Exotic states from $\Upsilon(1S, 2S)$ decays

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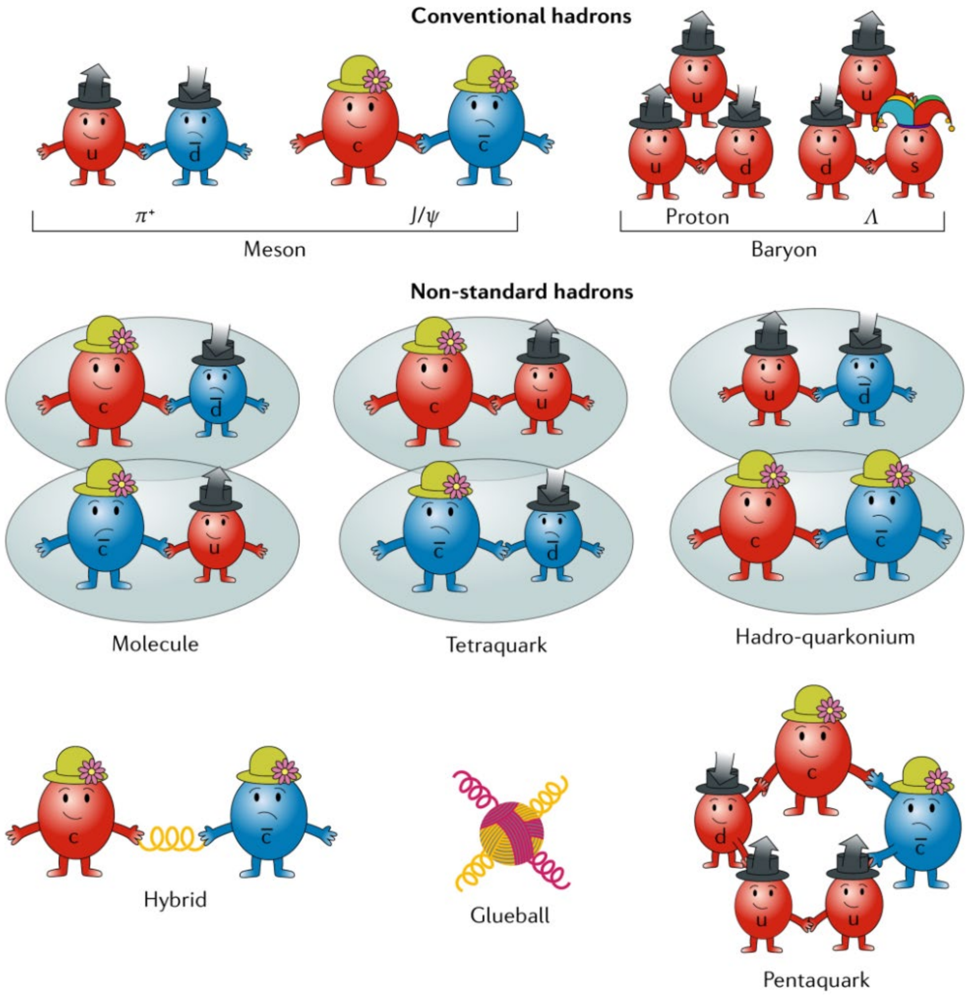
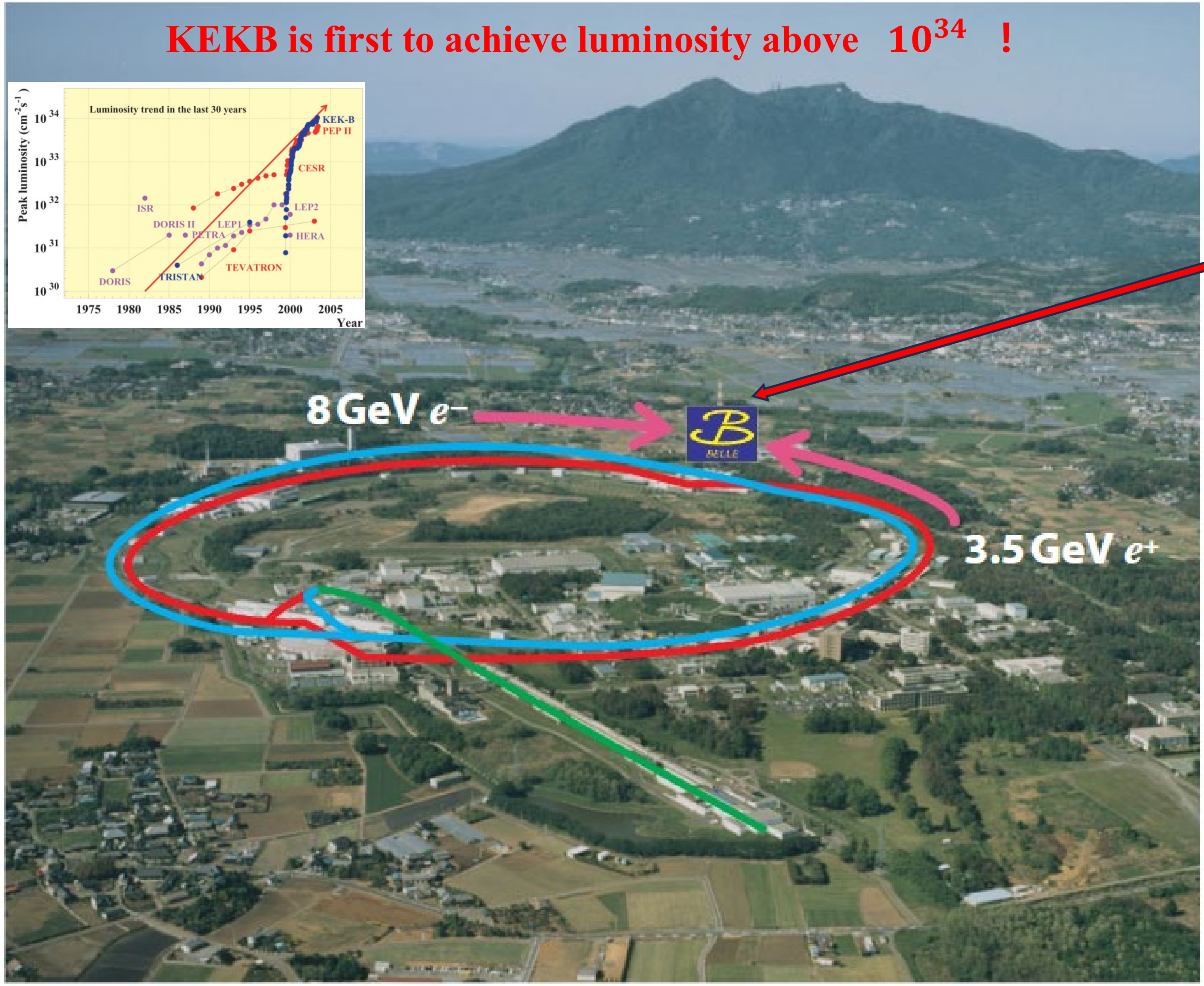
Overview

- Belle and Belle II detector.
- Previous results of exotic states from $\Upsilon(1S, 2S)$ decay.
- Charmed pentaquark candidates reported by LHCb.
- Study on $\Upsilon(1S, 2S) \to [P_c^{\pm} \to p(\bar{p})\, J/\psi] + X$.
- Study on $\Upsilon(1S, 2S) \to [P_{c\bar{c}s}^{0} \to \Lambda(\bar{\Lambda})\, J/\psi] + X$
- Summary

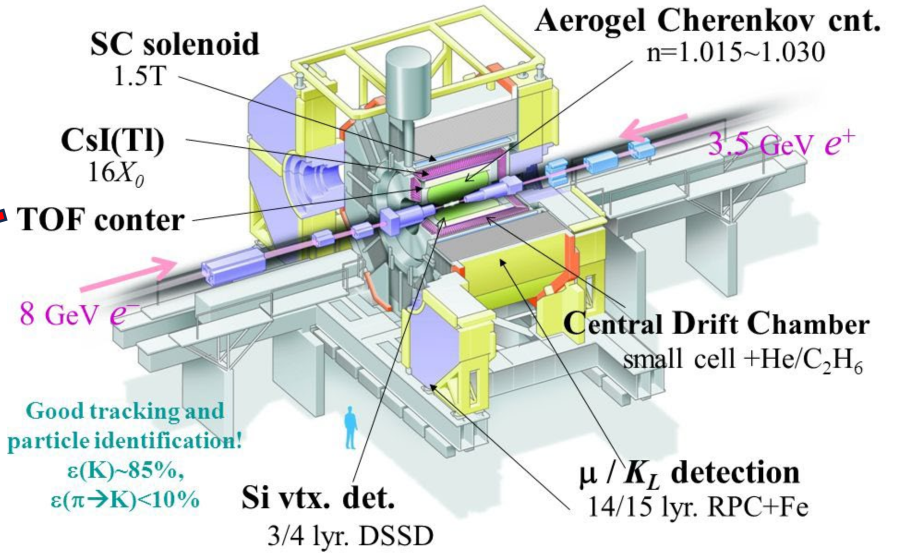


From Yuan & Olsen, Nature Rev. Phys. 1 (2019) no.8, 480-494

KEKB and Belle Detector



Belle Detector



Belle also has $\Upsilon(1S, 2S)$ data samples:

- 102M $\Upsilon(1S)$
- 158M $\Upsilon(2S)$

Belle (1999-2010) Luminosity

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

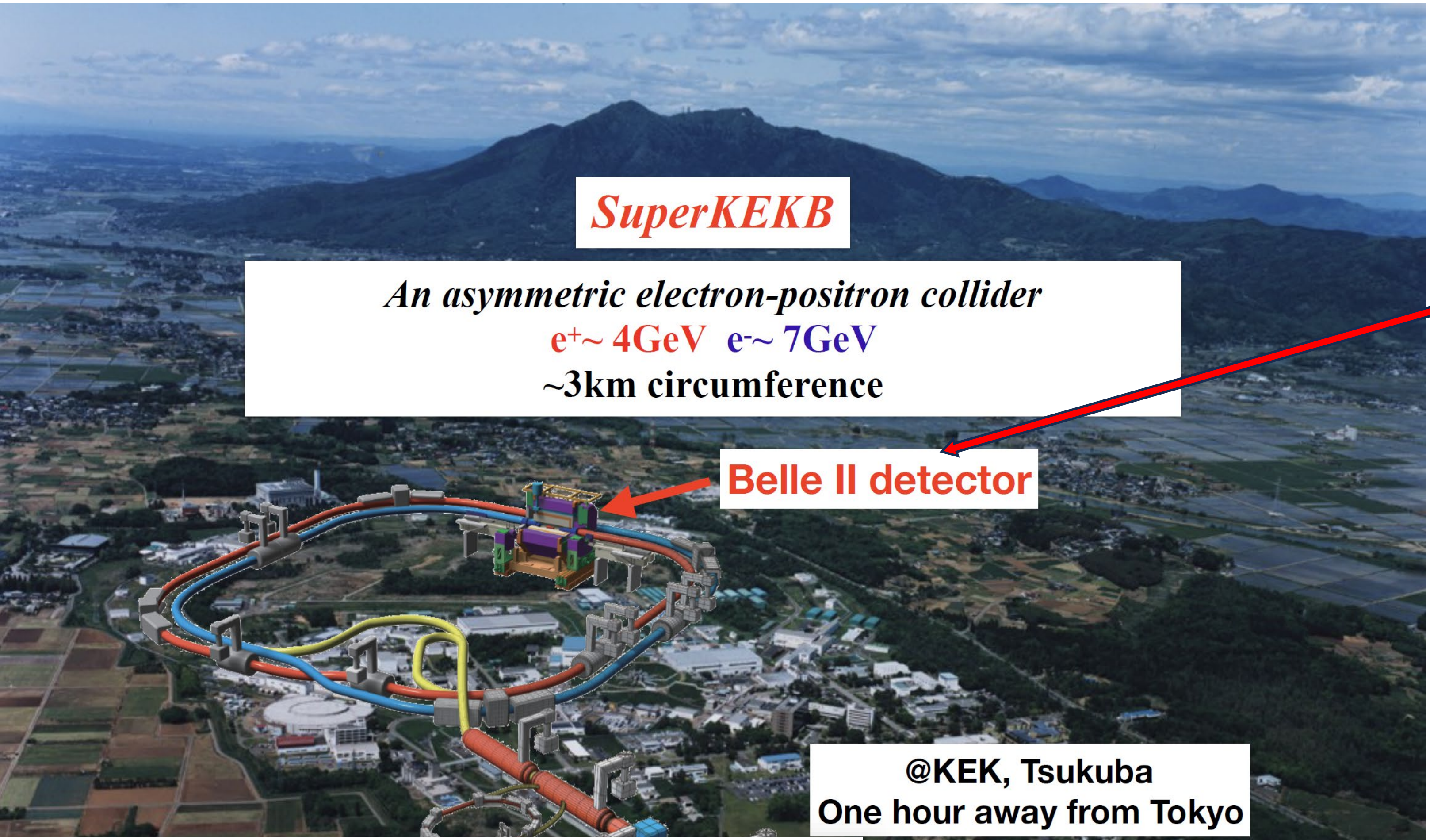
$$\int \mathcal{L}_{\Upsilon(4S)}\, dt = 711\ {\rm fb}^{-1}$$

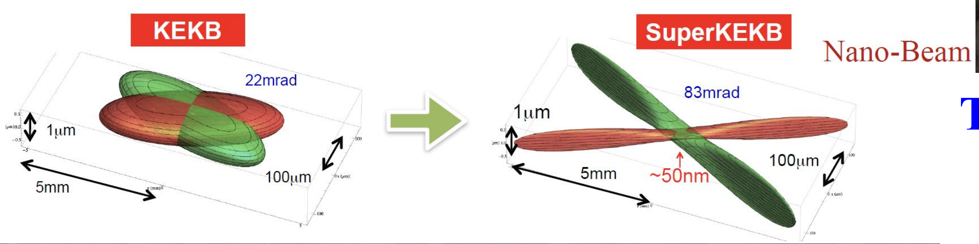
$$\int \mathcal{L}_{\Upsilon(1S)}\, dt = 5.8\ {\rm fb}^{-1}$$

