Recent progress ~~and future prospects~~ of Hadron Physics at the Belle and Belle II experiments

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On behalf of Belle/Belle II Collaboration

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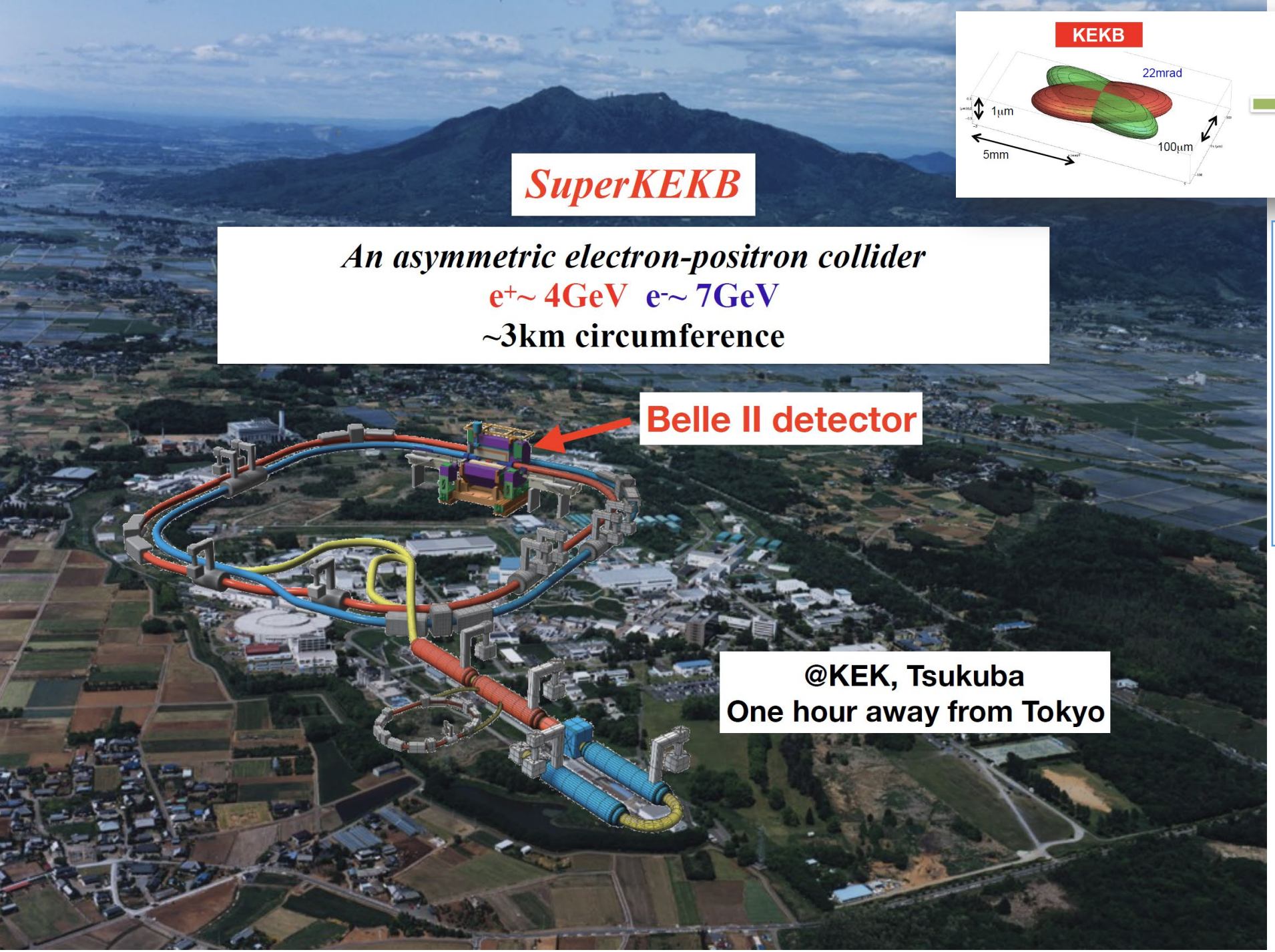
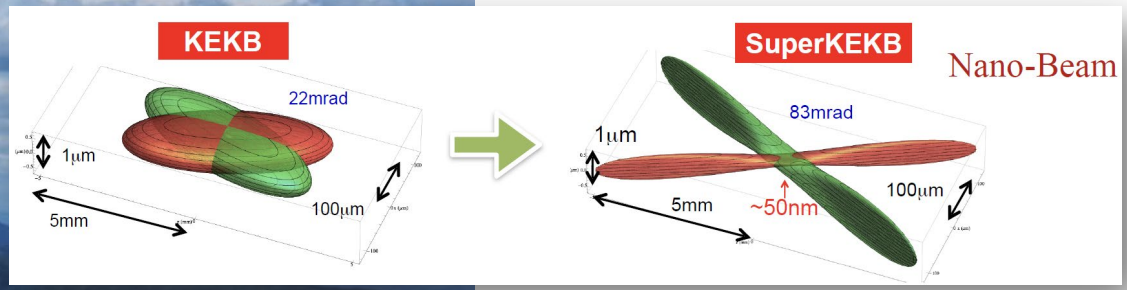
Outline

- Introduction to Belle II and hadrons
- Evidence of Pcs(4459) in $\Upsilon(1S, 2S)$ inclusive decays
- Confirmation of $\Upsilon(10753)$ at Belle II
- Energy dependence of $\sigma\left[e^+e^- \to B^{(*)}\bar{B}^{(*)}\right]$
- Bottomonium transitions



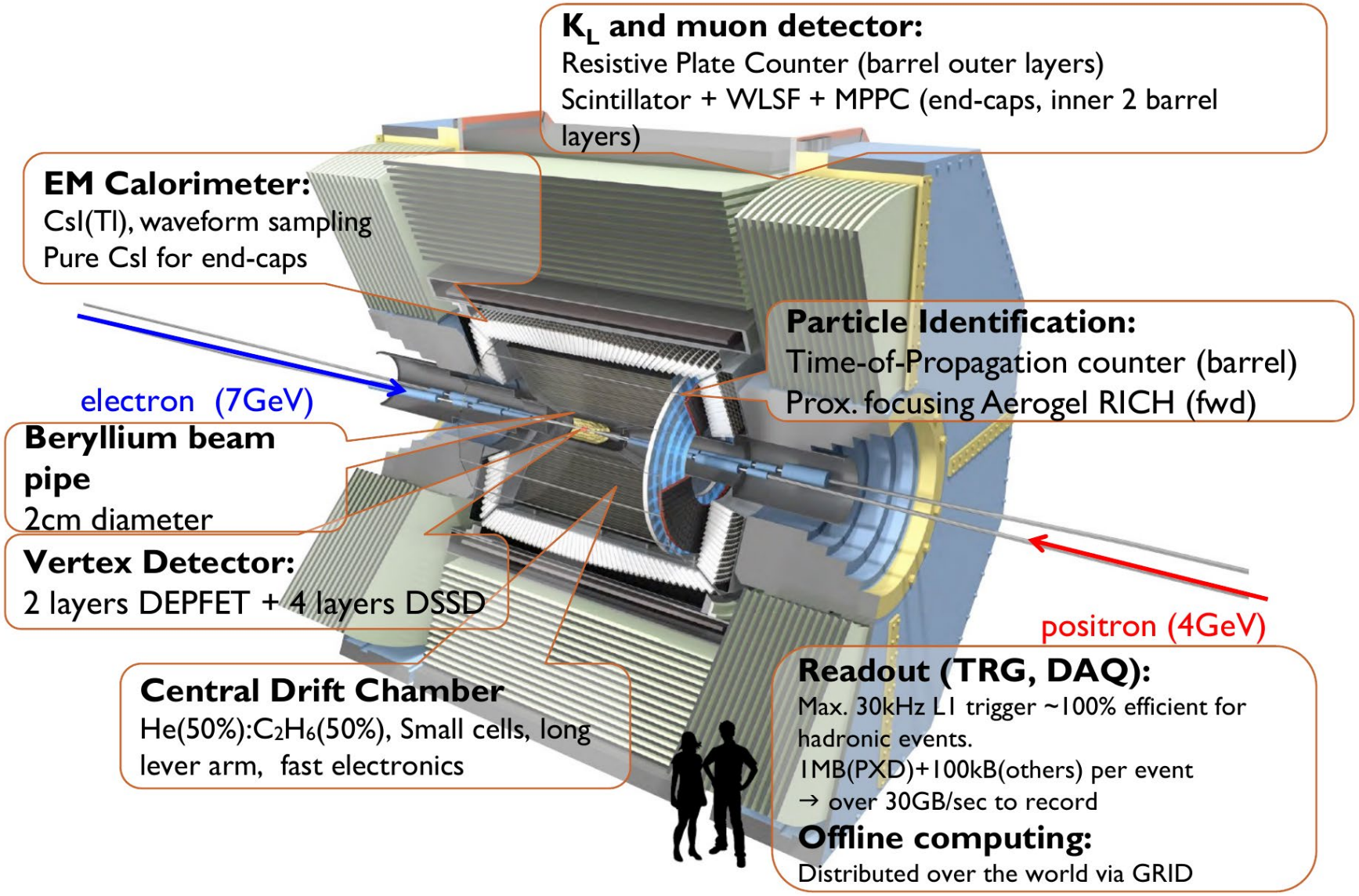


- Belle data: 980 fb^{-1}
- Belle II: rebuild a new detector.
- Aim to achieve luminosity of $6 \times 10^{35} cm^{-2} s^{-1}$
- $0.5 \times 10^{35} cm^{-2} s^{-1}$ has been achieved.

