Studies of Hadron Spectroscopy at Belle and Belle II

XXXII International Workshop on Deep Inelastic Scattering (DIS2025)

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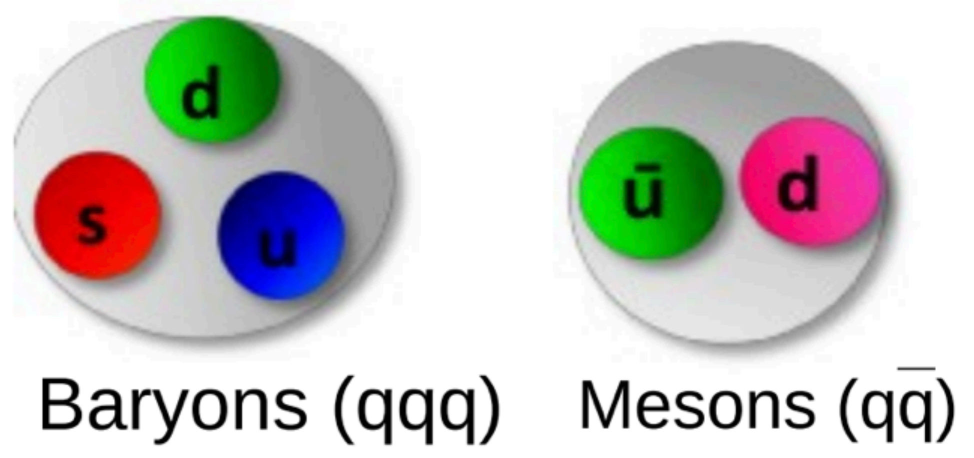
Hadron Spectroscopy

Quark model:

M. Gell-Mann, Phys.Lett. 8, 214 (1964)

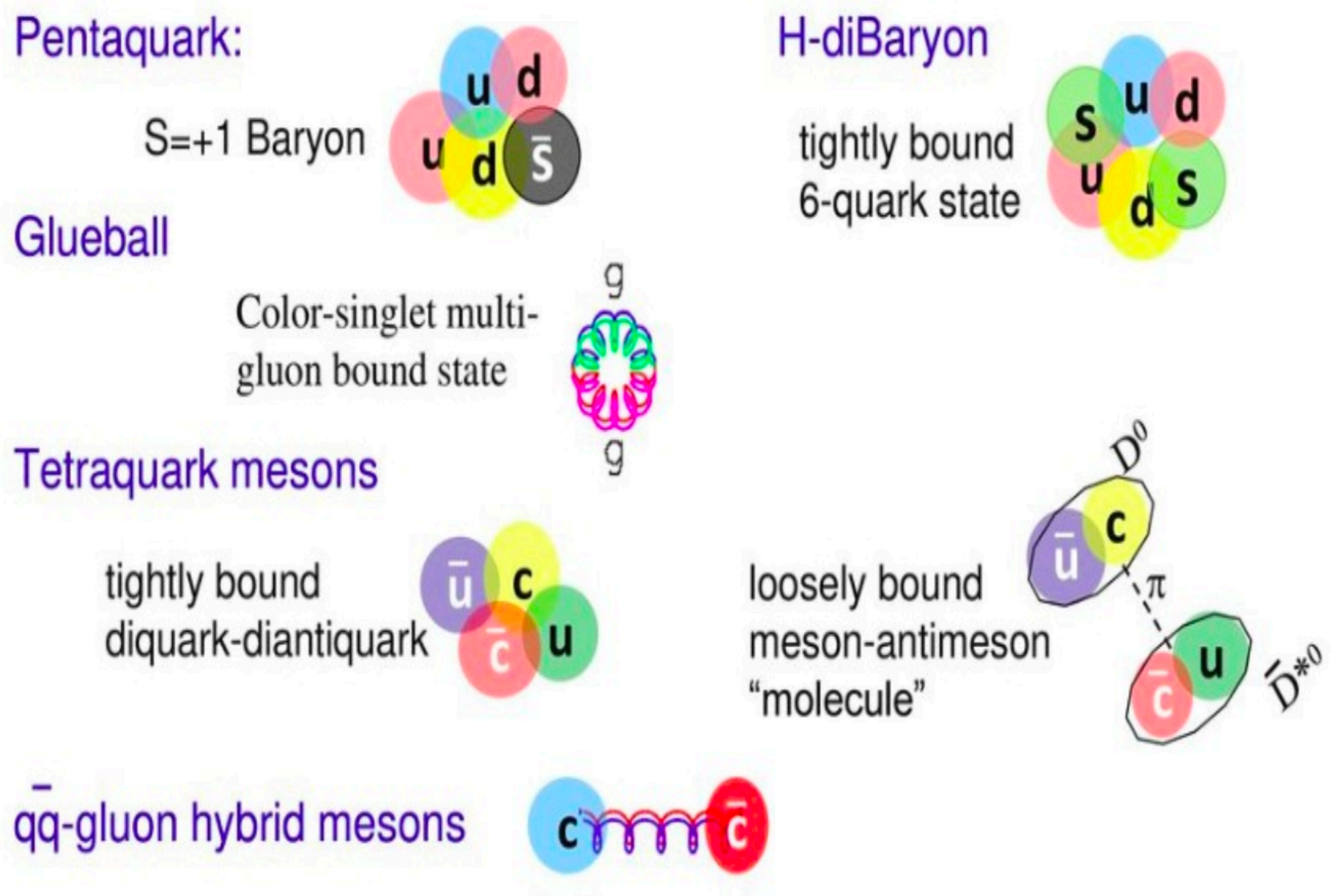
Classification scheme for hadrons in terms of valance quarks.

Hadrons are composed of mesons ($q\bar{q}$, $qq\bar{q}\bar{q}$, ...) and baryons (qqq, $qqqq\bar{q}$, ...).

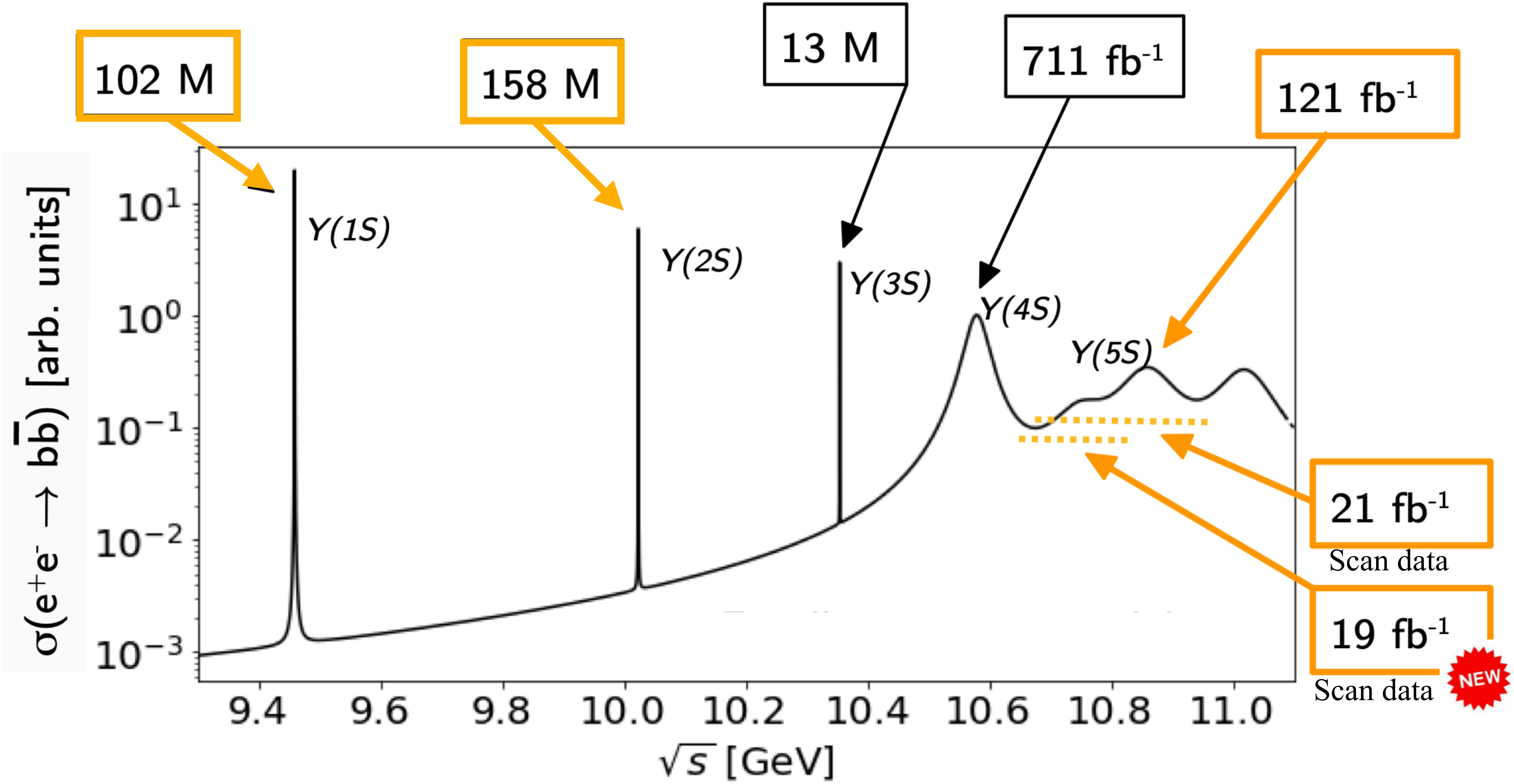


- $q\bar{q}$ spectroscopy with heavy quark (mostly c or b) are best place to study quark model.
- Simple two body system, non-relativistic and narrow (with OZI suppression).
- Further, one can search for exotics with them.

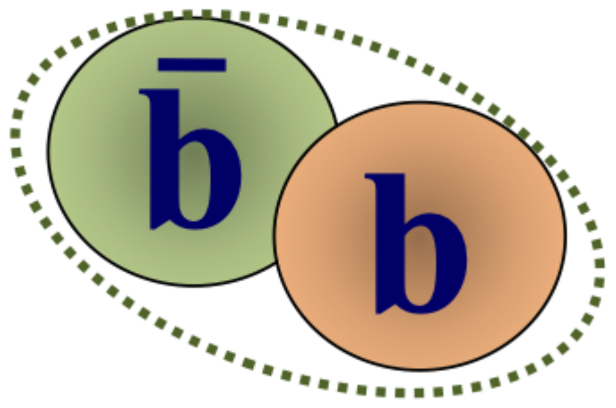
Many exotic hadron states are observed experimentally, such as the $X(3872)$, $Y(4260)$ and $\Upsilon(10753)$, but no unambiguous interpretation exists



Belle + Belle II relevant datasets

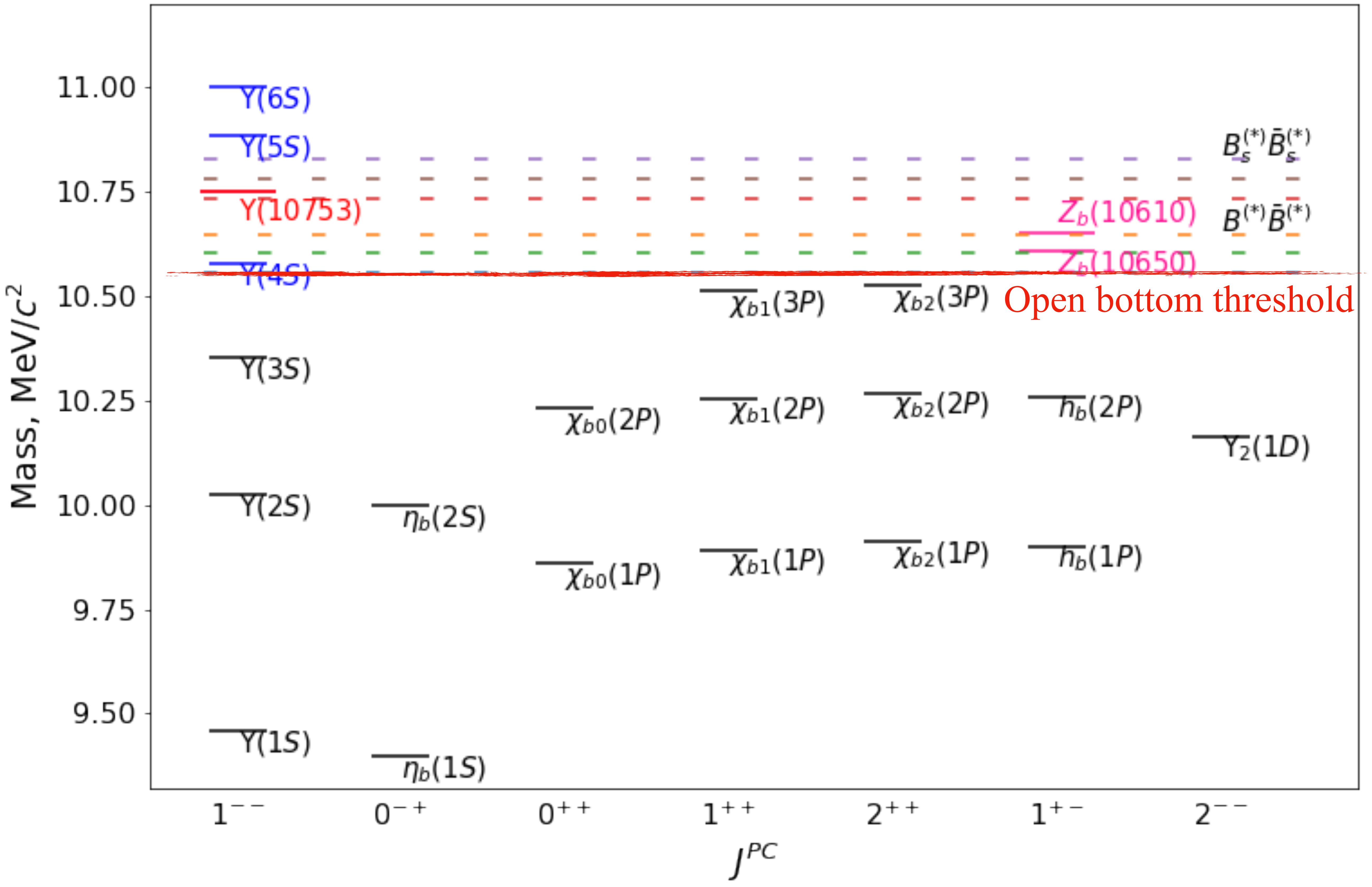


Bottomonium Spectrum



- **Below the $B\bar{B}$ threshold** states are well described by potential models.
- **Above $B\bar{B}$ threshold states** exhibit unexpected properties:
  - Hadronic transitions to lower bottomonia are strongly enhanced.
  - The η transitions are not suppressed compared to $\pi^+\pi^-$ transitions. Strong violation of Heavy Quark Spin Symmetry.
  - $Z_b^+(10610)$ **or** $Z_b^+(10650)$: observed near the $B^{(*)}\bar{B}*$ thresholds, properties are consistent with $B^{(*)}\bar{B}*$ molecules.

Exotic: molecule, compact tetra-quark.

