Hadronic Physics and Exotics

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Insight into what holds hadrons together
$\Rightarrow$ access to the strong force

Hadrons come in many different shapes and sizes
$\Rightarrow$ access to different manifestations of the strong force

Hadron spectroscopy and decay as a study ground for QCD

Compare expected system of states (mesons, baryons, glueballs, …) against observations

Observables: masses, widths, decay dynamics

New observations just as important as comprehensive surveys – and planning for the unexpected, too!

Unless a heavy-system decay, this is non-perturbative QCD.

3-step program to make headway on Route QCD

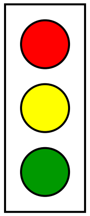
(1) FIND	Search for the expected Observe the unexpected	Example: A new state is seen
(2) SORT	Systematically probe properties: Confirmation Cross-check Anti-checks	Study production and decay in different and in similar production and decay scenarios
(3) ✔	Categorize within the framework Perform precision studies Deviations from expectation? Back to (1)!	Assign a place in the system of states Leaving out (2) gets you a ticket!

This talk: Examples from all three categories.

Q=c,b

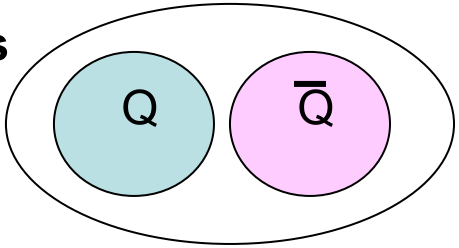
q=u,d,s

Overview



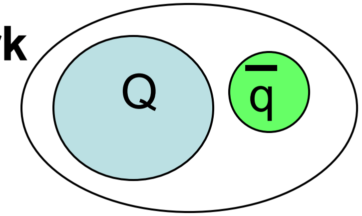
General goal:
Explore QCD phenomena
at different scales

Two heavy quarks

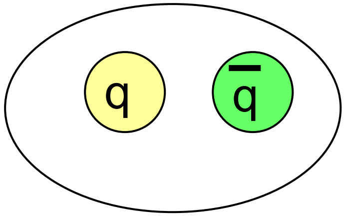


ψ(2S) width
J/ψ, χ_{cJ} decay to light q
B decay to charmonium
States above DD threshold
Charmonium-like states

One heavy quark



Zero heavy quarks



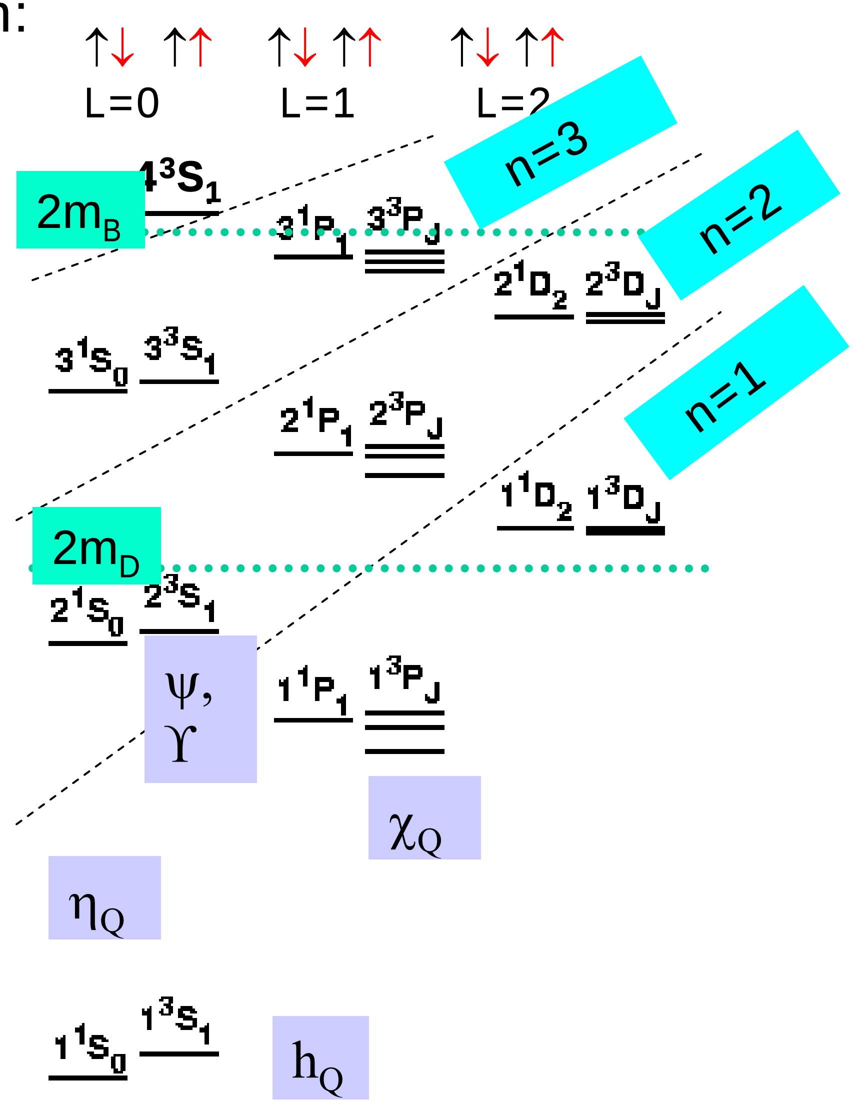
This talk: mostly mesons, but many new results on baryons as well. See list of topics at the end.

$(Q\bar{Q})$ States

Notation:
$n^{2S+1}L_J$
$\vec{J}=\vec{L}+\vec{S}$

Study system of states, governed by underlying binding force: strong force.

Charmonium and bottomonium very similar.
$(b\bar{b})$: less relativistic
$(c\bar{c})$: more data available



- ? Masses
- ? Widths
- ? Production and decay dynamics

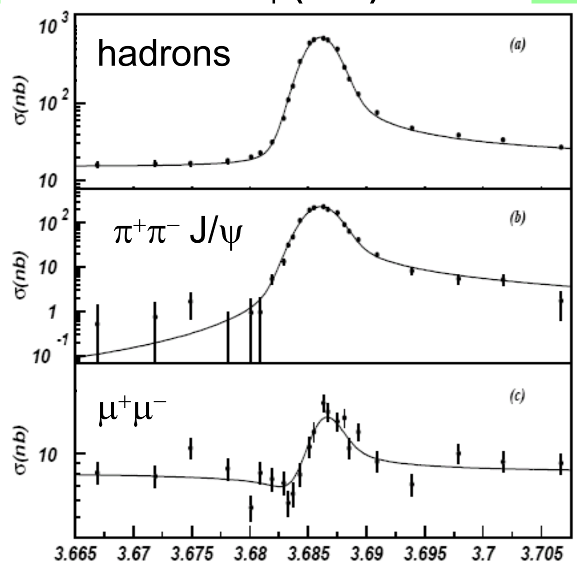
J/ψ: 3.10 GeV
$\Upsilon(1S)$: 9.46 GeV
$\Delta(1^3S_1, 2^3S_1) \sim 600$ MeV

Partly discovery, partly precision measurements

This summer – mostly charmonium results.

ψ(2S) width measurements

BES scan: ψ(2S)→…



BES, PLB 550, 24 (2002)

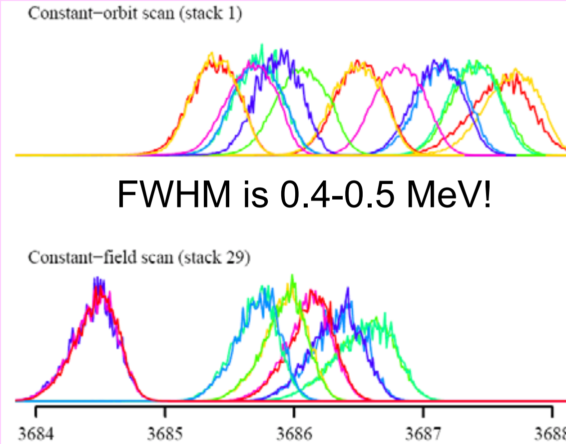
4MeV

E_{CM} (GeV)

E835 ($p\bar{p}$):
beam energy spread is ~ψ(2S) width, can directly observe the line shape

BES (e^+e^-):
beam energy spread is O(MeV), can measure width through effect on observed cross-sections

E835

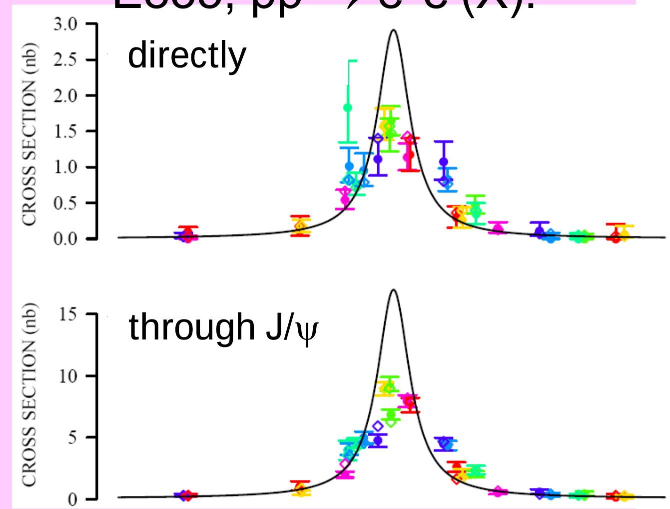


E835, hep-ex/0703012

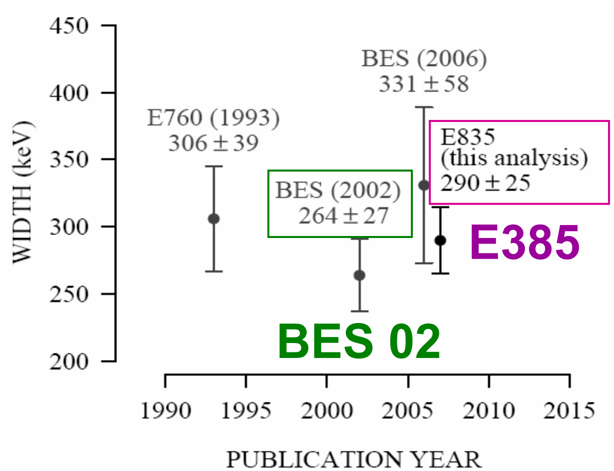
E_{CM} (GeV)

4MeV

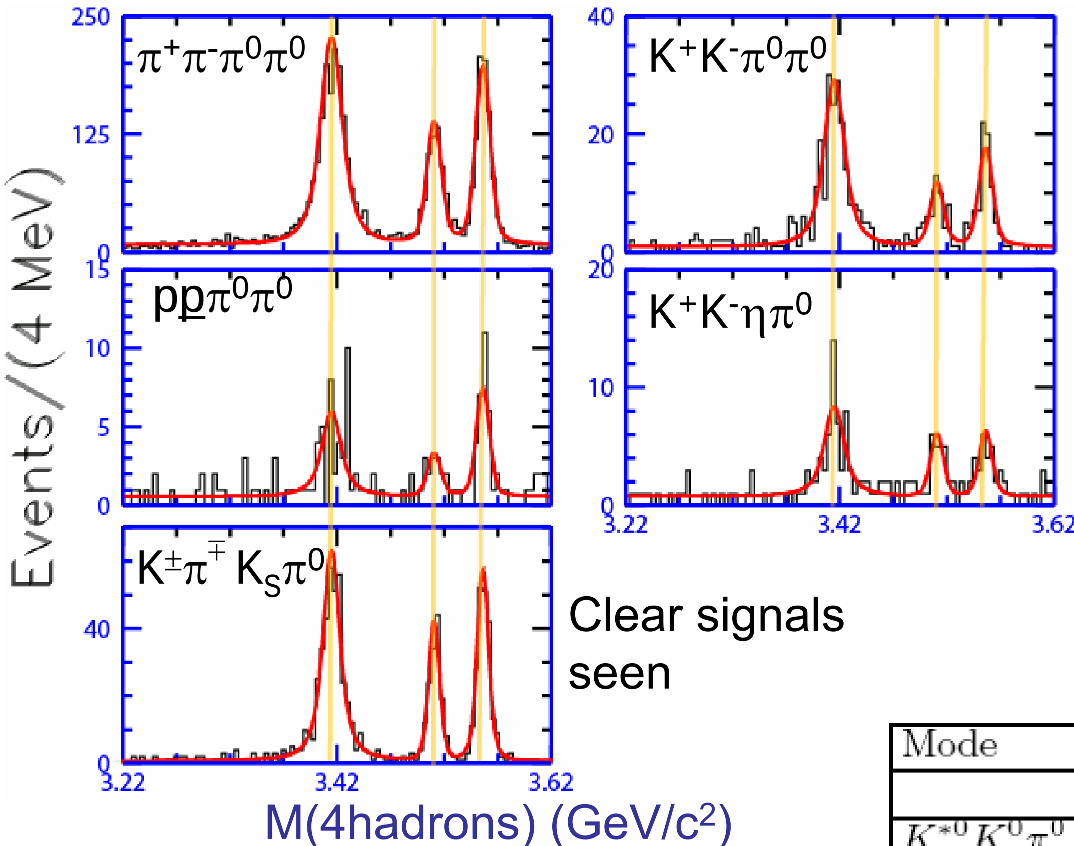
E835, $p\bar{p} \to e^+e^-(X)$:



Γ_{total}:
Different methods, different channels, consistent results



$\chi_{cJ} \rightarrow h^+h^-h^0\pi^0$



Clear signals seen

Survey of four-body decays

Resonant substructure is important for 4π and $KK\pi\pi$, ($\rho\pi\pi$ or $K^*K\pi$ or $KK\rho$ or …)

Branching fractions and contributions from intermediate resonances determined

Isospin relations:

