ICHEP 2024, 17 – 24 July 2024, Prague

Hadron spectroscopy studies at Belle and Belle II

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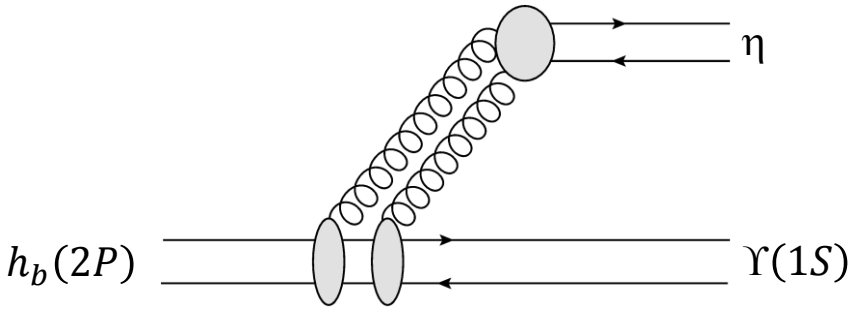
Contents

- Belle
  - Υ(4S) : 711 fb^{-1}
  - Υ(5S) : 121 fb^{-1}
  - continuum : 80 fb^{-1}
  - Υ(1S,2S,3S) : 34 fb^{-1}
  - energy scan : 22 fb^{-1}
- Belle II
  - Υ(4S) : 362 fb^{-1}
  - continuum : 42 fb^{-1}
  - energy scan : 19 fb^{-1}

Bottomonium decays

Bottomonium ($b\bar{b}$) – spin-singlet $S_{b\bar{b}} = 0$ or spin-triplet $S_{b\bar{b}} = 1$.

Transitions between spin-singlet and spin-triplet states are suppressed, amplitude $\propto 1/m_b$.



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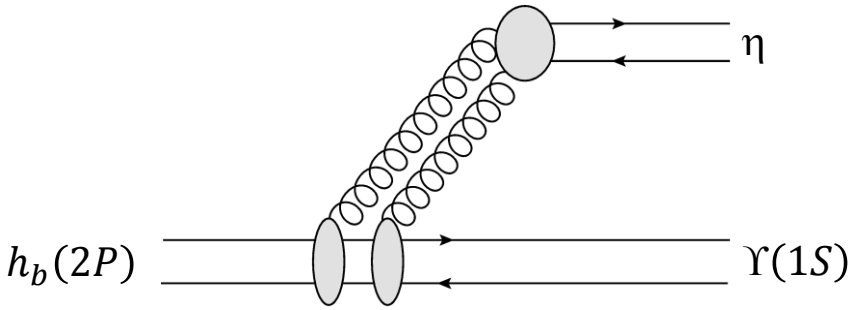
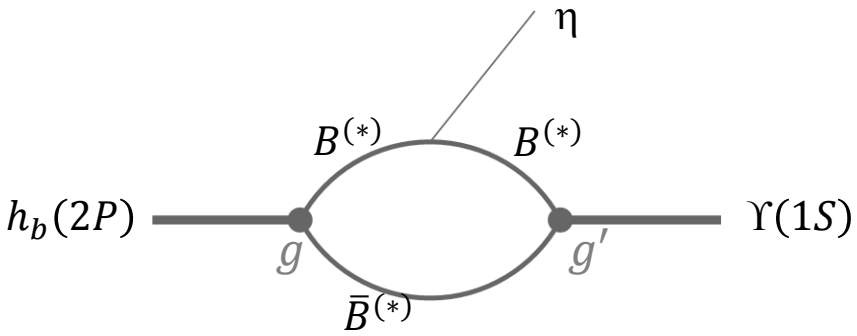




Suppression might be somewhat lifted due to hadron loops (g, g' – Lattice or exp).

BaBar PRD 84, 091101 (2011)

Below $B\bar{B}$ threshold: $BF[\Upsilon(3S) \to h_b(1P)\,\pi^0] \sim 10^{-3}$ significance 3.1σ

