Recent Results on Bottomonium from Belle

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(on behalf of the Belle Collaboration)

Outline

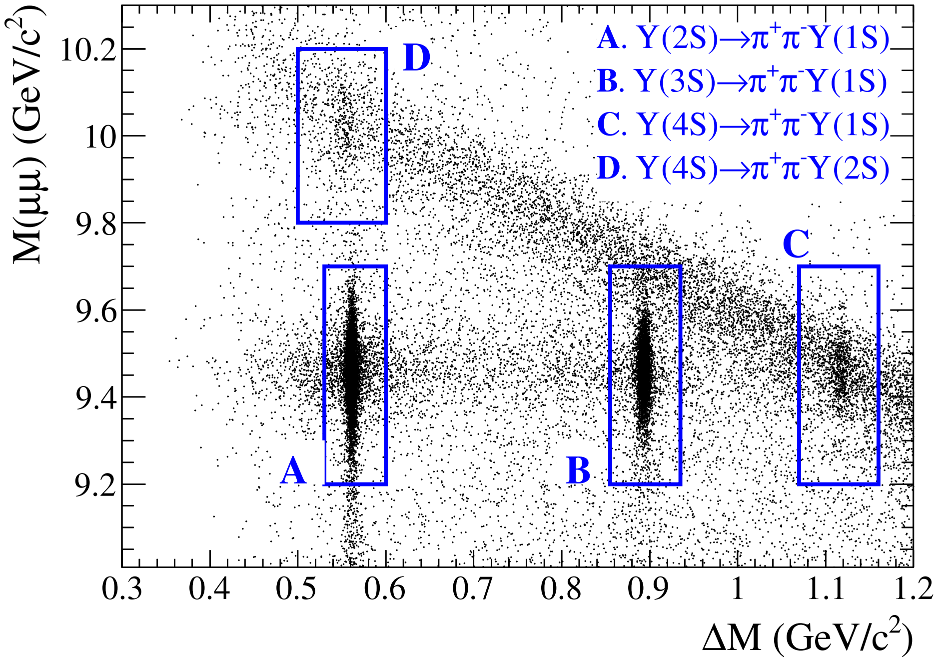
1. Transitions in bottomonium at Belle
2. Prospects for BelleII
3. Conclusions

General

- Spectroscopy of heavy quarkonia provides crucial information for understanding strong interactions since QCD calculations become possible: heavy-quark spin symmetry (HQSS), multipole expansion etc.
- Measurements of hadronic and radiative transitions between $b\bar{b}$ $(\pi^+\pi^-,\ \eta,\ \eta', \gamma, \ldots)$ yield important input for QCD
- η transitions are believed to be suppressed compared to $\pi^+\pi^-$ because of the spin flip
- $\pi^+\pi^-$ transitions and their peculiarities were studied by both BaBar and Belle, the contribution of Belle being particularly strong due to high statistics and versatile analyses like use of missing mass distributions
- Large integrated luminosity collected by Belle at the $\Upsilon(4S)$ and above opened unique possibilities resulting in exciting observations of $h_b(1P),\ h_b(2P),\ \eta_b(2S),\ Z_b(10610)$ and $Z_b(10650)$

Study of η and $\pi^+\pi^-$ Transitions in $\Upsilon(4S)$ Decays to Lower $(b\bar{b})$ – I

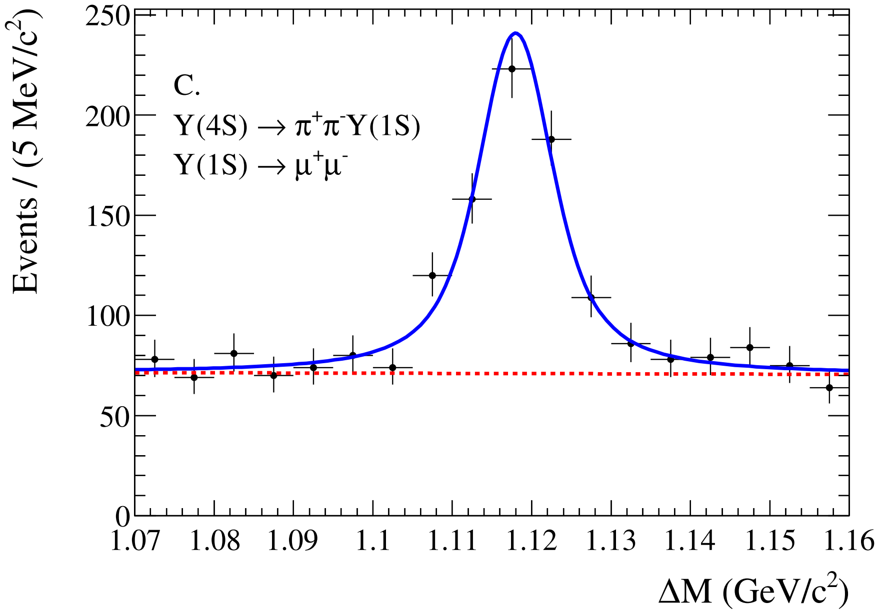
From 538M $\Upsilon(4S)$ Belle studied $\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S, 2S)$, $\Upsilon(4S) \to \eta\Upsilon(1S)$ and searched for inclusive $\Upsilon(1^3D_{1,2}) \to \eta\Upsilon(1S)$, $\eta \to \pi^+\pi^-\pi^0$, $\Upsilon(1S, 2S) \to \mu^+\mu^-$

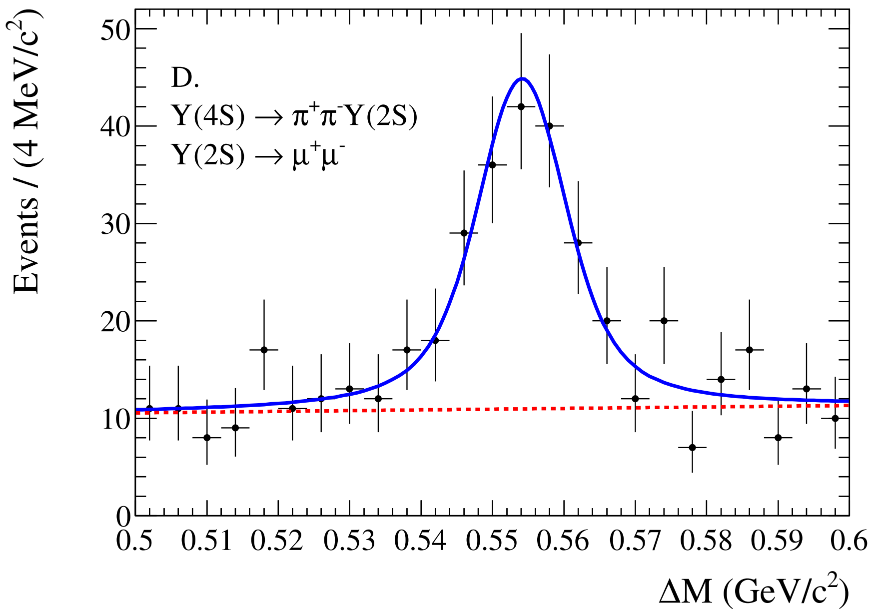


$$\Delta M = M(\pi\pi\mu\mu) - M(\mu\mu),$$

E. Guido et al., Phys. Rev.D 96, 052005 (2017)

Study of η and $\pi^+\pi^-$ Transitions in $\Upsilon(4S)$ Decays to Lower $(b\bar{b})$ – II

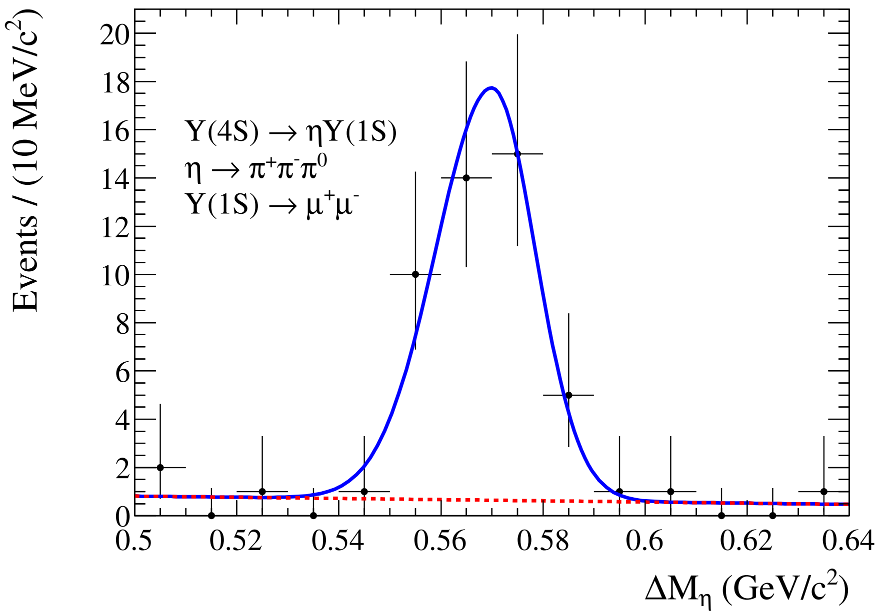


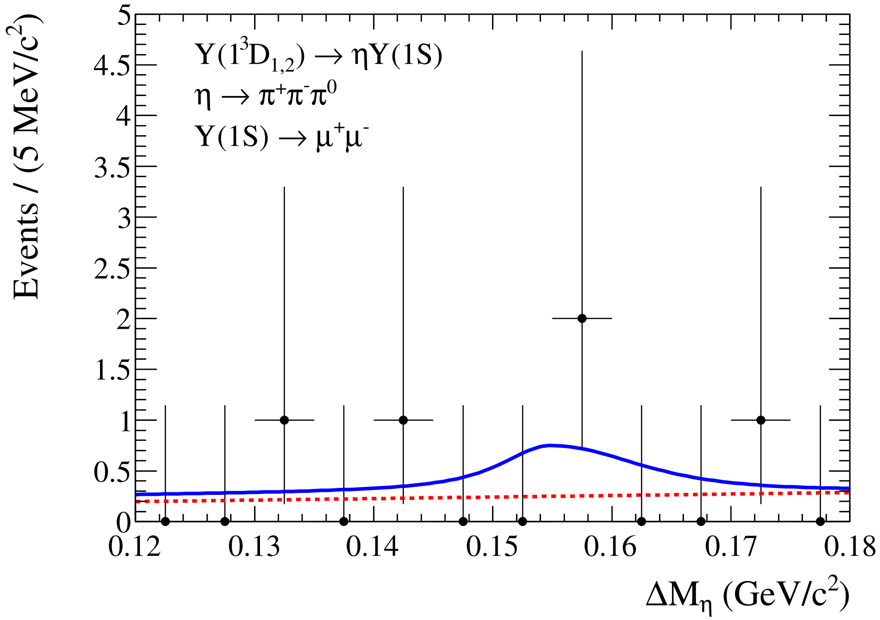


Decay	Events	$\mathcal{B}, 10^{-5}$	$\mathcal{B}_{\rm PDG}, 10^{-5}$
$\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S)$	1095 ± 74	$8.2 \pm 0.5 \pm 0.4$	8.1 ± 0.6
$\Upsilon(4S) \to \pi^+\pi^-\Upsilon(2S)$	821 ± 107	$7.9 \pm 1.0 \pm 0.4$	8.6 ± 1.3

E. Guido et al., Phys. Rev.D 96, 052005 (2017)

Study of η and $\pi^+\pi^-$ Transitions in $\Upsilon(4S)$ Decays to Lower $(b\bar{b})$ – III

