Test of QCD at large Q^2 with exclusive hadronic processes

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for Belle Collaboration

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Outline:

- The Belle experiment
- Y(1S,2S) → Vector-Peseudoscalar
- $e^+e^- \longrightarrow \omega\,\pi^0$, K*K, K^2*K

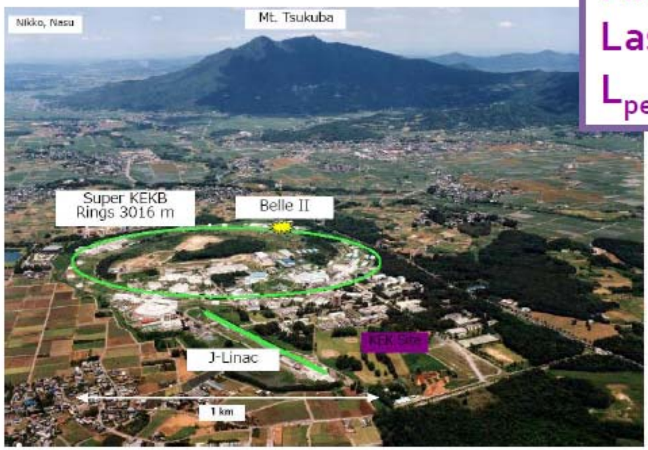
*More Y(1S/2S) →Vector-Tensor, Axial-vector-Pseudoscalar results, please refer to Phys. Rev. D 86, 031102(R) (2012)

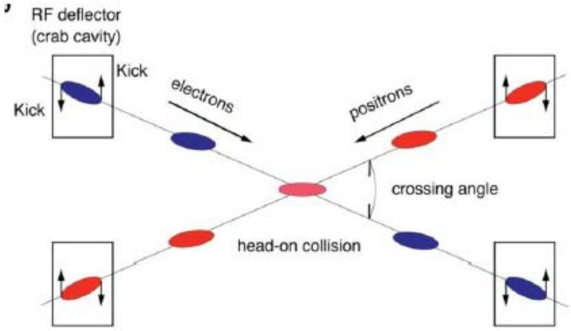
KEKB/Belle

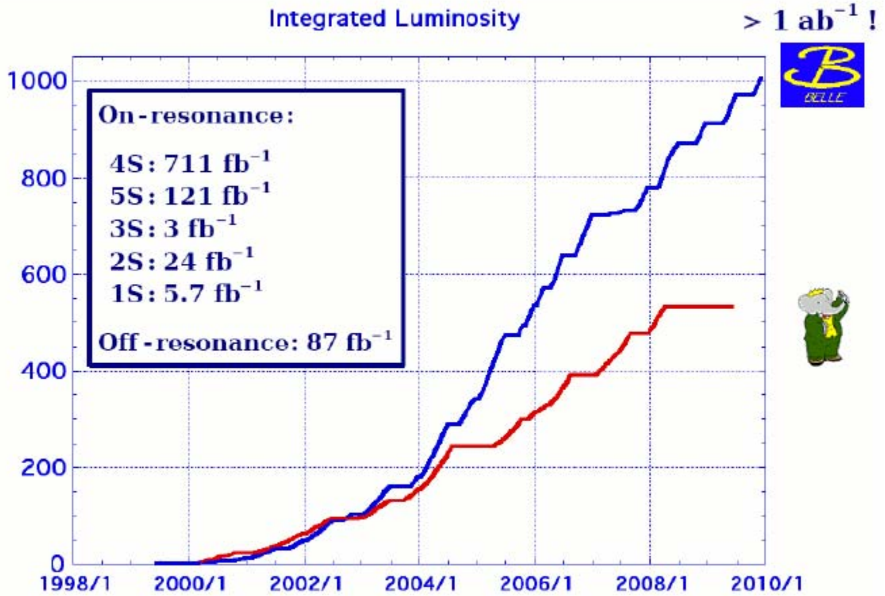
World maximum luminosity

First physics run on June 2, 1999
Last physics run on June 30, 2010
L_{peak} = 2.1x10^{34}/cm^2/s   Ltot > 1ab^{-1}

KEKB:
HER: 8.0 GeV
LER: 3.5 GeV
crossing: 22 mrad
E_{CMS}=M(U(4S))
bg=0.425







Peak lumi record at KEKB: L=2.1 x 10^{34}/cm^2/sec with crab cavities

$\Upsilon(1S,2S) \to$ Vector-Pseudoscalar

Phys. Rev. D 88, 011102(R) (2013)

