Review of Belle QCD Results

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on behalf of the Belle Collaboration
2013/7/20

Outline

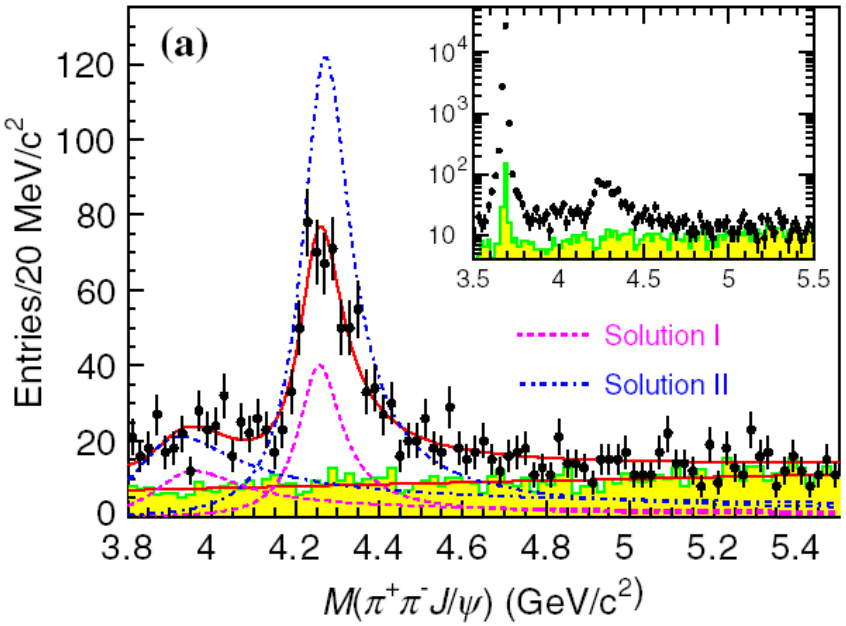
- $e^+e^- \to \pi^+\pi^- J/\Psi$
- $Y(1S,2S) \to VP$
- $e^+e^- \to \omega\pi^0, K^*\overline{K}, K_2^*\overline{K}$
- $\gamma\gamma \to K_s^0 K_s^0$
- Summary

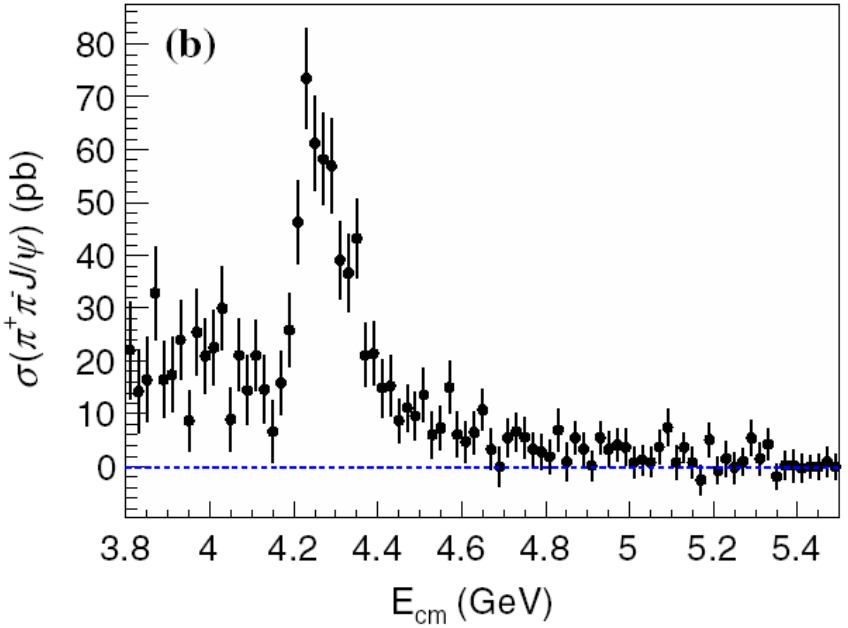
$e^+e^- \to \pi^+\pi^- J/\Psi$

Phys.Rev.Lett. 110, 252002 (2013)

- Using Belle data sample ~967 fb^{-1}
- Good trigger eff. with 4 charged tracks
- Using ISR method e^+e^- C.M. energy radiated return to 3.5-5.5 GeV region
- Signal generator PHOKHARA
- Background estimation with J/Ψ mass sideband
- Ψ(2S) as control sample for systematic study

