Recent Results on Exotic Quarkonium States from BELLE

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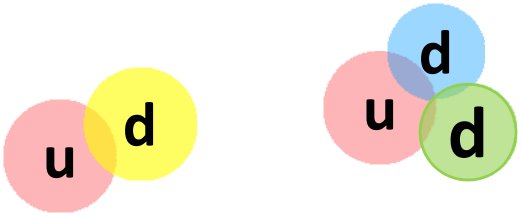
(on behalf of the BELLE collaboration)

- Introduction
- Exotics in Charmonium Sector
- Exotics in Bottomonium Sector
- Conclusions

Introduction

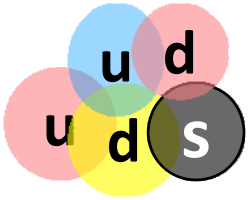
Possible "white" combinations of quarks & gluons:

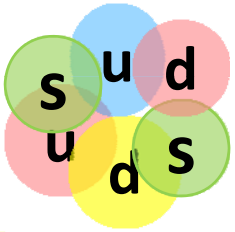
- **Conventional mesons & baryons**

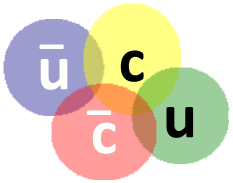


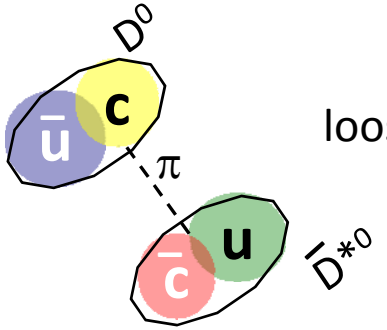
- **Allowed but "exotic" combinations**

tightly bound multi-quark





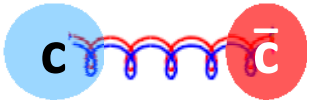




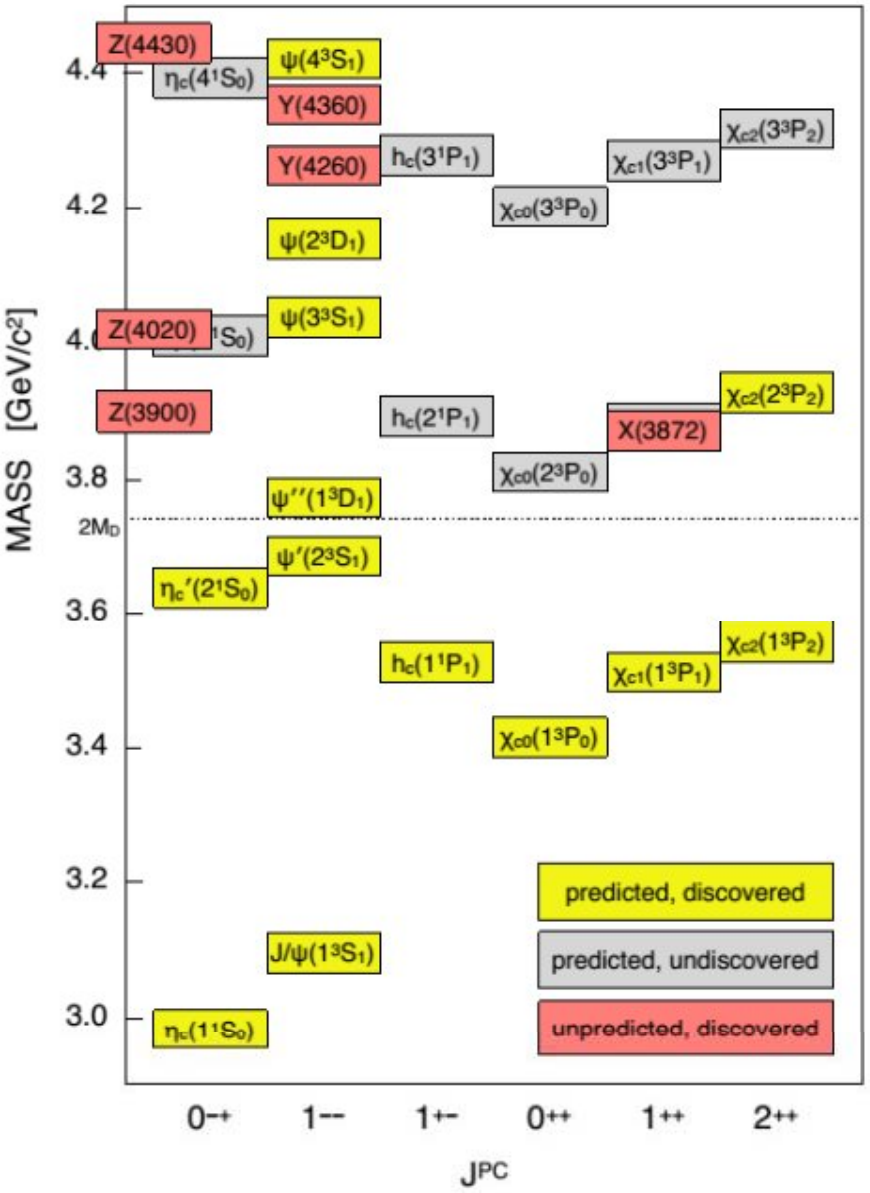
loosely bound meson-antimeson "molecule"

Color-singlet multigluon bound state (glueball)

hybrids



Introduction



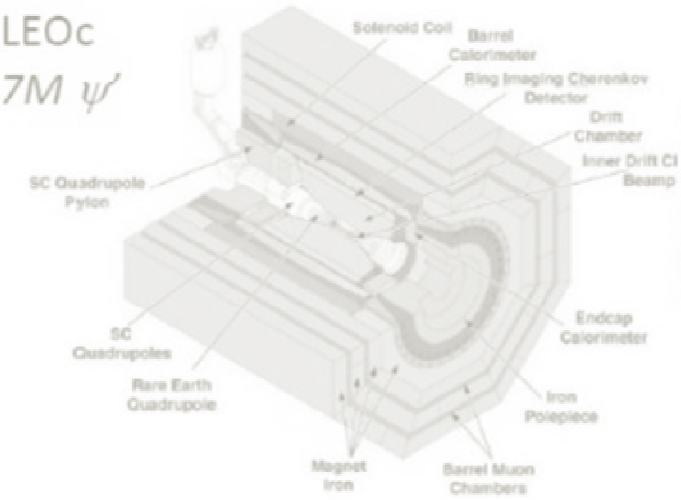
- >20 new resonances observed within last decade; most of them in charm sector, few in bottom sector
- The most notable of them are: X(3872), Y(4260), Zc(3900)/Zc(4020) and Zb(10610)/Zb(10650)
- Not predicted by potential models, do not fit into quarkonia scheme
- Challenge for the theory/experiment

Exotic: any multi-quark meson,
or meson with $J^{PC} = 0^{--}, 0^{-+}, 1^{-+}, 2^{+-}$ …

