Decays and Spectroscopy at Υ(1S, 2S) at Belle

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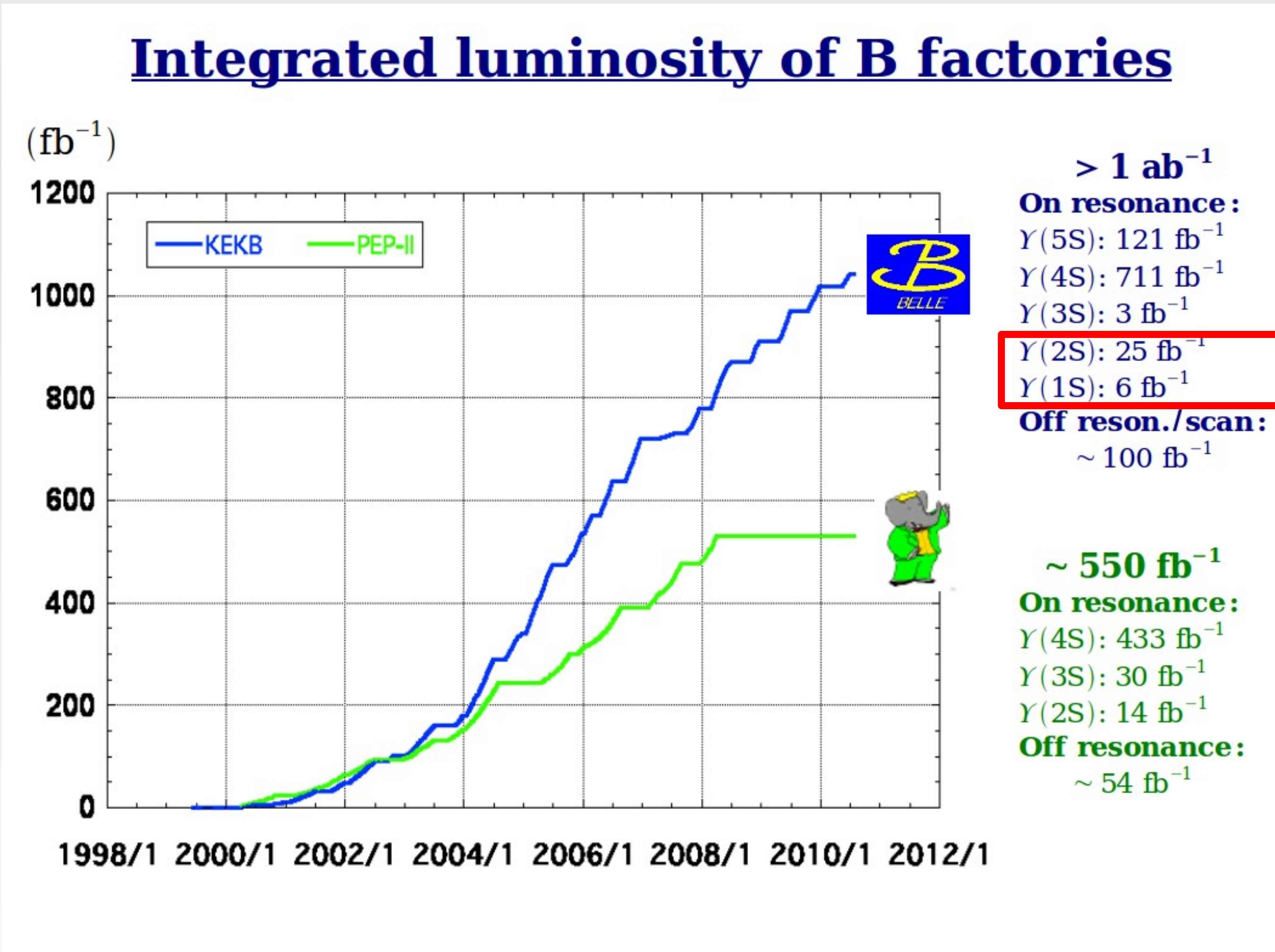
5 July 2012

ICHEP2012 Melbourne
36th International Conference on High Energy Physics
4 – 11 July 2012
Melbourne Convention and Exhibition Centre

Outline

- The Belle data sample.
- $\Upsilon(2S) \rightarrow \Upsilon(1S)\eta$.
- $\Upsilon(1S)/\Upsilon(2S)$ decays to light hadrons.
- Search for double charmonium decays from $\chi_{bJ}(1P)$.
- Bottomonium exclusive decays to hyperon-antihyperon pairs - New.

The Belle dataset



102 million $\Upsilon(1S)$
158 million $\Upsilon(2S)$

World's Largest samples of $\Upsilon(1S)$ and $\Upsilon(2S)$!

Dominant decays
$\Upsilon(1S, 2S) \to ggg$
$\Upsilon(1S)$: 82%
$\Upsilon(2S)$: 59%