$\sigma(e^+e^- \to \pi^+\pi^- J/\Psi)$

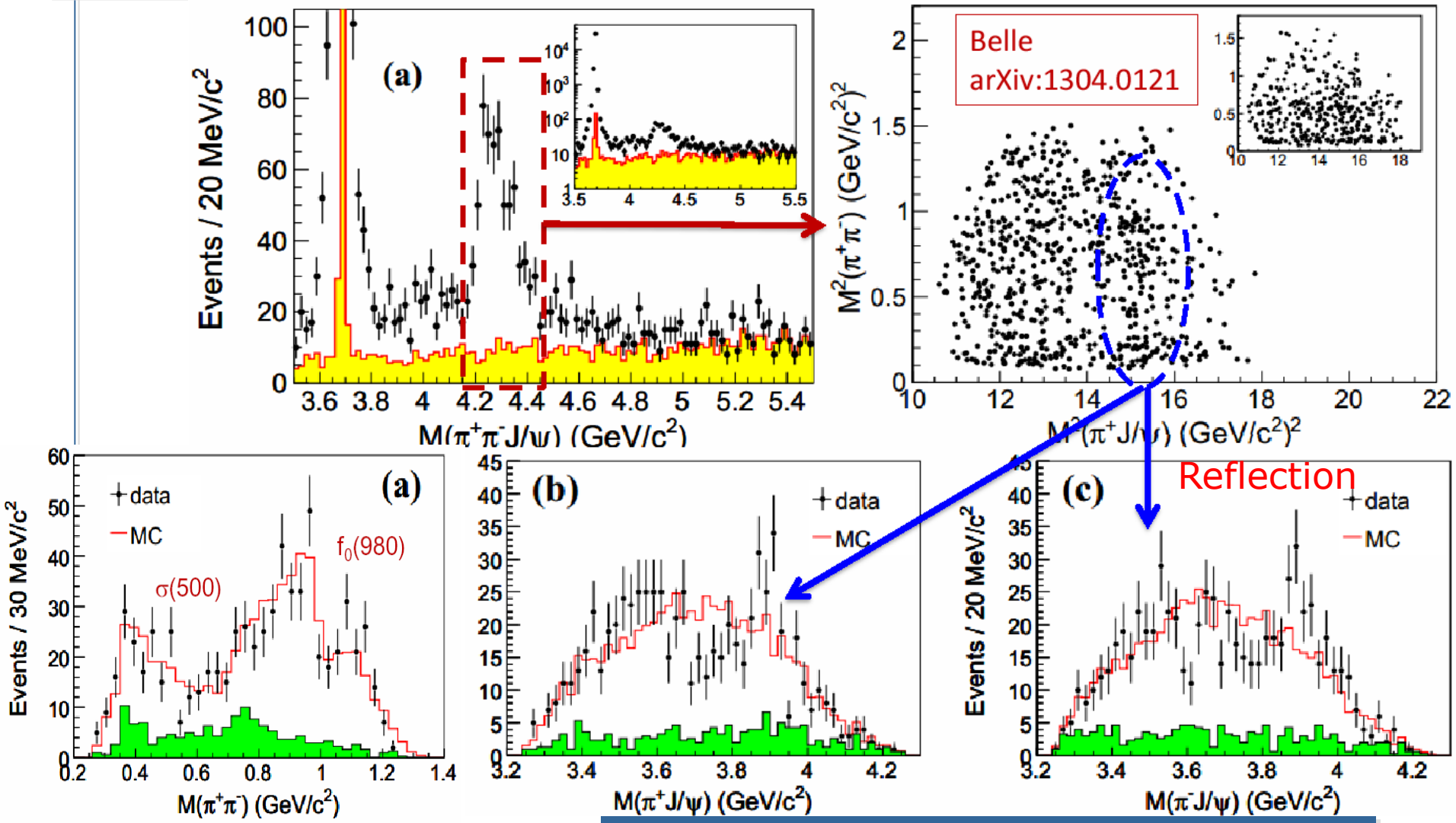




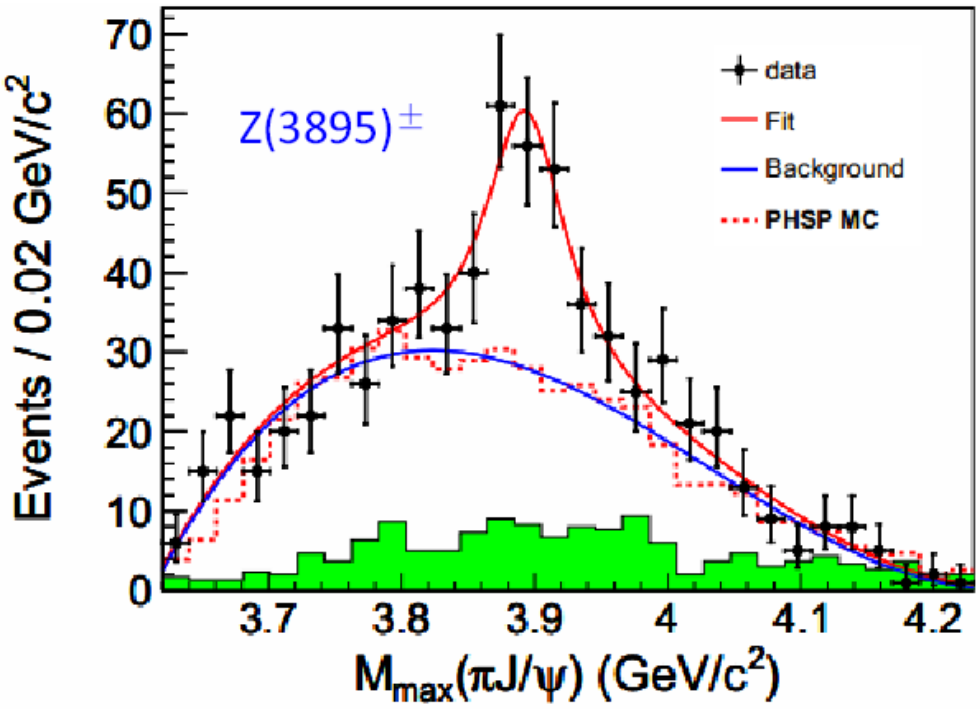
Parameters	Solution I	Solution II
$M(R_1)$	$3890.8 \pm 40.5 \pm 11.5$	
$\Gamma_{tot}(R_1)$	$254.5 \pm 39.5 \pm 13.6$	
$\Gamma_{ee}\mathcal{B}(R_1 \to \pi^+\pi^- J/\psi)$	$(3.8 \pm 0.6 \pm 0.4)$	$(8.4 \pm 1.2 \pm 1.1)$
$M(R_2)$	$4258.6 \pm 8.3 \pm 12.1$	
$\Gamma_{tot}(R_2)$	$134.1 \pm 16.4 \pm 5.5$	
$\Gamma_{ee}\mathcal{B}(R_2 \to \pi^+\pi^- J/\psi)$	$(6.4 \pm 0.8 \pm 0.6)$	$(20.5 \pm 1.4 \pm 2.0)$
ϕ	$59 \pm 17 \pm 11$	$-116 \pm 6 \pm 11$

Two BW's with mass, total width, partial width and relative phase as fit parameters
$\to Y(4008)$, $Y(4260)$

Dalitz plot for $Y(4260) \rightarrow \pi^+\pi^- J/\Psi$



Observation of a charged charmoniumlike state



Non- $\pi^+\pi^-$J/Ψbackground estimated from J/Ψ sideband

Resonance on top of a phase space distribution

Fit significance ~5.2σ

BESIII reported the same finding, namely Z(3900) at the same time

Not a conventional charmonium state

M=(3894.5±6.6±4.5) MeV; Γ=(63±24±26) MeV

Y(1S,2S) → Vector-Pseudoscalar

To appear in Phys.Rev.D (RC)

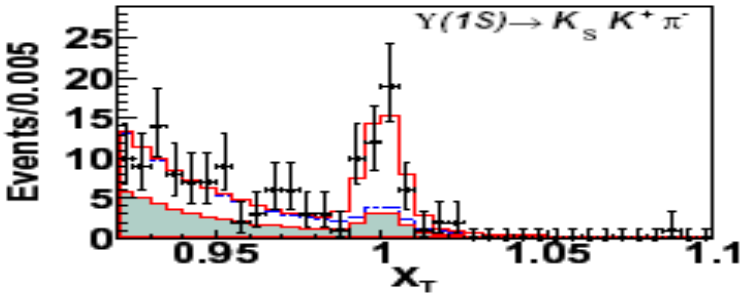
- OZI suppressed decays to hadrons
- pQCD calculations

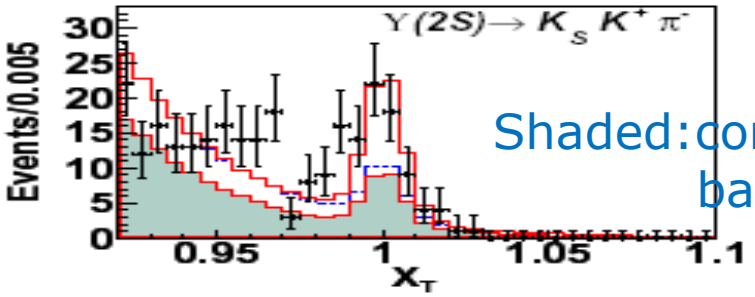
$$Q_\psi = \frac{\mathcal{B}_{\psi(2S)\to\text{hadrons}}}{\mathcal{B}_{J/\psi\to\text{hadrons}}} = \frac{\mathcal{B}_{\psi(2S)\to e^+e^-}}{\mathcal{B}_{J/\psi\to e^+e^-}} \approx 12\%$$

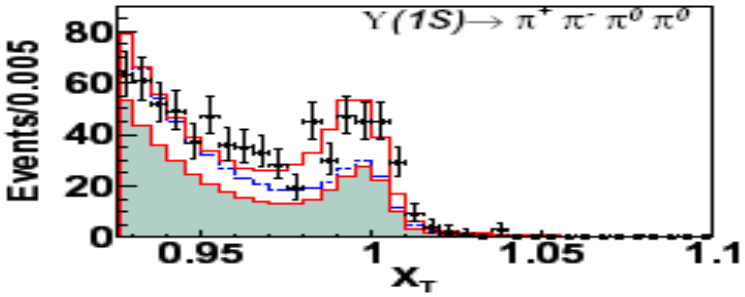
$$Q_\Upsilon = \frac{\mathcal{B}_{\Upsilon(2S)\to\text{hadrons}}}{\mathcal{B}_{\Upsilon(1S)\to\text{hadrons}}} = \frac{\mathcal{B}_{\Upsilon(2S)\to e^+e^-}}{\mathcal{B}_{\Upsilon(1S)\to e^+e^-}} = 0.77 \pm 0.07$$

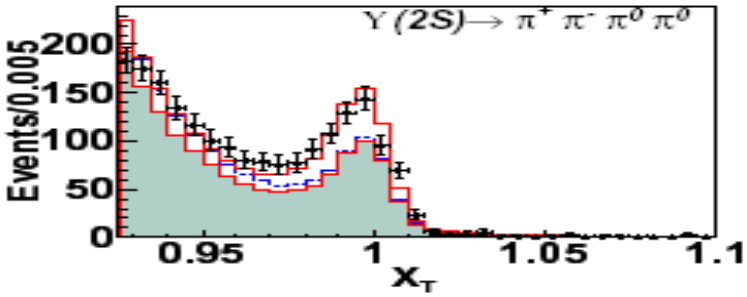
- Vector-Pseudoscalar: $\rho\pi$ puzzle at Ψ's
- Data samples: 102M Y(1S); 158M Y(2S)
- Continuum background estimated from $\sqrt{s}$=10.52GeV
- Look for final states: $K_s K^+\pi^-$, $\pi^+\pi^-\pi^0\pi^0$, $\pi^+\pi^-\pi^0$

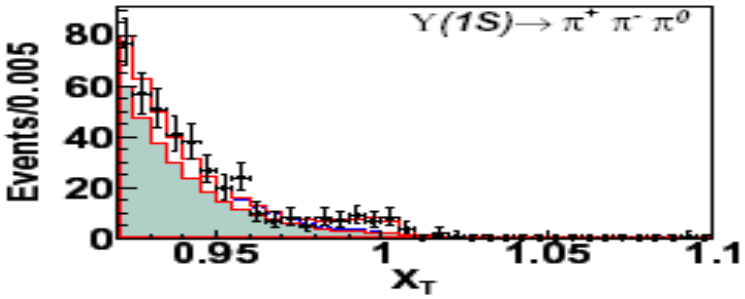
Signal extracted from the X_T distribution