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

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

SuperKEKB and Belle II Detector

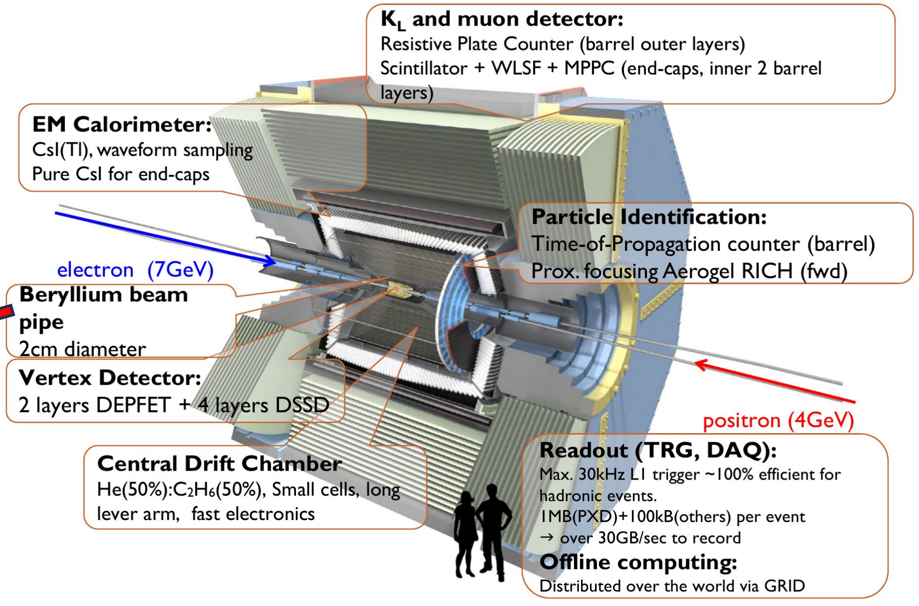


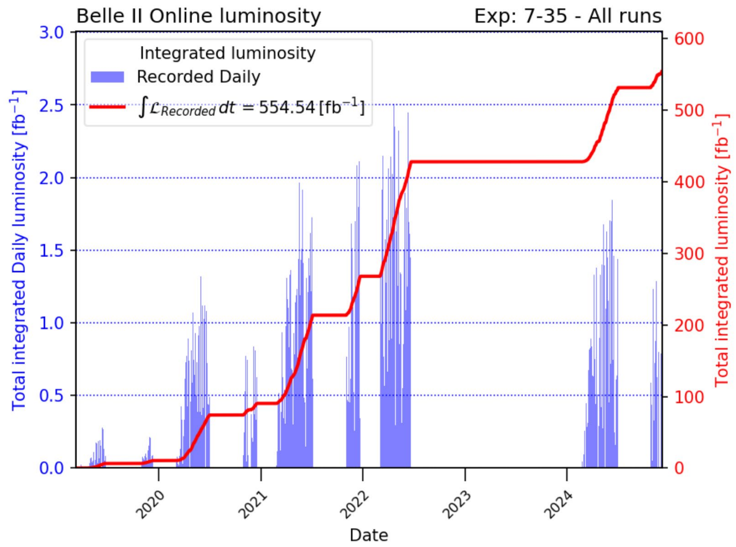


The newest luminosity record:

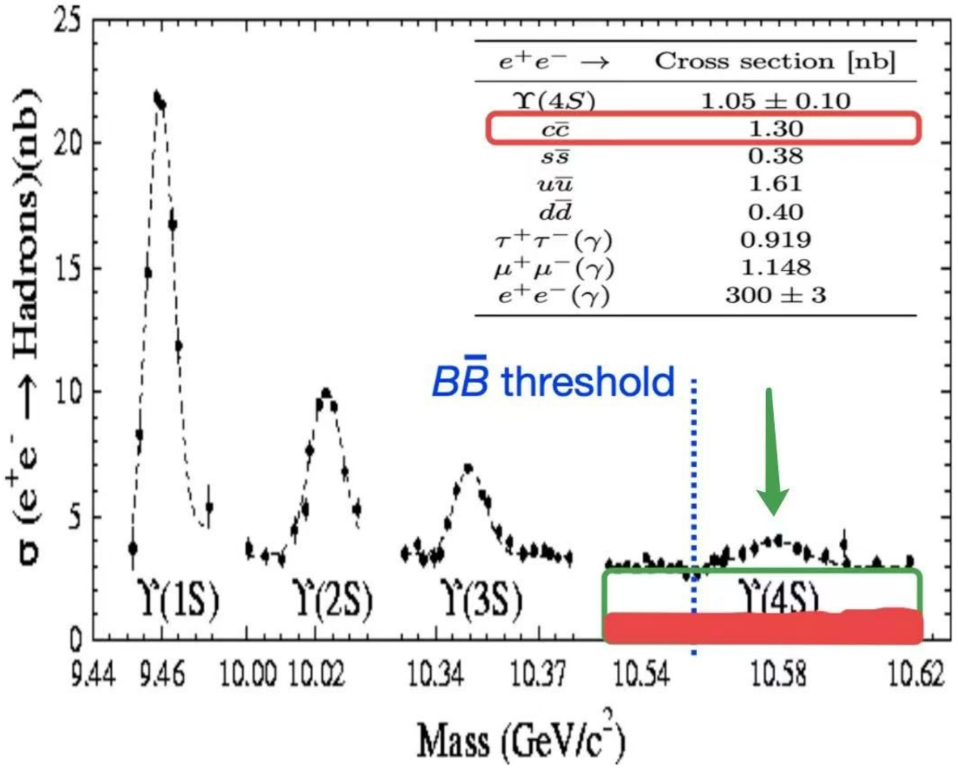
$5.1 \times 10^{34}\ \mathrm{cm^{-1}s^{-1}}$

(2024-12-27 01:40:59)





Decay characteristics of $\Upsilon(1S, 2S)$



$\Upsilon(1S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\tau^+\tau^-$	(2.60 ± 0.10) %	
Γ_2	e^+e^-	(2.39 ± 0.08) %	
Γ_3	$\mu^+\mu^-$	(2.48 ± 0.04) %	
	Hadronic decays		
Γ_4	ggg	(81.7 ± 0.7) %	
Γ_5	γgg	(2.2 ± 0.6) %	
Γ_6	$\eta'(958)$ anything	(2.94 ± 0.24) %	
Γ_7	$J/\psi(1S)$ anything	$(5.4 \pm 0.4) \times 10^{-4}$	S=1.4
Γ_8	$J/\psi(1S)\eta_c$	$< 2.2 \times 10^{-6}$	CL=90%
Γ_9	$J/\psi(1S)\chi_{c0}$	$< 3.4 \times 10^{-6}$	CL=90%
Γ_{10}	$J/\psi(1S)\chi_{c1}$	$(3.9 \pm 1.2) \times 10^{-6}$	
Γ_{11}	$J/\psi(1S)\chi_{c2}$	$< 1.4 \times 10^{-6}$	CL=90%

From PDG

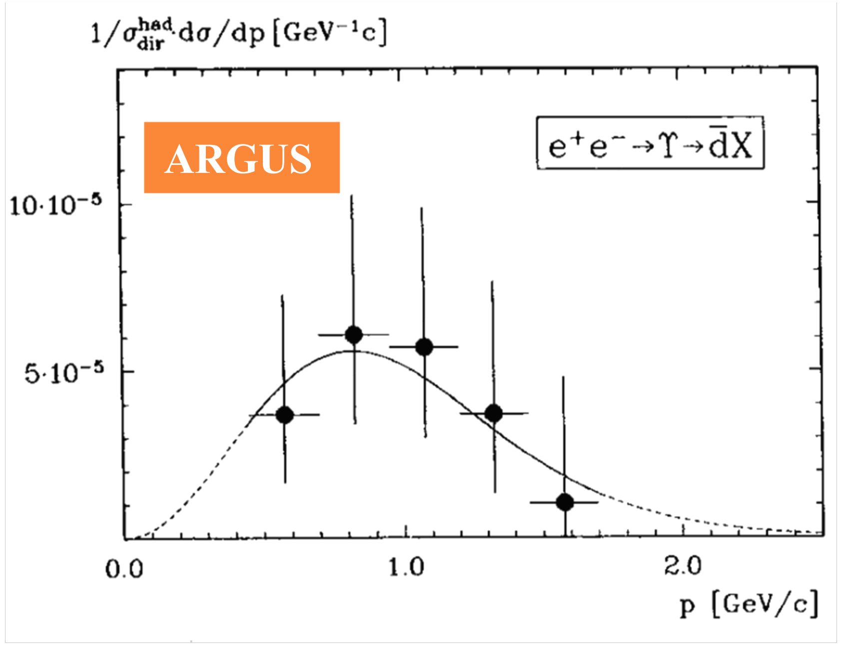
- $\Upsilon(1S, 2S)$ are the bound states of a bottom quark and its antiparticle, with masses **below the open-bottomonium threshold**.
- The decay of $\Upsilon(1S, 2S)$ has a **gluon-rich environment**, resulting in complex final states with a high multiplicity of hadrons.

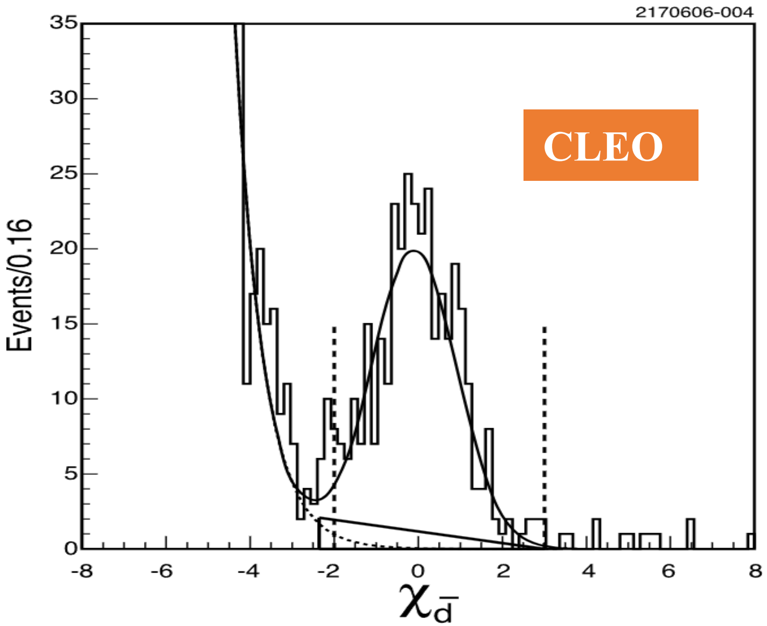
Anti-deuteron production in $\Upsilon(nS)$ decay

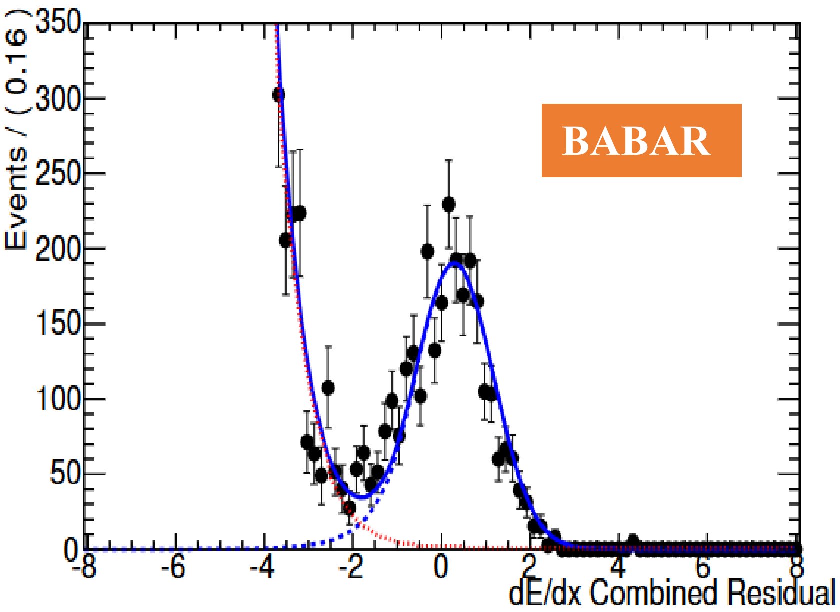
Phys.Lett. B 236,102(1990)

Phys.Rev.D 75,012009(2007)

Phys.Rev.D 89,111102(R)(2014)



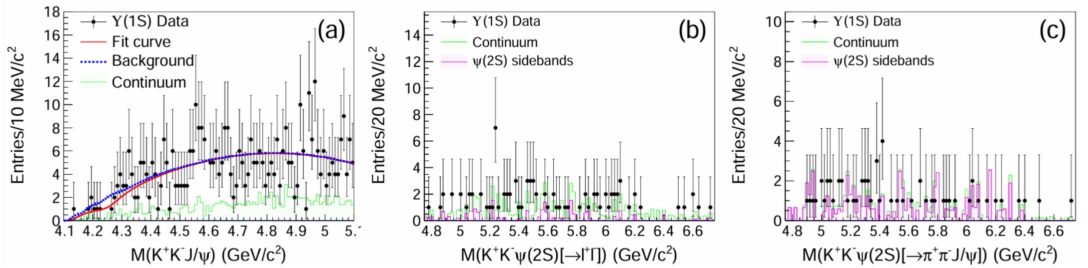




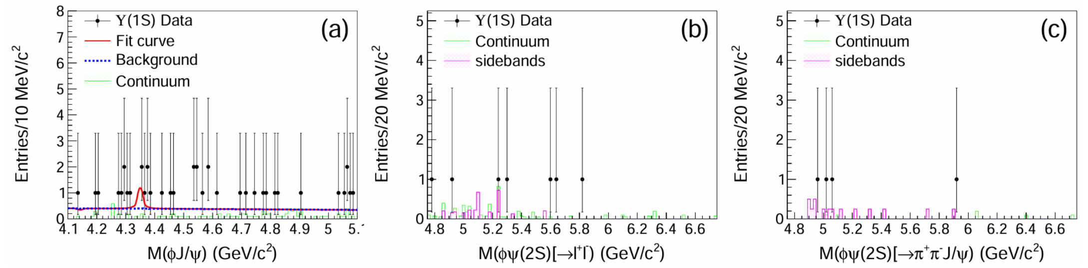
- ➢ The production of anti-deuteron in $\Upsilon(1S, 2S)$ inclusive decay was first measured by ARGUS in 1990.
- ➢ CLEO and BABAR experiments also found the anti-deuteron signal in $\Upsilon(1S, 2S)$ inclusive decay and continuum process, respectively.

A hint: maybe we can search for more exotic states in $\Upsilon(nS)$ inclusive decay?

