Belle II measurements from the energy scan near the $\Upsilon(10753)$ resonance

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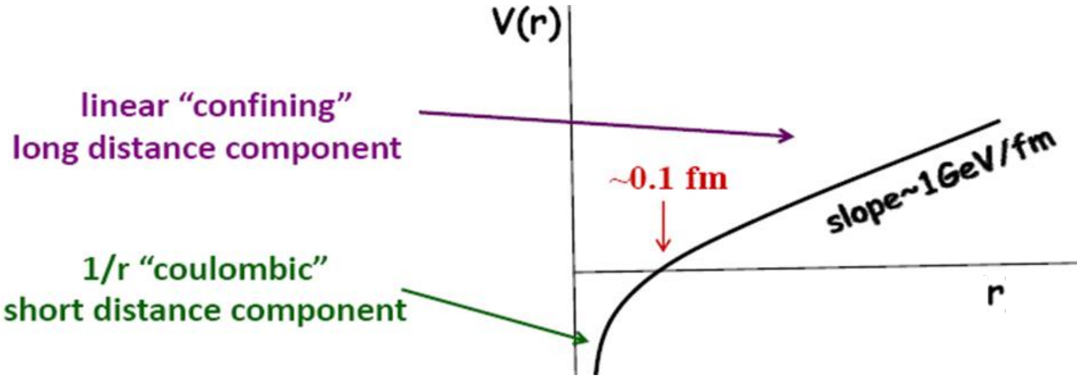
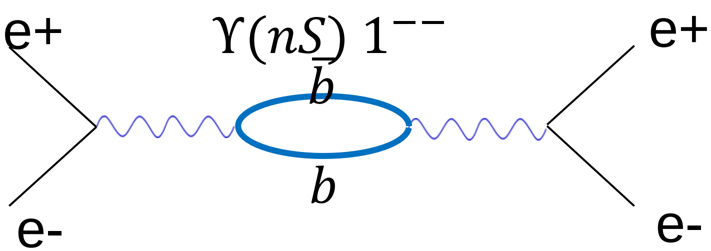
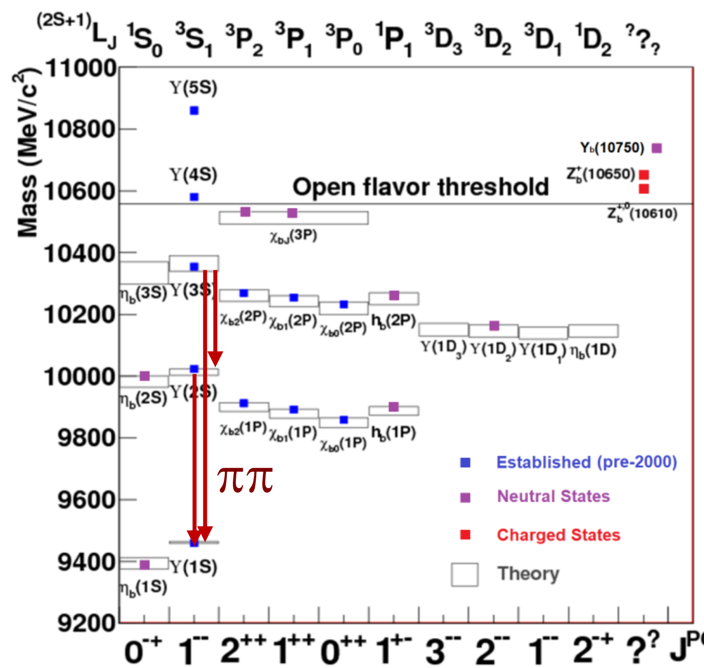
2025 European Physical Society Conference on High Energy Physics, Marseille, France

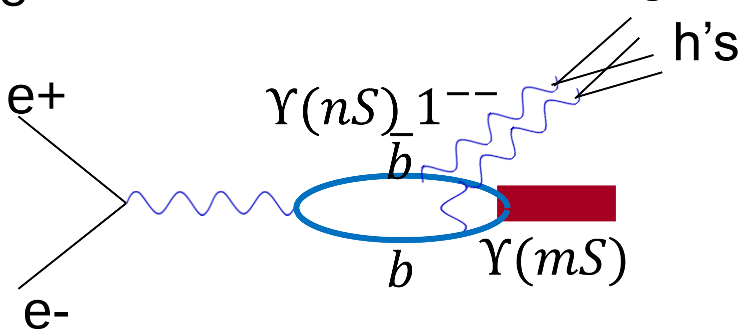


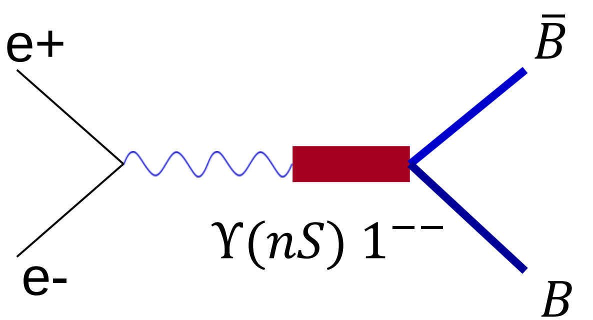
non-relativistic QM applies

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







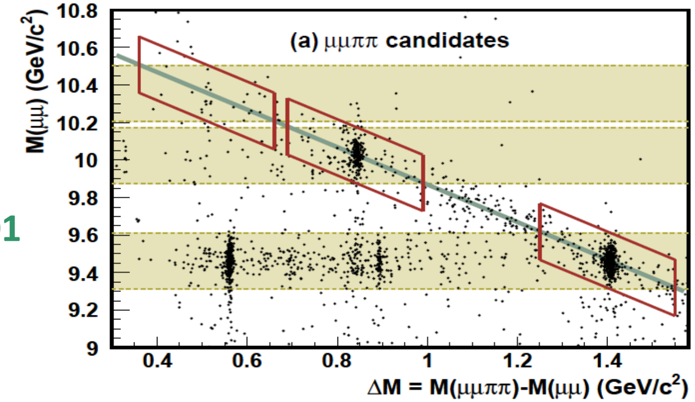


QCD multipole expansion

	Γ_{exp}(KeV)	Γ_{th}(KeV)
$\Upsilon(3S) \rightarrow \Upsilon(1S)\pi^+\pi^-$	0.89 ± 0.02	$1.3 - 6.2$
$\Upsilon(3S) \rightarrow \Upsilon(2S)\pi^+\pi^-$	0.57 ± 0.037	$0.4 - 1.0$
$\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-$	5.7 ± 0.083	~ 8-9

First observation of $\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-, \Upsilon(2S)\pi^+\pi^-$

