Physics at Belle experiment

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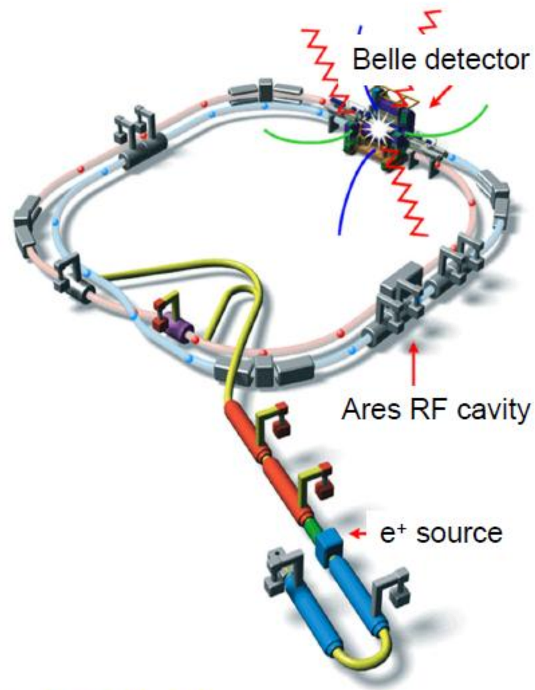
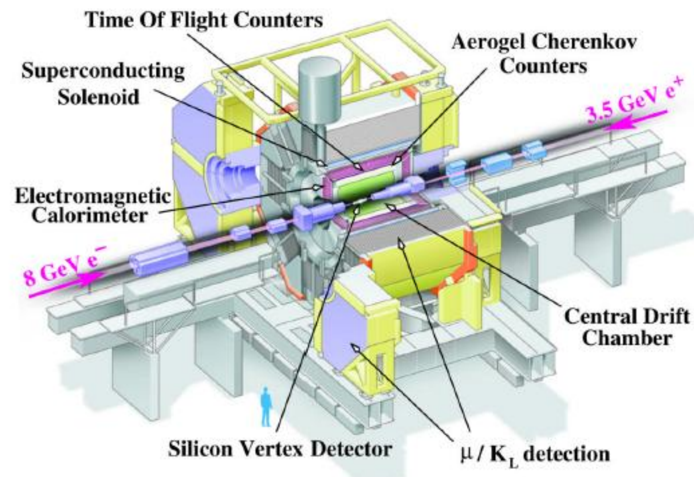
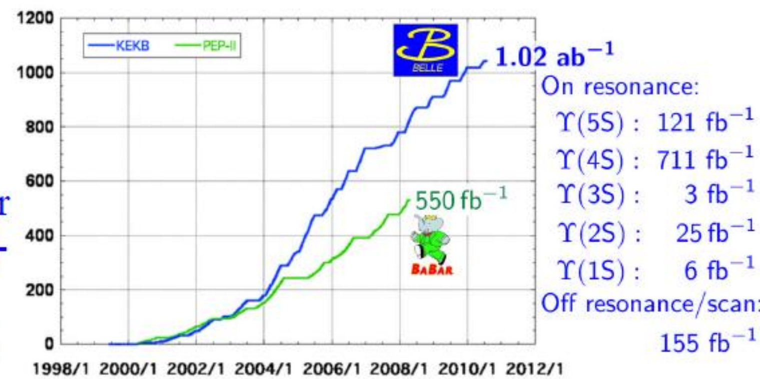
For the Belle Collaboration

XXX-th International Workshop on High Energy Physics "Particle and Astroparticle Physics, Gravitation and Cosmology: Predictions, Observations and new Projects"

Experiment and dataset



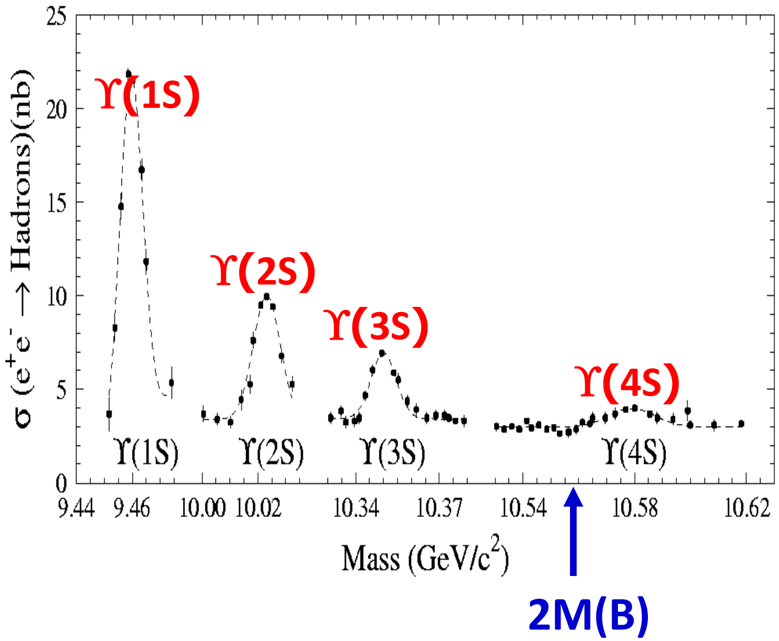


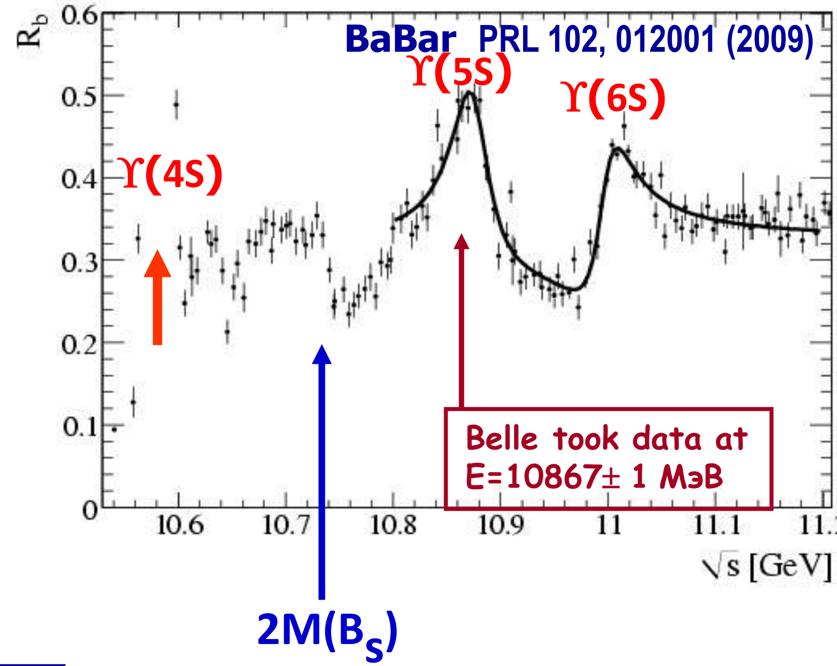


- Multitasking magnetic spectrometer that operated at KEKB asymmetric-energy e^+e^- collider in Japan
- Recorded the data at various $\Upsilon(nS)$ resonances till June 2010

2

Cross sections and numbers of events





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

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

$$\sigma(b\bar{b}) = 1.1 \text{ nb } N_{b\bar{b}} = 1.3 \times 10^9$$
$$\sigma(c\bar{c}) = 1.3 \text{ nb } N_{c\bar{c}} = 2.0 \times 10^9$$
$$\sigma(\tau\tau) = 0.9 \text{ nb } N_{\tau\tau} = 1.4 \times 10^9$$

B-factories are also charm- and τ-factories !

Recent Belle results

- Charm mixing in $D \to K\pi$ decays
  PRL 112, 111801 (2014)
- Mixing and CPV in $D \to K_S^0 \pi^+ \pi^-$
  PRD 89, 091103 (R) (2014)
- Lifetime of τ-lepton
  PRL 112, 031801 (2014)
- First observation of the $Z^0_b(10610)$ in Dalitz Analysis of $\Upsilon(10860) \to \Upsilon(nS)\pi^0\pi^0$
  PRD 88, 052016 (2013)
- Observation of $e^+e^- \to \pi^+\pi^-\pi^0\chi_{bj}$ and search for $X_b \to \omega\Upsilon(1S)$ at $\sqrt{s} \sim 10.867$ GeV
  To be submitted to PRL

$D^0\overline{D}^0$ mixing in $D \to K\pi$ decays

- Measure the time-dependent ratio of the $D^0 \to K^+\pi^-$ (wrong-sign) to $D^0 \to K^-\pi^+$ (right-sign) decay rates
- Tag RS and WS decays through the decay chain $D^{*+} \to D^0\left(K^{\mp}\pi^{\pm}\right)\pi_s^+$ by comparing charge of the pion from the D decay with that from the D^* decay

"Wrong-sign" $D^{*+} \to D^0\pi^+,\ D^0 \to K^+\pi^-$

interference: mixing, double Cabibbo-suppression (DCS)

$$R(\tilde{t}/\tau) \equiv \frac{\Gamma_{\rm WS}(\tilde{t}/\tau)}{\Gamma_{\rm RS}(\tilde{t}/\tau)} \approx R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$

Mixing $\begin{cases} x \equiv \Delta m/\Gamma & x' \equiv x\cos\delta + y\sin\delta \\ y \equiv \Delta\Gamma/2\Gamma & y' \equiv y\cos\delta - x\sin\delta \end{cases}$

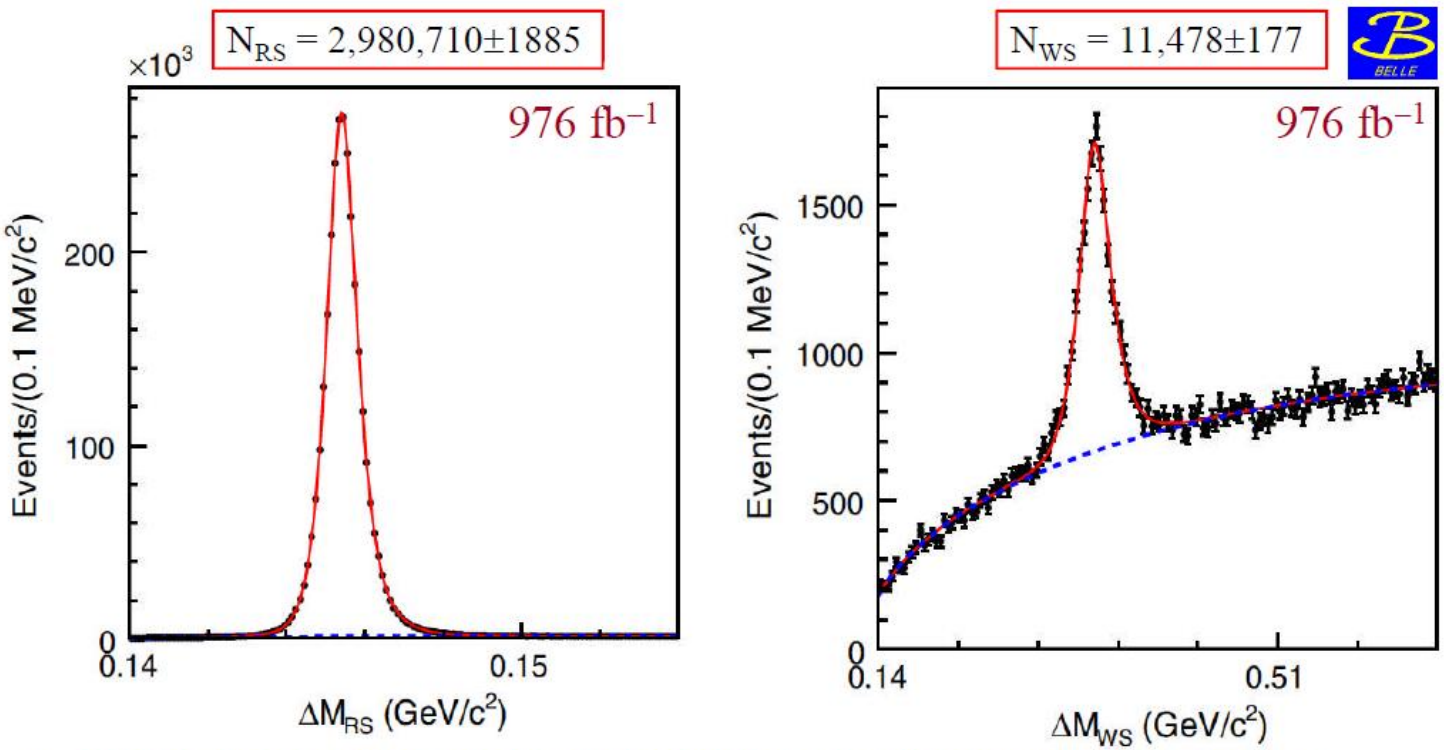
δ = relative phase

DCS $R_D \equiv \Delta\Gamma(DCS)/\Delta\Gamma(CF)$

- Take the resolution effect into account in the measurement of mean decay time of the tagged D's

Event yields in RS and WS decays

PRL 112, 111801 (2014)