Search for XYZ states in $\Upsilon(1S)$ decay

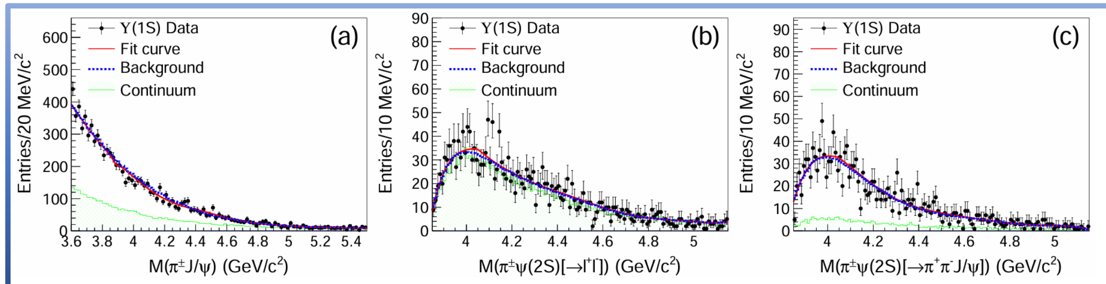


$Y(4260) \to K^+K^- J/\psi$



$Y(4140) \to \phi J/\psi$

$X(4350) \to \phi J/\psi$



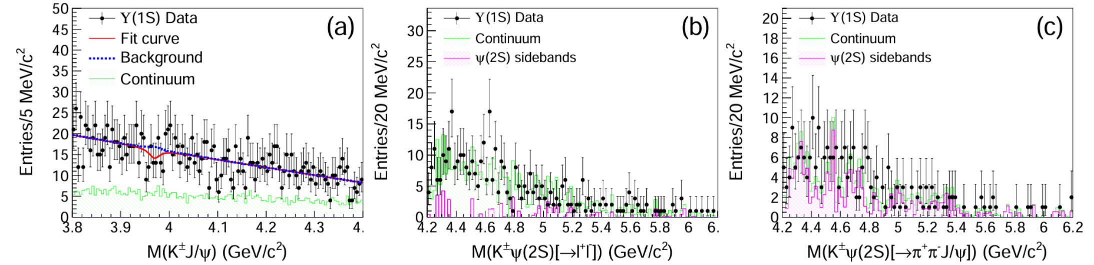
$Z_c(3900)^\pm \to \pi^\pm J/\psi$

$Z_c(4200)^\pm \to \pi^\pm J/\psi$

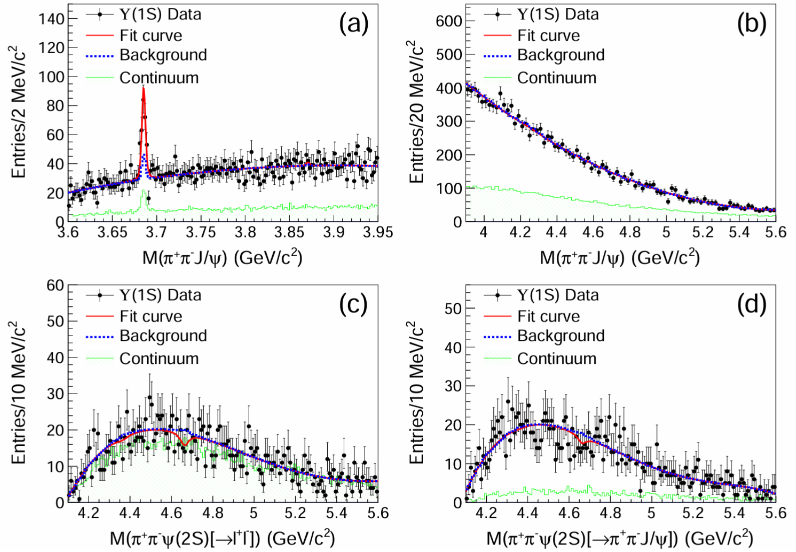
$Z_c(4430)^\pm \to \pi^\pm J/\psi$

$Z_c(4050)^\pm \to \pi^\pm \psi(2S)$

$Z_c(4430)^\pm \to \pi^\pm \psi(2S)$



$Z_{cs}^\pm \to K^\pm J/\psi$



$X(3872) \to \pi^+\pi^- J/\psi$

$Y(4260) \to \pi^+\pi^- J/\psi$

$Y(4260) \to \pi^+\pi^- \psi(2S)$

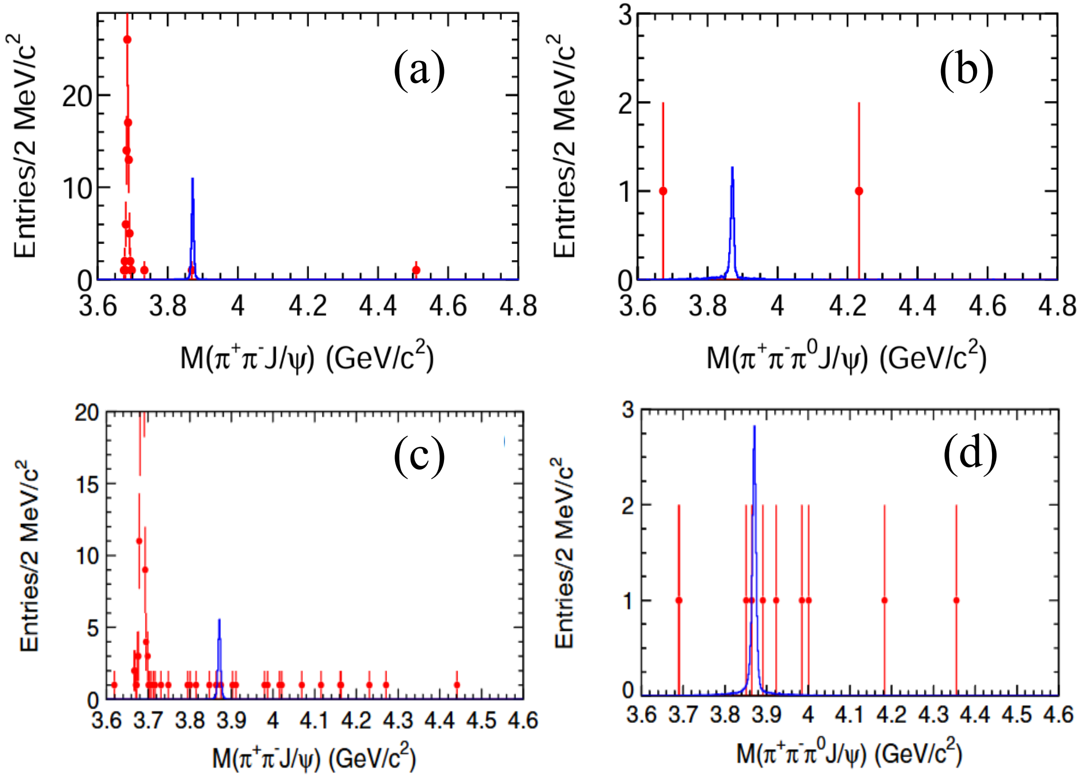
$Y(4360) \to \pi^+\pi^- \psi(2S)$

$Y(4660) \to \pi^+\pi^- \psi(2S)$

Belle searched for some XYZ states in $\Upsilon(1S)$ inclusive decay using 14 decay modes, while no evident signal was found.

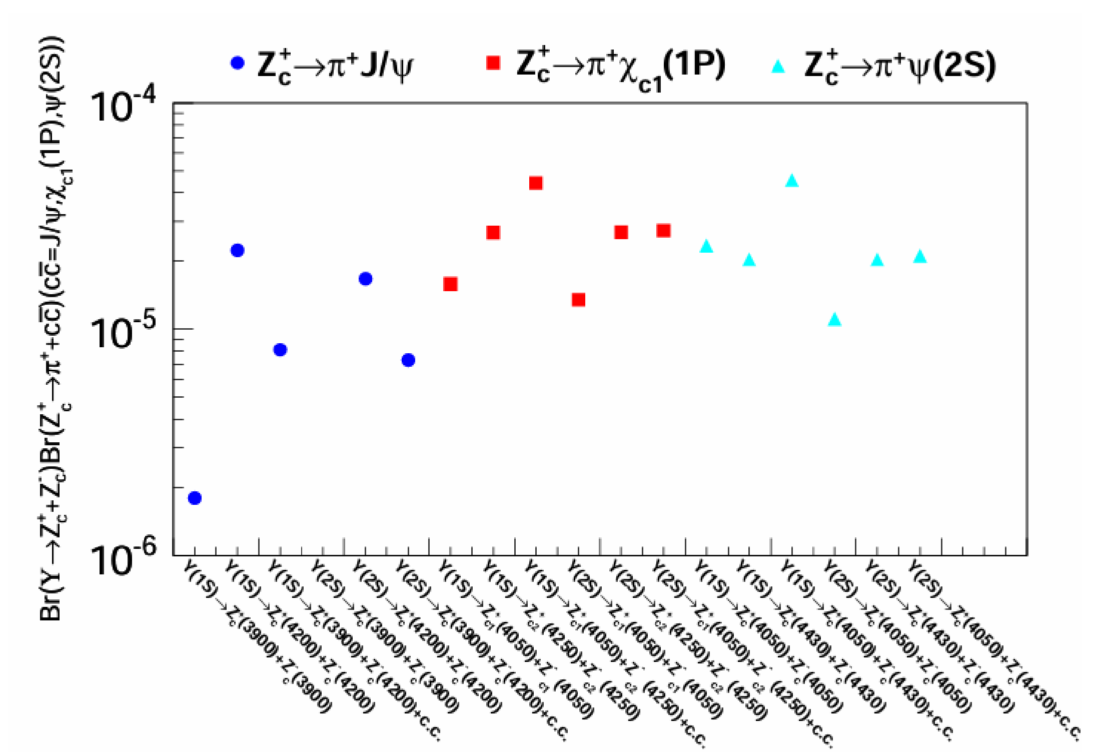
Phys.Rev.D 93 (2016) 11, 112013

Search for XYZ states in $\Upsilon(1,2S)$ decay



- Belle searched for $X(3872)$, $X(3915), Y(4160)$ in **$\Upsilon(1S,2S)$ radiative decay** [$\Upsilon(1S,2S) \to \gamma X(Y)$].
- (a)(b)~ $\Upsilon(1S)$; (c)(d)~ $\Upsilon(2S)$.
- No evident signal was found .

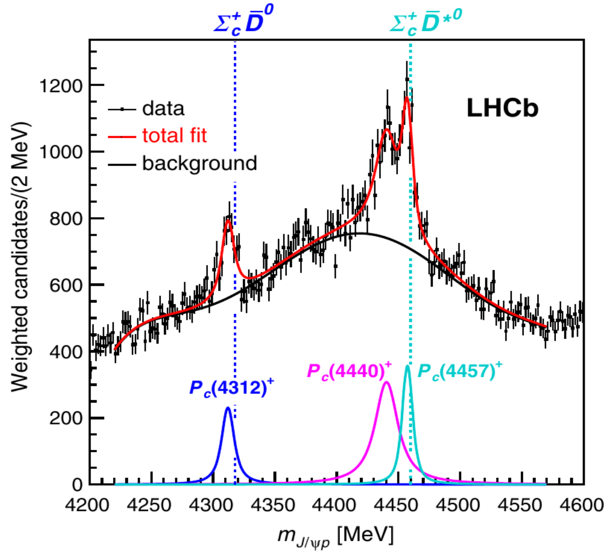
Phys. Rev. D 82, 051504(R) (2010) **Phys. Rev. D 87, 071107(R) (2011)**



- Belle searched for Z_c pair in the decay of $\boldsymbol{\Upsilon(1S,2S)}$.
- (a)(b)~ $\Upsilon(1S)$; (c)(d)~ $\Upsilon(2S)$.
- No evident signal was found and the upper limits on the product branching fraction were given.

Phys. Rev. D 97, 112004 (2018)

Candidates of pentaquark states

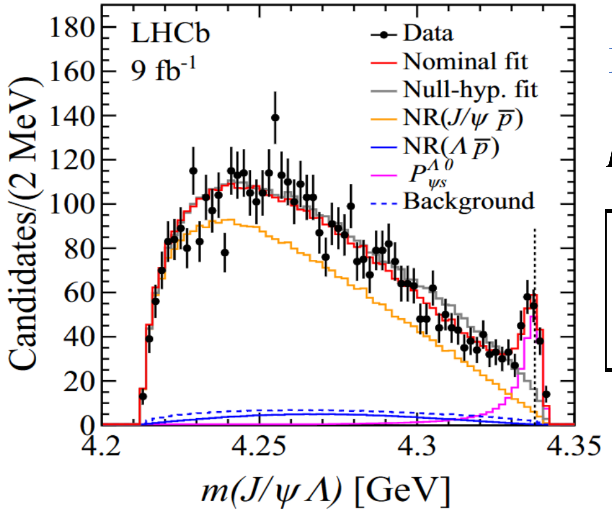


Phys. Rev. Lett. 115, 072001 (2015)

Phys. Rev. Lett. 122, 222001 (2019)

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

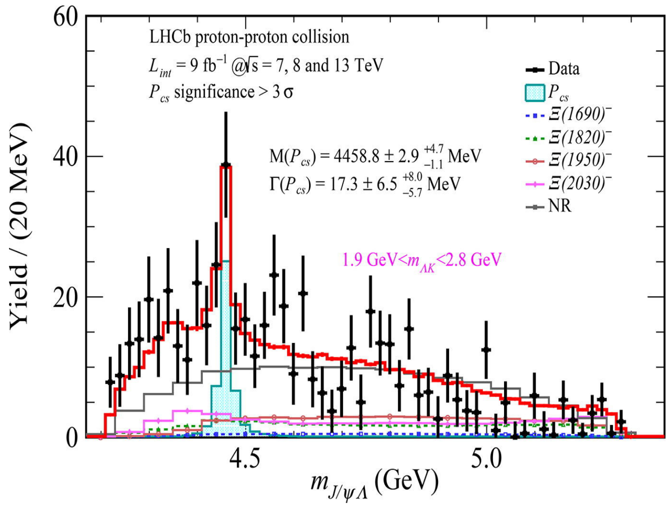
State	M (MeV/c²)	Γ (MeV)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$



Phys.Rev.Lett. 131, 031901 (2023)