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

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

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

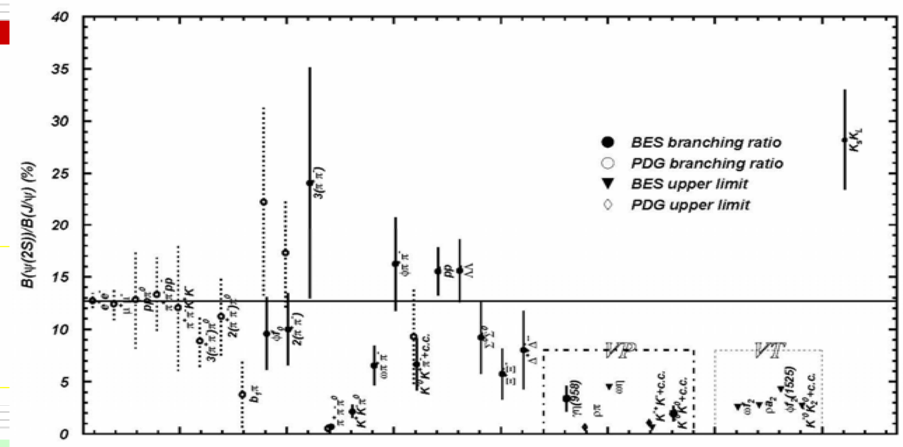
$$\Gamma_l = |M_l|^2 |\Psi(0)|^2 = \tfrac{1}{2}(\tfrac{2}{3}\alpha)^2(\tfrac{4}{3}\alpha_s)^3 m_{\varphi'}, \qquad (4)$$

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

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

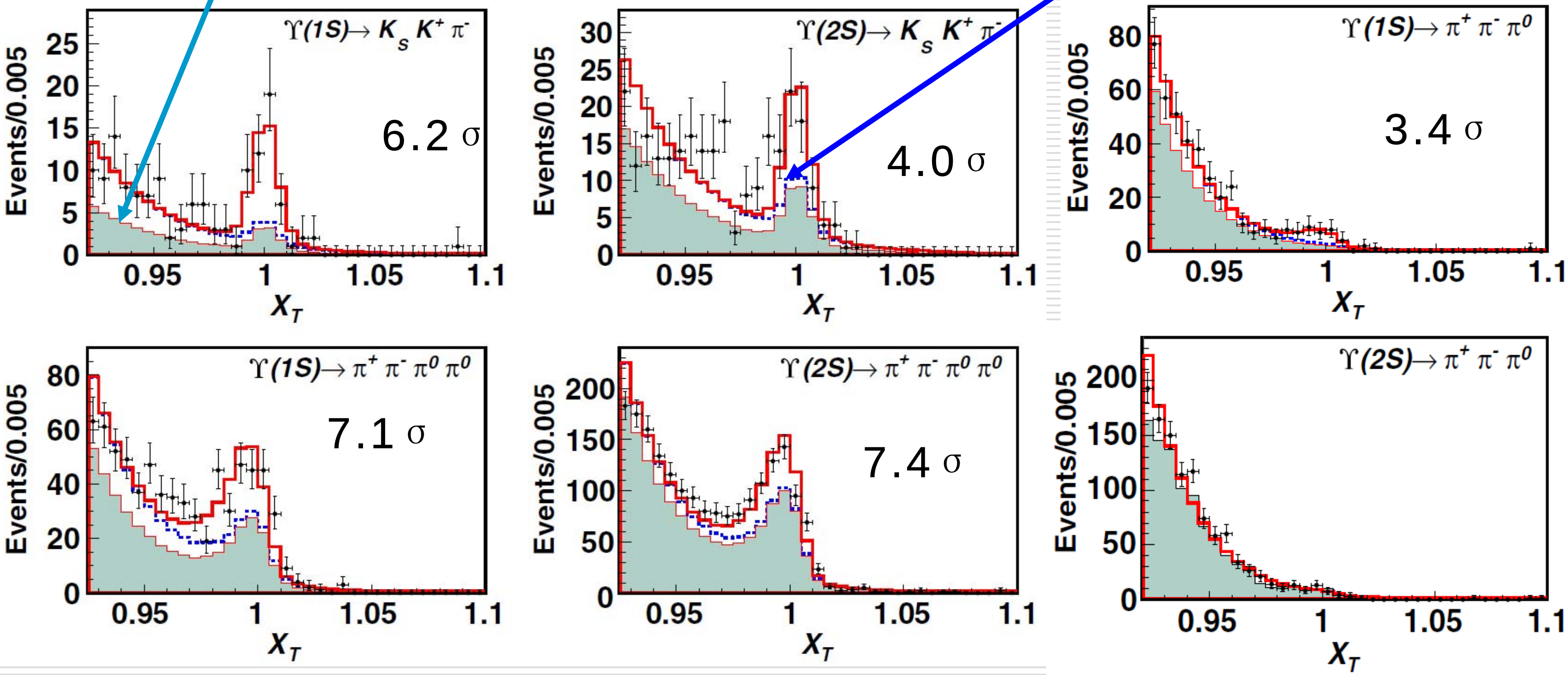
Data sample:
N(Y(1S))=102M
N(Y(2S))=158M

