Recent results from Belle and Belle II for exotic hadrons

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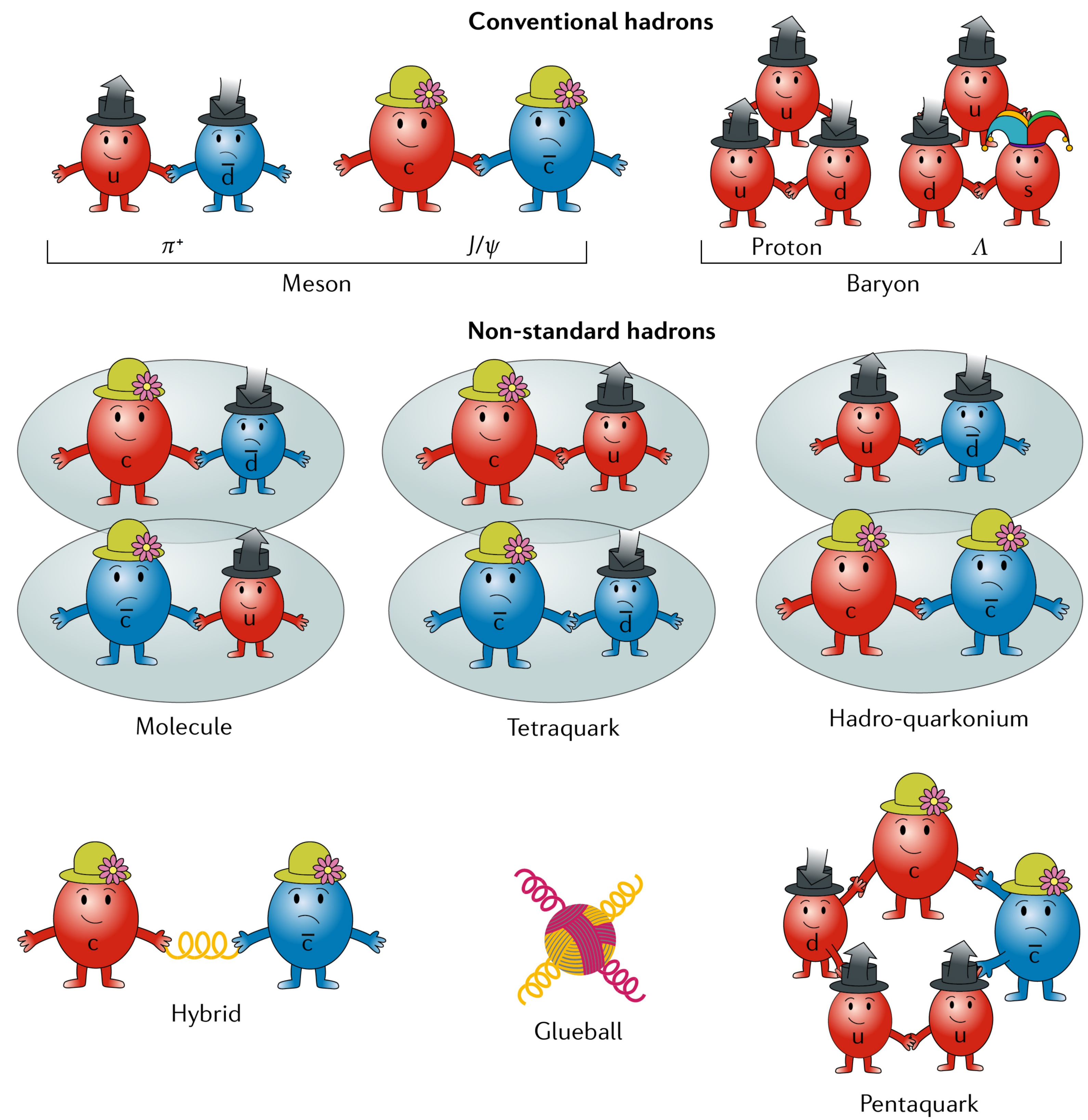
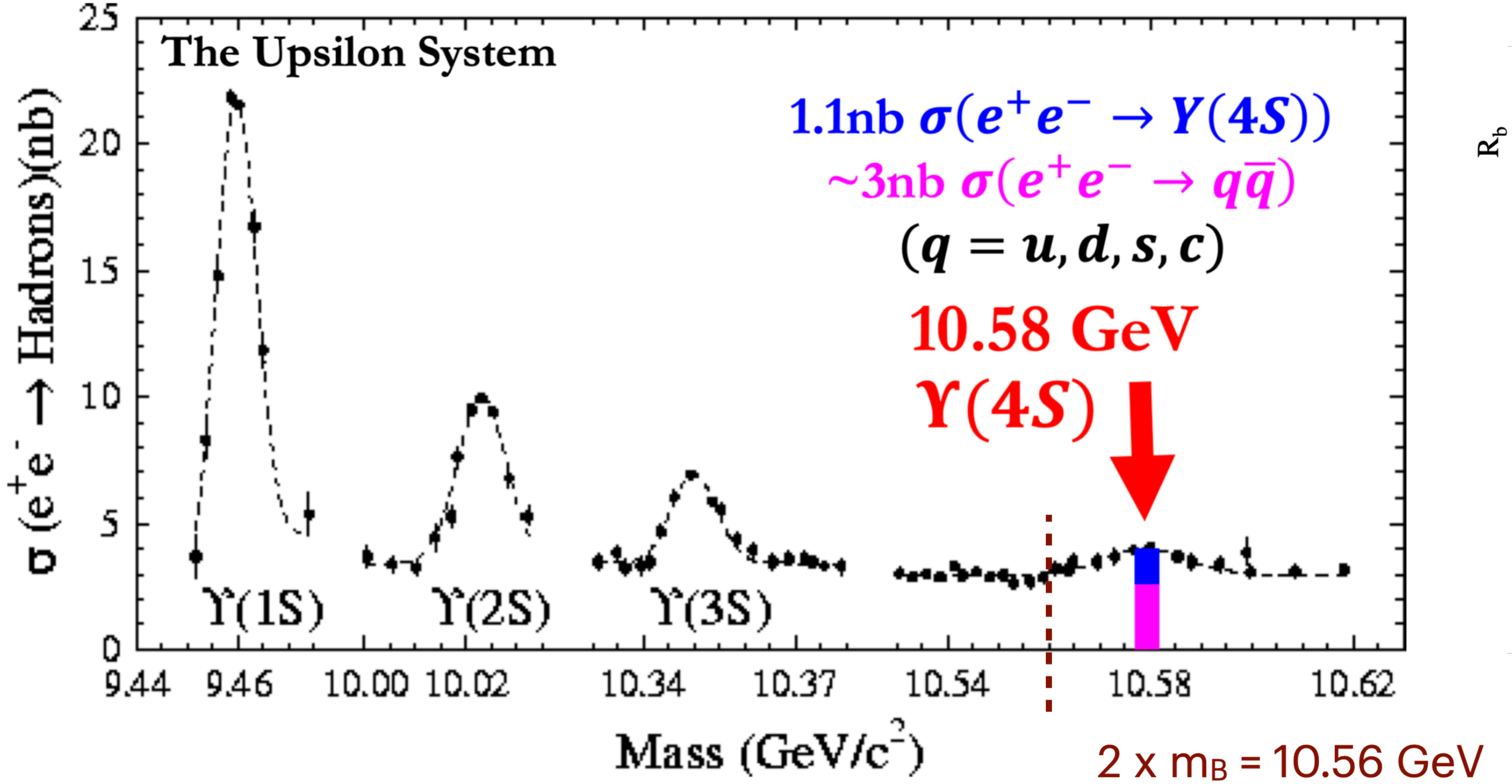
Overview

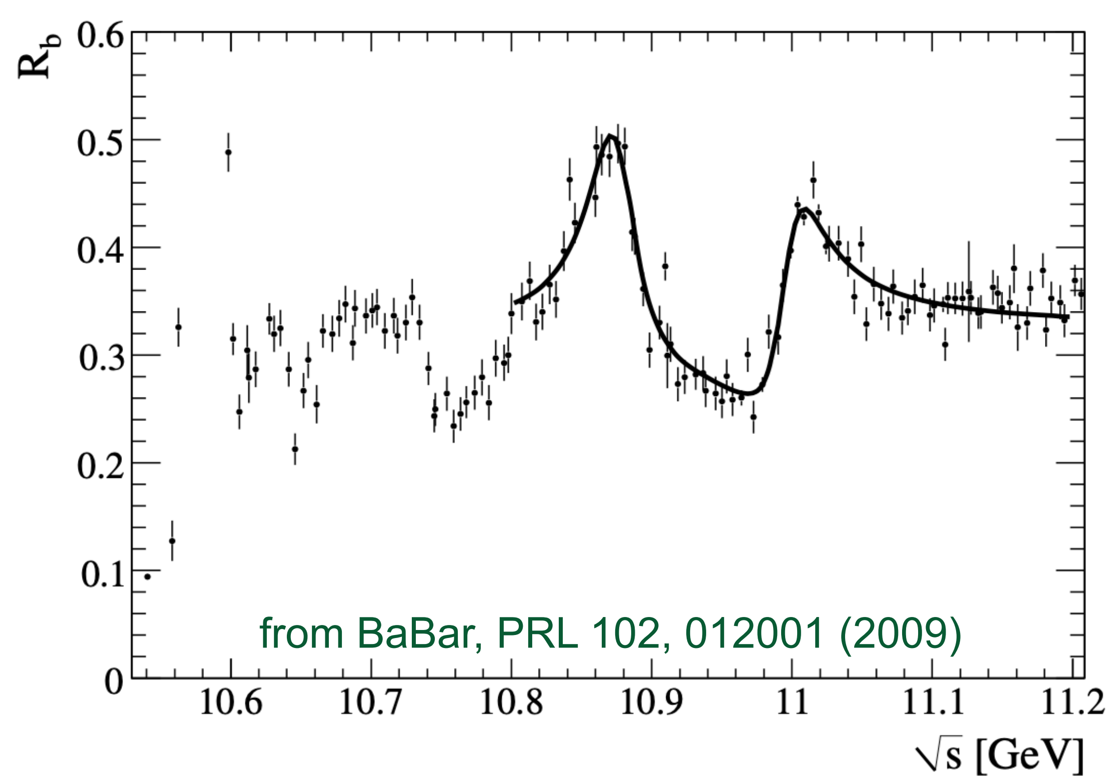
- Quick intro. to Belle & Belle II
- Charmed Pentaquark searches
  - ✓ $P_c^+ \to pJ/\psi$ in $\Upsilon(1S)$ and $\Upsilon(2S)$
  - ✓ $P_{cs}(4459)^0 \to \Lambda J/\psi$ in $\Upsilon(1S)$ and $\Upsilon(2S)$
- Updates on $\Upsilon(10753)$
- Closing