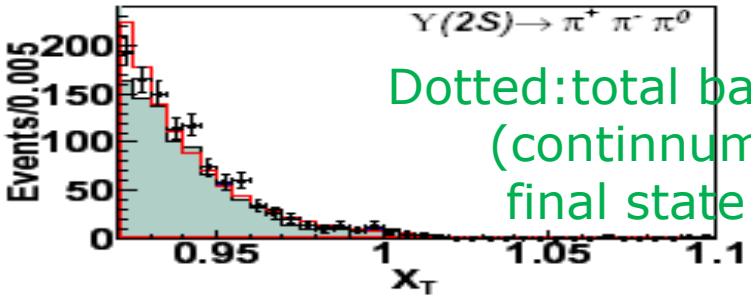












Shaded:continuum background

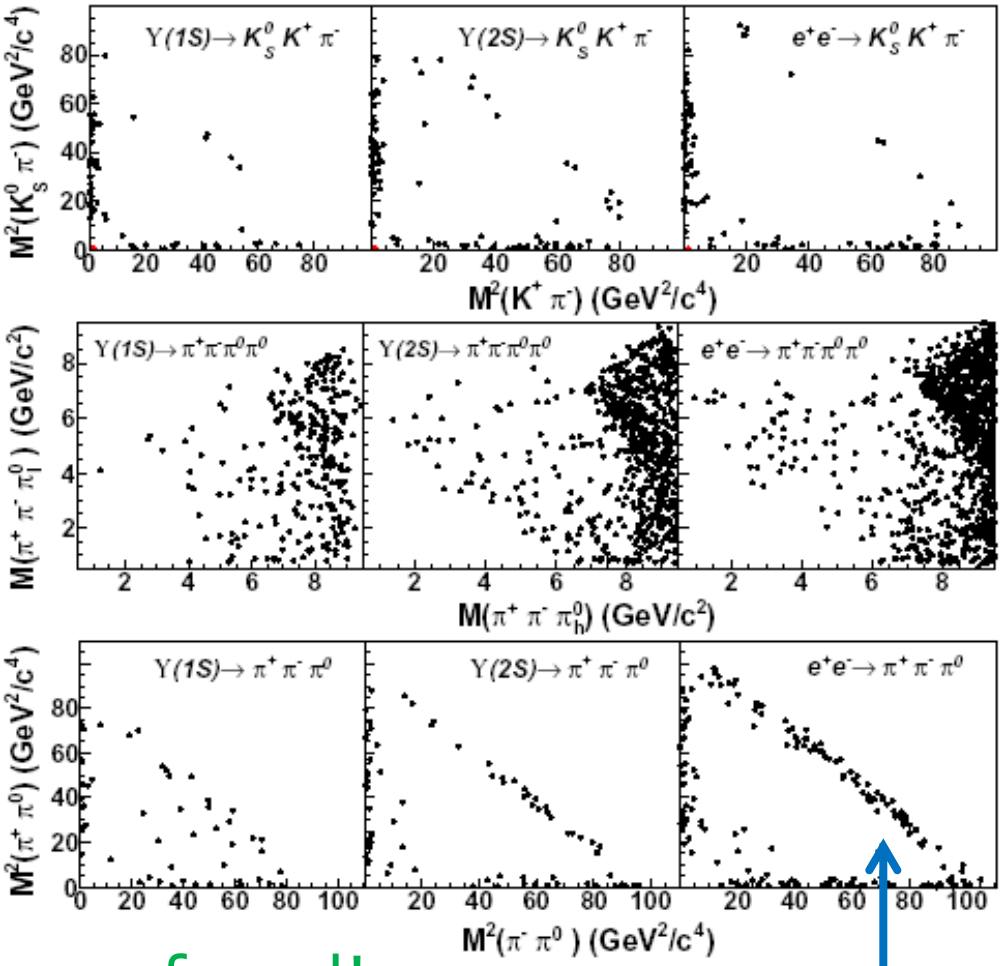
Dotted:total background (continnum+ extra final state particles)

PYTHIA

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

Dalitz or scatter plot in signal region

- $|X_T - 1| < 0.02$
- $|X_T - 1| < 0.025$
- $|X_T - 1| < 0.025$

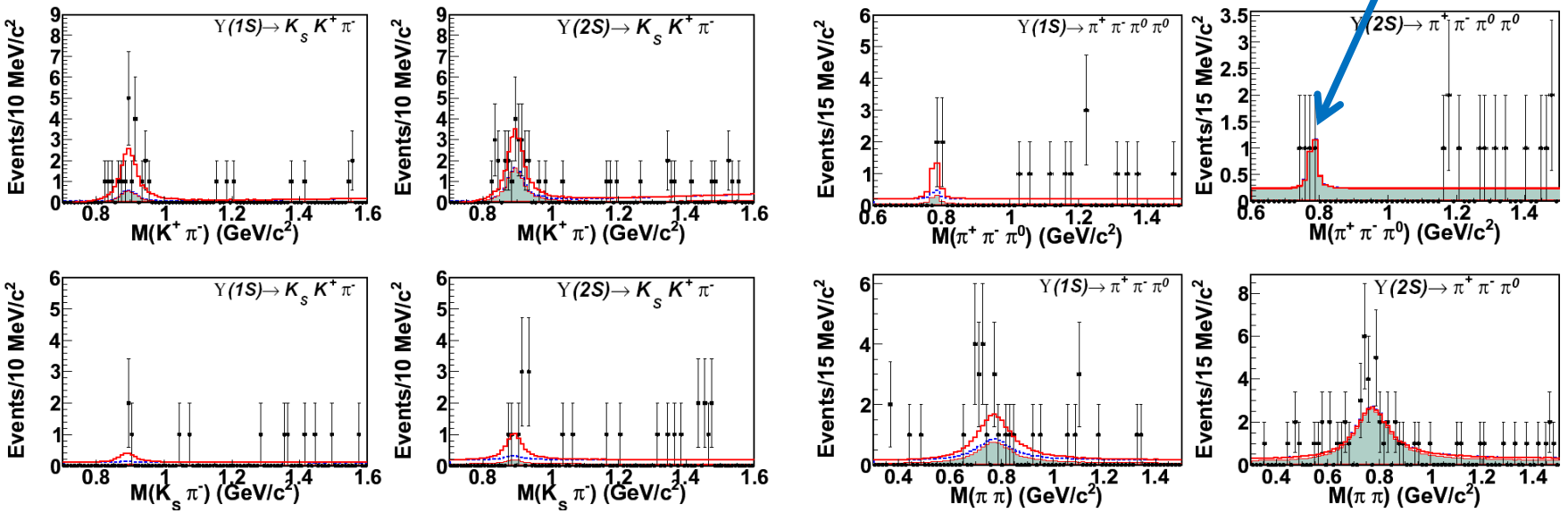


No visible features found!

Continuum

Summary for Y(1S,2S) → VP

Shaded:continuum background



Isospin or SU(3)violation?

Q_Υ consistent with pQCD

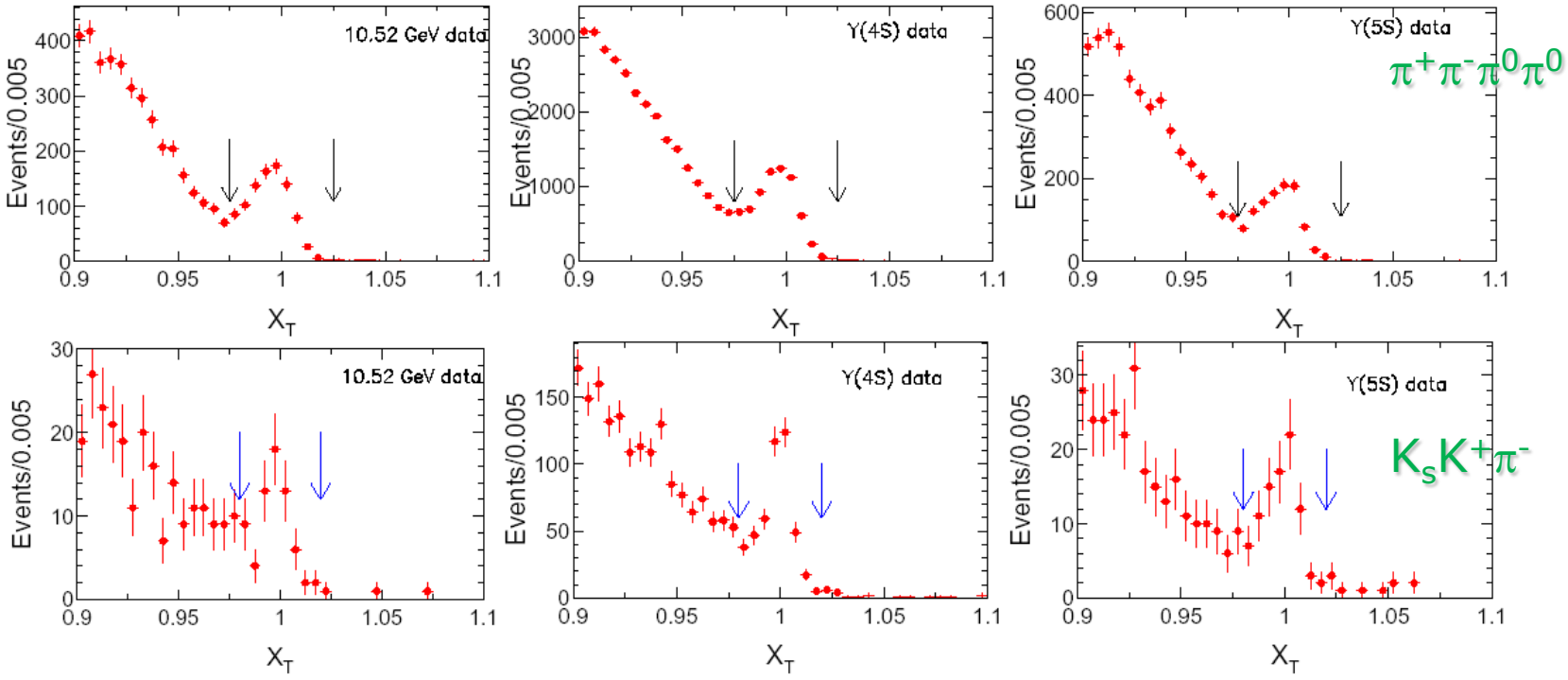
Channel	$\Upsilon(1S)$ $N_{\rm sig}$	$N_{\rm sig}^{\rm UL}$	ϵ	Σ	$\mathcal{B}$	$\mathcal{B}^{\rm UL}$	$\Upsilon(2S)$ $N^{\rm sig}$	$N_{\rm sig}^{\rm UL}$	ϵ	Σ	$\mathcal{B}$	$\mathcal{B}^{\rm UL}$	Q_Υ	$Q_\Upsilon^{\rm UL}$
$K_S^0K^+\pi^-$	37.2 ± 7.6	—	22.96	6.2	$1.30\pm0.33\pm0.18$	—	39.5 ± 10.3	—	21.88	4.0	$1.14\pm0.30\pm0.13$	—	$0.72\pm0.24\pm0.09$	—
$\pi^+\pi^-\pi^0\pi^0$	143.2 ± 22.4	—	11.20	7.1	$12.8\pm2.01\pm2.27$	—	260.7 ± 37.2	—	12.98	7.4	$13.0\pm1.86\pm2.08$	—	$1.01\pm0.22\pm0.23$	—
$\pi^+\pi^-\pi^0$	25.5 ± 8.6	—	11.86	3.4	$2.14\pm0.72\pm0.34$	—	-2.1 ± 9.5	15	13.19	—	$-0.10\pm0.46\pm0.02$	0.80	$-0.05\pm0.21\pm0.02$	0.42
$K^*(892)^0K^0$	16.1 ± 4.7	—	16.23	4.4	$2.92\pm0.85\pm0.37$	—	14.7 ± 6.0	30	15.59	2.7	$1.79\pm0.73\pm0.30$	4.22	$0.61\pm0.31\pm0.12$	1.20
$K^*(892)^-K^+$	2.0 ± 1.9	6.3	18.92	1.3	$0.31\pm0.30\pm0.04$	1.11	5.7 ± 3.4	13	18.77	2.0	$0.58\pm0.35\pm0.09$	1.45	$1.87\pm2.12\pm0.33$	5.52
$\omega\pi^0$	2.5 ± 2.1	6.8	2.11	1.6	$1.32\pm1.11\pm0.14$	3.90	0.1 ± 2.2	4.6	2.32	0.1	$0.03\pm0.68\pm0.01$	1.63	$0.02\pm0.50\pm0.01$	1.68
$\rho\pi$	11.3 ± 5.9	22	6.41	2.2	$1.75\pm0.91\pm0.28$	3.68	-1.4 ± 8.6	14	8.66	—	$-0.11\pm0.64\pm0.03$	1.16	$-0.06\pm0.38\pm0.02$	0.94