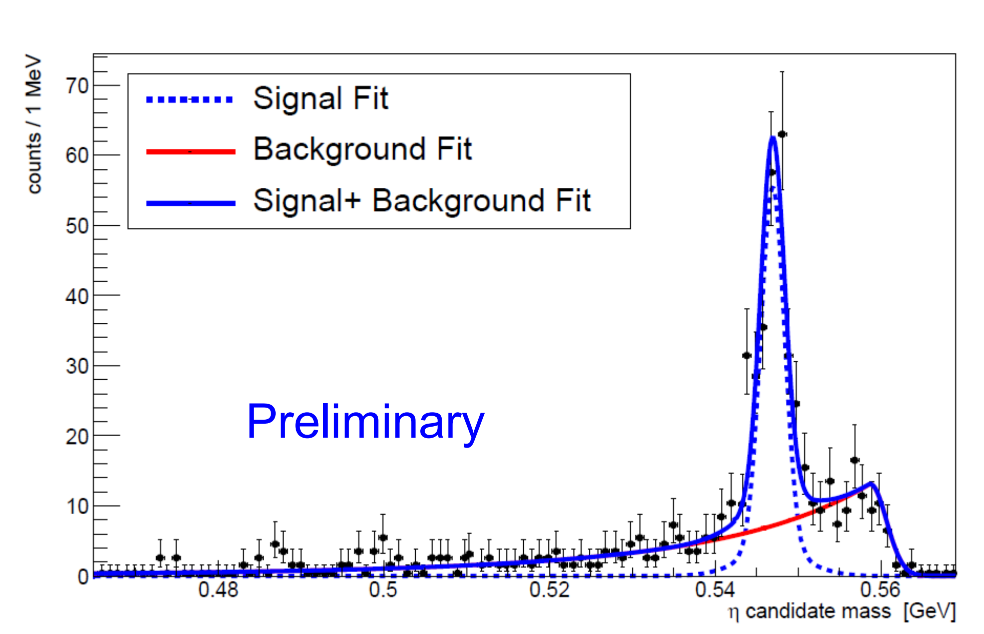
$\Upsilon(2S) \rightarrow \Upsilon(1S)\eta$

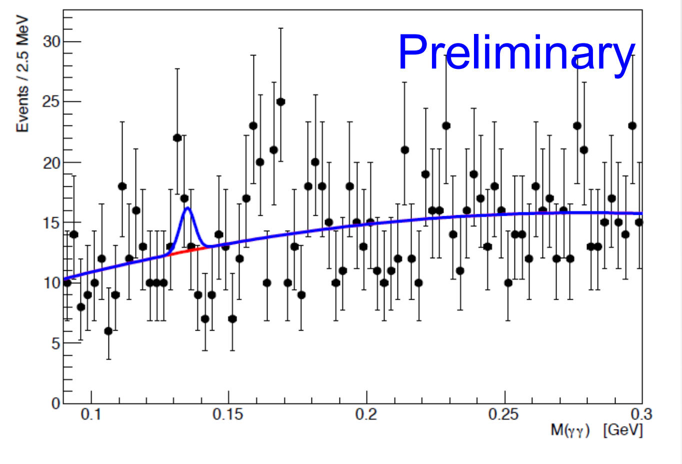
- $\Upsilon(nS) \rightarrow \Upsilon(mS)\pi^+\pi^-$: E1E1 transition - No spin flip.
- $\Upsilon(nS) \rightarrow \Upsilon(mS)\eta$, $Y(mS)\pi^0$: E1M2 transition - Requires spin flip.
  - QCD multipole expansion predicts suppression of η mode w.r.t. $\pi^+\pi^-$ mode (Kuang Front.Phys.China 1, 19 (2006))
- Measured branching fractions are either too small or too large:
- $B(\Upsilon(4S) \rightarrow \Upsilon(1S)\eta) = (1.96 \pm 0.11) \times 10^{-4}$ (BaBar) : 2.5 times larger than $\pi^+\pi^-$ mode.
- $B(\Upsilon(3S) \rightarrow \Upsilon(1S)\eta)$ $< 1.0 \times 10^{-4}$ (BaBar)
  $\approx (5\text{-}10) \times 10^{-4}$ (theory prediction)
- $B(\Upsilon(2S) \rightarrow \Upsilon(1S)\eta)$ $= 2.1 \times 10^{-4}$ (CLEO)
  $= 2.39 \times 10^{-4}$ (BaBar)
  $\approx (7\text{-}16) \times 10^{-4}$ (theory prediction)

CLEO: PRL101, 192001 (2008) BaBar: PRD78, 112002 (2008); PRD88, 092003 (2011)

$\Upsilon(2S) \rightarrow \Upsilon(1S)\eta$ Preliminary Result

- Reconstruct $\Upsilon(1S) \rightarrow l^+l^-$ ($l=e,\mu$)
  - $\eta \rightarrow \gamma\gamma$ or $\eta \rightarrow \pi^+\pi^-\pi^0$
- $B(\Upsilon(2S) \rightarrow \Upsilon(1S)\eta) =$ $(3.41 \pm 0.28(\text{stat.}) \pm 0.35(\text{syst.})) \times 10^{-4}$
- Higher than previous measurements, but still lower than theory predictions.
  - Current PDG (2012) value: $B(\Upsilon(2S) \rightarrow \Upsilon(1S)\eta) = (2.34 \pm 0.31) \times 10^{-4}$.
- Also search for $\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^0$:
  - further suppressed by isospin.
  - Upper limit set:
- $B(\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^0) < 0.43 \times 10^{-4}$ (90% CL)
  - Current limit: $B(\Upsilon(2S) \rightarrow \Upsilon(1S)\pi^0) < 1.8 \times 10^{-4}$ (CLEO).





