Energy scan results from Belle II

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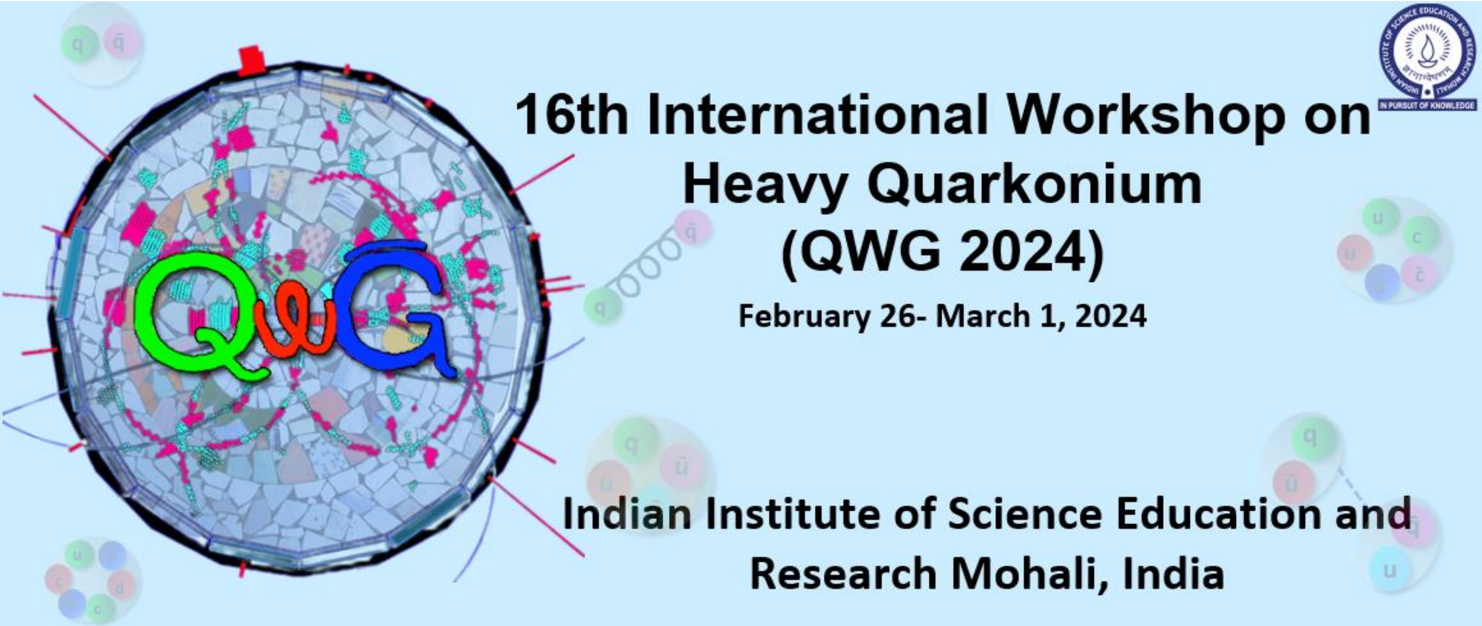
On behalf of Belle II Collaboration



16th International Workshop on
Heavy Quarkonium
(QWG 2024)
February 26- March 1, 2024

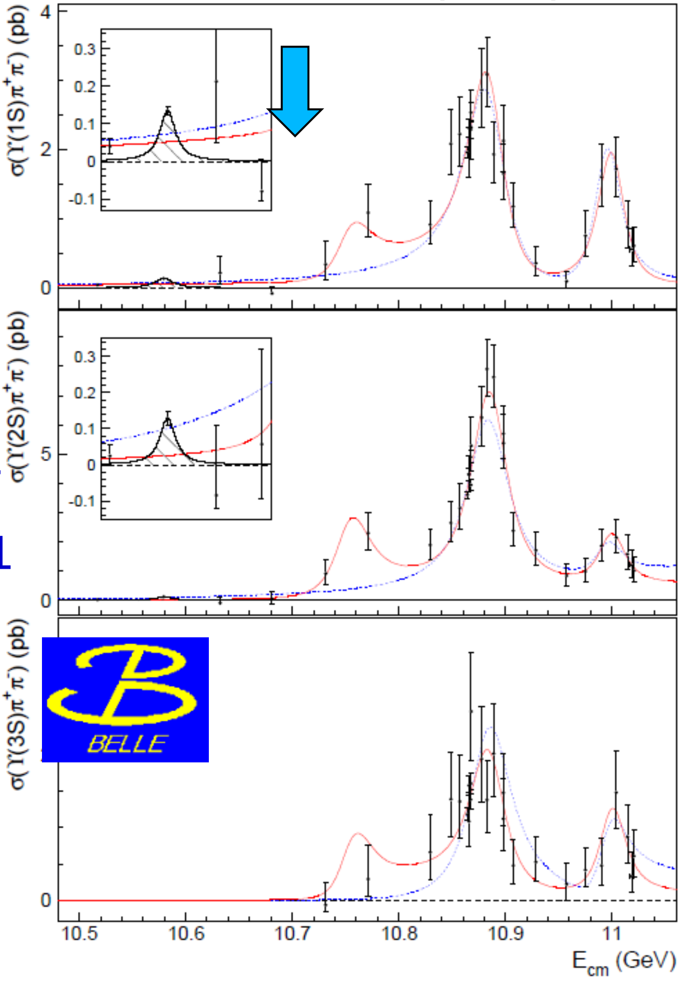
Indian Institute of Science Education and
Research Mohali, India

$\Upsilon(10750)$

- Scan points: ~1 fb-1 each
- 1 point "on-peak"
- 2-3 points in the region of interest
- Total significance: 5.2σ

- *S-D mixing* Zi-Yue Bai, PRD 105, (2022), 074007
  $b\bar{b}$ state Yu-Shuai Li, PRD 105,(2022),114041
  Shi-Dong Liu Arxiv:2312.02761
- *Hybrid* J.T.Castella, E.Passemar,
  PRD 104, (2021), 034014
- *Tetraquark* A.Ali et al, PLB 802, (2020), 135217
  Zhi-Gang Wang Chin.Phys.C 43,
  (2019),123102

JHEP 1910, 220 (2019)

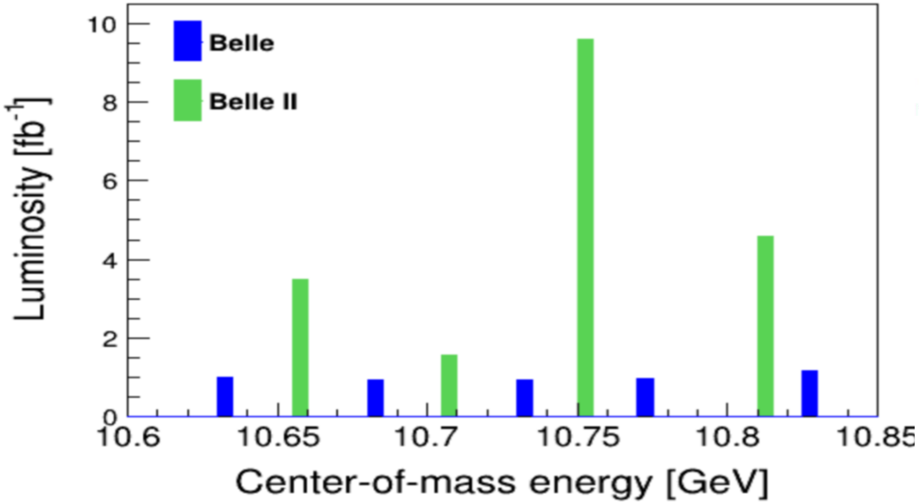


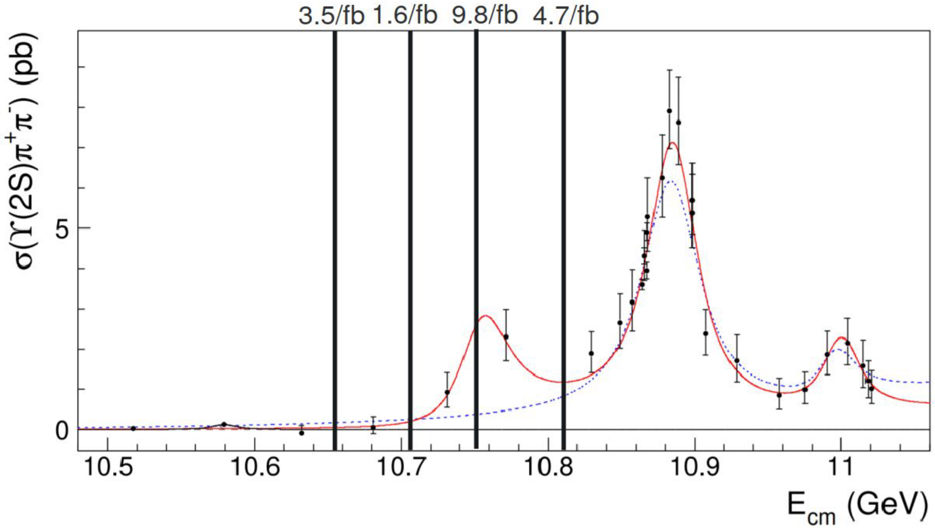
	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}\,^{+1.0}_{-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}\,^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}\,^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}\,^{+3.9}_{-3.3}$

Belle's experience showed that the data collected above Υ(4S) is important not only for the study of highly excited bottomonium, but also for the search for exotic states and states of ordinary bottomonium that have not been observed before.

Energy scan above $\Upsilon(4S)$ with main goal to confirm $\Upsilon(10753)$ and study it’s properties.

