CLEO Results on Hadronic Decays of Quarkonia

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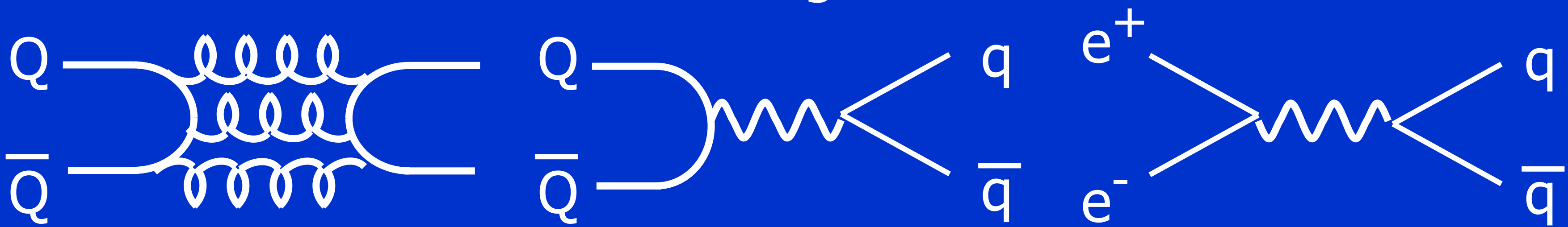
Quarkonia Hadronic Decays

- Motivation
- CLEO datasets
- Technique
- $\psi(2S) \to$ Vector Pseudoscalar (VP)
  - Comparisons w/subsequent BES results
- $\psi(2S) \to$ multibody
- $\Upsilon(nS) \to$ 2-body (LEPPHO 2003)

$\psi' \to$ 2 hadrons

resonant-strong | resonant electromagnetic | non-resonant



$\psi(2S)$ SIGNAL | CONTINUUM

"The ~~14~~% rule" 12?

$c\bar{c}$ annihilation ⇒ decay rate ~ $|\Psi(0)|^2$

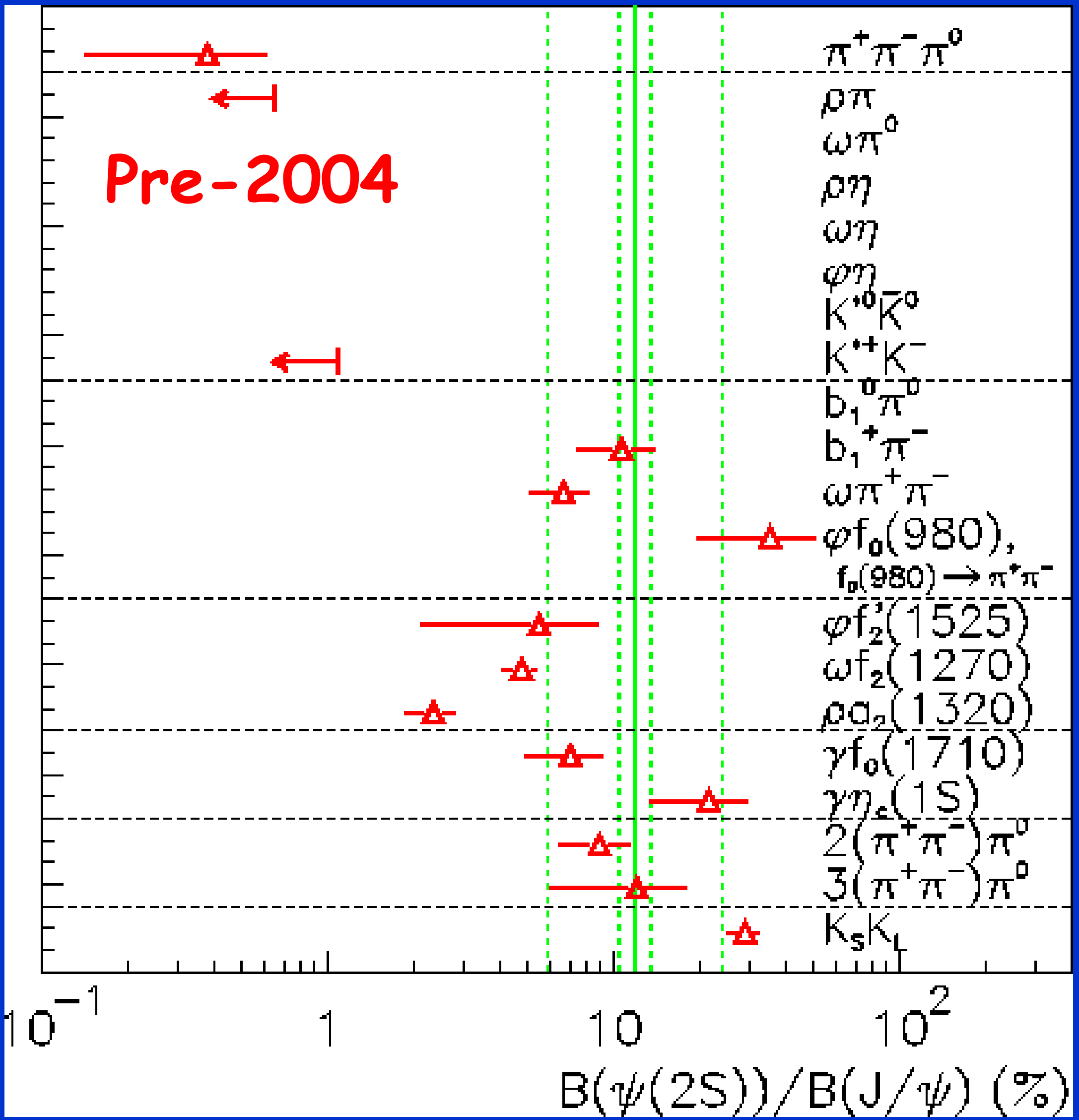
$$Q_h = \frac{B(\psi(2S) \to H)}{B(J/\psi \to H)} = \frac{B(\psi(2S) \to e^+e^-)}{B(J/\psi \to e^+e^-)} \approx (12.3 \pm 0.9)\%$$

Complications (& there are more):

- Powers of αS at mJ/ψ, mψ(2S) 0.845 hep-ph/09910406
- Form factor ECM dependence? (3.686/3.097)2=1.4
- Non-relativistic corrections
- Interference with continuum
- Only for cc→γ*, not cc→ggg? (Gerard/Weyers)
- Compliance within a factor of two: "agreement"

Exclusive hadronic ψ(2S) decays

- ψ(2S) BR's: Not many precisely measured
- Good understanding of continuum background is crucial!
- hep-ex/0407028 subm. to PRL, ICHEP ABS 10-0753



Datasets

- $\psi(2S)$ (3.686GeV):
  - $\int Ldt = 5.46 pb^{-1}$, 3.08M ψ' $\Rightarrow$ 10^{-5} BR within reach
- Continuum (3.67GeV):
  - $\int Ldt = 20.46\ pb^{-1}$ $\Rightarrow$ ~ pb cross sections
  - This quantity essential, as continuum bgds are typically ~1/3 of signals
  - CLEO doubled its continuum sample after glimpsing the apparent size of cross sections
  - Difficult to establish $\psi(2S)$ signal as being very different from continuum without large ratio of continuum:$\psi(2S)$ luminosity (we have ~4:1)
  - Consider $\rho\pi$
    - 32 in the $\psi(2S)$ sample, 41 in the continuum sample
    - So 32 on a bgd of ~11±2: "only" 3.7σ