- 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

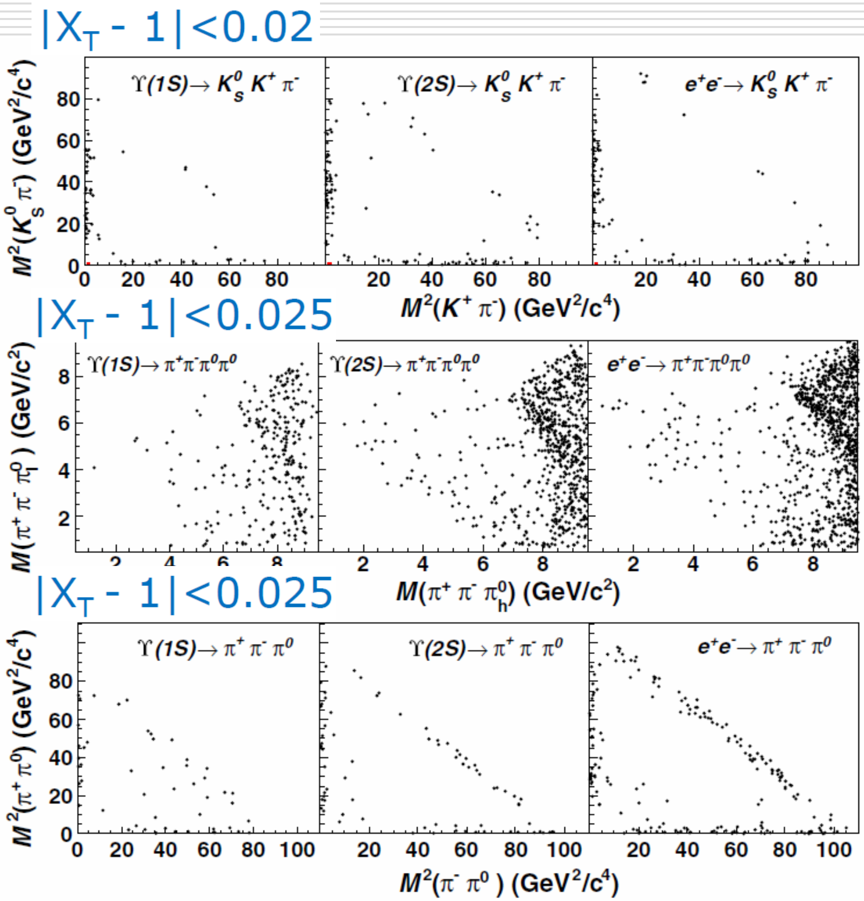
shaded histograms: continuum contributions.

