y(4260), Y(4360), Y(4660), ψ(4040), ψ(4160)
  → overpopulation of states!
- Y(4260): $DD_1(2460)$ molecule? P-wave tetraquark?
- Remarkable: decay to $D^{(*)}D^{(*)}$ not seen (although the phase space is large)
  - $J/\psi f_0(980)$ hadrocharmonium?
  - (ccg) hybrid? (blocked by gluon fluxtube)
- Y(4260) → $\pi^+\pi^-\psi(2S)$ observed

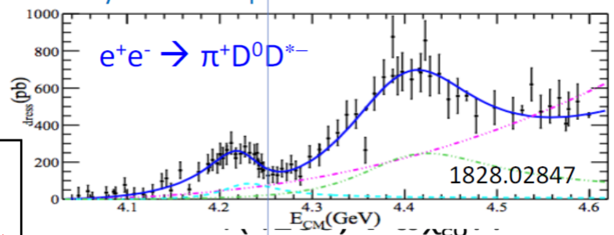


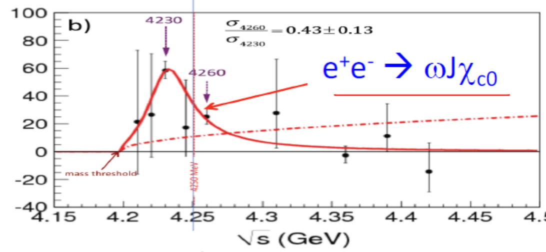


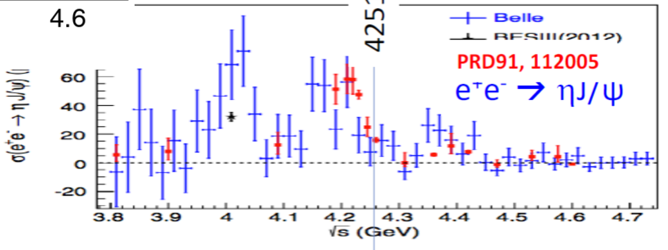


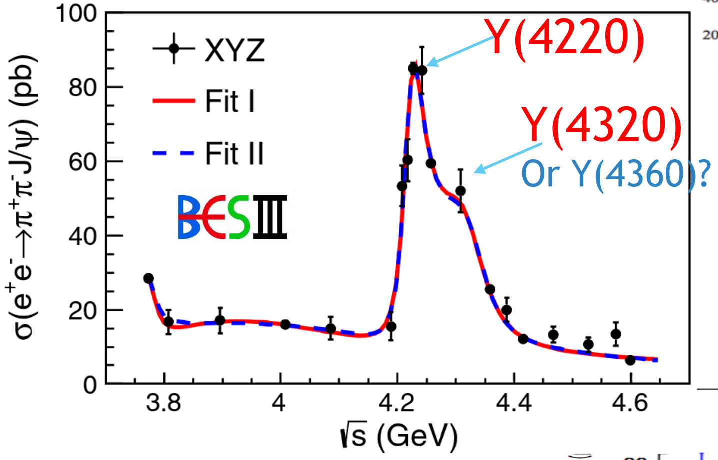


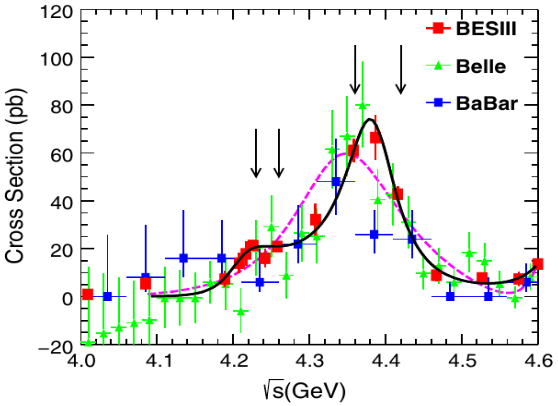
only the lower peak seen in other channels

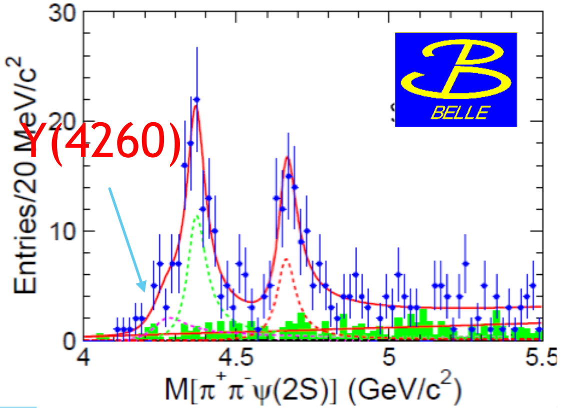










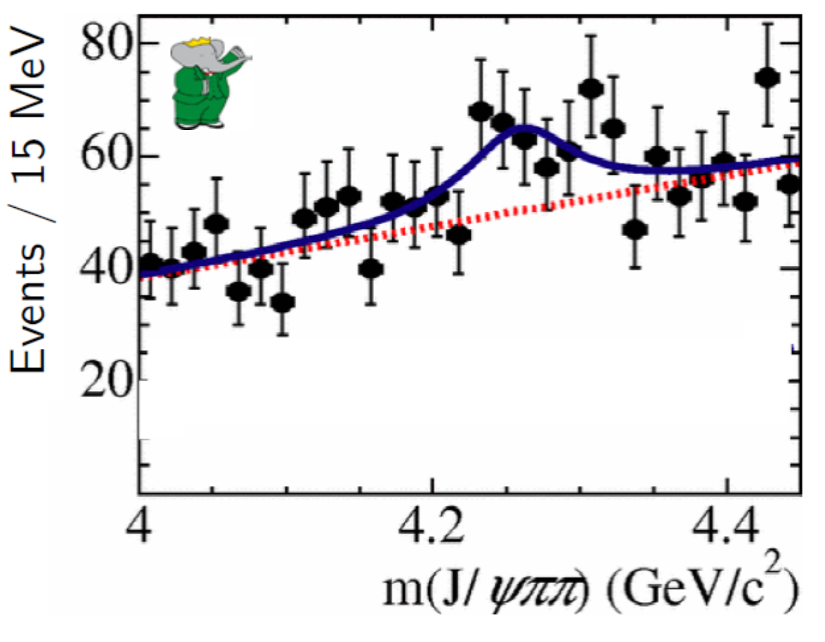


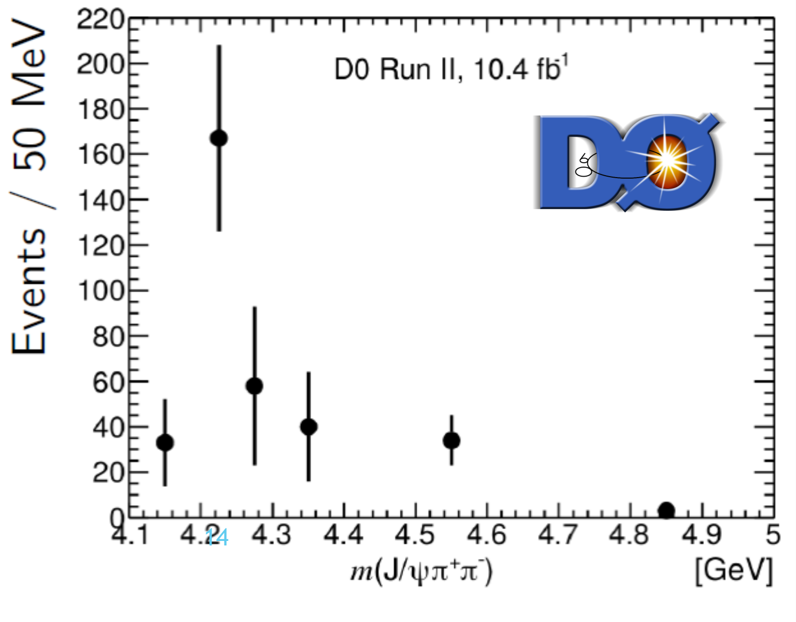
Y(4260) in B decays

- Some predictions (e.g. mixed-state model based upon QCD sum rules), suggest $B^+ \rightarrow K^+Y(4260)$ with $Y(4260) \rightarrow \pi^+\pi^- J/\psi$ may have a branching fraction in the range 3.0×10^{-8} – 1.8×10^{-6}

- BaBar, Phys. Rev. D73, 011101(2006)
  - $B^+ \rightarrow K^+Y(4260)$, $Y(4260) \rightarrow \pi^+\pi^- J/\psi$
  - 211 fb^{-1}, 128 ± 42 signal events (3.1σ)
  - Scaling for total Belle luminosity 711 fb^{-1} would give S/sqrt(S+B) = 5.7

- D0, Phys. Rev. D98, 052010(2018)
  - 10.4 fb^{-1}, 167 ± 41 signal events (4.3σ) b-flavoured hadrons (B, Bs, B*,…)
  - Semi-inlusive (require $\pi^+\pi^- J/\psi$ secondary vertex)



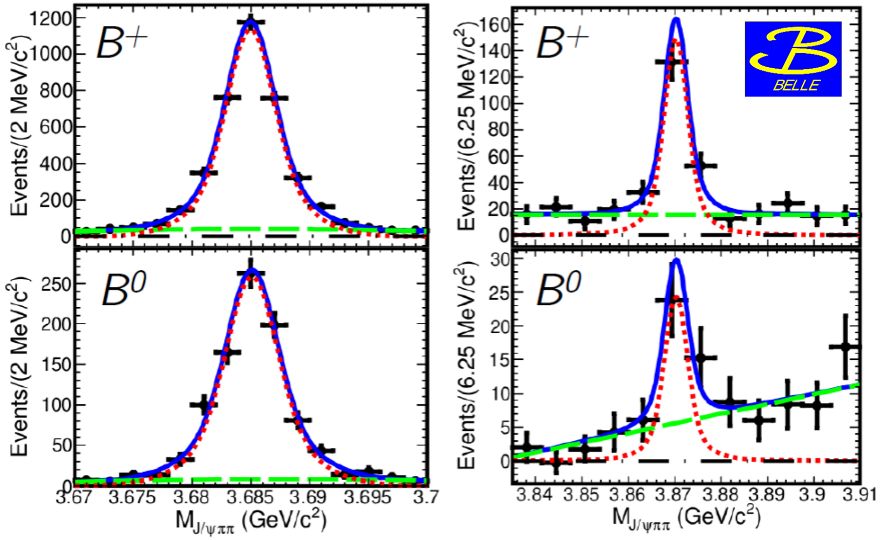


Y(4260) in B decays – NEW Belle Result

CONTROL SIGNALS

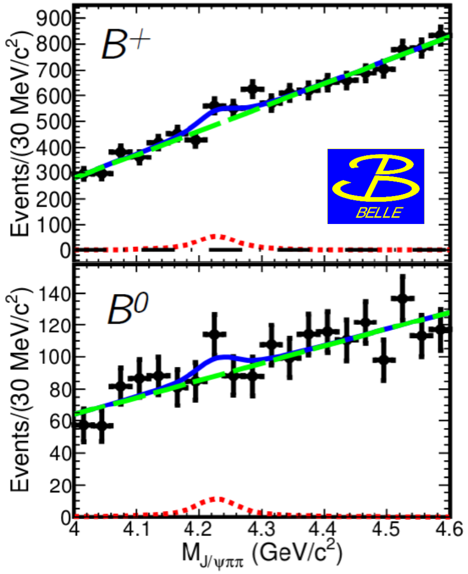
Belle, 711 fb^{-1} (full Belle data)