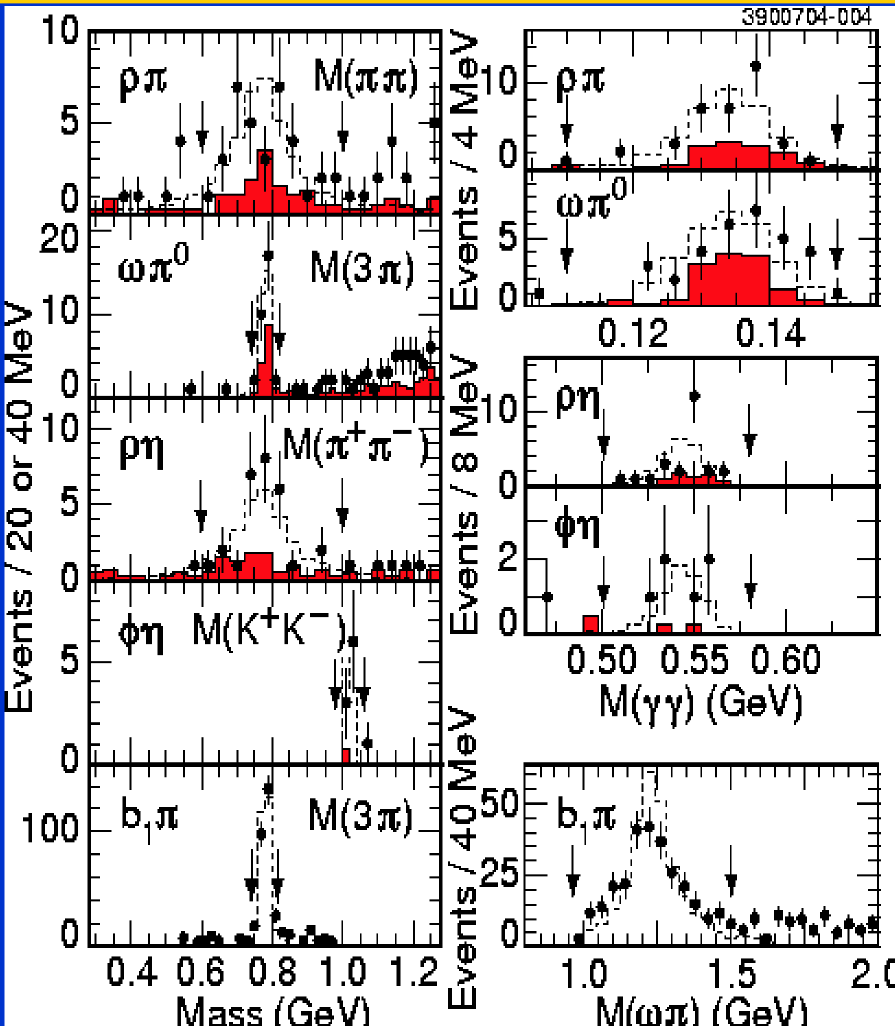
Analysis Overview

- Signal event selection:
  - Energy/momentum conservation
    $0.98 < E_{VIS}/E_{CM} < 1.015$, $|| p_1 |-| p_2 ||/E_{BEAM} < 0.04$
  - Mass windows (determined using MC)
  - $K_S \to \pi^+\pi^-$, π^0, & $\eta \to \gamma\gamma$ with kinematic fitting
  - Standard particle ID (RICH, dE/dx), very low fake rates
- Background: Suppress $\psi(2S) \to \pi^0 J/\psi$, $\pi^+\pi^- J/\psi$, $\pi^0\pi^0 J/\psi$ with mass & missing mass cuts
  - Subtract small remaining levels using appropriate sidebands
- Efficiencies: 4-31%

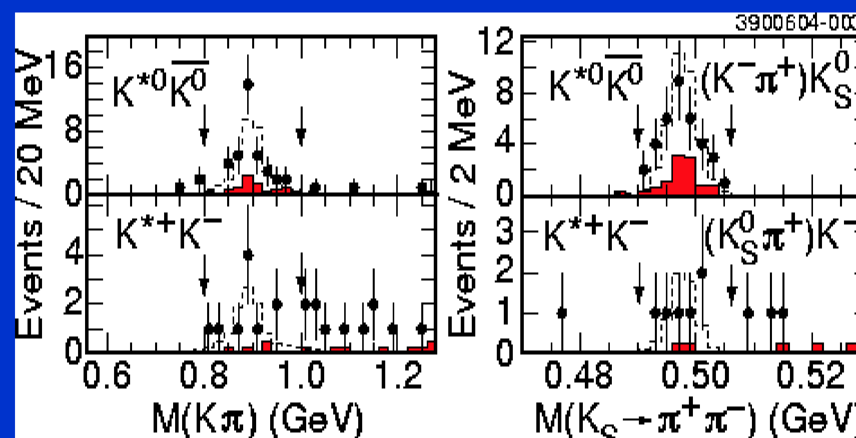
Signal Handling

- Yields: a handful to few 100
- Significance of signals
  - Establish $\psi(2S)$ yields as different from continuum, regardless of BR extraction technique
  - Feldman-Cousins style Poisson fluctuation of bgd mean & bgd around that mean, along with signal to compute probability that observed yield is due to continuum alone
- Branching fraction: interference w/cont?
  - We quote straight subtraction of continuum. Why?
  - Strong phases are model dependent
    - We provide enough information for model builders/testers
  - This convention can be followed by any expmt:
    - Common ground for comparison can be found
  - If decay is e-m (virtual γ), our procedure is ~the "right" thing
    - Because beam energy spread (1.5-2.3 MeV) >> Γ (~270 keV), the data integrates over constructive & destructive interference
    - Isospin-violating decays ($\omega\pi$, $\rho\eta$)
    - Some models: e.g. intrinsic flavor

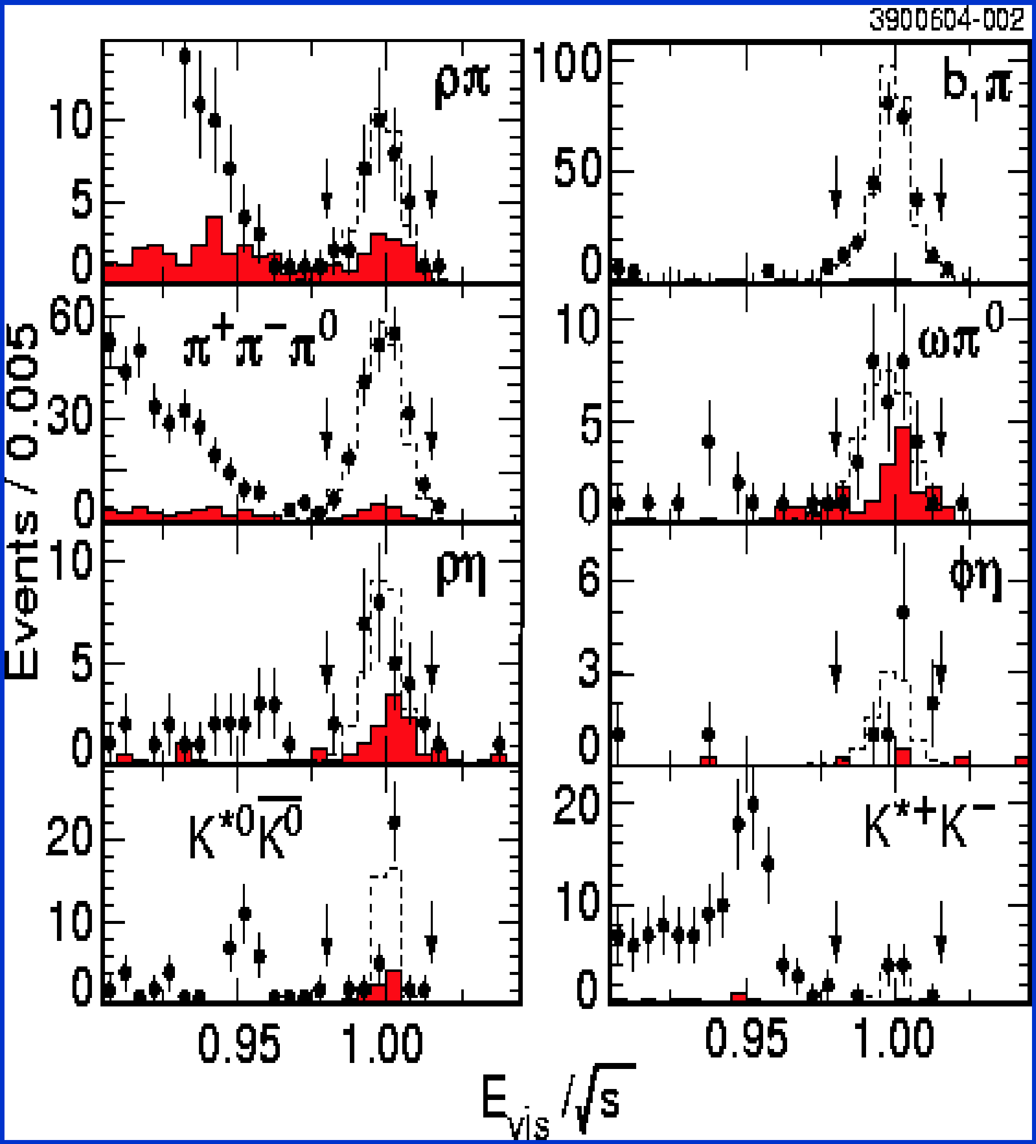
Masses: $\psi(2S)\to VP$ & $b_1\pi$



- $\psi(2S)$ data
- ■ Scaled Continuum
- -- signal MC, arb. Scale
- Arrows show cut values