Belle, *Phys.Rev.Lett.* 100 (2008) 112001

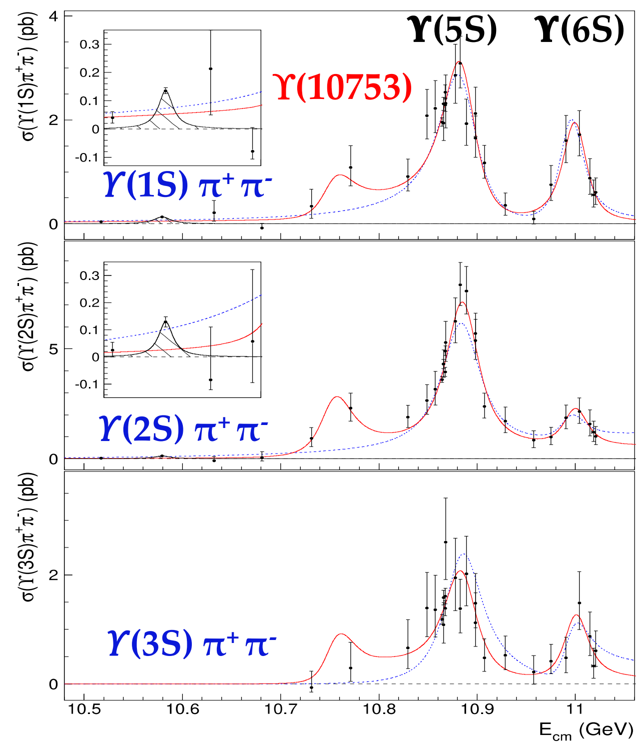


First Observation of the $\Upsilon(10753)$

significance 5.2σ

Belle, JHEP 10 (2019) 220

$e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$ cross sections

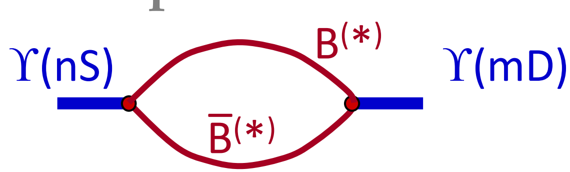


Very high partial widths of hadronic transitions.

Explanation "molecule" hybrid compact tetraquark

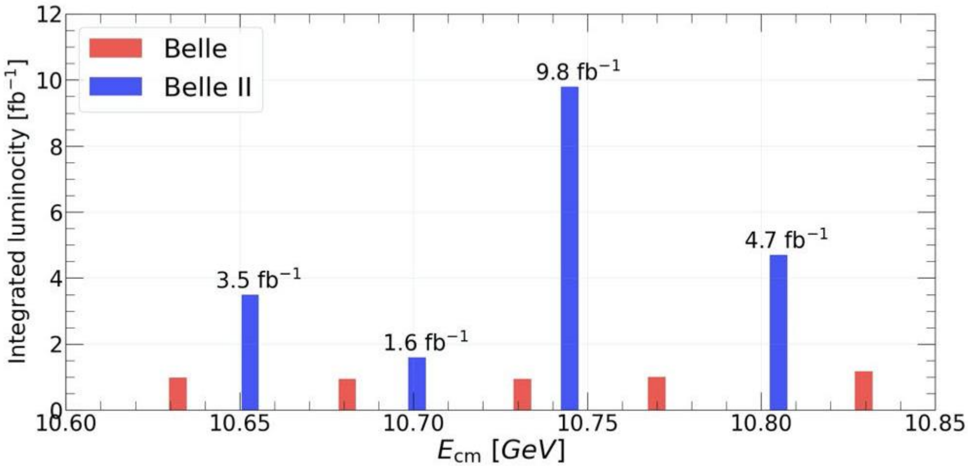
$$|b\bar{b}\rangle + |B^{(*)}\bar{B}^{(*)}\rangle + |b\bar{b}g\rangle + |bq\,\bar{b}\bar{q}\rangle$$

$\Upsilon(10753)$: D-wave state with S-D mixing enhanced due to hadron loops.
Or exotics.

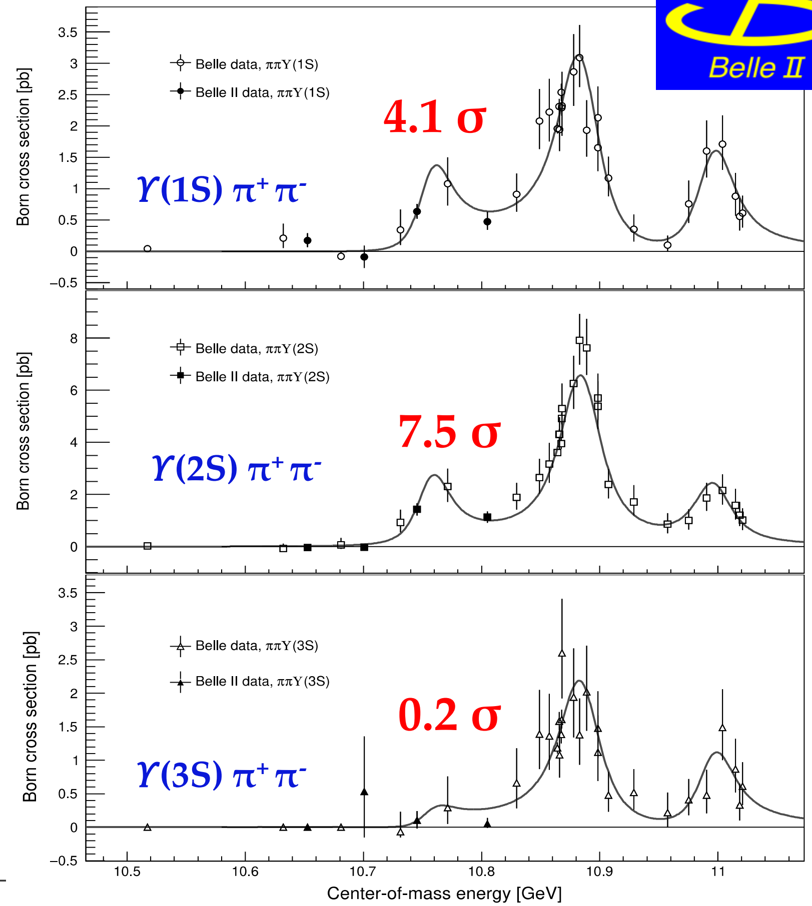


November 2021 Scan Points from Belle II (19.6 fb^{-1} in total)

BELLE-II,JHEP 07, 116 (2024)

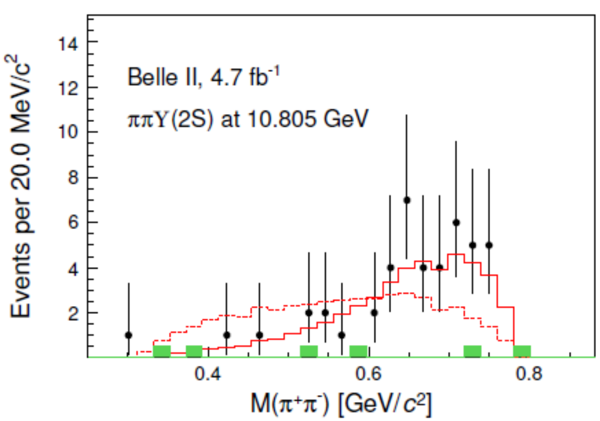


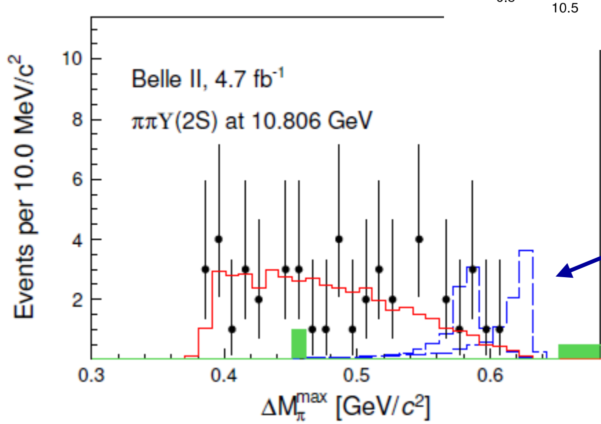
Belle II = filled circles



Excellent confirmation

- $M = (10756.6 \pm 2.7 \pm 0.9)\ \mathrm{MeV}/c^2$
- $\Gamma = (29.0 \pm 8.8 \pm 1.2)\ \mathrm{MeV}$





