Hadron Spectroscopy

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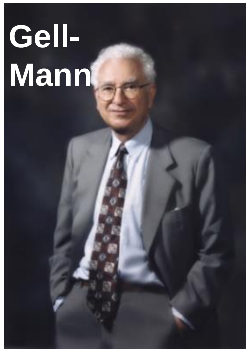


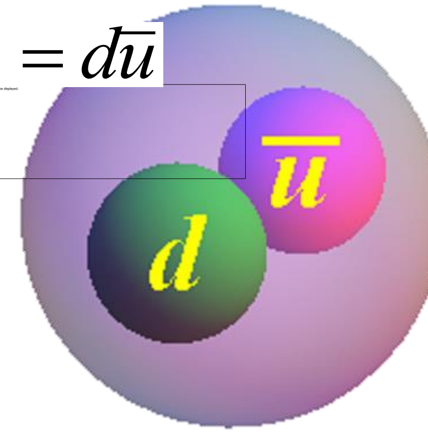
Constituent Quark Model

<u>Mesons</u> are bound states of quark and anti-quark:

$$\pi^+ = u\bar{d} \quad \pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) \quad \pi^- = d\bar{u}$$

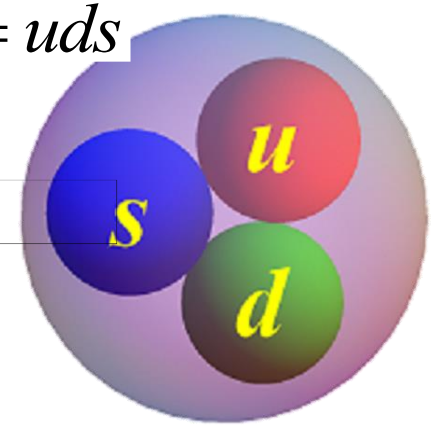
$$K^+ = u\bar{s} \quad K^0 = d\bar{s} \quad \bar{K}^0 = s\bar{d} \quad K^- = s\bar{u}$$

$$\pi^- = d\bar{u}$$



<u>Baryons</u> are bound states of 3 quarks:

$$\Lambda = uds$$



$$p = uud \quad n = udd \quad \Lambda = uds$$

$$\bar{p} = \bar{u}\bar{u}\bar{d} \quad \bar{n} = \bar{u}\bar{d}\bar{d} \quad \bar{\Lambda} = \bar{u}\bar{d}\bar{s}$$

Quarkonium Basics

c, b -quarks are heavy:

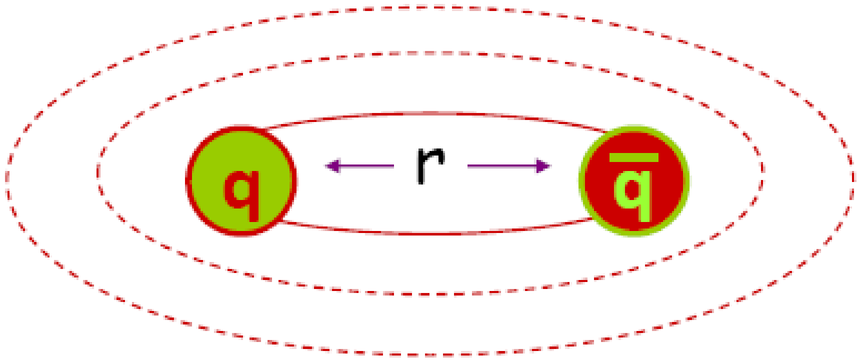
m_c ~ 1.5 GeV ~1.6 m_p ;

m_b ~ 4.5 GeV ~4.8 m_p ;

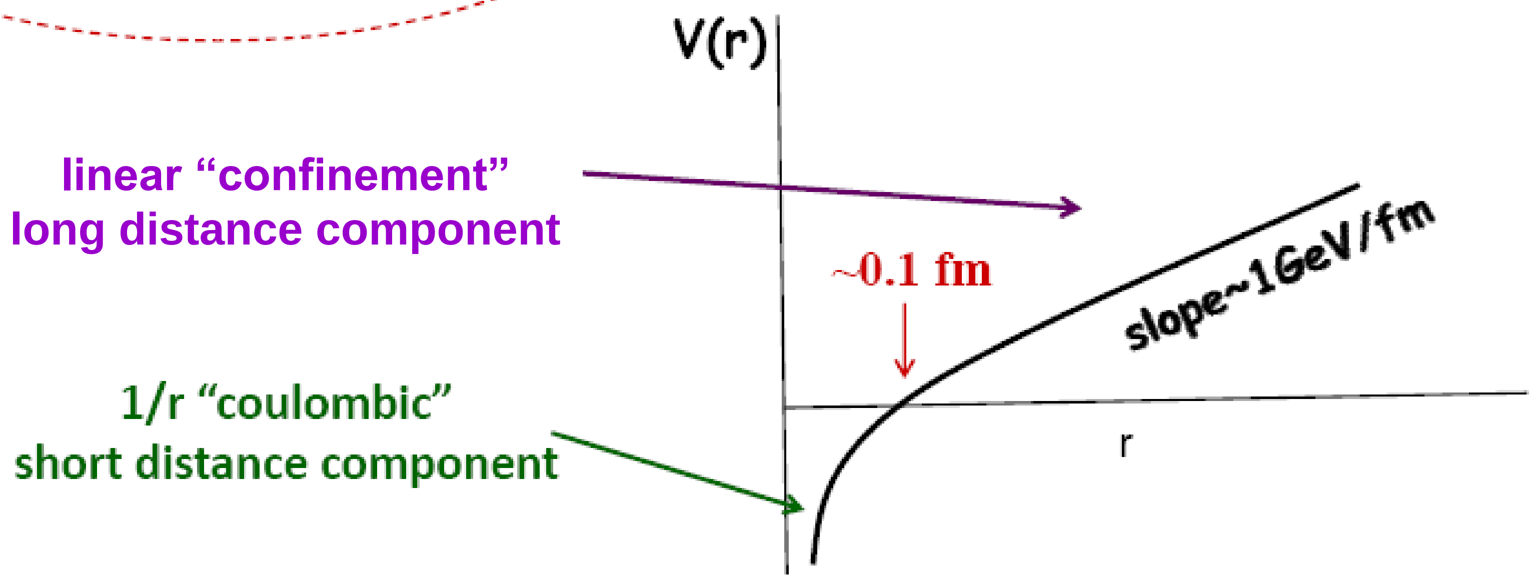
velocities are small:

v/c~1/4 (for $b\bar{b}$, v/c~0.1)

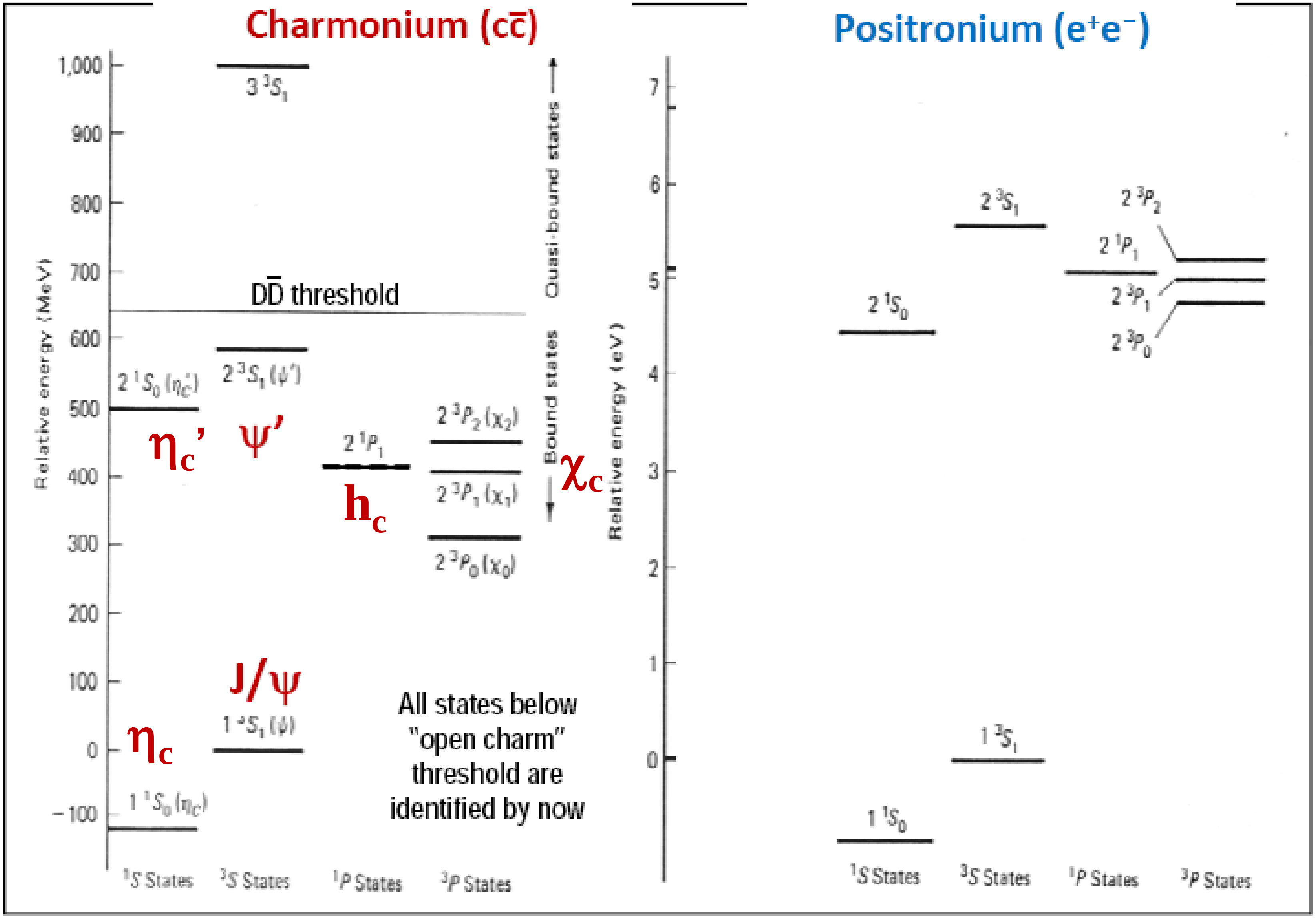
non-relativistic QM applies



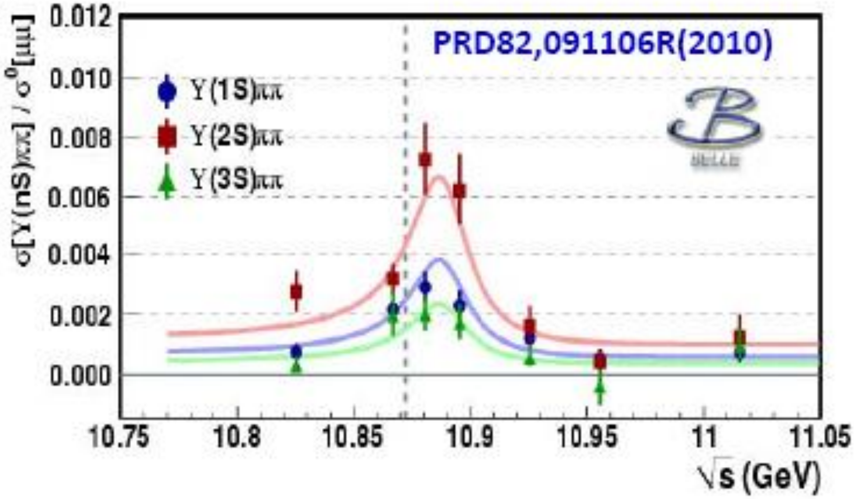
$$-\frac{\hbar^2}{2m_r}\nabla^2\Psi + V(r)\Psi = E\Psi$$

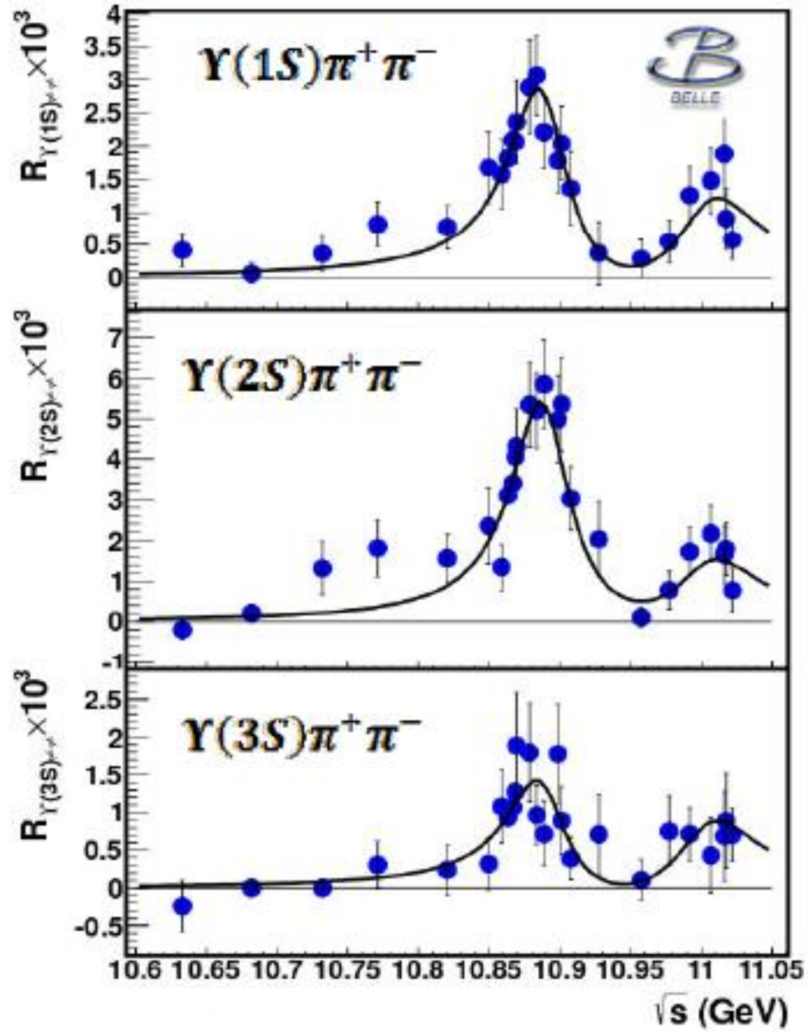


Quarkonium vs Positronium



Anomalous $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ Rates





hep-ex :1501.01137

Υ(10680):

$$M(\Upsilon(10680)) = 10891.1 \pm 3.2^{+0.6}_{-1.5}\ \mathrm{MeV}/c^2$$

$$\Gamma(\Upsilon(10680)) = 53.7^{+7.1+0.9}_{-5.6-5.4}\ \mathrm{MeV}$$

Υ(11020):

$$M(\Upsilon(11020)) = 10987.5^{+6.4+9.0}_{-2.5-2.1}\ \mathrm{MeV}/c^2$$

$$\Gamma(\Upsilon(11020)) = 61^{+9}_{-19}{}^{+2}_{-20}\ \mathrm{MeV}$$

$$\Delta\phi = -1 \pm 0.4^{+1.0}_{-0.1}\ \mathrm{rad}$$

Energy dependence of $h_b(1P,2P)\pi^+\pi^-$

Υ(10680):