Decay	ϵ (%)	N_S	$\mathcal{B}$	$\mathcal{B}_{PDG}$
$B^+ \to \psi(2S)K^+$	16.8	3481±95	$(6.54\pm0.18)\times10^{-4}$	$(6.21\pm0.23)\times10^{-4}$
$B^0 \to \psi(2S)K^0$	10.3	856±74	$(5.25\pm0.45)\times10^{-4}$	$(5.8\pm0.5)\times10^{-4}$
$B^+ \to X(3872)K^+, X(3872) \to J/\psi\pi^+\pi^-$	22.2	185±13	$(9.07\pm0.64)\times10^{-6}$	$(8.6\pm0.8)\times10^{-6}$
$B^0 \to X(3872)K^0, X(3872) \to J/\psi\pi^+\pi^-$	13.1	29.9±6.2	$(4.97\pm1.03)\times10^{-6}$	$(4.3\pm1.3)\times10^{-6}$



R. Garg, V. Bhardwaj, J. B. Singh, et al. (Belle Collaboration), arXiv:1901.06470 [hep-ex]

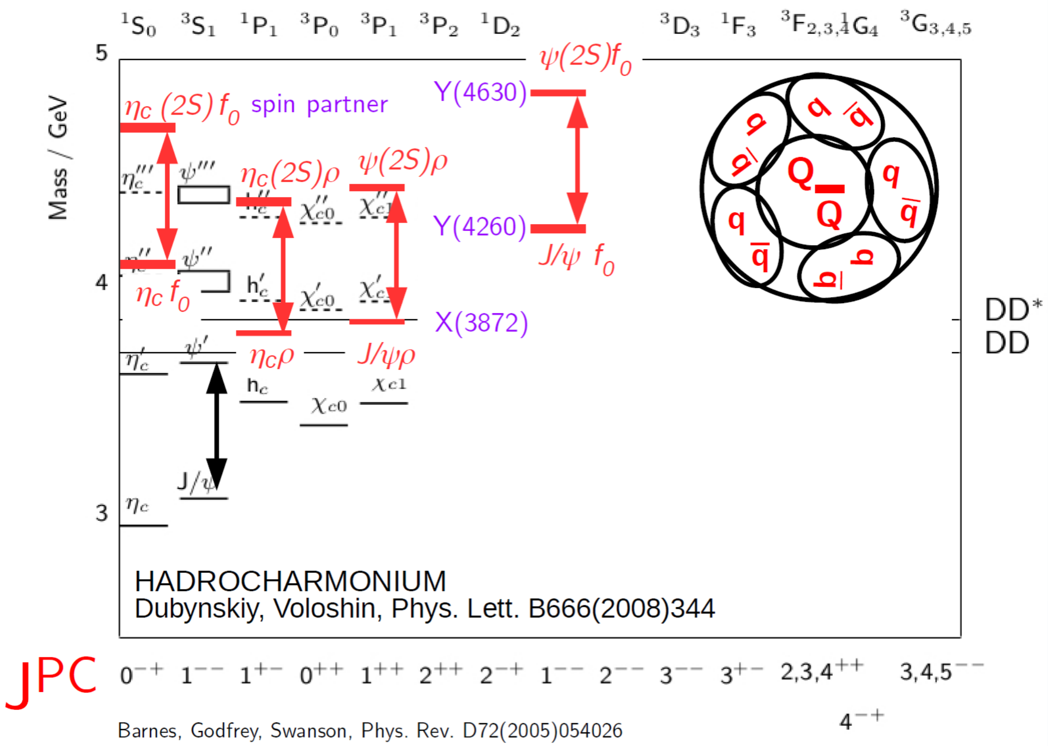
Decay	ϵ (%)	N_S	$\mathcal{B}$	Σ (σ)	U.L.
$B^+ \to Y(4260)K^+, Y(4260) \to J/\psi\pi^+\pi^-$	19.8	$179\pm61^{+55}_{-41}$	$(9.8\pm3.3^{+3.0}_{-2.3})\times10^{-6}$	2.1	1.4×10^{-5}
$B^0 \to Y(4260)K^0, Y(4260) \to J/\psi\pi^+\pi^-$	10.6	$39\pm28^{+7}_{-31}$	$(8.0\pm5.7^{+1.4}_{-6.3})\times10^{-6}$	0.9	1.7×10^{-5}



Factor ~3.3 more data than BaBar
Neutral B decays added
No signal observed
Upper limit consistent with BaBar
(branching fraction reaches 10^{-6} level)

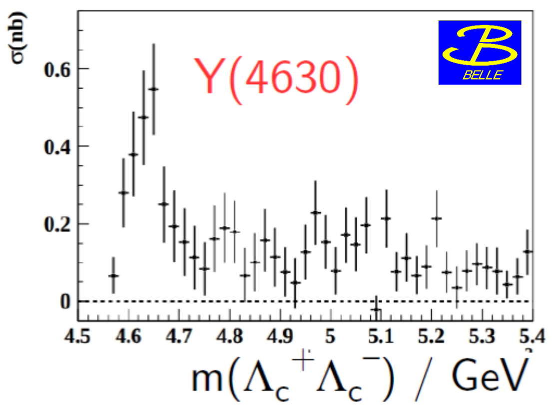
Y(4630)/Y(4660)

- Discovered in ISR → $J^{PC}=1^{--}$
- Y(4630) → $\Lambda_c^+\Lambda_c^-$ and Y(4660) → $\pi^+\pi^-\psi(2S)$ may be same state
  - Guo, Haidenbauer, et al., Phys. Rev. D82, 094008(2010)
- Highest charmed XYZ stated observed and confirmed so far
- → if a ccbar state, radius is about 2.2 fm (unstable, far beyond string breaking limit)
- The only quarkoniumlike state observed decaying into baryons*
- PDG2018, only Y(4660)

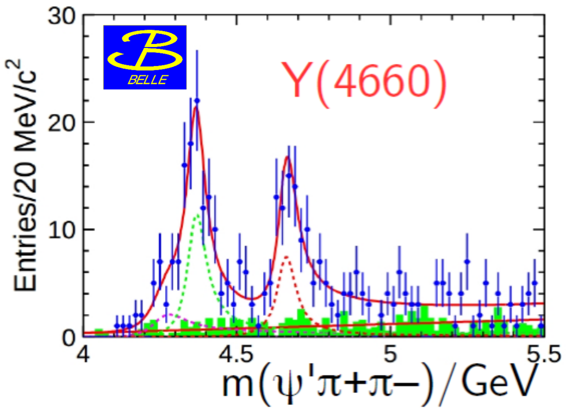


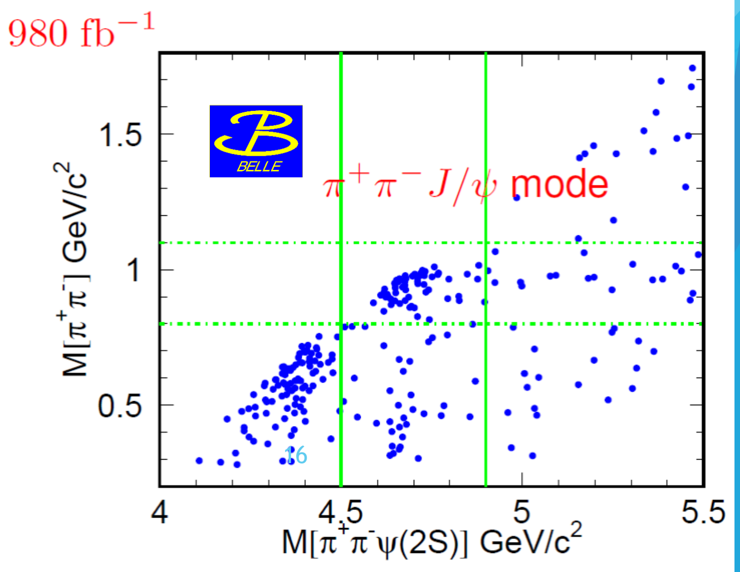
Barnes, Godfrey, Swanson, Phys. Rev. D72(2005)054026

Belle, Phys. Rev. Lett. 101 (2008) 172001



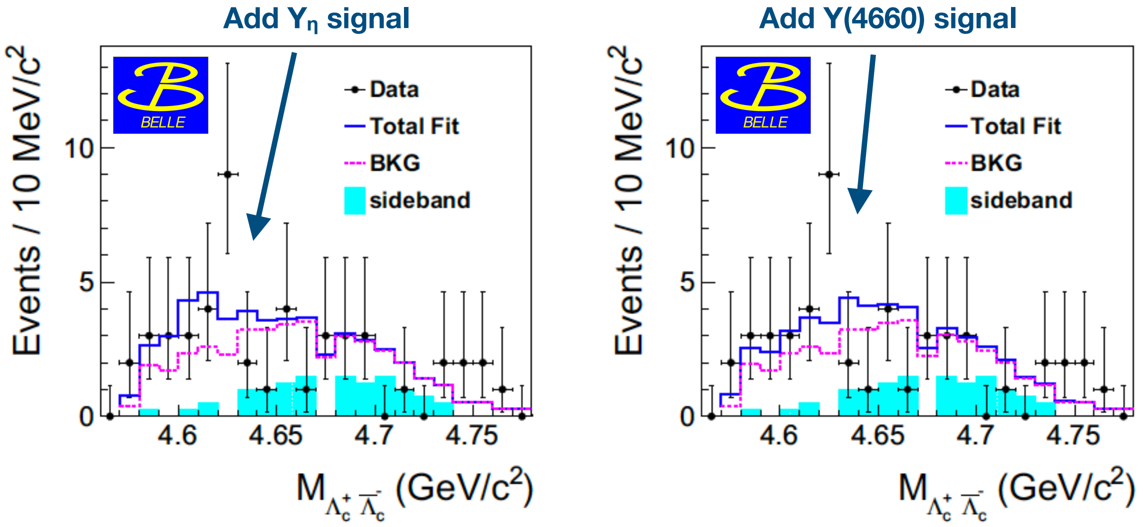
Belle, Phys. Rev. D91 (2015) 112007





Search for spin partner state of Y(4630) in B decays

- $\eta_c(2S)f_0(980)$, mass 4613 ± 4 MeV, width ≈ 30 MeV [width dominated by $\eta_c(2S)$] → called Y_η
  - F.K. Guo, J. Haidenbauer, C. Hanhart, U.G. Meißner, Phys. Rev. D 82, 094008 (2010)
- $J^{PC} = 0^{-+}$, cannot be produced in ISR but can be sought in B decays
- Y(4660) and its spin partner are sought in the $\Lambda_c^+\Lambda_c^-$ invariant mass spectrum



Neutral B decays: Belle EPJC.78.252 (2018)

Neutral B decays: Belle EPJC.78.928 (2018)

- No significant signals seen in the $\Lambda_c^+\bar{\Lambda}_c^-$ mass spectrum.
  - $\mathcal{B}(B^- \to K^- Y(4660))\mathcal{B}(Y(4660) \to \Lambda_c^+\bar{\Lambda}_c^-) < 1.2 \times 10^{-4}$ at 90% C.L.
  - $\mathcal{B}(B^- \to K^- Y_\eta)\mathcal{B}(Y_\eta \to \Lambda_c^+\bar{\Lambda}_c^-) < 2.0 \times 10^{-4}$ at 90% C.L.