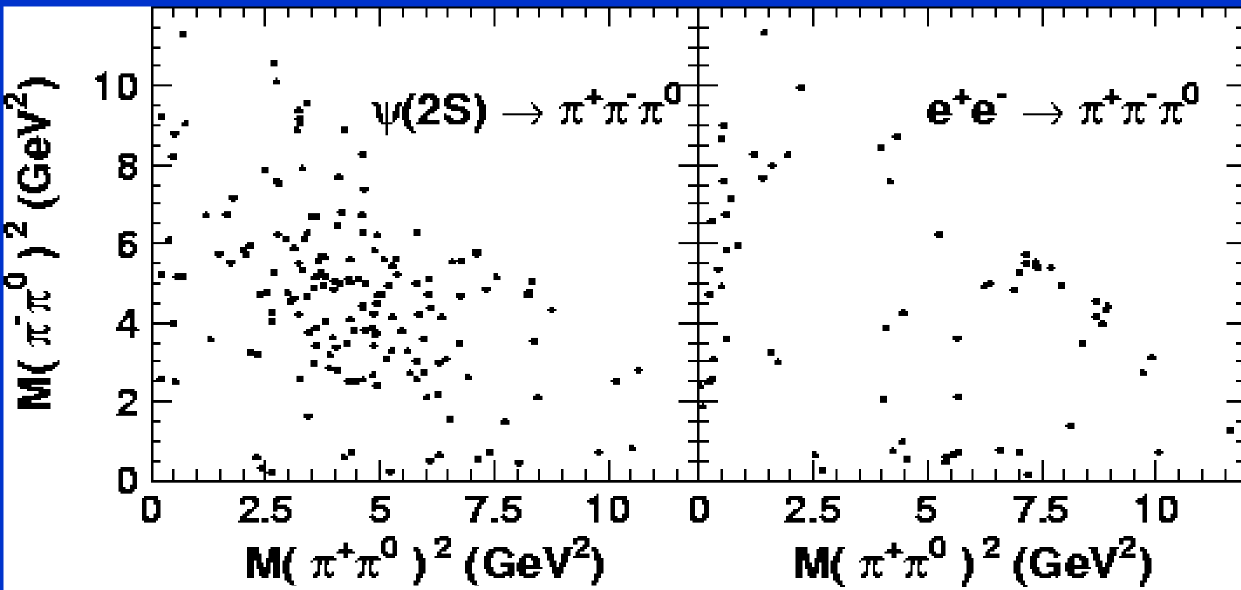


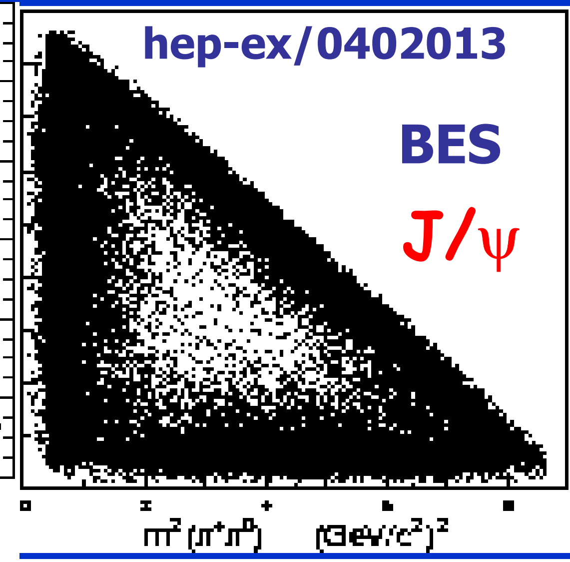
Evis: $\psi(2S)\to VP$ & $b_1\pi$

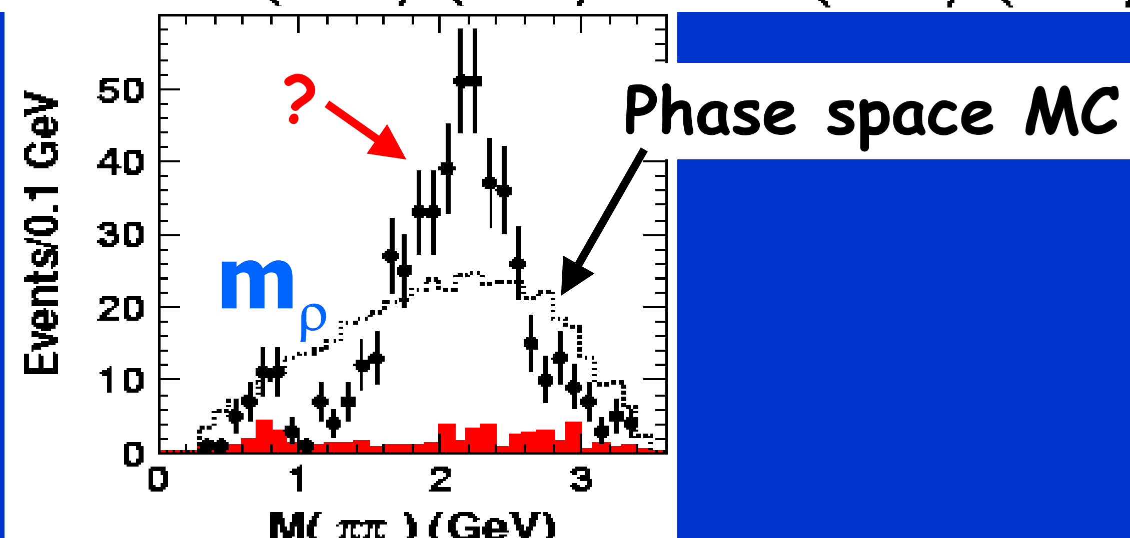


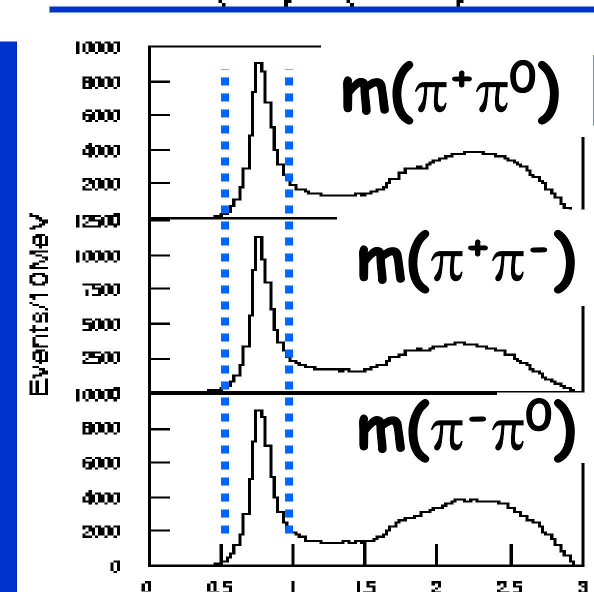
- $\psi(2S)$ data
- Continuum, to scale
- -- signal MC, arb. scale

$\psi(2S) \to \pi^+\pi^-\pi^0$ ($\rho\pi$)









Normalization

- $\psi' \to \pi^+\pi^-$ J/ψ,   J/$\psi \to \mu^+\mu^-$
  - Copious production
  - Clean (almost no background)
  - Simple exclusive final state like others
  - High trigger efficiency
  - Some systematic errors cancel
  - Modeled well

The Measurements

$\psi(2S)$ ($\sqrt{s}$=3.686GeV)

$$\frac{B(\psi(2S)\to X)}{B(\psi(2S)\to\pi^+\pi^- J/\psi,\ J/\psi\to\mu^+\mu^-)} = \frac{N^{obs,\psi(2S)} - N^{cont}\times\frac{\text{cont}\to 2S}{\text{scale factor}} - N^{xfeed,\psi(2S)}}{\varepsilon(X)\ N(\pi^+\pi^-\mu^+\mu^-)\ /\ \varepsilon(\pi^+\pi^-\mu^+\mu^-)} \pm stat \pm syst$$

No treatment of interference.

