Recent Charmonium Results from BES

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Outline

1. Introduction
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3. $\psi(2S)$ Hadronic Decays
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Help from F. Liu, D. Paluselli and W. Yang.

Introduction

BEPC: Energy Range 2 - 5 GeV.
Data Sets:

- J/ψ - 9 M
- τ mass scan - 5 pb^{-1}
- D_s - 22.3 pb^{-1} at 4.03 GeV
- $\psi(2S)$ - 3.8 M
  World's largest sample.
- R-scan - 1998 and 1999
  Yongsheng Zhu: BES R-scan

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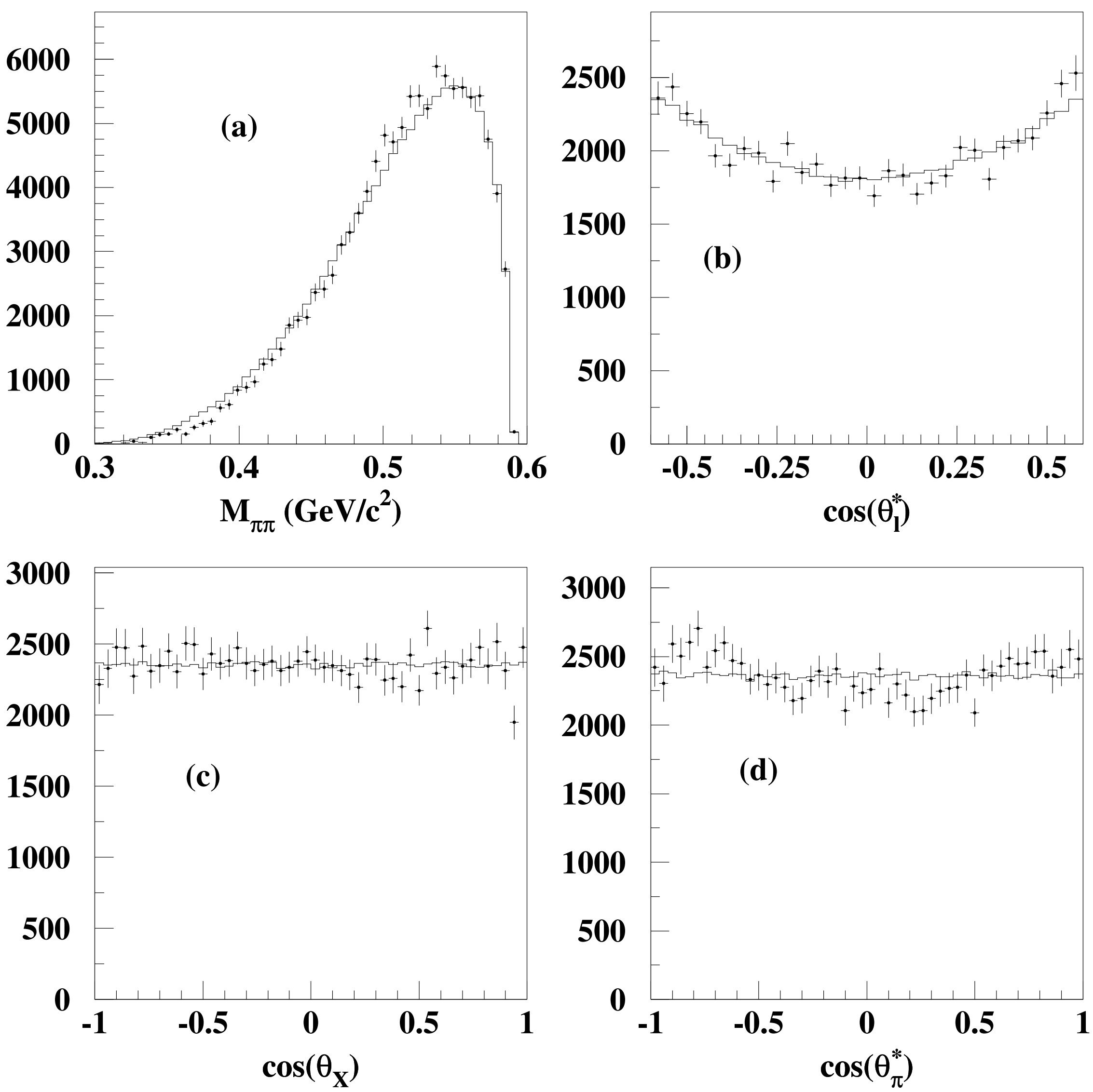
$\psi(2S) \to \pi^+\pi^- J/\psi$ Decay Distributions - PRELIMINARY

- Largest decay mode of the $\psi(2S)$ ($B = 30.2 \pm 1.9\%$).
- Use $\psi(2S) \to \pi^+\pi^- J/\psi$, $J/\psi \to \ell^+\ell^-$ sample.
  $\approx$ 23 K events.
- Early investigation by Mark I found:
  - the $\pi^+\pi^-$ mass distribution strongly peaked towards higher mass values.
  - the angular distributions strongly favored s-wave production of $\psi\pi\pi$, as well as an s-wave decay of dipion system.



(a)
(b)
(c)
(d)
$M_{\pi\pi}$ (GeV/c^2)
$\cos(\theta_l^*)$
$\cos(\theta_X)$
$\cos(\theta_\pi^*)$

Novikov-Shifman Model

Phys. Lett. 209, 342 (1991).

- Nonperturbative process.
- Theory: Two step process.
  - multipole expansion to describe $\psi(2S) \to J/\psi$ and gluon emission.
  - current algebra, PCAC, and gauge invariance to describe hadronization of gluons.

$$
\begin{aligned}
A \;\propto\; & \{q^2 - \kappa(\Delta M)^2(1 + \frac{2m_\pi^2}{q^2}) \\
& + \frac{3}{2}\kappa[(\Delta M)^2 - q^2](1 - \frac{4m_\pi^2}{q^2})(\cos^2\theta_\pi^* - \frac{1}{3})\},
\end{aligned}
$$

where $\Delta M = M_{\psi(2S)} - M_{J/\psi}$.

- $\kappa = (9/6\pi)\alpha_s(\mu)\rho_\mu^G(\mu)$, where ρ^G is the gluon share of the π's momentum.
- κ is predicted to be ≈ 0.15 to 0.2.
- Parity and charge conjugation invariance require that the spin be even.
- If κ nonzero, D-wave predicted.