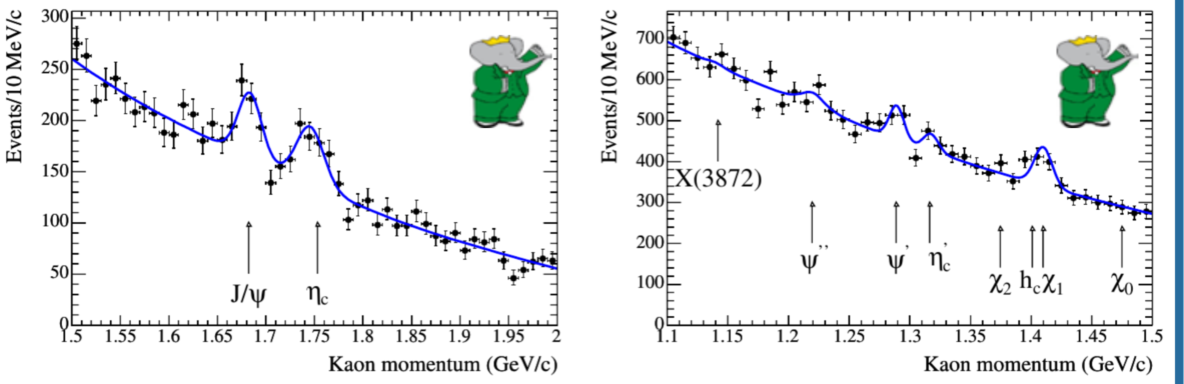
BRs of B → KX_{cc} and absolute production of X(3872) in B decays

$$Bf(B^- \to XK^-)Bf(X \to J/\psi\pi^+\pi^-) = (8.20 \pm 0.93)\times 10^{-6}$$
$$Bf(B^- \to XK^-)Bf(X \to J/\psi\pi^+\pi^-\pi^0) = (8.2 \pm 4.2)\times 10^{-6}$$
$$Bf(B^- \to XK^-)Bf(X \to J/\psi\gamma) = (2.8 \pm 0.8 \pm 0.1)\times 10^{-6}$$
$$Bf(B^- \to XK^-)Bf(X \to \psi(2S)\gamma) = (9.5 \pm 2.7 \pm 0.6)\times 10^{-6}$$
$$Bf(B^- \to XK^-)Bf(X \to D^0\overline{D}^{0*} + c.c.) = (1.67 \pm 0.36 \pm 0.47)\times 10^{-4}$$
...
$$\Rightarrow Bf(X \to J/\psi\pi^+\pi^-) < \frac{8.2+1\sigma}{8.2+8.2+2.8+9.5+167-1\sigma} \approx 6.6\% \quad @90\%\text{ C.L.}$$

$$2.3\% < Bf\left(X \to J/\psi\pi^+\pi^-\right) < 6.6\%$$
$$1.4\times 10^{-4} < Bf\left(B^- \to X(3872)K^-\right) < 3.2\times 10^{-4} \quad \text{at } 90\%\text{ C.L.}$$

$$Bf\left(B^- \to \psi(2S)K^-\right) = (6.48 \pm 0.35)\times 10^{-4}$$
$$Bf\left(B^- \to \chi_{c1}K^-\right) = (4.9 \pm 0.5)\times 10^{-4}$$
$$Bf\left(B^- \to \eta_c K^-\right) = (9.1 \pm 1.3)\times 10^{-4}$$

BaBar: PRL96, 052002(2006)



- Clear signals of J/ψ , x_{c1}, ψ(2S), etc.
- Br(B →X(3872)K) < 3.2 × 10^{-4} at 90% C.L.

$\chi_{c1}(3872)$ ▶ PDG2018 $I^G(J^{PC}) = 0^+(1^{++})$

Mass $m = 3871.69 \pm 0.17$ MeV
$m_{\chi_{c1}(3872)} - m_{J/\psi} = 775 \pm 4$ MeV
Full width $\Gamma < 1.2$ MeV, CL = 90%

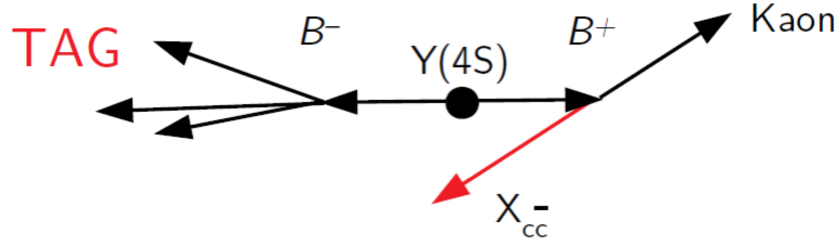
$\chi_{c1}(3872)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi^+\pi^- J/\psi(1S)$	> 3.2 %	650
$\omega J/\psi(1S)$	> 2.3 %	†
$D^0\overline{D}^0\pi^0$	>40 %	117
$\overline{D}^{*0}D^0$	>30 %	3
$\gamma J/\psi$	> 7 $\times 10^{-3}$	697
$\gamma\psi(2S)$	> 4 %	181
$\pi^+\pi^-\eta_c(1S)$	not seen	746
$\pi^+\pi^-\chi_{c1}$	not seen	218
$p\overline{p}$	not seen	1693

Total branching fraction not known

100% ?

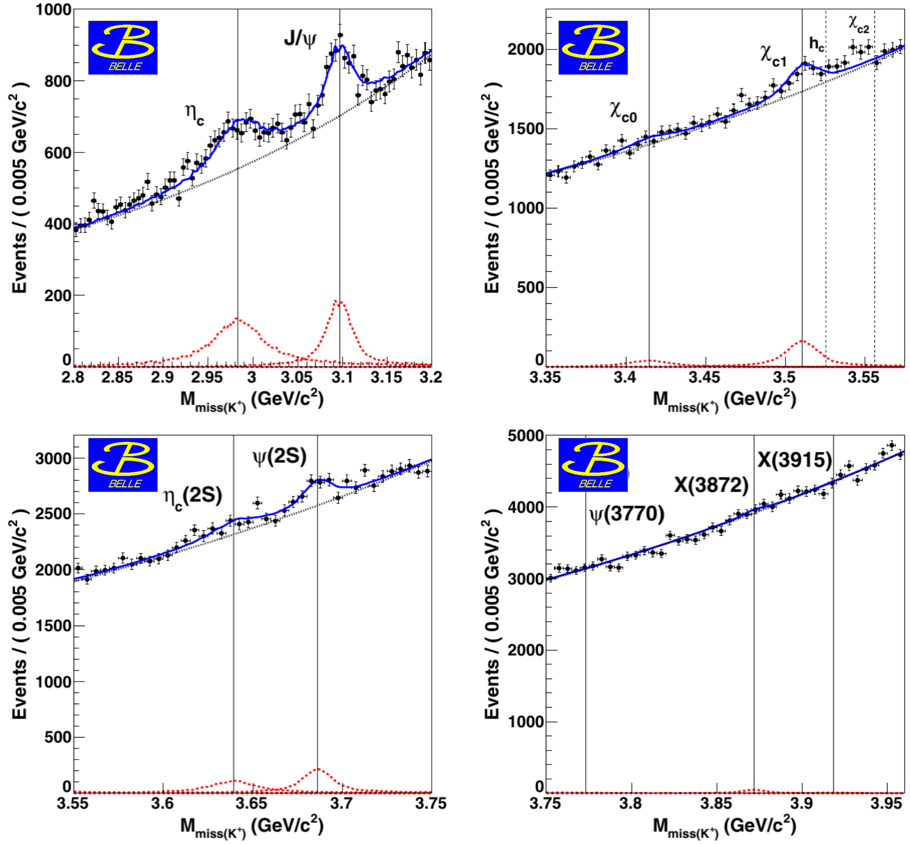
$B^+ \rightarrow K^+X_{cc}$

- Particular situation at Υ(4S): m(Υ(4S)) = $m_B+m_{\overline{B}}$
- B mesons at rest in center of mass system



- Hierarchical full reconstruction of 1104 hadronic decays
- NeuroBayes neural-network package
- M. Feindt et al., NIM. A654, 432(2011)

$$M_{\mathrm{miss(h)}} = \sqrt{(p^*_{\mathrm{e^+e^-}} - p^*_{\mathrm{tag}} - p^*_{\mathrm{h}})^2/c}$$



Mode	Yield	Significance (σ)	$\epsilon(10^{-3})$	$\mathcal{B}$ (10^{-4})	World average for $\mathcal{B}$ (10^{-4}) [10]
η_c	2590 ± 180	14.2	2.73 ± 0.02	$12.0 \pm 0.8 \pm 0.7$	9.6 ± 1.1
J/ψ	1860 ± 140	13.7	2.65 ± 0.02	$8.9 \pm 0.6 \pm 0.5$	10.26 ± 0.031
χ_{c0}	430 ± 190	2.2	2.67 ± 0.02	$2.0 \pm 0.9 \pm 0.1$ (< 3.3)	$1.50^{+0.15}_{-0.14}$
χ_{c1}	1230 ± 180	6.8	2.68 ± 0.02	$5.8 \pm 0.9 \pm 0.5$	4.79 ± 0.23
$\eta_c(2S)$	1050 ± 240	4.1	2.77 ± 0.02	$4.8 \pm 1.1 \pm 0.3$	3.4 ± 1.8
$\psi(2S)$	1410 ± 210	6.6	2.79 ± 0.02	$6.4 \pm 1.0 \pm 0.4$	6.26 ± 0.24
$\psi(3770)$	-40 ± 310	-	2.76 ± 0.02	$-0.2 \pm 1.4 \pm 0.0$ (< 2.3)	4.9 ± 1.3
$X(3872)$	260 ± 230	1.1	2.79 ± 0.01	$1.2 \pm 1.1 \pm 0.1$ (< 2.6)	(< 3.2)
$X(3915)$	80 ± 350	0.3	2.79 ± 0.01	$0.4 \pm 1.6 \pm 0.0$ (< 2.8)	-

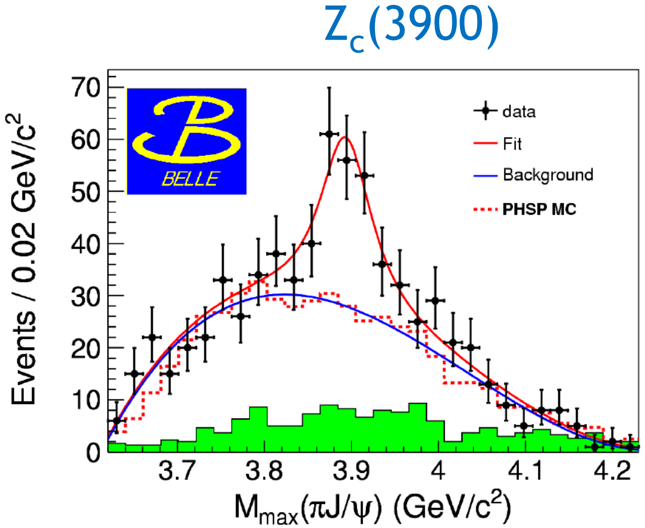
Almost reaching the sensitivity of product branching fraction
$B^+ \rightarrow K^+X(3872)$, $X(3872) \rightarrow D^0\overline{D}^0\pi^0$
$\mathcal{B}=(1.0\pm0.4)\times10^{-4}$ (PDG 2018)

