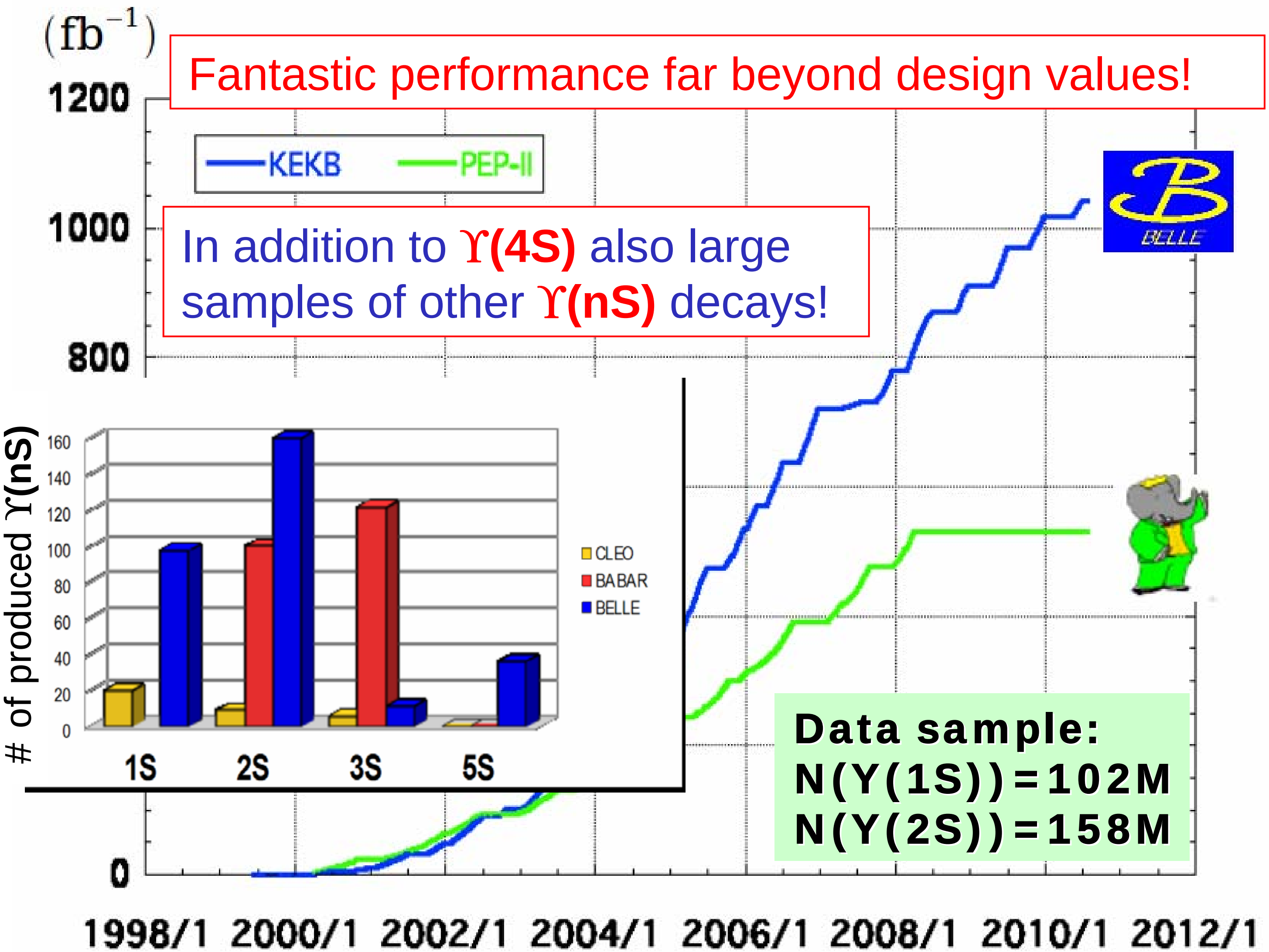
Bottomonium decays into light hadrons and double-charmonium

Chengping Shen for Belle Collaboration
Beihang University

Integrated luminosity at B factories

Fantastic performance far beyond design values!



In addition to **Υ(4S)** also large samples of other **Υ(nS)** decays!

Data sample:
N(Υ(1S))=102M
N(Υ(2S))=158M

> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 25 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

Υ(1S/2S)→ light hadrons: 77% rule ?

$$\Gamma_h = |M_h|^2 |\Psi(0)|^2$$

$$= (2/9\pi)(\pi^2 - 9)\tfrac{5}{18}\alpha_s^3 (\tfrac{4}{3}\alpha_s)^3 m_{\Phi'}. \qquad (3)$$

The leptonic width via one photon into $\bar{l}l$ is

$$\Gamma_l = |M_l|^2 |\Psi(0)|^2 = \tfrac{1}{2}(\tfrac{2}{3}\alpha)^2 (\tfrac{4}{3}\alpha_s)^3 m_{\Phi'}, \qquad (4)$$

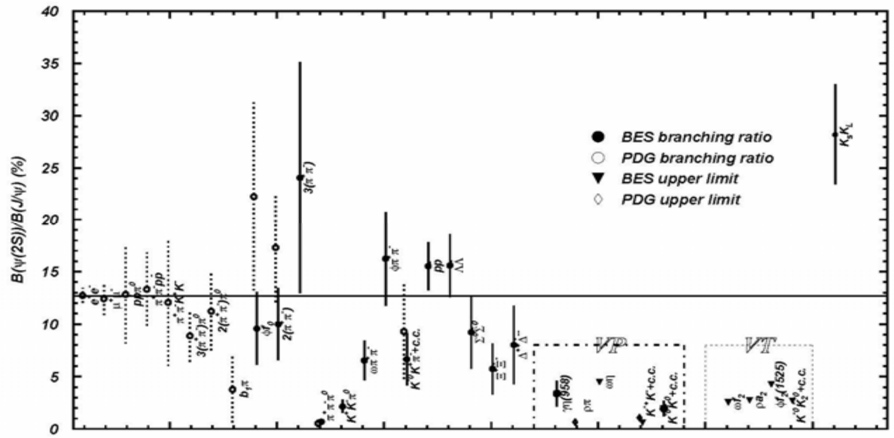
where $\alpha \approx \frac{1}{137}$. Although separately these calculations are not trustworthy, the ratio

$$\frac{\Gamma_l}{\Gamma_h} = \frac{\frac{2}{9}\alpha^2}{(2/9\pi)(\pi^2 - 9)5/\alpha_s^3} \qquad (5)$$

is independent of wave-function effects.