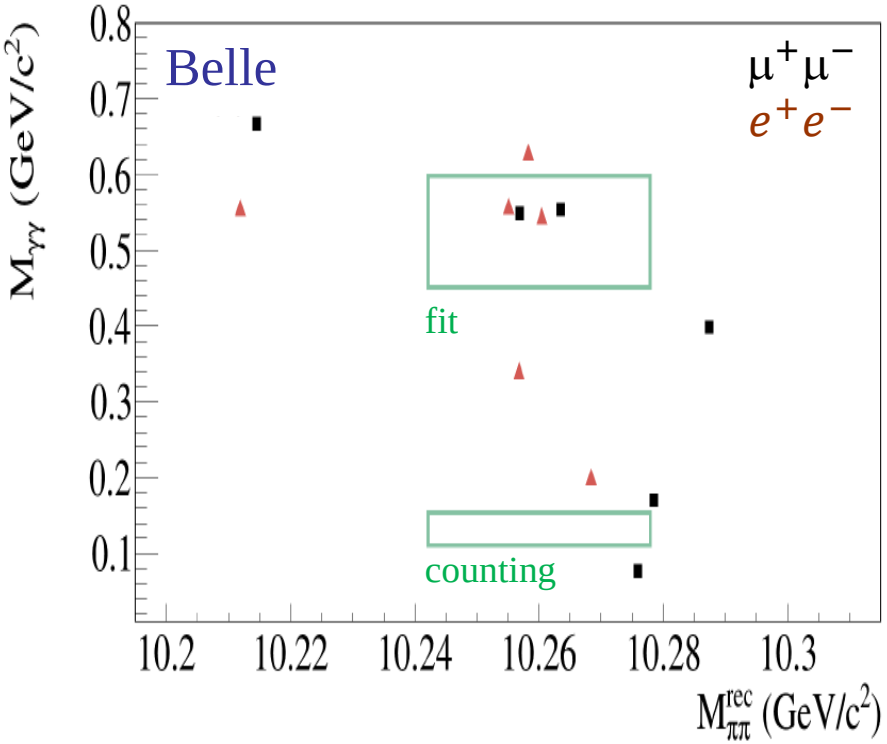
X. Li and M. Voloshin, PRD 86, 094013 (2012)

Prediction based on BaBar result: $BF[h_b(2P) \to \Upsilon(1S)\,\eta] \sim 10\%$

$h_b(2P) \to \Upsilon(1S)\,\eta$

arxiv:2407.03783

$\Upsilon(5S)$ data, 121 fb^{-1}. Full reconstruction: $\Upsilon(5S) \to Z_b^+\,\pi^- \to h_b(2P)\,\pi^+\pi^-$, $h_b(2P) \to \Upsilon(1S)\,\eta \to (\mu^+\mu^-, e^+e^-)\,(\gamma\,\gamma)$.



2D fit to $M(\gamma\,\gamma)$ vs. $M_{\rm rec}(\pi^+\pi^-)$

Significance: 3.5σ including systematics

$$\mathcal{B}[h_b(2\mathrm{P}) \to \Upsilon(1\mathrm{S})\eta] = (7.1\ ^{+3.7}_{-3.2} \pm 0.8) \times 10^{-3}$$

10× lower than the expectations based on experimental $BF(\Upsilon(3S) \to h_b(1P)\,\pi^0)$. Disfavors the latter evidence?

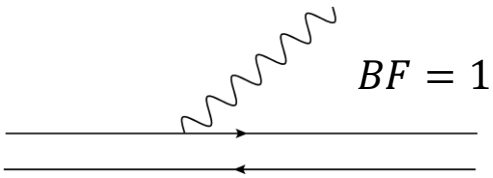
No signal of isospin violating decay $h_b(2P) \to \Upsilon(1S)\,\pi^0$

$\mathcal{B} < 1.8 \times 10^{-3}$ at 90% CL

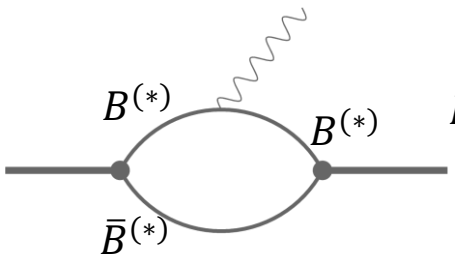
Search for $h_b(2P) \to \chi_{bJ}(1P)\,\gamma$

preliminary

Expectation K.-F. Guo et al., PLB 760, 417 (2016)



$BF = 10^{-6} \div 10^{-5}$



$BF = 10^{-2} \div 10^{-1}$

Full reconstruction:

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

$h_b(2P) \to \chi_{bJ}(1P)\,\gamma \to [\Upsilon(1S)\,\gamma_2]\,\gamma$

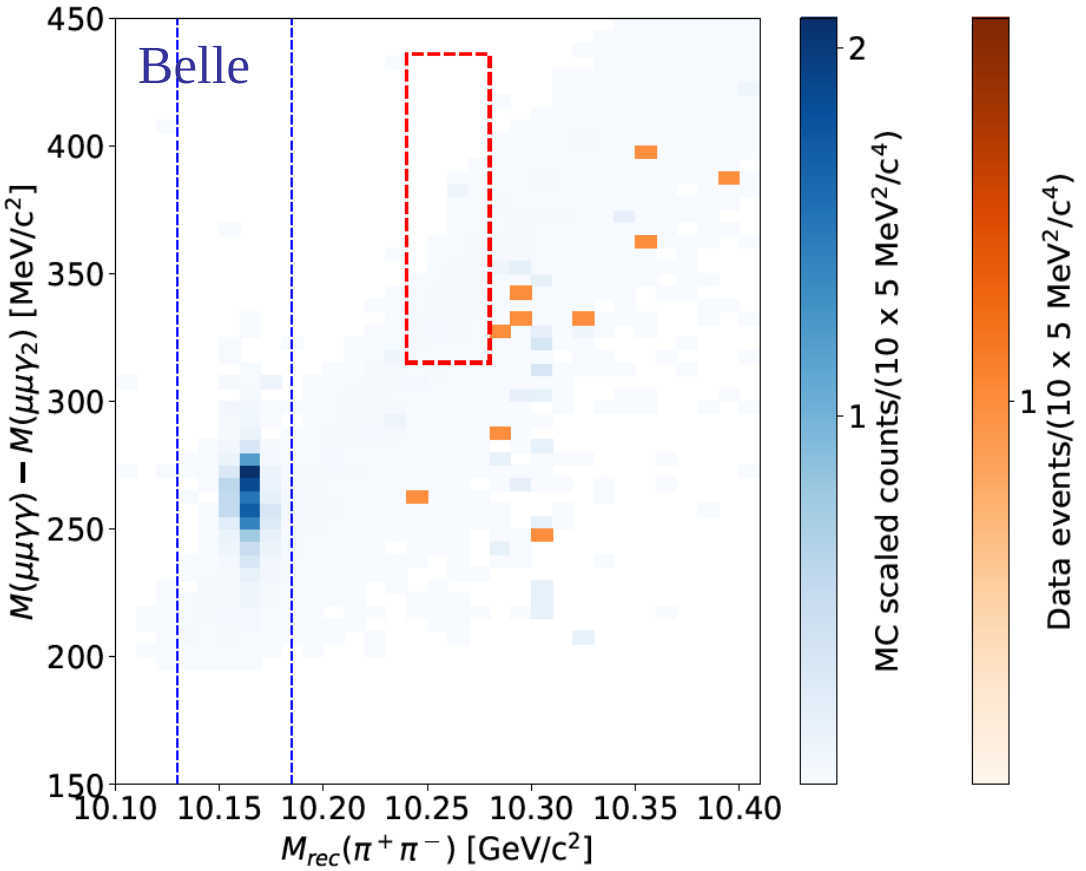
$\to [(\mu^+\mu^-)\,\gamma_2]\,\gamma$

No events in the signal region

$$\begin{aligned} h_b(2P) \to \gamma\chi_{b2}(1P) &< 1.3 \times 10^{-2} \\ h_b(2P) \to \gamma\chi_{b1}(1P) &< 5.4 \times 10^{-3} \\ h_b(2P) \to \gamma\chi_{b0}(1P) &< 2.7 \times 10^{-1} \end{aligned}$$

$\mathcal{B}$

ULs are consistent with expectations.