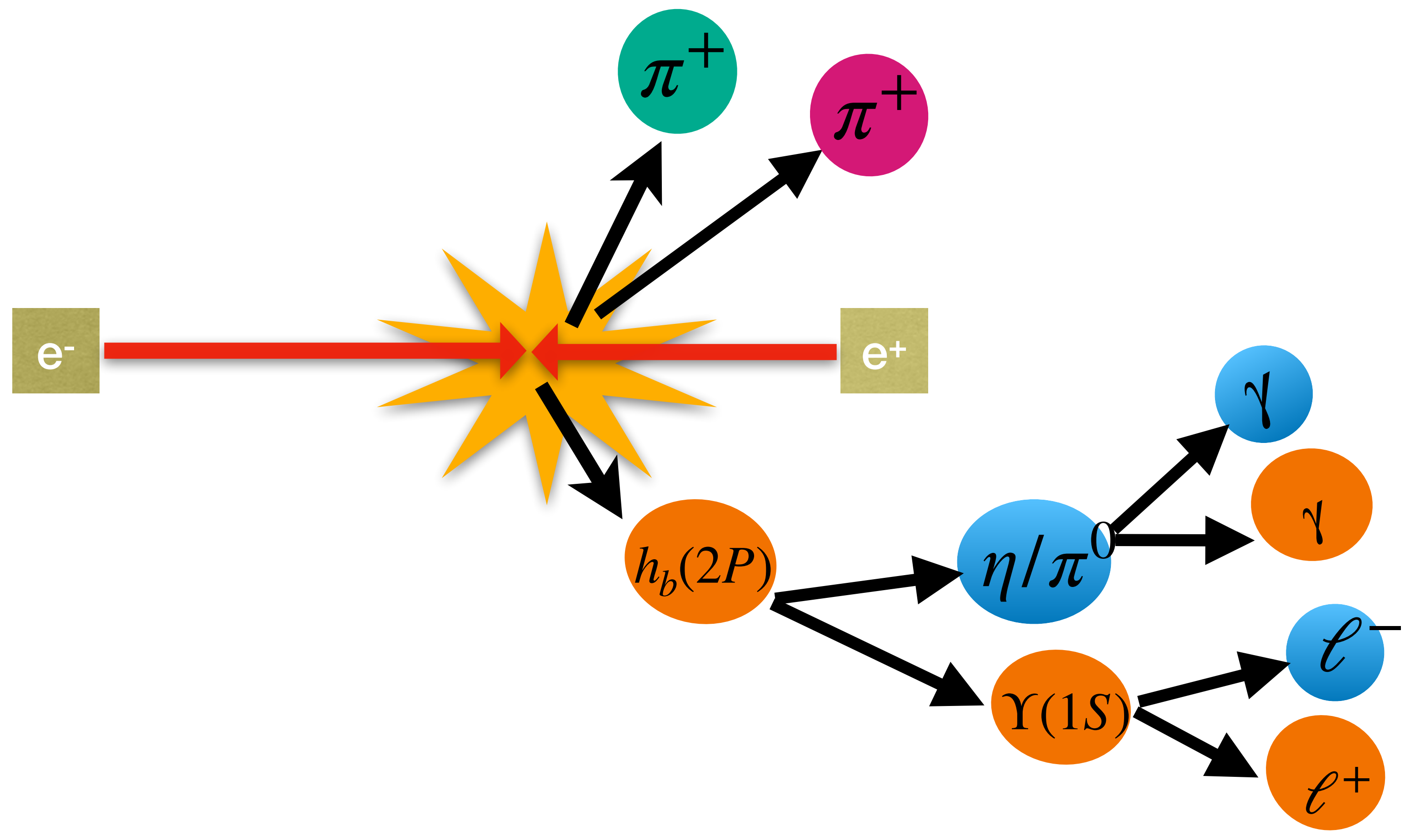


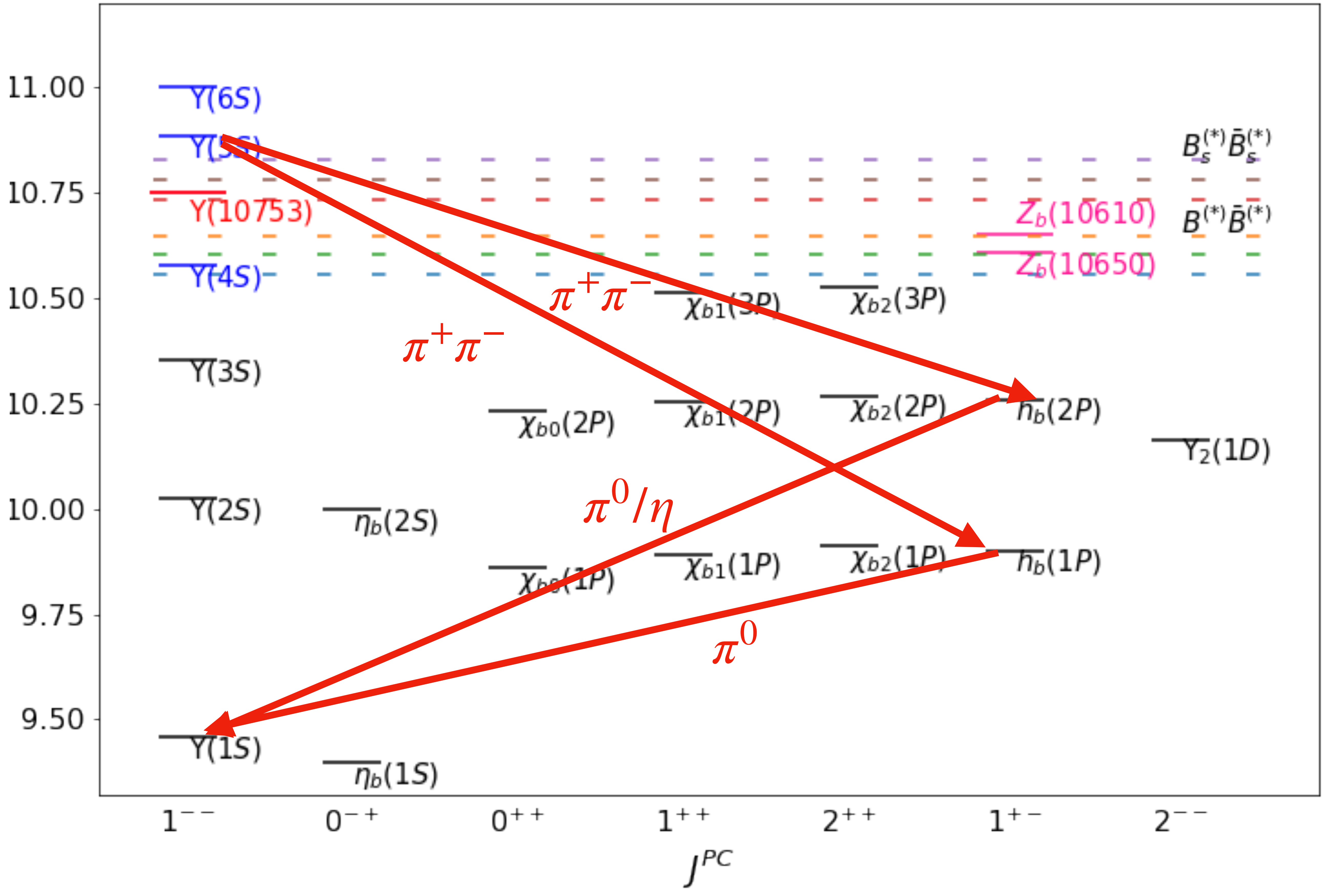
- Conventional bottomonium (pure $b\bar{b}$ state)
- Bottomonium like states (mix of $b\bar{b}$ and $B\bar{B}$)
- Purely exotic states (Z_b)

Bottomonium below $B\bar{B}$ threshold

Search for $h_b(2P) \to \Upsilon(1S)\eta$ and $h_b(1P,2P) \to \Upsilon(1S)\pi^0$ at Belle

- The properties of spin-singlet $h_b(1P,2P)$ are expected to be similar to spin-triplet partners $\chi_{b1}(1P,2P)$ state.
- **Theoretical prediction:** the ratio of the annihilation rates for the $h_b(1P)$ and $h_b(2P)$ is the same as the corresponding ratio for $\chi_{b1}(1P)$ and $\chi_{b1}(2P)$, $R_{h_b} = R_{\chi_{b1}}$. PRD 86, 094013 (2012)
- Based on current results, the $R_{h_b}/R_{\chi_{b1}} = 0.24^{+0.47}_{-0.24}$ with 1.5σ discrepancy from unity. This discrepancy will increase if the rate of $h_b(2P) \to \Upsilon(1S)\eta$ is as large as 10%