dashed curves: total background estimates

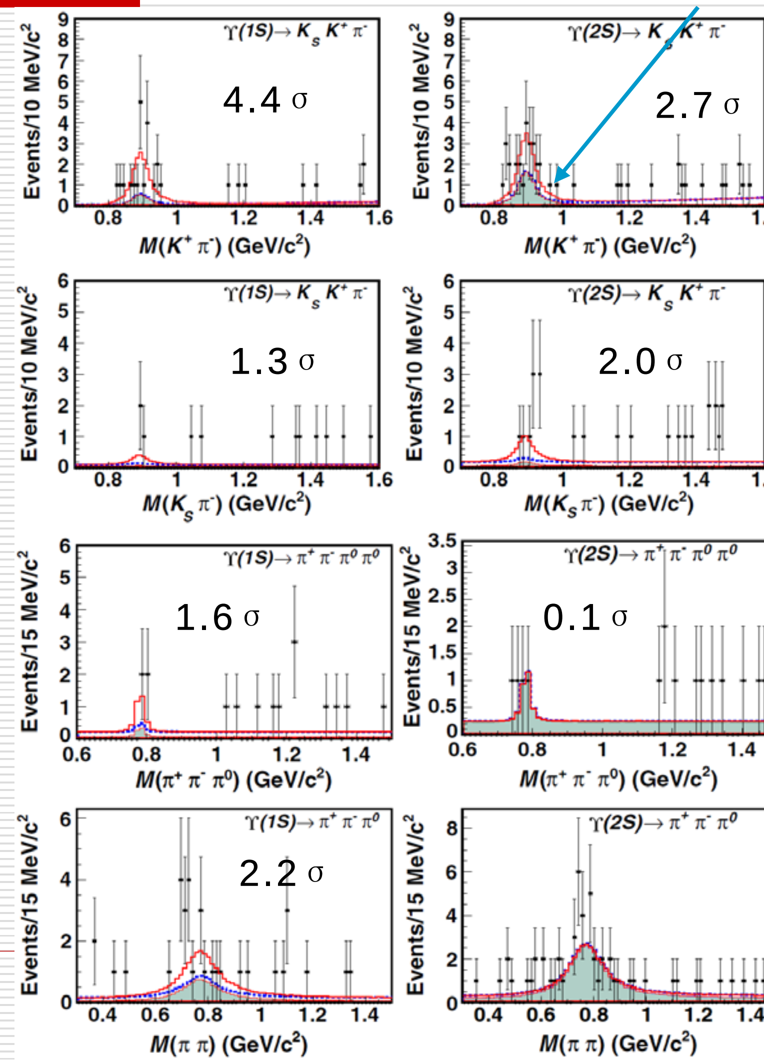


X_T :total final-state particle energy at CM over $\sqrt{s}$

Summary for $\Upsilon(1S,2S) \rightarrow VP$



continuum background



No significant VP signals!

Υ(1S/2S)→VP Results and Discussions

Channel	Υ(1S) $N_{\rm sig}$	Υ(1S) $\mathcal{B}$	Υ(1S) $\mathcal{B}^{\rm UL}$	Υ(2S) $N^{\rm sig}$	Υ(2S) $\mathcal{B}$	Υ(2S) $\mathcal{B}^{\rm UL}$	$Q_\Upsilon/Q_\Upsilon^{\rm UL}$
$K_S^0K^+\pi^-$	37.2 ± 7.6	$1.59 \pm 0.33 \pm 0.18$	—	39.5 ± 10.3	$1.14 \pm 0.30 \pm 0.13$	—	$0.72 \pm 0.24 \pm 0.09$
$\pi^+\pi^-\pi^0\pi^0$	143.2 ± 22.4	$12.8 \pm 2.01 \pm 2.27$	—	260.7 ± 37.2	$13.0 \pm 1.86 \pm 2.08$	—	$1.01 \pm 0.22 \pm 0.23$
$\pi^+\pi^-\pi^0$	25.5 ± 8.6	$2.14 \pm 0.72 \pm 0.34$	—	-2.1 ± 9.5	$-0.10 \pm 0.46 \pm 0.02$	0.80	0.42
$K^*(892)^0\bar{K}^0$	16.1 ± 4.7	$2.92 \pm 0.85 \pm 0.37$	—	14.7 ± 6.0	$1.79 \pm 0.73 \pm 0.30$	4.22	1.20
$K^*(892)^-K^+$	2.0 ± 1.9	$0.31 \pm 0.30 \pm 0.04$	1.11	5.7 ± 3.4	$0.58 \pm 0.35 \pm 0.09$	1.45	5.52
$\omega\pi^0$	2.5 ± 2.1	$1.32 \pm 1.11 \pm 0.14$	3.90	0.1 ± 2.2	$0.03 \pm 0.68 \pm 0.01$	1.63	1.68
$\rho\pi$	11.3 ± 5.9	$1.75 \pm 0.91 \pm 0.28$	3.68	-1.4 ± 8.6	$-0.11 \pm 0.64 \pm 0.03$	1.16	0.94

Observed for the 1st time — indication for large isospin violation

1. For the processes Ks K π and $\pi^+ \pi^- \pi^0 \pi^0$, the Q_Y ratios are consistent with the expected value.
2. For $\pi^+ \pi^- \pi^0$, the Q_Y 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.