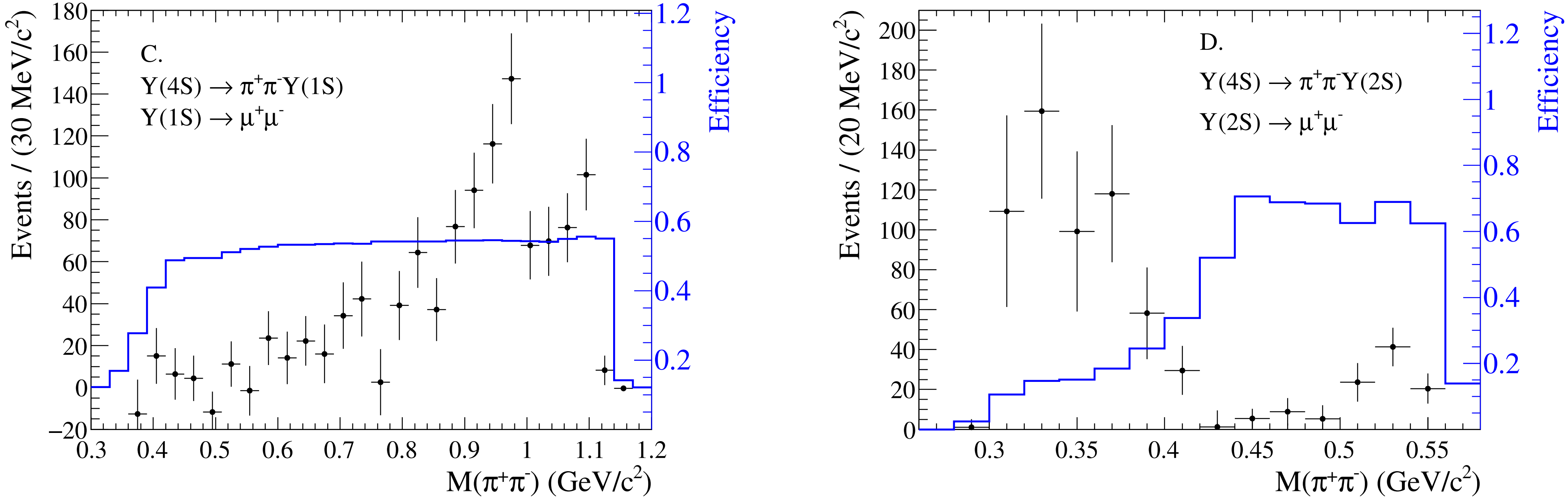




Decay	Events	$\mathcal{B}, 10^{-4}$	$\mathcal{B}_{\rm PDG}, 10^{-5}$
$\Upsilon(4S) \to \eta\Upsilon(1S)$	49 ± 7	$1.70 \pm 0.23 \pm 0.08$	1.96 ± 0.28
$\Upsilon(1^3D_{1,2}) \to \eta\Upsilon(1S)$	2.1 ± 3.0	< 0.23	–

E. Guido et al., Phys. Rev.D 96, 052005 (2017)

Study of η and $\pi^+\pi^-$ Transitions in $\Upsilon(4S)$ Decays to Lower $(b\bar{b})$ – IV



Striking difference of $M(\pi\pi)$ spectra

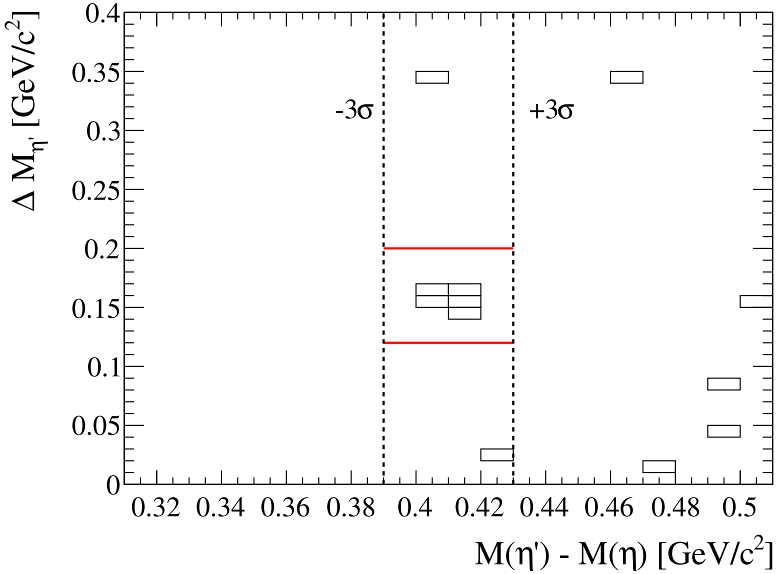
Similar effect in $\pi\pi$ transitions btw. narrow bottomonia

E. Guido et al., Phys. Rev.D 96, 052005 (2017)

Observation of $\Upsilon(4S) \to \eta' \, \Upsilon(1S)$ – I

From 538M $\Upsilon(4S)$ Belle searched for $\Upsilon(4S) \to \eta' \Upsilon(1S)$,

$\eta' \to \eta\pi^+\pi^-(\rho^0\gamma), \ \eta \to \gamma\gamma, \ \Upsilon(1S) \to \mu^+\mu^-$



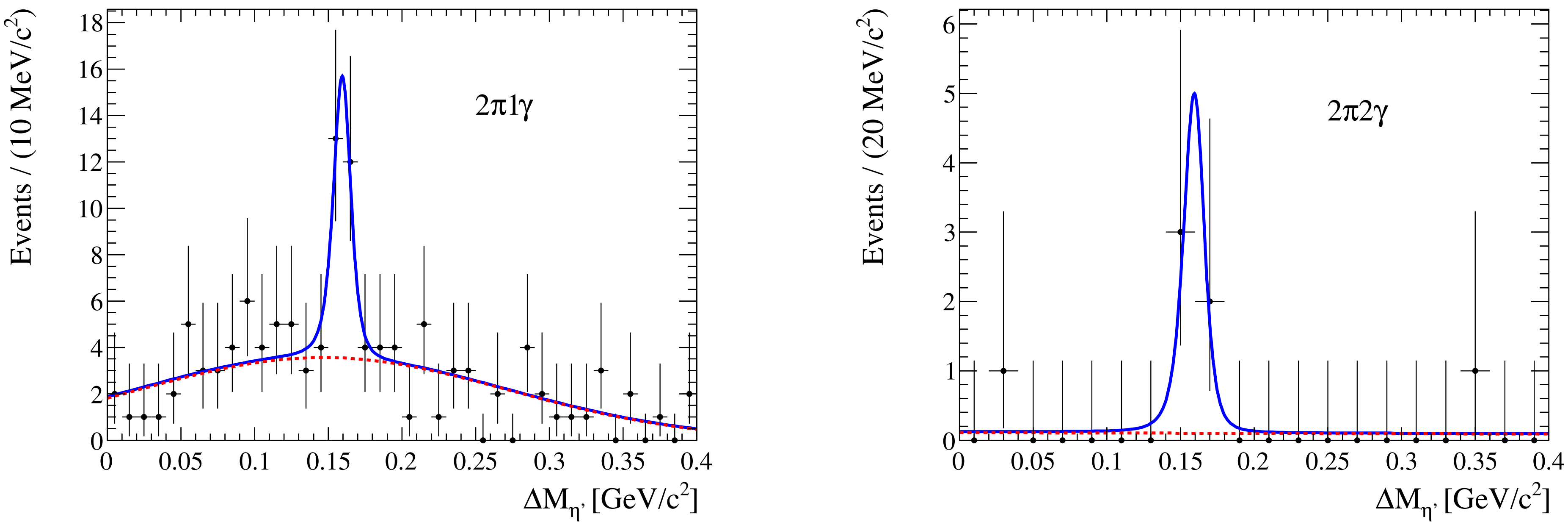
$\Delta M_{\eta'} = M(\Upsilon(4S)) - M(\Upsilon(1S)) - M(\eta')$ identifies the signal,

$2\pi 1\gamma: \ N_{\rm sig} = 22 \pm 7 (4.2\sigma)$, $2\pi 2\gamma: \ N_{\rm sig} = 5.0 \pm 2.3 (4.1\sigma)$,

Systematic uncertainties: 7.6%($2\pi 1\gamma$) and 3.5%($2\pi 2\gamma$)

E. Guido et al., Phys.Rev.Lett. 121, 062001 (2018)

Observation of $\Upsilon(4S) \to \eta' \, \Upsilon(1S)$ – II



$$\mathcal{B}(\Upsilon(4S) \to \eta'\Upsilon(1S)) = (3.43 \pm 0.88 \pm 21) \cdot 10^{-5},$$

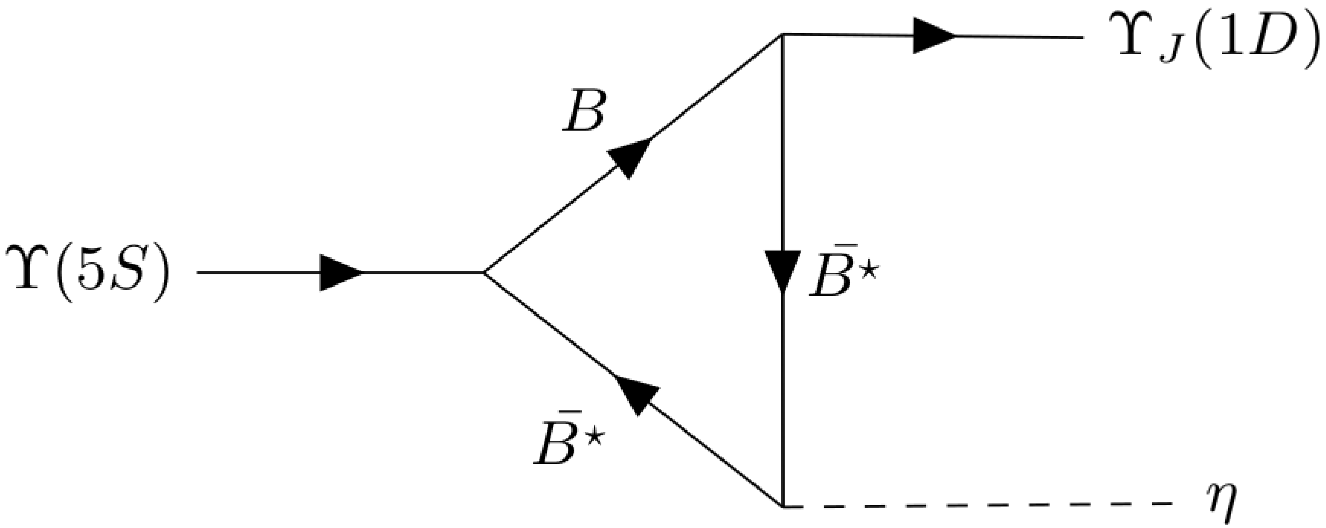
$$R_{\eta'/h} = \mathcal{B}(\Upsilon(4S) \to \eta'\Upsilon(1S))/\mathcal{B}(\Upsilon(4S) \to h\Upsilon(1S)),$$

$$R_{\eta'/\eta} = 0.20 \pm 0.06, \;\; R_{\eta'/\pi^+\pi^-} = 0.42 \pm 0.11$$

E. Guido et al., Phys.Rev.Lett. 121, 062001 (2018)

$e^+e^- \to \eta\ (b\bar{b})$ Near $\Upsilon(5S)$ – I

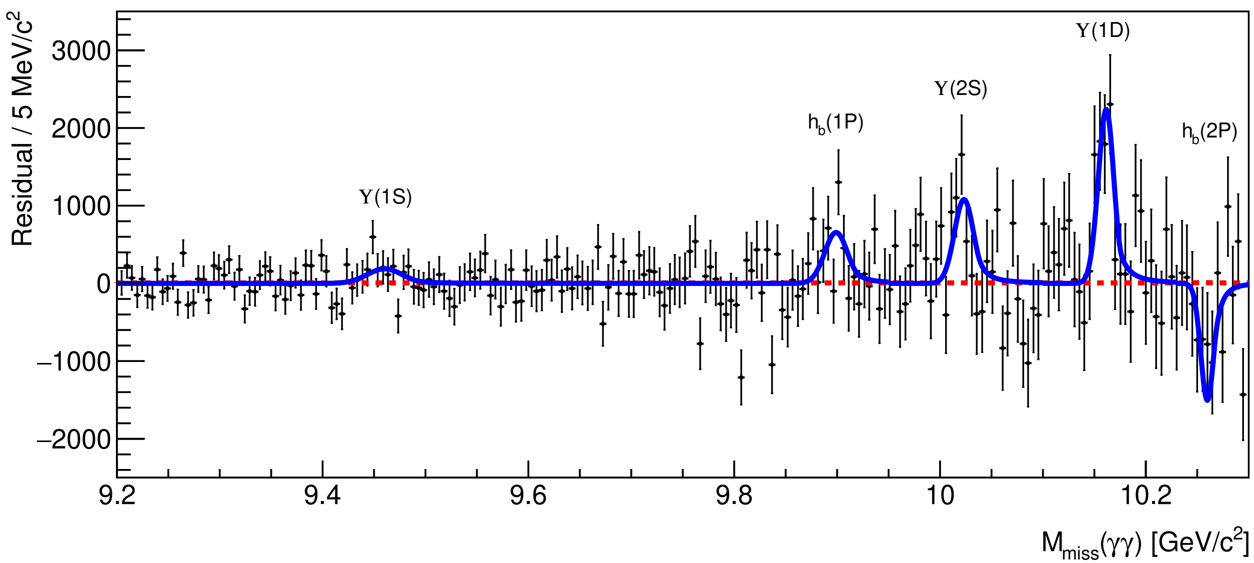
From 121.4 fb^{-1} Belle studied $e^+e^- \to \eta\ (b\bar{b})$ near $\sqrt{s} = 10.966$ GeV,
$\eta \to \gamma\gamma$ only reconstructed, $M_{\rm miss}(\eta)$ studied