CLEO: PRL101, 192001 (2008) 2012 PDG: J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012)

$\Upsilon(1S)$, $\Upsilon(2S)$ decays to light hadrons

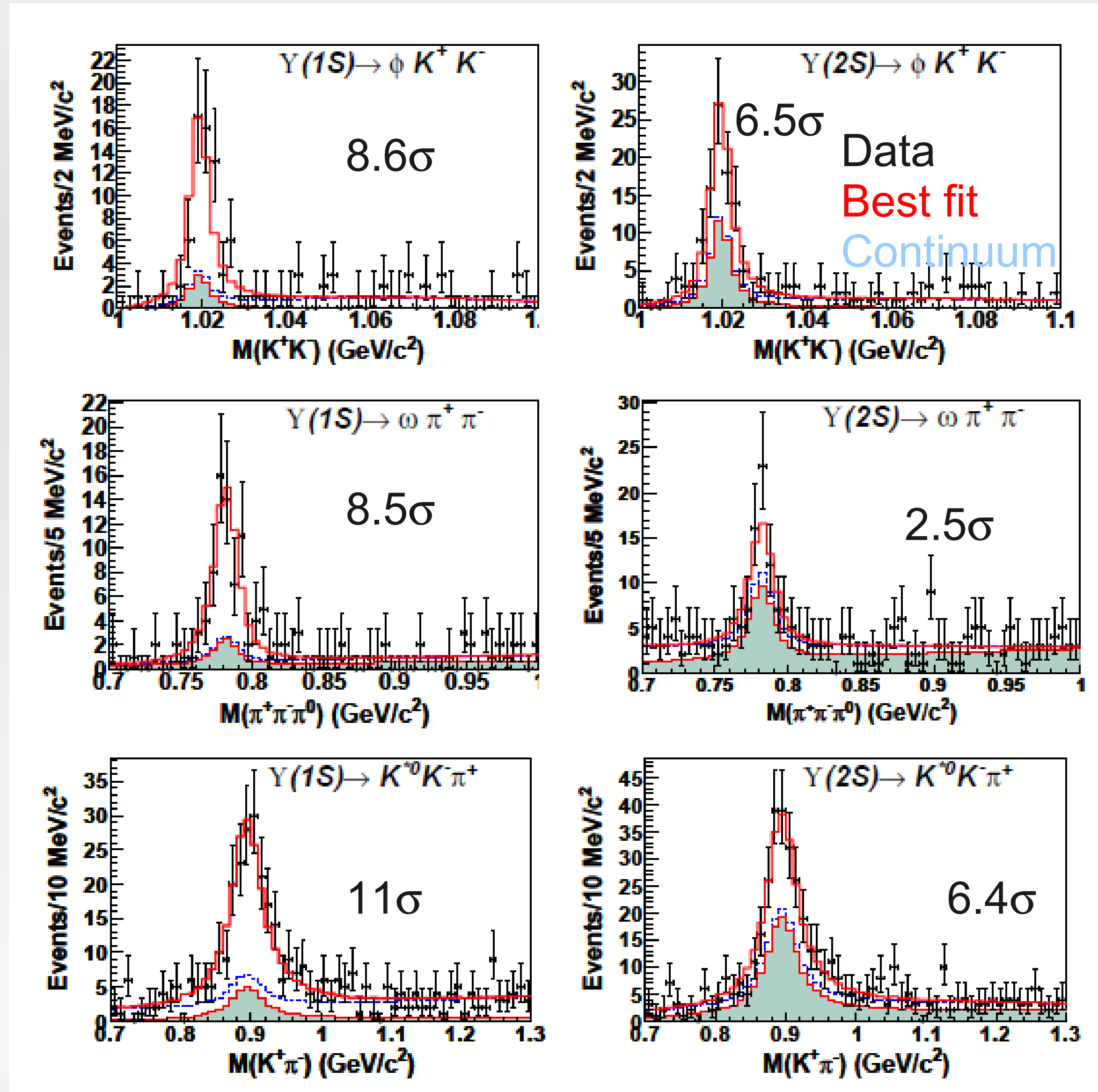
- Charmonium: "12% Rule": $$Q_\psi = \frac{\mathcal{B}_{\psi(2S)\to \text{hadrons}}}{\mathcal{B}_{J/\psi\to \text{hadrons}}} = \frac{\mathcal{B}_{\psi(2S)\to e^+e^-}}{\mathcal{B}_{J/\psi\to e^+e^-}} \approx 12\%$$
  - Violated in some Vector-Pseudoscalar (VP) and Vector-Tensor (VT) decays; e.g. $\rho\pi$.
- Bottomonium prediction: $$Q_\Upsilon = \frac{\mathcal{B}_{\Upsilon(2S)\to \text{hadrons}}}{\mathcal{B}_{\Upsilon(1S)\to \text{hadrons}}} = \frac{\mathcal{B}_{\Upsilon(2S)\to e^+e^-}}{\mathcal{B}_{\Upsilon(1S)\to e^+e^-}} = 0.77 \pm 0.07$$
  - Expected to hold better for the higher mass Upsilon mesons.

- Study $\Upsilon(1S)$ and $\Upsilon(2S)$ decays to light hadrons in 10 channels (each):
- 3 three-body modes: ϕK^+K^-, $\omega\pi^+\pi^-$, $K^{*0}K^-\pi^+$;
- 4 VT modes: $\phi f'_2$, ωf_2, ρa_2, $K^{*0}K_2^{*0}$;
- 3 Axial-vector-Pseudoscalar (AP): $K_1(1270)^+K^-$, $K_1(1400)K^-$, $b_1(1235)^+\pi^-$.