$\rho^+\pi^-\pi^0 = \rho^0\pi^+\pi^-$? ✓

$K^*K\pi$ modes: ✓

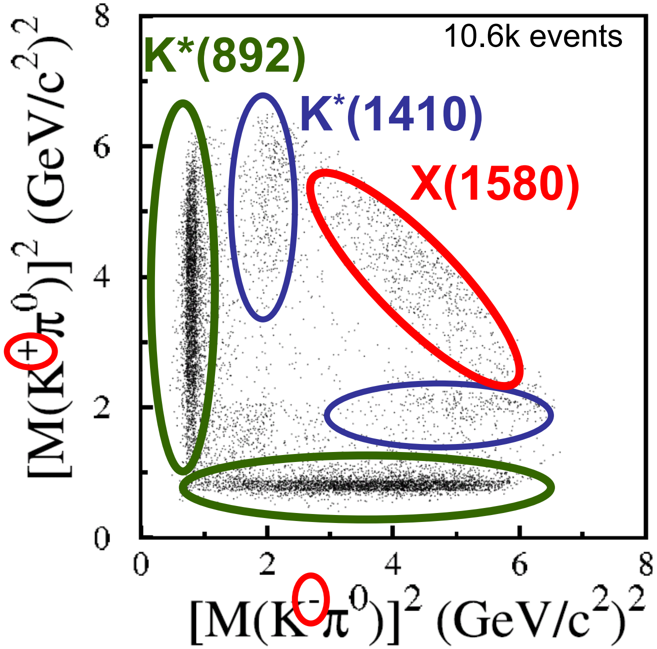
Expect 1:2

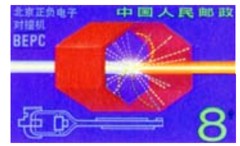
Mode	χ_{c0}	χ_{c1}	χ_{c2}
	B.F. (%)	B.F. (%)	B.F. (%)
$K^{*0}K^0\pi^0$	0.56±0.15	0.38±0.11	0.59±0.14
$K^{*0}K^{\pm}\pi^{\mp}$	-	-	0.90±0.25
$K^{*\pm}K^{\mp}\pi^0$	0.74±0.18	-	0.57±0.13
$K^{*\pm}\pi^{\mp}K^0$	0.96±0.25	-	0.90±0.25

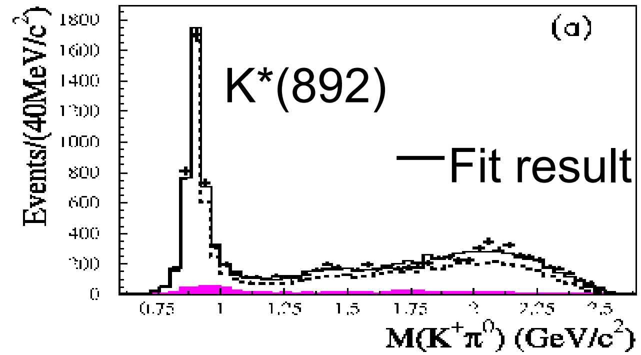
see talk by D. Cassel at this conference

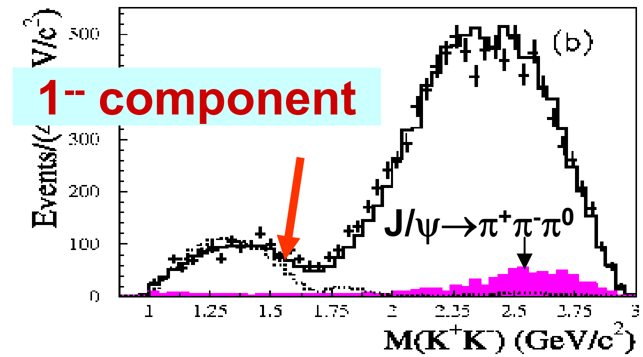
Phys. Rev. Lett. 97 (2006) 142002
and talk by J. Chen at this conference

Observation of a broad 1^{-} resonance in $J/\psi \to K^{+}K^{-}\pi^{0}$









C-parity cons: X should have $J^{PC} = 1^{--}, 3^{--}, \ldots$

PWA results:

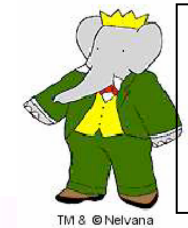
- Need $K^*(892)$, $K^*(1410)$, $\rho(1700)$, X, non-res.
  - using rho excitations to describe signal doesn't work
- Big destructive interference among X, $\rho(1700)$ and phase space
  - ("hole" in the middle of the Dalitz plot)
- 1^{-} is much better than 3^{-}
- Pole position of X $(1576^{+49}_{-55}{}^{+98}_{-91}) - i(409^{+11}_{-12}{}^{+32}_{-67})\ \mathrm{MeV}/c^2$
- Br $(J/\psi \to X\pi^0, X \to K^+K^-) = (8.5 \pm 0.6^{+2.7}_{-3.6}) \times 10^{-4}$

Further check: $K_S K^{+/-}\pi^{-/+}$

Width(X) »
width($\rho(1450)$, $\rho(1700)$):

4-quark state?

BABAR-CONF-07/001, SLAC-PUB-12665
S. Tosi, talk at this conference



Production: $B \to \eta_c K(*)$, $h_c K(*)$

(η_c: $K_S K^+ \pi^-$, $K^+ K^- \pi^0$; h_c: $\gamma\eta_c$)

Goal: insight into production mechanisms of $B \Rightarrow c\bar{c}$, comparison btw different $c\bar{c}$

$b \to c\bar{c}s$ produces
- η_c, J/ψ ($B \sim 0.1\%$)
- and χ_{c1} $B \sim 0.03$-0.05% (and excitations)
- but not $h_c, \chi_{c0}, \chi_{c2}$, need other mechanism

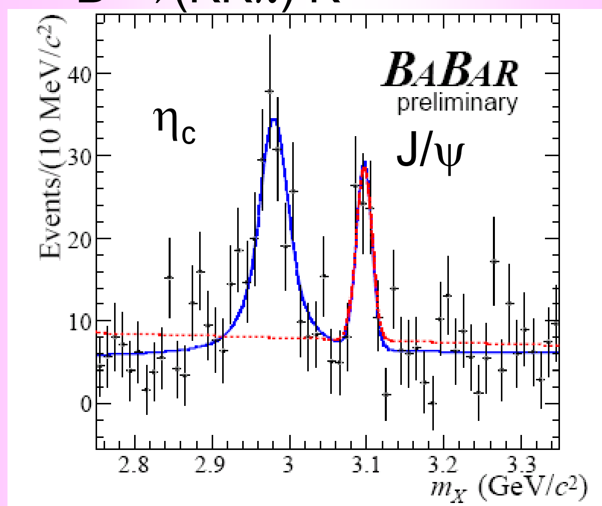
Prediction: $h_c, \chi_{c0}, \chi_{c2}$ + K(*) as copious as χ_{c1} + K(*)

χ_{c0} + K(*) ~ 10^{-4} ✓

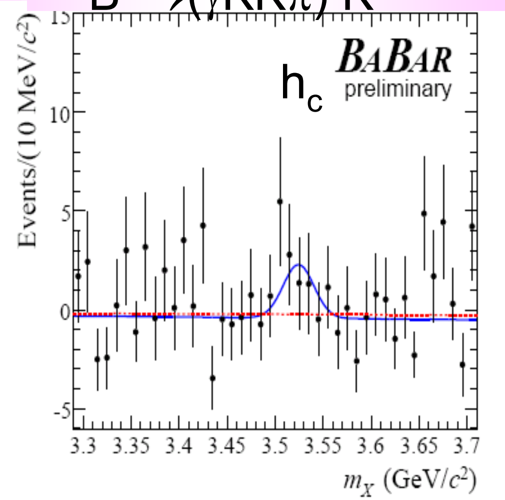
χ_{c2}, h_c + K(*): UL ~ 10^{-5} ✗

Godwin et al., PRD 51, 1125 (1995)

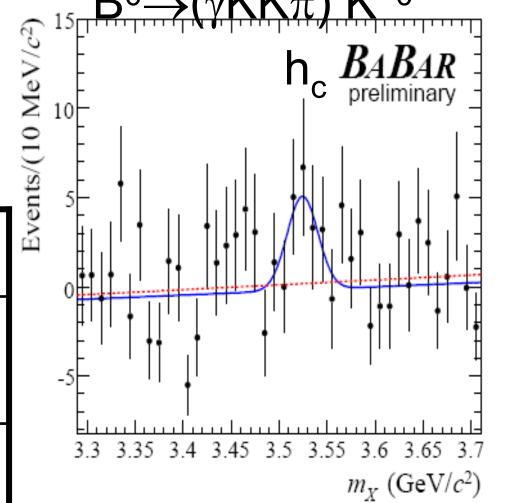
$B^0 \to (KK\pi)\, K^{*0}$



$B^+ \to (\gamma KK\pi)\, K^+$



$B^0 \to (\gamma KK\pi)\, K^{*0}$



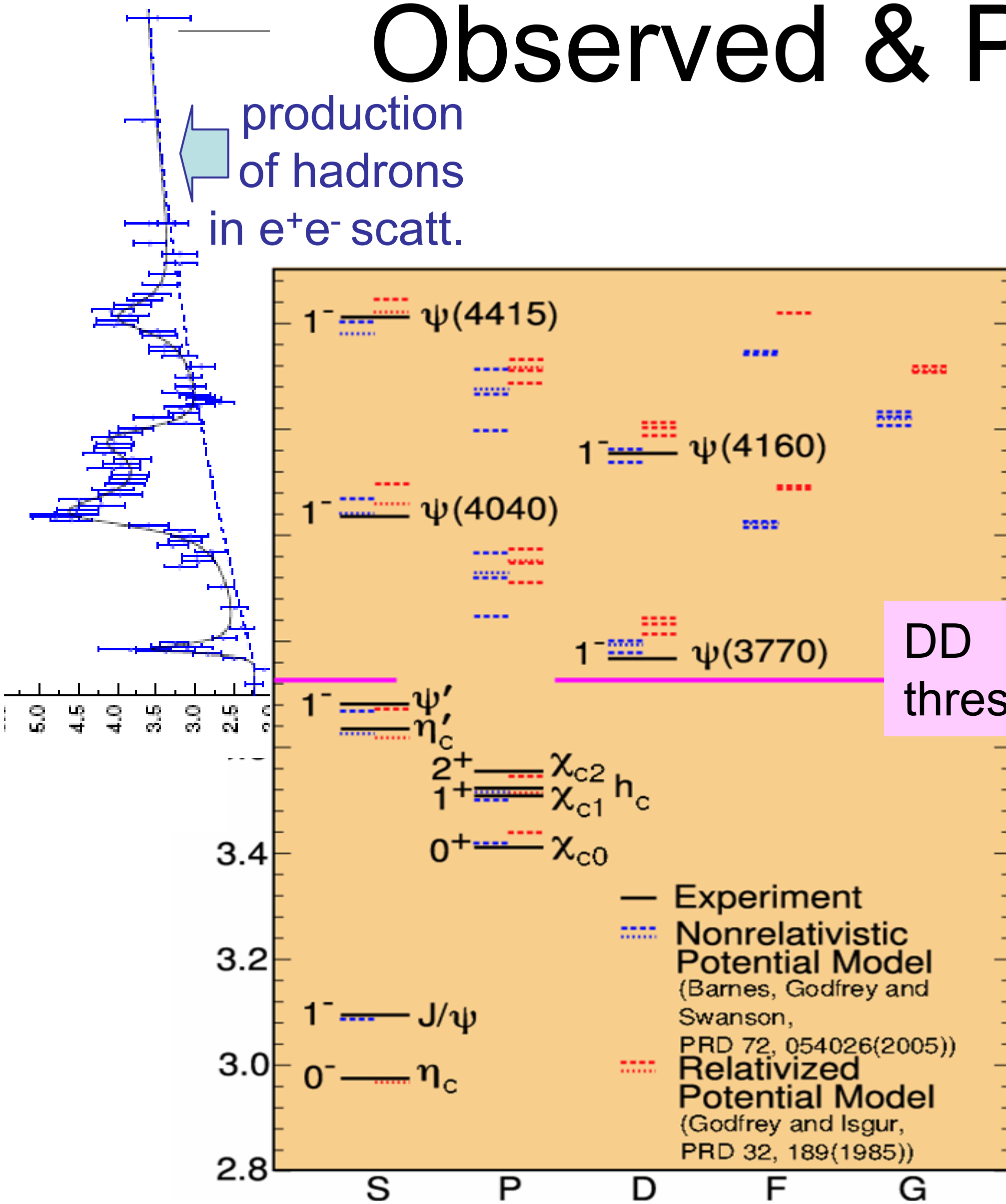
$m(KK\pi(\gamma))$ spectra after subtraction of background

BaBar preliminary

Uncertainty reduced by 50%	$\eta_c K^{*0}$	$(6.1 \pm 0.8 \pm 0.8 \pm 0.9)$	$\times 10^{-4}$
confirms Belle	$h_c K^+ \times$ $h_c \to \eta_c\gamma$	<5.2	$\times 10^{-5}$
First limit	$h_c K^{*0} \times$ $h_c \to \eta_c\gamma$	<2.41	$\times 10^{-4}$

Confirms h_c suppression in B decays

Observed & Predicted States

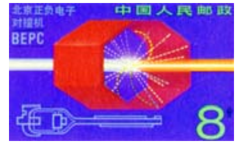


production of hadrons in e^+e^- scatt.

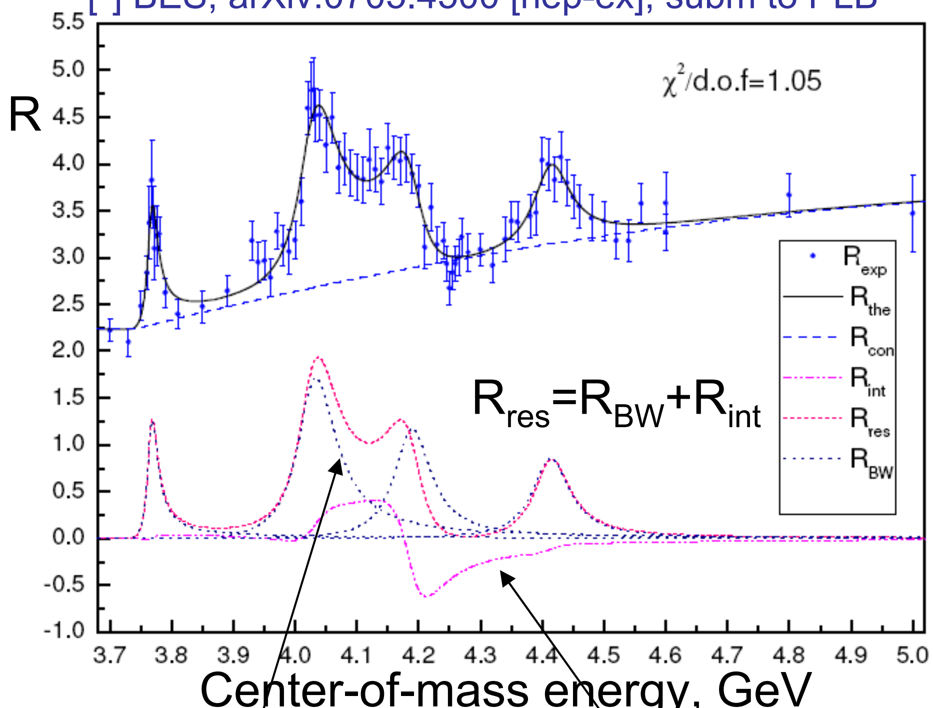
DD threshold

Mass of charmonium states (GeV)

States not accessible in e^+e^- can be reached through transitions, in $p\bar{p}$, or in $\gamma\gamma$ production – a systematic approach to identify the missing states is needed.