Still limited by statistics

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

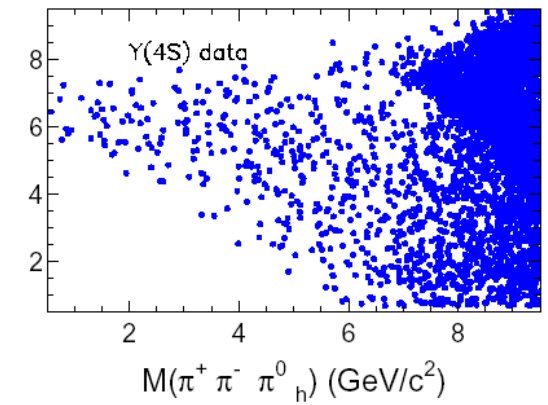
- Data samples: 89fb^{-1} 10.52GeV, 703fb^{-1} Y(4S), 121fb^{-1} Y(5S)
- Signal generator: MCJPG
- Background: PYTHIA
- Same techniques as Y(1S,2S) → VP

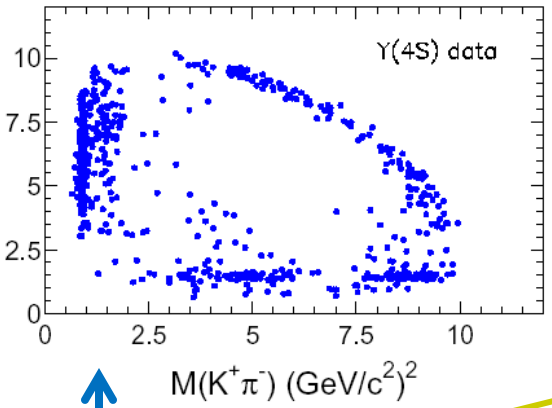
preliminary

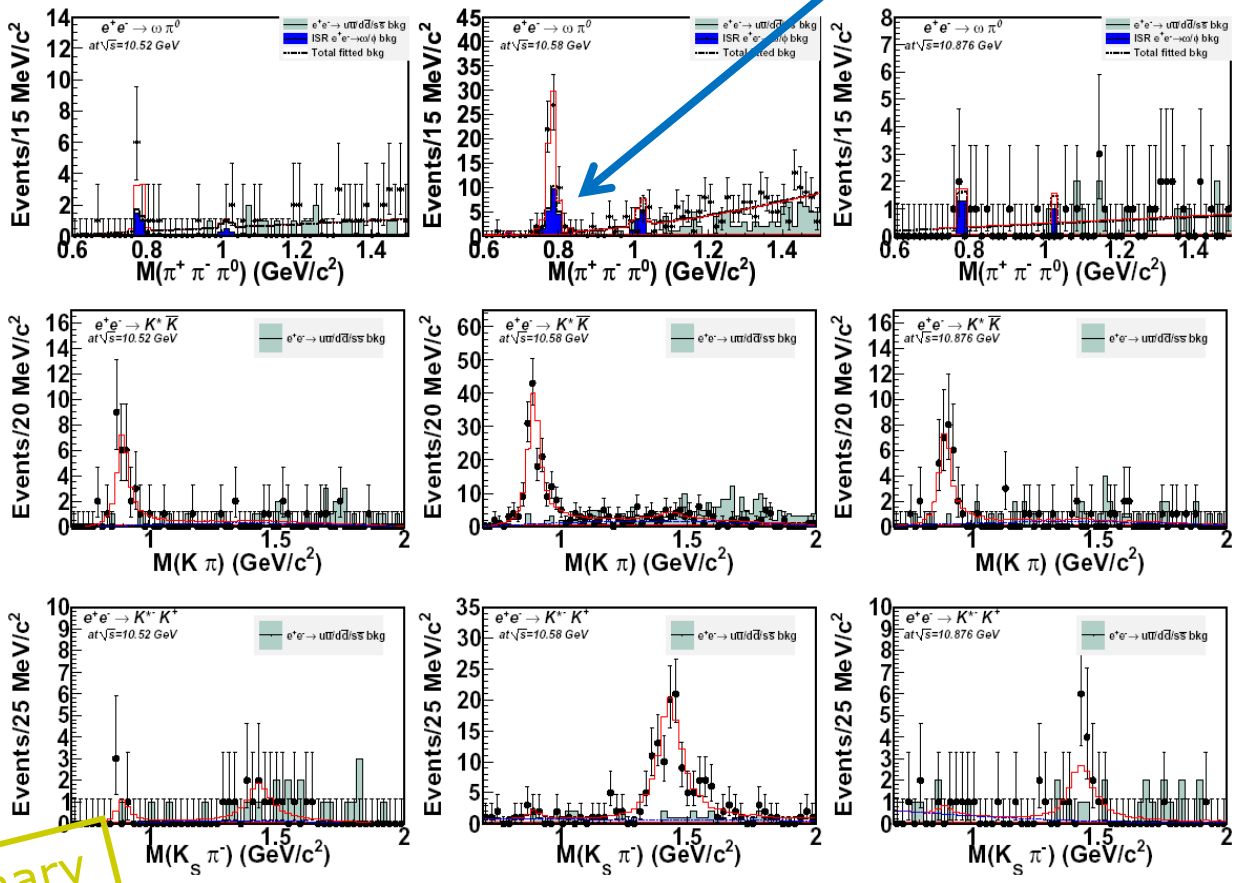


Projection plots to extract ω, K^*, K_2^* in signal region

PYTHIA background







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Y(4S) as an example

10.52GeV 10.58GeV 10.876GeV

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

σ_B:Born order cross section with radiative $E\gamma<0.5$GeV

Channel	$\sqrt{s}$	$N_{\rm sig}$	$N_{\rm sig}^{\rm UL}$	ϵ	Σ	σ_B	$\sigma_B^{\rm UL}$
$\omega\pi^0$	10.52	4.10 ± 2.93	9.90	1.25	1.7	$4.81 \pm 3.44 \pm 0.52$	13.1
	10.58	38.8 ± 7.93	—	1.10	6.8	$6.39 \pm 1.31 \pm 0.59$	—
	10.876	0.00 ± 4.89	6.98	1.07	—	$0.00 \pm 4.81 \pm 0.00$	9.25
$K^*(892)^0\bar{K}^0$	10.52	34.6 ± 6.74	—	11.41	7.5	$11.56 \pm 2.25 \pm 0.77$	—
	10.58	187 ± 16.7	—	11.28	> 10	$8.04 \pm 0.72 \pm 0.51$	—
	10.876	34.6 ± 7.06	—	11.94	7.3	$8.17 \pm 1.67 \pm 0.65$	—
$K^*(892)^-K^+$	10.52	4.55 ± 3.12	9.27	14.12	1.4	$1.23 \pm 0.84 \pm 0.16$	2.88
	10.58	5.88 ± 4.20	14.0	14.55	1.6	$0.20 \pm 0.14 \pm 0.03$	0.53
	10.876	1.58 ± 3.33	8.44	14.73	0.5	$0.30 \pm 0.64 \pm 0.10$	2.41
$K_2^*(1430)^0\bar{K}^0$	10.52	1.30 ± 4.11	6.84	12.20	0.4	$0.81 \pm 2.57 \pm 0.15$	5.22
	10.58	21.1 ± 10.5	39.7	11.56	2.2	$1.78 \pm 0.88 \pm 0.29$	3.98
	10.876	0.96 ± 4.25	8.85	13.16	0.3	$0.41 \pm 1.82 \pm 0.07$	4.58
$K_2^*(1430)^-K^+$	10.52	12.0 ± 5.98	20.9	14.09	2.2	$6.48 \pm 3.24 \pm 1.43$	14.6
	10.58	129 ± 14.6	—	13.96	> 10	$9.02 \pm 1.02 \pm 0.64$	—
	10.876	17.6 ± 4.95	—	14.88	4.6	$6.67 \pm 1.88 \pm 0.67$	—