$B^- \to \bar{p} + \Lambda J/\psi$

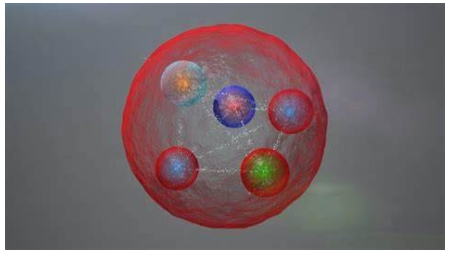
$P_{c\bar{c}s}(4338)$:
M = $4338.3 \pm 0.7 \pm 0.4$ MeV
$\Gamma = 7.0 \pm 1.2 \pm 1.3$ MeV



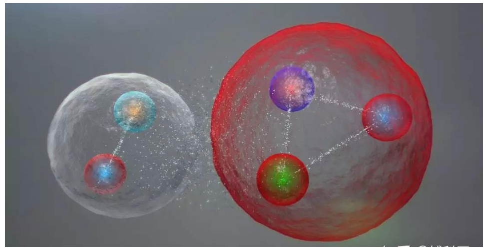
Sci.Bull. 66 1278 (2021)

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

$P_{c\bar{c}s}(4459)$:
M = $4458.8 \pm 0.7 \pm 0.4$ MeV
$\Gamma = 17.3 \pm 1.2 \pm 1.3$ MeV



OR

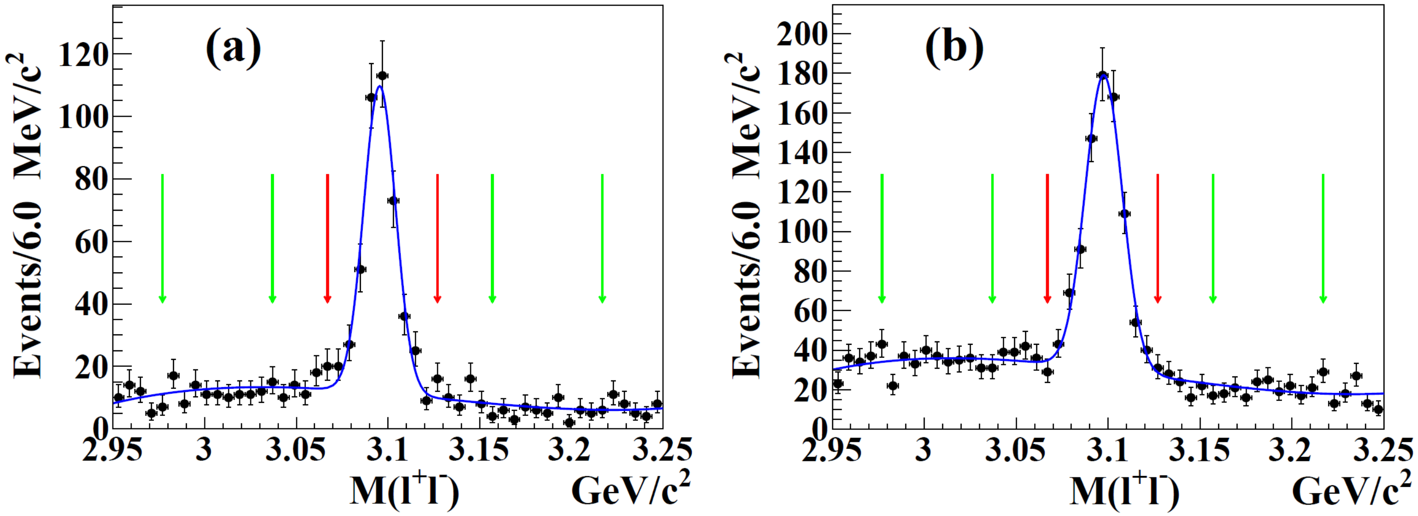


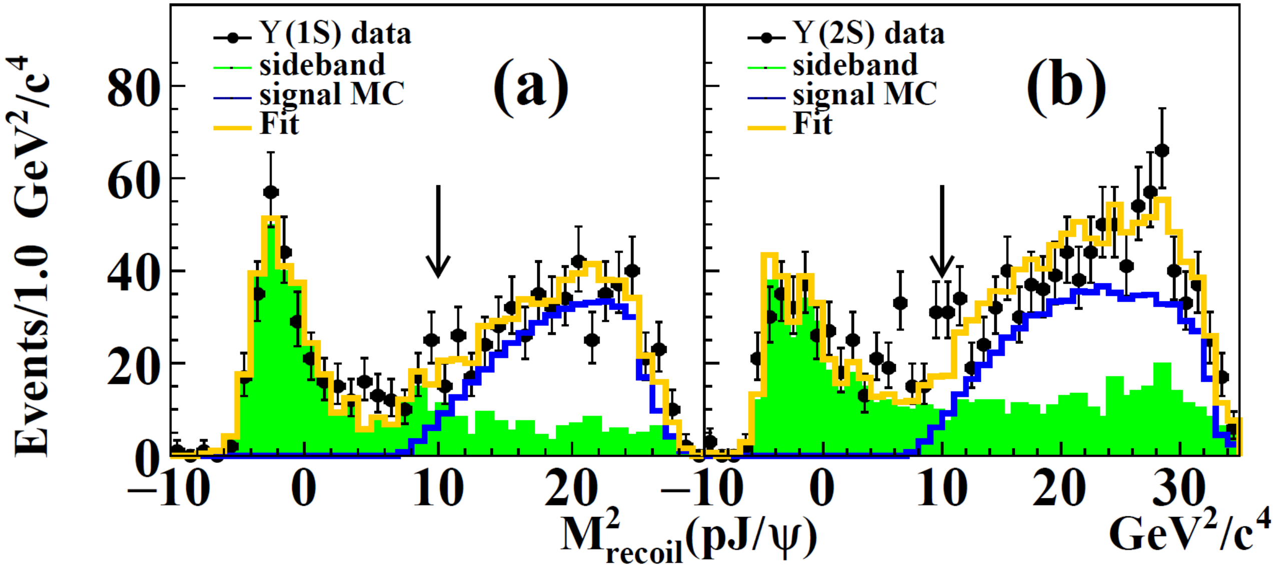
- Where to search for these potential pentaquark states at Belle/Belle II?
- A clue: production of hyperons and deutrons is enhanced in $\Upsilon(1S, 2S)$ inclusive decays.

Study on $P_c^{\pm} \to p(\bar{p})\, J/\psi$ in $\Upsilon(1S, 2S)$ inclusive decay

(arXiv:2403.04340)

Event selection



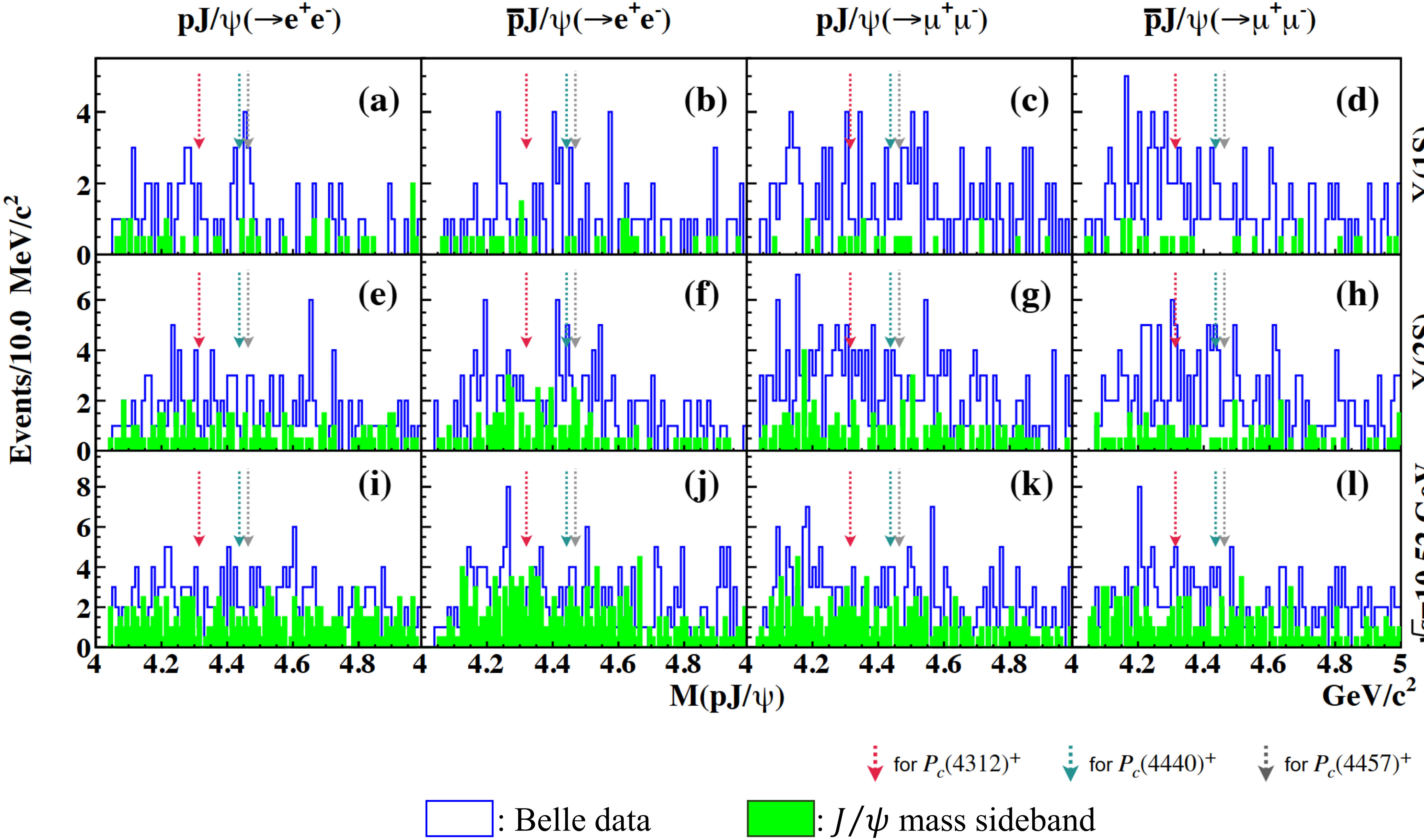


We search for P_c states in pJ/ψ final states in $\Upsilon(1S,2S)$ inclusive decay.

$$J/\psi \to l^+l^-, l = e \text{ or } \mu$$

- **Basic event Selection**
  - 3 well measured charged tracks.
  - Identification of $e^\pm, \mu^\pm$, and $p^\pm$.
  - Λ veto for p candidates.
  - Impact parameters between p and leptons ($\Delta dz < 0.5$ cm).
- **Cut on $M^2_{recoil}(pJ/\psi)$**
  - $M^2_{recoil}(pJ/\psi) > 10\ (\mathrm{GeV/c^2})^2$

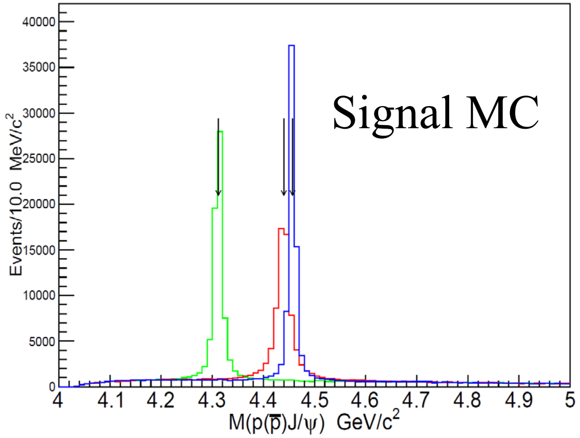
Invariant mass distributions

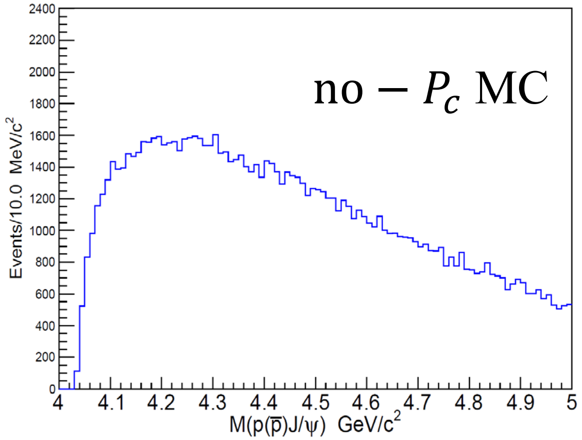


Fit to M(pJ/ψ)