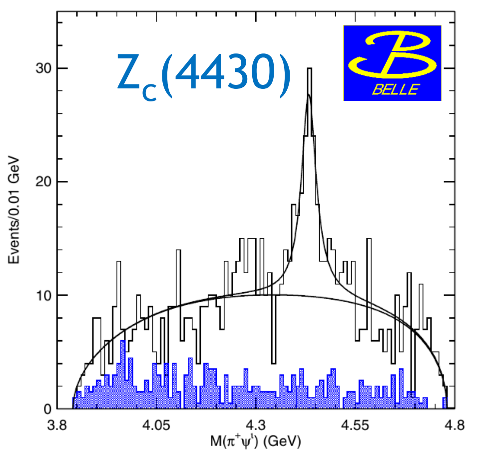
Y. Kato, T. Iijima, et al. (Belle Collaboration), Phys. Rev. D97 (2018) 012005

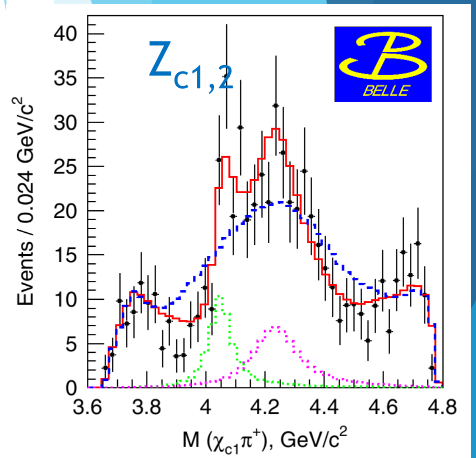
Search for double Z_c production at Belle

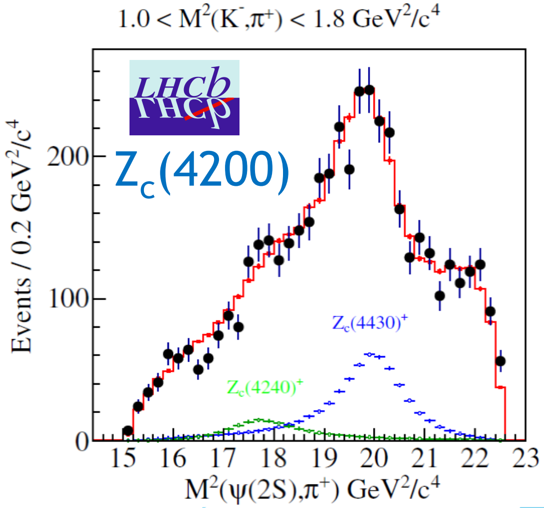
- $e^+e^- \to Z_c(3900)^+\pi^-$ observed at BESIII and Belle
- $e^+e^- \to Z_b^+\pi^-$ observed at Belle, near 10.86 GeV
- Search for $e^+e^- \to Z_c^+Z_c^-$ at 10.52, 10.58 and 10.86 GeV
- Search also in Υ(1S) and Υ(2S) decays (9.46 GeV and 10.02 GeV)

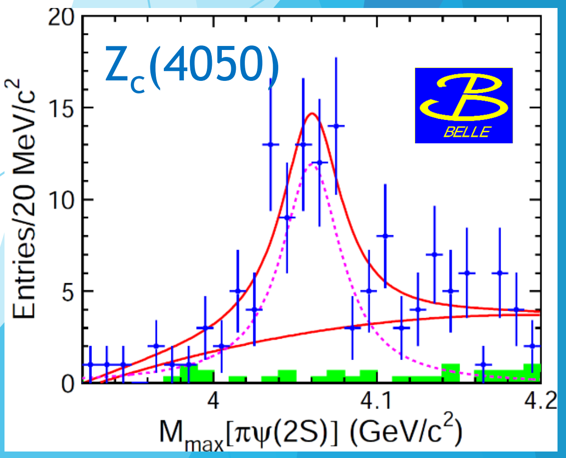
Z_c states	Z_c labels in Ref. [23]	Mass	Width
$Z_c^+(3900)$	$X^+(3900)$	3886.6 ± 2.4	28.1 ± 2.6
$Z_c^+(4200)$	$X^+(4200)$	4196^{+35}_{-32}	370^{+100}_{-150}
$Z_{c1}^+(4050)$	$X^+(4050)$	4051^{+24}_{-40}	82^{+50}_{-28}
$Z_{c2}^+(4250)$	$X^+(4250)$	4248^{+190}_{-50}	177^{+320}_{-70}
$Z_c^+(4050)$	$X^+(4055)$	4054 ± 3.2	45 ± 13
$Z_c^+(4430)$	$X^+(4430)$	4478^{+15}_{-18}	181 ± 31



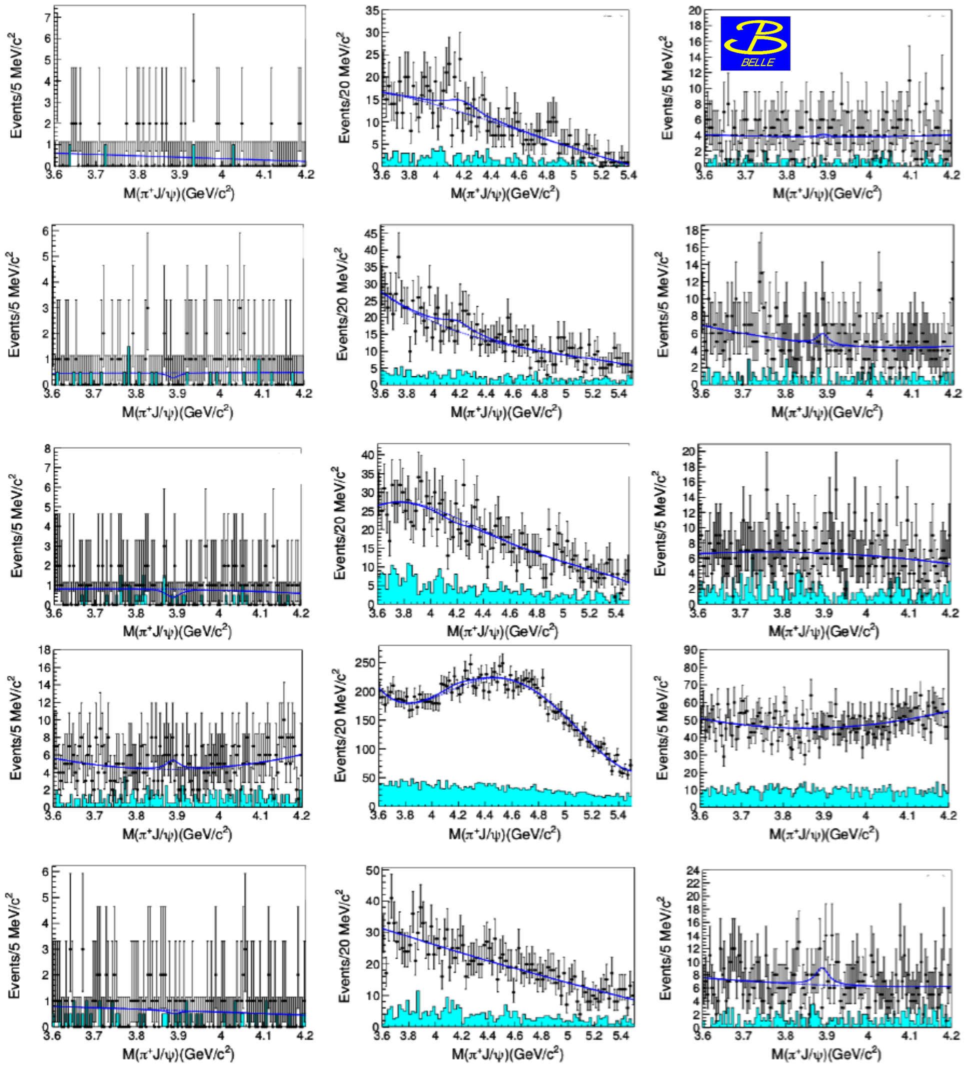








Search for double Z_c production at Belle



Born cross section in [fb]

Mode	$\sqrt{s}$ (GeV)	$N^{\rm fit}$	$N^{\rm UL}$	ε (%)	Σ (σ)	$\sigma_{\rm syst}$ (%)	$\sigma\times\mathcal{B}(Z_c^+\to\pi^+J/\psi)$	$\sigma^{\rm UL}\times\mathcal{B}(Z_c^+\to\pi^+J/\psi)$
$e^+e^-\to Z_c^+(3900)Z_c^-(3900)$	10.52	-4.9 ± 3.6	7.2	41.5	-	10.3	-1.6 ± 1.2	2.3
$e^+e^-\to Z_c^+(4200)Z_c^-(4200)$	10.52	-27.5 ± 57.8	82.8	43.7	-	34.2	-8.5 ± 18.1	26.5
$e^+e^-\to Z_c^+(3900)Z_c^-(4200)+c.c.$	10.52	-0.5 ± 15.0	28.4	21.0	-	22.9	-0.3 ± 9.7	18.3
$e^+e^-\to Z_c^+(3900)Z_c^-(3900)$	10.58	11.8 ± 13.0	32.2	41.5	0.9	12.7	0.5 ± 0.5	1.3
$e^+e^-\to Z_c^+(4200)Z_c^-(4200)$	10.58	132.1 ± 173.0	390.1	43.4	0.8	35.4	5.1 ± 6.9	15.5
$e^+e^-\to Z_c^+(3900)Z_c^-(4200)+c.c.$	10.58	-7.7 ± 39.4	63.4	20.8	-	20.7	-0.6 ± 3.2	5.1
$e^+e^-\to Z_c^+(3900)Z_c^-(3900)$	10.867	-1.4 ± 4.6	9.0	41.5	-	17.0	-0.3 ± 1.1	2.2
$e^+e^-\to Z_c^+(4200)Z_c^-(4200)$	10.867	-0.2 ± 41.6	93.7	43.7	-	33.2	-0.1 ± 9.4	21.9
$e^+e^-\to Z_c^+(3900)Z_c^-(4200)+c.c.$	10.867	30.3 ± 16.7	53.9	20.5	1.9	16.3	14.6 ± 8.4	26.6

Typical cross sections $\sigma(e^+e^-\to\Upsilon(5S))=0.3$ nb at $\sqrt{s}=10.86$ GeV and $\sigma(e^+e^-\to Y(4260))\simeq65$ pb at $\sqrt{s}=4.26$ GeV (with $\Upsilon(5S)\to Z_b^{(\prime)\pm}\pi^\mp$ and $Y(4260)\to Z_c^\pm(3900)\pi^\mp$)

Row:

$\sqrt{s}=9.46$ GeV

$\sqrt{s}=10.02$ GeV

$\sqrt{s}=10.52$ GeV

$\sqrt{s}=10.58$ GeV

$\sqrt{s}=10.86$ GeV

Column:

$e^+e^-\to Z_c^\pm(3900)\ Z_c^\mp(3900)$

$e^+e^-\to Z_c^\pm(3900)\ Z_c^\mp(4200)$

$e^+e^-\to Z_c^\pm(4200)\ Z_c^\mp(4200)$

Data set, in which $Z_b^{(\prime)}$ were observed

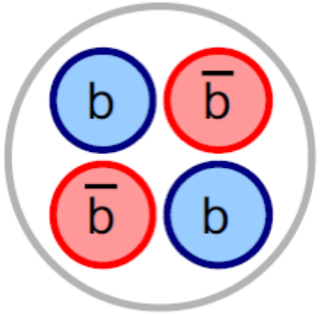
- Search for Z_c pair productions in e^+e^- collision
- No obvious signal observed
- The ULs of Born cross sections are set at the fb level