Re-analysis of  R data and extraction of charmonium resonance parameters

[*] BES, arXiv:0705.4500 [hep-ex], subm to PLB



Resonance shapes

Interference term

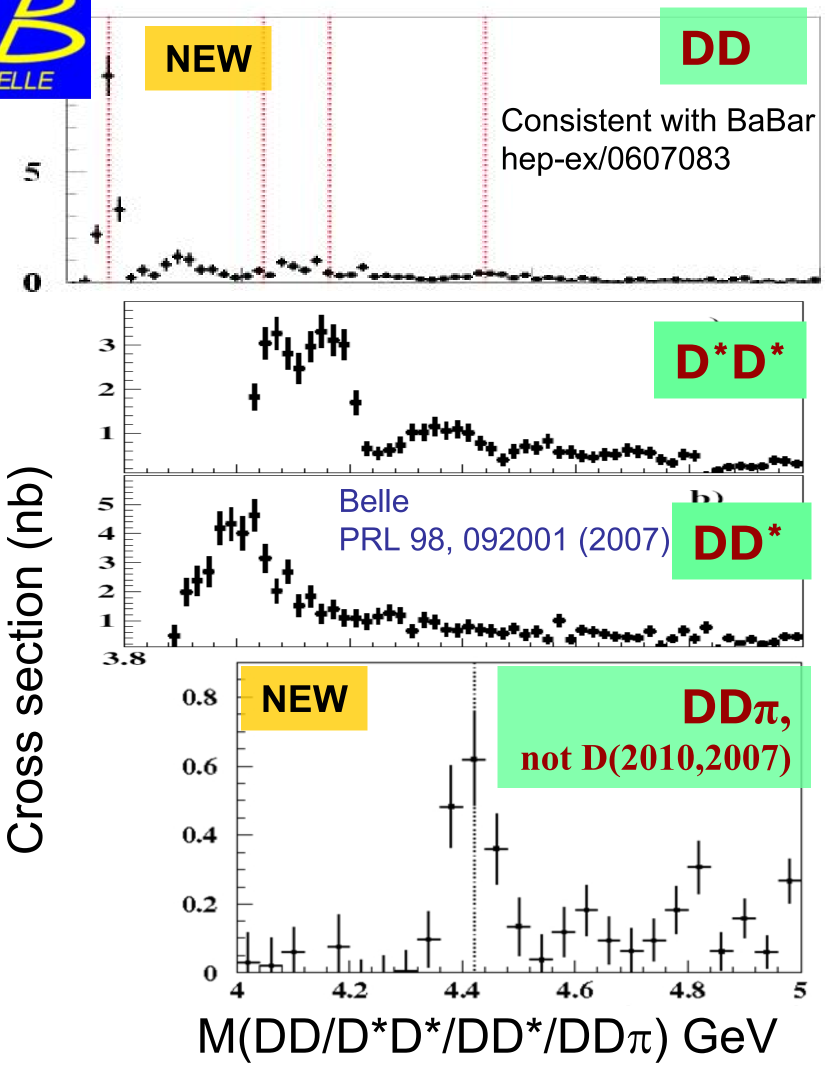
Resonance properties:

		$\psi(3770)$	$\psi(4040)$	$\psi(4160)$	$\psi(4415)$
M (MeV/c^2)	PDG2004	3769.9±2.5	4040±10	4159±20	4415±6
	PDG2006	3771.1±2.4	4039±1.0	4153±3	4421±4
	CB (Seth)	-	4037±2	4151±4	4425±6
	BES (Seth)	-	4040±1	4155±5	4455±6
	BES (this work)	3771.4±1.8	4038.5±4.6	4191.6±6.0	4415.2±7.5
Γ_{tot} (MeV)	PDG2004	23.6±2.7	52±10	78±20	43±15
	PDG2006	23.0±2.7	80±10	103±8	62±20
	CB (Seth)	-	85±10	107±10	119±16
	BES (Seth)	-	89±6	107±16	118±35
	BES (this work)	25.4±6.5	81.2±14.4	72.7±15.1	73.3±21.2
Γ_{ee} (keV)	PDG2004	0.26±0.04	0.75±0.15	0.77±0.23	0.47±0.10
	PDG2006	0.24±0.03	0.86±0.08	0.83±0.07	0.58±0.07
	CB (Seth)	-	0.88±0.11	0.83±0.08	0.72±0.11
	BES (Seth)	-	0.91±0.13	0.84±0.13	0.64±0.23
	BES (this work)	0.18±0.04	0.81±0.20	0.50±0.27	0.37±0.14
δ (degree)	BES (this work)	0	133±68	301±61	246±86

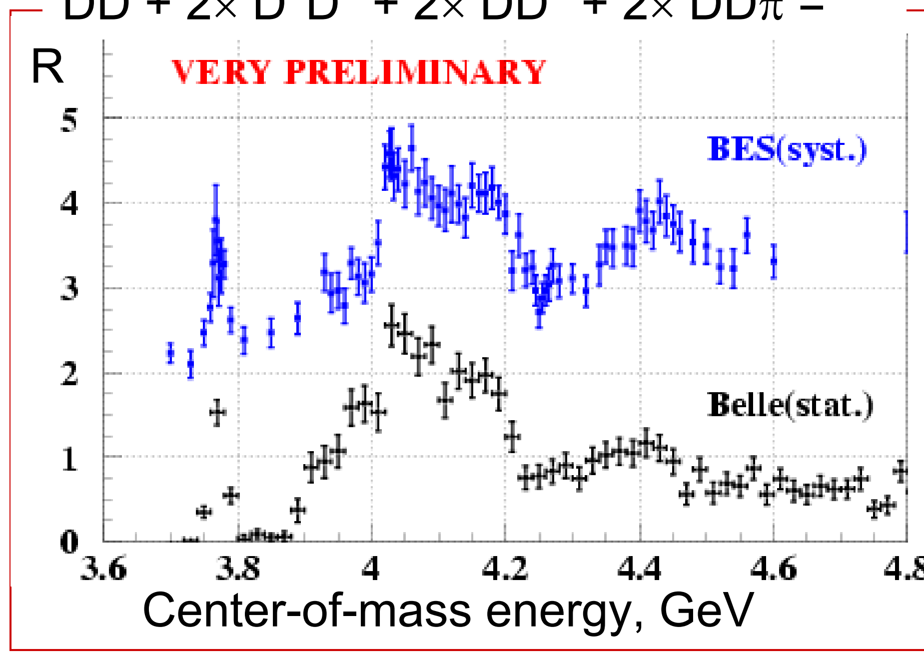
Substantial difference between fits with or without interference!

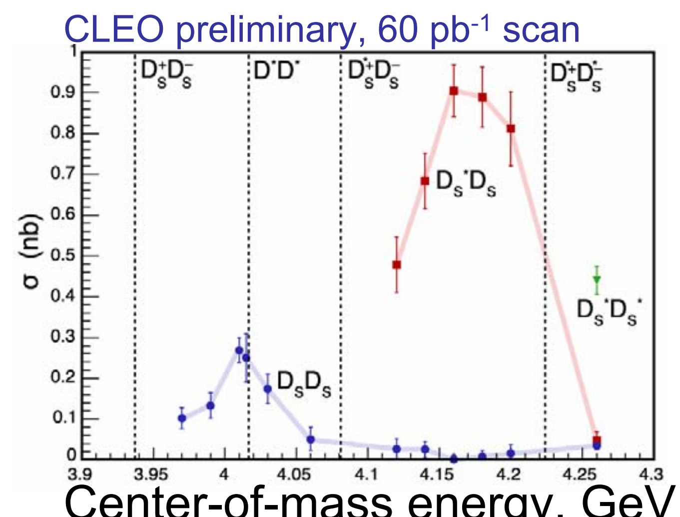
Contributions to the inclusive hadronic cross-section at 4-5GeV

P. Pakhlov, talk at this conference



DD + 2× D*D* + 2× DD* + 2× DDπ =



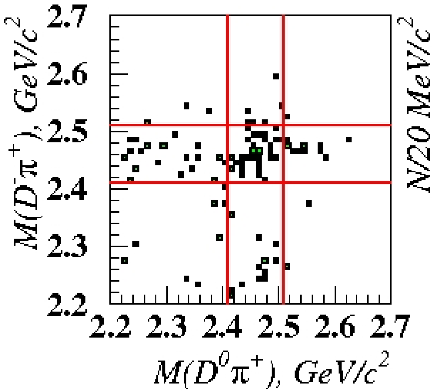


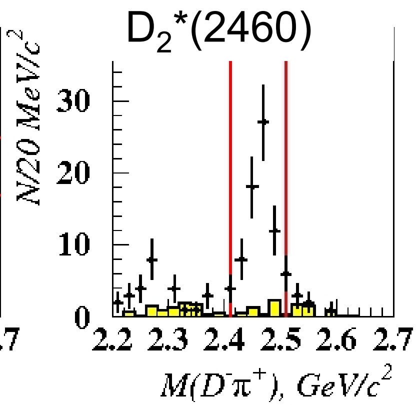
What else is there:

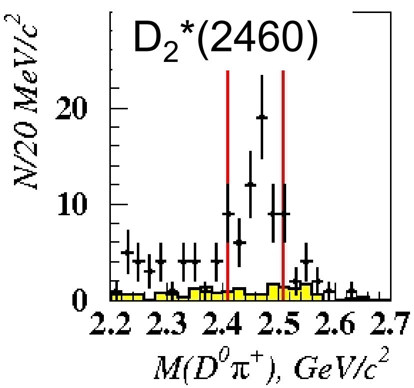
* charmonium production in the continuum, $\mathcal{O}$(pb)
* D_s production ....➝
* other DDnπ rates (non-resonant)
* Charm baryons

P. Pakhlov, talk at this conference

Resonant structure in $\psi(4415) \to DD\pi$







$M(D^0\pi^+)$ vs $M(D^-\pi^+)$ from **$\psi(4415)$** region

(D(2010,2007) vetoed)

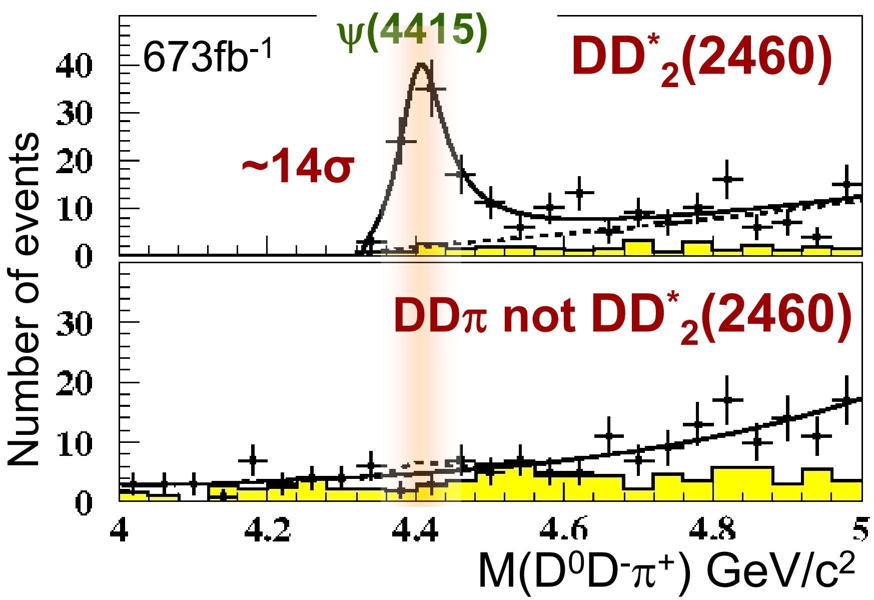
- Clear **$D^*_2(2460)$** signals
- Positive interference
- **Non $D^*_2(2460)$** contribution **smooth**
- **1^{st} exclusive decay mode of $\psi(4415)$**

$M = 4411 \pm 7 \pm 3$ MeV

$\Gamma_{tot} = 77 \pm 20 \pm 12$ MeV

$N_{ev} = 109 \pm 25 \pm 11$

Consistent with BES, hep-ex/0705.4500, PDG06, Barnes at.al PRD72,054026 (2005)



$\sigma(e^+e^- \to \psi(4415)) \times Br(\psi(4415) \to DD^*_2(2460)) \times Br(D^*_2(2460) \to D\pi) = (0.74 \pm 0.17 \pm 0.07)nb$

$Br(\psi(4415) \to D(D\pi)_{non\ D2(2460)}) / Br(\psi(4415) \to DD^*_2(2460)) < 0.2$

Above DD threshold:

Observed & Predicted States

X(4350)

Y(4260) in ISR and e^+e^-

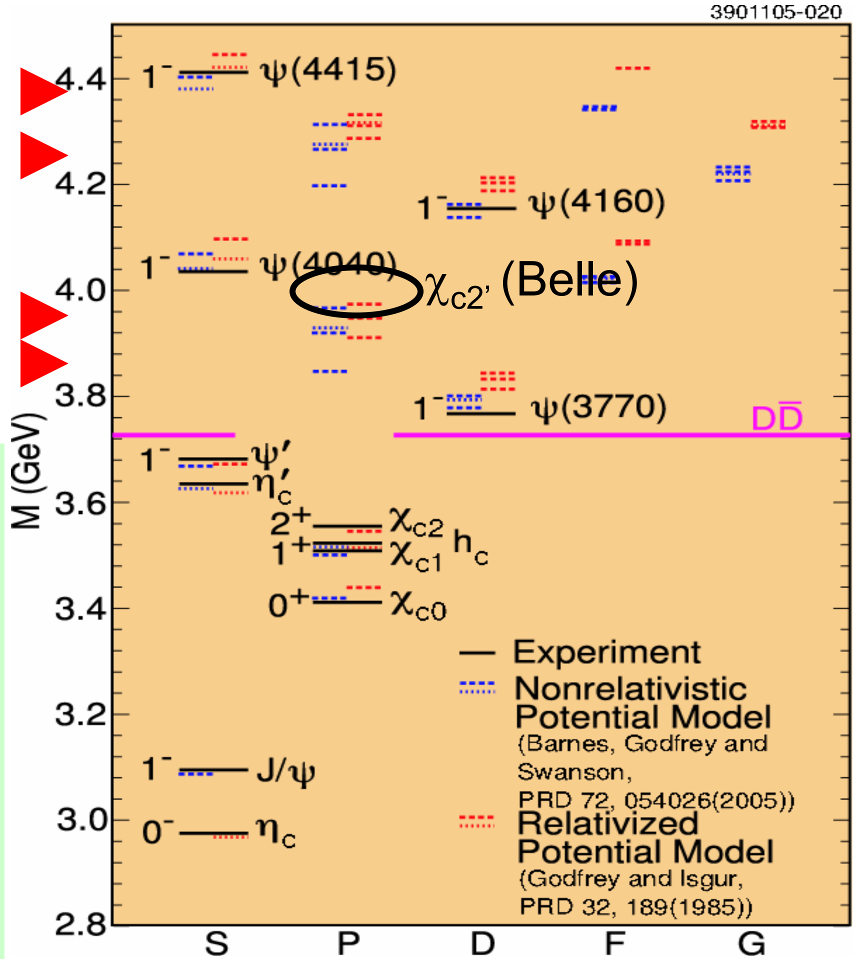
X(3940)→D*D in $c\underline{c}$ J/ψ,

Y(3940) in B→ ωJ/ψ

BaBar: Talk by G. Cibinetto

CLEO: PRL 98, 092002 (2007)