A possible way to observe $\Upsilon_J(1D)$ via triangular $B^{(*)}$ loops

U. Tamponi et al., Eur.Phys.J. C78, 633 (2018)

$e^+e^- \to \eta\ (b\bar{b})$ Near $\Upsilon(5S)$ – II

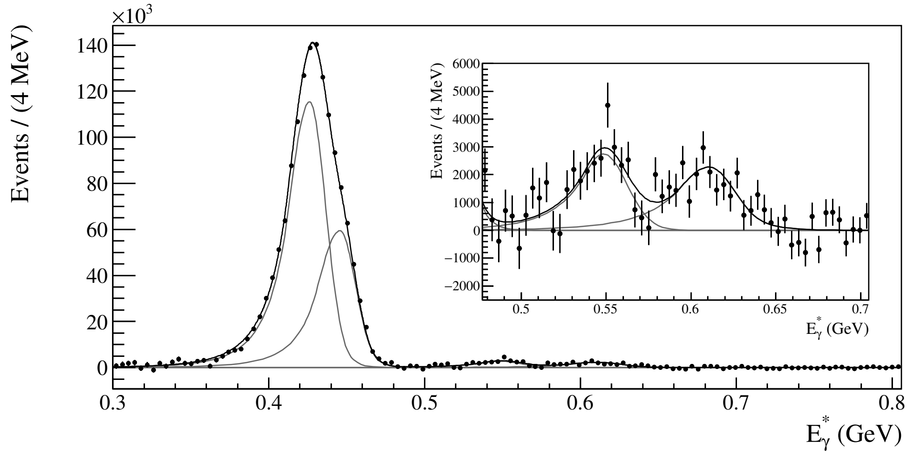


Process	Σ	$N, 10^3$	Process	Σ	$N, 10^3$
$\eta\Upsilon(1S)$	1.5σ	1.7 ± 1.0	$\eta\Upsilon(2S)$	3.3σ	5.6 ± 1.6
$\eta\ h_b(1P)$	2.7σ	3.9 ± 1.5	$\eta\Upsilon(1D)$	5.3σ	9.3 ± 1.8

U. Tamponi et al., Eur.Phys.J. C78, 633 (2018)

Observation of $\Upsilon(2S) \to \gamma\eta_b(1S)$ Decay

From 157.8M $\Upsilon(2S)$ decays Belle reports the first observation of $\Upsilon(2S) \to \gamma\eta_b(1S)$ decay ($> 7\sigma$)



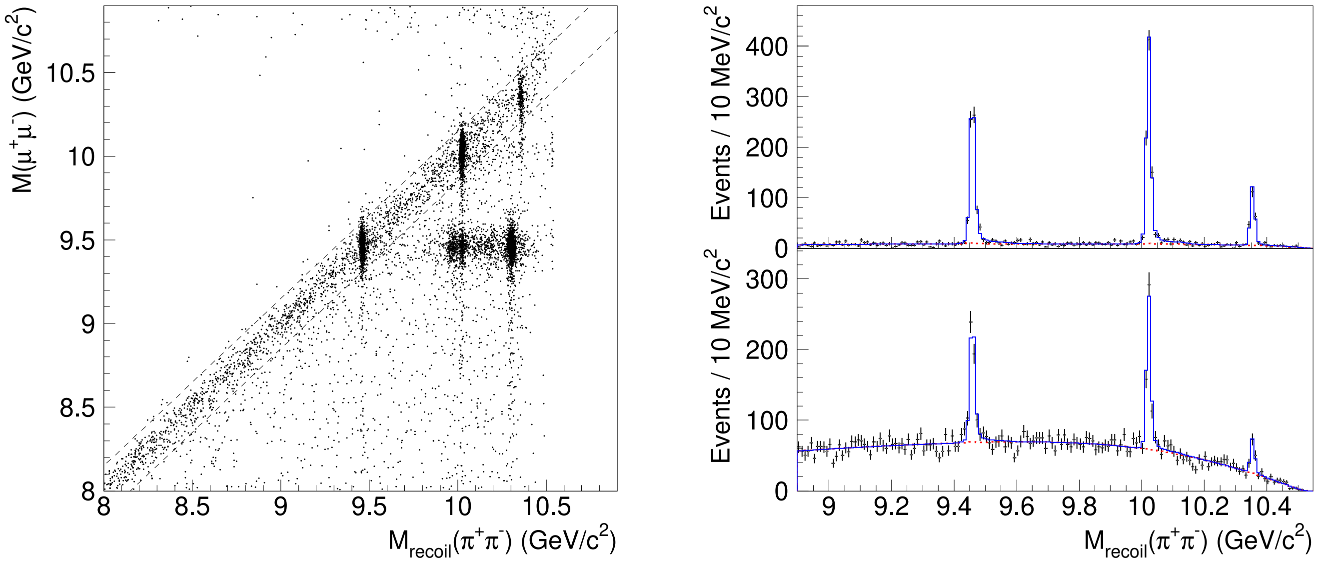
Mode	Yield (10^3)	$\mathcal{B}$ (%)	E^*_γ (MeV)
$\chi_{b1}(1P) \to \gamma\Upsilon(1S)$	964 ± 8	$2.45 \pm 0.02^{+0.11}_{-0.15}$	$423.1 \pm 0.1 \pm 0.5$
$\chi_{b2}(1P) \to \gamma\Upsilon(1S)$	503 ± 6	$1.17 \pm 0.01^{+0.06}_{-0.07}$	$442.1 \pm 0.2^{+0.5}_{-0.6}$
$\Upsilon(2S) \to \gamma\eta_b(1S)$	$28.8^{+2.6}_{-3.2}$	$(6.1^{+0.6+0.9}_{-0.7-0.6}) \times 10^{-2}$	$606.1^{+2.3+3.6}_{-2.4-3.4}$

B.G. Fulsom et al., Phys. Rev. Lett. 121, 232001 (2018)

New Structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ – I

With 141 fb^{-1} at 10.63-11.02 GeV and 60 fb^{-1} at 10.52 GeV

Belle searched for $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$, $\Upsilon(nS) \to e^+e^-, \mu^+\mu, n = 1, 2, 3$



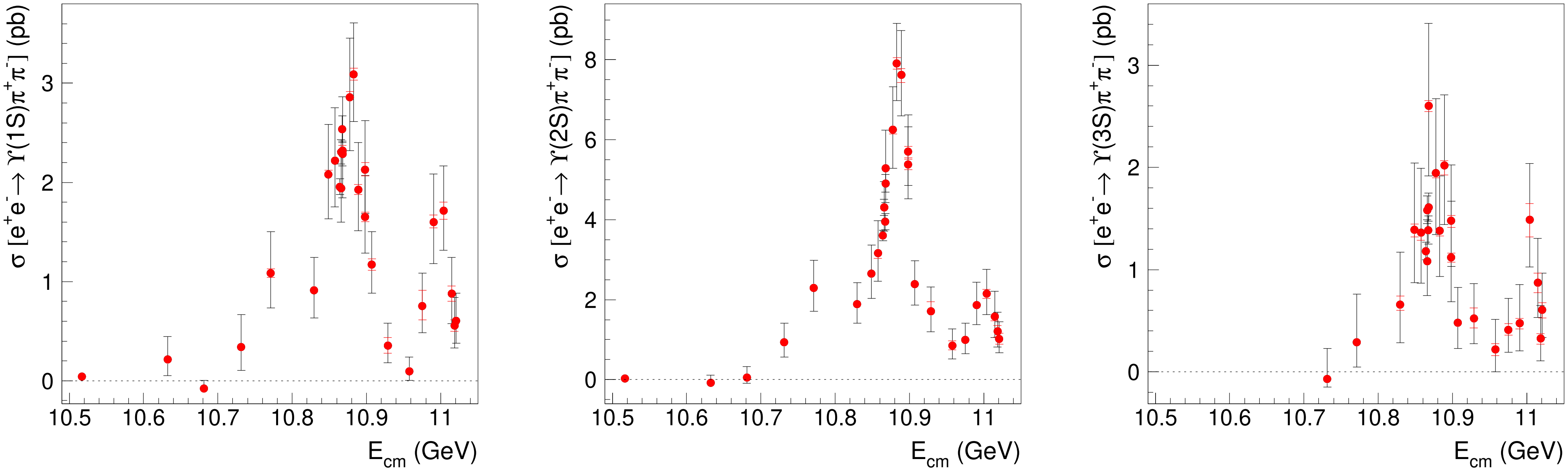
The recoil $M_{\mathrm{recoil}}(\pi^+\pi^-) = \sqrt{(E_{c.m.} - E_{\pi^+\pi^-})^2 - p^2_{\pi^+\pi^-}}$

The fully reconstructed events (diagonal): $|M_{\mathrm{recoil}}(\pi^+\pi^-) - M(l^+l^-)| < 150$ MeV.

Two populated regions below the diagonal are due to transitions from the $\Upsilon(10860)$ to the $\Upsilon(2S, 3S)$ via ISR and light mesons

R. Mizuk et al., JHEP 10, 220 (2019)

New Structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ – II

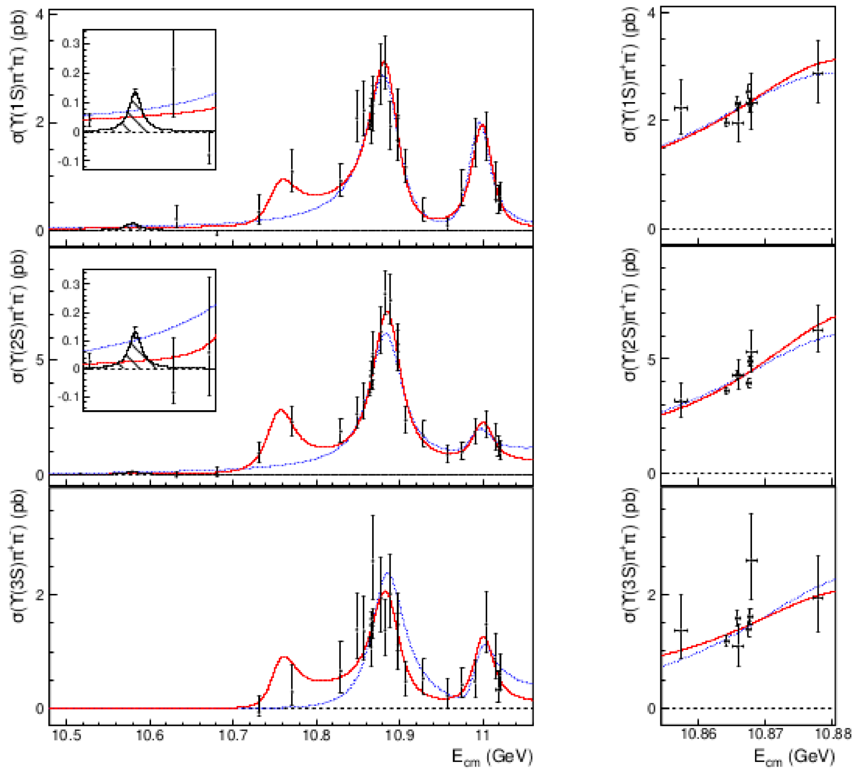


The Born cross sections are obtained from the $M_{\rm recoil}(\pi^+\pi)$ fit.

Clear $\Upsilon(10860)$ and $\Upsilon(11020)$ peaks are seen, also a structure at 10.75 GeV.