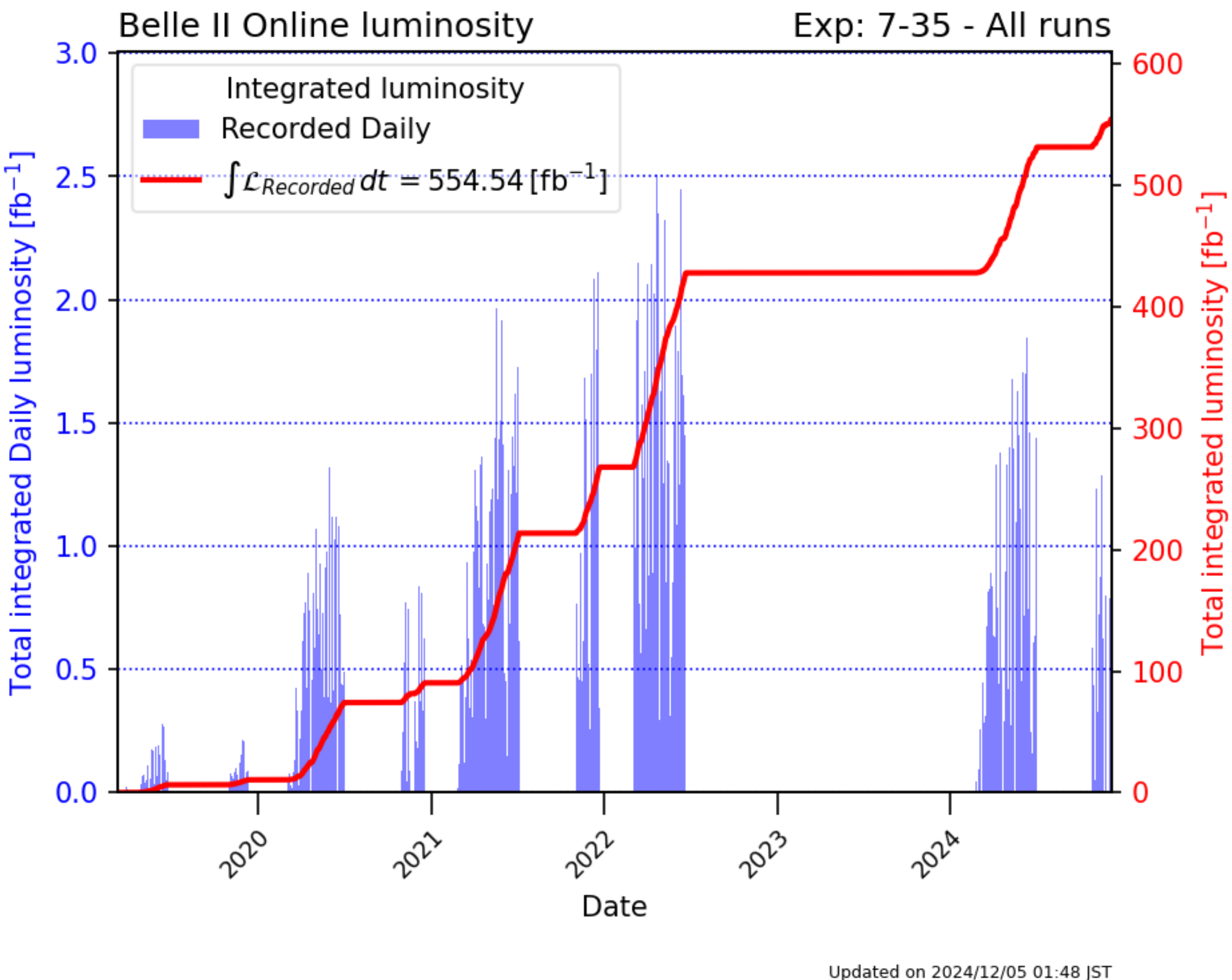
from Yuan & Olsen, Nature Rev. Phys. 1 (2019) no.8, 480-494

e^+e^- collision near Υ resonances





Luminosities of Belle II and Belle



Belle (1999-2010) Luminosity

$$\int \mathscr{L}_{\text{total}}\, dt = 1039\ \text{fb}^{-1}$$

$$\int \mathscr{L}_{\Upsilon(4S)}\, dt = 711\ \text{fb}^{-1}$$

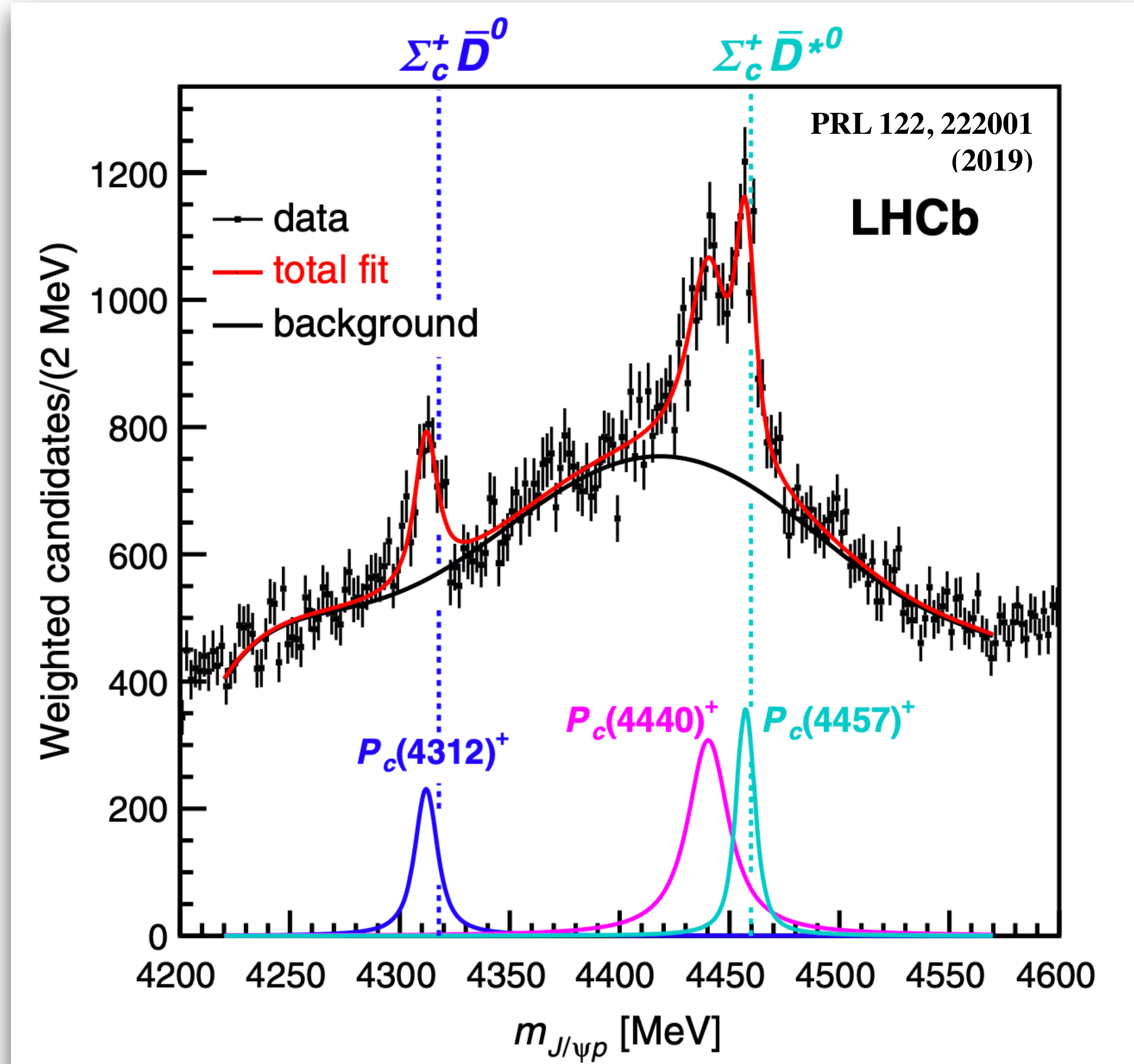
$$\int \mathscr{L}_{\Upsilon(1S)}\, dt = 5.8\ \text{fb}^{-1}$$