$$M(\Upsilon(10680)) = 10884.7^{+3.2\,+8.6}_{-2.9\,-0.6}\ \mathrm{MeV}/c^2$$

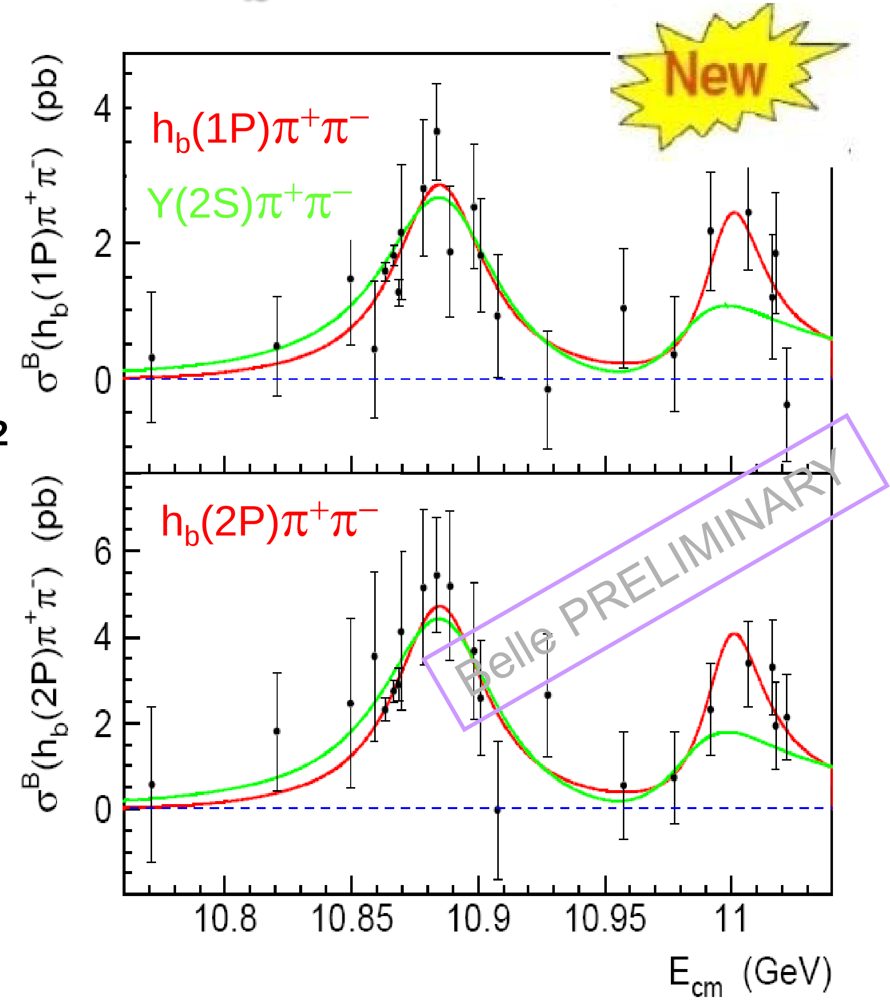
$$\Gamma(\Upsilon(10680)) = 44.2^{+11.9\,+2.2}_{-7.8\,-15.8}\ \mathrm{MeV}$$

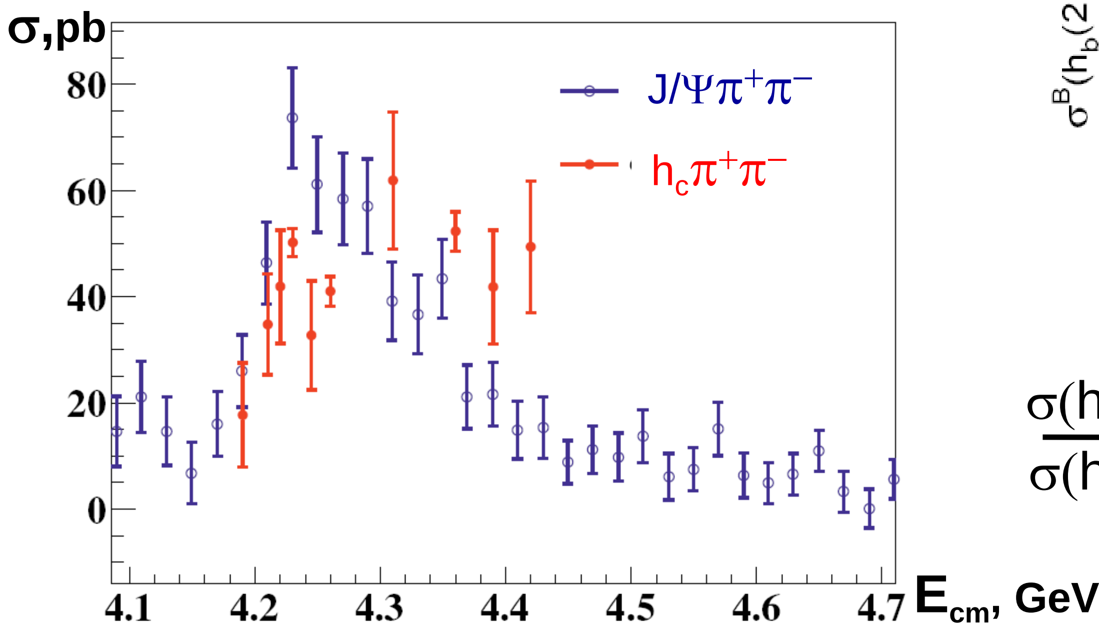
Υ(11020):

$$M(\Upsilon(11020)) = 10998.6 \pm 6.1^{+16.1}_{-1.1}\ \mathrm{MeV}/c^2$$

$$\Gamma(\Upsilon(11020)) = 29^{+20\,+2}_{-12\,-7}\ \mathrm{MeV}$$

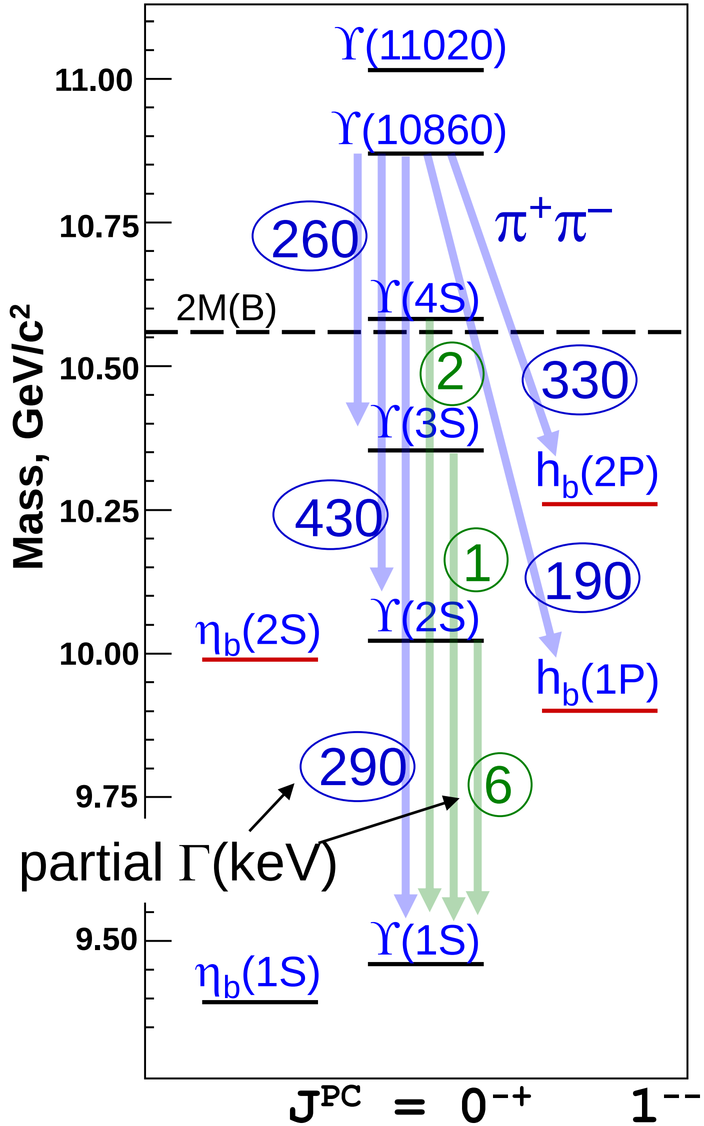
$$\Delta\phi = 0.3^{+1.0}_{-1.5}\ \mathrm{rad.}$$





$$\frac{\sigma(h_c\pi\pi)}{\sigma(h_b\pi\pi)} = \frac{m^2_{\Upsilon(5S)}\, q_c^2\, \Gamma_{\Upsilon(5S)}}{m^2_{Y(4260)}\, q_b^2\, \Gamma_{Y(4260)}} \sim 7$$

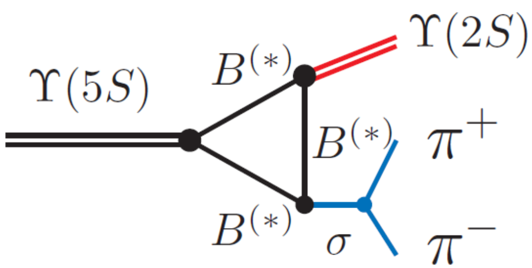
Anomalies in $\Upsilon(5S)\to(b\bar{b})\pi^+\pi^-$ transitions



Belle: PRL100, 112001 (2008)

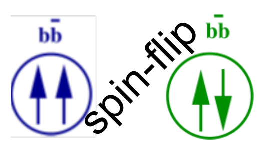
$$\Gamma[\Upsilon(\mathbf{5S})\to\Upsilon(1,2,3S)\,\pi^+\pi^-] \overset{\sim 100}{>>} \Gamma[\Upsilon(\mathbf{4,3,2S})\to\Upsilon(1S)\,\pi^+\pi^-]$$

$\Leftarrow$ Rescattering of on-shell $B^{(*)}\bar{B}^{(*)}$?



Belle: PRL108, 032001 (2012)

> **$\Upsilon(5S)\to h_b(1,2P)\,\pi^+\pi^-$ are not suppressed**



expect suppression $\sim\Lambda_{QCD}/m_b$

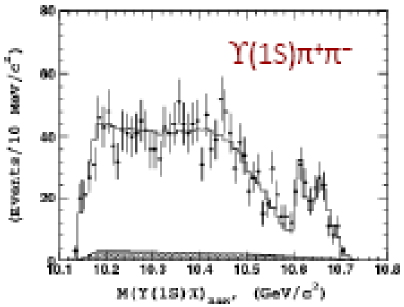
~~Heavy Quark Symmetry~~

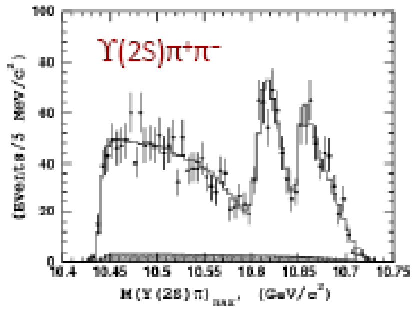
h_b production mechanism? $\Rightarrow$ Study resonant structure in $h_b(mP)\pi^+\pi^-$

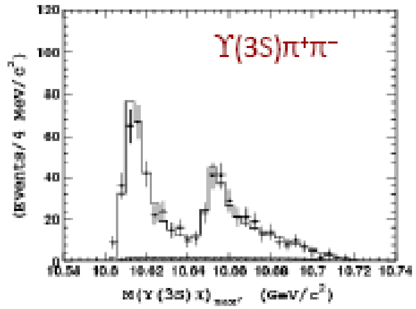
Properties of $Z_b(10610)$ & $Z_b(10650)$

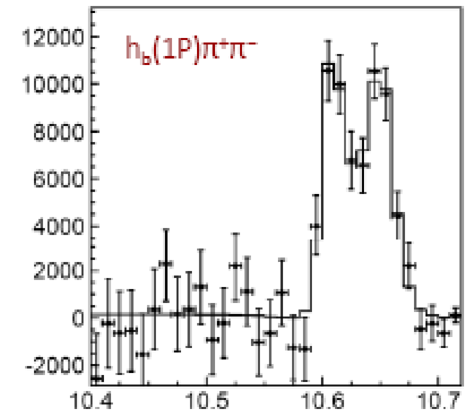
$Z_b^{\pm}$ Observed in five different modes:

PRL 108, 122001(2012)

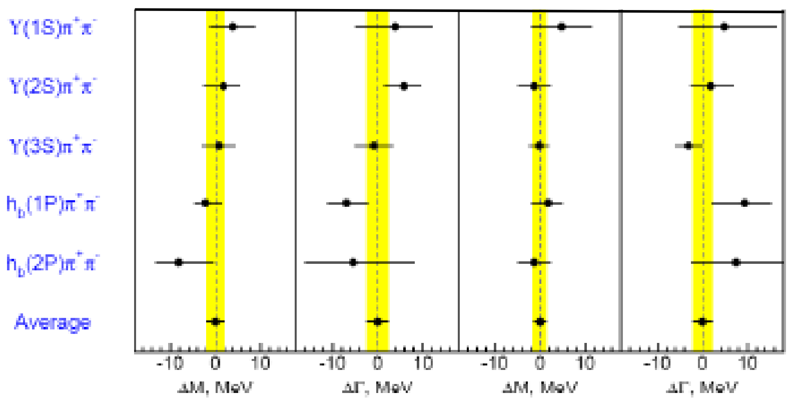








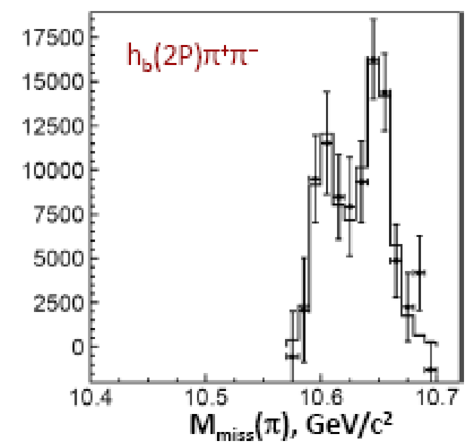
$Z_b(10610)$ $Z_b(10650)$



Average for $Z_b^{\pm}$:

$$\langle M_1 \rangle = 10607.2 \pm 2.0 \text{ MeV}$$
$$\langle \Gamma_1 \rangle = 18.4 \pm 2.4 \text{ MeV}$$

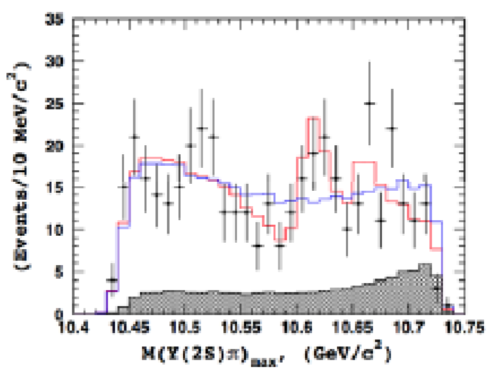
$$\langle M_2 \rangle = 10652.2 \pm 1.5 \text{ MeV}$$
$$\langle \Gamma_2 \rangle = 11.5 \pm 2.2 \text{ MeV}$$



Z_b^0 Results:

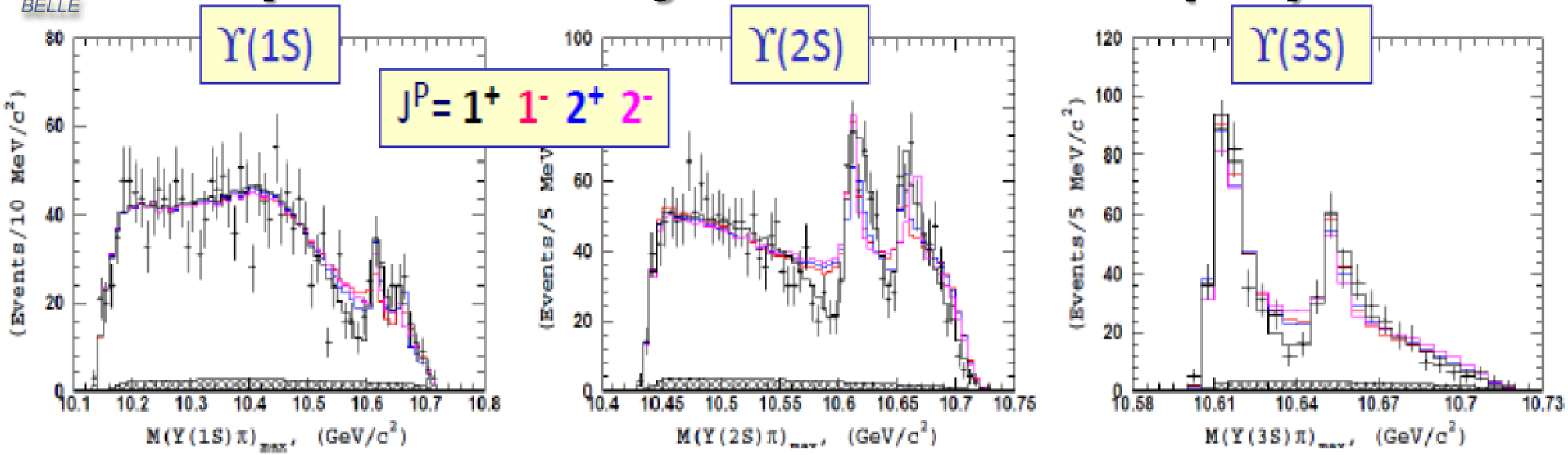
$$\langle M_1 \rangle = 10609 \pm 7 \pm 6 \text{ MeV}$$

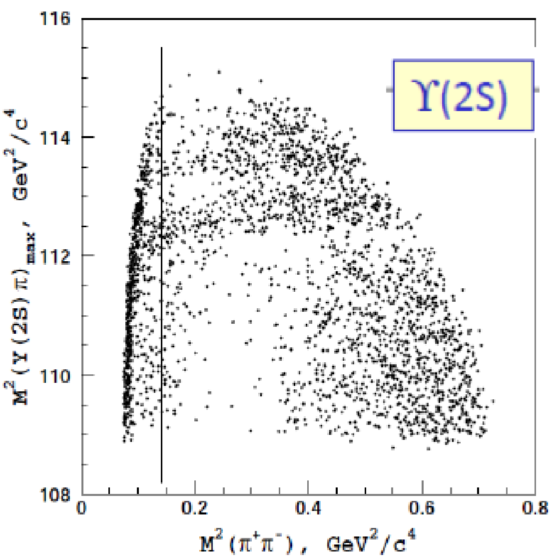
Consistent with $Z_b^{\pm}$



$M_1 - M_B - M_{B*} = 2.36 \pm 2.1$ MeV
$M_2 - M_{B*} - M_{B*} = 1.8 \pm 1.75$ MeV

Amplitude analysis of $e^+e^- \to Y(nS)\pi^+\pi^-$





$Z_b(10610)$ \ $Z_b(10650)$	1^+	1^-	2^+	2^-
1^+	0 (0)	60 (33)	42 (33)	77 (63)
1^-	226 (47)	264 (73)	224 (68)	277 (106)
2^+	205 (33)	235 (104)	207 (87)	223 (128)
2^-	289 (99)	319 (111)	321 (110)	304 (125)

Spin-parity of Zb(10610) and Zb(10650) is 1^+.
All other J^P<3 are excluded.

Belle: PRD 91,072003 (2015)

Molecule?

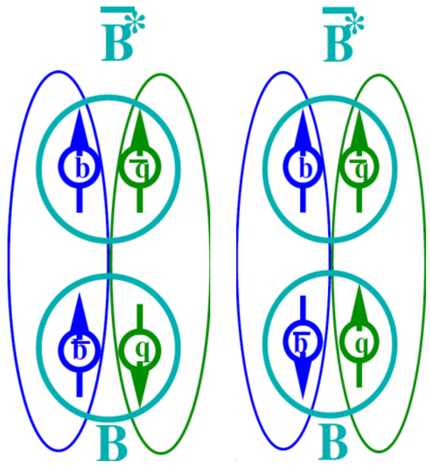
Heavy quark structure in Z_b

A.B.,A.Garmash,A.Milstein,R.Mizuk,M.Voloshin PRD84 054010 (arXiv:1105.4473)

Wave func. at large distance – B(*)B*

$$\left|Z_b'\right\rangle = \frac{1}{\sqrt{2}} 0^-_{bb} \otimes 1^-_{Qq} - \frac{1}{\sqrt{2}} 1^-_{bb} \otimes 0^-_{Qq}$$

$$\left|Z_b\right\rangle = \frac{1}{\sqrt{2}} 0^-_{bb} \otimes 1^-_{Qq} + \frac{1}{\sqrt{2}} 1^-_{bb} \otimes 0^-_{Qq}$$



Explains

- Why $h_b\pi\pi$ is unsuppressed relative to $\Upsilon\pi\pi$
- Relative phase ~0 for Υ and ~180^0 for h_b
- Production rates of Z_b(10610) and Z_b(10650) are similar
- Widths –”–
- Dominant decays to B(*)B*

Other Possible Explanations

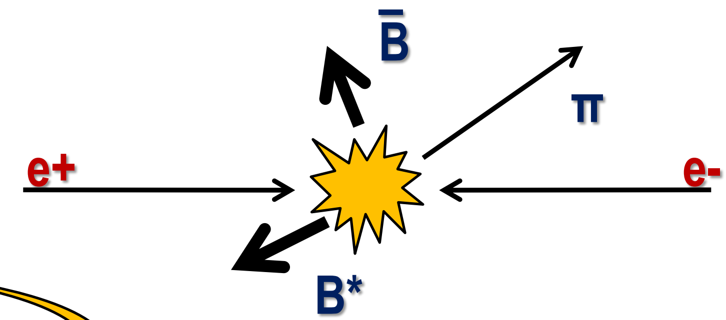
- Coupled channel resonances (I.V.Danilkin et al, arXiv:1106.1552)
- Cusp (D.Bugg Europhys.Lett.96 (2011),arXiv:1105.5492)
- Tetraquark (M.Karliner, H.Lipkin, arXiv:0802.0649)

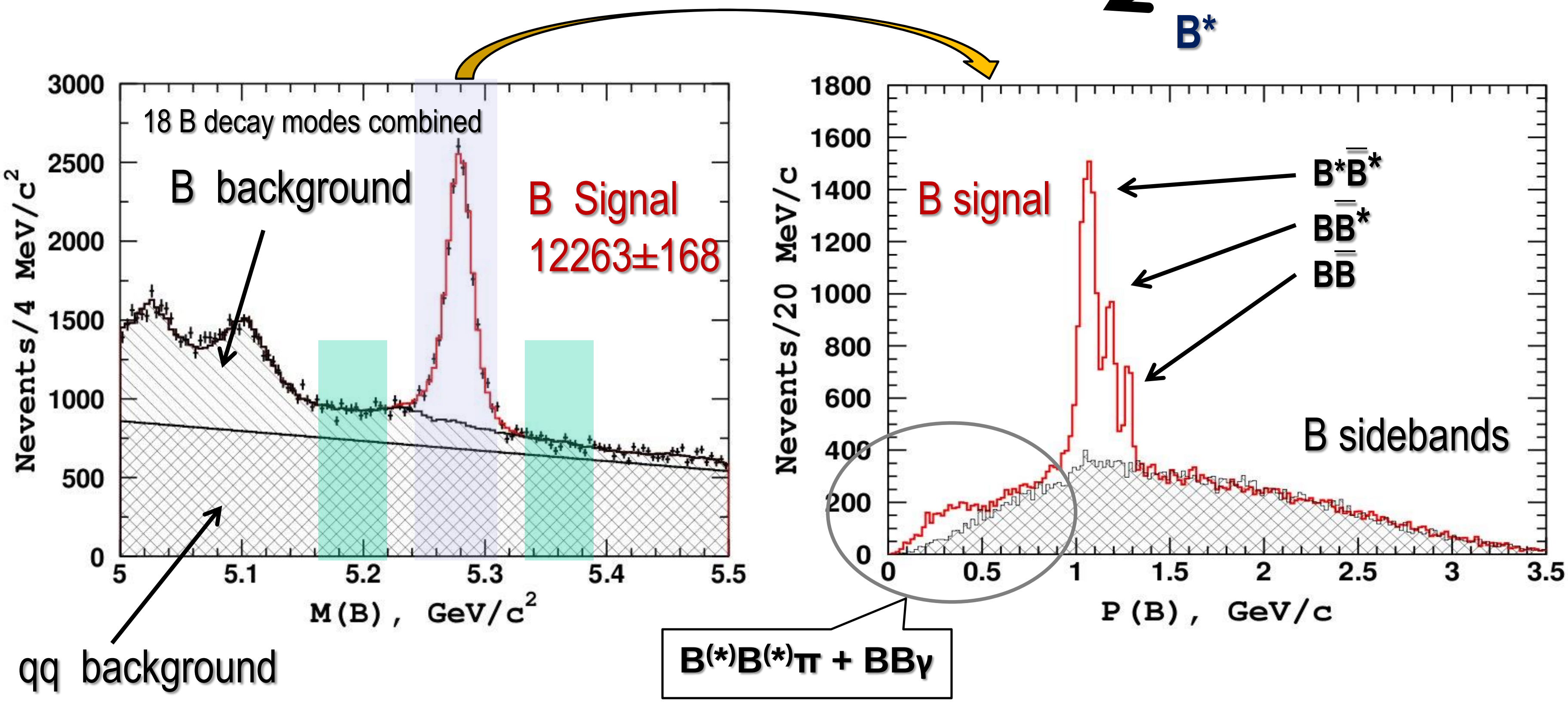
$\Upsilon(5S) \to Z_b\,\pi^{\pm}$

Masses of the observed Z_b resonances are close to the BB* and B*B* thresholds, respectively: branching fractions $Z_b \to B^{(*)}B^*$ might be large (dominant).

Analysis strategy:

- Full reconstruction of one B meson

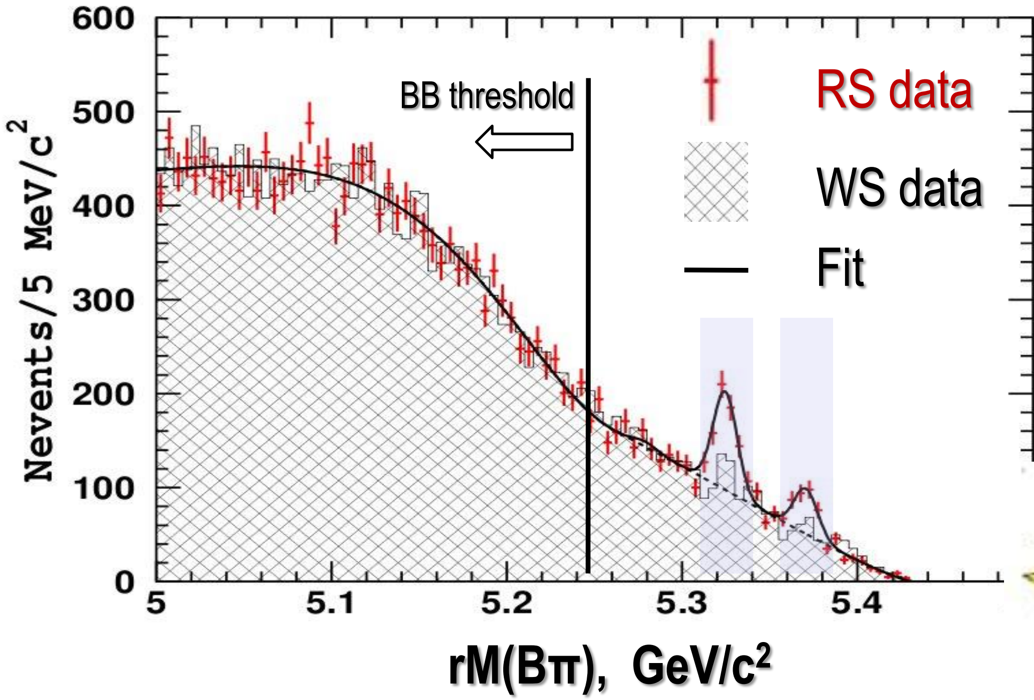


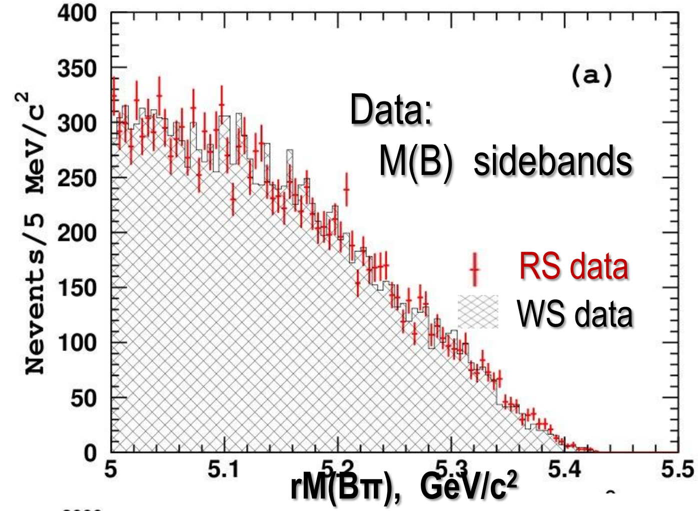


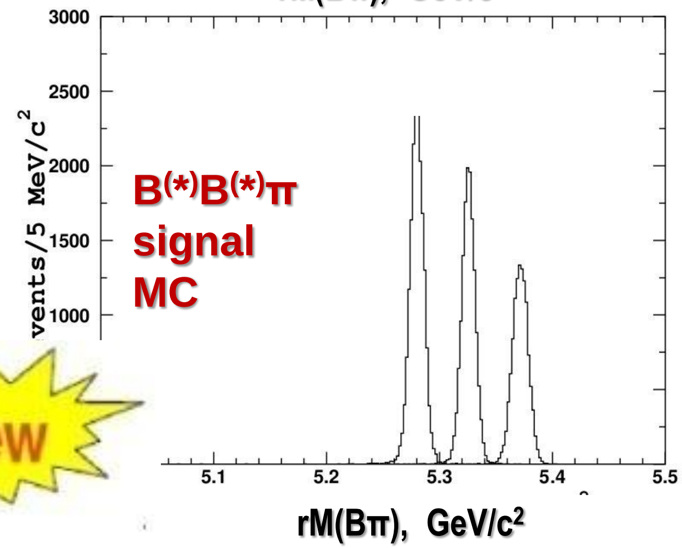
$\Upsilon(5S)\to Z_b\,\pi^{\pm}$

Analysis strategy:

- Combine the B with a charged pion from the rest of the event → calculate recoil mass against the Bπ system