- Signal: A sum of a Gaussian and a Johnson distribution of common mean

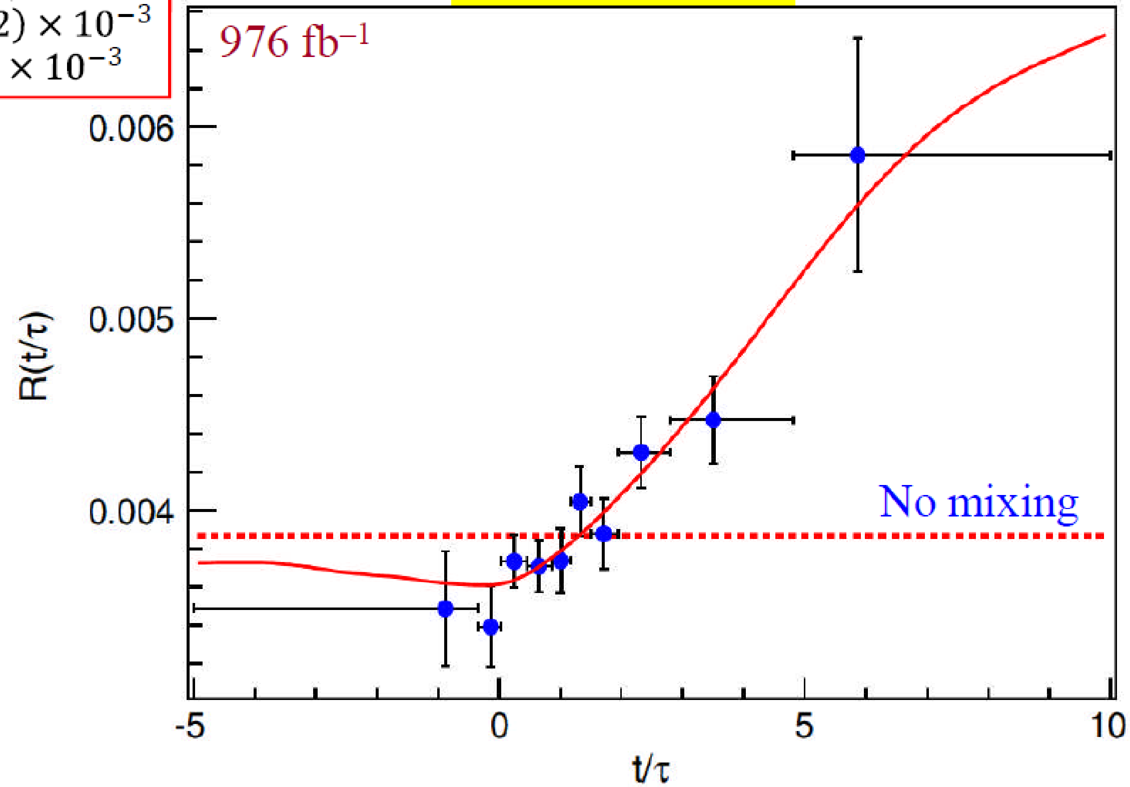
Biometrika 36, 149 (1949)

- Background: An empirical threshold function $(x - m_\pi)^\alpha e^{-\beta(x-m_\pi)}$

Observation of D^0-$\overline{D}^0$ mixing

$R_D = (3.53 \pm 0.13) \times 10^{-3}$
$x'^2 = (0.09 \pm 0.22) \times 10^{-3}$
$y' = (4.6 \pm 3.4) \times 10^{-3}$

PRL 112, 111801 (2014)



- No mixing hypothesis is ruled out at the 5.1 standard deviation (σ) level
- Constitutes the first observation of D^0-$\overline{D}^0$ mixing in e^+e^- collisions

CP violation in charm decays

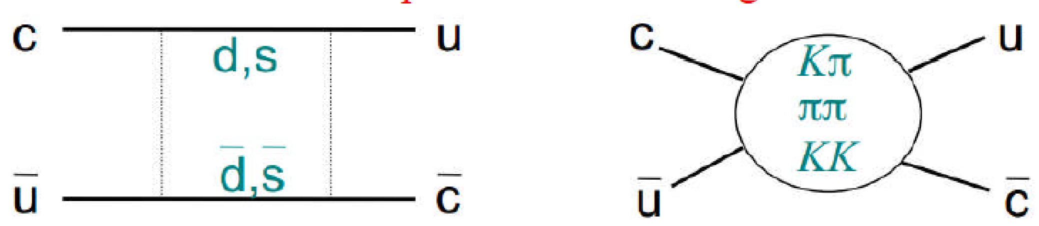
- Provides an interesting test bed for new physics as the standard model (SM) predicts a very small asymmetry, owing to
  - Large GIM/CKM suppression
  - Lack of a large hierarchy in the down-type quark masses

- Typical SM value of the order of 10^{-3} ➡ most promising candidates to study are singly Cabibbo-suppressed (SCS) decays

Grossman, Kagan and Nir
PRD 75, 036008 (2007)

- While talking about a percentage effect, we need a good control on the SM predictions, something that is in general lacking in this sector due to long-distance effects

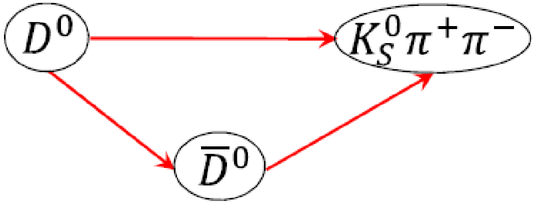
An example of "short vs. long"



- Further, with D^0-$\bar{D}^0$ mixing being firmly established, what about CP violation (CPV) in the mixing or due to interference between mixing and decay?

Study of mixing and CPV in $D^0 \to K_S^0\pi^+\pi^-$

- Determine D^0-$\overline{D}^0$ mixing and CPV effects by studying the time-dependent decay rate of self-conjugated $D^0 \to K_S^0\pi^+\pi^-$ decays



- Expressing A_f ($\bar{A}_f$), amplitude of the D^0 ($\overline{D}^0$) decay into $f \equiv K_S^0\pi^+\pi^-$, as a function of the Dalitz plot variables $(m^2_{K_S^0\pi^+}, m^2_{K_S^0\pi^-})$, the corresponding time-dependent decay rates are:

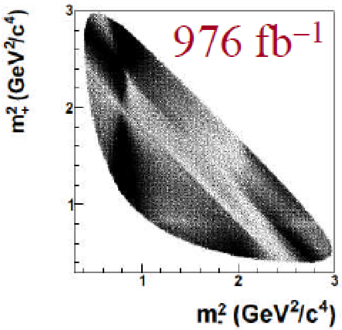
$$|\mathcal{M}(f,t)|^2 = \frac{e^{-\Gamma t}}{2}\{(|\mathcal{A}_f|^2 + |\tfrac{q}{p}|^2|\mathcal{A}_{\bar{f}}|^2)\cosh(\Gamma y t) + (|\mathcal{A}_f|^2 - |\tfrac{q}{p}|^2|\mathcal{A}_{\bar{f}}|^2)\cos(\Gamma x t) + 2\Re(\tfrac{q}{p}\mathcal{A}_{\bar{f}}\mathcal{A}_f{}^*)\sinh(\Gamma y t) - 2\Im(\tfrac{q}{p}\mathcal{A}_{\bar{f}}\mathcal{A}_f{}^*)\sin(\Gamma x t)\}$$

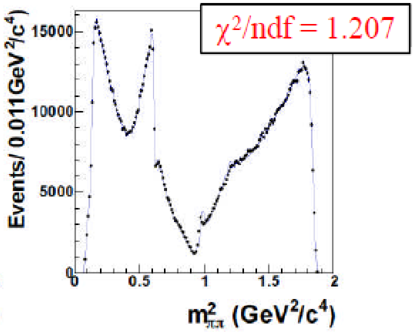
$$|\overline{\mathcal{M}}(f,t)|^2 = \frac{e^{-\Gamma t}}{2}\{(|\mathcal{A}_{\bar{f}}|^2 + |\tfrac{p}{q}|^2|\mathcal{A}_f|^2)\cosh(\Gamma y t) + (|\mathcal{A}_{\bar{f}}|^2 - |\tfrac{p}{q}|^2|\mathcal{A}_f|^2)\cos(\Gamma x t) + 2\Re(\tfrac{p}{q}\mathcal{A}_f\mathcal{A}_{\bar{f}}{}^*)\sinh(\Gamma y t) - 2\Im(\tfrac{p}{q}\mathcal{A}_f\mathcal{A}_{\bar{f}}{}^*)\sin(\Gamma x t)\}$$

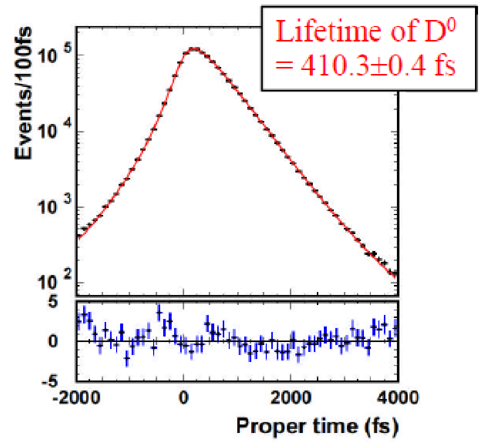
- Γ is the mean decay width of the two mass eigenstates: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$
- x and y are the D^0-$\overline{D}^0$ mixing parameters, defined earlier
- p and q are complex coefficients that satisfy $|p|^2 + |q|^2 = 1$ in case of no CP violation, whereas possible CPV can lead to ${}^{q}/_{p} \neq 1$

Mixing and CPV results from $D^0 \to K_S^0\pi^+\pi^-$

- Time-dependent fit to the Dalitz plot (shown below together with one of its projections)







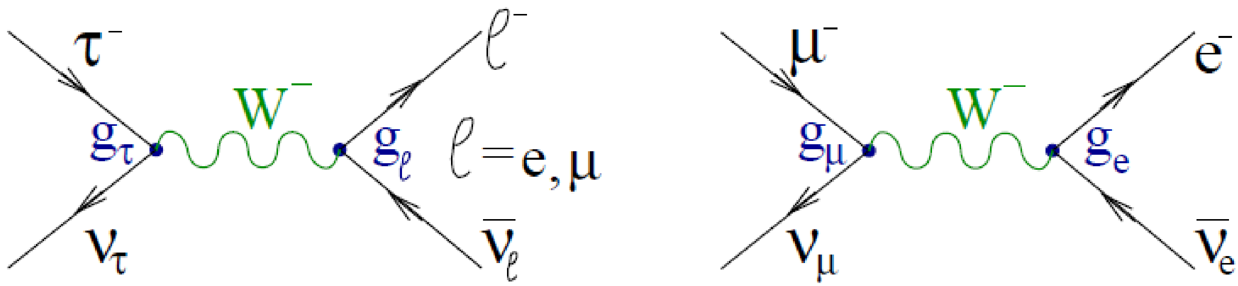
Fit type	Parameter	Fit result
No *CPV*	$x(\%)$	$0.56 \pm 0.19^{+0.03}_{-0.09}{}^{+0.06}_{-0.09}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04}_{-0.05}{}^{+0.03}_{-0.06}$
CPV	$x(\%)$	$0.56 \pm 0.19^{+0.04}_{-0.08}{}^{+0.06}_{-0.08}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04}_{-0.05}{}^{+0.03}_{-0.07}$
	$\lvert q/p \rvert$	$0.90^{+0.16}_{-0.15}{}^{+0.05}_{-0.04}{}^{+0.06}_{-0.05}$
	$\arg(q/p)(^\circ)$	$-6 \pm 11 \pm 3^{+3}_{-4}$

Assume no direct CP violation $\Rightarrow$ $A_f = \bar{A}_f$ for the $K_S^0\pi^+\pi^-$ mode

- 2.5σ away from the no-mixing hypothesis
- No evidence for indirect CP violation

Measurement of τ-lepton lifetime, motivation

Precise measurement of the tau lifetime is necessary for the tests of lepton universality in the SM: $g_e = g_\mu = g_\tau$



$$\Gamma(L^- \to \ell^- \bar{\nu}_\ell \nu_L(\gamma)) = \frac{\mathcal{B}(L^- \to \ell^- \bar{\nu}_\ell \nu_L(\gamma))}{\tau_L} = \frac{g_L^2 g_\ell^2}{32 M_W^4} \frac{m_L^5}{192\pi^3} F_{\rm corr}(m_L, m_\ell)$$

$$F_{\rm corr}(m_L, m_\ell) = f(x)\left(1 + \frac{3}{5}\frac{m_L^2}{M_W^2}\right)\left(1 + \frac{\alpha(m_L)}{2\pi}\left(\frac{25}{4} - \pi^2\right)\right)$$