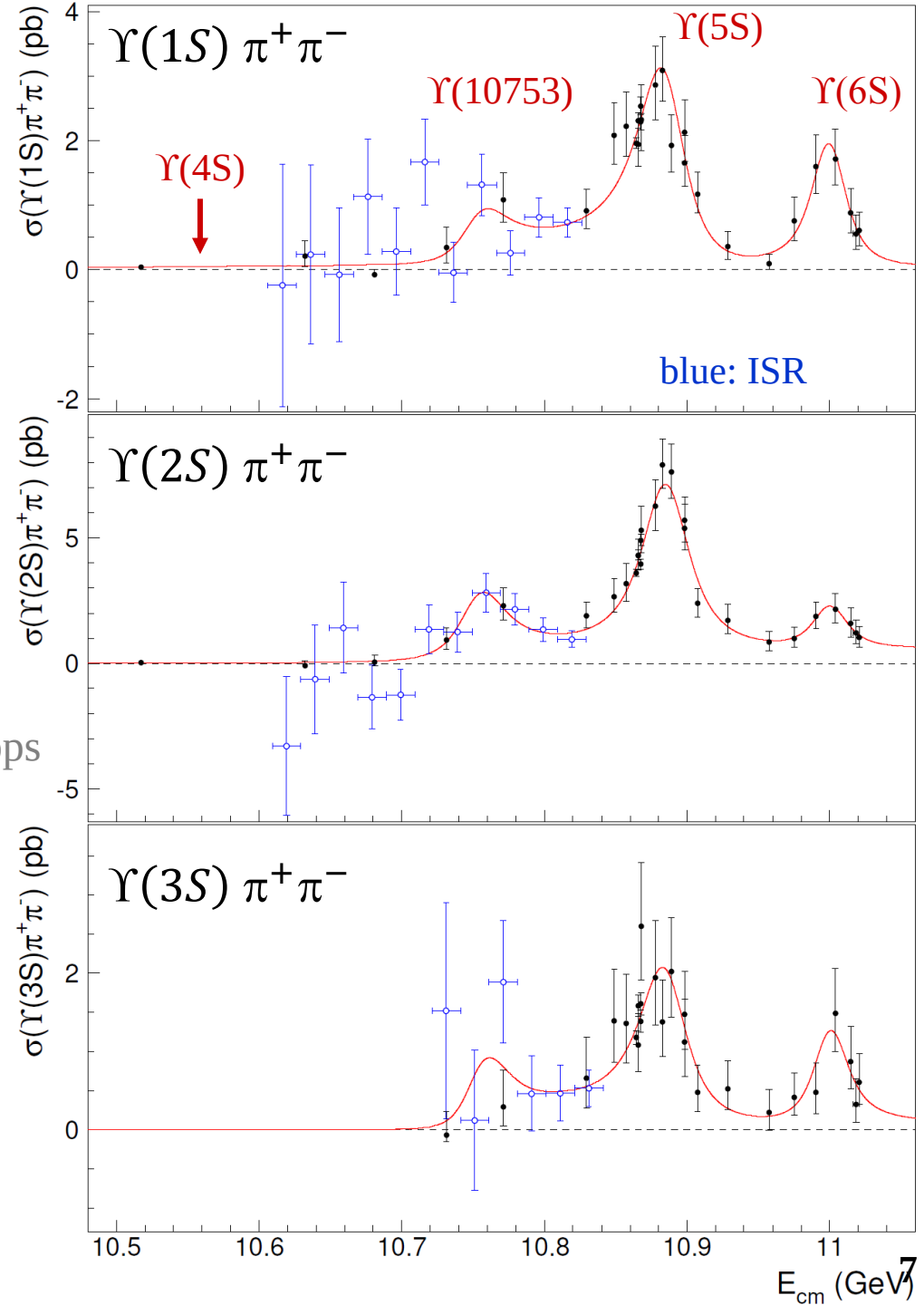
$\Upsilon(10753)$

Observed by Belle JHEP 10, 220 (2019)

$$M = (10752.7 \pm 5.9^{+0.7}_{-1.1})\ MeV$$
$$\Gamma = (35.5^{+17.6\ +3.9}_{-11.3\ -3.3})\ MeV$$

Interpretations:
- $\Upsilon(3D)$ mixed with $\Upsilon(4S)$ via hadron loops
- hybrid
- compact tetraquark

Belle: global significance 5.2σ



Belle II: confirmation of $\Upsilon(10753)$

arxiv:2401.12021

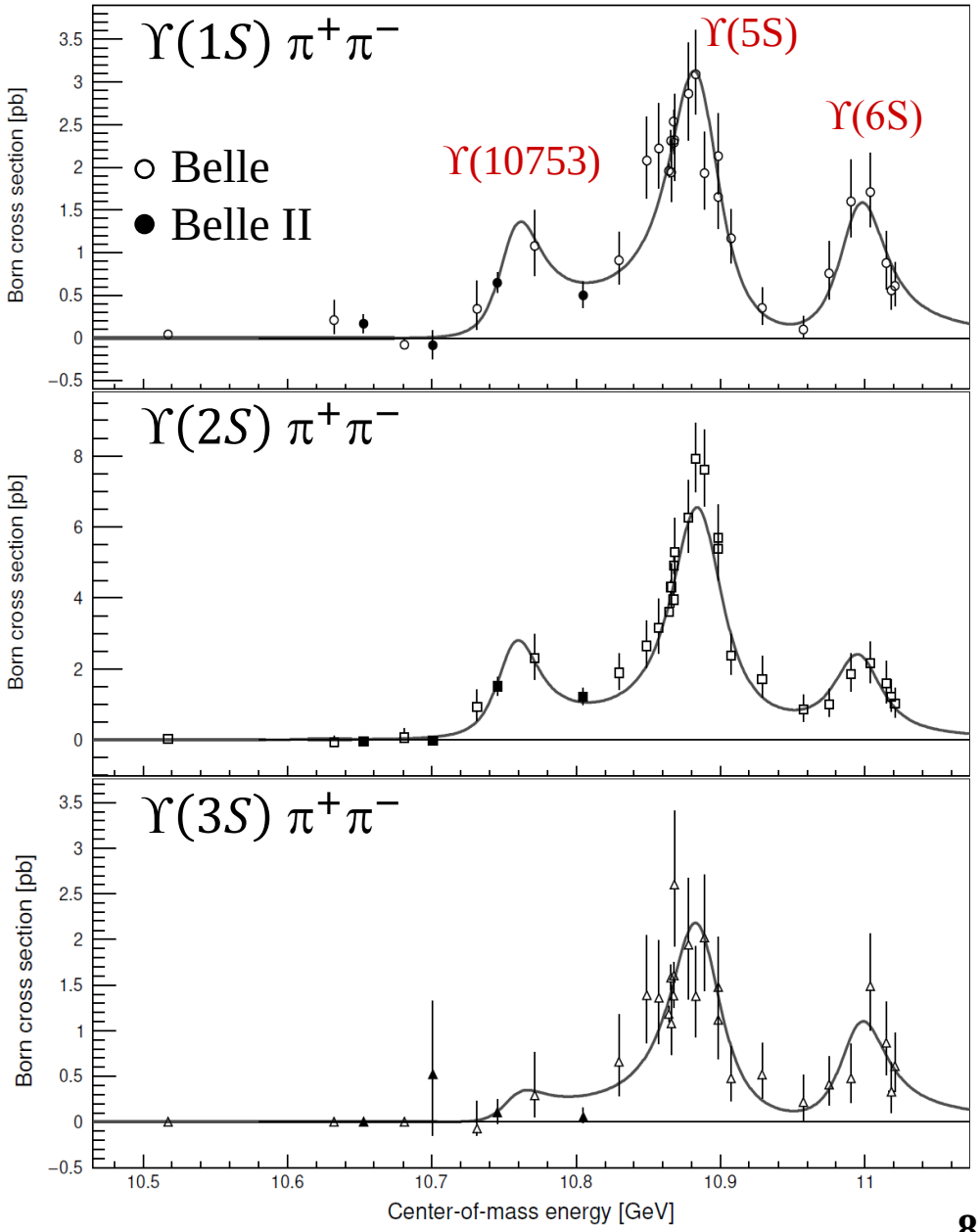
Belle II: energy scan in Nov 2021
4 points, total $L = 19\ \text{fb}^{-1}$