New

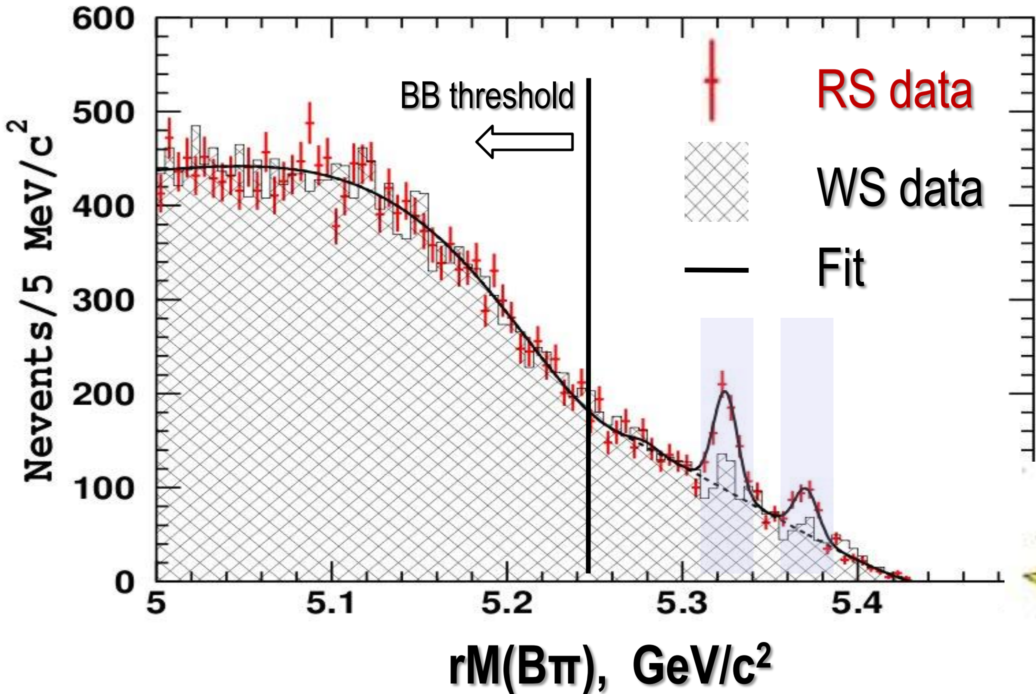
$N(BB\pi) = 13 \pm 25$
$N(BB^{(*)}\pi) = 357 \pm 30$
$N(B^{(*)}B^{(*)}\pi) = 161 \pm 21$

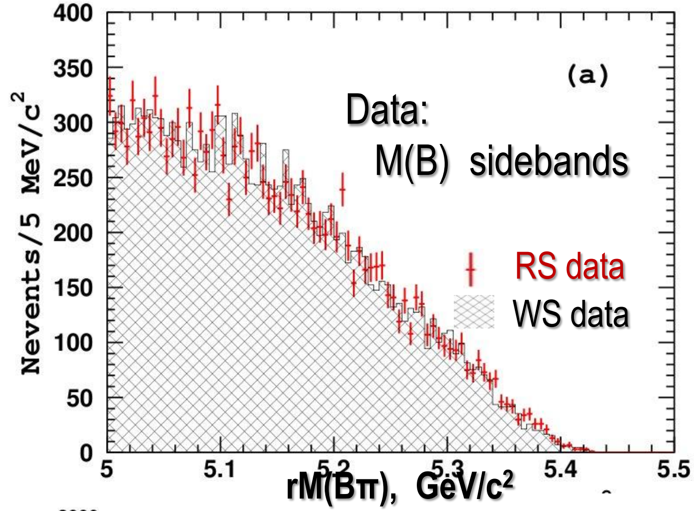
$\sigma(e^+e^-\to BB\pi) <$
$\sigma(e^+e^-\to BB^{(*)}\pi) =$
$\sigma(e^+e^-\to B^{(*)}B^{(*)}\pi) =$

$\Upsilon(5S) \to Z_b \pi^{\pm}$

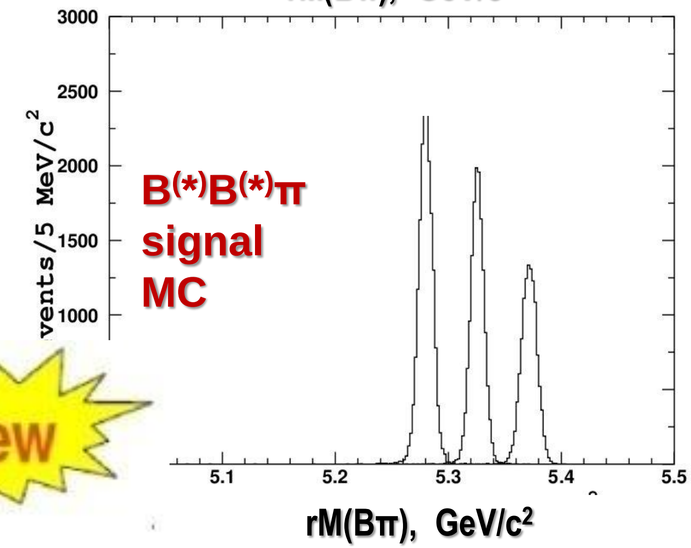
Analysis strategy:

- Combine the B with a charged pion from the rest of the event → calculate recoil mass against the Bπ system





New



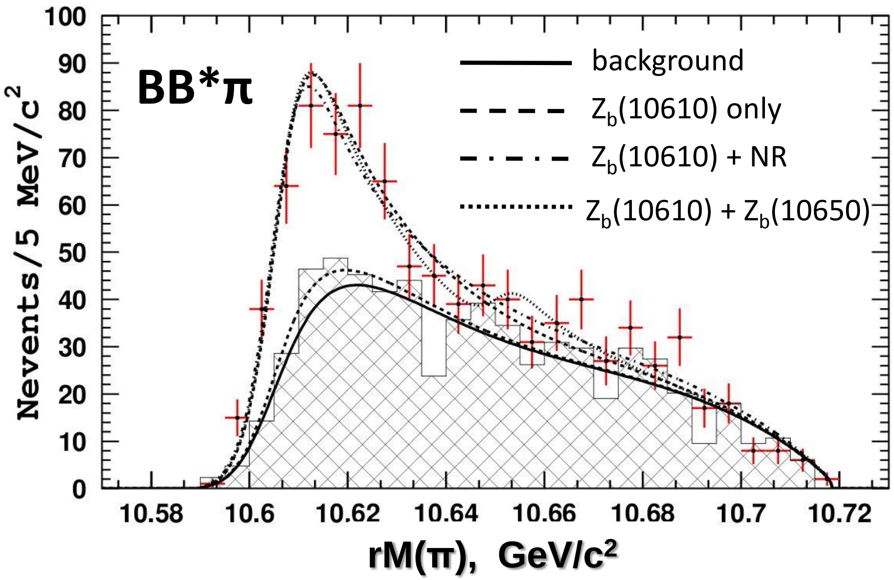
N(BBπ) = 13 ± 25
N(BB(*)π) = 357 ± 30
N(B(*)B(*)π) = 161 ± 21

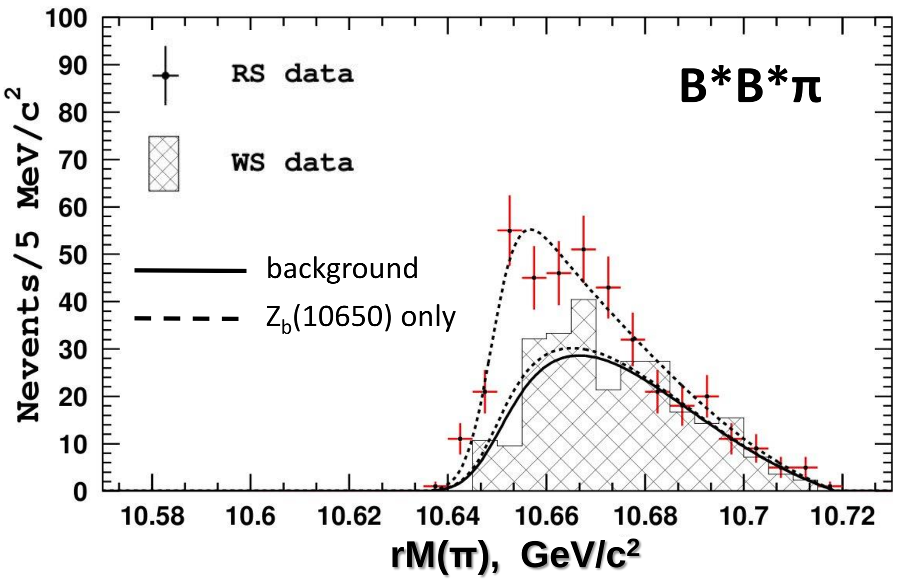
σ(e+e−→BBπ
σ(e+e−→BB(*)π
σ(e+e−→ B(*)B(*)π

Oops… Sorry, Belle Collaboration is not ready yet to show official numbers.

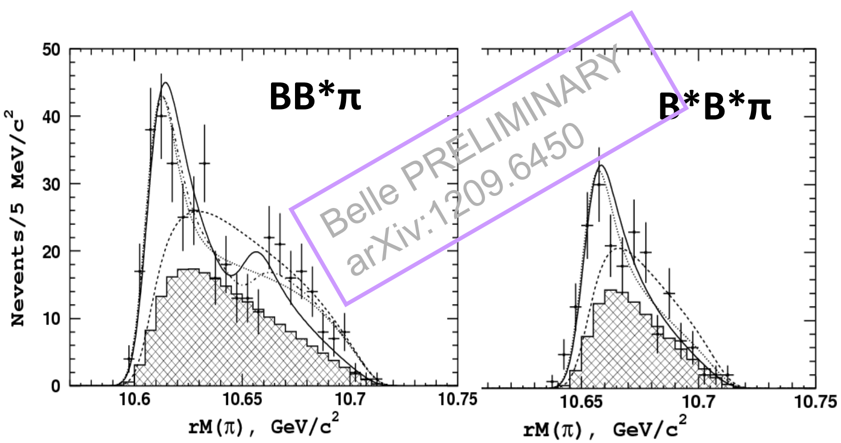
$\Upsilon(5S)\rightarrow Z_b\,\pi^{\pm}$

- For events from 3-body sig. region → recoil mass against primary $\pi^{\pm}$





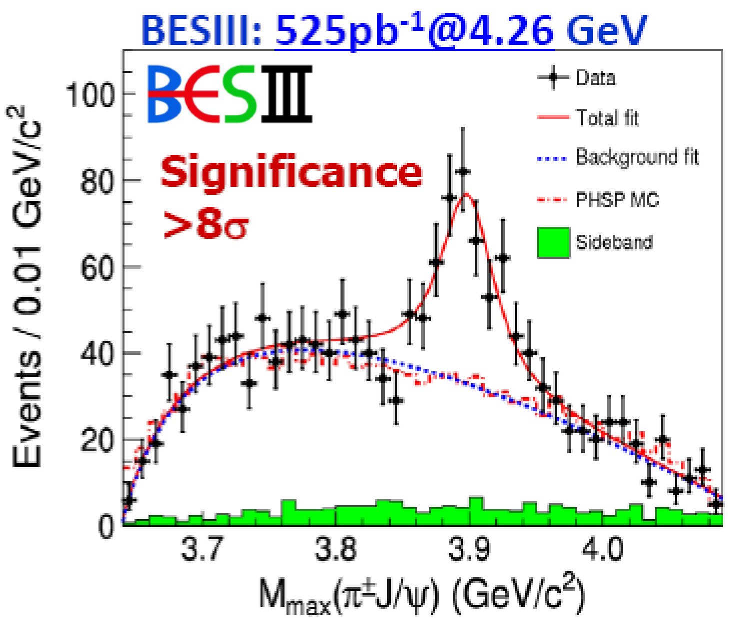
BB*π and B*B*π data fits well to just $Z_b(10610)$ and $Z_b(10650)$ signal, respectively

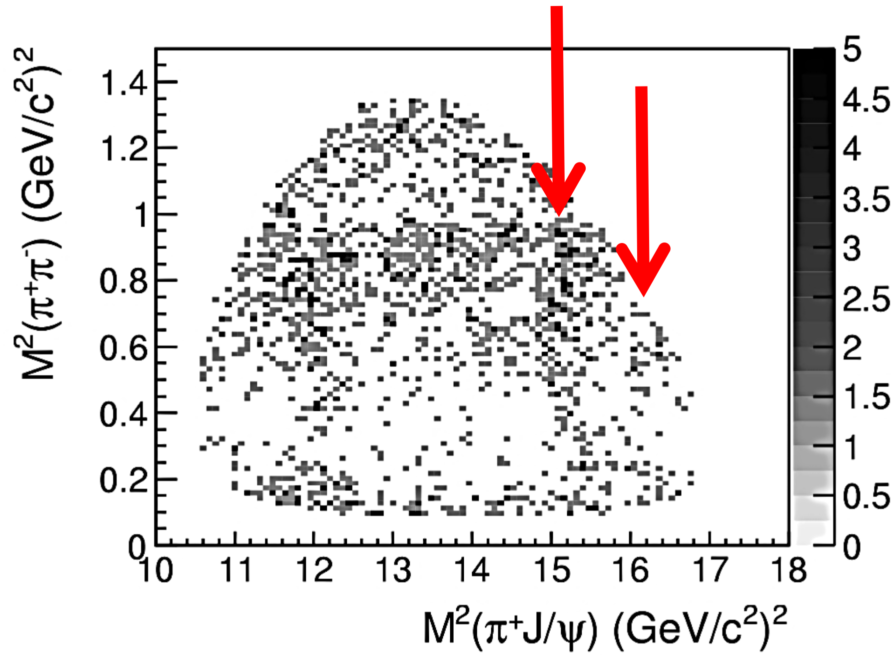


Assuming Z_b decays are saturated by already observed channels

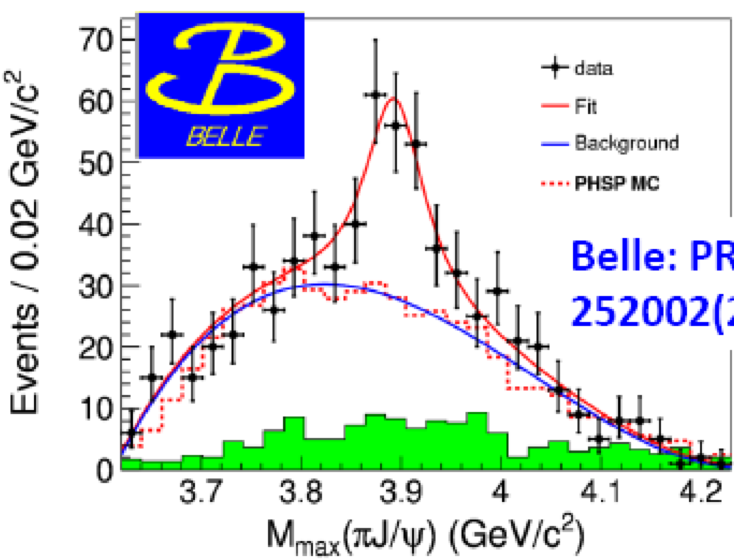
$B^{(*)}B^*$ channels dominate the Z_b decays

Observation of $Z_c(3900)$ at BESIII & Belle





BESIII: PRL110, 252001 (2013)



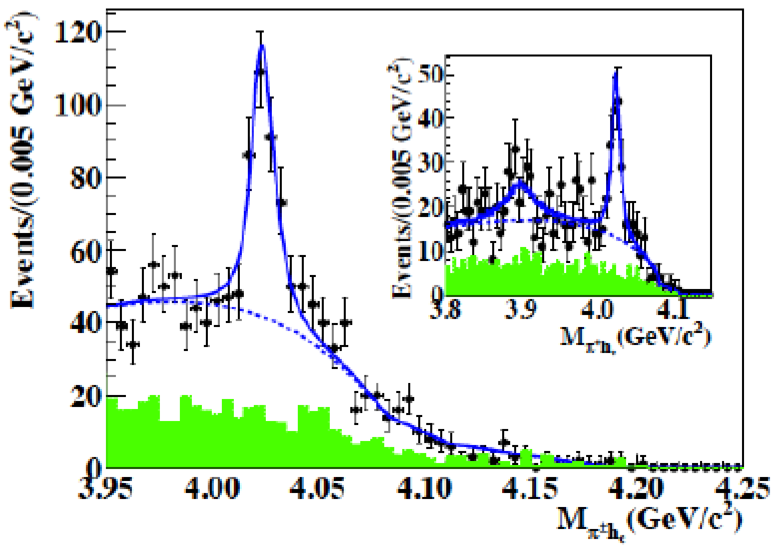
Belle: PRL 110, 252002(2013)

- $M = 3899.0 \pm 3.6 \pm 4.9$ MeV
- $\Gamma = 46 \pm 10 \pm 20$ MeV
- 307 ± 48 events

The mass position is 24 MeV away from DD* threshold!