Continuum ($\sqrt{s}$=3.670GeV)

$$\sigma(e^+e^-\to X) = \frac{N^{cont} - N^{xfeed,cont}}{\varepsilon^{cont}\times\int\mathcal{L}^{3670}} \pm stat \pm syst$$

Continuum scale factor

count

$\psi(2S)$ ($\sqrt{s}$=3.686GeV)

$$\frac{B(\psi(2S)\to X)}{B(\psi(2S)\to\pi^+\pi^- J/\psi,\ J/\psi\to\mu^+\mu^-)} = \frac{N^{obs,\psi(2S)} - N^{cont} \times \text{cont}\to\text{2S scale factor} - N^{xfeed,\psi(2S)}}{\varepsilon(X)\ N(\pi^+\pi^-\mu^+\mu^-)\ /\ \varepsilon(\pi^+\pi^-\mu^+\mu^-)}$$

Luminosity ratio: 5.46/20.46=0.267

(use $\gamma\gamma$ events: unlike e^+e^-, no interference w/direct ψ(2S) decays)

$\times$ $1/s^n$ dependence: $\to$ 0.99-0.97

$\times$ Efficiency: ε(cont)/ε(ψ(2S))=0.99-1.07

Results

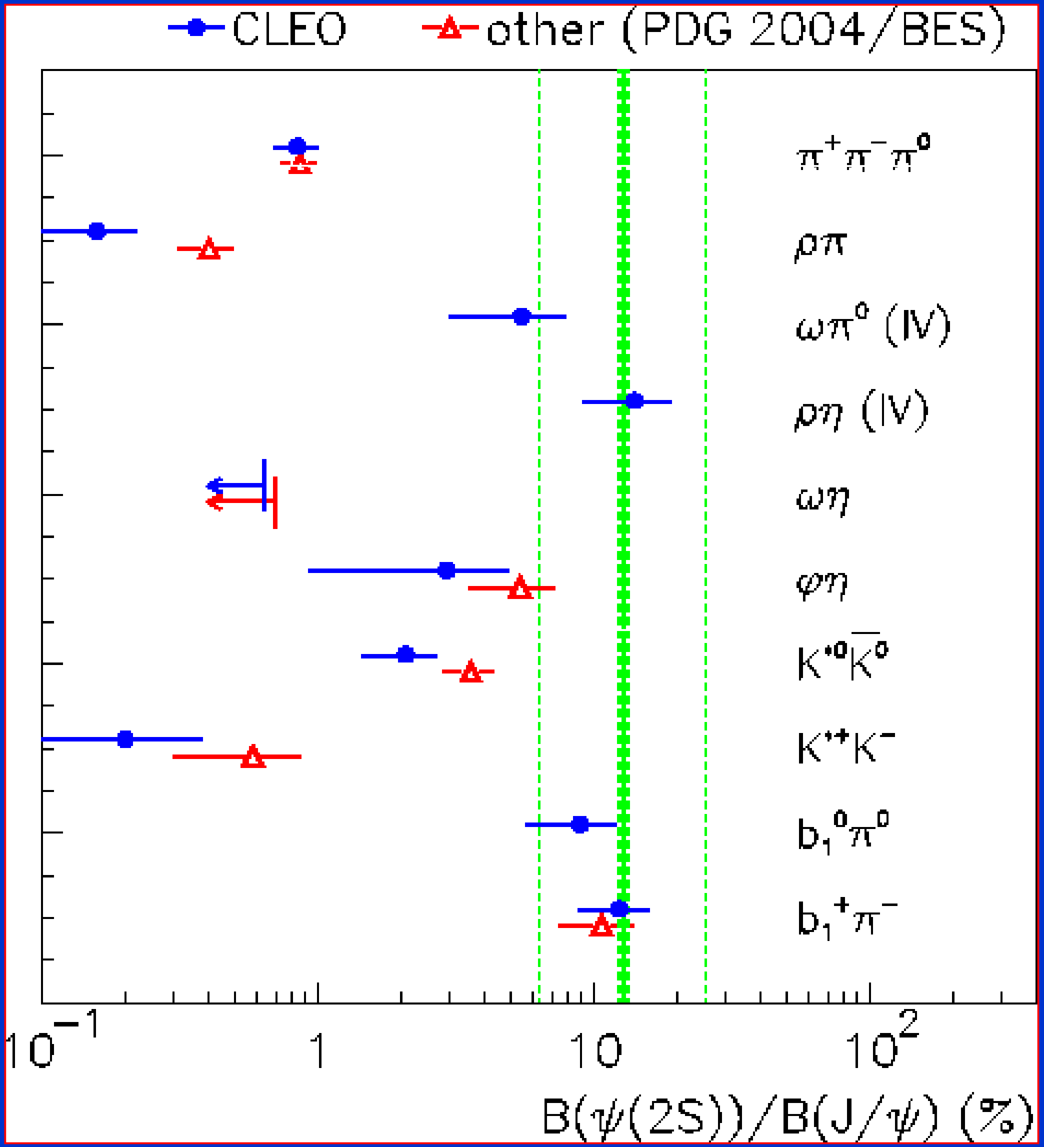
Channel	ε(%)	# Cont	# ψ(2S)	Sig. (#σ)	BR (10^{-6})			$Q/Q_{\|\|}$(%)	Cont σ (pb)		
$\pi^+\pi^-\pi^0$	30.6	85	217	~6	136	$^{+12}_{-13}$	±21	6.6±1.2	13.1	$^{+2.0}_{-1.8}$	±3.0
$\rho\pi$	28.2	47	35	3.7	24	$^{+7}_{-8}$	±2	1.2±0.5	8.3	$^{+1.7}_{-1.4}$	±1.2
$\rho^0\pi^0$	30.8	21	15	3.0	9	±4	±1	1.7±0.9	3.2	$^{+1.1}_{-0.9}$	±0.5
$\rho^+\pi^-$	26.9	26	20	2.5	15	$^{+6}_{-7}$	±2	1.0±0.6	5.2	$^{+1.4}_{-1.1}$	±0.5
$\omega\pi^0$	18.3	55	31	3.1	23	$^{+9}_{-11}$	±2	44±22	14.2	$^{+2.7}_{-2.4}$	±2.0
$\phi\pi^0$	15.0	3	1	<1	<7			--	0.8	$^{+1.3}_{-0.6}$	±1.1
$\rho^0\eta$	19.5	38	28	4.2	31	$^{+11}_{-7}$	±2	109±41	10.2	$^{+2.2}_{-1.9}$	±1.6
$\omega\eta$	9.4	3	1	<1	<10			<5.5	1.8	$^{+1.7}_{-0.9}$	±0.2
$\phi\eta$	8.8	3	9	2.1	19	$^{+10}_{-15}$	±4	22±18	2.0	$^{+2.0}_{-1.1}$	±0.2
$K^{*0}K^0$	8.1	36	35	5.2	87	$^{+21}_{-25}$	±9	16±5	24.6	$^{+5.1}_{-4.4}$	±3.0
$K^{*+}K^-$	15.5	4	10	2.0	17	$^{+8}_{-10}$	±4	1.6±1.5	0.8	$^{+1.4}_{-0.6}$	±0.8
$b_1^0\pi^0$	5.9	5	54	~6	205	$^{+38}_{-45}$	±30	70±26	1.9	$^{+3.9}_{-1.7}$	±1.4
$b_1^+\pi^-$	12.2	17	226	~6	369	$^{+40}_{-41}$	±76	97±28	6.4	$^{+2.5}_{-2.0}$	±1.0

Systematic Errors

- Statistical errors dominate here: sys>stat only for $\pi^+\pi^-\pi^0$, $b_1\pi$, $\omega\pi^+\pi^-$
- Common to all:
  - #$\psi'\rightarrow\pi^+\pi^- J/\psi$ (1.7%), trigger (1%), $e^\pm$ veto (1%), MC stats (<2%): 3%
  - for cross sections: +luminosity (5%): 6%
- Mode by mode
  - 2%/(π^0/η), 5%/K_S, 3%/PID, 2.5-4% tracking due to partial cancellation w/ $\psi'\rightarrow\pi^+\pi^- J/\psi$
  - ±50% of the cross-feed contribution: large errors for $K^{*+}K^-$, $\phi\eta$, $\phi f_2'$, K^*K^*

$Q = \psi(2S)/J/\psi$

- $\rho\pi$, K^*K measured
- IV modes ~obey 12% rule
- $b_1\pi$ too
- Large K^*K charge/neutral difference
  - Unlike J/ψ! Why?
- Biggest violators
  - $\pi^+\pi^-\pi^0$, $\rho\pi$, $K^{*+}K^-$, $\omega\eta$