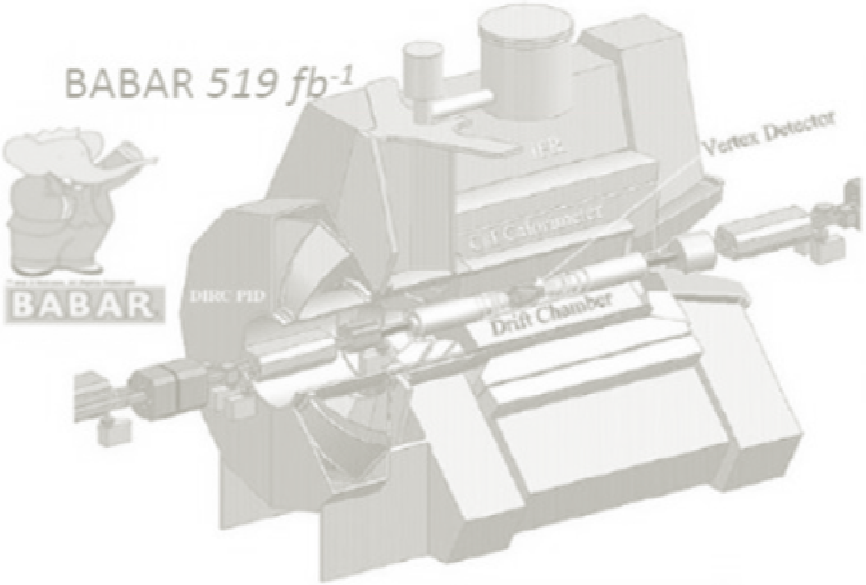
Main Suppliers of Exotics

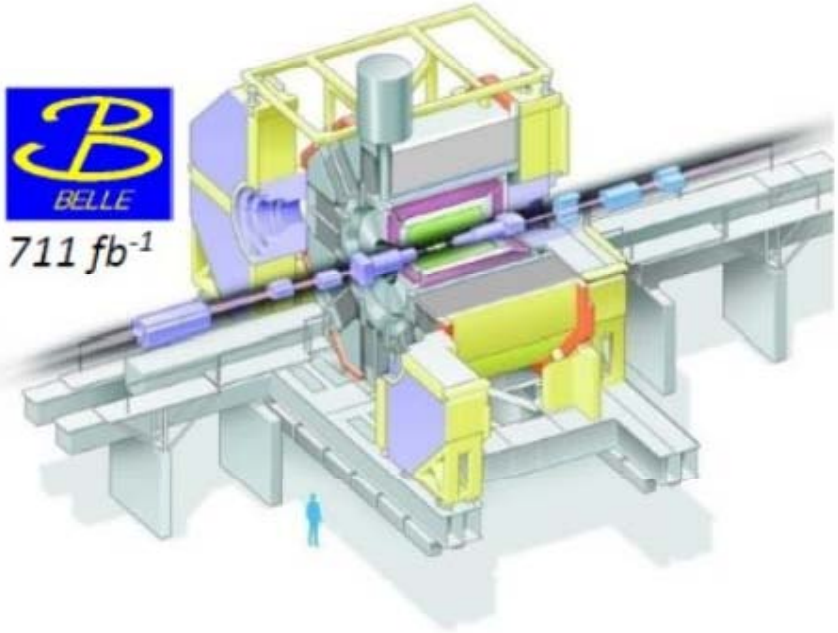
CLEOc

27M ψ'