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

PRD 75 (2007)

$$R_{\rm VP} = \frac{\sigma_B(e^+e^- \to K^*(892)^0\bar{K}^0)}{\sigma_B(e^+e^- \to K^*(892)^-K^+)}$$

> pQCD calculated value 6 at Y(4S)

S^{-n} dependence for $e^+e^- \to K^*(892)^0\bar{K}^0$

CLEO-C measurements

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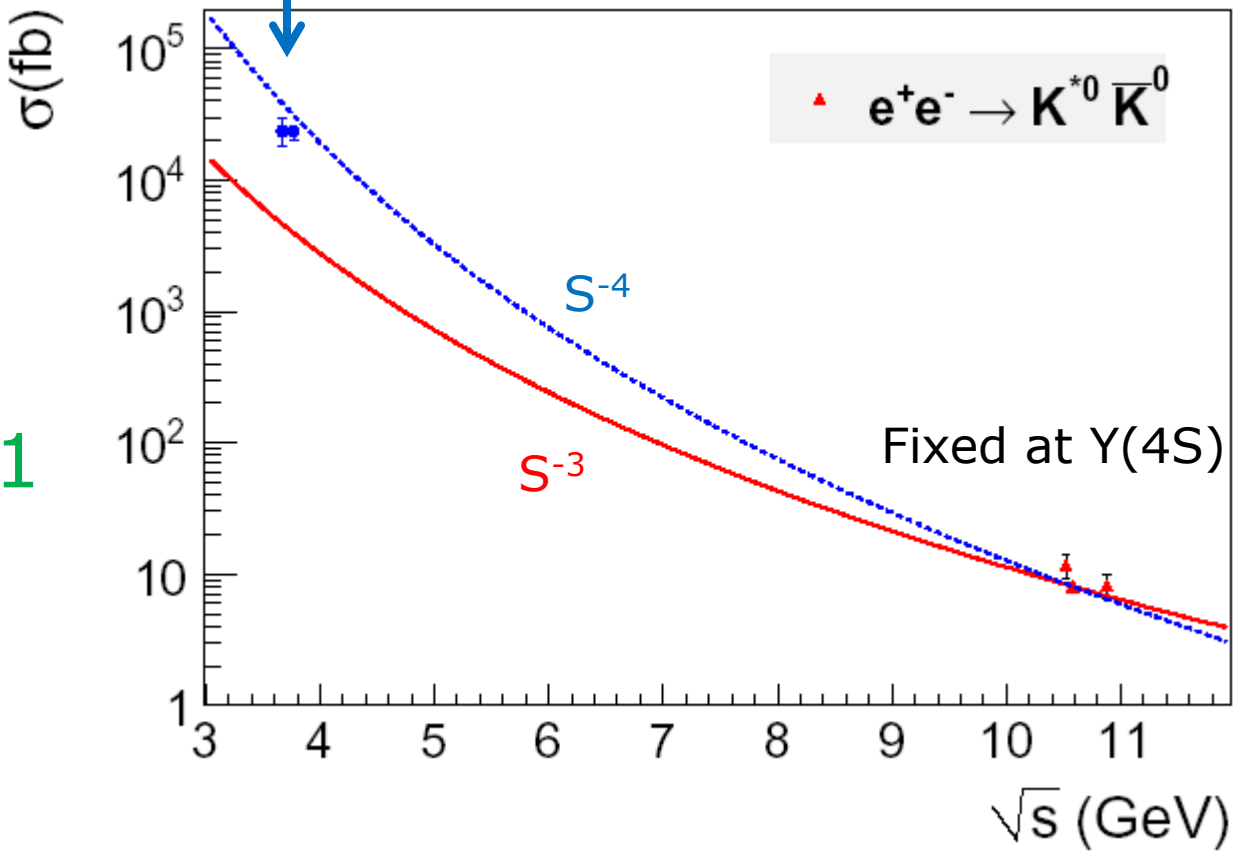
Fit result

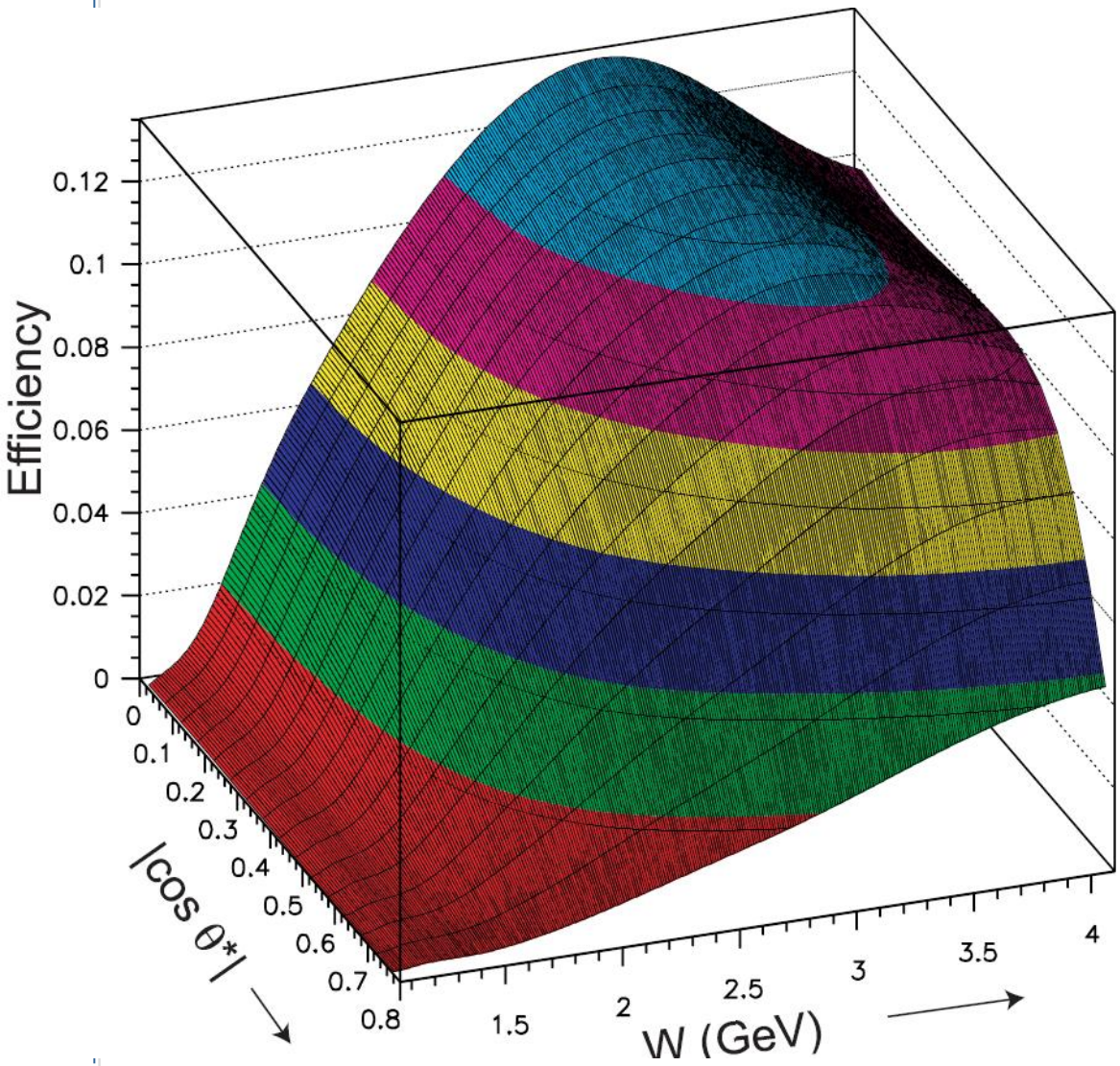
n = 3.8±0.1



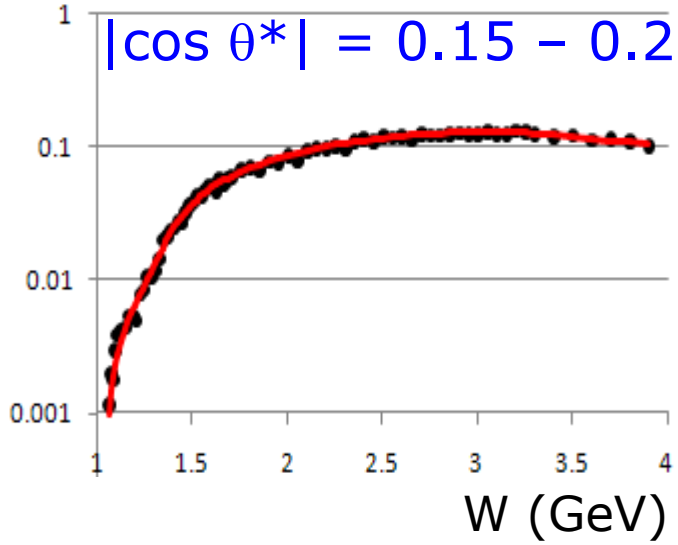
$\gamma\gamma \rightarrow K_s K_s$

- Cross section measurement in W($\gamma\gamma \rightarrow K_s K_s$) starting from threshold
- Angular analysis in $\cos\theta^*$:K_s average scattering angle w.r.t beam axis
- Data sample: 972 fb^{-1}
- Select two K_s's only and $|\Sigma \mathbf{p}_t(Ks)| < 0.1$ GeV/c
- KsKsX and non-KsKs background subtracted using $|\Sigma \mathbf{p}_t^*|$ and M_{Ks} sideband information