Energy scan took place Nov. 10 –29, 2021

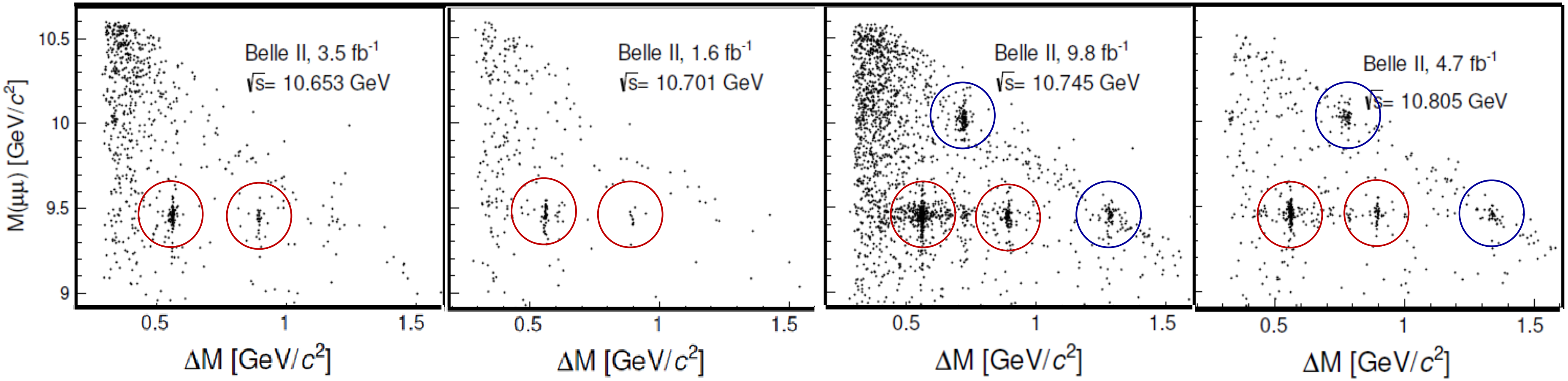




Event Selections

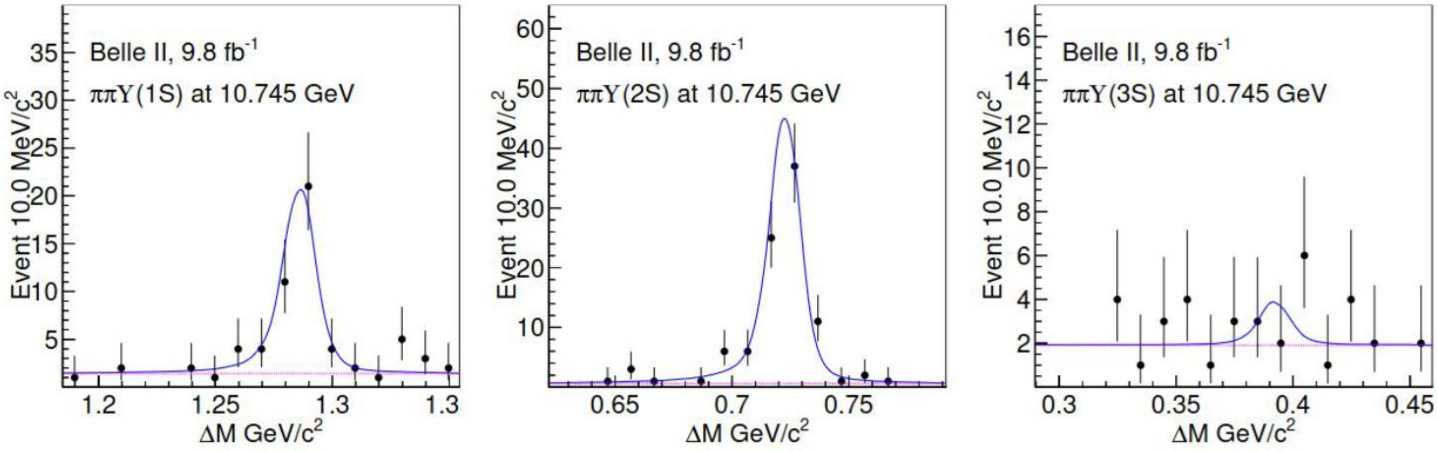
- The full reconstruction is used: $e^+e^- \to [\Upsilon(nS) \to \mu^+\mu^-]\pi^+\pi^-$
- Plot $\Delta M = M(\pi^+\pi^-\mu^+\mu^-) - M(\mu^+\mu^-)\ vs\ M(\mu^+\mu^-)$: clear signals $\Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$

Belle-II preliminary, arxiv:2401.12021

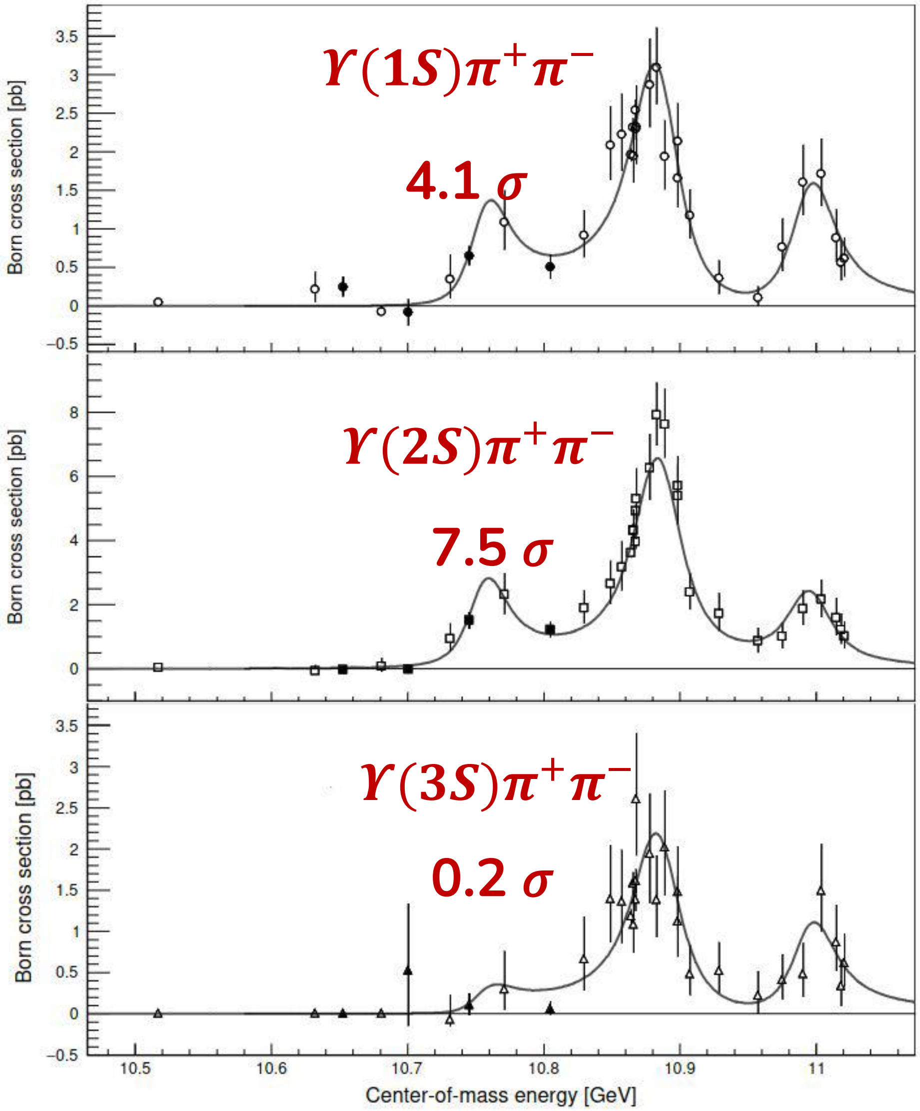


ISR $\Upsilon(2S,3S) \to \Upsilon(1S)\pi^+\pi^-$

Signal $e^+e^- \to [\Upsilon(nS) \to \mu^+\mu^-]\pi^+\pi^-$



Energy dependence of $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ cross section



Belle-II preliminary, arxiv:2401.12021

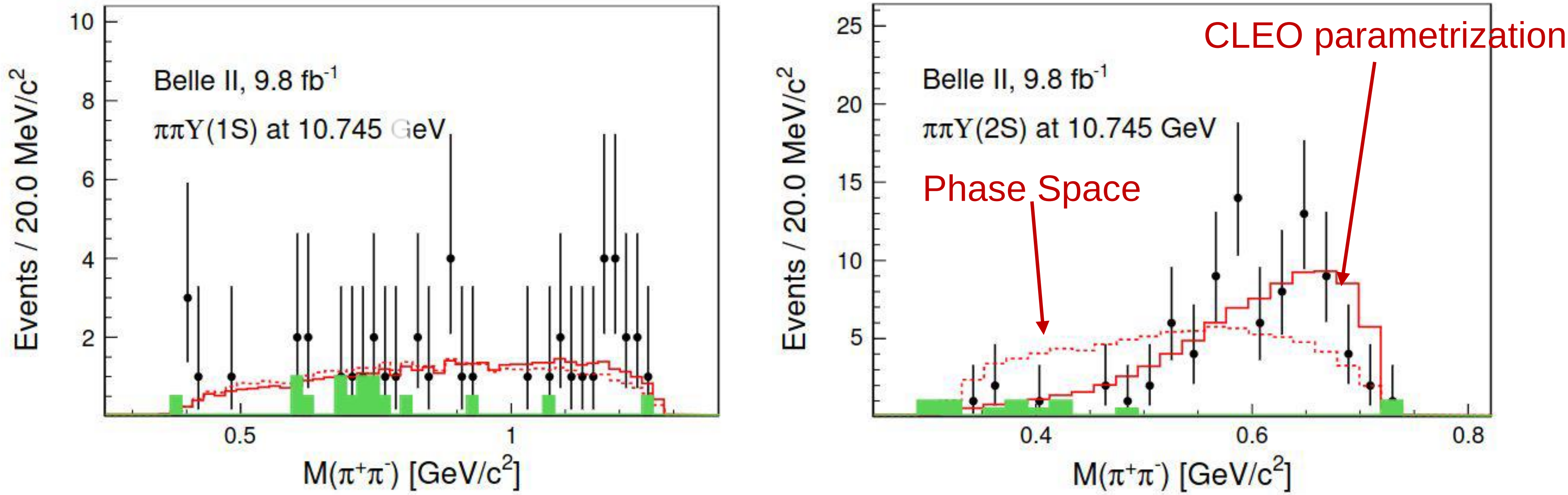
- New measurement confirms previous Belle result
- Fit: use coherent sum of Breit-Wigner amplitudes, convolve with a Gaussian to account for energy spread

$$M_{\Upsilon(10753)} = (10756.3 \pm 2.7_{stat} \pm 0.6_{syst})MeV/c^2$$
$$\Gamma_{\Upsilon(10753)} = (29.8 \pm 8.5_{stat} \pm 1.1_{syst})MeV$$

	$\mathcal{R}^{\Upsilon(10753)}_{\sigma(1S/2S)}$	$\mathcal{R}^{\Upsilon(10753)}_{\sigma(3S/2S)}$
Ratio	$0.46^{+0.15}_{-0.12}$	$0.10^{+0.05}_{-0.04}$