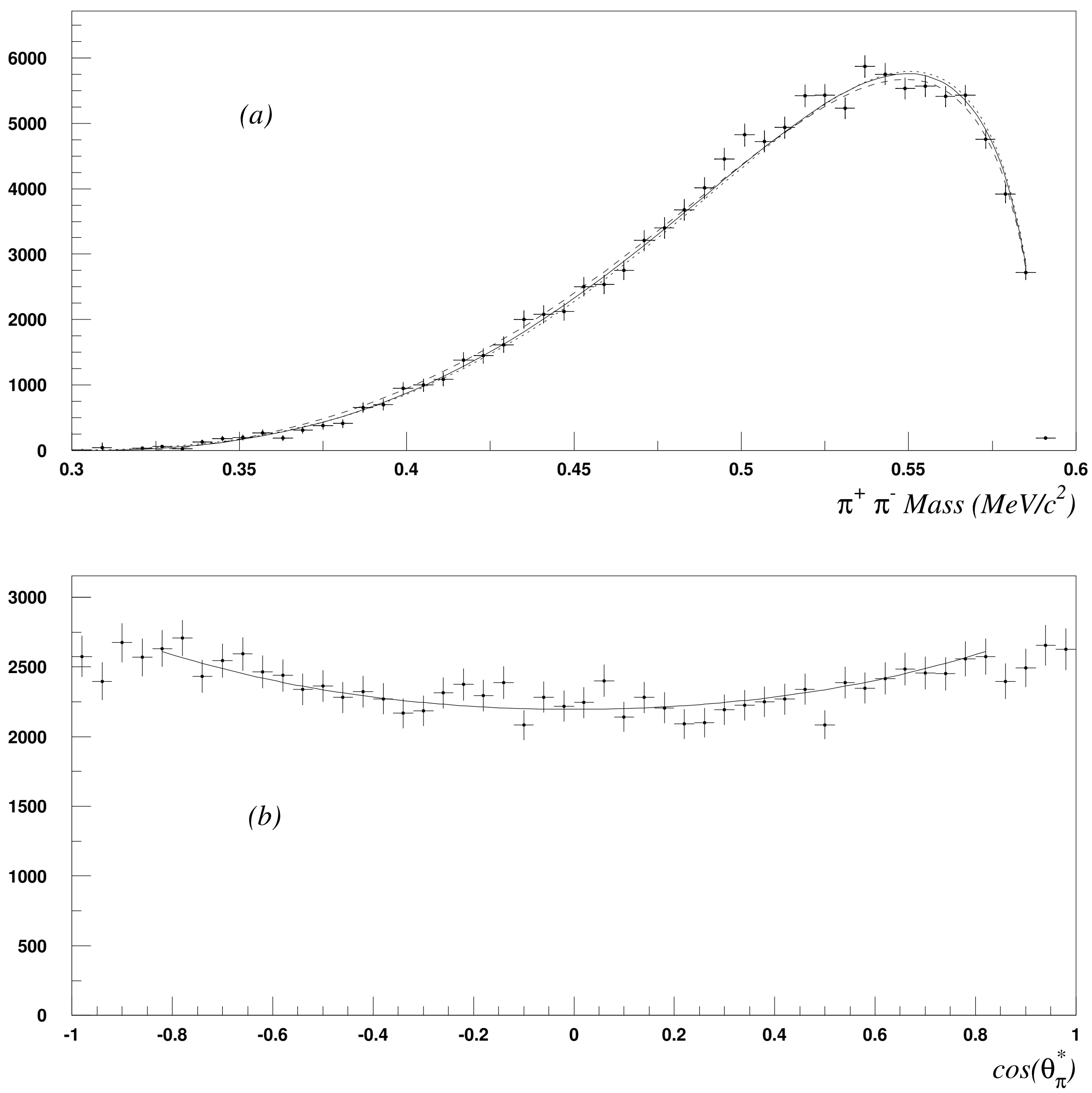


Table 1: Fit results for κ for the Novikov-Shifman model.

Distribution	κ	χ^2/DOF
$m_{\pi\pi}$	$0.186 \pm 0.003 \pm 0.010$	55/45
$\cos\theta^*_\pi$	$0.210 \pm 0.027 \pm 0.050$	26/40
$m_{\pi\pi}$ vs $\cos\theta^*_\pi$	$0.183 \pm 0.003 \pm 0.005$	1618/1482

Table 2: Fit Results for the $m_{\pi\pi}$ distribution.

Model	BES	Argus - MKII
Novikov-	$\kappa = 0.186 \pm 0.003 \pm 0.010$	0.194 ± 0.010
Shifman	$\chi^2/DOF = 55/45$	$38/24$

D-wave versus $m_{\pi\pi}$

The amount of D wave as a function of $m_{\pi\pi}$ has been fit using

$$N(\cos\theta) \propto 1.0 + 2(\frac{D}{S}) * (\cos^2\theta - 1/3) + (\frac{D}{S})^2 * (\cos^2\theta - 1/3)^2$$

Table 3: Fit results to $\cos\theta^*_\pi$ distribution using a χ^2 fit.

$m_{\pi\pi}$ Range (GeV/c^2)	$\frac{D}{S}$	χ^2/DOF	Events
0.34 - 0.45	$0.319 \pm 0.097 \pm 0.125$	24/37	2016
0.45 - 0.48	$0.085 \pm 0.068 \pm 0.036$	29/40	1995
0.48 - 0.51	$0.144 \pm 0.045 \pm 0.031$	33/40	3729
0.51 - 0.54	$0.037 \pm 0.025 \pm 0.014$	35/48	5620
0.54 - 0.57	$0.062 \pm 0.022 \pm 0.016$	44/48	6403
0.57 - 0.60	$0.047 \pm 0.036 \pm 0.016$	48/48	2959

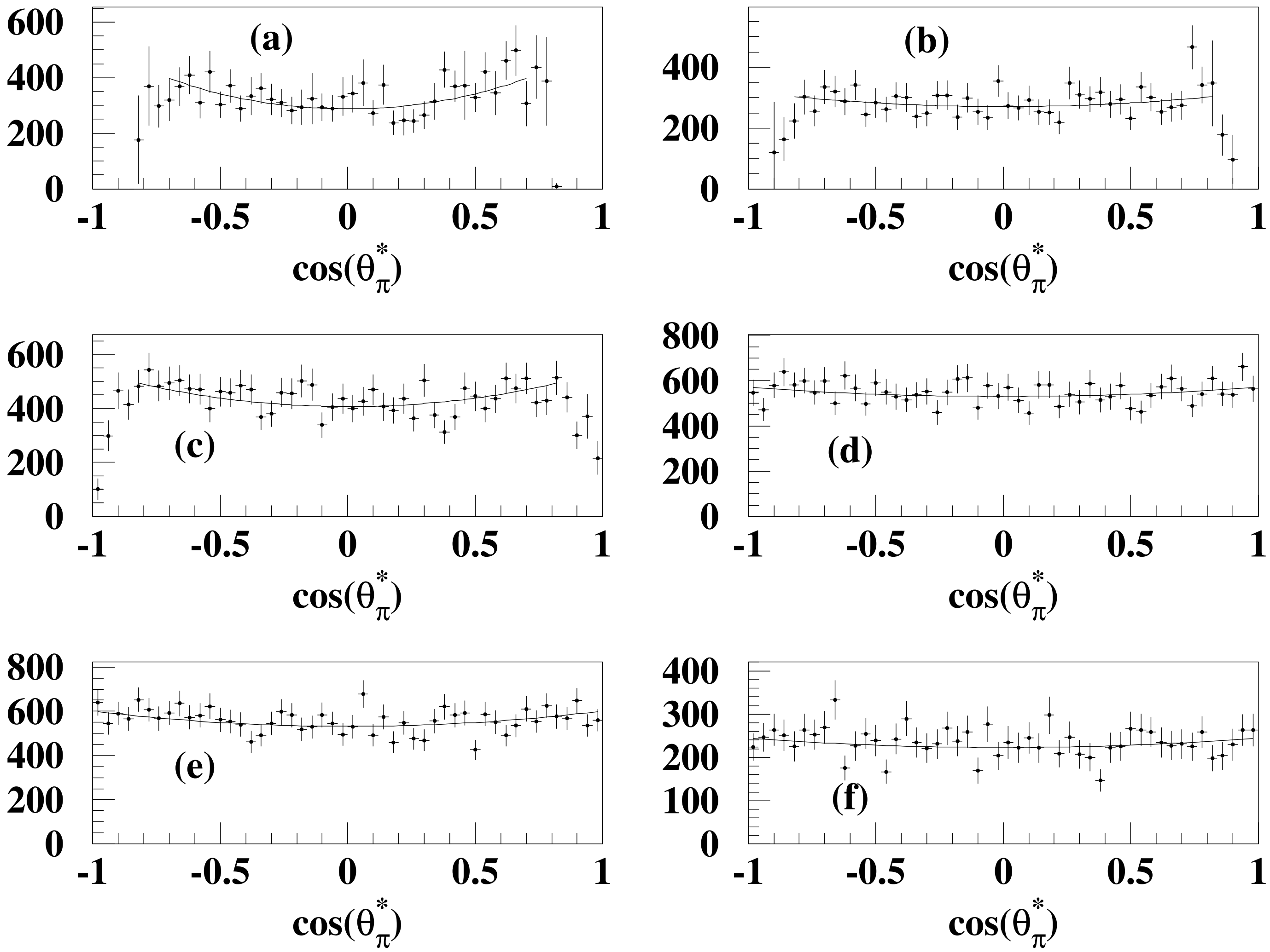
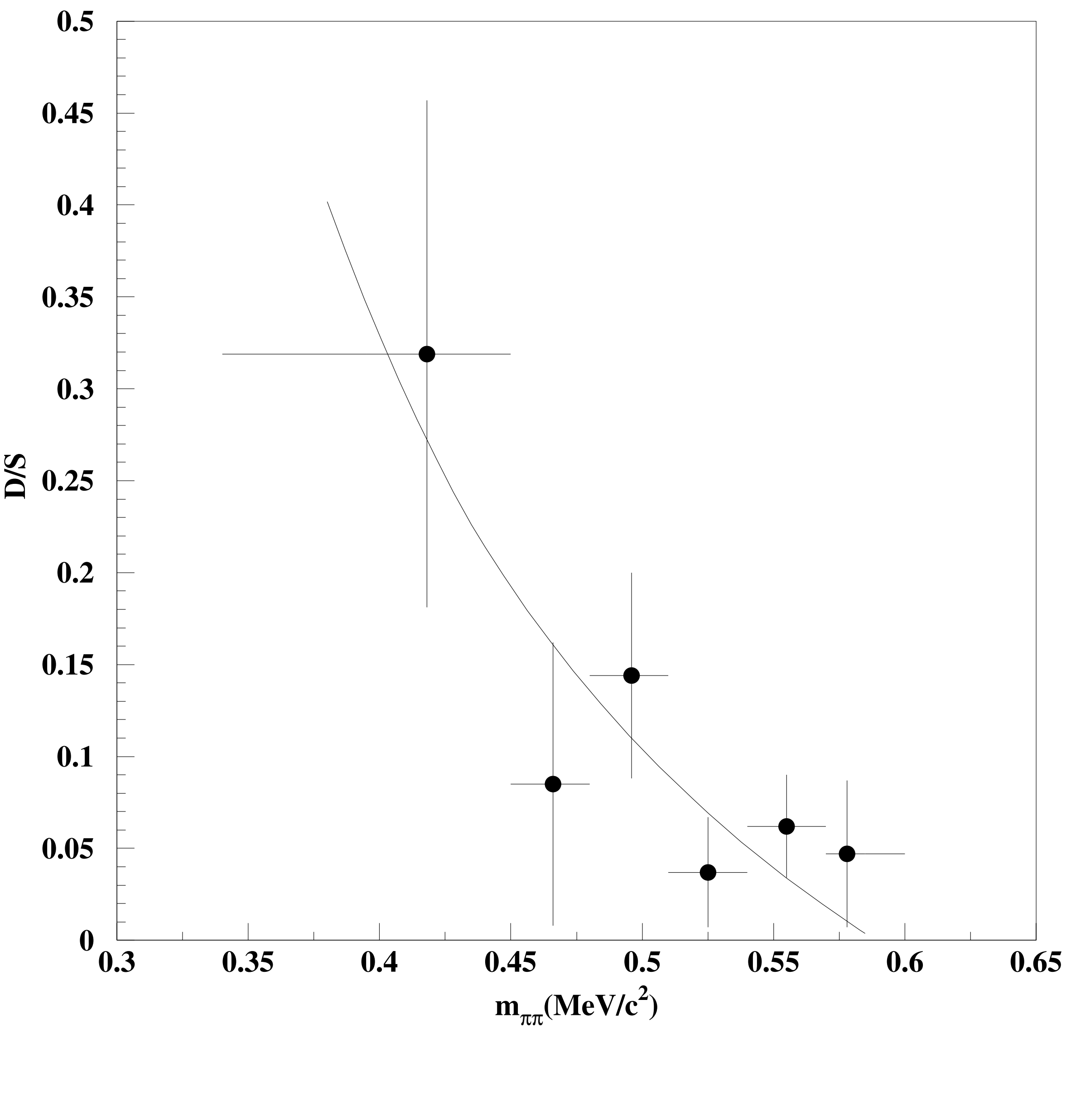