$$\int \mathscr{L}_{\Upsilon(2S)}\, dt = 24.5\ \text{fb}^{-1}$$

$$\int \mathscr{L}_{\Upsilon(5S)}\, dt = 121\ \text{fb}^{-1}$$

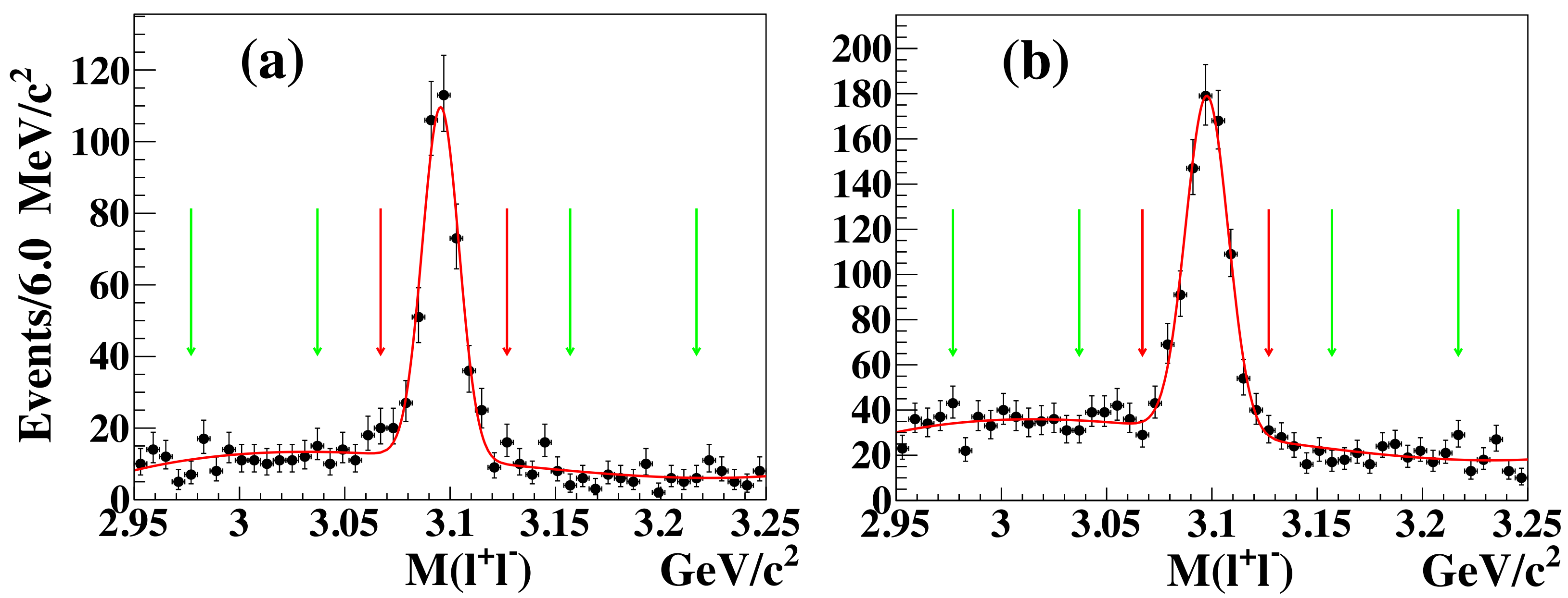
Search for P_c^+ states in pJ/ψ

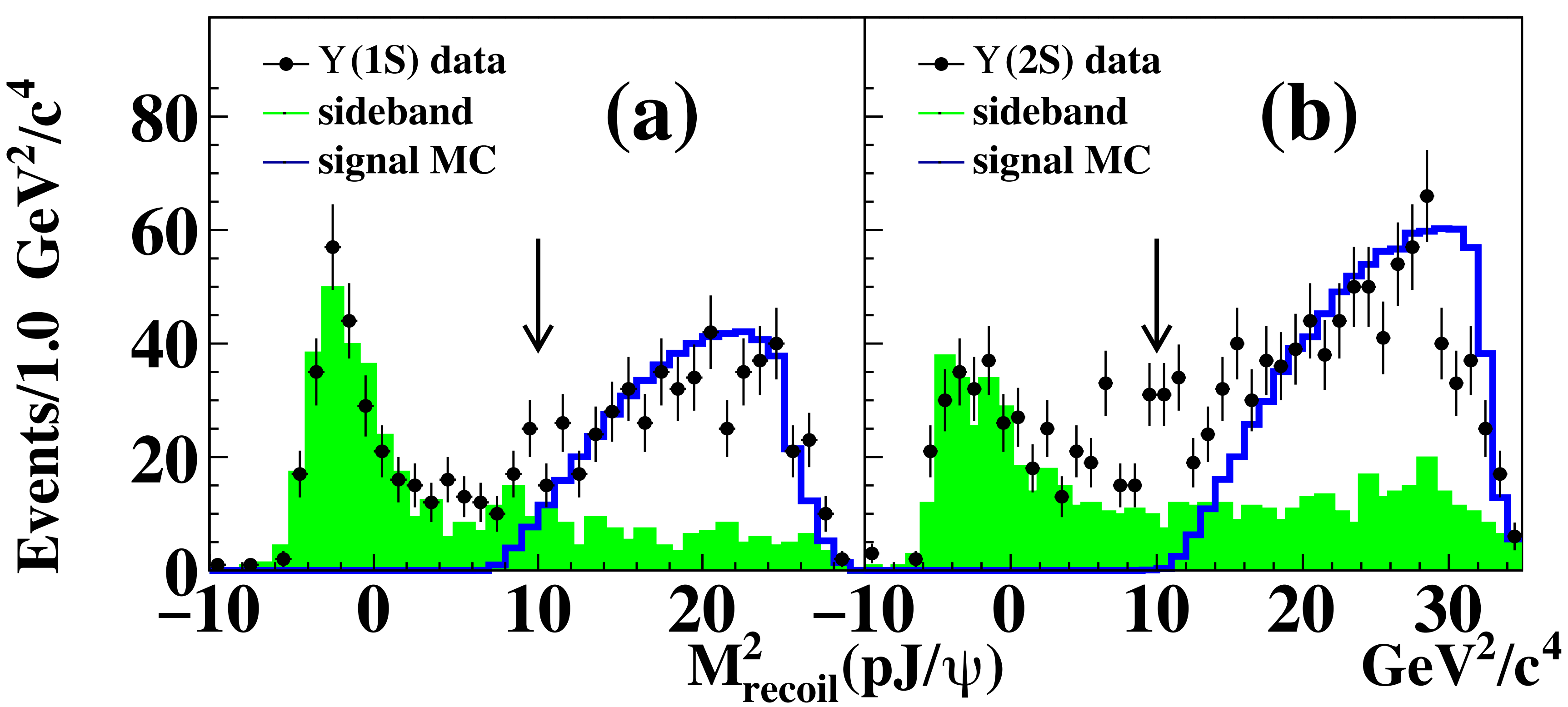
motivation



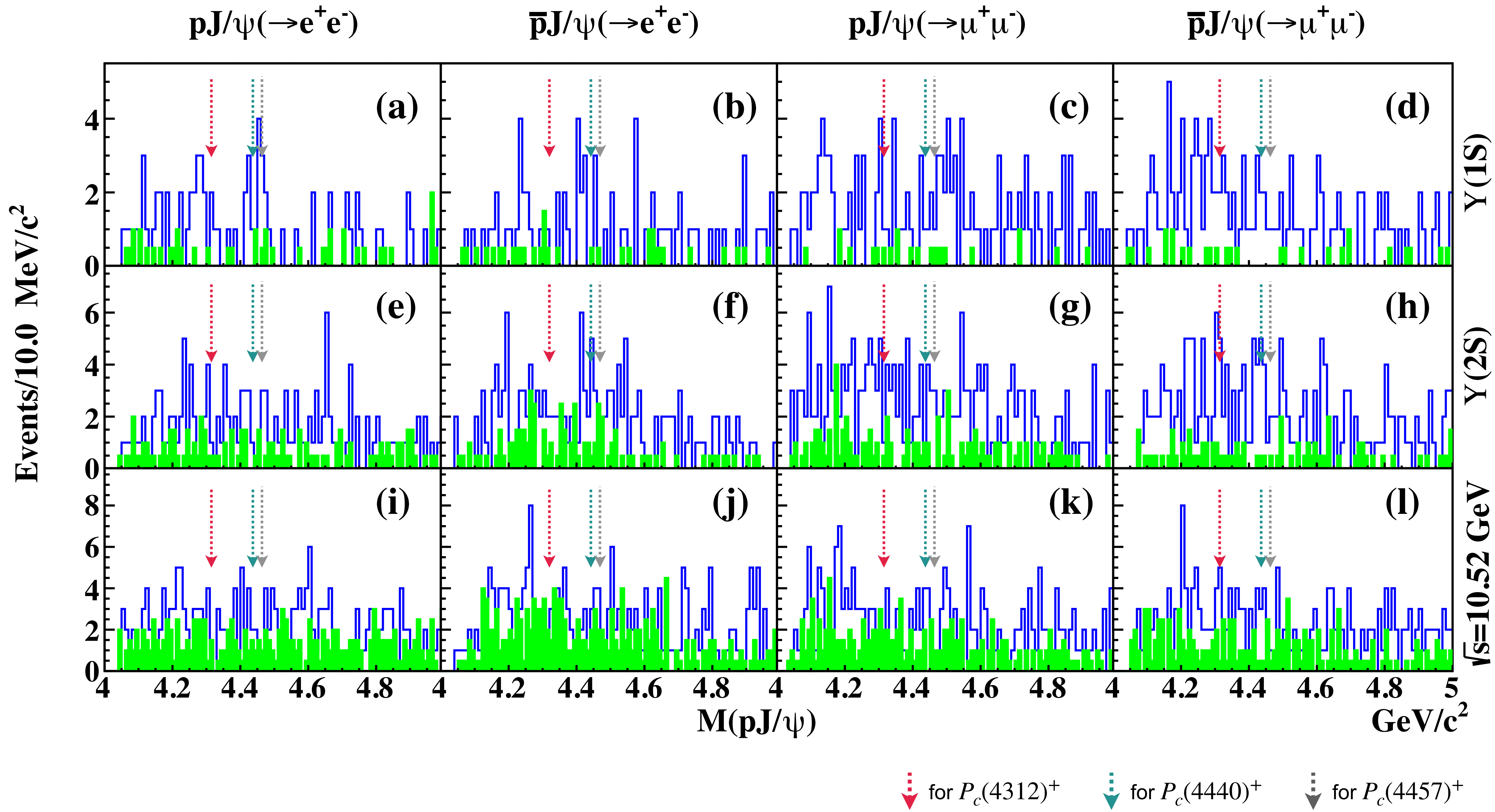
- Charmed pentaquark (P_c) states have been discovered by LHCb.
  - $P_c(4312)^+$, $P_c(4440)^+$, and $P_c(4457)^+$ in $\Lambda_b \to K + pJ/\psi$
- not possible to confirm with e^+e^- B factory,
  - not enough energy to produce Λ_b pair
  - OTOH, deuterons are observed in $\Upsilon(nS)$ by ARGUS, CLEO and BaBar.
- Why not then look for P_c in $\Upsilon(nS)$?
- Belle has world-largest sample of $\Upsilon(1S)$ and $\Upsilon(2S)$.
- We search for $P_c^+ \to pJ/\psi$ from $\Upsilon(1S)$ and $\Upsilon(2S)$ at Belle.

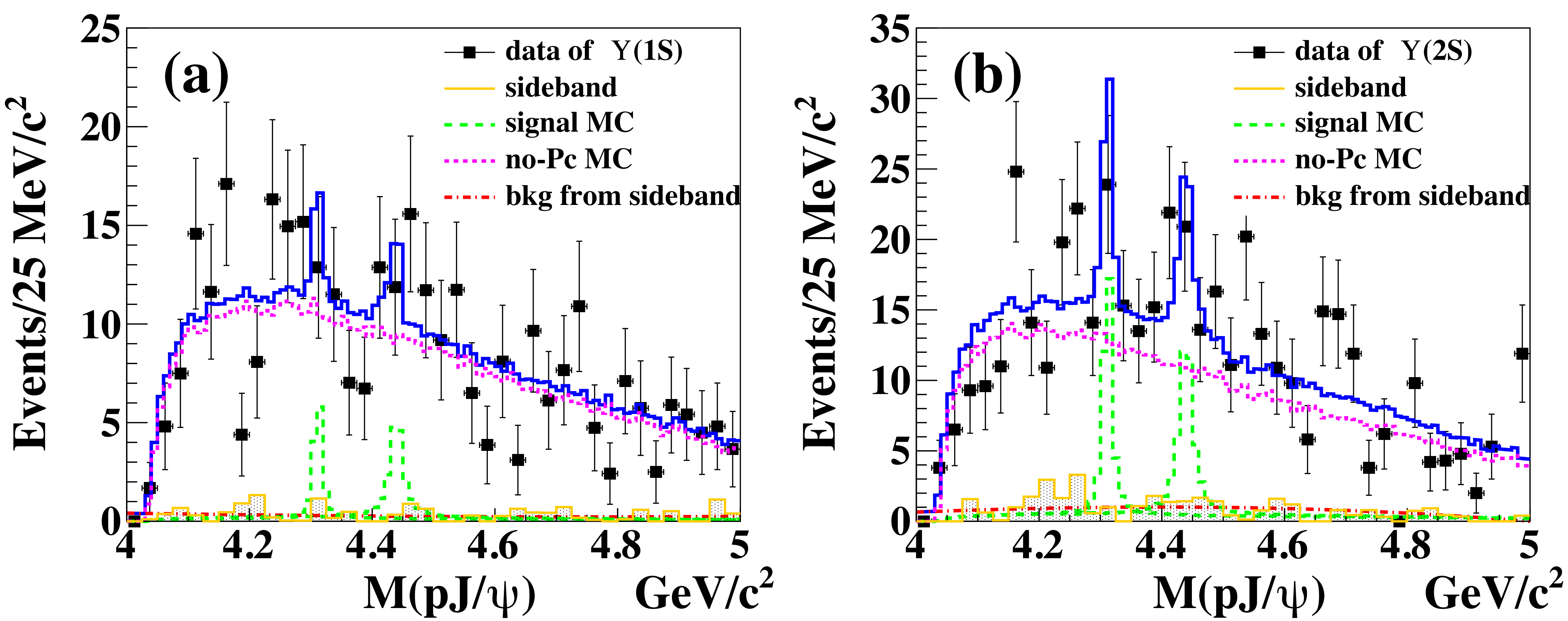
Analysis procedure





- Event selection
  - 3 well-measured charged tracks
  - Identification of $e^{\pm}$, $\mu^{\pm}$ and p
  - Λ veto for p candidates
  - sideband for non-J/ψ bkg.
- Cut on $M^2_{\rm recoil}(pJ/\psi)$
  - to suppress non-J/ψ bkg. with $M^2_{\rm recoil}(pJ/\psi) > 10$ GeV^2
- Study $M(pJ/\psi)$ distributions (next page)
  - in $\Upsilon(1S)$,
  - in $\Upsilon(2S)$,
  - in continuum ($\sqrt{s} = 10.52$ GeV)


pJ/ψ(→e+e-)
p̄J/ψ(→e+e-)
pJ/ψ(→μ+μ-)
p̄J/ψ(→μ+μ-)
(a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k) (l)
Υ(1S)
Υ(2S)
√s=10.52 GeV
Events/10.0 MeV/c²
M(pJ/ψ)
GeV/c²
4 4.2 4.4 4.6 4.8 5
for $P_c(4312)^+$
for $P_c(4440)^+$
for $P_c(4457)^+$