Combined fit to Belle + Belle II data

Significance

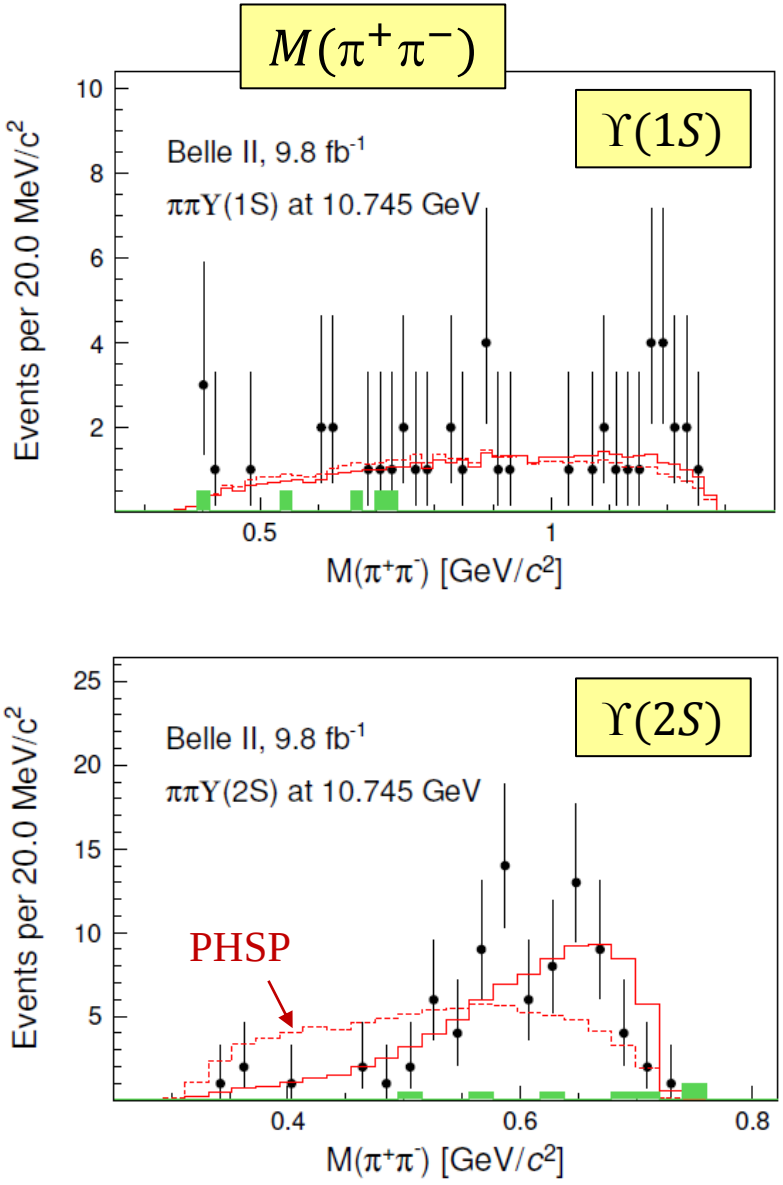
$\Upsilon(1S)\,\pi^+\pi^-$	4.1σ
$\Upsilon(2S)\,\pi^+\pi^-$	7.5σ

$$M = (10756.6 \pm 2.7 \pm 0.9)\ MeV$$
$$\Gamma = (29.0 \pm 8.8 \pm 1.2)\ MeV$$

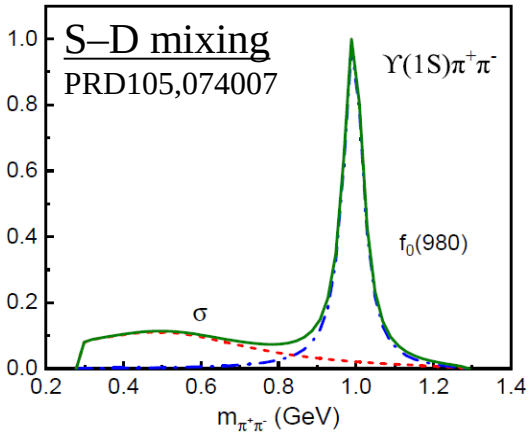


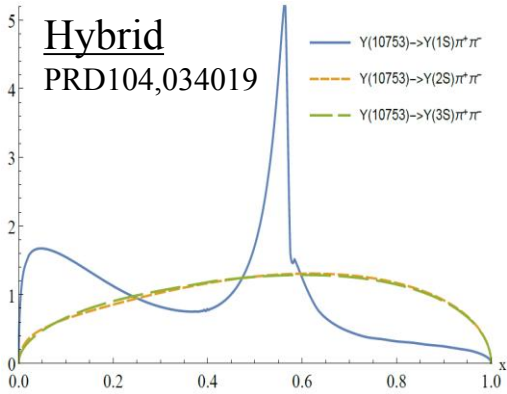
Resonant substructure of $\Upsilon(10753) \to \Upsilon(nS)\pi^+\pi^-$