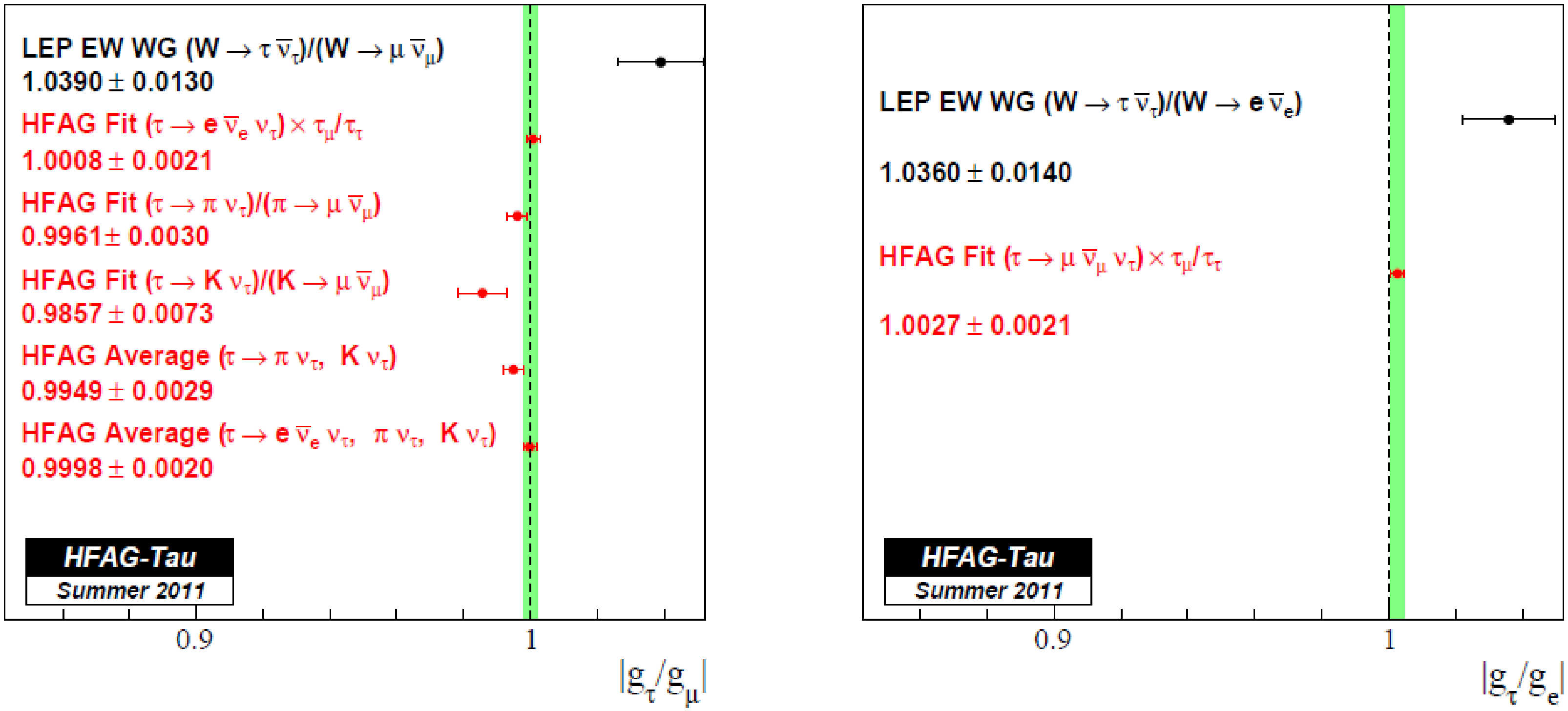
$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x, \quad x = m_\ell / m_L$$

$$\mathcal{B}(\mu^- \to e^- \bar{\nu}_e \nu_\mu(\gamma)) = 1$$

$$\frac{g_\tau}{g_e} = \sqrt{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau(\gamma)) \frac{\tau_\mu}{\tau_\tau} \frac{m_\mu^5}{m_\tau^5} \frac{F_{\rm corr}(m_\mu, m_e)}{F_{\rm corr}(m_\tau, m_\mu)}}, \quad \frac{\mathbf{g}_\tau}{\mathbf{g}_e} = \mathbf{1.0024 \pm 0.0021} \text{ (HFAG2012)}$$

$$\frac{g_\tau}{g_\mu} = \sqrt{\mathcal{B}(\tau^- \to e^- \bar{\nu}_\mu \nu_\tau(\gamma)) \frac{\tau_\mu}{\tau_\tau} \frac{m_\mu^5}{m_\tau^5} \frac{F_{\rm corr}(m_\mu, m_e)}{F_{\rm corr}(m_\tau, m_e)}}, \quad \frac{\mathbf{g}_\tau}{\mathbf{g}_\mu} = \mathbf{1.0006 \pm 0.0021} \text{ (HFAG2012)}$$

Measurement of τ-lepton lifetime, motivation



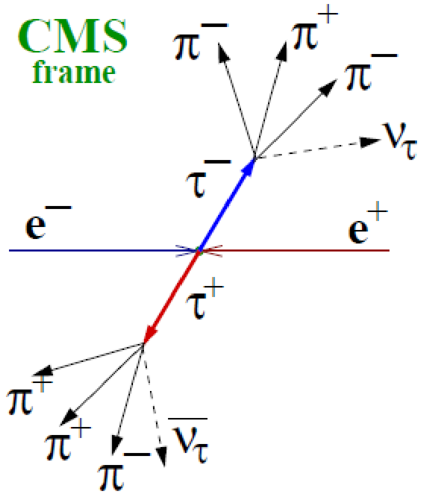
S. Schael *et al.* [ALEPH, DELPHI, L3, OPAL, LEP EWG]
Phys. Rep. 532, 119 (2013)

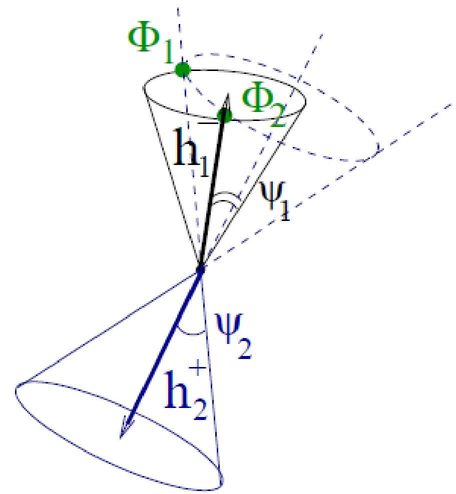
$$\frac{2\mathcal{B}(W \to \tau\nu_\tau)}{\mathcal{B}(W \to \mu\nu_\mu) + \mathcal{B}(W \to e\nu_e)} = 1.066 \pm 0.025$$

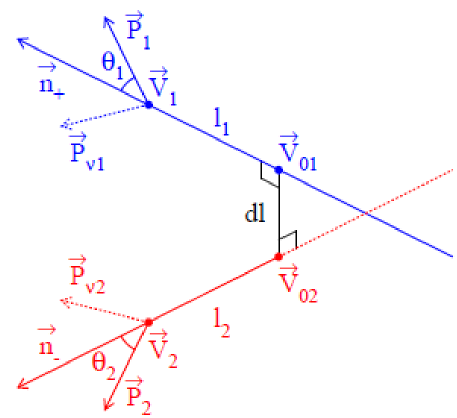
2.6σ deviation from the Standard Model

Measurement of τ-lepton lifetime, method

We analyze $e^+e^- \to \tau^+\tau^- \to (\pi^+\pi^+\pi^-\bar{\nu}_\tau,\ \pi^+\pi^-\pi^-\nu_\tau)$ events.







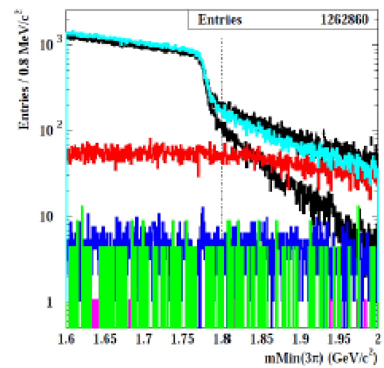
$$\cos\psi_{1,2} = \frac{2E_\tau E_{h_{1,2}} - M_\tau^2 - m_{h_{1,2}}^2}{2p_\tau p_{h_{1,2}}}$$

$$x = \frac{\ell}{\beta_\tau\gamma_\tau}$$

- τ momentum direction is determined with two-fold ambiguity in CMS, for the analysis we use the average axis.
- Asymmetric-energy layout of experiment allows us to determine $\tau^+\tau^-$ production point in LAB independently from the position of beam IP.
- Possibility to test CPT conservation measuring τ^- and τ^+ lifetimes separately.

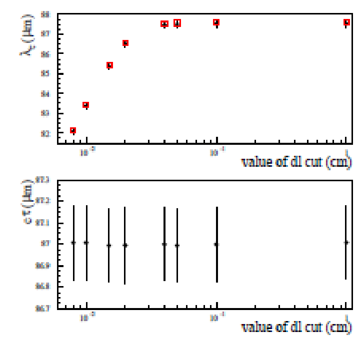
Measurement of τ-lepton lifetime, selections

Use the data sample of $\int Ldt = 711$ fb^{-1} with $N_{\tau\tau} = 650 \times 10^6$



Selection criteria:

- Event is separated into two hemispheres in CMS, Thrust>0.9.
- Each hemisphere contains 3 charge pions with the ±1 net charge.
- There are no additional K_S^0, Λ, π^0 candidates. Number of additional photons $N_\gamma < 6$ with $E_\gamma^{\mathrm{TOT}} < 0.7$ GeV.
- $P_\perp(6\pi) > 0.5$ GeV/c, 4 GeV/$c^2 < M_{\mathrm{inv}}(6\pi) < 10.25$ GeV/c^2.
- Pseudomass $\sqrt{M_h^2 + 2(E_{\mathrm{beam}} - E_h)(E_h - P_h)} < 1.8$ GeV/c^2, $h = (3\pi)^-, (3\pi)^+$.
- Cuts on the quality parameters of the vertex fits and tau axis reconstruction.
- Minimal distance between τ^- and τ^+ axes in LAB $dl < 0.02$ cm.



1148360 events were selected with $\sim$2% background contamination, the main background comes from $e^+e^- \to q\bar{q}$ ($q =$u, d, s).

Fit of proper time distributions

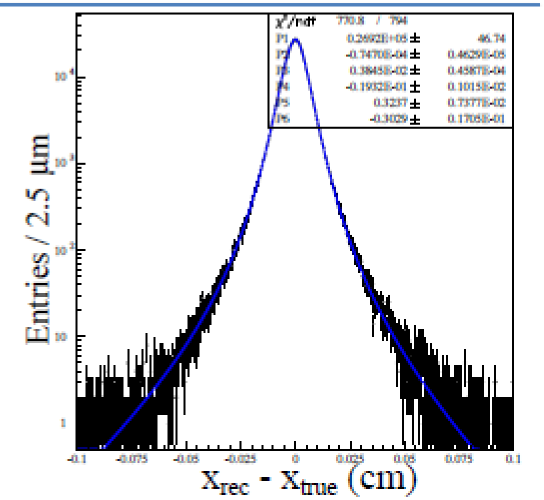
$$\mathcal{P}(x) = \mathcal{N} \int e^{-x'/\lambda_\tau} R(x - x'; \vec{P}) dx' + \mathcal{N}_{uds} R(x; \vec{P}) + \mathcal{P}_{cb}(x),$$

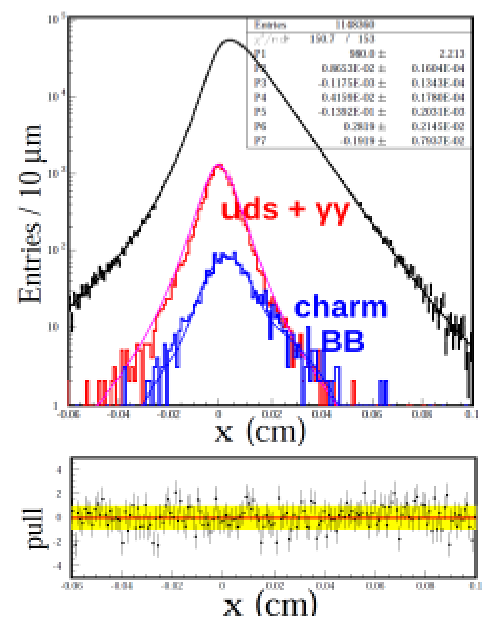
$$R(x; \vec{P}) = (1 - 2.5x) \cdot \exp\left(-\frac{(x - P_1)^2}{2\sigma^2} \right),$$

$$\sigma = P_2 + P_3 |x - P_1|^{1/2} + P_4 |x - P_1| + P_5 |x - P_1|^{3/2}$$

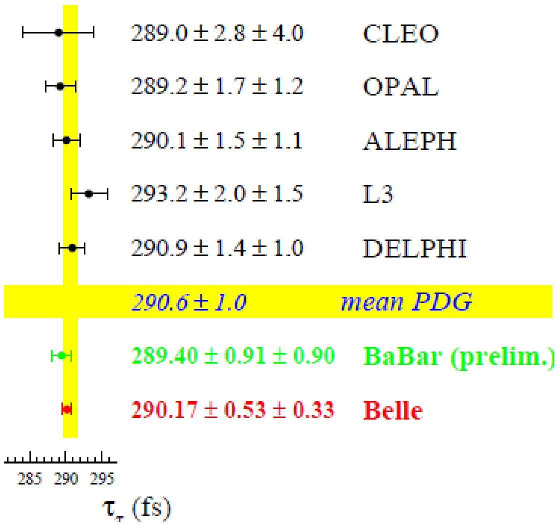
- Free parameters of the fit: λ_τ, $\mathcal{N}$, $\vec{P} = (P_1, \ldots, P_5)$
- λ_τ - estimator of $c\tau_\tau$, $c\tau_\tau = \lambda_\tau + \Delta_{\text{corr}}$, Δ_{corr} is determined from MC;
- $R(x; \vec{P})$ - detector resolution function;
- $\mathcal{N}_{uds}$ - contribution of background from $e^+e^- \to q\bar{q}$ ($q = u, d, s$) (predicted by MC)
- $\mathcal{P}_{cb}(x)$ - PDF for background from $e^+e^- \to q\bar{q}$ ($q = c, b$) (fixed from MC)