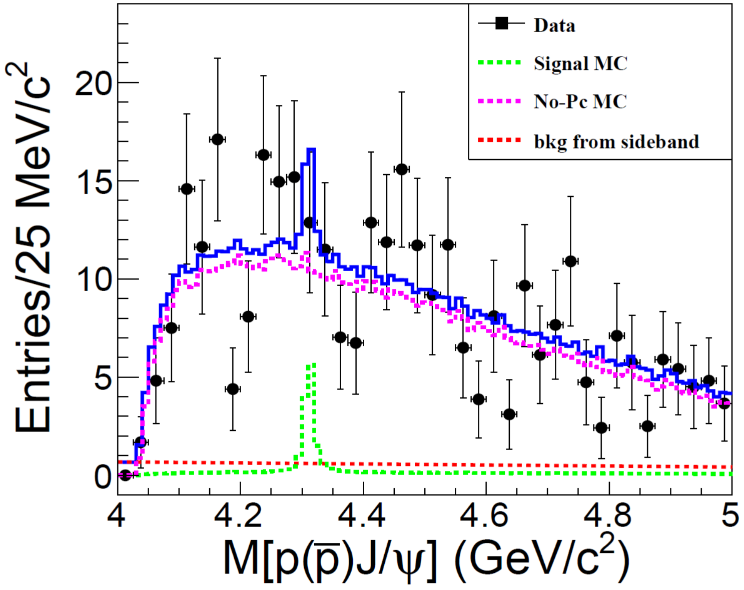
The formula used in the fit to events from J/ψ mass region is:

$$f_{PDF} = f_R + f_{\text{no}-P_c} + f_{bkg}$$

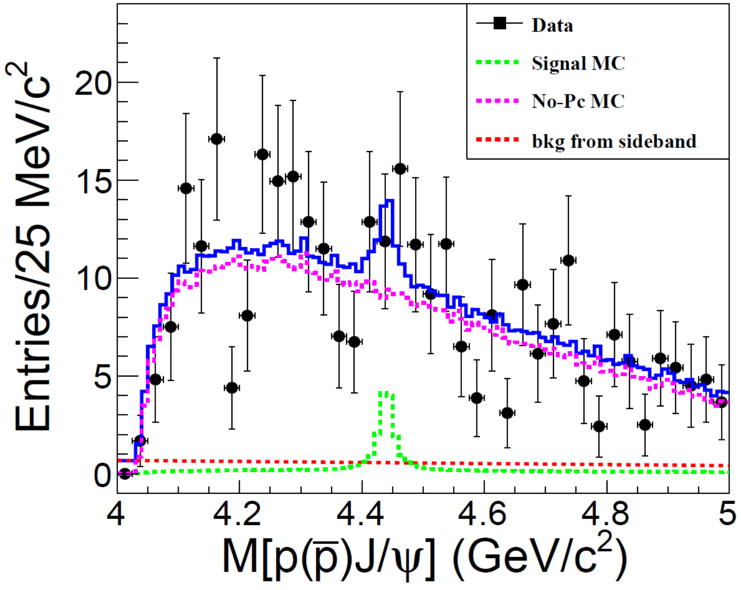




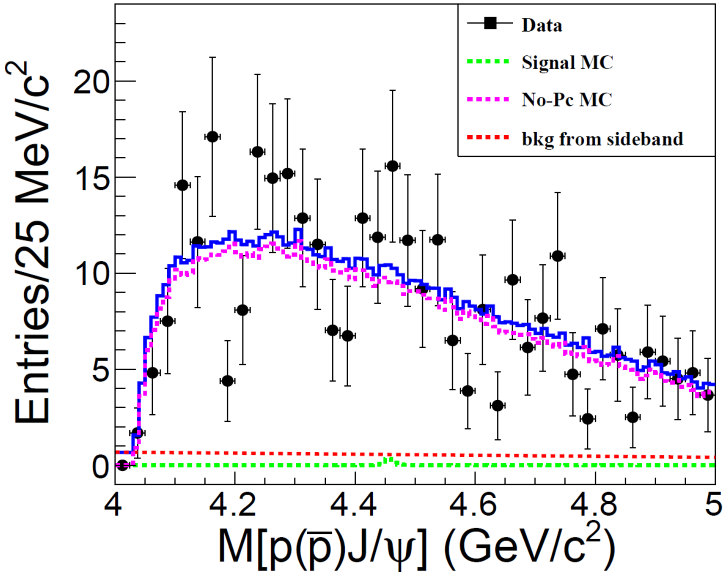
no − P_c MC is used to simulate the non-resonance process.



$P_c(4312)^+$

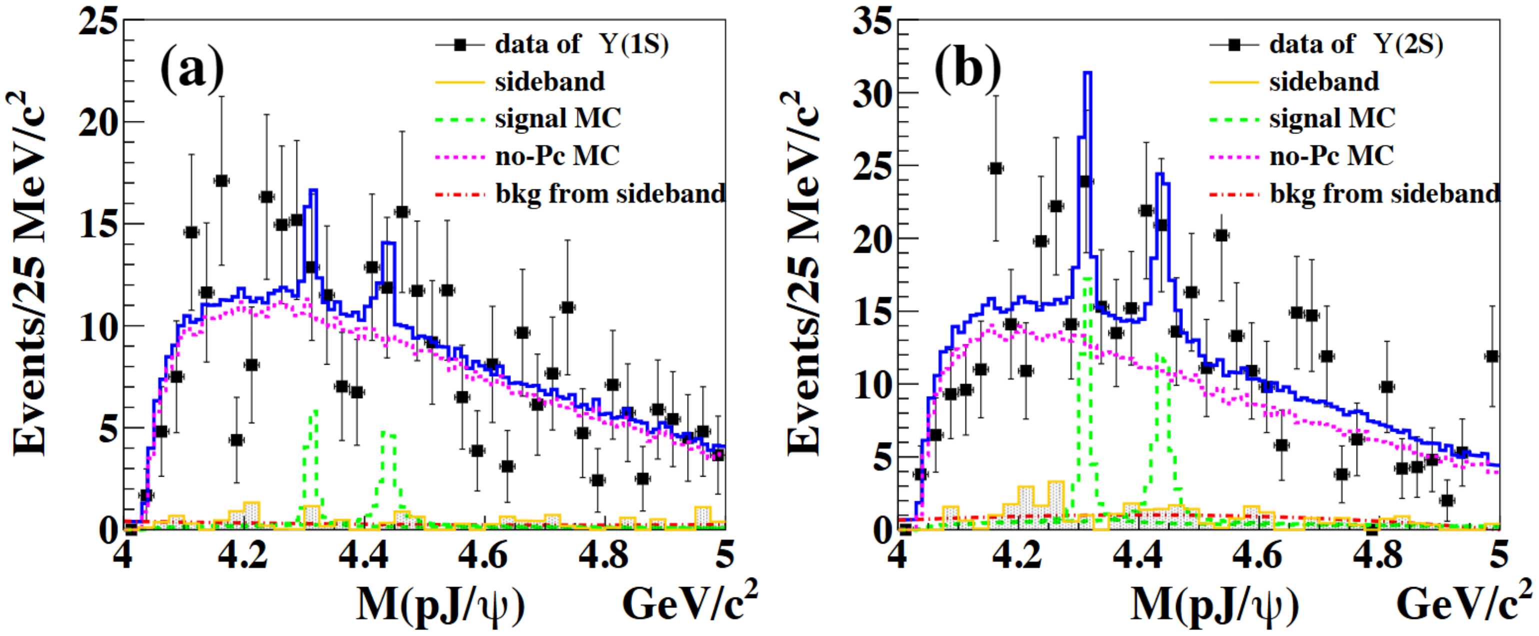


$P_c(4440)^+$



$P_c(4457)^+$

Fit to $M(pJ/\psi)$



	$\Upsilon(1S)$ decays			$\Upsilon(2S)$ decays		
—	$P_c(4312)^+$	$P_c(4440)^+$	$P_c(4457)^+$	$P_c(4312)^+$	$P_c(4440)^+$	$P_c(4457)^+$
$N_{\rm fit}^{\rm A}$	6 ± 8	10 ± 11	13 ± 10	23 ± 9	30 ± 13	2 ± 15
$N_{\rm fit}^{\rm A,UL}$	20	27	30	40	54	13
$N_{\rm fit}^{\rm B}$	8 ± 9	10 ± 11	10 ± 9	24 ± 9	29 ± 11	3 ± 12
$N_{\rm fit}^{\rm B,UL}$	24	28	31	42	53	15
$N_{\rm sig}^{\rm UL}$	27	43	38	50	77	28
$\mathcal{B}^{\rm UL}$ $(\times 10^{-6})$	3.9	6.2	5.5	4.7	7.2	2.6

- No significant P_c state is obtained in the pJ/ψ of $\Upsilon(1S, 2S)$ inclusive decays.
- We set upper limits on P_c productions from $\Upsilon(1S, 2S)$ inclusive decay.
- We measure the branching fractions of pJ/ψ productions from $\Upsilon(1S, 2S)$ inclusive decay:
  - $Br[\Upsilon(1S) \rightarrow pJ/\psi + anything] = (4.27 \pm 0.16 \pm 0.20) \times 10^{-5}$
  - $Br[\Upsilon(2S) \rightarrow pJ/\psi + anything] = (3.59 \pm 0.14 \pm 0.16) \times 10^{-5}$

Study on $P^{0}_{c\bar{c}s} \to J/\psi\,\Lambda/\bar{\Lambda}$ in $\Upsilon(1S, 2S)$ inclusive decay

(arXiv:2502.09951)

Event selection

We search for $P^0_{c\bar{c}s}$ states in $\Lambda J/\psi$ final states in $\Upsilon(1S,2S)$ inclusive decay.

$J/\psi \to l^+l^-, l = e$ or μ

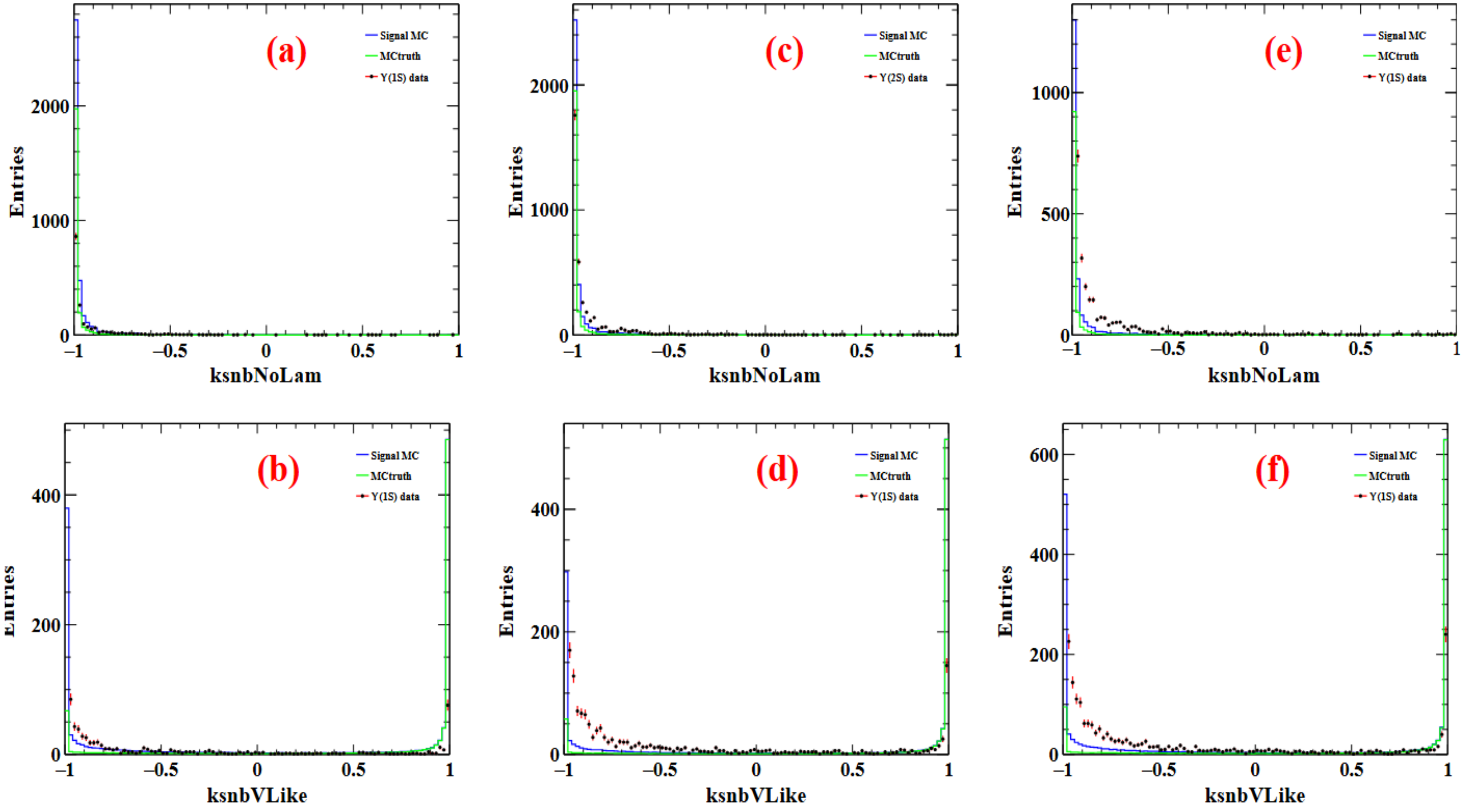
$\Lambda \to p\pi^-$

➢ Basic event Selection

- 4 well measured charged tracks.
- Identification of $e^{\pm}, \mu^{\pm}$.

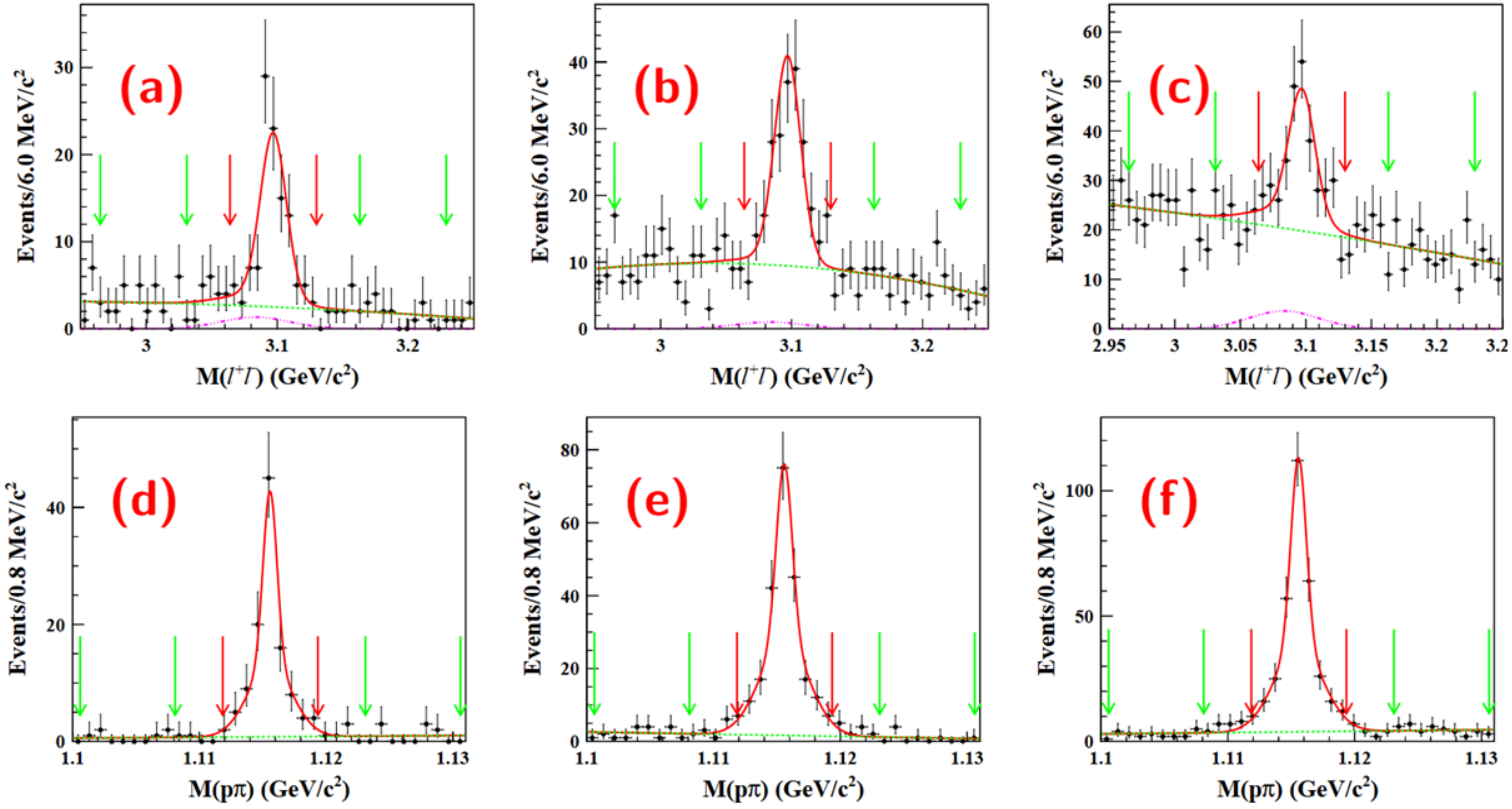
➢ Λ selection

- Select Λ with neural network framework (nisKsFinder).
- We can get about 96% selection efficiency for Λ with nisKsFinder.