$e^+e^- \to \omega\pi^0, K^*\overline{K}, K_2^*\overline{K}$

NEW

1. Investigate the energy dependence of various meson form factors and shed light on hadron structure and hence the strong interaction.
2. $e^+e^- \to \omega\, \pi$ is a EM process. Form factor is predicted to be 1/s dependence [PLB425,365]
3. At large $\sqrt{s}$, cross sections ratio $\omega\pi^0 : K^{*0}\overline{K}^0 : K^{*-}K^+ = 9:8:2$ if $SU(3)_f$ symmetry is perfect. But, this relation was severely violated at 3.67 and 3.773 GeV from CLEO results:

$$R_{\rm VP} = \frac{\sigma_B(e^+e^-\to K^*(892)^0\bar{K}^0)}{\sigma_B(e^+e^-\to K^*(892)^-K^+)}$$ >9 and 33 at 3.67 and 3.77 GeV

4. A pQCD calculation [PRD75,094020] predicts R_{VP}=6
5. In the quark model, we expect:

$$R_{\rm TP} = \frac{\sigma_B(e^+e^- \to K_2^*(1430)^0\bar{K}^0)}{\sigma_B(e^+e^- \to K_2^*(1430)^-K^+)} = R_{\rm VP}$$

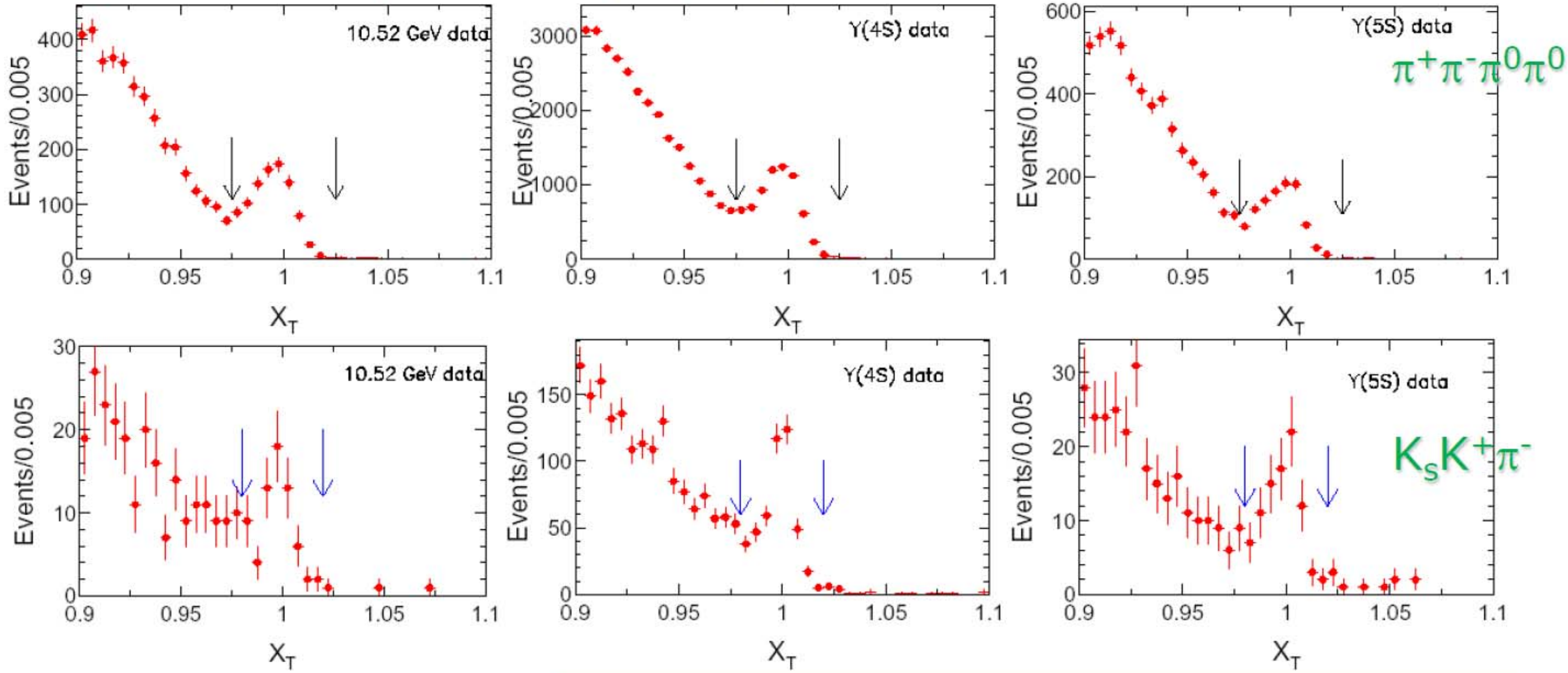
$e^+e^- \to \omega\pi^0, K^*\bar{K}, K_2^*\bar{K}$