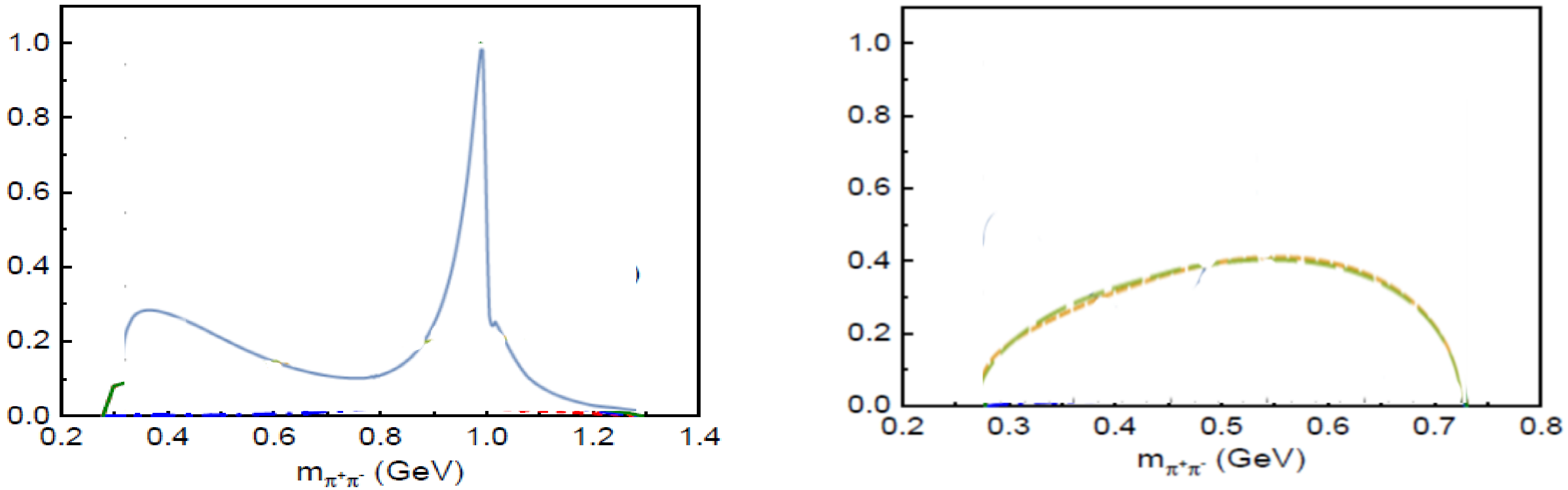
$M(\pi^+\pi^-)$ Distribution vs Expectation for Hybrid

Belle-II preliminary, arxiv:2401.12021



CLEO parametrization

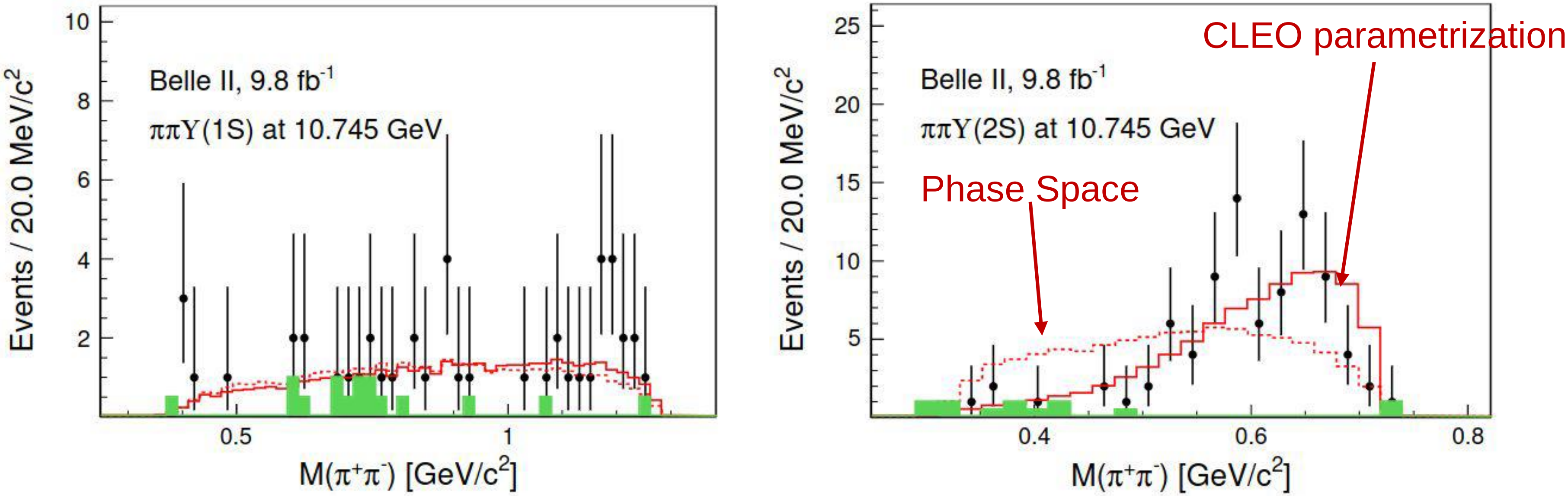
Phase Space



Hybrid J.T.Castella, E.Passemar, PRD 104, 034014

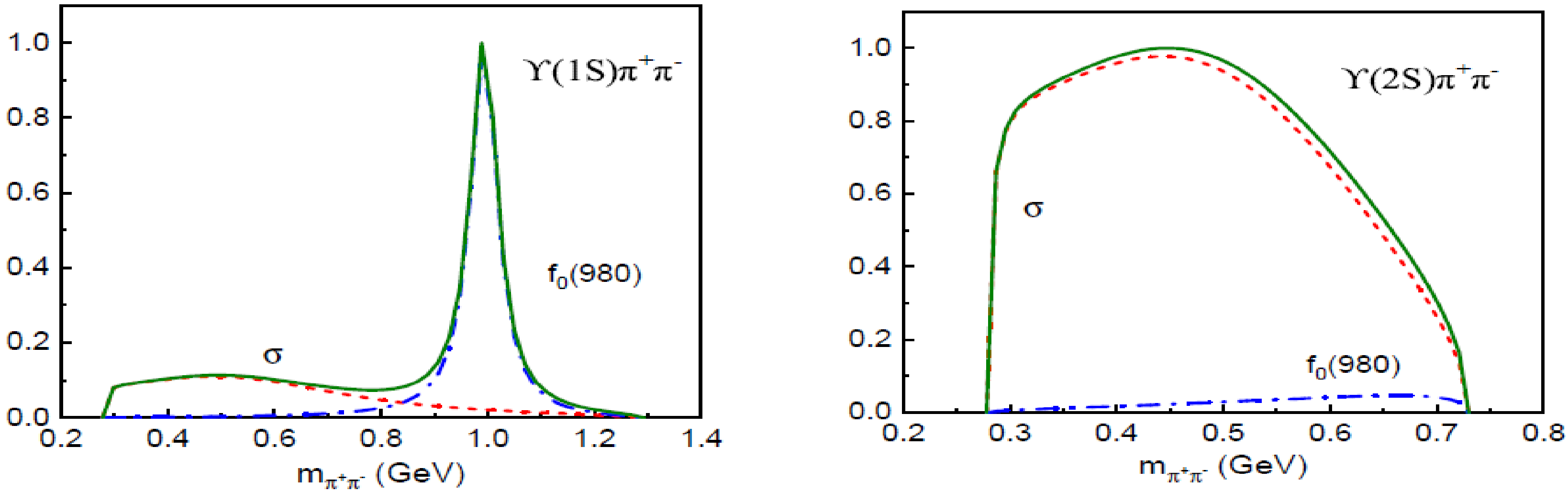
$M(\pi^+\pi^-)$ Distribution vs Expectation for S-D mixing

Belle-II preliminary, arxiv:2401.12021



CLEO parametrization

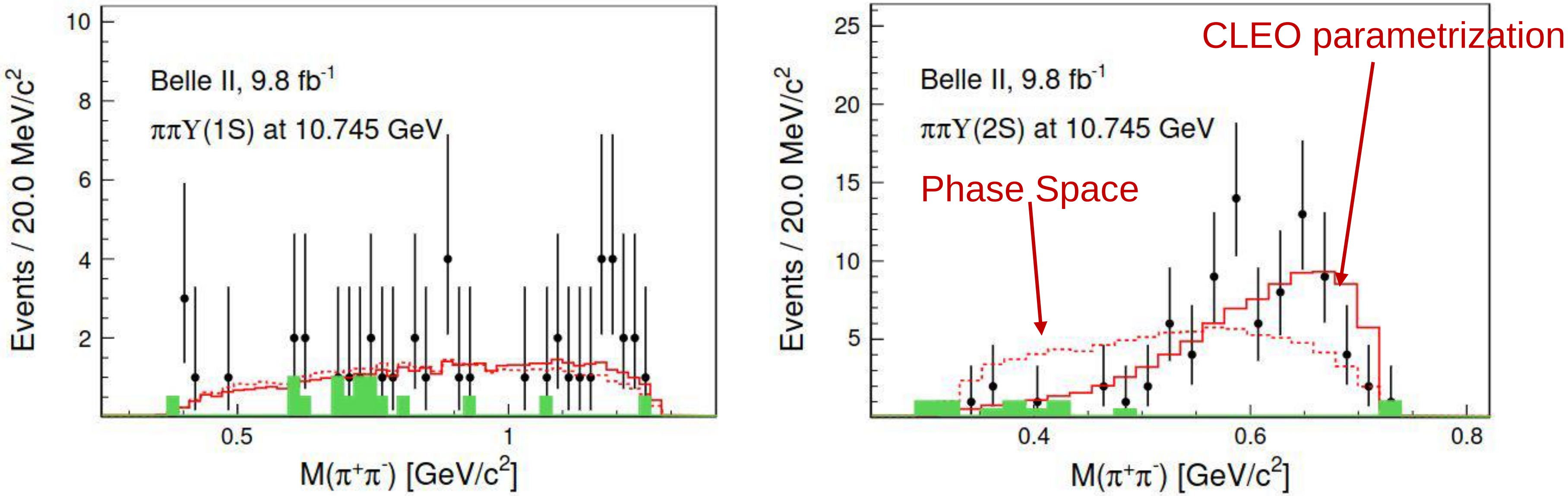
Phase Space



S-D mixing $b\bar{b}$ state Zi-Yue Bai, PRD 105, 074007

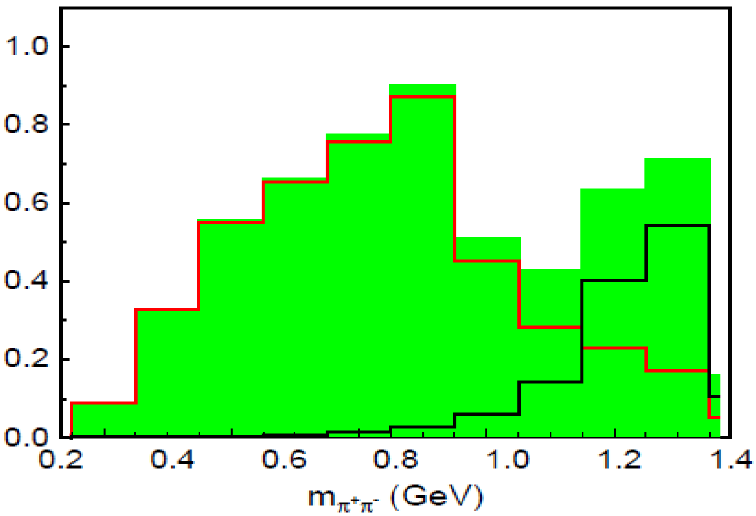
$M(\pi^+\pi^-)$ Distribution vs Expectation for Tetraquark