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

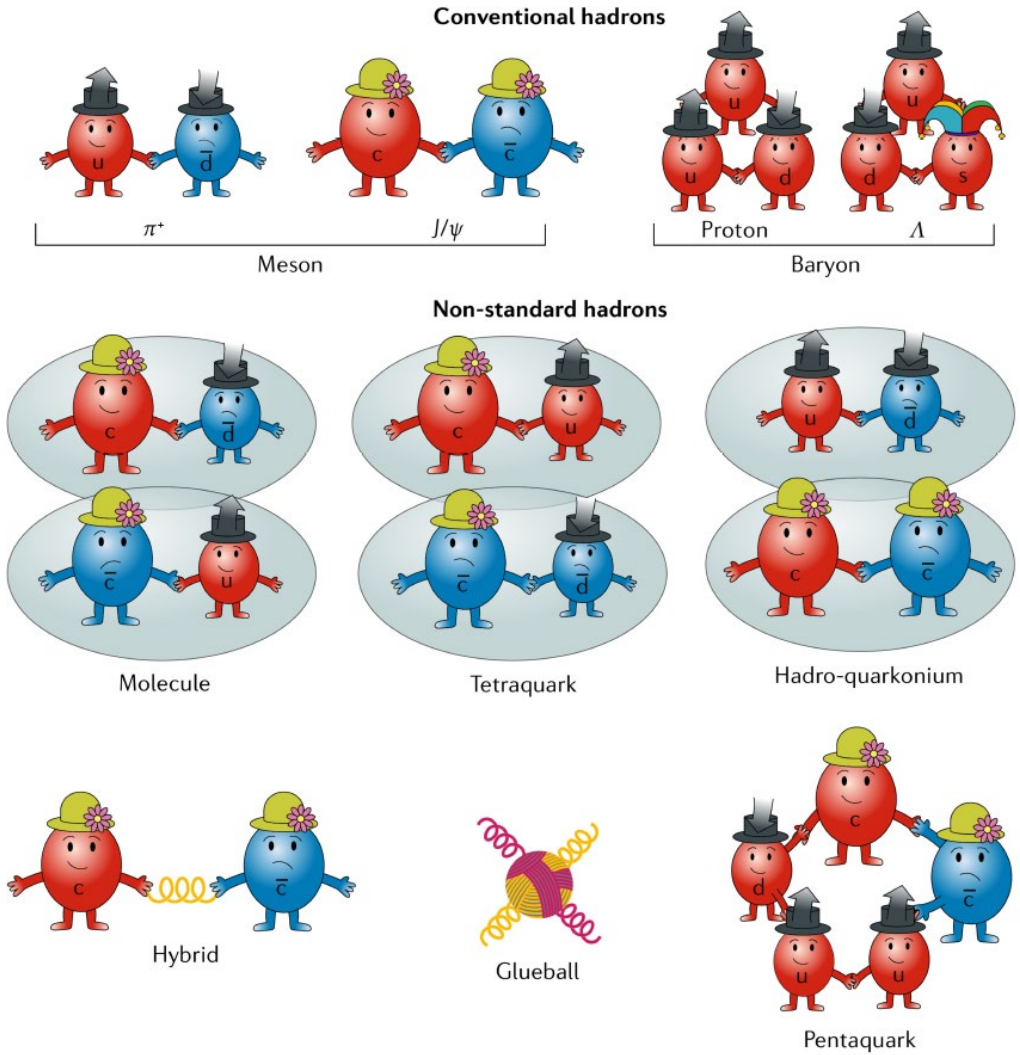
Belle II detector

$H = 7.1m, L = 7.4m, W = 1400$ Ton

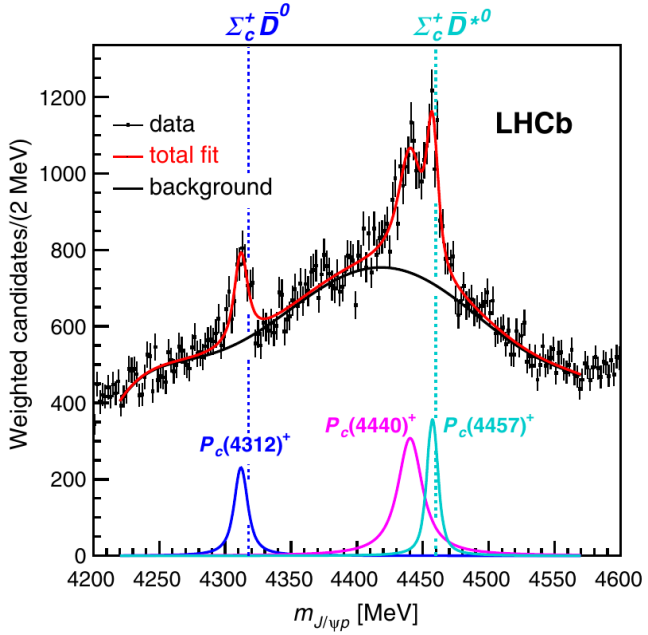


Structures of hadrons

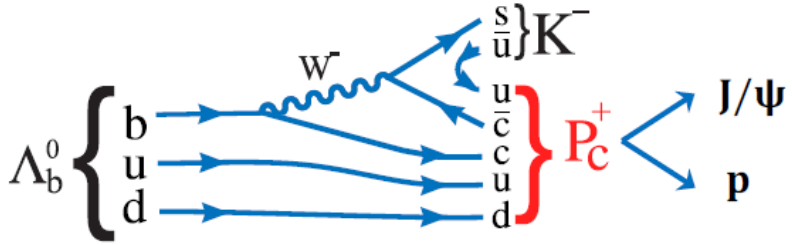
- Conventional hadrons:
  - Meson: $q\bar{q}$
  - Baryon: qqq or $\bar{q}\bar{q}\bar{q}$
- Others: exotic states, or XYZ particles
- Since the X(3872) observed by Belle, there have been more and more exotic candidates discovered.



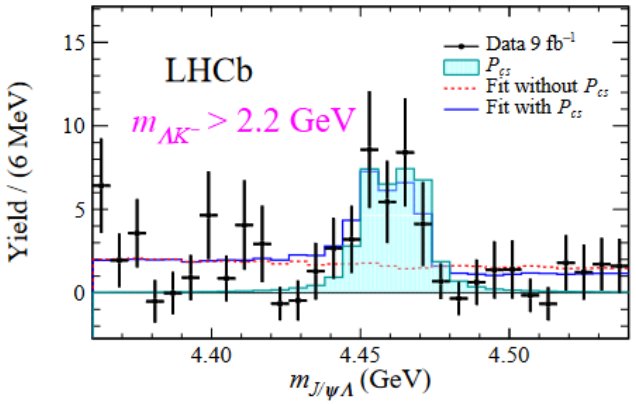
Candidates of pentaquark states: P_c and P_{cs}



$\Lambda_b^- \to K^- + pJ/\psi$

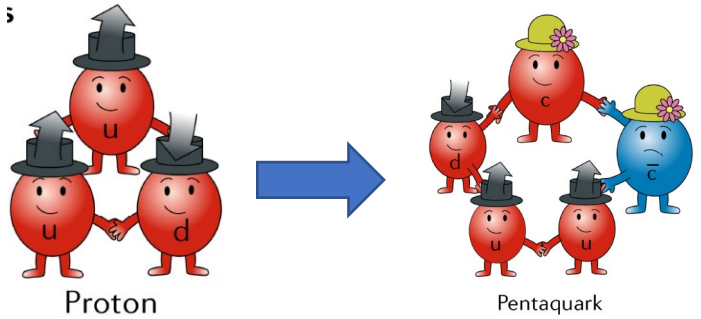


State	M[MeV/c^2]	Γ [MeV]	(95% C.L.)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(< 27)
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	(< 49)
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	(< 20)



$\Xi_b^- \to K^- + \Lambda J/\psi$

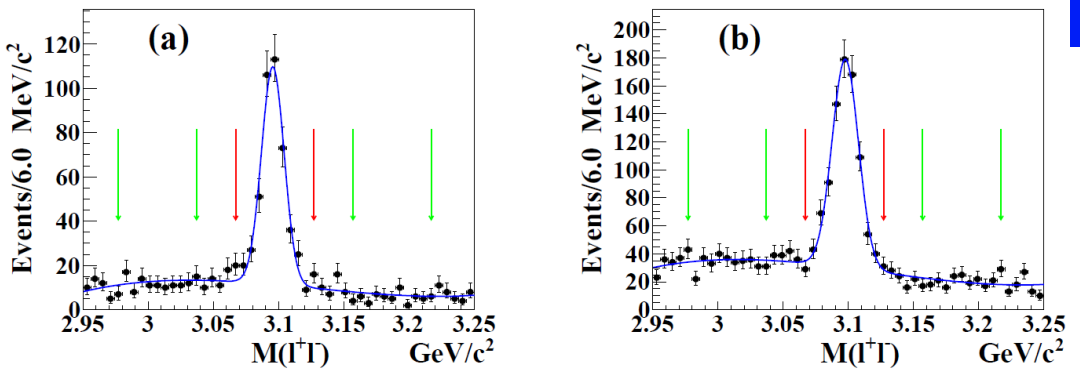
State	M[MeV/c^2]	Γ [MeV]	Br(%)
$P_{cs}^0(4459)$	$4458.8 \pm 2.9^{+4.7}_{-1.1}$	$17.3 \pm 6.5^{+8.0}_{-5.7}$	$2.7^{+1.9+0.7}_{-0.6-1.3}$