R. Mizuk et al., JHEP 10, 220 (2019)

New Structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ – III



The fit of the $\sigma(\Upsilon(nS))$ and $M_{\rm recoil}(\pi^+\pi^-)$ includes the $\Upsilon(10860)$, $\Upsilon(11020)$, the new structure and the $\Upsilon(2S, 3S)$ tails

R. Mizuk et al., JHEP 10, 220 (2019)

New Structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ – IV

The fit: Born cross sections, the new structure, $\Upsilon(2S,3S)$ tails and $\Gamma_f(s)$

State	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M, MeV	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}\,^{+1.0}_{-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ, MeV	$36.6^{+4.5}_{-3.9}\,^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}\,^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}\,^{+3.9}_{-3.3}$

The range of $\Gamma_{ee}\mathcal{B}$ from multiple solutions in eV

State	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
$\Upsilon(1S)\pi^+\pi^-$	0.75 – 1.43	0.38 – 0.54	0.12 – 0.47
$\Upsilon(2S)\pi^+\pi^-$	1.35 – 3.80	0.13 – 1.16	0.53 – 1.22
$\Upsilon(3S)\pi^+\pi^-$	0.43 – 1.03	0.17 – 0.49	0.21 – 0.26

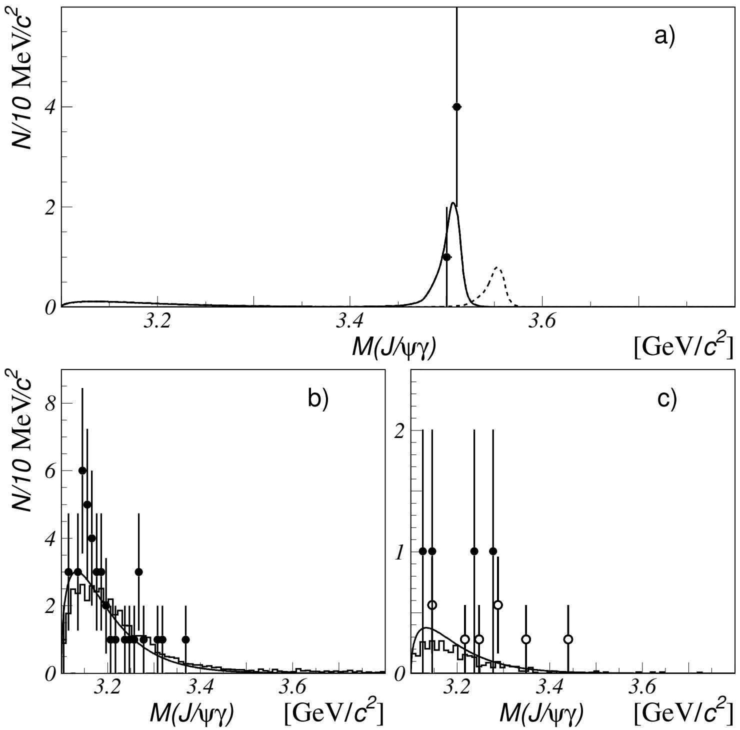
4 or 8 solutions are found for the sum of 3 or 4 Breit-Wigners

The new state could be an $\Upsilon(^3D_1)$ state or other exotic or ...

R. Mizuk et al., JHEP 10, 220 (2019)

Observation of the Radiative Decays of $\Upsilon(1S)$ to χ_{c1} – I

From $(157.3 \pm 3.6) \times 10^6$ $\Upsilon(2S)$ decays Belle searched for $\Upsilon(1S) \to \gamma(c\bar{c})_{\rm res}$ using $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(1S) \to \gamma(\chi_{c0,1,2},\ \eta_c(1S, 2S))$, $\chi_{c0} \to K^+K^-\pi^+\pi^-$, $\chi_{c1,2} \to J/\psi(\mu^+\mu^-)\gamma$, $\eta_c(1S, 2S) \to K^0_S K^{\pm}\pi^{\mp}$



P. Katrenko et al., Phys.Rev.Lett. 124, 122001 (2020)

Observation of the Radiative Decays of $\Upsilon(1S)$ to χ_{c1} – II

Mode	Result	Previous UL	Prediction
χ_{c1}	$4.7^{+2.4+0.4}_{-1.8-0.5}$	< 2.3	$0.45 - 0.9$
χ_{c2}	< 3.3	< 0.76	$0.51 - 0.56$
χ_{c0}	< 6.6	< 65	$0.32 - 0.4$
$\eta_c(1S)$	< 2.9	< 5.7	$2.9 - 4.9$
$\eta_c(2S)$	< 40	–	–

Previous UL (Belle), C.-P. Shen et al., Phys.Rev. D82, 051504 (2010)

Prediction, Y.-I. Gao et al., hep-ph 0701009

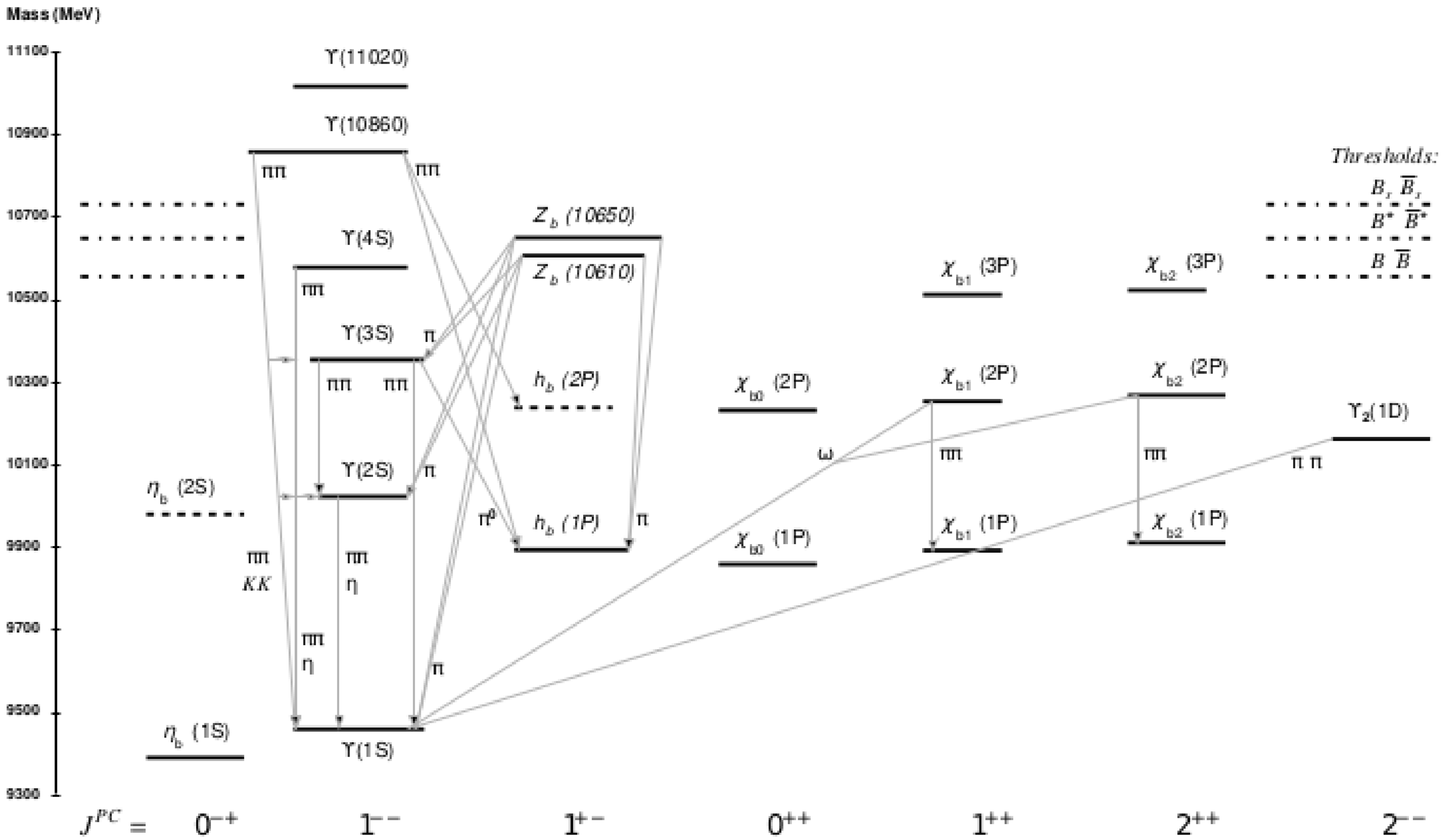
P. Katrenko et al., Phys.Rev.Lett. 124, 122001 (2020)

Prospects for BelleII and Conclusions

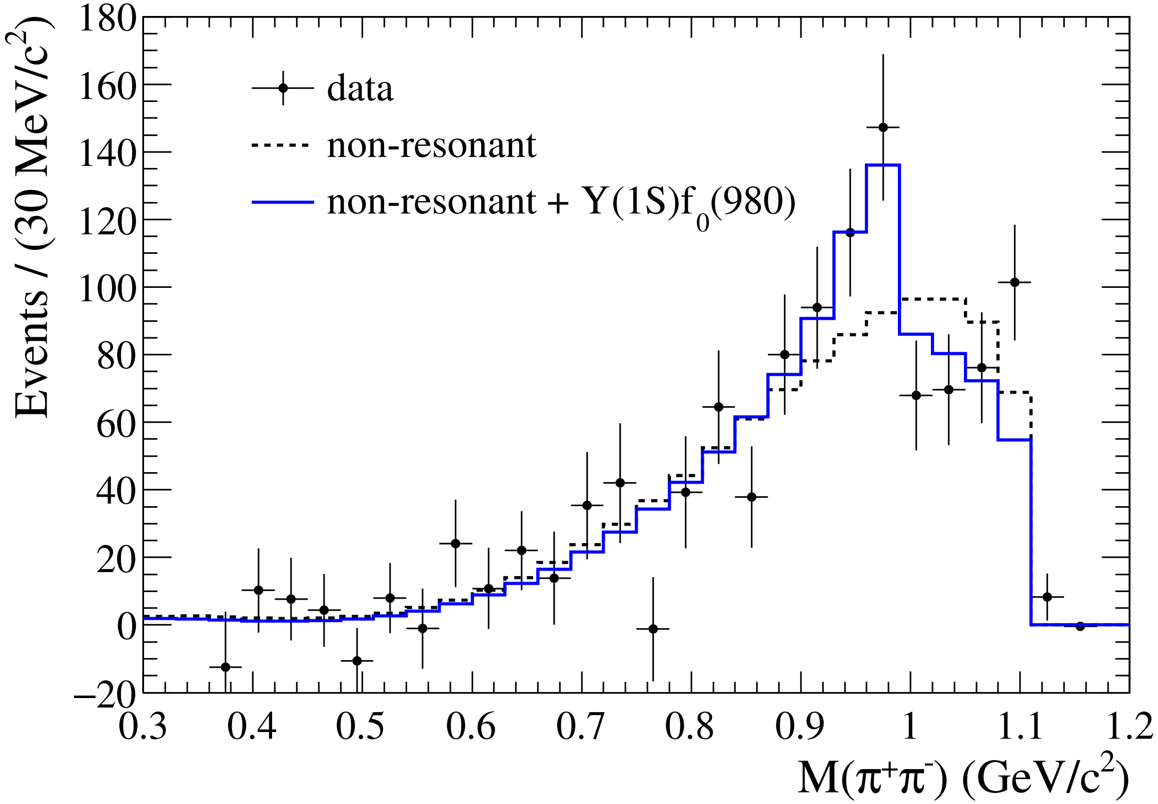
- 50-fold increase of the number of $\Upsilon(4S)$ together with improved resolution will allow extensive studies of its decays as well as of the $\Upsilon(1S, 2S, 3S)$ via ISR in addition to their separate scans
- It is extremely important to invest into the higher-energy region, moving if possible to $\sim$11.5 GeV to study the $\Upsilon(10860)$, $\Upsilon(11020)$, bottom baryons (?) and search for higher-mass states
- Of paramount importance is the precise measurement of R_b making possible measurements of various branching fractions and understanding full pattern of $\Upsilon(10860)$ and $\Upsilon(11020)$ decays
- Relatively rare hadronic and radiative transitions ($\pi^+\pi^-$, η, η', ω, γ) will be measured due to both high luminosity and better resolution improving the signal-to-background ratio
- It is important to have a bridge btw. charmonia and bottomonia

Backup Slides

Bottomonium System



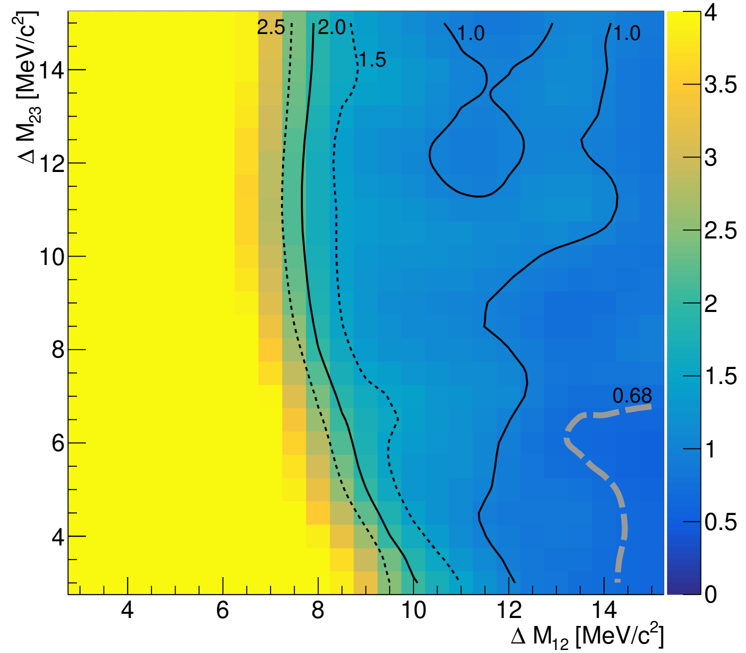
Study of η and $\pi^+\pi^-$ Transitions in $\Upsilon(4S)$ Decays to Lower $(b\bar{b})$ – V