Belle-II preliminary, arxiv:2401.12021



CLEO parametrization

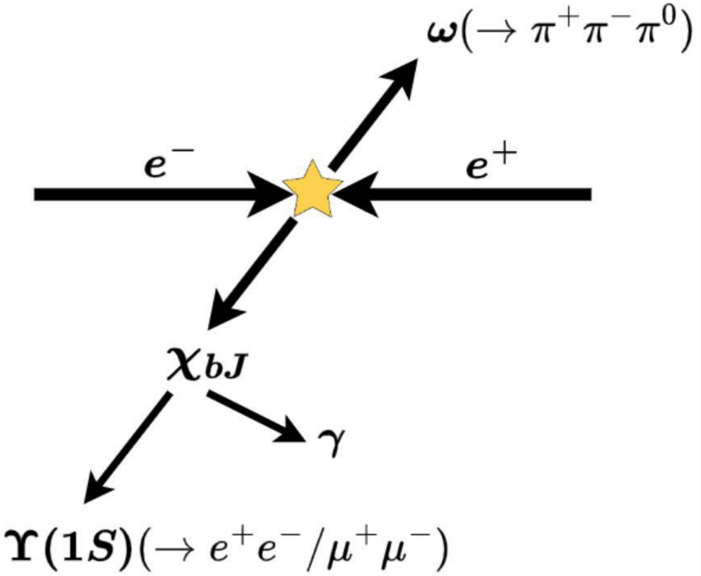
Phase Space

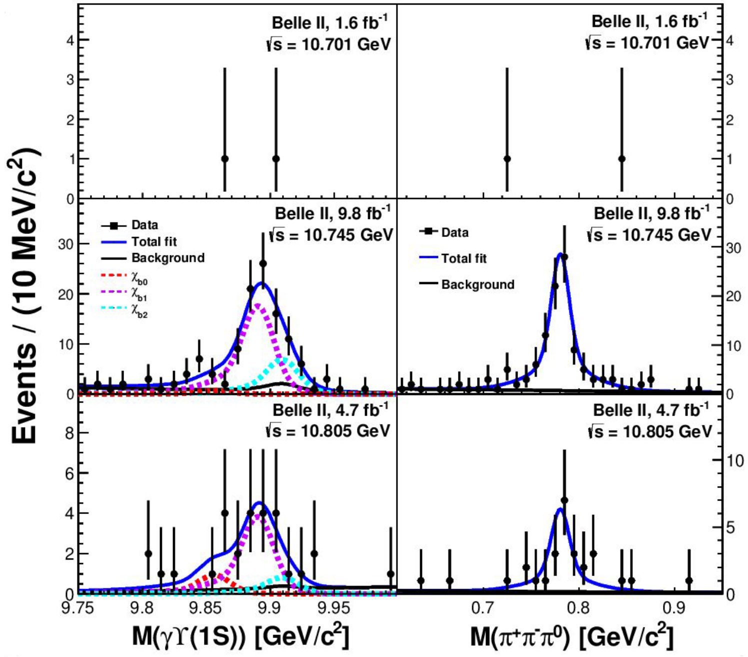


Tetraquark

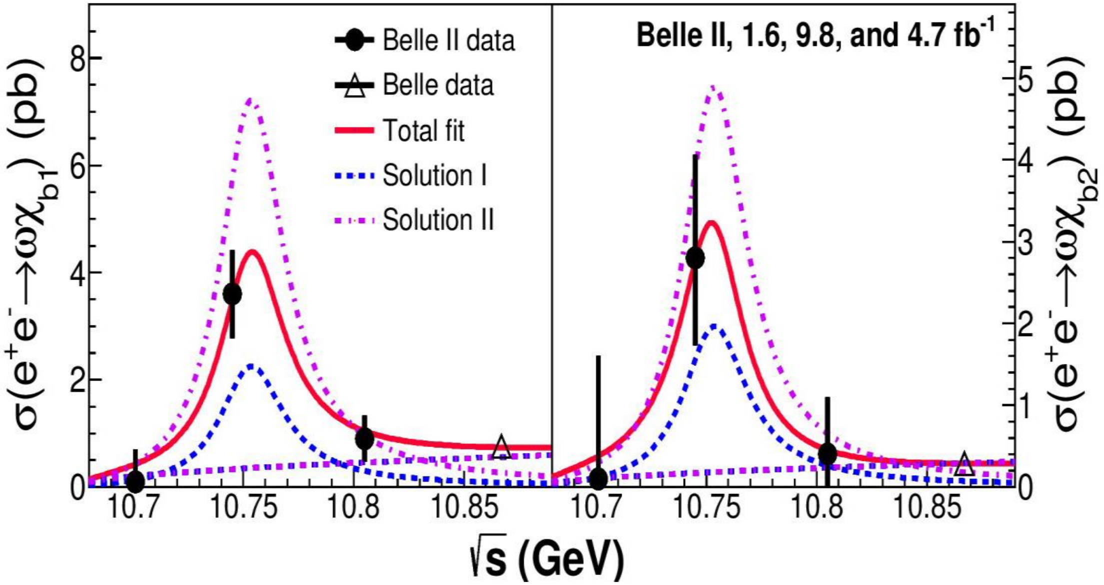
A.Ali et al, PLB 802, 135217

$\Upsilon(10753) \rightarrow \chi_{bJ}\omega$





Belle-II, PRL 130, 9, 091902, (2023)



- Cross sections show a peak in the Υ(10753) region
- Confirmation of Υ(10753) and observation of its new decay channel
- $\frac{\chi_{b1}\omega}{\Upsilon(nS)\pi^+\pi^-}$ ratio one order higher at $\Upsilon(10753)$ than at $\Upsilon(5S)$

$\Upsilon(10753) \to \chi_{b0}\omega \,/\, \eta_b\omega$

Belle-II preliminary, arxiv:2312.13043

Tetraquark (diquark-antidiquark) interpretation of this state predicts enhancement of $\Upsilon(10753) \to \omega\eta_b(1S)$ transition (Zhi-Gang Wang Chin.Phys.C 43, 123102)

$$\frac{\Gamma(\omega\eta_b)}{\Gamma(\Upsilon\pi^+\pi^-)} \sim 30$$

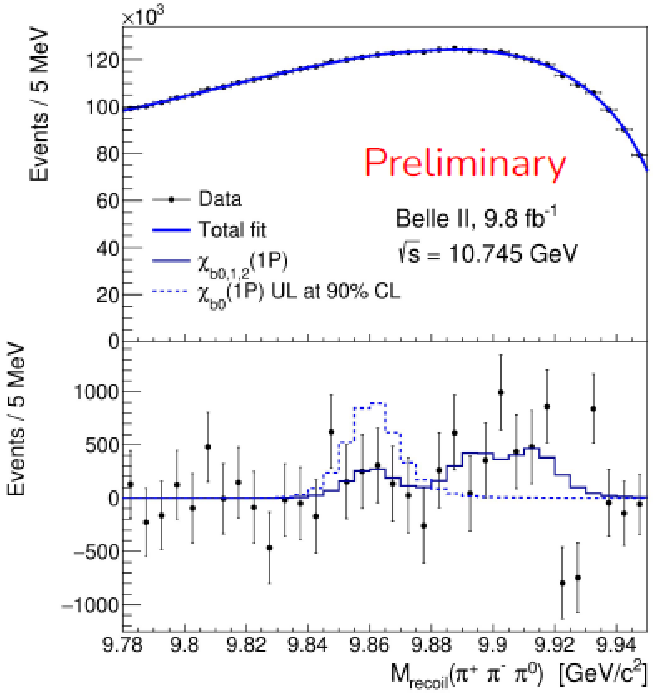
We first reconstructed $\omega \to \pi^+\pi^-\pi^0$,since $\eta_b(1S)$ does not have convenient for reconstruction decay channels, and than use its recoil mass to identify the signal

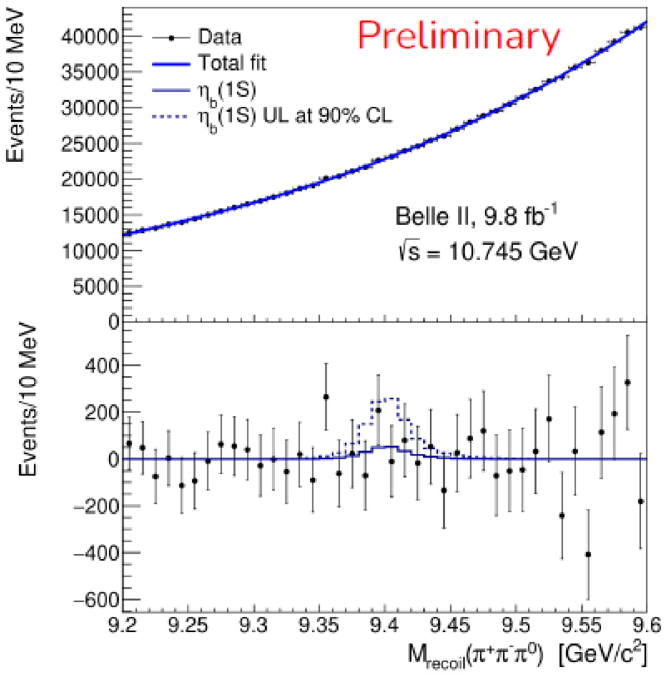
$$M_{recoil}(\omega) = \sqrt{(E_{CM} - E_\omega)^2 - {p_\omega}^2}$$

$e^+e^- \to \omega\chi_{b0}(1P)$ transition was not observed using full reconstruction due to low decay probability χ_{b0} to $\Upsilon(1S)\gamma$. But in charmonium $Y(4220) \to \omega\chi_{c0}$ decay was found to be enhanced compare to $Y(4220) \to \omega\chi_{c1,2}$ by BES III