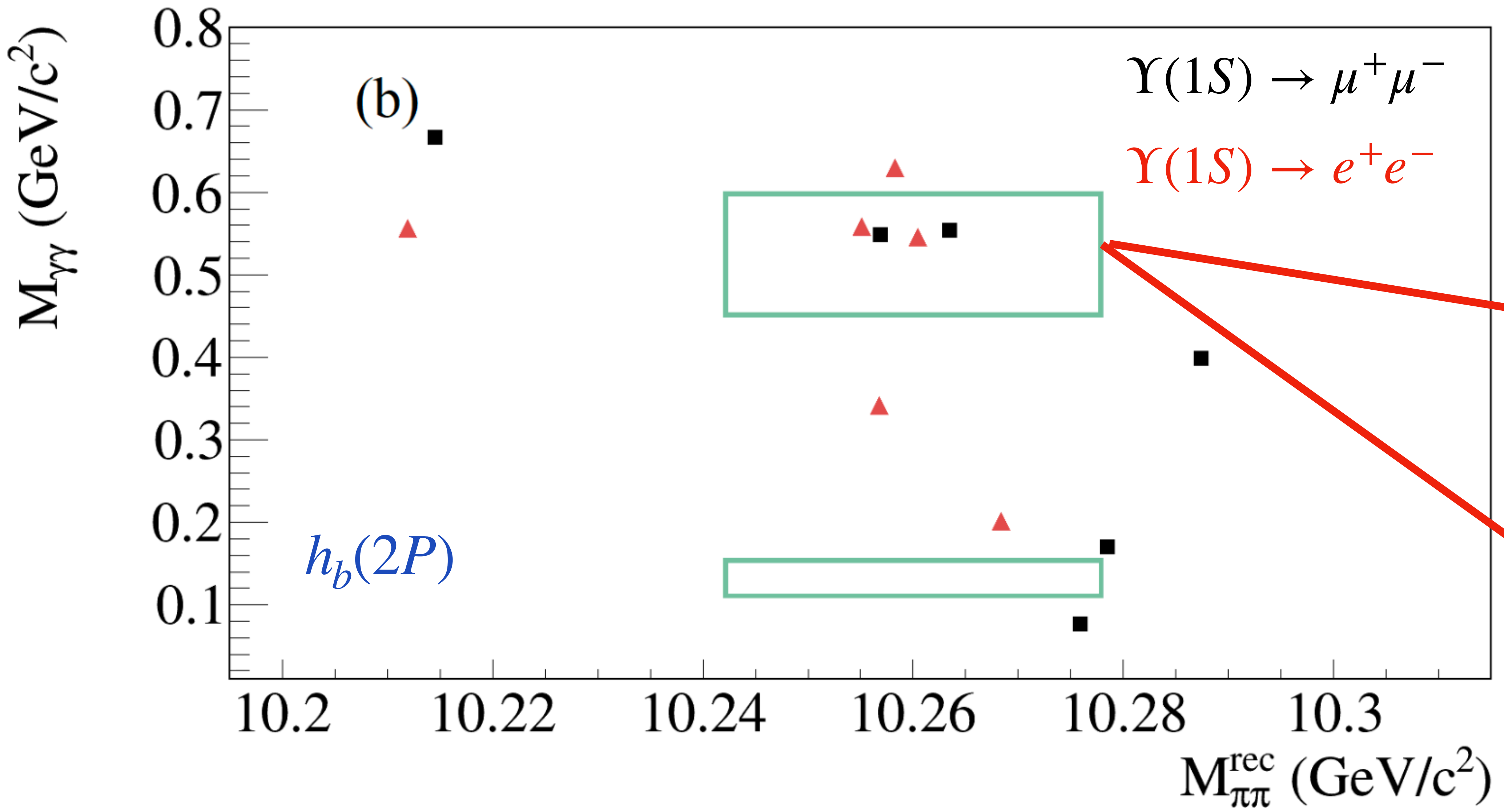


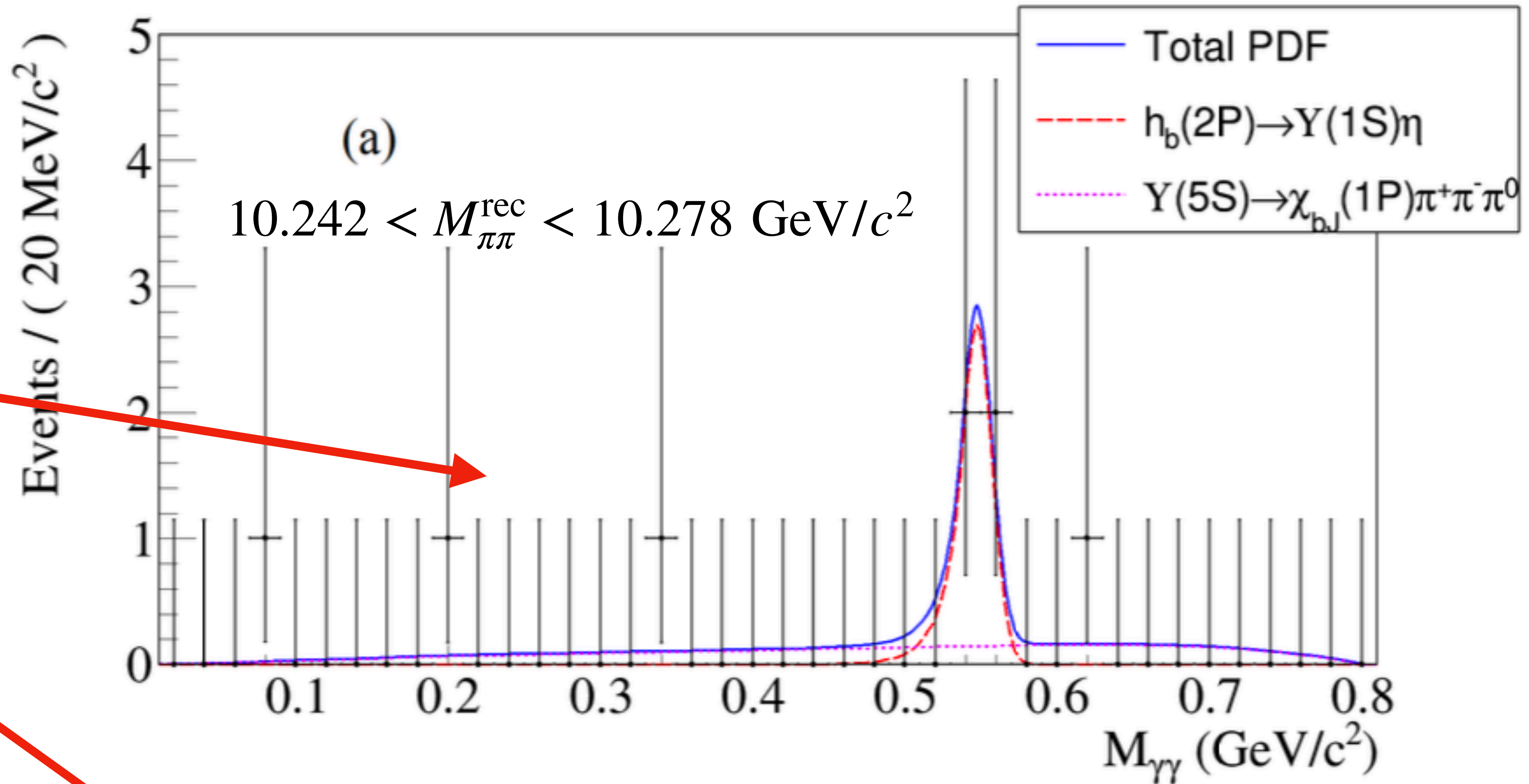


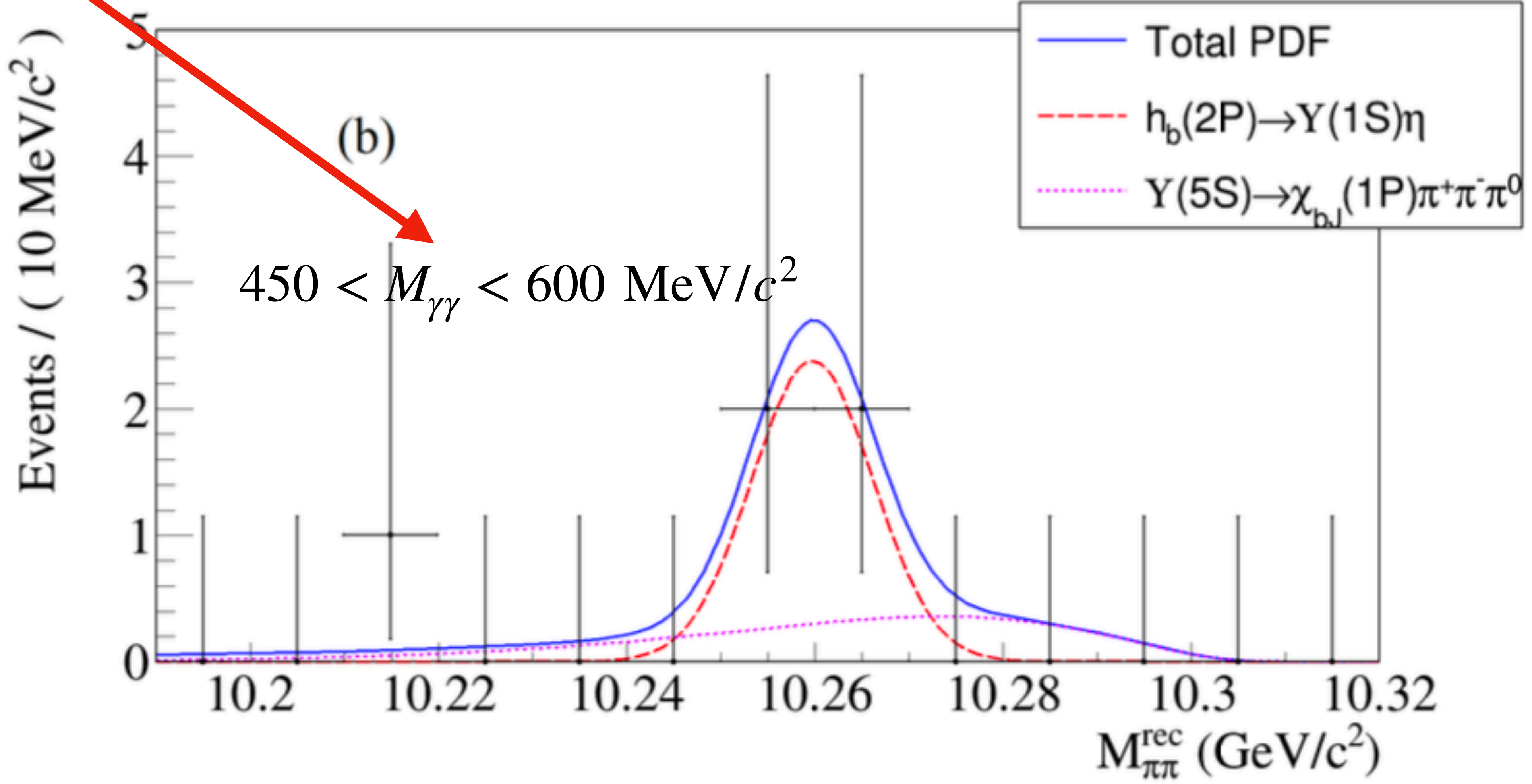
Search for $h_b(2P) \to \Upsilon(1S)\eta$ and $h_b(1P,2P) \to \Upsilon(1S)\pi^0$ at Belle

$\Upsilon(5S)$ data, 121 fb^{-1}

PRL 133, 261901 (2024)







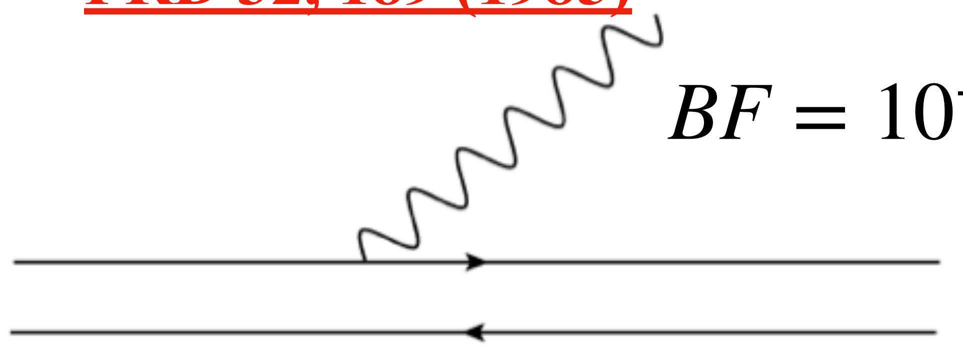
- Evidence for $h_b(2P) \to \Upsilon(1S)\eta$ with 3.5σ significance.
  - $\mathscr{B}(h_b \to \Upsilon(1S)\eta) = (7.1^{+3.7}_{-3.2} \pm 0.8) \times 10^{-3}$
- No significant $h_b(1P,\ 2P) \to \Upsilon(1S)\pi^0$ signal is observed.
  - Upper limits at the 90% C.L. are set.
  - $\mathscr{B}(h_b(1P,2P) \to \Upsilon(1S)\pi^0) < 1.8 \times 10^{-3}$ at 90% C.L

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

PRD 111, L011102 (2025)

Expectation

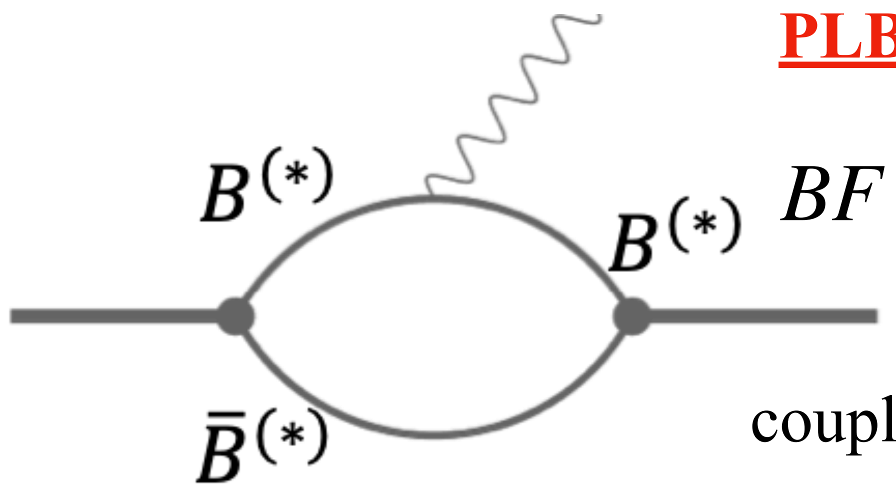
PRD 32, 189 (1985)



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

Relativized quark model

PLB 760, 417 (2016)



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

coupled channel effect

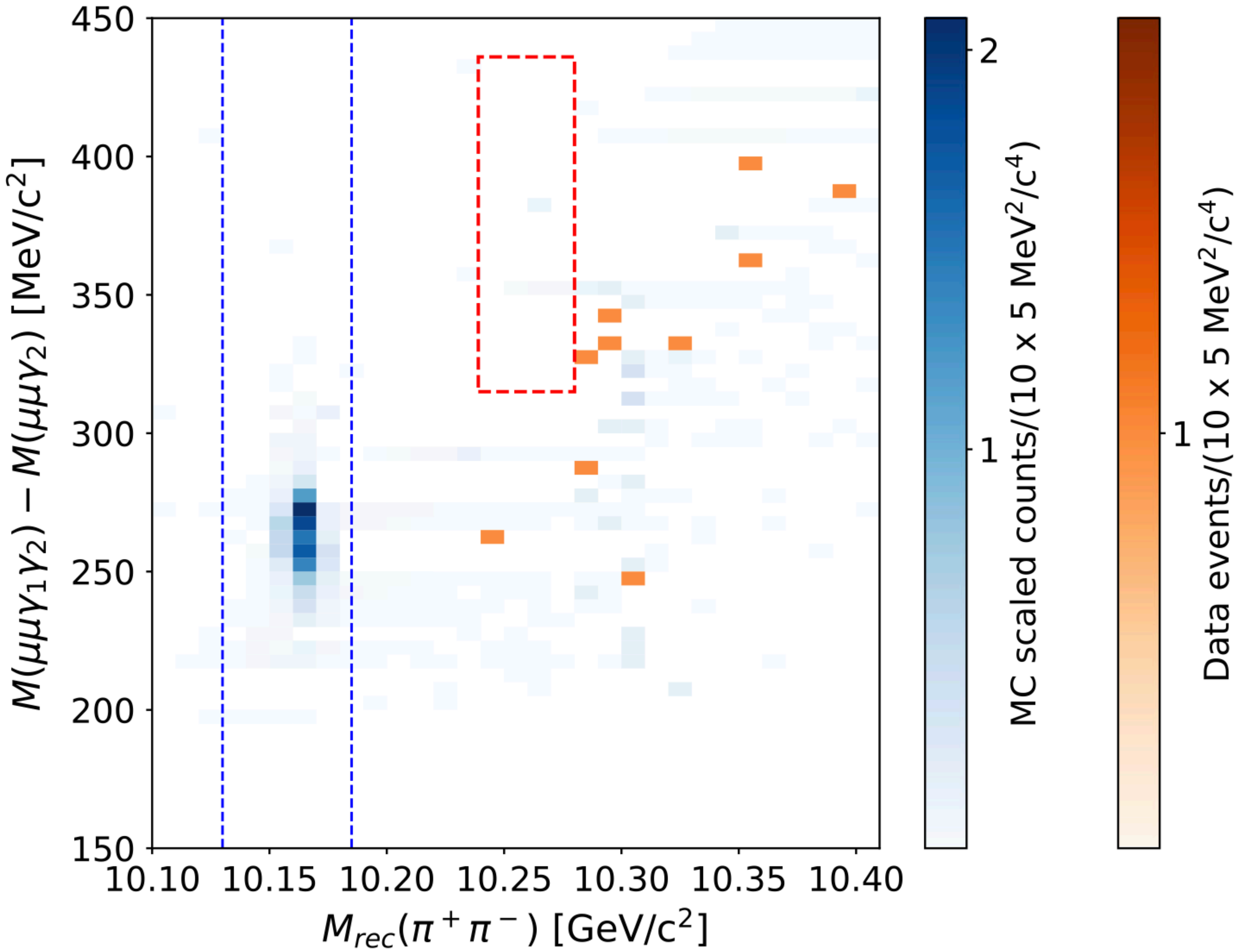
Full reconstruction:

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

- No significant $h_b(2P) \to \gamma\chi_{bJ}(1P)$ signal is observed.
- Upper limits at the 90% C.L. are set.

TABLE IV. Observed upper limits at 90% CL for the branching fractions of the investigated transitions.

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



ULs are consistent with expectations

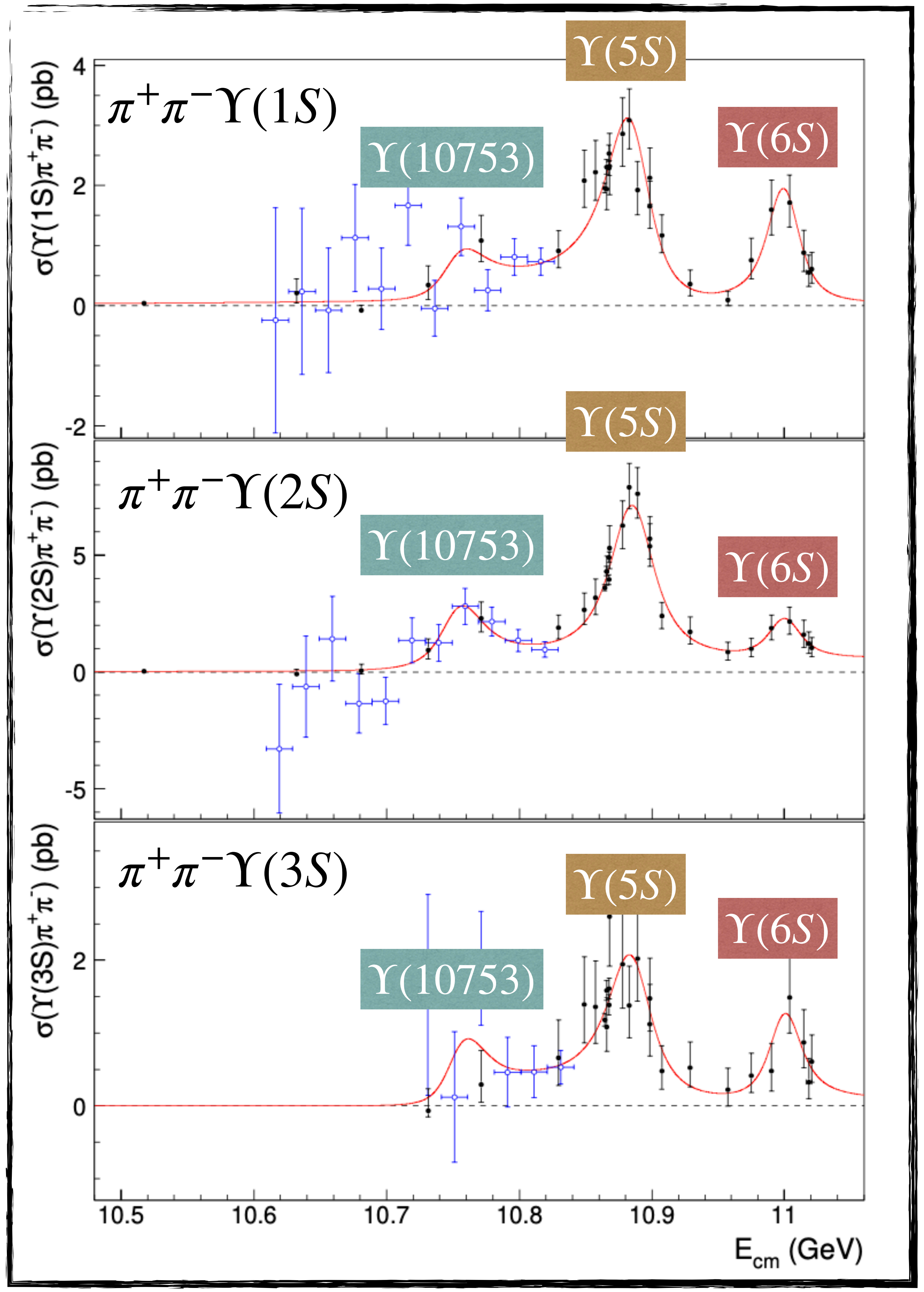
Bottomonium-like states above $B\bar{B}$ threshold