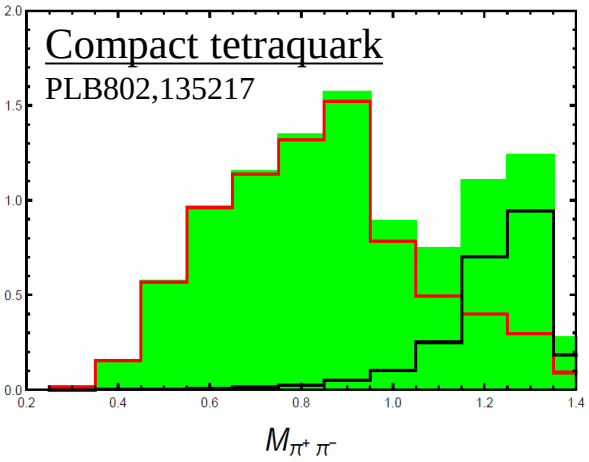
arxiv:2401.12021



- $M(\pi^+\pi^-)$ and $M[\Upsilon(nS)\,\pi^+]$ – no significant structures
- Models predict production of $f_0(980)$ – ?







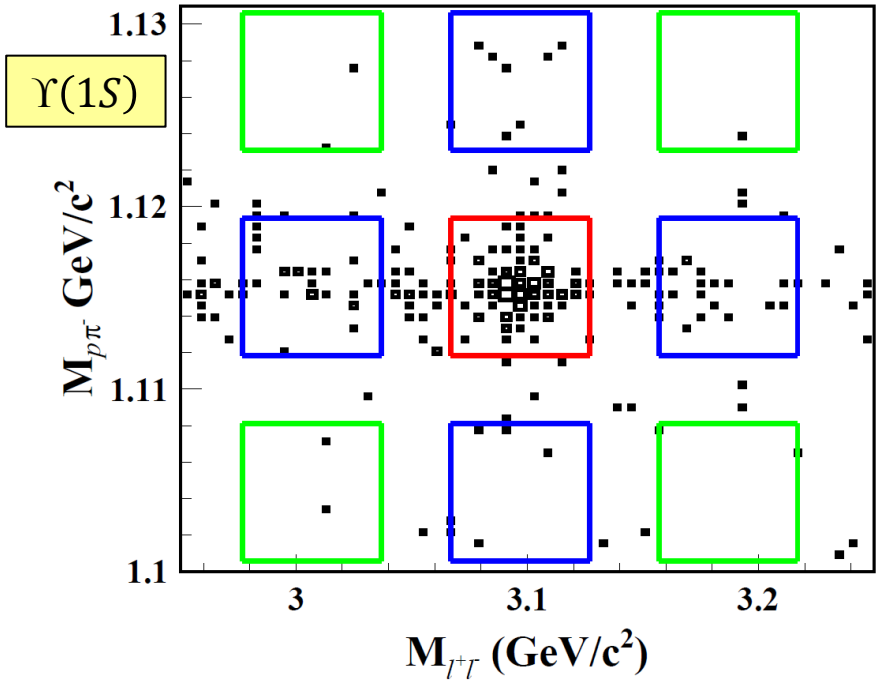
Pentaquarks in $\Upsilon(1S, 2S)$ decays

$\Upsilon(1S, 2S)$ decays: production of baryons and deuterons is enhanced ⇒ search for exotics

Belle: world-largest data samples 6 fb^{-1} at Υ (1S) [102M decays]
25 fb^{-1} at Υ(2S) [158M decays]

Search for $\Upsilon(1S, 2S) \to P_c\, X \to (J/\psi\, p)\, X$ ⇒ no pentaquark signals. arxiv:2403.04340

New: search for $\Upsilon(1S, 2S) \to P_{cs}\, X \to (J/\psi\, \Lambda)\, X$ preliminary