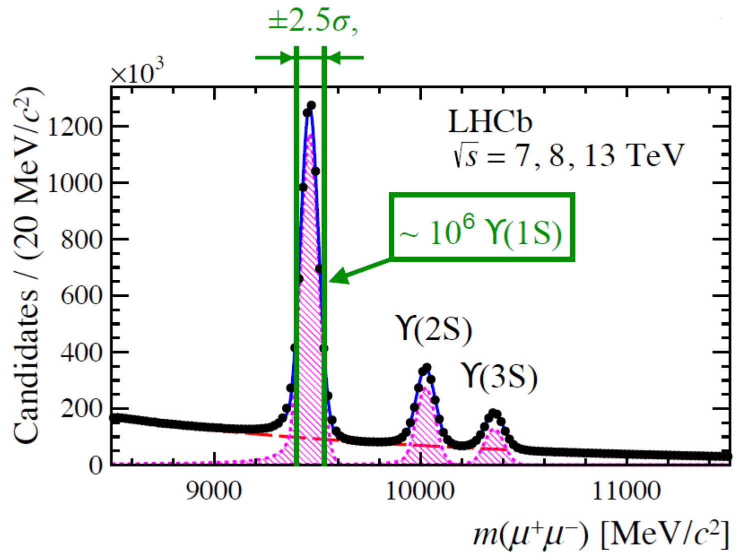
S. Jia, C. P. Shen, C. Z. Yuan, et al. (Belle Collaboration) Phys. Rev. D 97 (2018) 112004

Search for beautiful tetraquarks

Motivation

- No hadron containing more than two heavy quarks has been observed so far
- Theoretical predictions for $X_{b\bar{b}b\bar{b}}$:
  - Mass within [18.4; 18.8] GeV/c^2
  - Mass typically below $\eta_b\eta_b$ threshold, therefore decay to Υl^+l^-(l = e, μ)
  - Cross-section: $\sigma(pp \to X_{b\bar{b}b\bar{b}}) \times Br(X_{b\bar{b}b\bar{b}} \to 2l^+2l^-) \sim 1\,\text{fb}$
- Lattice QCD calculations do not find any evidence of this state

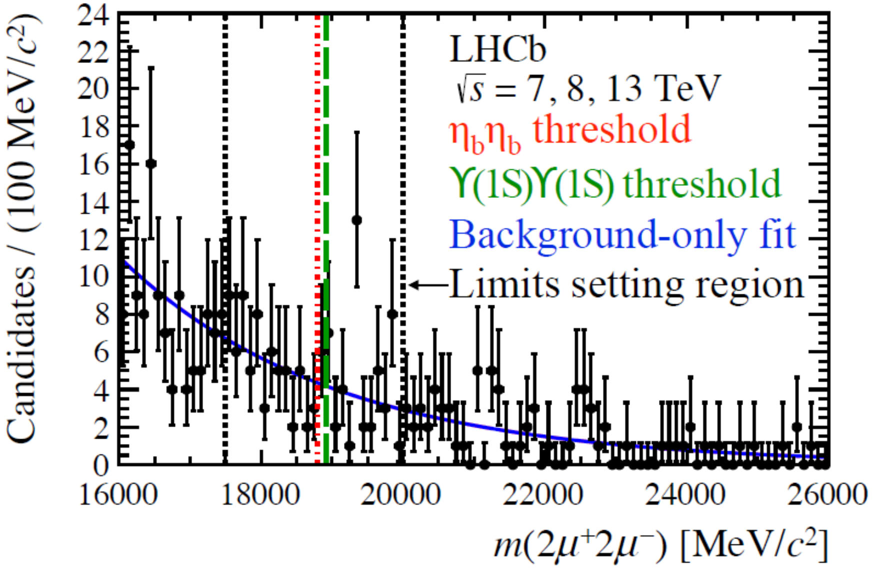




Analysis strategy

1. Search in $\Upsilon(1S)[\to \mu^+\mu^-]\mu^+\mu^-$ spectra
2. Normalization decay: $\Upsilon(1S) \to \mu^+\mu^-$
3. Data of 6.3fb^{-1} collected in
   I. 2011@7TeV,
   II. 2012@8TeV,
   III. 2015-2017@13TeV

Search for beautiful tetraquarks



- Cut-based selection
- J/ψ mass veto: $m(\mu^+\mu^-) \notin [3050; 3150]$ MeV/c^2
- Search for $X_{b\bar{b}b\bar{b}}$ in mass range [17.5; 20] GeV/c^2
- Fiducial region: $p_T(\mu^\pm) < 30$ GeV/c, $2.0 < y < 4.5$

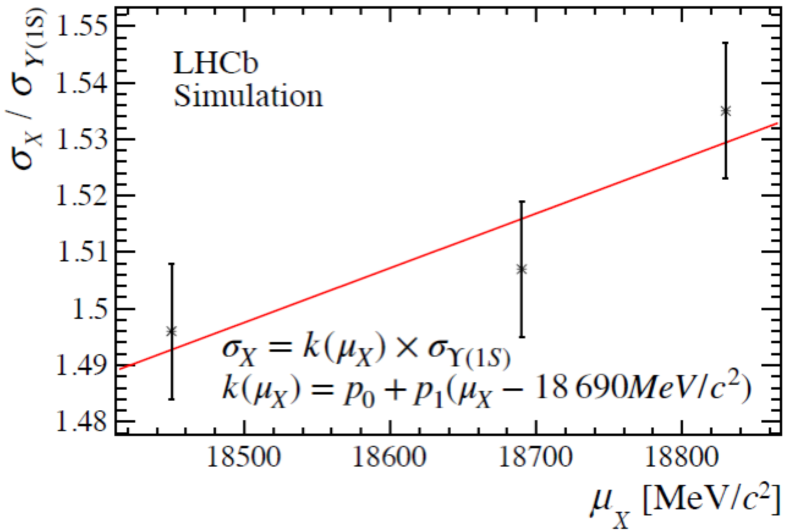
No significant excess is seen in data,

therefore upper limit is set:

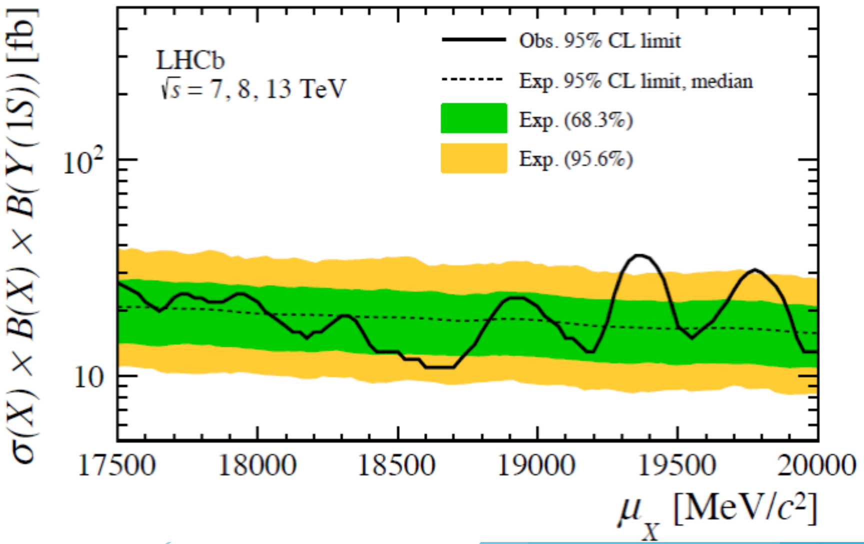
$$S = \sigma(pp \to X) \times Br(X \to \Upsilon(1S)\mu^+\mu^-) \times Br(\Upsilon(1S) \to \mu^+\mu^-)$$

- Likelihood profile as a function of S is integrated to determine upper limits

- $\sigma(X_{b\bar{b}b\bar{b}})$ ~ 60-70 MeV/c^2, multiplied by a scaling factor taken from simulation



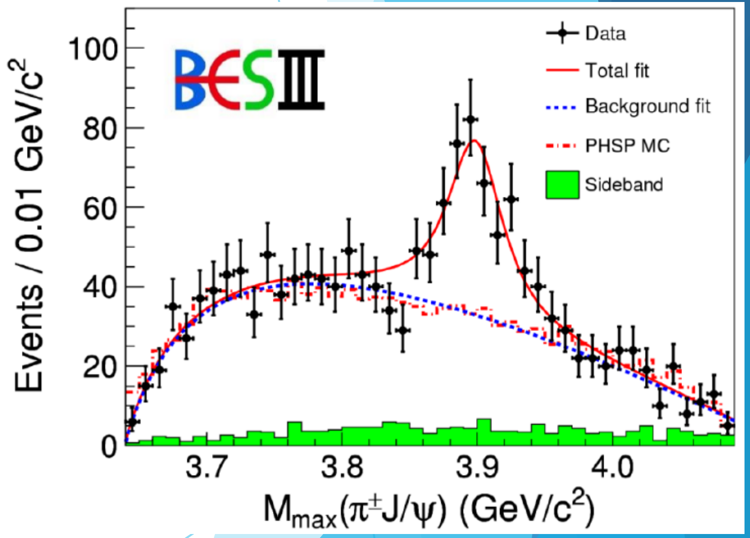
JHEP 10(2018)086

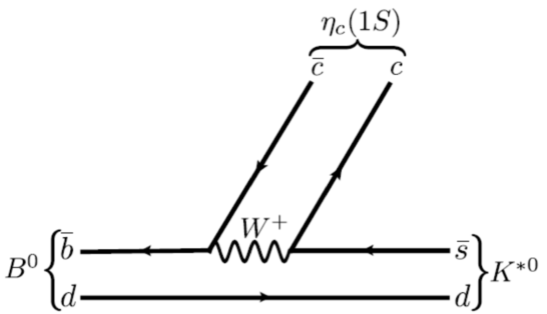


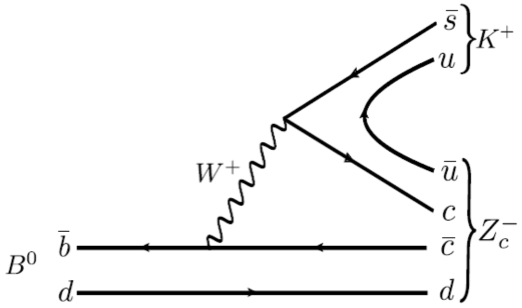
$\eta_c\pi^-$ resonance in $B^0 \to \eta_c\pi^-K^+$ decays

Motivation

- Important input for understanding nature of exotic hadrons, in particular of $Z_c(3900)^-$ discovered in $J/\psi\pi^-$ system from Y(4260) decays
  - $Z_c(3900)^-$ as analogue of quarkonium hybrids → $\eta_c\pi^-$ resonance $J^P = 0^+, 1^-, 2^+$ (based on lattice QCD)
    - E. Braaten, Phys. Rev. Lett. 111(2013)162003
  - $Z_c(3900)^-$ as hadrocharmonium → $\eta_c\pi^-$ resonance m = 3800 MeV/c²
    - M. B. Voloshin, Phys. Rev. D87, 091501(2013)
  - Diquark model → $\eta_c\pi^-$ resonance below the open-charm threshold $J^P = 0^+$
    - L. Maiani et al., Phys. Rev. D71, 014028(2005)
- Therefore, search for an $\eta_c\pi^-$ resonance in $B^0 \to \eta_c\pi^-K^+$ decays