	$\Upsilon(1S)$ decays			$\Upsilon(2S)$ decays		
—	$P_c(4312)^+$	$P_c(4440)^+$	$P_c(4457)^+$	$P_c(4312)^+$	$P_c(4440)^+$	$P_c(4457)^+$
$N^{\rm A}_{\rm fit}$	10 ± 8	14 ± 12	-3 ± 9	30 ± 16	33 ± 15	0 ± 3
$N^{\rm A,UL}_{\rm fit}$	26	37	14	52	60	6
$N^{\rm B}_{\rm fit}$	10 ± 8	12 ± 11	3 ± 9	29 ± 12	31 ± 15	0 ± 3
$N^{\rm B,UL}_{\rm fit}$	26	33	17	50	57	7
$N^{\rm UL}_{\rm sig}$	31	47	34	56	77	26
$\mathcal{B}^{\rm UL}$ $(\times 10^{-6})$	4.5	6.8	4.9	5.3	7.2	2.4

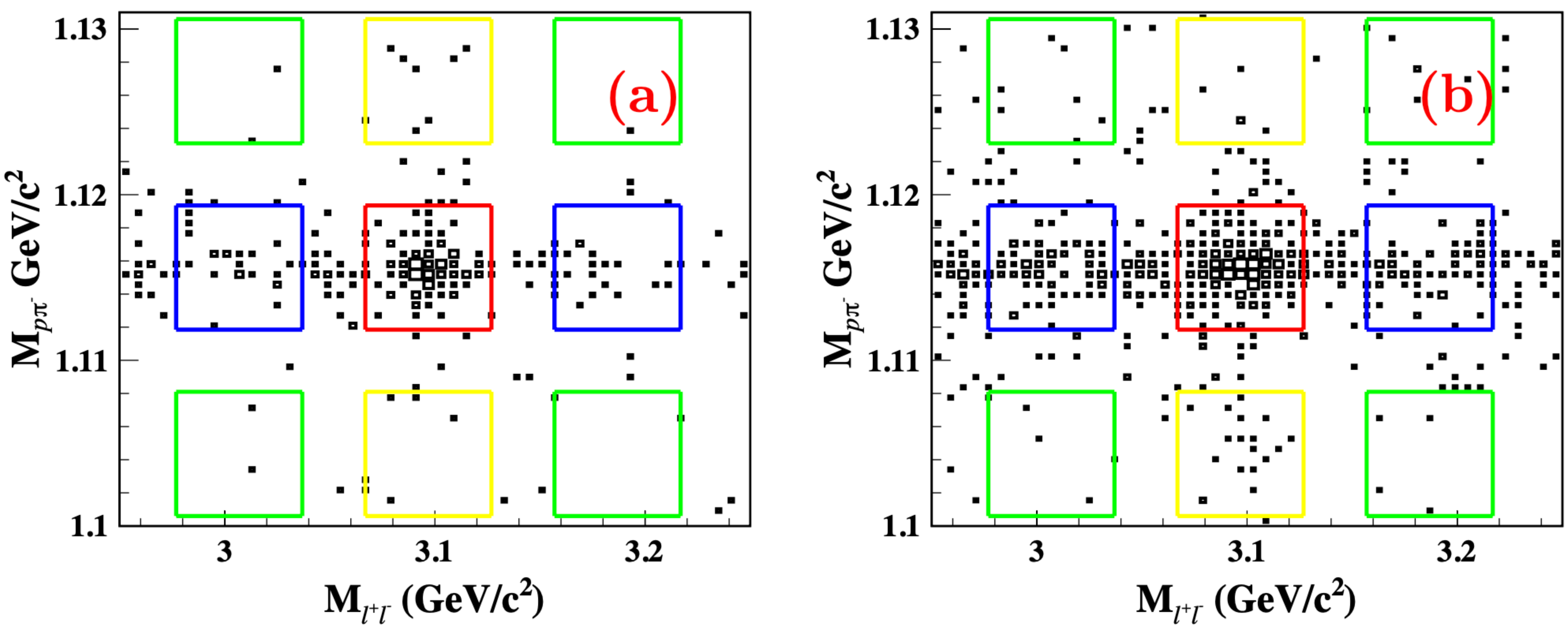
- no significant P_c^+ signals in any place
- major sources of systematic uncertainties
  - particle ID (2.1 %)
  - MC modeling (2.2 %, 2.8 %)
  - N_{1S}, N_{2S} (~2.2 %)
- We set upper limits on P_c^+ productions from $\Upsilon(1,2S)$

Evidence for $P_{cs}(4459)^0$ *in* $\Lambda J/\psi$

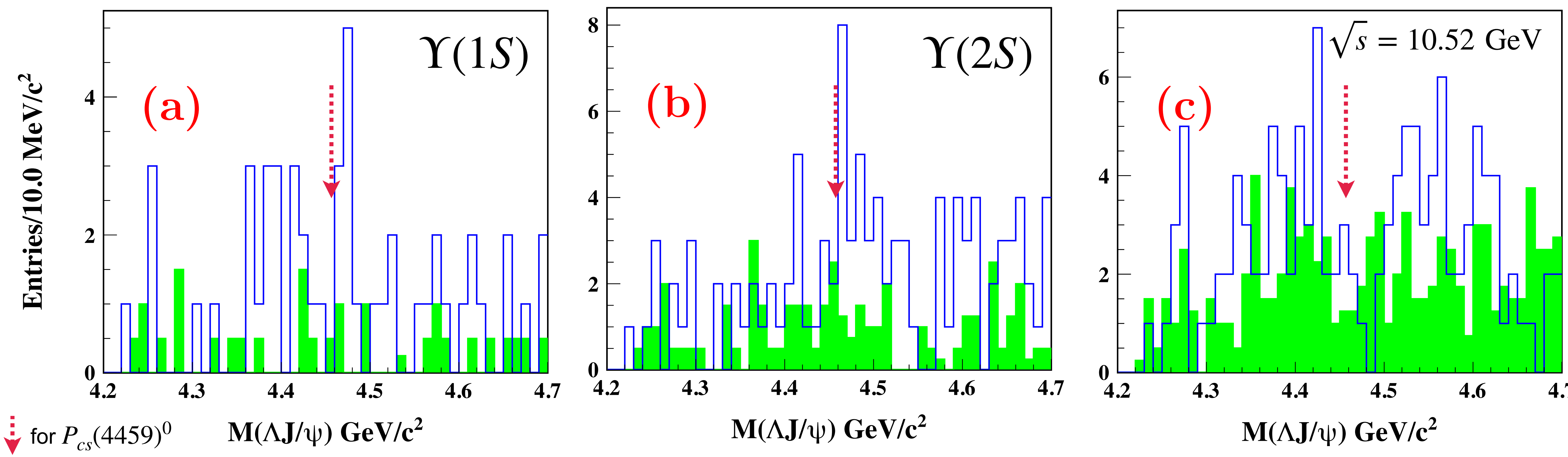
motivation and procedure

- Similar motivation as the previous paper (arXiv:2403.04340)
  - for neutral charmed pentaquark $P_{cs}(4459)^0$ in $\Upsilon(1S)$ and $\Upsilon(2S)$
- We search for $P_{cs}(4459)^0 \to \Lambda J/\psi$ from $\Upsilon(1S)$ and $\Upsilon(2S)$ at Belle.
  - $J/\psi \to \ell^+\ell^-$, $\Lambda \to p\pi$
  - 2D sideband for $M_{p\pi}$ vs. $M_{\ell^+\ell^-}$

(a) $\Upsilon(1S)$ sample
(b) $\Upsilon(2S)$ sample

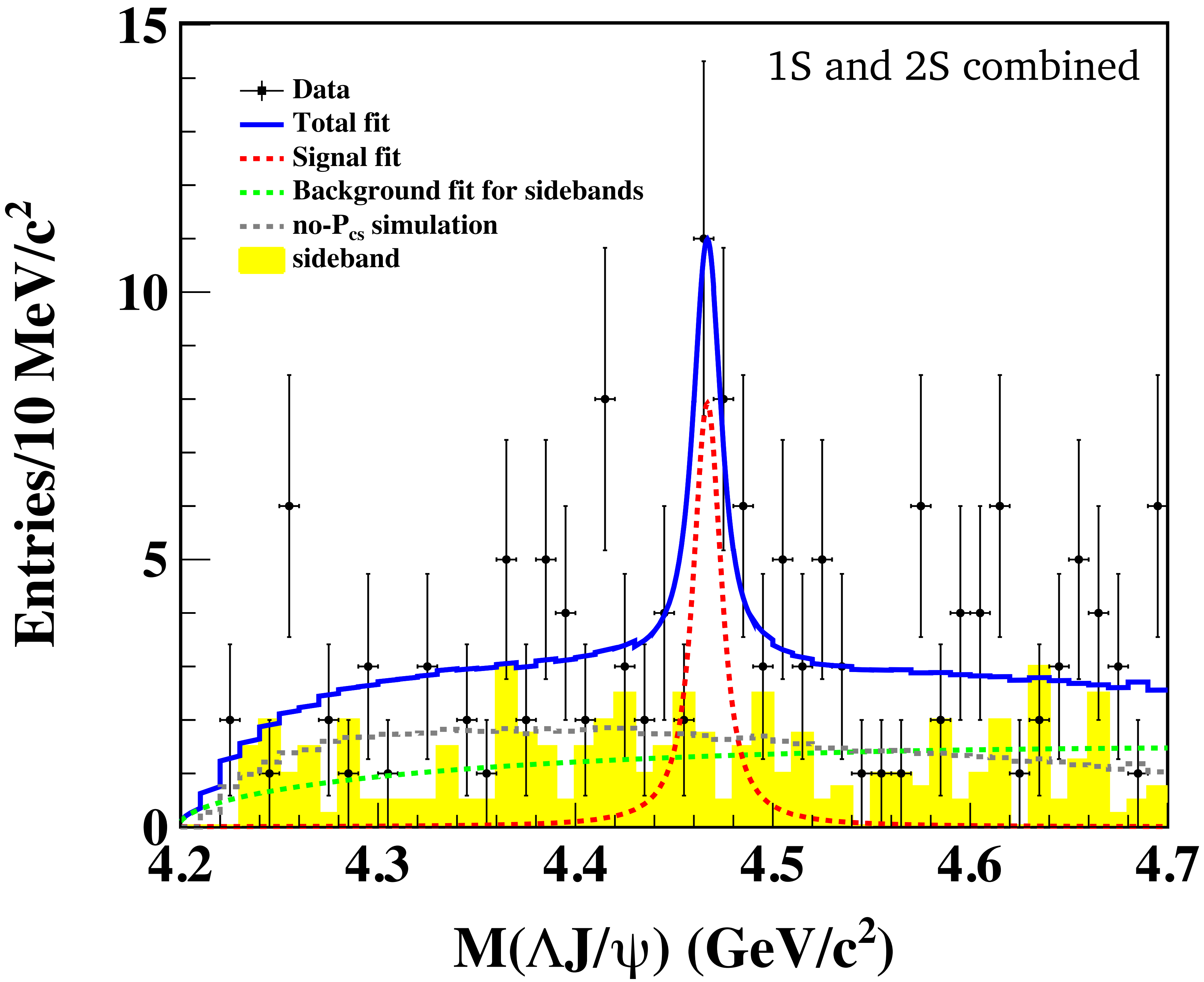


$\Lambda J/\psi$ Yield



- Assess signal yield in $M(\Lambda J/\psi)$
  - use $M_{\Lambda J/\psi} = M_{\ell^+\ell^- p\pi} - M_{\ell^+\ell^-} - M_{p\pi} + m_{J/\psi} + m_\Lambda$ to improve mass resolution σ_M (11.6 ➔ 2.8 MeV)
  - excess seen near 4.46 GeV in both $\Upsilon(1S)$ and $\Upsilon(2S)$ data