Three-body final states

- $\Upsilon(1,2S) \to \phi K^+K^-$:
  - $Q_\Upsilon = 0.79 \pm 0.54 \pm 0.13$;
- $\Upsilon(1,2S) \to \omega\pi^+\pi^-$:
  - $Q_\Upsilon = 0.30 \pm 0.13 \pm 0.11$;
  - UL: $Q_\Upsilon < 0.55$;

    2.6σ below prediction
- $\Upsilon(1,2S) \to K^{*0}K^-\pi^-$:
  - $Q_\Upsilon = 0.52 \pm 0.11 \pm 0.14$;



arXiv:1205.1246[hep-ex]

Υ(1S), Υ(2S) decays to light hadrons

- Significant signal observed in 5 channels
  - First observation of exclusive 3-body hadronic annihilations of Υ(1S, 2S).
- Values of Q_Υ are consistent with prediction in all channels, except a 2.6σ discrepancy for $\omega\pi^+\pi^-$.

$$Q_\Upsilon = \frac{\mathcal{B}_{\Upsilon(2S)\to \text{hadrons}}}{\mathcal{B}_{\Upsilon(1S)\to \text{hadrons}}} = \frac{\mathcal{B}_{\Upsilon(2S)\to e^+e^-}}{\mathcal{B}_{\Upsilon(1S)\to e^+e^-}} = 0.77 \pm 0.07$$

Channel	Υ(1S) N^{sig}	Υ(1S) $N^{\text{UP}}_{\text{sig}}$	Υ(1S) Σ	Υ(1S) $\mathcal{B}$	Υ(1S) $\mathcal{B}^{\text{UP}}$	Υ(2S) N^{sig}	Υ(2S) $N^{\text{UP}}_{\text{sig}}$	Υ(2S) Σ	Υ(2S) $\mathcal{B}$	Υ(2S) $\mathcal{B}^{\text{UP}}$	Q_Υ	Q^{UP}_Υ
ϕK^+K^-	56.3 ± 9.0		8.6	$2.36 \pm 0.38 \pm 0.29$		69 ± 36		6.5	$1.86 \pm 0.96 \pm 0.21$		$0.79 \pm 0.54 \pm 0.13$	
$\omega\pi^+\pi^-$	63.6 ± 9.5		8.5	$4.46 \pm 0.67 \pm 0.72$		29 ± 12	51	2.5	$1.32 \pm 0.54 \pm 0.45$	2.58	$0.30 \pm 0.13 \pm 0.11$	0.55
$K^{*0}K^-\pi^+$	173 ± 20		11	$4.42 \pm 0.50 \pm 0.58$		135 ± 23		6.4	$2.32 \pm 0.40 \pm 0.54$		$0.52 \pm 0.11 \pm 0.14$	
$\phi f_2'$	6.9 ± 3.9	15	2.1	$0.64 \pm 0.37 \pm 0.14$	1.63	8.3 ± 6.0	18	1.6	$0.50 \pm 0.36 \pm 0.19$	1.33	$0.77 \pm 0.70 \pm 0.33$	2.54
ωf_2	5.2 ± 4.0	13	1.5	$0.57 \pm 0.44 \pm 0.13$	1.79	-0.4 ± 3.3	6.1		$-0.03 \pm 0.24 \pm 0.01$	0.57	$-0.06 \pm 0.42 \pm 0.02$	1.22
ρa_2	29 ± 11	49	2.7	$1.15 \pm 0.47 \pm 0.18$	2.24	10 ± 11	30	0.9	$0.27 \pm 0.28 \pm 0.14$	0.88	$0.23 \pm 0.26 \pm 0.12$	0.82
$K^{*0}\bar{K}_2^{*0}$	42.2 ± 9.5		5.4	$3.02 \pm 0.68 \pm 0.34$		32 ± 11		3.3	$1.53 \pm 0.52 \pm 0.19$		$0.50 \pm 0.21 \pm 0.07$	
$K_1(1270)^+K^-$	3.7 ± 4.9	13	0.8	$0.54 \pm 0.72 \pm 0.21$	2.41	11.0 ± 4.4	26	1.2	$1.06 \pm 0.42 \pm 0.32$	3.22	$1.96 \pm 2.71 \pm 0.84$	4.73
$K_1(1400)^+K^-$	23.8 ± 8.2		3.3	$1.02 \pm 0.35 \pm 0.22$		9.2 ± 8.2	24	0.5	$0.26 \pm 0.23 \pm 0.09$	0.83	$0.26 \pm 0.25 \pm 0.10$	0.77
$b_1(1235)^+\pi^-$	14.4 ± 6.9	28	2.4	$0.47 \pm 0.22 \pm 0.13$	1.25	1.2 ± 3.5	13	0.2	$0.02 \pm 0.07 \pm 0.01$	0.40	$0.05 \pm 0.16 \pm 0.03$	0.35

arXiv:1205.1246[hep-ex]

Double charmonuim decays of χ_{bJ}(1P)

PRD **84**, 094031 (2011)

- NRQCD predicts a BF for $\chi_{bJ} \to J/\psi J/\psi$ of 10^{-5} (J=0,2) or 10^{-11} (J=1);
- Similar predictions exist for pQCD and light cone formalism:

PRD **72**, 094018 (2005)