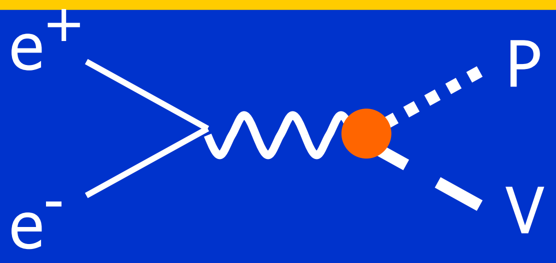
Comparing $\psi(2S) \rightarrow \rho\pi$

	CLEO	BES	
Efficiency	28.2%	10.5%	2.7:1
#$\psi(2S)$	3.1M	14.0M	1:4.5
#$\rho\pi$ @3.686GeV	31.8±6.2	~73±9	
	CLEO extrap:	53.5±10.4	1.4σ
Continuum	20.5 pb^{-1}	6.4 pb^{-1}	3.2:1
$\mathcal{L}^{\psi(2S)}/\mathcal{L}^{cont}$	0.26	3.1	1:12
#$\rho\pi$ cont @3.67[3.65]GeV	41 ± 7	~8 ± 3	
	CLEO extrap:	4.8 ±0.8	1.0 σ
Signal/Bgd	31.8 / 10.7(=41*.26)	~73 /~24.8(=8*3.1)	
BR (10^{-6})	20±7±2	51±7±8	
significance	3.7	7.8	

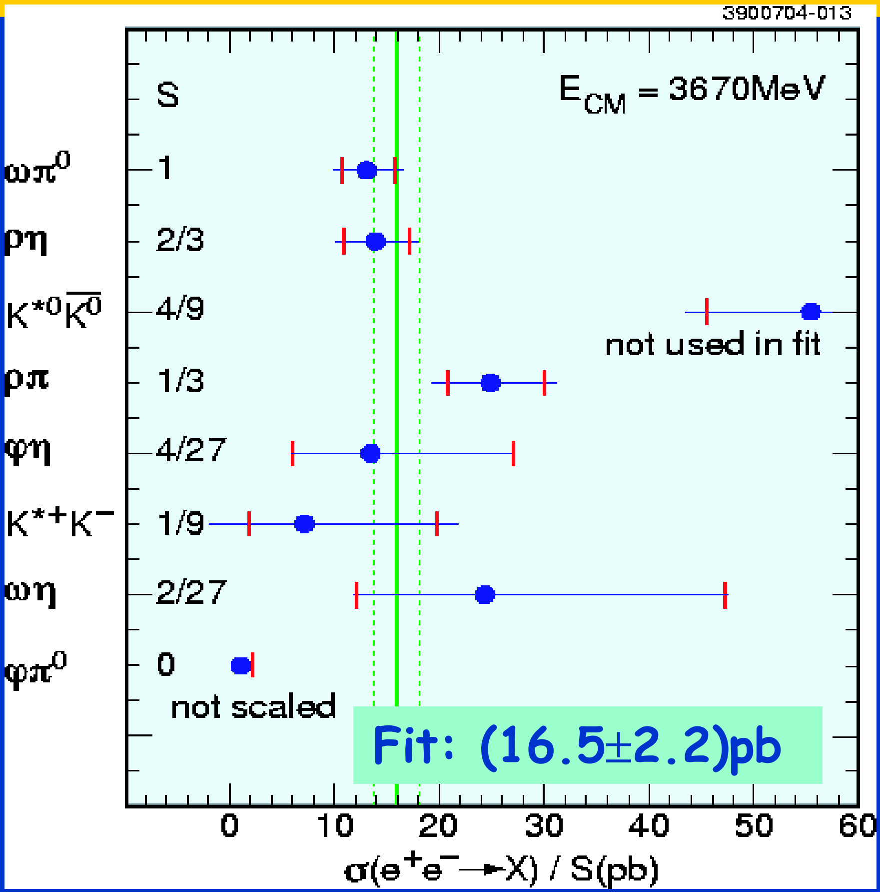
More on CLEO/BES comparisons…

- BES & CLEO VP event yields on continuum & $\psi(2S)$ are statistically compatible in all modes (accounting for ε's, lumi)
- Different BRs, significances
  - Different handling of continuum subtractions
  - Assumptions about interference phases
  - For $\rho\pi$, assumptions about the nature of the high $\pi\pi$ mass events (interference in ρ region)

Continuum cross sections



- First measurements
- Expected couplings per SU(3) quark counting relations; rates as shown below
- Most rates agree w/SU(3) ratio expectations
- $K^{*0}K^0$ much higher than expected

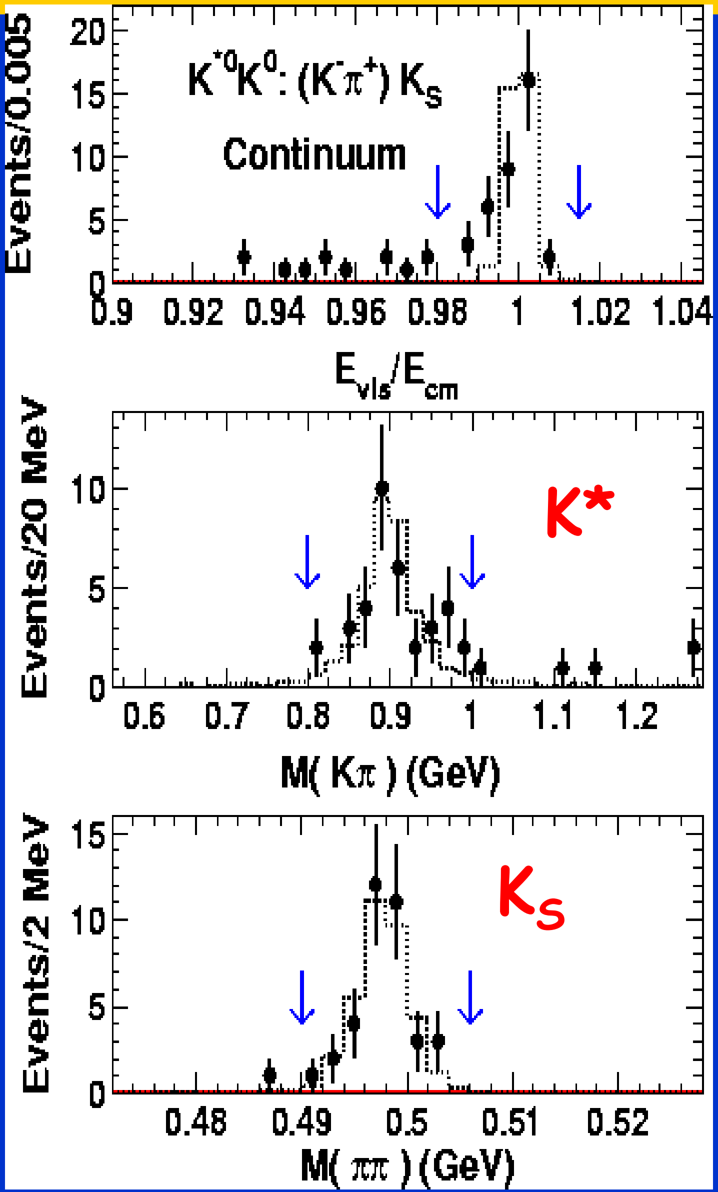


$\omega\pi^0$	:	$\rho\eta$	:	$K^{*0}K^0$	:	$\rho\pi$	:	$\phi\eta$	:	$K^{*+}K^-$	:	$\omega\eta$	:	$\phi\pi^0$
1	:	2/3	:	4/9	:	1/3	:	4/27	:	1/9	:	2/27	:	0