(a)(b)~ $\Upsilon(1S)$, (c)(d)~ $\Upsilon(1S)$, (e)(f)~continuum process

Event selection



(a)(d)~ $\Upsilon(1S)$, (b)(e)~ $\Upsilon(1S)$, (c)(f)~continuum process.

Both Λ and J/ψ are clear.

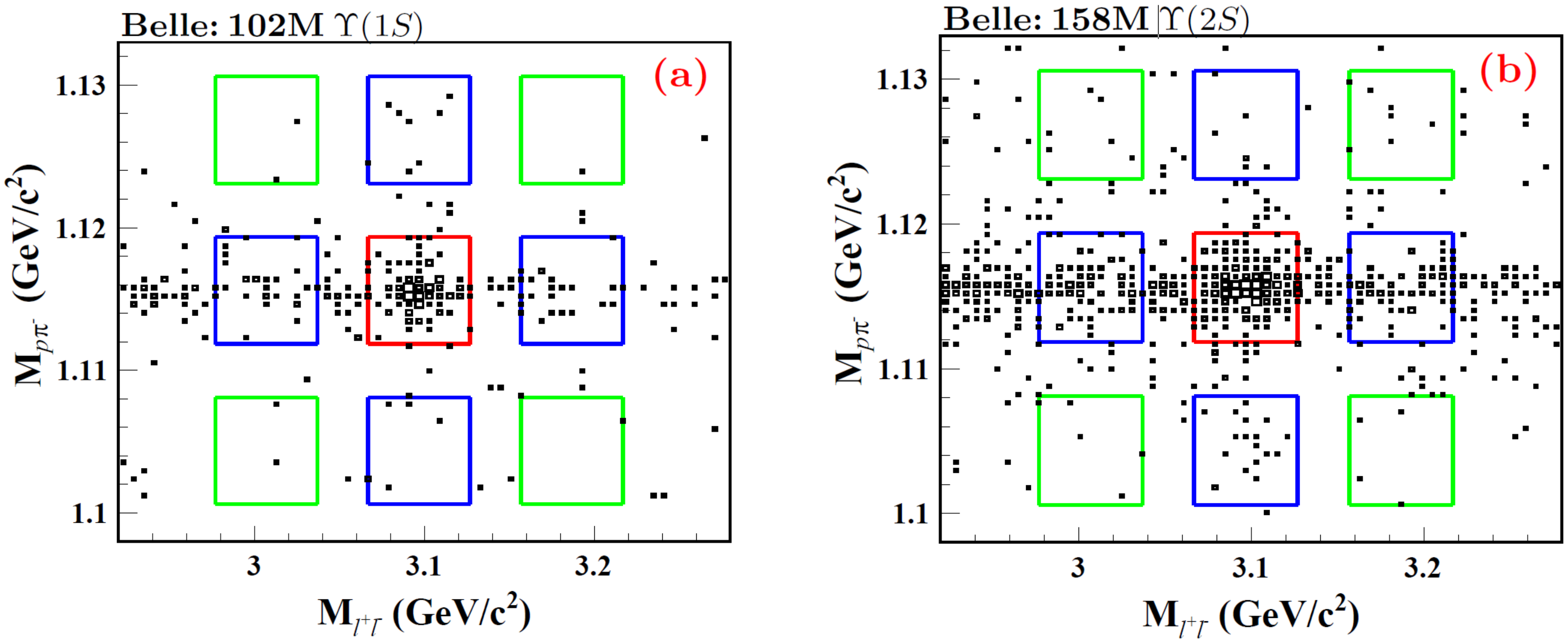
- 89 fb-1 data sample collected at 10.52 GeV is used to estimate the continuum production.
- J/ψ mass window:

  $|M_{l^+l^-} - 3.0969| < 3 * 10.0\ \mathrm{MeV/c^2}$
- Λ mass window:

  $|M_{p\pi^-} - 1.1156| < 3 * 1.4\ \mathrm{MeV/c^2}$

$\Lambda J/\psi$ production

Preliminary

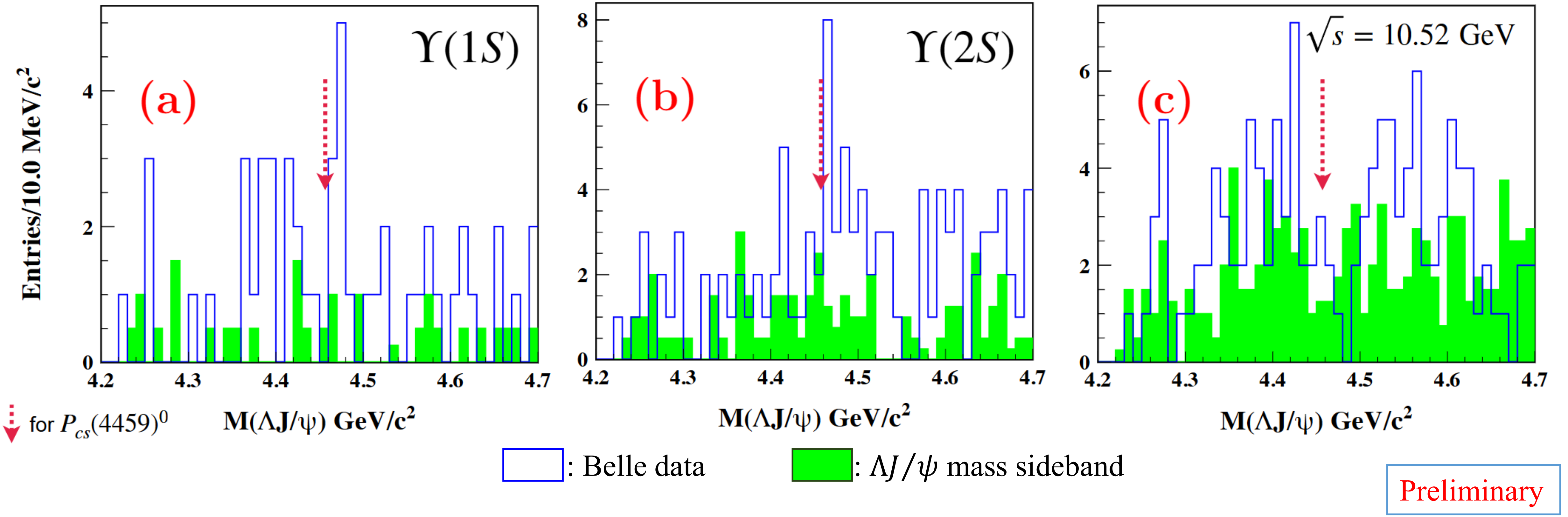


The data shows the first observation of $\Upsilon(1S)$, $\Upsilon(2S)$ decays into $\Lambda J/\psi$ final states and makes measurements of their branching fractions:

$$B[\Upsilon(1S) \to J/\psi\, \Lambda/\bar{\Lambda} + anything] = (36.9 \pm 5.3 \pm 2.4) \times 10^{-6}$$

$$B[\Upsilon(2S) \to J/\psi\, \Lambda/\bar{\Lambda} + anything] = (22.3 \pm 5.7 \pm 3.1) \times 10^{-6}$$

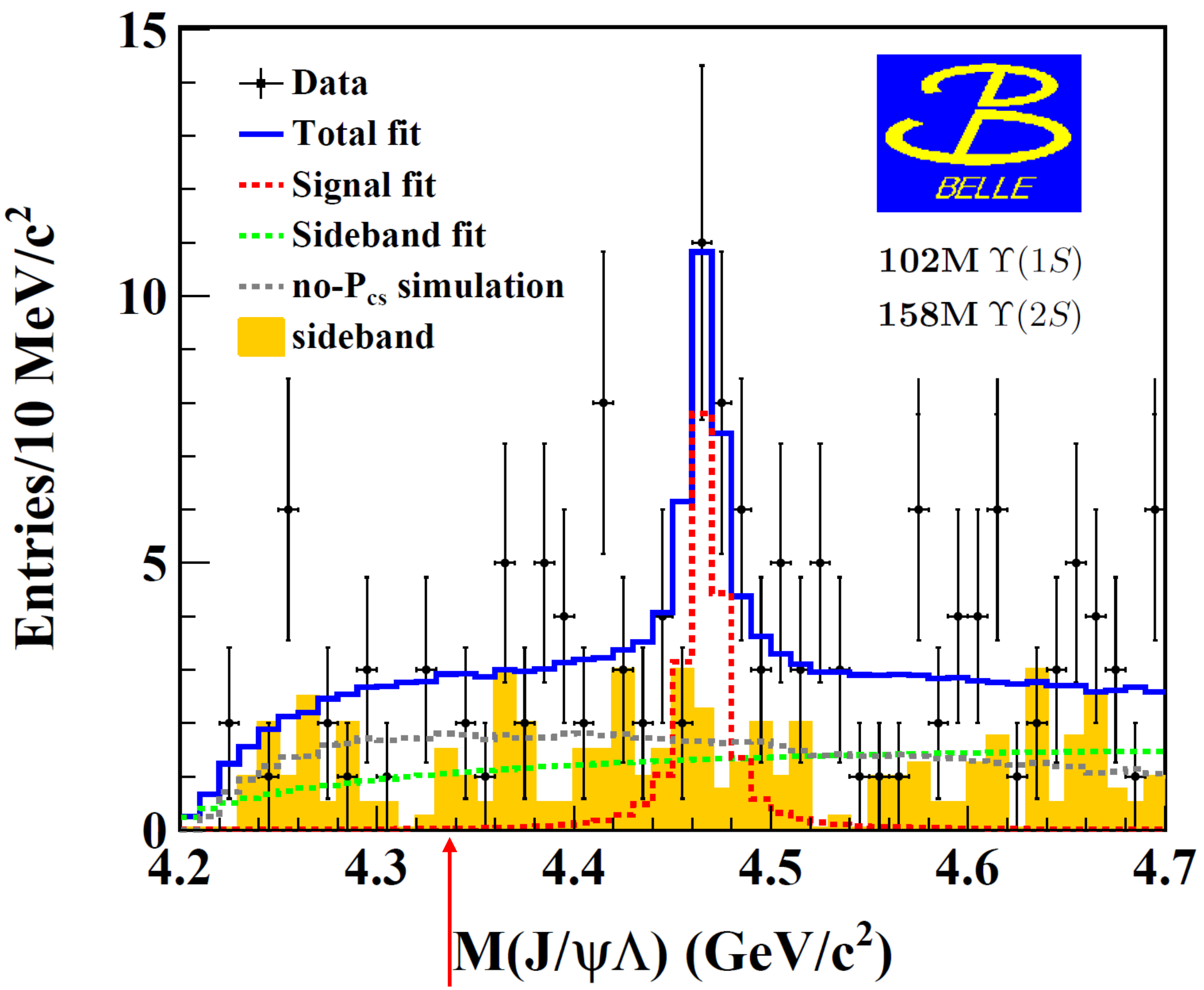
Invariant mass distributions of $\Lambda J/\psi$



- We use $M_{\Lambda J/\psi} = M_{l^+l^-p\pi^-} - M_{l^+l^-} - M_{p\pi^-} + m_\Lambda + m_{J/\psi}$ to improve the mass resolution σ_M ($11.6\ \mathrm{MeV/c^2} \rightarrow 2.8\ \mathrm{MeV/c^2}$)
- Excess seen near 4.46 GeV in both $\Upsilon(1S)$ and $\Upsilon(2S)$ data.

Fit to $M(\Lambda J/\psi)$

Peak observed in the region of the $P_{c\bar{c}s}(4459)^0$.