Figure 1: Fits of $\cos\theta^*_\pi$ as a function of $m_{\pi\pi}$. **(a)** $0.34 < m_{\pi\pi} < 0.45$ GeV/c^2, **(b)** $0.45 < m_{\pi\pi} < 0.48$ GeV/c^2, **(c)** $0.48 < m_{\pi\pi} < 0.51$ GeV/c^2, **(d)** $0.51 < m_{\pi\pi} < 0.54$ GeV/c^2, **(e)** $0.54 < m_{\pi\pi} < 0.57$ GeV/c^2, and **(f)** $0.57 < m_{\pi\pi} < 0.60$ GeV/c^2.



0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
D/S
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
$m_{\pi\pi}$(MeV/c^2)

Hadronic $\psi(2S)$ decays

We have measured the $\psi(2S)$ branching fractions for a large number of meson final states - many for the first time.

There is a lot of interest:

- Yu-Qi Chen and Eric Braaten Phys. Rev. Lett. **80**, 5060 (1998).
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- X.-Q.Li, D. V. Bugg, and B.-S. Zhou, Phys. Rev. D **55**, 1241 (1997).
- W-S. Hou, contributed paper to the Minneapolis DPF meeting, August 1996.
- Stephen S. Pinsky, Phys. Lett. **B236**, 479 (1990).
- M. Chaichian and N.A. Törnqvist, Nucl. Phys. **B323**, 75 (1989).
- A. Seiden, H.F-W. Sadrozinski, and H.E. Haber, Phys. Rev. **D38**, 824 (1988).
- S.J. Brodsky, G.P. LePage, and S.F. Tuan, Phys. Rev. Lett. **59**, 59 (1987).
- G. Karl and W. Roberts, Phys. Lett. B **144**, 243 (1984).
- W-S. Hou, and A. Soni, Phys. Rev. Lett. **50**, 569 (1983).

Expectation:

According to non relativistic perturbative QCD:

$$\frac{B(\psi(2S)\to X)}{B(J/\psi\to X)} \approx \frac{B(\psi(2S)\to ggg)}{B(J/\psi\to ggg)} \approx \frac{B(\psi(2S)\to e^+e^-)}{B(J/\psi\to e^+e^-)} = (14.7\pm 2.3)\%$$

Table 4: ψ_{2S} Branching Ratios for Decays to Hadrons (Preliminary).