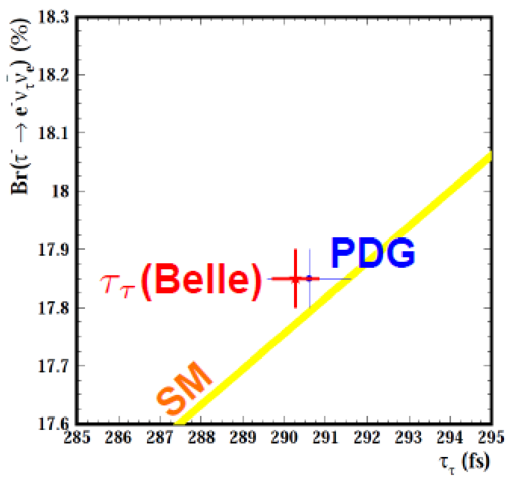
From the fit of experimental data $\lambda_\tau = 86.53 \pm 0.16$ μm, applying correction $\Delta_{\text{corr}} = 0.46$ μm we got: $c\tau_\tau = 86.99 \pm 0.16$ μm





Measurement of τ-lepton lifetime, result





Systematic uncertainties

Source	**$\Delta c\tau$ (μm)**
Silicon vertex detector alignment	0.090
Asymmetry fixing	0.030
Fit range	0.020
Beam energy, ISR, FSR	0.024
Background contribution	0.010
τ-lepton mass	0.009
Total	**0.101**

$$c\tau_\tau = (86.99 \pm 0.16(\text{stat}) \pm 0.10(\text{syst}))\ \mu\text{m}.$$

$$\tau_\tau = (290.17 \pm 0.53(\text{stat}) \pm 0.33(\text{syst}))\ \text{fs}.$$

$$|\tau_{\tau^+} - \tau_{\tau^-}|/\tau_{\text{average}} < 7.0 \times 10^{-3}\ \text{at 90\% CL}.$$

Lepton universality

$$g_\tau/g_e = 1.0024 \pm 0.0021\ (\text{HFAG2012})$$

$$\mathbf{g_\tau/g_e = 1.0031 \pm 0.0016}\ (\text{new Belle}\ \tau_\tau)$$

$$g_\tau/g_\mu = 1.0006 \pm 0.0021\ (\text{HFAG2012})$$

$$\mathbf{g_\tau/g_\mu = 1.0013 \pm 0.0016}\ (\text{new Belle}\ \tau_\tau)$$

Puzzles of Υ(5S) decays

Anomalous production of $\Upsilon(nS)\,\pi^+\pi^-$ with 21.7 fb^{-1}

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

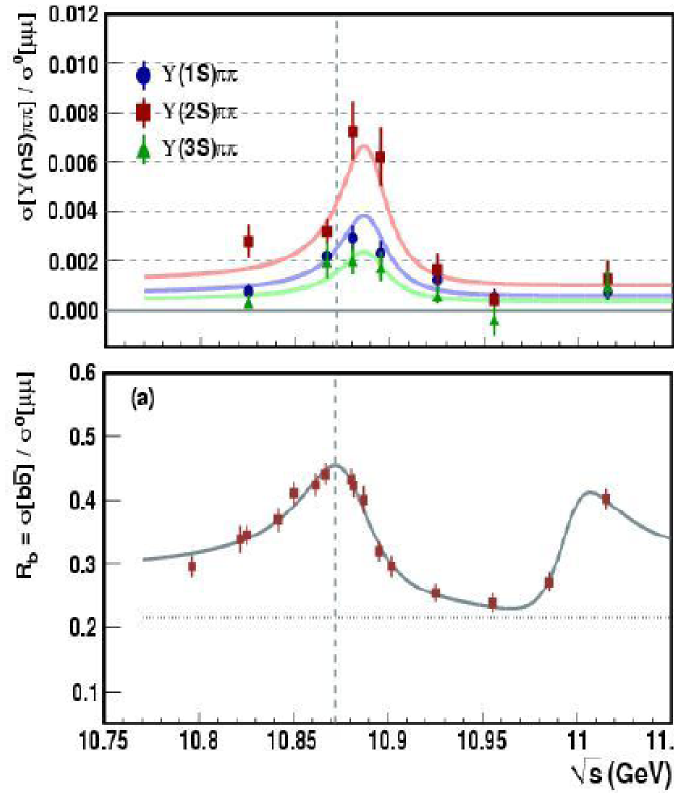
10^2

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

Simonov JETP Lett 87,147(2008)

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

PRD82,091106R(2010)



Dedicated energy scan ⇒
shapes of R_b and $\sigma(\Upsilon\pi\pi)$ different (2σ)

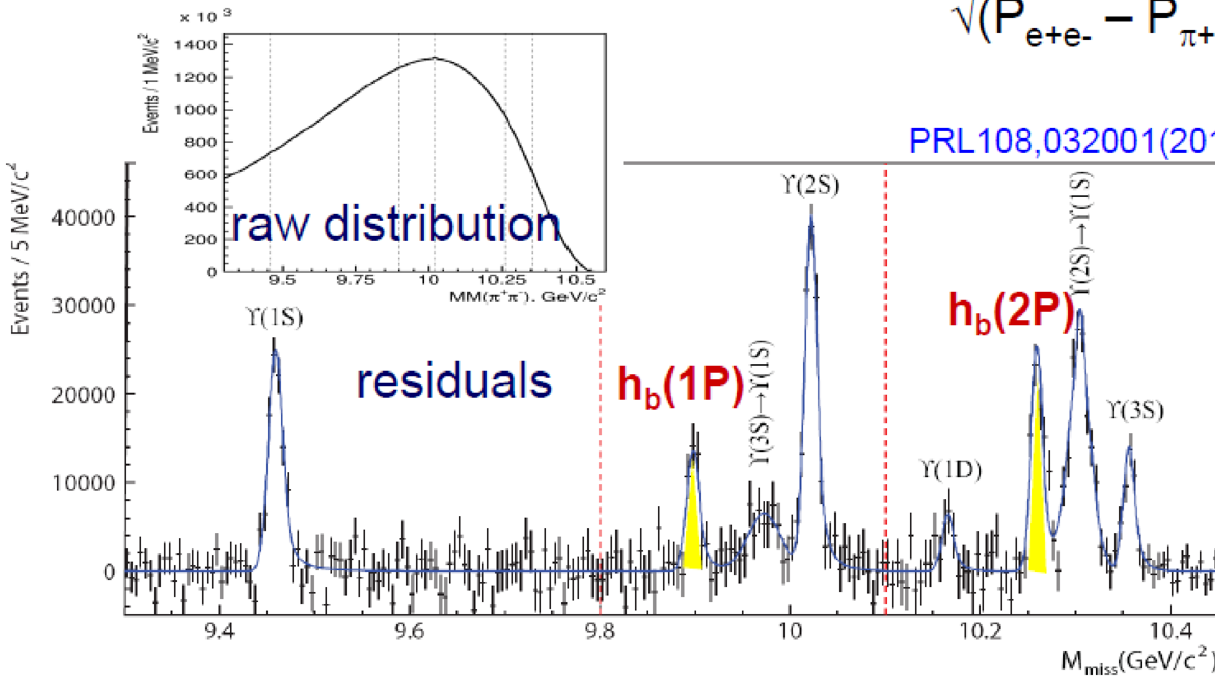
Υ(5S) is very interesting and not yet understood
Finally Belle recorded 121.4fb^{-1} data set at Υ(5S)

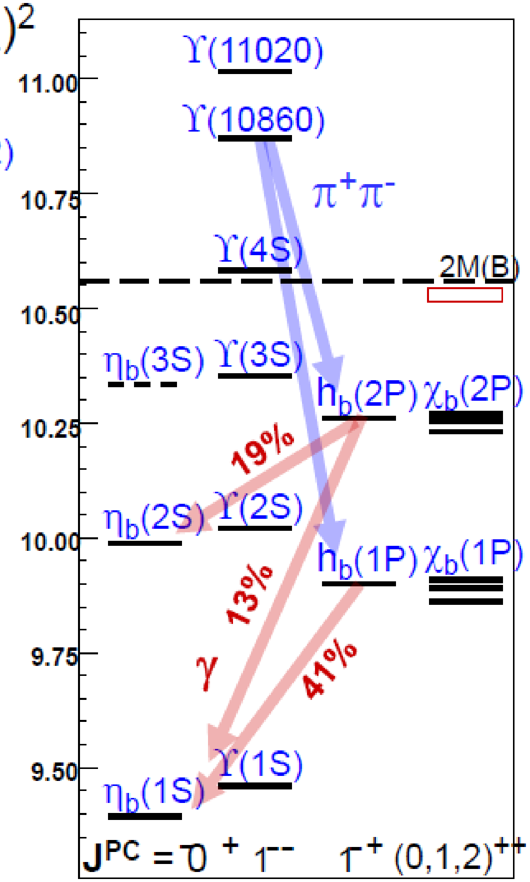
Observation of $h_b(1P,2P)$

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

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

PRL108,032001(2012)





Belle arxiv:1205.6351

$\Delta M_{HF}(\mathbf{1P}) = +0.8 \pm 1.1$ 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 $e^+e^- \to \psi(4170) \to h_c\ \pi^+\pi^-$

$h_b(nP)$ decays are a source of $\eta_b(mS)$

Observation of $h_b(1P,2P) \to \eta_b(1S)\,\gamma$

$e^+e^- \to \Upsilon(5S) \to h_b(nP)\,\pi^+\pi^-$ reconstruct

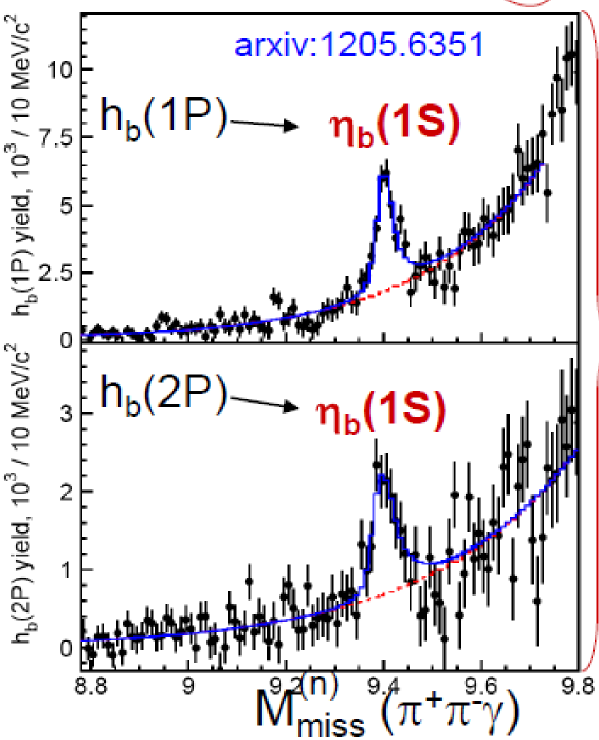
$\quad\quad\quad\quad\quad\quad\quad\quad\quad \hookrightarrow \eta_b(1S)\,\gamma$

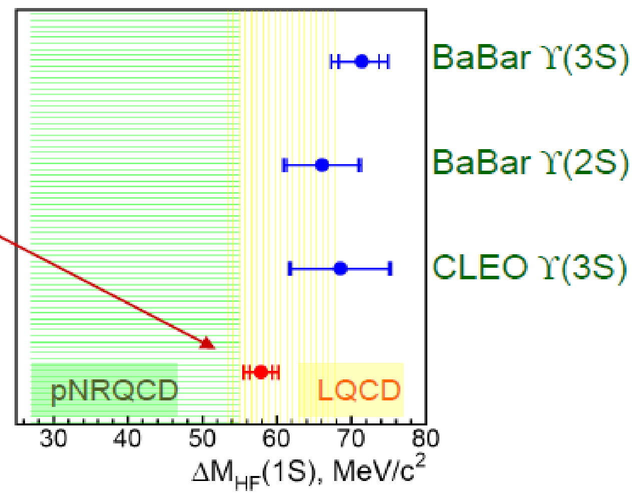
$\Delta M_{HF}(1S)$

Belle : 57.9 ± 2.3 MeV

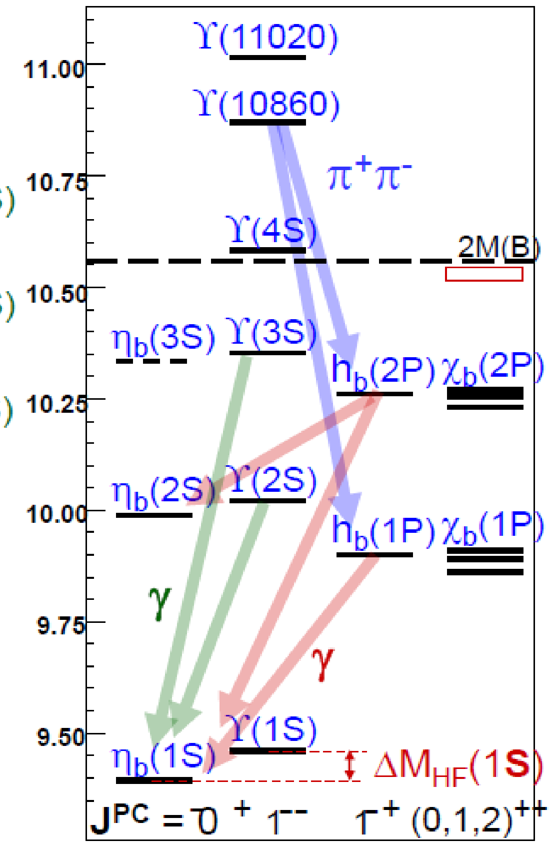
PDG'12 : 69.3 ± 2.8 MeV

3σ





Kniehl et al, PRL92,242001(2004)
Meinel, PRD82,114502(2010)