$\gamma\gamma \rightarrow K_s K_s$ over all efficiency

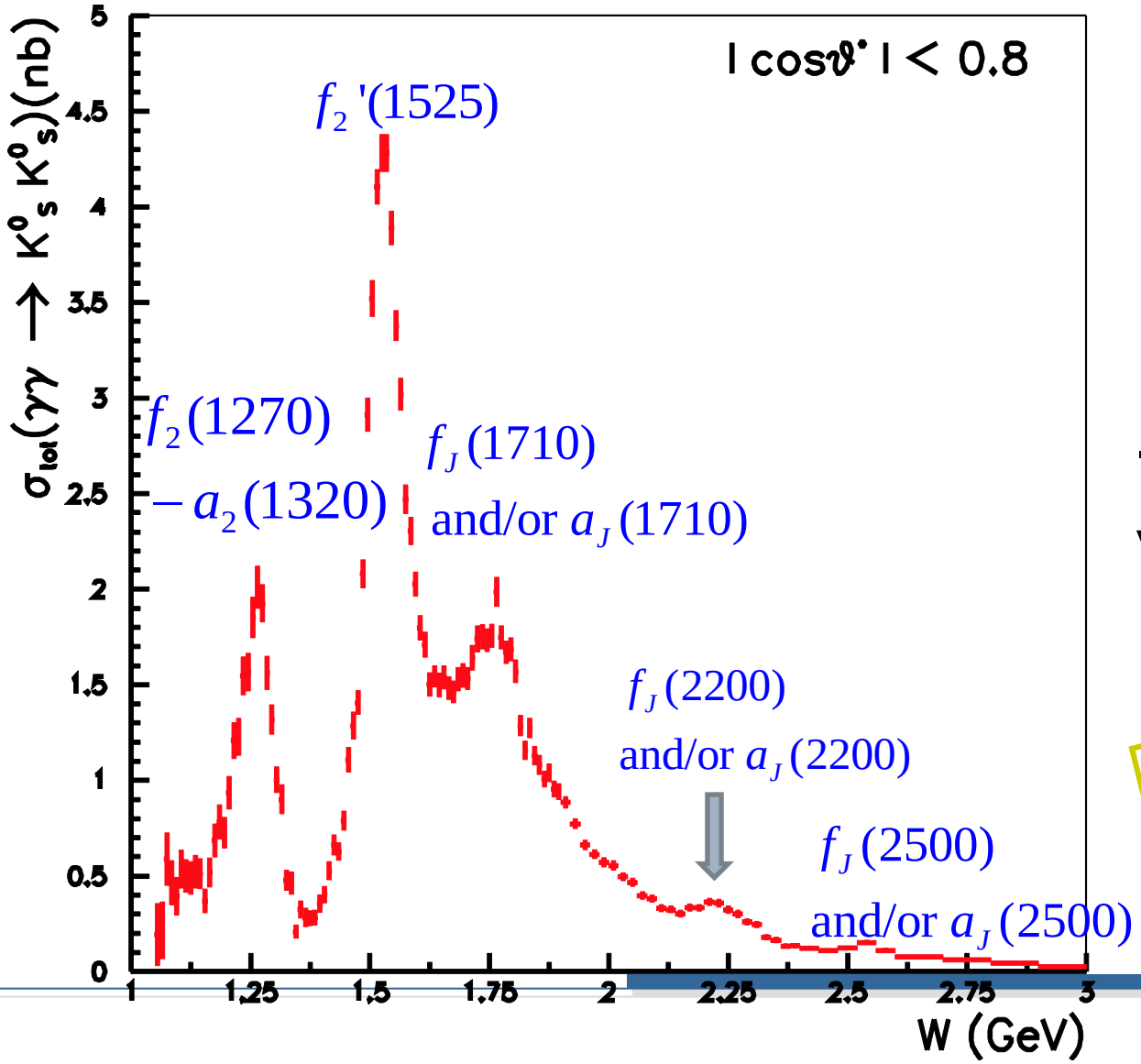


A slice for
$|\cos\theta^*| = 0.15 - 0.20$



Decrease in high-W
due to two-track-trigger inefficiency

Integrated cross section (|cosθ*|<0.8)



W<3GeV

5 resonance -like peaks visible

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Formula for differential cross section

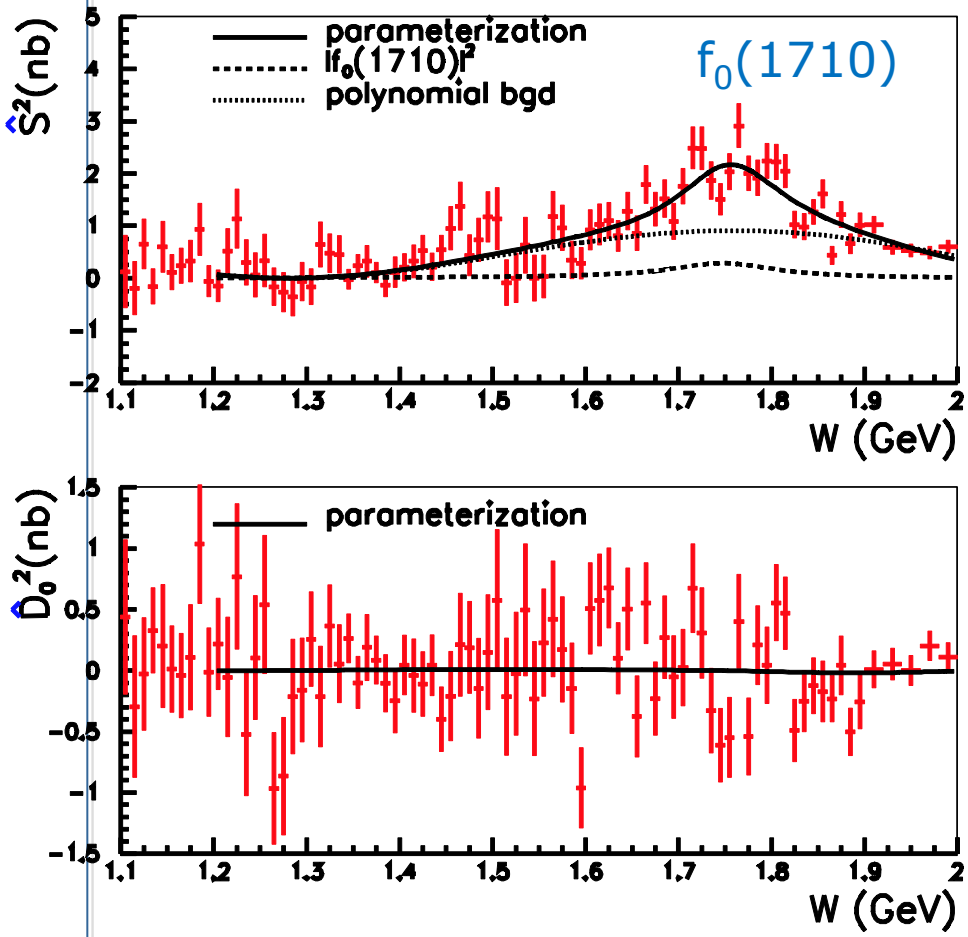
- Formula $\frac{d\sigma}{d\Omega} = \left|SY_0^0 + D_0Y_2^0 + G_0Y_4^0\right|^2 + \left|D_2Y_2^2 + G_2Y_4^2\right|^2$
- S, D_0, G_0, D_2 , G_2
  - Partial wave amplitudes (J = 0, 2, 4 (even only))
    - W dep. → extract resonance and non-res. info.
- Y_J^m : spherical harmonics
  - determine angular dependence
  - $|Y_J^m|$not mutually independent
- Using hat amp. to get partial wave amp.