X(3872)



Many charmonium-like states found, most could not be identified with a charmonium state (or have been ruled out as conventional $c\bar{c}$ state)

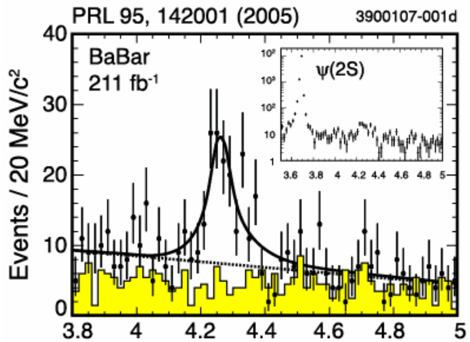
in order to claim new $c\bar{c}$ state, need to "prove" quantum numbers – angular distributions, decay modes, …

Need systematic approach from several fronts

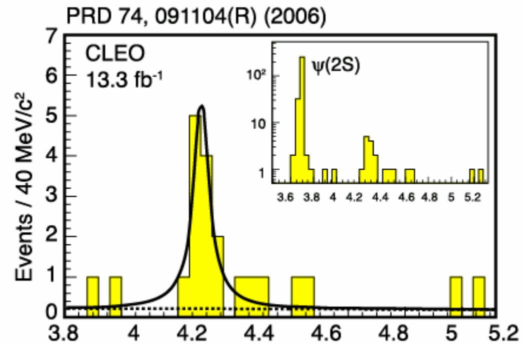
$J/\psi, \psi(2S)\pi^+\pi^-$ States

Reminder:

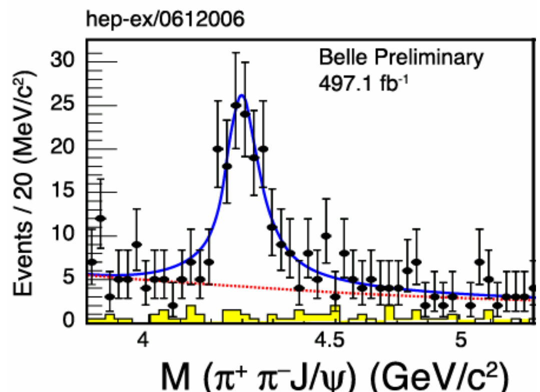
$Y(4260) \to J/\psi\ \pi^+\pi^-$ seen in ISR by BaBar,



CLEO,

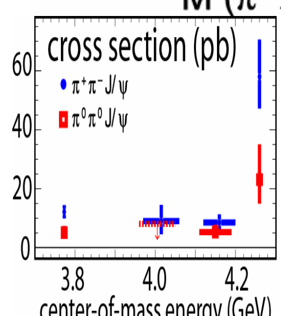


Belle:



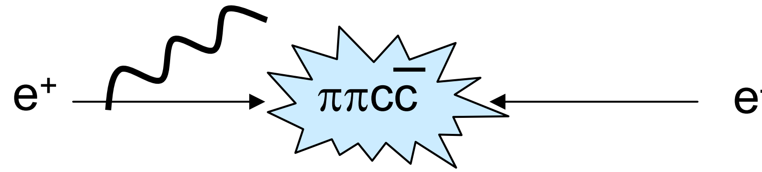
Simplest fit to peak uses single Breit-Wigner shape, multiple reonances possible

$J/\psi\ \pi^+\pi^-$, $J/\psi\ \pi^0\pi^0$, $J/\psi\ K^+K^-$, and more CLEO PRL 96, 162003 (2006)



2005/2006

Initial state radiation:



Quantities of interest:

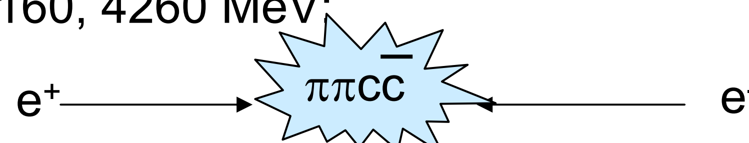
Mass

Width

Decay BR's to different final states and ratios

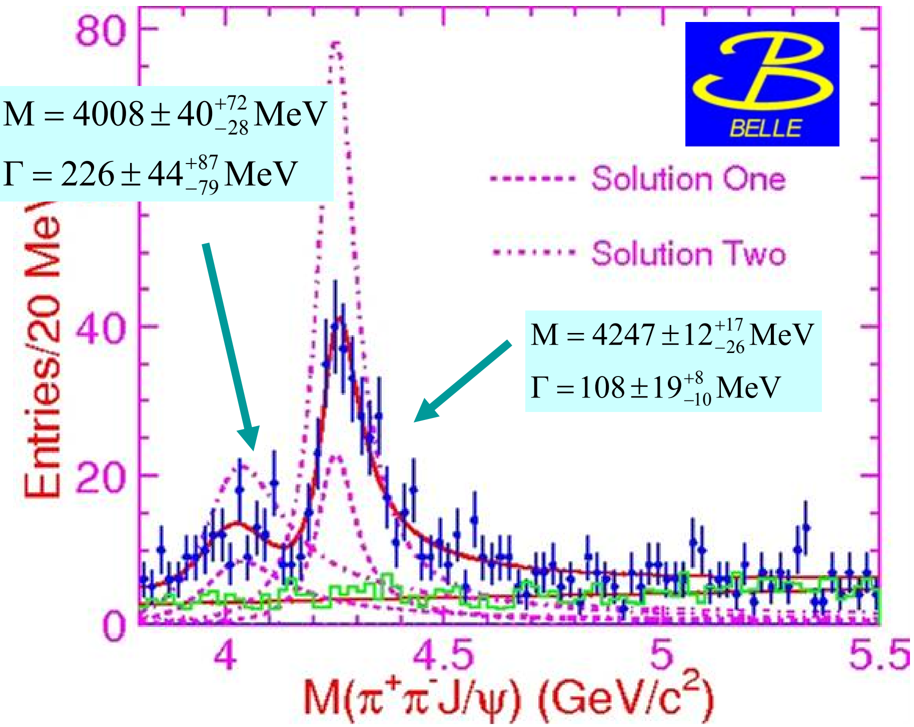
$M(\pi\pi)$ distribution

Direct production at 3770, 4040, 4160, 4260 MeV:



$J/\psi+\pi^+\pi^-$ in Initial State Radiation

550/fb



Quantities of interest:
mass, width, coupling

New fit to improve low-side description:
two overlapping resonances and
constructive / destructive interference

Parameters	Solution One	Solution Two
$M(R1)$	$4008 \pm 40^{+72}_{-28}$	
$\Gamma_{tot}(R1)$	$226 \pm 44^{+87}_{-79}$	
$\mathcal{B} \cdot \Gamma_{e^+e^-}(R1)$	$5.0 \pm 1.4^{+5.6}_{-0.9}$	$12.4 \pm 2.4^{+11.9}_{-1.1}$
$M(R2)$	$4247 \pm 12^{+17}_{-26}$	
$\Gamma_{tot}(R2)$	$108 \pm 19^{+8}_{-10}$	
$\mathcal{B} \cdot \Gamma_{e^+e^-}(R2)$	$6.0 \pm 1.2^{+1.7}_{-0.5}$	$20.6 \pm 2.3^{+4.9}_{-1.7}$
ϕ	$12 \pm 29^{+7}_{-66}$	$-111 \pm 7^{+28}_{-29}$

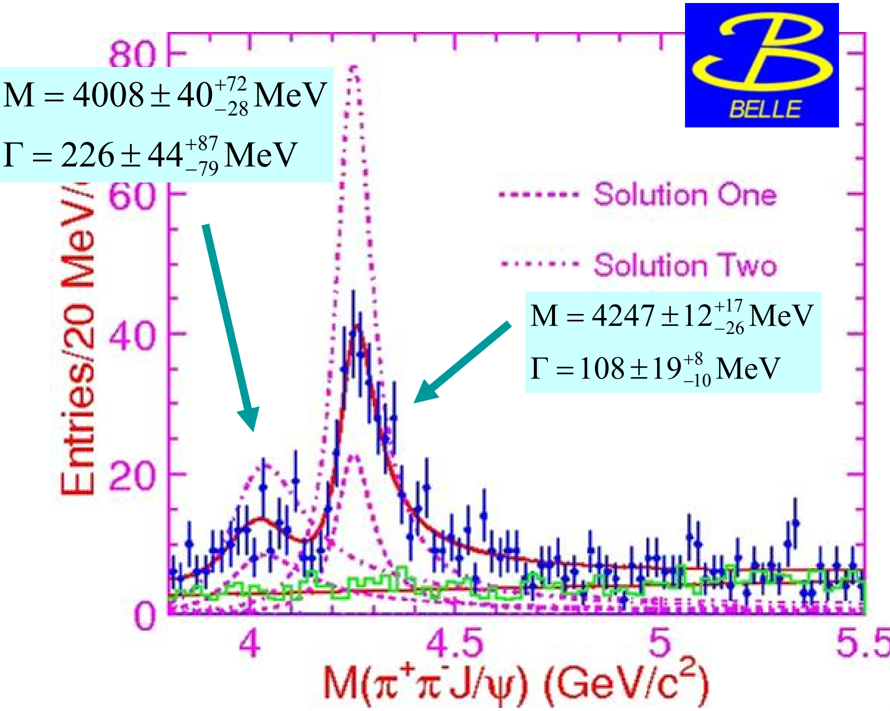
Earlier results, single BW fit:

Refs see end of talk	Mass, MeV	Width, MeV
BaBar	4259^{+8}_{-10}	88 ± 23
CLEO	4284 ± 17	73^{+39}_{-25}
Belle old	4295^{+14}_{-10}	133 ± 26
Belle new	4263 ± 6(st)	126 ± 18(st)

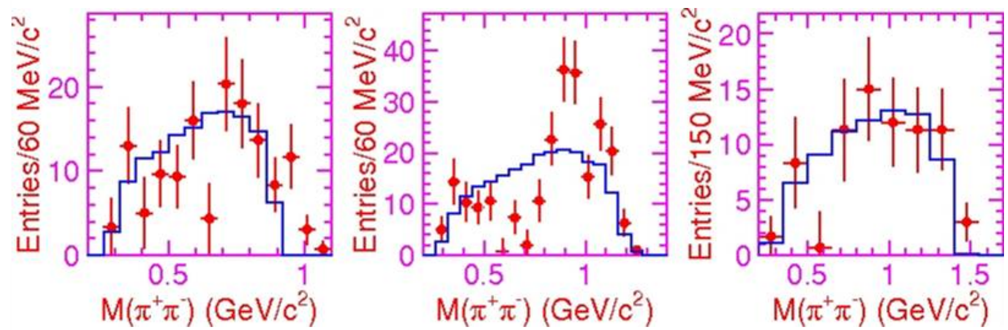
2 solutions reproduce
the data (same m,Γ), but
$B(Y(4260)\to\pi\pi J/\psi) \times\Gamma_{ee}$
a factor of 3.5 apart!

(cont'd) $J/\psi+\pi^+\pi^-$ in Initial State Radiation

Fit input: assume two overlapping resonances
$\Rightarrow$ 2 solutions reproduce the data (same m,Γ)
$B(Y(4260)\to\pi\pi J/\psi)\times\Gamma_{ee}$ a factor of 3.5 apart!



below | 4.2-4.4 GeV | above

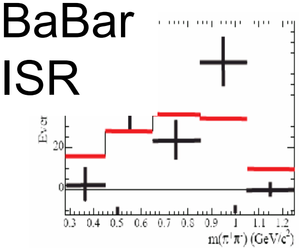


MC:

Belle, BaBar: 3body phase space

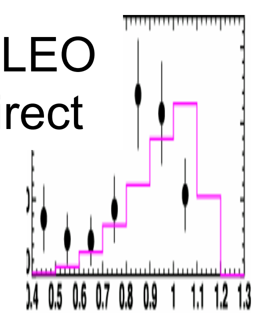
CLEO: like $\psi(2S)\to\pi\pi J/\psi$

BaBar ISR



PRL 95, 142001 (2005)

CLEO direct

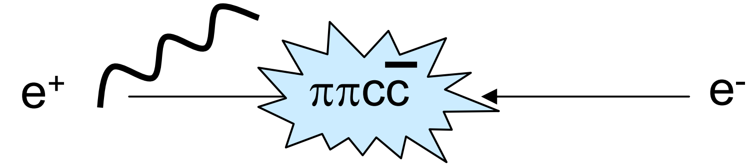


PRL 96, 162003 (2006)

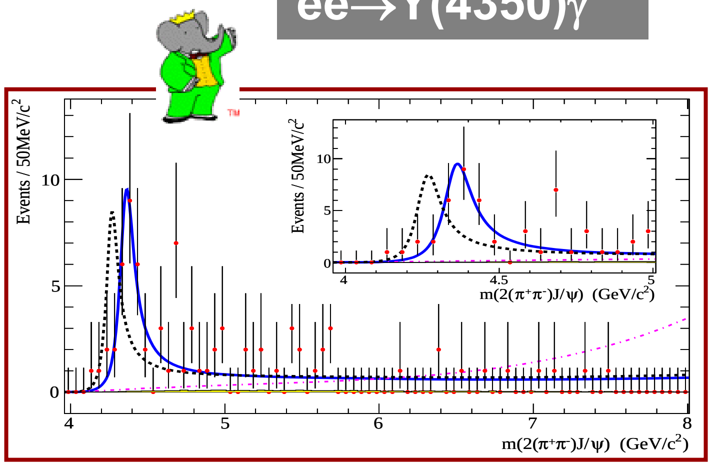
M($\pi\pi$) (GeV)

M($\pi\pi$) distribution distinctly different for Y(4260) signal region than for sidebands