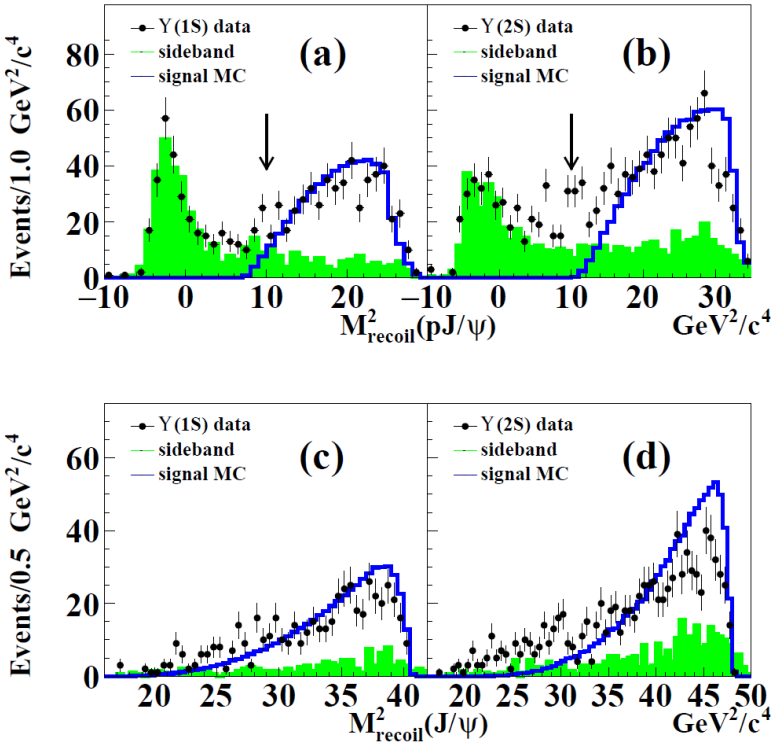


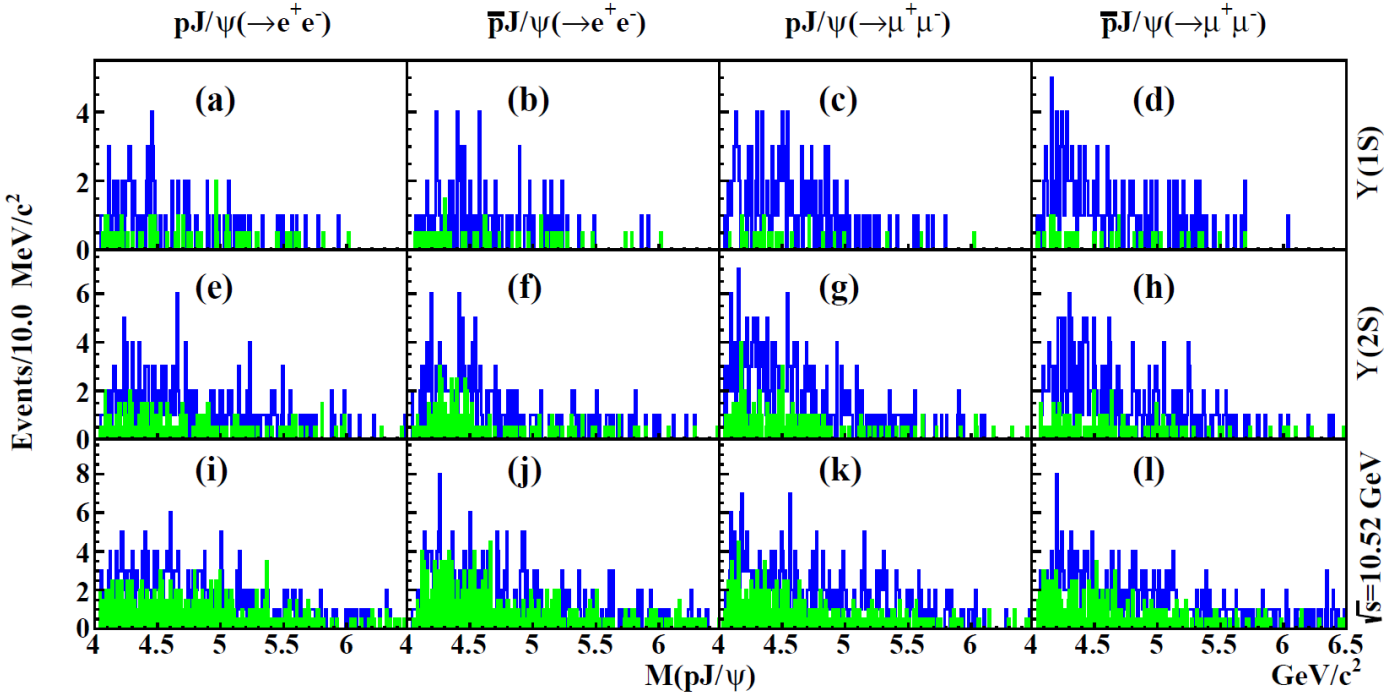
- Where to search for pentaquark states at Belle/Belle II?
- A clue: production of baryons and deutrons is enhanced in $\Upsilon(1S, 2S)$ inclusive decays.
- Belle has the world-largest data samples: 102M $\Upsilon(1S)$ and 158M $\Upsilon(2S)$

Search for P_c states in $\Upsilon(1S, 2S)$ decays

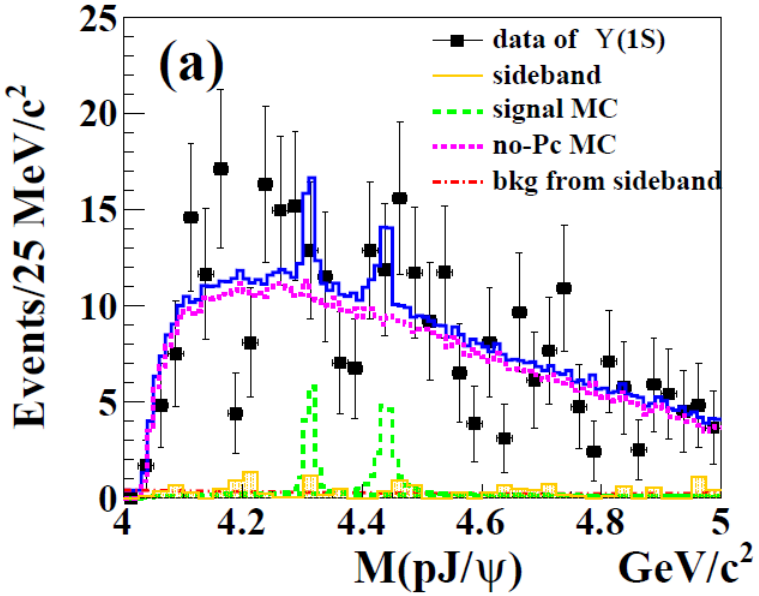
- $J/\psi \to e^+e^-$ or $\mu^+\mu^-$,
- Proton selection according to PID and veto those of secondary particles.
- Backgrounds from Bhabha events removed with $M^2_{recoil}(pJ/\psi) > 10\ \mathrm{GeV}^2/c^4$

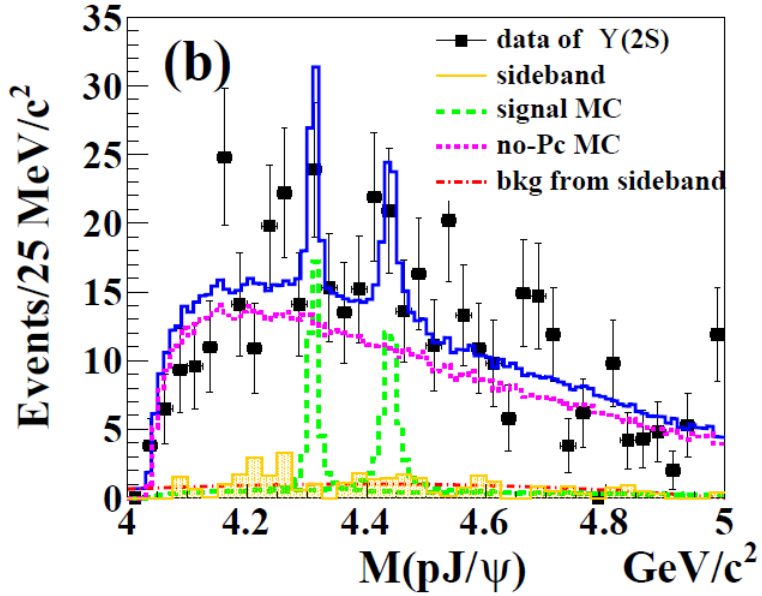






Search for P_c states in $\Upsilon(1S, 2S)$ decays





- No significant Pc state is obtained in the pJ/ψ of $\Upsilon(1S, 2S)$ inclusive decays.
- The upper limits of their productions are determined.
- $Br[\Upsilon(1S) \to pJ/\psi + anything] = (4.27 \pm 0.16 \pm 0.20) \times 10^{-5}$
- $Br[\Upsilon(2S) \to pJ/\psi + anything] = (3.59 \pm 0.14 \pm 0.16) \times 10^{-5}$

$$\mathcal{B}[\Upsilon(1S) \to P_c(4312)^+ + anything] \cdot \mathcal{B}[P_c(4312)^+ \to pJ/\psi] < 4.5 \times 10^{-6}$$
$$\mathcal{B}[\Upsilon(1S) \to P_c(4440)^+ + anything] \cdot \mathcal{B}[P_c(4440)^+ \to pJ/\psi] < 6.8 \times 10^{-6}$$
$$\mathcal{B}[\Upsilon(1S) \to P_c(4457)^+ + anything] \cdot \mathcal{B}[P_c(4457)^+ \to pJ/\psi] < 4.9 \times 10^{-6}$$
$$\mathcal{B}[\Upsilon(2S) \to P_c(4312)^+ + anything] \cdot \mathcal{B}[P_c(4312)^+ \to pJ/\psi] < 5.3 \times 10^{-6}$$
$$\mathcal{B}[\Upsilon(2S) \to P_c(4440)^+ + anything] \cdot \mathcal{B}[P_c(4440)^+ \to pJ/\psi] < 7.2 \times 10^{-6}$$
$$\mathcal{B}[\Upsilon(2S) \to P_c(4457)^+ + anything] \cdot \mathcal{B}[P_c(4457)^+ \to pJ/\psi] < 2.4 \times 10^{-6}$$