This is the famous (or notorious) "12% rule".

M. Appelquist and H. D. Politzer, PRL34, 43 (1975)



$$Q_h = \frac{B_{\psi' \to X}}{B_{J/\psi \to X}} = \frac{B_{\psi' \to e^+e^-}}{B_{J/\psi \to e^+e^-}} = 12\%$$

The violation of the above rule was first observed in the rho pi and K*K ("**rho pi puzzle**") more than thirty years ago.

- Similarly, we expect

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

- 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): $K_1(1270)^+K^-$, $K_1(1400)K^-$, $b_1(1235)^+\pi^-$.

Phys. Rev. D 86, 031102(R) (2012)

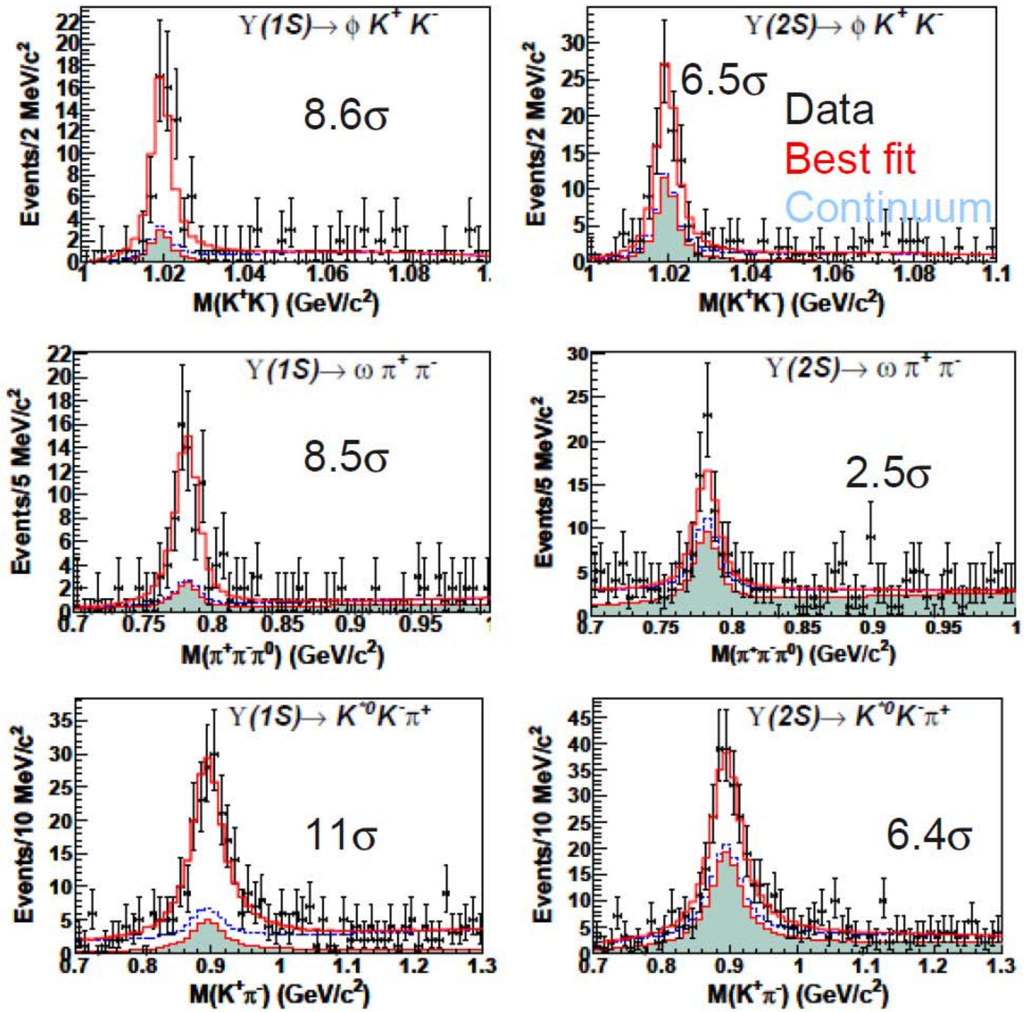
- Look for final states: $K_sK^+\pi^-$, $\pi^+\pi^-\pi^0\pi^0$, $\pi^+\pi^-\pi^0$

Phys. Rev. D 88, 11102(R) (2013)

3 three-body modes: ϕK^+K^-, $\omega\pi^+\pi^-$, $K^{*0}K^-\pi^+$;