Upper limits on $\Upsilon(10753) \rightarrow \chi_{b0}\omega$ / $\eta_b\omega$ decays

Belle-II preliminary, arxiv:2312.13043





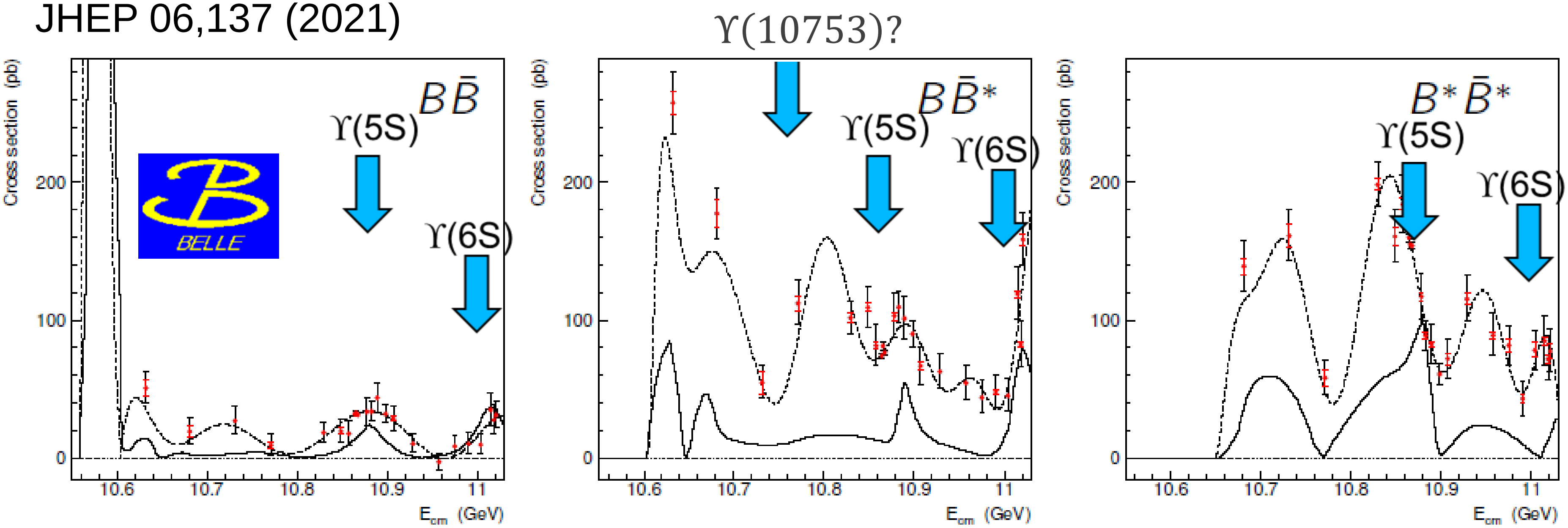
- ❑ $\sigma[e^+e^- \rightarrow \omega\chi_{b0}] < 8.7$ pb

- ❑ $\sigma[e^+e^- \rightarrow \omega\eta_b(1S)] < 2.5$ pb
- ❑ c.f. $\sigma[e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-] \sim 2.0$ pb (JHEP 10 (2019) 220)

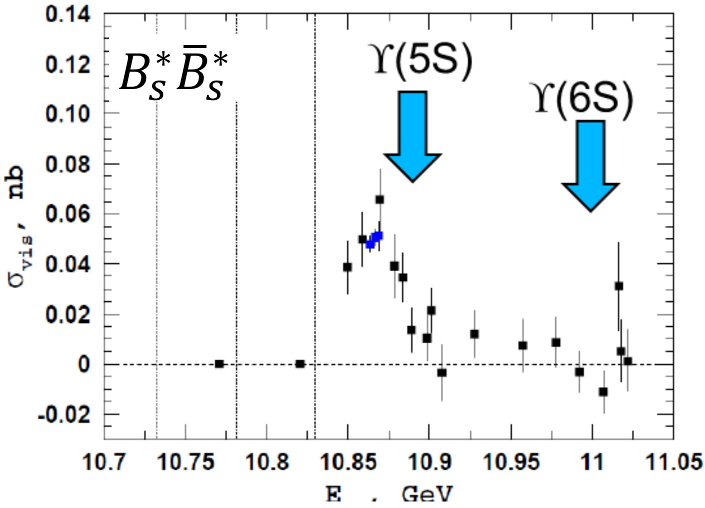
This result does not support the prediction of the tetraquark model in CPC 43 (2019) 12, 123102

Belle measurement of $e^+e^- \longrightarrow B^{(*)}\bar{B}^{(*)}$

JHEP 06,137 (2021)



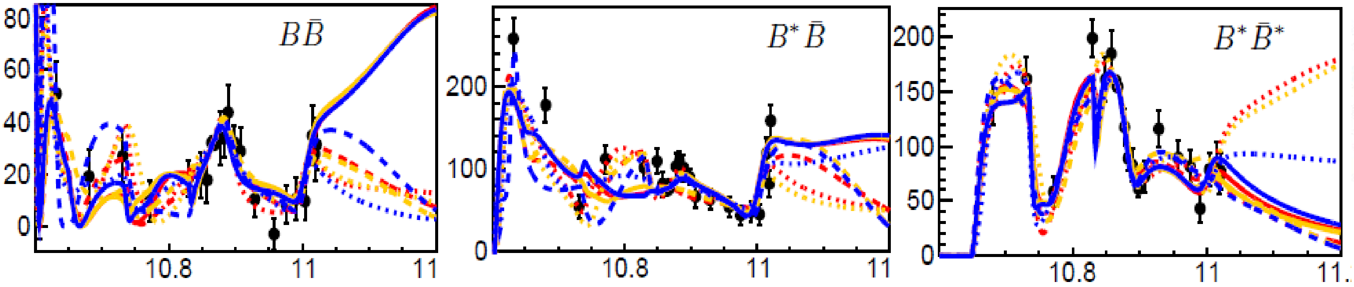
- Oscillatory behavior
- Positions of minima roughly coincide with Unitarized Quark Model prediction: Ono,Sanda,Tornqvist PRD34,186(1986)
- Peaks not coincide with Υ(5S),Υ(6S) mass positions

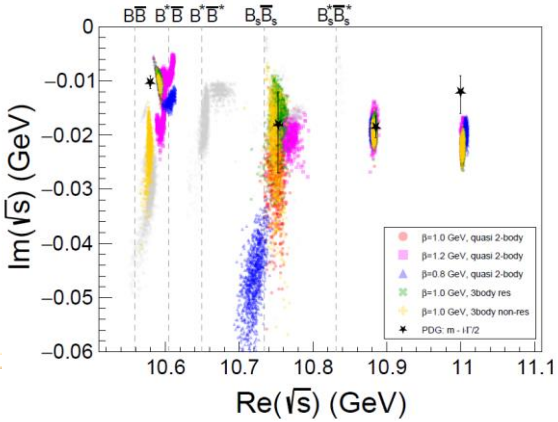


Combined analysis of Belle scan data

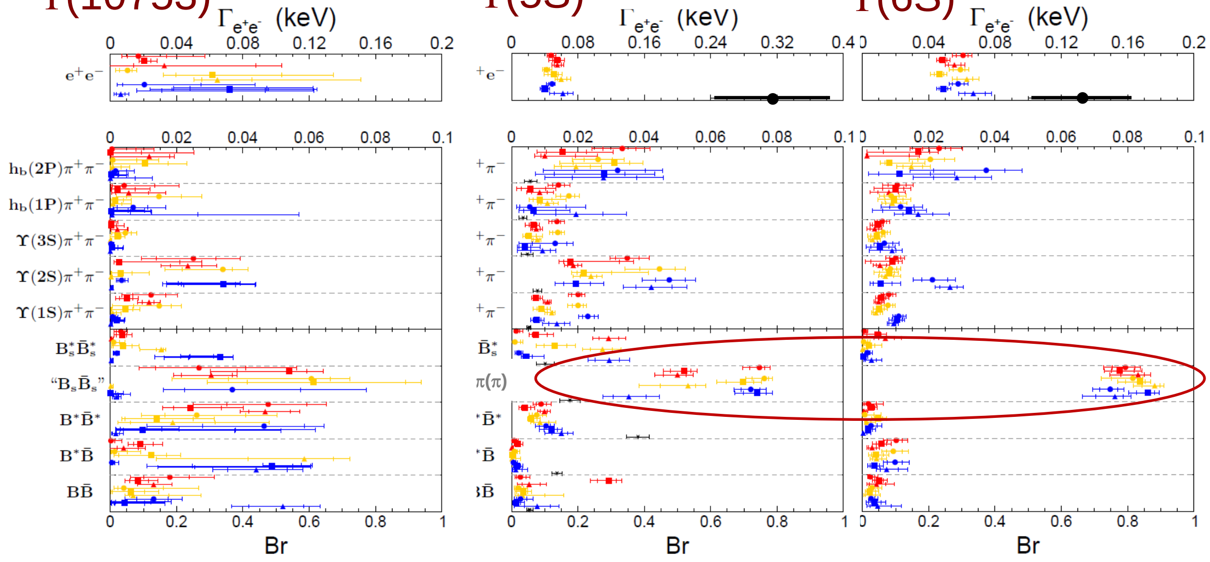
Hüsken, Mitchell and Swanson, *Phys.Rev.D* 106 (2022) 9, 094013

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





ϒ(10753) ϒ(5S) ϒ(6S)



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

(—•— - PDG)