No $\Upsilon(10753) \to Z_b\pi^+$ signal

Points with error bars – signal
Green shaded - sidebands

$$\Delta M_\pi^{max} = \max(M(\mu\mu\pi\pi) - M(\mu\mu))$$

$Z_b^{+,0}$ states in bottomonium

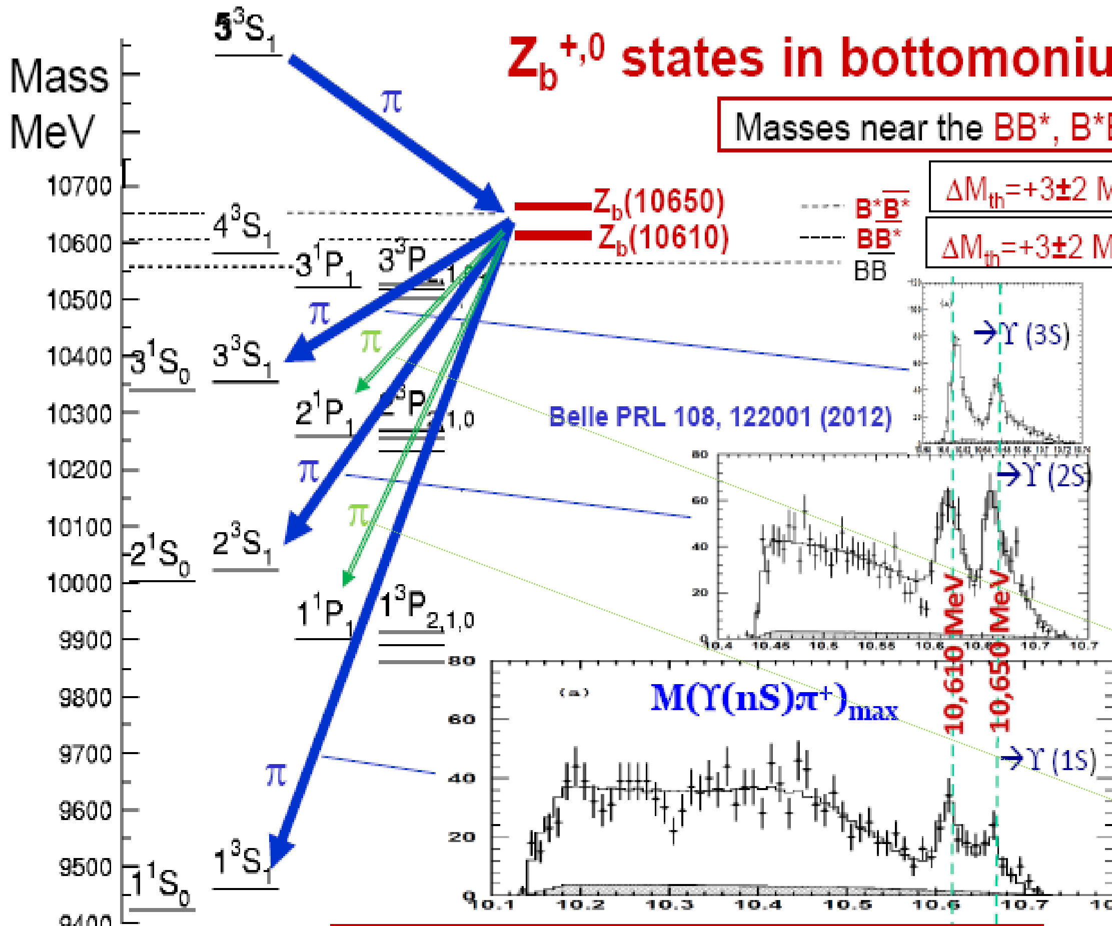
Masses near the BB*, B*B* thresholds

ΔM_{th}=+3±2 MeV

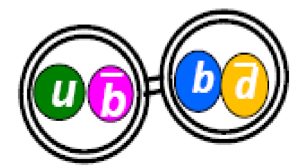
ΔM_{th}=+3±2 MeV

Γ 11.5 ± 2.2 / 18.4 ± 2.4 MeV

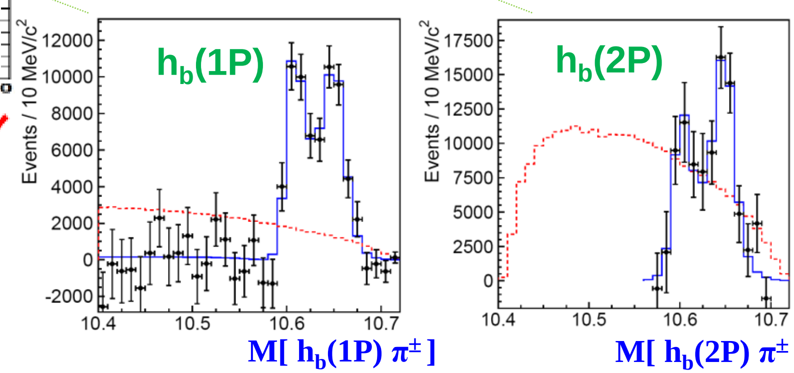
Both $J^{P(C)}=1^{+(-)}$



Charged and **neutral** versions detected $I^G=1^+$

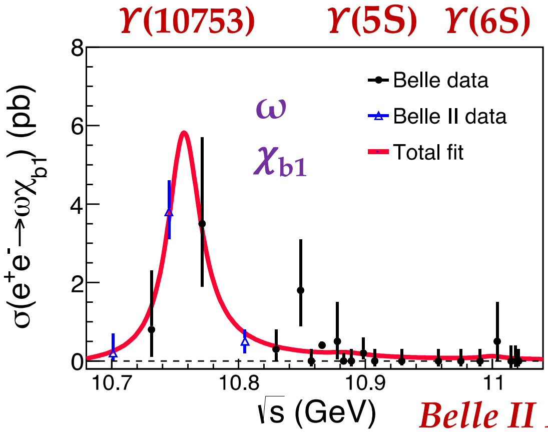


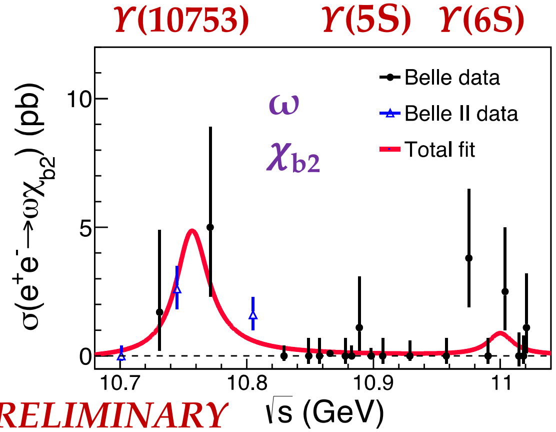
Large rate to fall-apart modes observed



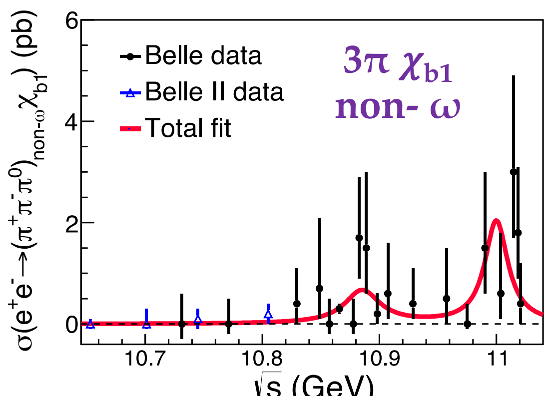
$e^+e^- \to \omega\,\chi_{bJ}$ vs. $(\pi^+\pi^-\pi^0)_{\text{non-}\omega}\,\chi_{bJ}$