Mizuk et al. Belle PRL 109 (2012) 232002

Belle result decreases tension with theory

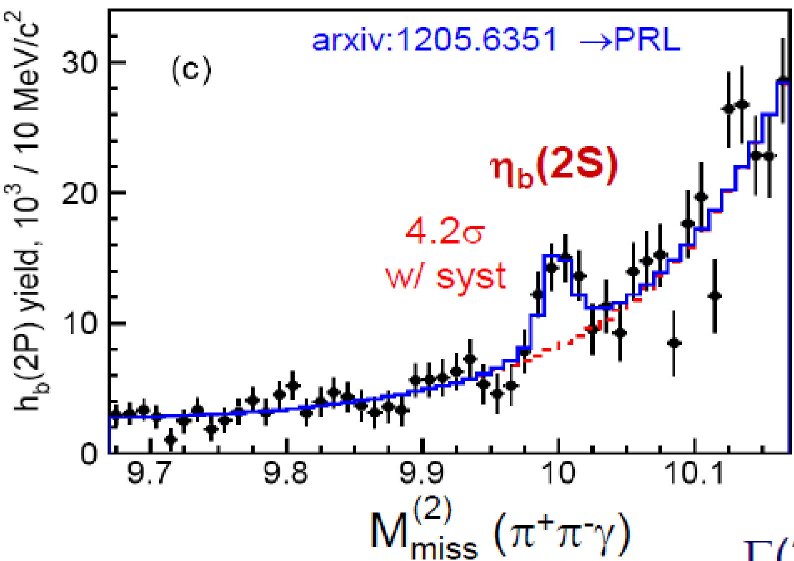
First measurement $\Gamma = 10.8\,^{+4.0}_{-3.7}\,^{+4.5}_{-2.0}$ MeV

as expected

First evidence for $\eta_b(2S)$

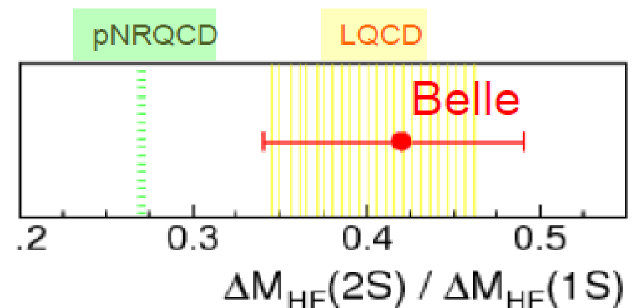
$e^+e^- \to \Upsilon(5S) \to h_b(2P)\,\pi^+\pi^-$
$\to \eta_b(2S)\,\gamma$

Mizuk et al. Belle PRL 109 (2012) 232002



$\Delta M_{HF}(2S) = 24.3\,^{+4.0}_{-4.5}$ MeV

First measurement



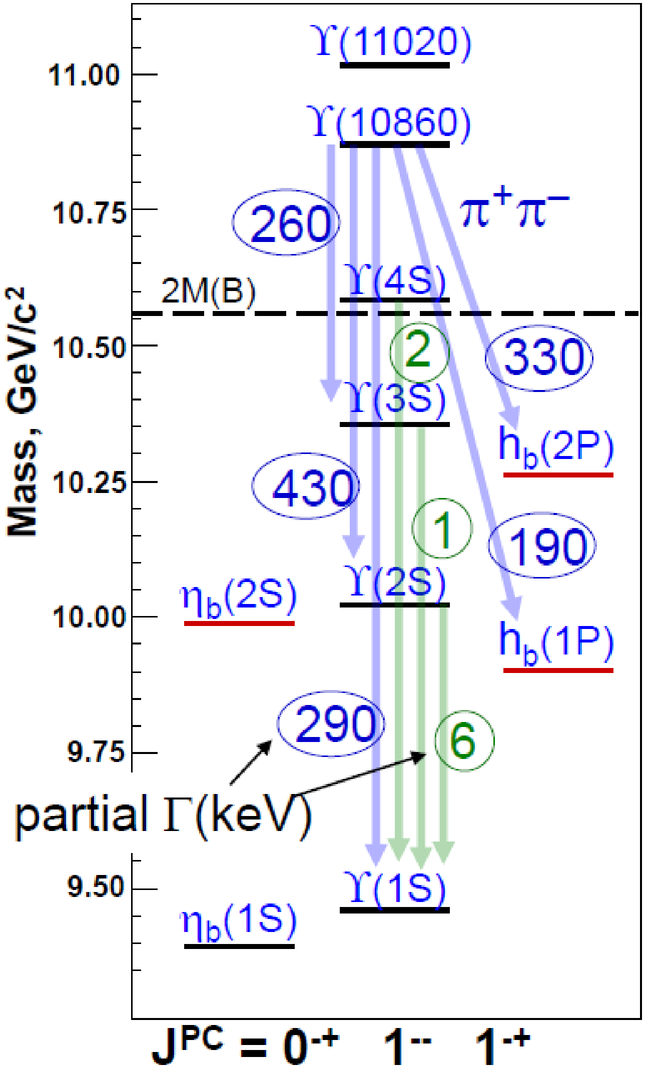
In agreement with theory

$\Gamma(2S) = 4 \pm 8$ MeV, < 24MeV @ 90% C.L.
expect ~4MeV

Branching fractions		Expectations
$BF[h_b(1P) \to \eta_b(1S)\,\gamma]$ =	$49.2 \pm 5.7^{+5.6}_{-3.3}$ %	41% Godfrey Rosner PRD66,014012(2002)
$BF[h_b(2P) \to \eta_b(1S)\,\gamma]$ =	$22.3 \pm 3.8^{+3.1}_{-3.3}$ %	13%
$BF[h_b(2P) \to \eta_b(2S)\,\gamma]$ =	$47.5 \pm 10.5^{+6.8}_{-7.7}$ %	19%

c.f. BESIII $BF[h_c(1P) \to \eta_c(1S)\,\gamma] = 54.3 \pm 8.5$ % 39%

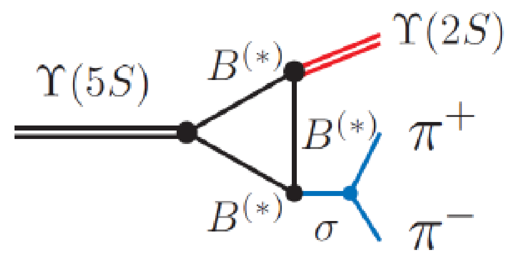
Anomalies in $\Upsilon(5S)\to(b\bar{b})\pi^+\pi^-$ transitions



Belle: PRL100, 112001 (2008)

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

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



Belle: PRL108, 032001 (2012)

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

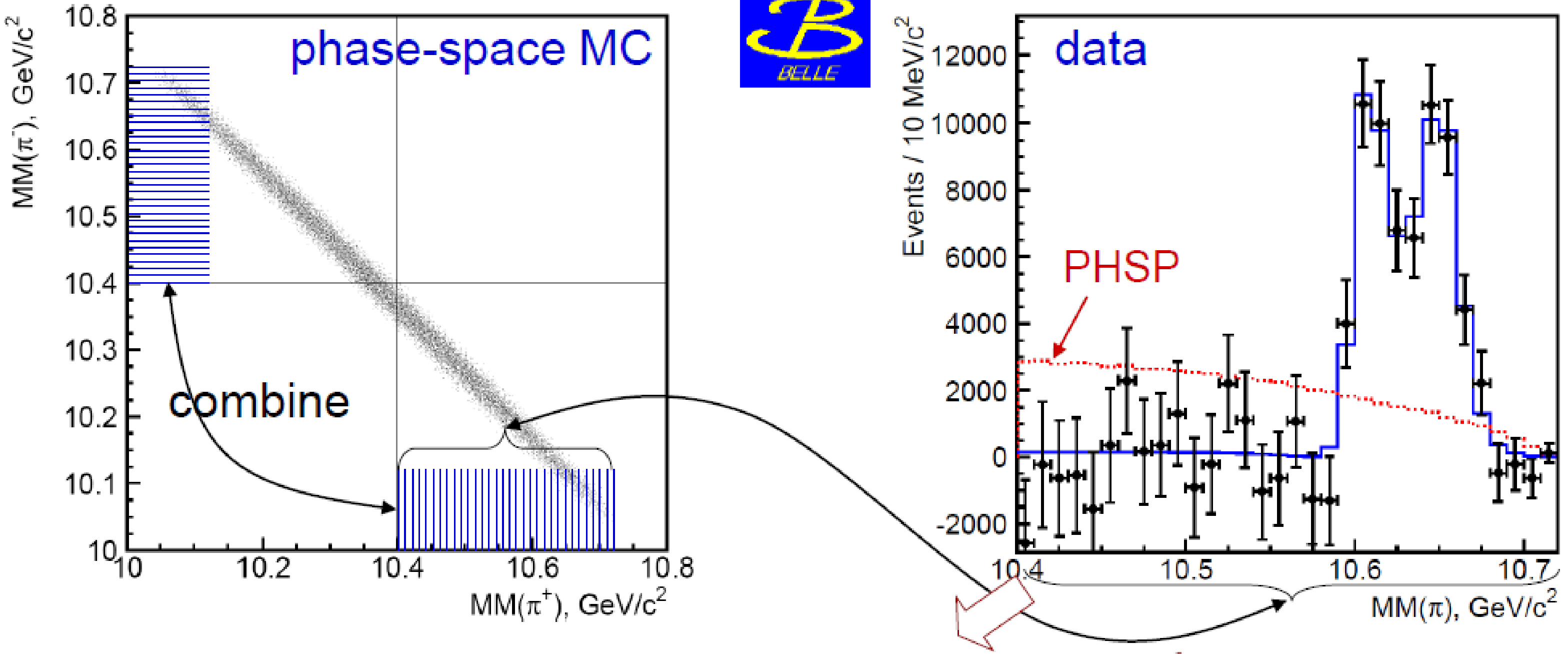
~~Heavy Quark Symmetry~~

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

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

Resonant substructure of $\Upsilon(5S) \to h_b(1P)\,\pi^+\pi^-$

$P(h_b) = P_{\Upsilon(5S)} - P(\pi^+\pi^-) \Rightarrow$ **$M(h_b\pi^+) = MM(\pi^-)$** $\Rightarrow$ ***measure $\Upsilon(5S) \to h_b\pi\pi$ yield in bins of $MM(\pi)$***



Fit function $|BW(s, M_1, \Gamma_1) + ae^{i\phi}BW(s, M_2, \Gamma_2) + be^{i\psi}|^2 \,\frac{qp}{\sqrt{s}}$

Results

$M_1 = 10605.1 \pm 2.2\,^{+3.0}_{-1.0}$ MeV/c² ~$B\bar{B}^*$ threshold

$\Gamma_1 = 11.4\,^{+4.5}_{-3.9}\,^{+2.1}_{-1.2}$ MeV

$a = 1.8\,^{+1.0}_{-0.7}\,^{+0.1}_{-0.5}$

$M_2 = 10654.5 \pm 2.5\,^{+1.0}_{-1.9}$ MeV/c² ~$B^*\bar{B}^*$ threshold

$\Gamma_2 = 20.9\,^{+5.4}_{-4.7}\,^{+2.1}_{-5.7}$ MeV

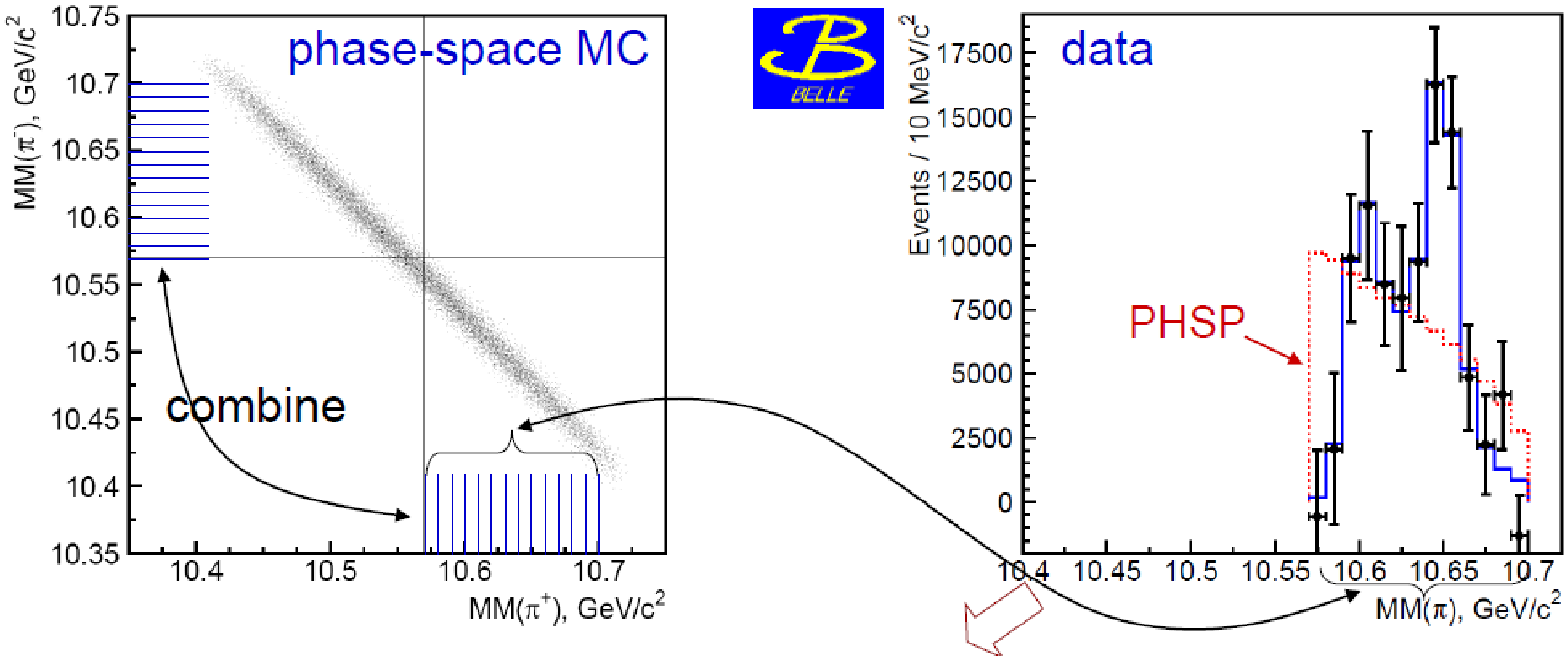
$\varphi = 188\,^{+44}_{-58}\,^{+4}_{-9}$ degree