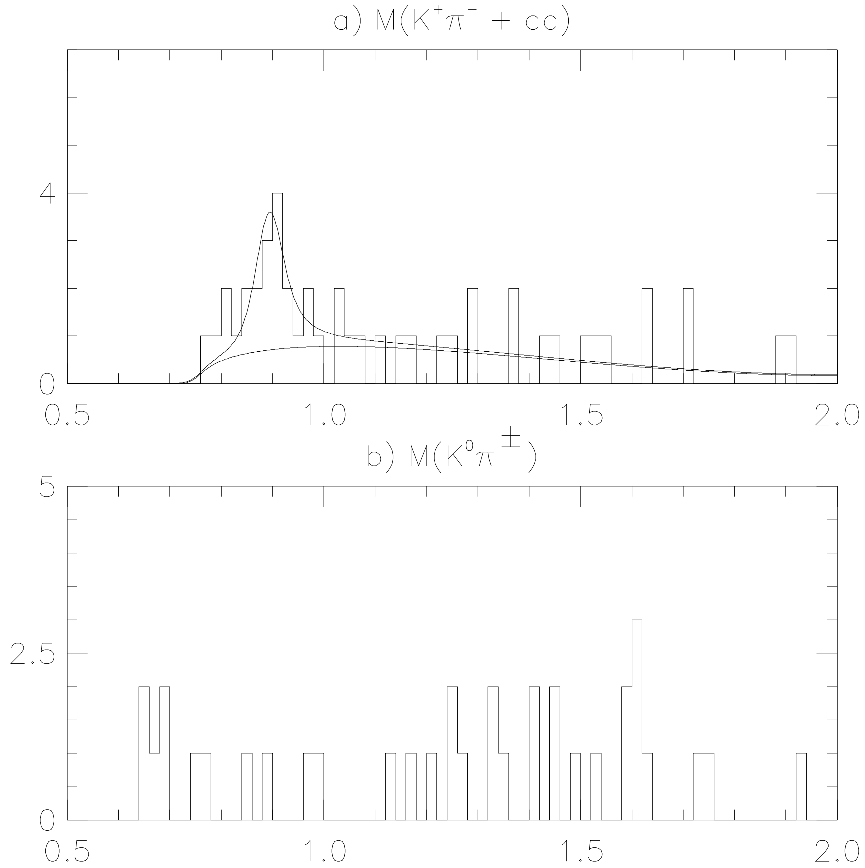
Channel	$\mathcal{B}(\psi' \to X_h)(\times 10^{-4})$ (PDG)	$\mathcal{B}(\psi' \to X_h)$ $(\times 10^{-4})$ (BES)	$S = 0.14 \times \frac{\mathcal{B}_{J/\psi}(PDG)}{\mathcal{B}_{\psi'}(BES)}$
$\rho\pi$	< 0.83	< 0.28	> 64
$K^+\overline{K}^*(892)^- + c.c.$	< 0.54	< 0.30	> 23
$K^0\overline{K}^*(892)^0 + c.c.$	–	$0.81 \pm 0.24 \pm 0.16$	7.3 ± 2.7
$\omega\pi^0$	–	$0.38 \pm 0.17 \pm 0.11$	1.5 ± 0.8
$\omega\eta$	–	< 0.33	> 6.7
$\omega\eta'(958)$	–	$0.76 \pm 0.44 \pm 0.18$	0.3 ± 0.2
$\gamma\eta$	–	$0.53 \pm 0.31 \pm 0.08$	2.3 ± 1.4
$\gamma\eta'(958)$	–	$1.54 \pm 0.31 \pm 0.20$	3.9 ± 1.2
ωf_2	–	< 1.7	> 3.5
ρa_2	–	< 2.3	> 6.6
$K^*(892)^0\overline{K}_2^*(1430)^0 + c.c.$	–	< 1.2	> 7.8
$\phi f_2'(1525)$	–	< 0.45	> 2.5
$\gamma f_2(1270)$	–	$3.01 \pm 1.12 \pm 1.07$	0.6 ± 0.3
$K^*(892)^0\overline{K}^*(892)^0$	–	$0.45 \pm 0.25 \pm 0.07$	< 1.6
$\phi\phi$	–	< 0.26	
$b_1\pi$	–	$5.3 \pm 0.8 \pm 0.8$	0.8 ± 0.2
$K_1(1270)\overline{K}$	–	$10.0 \pm 1.8 \pm 1.8$	< 0.41
$K_1(1400)\overline{K}$	–	< 2.9	> 1.8
$\pi^+\pi^-K^+K^-$	16 ± 4.0	$6.9 \pm 0.3 \pm 1.2$	1.5 ± 0.5
$K^+K^-K^+K^-$	–	$0.65 \pm 0.10 \pm 0.11$	1.5 ± 0.7
$\pi^+\pi^-\pi^0$	0.9 ± 0.5	$1.06 \pm 0.11 \pm 0.16$	2.0 ± 0.7
$K\overline{K}\pi$	–	$1.25 \pm 0.18 \pm 0.26$	6.8 ± 2.1
$K^*(892)^0K^-\pi^+$ $c.c.$	–	$4.8 \pm 0.5 \pm 0.7$	
ϕK^+K^-	–	$0.51 \pm 0.13 \pm 0.09$	4.0 ± 1.4
$\phi\pi^+\pi^-$	–	$1.3 \pm 0.2 \pm 0.2$	0.9 ± 0.2
$\omega\pi^+\pi^-$	–	$4.7 \pm 0.7 \pm 1.0$	2.1 ± 0.5
$\rho^0\pi^+\pi^-$	4.2 ± 1.5	$3.7 \pm 0.6 \pm 0.9$	
$\Lambda\overline{\Lambda}$	< 4.0	$2.11 \pm 0.23 \pm 0.26$	0.9 ± 0.2
$\Sigma^0\overline{\Sigma^0}$	–	$0.94 \pm 0.30 \pm 0.38$	1.5 ± 0.5
$\Xi\overline{\Xi}$	< 2.0	$0.83 \pm 0.28 \pm 0.12$	1.5 ± 0.6
$\Delta^{++}\overline{\Delta}^{--}$	–	$0.89 \pm 0.10 \pm 0.24$	1.7 ± 0.5

Results:

- VP final states, such as $\rho\pi$ and $K^*\overline{K}$, are strongly suppressed - **"$\rho\pi$-puzzle"**.
  - first seen with a suppression factor of $\sim$20 by Mark II.
  - we find a suppression factor of $\sim$60.
  - isospin violating process $\psi(2S) \to \omega\pi^0$ has a branching fraction that is larger than the isospin-conserving, $SU(3)$-allowed, $\psi(2S) \to \rho\pi$ decay.
  - see large isospin violations between the branching fractions for charged and neutral $\psi(2S) \to K^*\bar{K}$ decays.

$$\psi(2S) \to \overline{K^{*0}}\, K^0 , \quad K^0 \to \pi^+\pi^- , \quad \overline{K^{*0}} \to K^-\pi^+$$

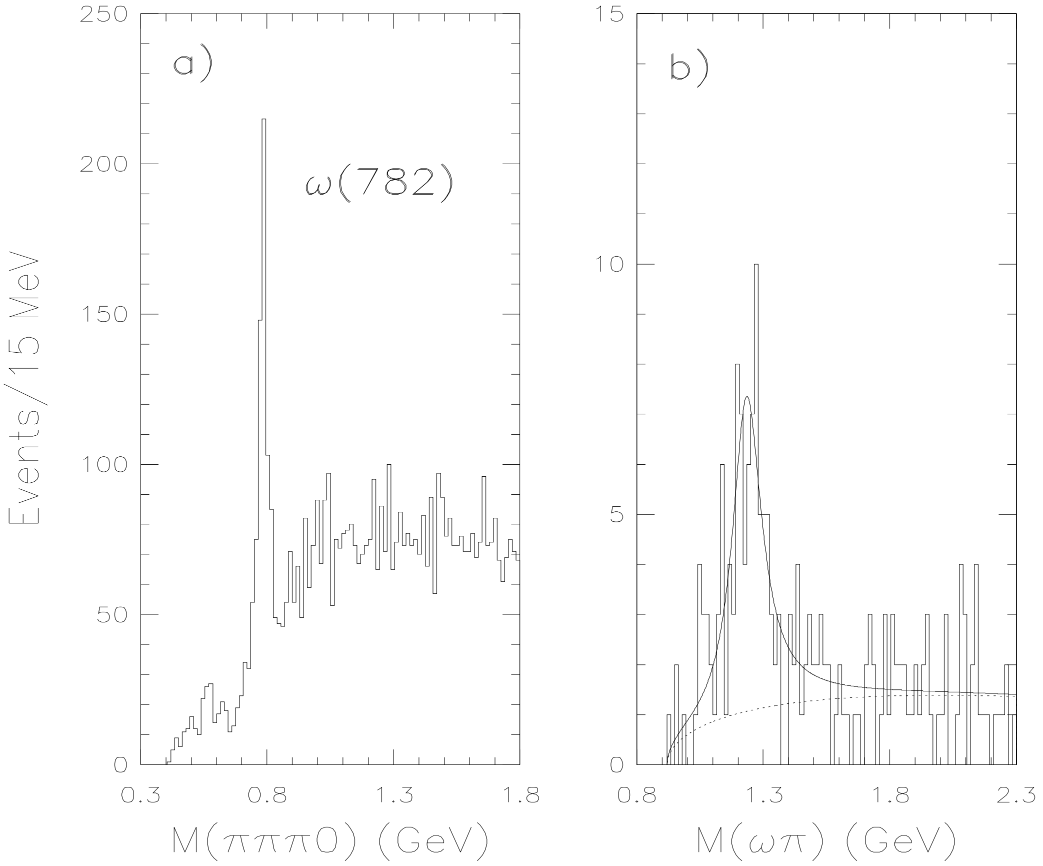
$$\psi(2S) \to K^{*+}\, K^- , \quad K^{*+} \to K^0\pi^+ , \quad K^0 \to \pi^+\pi^-$$



a) M(K⁺π⁻ + cc)
4
0
0.5
1.0
1.5
2.0
b) M(K⁰π±)
5
2.5
0
0.5
1.0
1.5
2.0

- The $\psi(2S) \to AP$ decays $b_1^+\pi^-$ and $K_1^+(1270)K^-$ are relatively strong decay channels of the $\psi(2S)$. For $\psi(2S) \to b_1^+\pi^-$, the result is higher than, but consistent with what is expected from the 14 % rule.