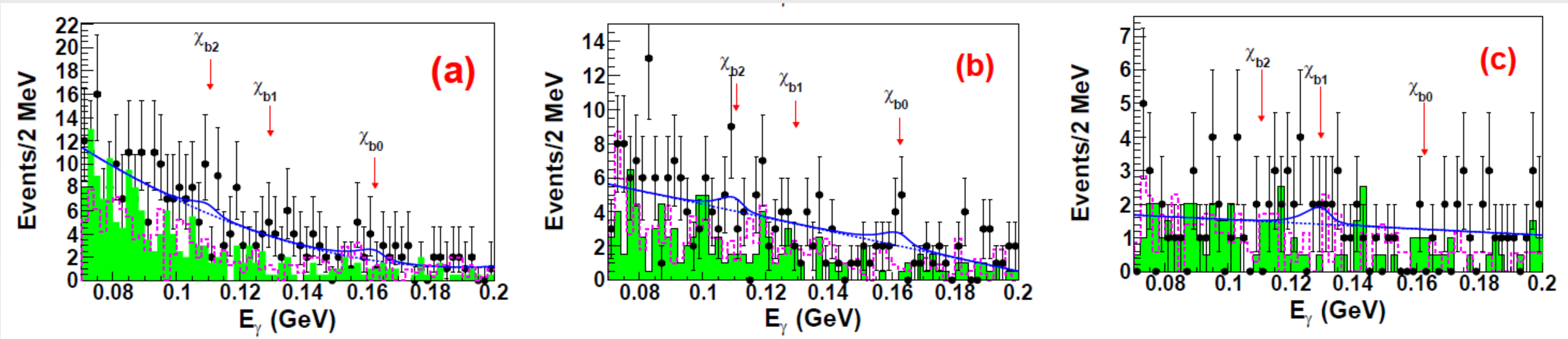
PRD **84**, 074026 (2011)

	J = 0	J = 2
$\chi_{bJ} \to J/\psi J/\psi$	9.6×10^{-5}	1.1×10^{-3}
$\chi_{bJ} \to J/\psi\psi'$	1.6×10^{-4}	1.6×10^{-3}
$\chi_{bJ} \to \psi'\psi'$	6.6×10^{-5}	5.9×10^{-4}

- Measurement of these modes would allow for some discrimination and refinement between these models.
- Search for 9 different decay modes:
  - $\chi_{bJ} \to J/\psi J/\psi$, $\chi_{bJ} \to J/\psi\psi'$, $\chi_{bJ} \to \psi'\psi'$ for each of J = 0, 1, 2;
  - Search via radiative decays of $\Upsilon(2S)$: $\Upsilon(2S) \to \gamma\, \chi_{bJ}$.
- Fully reconstruct one of the charmonium particles, and require that the missing mass is equivalent to a second charmonuim particle:

Double charmonium decays of $\chi_{bJ}(1P)$

PRD 85, 071102(R) (2012)



$\chi_{bJ} \to J/\psi J/\psi$ $\chi_{bJ} \to J/\psi\psi'$ $\chi_{bJ} \to \psi'\psi'$

- No significant signal in any channel.
- Upper limits are much lower than central values predicted by LC formalism and pQCD.
- Upper limits are consistent with NRQCD calculations.

Upper limit

Channel	n^{up}	$\varepsilon(\%)$	$\sigma_{\text{sys}}(\%)$	$\mathcal{B}_R$
$\chi_{b0} \to J/\psi J/\psi$	21	5.8	16	7.1×10^{-5}
$\chi_{b1} \to J/\psi J/\psi$	13	6.3	30	2.7×10^{-5}
$\chi_{b2} \to J/\psi J/\psi$	22	5.9	27	4.5×10^{-5}
$\chi_{b0} \to J/\psi\psi'$	20	3.4	17	1.2×10^{-4}
$\chi_{b1} \to J/\psi\psi'$	5.8	3.8	15	1.7×10^{-5}
$\chi_{b2} \to J/\psi\psi'$	17	3.5	16	4.9×10^{-5}
$\chi_{b0} \to \psi'\psi'$	3.0	2.1	20	3.1×10^{-5}
$\chi_{b1} \to \psi'\psi'$	12	2.2	17	6.2×10^{-5}
$\chi_{b2} \to \psi'\psi'$	3.3	2.1	12	1.6×10^{-5}

Bottomonium exclusive decays to hyperon-antihyperon pairs

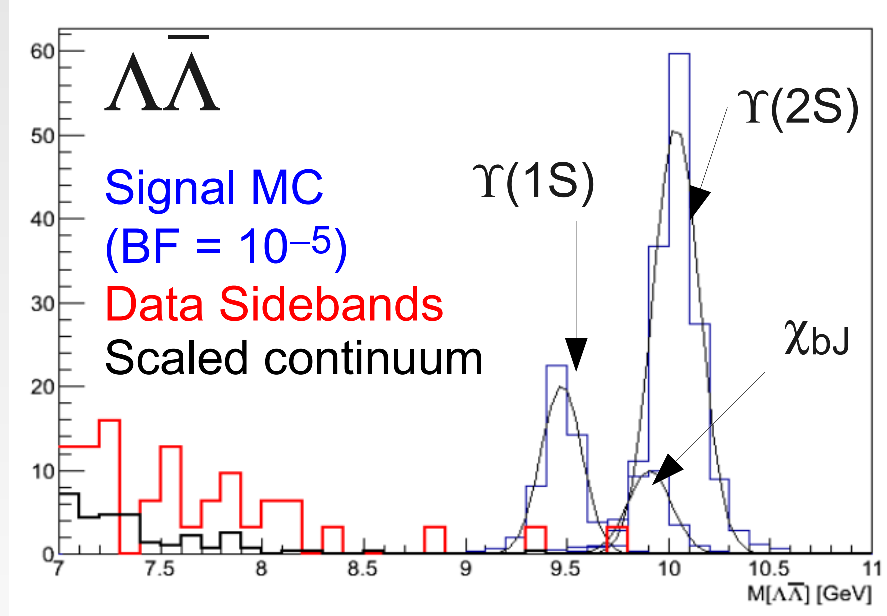
- Search for decays of bottomonium states to strange hyperon-antihyperon pairs ($\Lambda\bar{\Lambda}$, $\Xi\bar{\Xi}$, $\Omega\bar{\Omega}$) with up to two light mesons (0, η, π^0 or $\pi^+\pi^-$).
- Some of these modes have been observed in charmonium (BF = 10^{-4} - 10^{-5}).
  - Scaling would predict BF = 10^{-5} to 10^{-7} for bottomonium.
- Fully reconstruct the decay.
  - Υ(1S) and χ_{bJ} are not tagged.
- Select events with exactly 1 hyperon and 1 antihyperon.
- Signal yields extracted from mass distribution.