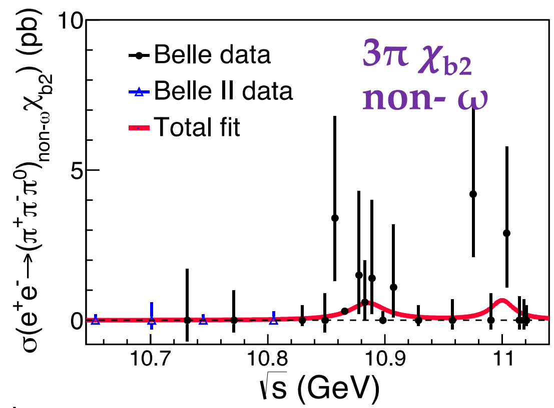
Belle II PRELIMINARY





Belle II PRELIMINARY





Υ(10753) mass and width obtained here are consistent with π π Υ(nS)

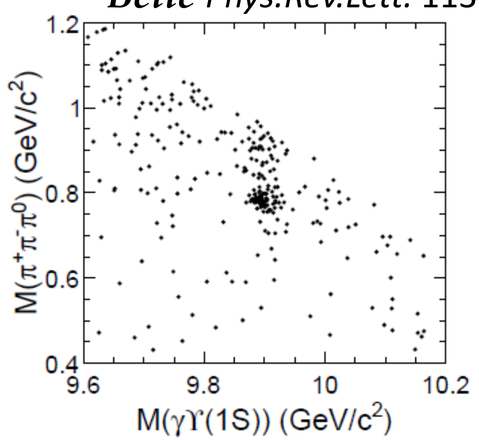
Different resonances display different preferences for ω vs. 3π (non- ω) decays !

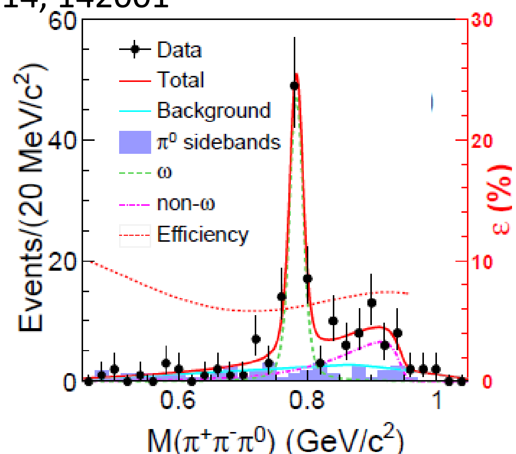
M.Voloshin *Phys.Rev.D* 90, 014036 (2014)

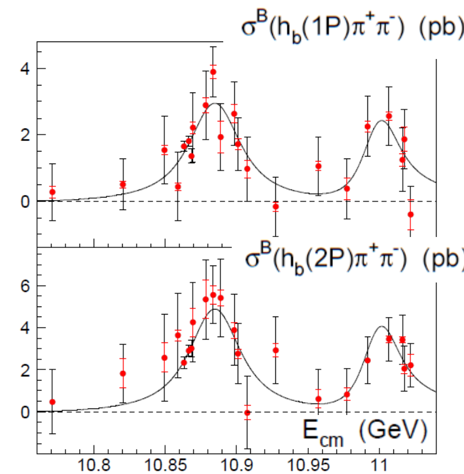
Perhaps the non- ω is from a cascade decay ?

$\Upsilon(5S,6S) \to Z_b\,\pi \to \chi_{bJ}\,\rho\,\pi$

Belle *Phys.Rev.Lett.* 113 (2014) 14, 142001







Belle *Phys.Rev.Lett.* 117 (2016) 14, 142001

Energy Dependence of $B^{(*)}\bar{B}^{(*)}$ Cross Sections

BELLE-II, JHEP 10, 114 (2024)

The same method as in BELLE, JHEP 06, 137 (2021)

Multivariate Full Event Interpretation

M_{bc} plots at four CM energies:

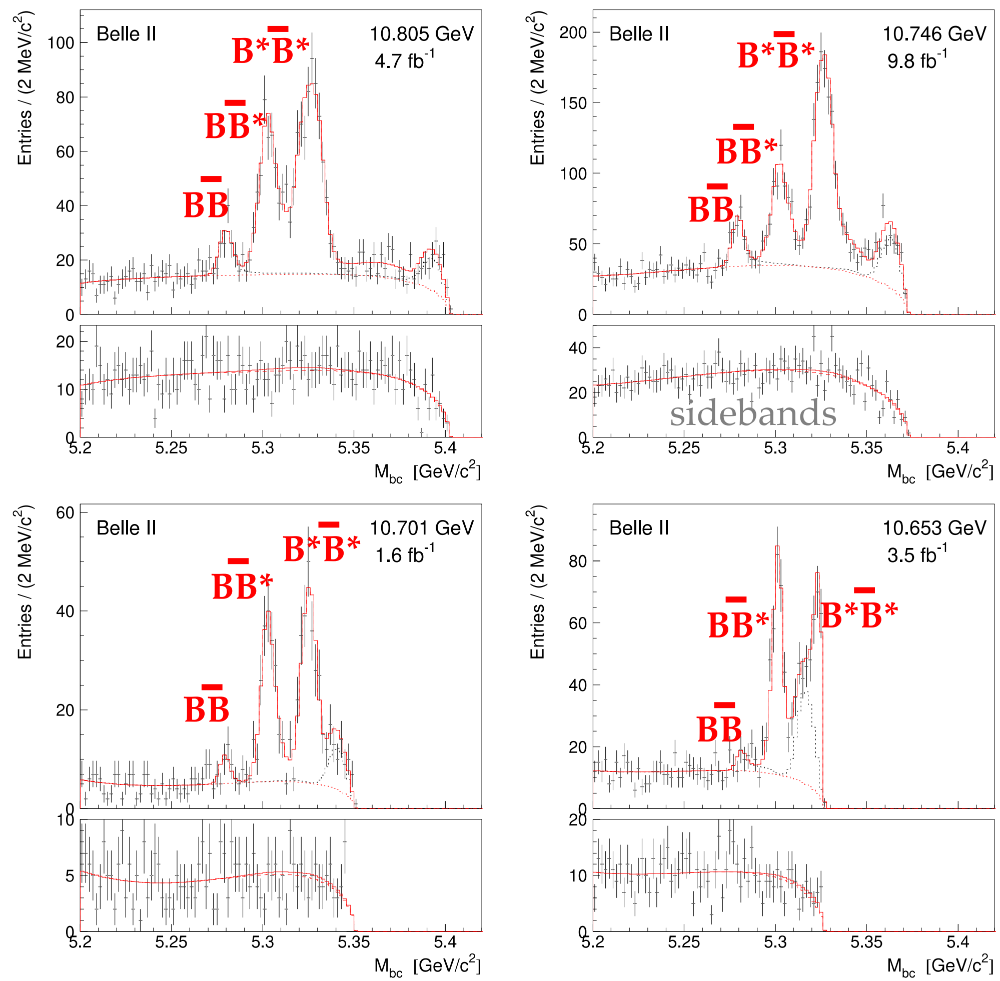
- Signal region on top
- $\Delta E'$ sideband below

$$M_{bc} = [(E_{CM}/2)^2 - P_B^{\,2}]^{1/2}$$

Four peaks:

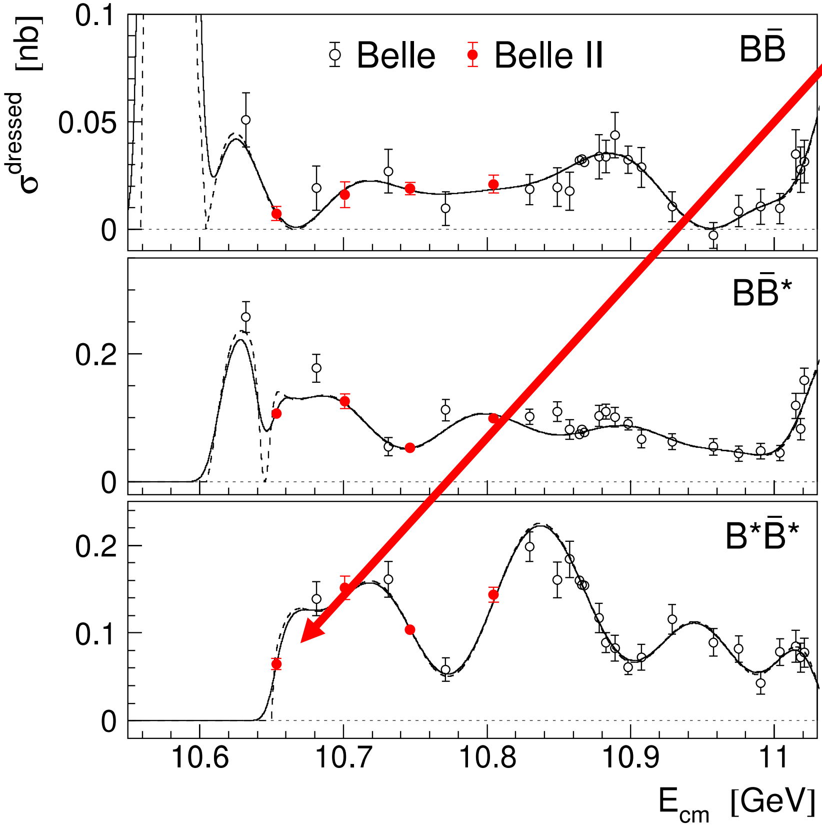
- Three from $B\bar{B}$, $B\bar{B}^*$, $B^*\bar{B}^*$
- Also, a peak from ISR to $\Upsilon(4S)$

(dashed peak @ high endpoint; above $B^*\bar{B}^*$ except in last plot)



Energy Dependence of $B^{(*)}\bar{B}^{(*)}$ Cross Sections

BELLE-II, JHEP 10, 114 (2024)

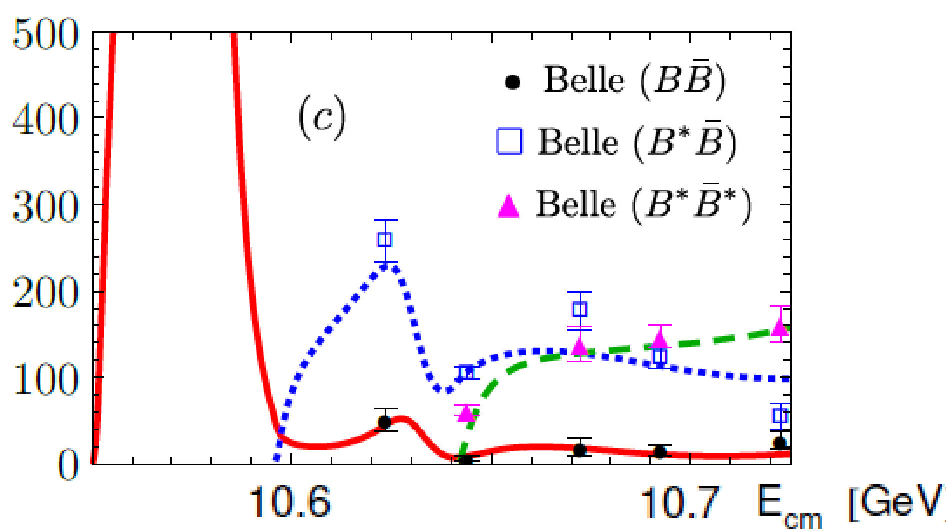


Rapid cross-section increase above $B^*\bar{B}^*$ threshold

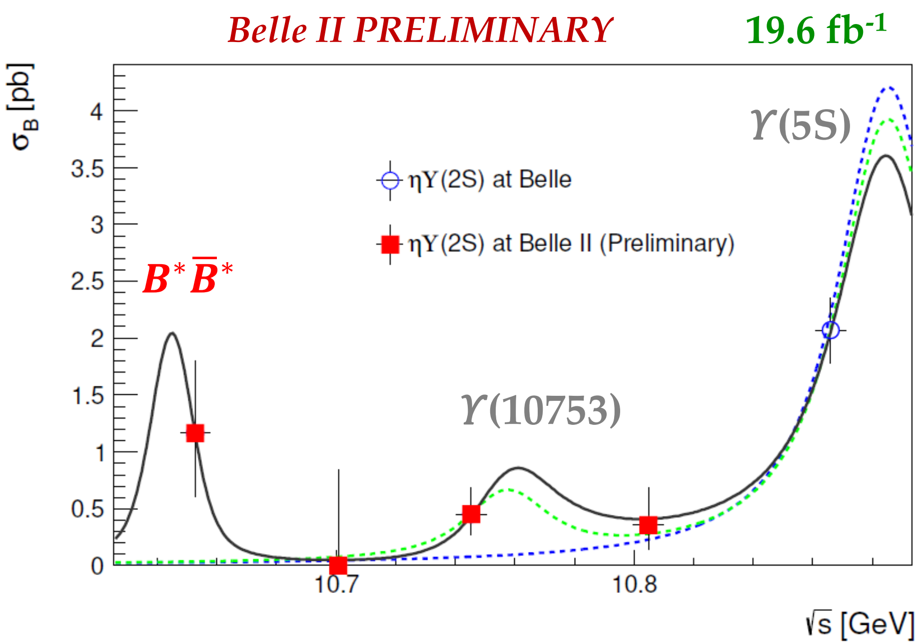
Possibly a resonance, or a $B^*\bar{B}^*$ bound-state, near threshold