Discovery of $\Upsilon(10753)$

- $\Upsilon(10753)$ was observed in energy dependence of $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ $(n = 1,2,3)$ cross sections by Belle.
- The global significance is 5.2σ

JHEP 10 (2019) 220

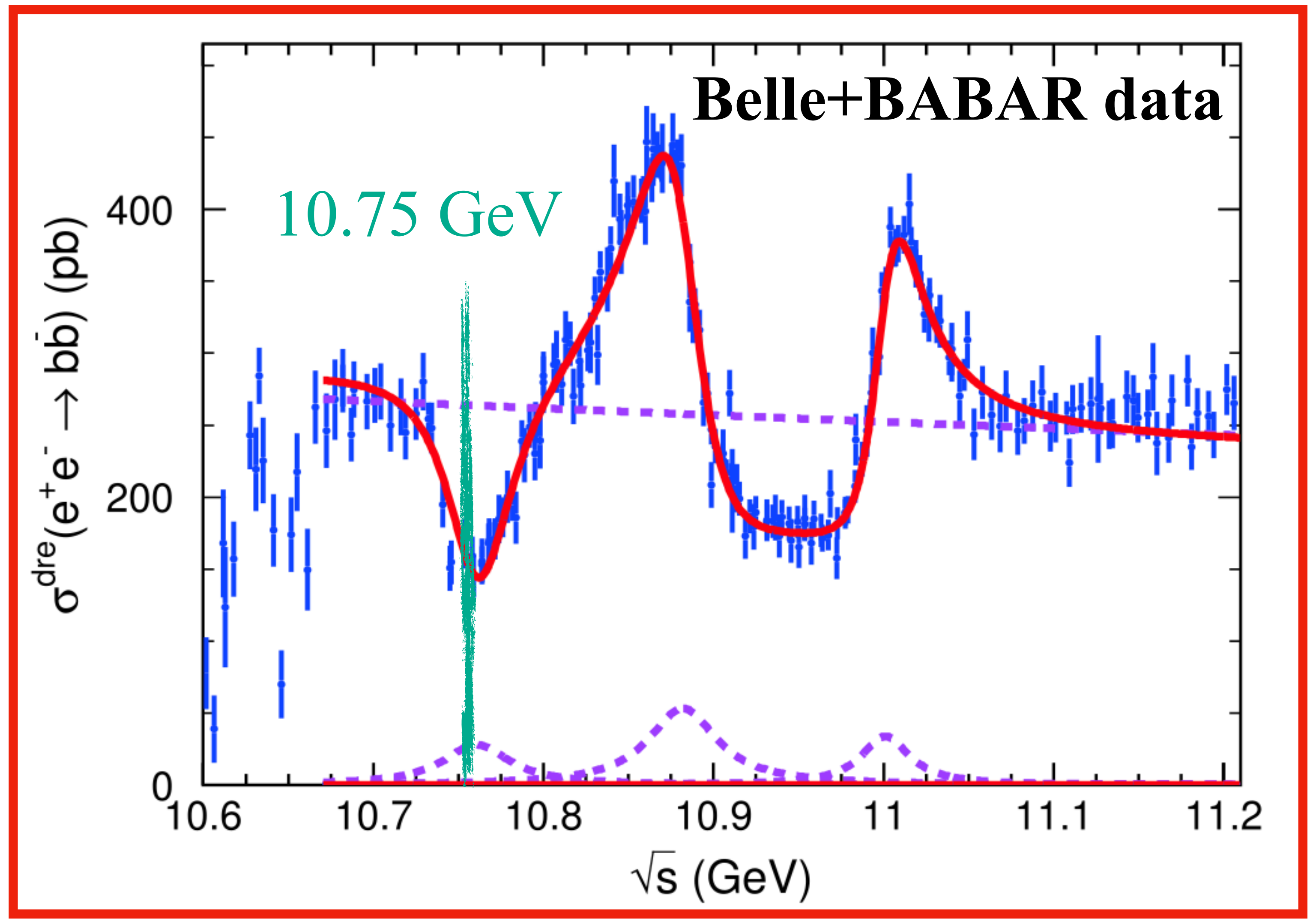
	$\Upsilon(5S)$	$\Upsilon(6S)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5{}^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}{}^{+1.0}_{-1.3}$	$10752.7 \pm 5.9{}^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}{}^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}{}^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}{}^{+3.9}_{-3.3}$



Fit function: 3 BW+smooth component

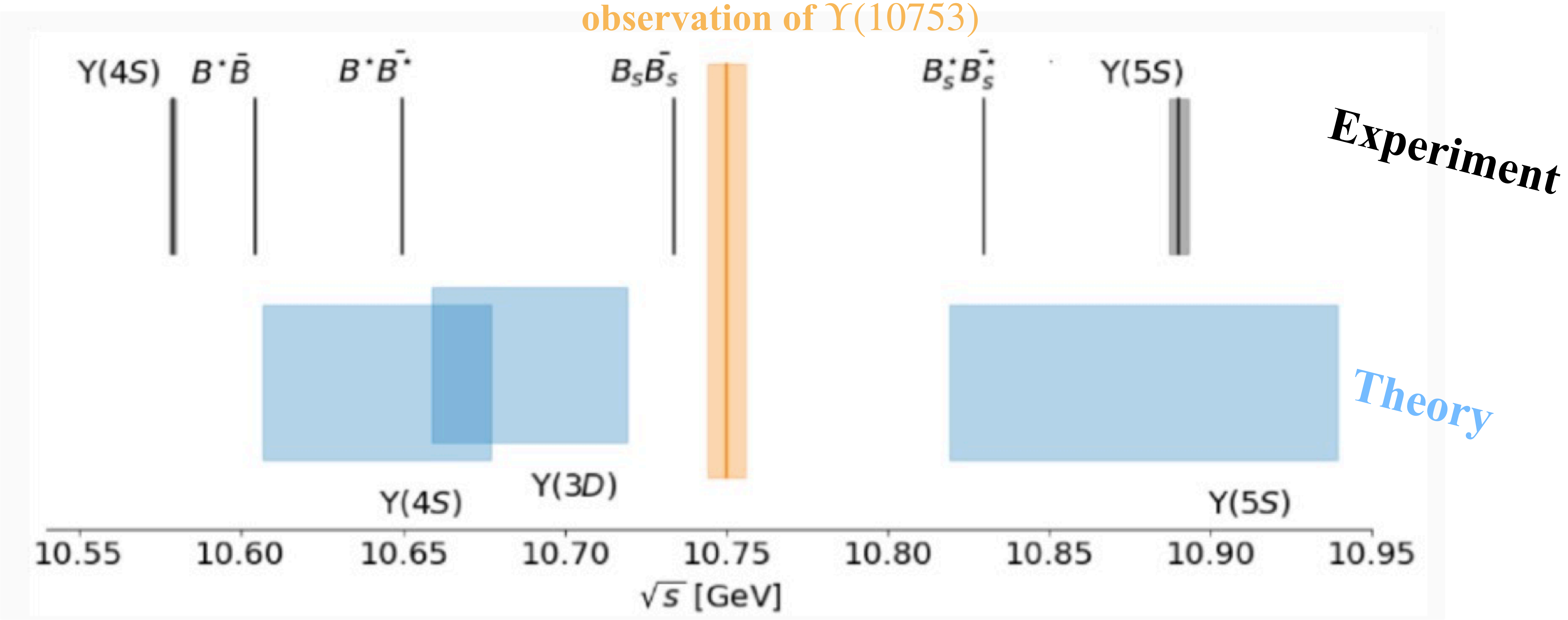
- $e^+e^- \to b\bar{b}$ cross section in bottomonium energy region based on the Belle and BABAR measurement.
  - A dip near 10.75 GeV likely caused by interference between BW and smooth component.

CPC 44, 8, 083001 (2020)



$\Upsilon(10753)$: theoretical interpretation

Experimental observation of $\Upsilon(10753)$



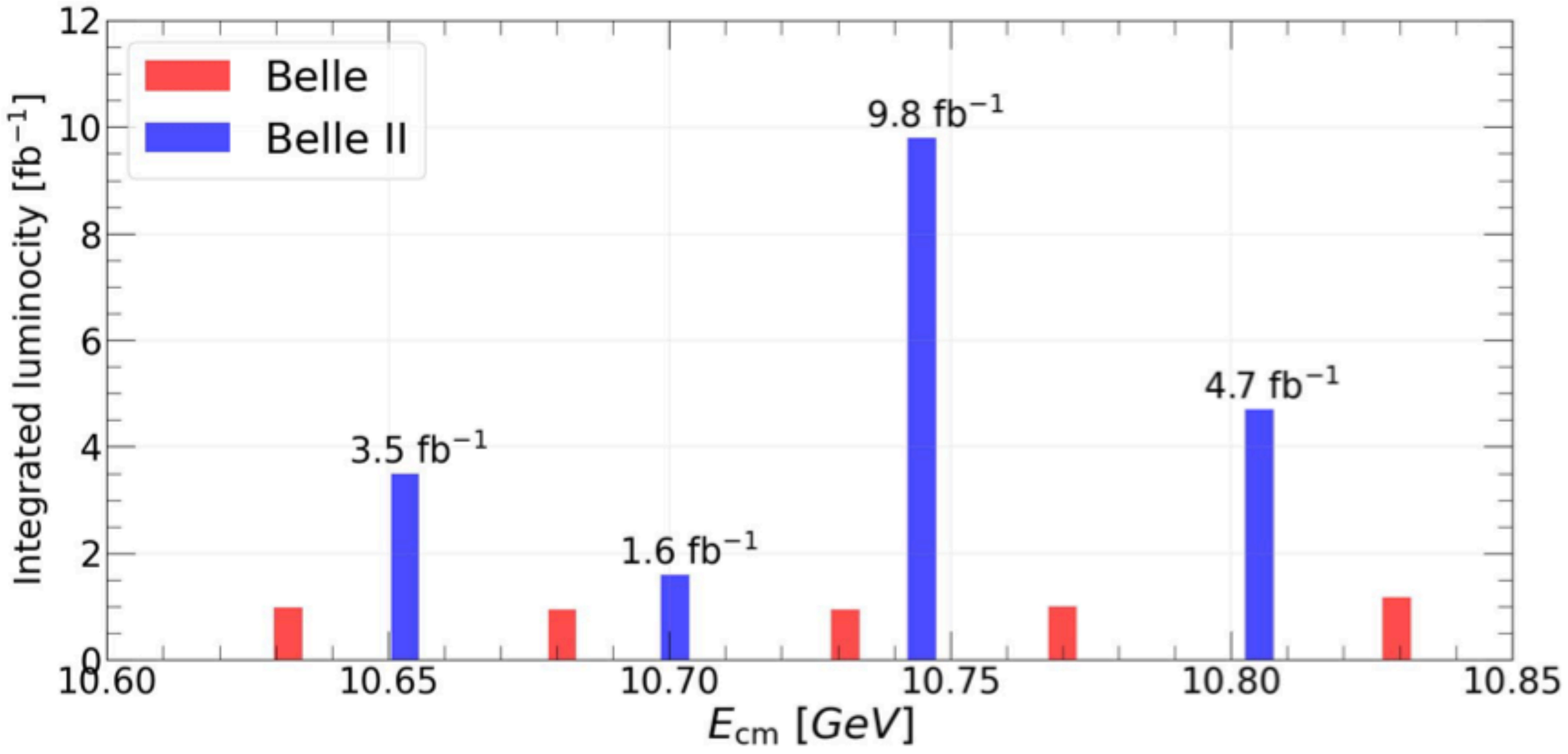
Possible interpretations:

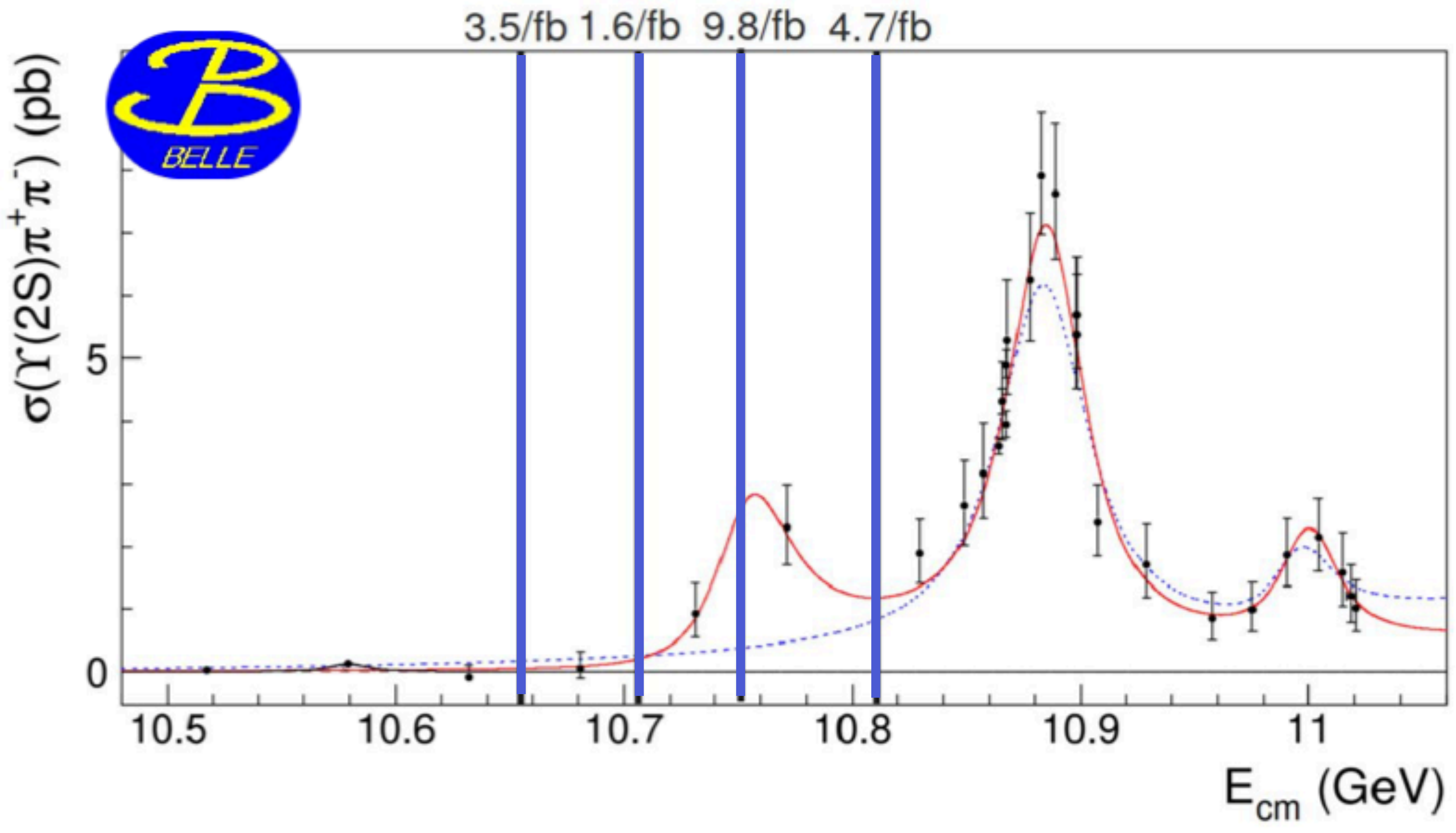
- Conventional bottomonium?
  - Phys. Rev. D 105, 114041 (2022)
  - Phys. Rev. D 106, 094013 (2022)
  - Phys. Rev. D 105, 074007 (2022)
- Hybrid state?
  - Phys. Rept. 873, 1 (2020)
  - Phys. Rev. D 104, 034019 (2021)
- Tetraquark state?
  - Phys. Rev. D 103, 074507 (2021)
  - Phys. Rev. D 107, 094515 (2023)
- Hadronic molecule with a small admixture of a bottomonium?