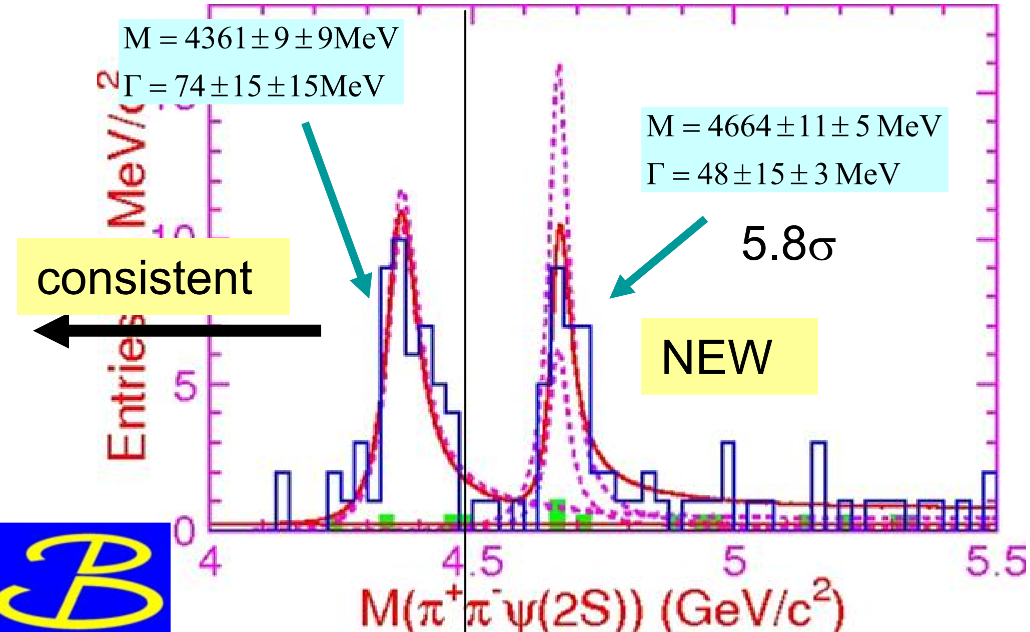
$\psi(2S)+\pi^+\pi^-$ in Initial State Radiation



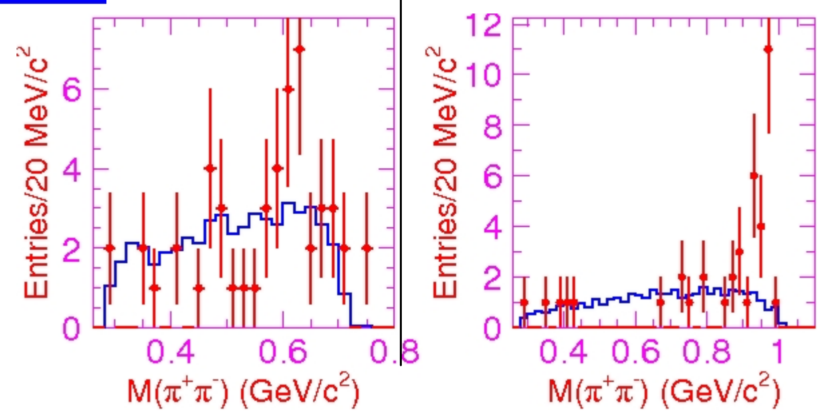
ee→Y(4350)γ



Phys. Rev. Lett. 98, 212001 (2007)

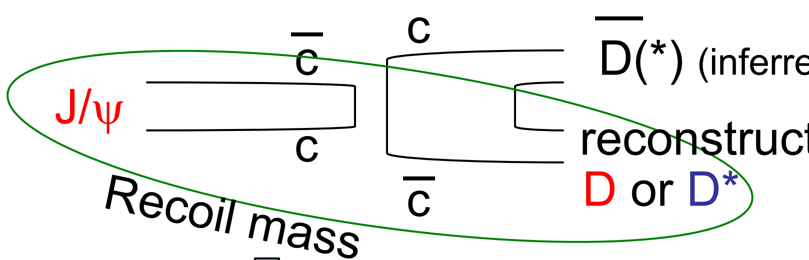


Parameters	Solution one	Solution two
$M(Y(4360))$	$4361 \pm 9 \pm 9$	
$\Gamma_{\rm tot}(Y(4360))$	$74 \pm 15 \pm 10$	
$\mathcal{B}\cdot\Gamma_{e^+e^-}(Y(4360))$	$10.4 \pm 1.7 \pm 1.5$	$11.8 \pm 1.8 \pm 1.4$
$M(Y(4660))$	$4664 \pm 11 \pm 5$	
$\Gamma_{\rm tot}(Y(4660))$	$48 \pm 15 \pm 3$	
$\mathcal{B}\cdot\Gamma_{e^+e^-}(Y(4660))$	$3.0 \pm 0.9 \pm 0.3$	$7.6 \pm 1.8 \pm 0.8$
ϕ	$39 \pm 30 \pm 22$	$-79 \pm 17 \pm 20$



$e^+e^- \rightarrow J/\psi\ D^{(*)}D^{(*)}$

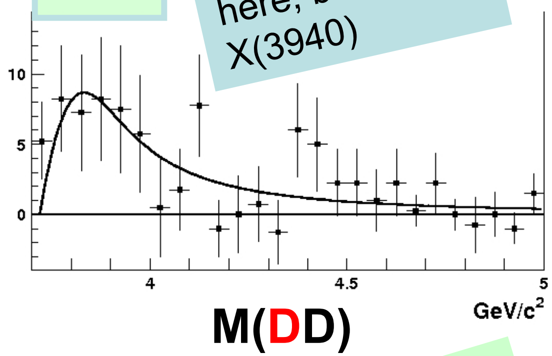
Obtain J/ψ+D(*)D(*) samples through kinematic separation, look at m(D(*)D(*)) after background subtraction:



M = 3942 ±6 MeV
Γ_{tot} =37 ±12 MeV
N_{ev}= 52 ±11

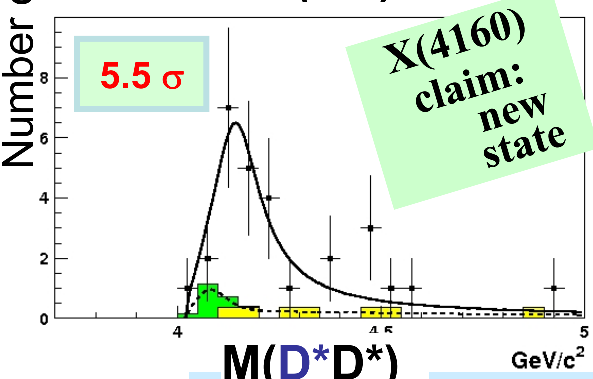
3.8 σ

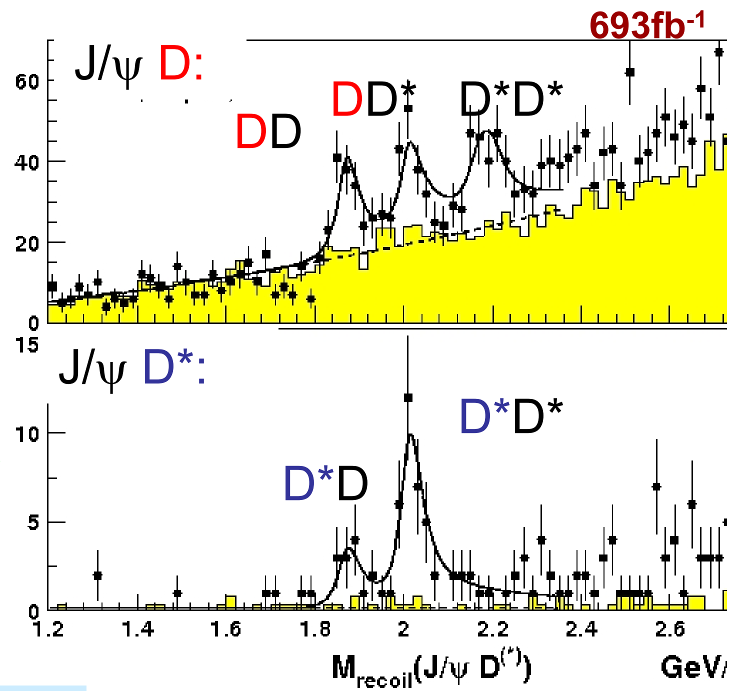
Something's here, but it's not X(3940)



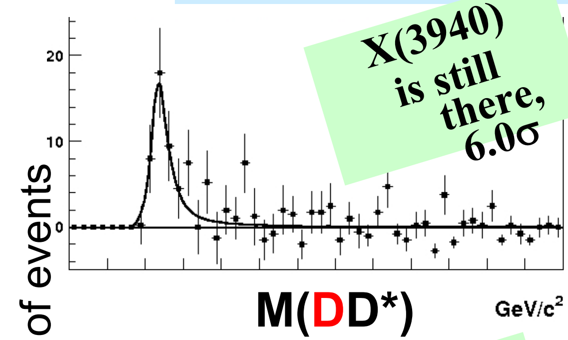
5.5 σ

X(4160) claim: new state

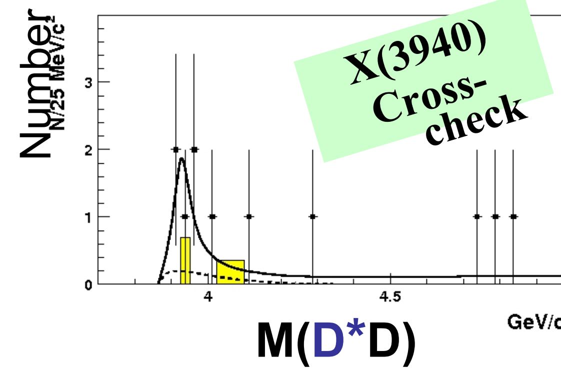




X(3940) is still there, 6.0σ



X(3940) Cross-check



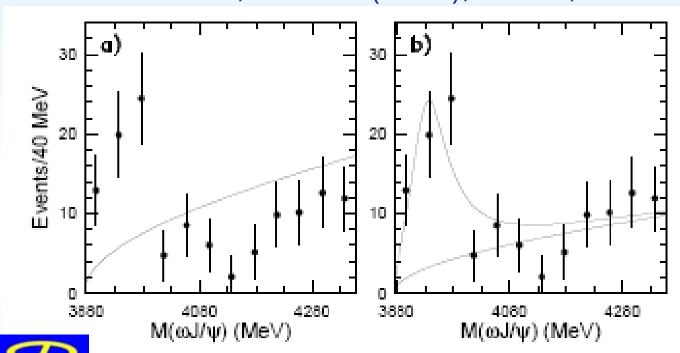
M = 4156 $^{+25}_{-20}$ ±15MeV
Γ_{tot} = 37 $^{+111}_{-61}$ ±21MeV
N_{ev}= 24 $^{+12}_{-8}$

P. Pakhlov,
talk at this conference,

Confirmation of Y(3940) ($B \to K\omega J/\psi$)

$\omega \to \pi^+\pi^-\pi^0$

Belle PRL 94, 182002 (2005), 253/fb, >8σ

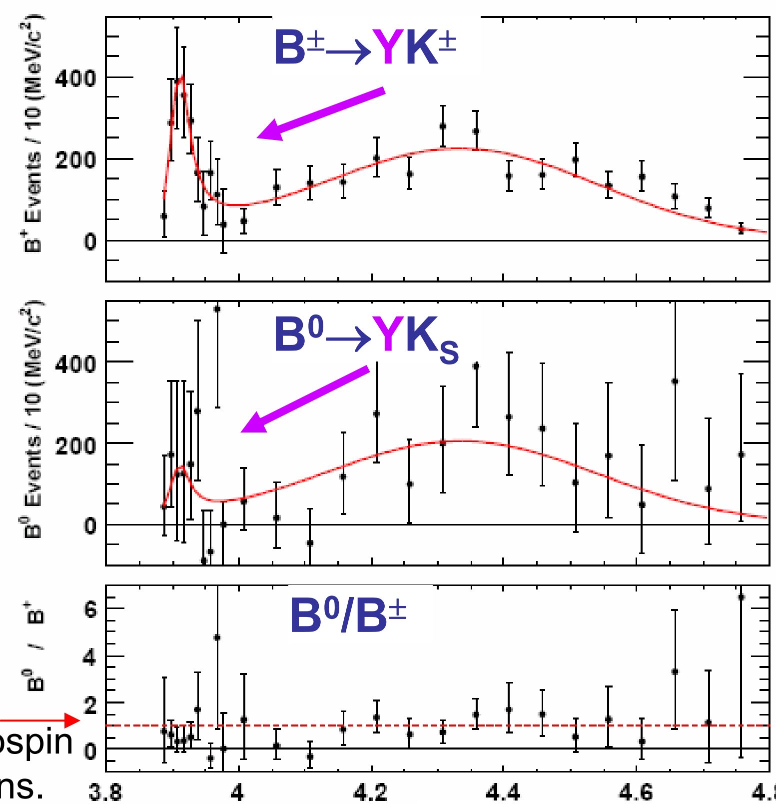


M=3943±11±13 MeV

Γ=87±22±26 MeV

Unexplained state; mass and width compatible with radially excited P-wave cc state, but decay to hidden charm

preliminary



Isospin cons.