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

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

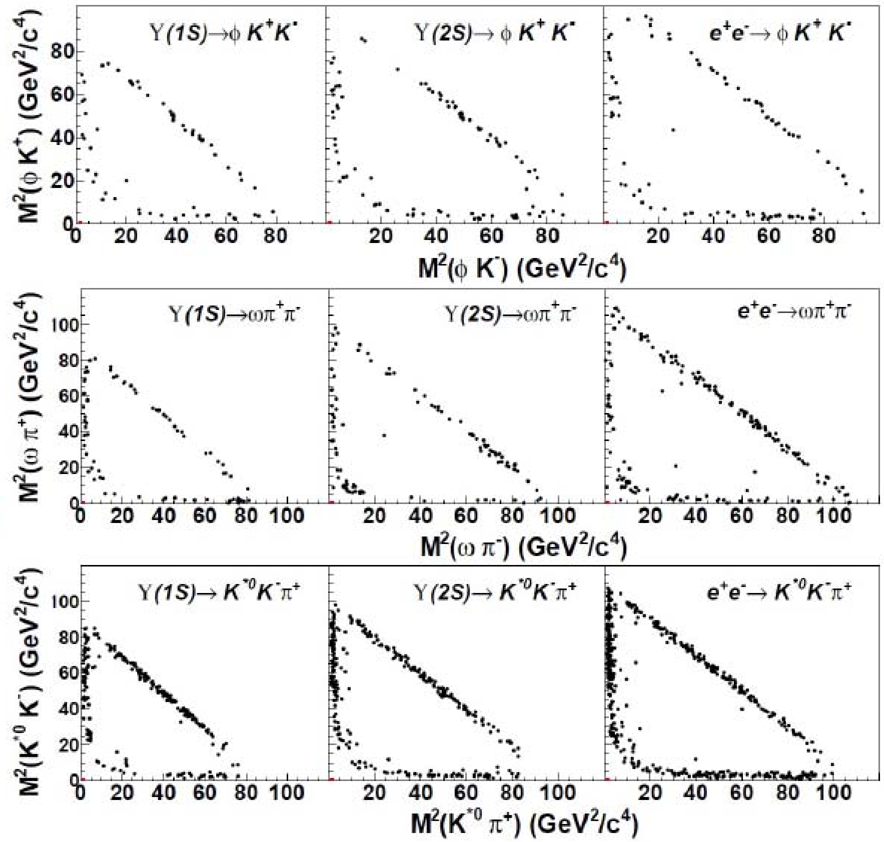


Phys. Rev. D **86**, 031102(R) (2012)

4 VT modes: $\phi f'_2$, ωf_2, ρa_2, $K^{*0}K_2^{*0}$;

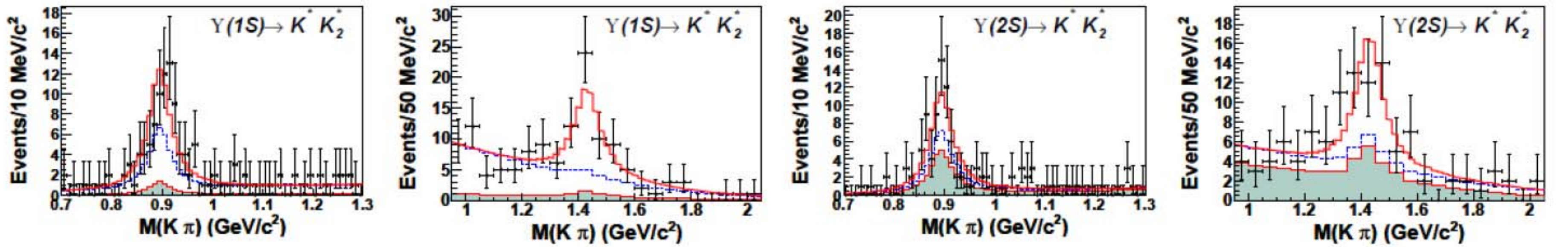
3AP $K_1(1270)^+K^-$, $K_1(1400)K^-$, $b_1(1235)^+\pi^-$.

- After requiring $|M_{K^+K^-} - m_\phi| < 8$ $|M_{\pi^+\pi^-\pi^0} - m_\omega| < 30$, and $|M_{K^+\pi^-} - m_{K^{*0}(892)}| < 100$ MeV$/c^2$, the Dalitz plots are obtained.
- Interestingly, the events accumulate near the phase space boundary, reflecting the quasi-two-body nature of these decays.

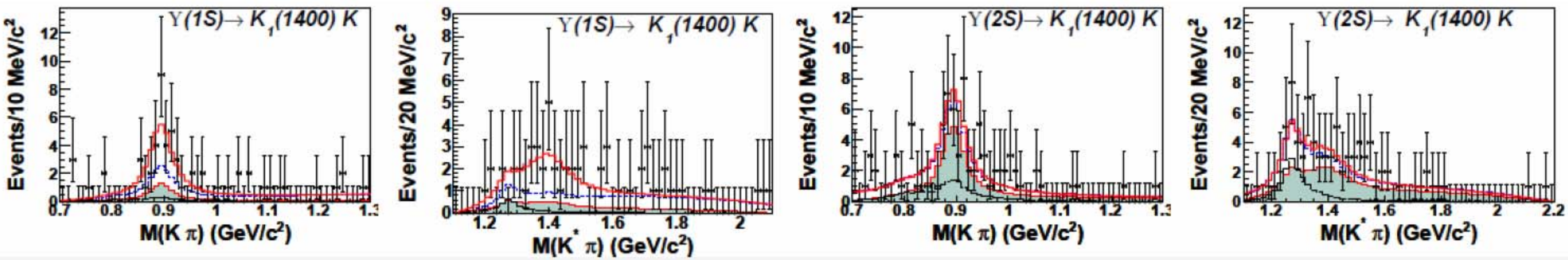


4 VT modes: $\phi f'_2$, ωf_2, ρa_2, $K^{*0}K_2^{*0}$;

3AP $K_1(1270)^+K^-$, $K_1(1400)K^-$, $b_1(1235)^+\pi^-$.



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



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

arXiv:1205.1246[hep-ex]

✔ Assume no interference due to the limited statistics.

Results

Channel	$\Upsilon(1S)$ $\mathcal{B}$	$\mathcal{B}^{\mathrm{UP}}$	$\Upsilon(2S)$ $\mathcal{B}$	$\mathcal{B}^{\mathrm{UP}}$	Q_Υ	Q_Υ^{UP}
ϕK^+K^-	$2.36 \pm 0.37 \pm 0.29$		$1.58 \pm 0.33 \pm 0.18$		$0.67 \pm 0.18 \pm 0.11$	
$\omega\pi^+\pi^-$	$4.46 \pm 0.67 \pm 0.72$		$1.32 \pm 0.54 \pm 0.45$	2.58	$0.30 \pm 0.13 \pm 0.11$	0.55
$K^{*0}K^-\pi^+$	$4.42 \pm 0.50 \pm 0.58$		$2.32 \pm 0.40 \pm 0.54$		$0.52 \pm 0.11 \pm 0.14$	
$\phi f_2'$	$0.64 \pm 0.37 \pm 0.14$	1.63	$0.50 \pm 0.36 \pm 0.19$	1.33	$0.77 \pm 0.70 \pm 0.33$	2.54
ωf_2	$0.57 \pm 0.44 \pm 0.13$	1.79	$-0.03 \pm 0.24 \pm 0.01$	0.57	$-0.06 \pm 0.42 \pm 0.02$	1.22
ρa_2	$1.15 \pm 0.47 \pm 0.18$	2.24	$0.27 \pm 0.28 \pm 0.14$	0.88	$0.23 \pm 0.26 \pm 0.12$	0.82
$K^{*0}\bar{K}_2^{*0}$	$3.02 \pm 0.68 \pm 0.34$		$1.53 \pm 0.52 \pm 0.19$		$0.50 \pm 0.21 \pm 0.07$	
$K_1(1270)^+K^-$	$0.54 \pm 0.72 \pm 0.21$	2.41	$1.06 \pm 0.42 \pm 0.32$	3.22	$1.96 \pm 2.71 \pm 0.84$	4.73
$K_1(1400)^+K^-$	$1.02 \pm 0.35 \pm 0.22$		$0.26 \pm 0.23 \pm 0.09$	0.83	$0.26 \pm 0.25 \pm 0.10$	0.77
$b_1(1235)^+\pi^-$	$0.47 \pm 0.22 \pm 0.13$	1.25	$0.02 \pm 0.07 \pm 0.01$	0.40	$0.05 \pm 0.16 \pm 0.03$	0.35