- Mass does not match $\Upsilon(3D)$ theoretical predictions.
- $\Upsilon(4S) - \Upsilon(3D)$ mixing can be enhanced due to hadronic loops.

Unique data with energy scan near $\sqrt{s} = 10.75$ GeV

- Belle II / SuperKEKB performed an energy scan in November 2021 with a total luminosity of 19 fb^{-1}.
- **Physics Goals:**
  - Confirm and study the $\Upsilon(10753)$.
  - Improve the precision of exclusive cross-section below the $\Upsilon(5S)$.

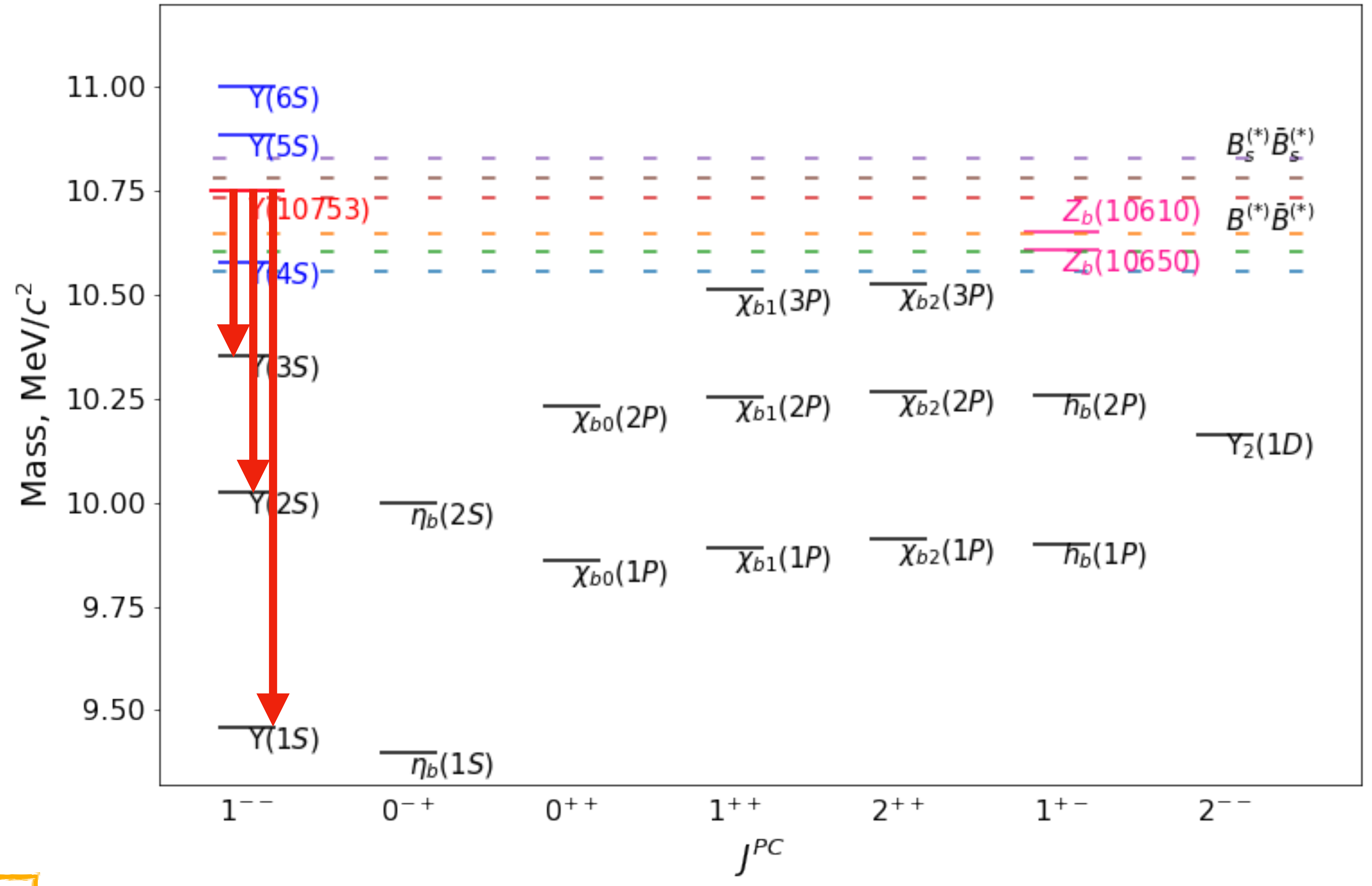




- Belle II collected data in the gaps between the Belle points.
- The point with the highest statistics (9.8 fb^{-1}) is near the $\Upsilon(10753)$ peak.

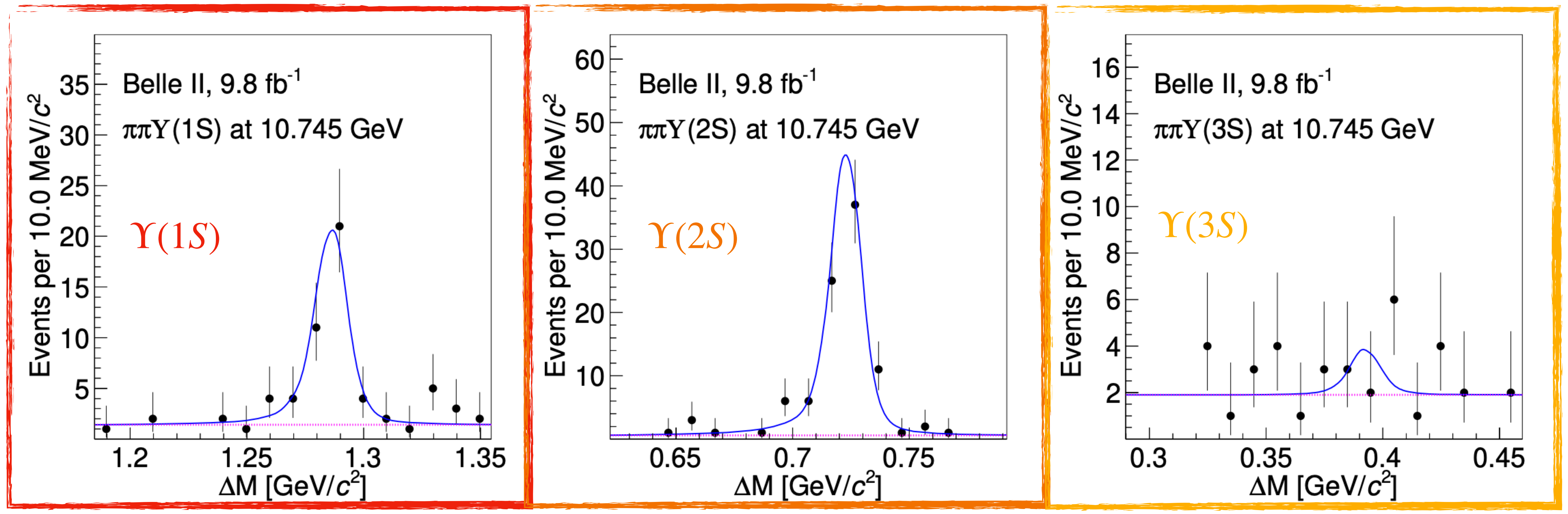
Search for $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$ at Belle II

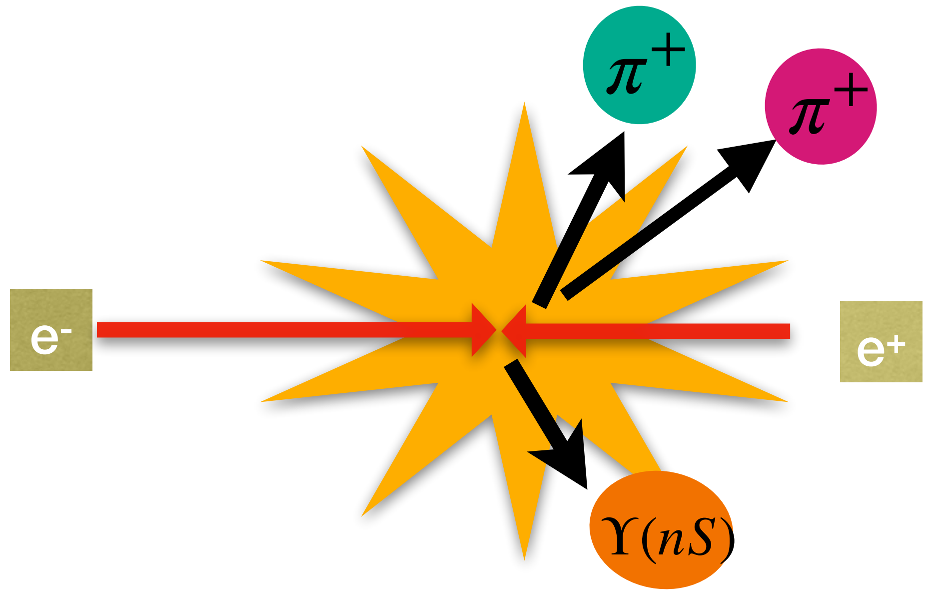
- Discovery mode of the $\Upsilon(10753)$ (Next few slides will cover):
  - Confirm its existence
  - Measure the di-pion spectrum
  - Look for $Z_b^+(10610)$ **or** $Z_b^+(10650)$ intermediate contributions



Confirm $\Upsilon(10753)$ existence

- Clear signal for $\Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(2S)\pi^+\pi^-$ decay mode.
- No evidence of $\Upsilon(3S)\pi^+\pi^-$





Search for $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$ at Belle II

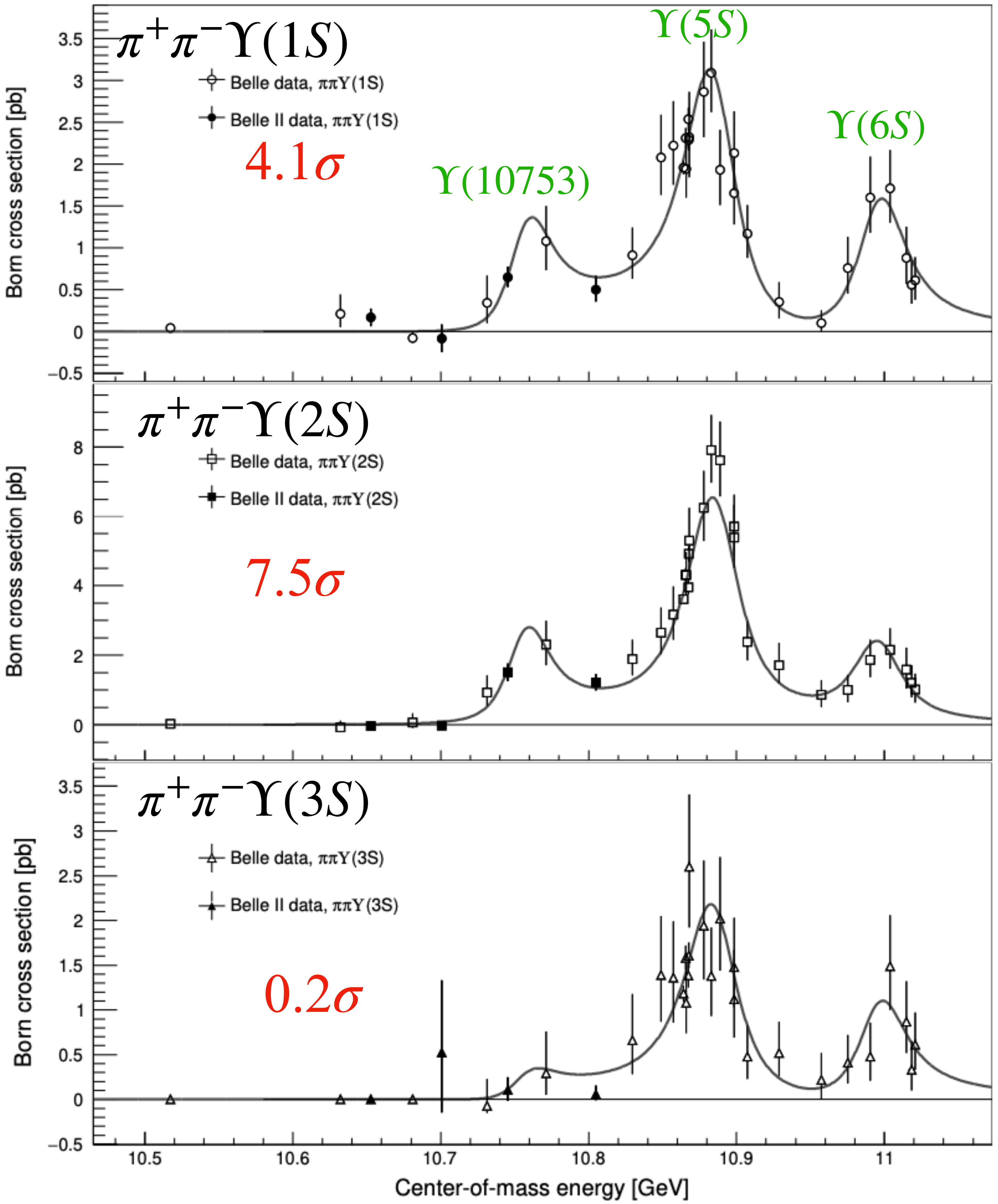
JHEP 07 2024, 116

Confirm $\Upsilon(10753)$ existence

- New measurement confirms previous Belle result: cross section is peaking near 10.75 GeV.

	Belle + Belle II (MeV)	Belle (MeV)
$M_{\Upsilon(10753)}$	$10756.6 \pm 2.7 \pm 0.9$	$10752.7 \pm 5.9^{+0.7}_{-1.1}$
$\Gamma_{\Upsilon(10753)}$	$29.0 \pm 8.8 \pm 1.2$	$35.5^{+17.6+3.9}_{-11.3-3.3}$

- Results are consistent with the Belle results.
- Uncertainties are improved by a factor of two from previous Belle results.