Results



- Signal yield of $M(\Lambda J/\psi)$
  - determined by a binned max. likelihood fit, with

    $$f_{\rm PDF} = f_{\rm R} + f_{{\rm no}P_{cs}} + f_{\rm SB}$$

  - fit with fixed mass, width (from LHCb value) gives

    $$N_{P_{cs}} = 19 \pm 5$$

    $$\Delta(-2\ln \mathscr{L}) = 13.01$$ (3.4σ evidence by pseudo-experiment technique)

- Fit result with free mass, width

  $$M_{\rm R} = 4469.5 \pm 4.1 \pm 4.1 \text{ MeV}$$

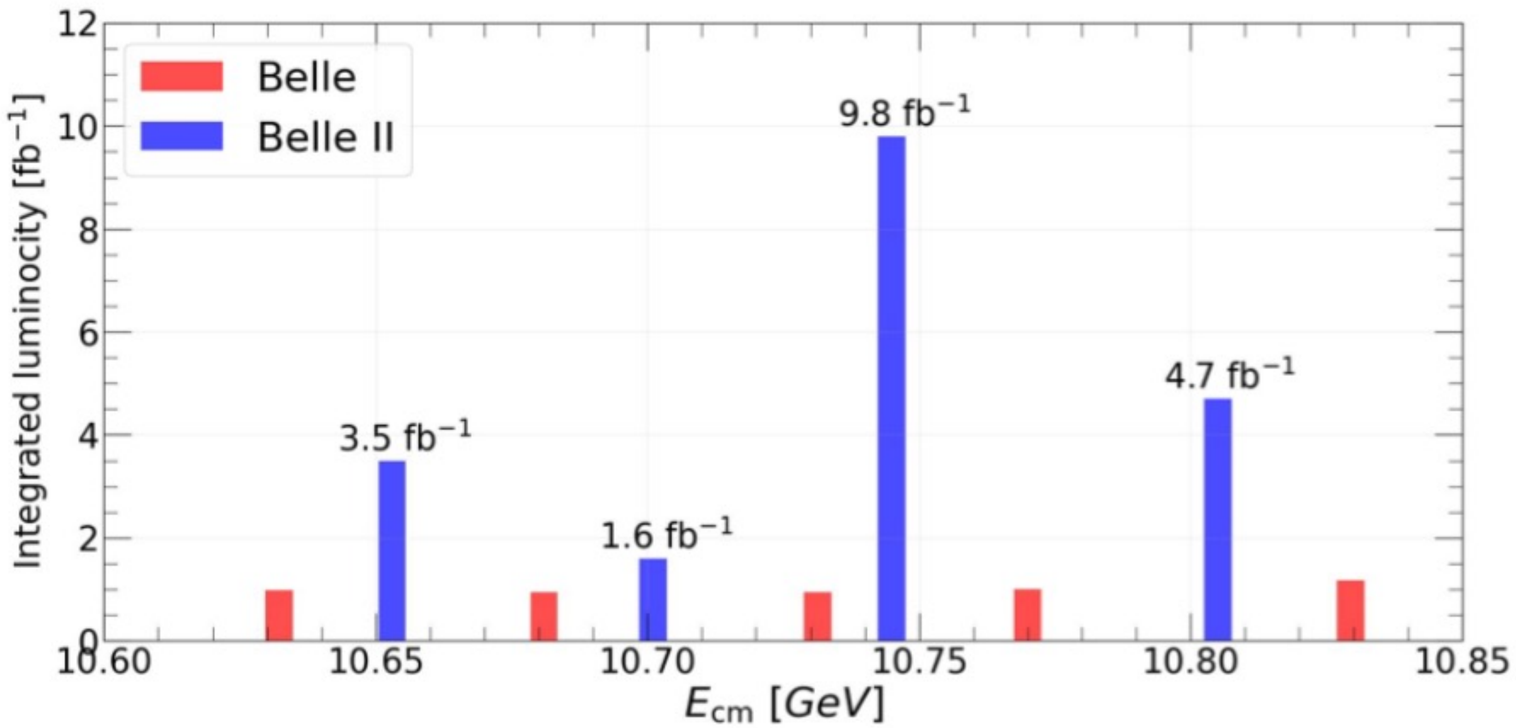
  $$\Gamma_{\rm R} = 14.3 \pm 9.2 \pm 6.3 \text{ MeV}$$

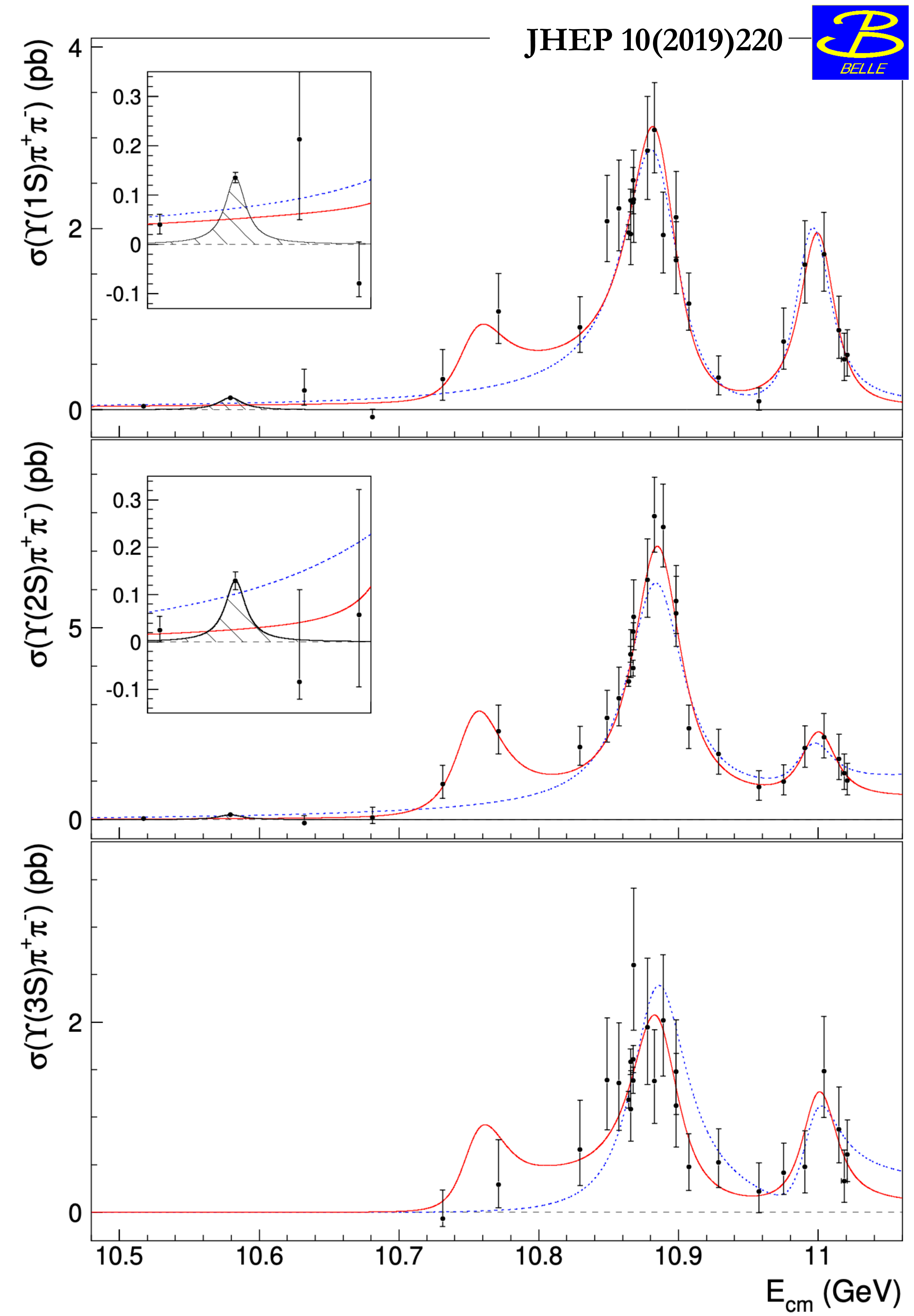
- Systematic uncertainty
  - Λ selection (determined by $B^\pm \to K^\pm \Lambda \bar{\Lambda}$) ~ O(5%); BF of $\Upsilon(2S) \to \Upsilon(1S)$ ~ O(6%)
  - for $M_{\rm R}$, $\Gamma_{\rm R}$ parameters: fit range (2.5, 3.5 MeV), N(bins) (3.2, 5.2 MeV)