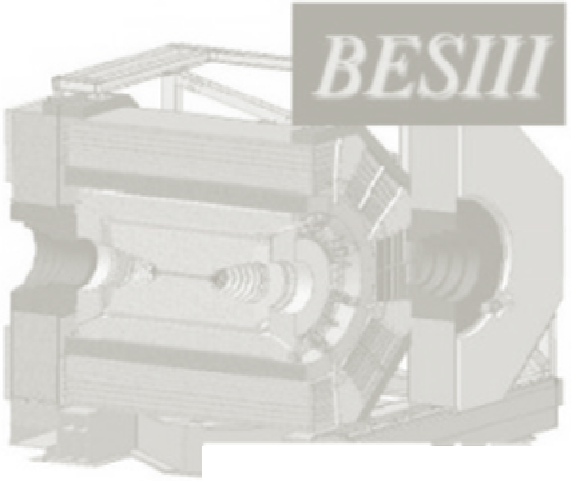


BABAR *519 fb^{-1}*

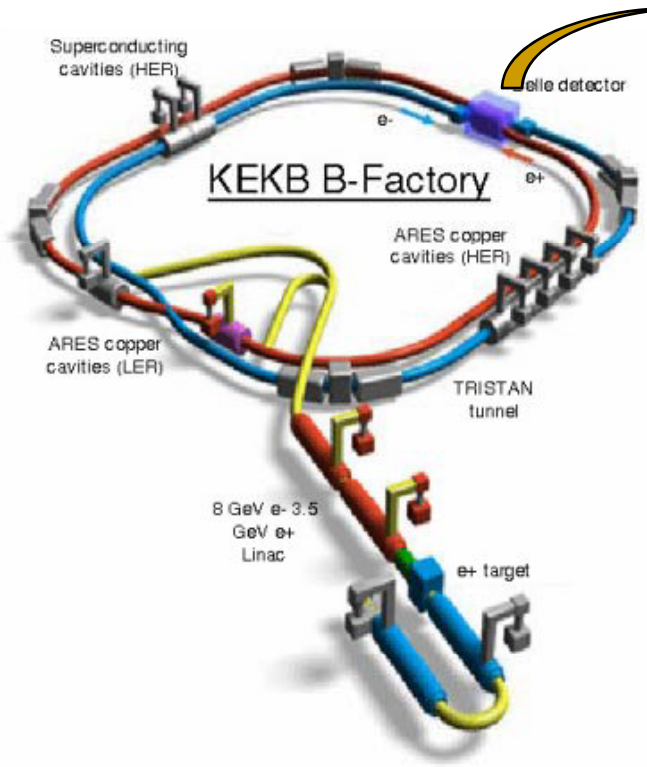


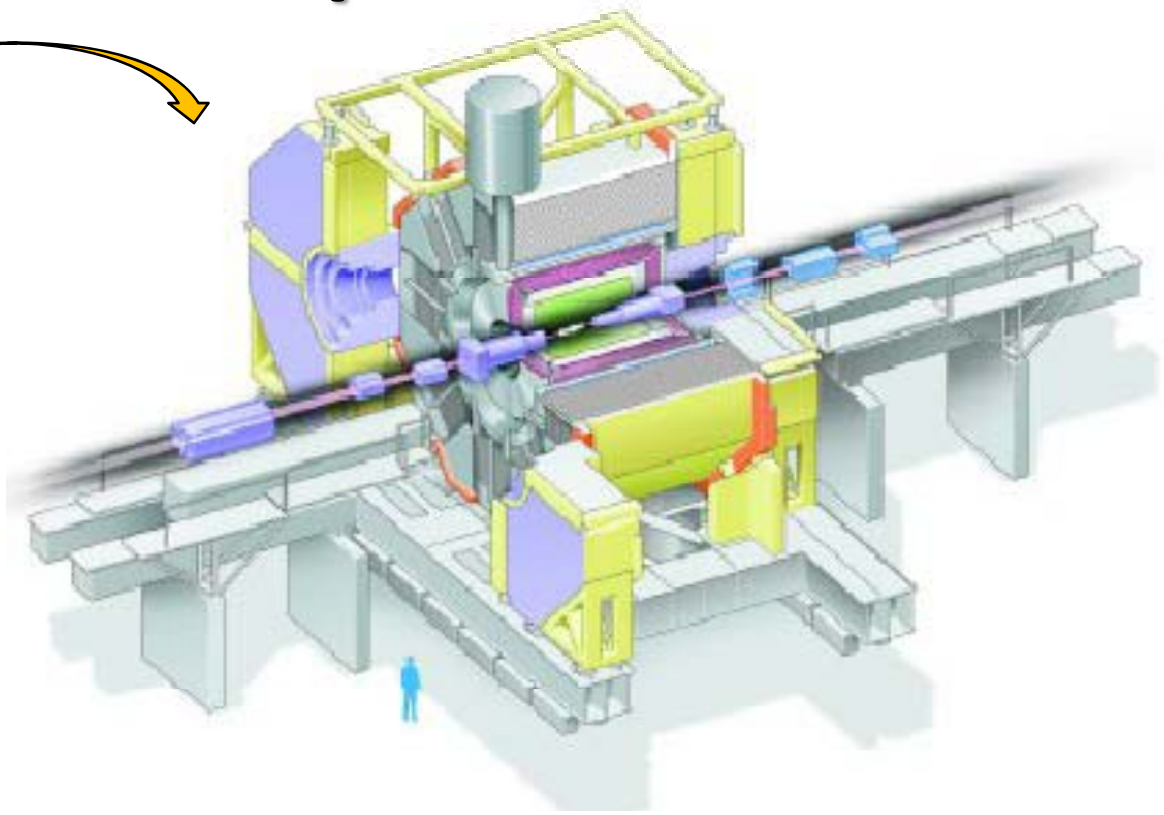


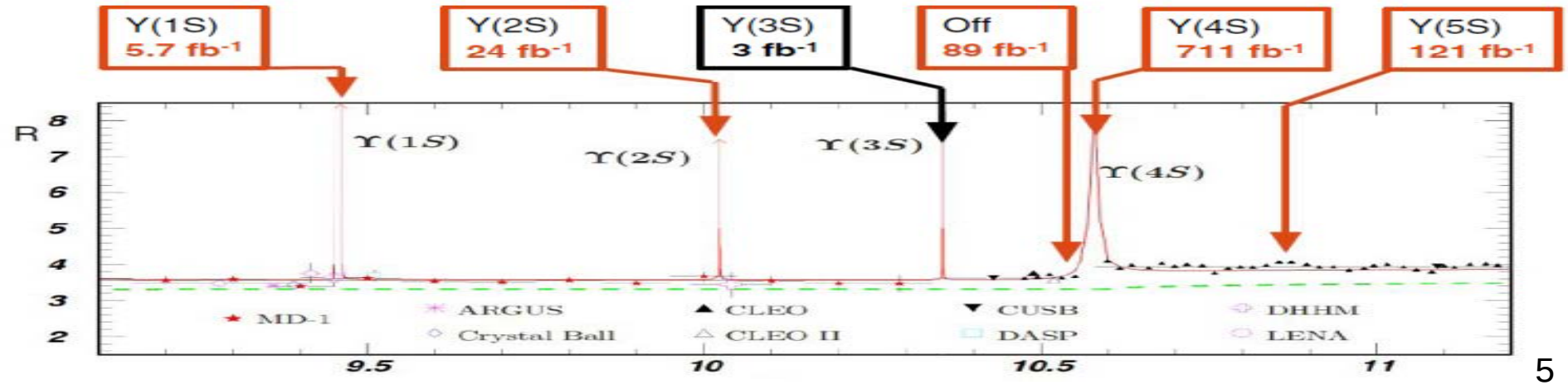
711 fb^{-1}



The BELLE Experiment







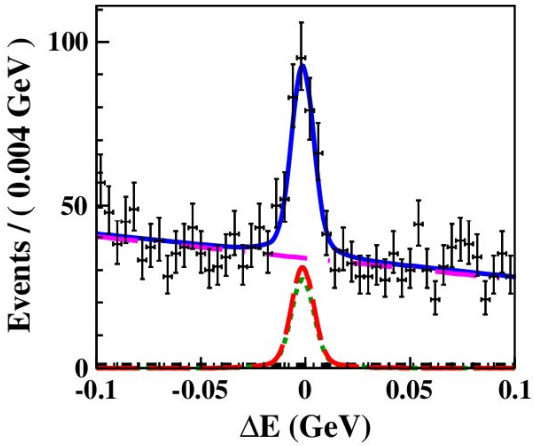
X(3872) & Alike (I)

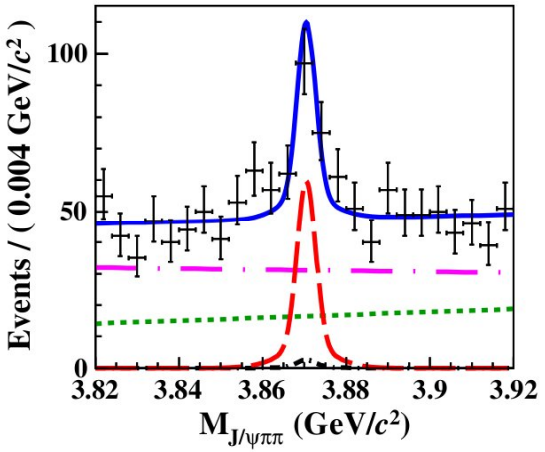
Analysis of

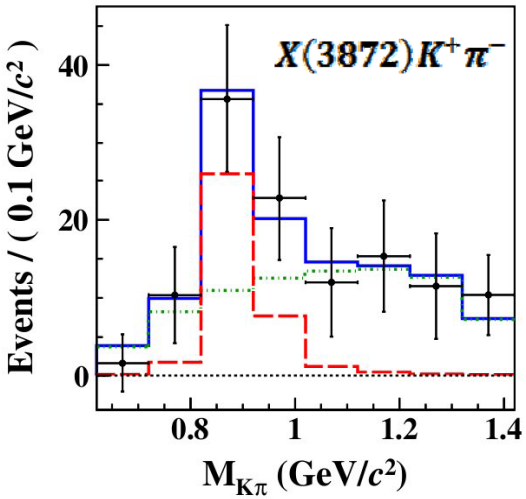
$B \to (J/\psi\pi^+\pi^-)K\pi$

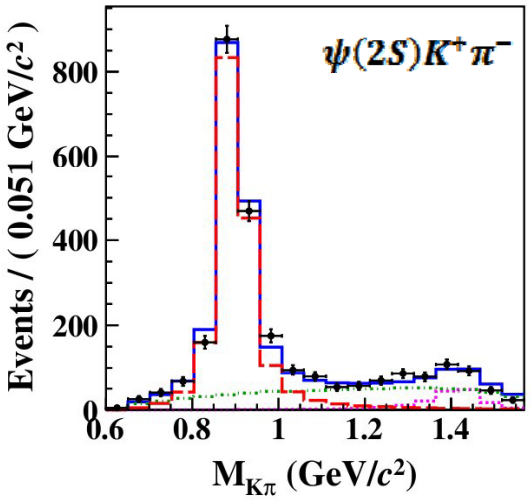
$X(3872)$ (signal)

$\psi(2S)$ (reference)









PRD 91, 051101(R) (2015)

New

$$\frac{\mathcal{B}(B^0 \to X(3872)K^*(892)^0) \times \mathcal{B}(K^*(892)^0 \to K^+\pi^-)}{\mathcal{B}(B^0 \to X(3872)K^+\pi^-)} = 0.34 \pm 0.09(\text{stat}) \pm 0.02(\text{syst}).$$

Decay mode	$\mathcal{B}(B \to X(3872)K\pi) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$
$B^0 \to X(3872)K^+\pi^-$	$(7.9 \pm 1.3 \pm 0.4) \times 10^{-6}$
$B^+ \to X(3872)K^0\pi^+$	$(10.6 \pm 3.0 \pm 0.9) \times 10^{-6}$

X(3872) & Alike (II)

- Motivation:
  - $X(3872)$: observed by Belle in $B \to K(J/\psi\pi^+\pi^-)$; $J^{PC} = 1^{++}$ determined by LHCb from angular analysis.
  - If $X(3872)$ is a $D^0\bar{D}^{*0}$ molecule, there may be other "X-like" particles.