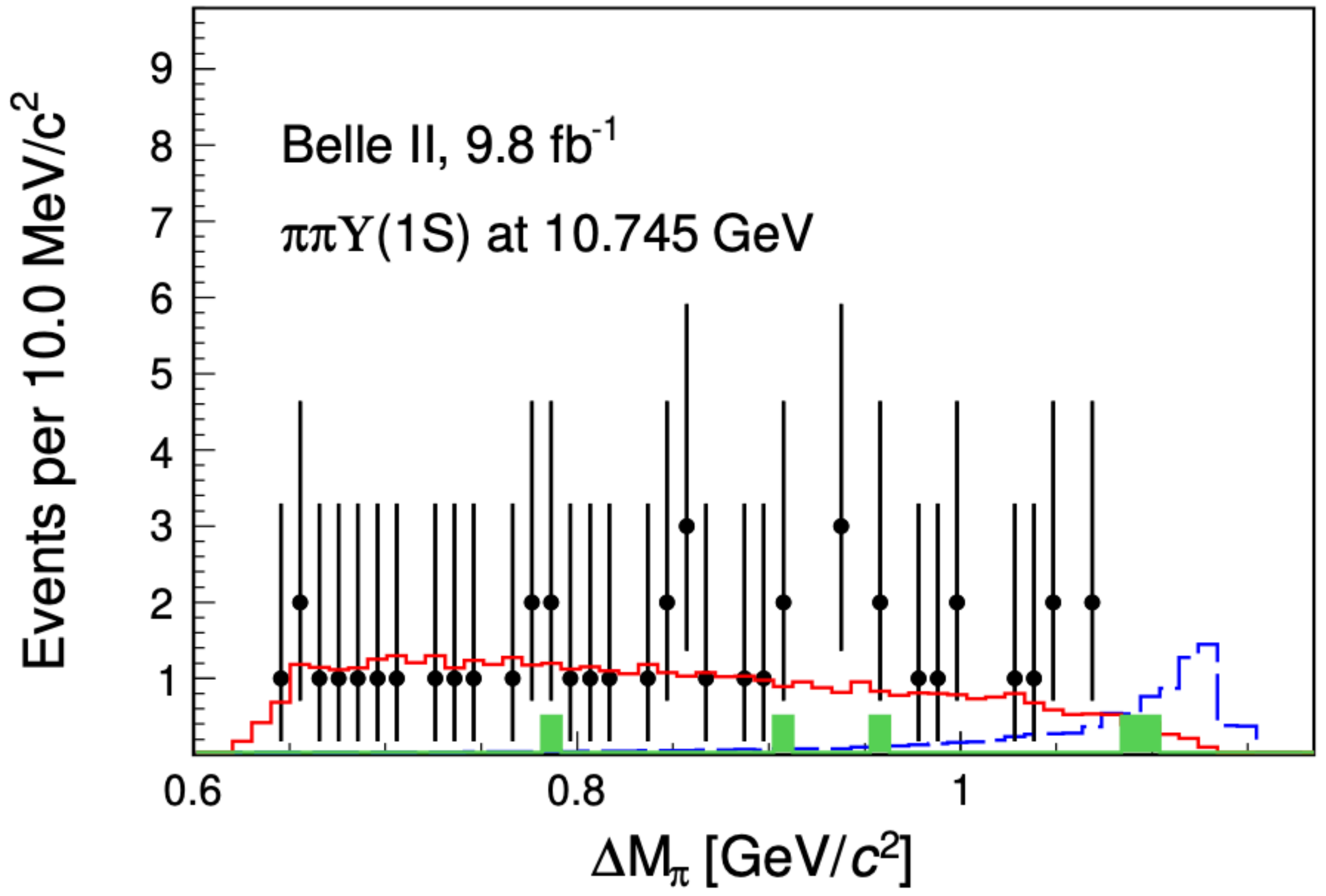
Resonant structure in $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$

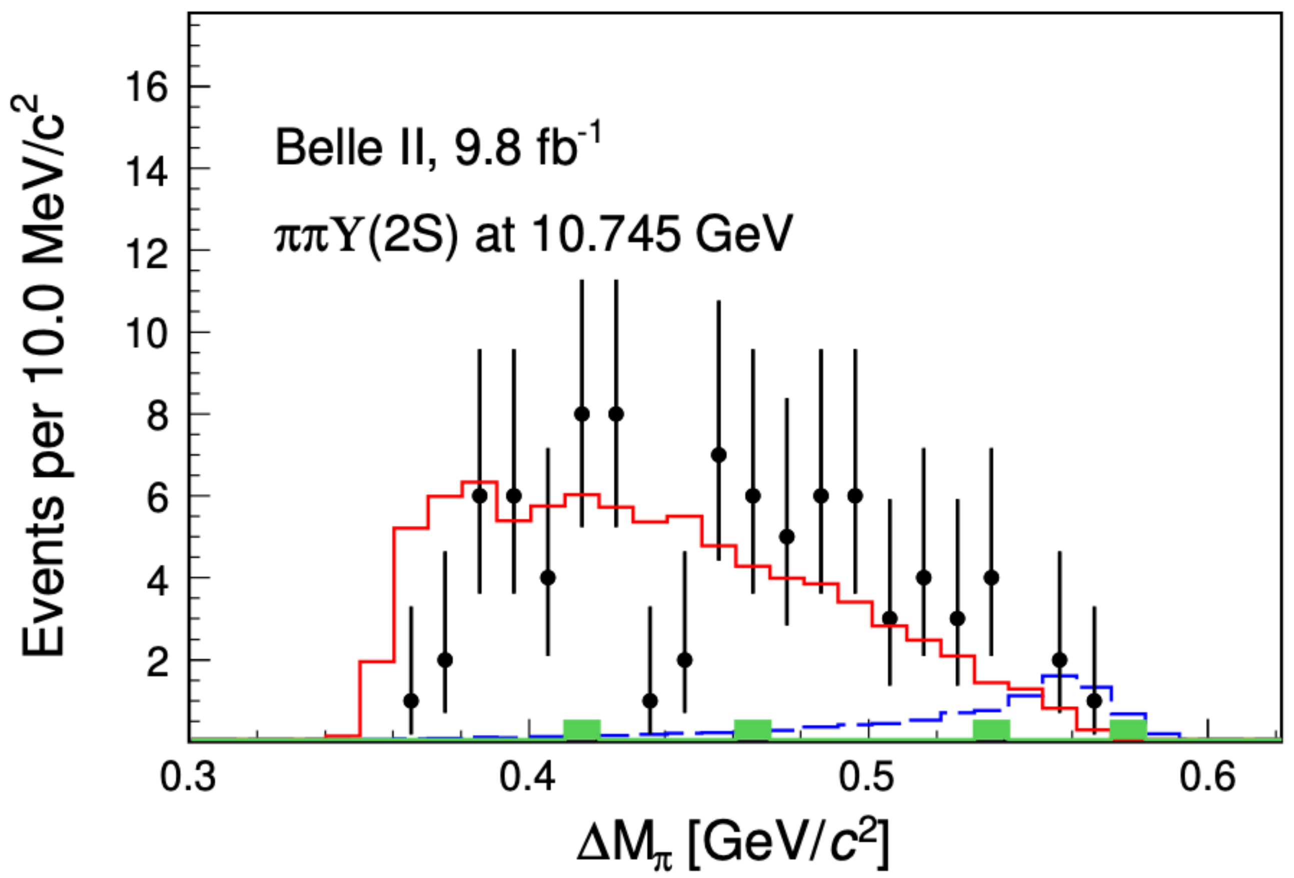
JHEP 07 2024, 116

$Z_b^+(10610)$ or $Z_b^+(10650)$ intermediate resonances

$$\Delta M_\pi = M(\pi^\pm\mu^+\mu^-) - M(\mu^+\mu^-)$$

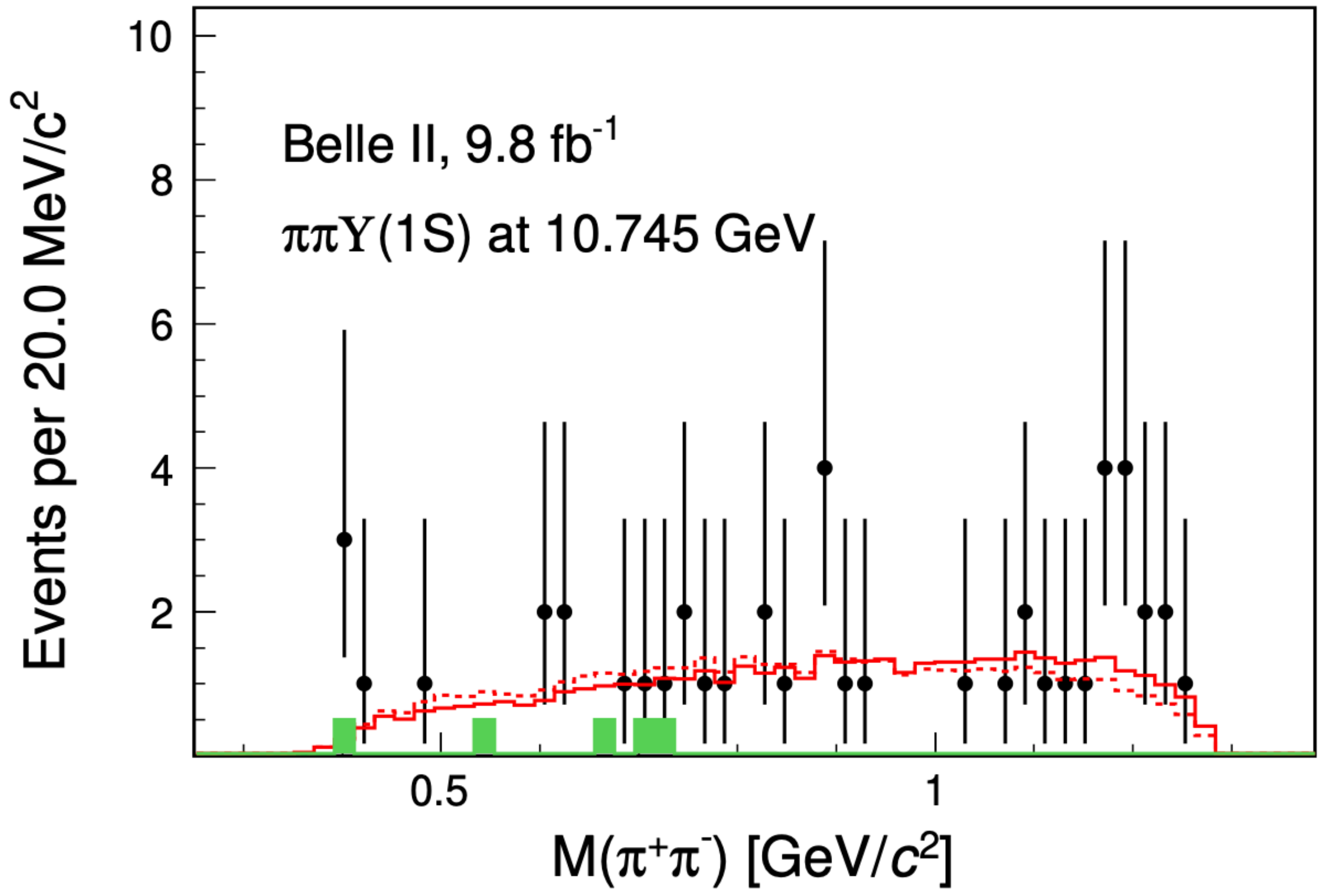
- No signal of intermediate $Z_b^+(10610)$ **or** $Z_b^+(10650)$ resonances are observed.

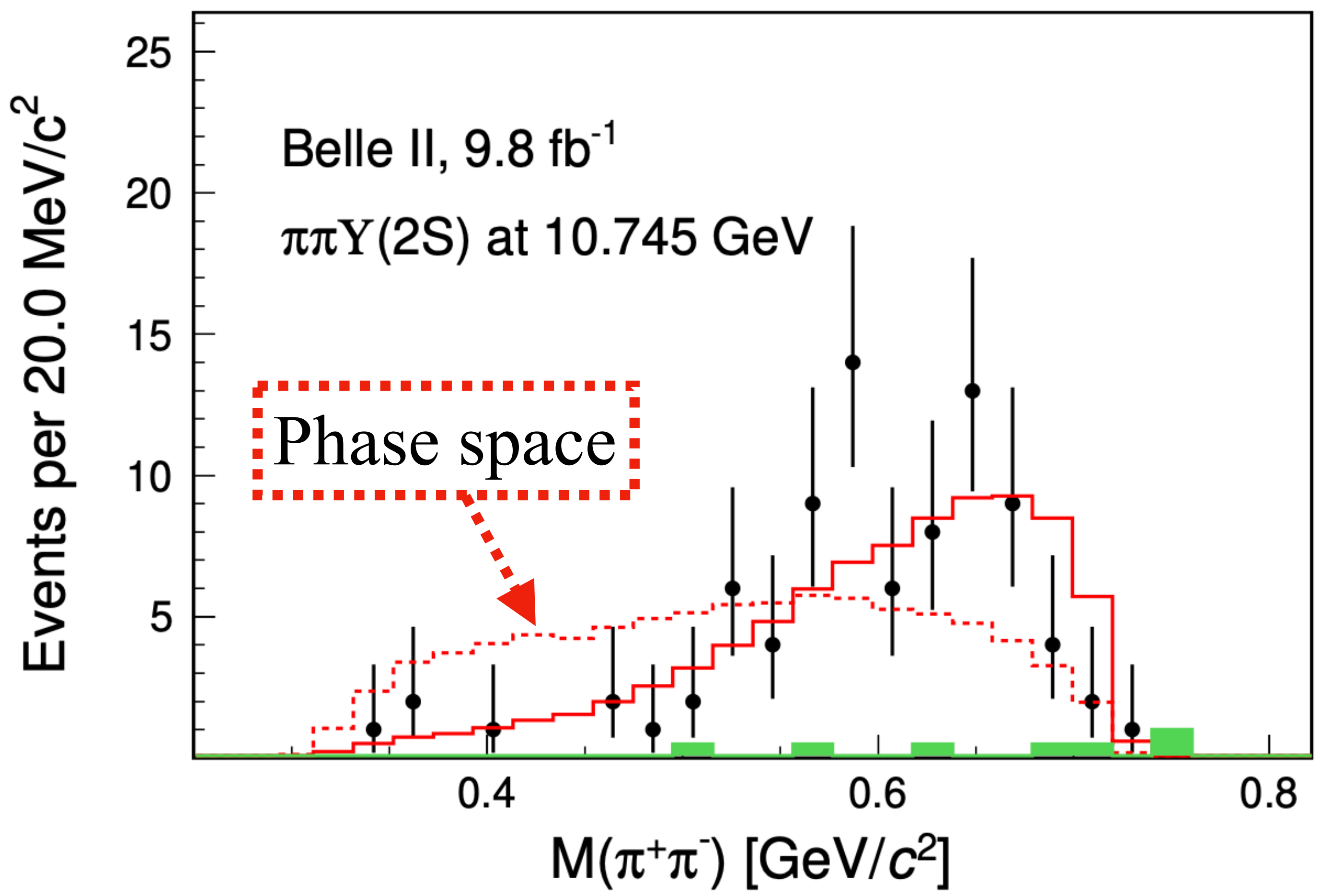




Di-pion spectrum

- $\pi^+\pi^-\Upsilon(1S)$: $M(\pi^+\pi^-)$ distribution is consistent with phase space.
- $\pi^+\pi^-\Upsilon(2S)$: larger values of $M(\pi^+\pi^-)$ enhanced (similar to $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ process)