Updates regarding $\Upsilon(10753)$

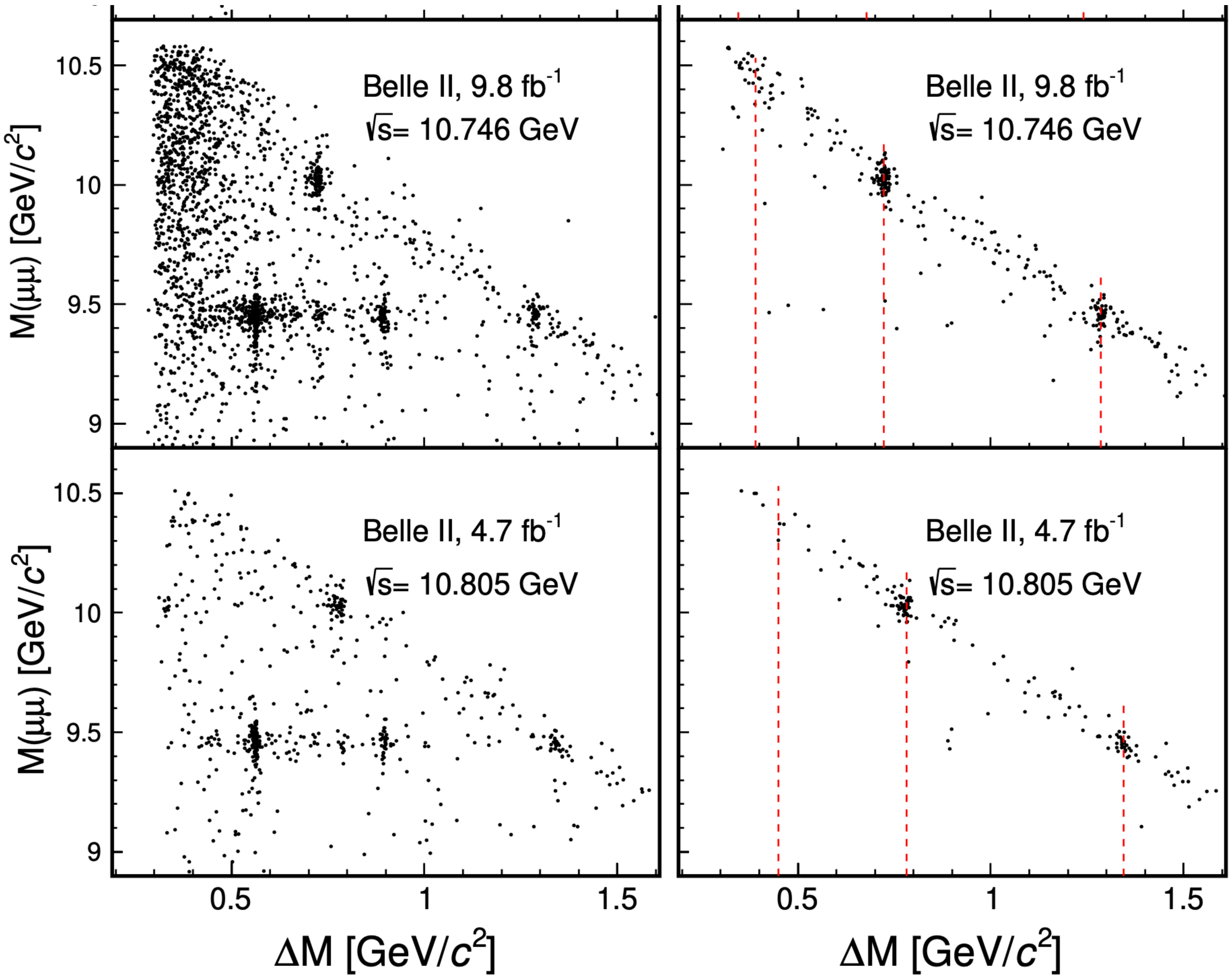
Energy scan for $\Upsilon(10753)$

- $\Upsilon(10753)$ — a reminder
  - first observed by Belle, [JHEP 10 (2019) 220] with 5.2σ
  - in the energy dependence of $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$
  - $\exists$ several competing interpretations
  - Belle also had exotic candidates $Z_b(10610)^\pm$, $Z_b(10650)^\pm$ [PRL 108, 122001 (2012)]
- Belle II added scan points
  - JHEP 07 (2024) 116





Confirmation of $\Upsilon(10753)$ signal



- Left-column figures for all events
- Right-column figures for $p(\pi\pi\mu\mu) < 0.1$ GeV to suppress events from ISR
- Red dash (----) corresponding to $\Upsilon(nS)$

Energy scan for $\Upsilon(10753)$

- $\Upsilon(10753)$ — a reminder
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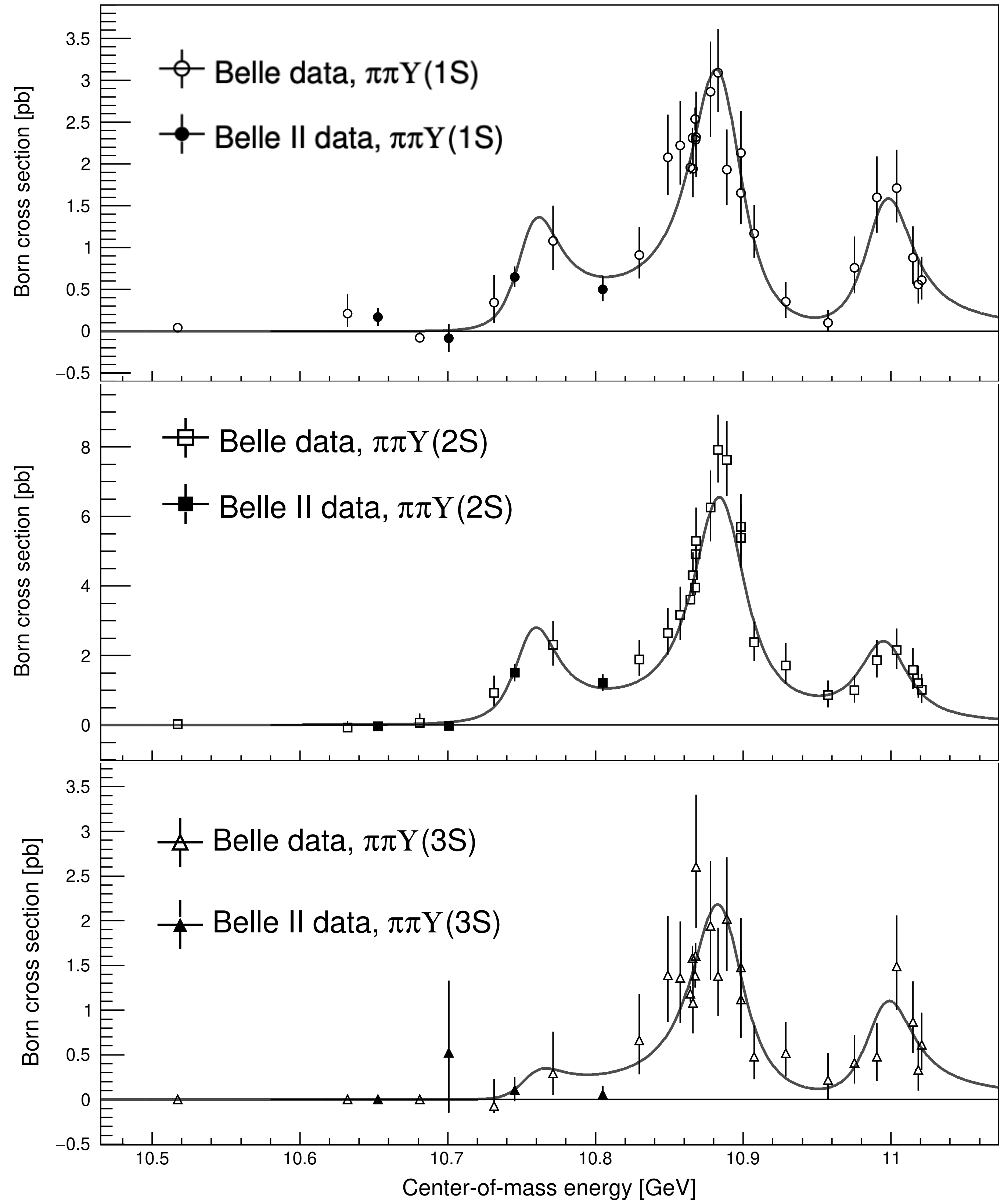
  - in the energy dependence of $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$
  - $\exists$ several competing interpretations
  - Belle also had exotic candidates $Z_b(10610)^\pm$, $Z_b(10650)^\pm$ [PRL 108, 122001 (2012)]
- Belle II added scan points
  - JHEP 07 (2024) 116
  - $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ with $\Upsilon(nS) \to \mu^+\mu^-$
  - confirms Belle results of $\Upsilon(10753)$

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

small

  - no signals for $Z_b(10610)^\pm$, $Z_b(10650)^\pm$



Cross-section ratios, etc.

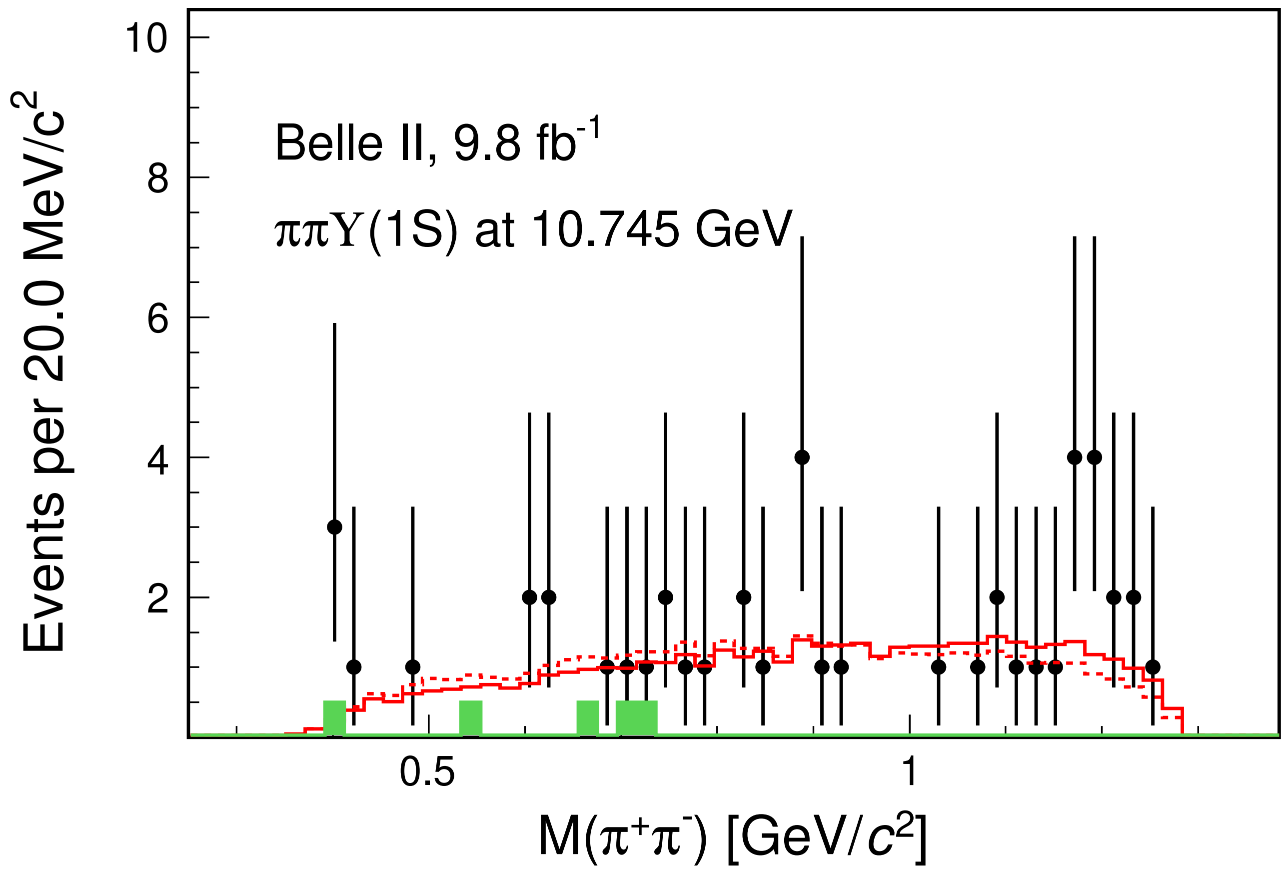
	$\mathcal{R}^{\Upsilon(10753)}_{\sigma(1S/2S)}$	$\mathcal{R}^{\Upsilon(10753)}_{\sigma(3S/2S)}$	$\mathcal{R}^{\Upsilon(5S)}_{\sigma(1S/2S)}$	$\mathcal{R}^{\Upsilon(5S)}_{\sigma(3S/2S)}$	$\mathcal{R}^{\Upsilon(6S)}_{\sigma(1S/2S)}$	$\mathcal{R}^{\Upsilon(6S)}_{\sigma(3S/2S)}$
Ratio	$0.46^{+0.15}_{-0.12}$	$0.10^{+0.05}_{-0.04}$	$0.45^{+0.04}_{-0.04}$	$0.32^{+0.04}_{-0.03}$	$0.64^{+0.23}_{-0.13}$	$0.41^{+0.16}_{-0.12}$