Q_Υ is the ratio of the $\Upsilon(2S)$ and $\Upsilon(1S)$ branching fractions. Branching fractions are in units of 10^{-6} and upper limits are given at the 90% C.L.

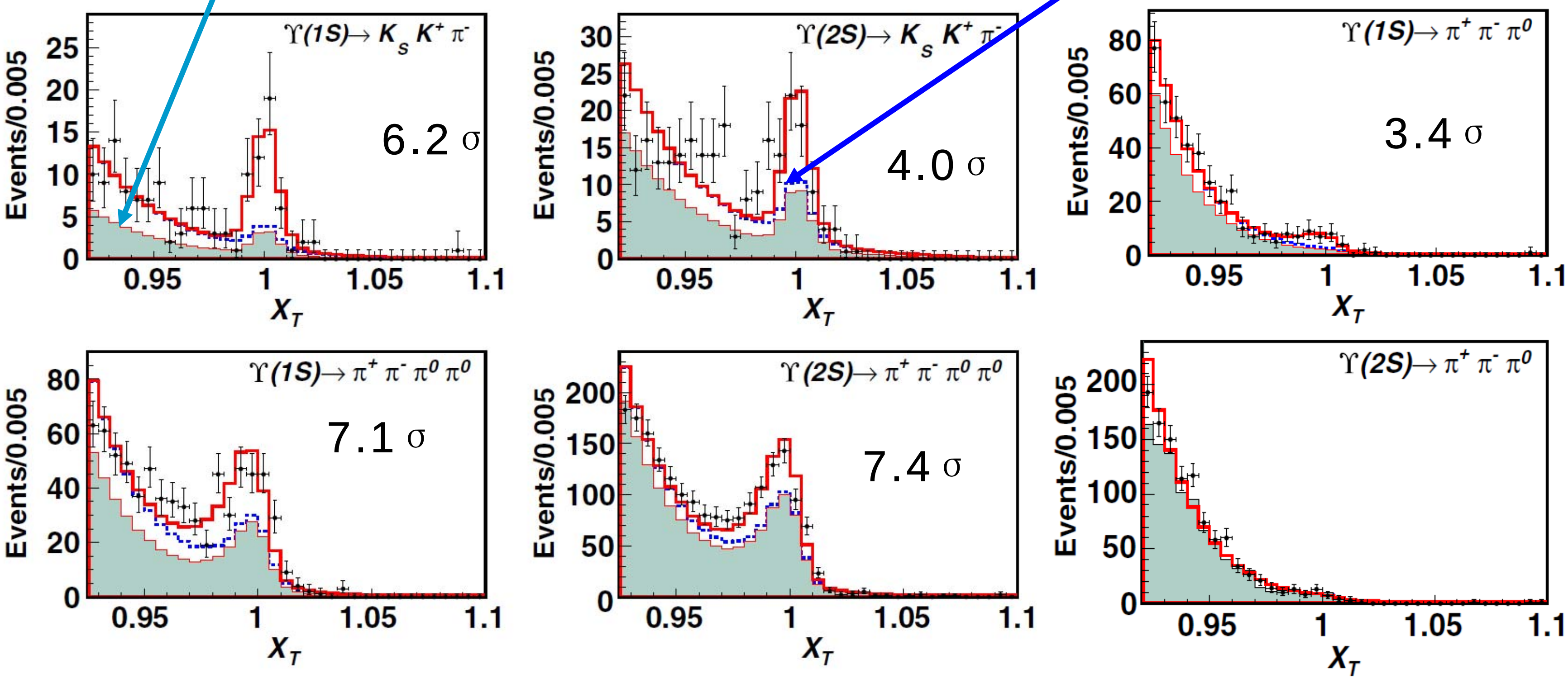
- Signals are observed for the first time in the $\Upsilon(1S) \to \phi K^+K^-$ (8.6σ), $\omega\pi^+\pi^-$ (8.5σ), $K^{*0}K^-\pi^+$, $K^{*0}K_2^{*0}$ (11σ) and $\Upsilon(2S) \to \phi K^+K^-$ (6.5σ), $K^{*0}K^-\pi^+$ (6.4σ) decay modes.
- We find that for the processes ϕK^+K^-, $K^{*0}K^-\pi^+$, and $K^{*0}\bar{K}_2^{*0}(1430)$, the Q_Υ ratios are consistent with the expected value, while for $\omega\pi^+\pi^-$, the measured Q_Υ ratio is 2.6σ below the pQCD expectation.