Can have destructive interference between $B\bar{B}^*$ & $B^*\bar{B}^* \rightarrow B\bar{B}^*$

Couple channel model confirms $B^*\bar{B}^*$ bound state Nucl.Phys.A, 1041,122764,(2024)



Search for $e^+e^- \to \eta\Upsilon(1S,2S)$ near $\Upsilon(10753)$



Fit with B*B* threshold bound state, Υ(10753), Υ(5S)

Fit with Υ(10753), Υ(5S)

Fit with only the Υ(5S)

Note: B*B̄* bound state significance is always >3.2 σ, in these and other fit variations

Belle II PRELIMINARY

Mode	$N_{\rm prod}$ ($\times 10^3$)	$(1+\delta)$	$\epsilon(\%)$	$\sigma_{\rm B}^{\rm (UL)}$ (pb)
(10653.30 ± 1.14) MeV				
$\eta\Upsilon(2S)$	$(3.7^{+1.6}_{-1.3})$, 4.3σ	0.881	19.2/15.1	$1.11^{+0.49}_{-0.39} \pm 0.36$
$\eta\Upsilon(1S)$	< 0.4	0.895	23.9	< 0.10
γX_b	< 0.3	0.784	32.0	< 0.14
(10700.90 ± 0.63) MeV				
$\eta\Upsilon(2S)$	$(0.0^{+1.0}_{-0.0})$	1.832	12.9/7.0	$0.00^{+0.31}_{-0.00} \pm 0.53$
$\eta\Upsilon(1S)$	< 0.4	0.901	24.0	< 0.22
γX_b	< 0.1	0.803	31.3	< 0.09
(10746.30 ± 0.48) MeV				
$\eta\Upsilon(2S)$	$(3.3^{+1.6}_{-1.2})$, 4.2σ	0.687	17.1/14.0	$0.45^{+0.22}_{-0.17} \pm 0.05$
$\eta\Upsilon(1S)$	< 0.9	0.906	23.8	< 0.09
γX_b	< 1.4	0.817	29.8	< 0.17
(10804.50 ± 0.70) MeV				
$\eta\Upsilon(2S)$	$(1.5^{+1.4}_{-0.9})$, 2.8σ	0.848	16.6/14.7	$0.36^{+0.32}_{-0.21} \pm 0.04$
$\eta\Upsilon(1S)$	< 0.4	0.912	24.6	< 0.08
γX_b	< 1.3	0.833	28.2	< 0.32

Also search for the X_b, a b-quark partner of the X(3872)

- No signal seen in $X_b \to \pi^+\pi^-\chi_{b1,2}$, $\chi_{b1,2} \to \gamma\Upsilon(nS)$
- Limits are set …

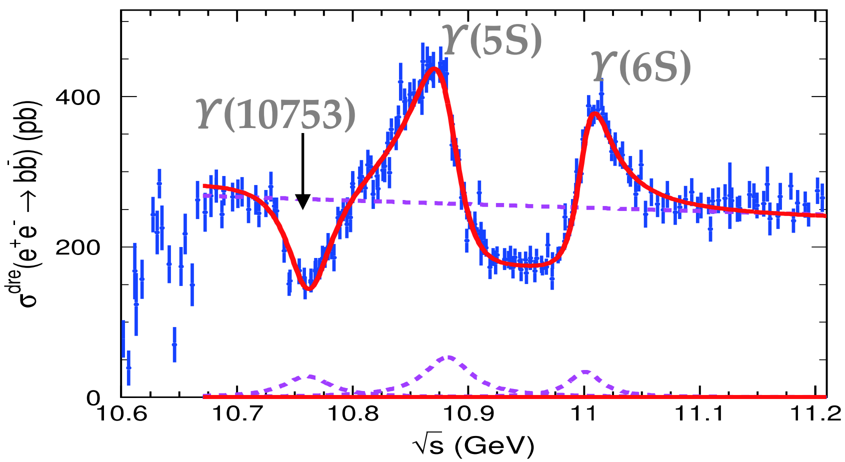
The $\Upsilon(10753)$ & the $b\bar{b}$ Cross Section

An analysis published by Dong, Mo, Wang & Yuan; China Phys.C 44, 083001 (2020)

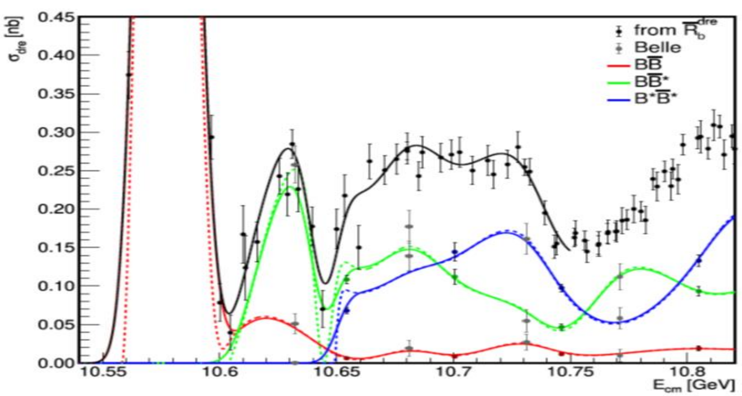
Analyzed the dressed (ISR-corrected) $b\bar{b}$ cross-sections from BaBar, Belle

Fit to a continuum term and three resonances: $\Upsilon(10753)$, $\Upsilon(5S)$, $\Upsilon(6S)$

Solid curve: total fit **Dashed:** each component



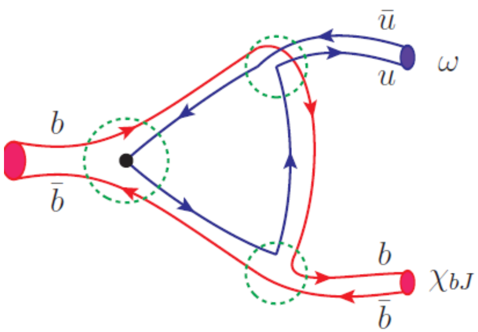
The dip in the cross-section near 10750 is simply explained as destructive interference with a resonance, the $\Upsilon(10753)$



Solution	Parameter	$\Upsilon(10750)$	$\Upsilon(5S)$	$\Upsilon(6S)$
1–8	Mass (MeV/c^2)	10761 ± 2	10882 ± 1	11001 ± 1
	Width (MeV)	48.5 ± 3.0	49.5 ± 1.5	35.1 ± 1.2
1	$\Gamma_{e^+e^-}$ (eV)	10.7 ± 0.9	21.3 ± 1.0	9.8 ± 0.5
	ϕ (degree)	260 ± 3	144 ± 2	34 ± 3
2	$\Gamma_{e^+e^-}$ (eV)	11.1 ± 0.9	24.8 ± 1.3	307 ± 9
	ϕ (degree)	270 ± 3	164 ± 2	280 ± 1
3	$\Gamma_{e^+e^-}$ (eV)	12.6 ± 1.1	479 ± 14	11.5 ± 0.6
	ϕ (degree)	295 ± 3	254 ± 1	3 ± 3
4	$\Gamma_{e^+e^-}$ (eV)	13.0 ± 1.1	558 ± 19	363 ± 13
	ϕ (degree)	296 ± 3	274 ± 1	249 ± 1
5	$\Gamma_{e^+e^-}$ (eV)	324 ± 24	23.7 ± 1.2	10.0 ± 0.5
	ϕ (degree)	265 ± 1	129 ± 2	26 ± 3
6	$\Gamma_{e^+e^-}$ (eV)	336 ± 27	27.6 ± 1.6	314 ± 10
	ϕ (degree)	275 ± 1	149 ± 2	272 ± 1
7	$\Gamma_{e^+e^-}$ (eV)	380 ± 32	534 ± 18	11.8 ± 0.6
	ϕ (degree)	291 ± 1	239 ± 1	355 ± 3
8	$\Gamma_{e^+e^-}$ (eV)	394 ± 34	622 ± 25	370 ± 14
	ϕ (degree)	301 ± 1	259 ± 2	241 ± 1