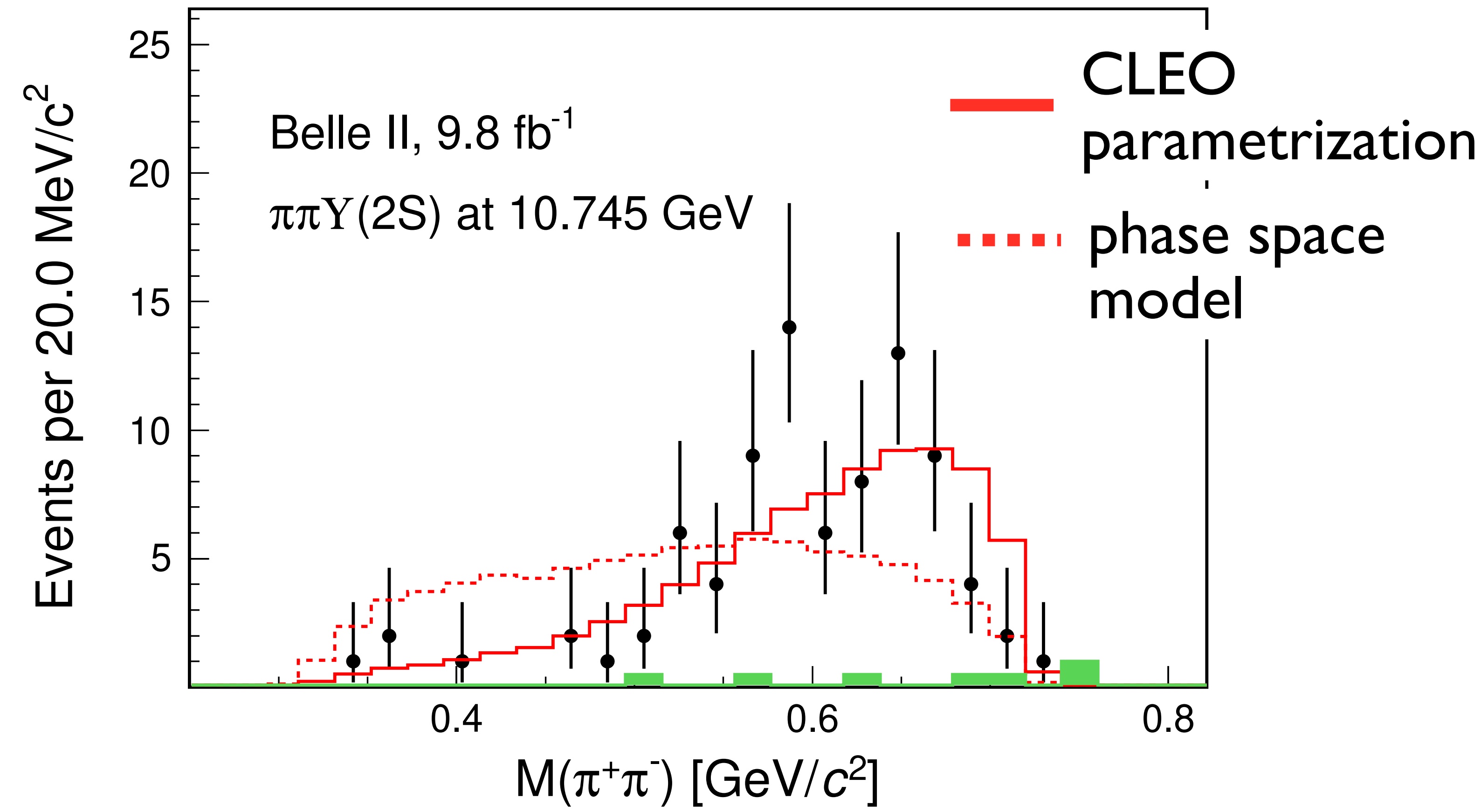
Table 2. Cross-section ratios at resonance peaks above the $\Upsilon(4S)$. Uncertainty in this table combines statistical and systematic uncertainties.

Mode	$N_{Z_{b1}}$	$N^{\mathrm{UL}}_{Z_{b1}}$	$\sigma_{Z_{b1}}$ (pb)	$\sigma^{\mathrm{UL}}_{Z_{b1}}$ (pb)	$N^{\mathrm{UL}}_{Z_{b2}}$	$N_{Z_{b2}}$	$\sigma_{Z_{b2}}$ (pb)	$\sigma^{\mathrm{UL}}_{Z_{b2}}$ (pb)
10.746 GeV								
$\pi\Upsilon(1S)$	$0.0^{+1.6}_{-0.0}$	<4.9	$0.00^{+0.04}_{-0.00}$	<0.13	–	–	–	
$\pi\Upsilon(2S)$	$5.8^{+5.9}_{-4.6}$	<13.8	$0.06^{+0.06}_{-0.05}$	<0.14	–	–	–	
10.805 GeV								
$\pi\Upsilon(1S)$	$2.5^{+2.4}_{-1.6}$	<5.2	$0.21^{+0.20}_{-0.13}$	<0.43	$0.0^{+0.7}_{-0.0}$	<5.8	$0.00^{+0.03}_{-0.00}$	<0.28
$\pi\Upsilon(2S)$	$5.2^{+3.8}_{-3.0}$	<12.3	$0.15^{+0.11}_{-0.09}$	<0.35	$0.0^{+0.8}_{-0.0}$	<6.0	$0.00^{+0.04}_{-0.00}$	<0.30

Table 3. Signal yields and upper limits at 90% credibility for $e^+e^- \to \pi Z_b(10610, 10650)$, $Z_b(10610, 10650) \to \pi\Upsilon(1S, 2S)$ processes and corresponding Born cross-section measurement limits. Uncertainties for the numbers of signal events are statistical only. Here we use Z_{b1} and Z_{b2} as shorthand for $Z_b(10610)$ and $Z_b(10650)$, respectively.

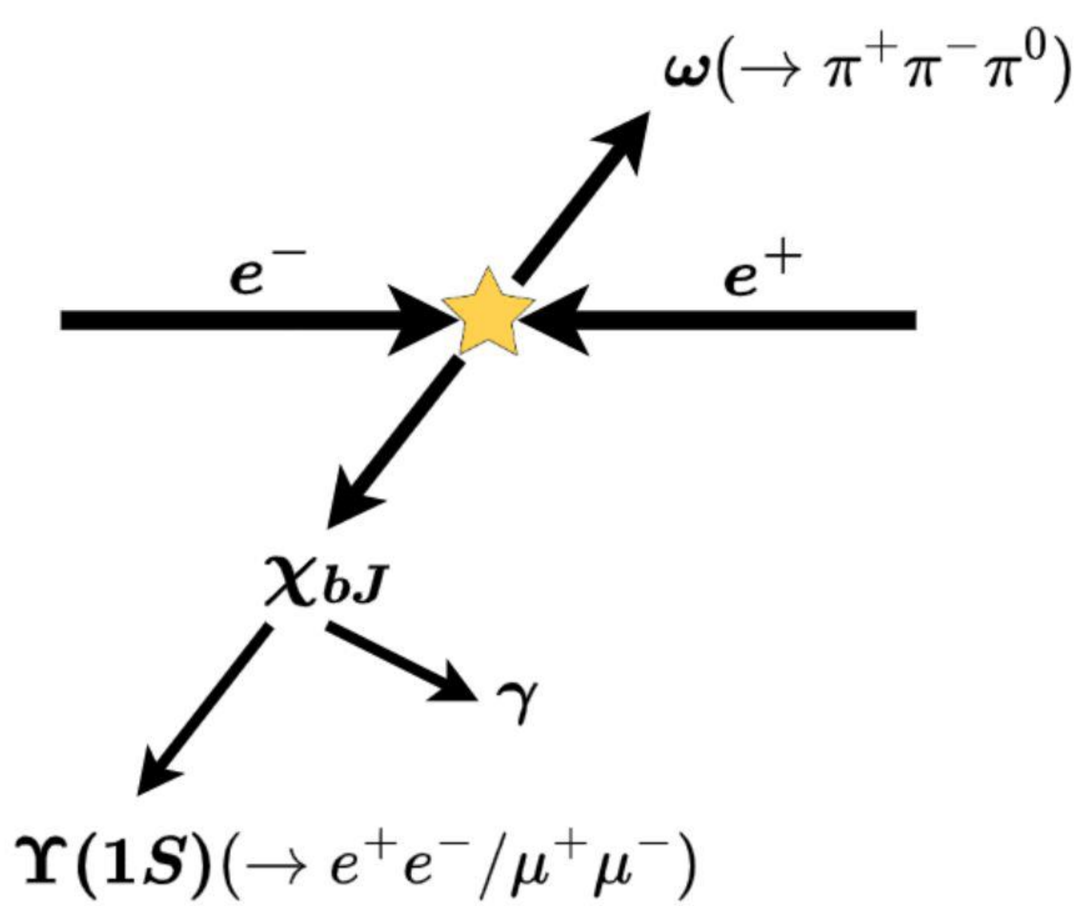
Di-pion mass distribution for $\Upsilon(10753)$