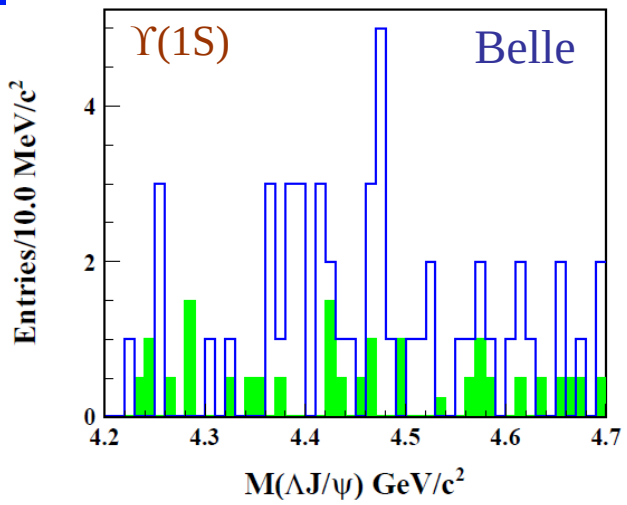
Subtract sidebands and continuum →

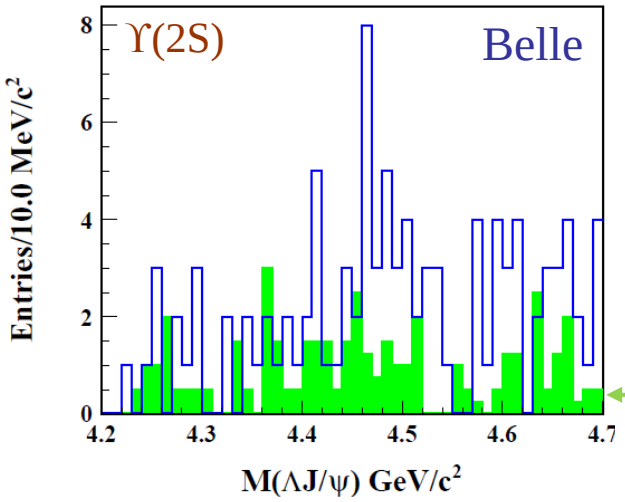
$$\mathcal{B}[\Upsilon(1S) \to \Lambda J/\psi + anything] = (17.7 \pm 2.8 \pm 1.2) \times 10^{-6}$$

$$\mathcal{B}[\Upsilon(2S) \to \Lambda J/\psi + anything] = (11.2 \pm 3.1 \pm 1.5) \times 10^{-6}$$

Evidence for $\Upsilon(1S, 2S) \to P_{cs}(4459)\, X$

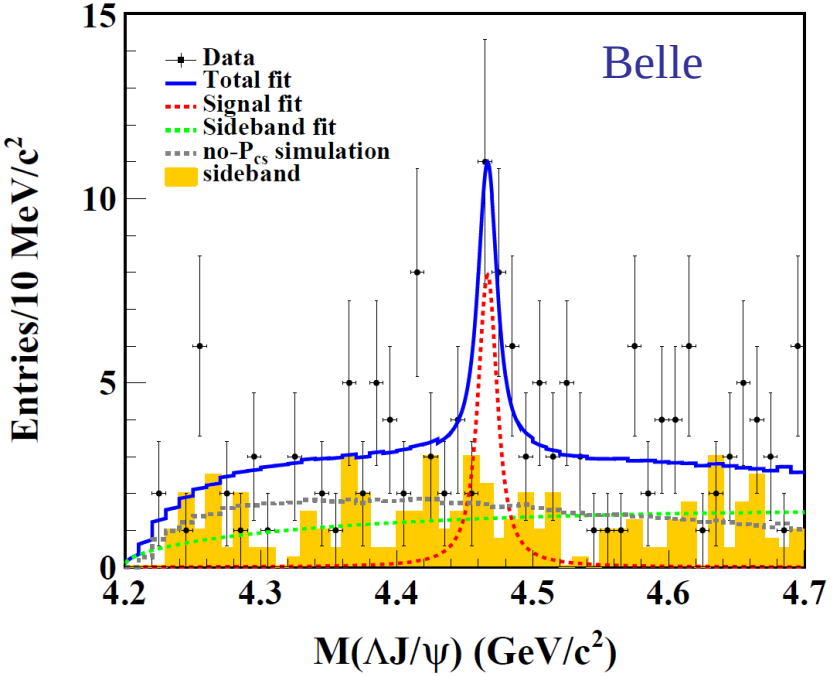
preliminary





← 2D sideband

Combine Υ(1S) and Υ(2S) data



Local significance is 4.0σ.

$$M = 4469.5 \pm 4.1 \pm 4.1\ MeV$$
$$\Gamma = 14.3 \pm 9.2 \pm 6.3\ MeV$$

c.f. $P_{cs}(4459)$ LHCb, SB 66, 1278 (2021)

$$4458.8 \pm 2.9\ ^{+4.7}_{-1.1}\ MeV$$
$$17.3 \pm 6.5\ ^{+8.0}_{-5.7}\ MeV$$

Add Gaussian constraint on M and Γ
⇒ significance is 3.3σ including systematics.

Conclusions

Evidence for $h_b(2P) \to \Upsilon(1S)\,\eta$ arxiv:2407.03783

No signal of $h_b(2P) \to \chi_{bJ}(1P)\,\gamma$ preliminary

Confirmation of $\Upsilon(10753)$ in $\Upsilon(1S, 2S)\,\pi^+\pi^-$ channels arxiv:2401.12021

$M(\pi^+\pi^-)$, $M[\Upsilon(nS)\,\pi^+]$ distributions are featureless

Energy dependence of $e^+e^- \to B\bar{B}, B\bar{B}^*, B^*\bar{B}^*$ arxiv:2405.18928

Important for coupled-channel analysis. P-wave $B^*\bar{B}^*$ molecule?