Partial widths of hadronic transitions of highly exited bottomonium to low lying states in keV

	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$\Upsilon(1S)\eta$	$\Upsilon(2S)\eta$	$\chi_{b1}\omega$	$\chi_{b2}\omega$
Υ(2S) Γ_{ee}= 608 eV	5.8			0.01			
Υ(3S) Γ_{ee}= 443 eV	0.9	0.6		<0.02			
Υ(4S) Γ_{ee}= 322 eV	1.7	1.7		3.7			
Υ(10753) Γ_{ee}=300-400 eV	15-80	60-200	<10	< 10	~ 50	170-240	150-220
Υ(5S) Γ_{ee}=465-650 eV	60-150	100-400	50-110	42	200	< 15	< 11
Υ(6S) Γ_{ee}=300-380 eV	35-65	10-140	15-60			< 8	< 50



4S -3D mixing +hadronic loop mechanism to understand the hidden-bottom hadronic decays

Z.Y.Bai et.al. Phys.Rev. D 105, 074007 (2022)
Phys.Rev. D 104, 034036 (2021)

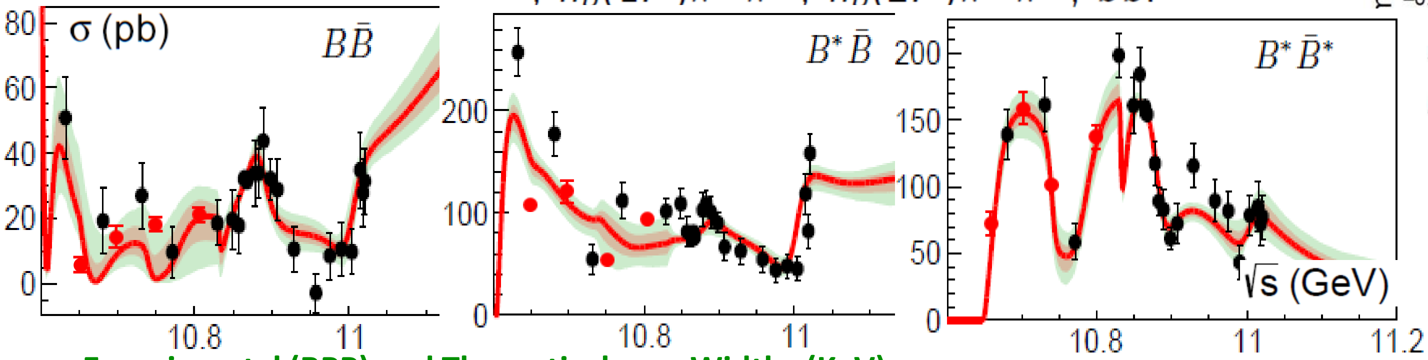
$$\Gamma(\Upsilon(10753)\to\Upsilon(1S)\pi^+\pi^-) = (75\pm56)\ keV$$
$$\Gamma(\Upsilon(10753)\to\Upsilon(2S)\pi^+\pi^-) = (267\pm117)\ keV$$
$$\Gamma(\Upsilon(10753)\to\Upsilon(3S)\pi^+\pi^-) = (72\pm16)\ keV$$

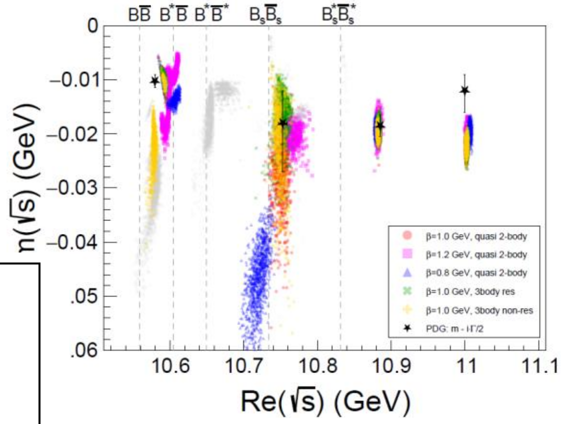
$$\Gamma(\Upsilon(10753)\to\Upsilon(1S)\eta) = (16-194)\ keV$$
$$\Gamma(\Upsilon(10753)\to\chi_{b1}\omega) = (8.8\ -77)\ keV$$
$$\Upsilon(10753)\to\Upsilon(1S)\eta/\chi_{b1}\omega = 1.8\ -2.5$$
$$\Upsilon(10753)\to\chi_{b1}\omega/\chi_{b2}\omega = 0.18\ -0.22$$

K-matrix analysis of Belle scan data

N.Hüsken, R.E.Mitchell, E.S.Swanson *Phys.Rev.*D 106, 9, 094013 (2022)

Channels considered: $B\bar{B}$, $B\bar{B}^*$, $B^*\bar{B}^*$, $B_s^*\bar{B}_s^*$, $\Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$, $\Upsilon(3S)\pi^+\pi^-$, $h_b(1P)\pi^+\pi^-$, $h_b(2P)\pi^+\pi^-$, $b\bar{b}$.





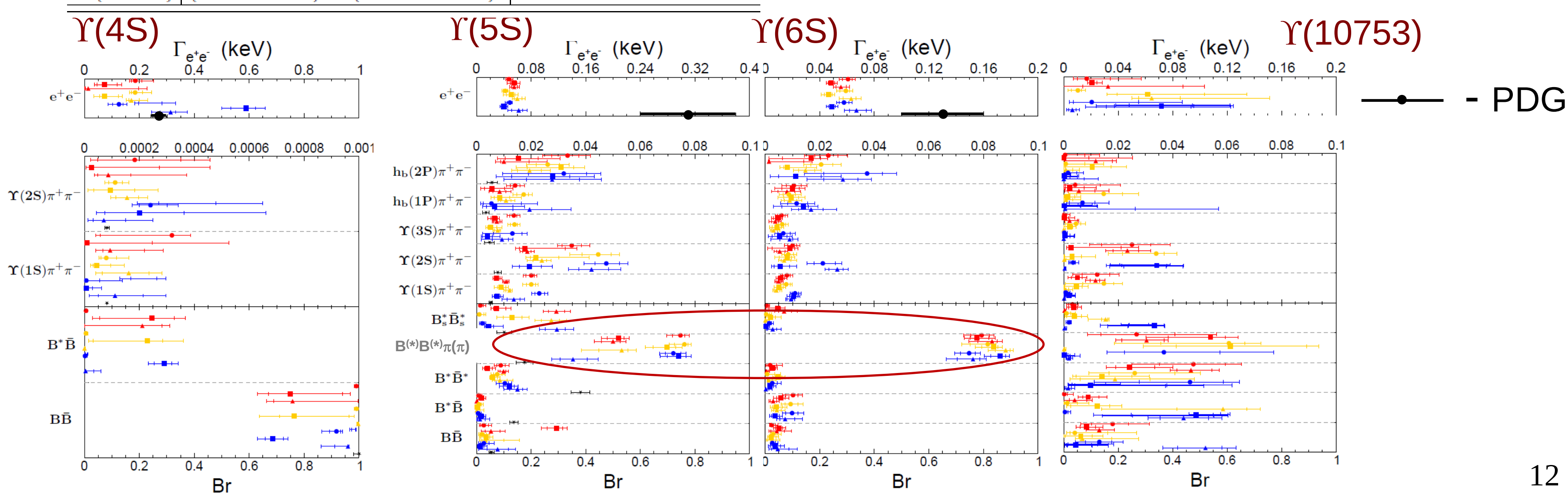
Need 4 poles to describe data: $\Upsilon(4S)$, $\Upsilon(10753)$, $\Upsilon(5S)$, $\Upsilon(6S)$. Determine