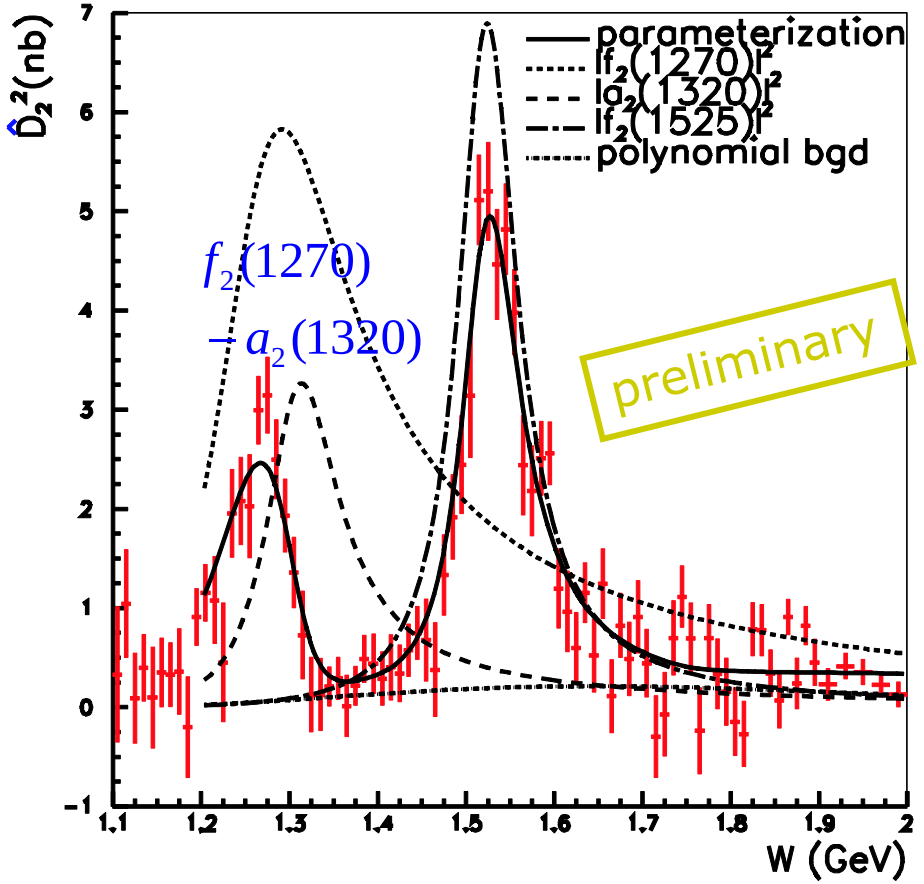
$$\frac{d\sigma}{d\Omega} = \hat{S}^2\left|Y_0^0\right|^2 + \hat{D}_0^2\left|Y_2^0\right|^2 + \hat{G}_0^2\left|Y_4^0\right|^2 + \hat{D}_2^2\left|Y_2^2\right|^2 + \hat{G}_2^2\left|Y_4^2\right|^2$$

SD fit Example for W<2GeV

Hat amplitudes

at low W, G component negligible





Fit results for $W < 2.0$ GeV

- Combine sol. H and L statistically

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Parameter	Sol. H	Sol. L	H,L combined	Incoh. fit	PDG [23]
χ^2/ndf	375.09/387	375.22/387	–	406.6/388	–
$\phi_{a_2(1320)}$ (deg.)	$178.1^{+1.7+6.7}_{-1.3-12.5}$	$172.6^{+1.3+6.7}_{-1.0-3.1}$	$172.6^{+6.0+12.2}_{-0.7-7.0}$	$173.6^{+1.3}_{-1.4}$	–
Mass($f_2'(1525)$) (MeV/c^2)	$1526.1^{+0.9+2.9}_{-1.0-2.8}$	$1524.3^{+1.0+1.6}_{-0.9-1.1}$	$1525.3^{+1.2+3.7}_{-1.4-2.1}$	1530.7 ± 0.4	1525 ± 5
$\Gamma_{\rm tot}(f_2'(1525))$ (MeV)	$83.4^{+1.9+2.0}_{-1.7-3.4}$	$81.8^{+2.3+4.4}_{-2.0-0.9}$	$82.9^{+2.1+3.3}_{-2.2-2.0}$	82.7 ± 1.4	73^{+6}_{-5}
$\Gamma_{\gamma\gamma}\mathcal{B}(K\bar{K})(f_2'(1525))$ (eV)	113^{+25+43}_{-28-77}	$48 \pm 4^{+33}_{-10}$ $48^{+67+108}_{-8\ -12}$	79.1 ± 1.4	72 ± 7	

$f_2(1270)$ $-a_2(1320)$

- Destructive interference btw. f_2 and a_2 confirmed
- First attempt to include interference effect in measuring $\Gamma_{\gamma\gamma}B(K\bar{K})$ of $f_2'(1525)$.

Fit results for $W < 2.0$ GeV (cont'd)

preliminary

- $f_0(1710)$

Parameter	$f_0(1710)$ fit				$f_2(1710)$ fit	
	fit-H	fit-L	H,L combined	PDG	fit-H	fit-L
χ^2/ndf	694.2/585	701.6/585	–	–	796.3/585	831.5/585
Mass(f_J) (MeV/c^2)	1750^{+5+29}_{-6-18}	1749^{+5+31}_{-6-42}	1750^{+6+29}_{-7-18}	1720 ± 6	1750^{+6}_{-7}	1729^{+6}_{-7}
$\Gamma_{\rm tot}(f_J)$ (MeV)	138^{+12+96}_{-11-50}	145^{+11+31}_{-10-54}	139^{+11+96}_{-12-50}	135 ± 6	132^{+12}_{-11}	150 ± 10
$\Gamma_{\gamma\gamma}\mathcal{B}(K\bar{K})_{f_J}$ (eV)	12^{+3+227}_{-2-8}	21^{+6+38}_{-4-26}	12^{+3+227}_{-2-8}	unknown	$2.1^{+0.5}_{-0.3}$	1.6 ± 0.2

- Scalar rather than tensor! (in contrast to L3)
- $\Gamma_{\gamma\gamma} B(K\bar{K})$ measured for the first time.
  - indicate $f_0(1710)$ is likely not a glueball since $\Gamma_{\gamma\gamma}$ is too large

Fit results for W>2GeV

- $f_2(2200)$-$f_0(2500)$ is the best

13 assumptions tested

Assumption	No. of sol.	χ^2	ndf
f_0-f_0	2	293.3, 293.9	214
f_0-f_2	4	320.9, 321.9, 324.5, 327.6	214
f_0-f_4	1	291.4	214
f_2-f_0	1	228.3	214
f_2-f_2	1	260.4	214
f_2-f_4	1	323.6, 306.7	214
f_4-f_0	1	411.6	214
f_4-f_2	2	468.6, 472.1	214
f_4-f_4	4	459.6, 464.1, 466.4, 467.5	214
Only-f_0	1	390.0	218
Only-f_2	1	323.6	218
Only-f_4	1	518.7	218
No resonances	1	659.32	222

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Fit results for W > 2.0 GeV (cont'd)

- Parameters

preliminary

Parameter	$f_2(2200)$	$f_0(2500)$
Mass (MeV/c^2)	2243^{+7+3}_{-6-29}	$2539 \pm 14^{38}_{14}$
Γ_{tot} (MeV)	$145 \pm 12^{+27}_{-34}$	$274^{+77+126}_{-61-163}$
$\Gamma_{\gamma\gamma}\mathcal{B}(K\bar{K})$ (eV)	$3.2^{+0.5+1.3}_{-0.4-2.2}$	40^{+9+17}_{-7-40}

unlikely a glueball ($\Gamma_{\gamma\gamma}$ >>1 eV)

- Significance
  - 3.4σ for $f_2(2200)$ over $f_0(2200)$
  - 4.3σ for $f_0(2500)$ over $f_2(2500)$
  - evaluated from min.($\Delta\chi^2$) for every sys. source