Evidence for $\Upsilon(10753) \to \chi_{b1,2}(1P)\,\omega$ PRL 130, 091902 (2023)

No signal of $\Upsilon(10753) \to \eta_b(1S)\,\omega$ PRD 109, 072013 (2024)

Evidence for $P_{cs}(4459) \to J/\psi\,\Lambda$ in inclusive $\Upsilon(1S, 2S)$ decays NEW

Back-up

$e^+e^- \to B\bar{B}, B\bar{B}^*, B^*\bar{B}^*$

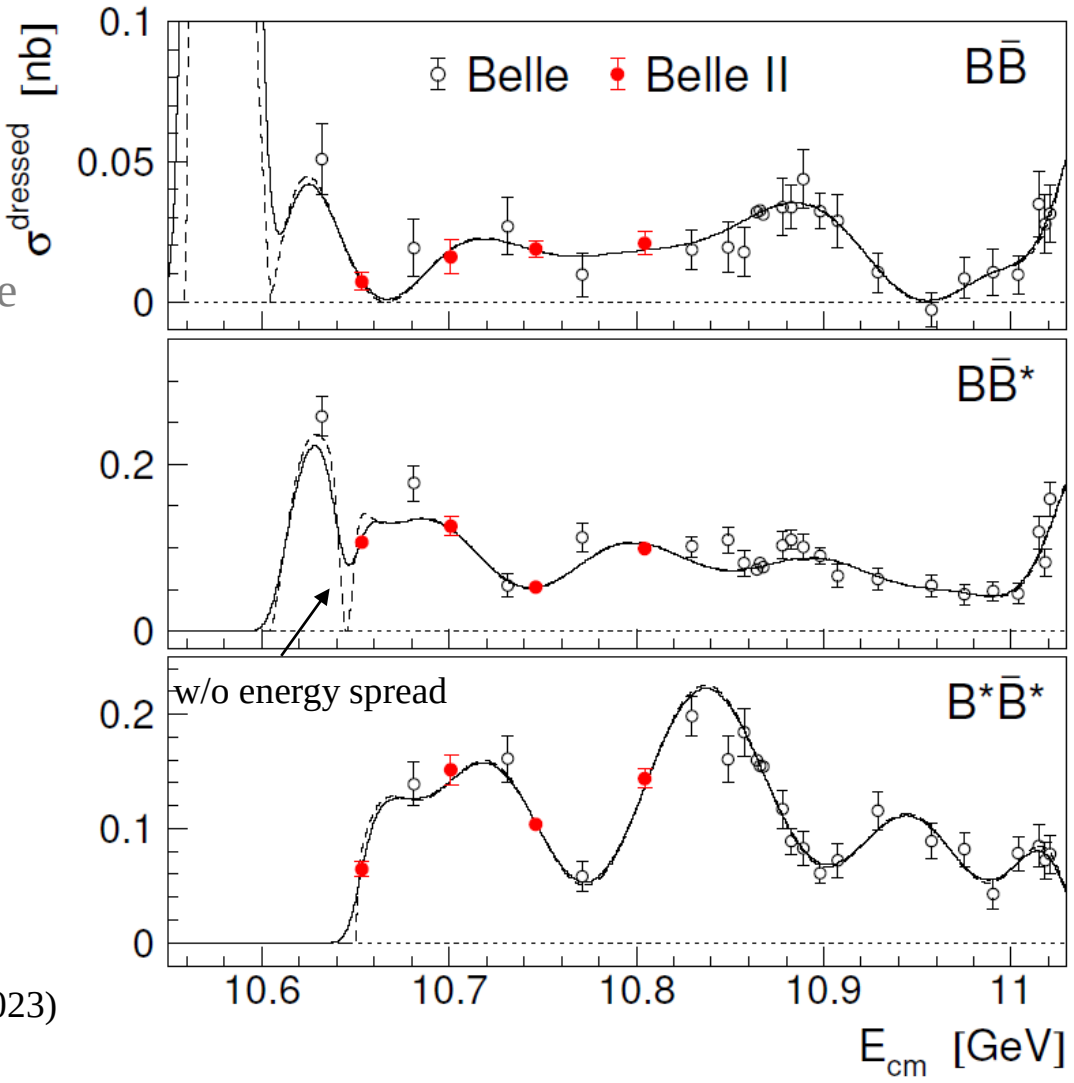
arxiv:2405.18928

Dominant contribution to $\sigma_{b\bar{b}}$
Crucial for coupled-channel analysis

Reconstruct one B (hadronic tagging),
use momentum as discriminating variable

Belle II data significantly improve
accuracy in cross-section shapes

Rapid rise of $\sigma(B^*\bar{B}^*)$ near threshold.
$B^*\bar{B}^*$ are in P-wave $\Rightarrow$ PHSP $\propto p^3_{B^*}$
$\Leftarrow B^*\bar{B}^*$ molecular state



Dubynskiy, Voloshin, MPLA 21, 2779 (2006)

Salnikov, Bondar, Milstein, NPA 1041, 122764 (2023)

Dip in $\sigma(B\bar{B}^*)$ – destructive interference.
Transitions to bottomonium are expected – need more data.