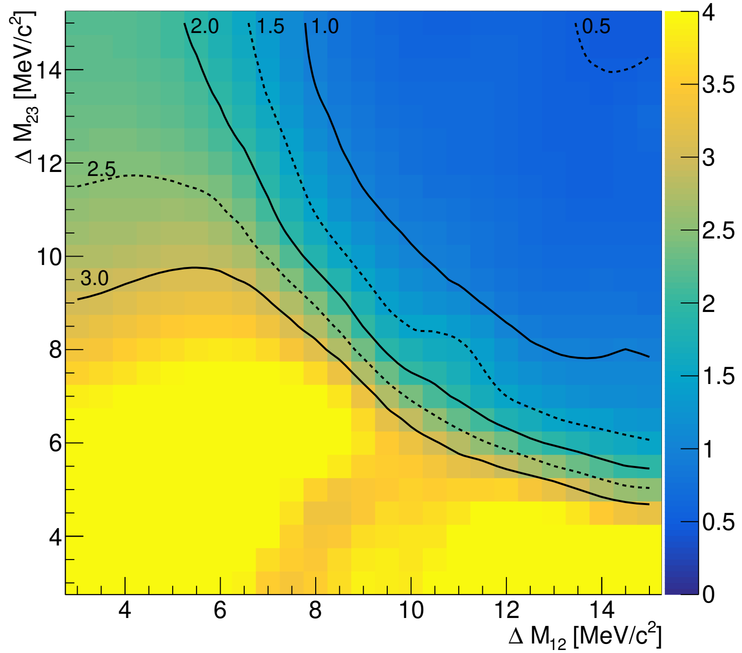


The model with the $f_0(980)$ is preferred with 2.8σ

E. Guido et al., Phys. Rev.D 96, 052005 (2017)

$e^+e^- \to \eta\ (b\bar{b})$ Near $\Upsilon(5S)$ – III





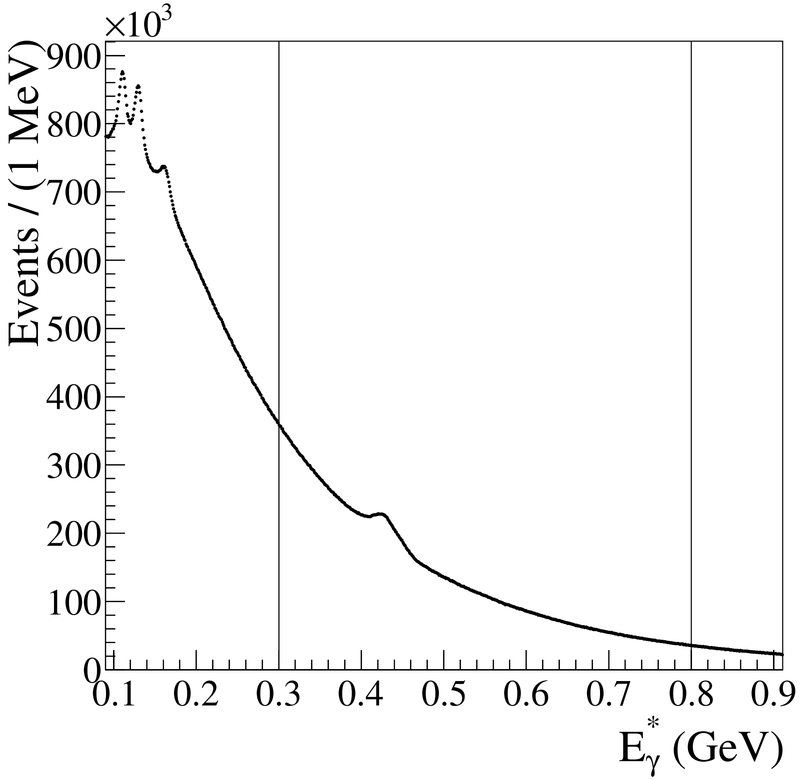
$f_{1,3} = \mathcal{B}(\Upsilon(5S) \to \eta\Upsilon_{1,3}(1D))/\mathcal{B}(\Upsilon(5S) \to \eta\Upsilon_2(1D))$ are compatible with 0

$$\mathcal{B}[\Upsilon(5S) \to \eta\Upsilon_J(1D)] = (4.82 \pm 0.92 \pm 0.67) \cdot 10^{-3}$$

U. Tamponi et al., Eur.Phys.J. C78, 633 (2018)

Observation of $\Upsilon(2S) \to \gamma\eta_b(1S)$ Decay

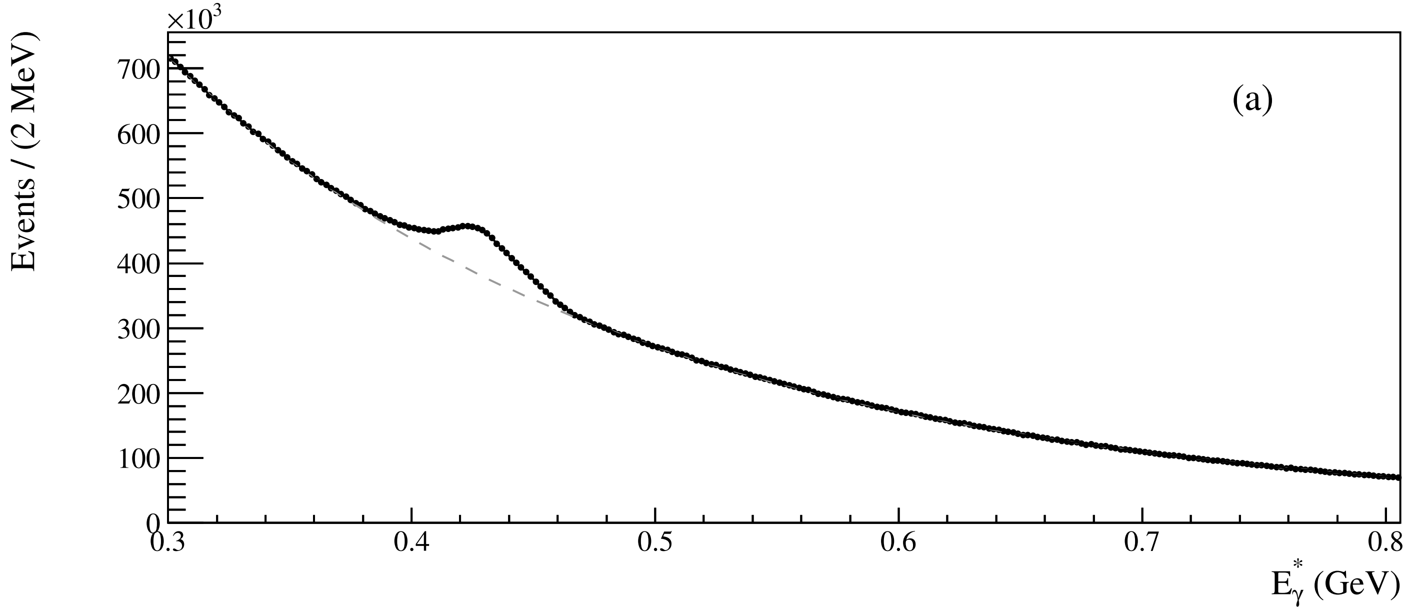
From 157.8M $\Upsilon(2S)$ decays Belle reports the first observation of $\Upsilon(2S) \to \gamma\eta_b(1S)$ decay ($> 7\sigma$)



B.G. Fulsom et al., Phys. Rev. Lett. 121, 232001 (2018)

Observation of $\Upsilon(2S) \to \gamma\eta_b(1S)$ – I

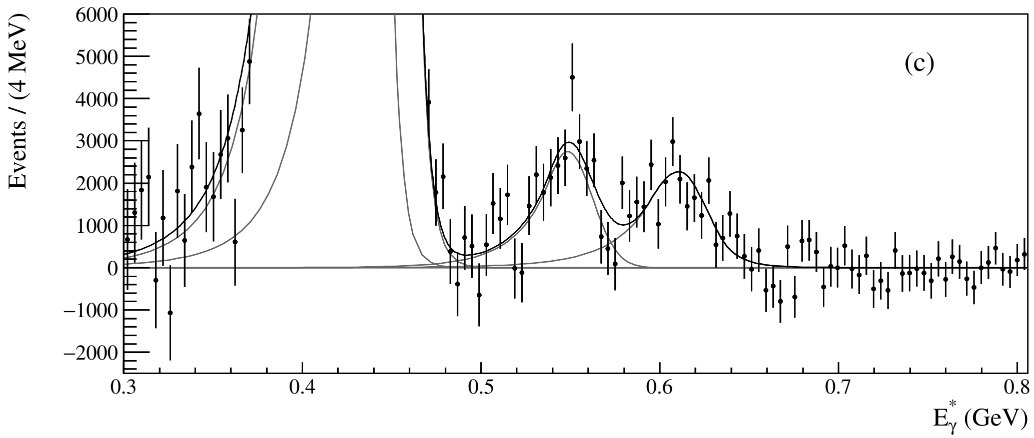
Using the world-largest sample of the $(157.8 \pm 3.6) \cdot 10^6$ $\Upsilon(2S)$
Belle studied the inclusive γ spectrum in a search for $\Upsilon(2S) \to \gamma\eta_b(1S)$



The peak due to the $\chi_{bJ}(1P) \to \gamma\Upsilon(1S)$ is clearly visible

B. Fulsom et al., Phys. Rev. Lett. 121, 232001 (2018)

Observation of $\Upsilon(2S) \to \gamma\eta_b(1S)$ – III

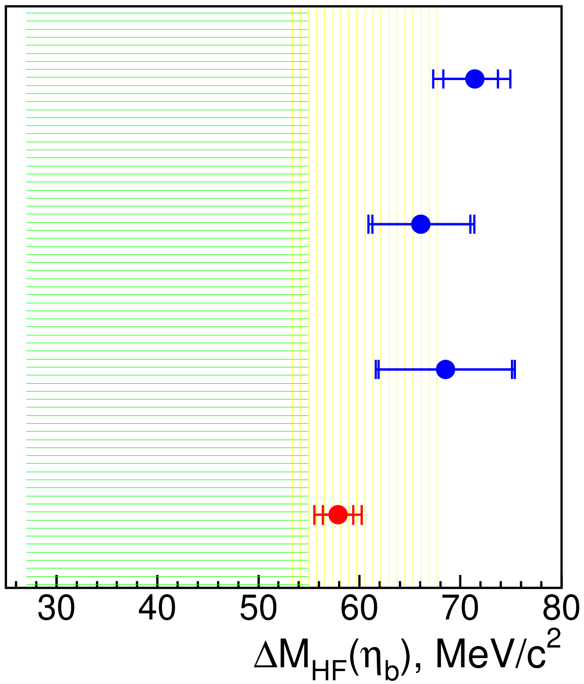


From $(28.9^{+2.6+4.2}_{-3.2-2.2}) \cdot 10^3$ events $\mathcal{B}(\Upsilon(2S) \to \gamma\eta_b(1S)) = (6.1^{+0.6+0.9}_{-0.7-0.5}) \cdot 10^{-4}$

With the lineshape $\propto E^{*3}_\gamma$ $M_{\eta_b(1S)} = 9394.8^{+2.7+4.5}_{-3.1-2.7}$ MeV