- Pole positions
- Branching fractions
- Electron widths
- Energy dependence of all scattering amplitudes

Experimental (RPP) and Theoretical e+e- Widths (KeV)

state	RPP	HMS estimate	LS	GM	SOEF
$\Upsilon(4S)$	0.272	(0.003 - 0.62)	0.31	0.39	0.21
$\Upsilon(5S)$	0.31	(0.037 - 0.068)	0.28	0.33	0.18
$\Upsilon(6S)$	0.13	(0.043 - 0.074)	0.26	0.27	0.15
$\Upsilon(10750)$	(0.01 - 0.40)[a]	(0.004 - 0.10)		2.38 eV [b]	

LS Phys.Rev.D 74, 014012 (2006)
GM Phys.Rev.D 92 5, 054034 (2015)
SOEF Phys.Rev.D 93 7, 074027 (2016)



Conclusion

Belle II obtained new interesting results based on the data above Y(4S):

- Confirmation $\Upsilon(10753) \to \Upsilon(1S)\pi^+\pi^-, \Upsilon(2S)\pi^+\pi^-$
- Measurement of the $e^+e^- \to \omega\,\chi_{bJ}$ **and** $(\pi^+\pi^-\pi^0)_{non\text{-}\omega}\,\chi_{bJ}$ energy dependence
- Energy dependence of the $B^{(*)}\bar{B}^{(*)}$ **cross sections**
- Search for $e^+e^- \to \eta\,\Upsilon(1S,2S)$ **near** $\Upsilon(10753)$
- Search for $e^+e^- \to \gamma\,\chi_{bJ}$ **near** $\Upsilon(10753)$ (not shown in the talk, see backup)

Based on these results one may conclude that understanding of the hidden bottom hadronic transitions is very incomplete. More experimental data are needed.

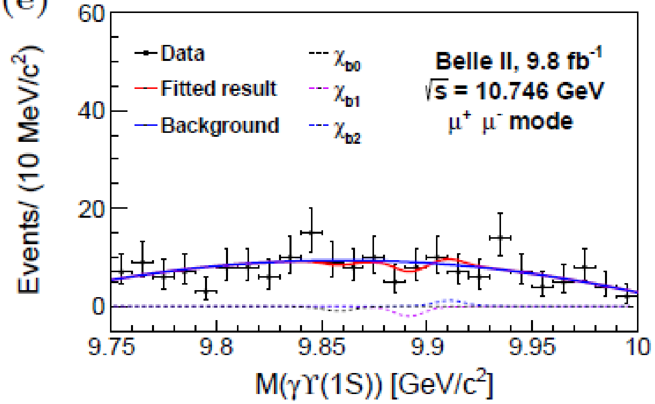
SuperKEKB is a unique experimental facility in which the phenomena discussed can be studied under well controlled conditions.

Thank you for your attention!

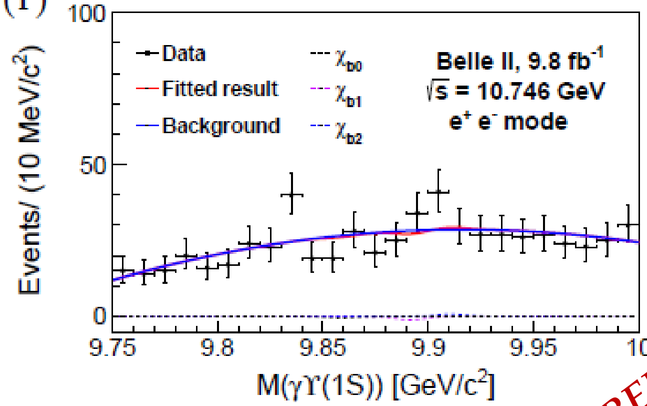
Back-up

Search for $e^+e^- \to \gamma\,\chi_{bJ}$ near $\Upsilon(10753)$

(e)



(f)



Belle II PRELIMINARY

$\sqrt{s}$ (GeV)	$\mathcal{L}$ (fb^{-1})	Channel	$N^{\rm fit}$	$N^{\rm UL}$	$\varepsilon_{e^+e^-}$	$\varepsilon_{\mu^+\mu^-}$	$\mathcal{B}_{\rm int}$	$\lvert 1-\Pi\rvert^2$	$1+\delta_{\rm ISR}$	syst (%)	$\sigma^{\rm UL}_{\rm Born}$ (pb)
		$\gamma\chi_{b0}$	-5.6 ± 4.8	8.4	0.215	0.361	0.00048	0.930	0.901	15.5	8.93
10.653	3.512	$\gamma\chi_{b1}$	10.2 ± 6.8	20.8	0.223	0.353	0.00866	0.930	0.898	9.0	1.23
		$\gamma\chi_{b2}$	-0.7 ± 5.5	10.4	0.212	0.341	0.00443	0.930	0.896	8.9	1.25
		$\gamma\chi_{b0}$	-1.7 ± 2.8	7.0	0.214	0.346	0.00048	0.931	0.905	15.5	16.42
10.701	1.632	$\gamma\chi_{b1}$	-0.2 ± 3.7	8.4	0.217	0.351	0.00866	0.931	0.905	9.0	1.08
		$\gamma\chi_{b2}$	-0.5 ± 3.4	7.9	0.219	0.341	0.00443	0.931	0.901	8.9	2.02
		$\gamma\chi_{b0}$	-3.0 ± 9.6	13.8	0.216	0.356	0.00048	0.931	0.909	15.5	5.24
10.746	9.818	$\gamma\chi_{b1}$	-6.1 ± 8.5	12.0	0.212	0.361	0.00866	0.931	0.906	9.0	0.25
		$\gamma\chi_{b2}$	3.9 ± 9.8	19.1	0.218	0.358	0.00443	0.931	0.904	8.9	0.79
		$\gamma\chi_{b0}$	16.9 ± 8.1	30.4	0.222	0.361	0.00048	0.932	0.914	15.5	23.62
10.804	4.689	$\gamma\chi_{b1}$	-4.0 ± 5.6	9.9	0.224	0.366	0.00866	0.932	0.911	9.0	0.42
		$\gamma\chi_{b2}$	-0.1 ± 5.7	11.2	0.228	0.364	0.00443	0.932	0.909	8.9	0.93