Observation of $Z_c(4020)$ in $e^+e^- \rightarrow h_c\pi^+\pi^-$

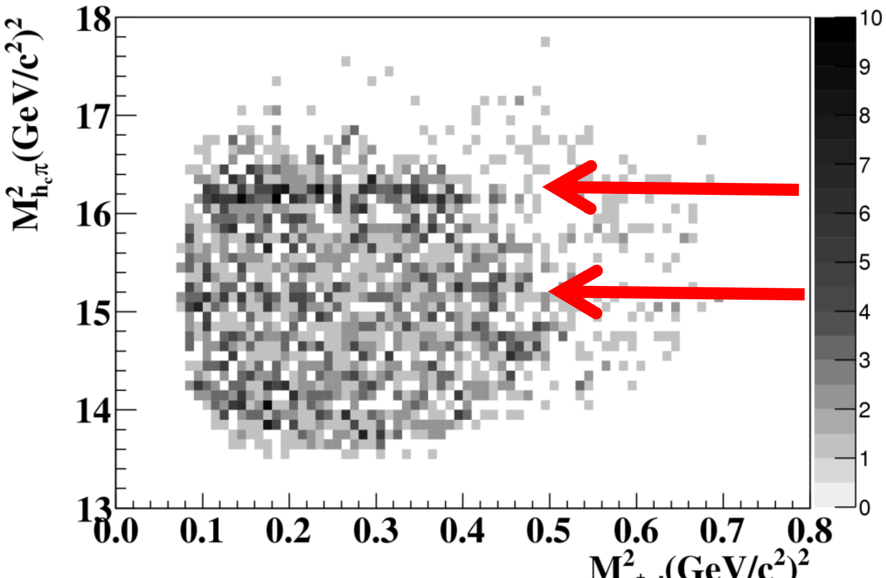
BESIII: PRL 111, 242001 (2013)



Simultaneous fit to 4.23/4.26/4.36 GeV data, 16 η_c decay modes.

$M = 4022.9 \pm 0.8 \pm 2.7$ MeV/c^2

$\Gamma = 7.9 \pm 2.7 \pm 2.6$ MeV

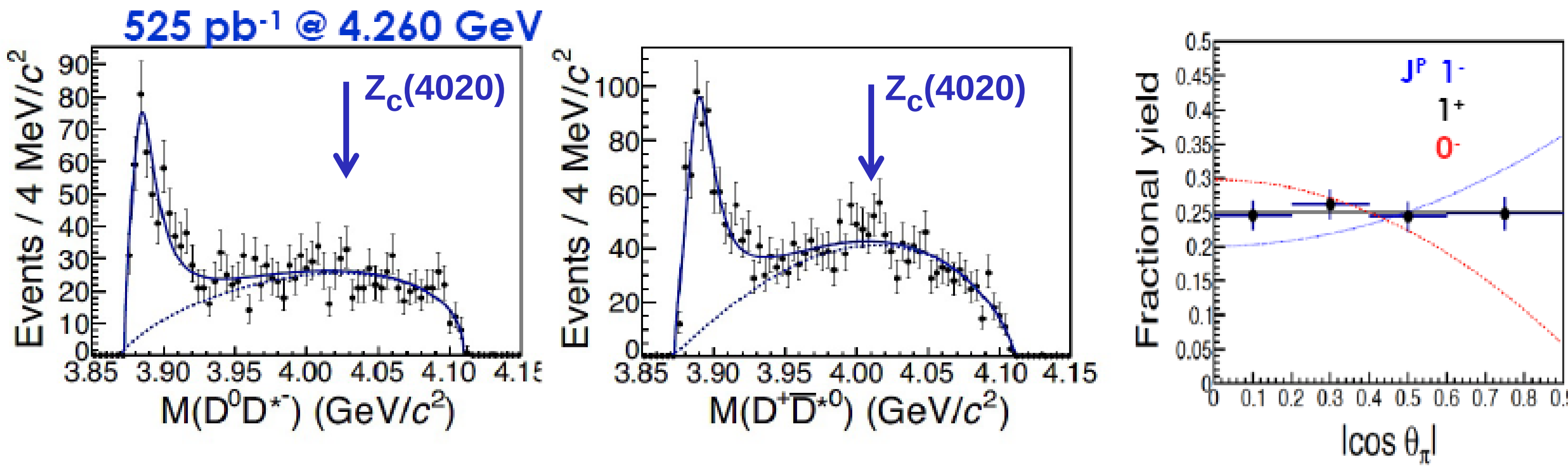


Significance: 8.9σ ($Z_c(4020)$)

No significant $Z_c(3900)$ (2.1σ)

Observation of $Z_c(3885)$ in e^+e^- -> $\pi^-(D^*D)^+$

BESIII: PRL 112, 022001 (2014)



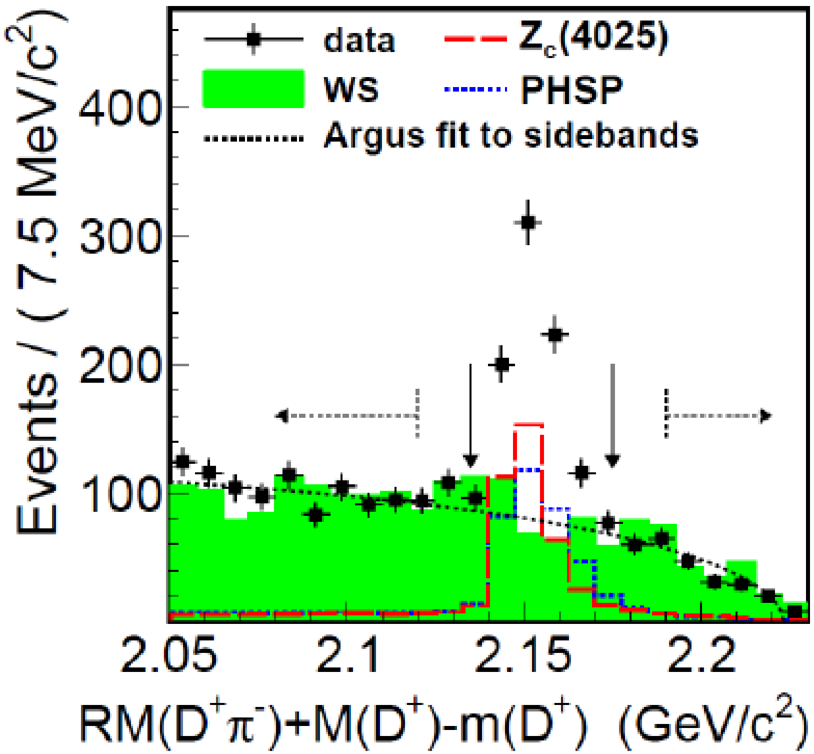
- $M = 3883.9 \pm 1.5 \pm 4.2$ MeV; $\Gamma = 24.8 \pm 3.3 \pm 11.0$ MeV
- $\sigma \times B = 85.3 \pm 6.6 \pm 22.0$ pb
- **fits favor 1^+ distribution assumption**

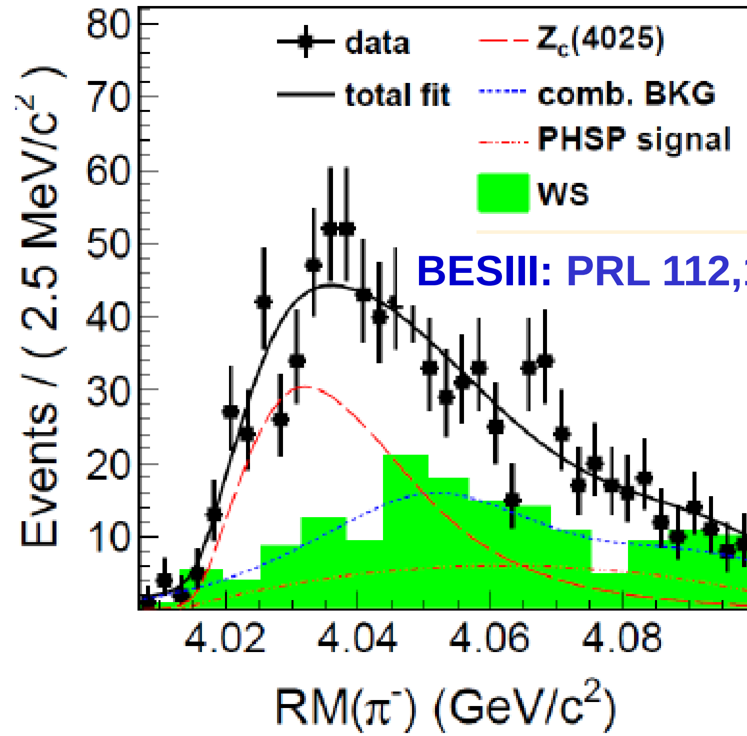
fit with mass-dependent-width BW with phase space and efficiency correction

$$\frac{\Gamma(Z_c(3885) \to D\bar{D}^*)}{\Gamma(Z_c(3900) \to \pi J/\psi)} = 6.2 \pm 1.1 \pm 2.7$$

Assuming $Z_c(3885)$ due to $Z_c(3900)$

Observation of $Z_c(4025)$ in $e^+e^- \to \pi^-(D^*D^*)^+$





BESIII: PRL 112,132001(2014)

Fit to $\pi^\pm$ recoil mass yields 401±47 $Z_c(4025)$ events. **>10σ**

$M(Z_c(4025)) = 4026.3 \pm 2.6 \pm 3.7$ MeV; $\Gamma(Z_c(4025)) = 24.8 \pm 5.6 \pm 7.7$ MeV

$$\sigma(e^+e^- \to \pi^\pm(D^*\bar{D}^*)^\mp) = (137 \pm 9 \pm 15)\ \text{pb}$$

$$R = \frac{\sigma(e^+e^- \to \pi^\pm Z_c^\mp(4025) \to \pi^\pm(D^*\bar{D}^*)^\mp)}{\sigma(e^+e^- \to \pi^\pm(D^*\bar{D}^*)^\mp)} = (65 \pm 9 \pm 6)\%$$

Summary of the Z_c states

Channel	Mass (MeV/c^2)	Width (MeV)
$\pi^{\pm}J/\psi$	$3899.0\pm3.6\pm4.9$	$46\pm10\pm20$
$(D\bar{D}^*)^{\pm}$	$3883.9\pm1.5\pm4.2$	$24.8\pm3.3\pm11.0$
	2σ difference	1σ difference
$\pi^{\pm}h_c$	$4022.9\pm0.8\pm2.7$	$7.9\pm2.7\pm2.6$
$(D^*\bar{D}^*)^{\pm}$	$4026.3\pm2.6\pm3.7$	$24.8\pm5.6\pm7.7$
	1σ difference	2σ difference

Close to $D\bar{D}^*$ threshold (3875 MeV)

Close to $D^*\bar{D}^*$ threshold (4017 MeV)

- Near threshold, but all the measurements are the results of 1D fits without interference, to be improved by amplitude analysis;
- Couple to $D^*D^{(*)}$ final states stronger than to final states with charmonium;
- Necessary to measure the energy dependence of the $Z_c\pi^+$ production cross-sections;
- As well as $D^{(*)}D^*\pi$;

Bottomonium-like vs Charmonium-like states

- Z_b are very close to $\bar{B}B^*$, $B^*\bar{B}^*$ threshold
- $I^G J^{P(C)} = 1^+ \, 1^{+\,(-)}$
- Observed both in the hidden-bottom modes: $\pi\Upsilon$(1S,2S,3S), $\pi\, h_b$(1P,2P) and open-bottom modes: $\bar{B}B^*$, $B^*\bar{B}^*$
- $B^{(*)}\bar{B}^*$ dominate Z_b decays with the branching ratio 86% and 73%
- Energy behaviors $h_b(mP)\pi\pi$ and $\Upsilon(nS)\pi\pi$ are similar

- Z_c are very close to $\bar{D}D^*$, $D^*\bar{D}^*$ threshold
- $I^G J^{P(C)} = 1^+ \, 1^{+\,(-)}$
- Observed both in the hidden-charm modes: $\pi\, J/\psi$, $\pi\, h_c$ and open-charm modes: $\bar{D}D^*$, $D^*\bar{D}^*$
- $\bar{D}D^*$ dominates $Z_c(3900)$ decay; $\bar{D}^*D^*$ dominates $Z_c(4020)$
- no $Z_c(3900)$ decay to $\pi\, h_c$?
- no $Z_c(4020)$ decay to $\pi\, J/\psi$?
- Energy behaviors $h_c\pi\pi$ and $J/\psi\, \pi\pi$ are different

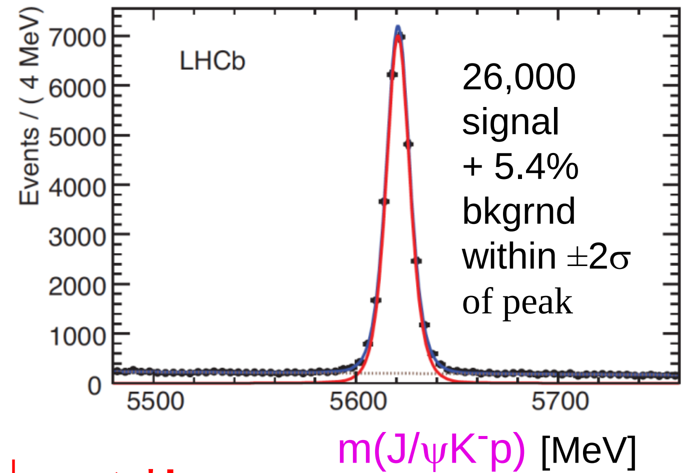
Z_b properties agree well with $B^{(*)}\bar{B}^*$ molecular structure, while in case of Z_c the situation is still unclear (masses too far above thresholds, no $J/\Psi\, \pi^+$ at D^*D^* threshold)

Pentaquark?