B. Fulsom et al., Phys. Rev. Lett. 121, 232001 (2018)

$\eta_b(1S)$ Mass

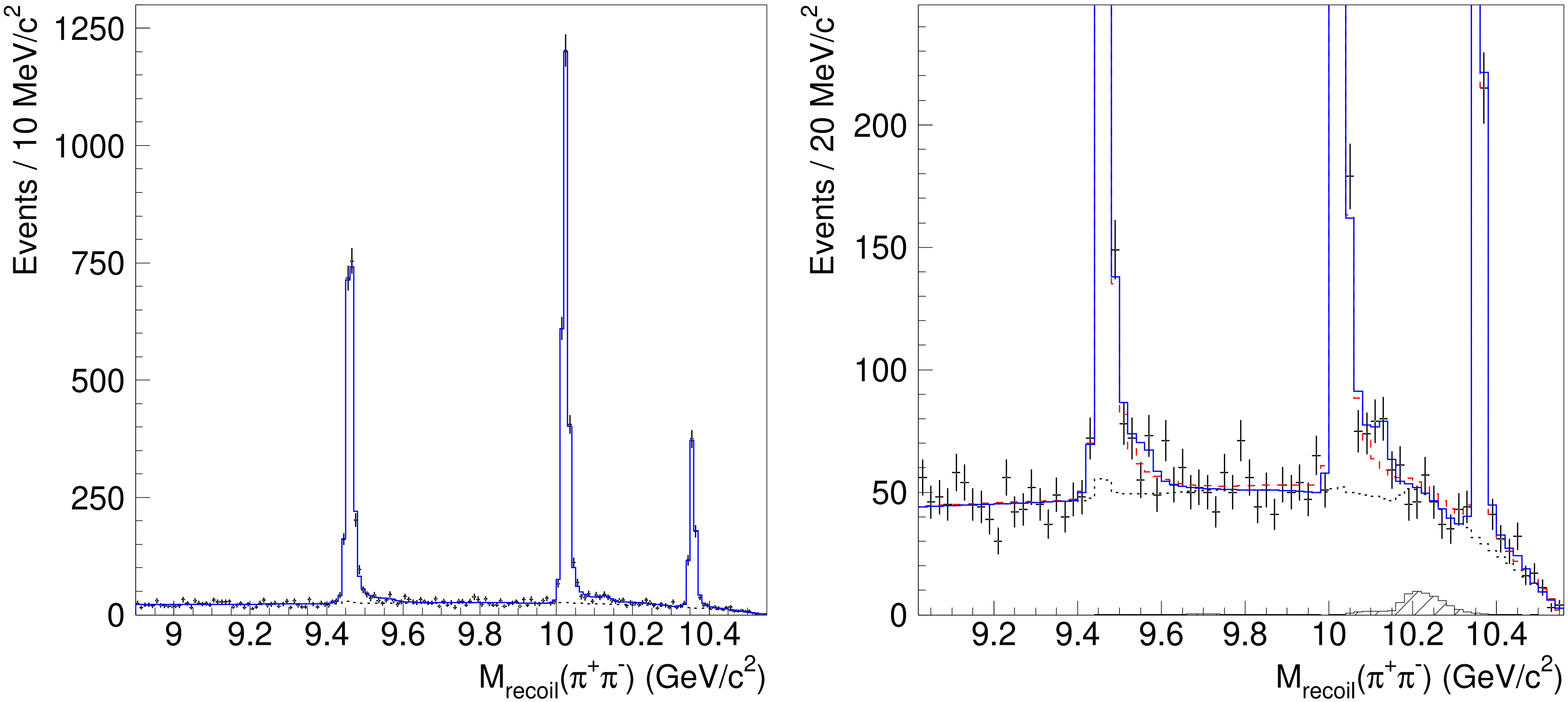


Group	Mass, MeV
BaBar,2008	$9388.9^{+3.1}_{-2.3} \pm 2.7$
BaBar,2009	$9394.2^{+4.8}_{-4.9} \pm 2.0$
CLEO,2010	$9391.8 \pm 6.6 \pm 2.0$
*CLEO,2012	$9393.2 \pm 3.4 \pm 2.3$
Belle,2012	$9402.4 \pm 1.5 \pm 1.8$
Belle,2015	$9400.7 \pm 1.7 \pm 1.6$
Belle, 2018	$9394.8^{+2.7+4.5}_{-3.1-2.7}$

Two groups of results: inclusive radiative decays yield a smaller value, there might be a bias due to the lineshape problem

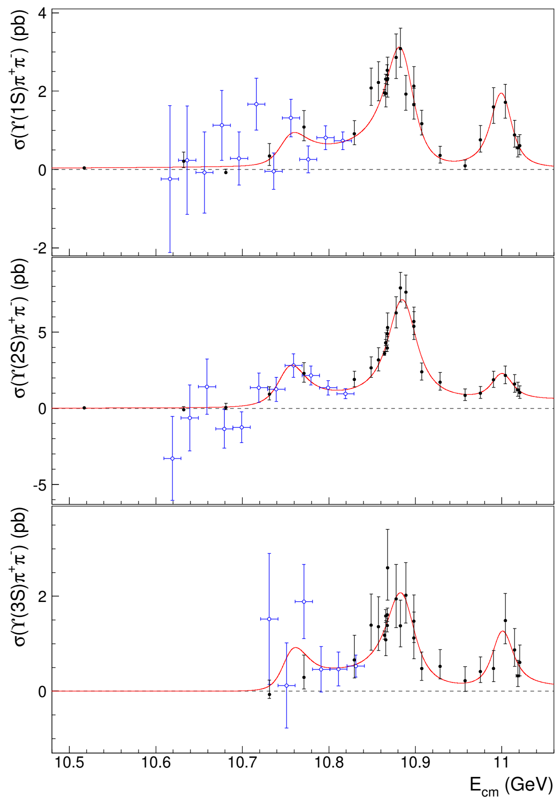
PDG-2018: 9399.0 ± 2.3 MeV

New Structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ – IV



R. Mizuk et al., JHEP 10, 220 (2019)

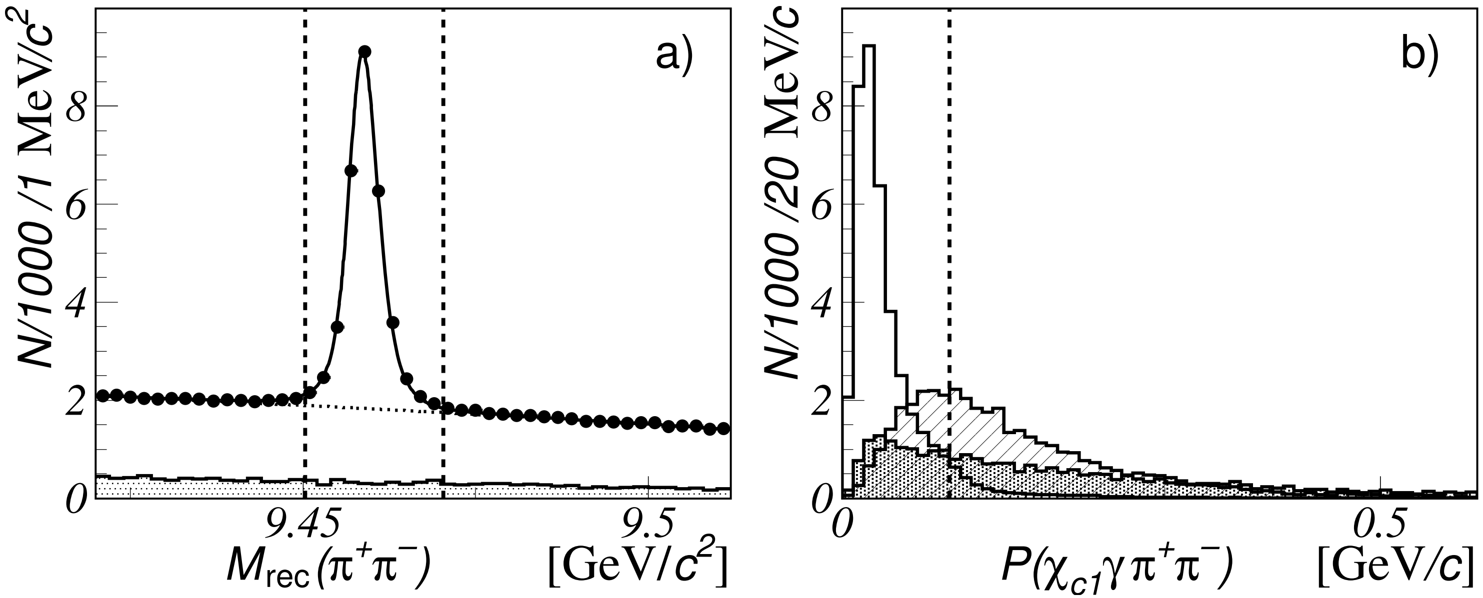
New Structure near 10.75 GeV in $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ – VI



R. Mizuk et al., JHEP 10, 220 (2019)

Observation of the Radiative Decays of $\Upsilon(1S)$ to χ_{c1} – I

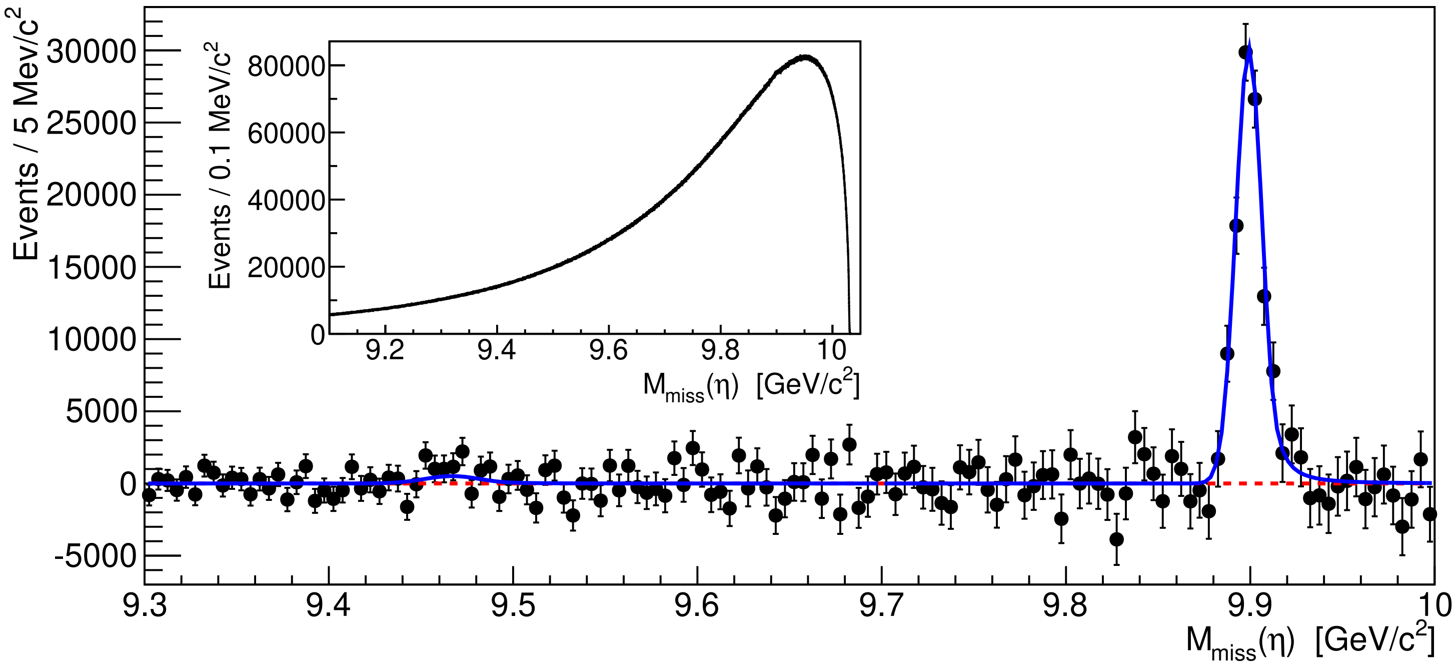
From $(157.3 \pm 3.6) \times 10^6 \Upsilon(2S)$ decays Belle searched for $\Upsilon(1S) \to \gamma(c\bar{c})_{\rm res}$ using $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(1S) \to \gamma(\chi_{c0,1,2},\ \eta_c(1S,2S))$, $\chi_{c0} \to K^+K^-\pi^+\pi^-$, $\chi_{c1,2} \to J/\psi(\mu^+\mu^-)\gamma$, $\eta_c(1S,2S) \to K^0_S K^\pm\pi^\mp$



P. Katrenko et al., Phys.Rev.Lett. 124, 122001 (2020)

Observation of the $\Upsilon(4S) \to \eta h_b(1P)$ Transition – I

From 771.6M $\Upsilon(4S)$ decays Belle studied $\Upsilon(4S) \to \eta h_b(1P)$ using the η missing mass, $M_{\rm miss} = \sqrt{(P_{e^+e^-} - P_\eta)^2}$, $\eta \to \gamma\gamma$.