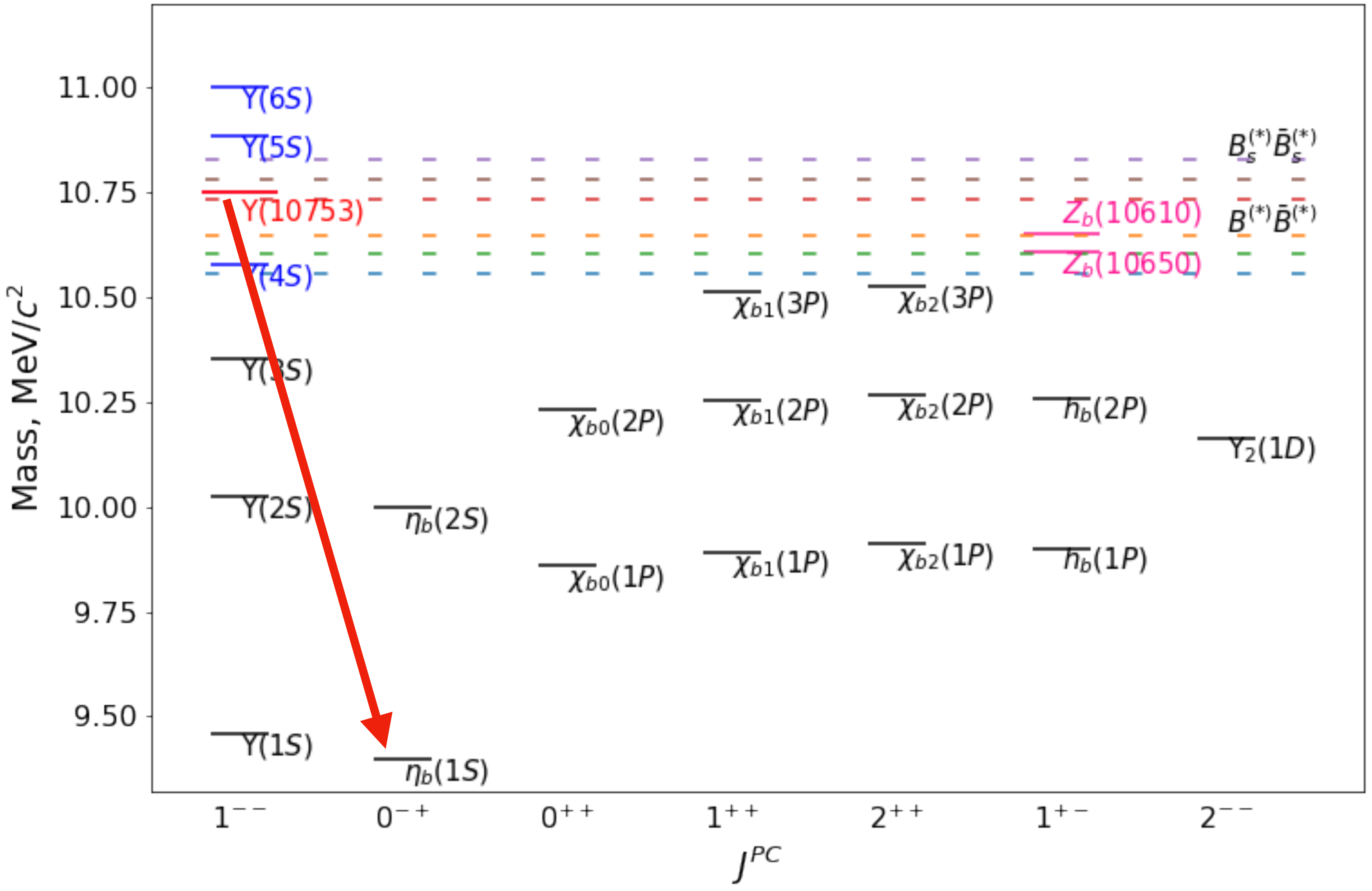


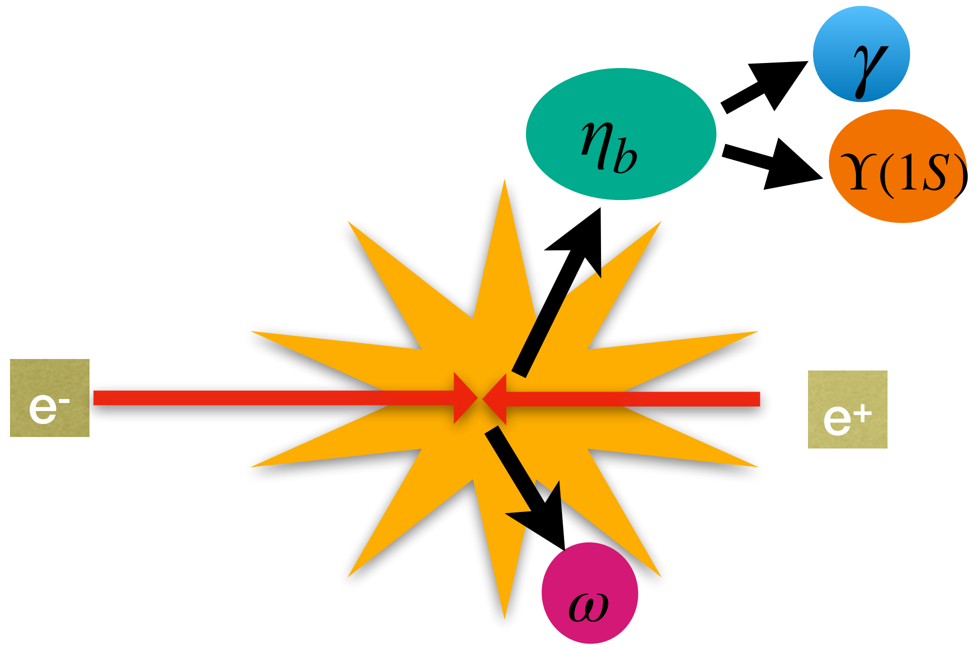


Search for $\Upsilon(10753) \to \omega\eta_b(1S)$ at Belle II

- **Motivation:**
  - Theoretically, tetra-quark interpretation predicts, a strong enhancement of the decay $\omega\ \eta_b(1S)$ compared to $\pi^+\pi^-\Upsilon(nS)$ CPC 43 (2019) 12, 123102
  - $4S - 3D$ mixed model predicts that decay rate of $\omega\ \eta_b(1S)$ is smaller than $\pi^+\pi^-\Upsilon(nS)$ by a factor of 0.2-0.4 PRD 109, 014039 (2024)

- **Strategy**
  - Partial reconstruction:
    - Reconstructed ω meson in $\pi^+\pi^-\pi^0$ and use the recoil mass of ω as signal variable
    - $$M_{\mathrm{recoil}}(\pi^+\pi^-\pi^0) = \sqrt{\left(\frac{\sqrt{s} - E^*}{c^2}\right)^2 - \left(\frac{p^*}{c}\right)^2}$$
    - Recoil mass of ω will peak at $\eta_b(1S)$



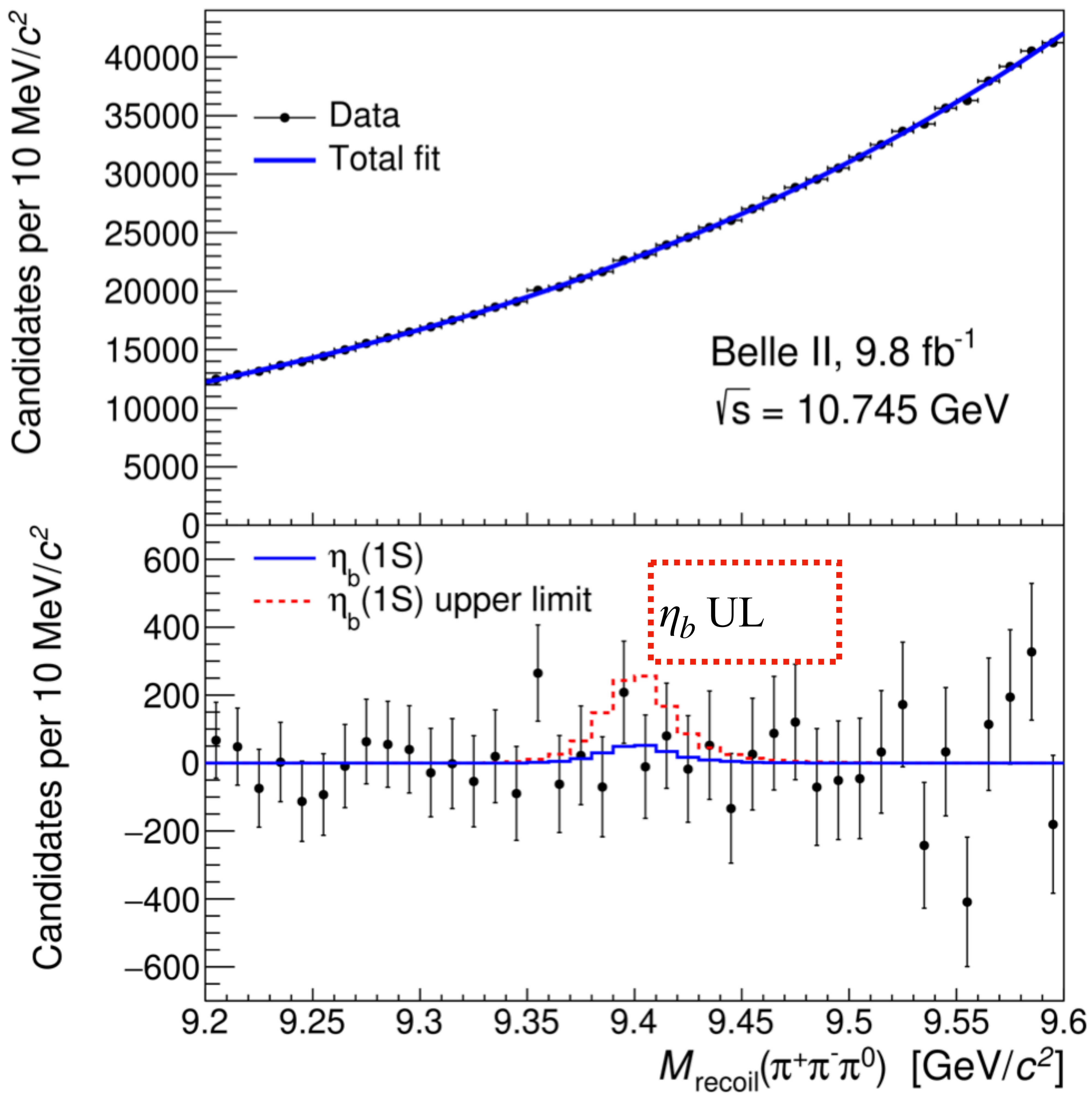


Search for $\Upsilon(10753) \to \omega\eta_b(1S)$ at Belle II

PRD 109, 072013 (2024)

- No significant $\omega\ \eta_b(1S)$ signal is observed.
- Upper limits at the 90% C.L. on the Born cross section are set.
- $\sigma(e^+e^- \to \omega\eta_b(1S)) < 2.5$ pb

$\omega \to \pi^+\pi^-\pi^0$ recoil mass distributions



Ratio:

- $$\frac{\sigma(\omega\eta_b)}{\sigma(\pi^+\pi^-\Upsilon(nS))} < 1.25$$
- Prediction for a tetra quark model: ~30 CPC 43 (2019) 12, 123102
- Prediction for a $4S-3D$ mixed state: 0.2 - 0.4

PRD 109, 014039 (2024)

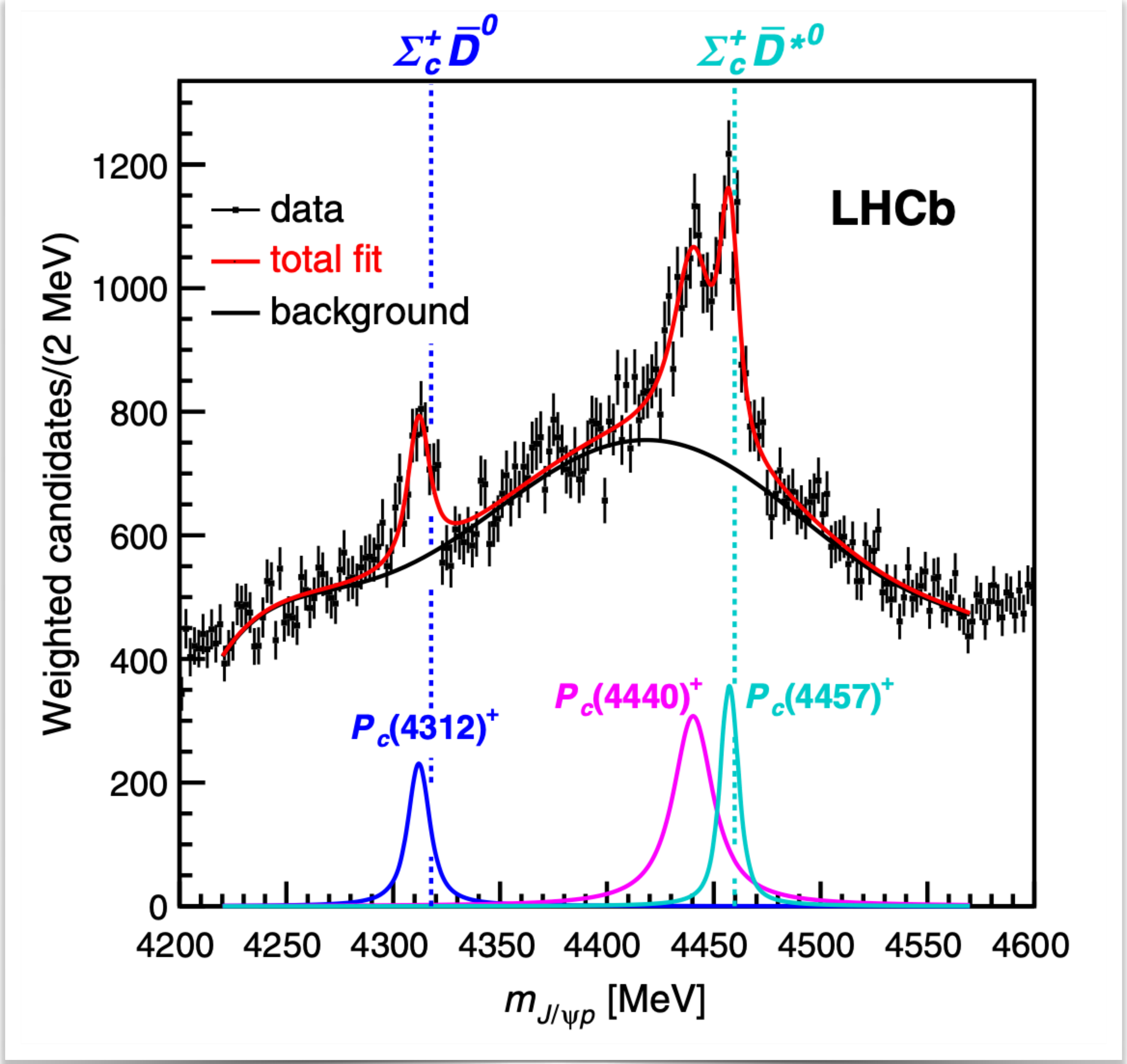
Evidence against the tetraquark model predictions.