- Assumption:

Candidate	Combination	Quantum number J^{PC}	Decay modes
$X_1(3872)$	$D^0\bar{D}^{*0} - \bar{D}^0 D^{*0}$	1^{+-}	$\eta_c\omega$, $\eta_c\rho$
$X(3730)$	$D^0\bar{D}^0 + \bar{D}^0 D^0$	0^{++}	$\eta_c\eta$, $\eta_c\pi^0$
$X(4014)$	$D^{*0}\bar{D}^{*0} + \bar{D}^{*0} D^{*0}$	0^{++}	$\eta_c\eta$, $\eta_c\pi^0$

X(3872) & Alike (III)

No signal is observed in any of the studied decay channels. The upper limits on their production are set at 90% C.L.

Upper limits of $\mathcal{B}(B^{\pm} \to K^{\pm} X(\to \eta_c h)) \ (\times 10^{-5})$

	Decay mode	Yield	UL
$X_1(3872)$	$\eta_c \pi^+ \pi^-$	17.9 ± 16.5	3.0
	$\eta_c \omega$	6.0 ± 12.5	6.9
$X(3730)$	$\eta_c \eta(\gamma\gamma)$	13.8 ± 9.9	4.6
	$\eta_c \eta(\pi^+ \pi^- \pi^0)$	1.4 ± 1.0	
$X(3730)$	$\eta_c \pi^0$	-25.6 ± 10.4	5.7
$X(4014)$	$\eta_c \eta(\gamma\gamma)$	8.9 ± 11.0	3.9
	$\eta_c \eta(\pi^+ \pi^- \pi^0)$	1.3 ± 1.6	
$X(4014)$	$\eta_c \pi^0$	-8.1 ± 13.2	1.2

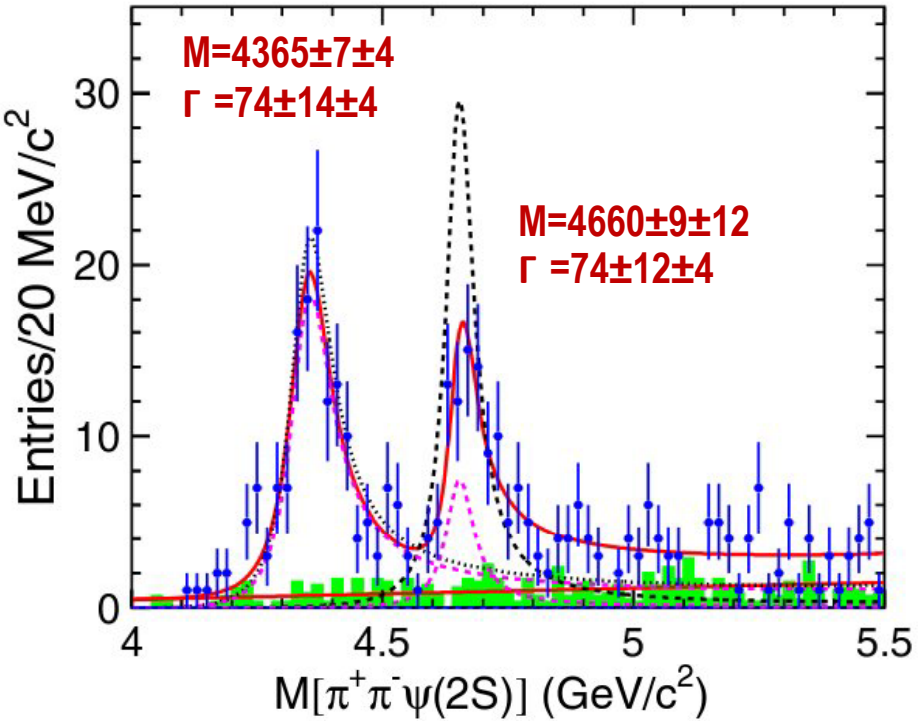
Upper limits of $\mathcal{B}(B^{\pm} \to K^{\pm} + \eta_c h) \ (\times 10^{-5})$ at 90% C.L.

Mode	Yield	UL
$\eta_c \pi^+ \pi^-$	155 ± 72	3.9
$\eta_c \omega$	-41 ± 27	5.3
$\eta_c \eta(\gamma\gamma)$	-14.1 ± 26.1	2.2
$\eta_c \eta(3\pi)$	-1.8 ± 3.4	
$\eta_c \pi^0$	-1.9 ± 12.1	6.2

JHEP 1506, 132 (2015) New

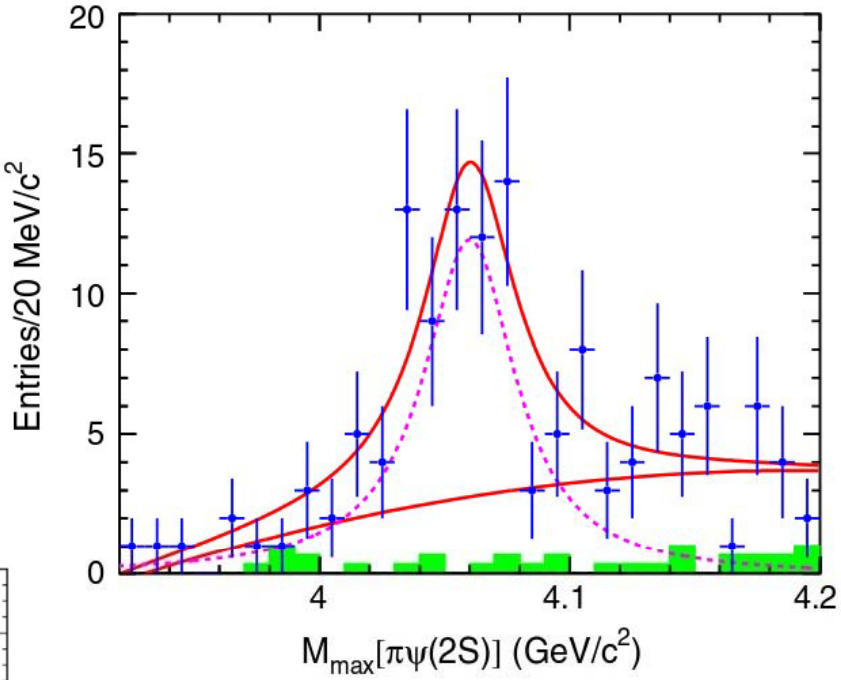
Y Studies in The ISR Process

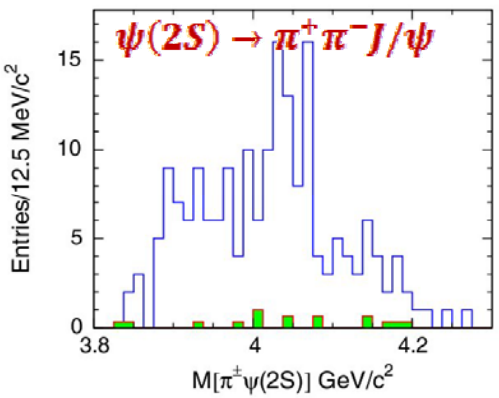
Update of the 2007 analysis with extra Lumi & much improved efficiency:

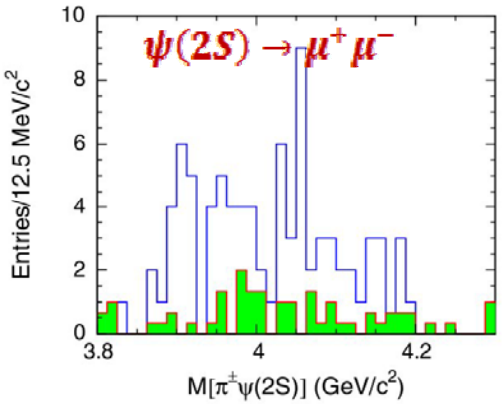


N_{sig}: **110** events →

363 (84% purity)





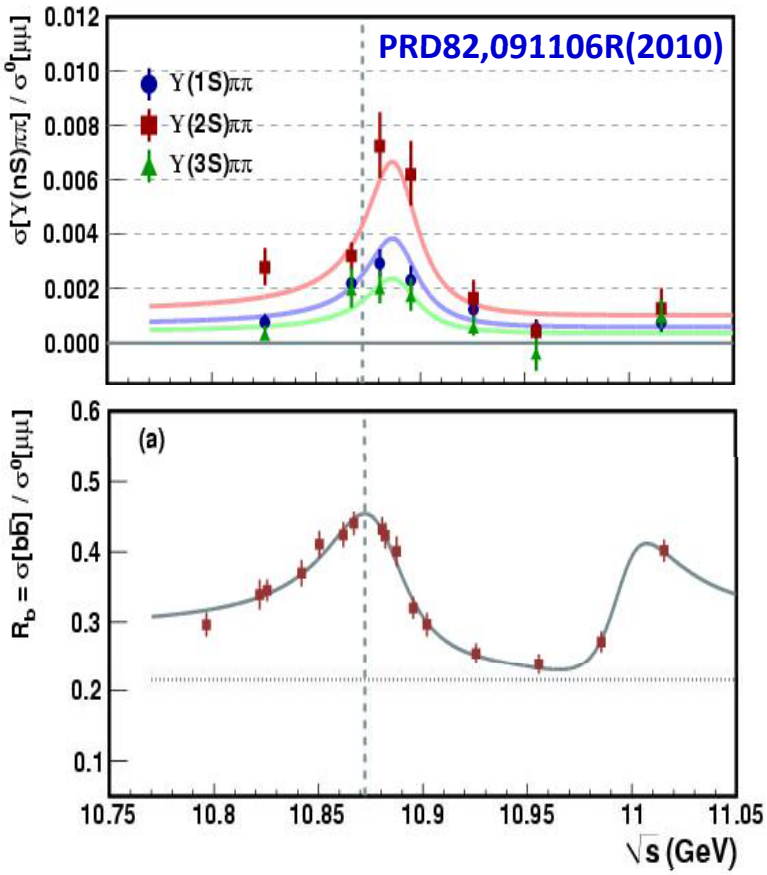


- $M = (4054 \pm 3(\text{stat.}) \pm 1(\text{syst.}))$ MeV/c^2
- $\Gamma = (45 \pm 11(\text{stat.}) \pm 6(\text{syst.}))$ MeV
- The significance is 3.5σ.

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

PRL100,112001(2008)	Γ(MeV)
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019

10^2



(1) Rescattering $\Upsilon(5S)\to BB\pi\pi\to\Upsilon(nS)\pi\pi$

Simonov JETP Lett 87,147(2008);
Meng et al. Phys.Rev.D78:034022,2008

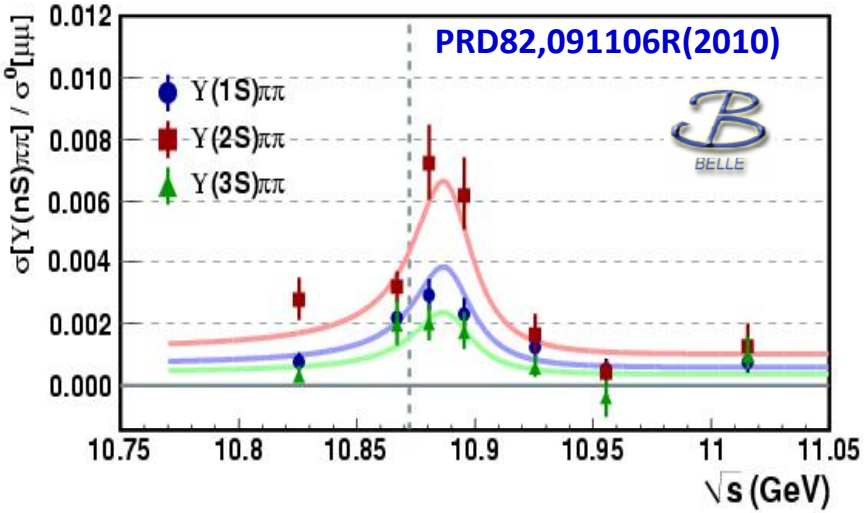
(2) Exotic resonance Y_b near $\Upsilon(5S)$ analogue of Y(4260) resonance with anomalous $\Gamma(J/\psi\,\pi^+\pi^-)$

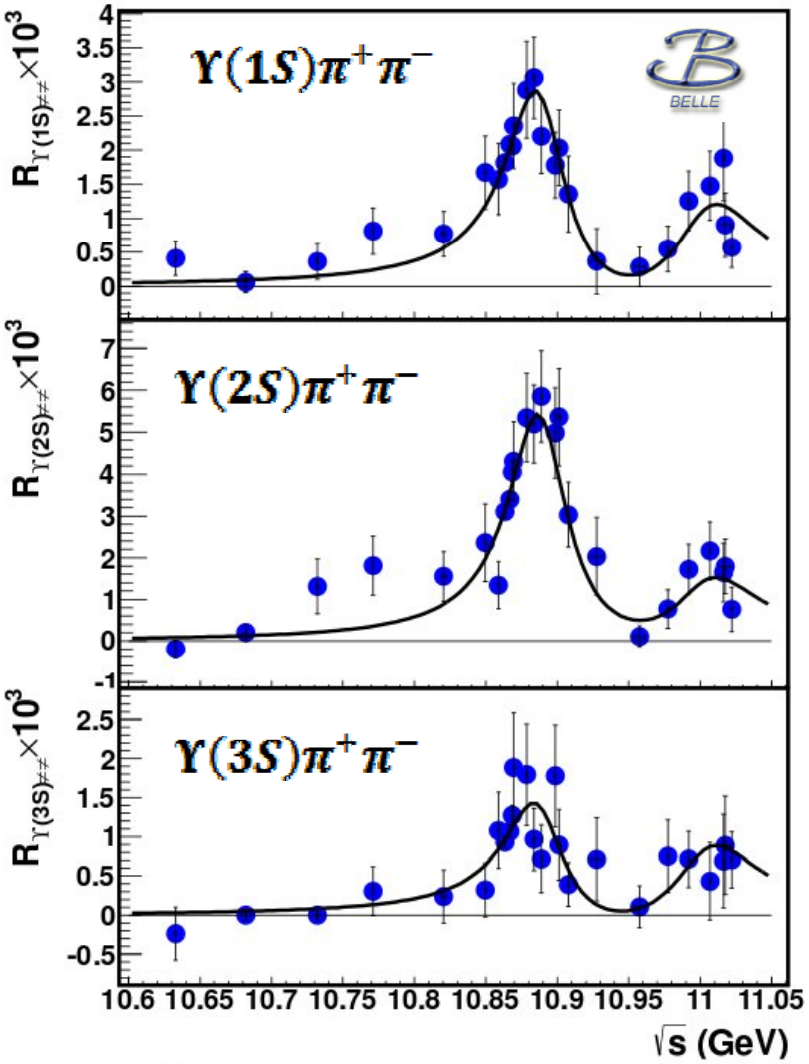
Hou et al., Phys.Rev.D74:017504,2006
Ali et al. Phys.Rev.Lett.104:162001,2010