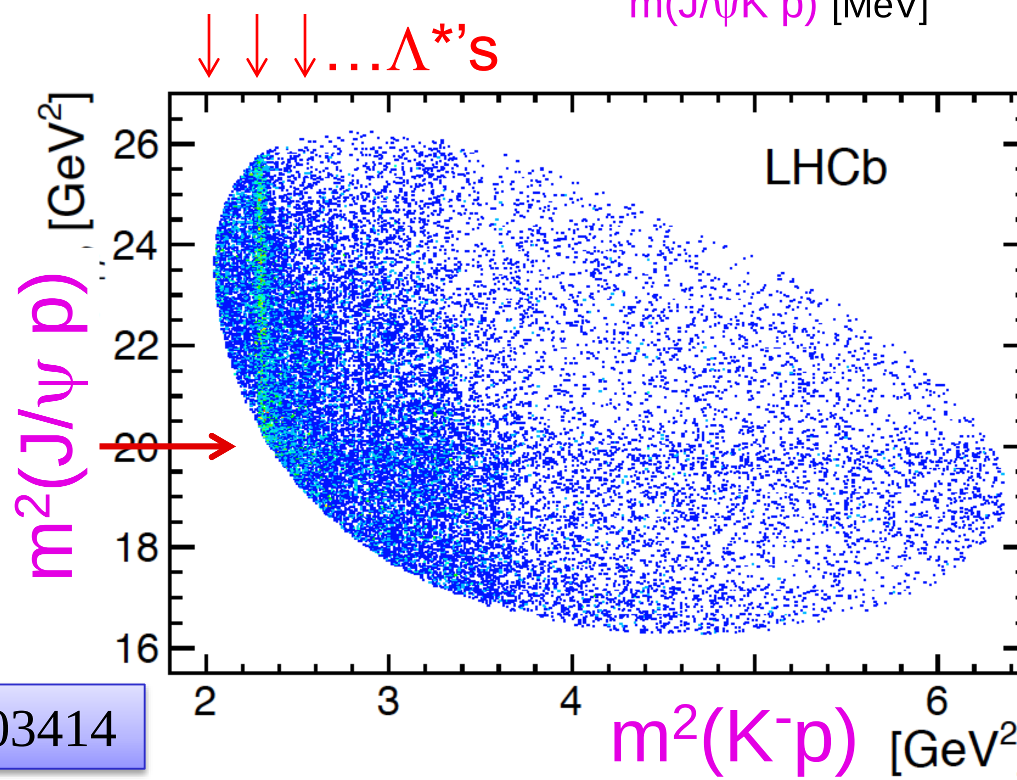
See for details Tomasz Skwarnicki presentation

$\Lambda_b \to J/\psi K^- p$

- First looked for at LHCb as a potential background for $B^0 \to J/\psi K^+ K^-$
- Large signal found, used for Λ_b lifetime

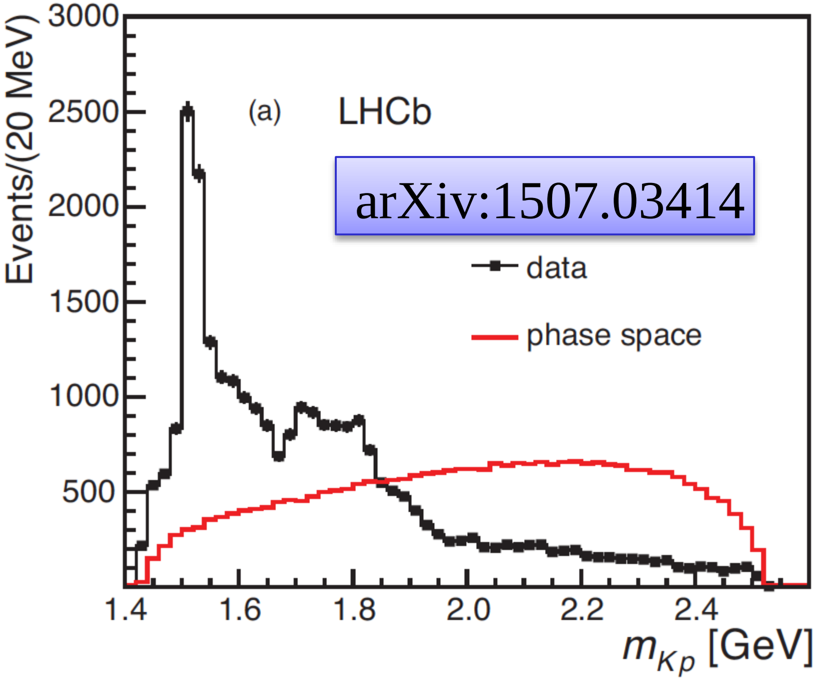


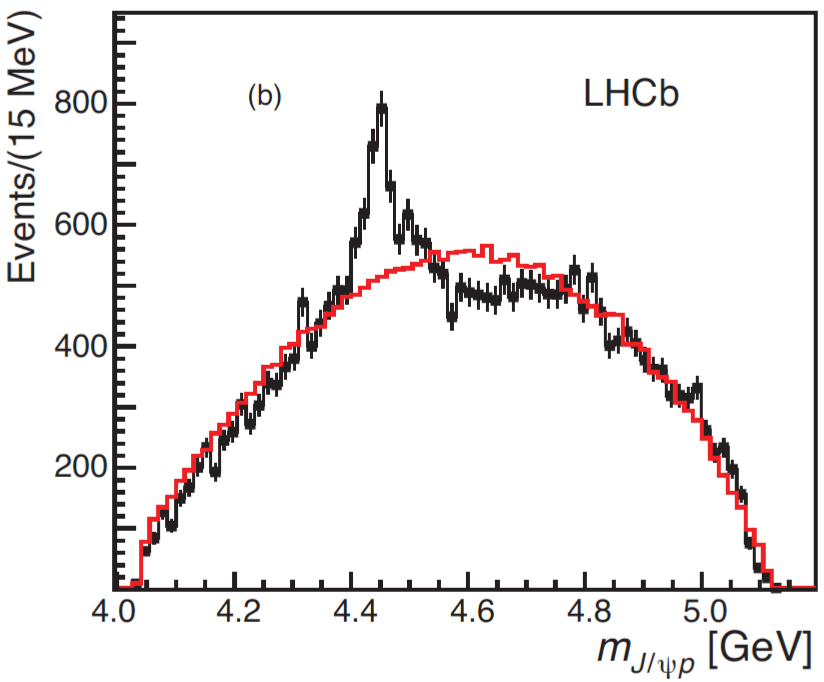
Dalitz plot showed an unusual feature

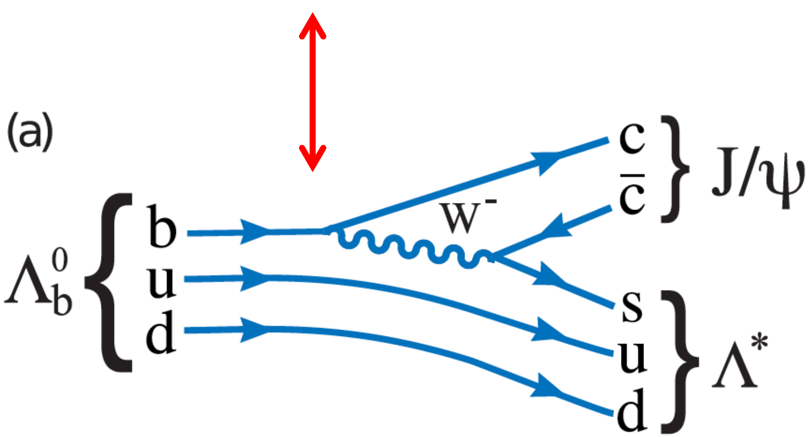


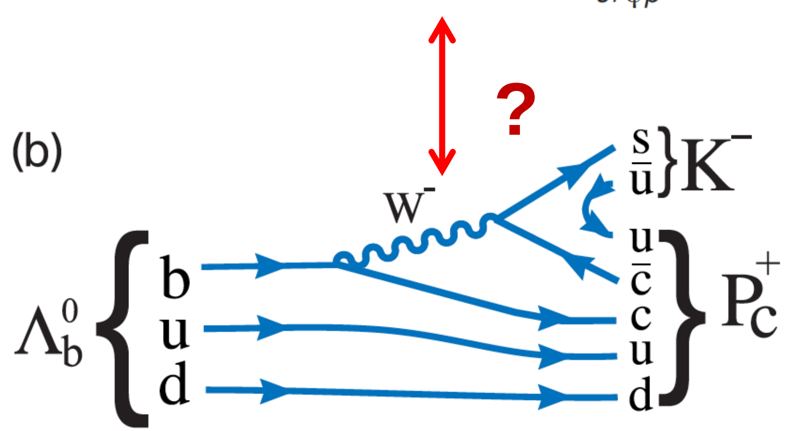
PRL 115, 072001 (2015) ,arXiv:1507.03414

Projections

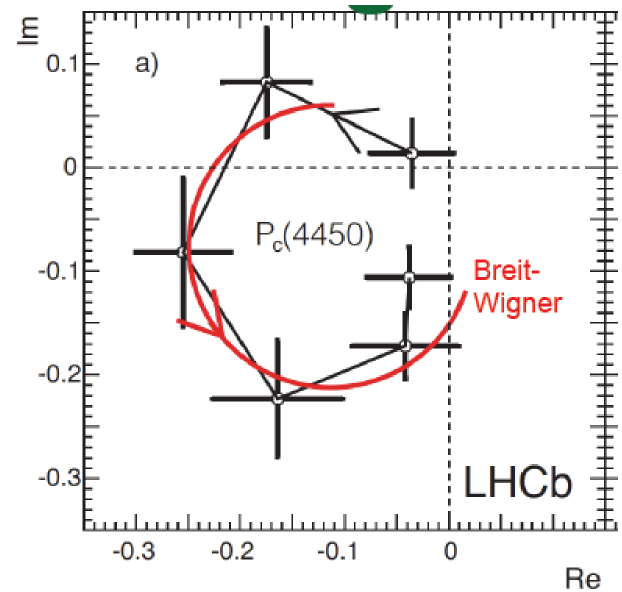


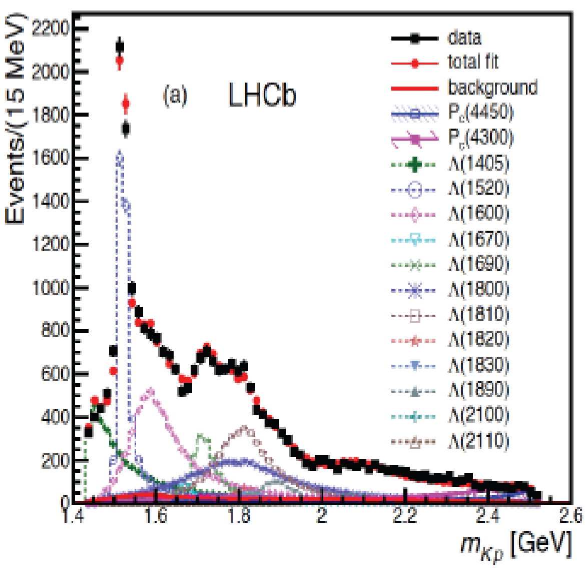


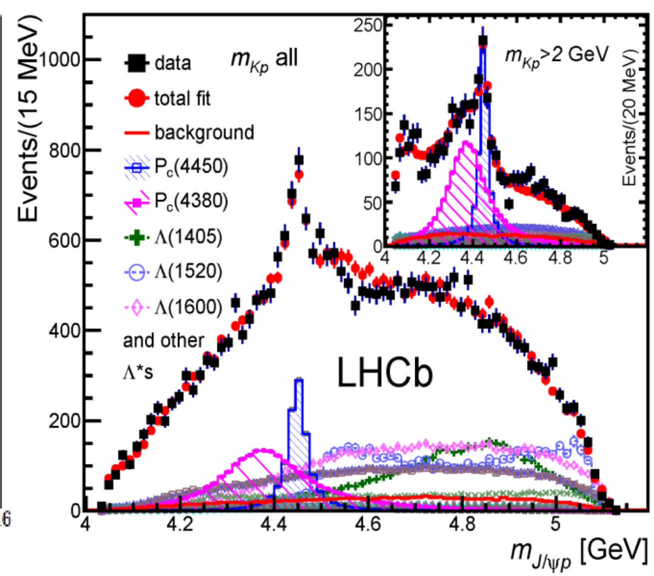


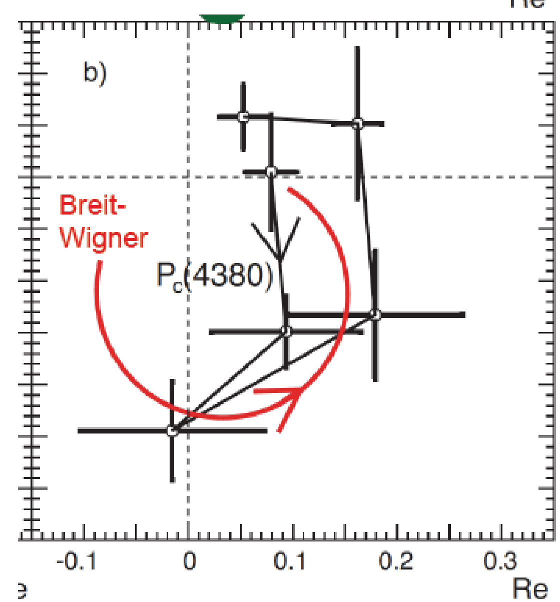


Mass (MeV)	Width (MeV)	Fit fraction (%)
4380±8±29	205±18±86	8.4±0.7±4.2
4449.8±1.7±2.5	39±5±19	4.1±0.5±1.1
Λ(1405)		15±1±6
Λ(1520)		19±1±4









Models

Tightly bound quarks

Two colored diquarks plus the anti-quark, L.Maiani, et. al, [arXiv:1507.04980], ibid [PRD20(1979) 748]

Colored diquark + colored triquark, R. Lebed [arXiv:1507.05867]

Hadroquarkonium

χ_{c1}p resonance ,U. Meißner,J. Oller[arXiv:1507.07478]

Rescattering

The narrow peak in pJ/ψ spectra at 4450 MeV is antiquark diquark-diquark state, while the broad bump is the result of rescatterings in the (pJ/ψ)-channel, V.V.Anisovich et.al [arXiv:1507.07652]

Molecule

Baryon-meson molecule generally with meson exchange for binding ,

Törnqvist [Z.Phys. C61 (1994) 525]

π exchange dominance, Σ_c (2445)D* S-wave molecule,

M.Karliner/J.Rosner [arXiv:1506.06386]

What can we do more?

- Search for other possible P_c decay channels ($J/\Psi\ p\pi$, $\chi_{c1}p$, $\Sigma_c^{(*)}\ D^{(*)}$, $\Lambda_c\ D^{(*)}$ …)
- Search in the inclusive production at LHC
- Search in the inclusive production at e^+e^- factories
- Similar structures in the $\Xi_b \to J/\Psi \Lambda K$?
- Photoproduction in γ-nucleon interactions

Qian Wang, Xiao-Hai Liu, Qiang Zhao [arXiv:1508.00339],V.Kubarovsky, M.Voloshin [1508.00888],M.Karliner/J.Rosner [arXiv:1508.01496]

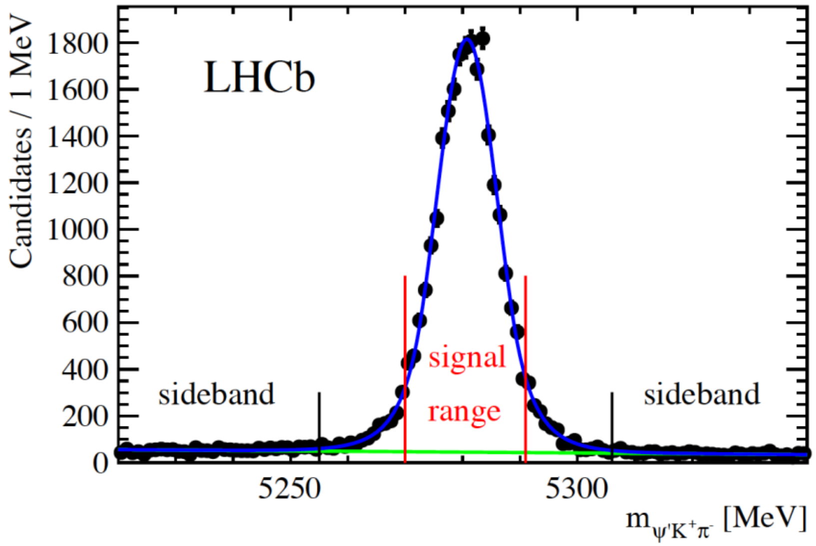
Peak cross section for $\gamma + p \to Pc \to J/\psi + p$, proportional to $[Br(Pc \to J/\psi + p)]^2$, can reach tens of nanobarns or more, if $Br(Pc \to J/\psi + p) \sim 10\%$ ($E\gamma \sim 10$GeV)

Tetraquark?