Compatible with $S-D$ mixed model

Pentaquarks

Motivation

- Charmed pentaquark (P_c) states have been discovered by LHCb.
  - $P_c(4312)^+$, $P_c(4440)^+$, $P_c(4457)^+$ in $\Lambda_b \to K + pJ/\psi$
- Not possible to confirm with e^+e^- B-factory
  - Not enough energy to produce Λ_b pair
  - On the other hand, anit-deuterons are observed in by ARGUS, CLEO and BaBar
- Why not look for P_c in $\Upsilon(nS)$ decays?
- Belle has world-largest data samples of $\Upsilon(1S)$ and $\Upsilon(2S)$
  - 6 fb^{-1} at $\Upsilon(1S)$ [102M decays]
  - 25 fb^{-1} at $\Upsilon(2S)$ [158M decays]

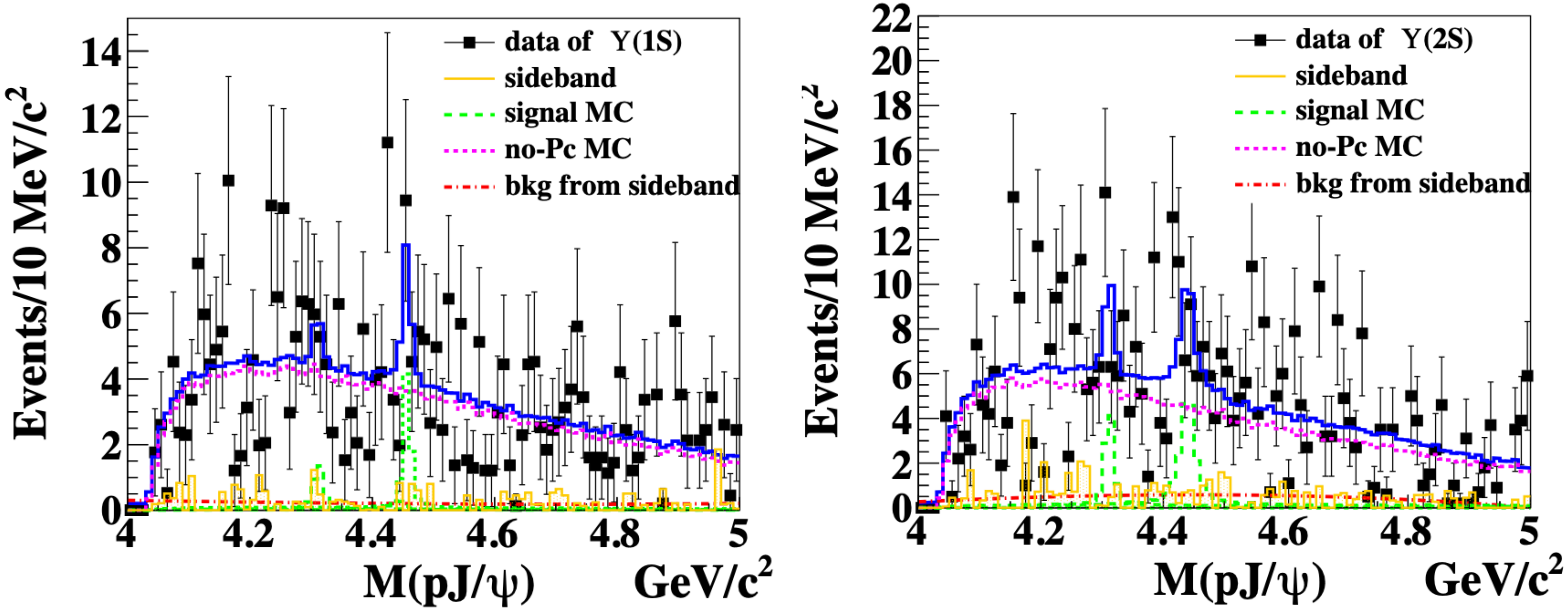


PRL 122, 222001 (2019)

Search for $P_c^+ \to pJ/\psi$ in $\Upsilon(1S)$ and $\Upsilon(2S)$

arXiv:2403.04340v4

- No significant P_c signal observed
- Major sources of systematic uncertainties
  - Particle ID (2.1 %)
  - MC modeling (2.2 %, 2.8 %)
  - N_{1S}, N_{2S} (~ 2.2 %)



Set upper limit on P_c productions from $\Upsilon(1S)$ and $\Upsilon(2S)$

	$\Upsilon(1S)$ decays			$\Upsilon(2S)$ decays		
—	$P_c(4312)^+$	$P_c(4440)^+$	$P_c(4457)^+$	$P_c(4312)^+$	$P_c(4440)^+$	$P_c(4457)^+$
$\mathcal{B}^{\rm UL}$ $(\times 10^{-6})$	3.9	6.2	5.5	4.7	7.2	2.6

Evidence of $P_{c\bar{c}s}(4459)^0 \to \Lambda J/\psi$ in $\Upsilon(1S,2S)$ decays

arXiv:2502.09951v1

- Observed $P_{c\bar{c}s}(4459)^0$ signal in combined $\Upsilon(1S,2S)$ with 3.3σ significance
- Major sources of systematic uncertainties
  - Λ selection (~4%),
  - BF of $\Upsilon(2S)$ (~6%)

Branching fraction for $P_{c\bar{c}s}(4459)^0$ productions in $\Upsilon(1S)$ and $\Upsilon(2S)$

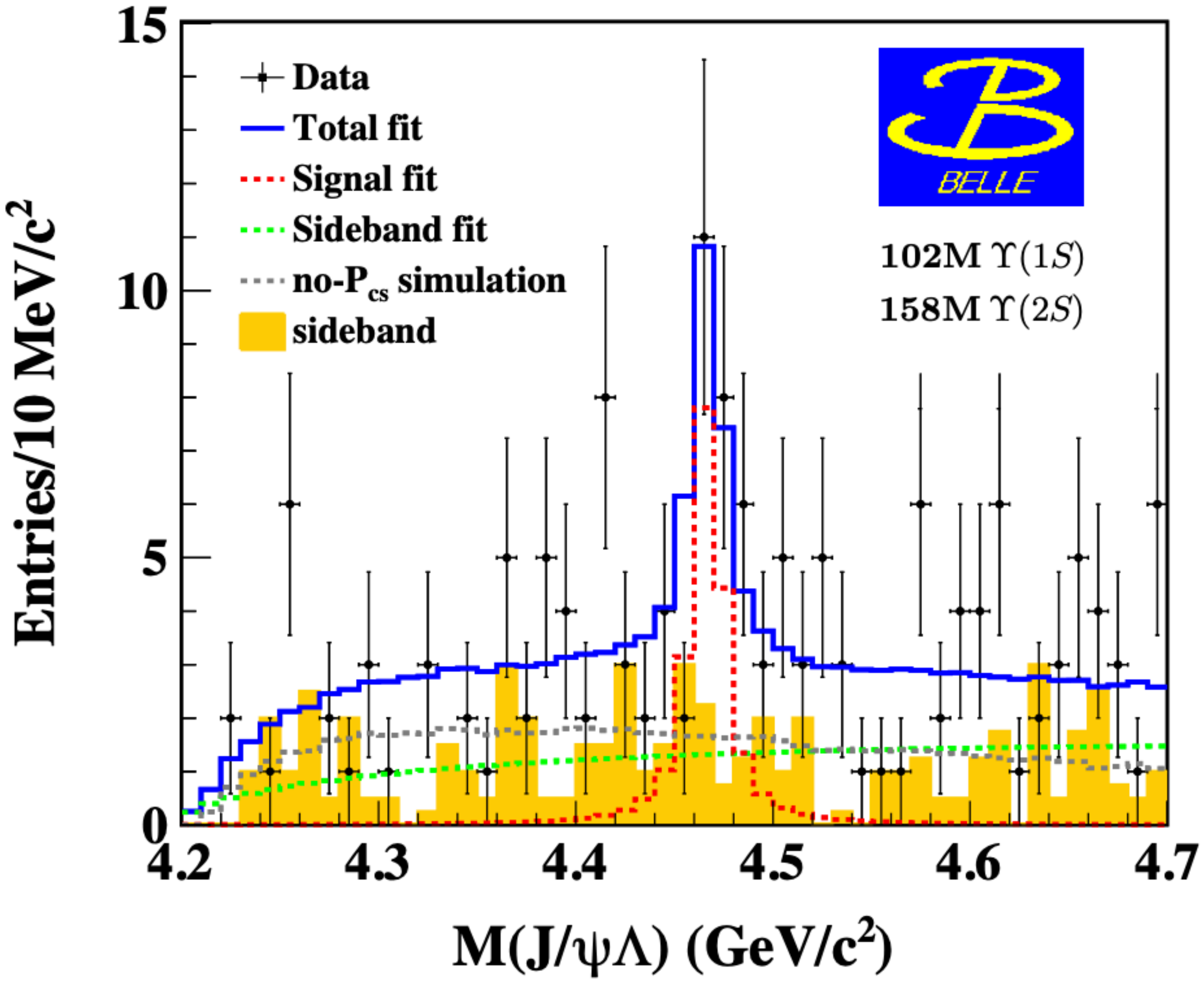
Mode	$\mathcal{B}(\times 10^{-6})$
$\Upsilon(1S) \to P_{c\bar{c}s}(4459)^0/\bar{P}_{c\bar{c}s}(4459)^0 + anything$	$3.5 \pm 2.0 \pm 0.2$
$\Upsilon(2S) \to P_{c\bar{c}s}(4459)^0/\bar{P}_{c\bar{c}s}(4459)^0 + anything$	$2.9 \pm 1.7 \pm 0.4$

Mass and Width of $P_{c\bar{c}s}(4459)^0$:

$M_R = (4471.7 \pm 4.8 \pm 0.6)$ MeV/c^2

$\Gamma_R = (21.9 \pm 13.1 \pm 2.7)$ MeV

Combined $\Upsilon(1S)$ and $\Upsilon(2S)$ data



Summary

- Continue studies of conventional and exotic states at Belle and Belle II (with growing datasets)

- The understanding of the physics of highly excited heavy bottomonium is very incomplete.
- First energy scan results from Belle II are quite interesting.
- Much higher significance confirmation of the $\Upsilon(10753)$ by Belle II
  - No clear indication on the nature of $\Upsilon(10753)$.
  - Improved results for mass and width of $\Upsilon(10753)$ using $\Upsilon(10753) \to \Upsilon(nS)\pi^+\pi^-$.
  - $S-D$ model compatible with $\Upsilon(10753) \to \omega\eta_b(1S)$.
  - No signal of intermediate $Z_b^+(10610)$ or $Z_b^+(10650)$ resonances are observed.

- Evidence of $P_{c\bar{c}s}(4459)^0 \to \Lambda J/\psi$ in $\Upsilon(1S)$ and $\Upsilon(2S)$ Belle data.

- Run2 is underway, with goal of collecting several ab^{-1} data in the coming years, allowing for further exploration of conventional and exotic states.

Backup

Belle II detector

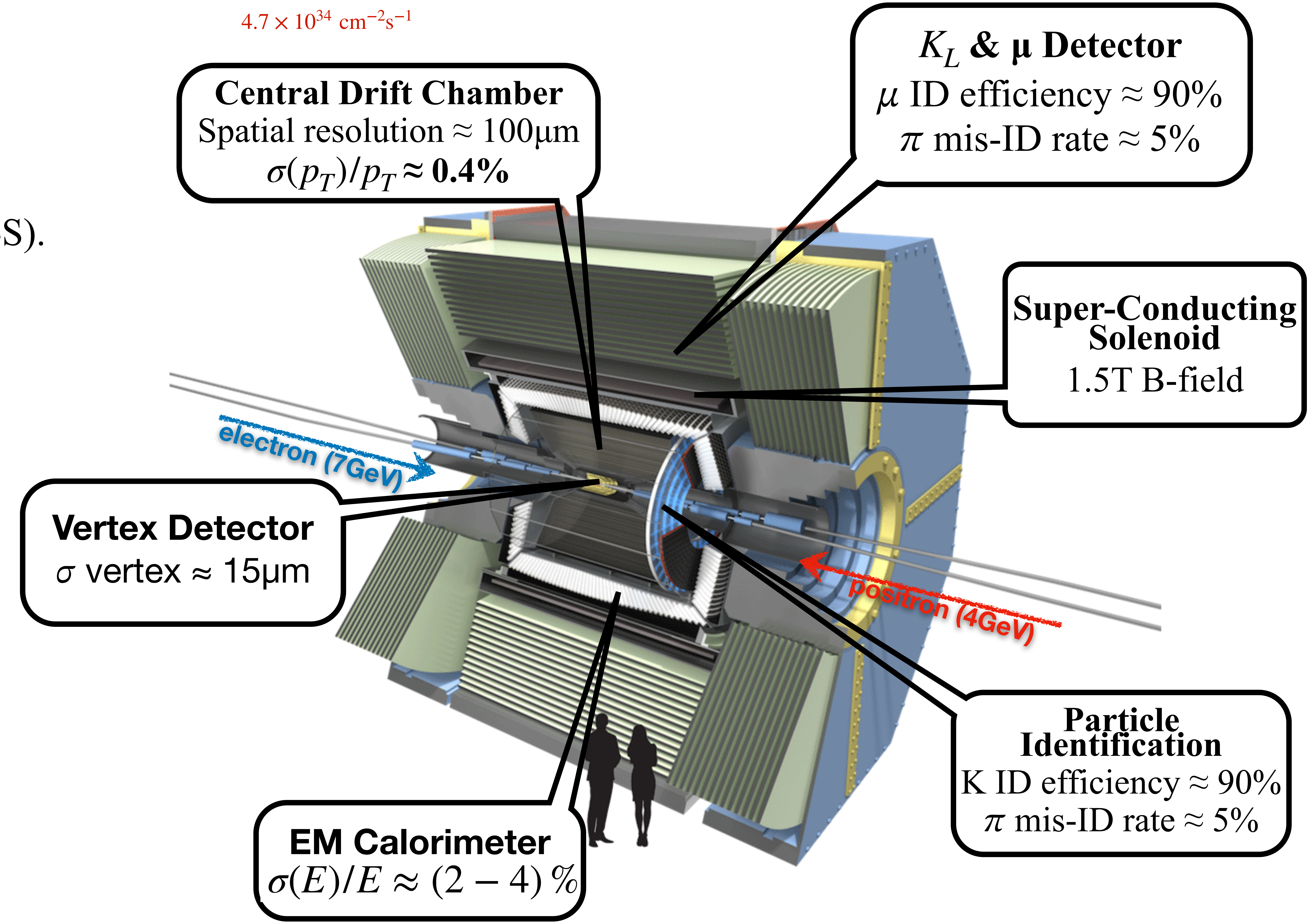
Record-breaking instantaneous luminosity:

$4.7 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$

- Asymmetric e^+e^- collider
- **Collected data**
  - ~ 362 $\mathrm{fb^{-1}}$ at Υ(4S)
  - 42 $\mathrm{fb^{-1}}$ off-resonance, 60 MeV below Υ(4S).
  - 19 $\mathrm{fb^{-1}}$ energy scan between 10.6 to 10.8 GeV for exotic hadron studies.

Features:

- Near-hermetic detector
- Excellent vertexing and tracking
- High-efficiency detection of neutrals (γ, π^0, η, η', …)
- Good charged particle reconstruction.



Search for $P_c^+ \to pJ/\psi$ in $\Upsilon(1S)$ and $\Upsilon(2S)$

arXiv:2403.04340v4

Invariant-mass distributions of pJ/ψ in the $\Upsilon(1S)$, $\Upsilon(2S)$, and continuum data