(3) Tetraquarks

Karliner et al. arXiv:0802.0649v2; Xiang Liu et al. Eur. Phys. J. C (2009) 61: 411;
Yan-Rui Liu et al. Eur.Phys.J.C56:63-73,2008; N. Brambilla et al, Eur.Phys.J. C71 (2011) 1534

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





$\Upsilon(10680)$:

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

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

$\Upsilon(11020)$:

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

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

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

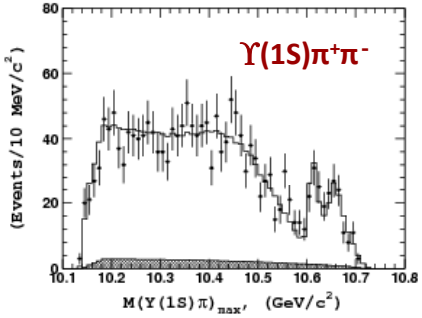
New

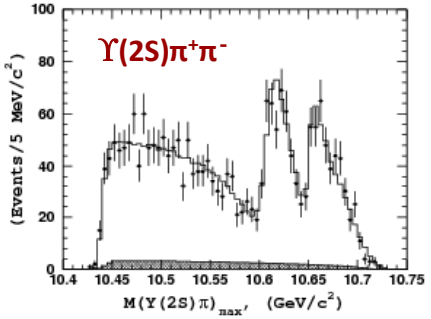
hep-ex :1501.01137

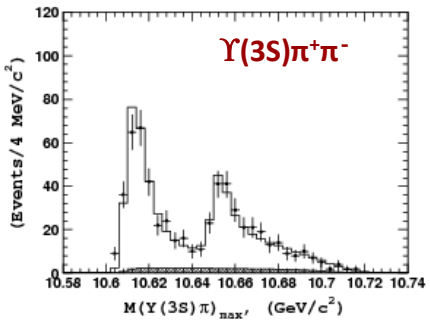
$\Upsilon(5S) \to Z_b \pi^{\pm}$

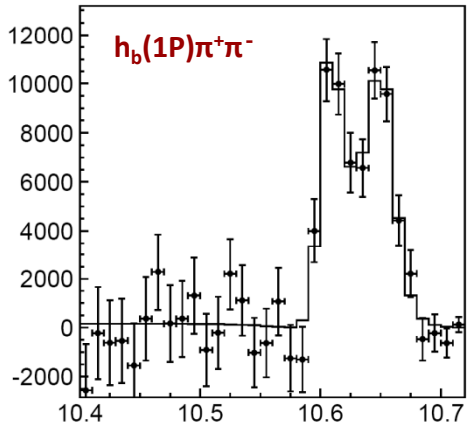
$Z_b^{\pm}$ Observed in five different modes:

PRL 108, 122001(2012)

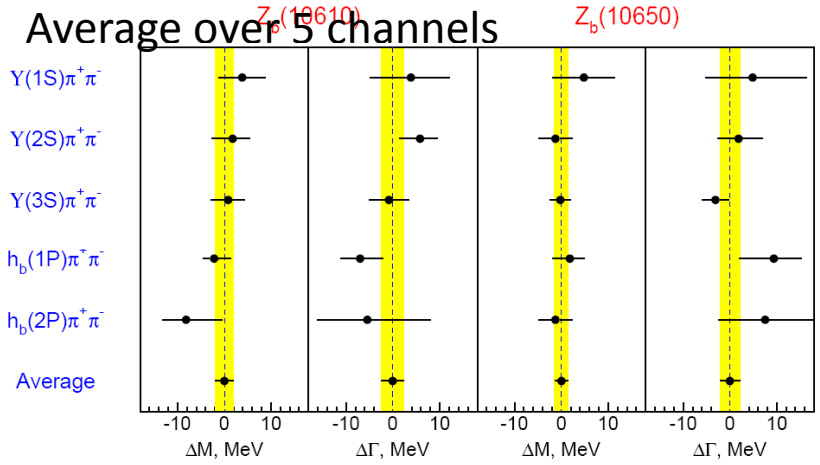








Average over 5 channels



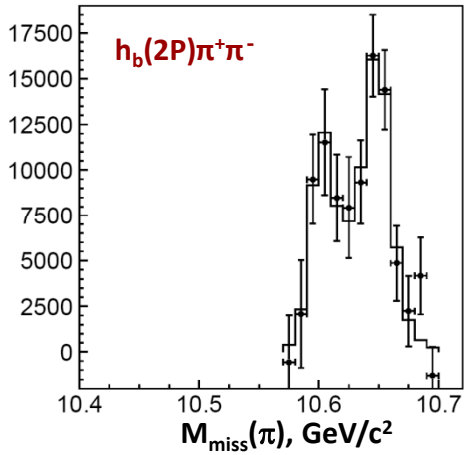
Average for $Z_b^{\pm}$:

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

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

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

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

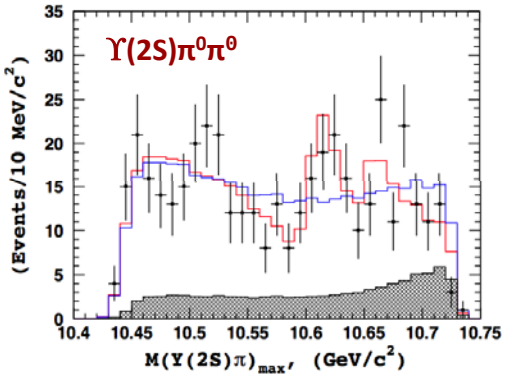


Z_b^0 Results:

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

Consistent with $Z_b^{\pm}$

PRD88,052016 (2013)



Angular analysis strongly favors $J^P=1^+$ assignement

PRD91,072003 (2015)