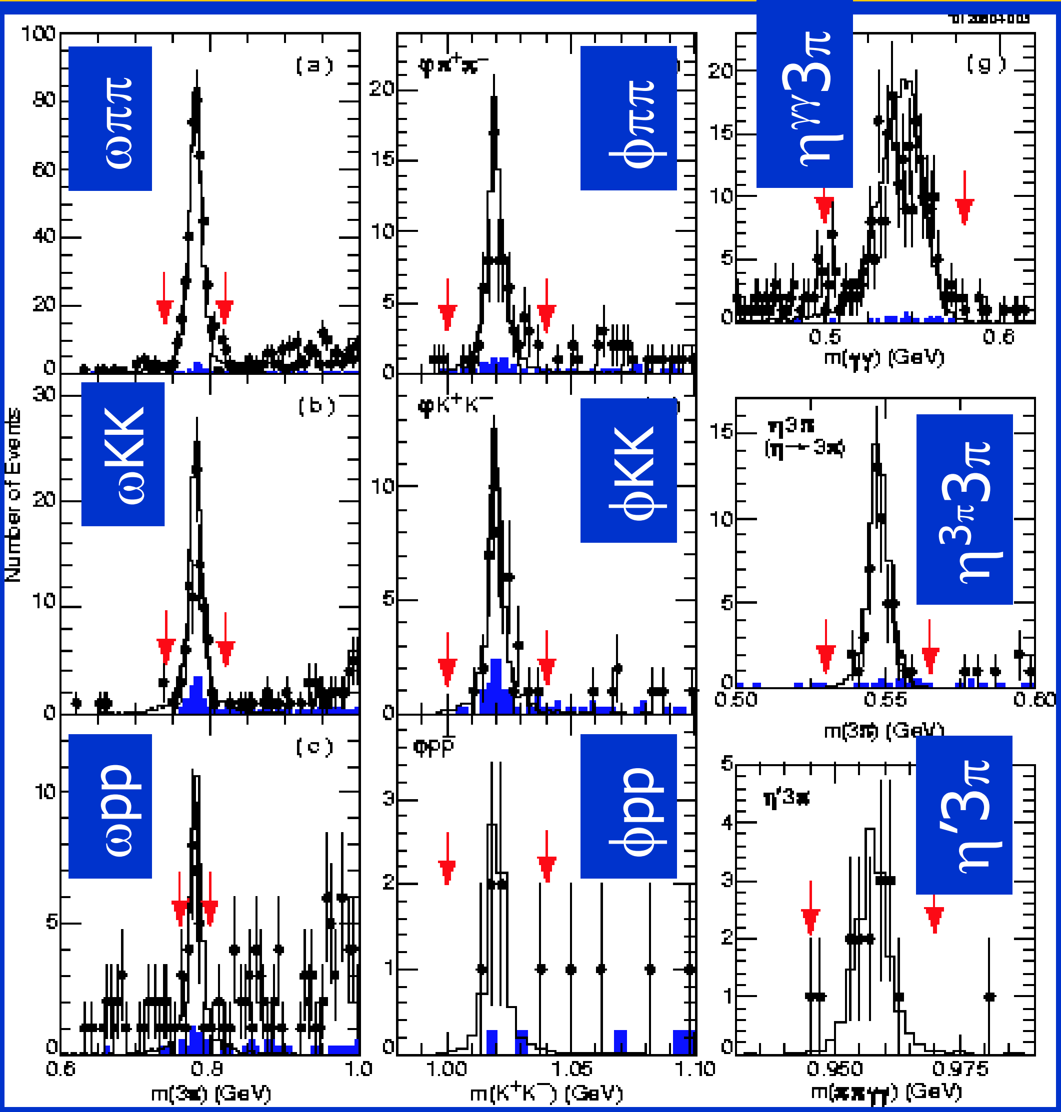
Rosner hep-ph/0405196 (subm to PRD); Haber/Perrier PRD 32 (1985) 2961.

$K^{*0}\overline{K^0}$ on continuum

Very clean signal



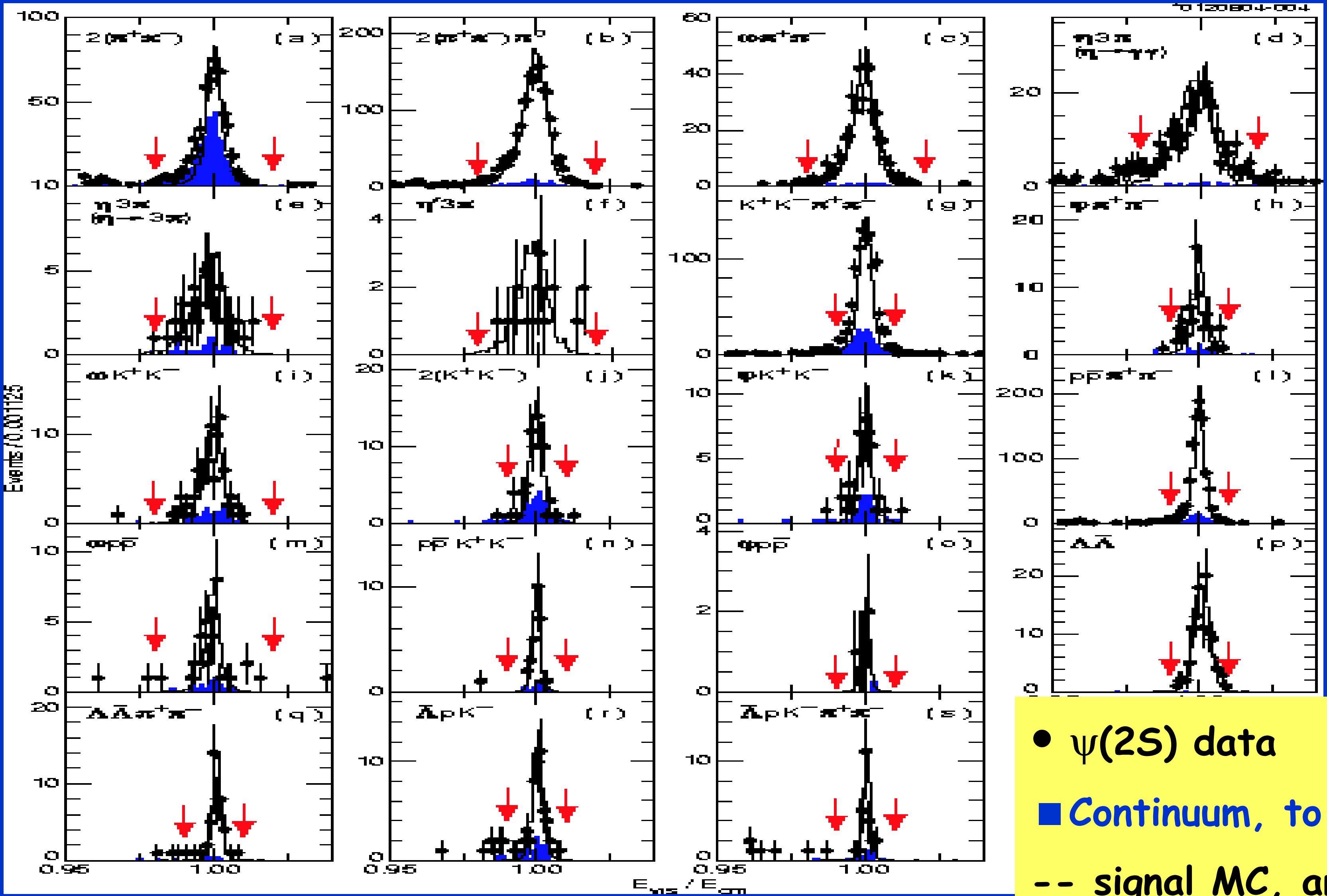
$\psi(2S) \rightarrow$ multibody



- $2(\pi^+\pi^-)$, $2(\pi^+\pi^-)\pi^0$, K^+K^-, $\pi^+\pi^-$, $2(K^+K^-)$
- $pp\pi^+\pi^-$, ppK^+K^-, $\Lambda\Lambda$, $\Lambda\Lambda\pi^+\pi^-$, ΛpK^+, $\Lambda pK^+\pi^+\pi^-$
  - $\omega\pi^+\pi^-$, ωK^+K^-, ωpp, $\eta 3\pi$, $\eta' 3\pi$, $\phi\pi^+\pi^-$, ϕK^+K^-, ϕpp