M(J/ψ ω) (GeV)

New result, based on 350 fb^{-1}:

$$M(Y) = (3914.3^{+3.8}_{-3.4}(stat)^{+1.6}_{-1.6}(syst))\ \mathrm{MeV/c^2}\,,$$
$$\Gamma(Y) = (33^{+12}_{-8}(stat)^{+0.6}_{-0.6}(syst))\ \mathrm{MeV}\,.$$

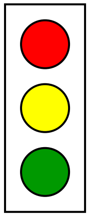
Belle's evidence for $B \to YK$, $Y \to J/\psi\omega$ confirmed

- ~30MeV lower mass than Belle's
- Narrower width
- Preliminary BF estimate similar to Belle's (~10^{-5})

Q=c,b

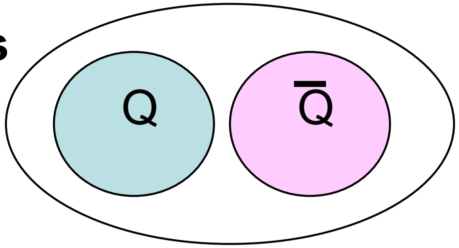
q=u,d,s

Overview



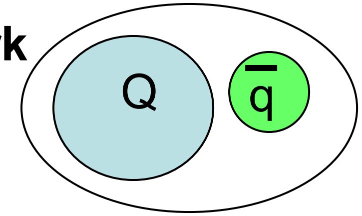
General goal:
Explore QCD phenomena
at different scales

Two heavy quarks



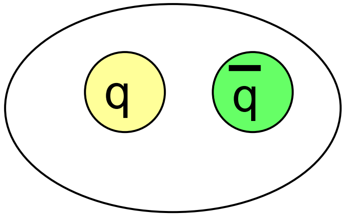
$\psi(2S)$ width
J/ψ, χ_{cJ} decay to light q
B decay to charmonium
States above DD threshold
Charmonium-like states

One heavy quark



$D_{s1}(2536)^+ \rightarrow D^{*+}K^0_S$
$\Xi_c(3077)$, $\Xi_c(3123)$

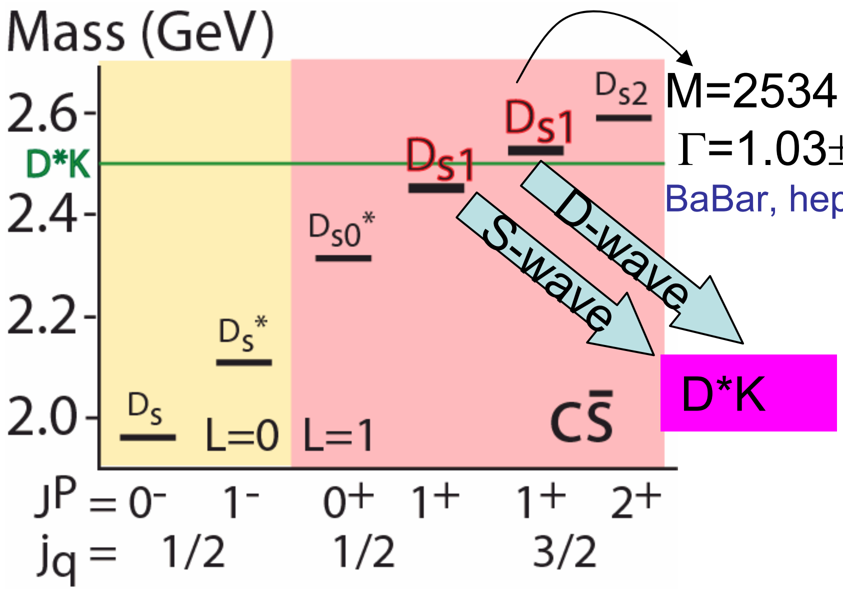
Zero heavy quarks



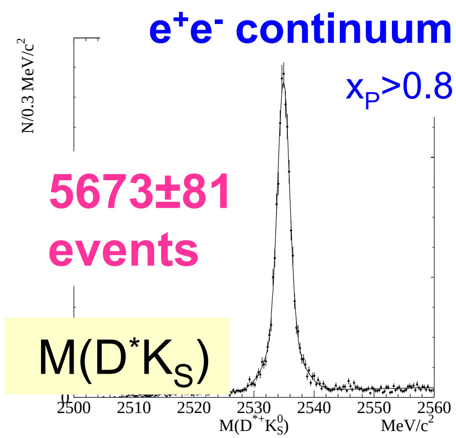
This talk: mostly mesons, but many new results on baryons as well. See list of topics at the end.

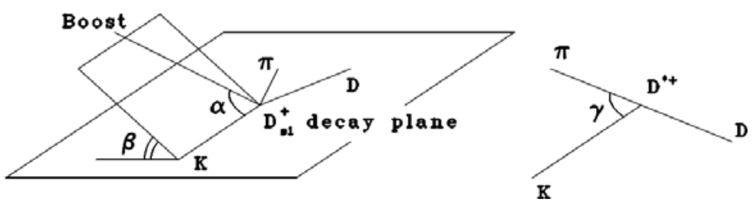
Partial Wave Analysis of $D_{s1}(2536)^+ \rightarrow D^{*+}K^0_S$

V. Balagura,
this conference



M=2534.85±0.02±0.40 MeV
Γ=1.03±0.05±0.12 MeV
BaBar, hep-ex/0607084





$D_{s1}(2536)^+$: j=3/2 with small admixture of j=1/2

Energy release is small
→ D-wave decay to D^*K_S is suppressed
→ j=1/2 can be visible

3-D fit results

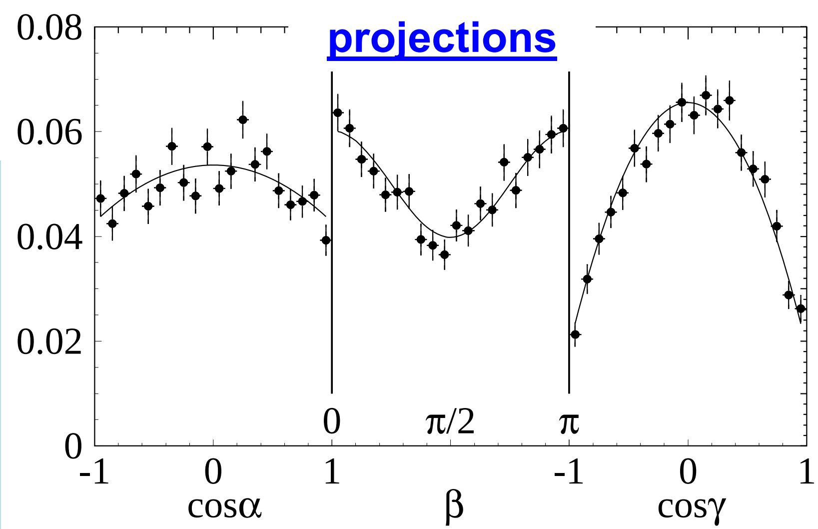
$$D/S = (0.63 \pm 0.07) \cdot \exp(\pm i \cdot (0.77 \pm 0.03))$$

$$\Gamma_S/\Gamma_{total} = 0.72 \pm 0.05$$

S-wave dominates

$$\rho_{00} = 0.490 \pm 0.013$$

ρ_{00} – longitudinal polarization



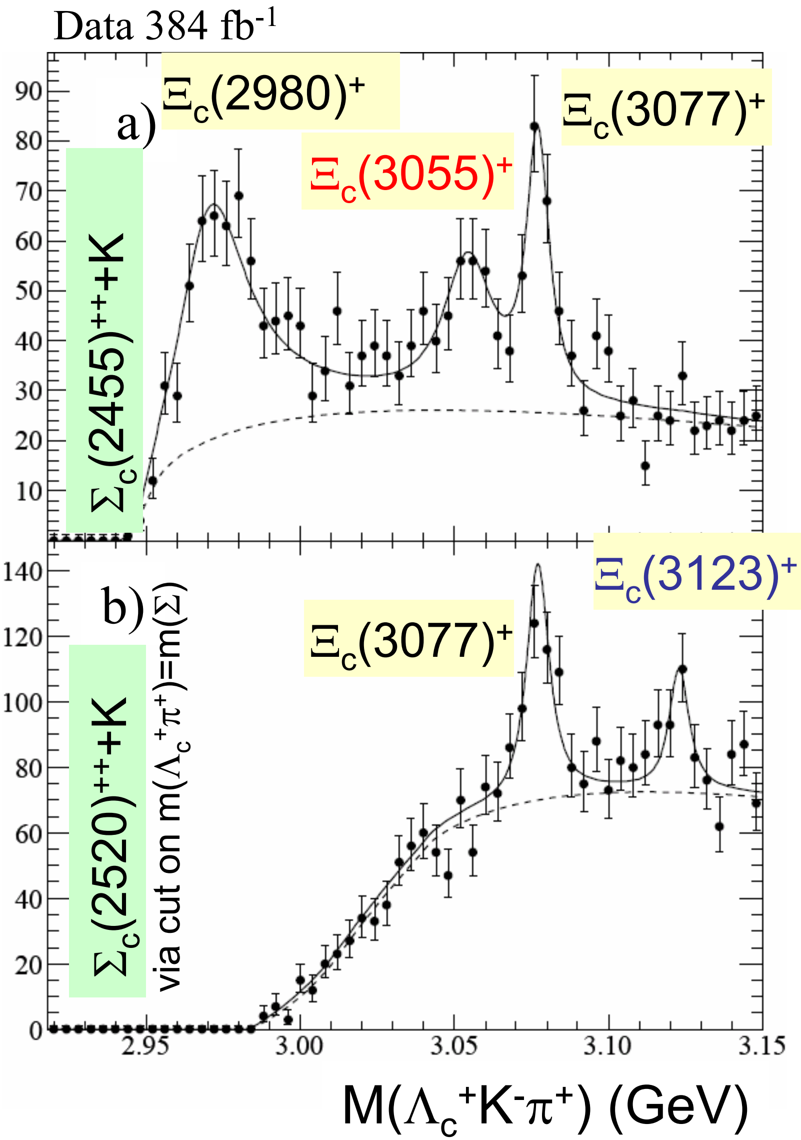
χ^2 difference between points and projected fit results corresponds to prob. 60%

T. Schroeder, talk at this conference

Excited charm-strange baryons

Search: cs baryons → Λ_c^++ K_S, K^-, $K^-\pi^+$, $K_S\pi^-$, $K_S\pi^-\pi^+$,$K^-\pi^-\pi^+$

preliminary



$\Xi_c(3055)^+$	
Mass (MeV/c^2)	3054.2 ± 1.2 ± 0.5
Width (MeV/c^2)	17 ± 6 ± 11
Yield	218 ± 53 ± 79
Significance	6.4σ

$\Xi_c(3123)^+$	
Mass (MeV/c^2)	3122.9 ± 1.3 ± 0.3
Width (MeV/c^2)	4.4 ± 3.4 ± 1.7
Yield	101 ± 34 ± 9
Significance	3.6σ

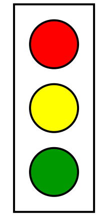
only observed in Σ_c^{++} K intermediate decays – c and s split up.

Further results:
confirmation of $\Xi_c(2980)^+$, $\Xi_c(3077)^{+,0}$
$\Xi_c(2980)^+$ mass and width measurements improved

Q=c,b

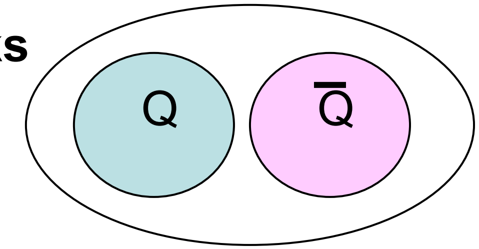
q=u,d,s

Overview



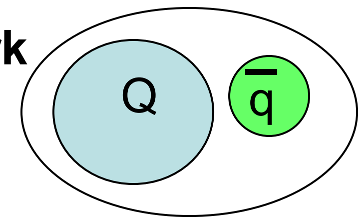
General goal:
Explore QCD phenomena
at different scales

Two heavy quarks



$\psi(2S)$ width
J/ψ, χ_{cJ} decay to light q
B decay to charmonium
States above DD threshold
Charmonium-like states

One heavy quark

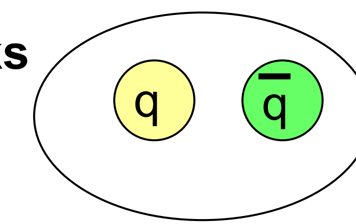


$D_{s1}(2536)^+ \rightarrow D^{*+} K^0_S$
$\Xi_c(3077)$, $\Xi_c(3123)$

Non-perturbative QCD

$a_0, f_0(980)$
η, η' mixing and glue in η'
η mass
$\eta(')$ decay
$K^{+-} \rightarrow \pi^+\pi^- e^{+-}\nu$, $\pi^{+-}\pi^0\pi^0$, $\pi^{\pm}\pi^0\gamma$

Zero heavy quarks



This talk: mostly mesons, but many new results on baryons as well. See list of topics at the end.

KLOE

$\phi \rightarrow \pi^0\pi^0\gamma$

Goal: Understand low-mass dimeson behavior; here: $\pi\pi$,KK.

EPJ C49 (2007) 473

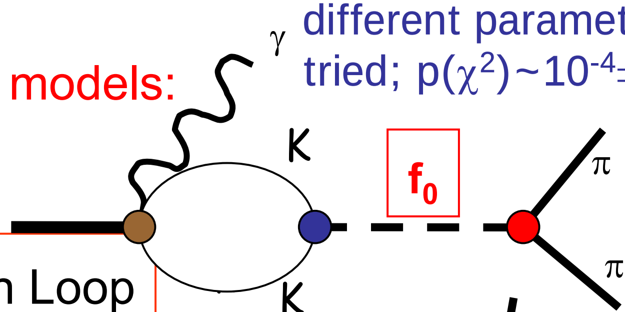
Context: Low-mass broad $\pi\pi$, $K\pi$ systems are "everywhere": π+K/π scattering, K decay, D decay, ...

"σ,κ" (low-mass $\pi\pi/K\pi$ S-wave), $a_0(980)\rightarrow\eta\pi^0$, **$f_0(980)$**$\rightarrow\pi^+\pi^-$,$\pi^0\pi^0$, K^+K^-, K^0K^{0bar}

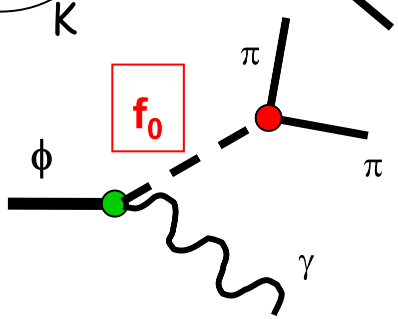
Parameters? Nature?

Fit needs $\phi \rightarrow \sigma(500)\gamma$, different parametrizations tried; $p(\chi^2)$~$10^{-4}\Rightarrow$14%

Two fit models:

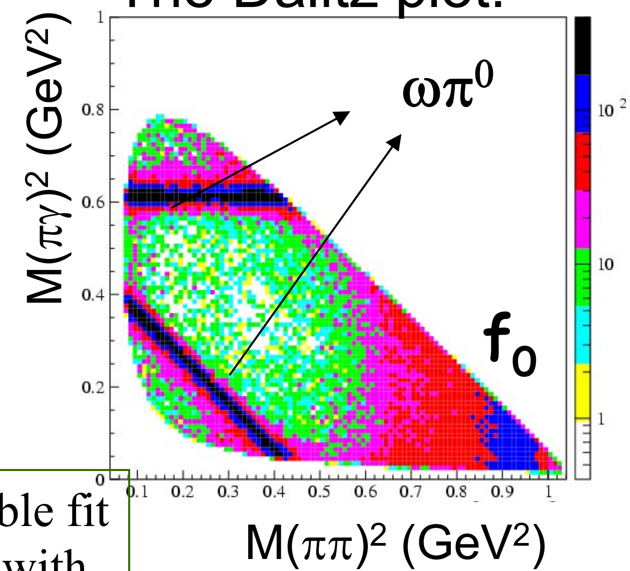


Kaon Loop



No Structure

The Dalitz plot:



Result 1:

An acceptable fit is obtained with both models:
$P(\chi^2)$(KL)=14%
$P(\chi^2)$(NS)= 4%

Result 2:

List of couplings for both models

Result 3:

BR($\phi \rightarrow \gamma f_0 \rightarrow \pi^0\pi^0\gamma$)

$$\left[1.07^{+0.01}_{-0.04}(fit)^{+0.04}_{-0.02}(syst)^{+0.06}_{-0.05}(mod)\right]\times10^{-4}$$

-- Also see $\phi\rightarrow\gamma f_0(980)\rightarrow\gamma\pi^+\pi^-$ and $\phi\rightarrow\gamma a_0(980)\rightarrow\gamma\eta\pi^0$ KLOE results

η/η' mixing; gluon content in the η'

$B(\phi\to\eta'\gamma) / B(\phi\to\eta\gamma) =$

$$(4.77 \pm 0.09_{stat.} \pm 0.19_{syst})\times 10^{-3}$$

Gives insight into η/η' mixing.