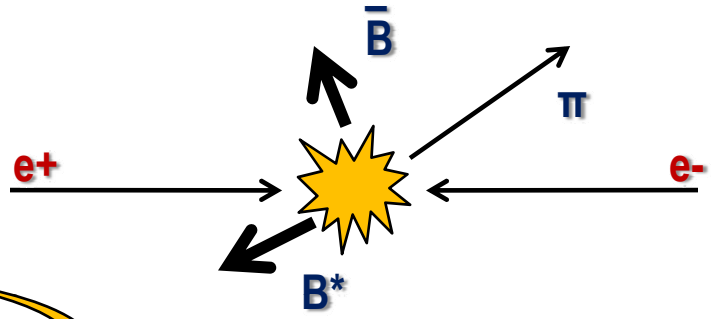
New

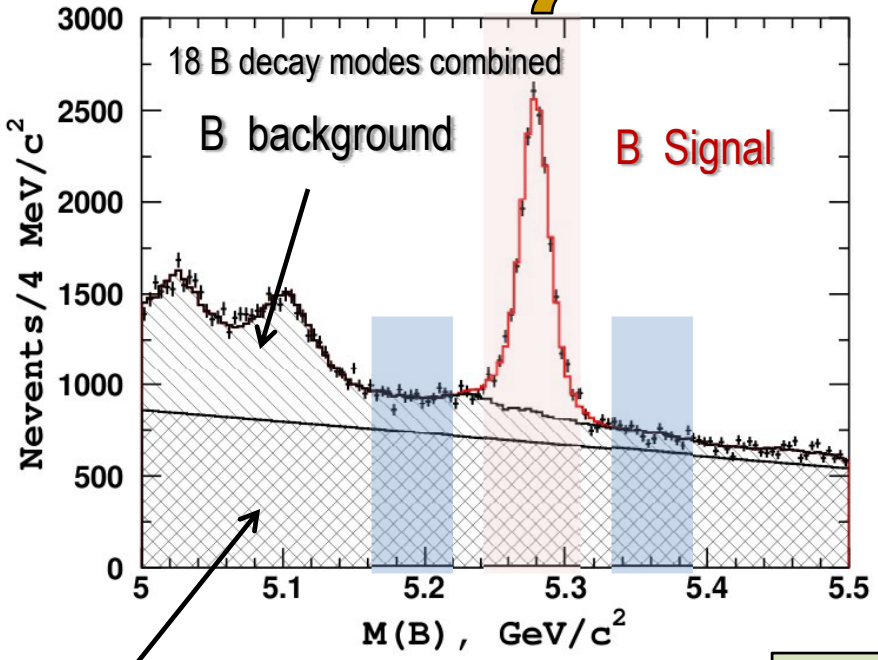
$\Upsilon(5S) \to Z_b \pi^{\pm}$

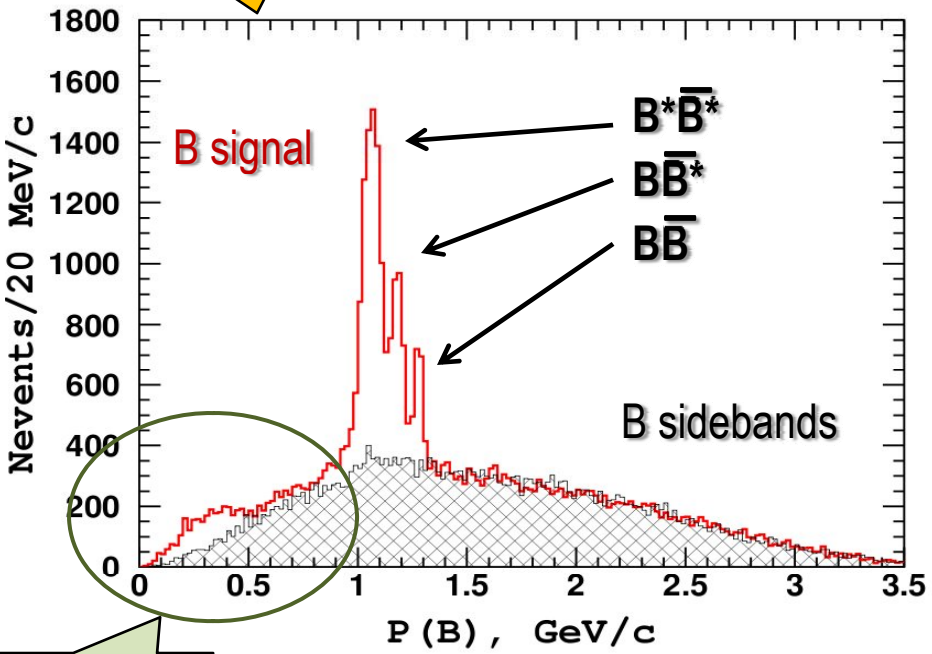
Masses of the observed Z_b resonances are suspiciously close to the BB* and B*B* thresholds, respectively: branching fractions $Z_b \to B(*)B*$ might be large (dominant).

Analysis strategy:

- Full reconstruction of one B meson





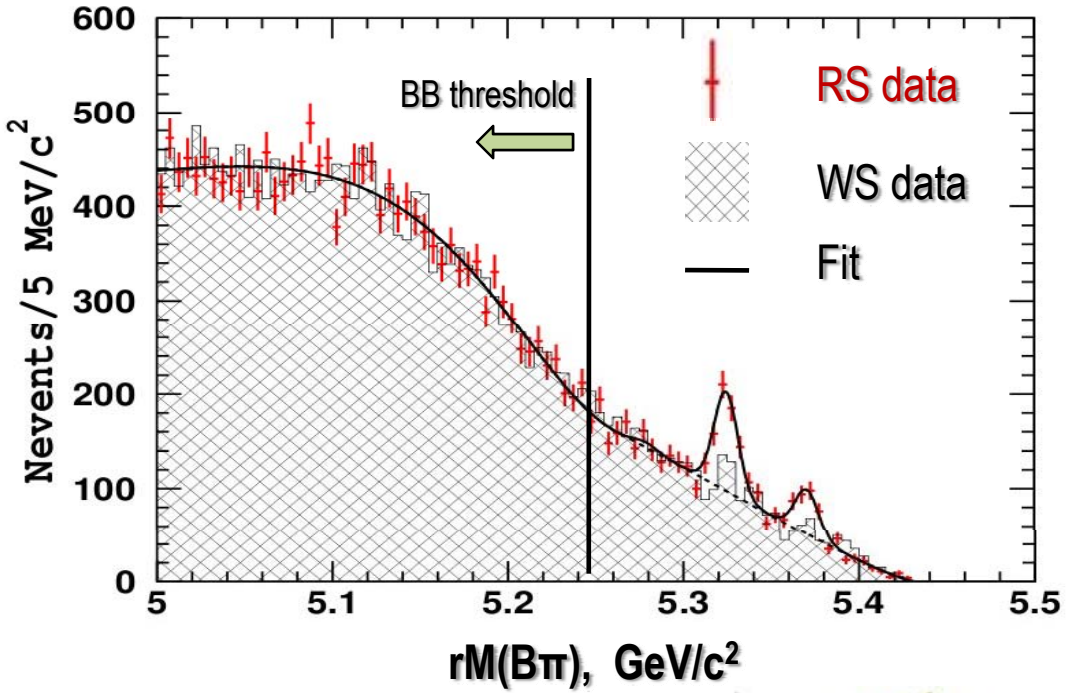


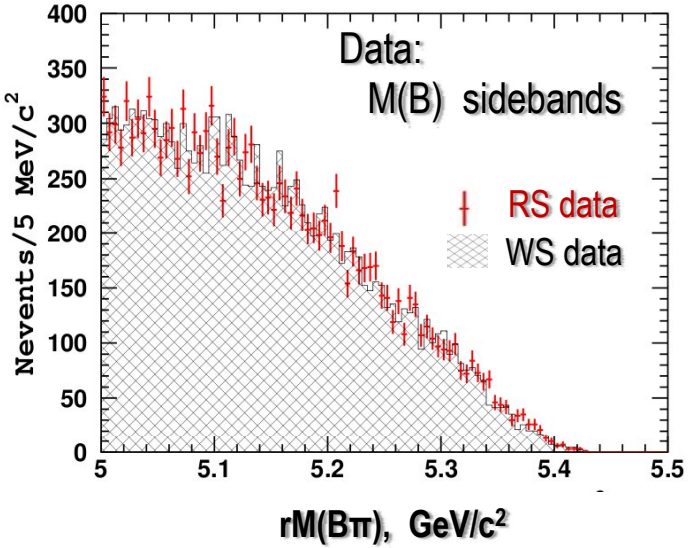
$B^{(*)}B^{(*)}\pi + BB\gamma$

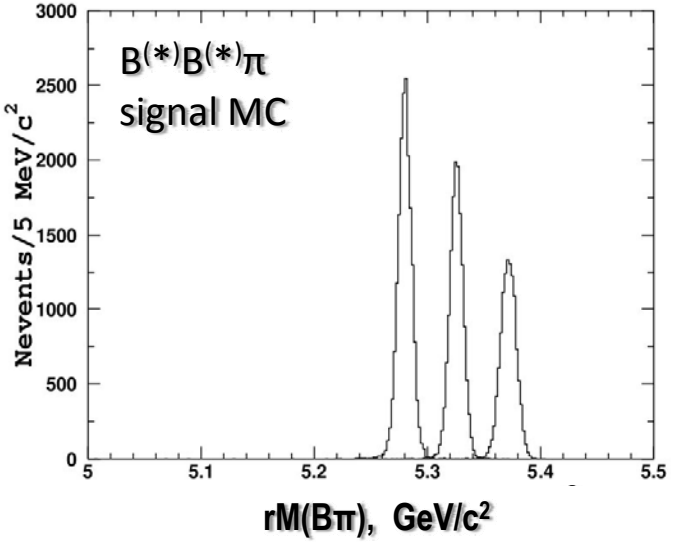
$\Upsilon(5S) \to Z_b \pi^{\pm}$

Analysis strategy:

- Combination with a charge pion from the rest of the event → calculate recoil mass against the Bπ system







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

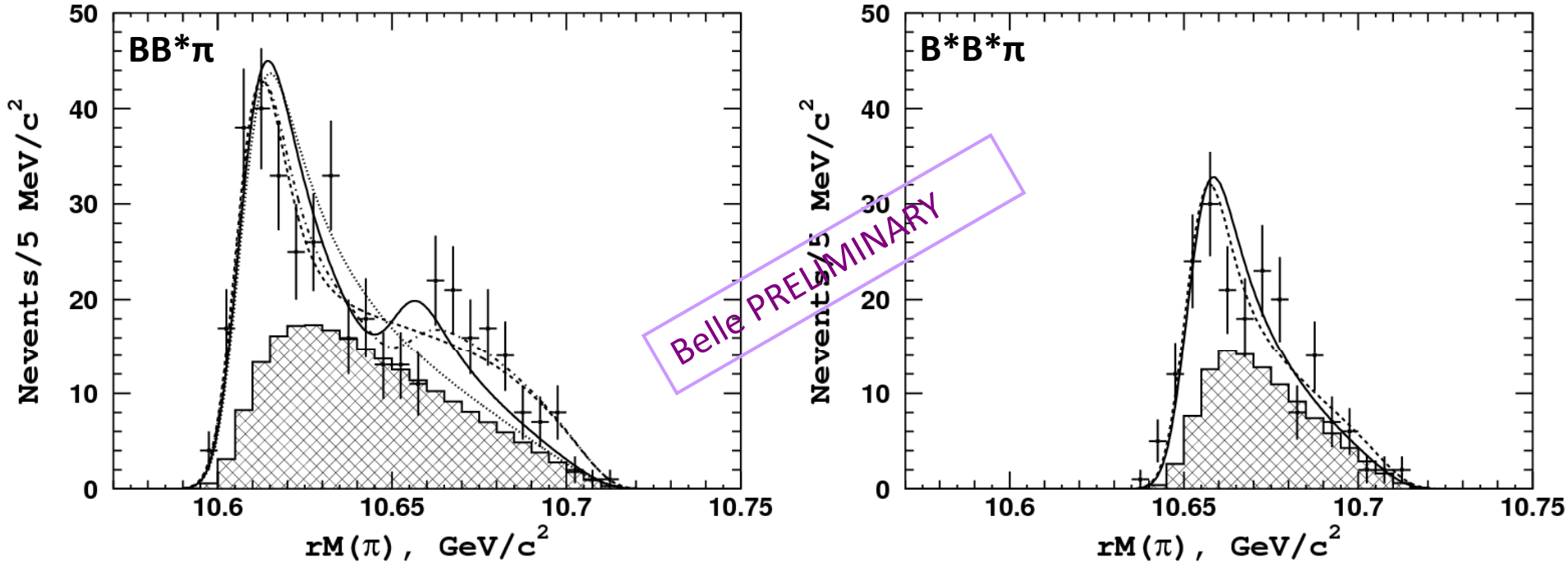
New

Summary

- **5 years after Belle experiment finished data taking & still one of the major players on the exotic field**
- **New (updated) results in both charm and bottom sectors:**
  - new results on X(3872) production in B decays
  - Y states studies with the ISR process $e^+e^- \to \psi(2S)h^+h^- + \gamma$ ($h = \pi, K$)
  - evidence for a structure near 4050 MeV in the $\psi(2S)\pi^\pm$ mass spectrum
  - $\sqrt{s}$ dependence of the $\sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-)$ first evidence for $\Upsilon(6S) \to \Upsilon(nS)\pi^+\pi^-$)
  - first observation the $\Upsilon(4S) \to \eta h_b(1P)$ transitions (1506.08914, submitted to PRL)
- **Several new analysis are near completion**
  - major update of the $Z_b \to B^{(*)}B^*$
  - $\sqrt{s}$ dependence of the $\sigma(e^+e^- \to h_b\pi^+\pi^-)$

New results are coming out soon! Stay tuned

Observation of $Z_b \to B^*B^{(*)}$



Points – right sign Bπ combinations (data);
Lines – fit to data with various models (times PHSP, convolved with resolution)
Hatched – background component

$B^*B^*\pi$ signal is well fit to just $Z_b(10650)$ signal alone

$B\bar{B}^*\pi$ data fits equally well to a sum of $Z_b(10610)$ and $Z_b(10650)$ or to a sum of $Z_b(10610)$ and non-resonant.

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

Assuming that Z_b decays are saturated by the $\Upsilon(nS)\pi$, $h_b(mP)\pi$ and $B^{(*)}B^*$ channels, one can calculate a complete table of relative branching fractions:

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	0.22 ± 0.06	0.26 ± 0.07
$\Upsilon(2S)\pi^+$	5.04 ± 1.37	2.60 ± 0.67
$\Upsilon(3S)\pi^+$	2.48 ± 0.64	1.78 ± 0.43
$h_b(1P)\pi^+$	3.23 ± 1.25	8.04 ± 2.90
$h_b(2P)\pi^+$	5.00 ± 2.36	16.1 ± 6.64
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	84.0 ± 4.0	–
$B^{*+}\bar{B}^{*0}$	–	71.3 ± 7.3

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

If the molecular model is correct, there should be other exotic states. To search for those states one needs to take data at higher c.m. energies, $E_{cm} \approx 11.5 – 12.0$ GeV