Search for P_{cs} states in $\Upsilon(1S, 2S)$ decays

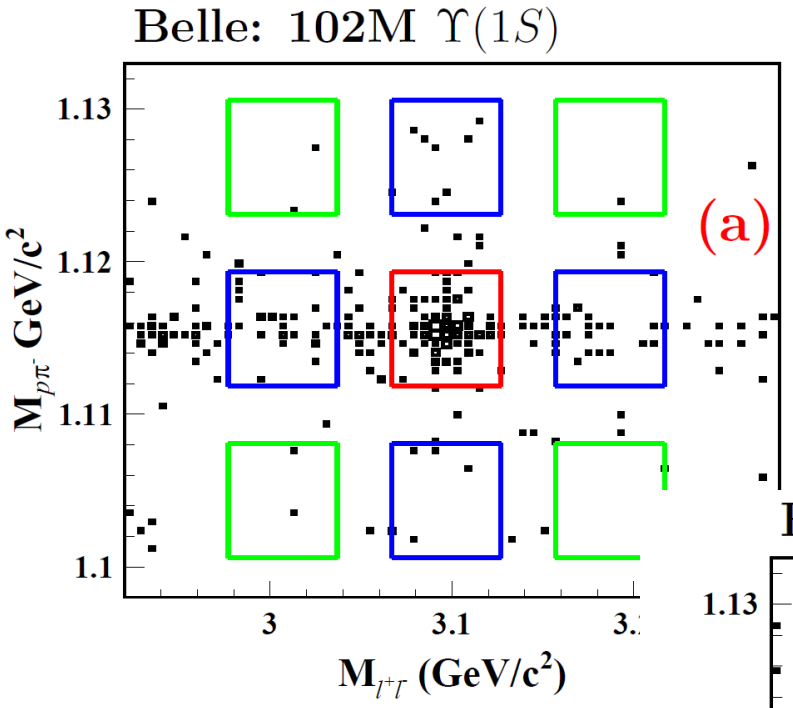
- J/ψ reconstructed from e^+e^- or $\mu^+\mu^-$.
- Select Λ with long flight distance.
- Both Λ and J/ψ have good purity.
- 89 fb-1 data sample at 10.52 GeV is used to estimate the continuum production.
- Resolution of $M_{\Lambda J/\psi}$ is better than 3 MeV/c^2

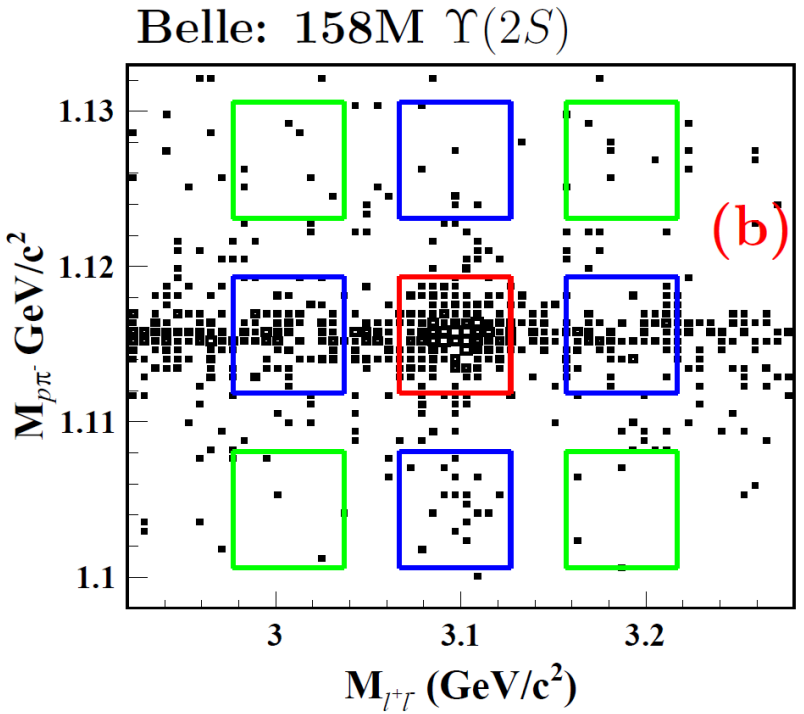
$$M_{\Lambda J/\psi} = M_{\ell^+\ell^- p\pi} - M_{\ell^+\ell^-} - M_{p\pi} + m_{J/\psi} + m_{\Lambda}$$

Subtract sidebands and continuum →

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

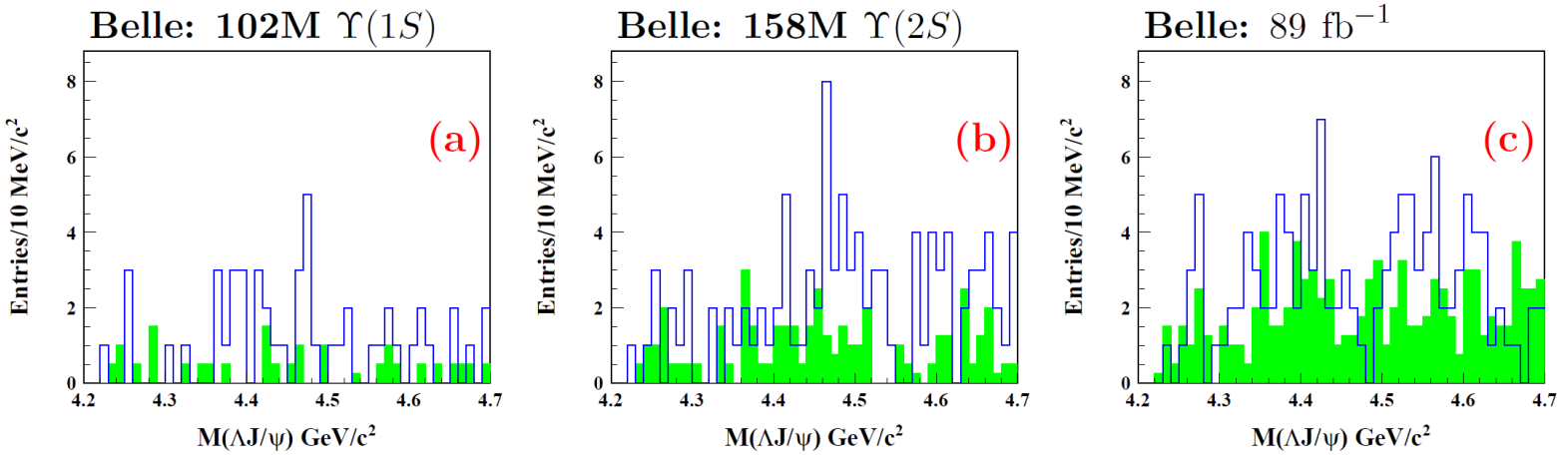
$$\mathcal{B}[\Upsilon(2S) \to \Lambda J/\psi + anything] = (11.2 \pm 3.1 \pm 1.5) \times 10^{-6}$$

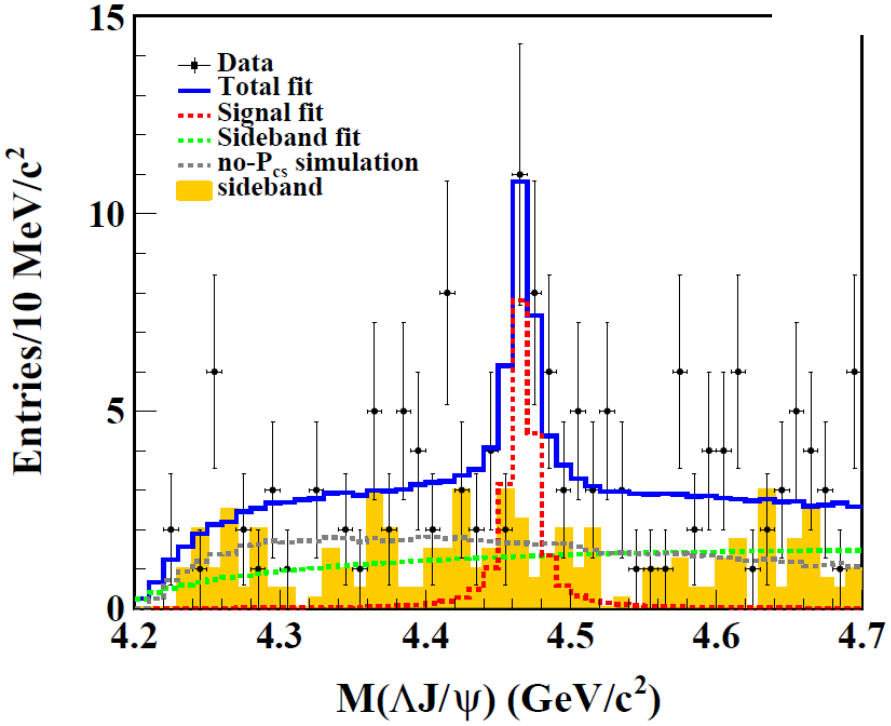




Evidence of $P_{cs}(4459)$ in $\Upsilon(1S, 2S)$ decays

- Enhancements near the mass of Pcs(4459)
- Combine $\Upsilon(1S)$ and $\Upsilon(2S)$ data and get the first evidence for a pentaquark candidate state in $\Upsilon(1S, 2S)$ inclusive decays.