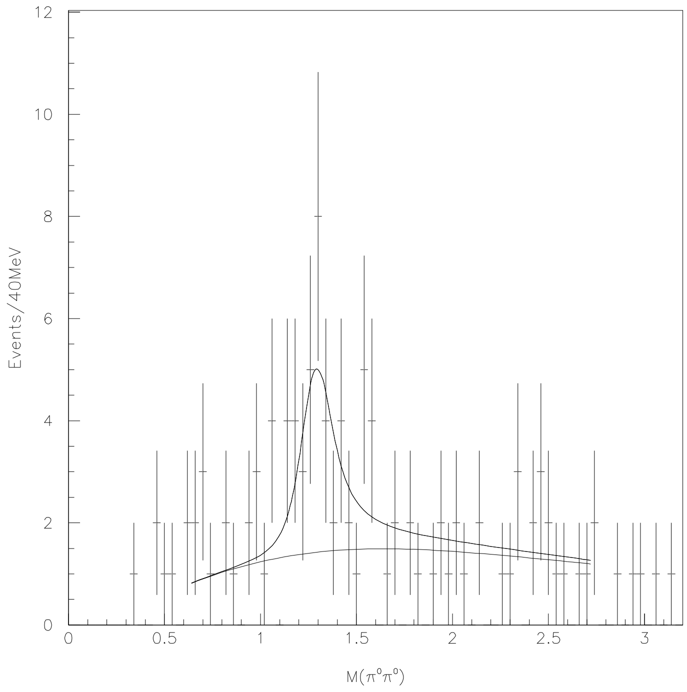
Rules out explanations for the $\rho\pi$ puzzle that suppress all $\psi(2S)$ decays to lowest lying two-body meson final states.



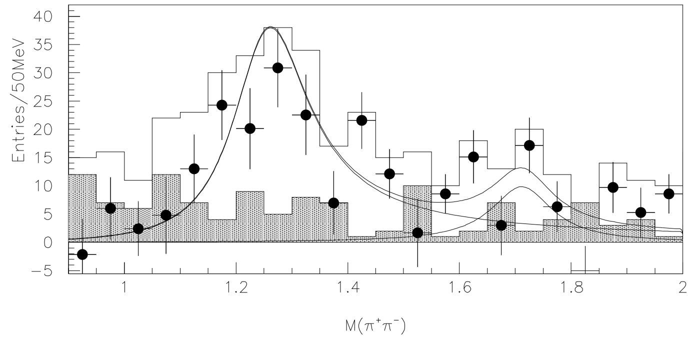
Submitted to PRL.

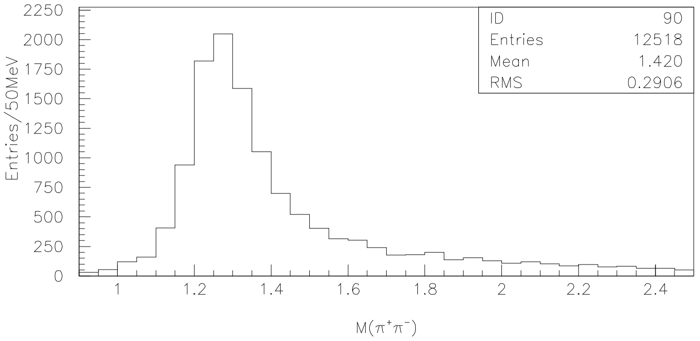
Recent Results: -PRELIMINARY

- $\psi(2S) \to \gamma f_2$, $f_2 \to \pi^o\pi^o$ and $f_2 \to \pi^+\pi^-$.



$$Br(\psi(2S) \to \gamma f_2) = (3.01 \pm 1.12 \pm 1.07) \times 10^{-4}$$





Use τ scan data to subtract QED background.

Fit with D-wave Breit-Wigner function.

$$B(\psi(2S) \to \gamma f_2(1270)) = (2.31 \pm 0.25 \pm 0.33) \times 10^{-4}$$

Combining:

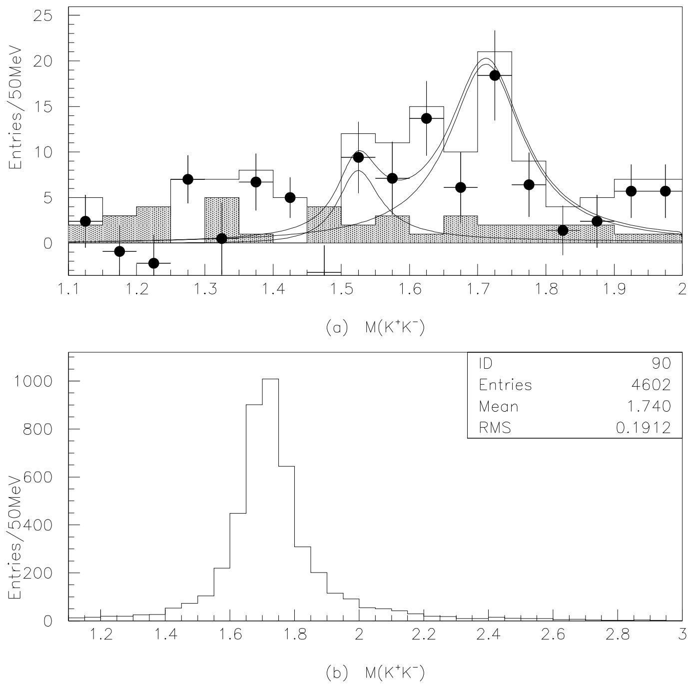
$$B(\psi(2S) \to \gamma f_2(1270)) = (2.36 \pm 0.24 \pm 0.32) \times 10^{-4}$$

$$Q = \frac{B(\psi(2S) \to \gamma f_2(1270))}{B(J/\psi \to \gamma f_2(1270))} = (17.1 \pm 1.7 \pm 2.3)\%$$

The "15% rule" holds for $\psi(2S)$ radiative decay to $f_2(1270)$.

PRELIMINARY

- $\psi(2S) \to \gamma f_J(1710)$, $f_J \to K^+K^-$ Results



Assuming spin of $f_J(1710)$ is zero:

$$B(\psi(2S) \to \gamma f_J(1710)) = (1.24 \pm 0.20 \pm 0.16) \times 10^{-4}$$

$$Q = \frac{B(\psi(2S) \to \gamma f_J(1710))}{B(J/\psi \to \gamma f_J(1710))} = (12.8 \pm 2.6 \pm 2.2)\%$$

The "15% rule" holds for $\psi(2S)$ radiative decay to $f_J(1710)$.