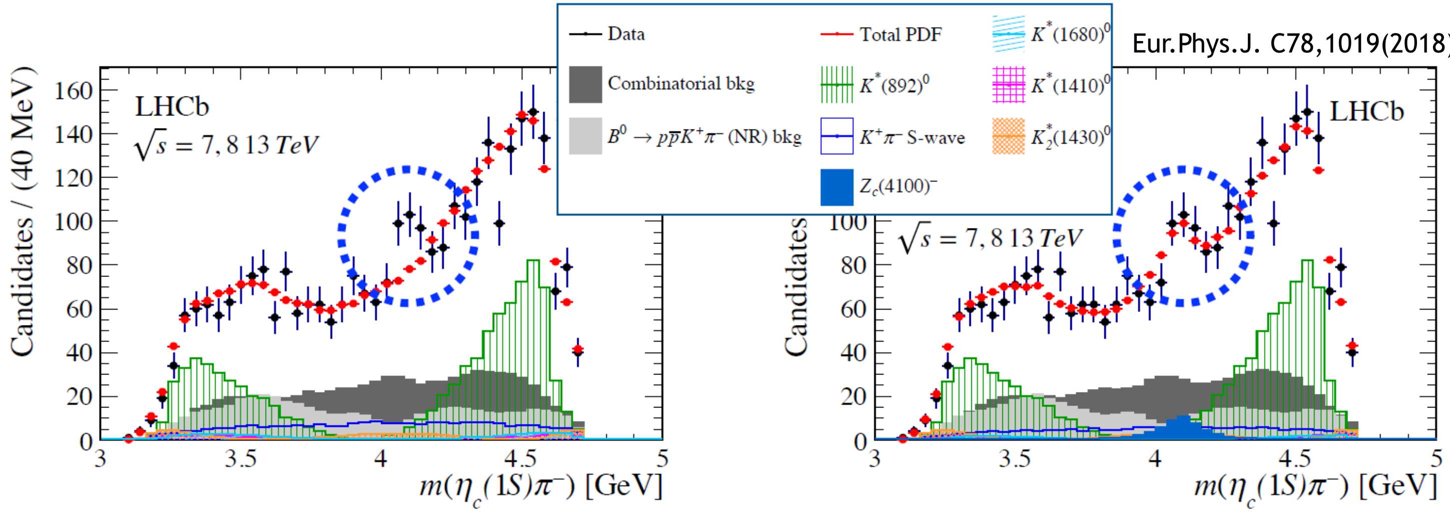




$\eta_c\pi^-$ resonance in $B^0 \to \eta_c\pi^-K^+$ decays

K$^+\pi^-$ only contributions   K$^+\pi^-$ and $\eta_c\pi^-$ contributions

Eur.Phys.J. C78,1019(2018)



- Good description is achieved by adding an exotic $Z_c(4100)^- \to \eta_c\pi^-$ component
- Evidence for exotic $Z_c(4100)^-$ resonance (3.4σ significance considering systematics)
- Both J^P= 0^+ and J^P= 1^- are consistent with the data

$$M = 4096 \pm 20^{+18}_{-22}\ \text{MeV/c2},\ \Gamma = 152 \pm 58^{+60}_{-35}\ \text{MeV}$$

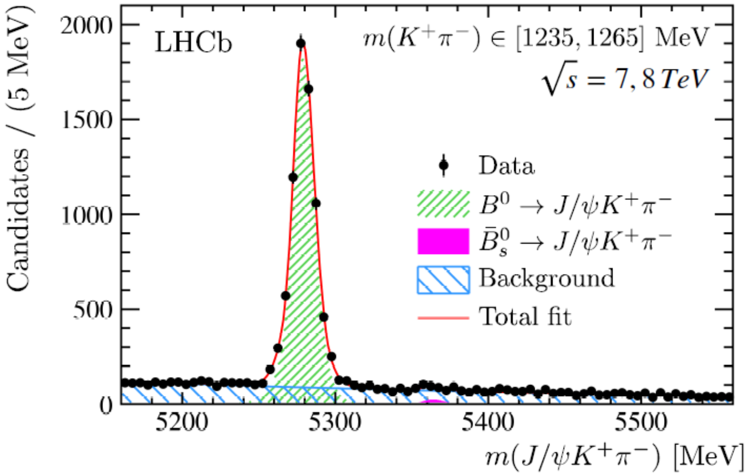
- Quasi-two-body branching fraction:

$$B(B^0 \to Z_c(4100)^- K^+,\ Z_c(4100)^- \to \eta_c\pi^-) = (1.89 \pm 0.64^{-0.67}_{+0.73}) \times 10^{-5}$$

Exotic contributions to $B^0 \to J/\psi\pi^-K^+$

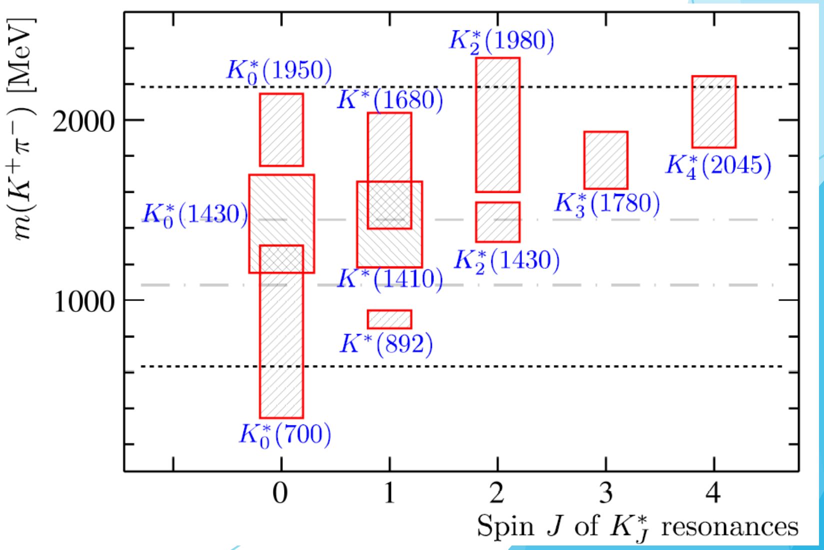
Motivation

- $Z_c(4430)^-$ state discovered by Belle in $Z_c(4430)^- \to \psi(2S)\pi^-$ (Phys.Rev.Lett.100,142001(2008))
  - not confirmed by BaBar (Phys.Rev.D79,112001(2009))
  - confirmed by LHCb (Phys.Rev.Lett.112,222002(2014))
- $Z_c(4430)^- \to J/\psi\pi^-$ not yet confirmed
  - Belle finds evidence for $Z_c(4430)^- \to J/\psi\pi^-$ in $B^0 \to J/\psi\pi^-K^+$, and also observed a new state $Z_c(4200)^- \to J/\psi\pi^-$ (Phys.Rev.D90,112009(2014))



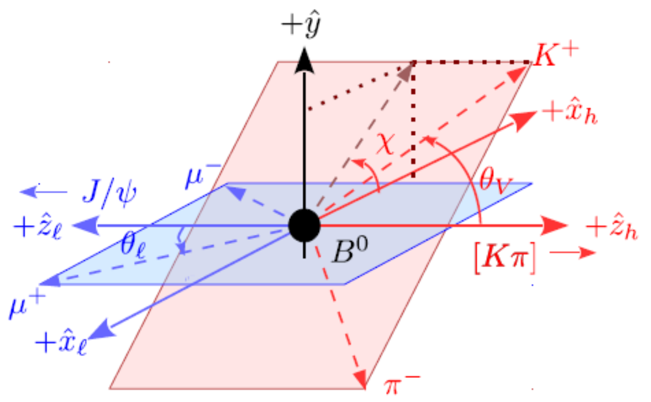
Analysis strategy

- Large statistics of ~5×10^5 events allow independent fits in bins over $m(K^+\pi^-)$
- Purity > 90% in all $m(K^+\pi^-)$ bins
- Poor knowledge of the conventional K^{*0} spectrum
- Use a model-independent approach only requiring knowledge of the J_{max} (highest spin of K^{*0} contributions)

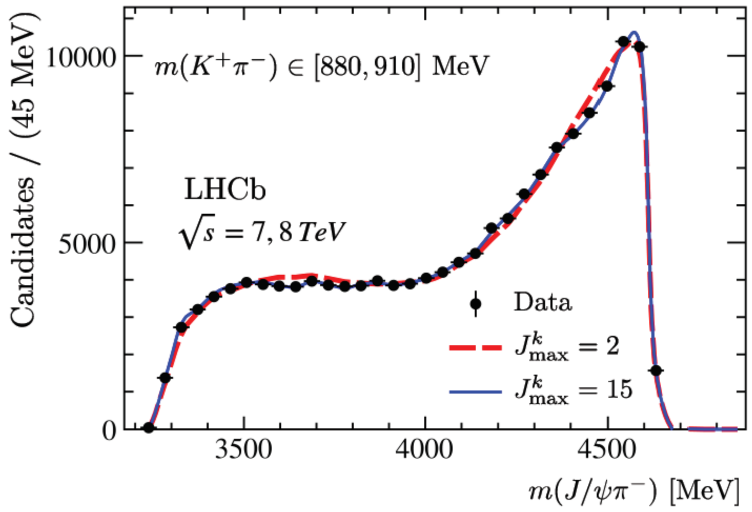


Exotic contributions to $B^0 \to J/\psi\pi^- K^+$

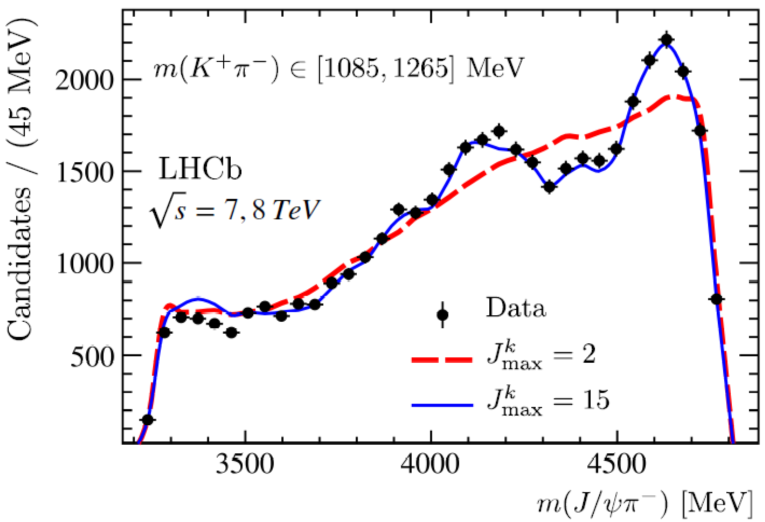
- Kinematic variables: $m(K^+\pi^-)$, χ, θ_l, θ_V
- 3D angular fits in bins of $m(K^+\pi^-)$
- Fit model includes only K^{*0} contributions with allowed J up to J_{max}
- Fine $m(K^+\pi^-)$ binning: conclusion is independent of K^{*0} line shapes



Region dominated by the $K^*(892)^0$



Outside $K^*(892)^0$ region

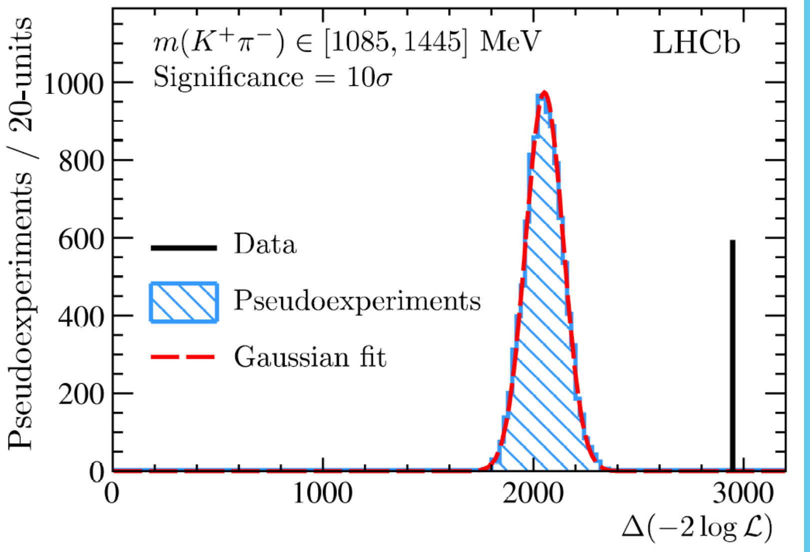


Need unphysical J_{max}=15 to describe data.