Belle measurement of $e^+e^- \rightarrow B^{(*)}\overline{B}^{(*)}$

Method

- Reconstruct one B meson using custom Full Event Identifier
- Use M_{bc} distributions to identify signals

$$M_{bc} = \sqrt{E_b^2 - P_B^2}$$

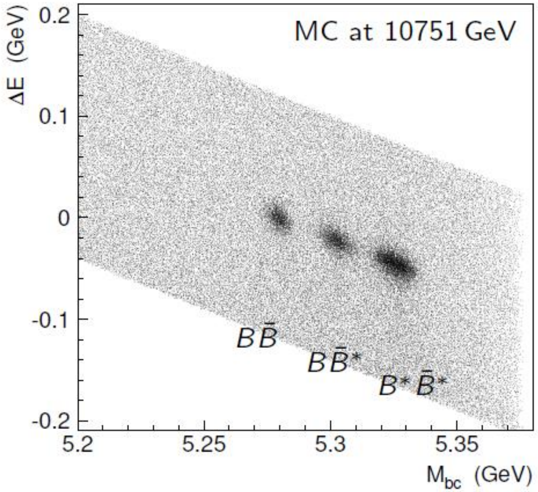
E_b – Beam energy

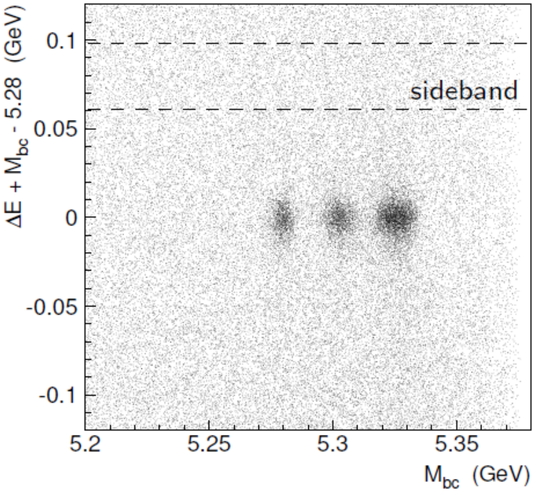
P_B –Measured B meson momentum

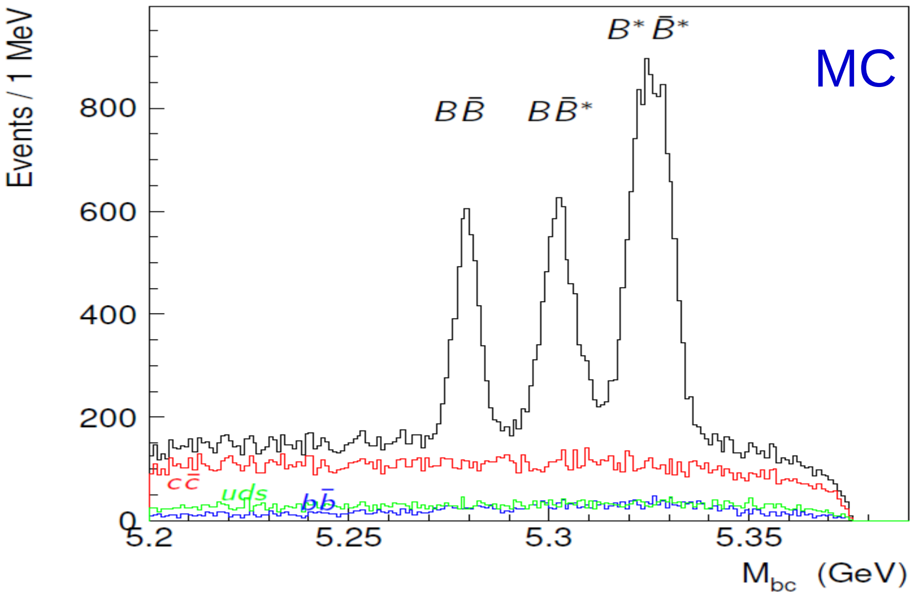
$$\Delta E' = \Delta E + M_{bc} - 5.28(GeV)$$

ω – Energy of the γ-quanta in $B^* \rightarrow B\gamma$

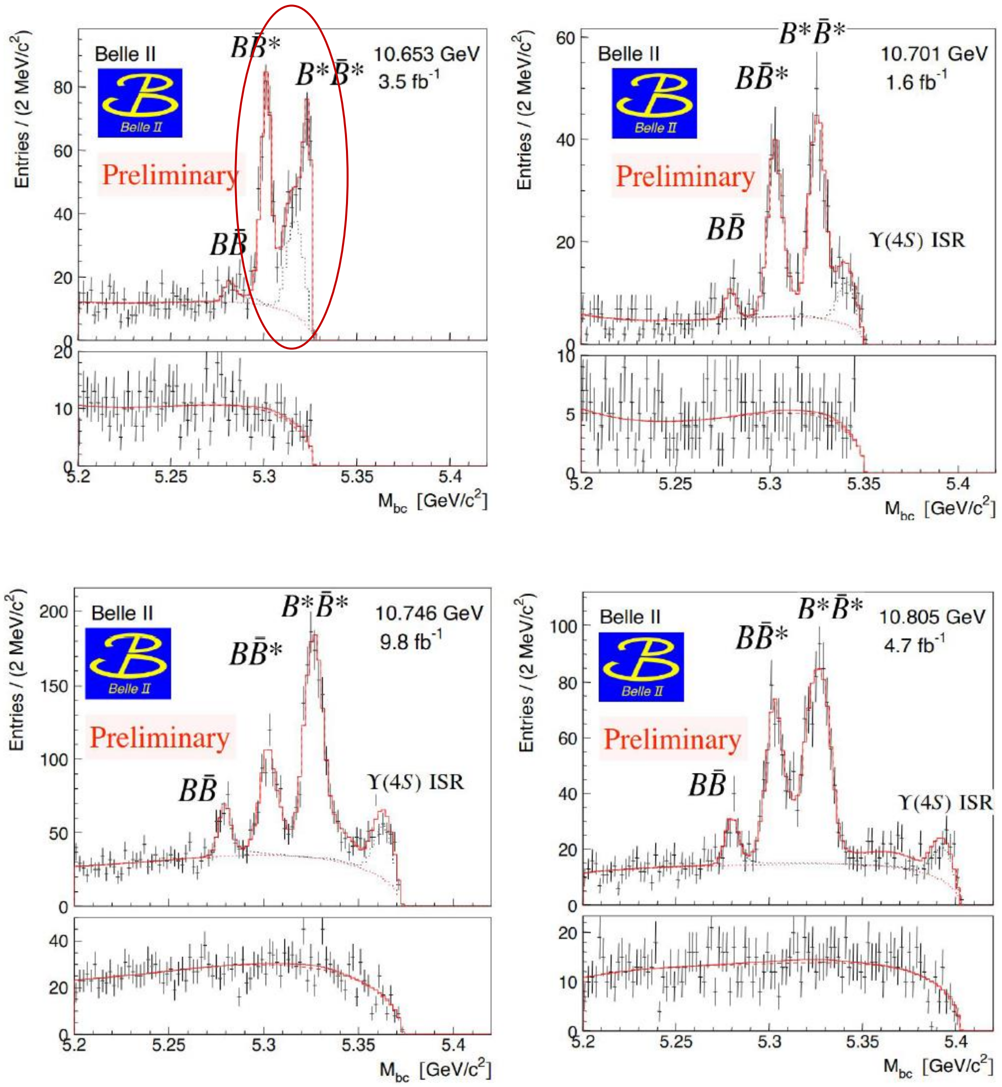
$$\sigma(M_{bc}) = \frac{P_B \cdot \sigma(P_B)}{M_{bc}} \otimes \frac{P_B}{M_{bc}}\omega \otimes \sigma(E_b)$$





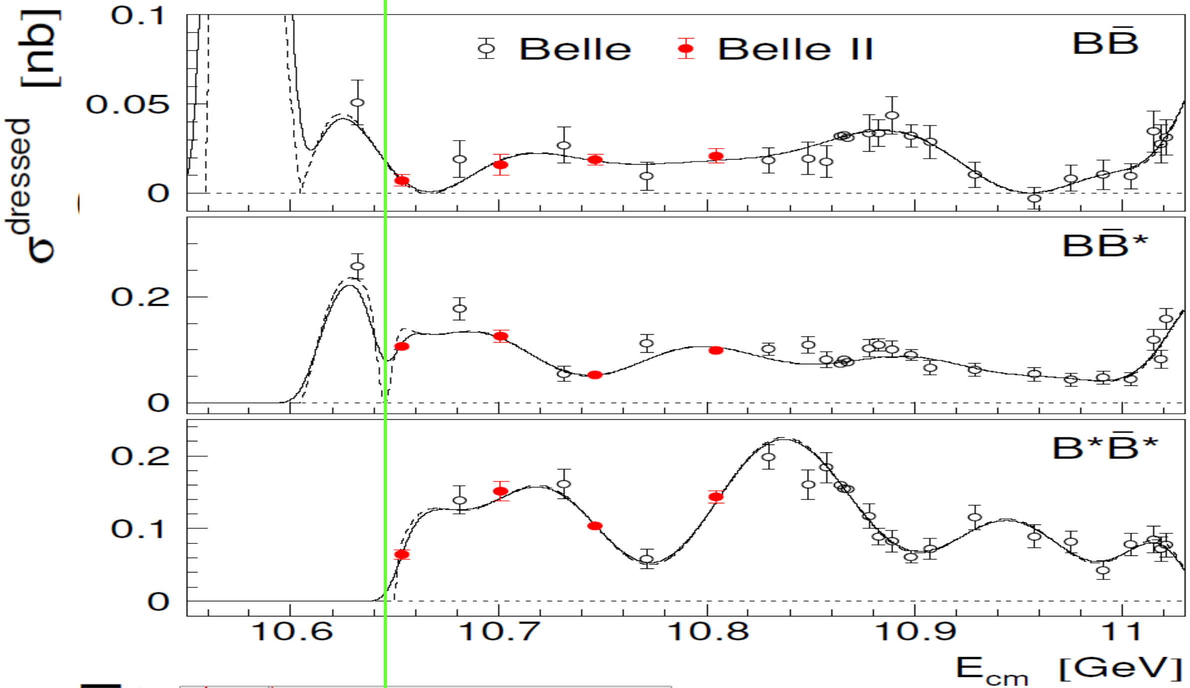


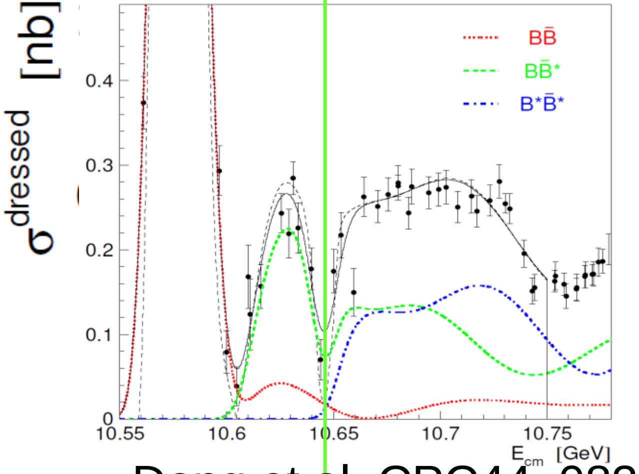
M_{bc} fit at scan energies



- Good description of the M_{bc} in data
- Contribution of $\Upsilon(4S) \to B\bar{B}$production via ISR is reasonably described by the fit.
- At lowest energy point (3MeV higher than the threshold) the signal of $B^*\bar{B}^*$ production is clearly seen.
- This phenomenon can be explained by the presence of a $B^*\bar{B}^*$molecular state near the threshold (Nucl.Phys.A 1041,122764, 669)

Energy dependence of the $e^+e^- \to B^{(*)}\bar{B}^{(*)}$





Dong et al. CPC44, 083001 (2020)

To verify the existence of a $B^*\bar{B}^*$ bound state near the threshold, a detailed scan must be performed in this energy region. We can also expect a significant violation of isospin in the near-threshold region.