Significances

2 vs.1 : 7.4σ (6.6σ w/ syst)

2 vs.0 : 18σ (16σ w/ syst)

Resonant substructure of $\Upsilon(5S) \to h_b(2P)\,\pi^+\pi^-$



$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M_1 = 10605.1 \pm 2.2\,^{+3.0}_{-1.0}$ MeV/c^2	$10596 \pm 7\,^{+5}_{-2}$ MeV/c^2
$\Gamma_1 = 11.4\,^{+4.5}_{-3.9}\,^{+2.1}_{-1.2}$ MeV	$16\,^{+16}_{-10}\,^{+13}_{-4}$ MeV
$M_2 = 10654.5 \pm 2.5\,^{+1.0}_{-1.9}$ MeV/c^2	$10651 \pm 4 \pm 2$ MeV/c^2
$\Gamma_2 = 20.9\,^{+5.4}_{-4.7}\,^{+2.1}_{-5.7}$ MeV	$12\,^{+11}_{-9}\,^{+8}_{-2}$ MeV
$a = 1.8\,^{+1.0}_{-0.7}\,^{+0.1}_{-0.5}$	$1.3\,^{+3.1}_{-1.1}\,^{+0.4}_{-0.7}$
$\varphi = 188\,^{+44}_{-58}\,^{+4}_{-9}$ degree	$255\,^{+56}_{-72}\,^{+12}_{-183}$ degree

consistent

[preliminary]

Significances

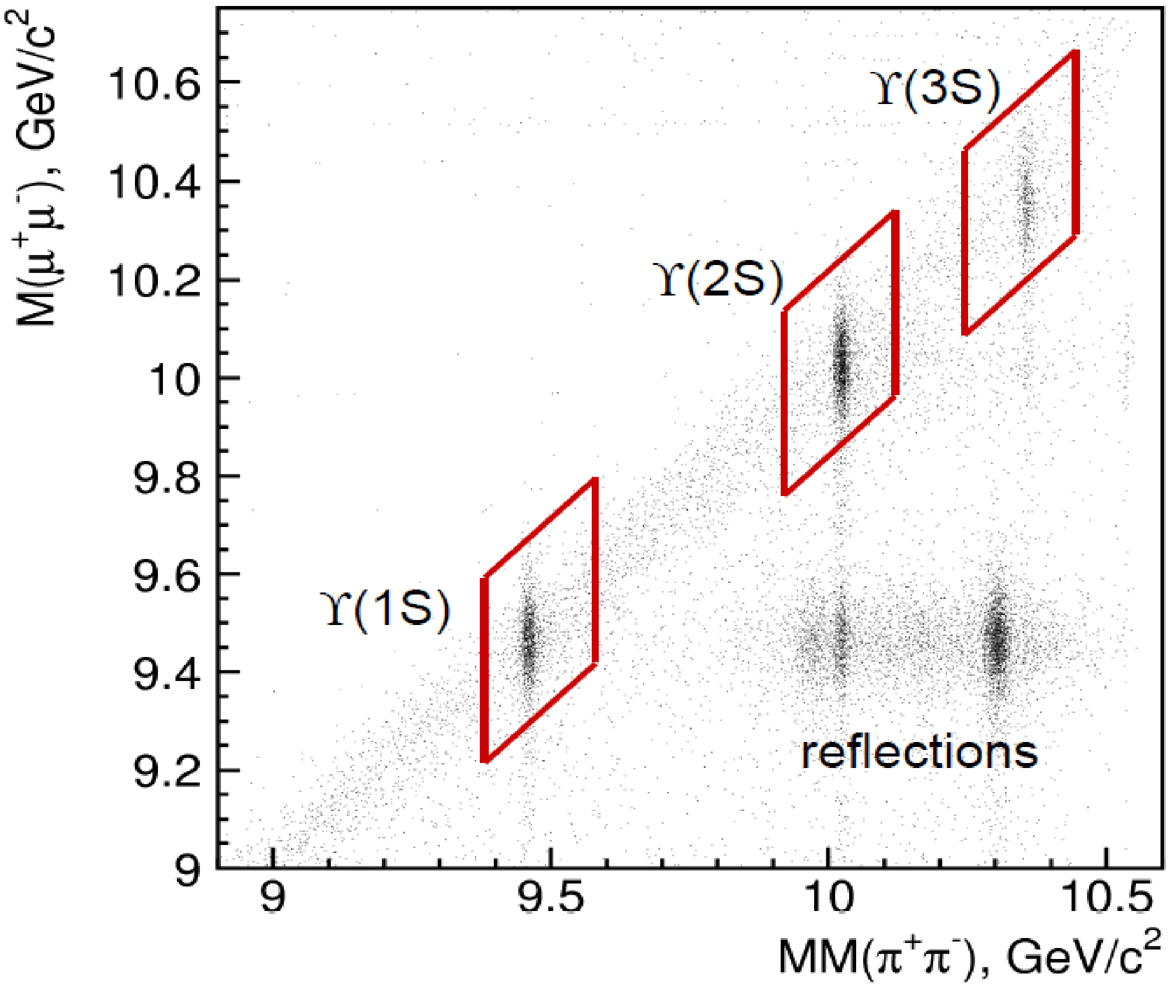
2 vs.1 : 2.7σ (1.9σ w/ syst)

2 vs.0 : 6.3σ (4.7σ w/ syst)

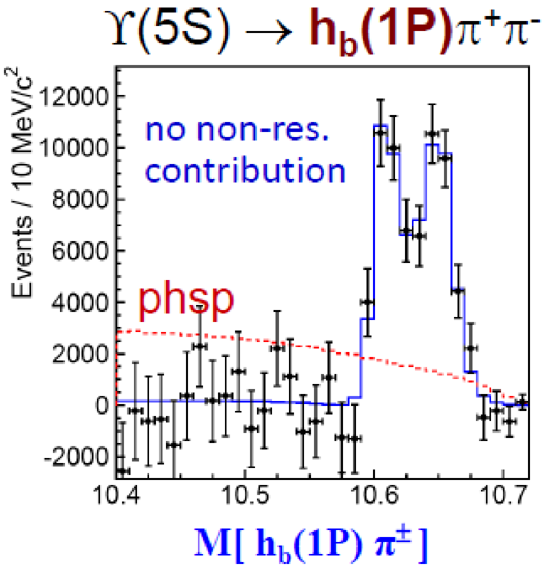
Exclusive $\Upsilon(5S) \to \Upsilon(nS)\ \pi^+\pi^-$

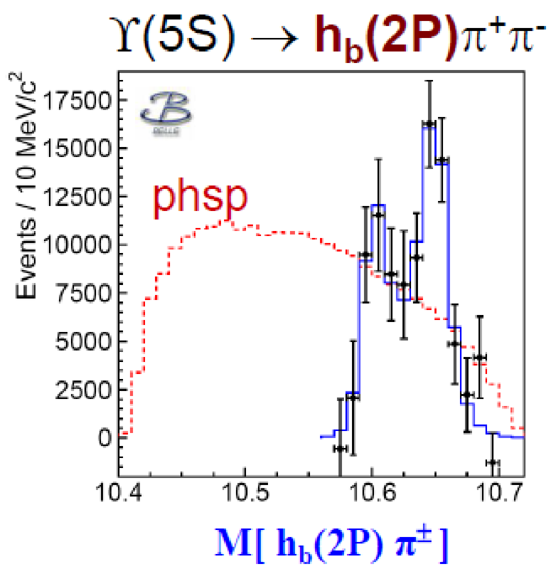
$\Upsilon(5S) \to \Upsilon(nS)\ \pi^+\pi^-$

$\Upsilon(nS) \to \mu^+\mu^-$ (n = 1,2,3)



Resonant structure of $\Upsilon(5S) \to (b\bar{b})\pi^+\pi^-$



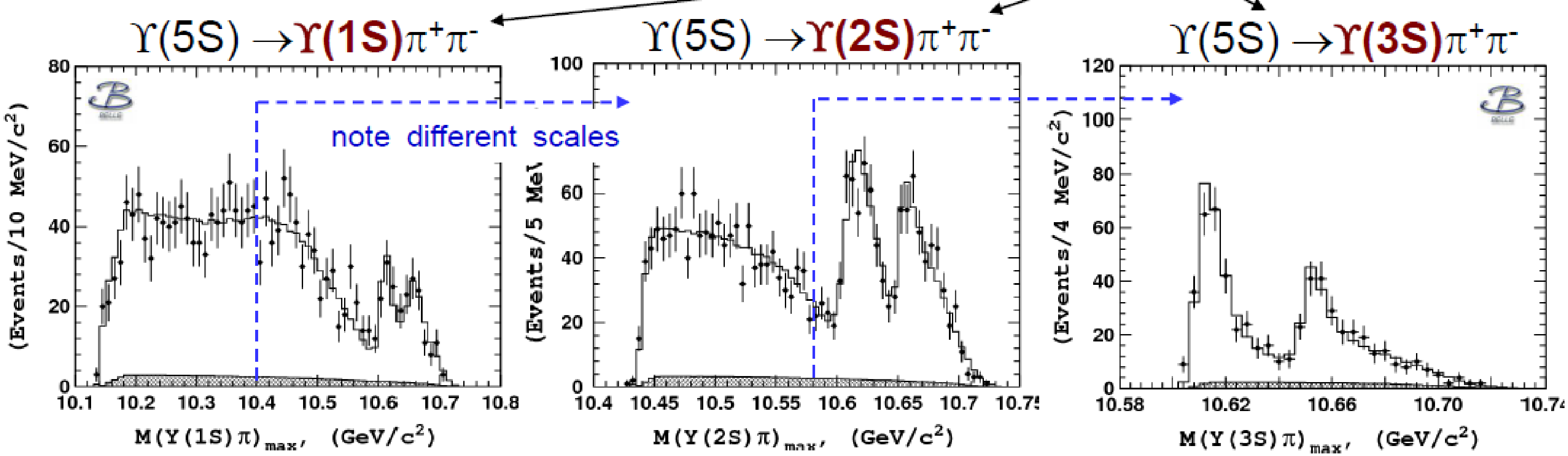


Two peaks are observed in all modes!