Look for final states: $K_S K^+ \pi^-, \pi^+\pi^-\pi^0\pi^0, \pi^+\pi^-\pi^0$

Signal extracted from the X_T distribution

shaded histograms: continuum contributions.

dashed curves: total background estimates



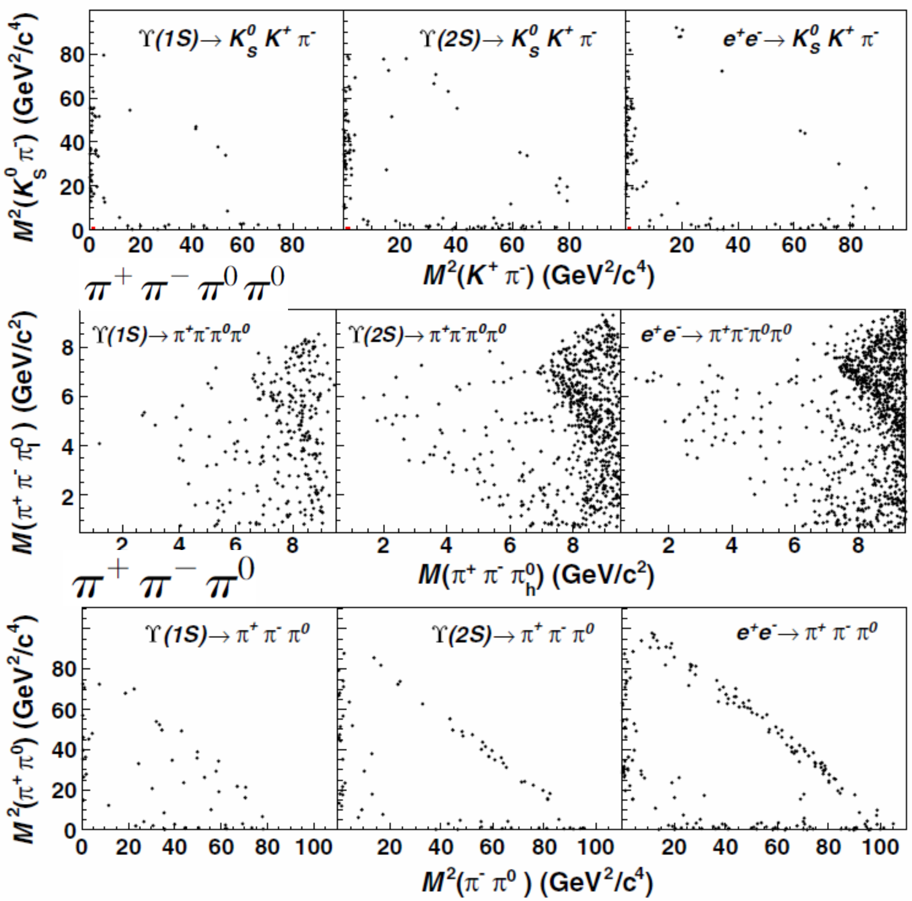
X_T :total final-state particle energy at CM over $\sqrt{s}$

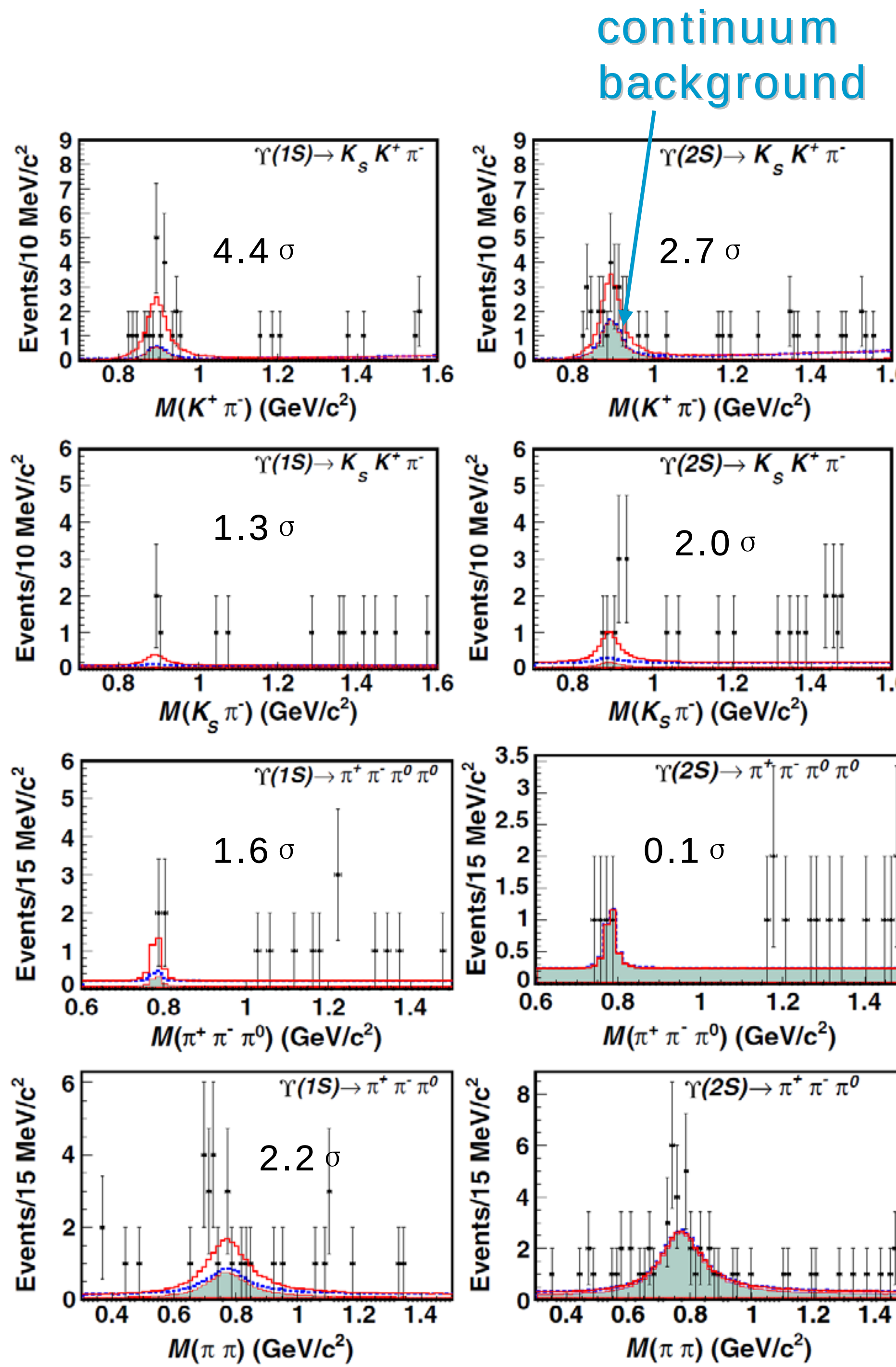
Υ(1S,2S) → VP

$K_S^0 K^+ \pi^-$

$\pi^+ \pi^- \pi^0 \pi^0$

$\pi^+ \pi^- \pi^0$





No significant VP signals!