QCD Studies on Angular dependence

W = 2.4 – 3.3 GeV

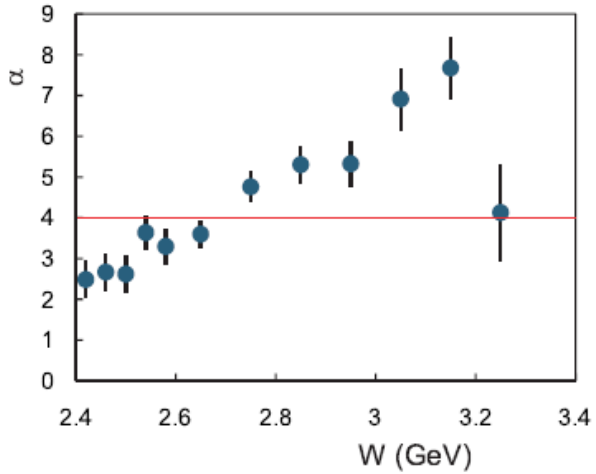
Assume no resonance 2.6 < W < 3.3 GeV

There is a resonance near 2.5GeV

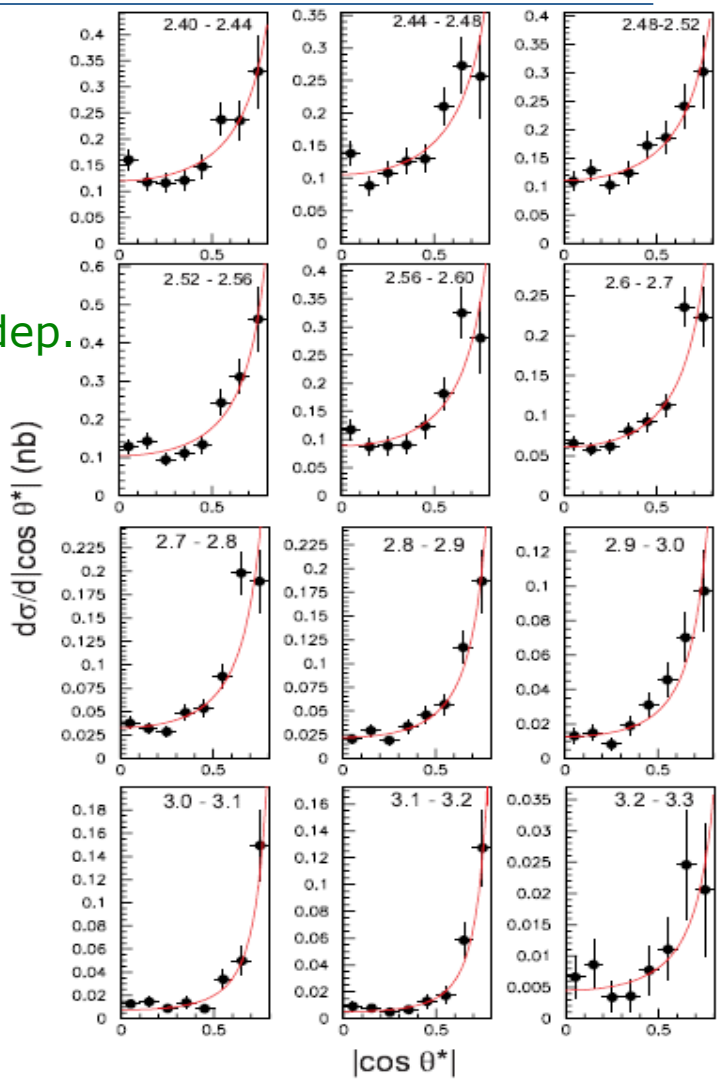
Angular dependence of DCS

$1/\sin^{\alpha}\theta^*$ $1/\sin^4\theta^*$- Handbag : const. 4

pQCD:not const. W dep.



preliminary

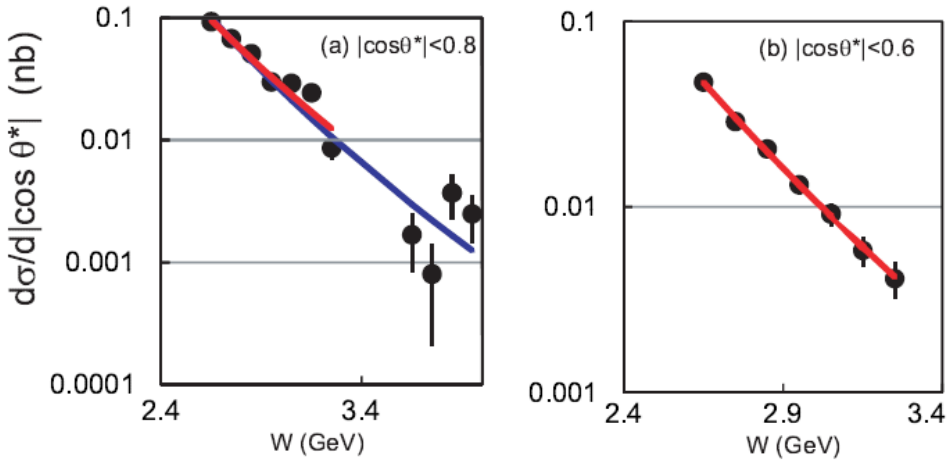


Around 4 for some W regions, but no tendency is seen to converge to 4 at high energies

W-dependence

- $\sigma \propto W^{-n}$ n = 6 – 7 for $\pi^+\pi^-$, K^+K^-, $\pi^0\pi^0$

n=10 for KsKs, predicted by pQCD Chernyak



PLB 640 (2006)
arXiv 1212.1304

preliminary

W range (GeV)	$\lvert\cos\theta^*\rvert$ range	n	note
$2.6-4.0$ (except $3.3-3.6$)	<0.8	$11.0\pm0.4\pm0.4$	
$2.6-3.3$	<0.8	$10.0\pm0.5\pm0.4$	
$2.6-3.3$	<0.6	$11.8\pm0.6\pm0.4$	
$2.4-4.0$ (except $3.3-3.6$)	<0.6	$10.5\pm0.6\pm0.5$	Belle 2007

Close to n=10

Summary

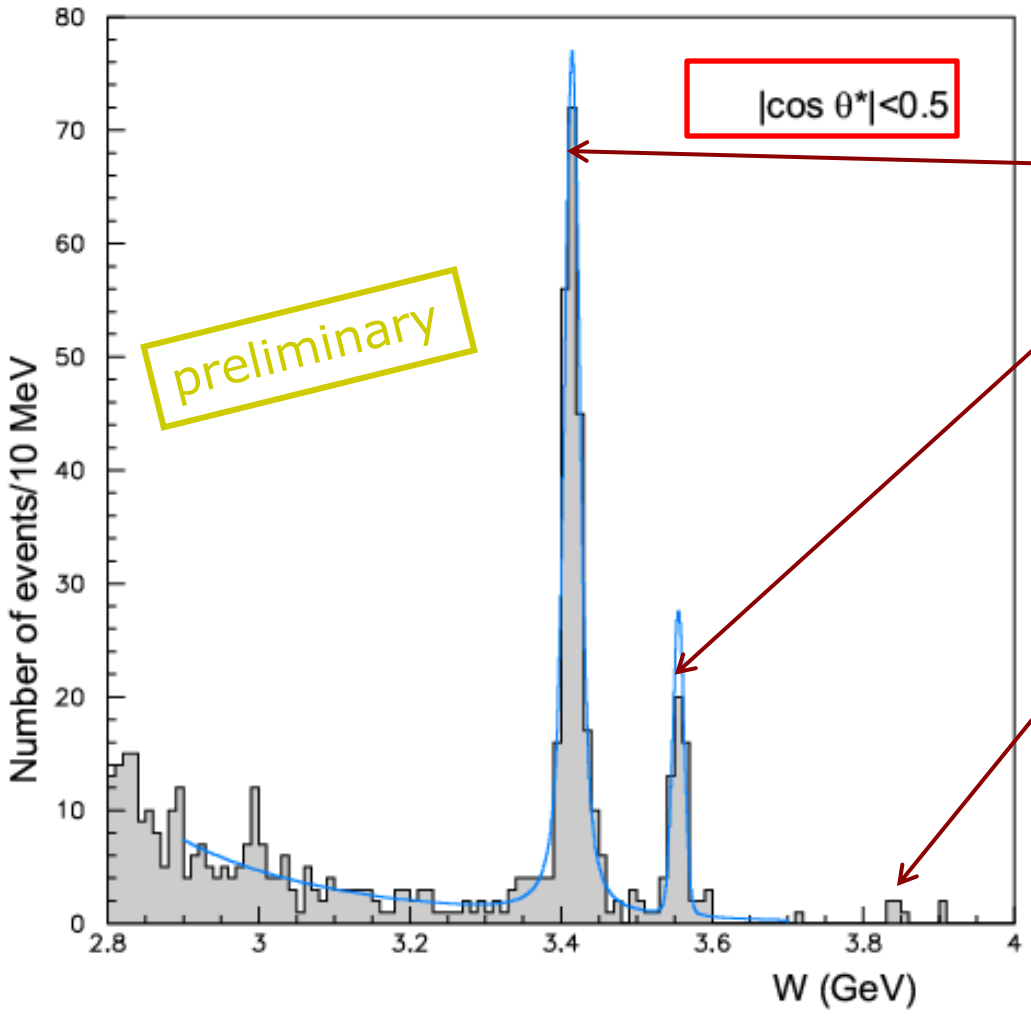
- With the world's largest Y's data set ~1ab^{-1}, many new QCD related results are reported
- *Y*(4008) ,*Y*(4260) properties studied in $e^+e^- \to \pi^+\pi^- J/\Psi$ via ISR
- Observation of a charged charmoniumlike state Z(3900)
- Cross sections of $e^+e^- \to K_s K^+\pi^-, \pi^+\pi^-\pi^0\pi^0, \pi^+\pi^-\pi^0$ as well as intermediate resonance two-body decays are studied at various energies of Y's

Summary (cont'd)

- $d\sigma/d\Omega$ of $\gamma\gamma \to K^0_S K^0_S$ is measured for the first time for $W > 1.05$GeV
- $f_2(1270)$ and $a_2(1320)$ interfere indeed destructively
- $f_0(1710)$ is favored over $f_2(1710)/a_2(1710)$
- $f_2(2200)$ and $f_0(2500)$ favored
- Angular distribution – varying around 4, no clear idea
- W-dependence n ~10, confirmed in contrast to $\pi^+\pi^-$, K^+K^- (n=6–7)

Charmonium Region

Set U.L. for η_c , X(3915), $\chi_{c2}(2P) \rightarrow KsKs$



χ_{c0} --- ~ 240 ev

χ_{c2} --- ~ 52 ev

"XYZ" Region
(3.80 – 3.95 GeV)
7 ev
(2.3 ev expected,
P-value = 0.9%)
3.7 – 4.0 GeV
8 ev for 5.1 ev