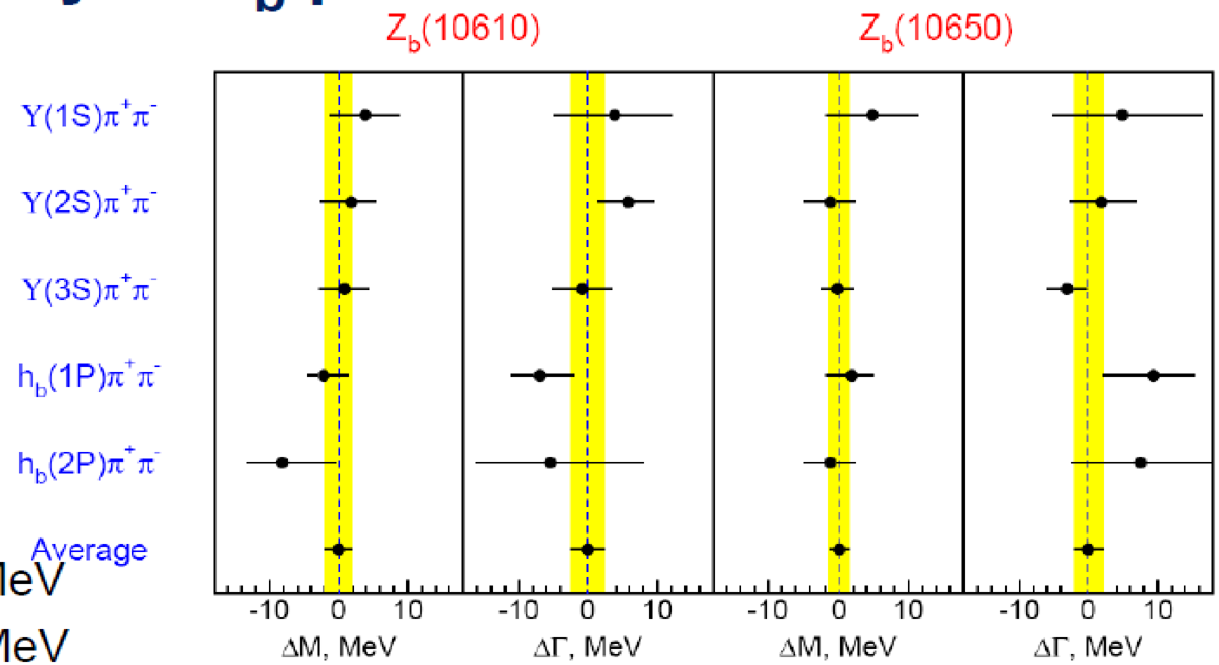
Belle: PRL108, 232001 (2012)

$Z_b(10610)$ and $Z_b(10650)$ should be multiquark states

Dalitz plot analysis



Summary of Z_b parameters



Average over 5 channels

$\langle M_1 \rangle = 10607.2 \pm 2.0$ MeV

$\langle \Gamma_1 \rangle = 18.4 \pm 2.4$ MeV

$\langle M_2 \rangle = 10652.2 \pm 1.5$ MeV

$\langle \Gamma_2 \rangle = 11.5 \pm 2.2$ MeV

$M_1 - (M_B + M_{B^*}) = +\,2.6 \pm 2.1$ MeV

$M_2 - 2M_{B^*} = +\,1.8 \pm 1.7$ MeV

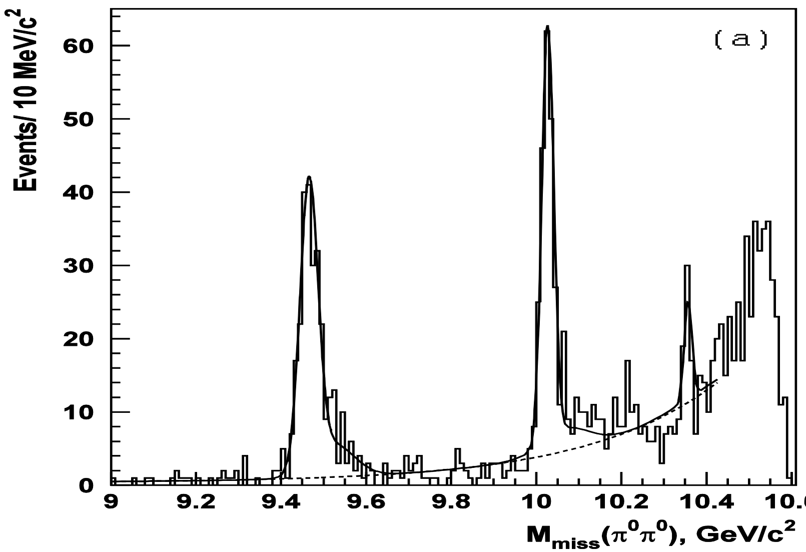
Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M[Z_b(10610)]$, MeV/c^2	$10611 \pm 4 \pm 3$	$10609 \pm 2 \pm 3$	$10608 \pm 2 \pm 3$	$10605 \pm 2^{+3}_{-1}$	10599^{+6+5}_{-3-4}
$\Gamma[Z_b(10610)]$, MeV	$22.3 \pm 7.7^{+3.0}_{-4.0}$	$24.2 \pm 3.1^{+2.0}_{-3.0}$	$17.6 \pm 3.0 \pm 3.0$	$11.4\ ^{+4.5+2.1}_{-3.9-1.2}$	$13\ ^{+10+9}_{-8-7}$
$M[Z_b(10650)]$, MeV/c^2	$10657 \pm 6 \pm 3$	$10651 \pm 2 \pm 3$	$10652 \pm 1 \pm 2$	$10654 \pm 3\ ^{+1}_{-2}$	10651^{+2+3}_{-3-2}
$\Gamma[Z_b(10650)]$, MeV	$16.3 \pm 9.8^{+6.0}_{-2.0}$	$13.3 \pm 3.3^{+4.0}_{-3.0}$	$8.4 \pm 2.0 \pm 2.0$	$20.9\ ^{+5.4+2.1}_{-4.7-5.7}$	$19 \pm 7\ ^{+11}_{-7}$
Rel. normalization	$0.57 \pm 0.21^{+0.19}_{-0.04}$	$0.86 \pm 0.11^{+0.04}_{-0.10}$	$0.96 \pm 0.14^{+0.08}_{-0.05}$	$1.39 \pm 0.37^{+0.05}_{-0.15}$	$1.6^{+0.6+0.4}_{-0.4-0.6}$
Rel. phase, degrees	$58 \pm 43^{+4}_{-9}$	$-13 \pm 13^{+17}_{-8}$	$-9 \pm 19^{+11}_{-26}$	187^{+44+3}_{-57-12}	$181^{+65+74}_{-105-109}$

$Z_b(10610)$ yield ~ $Z_b(10650)$ yield in every channel

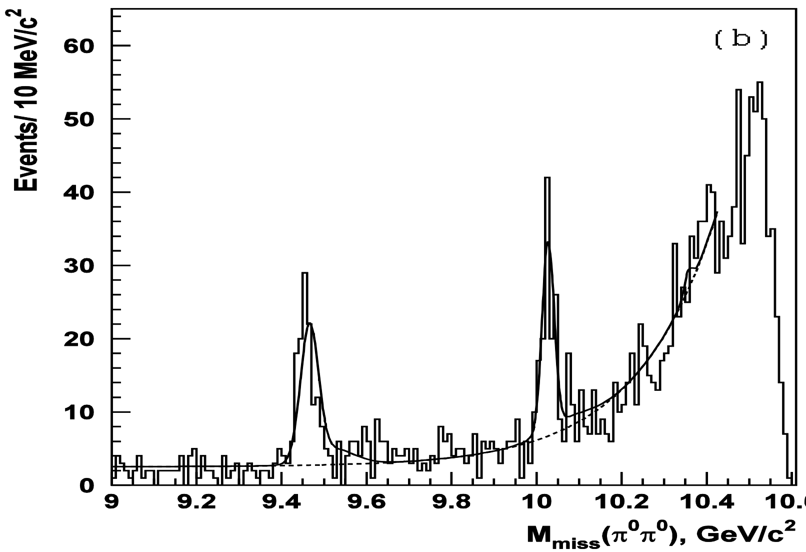
Relative phases: 0^o for $\Upsilon\pi\pi$ and 180^o for $h_b\pi\pi$

First observation of $Z_b^0(10610)$ in $\Upsilon(10860) \to \Upsilon(nS)\pi^0\pi^0$
PRD 88, 052016 (2013)

$\pi^0\pi^0$ missing mass for $\Upsilon \to \mu^+\mu^-$



$\pi^0\pi^0$ missing mass for $\Upsilon \to e^+e^-$

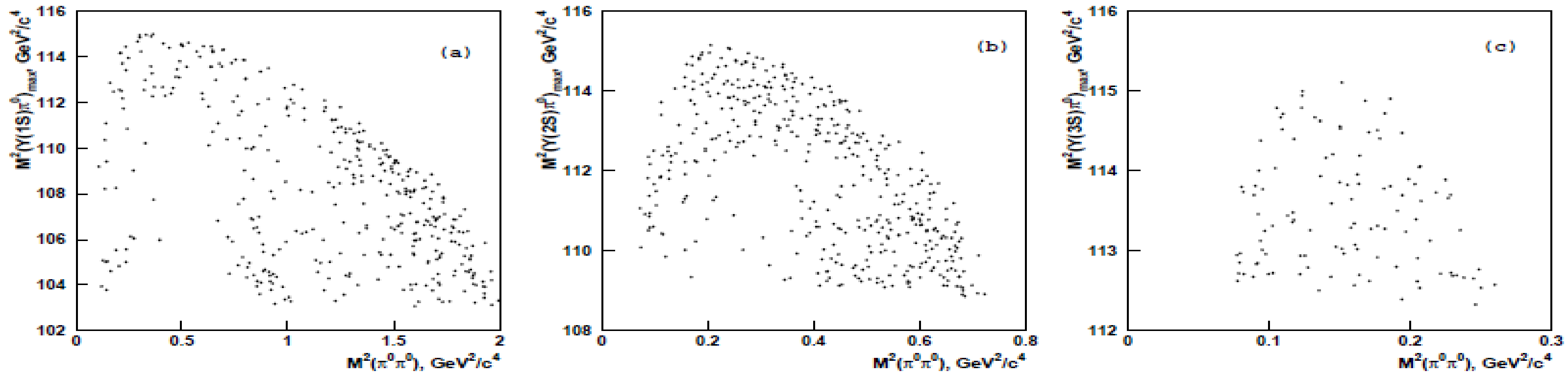


$$\sigma(e^+e^- \to \Upsilon(1S)\pi^0\pi^0) = (1.16 \pm 0.06 \pm 0.10)\,\text{pb}\,,$$

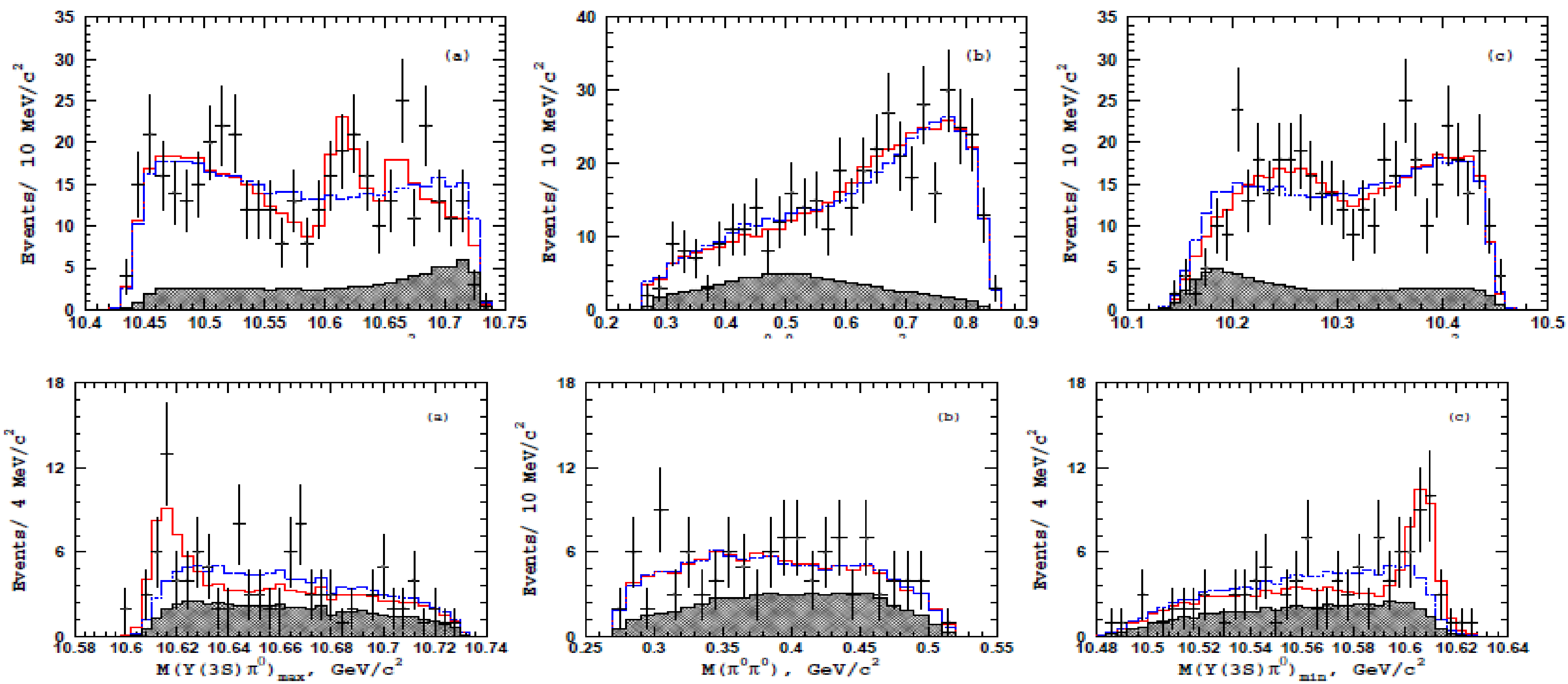
$$\sigma(e^+e^- \to \Upsilon(2S)\pi^0\pi^0) = (1.87 \pm 0.11 \pm 0.23)\,\text{pb}\,,$$

$$\sigma(e^+e^- \to \Upsilon(3S)\pi^0\pi^0) = (0.98 \pm 0.24 \pm 0.15)\,\text{pb}\,.$$