Υ(1S/2S)→VP Results and Discussions

BELLE

Channel	Υ(1S)			Υ(2S)			
	$N_{\rm sig}$	$\mathcal{B}$	$\mathcal{B}^{\rm UL}$	$N^{\rm sig}$	$\mathcal{B}$	$\mathcal{B}^{\rm UL}$	$Q_\Upsilon/Q_\Upsilon^{\rm UL}$
$K_S^0K^+\pi^-$	37.2 ± 7.6	$1.59\pm0.33\pm0.18$	—	39.5 ± 10.3	$1.14\pm0.30\pm0.13$	—	$0.72\pm0.24\pm0.09$
$\pi^+\pi^-\pi^0\pi^0$	143.2 ± 22.4	$12.8\pm2.01\pm2.27$	—	260.7 ± 37.2	$13.0\pm1.86\pm2.08$	—	$1.01\pm0.22\pm0.23$
$\pi^+\pi^-\pi^0$	25.5 ± 8.6	$2.14\pm0.72\pm0.34$	—	-2.1 ± 9.5	$-0.10\pm0.46\pm0.02$	0.80	0.42
$K^*(892)^0\bar{K}^0$	16.1 ± 4.7	$\boxed{2.92\pm0.85\pm0.37}$	—	14.7 ± 6.0	$\boxed{1.79\pm0.73\pm0.30}$	4.22	1.20
$K^*(892)^-K^+$	2.0 ± 1.9	$\boxed{0.31\pm0.30\pm0.04}$	1.11	5.7 ± 3.4	$\boxed{0.58\pm0.35\pm0.09}$	1.45	5.52
$\omega\pi^0$	2.5 ± 2.1	$1.32\pm1.11\pm0.14$	3.90	0.1 ± 2.2	$0.03\pm0.68\pm0.01$	1.63	1.68
$\rho\pi$	11.3 ± 5.9	$1.75\pm0.91\pm0.28$	3.68	-1.4 ± 8.6	$-0.11\pm0.64\pm0.03$	1.16	0.94

— Observed for the 1st time $\boxed{}$ indication for large isospin violation

1. For the processes Ks K π and $\pi^+\pi^-\pi^0\pi^0$, the Q_Υ ratios are consistent with the expected value.
2. For $\pi^+\pi^-\pi^0$, the Q_Υ ratio is a little lower than the pQCD prediction.
3. The results for the other modes are inconclusive due to low statistical significance.
4. These results may supply useful guidance for interpreting violations of the 12% rule for OZI-suppressed decays in the charmonium sector.

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

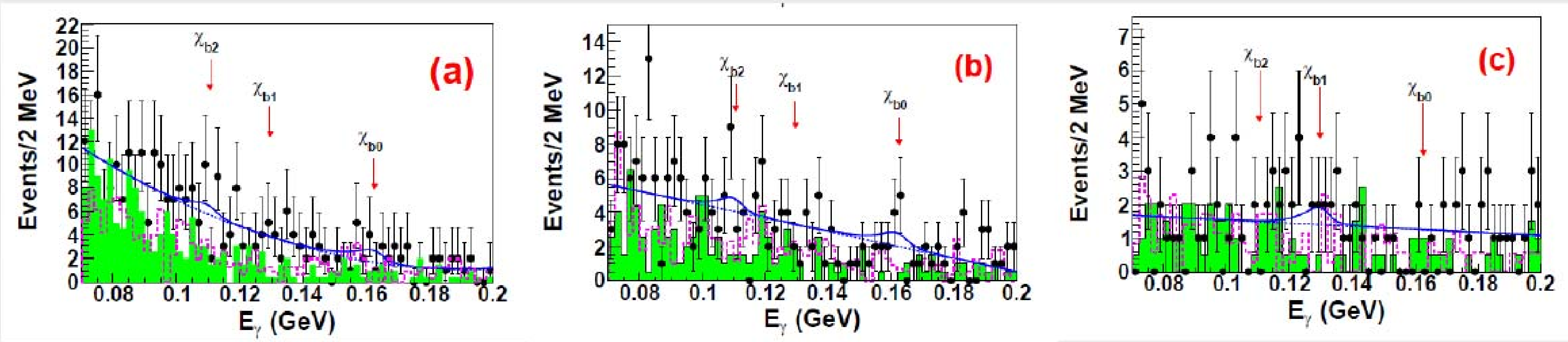
- NRQCD predicts a BF for $\chi_{bJ} \to J/\psi J/\psi$ of 10^{-5} (J=0,2) or 10^{-11} (J=1); PRD **84**, 094031 (2011)
- Similar predictions exist for pQCD and light cone formalism: PRD **72**, 094018 (2005) PRD **84**, 074026 (2011)

	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

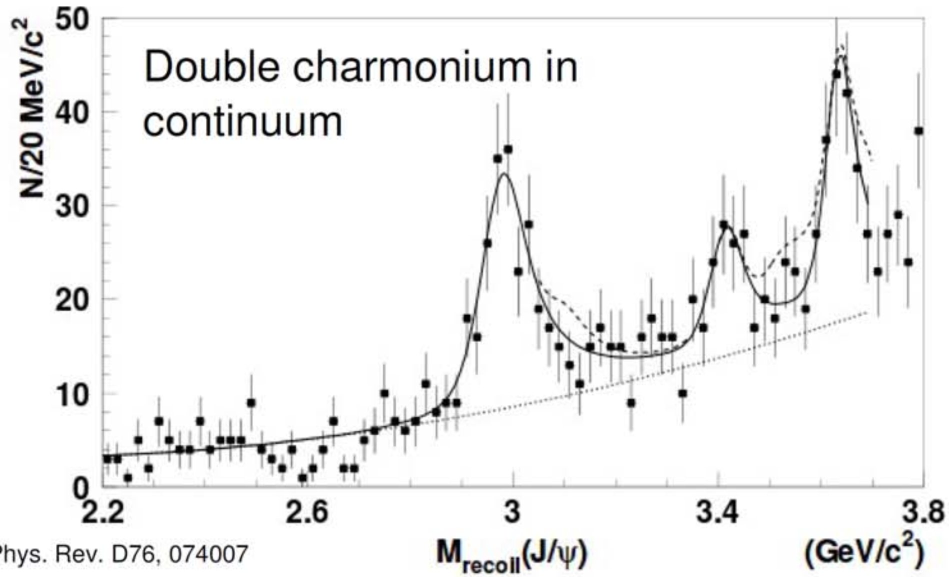
Channel	$n^{\rm up}$	$\varepsilon(\%)$	$\sigma_{\rm sys}(\%)$	$\mathcal{B}_R$
$\chi_{b0} \to J/\psi J/\psi$	21	5.8	16	7.1×10^{-5}
$\chi_{b1} \to J/\psi J/\psi$	13	6.3	30	2.7×10^{-5}
$\chi_{b2} \to J/\psi J/\psi$	22	5.9	27	4.5×10^{-5}
$\chi_{b0} \to J/\psi\psi'$	20	3.4	17	1.2×10^{-4}
$\chi_{b1} \to J/\psi\psi'$	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}