Preliminary

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.

The $\Upsilon(10753)$ state

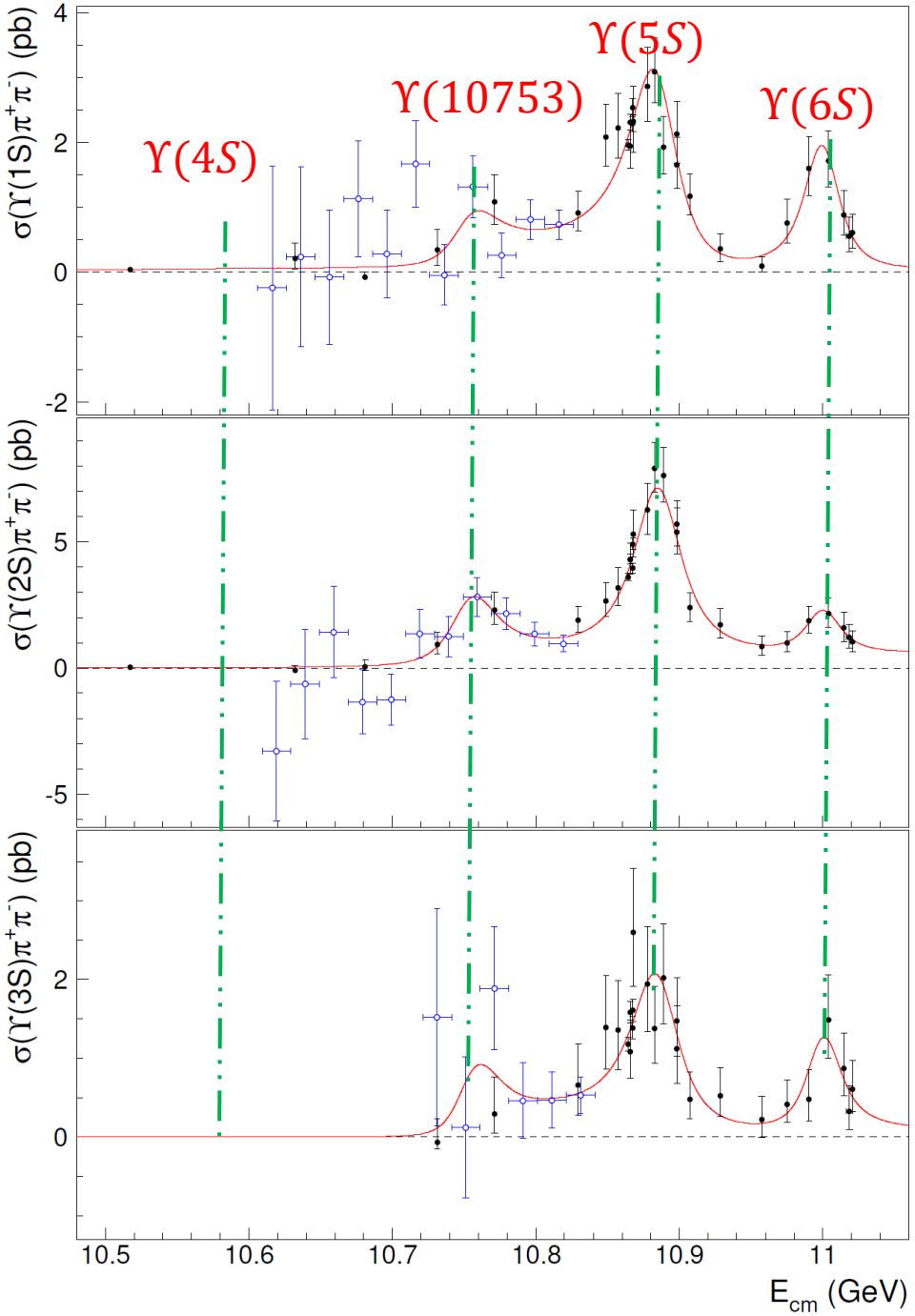
Observed by Belle JHEP 10, 220 (2019)

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

Interpretations:

- $\Upsilon(3D)$ mixed with $\Upsilon(4S)$ via hadron loops
- Hybrid
- Compact tetraquark

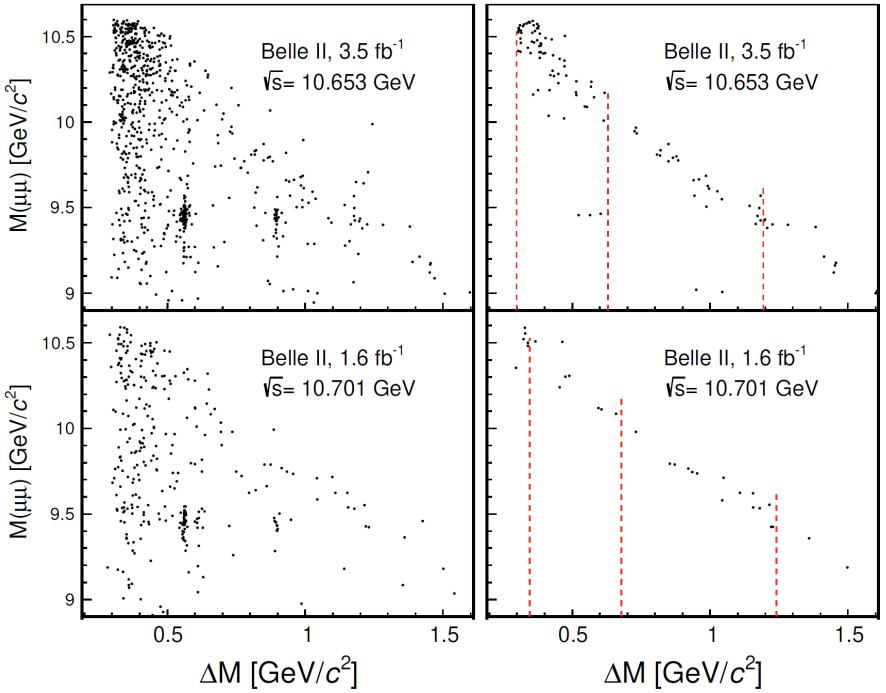
Belle: global significance: 5.2σ



Confirmation of $\Upsilon(10753)$

arxiv:2401.12021
JHEP 07 2024, 116 (2024)