Dalitz analysis of $\Upsilon(nS)\pi^0\pi^0$ systems



$$\mathcal{M}(s_1, s_2) = A_{Z1} + A_{Z2} + A_{f_0} + A_{f_2} + a^{\text{nr}}$$



Results of the Dalitz analysis of $\Upsilon(nS)\pi^0\pi^0$

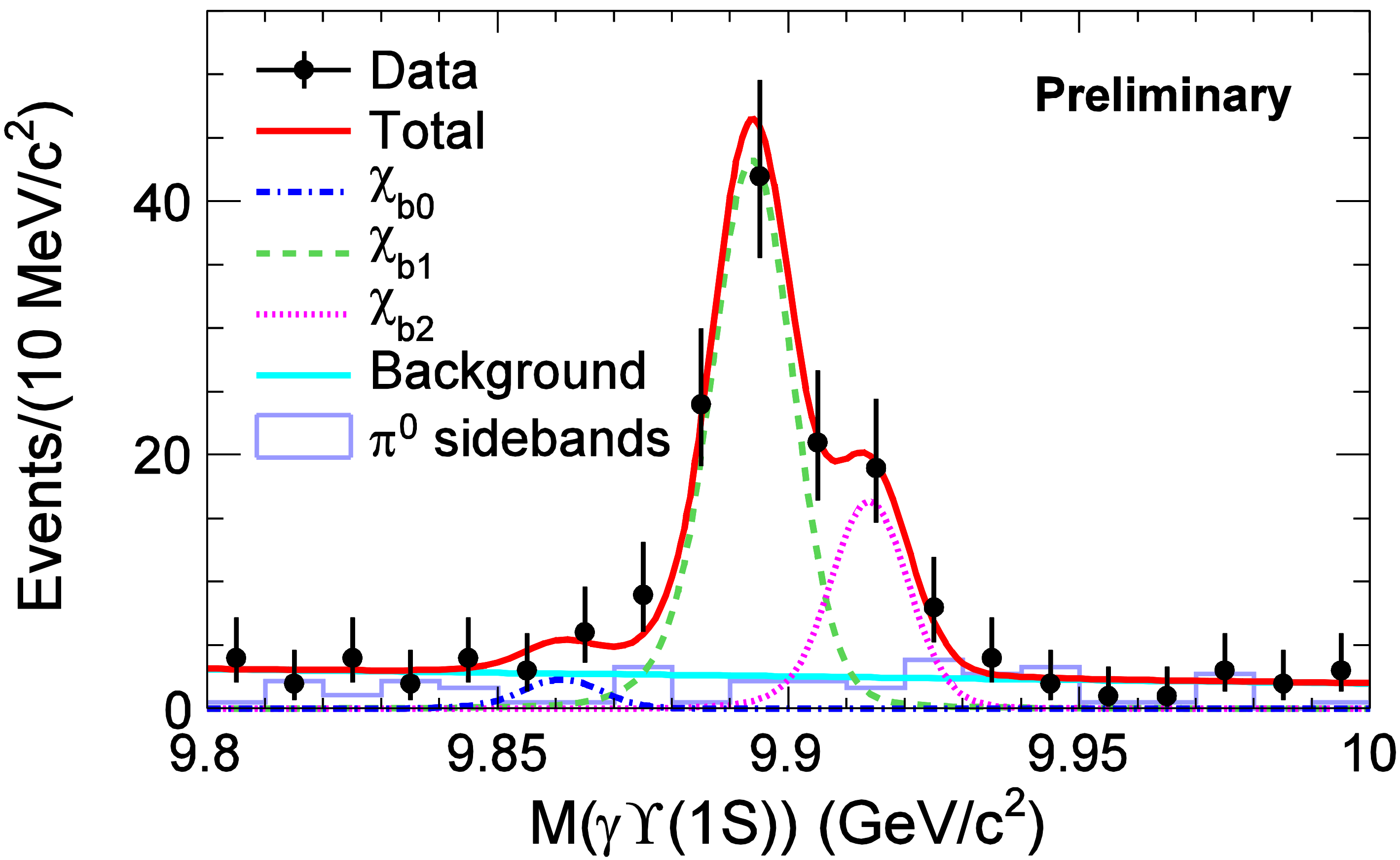
Significance of $Z_b^0(10610)$ in $\Upsilon(2S)\pi^0\pi^0$ is 5.3σ

Significance of $Z_b^0(10610)$ in $\Upsilon(3S)\pi^0\pi^0$ is 4.7σ

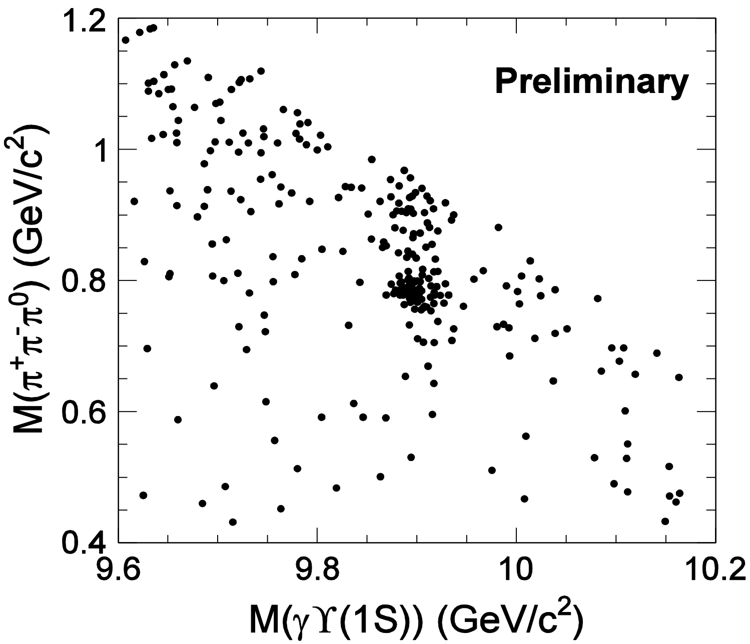
$Z_b^0(10610)$ in $\Upsilon(1S)\pi^0\pi^0$ is not significant

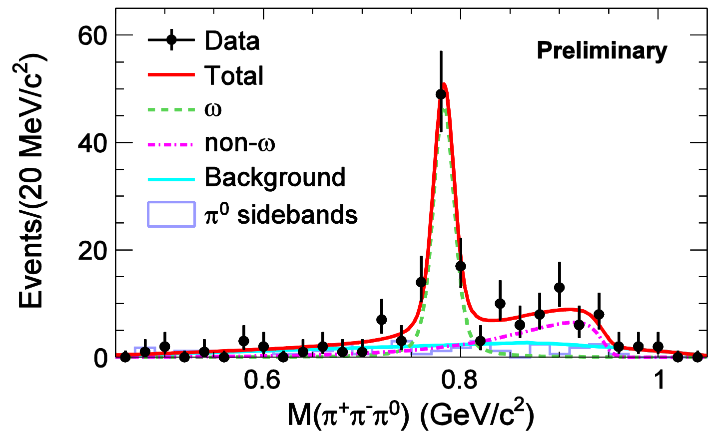
$Z_b^0(10650)$ in $\Upsilon(nS)\pi^0\pi^0$ is not significant

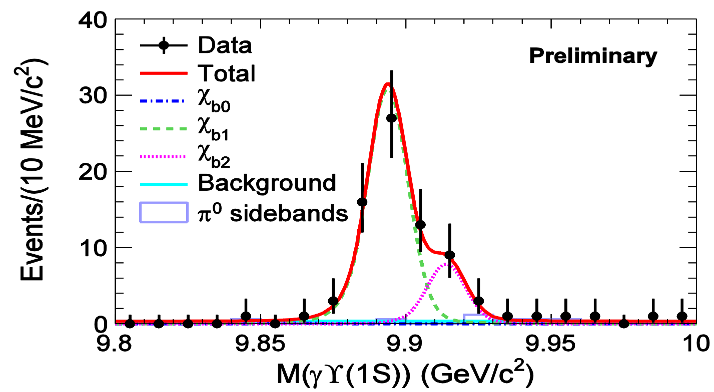
Study of reaction $e^+e^- \to \pi^+\pi^-\pi^0\chi_{bj}$ at $\sqrt{s}$ = 10.867 GeV



Results of the fit of scatter plot

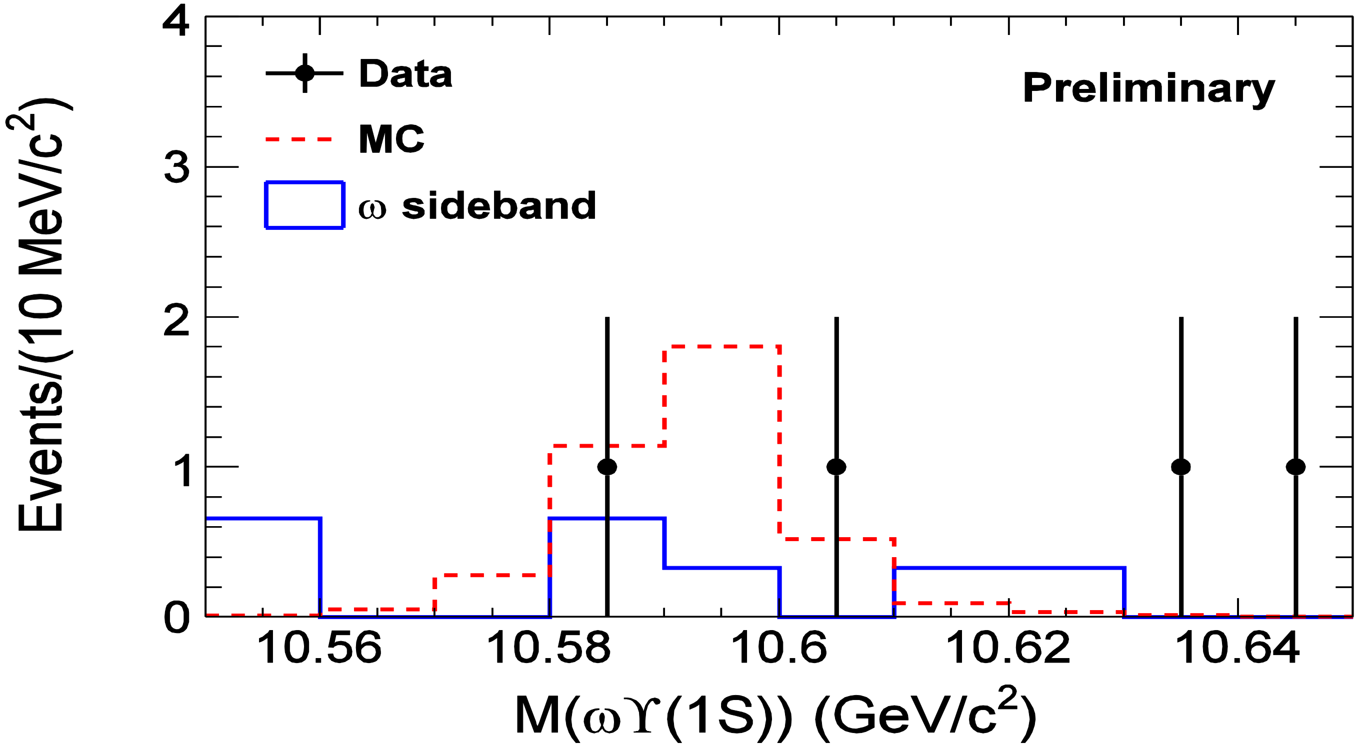






Mode	Yield	$\Sigma\,(\sigma)$	$\varepsilon\,(\%)$	σ_B (pb)	$\mathcal{B}\,(10^{-3})$	$\sigma^1_{sys}/\sigma^2_{sys}\,(\%)$
$\pi^+\pi^-\pi^0\chi_{b0}$	< 13.6	1.0	6.43	< 3.1	< 6.3	23/24
$\pi^+\pi^-\pi^0\chi_{b1}$	80.1 ± 9.9	12	6.61	$0.90 \pm 0.11 \pm 0.10$	$1.85 \pm 0.23 \pm 0.23$	11/12
$\pi^+\pi^-\pi^0\chi_{b2}$	28.6 ± 6.5	5.9	6.65	$0.57 \pm 0.13 \pm 0.07$	$1.17 \pm 0.27 \pm 0.14$	11/12
$\omega\chi_{b0}$	< 7.5	0.5	6.35	< 1.9	< 3.9	28/28
$\omega\chi_{b1}$	59.9 ± 8.3	12	6.53	$0.76 \pm 0.11 \pm 0.10$	$1.57 \pm 0.22 \pm 0.21$	12/13
$\omega\chi_{b2}$	12.9 ± 4.8	3.5	6.56	$0.29 \pm 0.11 \pm 0.08$	$0.60 \pm 0.23 \pm 0.15$	25/25

Search for the signal $e^+e^- \to \gamma X_b \to \gamma\omega\Upsilon(1S) \to \gamma\pi^+\pi^-\pi^0 l^+l^-$



$$\mathcal{B}(\Upsilon(5S) \to \gamma X_b)\mathcal{B}(X_b \to \omega\Upsilon(1S)) < 2.9 \times 10^{-5} \text{ at 90\% C.L.}$$

Conclusions

- Belle continues to produce high quality results after five years since the last data taking
- A part of those are presented here:

First observation of D^0-$\bar{D}^0$ mixing

2.5 σ indication for D^0-$\bar{D}^0$ mixing and no sign of CPV in $D \to K_S^0 \pi^+ \pi^-$

Measurement of the τ-lepton lifetime with the precision better than in PDG

Observation of the $Z^0(10610)$ in $\Upsilon(10860) \to \Upsilon(nS)\pi^0\pi^0$

Observation of the $e^+e^- \to \pi^+\pi^-\pi^0\chi_{bJ}$ and upper limit for $X_b \to \omega\Upsilon(1S)$

- The unique explorations at the intensity frontier will continue with the start of Belle II