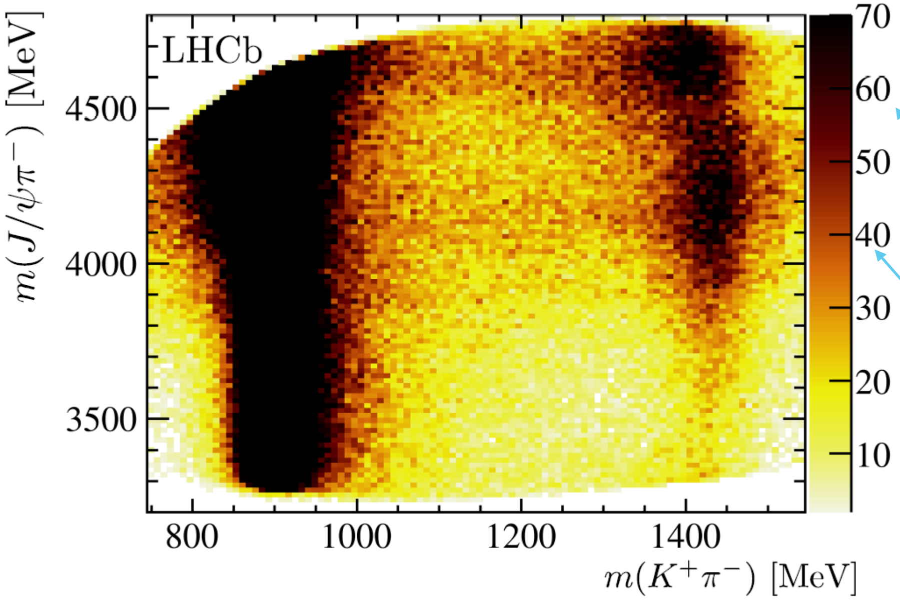
Observation of exotic contributions in a model-independent way

Exotic contributions to $B^0 \to J/\psi \pi^- K^+$

- The likelihood ratio test demonstrates that data reject K^{*0} only hypothesis with 10σ significance



Dalitz plot for background-subtracted data



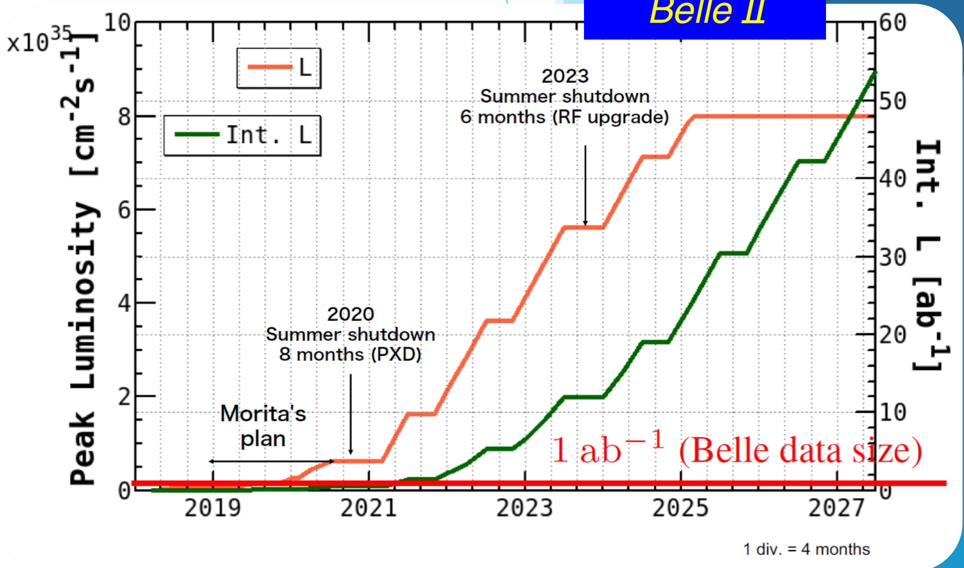
- **Some structure at $m(J/\psi\pi^-) \approx 4600$ MeV/c^2**
- **Indications of the $Z(4200)^-$ seen by Belle**

The nature of the non-K^{*0} contributions can be investigated with a future amplitude analysis

Summary

- The LHCb experiment provides a significant contribution to the knowledge of exotic hadron spectroscopy:
  - Search for beautiful tetraquarks $X_{b\bar{b}b\bar{b}} \to \Upsilon(1S)\mu^+\mu^-$, upper limit is set
  - Evidence for an $\eta_c(1S)\pi^-$ resonance in $B^0 \to \eta_c(1S)\pi^- K^+$ decays
  - Model-independent observation of exotic contributions to $B^0 \to J/\psi\pi^- K^+$ decays
- Analyses in Belle still ongoing:
  - Searches for partner states
  - Different production mechanisms (ISR vs. B decays vs. Υ decays)
  - Absolute branching fraction
  - Searches for Z_c pair production
- Belle II has started taking data!
  - Huge new data sample will be used to study exotic states

Thank you!



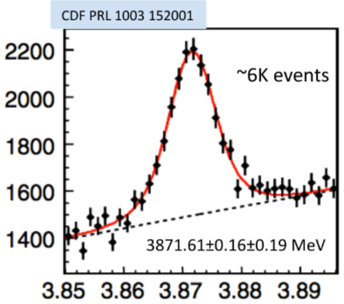
- Backup

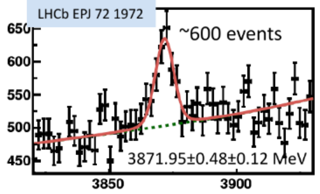
How exotic?
X(3872) as an example

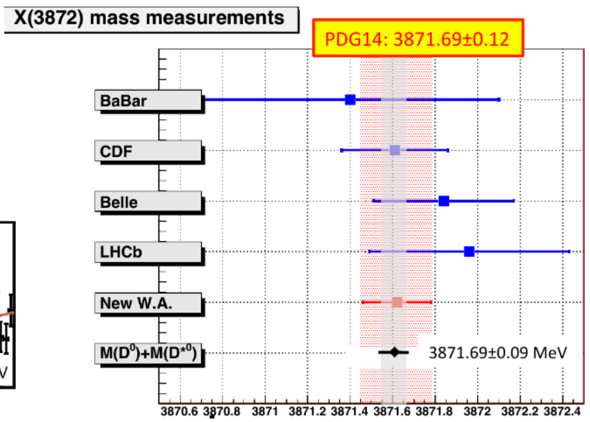
- $J^{PC} = 1^{++}$
- Strong coupling to DD*
- No charged or neutral partner observed
  - Coupled channel, good description
    - PTEP9, 093D01(2013)

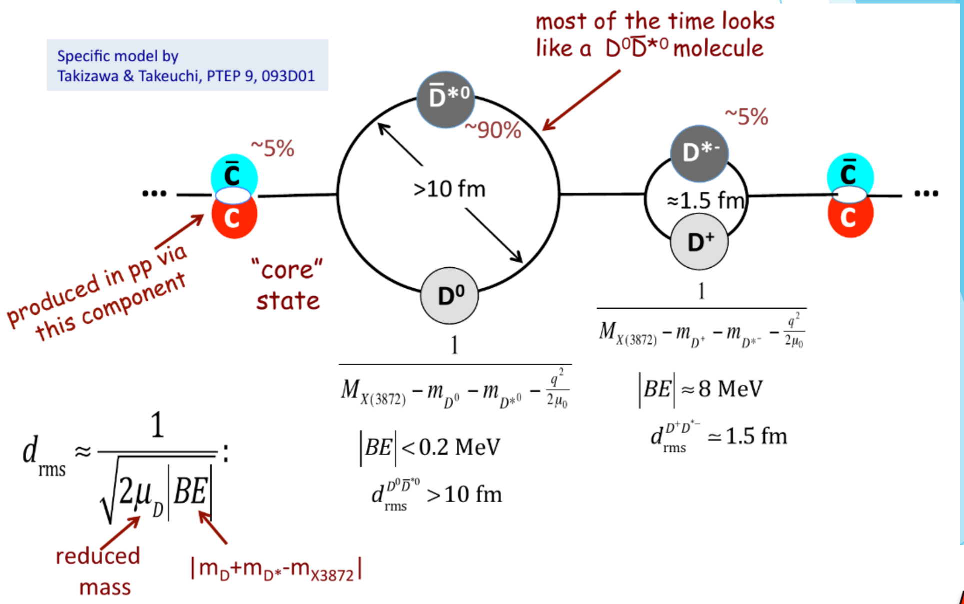
$M_{X(3872)}$ is indistinguishable from $m_{D0} + m_{D*0}$

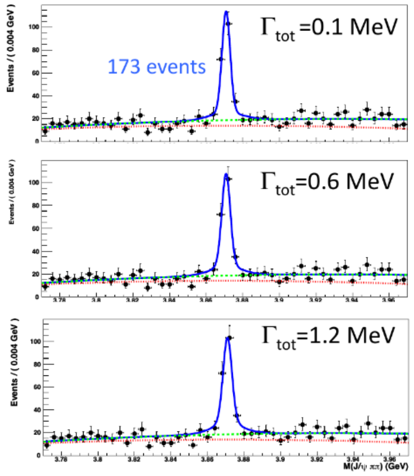
"B.E."=3 ± 193 keV



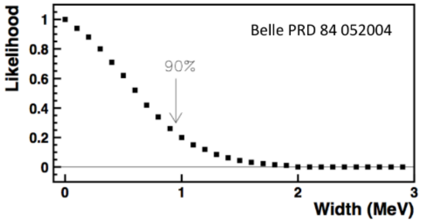








$$\frac{1}{(m-m_0)^2+(\Gamma/2)^2}\otimes \exp\left(-\frac{(m-m_0)^2}{2\sigma^2}\right)$$



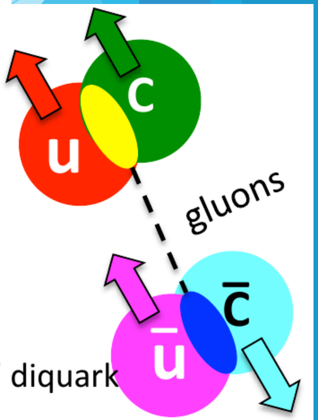
Γ_{tot}<1.2 MeV

For comparison: $\Gamma_{\chi c1}$ = 0.84+0.04 MeV

- Or QCD diquark-diantiquark
  - Maiani et al., PRD71, 014028(200!
  - No 1^{++} partner state seen