- Energy scan in Nov 2021
- 4 points, 19 fb^{-1} data

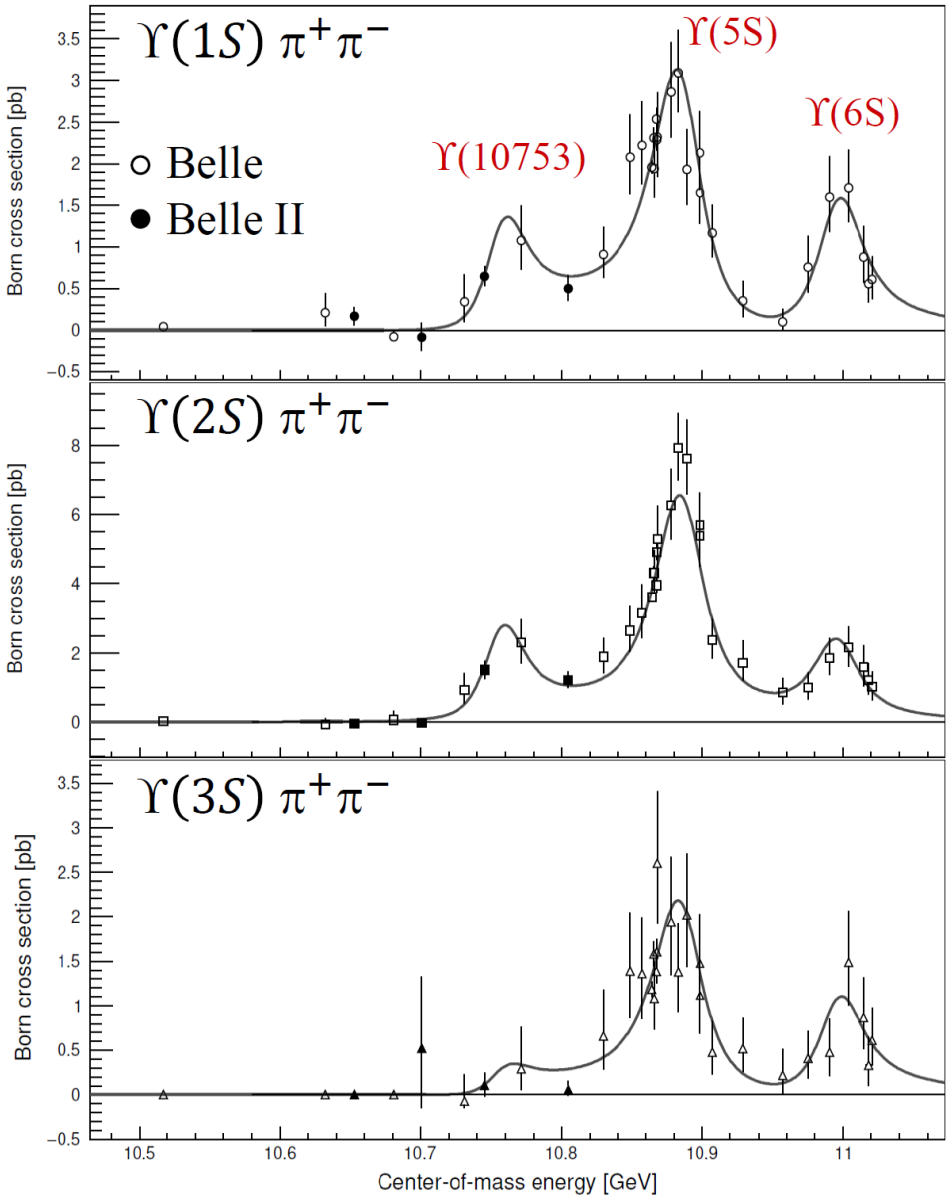


Combined fit to Belle + Belle II data

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

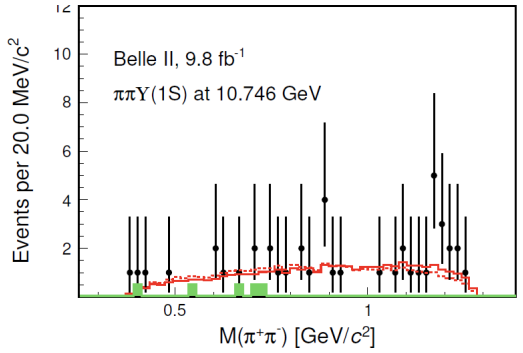
$M = (10756.6 \pm 2.7 \pm 0.9)\ MeV$

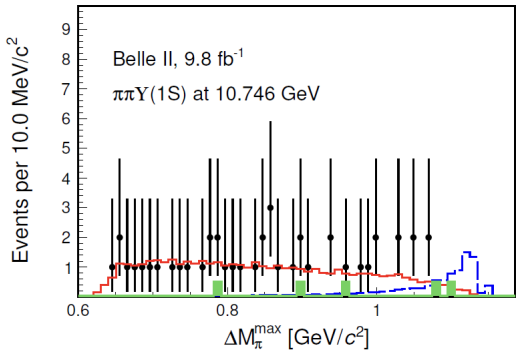
$\Gamma = (29.0 \pm 8.8 \pm 1.2)\ MeV$

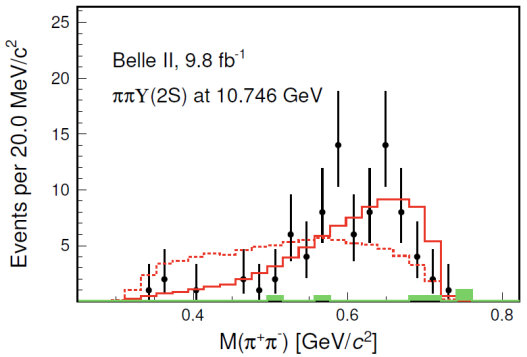


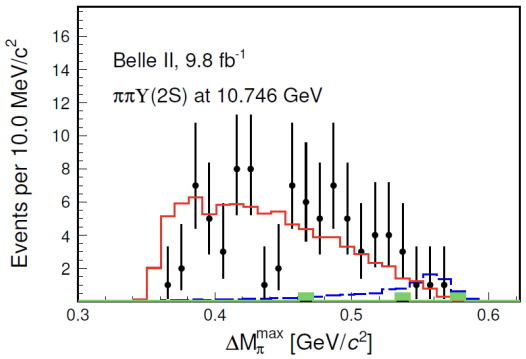
Search for resonant substructure

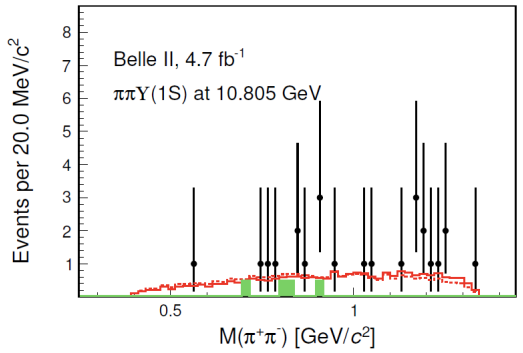
arxiv:2401.12021
JHEP 07 2024, 116 (2024)

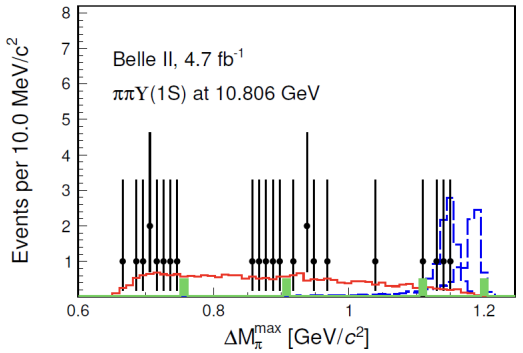


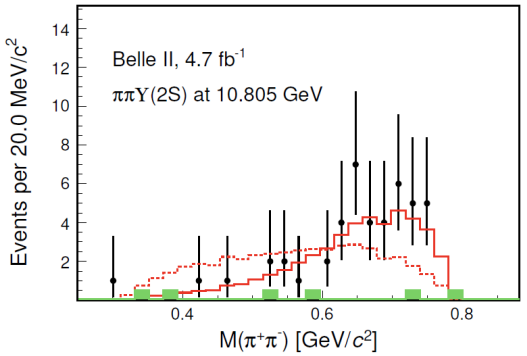


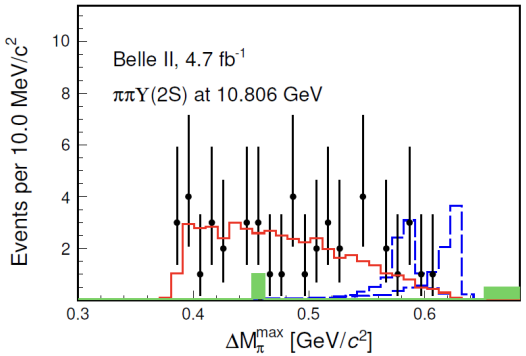




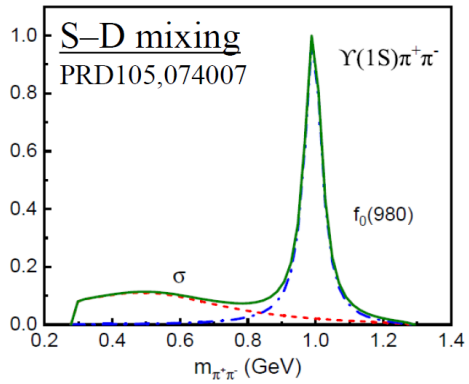


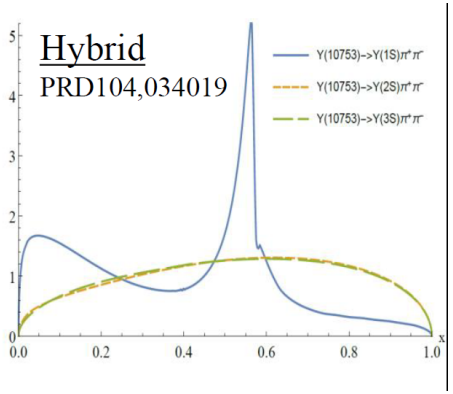


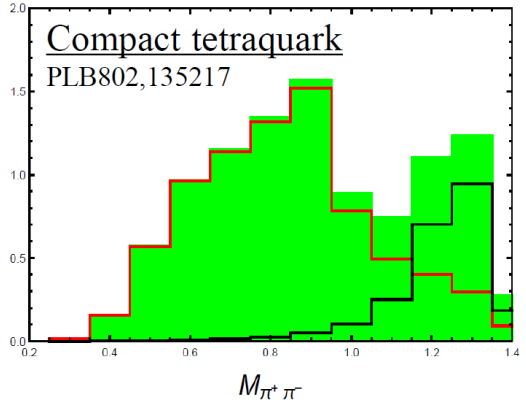




- $\pi\pi\Upsilon(1S)$ is consistent with phase space, but $\pi\pi\Upsilon(2S)$ is not.
- No significant structure in $M(\pi^+\pi^-)$ or $M(\pi^+\Upsilon)$, no Z_b signal.