$\Upsilon(1,2S) \to$ double charmonium

$e^+e^- \to \gamma^* \to$ double charmonium

PRL 89, 142001
PRD 70, 071102
PRD 72, 031101

~10 x theory



Phys. Rev. D76, 074007

$\chi_{bJ}(1P) \to$ double charmonium

PRD 85, 071102(R) U.L Only

Matching

Light Cone formalism PRD 80, 094008

NRQCD PRD 84,094031

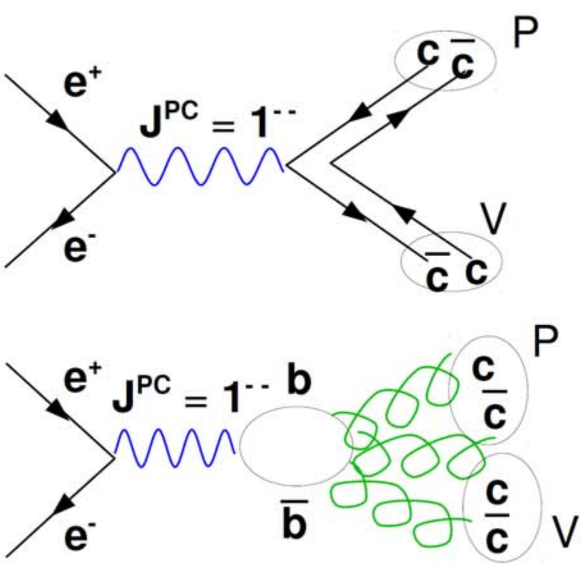
Not matching

Potential QCD PRD 72, 094018

$\Upsilon(1,2S) \to$ double charmonium

Perturbative QCD PRD 76, 074007

NRQCD PRD 87, 094004



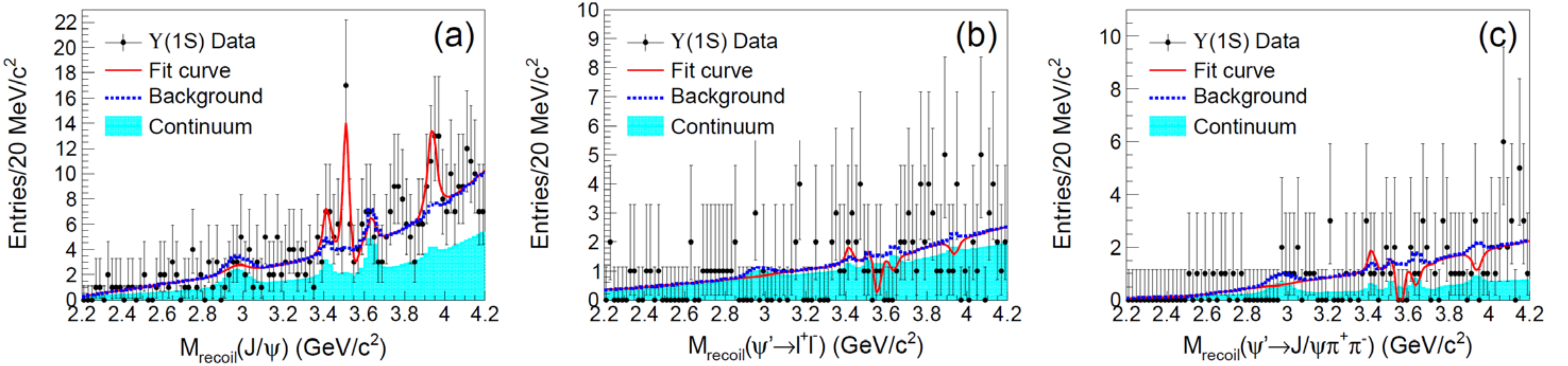
Quantum numbers
$V \to VP$

Reconstruct V in l^+l^- or $\pi\pi l^+l^-$

Identify P with missing mass

$\Upsilon(1S) \to$ double charmonium

arXiv:1409.7644



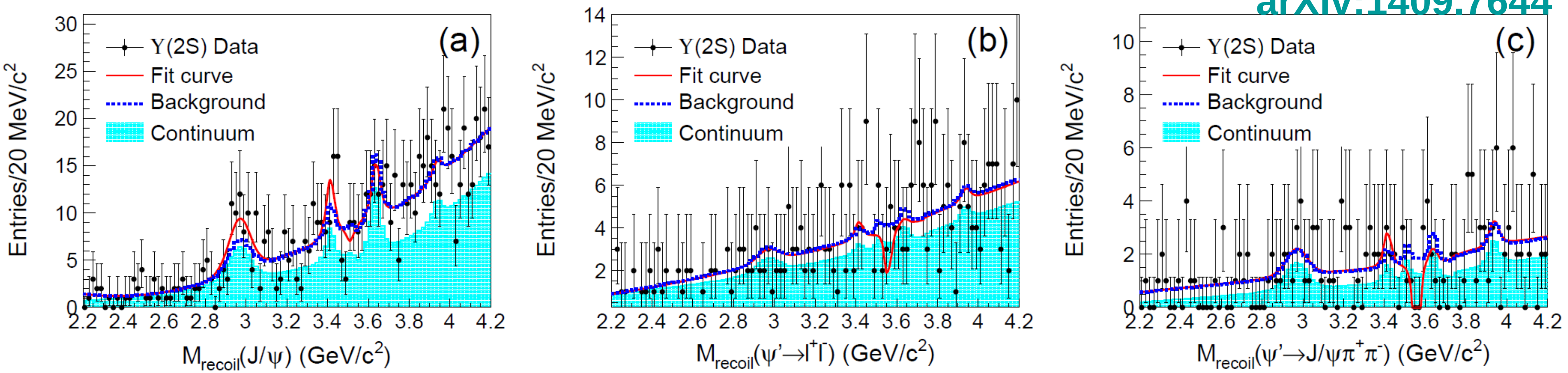
Channels	N_{fit}	$N_{\rm up}$	$\varepsilon(\%)$	$\sigma_{syst}(\%)$	$\Sigma\ (\sigma)$	$\mathcal{B}_R(\times10^{-6})$	$\mathcal{B}_{\rm th}(\times10^{-6})$
$\Upsilon(1S) \to J/\psi + \eta_c$	-5.0 ± 6.3	8.1	3.72	9.3	–	< 2.2	$3.9^{+5.6}_{-2.3}$
$\Upsilon(1S) \to J/\psi + \chi_{c0}$	6.0 ± 5.6	14.5	4.23	6.1	1.3	< 3.4	1.3
$\Upsilon(1S) \to J/\psi + \chi_{c1}$	19.9 ± 6.2	–	4.89	5.6	4.6	$3.98 \pm 1.24 \pm 0.22$	4.9
$\Upsilon(1S) \to J/\psi + \chi_{c2}$	-3.2 ± 4.0	6.4	4.55	5.1	–	< 1.4	0.20
$\Upsilon(1S) \to J/\psi + \eta_c(2S)$	-2.1 ± 6.0	9.4	4.32	6.3	–	< 2.2	$2.0^{+3.4}_{-1.4}$
$\Upsilon(1S) \to J/\psi + X(3940)$	19.0 ± 8.7	31.1	5.64	7.1	2.8	< 5.4	–
$\Upsilon(1S) \to \psi' + \eta_c$	-5.0 ± 3.9	5.7	1.58	12.6	–	< 3.6	$1.7^{+2.4}_{-1.0}$
$\Upsilon(1S) \to \psi' + \chi_{c0}$	2.1 ± 4.1	10.6	1.60	20.0	0.6	< 6.5	–
$\Upsilon(1S) \to \psi' + \chi_{c1}$	0.2 ± 3.6	7.7	1.68	20.4	0.1	< 4.5	–
$\Upsilon(1S) \to \psi' + \chi_{c2}$	-6.7 ± 2.3	3.4	1.63	7.6	–	< 2.1	–
$\Upsilon(1S) \to \psi' + \eta_c(2S)$	-5.7 ± 3.3	5.4	1.68	22.6	–	< 3.2	$0.8^{+1.4}_{-0.6}$
$\Upsilon(1S) \to \psi' + X(3940)$	-5.9 ± 4.0	6.6	1.90	8.0	–	< 2.9	–

First evidence

$\mathcal{B}_{\rm th}$ Y. Jia, Phys. Rev. D **76**, 074007 (2007).