Spin=1 "bad" diquark

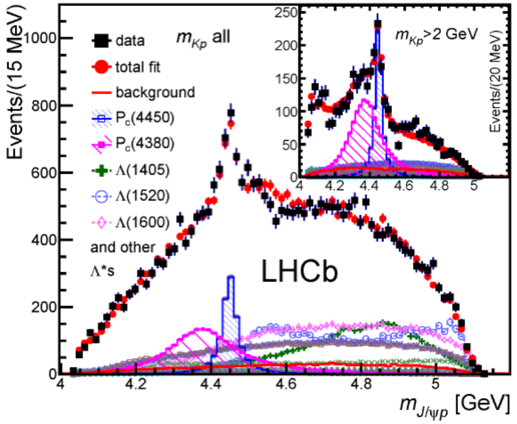
Spin=0 "good" diquark



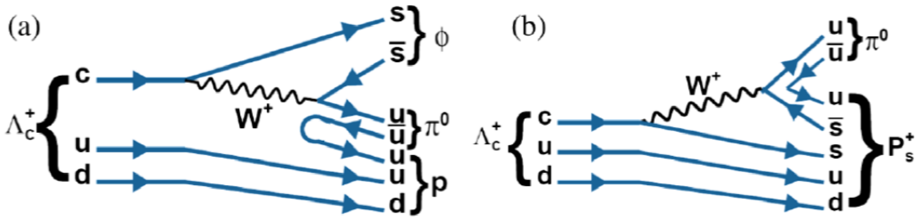
Search for a strange pentaquark P_s state at Belle

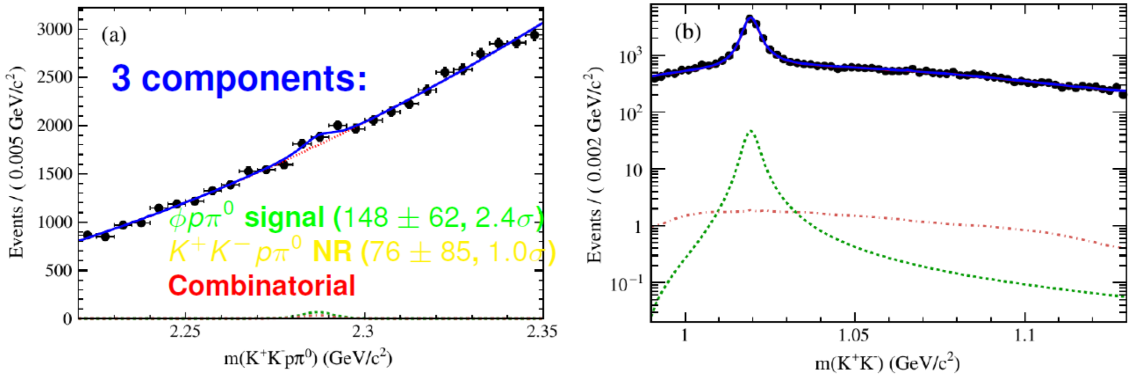
- LHCb observed hidden charm pentaquark state in $\Lambda_b^0 \to K^- P_c^+ \to K^-(J/\psi p)$.

R. Aaij et al., PRL115, 072002(2015)

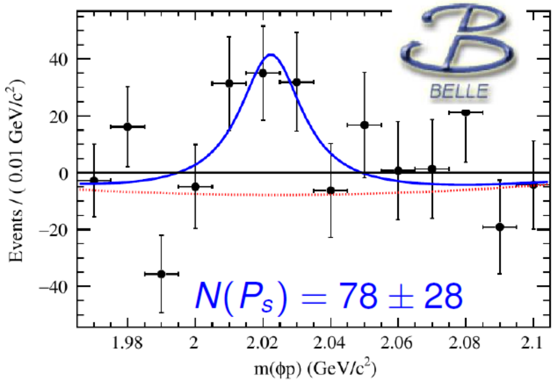


- Analogue search for hidden-strange pentaquark by switching $b \to c(\Lambda_b^0 \to \Lambda_c^+)$, $c \to s(J/\psi \to \phi)$: $\Lambda_c^+ \to \pi^0 P_s^+ \to \pi^0(\phi p)$.
- $\Lambda_c^+ \to \pi^0 \phi p$ decay has not been observed so far.





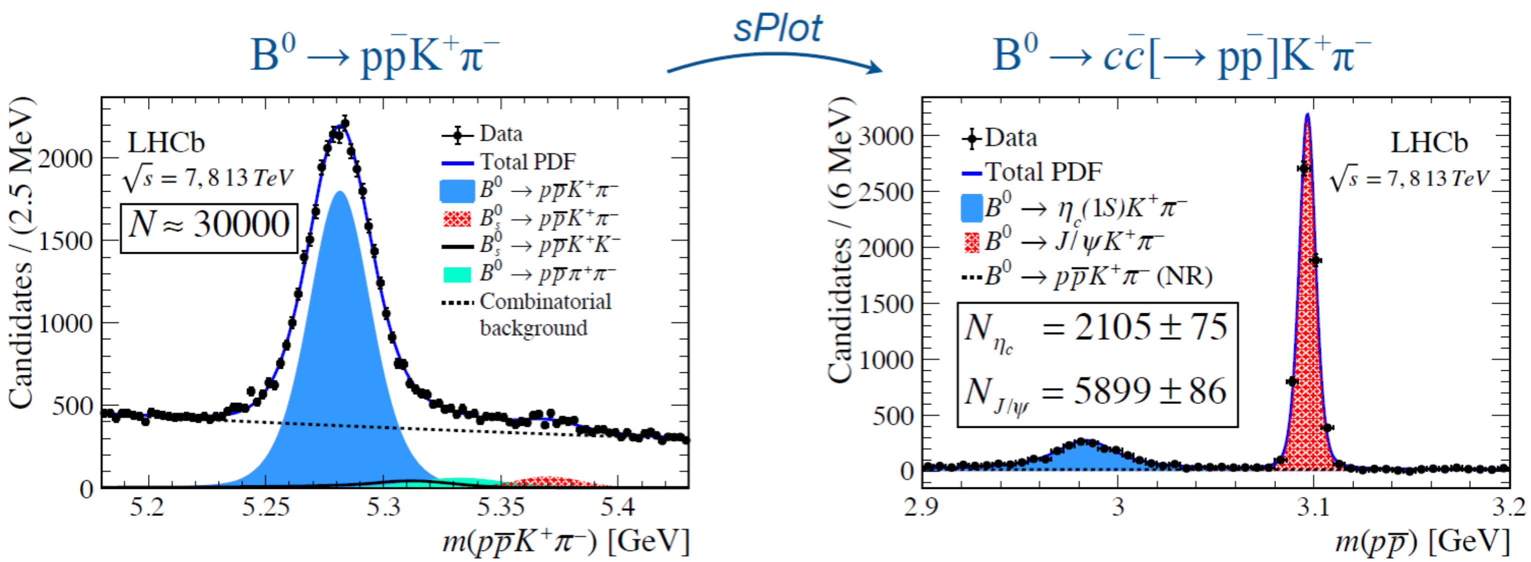
- Perform 2D fit to $M_{K^+K^-p\pi^0}$ vs $M_{K^+K^-}$ plane.



- No significant Λ_c^+ signal is observed. New upper limits:
  - $\mathcal{B}(\Lambda_c^+ \to \phi p \pi^0) < 15.3 \times 10^{-5}$
  - $\mathcal{B}(\Lambda_c^+ \to \phi p \pi^0)_{NR} < 6.3 \times 10^{-5}$
- Also perform 2D fit in each $M_{K^+K^-}$ bin. No significant P_s^+ signal.
  - $\mathcal{B}(\Lambda_c^+ \to \pi^0 P_s^+) \times \mathcal{B}(P_s^+ \to \phi p) < 8.3 \times 10^{-5}$.

B. Pal *et al.*, Phys.Rev.D96, 051102(R)(2017)

$\eta_c\pi^-$ resonance in $B^0 \to \eta_c\pi^-K^+$ decays



- Reconstruction using $\eta_c \to p\bar{p}$ mode
- Normalization decay: $B^0 \to J/\psi[\to p\bar{p}]\ \pi^-K^+$
- Reconstruction and selection efficiencies largely cancel in the ratio

- Data of 4.7fb^{-1} collected in
  - - 2011@7TeV,
  - - 2012@8TeV,
  - - 2016@13TeV

Branching fraction

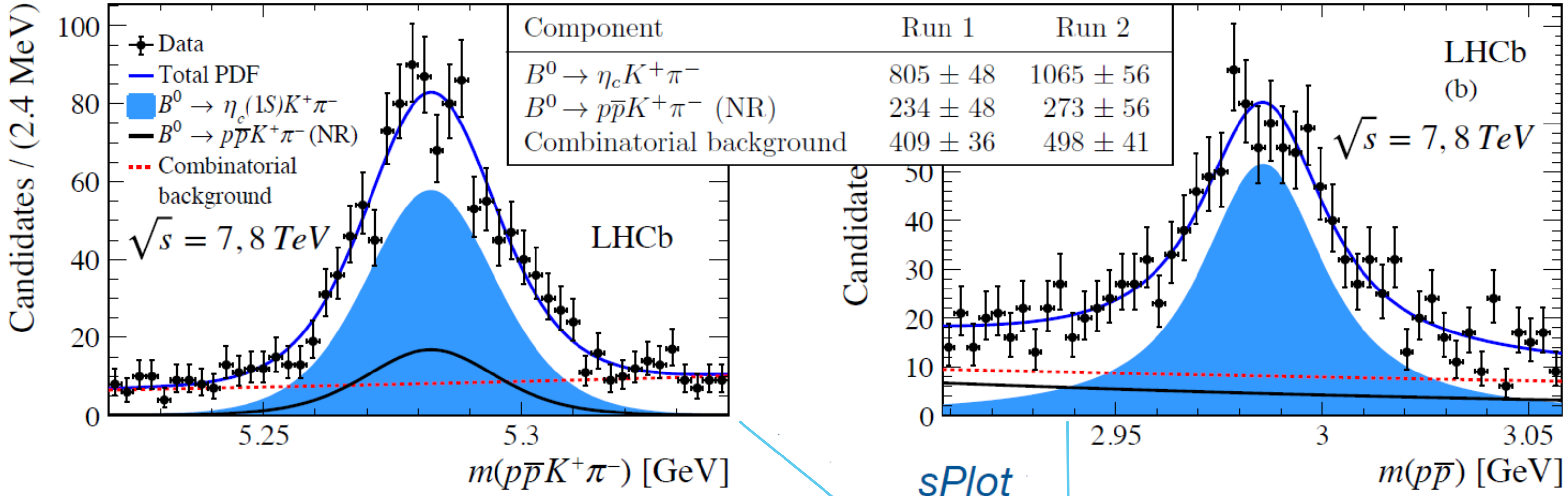
$$\mathcal{B}(B^0 \to \eta_c\pi^-K^+) = (5.73 \pm 0.24\,(stat) \pm 0.13\,(syst) \pm 0.66)\times 10^{-4}$$

Dominant uncertainty from external branching fractions

Eur.Phys.J. C78,1019(2018)

$\eta_c\pi^-$ resonance in $B^0 \to \eta_c\pi^-K^+$ decays

2D fit $m(p\bar{p}K^+\pi^-)$-$m(p\bar{p})$ for Run-I and Run-II



Component	Run 1	Run 2
$B^0 \to \eta_c K^+\pi^-$	805 ± 48	1065 ± 56
$B^0 \to p\bar{p}K^+\pi^-$ (NR)	234 ± 48	273 ± 56
Combinatorial background	409 ± 36	498 ± 41

sPlot

Dalitz plot analysis

- Fit model: signal + non-resonant + combinatorial
- Decay amplitude: sum of resonant $K^+\pi^-$ + nonresonant processes
- Six K^{*0} resonances give significant contributions
- Exotic $Z_c(4100)^- \to \eta_c\pi^-$ contribution added to improve the fit