Z(4430)$^+$

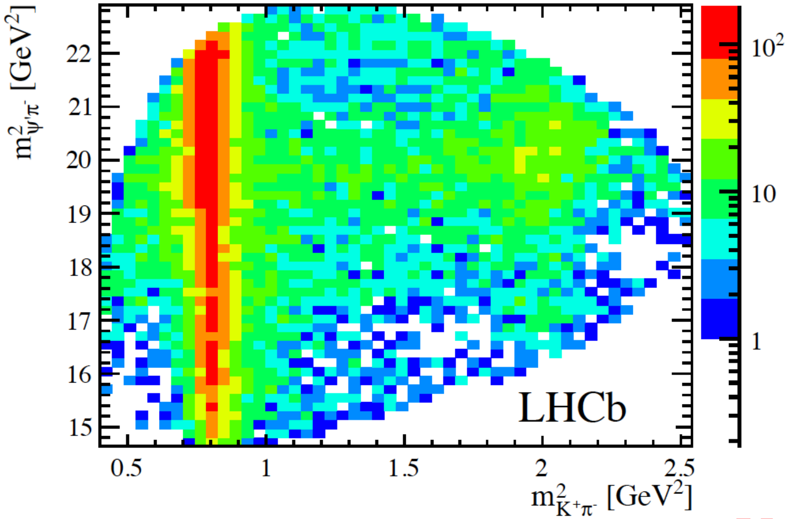
- $B^0 \to \psi' \pi^- K^+$, peak in $m(\psi' \pi^-)$, charged charmonium state must be exotic, not $q\bar{q}$
  - First observed by Belle M=4433±5 MeV, Γ=45 MeV
  - Challenged by BaBar: explanation in terms of K*'s
  - Belle reanalysis using full amplitude fit: $M = 4485 \pm 22^{+28}_{-11}$ MeV, Γ=200 MeV, 1^+ preferred [Belle PRD 88, 074026 (2013)]
- LHCb analysis also uses full amplitude fit
  - $M = 4475 \pm 7^{+15}_{-25}$ MeV
  - Γ=172 MeV

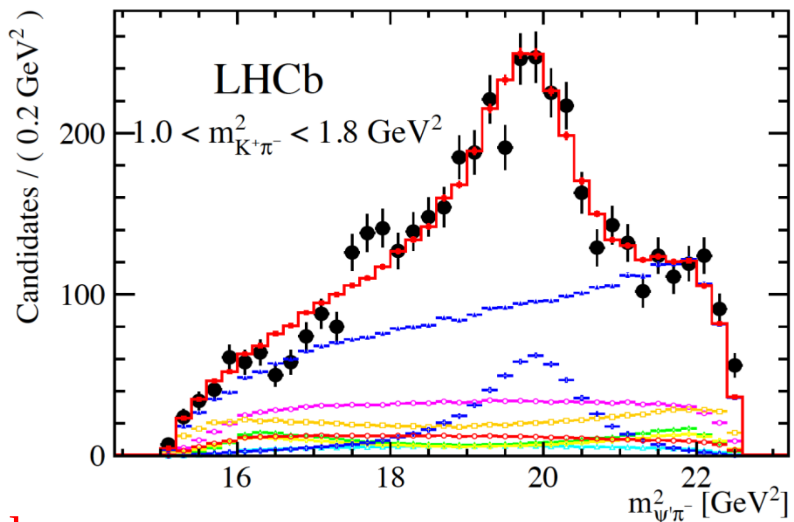
  [LHCb PRL 112, 222002 (2014)]



LHCb Amplitude analysis

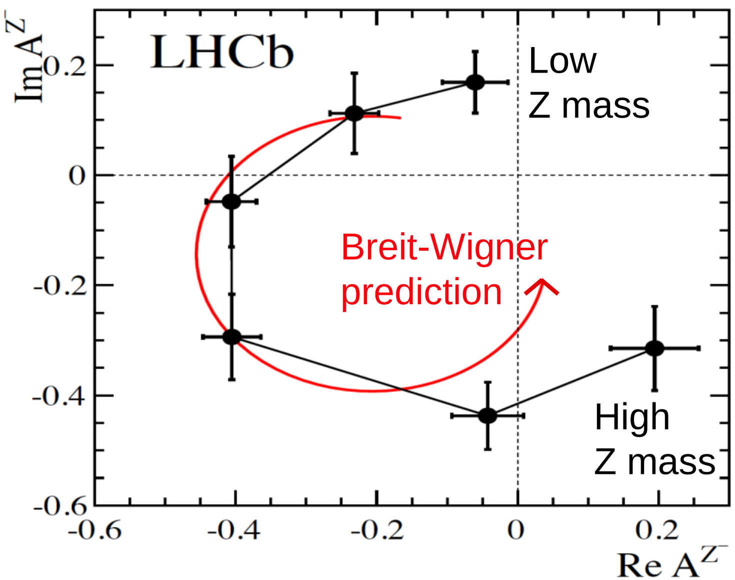
- Full 4D fit to both K*→$K^-\pi^+$ & Z→$\psi'\pi^-$ states

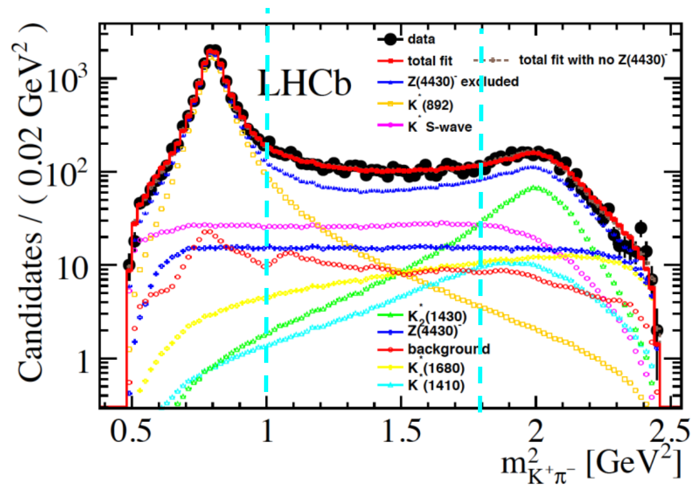




$J^P=1^+$

Unambiguously





Hadron Spectroscopy enters the new region – Physics of Highly Excited Quarkonium or/and Chemistry of Heavy Flavor

We can expect much more from Super B factory, BESIII and Run2 at LHC

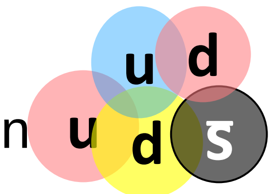
We need new Theoretical instruments for analysis

What about other color-singlet combinations?

Other possible "white" combinations of quarks & gluons:

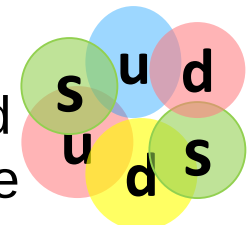
Pentaquark:

S=+1 Baryon



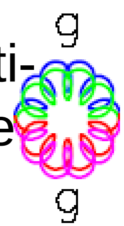
H-diBaryon

tightly bound
6-quark state



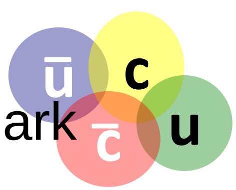
Glueball

Color-singlet multi-
gluon bound state

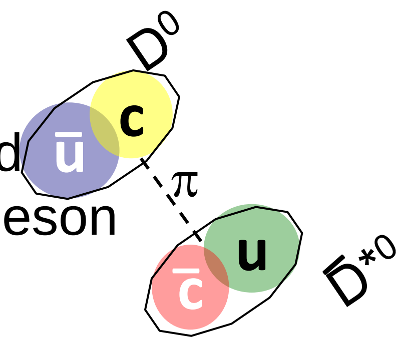


Tetraquark mesons

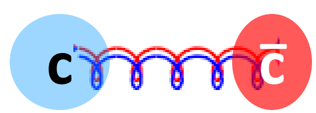
tightly bound
diquark-diantiquark

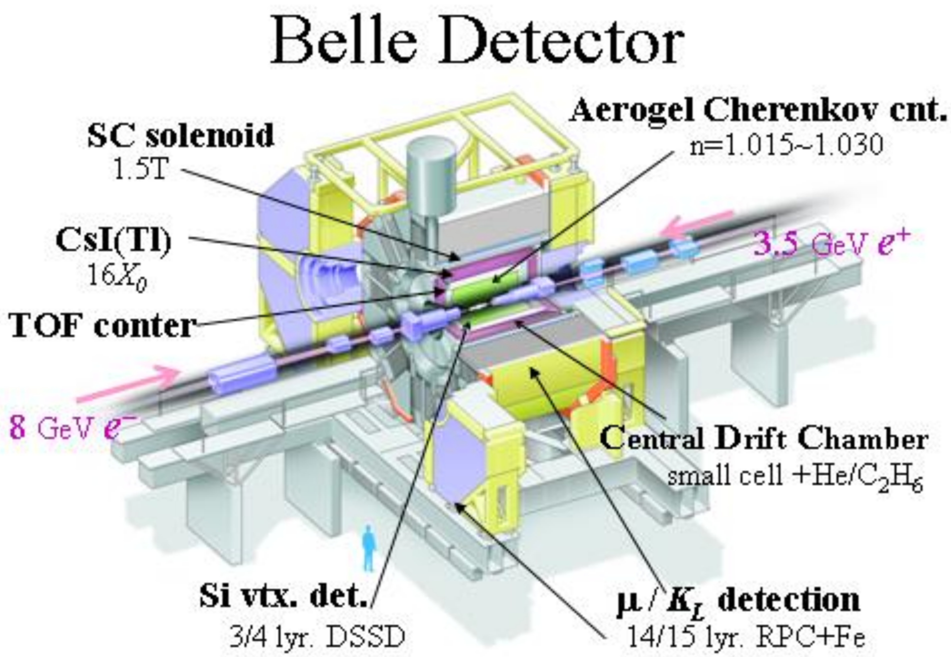


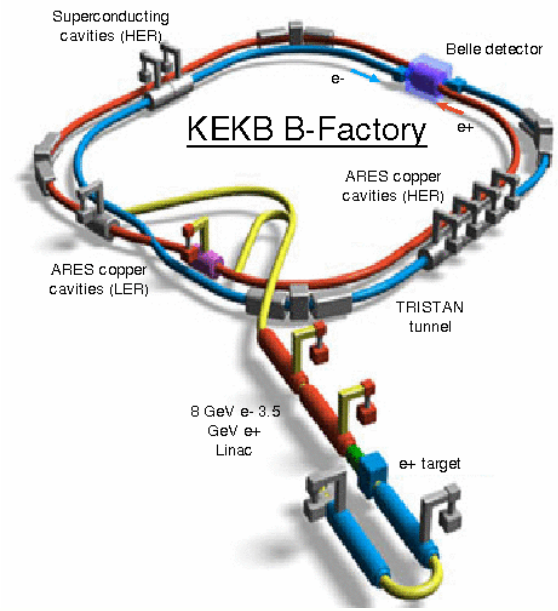
loosely bound
meson-antimeson
"molecule"

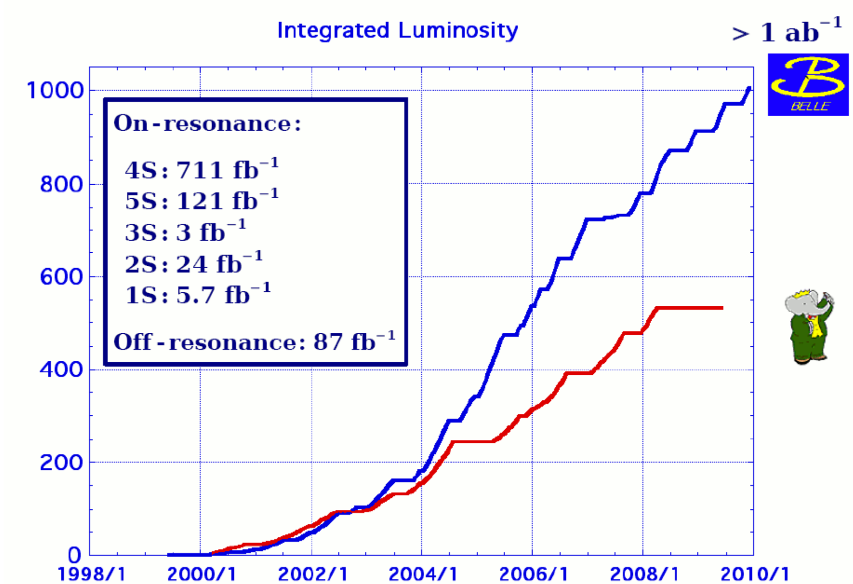


$q\bar{q}$-gluon hybrid mesons



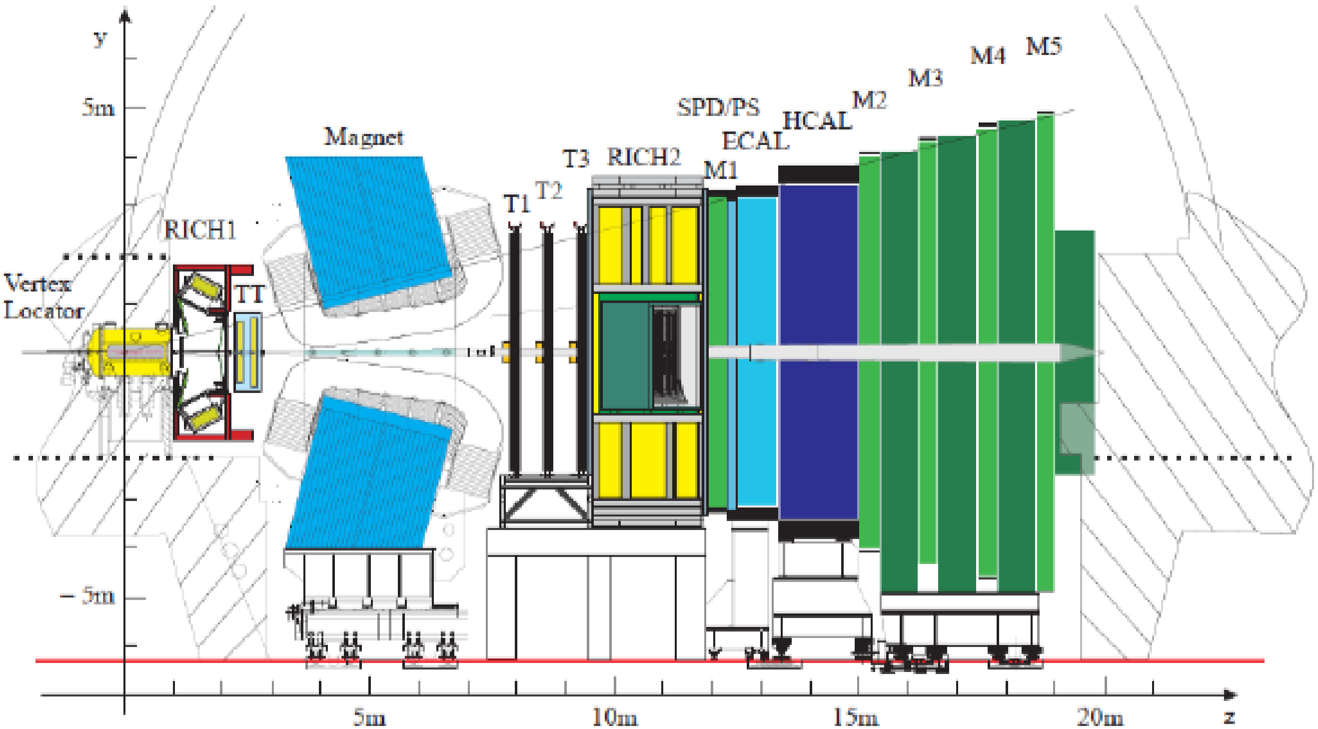






- **3.5 GeV $e^+ \times$ 8.0 GeV e^-.**
- $\mathcal{L}_{\max} = 2.1 \times 10^{34} cm^{-2} s^{-1}$
- **Continuous injection**
  $\rightarrow$ **1.1 fb^{-1}/day.**
- $\int \mathcal{L} dt \approx 1\, ab^{-1}$