No sign for $P_{c\bar{c}s}(4338)^0$

Preliminary

- **Fit strategy**
  - The data was fitted by a binned max likelihood fit, with

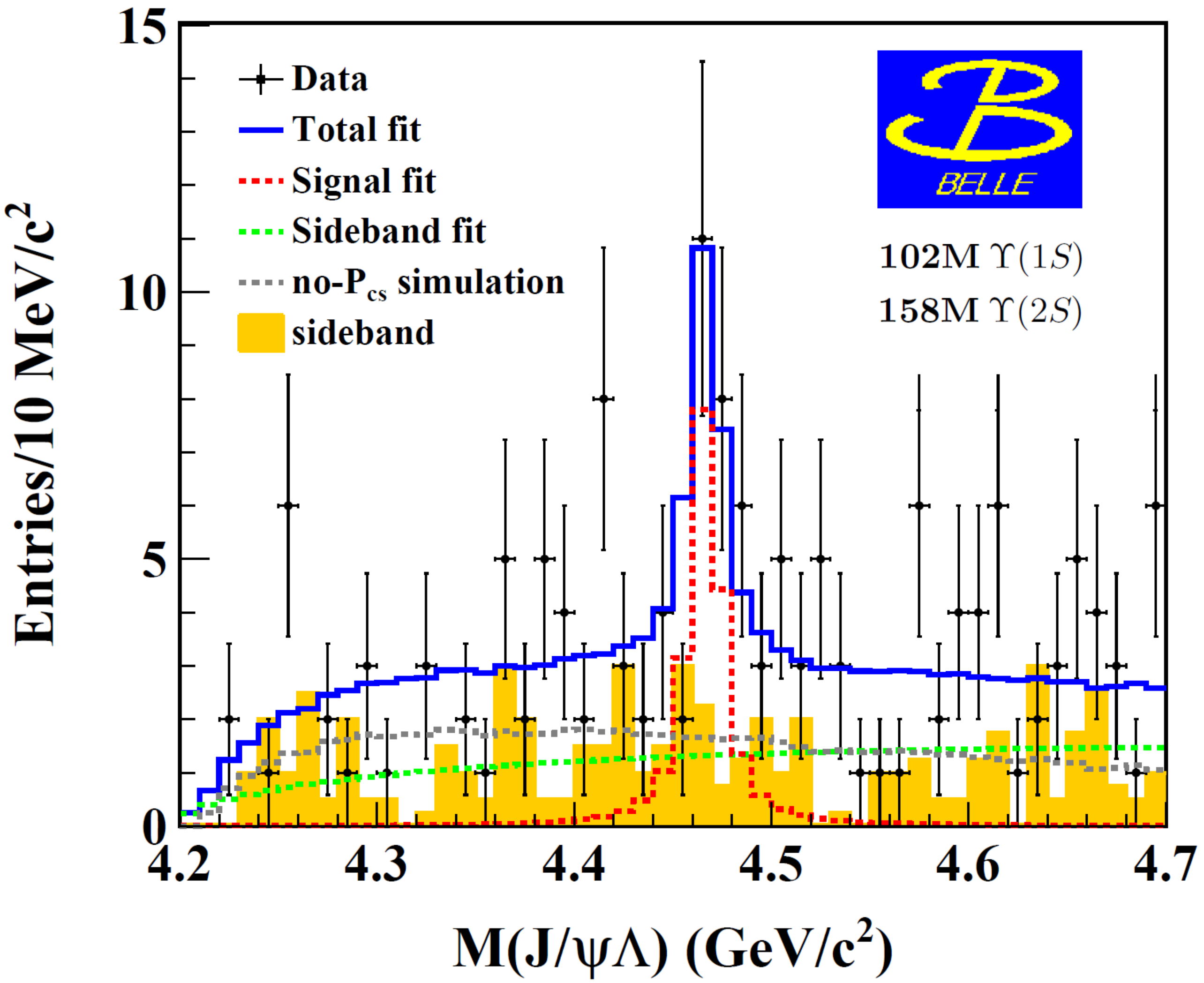
    $f_{PDF} = f_R + f_{no-P_{c\bar{c}s}} + f_{\mathrm{Sideband}}$

  - We include a Gaussian constraint using prior knowledge of the LHCb, and measurement and minimize the value of:

$$-2\ln L' \equiv -2\ln L + \frac{(m-m_{LHCb})^2}{\sigma^2_{m_{LHCb}}} + \frac{(m-\Gamma_{LHCb})^2}{\sigma^2_{\Gamma_{LHCb}}}$$

- **Signal yield**
  - $N_{P_{c\bar{c}s}(4459)} = 21 \pm 5$
  - Significance is determined to be **3.3σ**

Fit to $M(\Lambda J/\psi)$



- **Resonance parameters**
  - The Resonance parameters are determined by the fit without any constrain.
    - $\mathbf{M = 4471.7 \pm 4.8 \pm 0.6\ MeV/c^2}$
    - $\mathbf{\Gamma\ = 21.9 \pm 13.1 \pm 2.7\ MeV}$
    - $\mathbf{\Delta(-2lnL) = 14.58}$ (**local 3.8σ**)
- **$P_{c\bar{c}s}$ production**
  - $B[(\Upsilon(1S) \to P_{c\bar{c}s}(4459)^0/\bar{P}_{c\bar{c}s}(4459)^0\text{+anything}] =$ $\mathbf{(3.5 \pm 2.0 \pm 0.2) \times 10^{-6}}$
  - $B[(\Upsilon(2S) \to P_{c\bar{c}s}(4459)^0/\bar{P}_{c\bar{c}s}(4459)^0\text{+anything}] =$ $\mathbf{(2.9 \pm 1.7 \pm 0.4) \times 10^{-6}}$
  - The upper limits of $P_{c\bar{c}s}(4338)^0$ production are determined to be at 10^{-6} level.

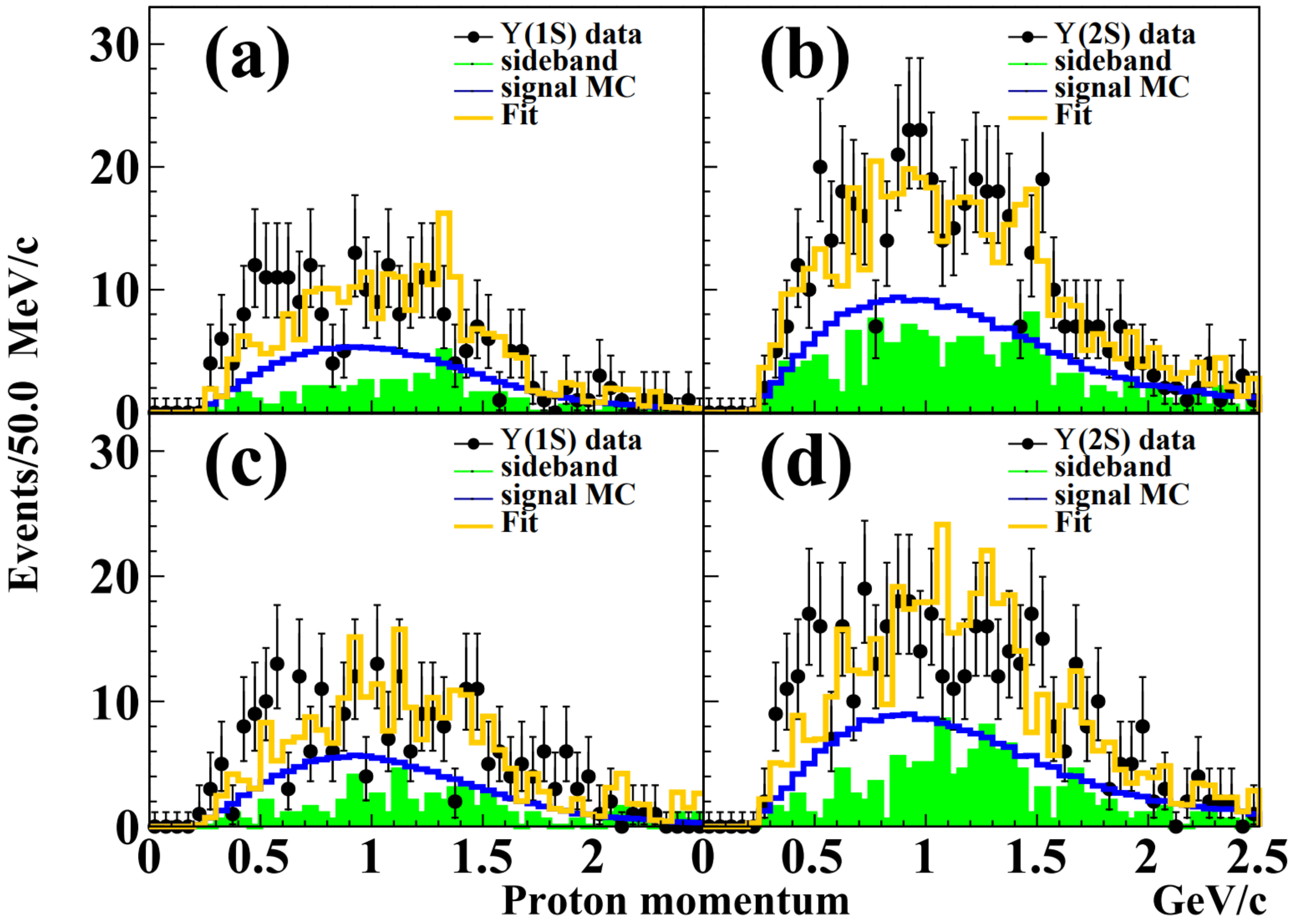
Summary

- We search for P_c states in the pJ/ψ final state from $\Upsilon(1S, 2S)$ inclusive decays and no significant P_c state is obtained.
- We search for $P_{c\bar{c}s}$ states in the $\Lambda J/\psi$ final state from $\Upsilon(1S, 2S)$ inclusive decays and a peak is found in the region of the $P_{c\bar{c}s}(4459)^0$ from $\Lambda J/\psi$ mass spectrum while no sign of $P_{c\bar{c}s}(4338)^0$.
- The significance of $P_{c\bar{c}s}(4459)^0$ is determined to be 3.3σ including systematics.
- Looking forward to more data at Belle II.

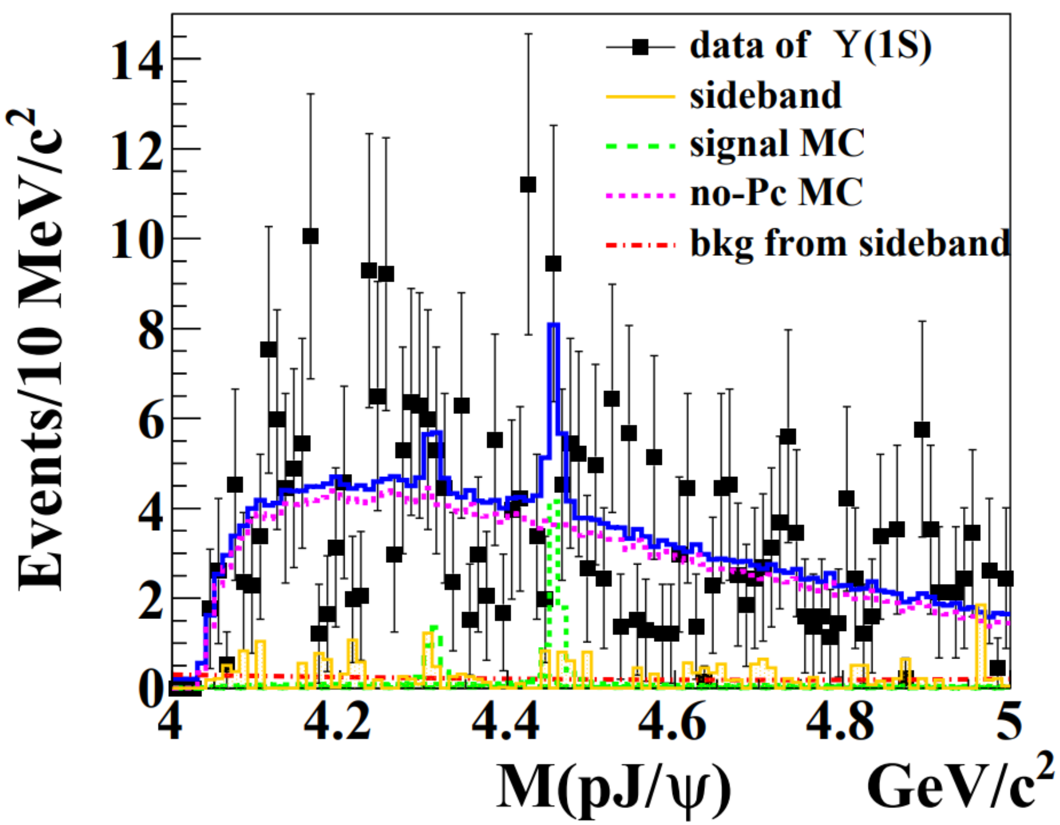
Thank you very much!