Particle	Decay mode ($S = \Lambda, \Omega^-, \Xi^-$)	Notes
$\Upsilon(2S) \to$	$S\bar{S}$	—
	$S\bar{S}\eta$	—
	$S\bar{S}\pi^0$	—
	$S\bar{S}\pi^+\pi^-$	—
$\Upsilon(1S) \to$	$S\bar{S}\eta$	via $\Upsilon(2S) \to \Upsilon(1S) + X$
	$S\bar{S}\pi^0$	via $\Upsilon(2S) \to \Upsilon(1S) + X$
	$S\bar{S}\pi^+\pi^-$	via $\Upsilon(2S) \to \Upsilon(1S) + X$
	$S\bar{S}$	via $\Upsilon(2S) \to \Upsilon(1S) + X$
$\chi_{bJ}(1P) \to$	$S\bar{S}\pi^+\pi^-$	via $\Upsilon(2S) \to \gamma\chi_{bJ}(1P)$
	$S\bar{S}$	via $\Upsilon(2S) \to \gamma\chi_{bJ}(1P)$

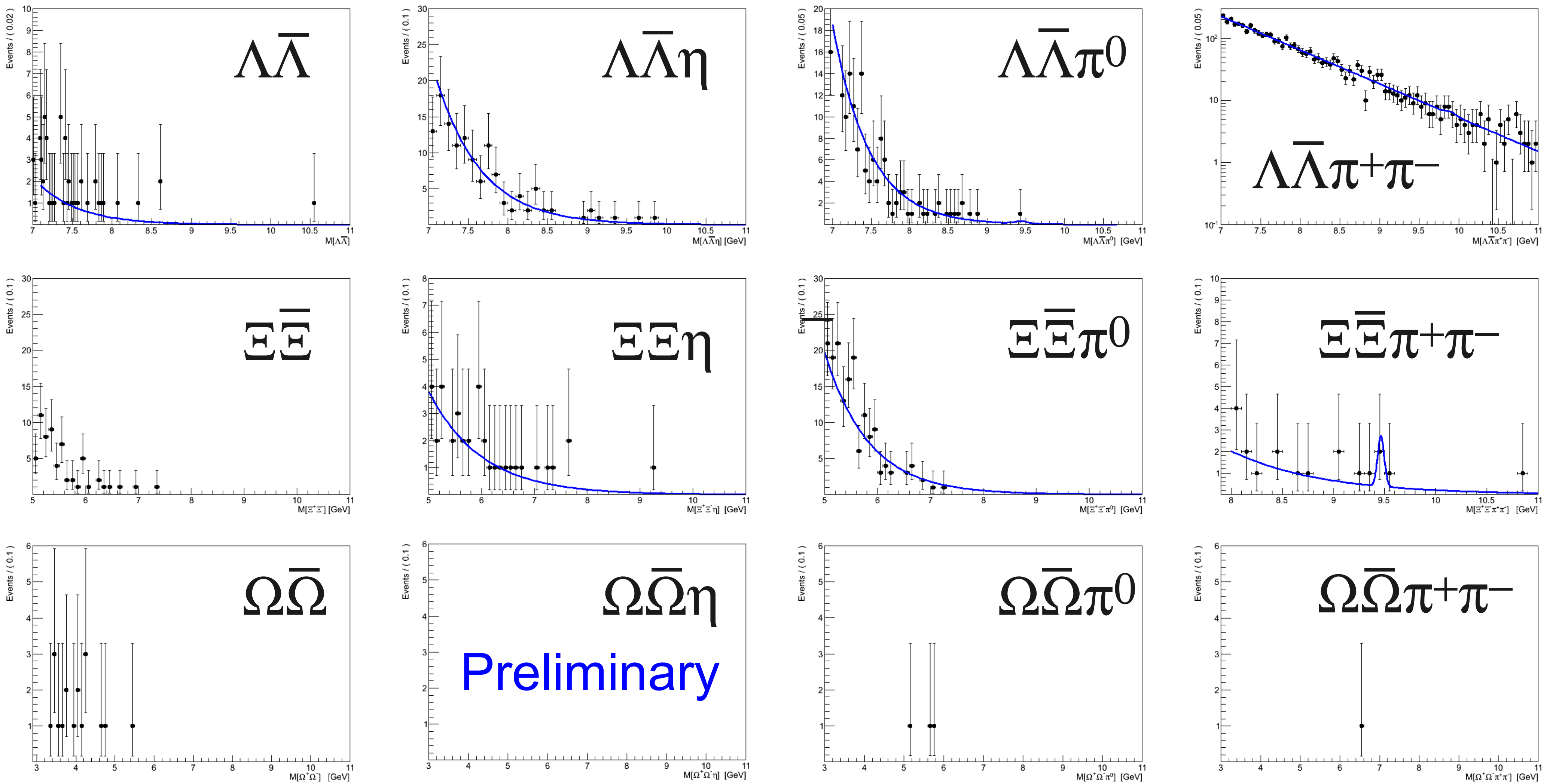
Bottomonium exclusive decays to hyperon-antihyperon pairs

- Efficiencies:
  - up to 25% for $\Lambda\bar{\Lambda}$, ε up to 8% for $\Xi\bar{\Xi}$, ε up to 5% for $\Omega\bar{\Omega}$.
- Fit for events at $\Upsilon(1S)$ $\Upsilon(2S)$ and χ_{bJ} masses in mass projection for each mode.
  - Very little or no background in $\Xi\Xi$ or $\Omega\bar{\Omega}$ channels.