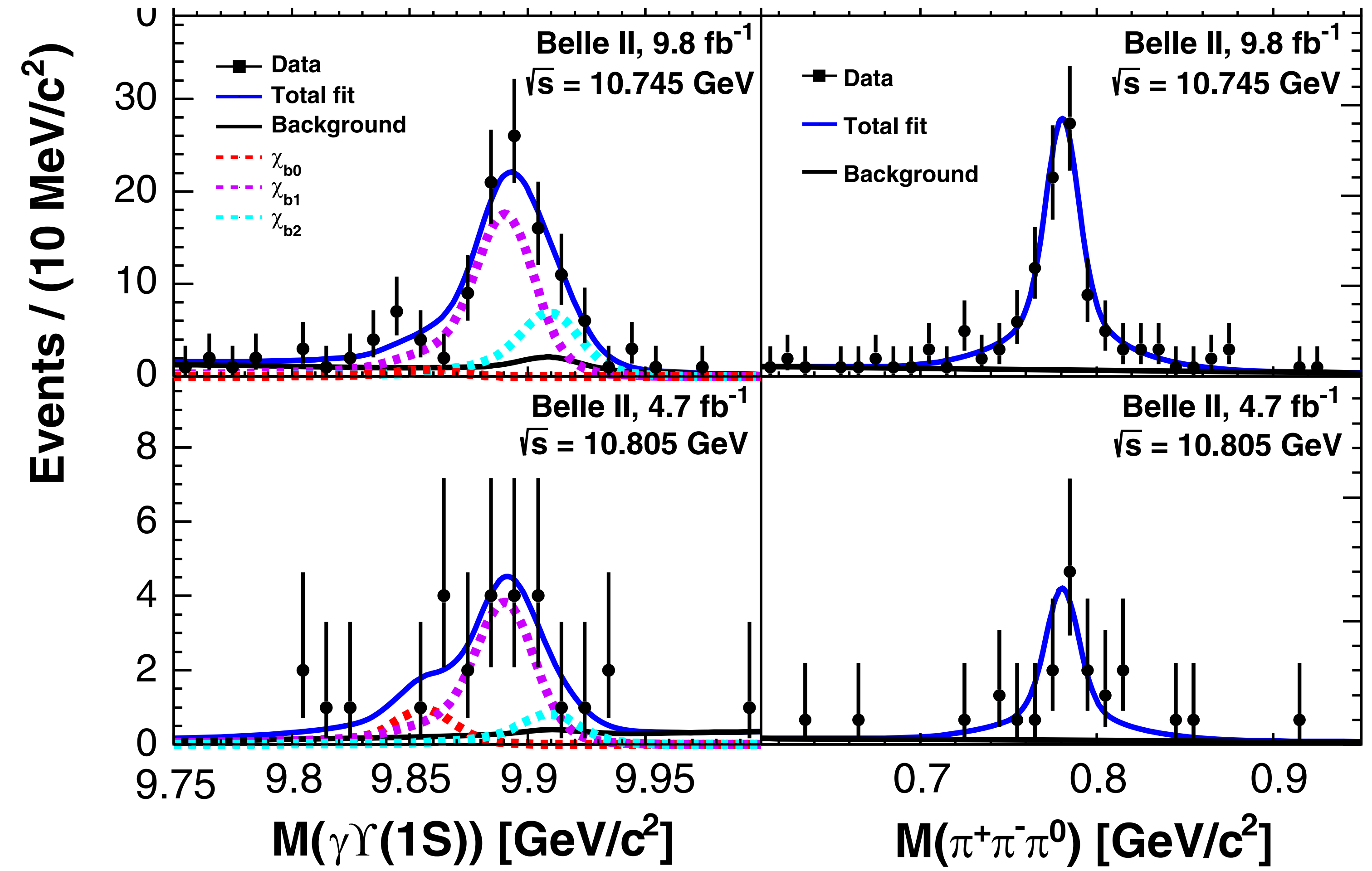


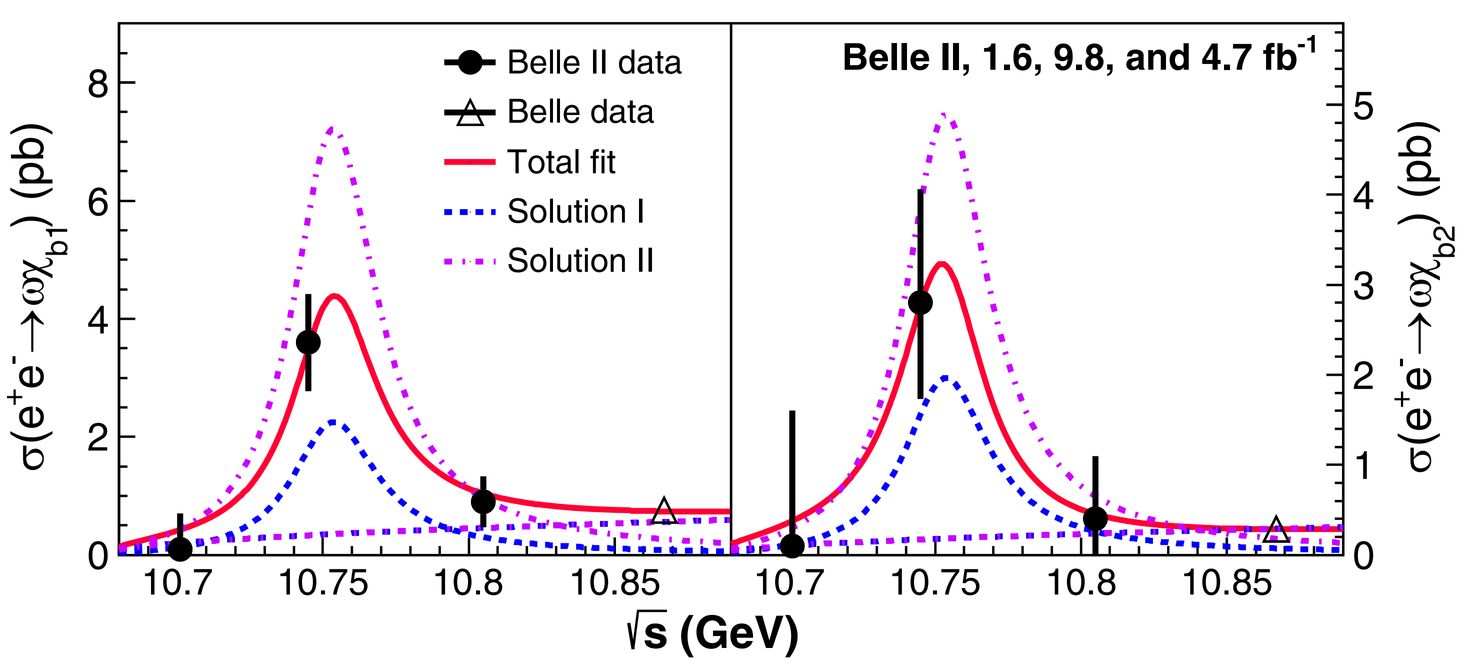


- similar to both phase-space model and $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ for $\pi^+\pi^-\Upsilon(1S)$
- but similar to $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ only for $\pi^+\pi^-\Upsilon(2S)$

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







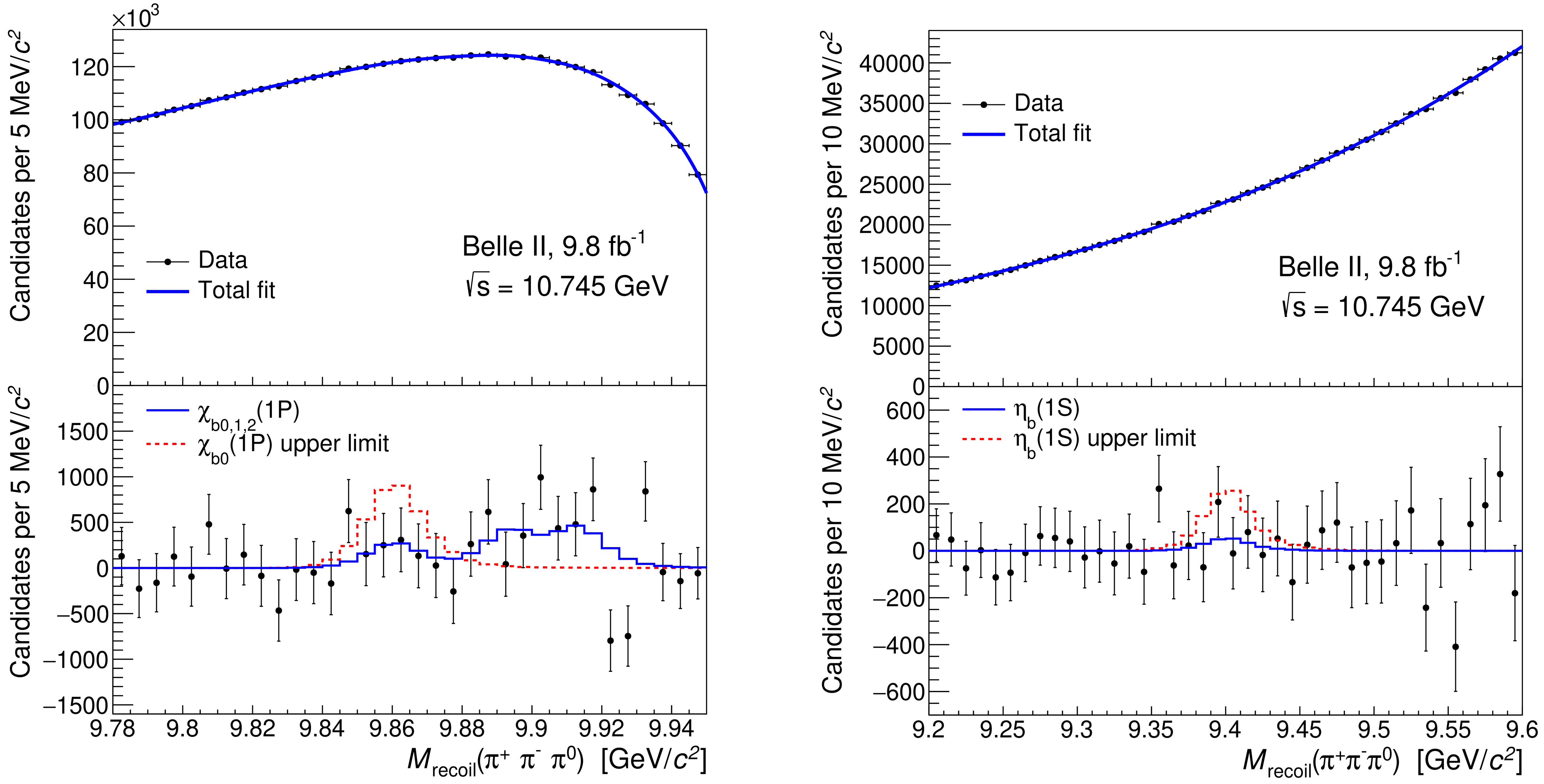
- cross section shows a peak at $\Upsilon(10753)$, hence a confirmation and a new decay channel
- the ratio $\chi_{b1}\omega/\pi\pi\Upsilon(nS) \sim$ one order of magnitude higher at $\Upsilon(10753)$ than at $\Upsilon(5S)$

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

- Tetraquark interpretation of this state predicts enhancement of $\Upsilon(10753) \to \eta_b(1S)\omega$

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

- we measure η_b indirectly by using recoil mass $M_{\rm recoil}(\omega) = \sqrt{(E_{\rm cm} - E_\omega)^2 - p_\omega^2}$
- no signals observed in either modes ➔ set upper limits



$$\sigma_{\rm B}(e^+e^- \to \eta_b(1S)\omega) < 2.5\,\text{pb},$$
$$\sigma_{\rm B}(e^+e^- \to \chi_{b0}(1P)\omega) < 8.7\,\text{pb}.$$

Summary

- As a B-factory, Belle II continues being a strong player in the study of exotic hadrons as well as spectroscopy of conventional ones.
- In this talk, we present the searches of charmed pentaquark states by Belle
  - Search for $P_c^+ \to pJ/\psi$ in $\Upsilon(1S)$ and $\Upsilon(2S)$
  - Evidence of $P_{cs}(4459)^0 \to \Lambda J/\psi$ in $\Upsilon(1S)$ and $\Upsilon(2S)$
- We also show Belle II results regarding $\Upsilon(10753)$, a new $b\bar{b}$-like state first observed by Belle in 2019.
  - Confirmation of $\Upsilon(10753)$
  - New decays channel $\Upsilon(10753) \to \chi_{bJ}\omega$
- Run 2 is underway with goal of collecting a several ab^{-1} data in the next few years. Please stay tuned!

Thank you!