LHCb detector



Impact parameter: $\sigma_{IP} = 20\ \mu\text{m}$

Proper time: $\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$

Momentum: $\Delta p/p = 0.4 \sim 0.6\%\ (5 - 100\ \text{GeV}/c)$

Mass : $\sigma_m = 8\ \text{MeV}/c^2$ for $B \to J/\psi X$ (constrainted $m_{J/\psi}$)

RICH $K-\pi$ separation: $\epsilon(K \to K) \sim 95\%$ mis-ID $\epsilon(\pi \to K) \sim 5\%$

Muon ID: $\epsilon(\mu \to \mu) \sim 97\%$ mis-ID $\epsilon(\pi \to \mu) \sim 1-3\%$

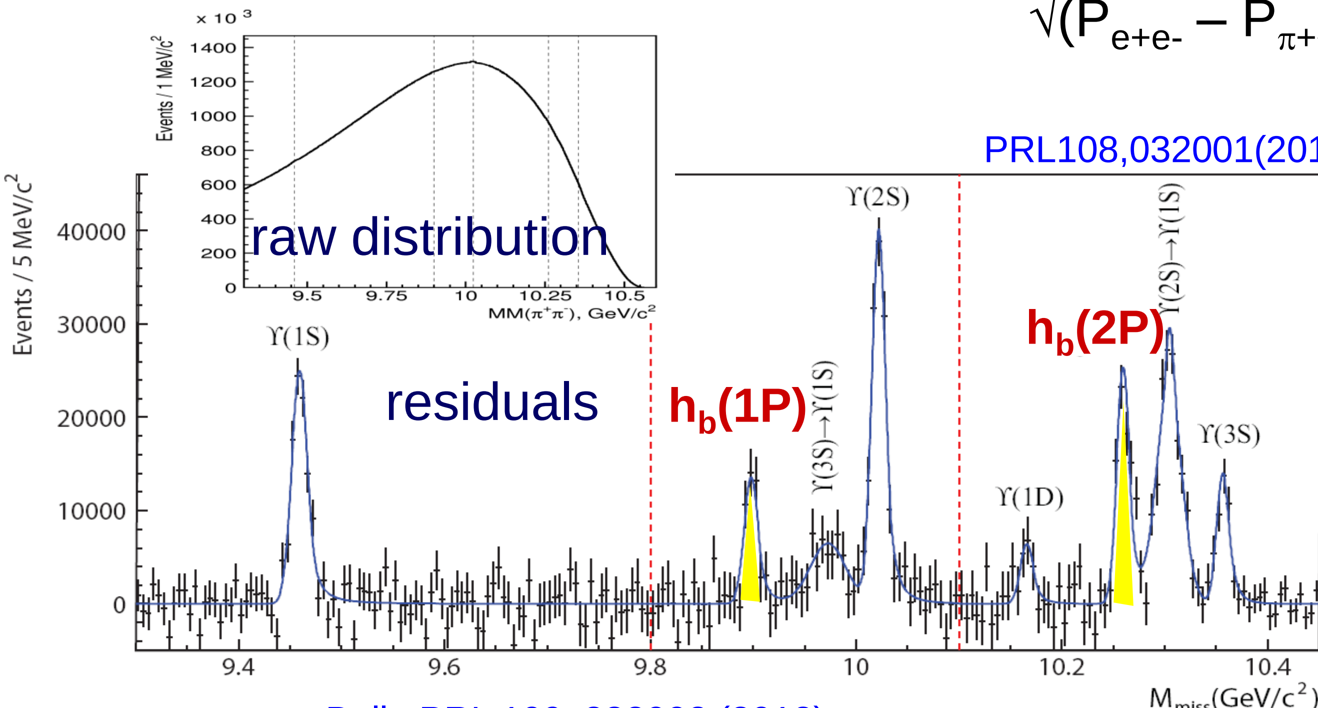
ECAL: $\Delta E/E = 1 \oplus 10\%/\sqrt{E(\text{GeV})}$

Observation of $h_b(1P,2P)$

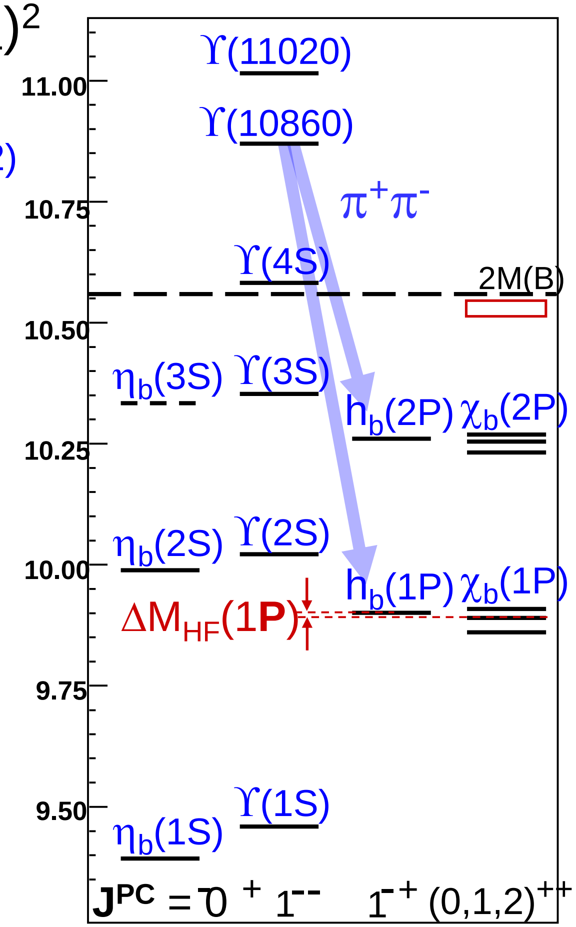
$e^+e^- \to \Upsilon(5S) \to h_b(nP)\ \pi^+\pi^-$ ← reconstructed, use $\mathbf{M_{miss}(\pi^+\pi^-)}$

$\sqrt{(P_{e+e-} - P_{\pi+\pi-})^2}$

PRL108,032001(2012)



Belle PRL 109. 232002 (2012)

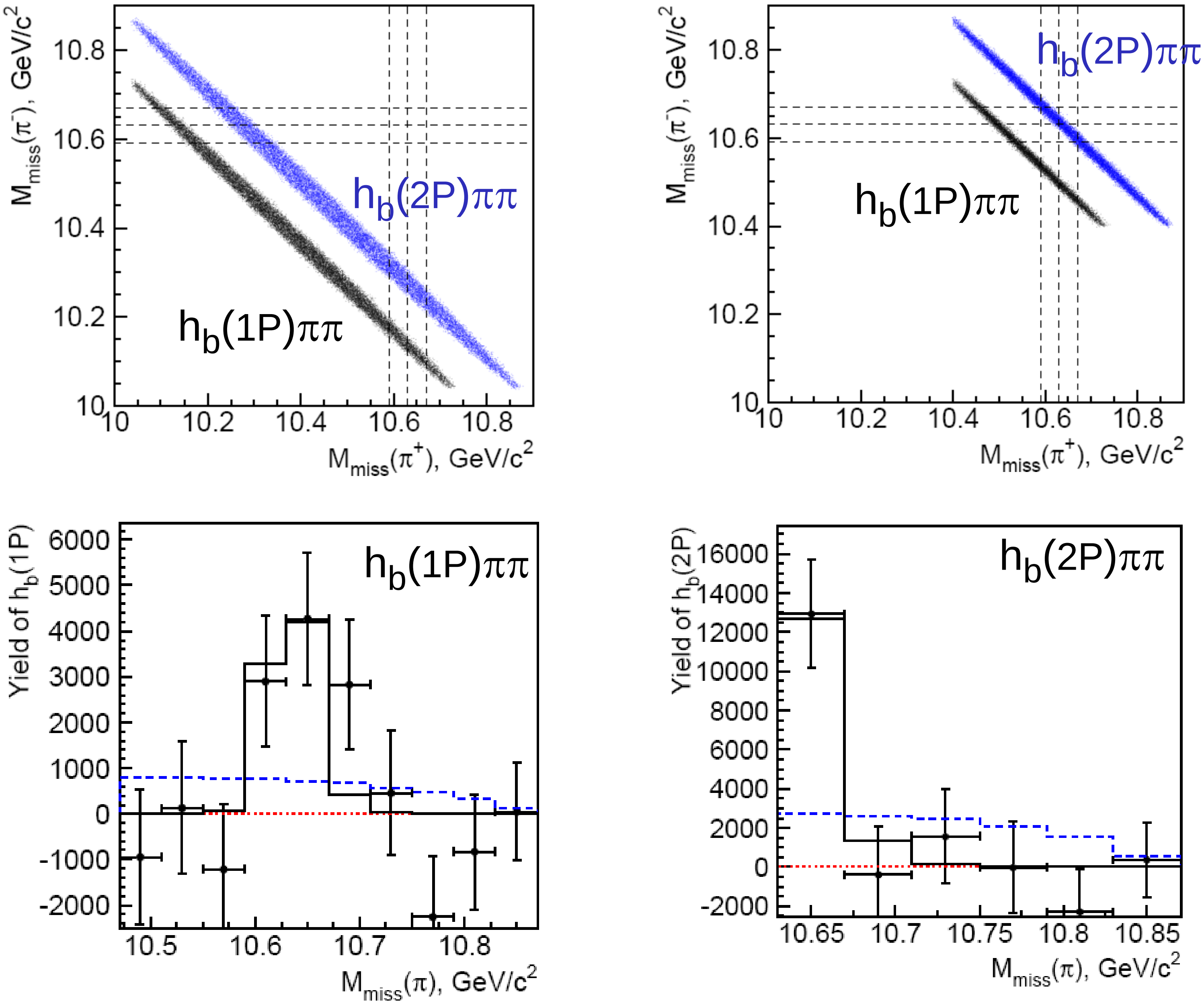


$\Delta M_{HF}(\mathbf{1P}) = +0.8 \pm 1.1$ MeV
$\Delta M_{HF}(\mathbf{2P}) = +0.5 \pm 1.2$ MeV

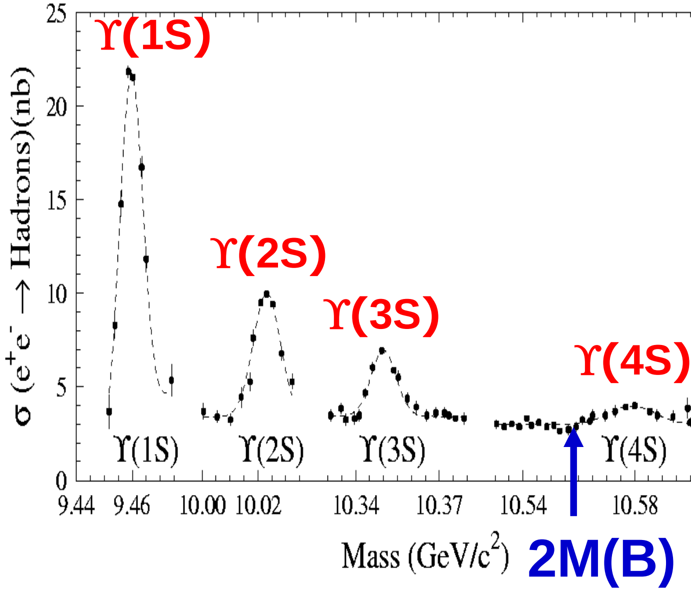
consistent with zero, as expected

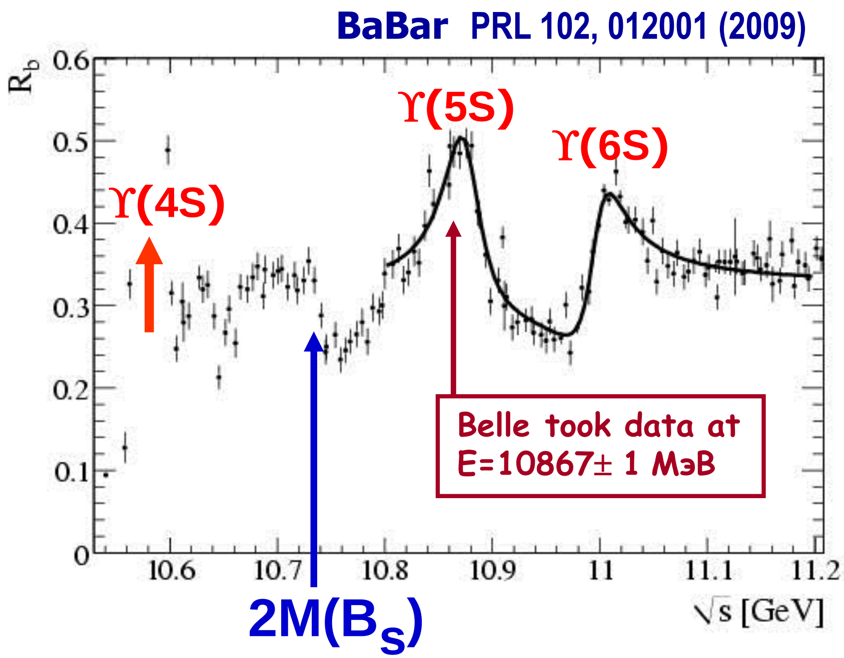
Large $h_b(1,2P)$ production rates

c.f. CLEO/BESIII $e^+e^- \to h_c\ \pi^+\pi^-$


hb(2P)ππ
hb(1P)ππ
Mmiss(π-), GeV/c2
Mmiss(π+), GeV/c2
Yield of hb(1P)
Yield of hb(2P)
Mmiss(π), GeV/c2

e^+e^- hadronic cross-section





$e^+ e^- \to \Upsilon(4S) \to B\bar{B}$, where B is B^+ or B^0

$e^+ e^- \to b\bar{b}\ (\Upsilon(5S)) \to B^{(*)}\bar{B}^{(*)}$, $B^{(*)}\bar{B}^{(*)}\pi$, $B\bar{B}\pi\pi$, $B_s^{(*)}\bar{B}_s^{(*)}$, $\Upsilon(1S)\,\pi\pi$, $\Upsilon\, X$ …

main motivation
for taking data at ϒ(5S)