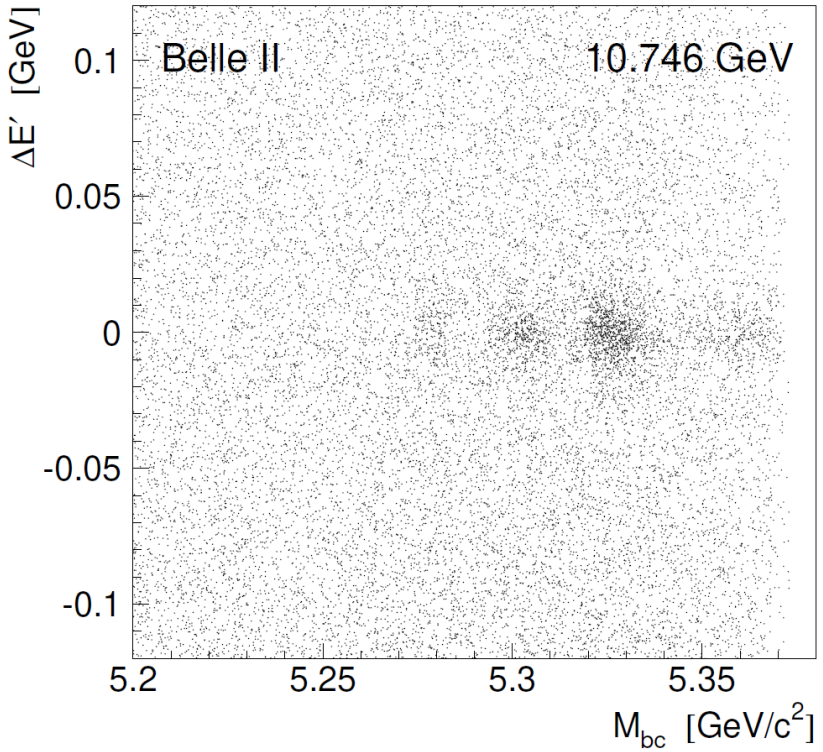




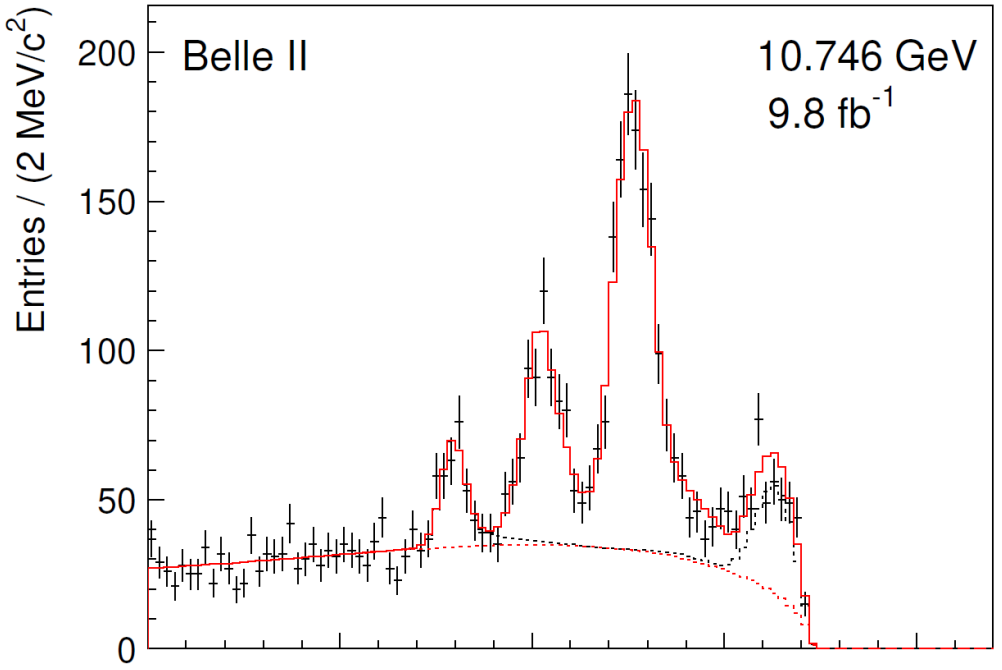
Energy dependence of $\sigma[e^+e^- \to B^{(*)}\bar{B}^{(*)}]$

arXiv:2405.18928

- Full Even Interpretation (FEI): Multivariate algorithm to reconstruct π^0, K_S^0, … then D, D^*, J/ψ, … then B/B^* meson.
- Efficiency $\epsilon = (0.580 \pm 0.003 \pm 0.012) \times 10^{-3}$ at $\Upsilon(4S)$decay.



Clear clusters of $B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ signals at 10.746 GeV.



From MC simulations: high purity, some $e^+e^- \to c\bar{c}$, small light-quark and broken $b\bar{b}$ backgrounds.

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

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 $\propto p_{B^*}^3$

$\Leftarrow B^*\bar{B}^*$ molecular state

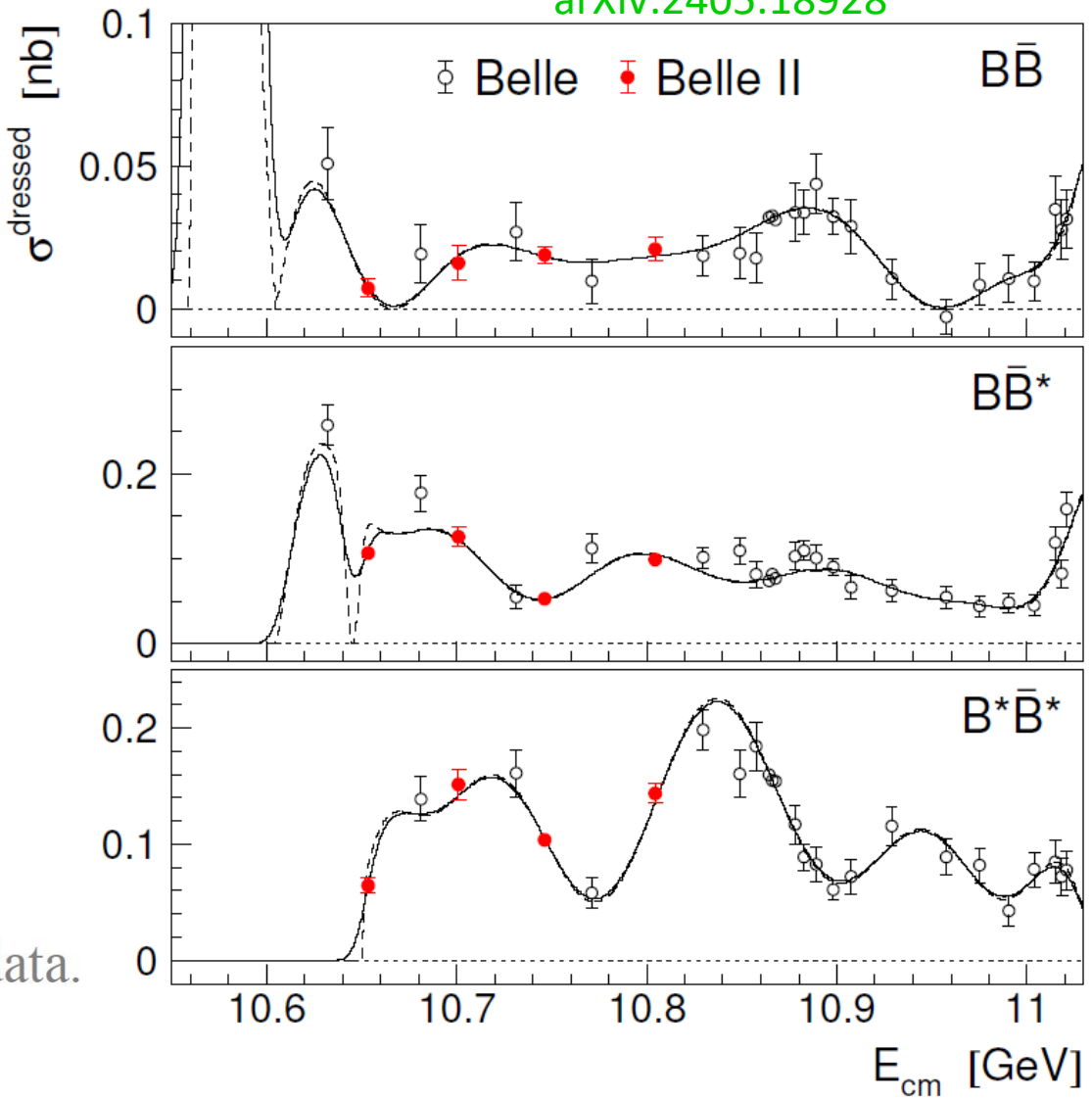
Dubynskiy, Voloshin, MPLA 21, 2779 (2006)

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

Dip in $\sigma(B\bar{B}^*)$ – destructive interference.

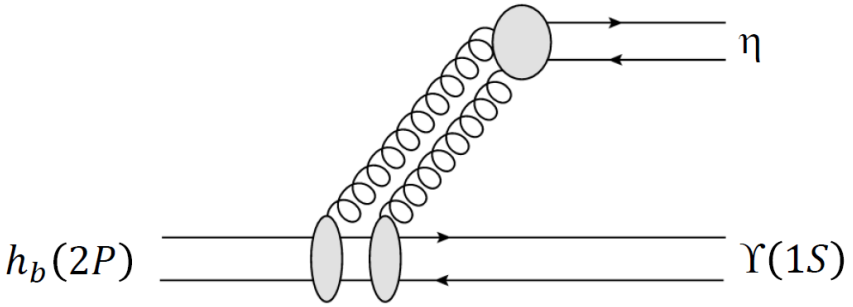
Transitions to bottomonium are expected – need more data.