J. Xu, H.-R. Dong, F. Feng, Y.-J. Gao, and Y. Jia, Phys. Rev. D **87**, 094004 (2013).

Υ(2S) → double charmonium

arXiv:1409.7644



Channels	N_{fit}	$N_{\rm up}$	$\varepsilon(\%)$	$\sigma_{syst}(\%)$	$\Sigma\ (\sigma)$	$\mathcal{B}_R(\times 10^{-6})$	$\mathcal{B}_{\rm th}(\times 10^{-6})$
$\Upsilon(2S) \to J/\psi + \eta_c$	16.3 ± 11.9	30.6	3.61	8.9	1.9	< 5.4	$2.6^{+3.7}_{-1.6}$
$\Upsilon(2S) \to J/\psi + \chi_{c0}$	7.8 ± 9.5	22.1	4.16	18.5	1.1	< 3.4	1.1
$\Upsilon(2S) \to J/\psi + \chi_{c1}$	-4.4 ± 6.6	8.6	4.72	14.3	–	< 1.2	4.1
$\Upsilon(2S) \to J/\psi + \chi_{c2}$	2.1 ± 7.4	13.4	4.43	13.4	0.4	< 2.0	0.17
$\Upsilon(2S) \to J/\psi + \eta_c(2S)$	-3.8 ± 10.8	16.7	4.23	24.6	–	< 2.5	$1.3^{+2.1}_{-0.9}$
$\Upsilon(2S) \to J/\psi + X(3940)$	0.7 ± 12.1	17.6	5.61	12.7	0.1	< 2.0	–
$\Upsilon(2S) \to \psi' + \eta_c$	-0.4 ± 7.9	12.4	1.56	8.2	–	< 5.1	$1.1^{+1.6}_{-0.7}$
$\Upsilon(2S) \to \psi' + \chi_{c0}$	2.6 ± 5.7	11.9	1.63	7.1	0.6	< 4.7	–
$\Upsilon(2S) \to \psi' + \chi_{c1}$	-2.8 ± 4.2	6.4	1.67	6.8	–	< 2.5	–
$\Upsilon(2S) \to \psi' + \chi_{c2}$	-13.3 ± 4.8	4.9	1.66	6.9	–	< 1.9	–
$\Upsilon(2S) \to \psi' + \eta_c(2S)$	-3.0 ± 5.9	8.5	1.65	7.6	–	< 3.3	$0.5^{+0.9}_{-0.4}$
$\Upsilon(2S) \to \psi' + X(3940)$	-0.3 ± 7.1	11.7	1.93	9.5	–	< 3.9	–

Summary

- Belle has the largest data samples of Υ(1S,2S) events
- Many exclusive decay modes to light hadrons have been measured and some are observed for the first time, like ϕK^+K^-,to test NRQCD, pQCD rule. Some channels, like $\pi^+\pi^-\pi^0$, are suppressed compared to 77% rule., which is the same as in charmonium decays.
- With large Υ(2S) data sample, χ_{bJ} to double charmonium decays were searched for. 90% U.L. on Br are consistent with NRQCD prediction.
- Υ(1S. 2S) to double charmonium decays were searched for. First evidence of Υ(1S)→J/Ψ+X_{c1} was observed.
- BelleII will have much larger data sample. Very promising results will come out in the future.

Thanks!