Conclusion

The understanding of the physics of highly excited heavy quarkonium is very incomplete.

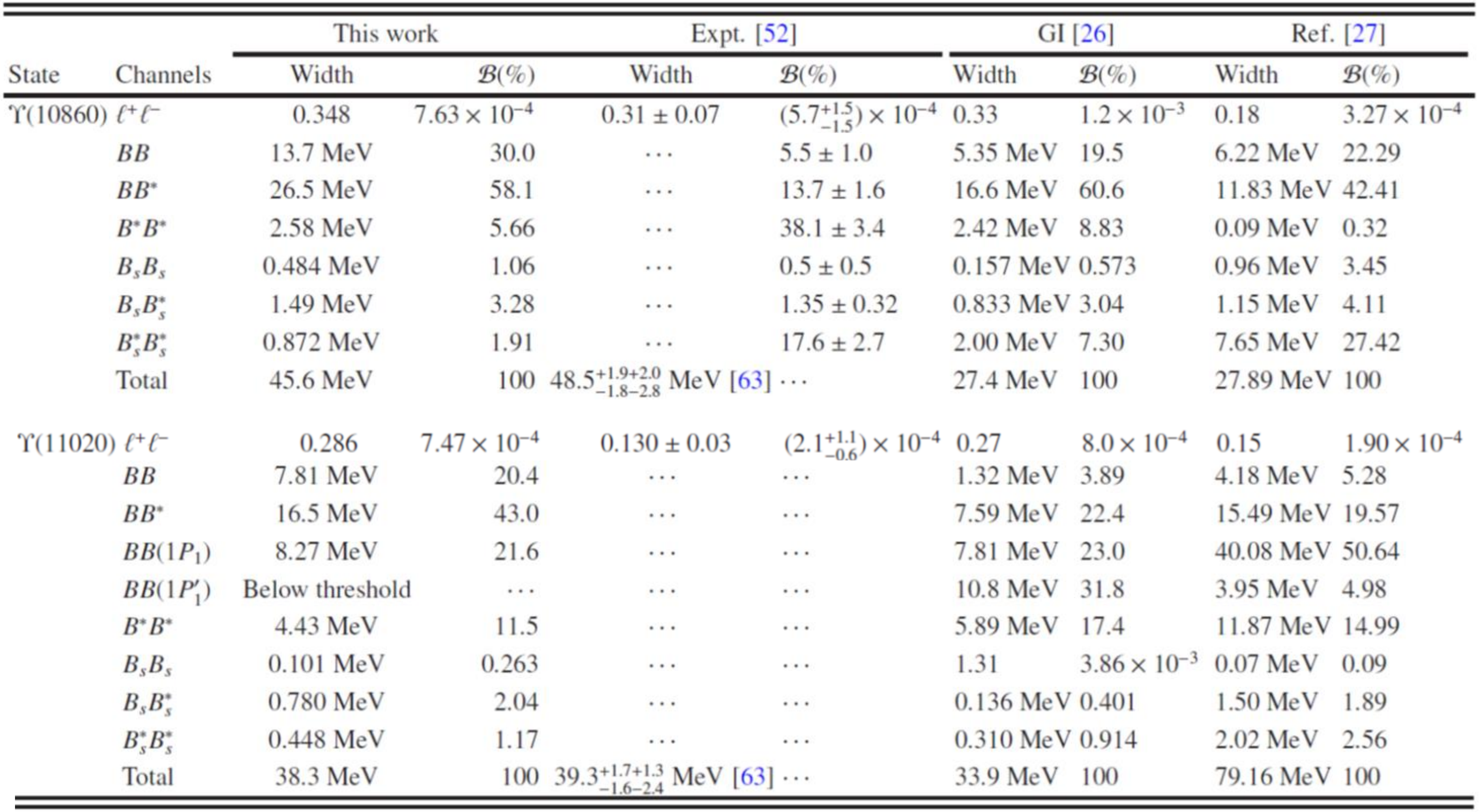
First energy scan results from Belle II are quite interesting, but not conclusive.

New data are needed to search for patterns that may indicate possible theoretical solutions.

Highly Excited Bottomonium is a good object for detailed study and tests of different theoretical models.

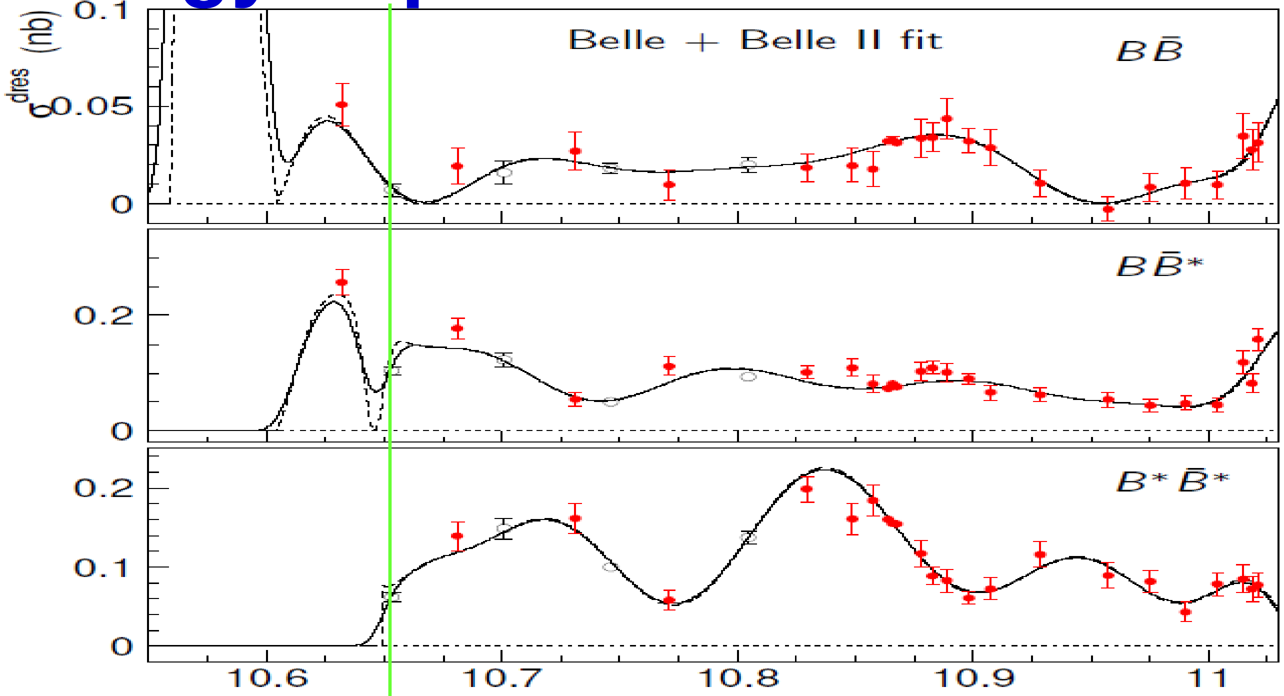
Super KEKB is a unique experimental facility in which the phenomena discussed can be studied under well controlled conditions.

Thank you for your attention!



		This work		Expt. [52]		GI [26]		Ref. [27]	
State	Channels	Width	$\mathcal{B}(\%)$	Width	$\mathcal{B}(\%)$	Width	$\mathcal{B}(\%)$	Width	$\mathcal{B}(\%)$
$\Upsilon(10860)$	$\ell^+\ell^-$	0.348	7.63×10^{-4}	0.31 ± 0.07	$(5.7^{+1.5}_{-1.5}) \times 10^{-4}$	0.33	1.2×10^{-3}	0.18	3.27×10^{-4}
	BB	13.7 MeV	30.0	⋯	5.5 ± 1.0	5.35 MeV	19.5	6.22 MeV	22.29
	BB^*	26.5 MeV	58.1	⋯	13.7 ± 1.6	16.6 MeV	60.6	11.83 MeV	42.41
	B^*B^*	2.58 MeV	5.66	⋯	38.1 ± 3.4	2.42 MeV	8.83	0.09 MeV	0.32
	B_sB_s	0.484 MeV	1.06	⋯	0.5 ± 0.5	0.157 MeV	0.573	0.96 MeV	3.45
	$B_sB_s^*$	1.49 MeV	3.28	⋯	1.35 ± 0.32	0.833 MeV	3.04	1.15 MeV	4.11
	$B_s^*B_s^*$	0.872 MeV	1.91	⋯	17.6 ± 2.7	2.00 MeV	7.30	7.65 MeV	27.42
	Total	45.6 MeV	100	$48.5^{+1.9+2.0}_{-1.8-2.8}$ MeV [63]	⋯	27.4 MeV	100	27.89 MeV	100
$\Upsilon(11020)$	$\ell^+\ell^-$	0.286	7.47×10^{-4}	0.130 ± 0.03	$(2.1^{+1.1}_{-0.6}) \times 10^{-4}$	0.27	8.0×10^{-4}	0.15	1.90×10^{-4}
	BB	7.81 MeV	20.4	⋯	⋯	1.32 MeV	3.89	4.18 MeV	5.28
	BB^*	16.5 MeV	43.0	⋯	⋯	7.59 MeV	22.4	15.49 MeV	19.57
	$BB(1P_1)$	8.27 MeV	21.6	⋯	⋯	7.81 MeV	23.0	40.08 MeV	50.64
	$BB(1P_1')$	Below threshold	⋯	⋯	⋯	10.8 MeV	31.8	3.95 MeV	4.98
	B^*B^*	4.43 MeV	11.5	⋯	⋯	5.89 MeV	17.4	11.87 MeV	14.99
	B_sB_s	0.101 MeV	0.263	⋯	⋯	1.31	3.86×10^{-3}	0.07 MeV	0.09
	$B_sB_s^*$	0.780 MeV	2.04	⋯	⋯	0.136 MeV	0.401	1.50 MeV	1.89
	$B_s^*B_s^*$	0.448 MeV	1.17	⋯	⋯	0.310 MeV	0.914	2.02 MeV	2.56
	Total	38.3 MeV	100	$39.3^{+1.7+1.3}_{-1.6-2.4}$ MeV [63]	⋯	33.9 MeV	100	79.16 MeV	100