Channel	$S = \Lambda$	$S = \Xi$	$S = \Omega$
$\Upsilon(2S) \to S\bar{S}$	24.2%	4.7%	4.9%
$\Upsilon(2S) \to S\bar{S}\pi^0$	5.3%	1.8%	1.5%
$\Upsilon(2S) \to S\bar{S}\eta$	12.0%	3.8%	3.1%
$\Upsilon(2S) \to S\bar{S}\pi^+\pi^-$	21.5%	6.7%	4.5%
$\Upsilon(1S) \to S\bar{S}$	26.1%	8.5%	5.0%
$\Upsilon(1S) \to S\bar{S}\pi^0$	5.9%	2.0%	1.4%
$\Upsilon(1S) \to S\bar{S}\eta$	11.0%	3.4%	3.6%
$\Upsilon(1S) \to S\bar{S}\pi^+\pi^-$	19.7%	5.7%	3.5%
$\chi_{bJ}(1P) \to S\bar{S}$	25.7%	6.3%	4.6%
$\chi_{bJ}(1P) \to S\bar{S}\pi^+\pi^-$	21.3%	7.0%	4.5%



Bottomonium decays to hyperon-antihyperon: Preliminary results - New



Bottomonium decays to hyperon-antihyperon: Preliminary Upper Limits

- No significant signal seen in any channel.
- Upper limits set for all channels using:
  - Feldman-Cousins (channels with no background).
  - Frequentist approach and background modelled as exponential (channels with background).

Upper limits on Branching Fractions (x10^{-6})

Channel	$S=\Lambda$	$S=\Xi$	$S=\Omega$
$\Upsilon(2S) \to S\bar{S}$	0.17	0.89	1.8
$\Upsilon(2S) \to S\bar{S}\pi^0$	0.79	2.3	6.6
$\Upsilon(2S) \to S\bar{S}\eta$	0.82	2.8	7.4
$\Upsilon(2S) \to S\bar{S}\pi^+\pi^-$	0.30	0.61	2.0
$\Upsilon(1S) \to S\bar{S}$	0.59	1.8	6.7
$\Upsilon(1S) \to S\bar{S}\pi^0$	3.7	7.8	23
$\Upsilon(1S) \to S\bar{S}\eta$	3.7	12	24
$\Upsilon(1S) \to S\bar{S}\pi^+\pi^-$	4.6	4.8	9.6
$\chi_{bJ}(1P) \to S\bar{S}$	0.9	3.7	11
$\chi_{bJ}(1P) \to S\bar{S}\pi^+\pi^-$	2.1	13	12