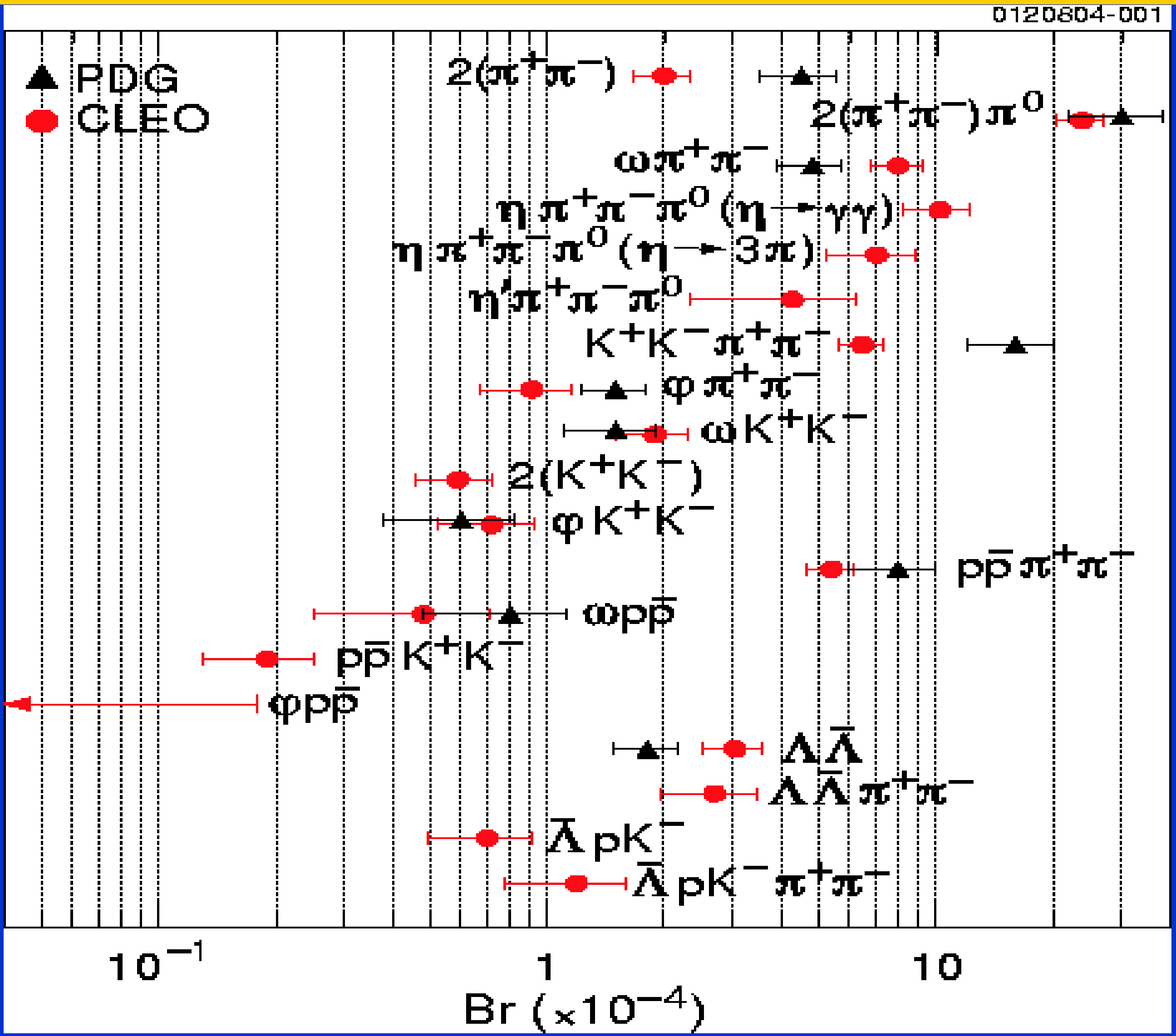
- $\psi(2S)$ data
- ■ Continuum, to scale
- -- signal MC, arb. scale

Evis: Multibody



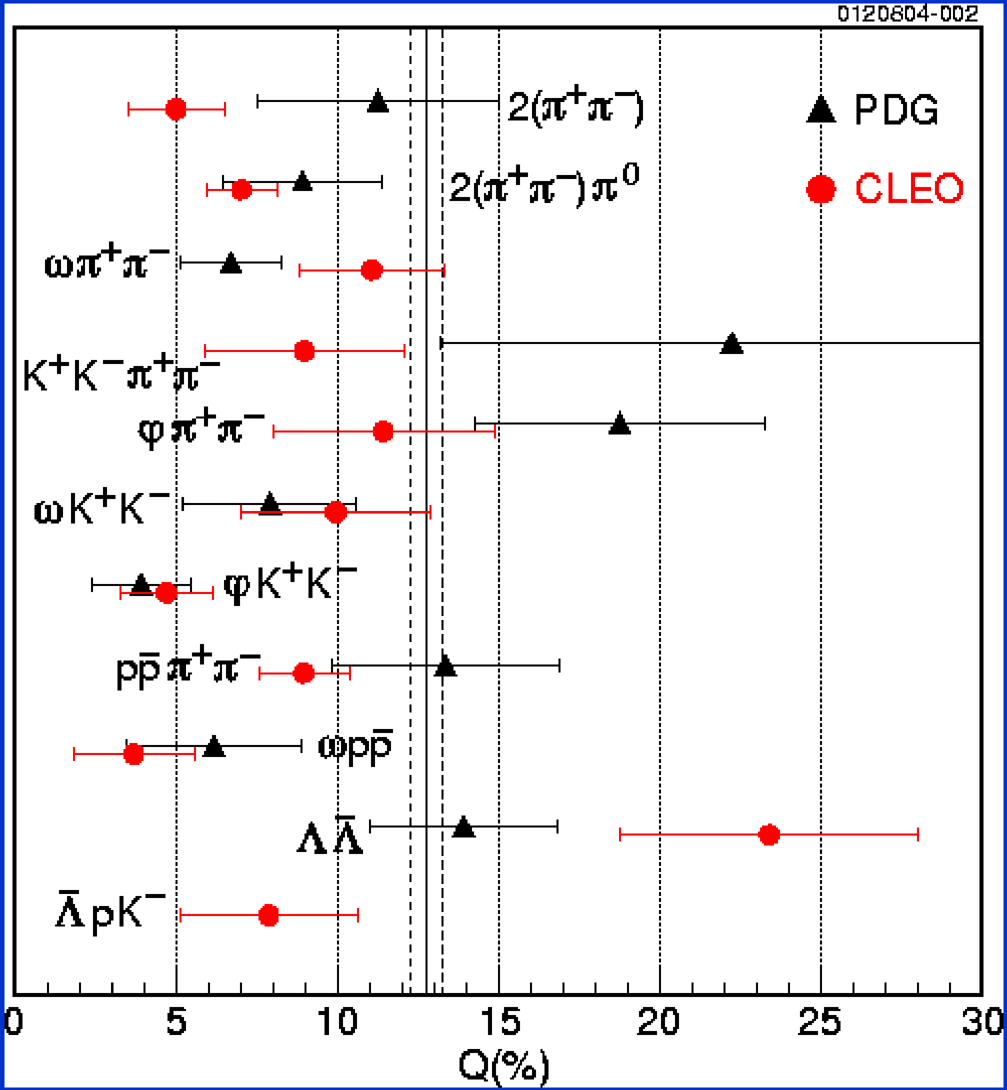
- $\psi(2S)$ data
- ■ Continuum, to scale
- -- signal MC, arb. scale