Energy dependence of the $e^+e^- \to B^{(*)}\bar{B}^{(*)}$



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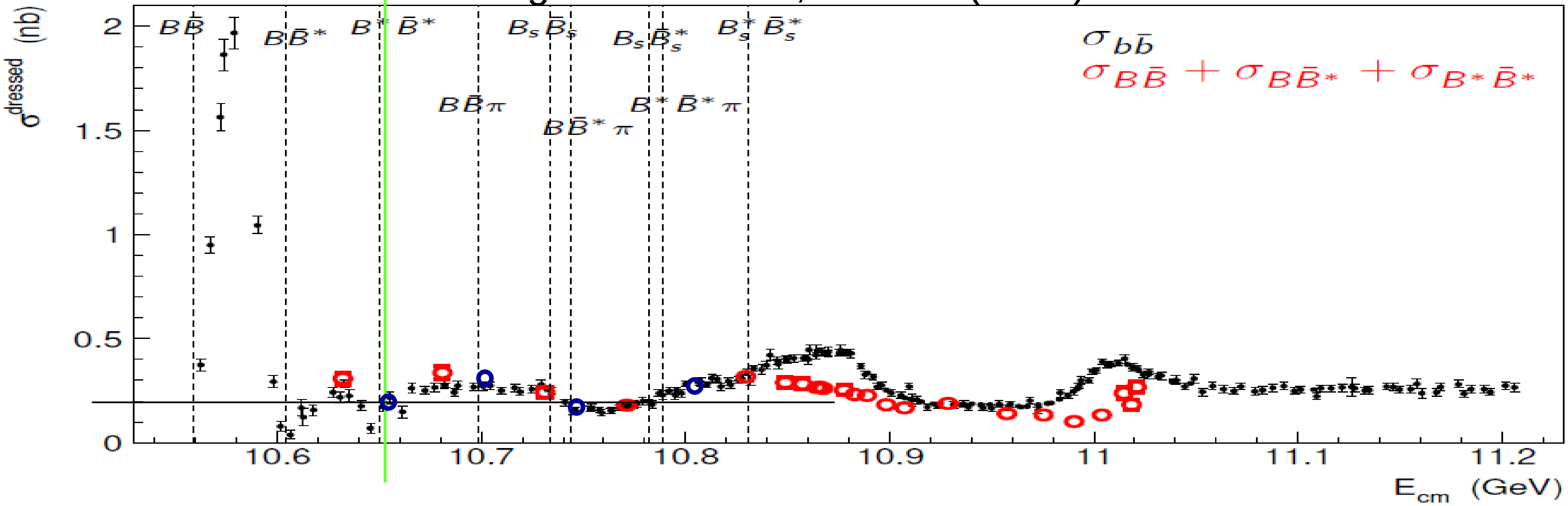
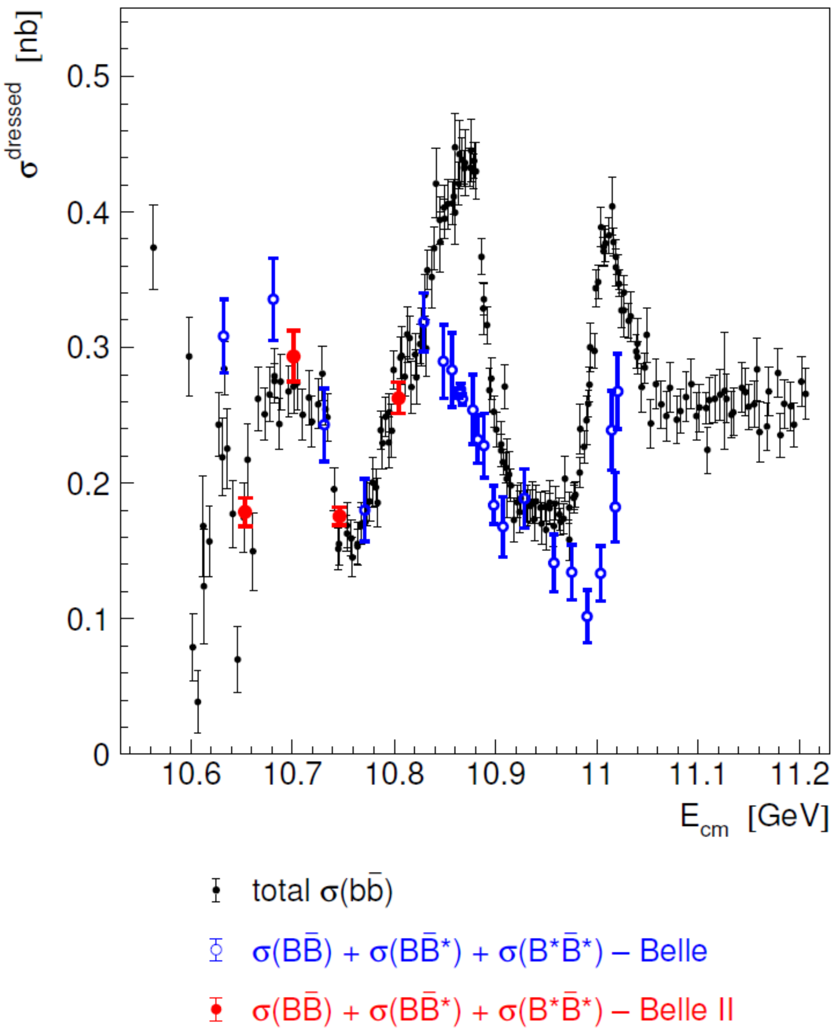
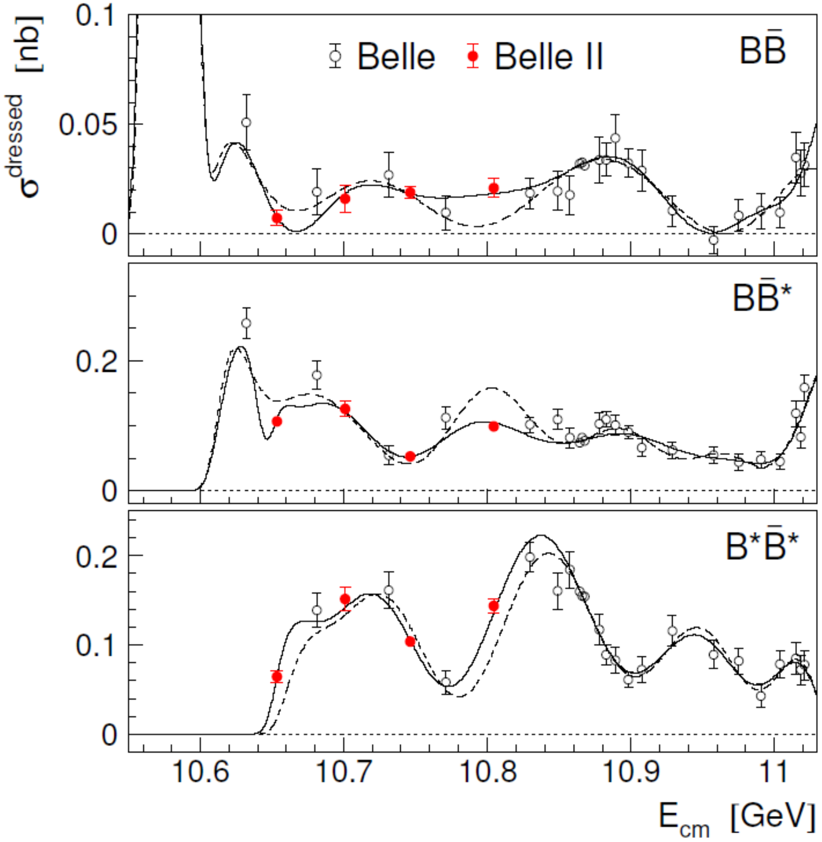
Dong et al. CPC44, 083001 (2020)




σ^dressed [nb]
0.5
0.4
0.3
0.2
0.1
0
10.6
10.7
10.8
10.9
11
11.1
11.2
E_cm [GeV]
total σ(bb̄)
σ(BB̄) + σ(BB̄*) + σ(B*B̄*) – Belle
σ(BB̄) + σ(BB̄*) + σ(B*B̄*) – Belle II


σ^dressed [nb]
Belle
Belle II
BB̄
0.1
0.05
0
BB̄*
0.2
0
B*B̄*
0.2
0.1
0
10.6
10.7
10.8
10.9
11
E_cm [GeV]

Decay channels of B^+ and B^0 mesons used in FEI..

$B^+ \rightarrow$	$B^0 \rightarrow$
$\bar{D}^0\pi^+$	$D^-\pi^+$
$\bar{D}^0\pi^+\pi^+\pi^-$	$D^-\pi^+\pi^+\pi^-$
$\bar{D}^{*0}\pi^+$	$D^{*-}\pi^+$
$\bar{D}^{*0}\pi^+\pi^+\pi^-$	$D^{*-}\pi^+\pi^+\pi^-$
$D_s^+\bar{D}^0$	$D_s^+D^-$
$D_s^{*+}\bar{D}^0$	$D_s^{*+}D^-$
$D_s^+\bar{D}^{*0}$	$D_s^+D^{*-}$
$D_s^{*+}\bar{D}^{*0}$	$D_s^{*+}D^{*-}$
$J/\psi\,K^+$	$J/\psi\,K_S$
$J/\psi\,K_S\,\pi^+$	$J/\psi\,K^+\pi^-$
$J/\psi\,K^+\pi^+\pi^-$	
$D^-\pi^+\pi^+$	$D^{*-}K^+K^-\pi^+$
$D^{*-}\pi^+\pi^+$	

Decay channels of D^0, D^+ and D_s^+ mesons used in FEI.

$D^0 \rightarrow$	$D^+ \rightarrow$	$D_s^+ \rightarrow$
$K^-\pi^+$	$K^-\pi^+\pi^+$	$K^+K^-\pi^+$
$K^-\pi^+\pi^0$	$K^-\pi^+\pi^+\pi^0$	K^+K_S
$K^-\pi^+\pi^+\pi^-$	$K_S\,\pi^+$	$K^+K^-\pi^+\pi^0$
$K_S\,\pi^+\pi^-$	$K_S\,\pi^+\pi^0$	$K^+K_S\,\pi^+\pi^-$
$K_S\,\pi^+\pi^-\pi^0$	$K_S\,\pi^+\pi^+\pi^-$	$K^-K_S\,\pi^+\pi^+$
K^+K^-	$K^+K^-\pi^+$	$K^+K^-\pi^+\pi^+\pi^-$
$K^+K^-K_S$		$K^+\pi^+\pi^-$
		$\pi^+\pi^+\pi^-$