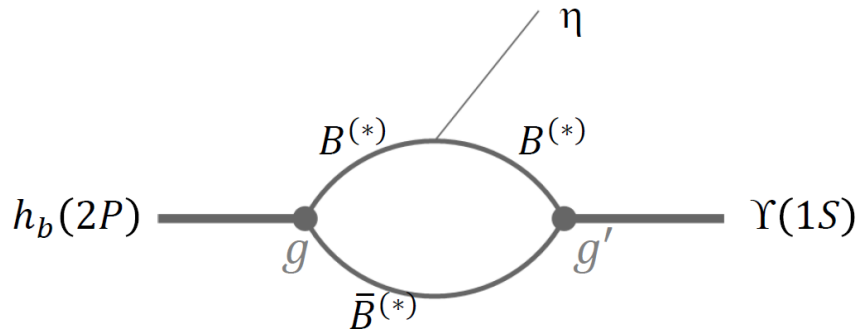
arXiv:2405.18928



Bottomonium transitions

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 $\propto 1/m_b$.





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

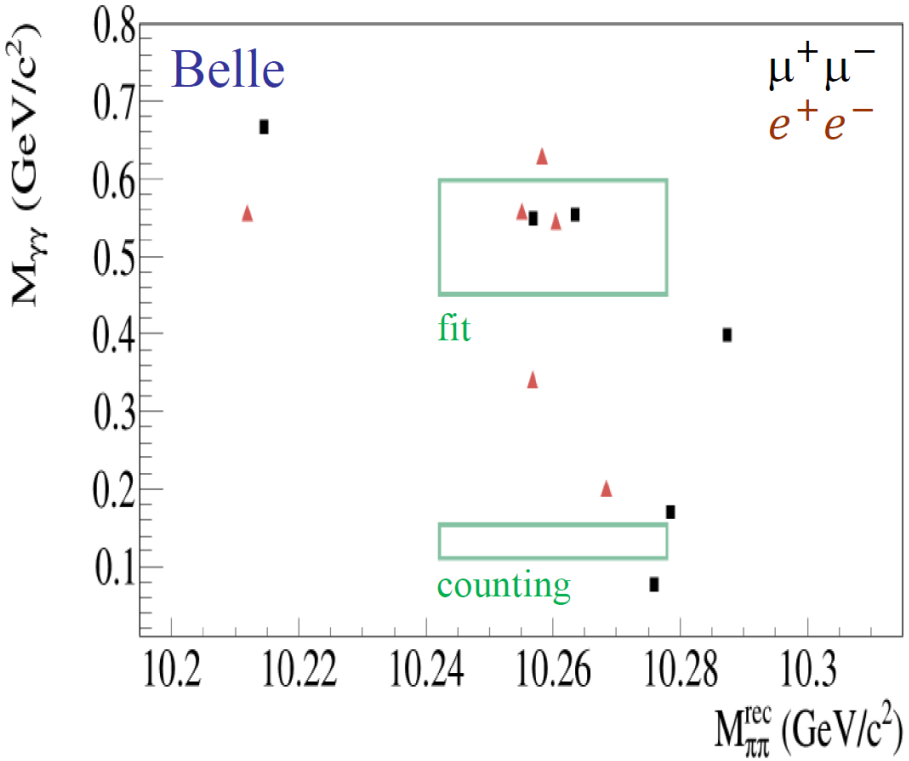
X. Li and M. Voloshin, PRD 86, 094013 (2012)

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

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

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

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

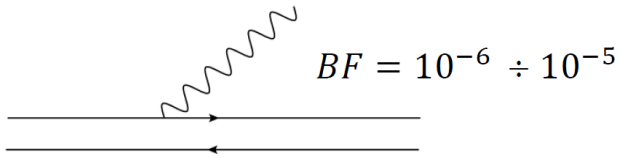
10× lower than the expectations based on experimental $BF(\Upsilon(3S) \to h_b(1P)\, \pi^0)$. Disfavors the latter evidence?

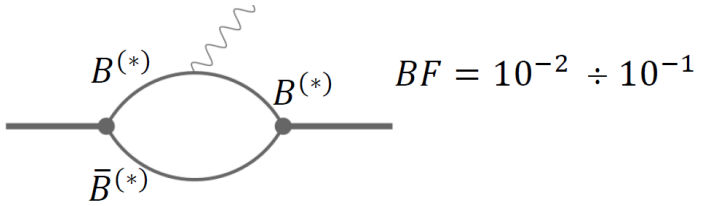
No signal of isospin violating decay $h_b(2P) \to \Upsilon(1S)\, \pi^0$

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

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

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





Full reconstruction:

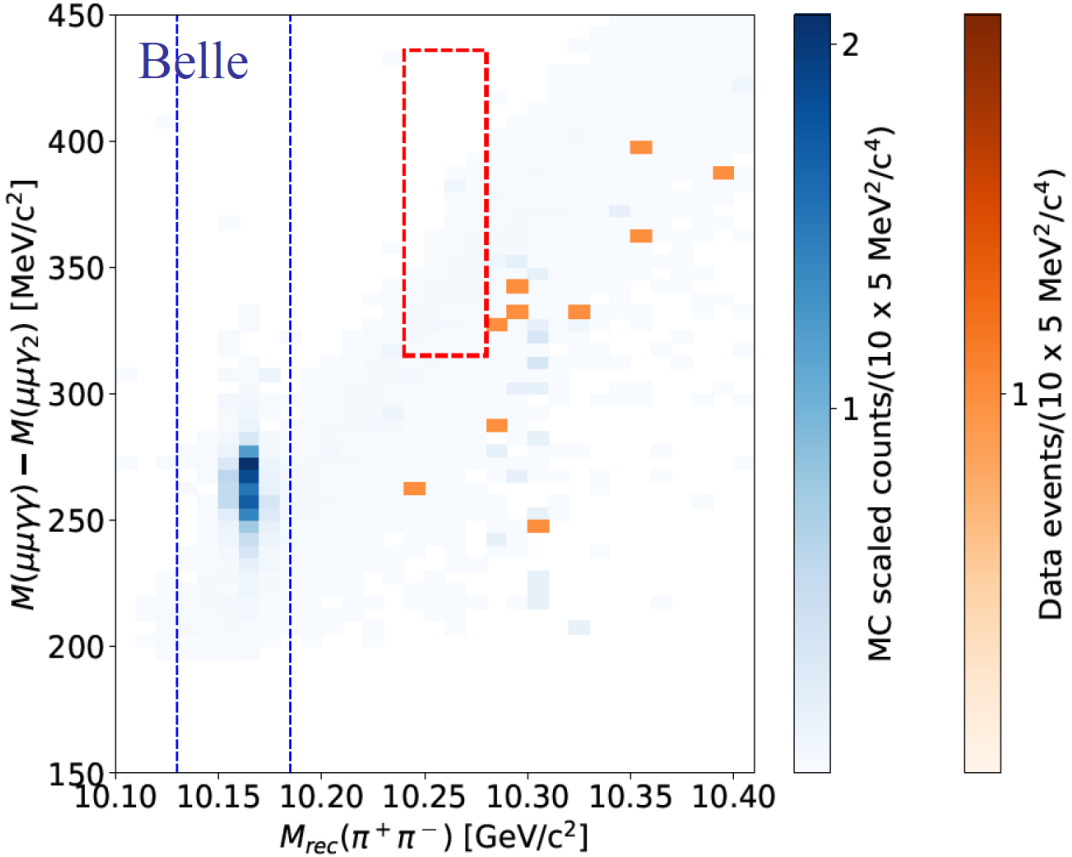
$\Upsilon(5S) \to Z_b^+ \pi^- \to h_b(2P)\, \pi^+\pi^-,$
$h_b(2P) \to \chi_{bJ}(1P)\, \gamma \to [\Upsilon(1S)\, \gamma_2]\, \gamma$
$\to [(\mu^+\mu^-)\, \gamma_2]\, \gamma$

No events in the signal region

$$\frac{\mathcal{B}}{h_b(2P) \to \gamma\chi_{b2}(1P) < 1.3 \times 10^{-2}}$$
$$h_b(2P) \to \gamma\chi_{b1}(1P) < 5.4 \times 10^{-3}$$
$$h_b(2P) \to \gamma\chi_{b0}(1P) < 2.7 \times 10^{-1}$$

ULs are consistent with expectations.

Preliminary



Summary

- Belle has a data sample of $980\ fb^{-1}$, Belle II also collected a sample of about $500\ fb^{-1}$.
- We search for pentaquark states in $\Upsilon(1S, 2S)$ inclusive decays.
  - There is no significant P_c in pJ/ψ final states.
  - First evidence of $P_{cs}(4459)$ in $\Lambda J/\psi$ final states in these decays.
- $\Upsilon(10753)$ is confirmed with new Belle II scan data on 4 energy points.
- Energy dependence of $\sigma[e^+e^- \to B^{(*)}\bar{B}^{(*)}]$ has been improved.
- In the study of bottomonium transitions, there is evidence of $h_b(2P) \to \eta\Upsilon(1\mathrm{S})$, but no significant $h_b(2P) \to \gamma\chi_{bJ}(1P)$ signal.

Thank you!