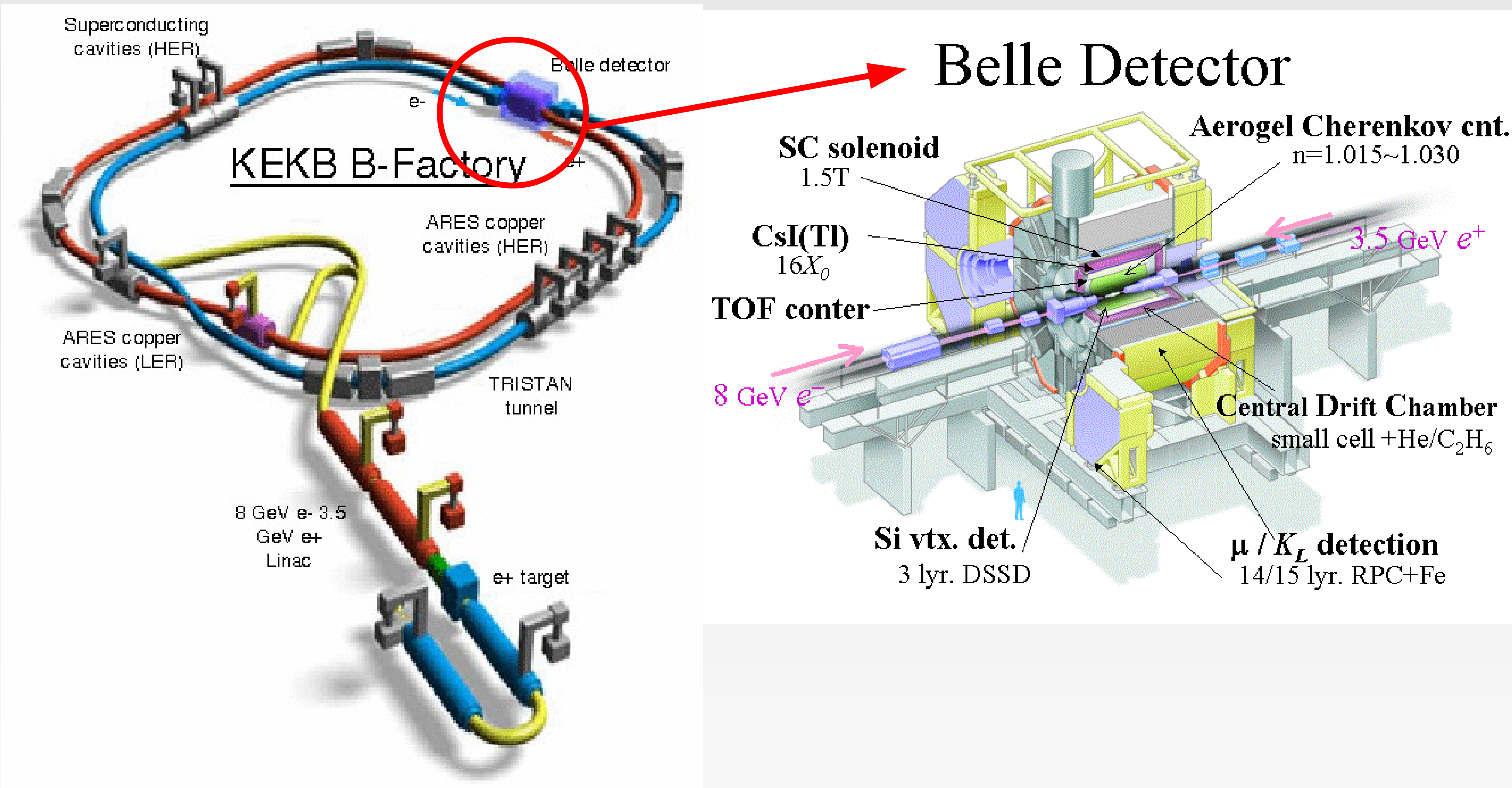
Preliminary

Summary

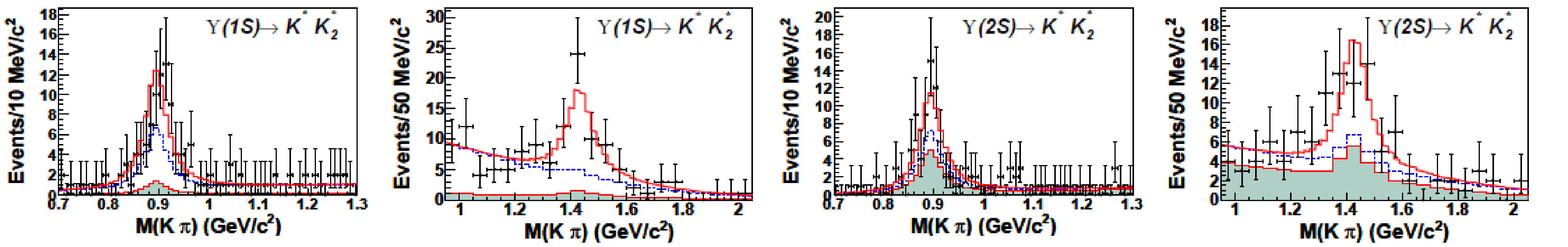
- $\Upsilon(2S) \to \Upsilon(1S)\eta$
  - Preliminary result: $B(\Upsilon(2S) \to \Upsilon(1S)\eta) = (3.41 \pm 0.28(stat.) \pm 0.35(syst.)) \times 10^{-4}$: Higher than previous measurements.
- $\Upsilon(1S)/\Upsilon(2S)$ decays to light hadrons.
  - First observation of exclusive 3-body hadronic annihilations of $\Upsilon(1S, 2S)$.
  - Ratio of $\Upsilon(1S)/\Upsilon(2S)$ BFs is consistent with expectations except in one channel ($\Upsilon(1,2S) \to \omega\pi^+\pi^-$: 2.6σ discrepancy with "0.77 rule").
- Search for double charmonium decays from $\chi_{bJ}(1P)$.
  - No significant signal seen, upper limits set in 9 channels.
- Search for exclusive $\Upsilon(1S, 2S)$ decays to hyperon/antihyperon pairs - New.
  - No significant signal: upper limits set in all modes.

Backup

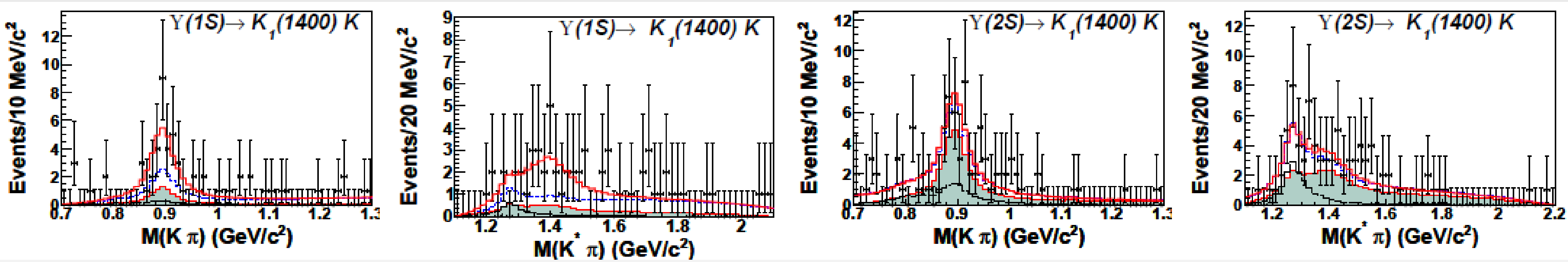
The Belle detector at KEK



Υ(1S), Υ(2S) decays to light hadrons: Observed VT and AP final states



- $\Upsilon(1,2S) \rightarrow K^{*0}K_2^{*0}$:
  - $Q_\Upsilon = 0.50 \pm 0.21 \pm 0.07$;



- $\Upsilon(1,2S) \rightarrow K_1(1400)^+K^-$:
  - $Q_\Upsilon < 0.77$;

arXiv:1205.1246[hep-ex]