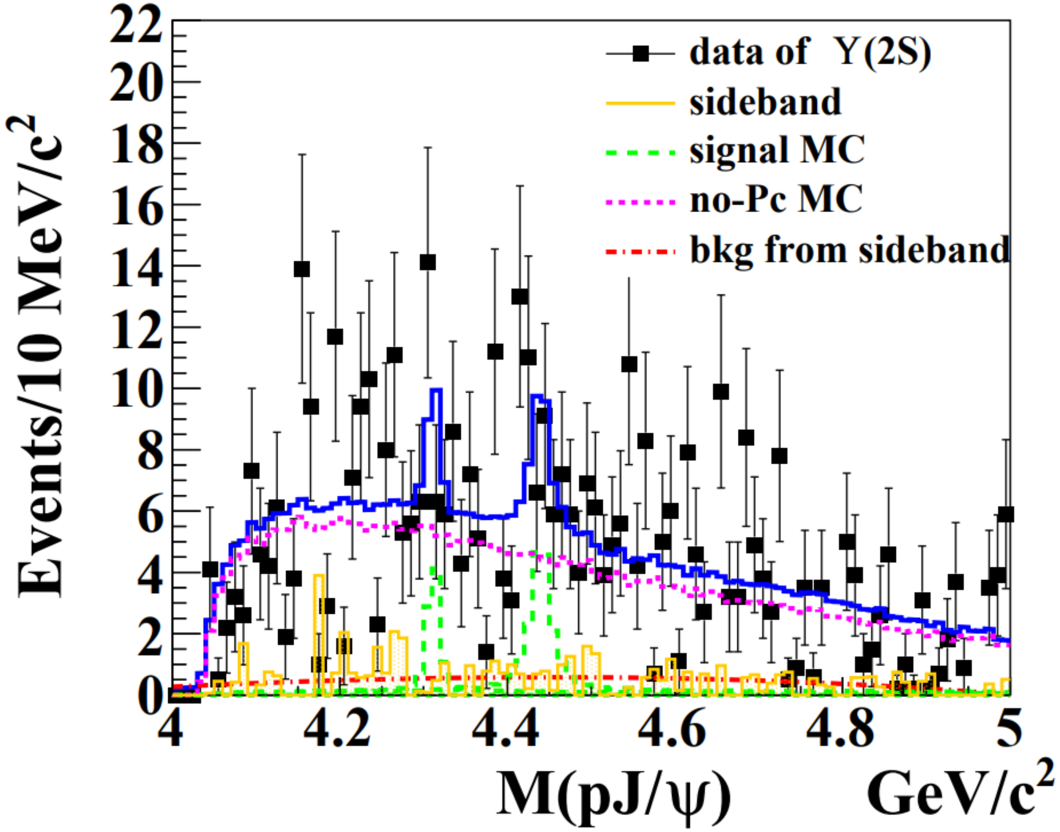
Momentum of proton

BACK UP

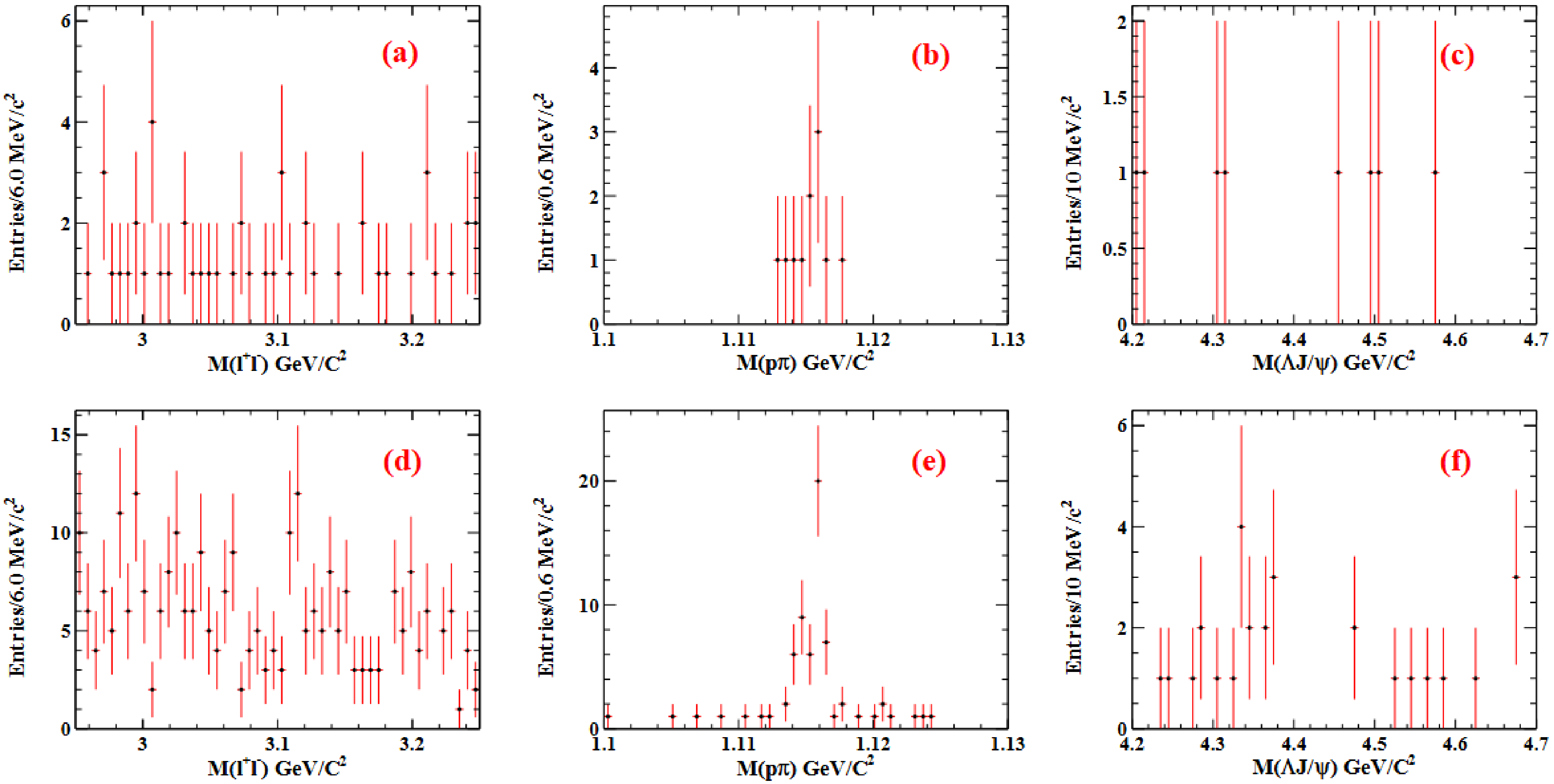

(a)
Υ(1S) data
sideband
signal MC
Fit
(b)
Υ(2S) data
sideband
signal MC
Fit
(c)
Υ(1S) data
sideband
signal MC
Fit
(d)
Υ(2S) data
sideband
signal MC
Fit
Events/50.0 MeV/c
Proton momentum
GeV/c
0
10
20
30
0.5
1
1.5
2
2.5

Fit to M(pJ/ψ)

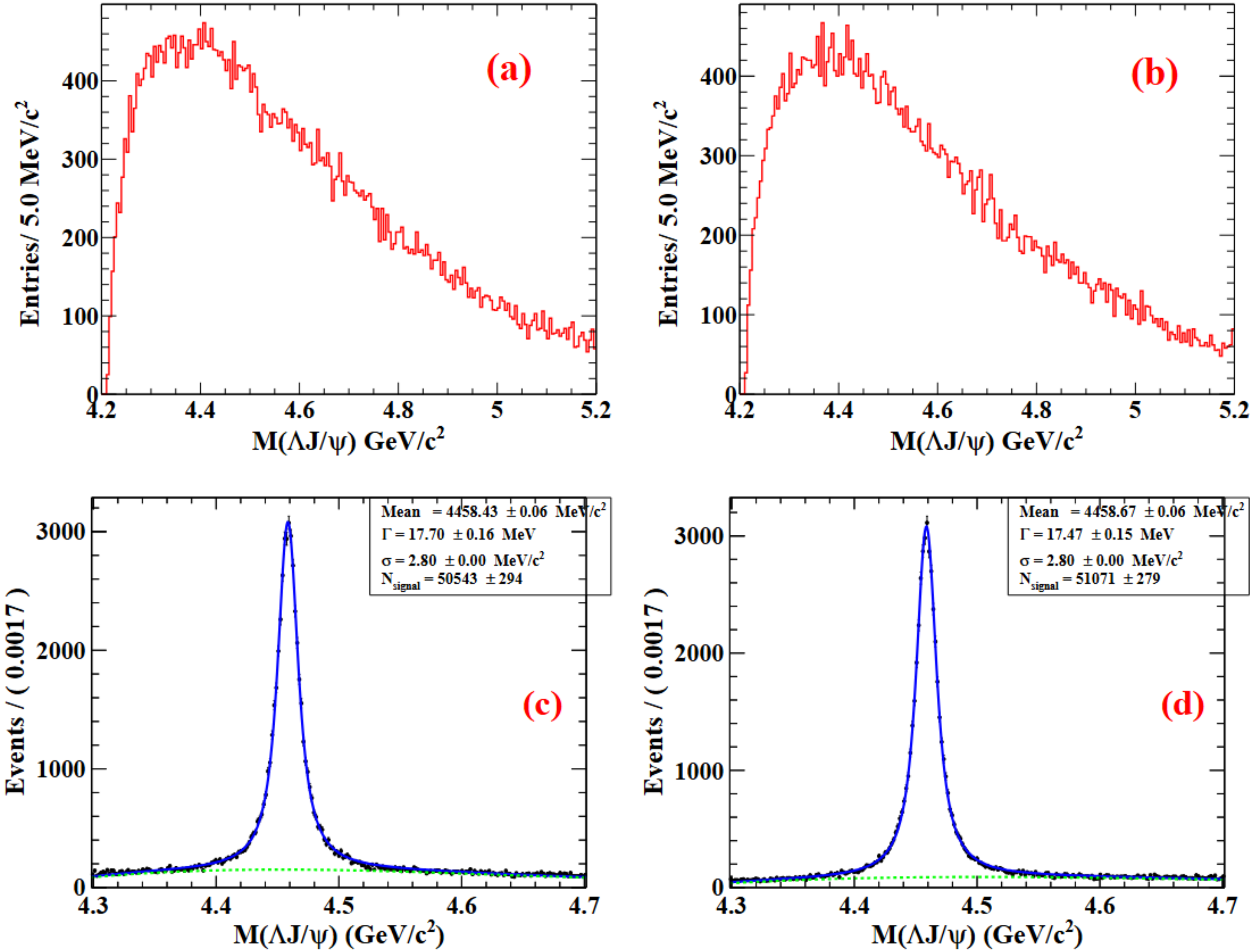




Generic MC


(a)
(b)
(c)
(d)
(e)
(f)
Entries/6.0 MeV/c²
Entries/0.6 MeV/c²
Entries/10 MeV/c²
M(l⁺l⁻) GeV/C²
M(pπ) GeV/C²
M(ΛJ/ψ) GeV/C²

Invariant mass from MC

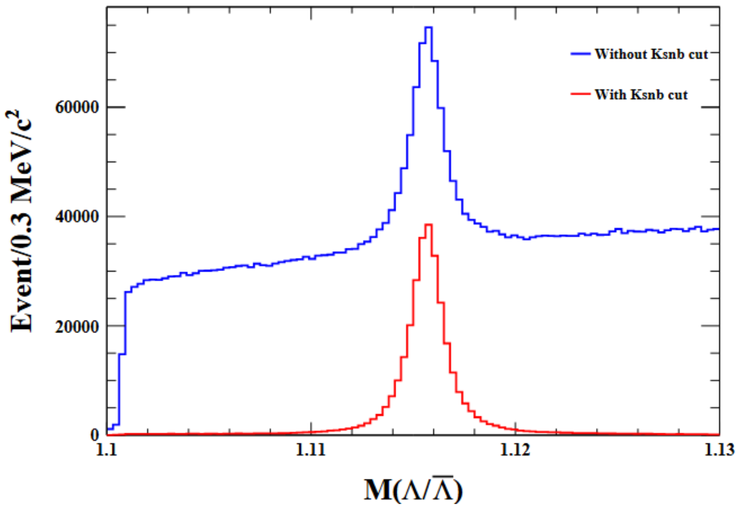


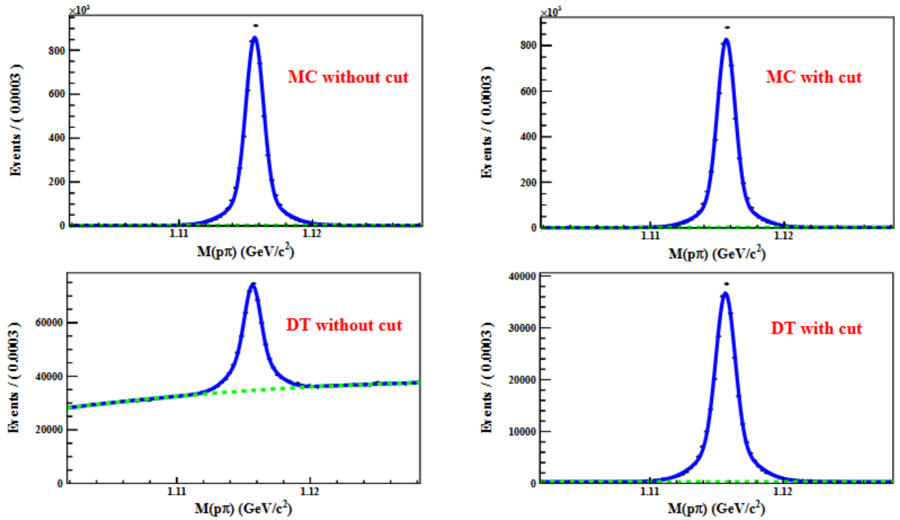
Systematics from Lambda selection

- The systematic error was studied by comparing data and MC. We use the $771 fb^{-1} \Upsilon(4S)$ data sample with HadronB(J) skim type which passed the $B^{\pm} \to \Lambda\bar{\Lambda}K^{\pm}$ pre-selection criteria, listing in Table below.
- The selection efficiency of Λ is $96.5 \pm 0.3\%$ for MC and $96.6 \pm 0.6\%$ for data.

Table: The pre-selection criteria for $B^{\pm} \to \Lambda\bar{\Lambda}K^{\pm}$.

	Selection criteria
$K^{\pm}$ selection	atcPIDBelle(3,2)>0.6 and atcPIDBelle(3,4)>0.6
	$dr(K^{\pm}) < 0.5$ cm and $dz(K^{\pm}) < 5$ cm
Λ selection	ksnbNoLam<-0.4
	ksnbVLike>0.5
Λ signal region	$\lvert M(p\pi) - 1.1156 \rvert < 3 * 0.0014$ GeV$/c^2$





Systematics from Lambda selection

- To determine the systematic uncertainties, We divide the samples into 6 momentum bins.
- The signal efficiency and data efficiency are compared before and after nisKsfinder variables cuts.
- We quote the double ratio($|\frac{\epsilon_{DT}}{\epsilon_{MC}} - 1|$) to be the systematic uncertainties.

Λ momentum	Data Efficiency(%)	MC Efficiency(%)	Ratio
$0 - 1.0$ GeV/c	99.32 ± 0.04	94.06 ± 0.01	1.056
$1.0 - 1.5$ GeV/c	92.68 ± 0.01	95.84 ± 0.01	0.967
$1.5 - 2.0$ GeV/c	95.28 ± 0.01	95.35 ± 0.01	0.999
$2.0 - 2.5$ GeV/c	93.04 ± 0.01	95.02 ± 0.01	0.979
$2.5 - 3.0$ GeV/c	95.50 ± 0.02	95.98 ± 0.01	0.995
> 3.0 GeV/c	97.76 ± 0.05	95.03 ± 0.01	1.029

Total Systematics ($\Lambda J/\psi$)

Source	$\Upsilon(1S)$	$\Upsilon(2S)$	e^+e^- annihilation
PID	1.4	1.4	1.4
Tracking	1.4	1.4	1.4
Λ selection	4.0	3.6	3.4
J/ψ mass window	2.1	1.0	2.0
Λ mass window	1.6	3.2	2.7
Mean mass of $q\bar{q}$ system	1.8	1.7	1.8
Accompanying particle	2.3	3.5	1.9
Branching fractions	1.4	6.3	1.4
$N_{\Upsilon(1S,2S)}$	2.0	2.6	–
Luminosity	–	–	1.4
MC sample statistics	0.5	0.5	0.5
$1+\delta_{\rm ISR}$	–	–	1.0
Sum in quadrature	6.4	9.5	6.2

Total Systematics (pJ/ψ)

Source	$\Upsilon(1S)$ decay	$\Upsilon(2S)$ decay	$\sigma(e^+e^- \to pJ/\psi + anything)$
Particle identification	2.1	2.1	2.1
Tracking	1.1	1.1	1.1
J/ψ signal region	0.5	0.4	0.2
$M^2_{\rm recoil}(pJ/\psi)$ requirement	0.4	1.1	2.2
$\mathcal{B}(J/\psi \to \ell^+\ell^-)$	0.6	0.6	0.6
$1 + \delta_{\rm ISR}$	—	—	1.0
[a]Scale factor $f_{\rm scale}$	11.2	4.9	—
Modeling in MC simulation	2.8	2.4	2.6
Number of $\Upsilon(1,2S)$ events	2.2	2.3	—
Integrated luminosity	—	—	1.4
Statistics of MC samples	0.5	0.5	0.5
Sum in quadrature	4.4	4.3	4.6