Multibody BR's



Q: ψ(2S)/(J/ψ) for multibody

Broad agreement w/12% rule observed…

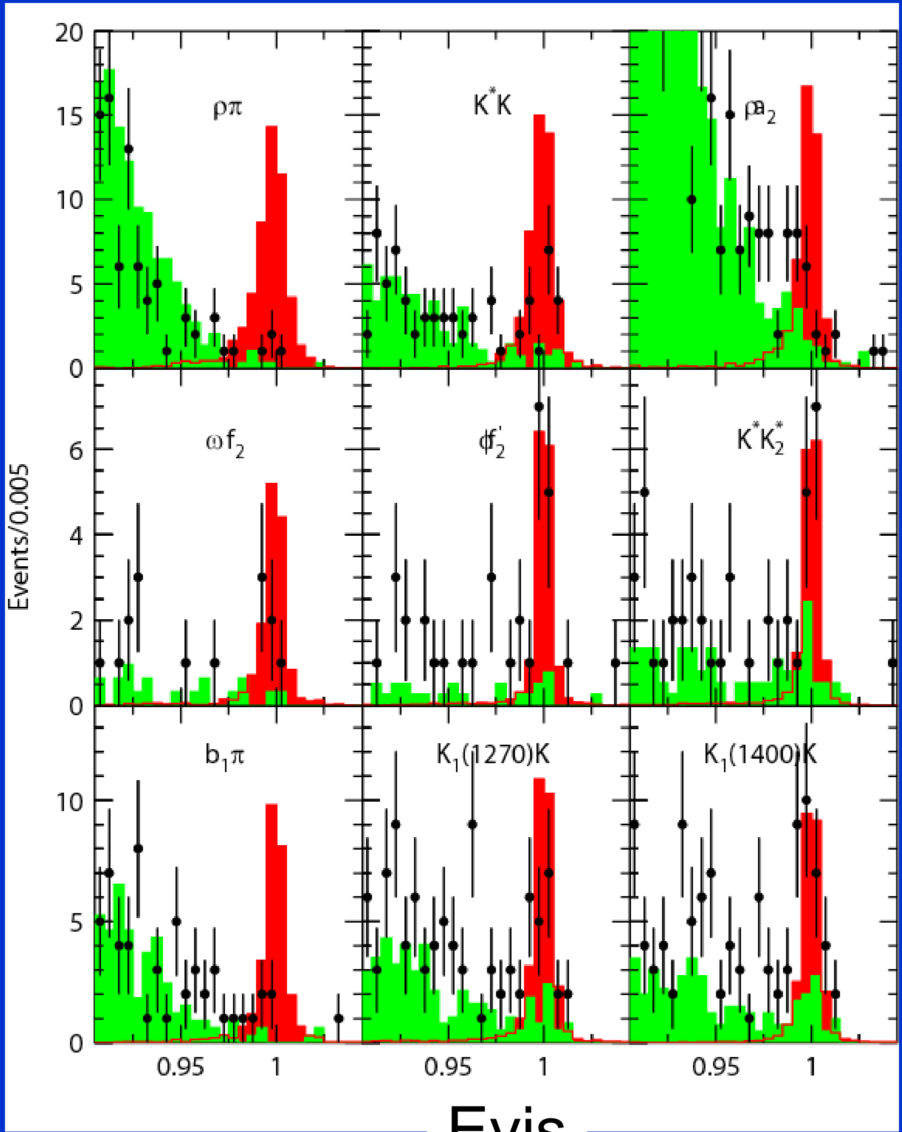


$\Upsilon \to$ 2-Body

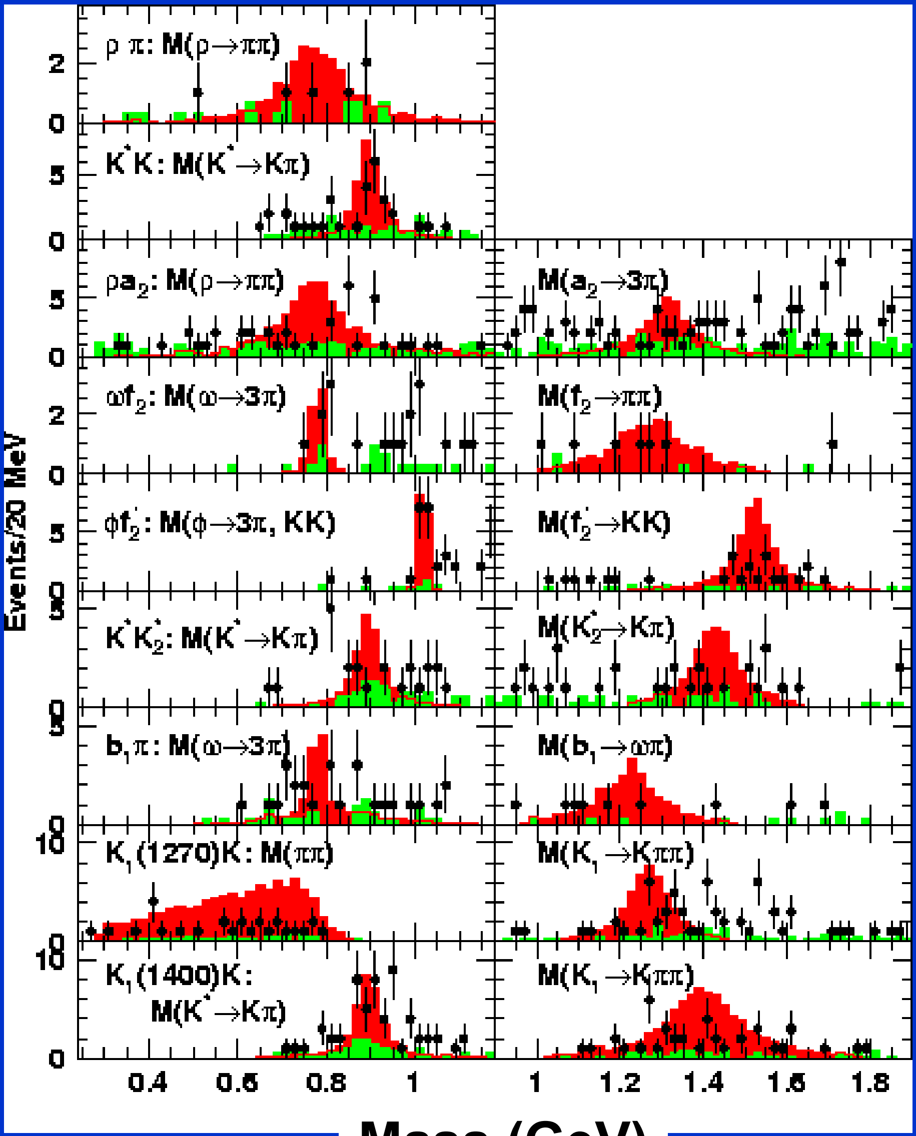
Reso-nance	Lumi (pb^{-1})	#decays
$\Upsilon(3S)$	1460	6.0
$\Upsilon(2S)$	1380	9.0
$\Upsilon(1S)$	1210	29.0

- Use CLEO's large Υ sample to search for 2-body hadronic decays
- Similar strategy as $\psi(2S)$ analysis
- Released LEPPHO 2003
- Sample several types of modes
  - VP: $\rho\pi$, K*K
  - AP: $b_1\pi$, $K_1(1270)K$, $K_1(1400)K$
  - VT: ωf_2, ϕf_2, $\phi f_2'$, $K^*K_2^*$
- Use $\Upsilon(4S)$ & nearby continuum as a source of bgd, scaling by lumi & $1/s^n$
- "12% rule" becomes
  - "48% rule" for $\Upsilon(2S)/\Upsilon(1S)$
  - "72% rule" for $\Upsilon(3S)/\Upsilon(1S)$
- Efficiencies 5-11%
- Sensitivity in BR: $\sim 10^{-5}$
- Theoretical expectations not clear

$\Upsilon(1S)$: Evis & Sub-Masses



Evis



Mass (GeV)

$\Upsilon \to$ 2-Body Results

Channel	$\Upsilon(1S)$ BR (10^{-6})	$\Upsilon(1S)$ Sig.	$\Upsilon(2S)$ BR (10^{-6})	$\Upsilon(2S)$ Sig.	$\Upsilon(3S)$ BR (10^{-6})	$\Upsilon(3S)$ Sig.
$\rho\pi$	<4	-	<11	-	<22	-
K^*K	$6^{+3}_{-2}\pm1$	3.6	<8	-	<14	-
ρa_2	$9\pm4\pm1$	3.0	<24	-	<30	-
ωf_2	<7	-	<11	-	<8	-
$\phi f_2'$	$7^{+3}_{-2}\pm1$	5.5	$6^{+6}_{-3}\pm1$	3.0	<14	-
$K^*K_2^*$	$9^{+5}_{-4}\pm1$	3.0	<32	-	<28	-
$b_1\pi$	<8	-	<12	-	<18	-
$K_1(1270)K$	<8	-	<11	-	<17	-
$K_1(1400)K$	$14^{+3}_{-2}\pm2$	5.6	<33	-	<22	-

Summary

- $\psi(2S)$ branching fractions measurement:
  - 10^{-3} – 10^{-5}, mostly statistics dominated
  - First evidence for $\psi(2S)\to\rho\pi$, $\omega\pi$, $\rho\eta$, $K^{*0}K^0$
  - $\pi^+\pi^-\pi^0$ Dalitz plot distinctly different than continuum or J/ψ
  - K*K charged vs neutral asymmetry
  - IV channels $\rho\eta$, $\omega\pi$ don't break 12% rule
  - Multibody channel msmts roughly obey 12% rule
- $e^+e^-\to X$ @$\sqrt{s}$=3670GeV cross sections
  - First measurements, picobarn range
  - Broad agreement with quark counting except $K^{*0}K^0$
- $\Upsilon\to$2-Body signals in $\Upsilon(1S)\to\phi f_2'(1525)$, $K_1(1400)K$ at BR~10^{-5}
  - Other BR upper limits of ~10^{-5}