Also using $\psi(2S) \to \gamma f_J(1710)$, $f_J \to K^o \bar{K^o}$

$$B(\psi(2S) \to \gamma f_J(1710) \to \gamma K\bar{K}) = (1.75 \pm 0.80 \pm 0.90) \times 10^{-4}$$

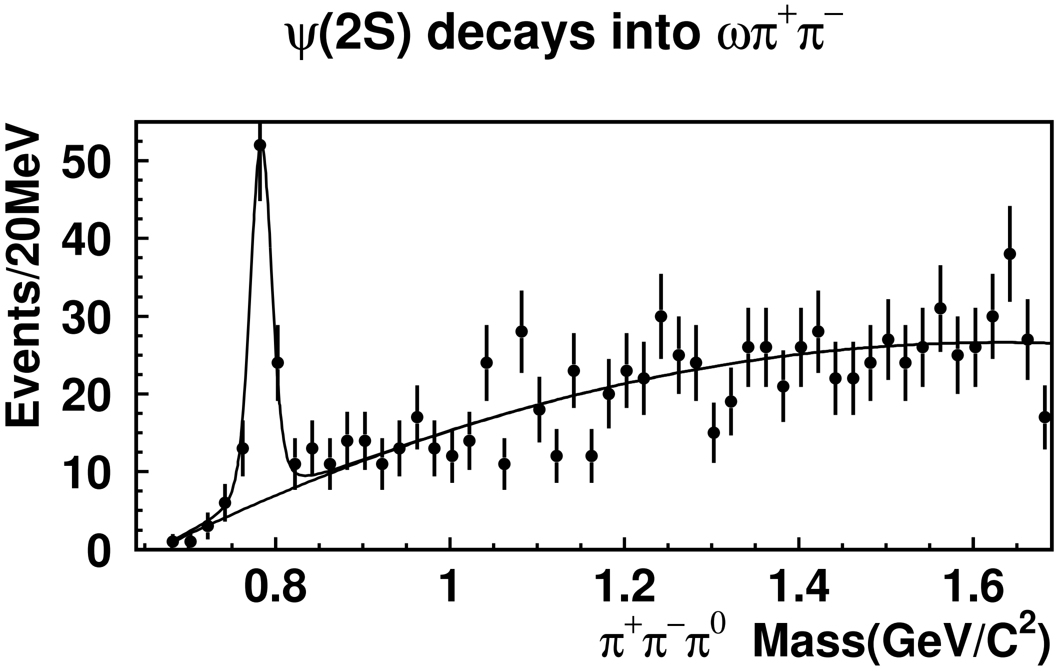
or

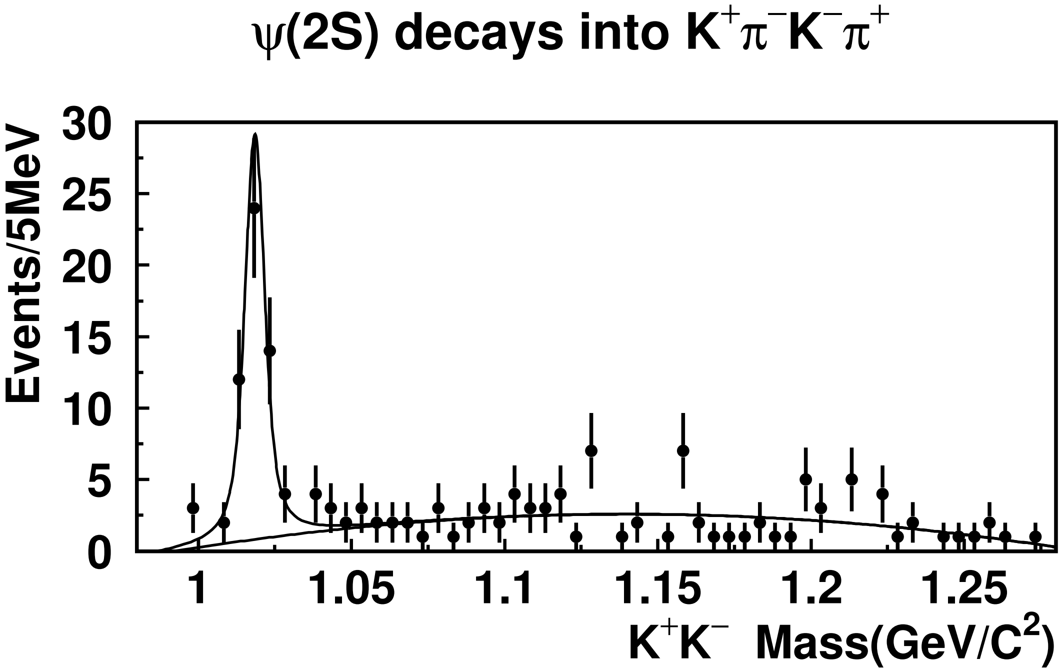
$$B(\psi(2S) \to \gamma f_J(1710) \to \gamma K\bar{K}) < 3.03 \times 10^{-4} \quad (\text{ at } 90\% \text{ C.L.})$$

Consistent with the result obtained from $\gamma K^+ K^-$ channel.

PRELIMINARY

• Decays Involving ω and ϕ





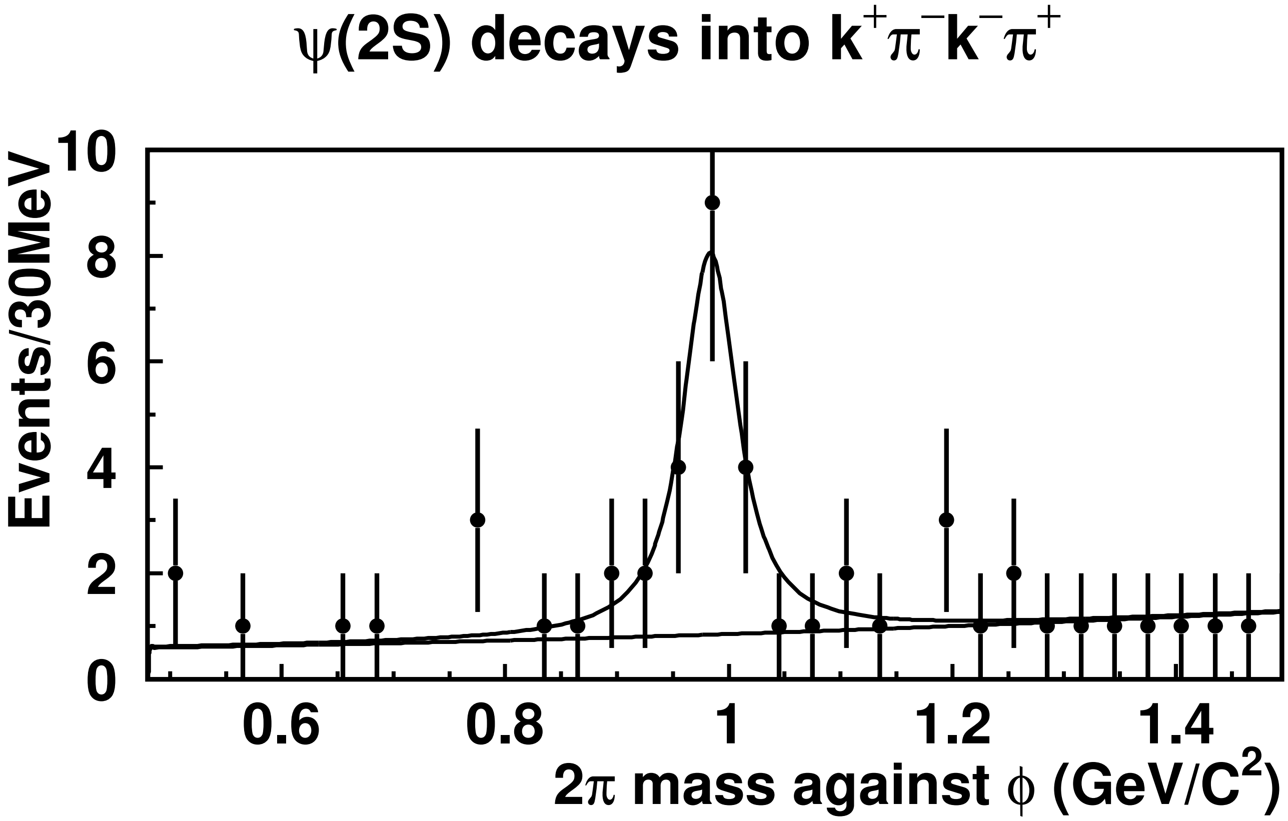


Table 5: Measurements of the $\Psi(2S)$ decay Branching Ratios.