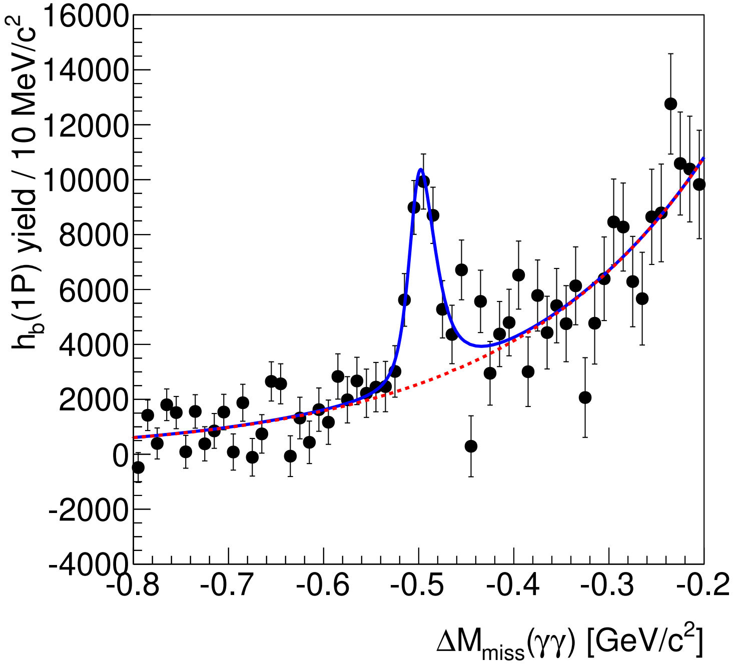


$N_{h_b(1P)} = 112469 \pm 5537$ (11σ significance)

U. Tamponi et al., Phys. Rev. Lett. 115, 142001 (2015)

Observation of the $\Upsilon(4S) \to \eta h_b(1P)$ Transition – II

Then $h_b(1P) \to \gamma\eta_b(1S)$ is searched via $\Delta M_{\rm miss} = M_{\rm miss}(\eta) - M_{\rm miss}(\eta)$



$N_{\eta_b(1S)} = 33116 \pm 4741$ (9σ significance)

U. Tamponi et al., Phys. Rev. Lett. 115, 142001 (2015)

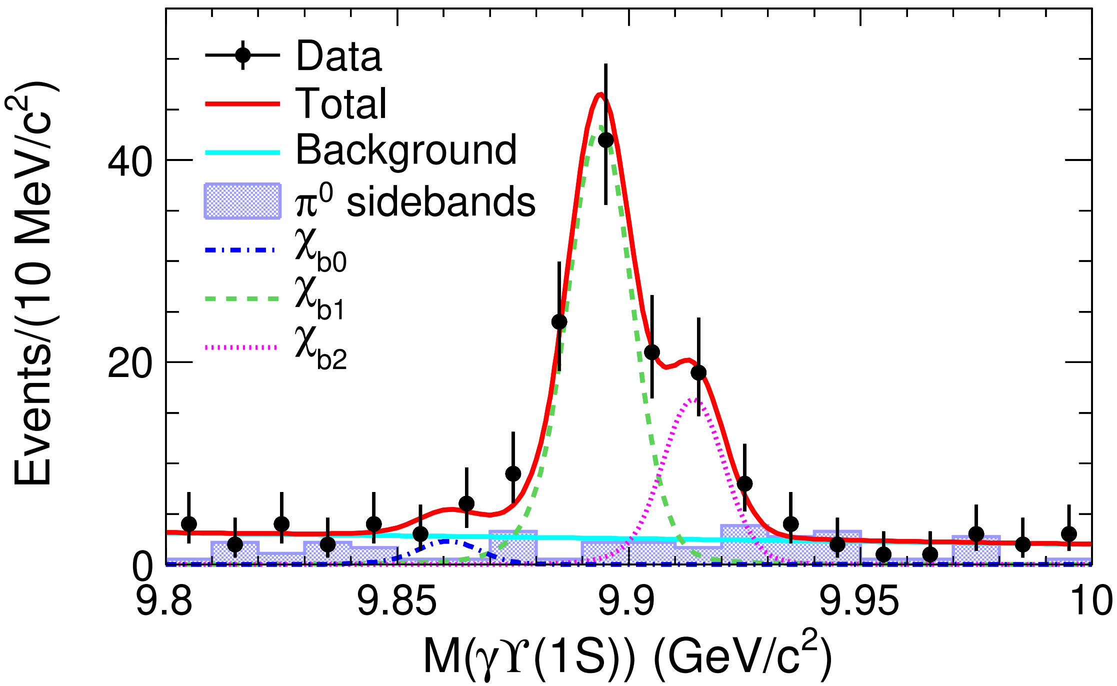
Observation of the $\Upsilon(4S) \to \eta h_b(1P)$ Transition – III

Observable	Value
$\mathcal{B}(\Upsilon(4S) \to \eta h_b(1P))$	$(2.18 \pm 0.11 \pm 0.18) \cdot 10^{-3}$
$\mathcal{B}(h_b(1P) \to \gamma \eta_b(1S))$	$(56 \pm 8 \pm 4)\%$
$M_{h_b(1P)}$	$(9899.3 \pm 0.4 \pm 1.0)$ MeV
$M_{\eta_b(1S)}$	$(9400.7 \pm 1.7 \pm 1.6)$ MeV
$\Gamma_{\eta_b(1S)}$	$(8^{+6}_{-5} \pm 5)$ MeV
$\Delta M_{\rm HF}(1P) = M^{\rm sa}_{\chi_{bJ}}(1P) - M_{h_b(1P)}$	$(+0.6 \pm 0.4 \pm 1.0)$ MeV
$\Delta M_{\rm HF}(1S) = M_{\Upsilon(1S)} - M_{\eta_b(1S)}$	$(59.6 \pm 1.7 \pm 1.6)$ MeV

U. Tamponi et al., Phys. Rev. Lett. 115, 142001 (2015)

Observation of $e^+e^- \to \pi^+\pi^-\pi^0\chi_{bJ}$ – I

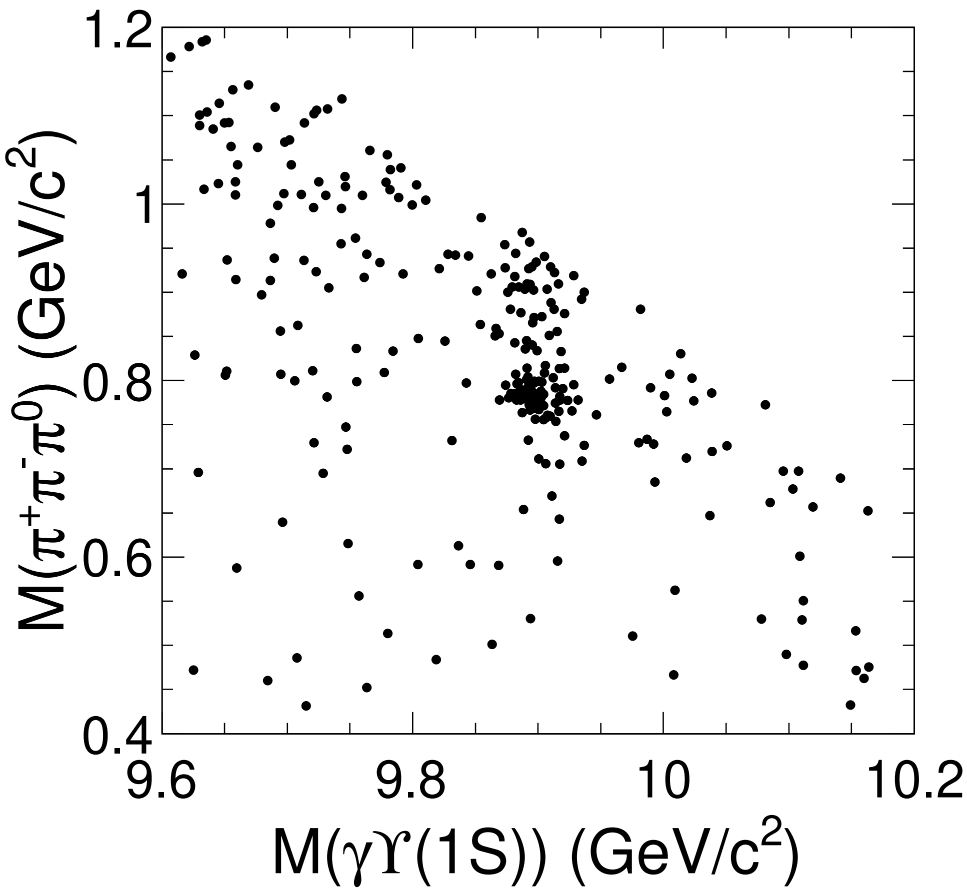
Belle used 118 fb^{-1} at 10.867 GeV to study $e^+e^- \to \pi^+\pi^-\pi^0\chi_{bJ},\ \chi_{bJ} \to \gamma\Upsilon(1S)$, $\Upsilon(1S) \to l^+l^-$ and search for $X_b \to \omega\Upsilon(1S)$, analogue of $\chi_{c1}(3872)$



The $\gamma\Upsilon(1S)$ spectrum shows clear signals of the $\chi_{b1}3\pi$ and $\chi_{b2}3\pi$

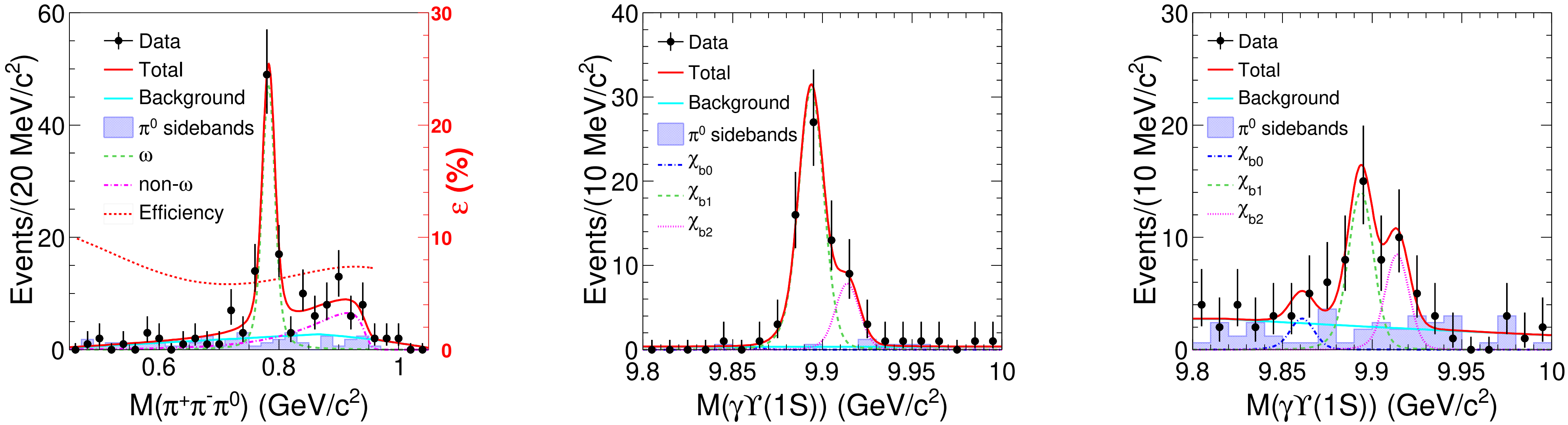
X.H. He et al., Phys. Rev. Lett. 113, 142001 (2014)

Observation of $e^+e^- \to \pi^+\pi^-\pi^0\chi_{bJ}$ – II



X.H. He et al., Phys. Rev. Lett. 113, 142001 (2014)

Observation of $e^+e^- \to \pi^+\pi^-\pi^0\chi_{bJ}$ – III



b/ The $M(3\pi)$ projection shows clear signals of ω and non-ω,

c/ and d/ show the $\gamma\Upsilon(1S)$ projection in the ω and non-ω

X.H. He et al., Phys. Rev. Lett. 113, 142001 (2014)