BELLE

NEW

- Data samples: $89 fb^{-1}$ 10.52GeV, $703 fb^{-1}$ $\Upsilon(4S)$, $121 fb^{-1}$ $\Upsilon(5S)$
- Signal generator: MCGPJ [next-to-leading order RC included]
- Background: PYTHIA
- Same techniques as $\Upsilon(1S,2S) \to VP$

preliminary

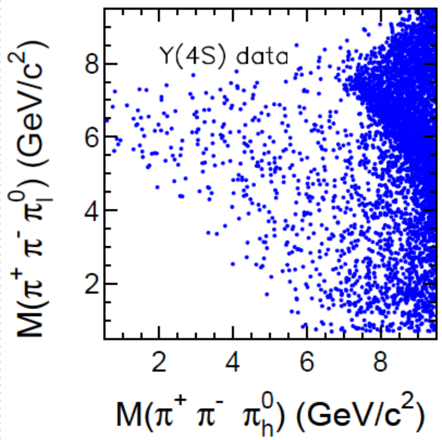


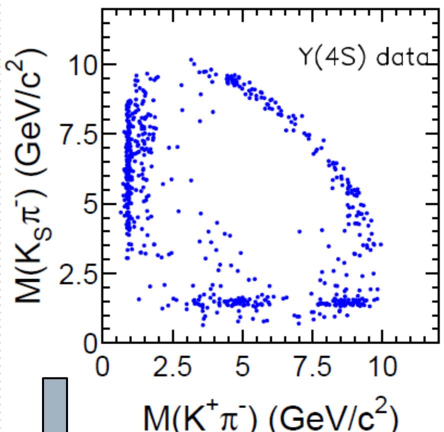
X_T :total final-state particle energy at CM over $\sqrt{s}$

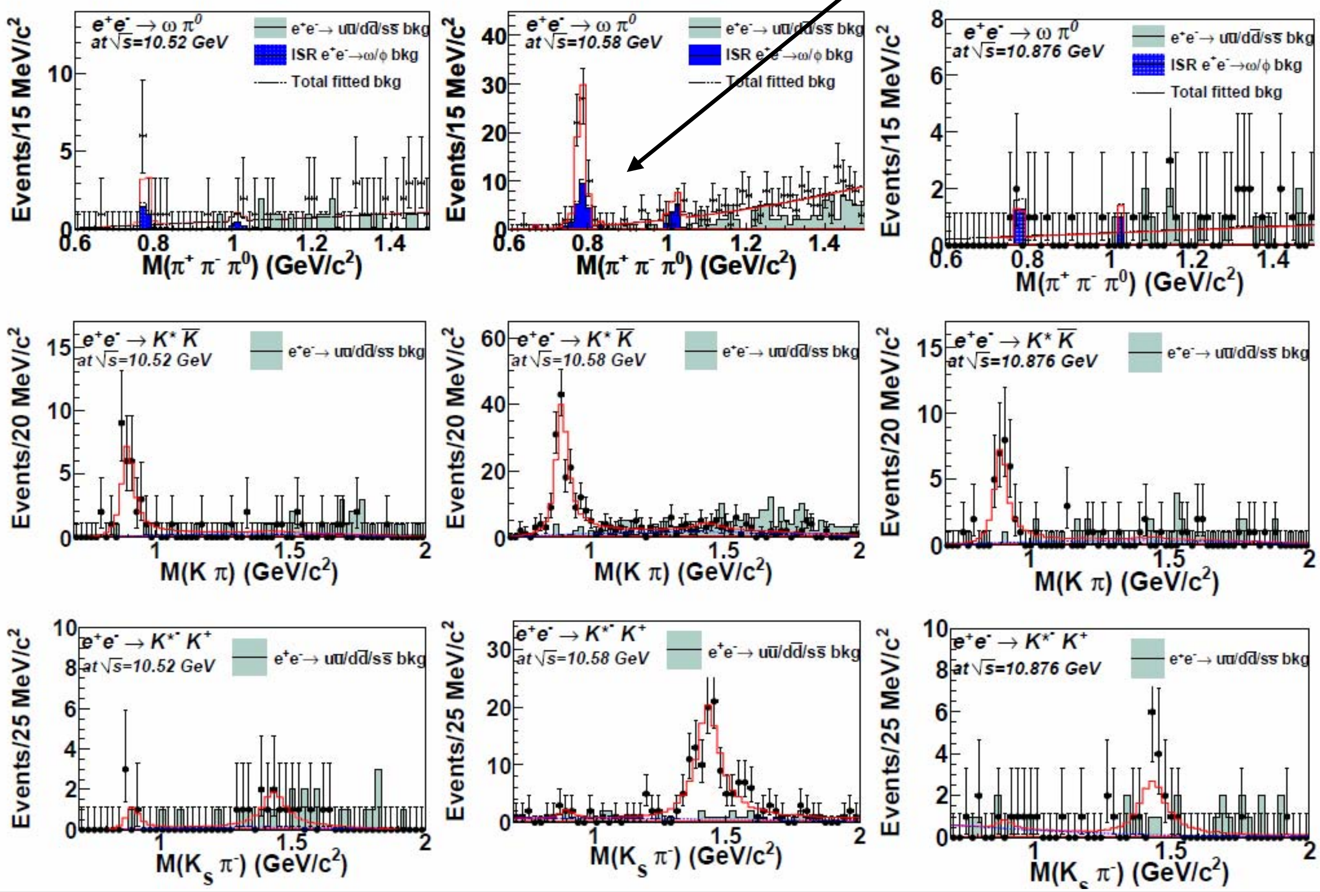
Projection plots to extract ω, K^*, K_2^* in signal region