$\Psi(2S)\ \Rightarrow$	N_{obs}	$Br(\times10^{-5})$	Q(%)
$\omega\pi^+\pi^-$	79.3±10.2	$44.7 \pm 5.7 \pm 5.4$	6.3 ± 1.4
ωK^+K^-	16.2±5.5	$12.6 \pm 4.3 \pm 3.9$	17.0 ± 9.6
$\phi\pi^+\pi^-$	57.4±7.2	$17.6 \pm 2.2 \pm 2.4$	22.0 ± 5.3
ϕK^+K^-	18.1± 5.3	$6.10 \pm 1.79 \pm 1.51$	7.3 ± 3.0
ϕf_0	20.3±5.2	$6.57 \pm 1.68 \pm 0.76$	20.5 ± 8.1
$\omega p\bar{p}$	11.0±4.3	$6.00 \pm 2.34 \pm 1.41$	4.6 ± 2.2
$\phi p\bar{p}$	3.0±1.7	$0.86 \pm 0.50 \pm 0.20$	18.9 ± 13.4
$\pi^+\pi^-\pi^0 p\bar{p}$	112.4±11.0	$38.5\pm3.7 \pm 5.5$	16.7 ± 7.1
$\eta\pi^+\pi^- p\bar{p}$	35.0±9.2	$25.8\pm6.8 \pm 7.3$	?
$\eta p\bar{p}$	3 ± 1.7	$8.36\pm4.8 \pm 4.8$	4.0 ± 4.0

Studies of $\chi_{c0,1,2}$ and η_c decays

The large sample of $\psi(2S)$ decays permits studies of $\chi_{c0,1,2}$ decays with unprecedented precision ($\sim 1{\times}10^6 \chi$'s).

There is a lot of interest:

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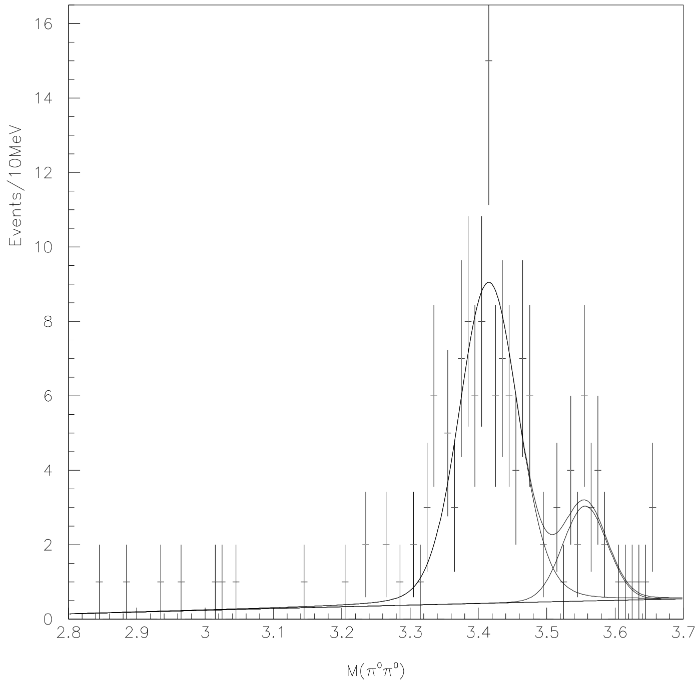
- G.T. Bodwin, E. Braaten and G.P. Lepage, Phys. Rev. **D51**, 1125 (1995).
- P. Kroll and S.M.H. Wong, hep-ph/9710464, Oct. 1997.
- V.L. Chernyak and A.R. Zhitnitsky, Nucl. Phys. **B201** (1982).
- S.J. Brodsky and G.P. Lepage, Phys. Rev. **D24**, 2848 (1981).
- A. Duncan and A.H. Mueller, Phys. Lett. **B93**, 119 (1980).

Results:

BES will fill up the Particle Data Tables

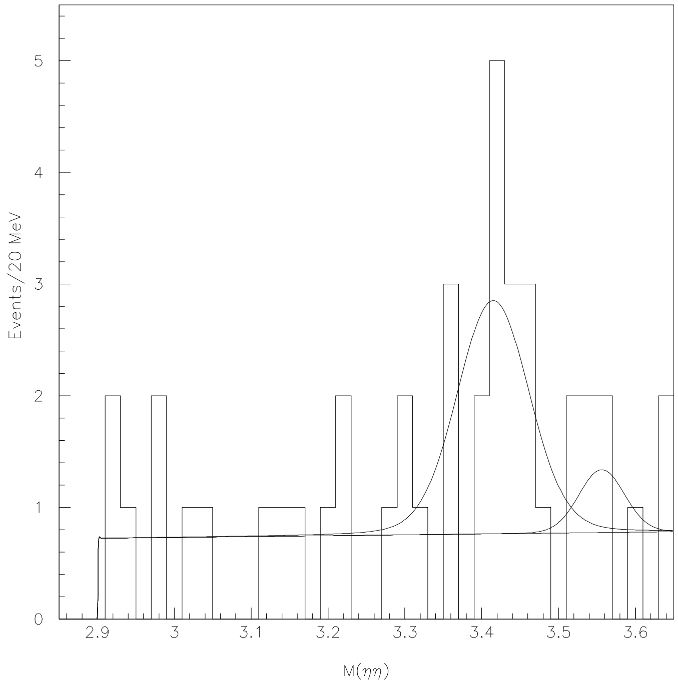
- $\psi(2S) \to \gamma\chi_c, \chi_c \to \pi^o\pi^o, \eta\eta$



$$Br(\chi_{c0} \to \pi^0\pi^0) = (2.80 \pm 0.32 \pm 0.51) \times 10^{-3}$$

$$Br(\chi_{c2} \to \pi^0\pi^0) = (9.2 \pm 2.7 \pm 5.2) \times 10^{-4}$$

PRELIMINARY



$$Br(\chi_{c0} \to \eta\eta) = (2.03 \pm 0.84 \pm 0.58) \times 10^{-3}$$

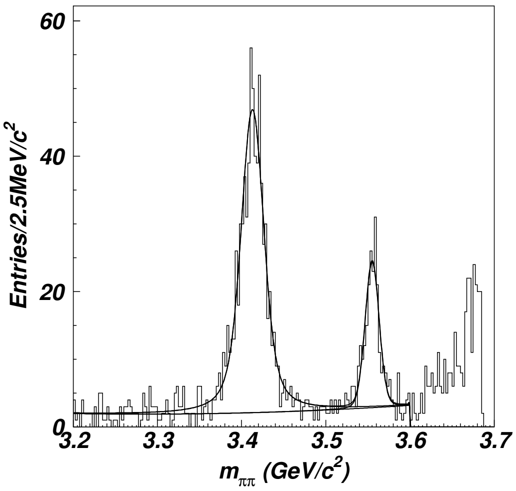
$$Br(\chi_{c2} \to \eta\eta) < 2.5 \times 10^{-3} \ \ (90\% \ C.L.)$$

$$\frac{Br(\chi_{c0} \to \eta\eta)}{Br(\chi_{c0} \to \pi^0\pi^0)} = 0.73 \pm 0.31 \pm 0.24$$

Expect 0.95 assuming SU(3) flavor symmetry.

PRELIMINARY

- $\Gamma_{\chi_0} = 14.3 \pm 3.6$ MeV. Improvement on the PDG value (14 ± 5 MeV) based on two discrepant measurements.



Phys. Rev. Lett. 81,3091,1998.