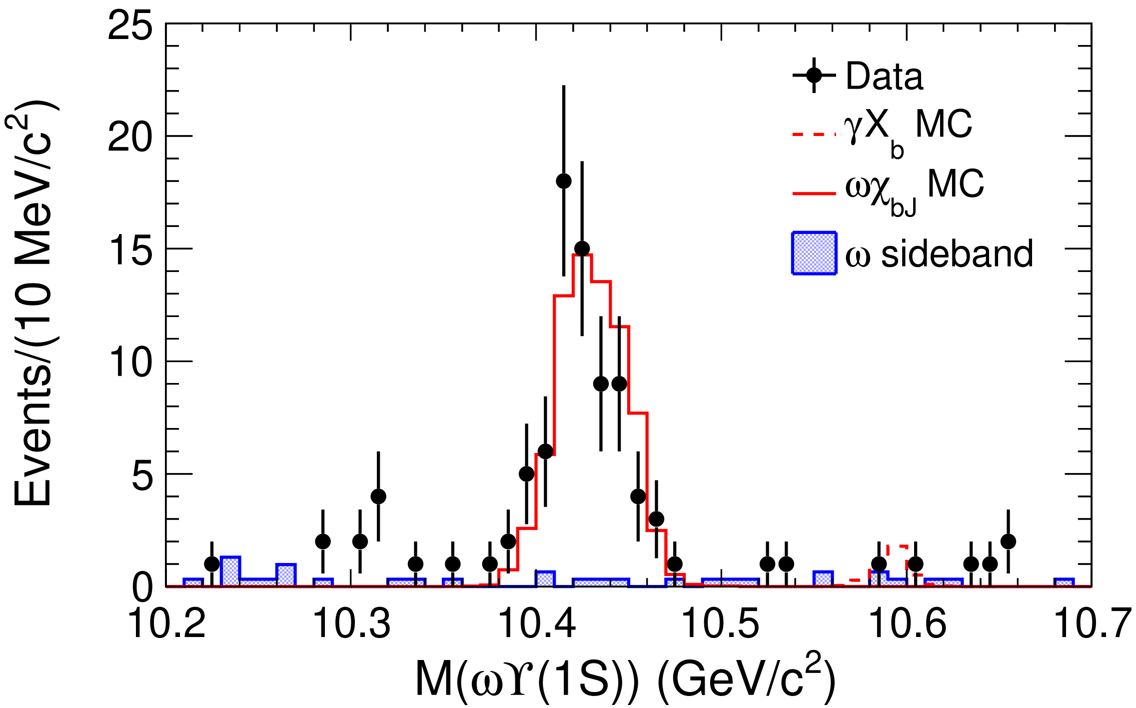
Observation of $e^+e^- \to \pi^+\pi^-\pi^0\chi_{bJ}$ – IV

Mode	Yield	Σ (σ)	$\mathcal{B}, 10^{-3}$
$3\pi\chi_{b0}$	< 13.6	1.0	< 6.3
$3\pi\chi_{b1}$	80.1 ± 9.9	12	$1.85 \pm 0.23 \pm 0.23$
$3\pi\chi_{b2}$	28.6 ± 6.5	5.9	$1.17 \pm 0.27 \pm 0.14$
$\omega\chi_{b0}$	< 7.5	0.5	< 3.9
$\omega\chi_{b1}$	59.9 ± 8.3	12	$1.57 \pm 0.22 \pm 0.21$
$\omega\chi_{b2}$	12.9 ± 4.8	3.5	$0.60 \pm 0.23 \pm 0.15$
$(3\pi)_{\mathrm{non}-\omega}\chi_{b0}$	< 10.7	0.4	< 4.8
$(3\pi)_{\mathrm{non}-\omega}\chi_{b1}$	23.6 ± 6.4	4.9	$0.52 \pm 0.15 \pm 0.11$
$(3\pi)_{\mathrm{non}-\omega}\chi_{b2}$	15.6 ± 5.4	3.1	$0.61 \pm 0.22 \pm 0.28$

X.H. He et al., Phys. Rev. Lett. 113, 142001 (2014)

Observation of $e^+e^- \to \pi^+\pi^-\pi^0\chi_{bJ}$ – V

Belle searches for X_b in $e^+e^- \to \gamma X_b,\ X_b \to \omega\Upsilon(1S)$



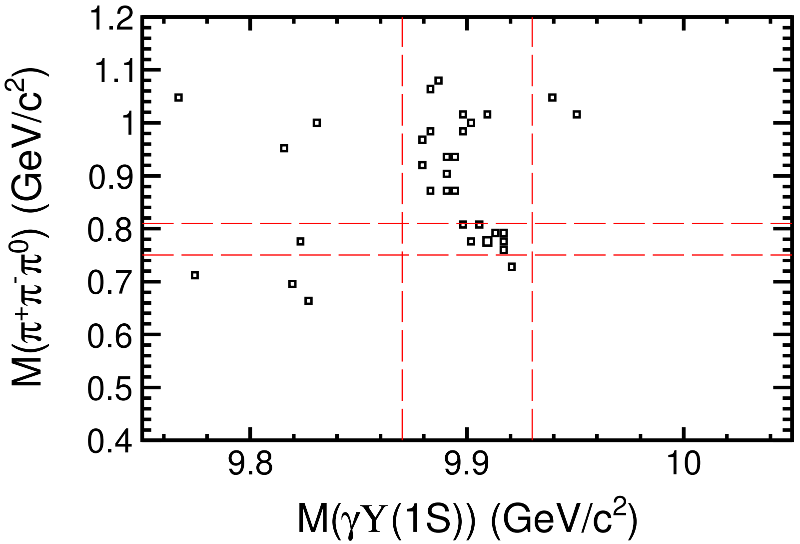
The peak in $M(\omega\Upsilon(1S))$ comes from $e^+e^- \to \omega\chi_{bJ},\ \chi_{bJ} \to \gamma\Upsilon(1S)$

$\mathcal{B}(\Upsilon(10860) \to \gamma X_b)\mathcal{B}(X_b \to \omega\Upsilon(1S)) < (2.6 - 3.8) \cdot 10^{-5}$ btw. 10.55 and 10.65 GeV

X.H. He et al., Phys. Rev. Lett. 113, 142001 (2014)

Observation of $e^+e^- \to \pi^+\pi^-\pi^0\chi_{bJ}$ and Search for $e^+e^- \to \phi\chi_{bJ}$ – I

Belle searches for $e^+e^- \to \pi^+\pi^-\pi^0\chi_{bJ},\ \phi\chi_{bJ}$ with 141 fb^{-1} in [10.77-11.05] GeV,
$\chi_{bJ} \to \gamma\Upsilon(1S)$, $\Upsilon(1S) \to l^+l^-$, $\omega \to \pi^+\pi^-\pi^0$, $\phi \to K^+K^-$

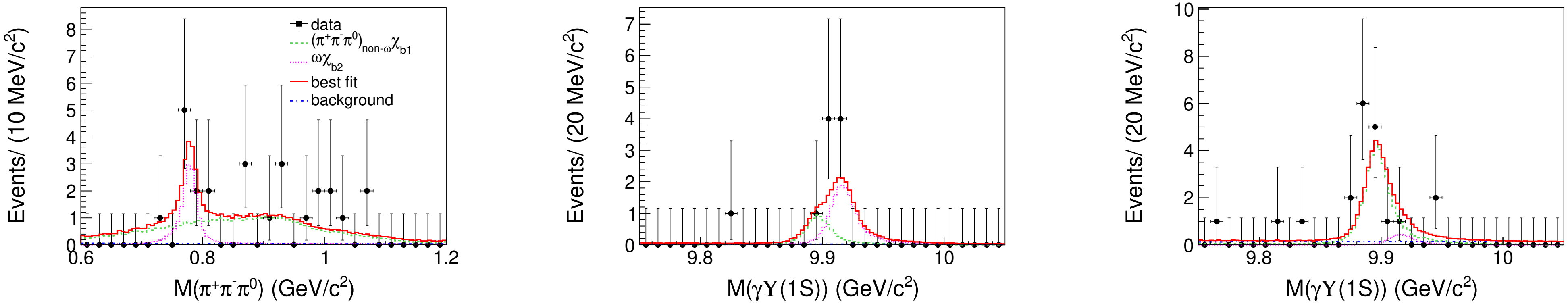


The scatter plot clealy shows clusters at $\omega\chi_{bJ}$ and above

The 2D fit yields 7.8 ± 3.2 (4.0σ) $\omega\chi_{b2}$ and 19.6 ± 5.3 (6.1σ) non-$\omega\chi_{b1}$

J.H. Yin et al., Phys.Rev. D98, 091102 (2018)

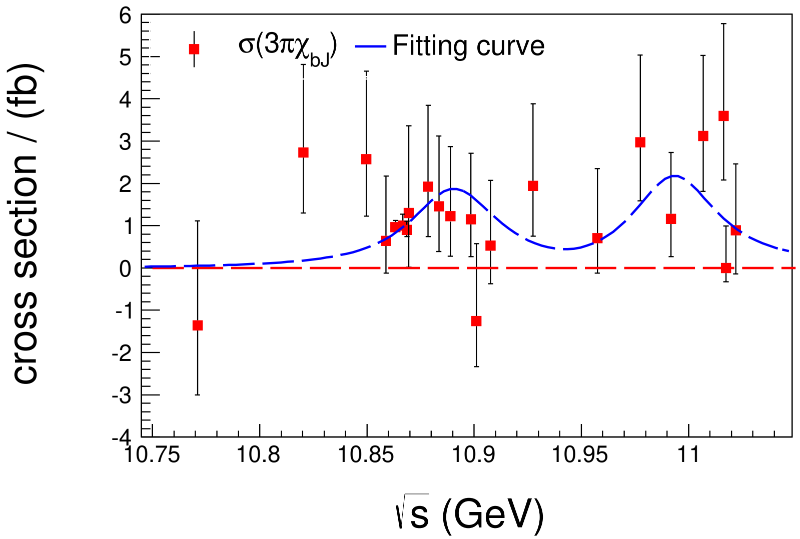
Observation of $e^+e^- \to \pi^+\pi^-\pi^0\chi_{bJ}$ and Search for $e^+e^- \to \phi\chi_{bJ}$ – II



1D projections: clear ω and non-ω, non-$\omega\chi_{b1}$, $\omega\chi_{b2}$

J.H. Yin et al., Phys.Rev. D98, 091102 (2018)

Observation of $e^+e^- \to \pi^+\pi^-\pi^0\chi_{bJ}$ and Search for $e^+e^- \to \phi\chi_{bJ}$ – III



Assuming the $3\pi\chi_{bJ}$ signal comes from the $\Upsilon(5S)$ and $\Upsilon(6S)$,

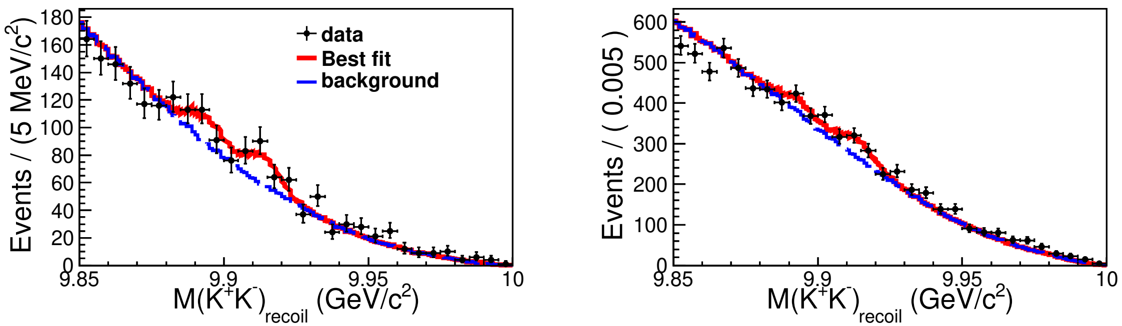
$\mathcal{B}(\Upsilon(5S) \to e^+e^-)\mathcal{B}(\Upsilon(5S) \to 3\pi\chi_{bJ}) = (15.3 \pm 3.7) \cdot 10^{-9}$,

$\mathcal{B}(\Upsilon(6S) \to e^+e^-)\mathcal{B}(\Upsilon(6S) \to 3\pi\chi_{bJ}) = (18.3 \pm 9.0) \cdot 10^{-9}$

Low data samples preclude from any conclusions

J.H. Yin et al., Phys.Rev. D98, 091102 (2018)

Observation of $e^+e^- \to \pi^+\pi^-\pi^0\chi_{bJ}$ and Search for $e^+e^- \to \phi\chi_{bJ}$ – IV



Two types of events: $M(\gamma K^+K^-)_{\rm recoil}$ around $M(\Upsilon(1S))$ and non-$\Upsilon(1S)$

Then in $M(K^+K^-)_{\rm recoil}$ no signals of $\phi\chi_{b1}$ (2.6σ) and $\phi\chi_{b2}$ (2.1σ) seen

$\sigma(\phi\chi_{b1}) < 1.4$ pb, $\sigma(\phi\chi_{b2}) < 1.2$ pb at 90% CL or $\mathcal{B} \sim 10^{-3}$

J.H. Yin et al., Phys.Rev. D98, 091102 (2018)