NEW

ISR background







Y(4S) data sample as an example

10.52GeV 10.58GeV 10.876GeV

NEW

BELLE

Results for $e^+e^- \to \omega\pi^0, K^*\bar{K}, K_2^*\bar{K}$

Channel	$\sqrt{s}$ (GeV)	$N_{\rm sig}$	$N_{\rm sig}^{\rm UL}$	ϵ (%)	Σ (σ)	σ_B (fb)	$\sigma_B^{\rm UL}$ (fb)
$\omega\pi^0$	10.52	$4.1^{+3.3}_{-2.6}$	9.9	1.25	1.6	$4.53^{+3.64}_{-2.88} \pm 0.50$	11
	10.58	$38.8^{+8.3}_{-7.6}$	—	1.10	6.7	$6.01^{+1.29}_{-1.18} \pm 0.57$	—
	10.876	$-0.7^{+2.9}_{-2.1}$	7.0	1.07	—	$-0.68^{+2.71}_{-1.97} \pm 0.20$	6.5
$K^*(892)^0\bar{K}^0$	10.52	$34.6^{+6.9}_{-6.1}$	—	16.49	7.4	$10.77^{+2.15}_{-1.90} \pm 0.77$	—
	10.58	187 ± 17	—	16.30	>10	$7.48 \pm 0.67 \pm 0.51$	—
	10.876	$34.6^{+7.5}_{-6.7}$	—	17.25	7.2	$7.58^{+1.64}_{-1.47} \pm 0.63$	—
$K^*(892)^-K^+$	10.52	$4.6^{+3.6}_{-2.7}$	9.3	20.40	1.4	$1.14^{+0.90}_{-0.67} \pm 0.15$	2.3
	10.58	$5.9^{+4.7}_{-3.8}$	14	21.03	1.5	$0.18^{+0.14}_{-0.12} \pm 0.02$	0.4
	10.876	$1.6^{+3.9}_{-3.0}$	8.5	21.29	0.3	$0.28^{+0.68}_{-0.52} \pm 0.10$	1.5
$K_2^*(1430)^0\bar{K}^0$	10.52	$1.3^{+4.3}_{-3.9}$	6.8	17.63	0.3	$0.76^{+2.53}_{-2.26} \pm 0.14$	4.0
	10.58	21^{+11}_{-10}	40	16.71	2.1	$1.65^{+0.86}_{-0.78} \pm 0.27$	3.1
	10.876	$1.0^{+4.5}_{-3.7}$	8.9	19.02	0.2	$0.38^{+1.79}_{-1.47} \pm 0.07$	3.5
$K_2^*(1430)^-K^+$	10.52	$12.0^{+6.2}_{-5.8}$	21	20.36	2.1	$6.06^{+3.13}_{-2.93} \pm 1.34$	11
	10.58	129 ± 15	—	20.17	>10	$8.36 \pm 0.95 \pm 0.62$	—
	10.876	$17.6^{+5.3}_{-4.6}$	—	21.50	4.5	$6.20^{+1.86}_{-1.63} \pm 0.64$	—