- χ_{c0} mass:

$$M_{\chi_{c0}} = 3414.1 \pm 0.6 \pm 0.8 \text{ MeV}$$

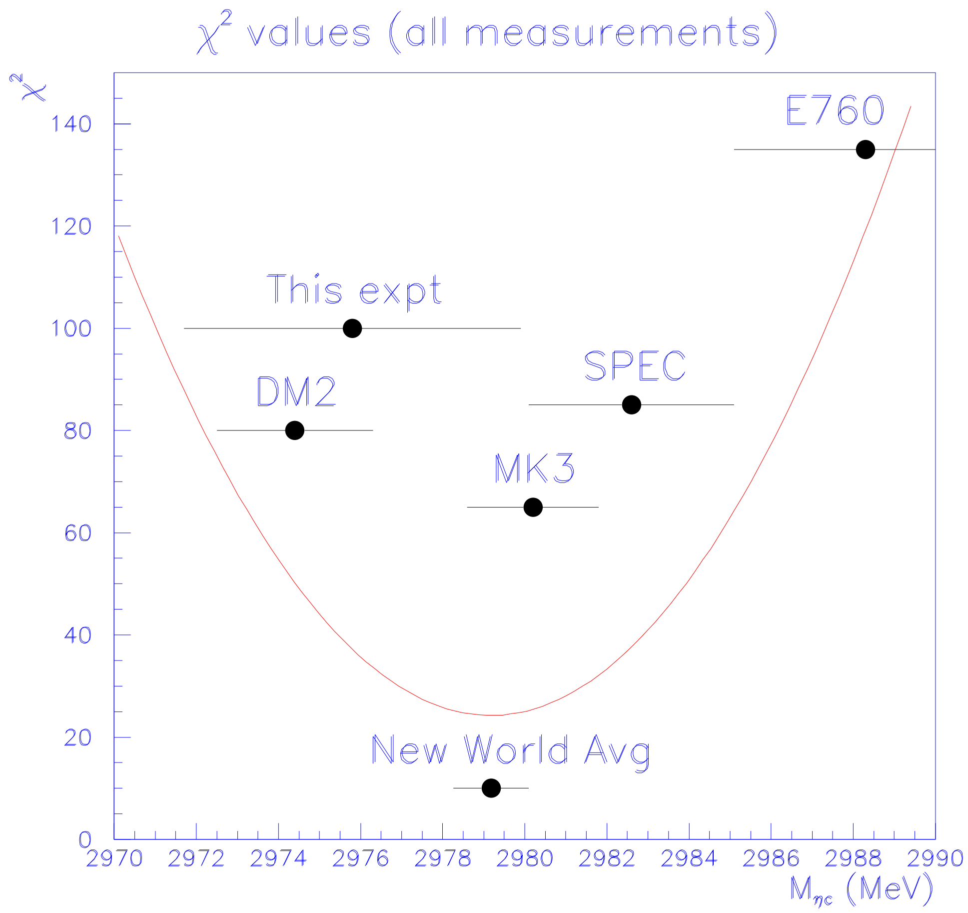
- η_c mass (from $\eta_c \to \pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-K^+K^-$, $K_sK^\pm\pi^\mp$, and $K^+K^-K^+K^-$) :

$$M_{\eta_c} = 2975.8 \pm 3.9 \pm 1.2 \text{ MeV}$$

hep-ex/9812016, accepted by PRD.

M_{η_c} Results Using J/ψ Data: Preliminary

$$M_{\eta_c} = 2977.0 \pm 3.2 \text{ MeV}$$



New World Average:

$$M_{\eta_c} = 2979.2 \pm 0.9 \text{ MeV}$$

Table 6: BES results on decay branching fractions of the $\chi_{c0,1,2}$ charmonium states

	BES ($\times 10^{-3}$)	PDG ($\times 10^{-3}$)
$B(\chi_{c0} \to \pi^+\pi^-)$	$4.68 \pm 0.26 \pm 0.65$	7.5 ± 2.1
$B(\chi_{c0} \to \pi^o\pi^o)$	$2.80 \pm 0.32 \pm 0.51$	–
$B(\chi_{c2} \to \pi^+\pi^-)$	$1.49 \pm 0.14 \pm 0.22$	1.9 ± 1.0
$B(\chi_{c2} \to \pi^o\pi^o)$	$0.92 \pm 0.27 \pm 0.52$	–
$B(\chi_{c0} \to \eta\eta)$	$2.03 \pm 0.84 \pm 0.58$	–
$B(\chi_{c2} \to \eta\eta)$	< 2.5	–
$B(\chi_{c0} \to K^+K^-)$	$5.68 \pm 0.35 \pm 0.85$	7.1 ± 2.4
$B(\chi_{c2} \to K^+K^-)$	$0.79 \pm 0.14 \pm 0.13$	1.5 ± 1.1
$B(\chi_{c0} \to p\overline{p})$	$0.159 \pm 0.043 \pm 0.053$	< 0.9
$B(\chi_{c1} \to p\overline{p})$	$0.042 \pm 0.022 \pm 0.028$	0.086 ± 0.012
$B(\chi_{c2} \to p\overline{p})$	$0.058 \pm 0.031 \pm 0.032$	0.10 ± 0.01
$B(\chi_{c0} \to \pi^+\pi^-\pi^+\pi^-)$	$15.4 \pm 0.5 \pm 3.7$	37 ± 7
$B(\chi_{c1} \to \pi^+\pi^-\pi^+\pi^-)$	$4.9 \pm 0.4 \pm 1.2$	16 ± 5
$B(\chi_{c2} \to \pi^+\pi^-\pi^+\pi^-)$	$9.6 \pm 0.5 \pm 2.4$	22 ± 5
$B(\chi_{c0} \to K^0_sK^0_s)$	$1.96 \pm 0.28 \pm 0.52$	-
$B(\chi_{c2} \to K^0_sK^0_s)$	$0.61 \pm 0.17 \pm 0.16$	-
$B(\chi_{c0} \to \pi^+\pi^-K^+K^-)$	$14.7 \pm 0.7 \pm 3.8$	30 ± 7
$B(\chi_{c1} \to \pi^+\pi^-K^+K^-)$	$4.5 \pm 0.4 \pm 1.1$	9 ± 4
$B(\chi_{c2} \to \pi^+\pi^-K^+K^-)$	$7.9 \pm 0.6 \pm 2.1$	19 ± 5
$B(\chi_{c0} \to \pi^+\pi^-p\bar{p})$	$1.57 \pm 0.21 \pm 0.54$	5.0 ± 2.0
$B(\chi_{c1} \to \pi^+\pi^-p\bar{p})$	$0.49 \pm 0.13 \pm 0.17$	1.4 ± 0.9
$B(\chi_{c2} \to \pi^+\pi^-p\bar{p})$	$1.23 \pm 0.20 \pm 0.35$	–
$B(\chi_{c0} \to K^+K^-K^+K^-)$	$2.14 \pm 0.26 \pm 0.40$	–
$B(\chi_{c1} \to K^+K^-K^+K^-)$	$0.42 \pm 0.15 \pm 0.12$	–
$B(\chi_{c2} \to K^+K^-K^+K^-)$	$1.48 \pm 0.26 \pm 0.32$	–
$B(\chi_{c0} \to \phi\phi)$	$0.92 \pm 0.34 \pm 0.38$	–
$B(\chi_{c2} \to \phi\phi)$	$2.00 \pm 0.55 \pm 0.61$	–
$B(\chi_{c0} \to K^0_sK^+\pi^- + c.c.)$	< 0.71	–
$B(\chi_{c1} \to K^0_sK^+\pi^- + c.c.)$	$2.46 \pm 0.44 \pm 0.65$	–
$B(\chi_{c2} \to K^0_sK^+\pi^- + c.c.)$	< 1.06	–
$B(\chi_{c0} \to 3(\pi^+\pi^-))$	$11.7 \pm 1.0 \pm 2.3$	15 ± 5
$B(\chi_{c1} \to 3(\pi^+\pi^-))$	$5.8 \pm 0.7 \pm 1.2$	22 ± 8
$B(\chi_{c2} \to 3(\pi^+\pi^-))$	$9.0 \pm 1.0 \pm 2.0$	12 ± 8

Summary

- Studied $\psi(2S) \to \pi^+\pi^- J/\psi$ Decay Distributions
- Many, many $\psi(2S)$ and χ_c Branching Ratios
- More information concerning the $\rho\pi$ puzzle
- New World Average: $M_{\eta_c} = 2979.2 \pm 0.9$ MeV
- $M_{\chi_{c0}} = 3414.1 \pm 0.6 \pm 0.8$ MeV