$\longrightarrow$ Born cross section

$$R_{\rm VP} = \frac{\sigma_B(e^+e^- \to K^*(892)^0\bar{K}^0)}{\sigma_B(e^+e^- \to K^*(892)^-K^+)} > 4.3, \;\; 20.0, \;\; 5.4,$$

$$R_{\rm TP} = \frac{\sigma_B(e^+e^- \to K_2^*(1430)^0\bar{K}^0)}{\sigma_B(e^+e^- \to K_2^*(1430)^-K^+)} < 1.1, \;\; 0.4, \;\; 0.6,$$

for 10.52,10.58 and 10.876 GeV

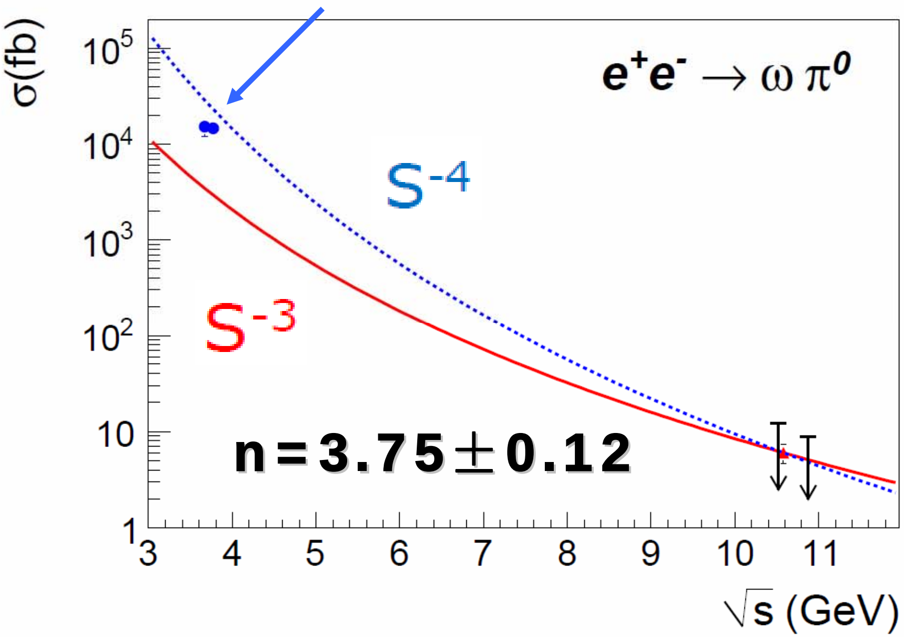
Consistent with theoretical prediction [PRD 75,094020]

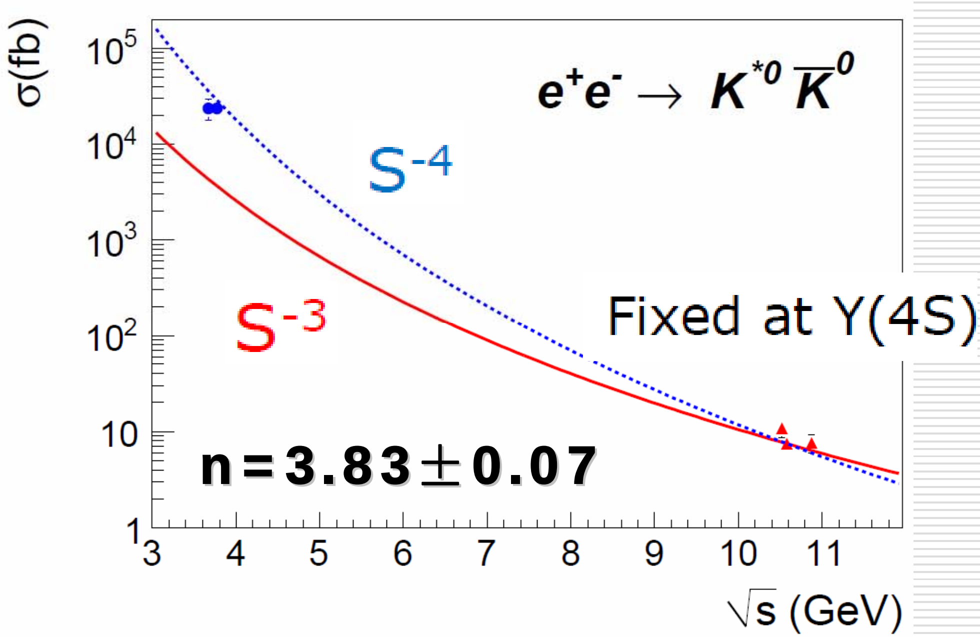
All the results on the cross sections at 10.52, 10.58, and 10.876 GeV, including upper limits, are the first measurements up to now.

Violate SU(3) sym. $\omega\pi^0 : K^*(892)^0\bar{K}^0 : K^*(892)^-K^+$ = 9: 8: 2

S^{-n} dependence

CLEO-C measurements





These are significantly different from the $1/s^2$ [PLB425,365] or $1/s^3$ [PRD75,094020] predictions and agree with $1/s^4$ [PRD22,2175; 24,2848; 78, 074032] within 2.5 σ .