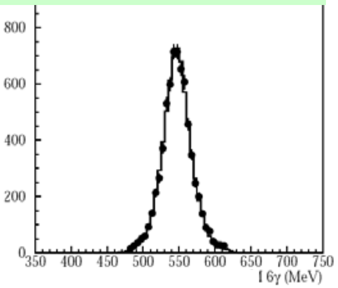
Assuming η'=uds only, no |gg>:

$\varphi_P = (41.4\pm0.3\pm0.7\pm0.6)^o$

$B(\phi\to\eta\gamma) = (1.301\pm0.024)\%$ from PDG

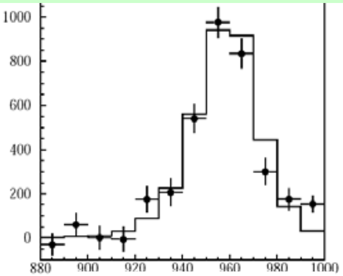
$B(\phi\to\eta'\gamma) = (6.20 \pm 0.09_{stat.} \pm 0.25_{syst.})\times 10^{-5}$

η signal (no bgd)



$M(6\gamma)$

η' signal (~10% bgd)



$M(6\gamma+\pi^+\pi^-)$

KLOE
PLB648 (2007) 267

Now allow η' to have |gg>:

$$|\eta> \;=\; cos(\varphi_p)|q\bar{q}> - sin(\varphi_p)|s\bar{s}>$$

$$|\eta'> = X_{\eta'}|q\bar{q}> + Y_{\eta'}|s\bar{s}> + Z_{\eta'}|gluon>$$

$$X_{\eta'} = \cos\phi_G \sin\varphi_P$$
$$Y_{\eta'} = \cos\phi_G \cos\varphi_P$$
$$Z_{\eta'} = \sin\phi_G$$

Mixes η,η'

Mixes gluonium into η'

Use SU(3) relations between modes involving $\pi^0,\omega,\rho,\eta,\eta'$ and measured branching ratios to obtain X,Y,Z(η') $\Rightarrow \phi_G,\ \varphi_P$

η' gluonium content

PLB648 (2007) 267

KLOE

Fit results

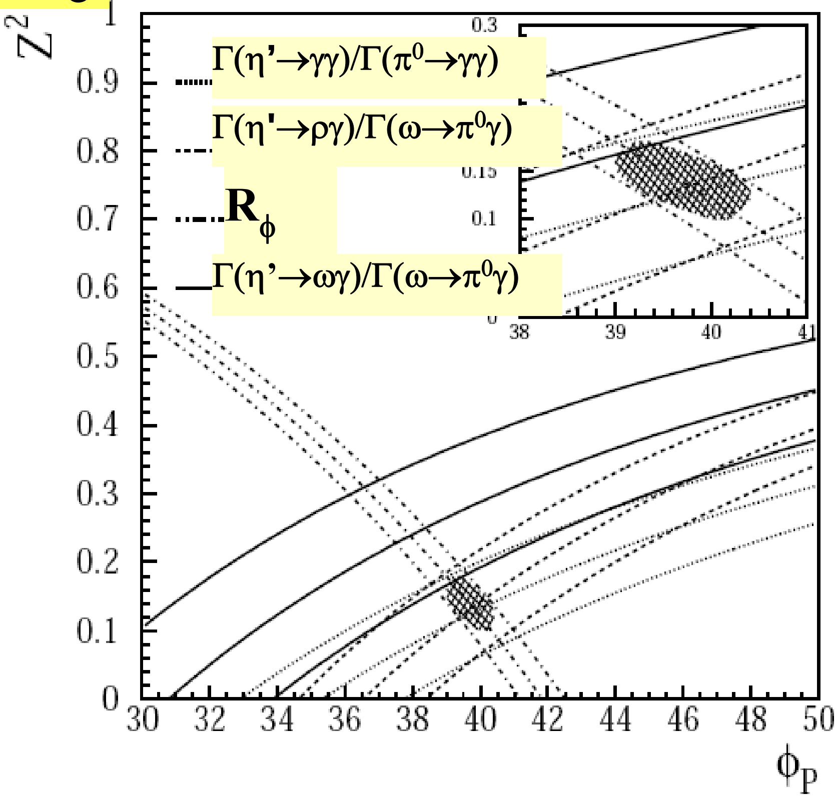
$\phi_P = (39.7 \pm 0.7_{tot})°$
$|\phi_G| = (22 \pm 3)°$

Gluonium coefficient:

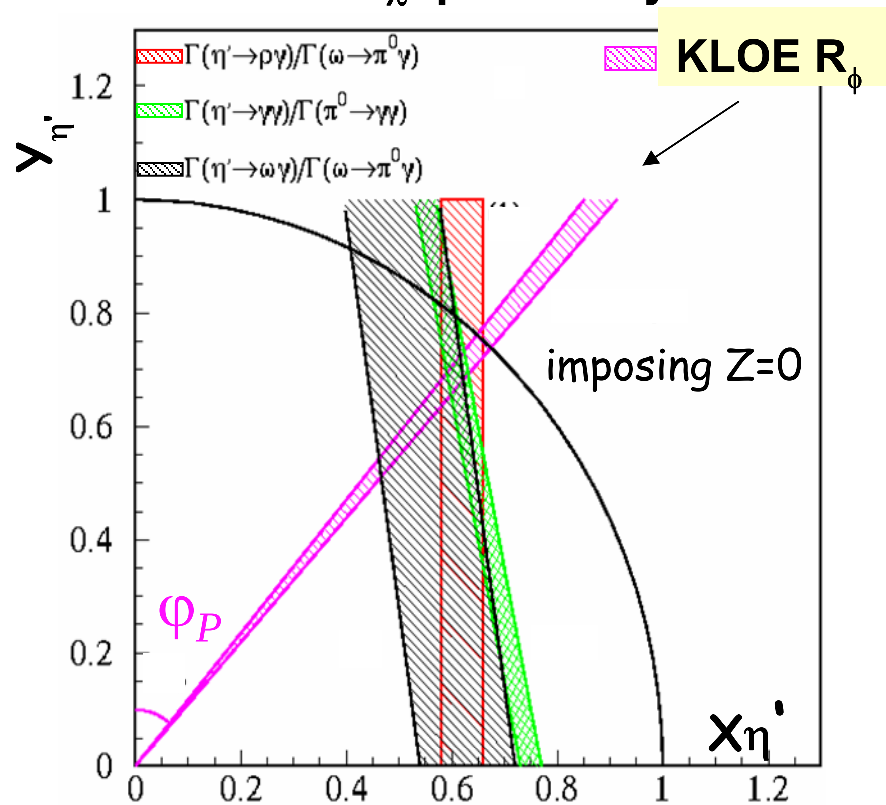
$\sin^2\phi_G = Z^2 = 0.14 \pm 0.04$

Sin ϕ_G

49 % χ^2 probability



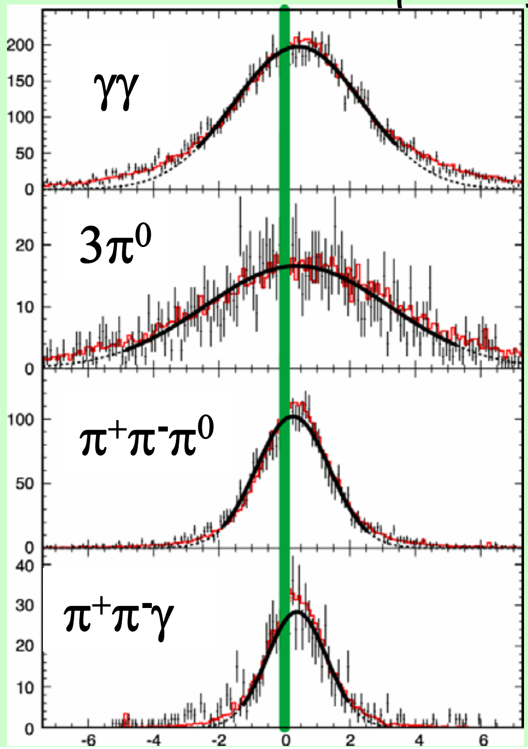
1 % χ^2 probability



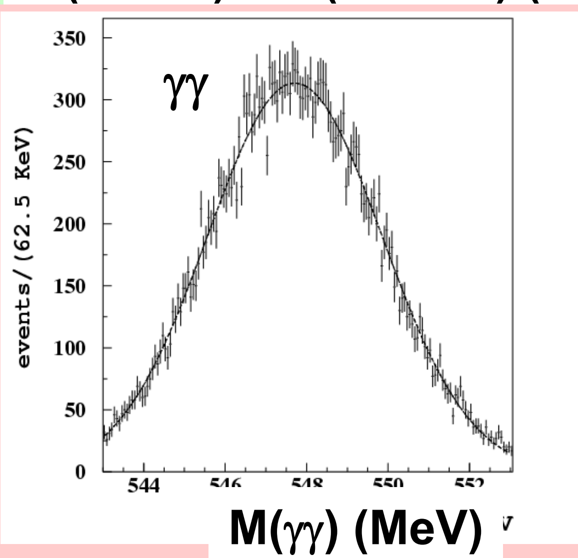
Bands – constraints from input branching fractions (depend on X,Y,Z(η') ⇒ ϕ_G, φ_P)

η Mass

Invariant mass of η decay products:



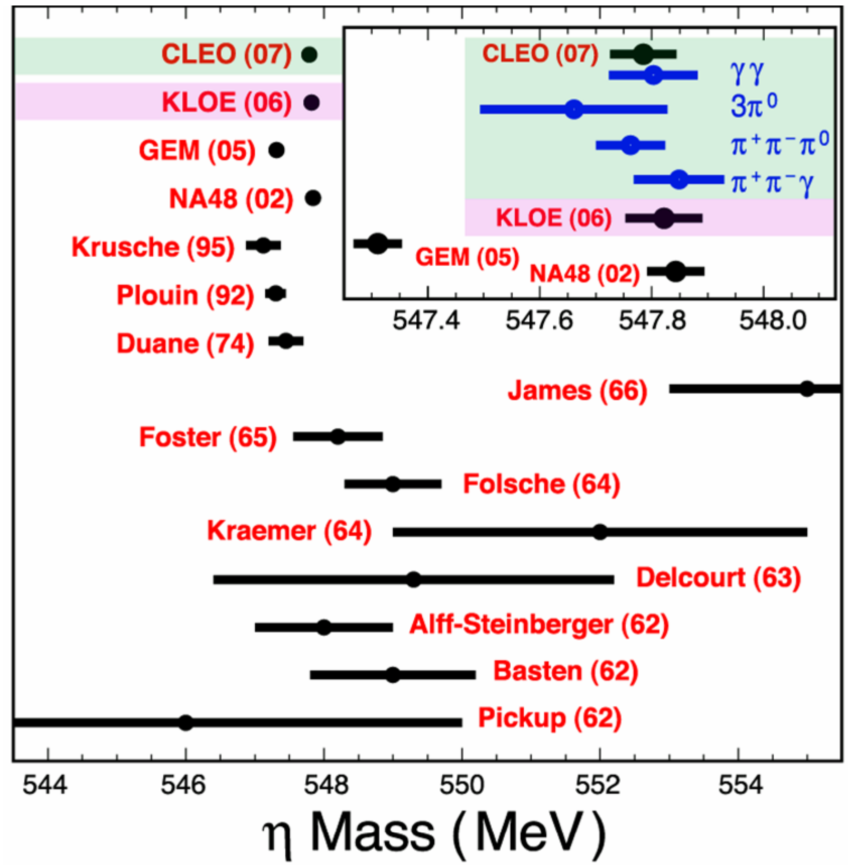
CLEO
$\psi(2S)\to\eta J/\psi$

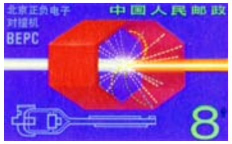


KLOE
$\phi\to\gamma\eta$

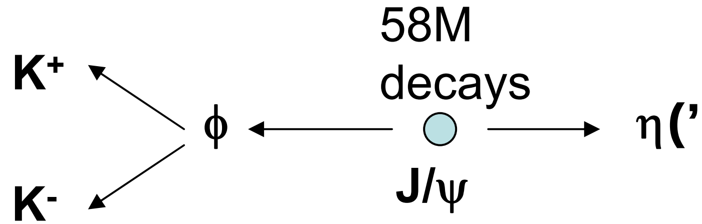
CLEO: $M(\eta) = 547.785 \pm 0.017 \pm 0.057$ MeV
arXiv:0707.1810

KLOE: $M(\eta) = 547.822 \pm 0.005 \pm 0.069$ MeV
preliminary

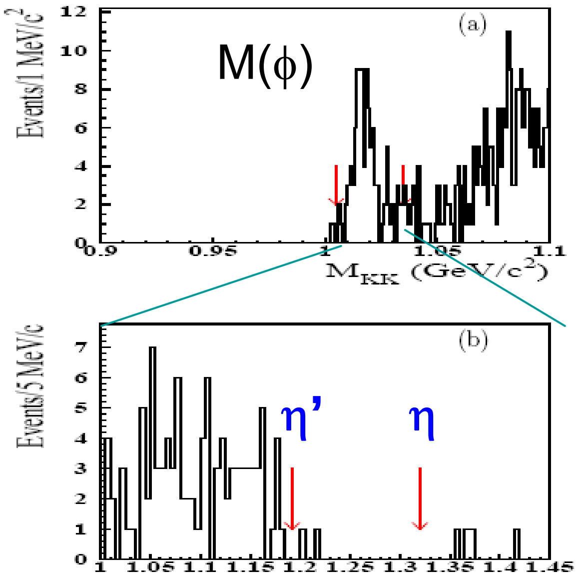




η(') Branching Ratios (1)

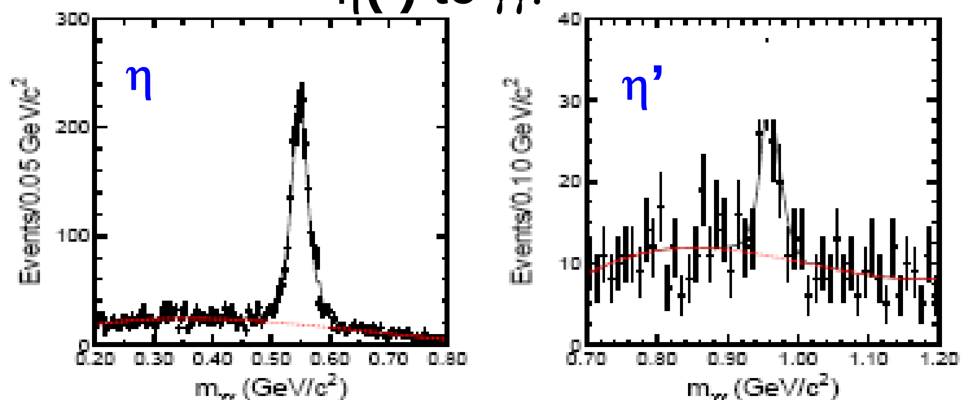


η to undetectable final states:



Missing momentum

η(') to γγ:



1760±49 72±13

UL, absolute:

$$\frac{B(\eta \to \text{invisible})}{B(\eta \to \gamma\gamma)} < 1.65 \times 10^{-3}$$ ~0.1%)

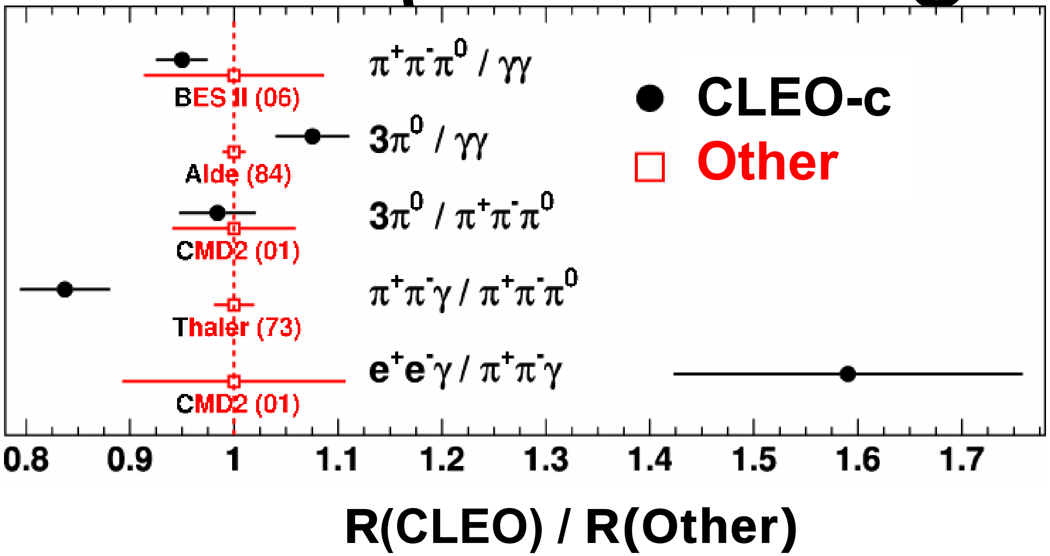
$$\frac{B(\eta' \to \text{invisible})}{B(\eta' \to \gamma\gamma)} < 6.69 \times 10^{-3}$$ ~0.01%

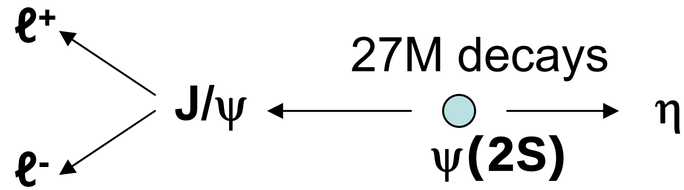
58M J/ψ,
$B(J/\psi \to \eta(')\phi) = 7.4\ (4.0) \times 10^{-4}$
$B(\phi \to K^+K^-) = 50\%$

BES PRL 97, 202002 (2006)

Other “invisible” BR measurements:
ϒ(1S): <0.39% (CLEO) PRD 75, 031104 (2007)
<0.29% (Belle) PRL 98, 132001 (2007)
Important as an input to total width measurements!

η branching fractions (2)





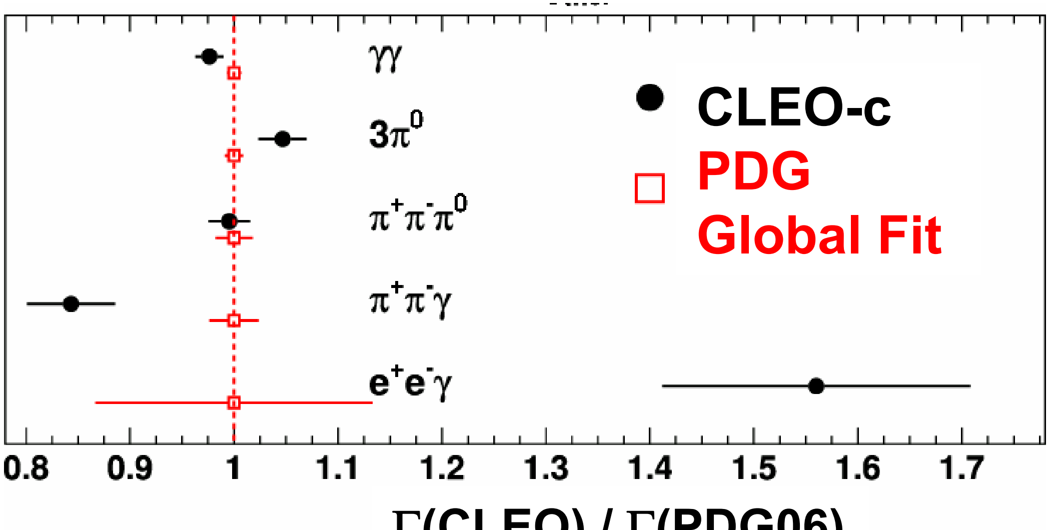
Fully reconstruct five final states:

$\gamma\gamma$ + $3\pi^0$ + $\pi^+\pi^-\pi^0$ + $\pi^+\pi^-\gamma$ + $e^+e^-\gamma$

38.5 34.0 22.6 4.0 0.9%

Follow PDG procedure: sum of the above five modes is ~ 100%

⇒ build absolute Br's from ratios



CLEO, arXiv:0707.1601

KLOE

arXiv:0707.2355v1

$\eta\to\pi^+\pi^-\pi^0$ decay dynamics

B. V. Martemyanov, V. S. Sopov, PRD 71 (2005) 017501

A good understanding of $\eta\to 3\pi$ dynamics can in principle lead to a very accurate determination of quark masses:

$$\Gamma(\eta\to 3\pi)\propto |A|^2$$

$$\mathbf{Amplitude(s,t,u)}\propto\frac{1}{\mathbf{Q}^2}\times\mathbf{M(s,t,u)}$$

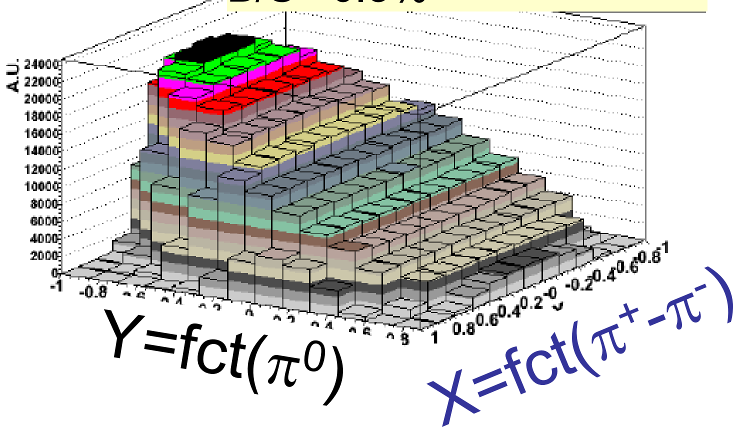
$$\mathbf{Q}^2=\frac{\mathbf{m}_s^2-\hat{\mathbf{m}}^2}{\mathbf{m}_d^2-\mathbf{m}_u^2},\quad \mathbf{M(s,t,u)}\overset{(*)}{=}\frac{\mathbf{3s-4m}_\pi^2}{\mathbf{m}_\eta^2-\mathbf{m}_\pi^2}$$

(*) lowest order Current Algebra

Measured matrix element:

$N_{obs}=(1.377\pm0.001)\times10^6$

B/S ≈0.3%



Fit parameters:

$|A(X,Y)|^2=$
$1+aY+bY^2+cX+dX^2+eXY+fY^3$

with X=fct(π^+-π^-), Y=fct(π^0)

Fit result:

$$a=-1.090\pm0.005(stat)^{+0.008}_{-0.019}(syst)$$

$$b=0.124\pm0.006(stat)\pm0.010(syst)$$

$$d=0.057\pm0.006(stat)^{+0.007}_{-0.016}(syst)$$

$$f=0.14\pm0.01(stat)\pm0.02(syst)$$

$$c=0.002\pm0.003(stat)\pm0.001(syst)$$

$$e=-0.006\pm0.007(stat)^{+0.005}_{-0.003}(syst)$$

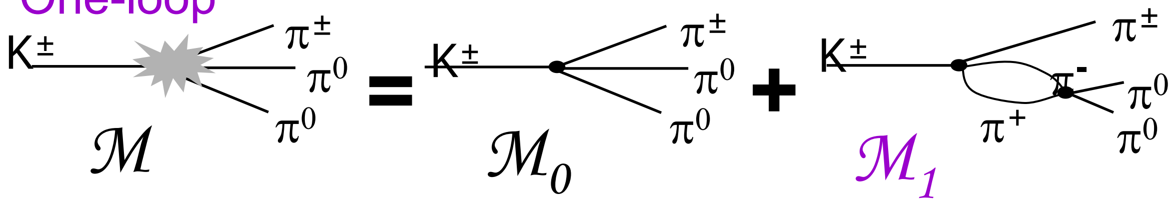
LOCA: $b = a^2/4$

⇒ Indicates need for higher order corrections compared to (*)

$K^{+/-} \rightarrow \pi^{+/-}\pi^0\pi^0$

Final state interactions

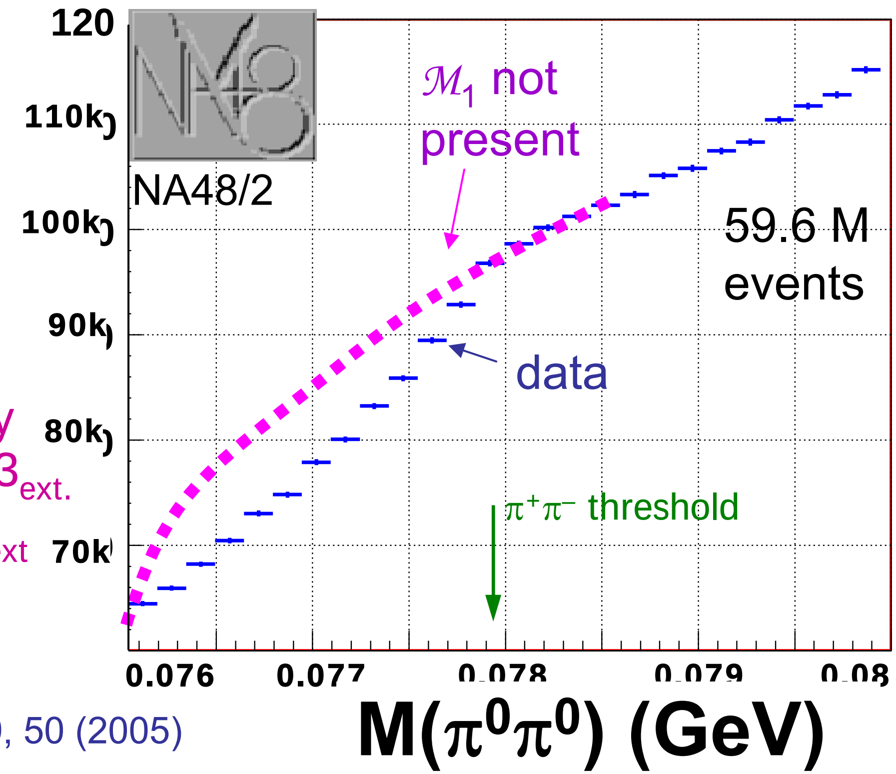
“One-loop”



Prop. to a_0-a_2

“Two-loop” introduces dependence on a_2 in ampl.

<u>Dalitz plot analysis. Look at $M(\pi^0\pi^0)$:</u>
“cusp” structure at $\pi^+\pi^-$ threshold
(due to $\pi^+\pi^- \rightarrow \pi^0\pi^0$ rescattering)
provides a new method to measure the $\pi\pi$ scattering lengths: a_0 and a_2
(χPT predictions exist)



preliminary

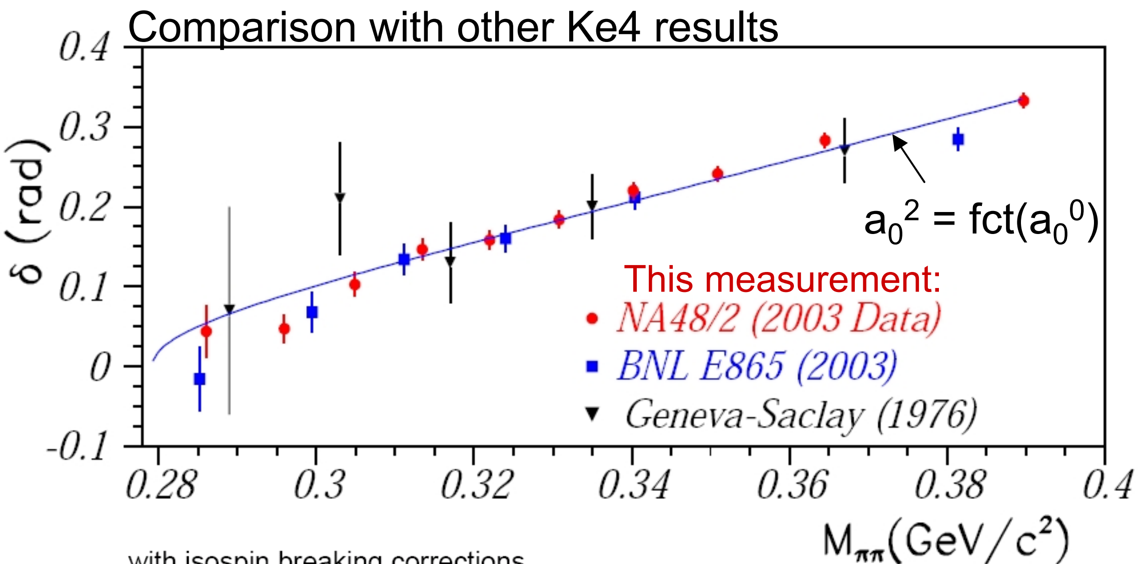
$(a_0-a_2)m_+ = 0.261 \pm 0.006_{stat.} \pm 0.003_{syst.} \pm 0.0013_{ext.}$
$a_2 m_+ = -0.037 \pm 0.013_{stat.} \pm 0.009_{syst.} \pm 0.0018_{ext}$

Dominated by the theoretical uncertainties, consistent with Ke4 measurement and with $|a_2-a_0|$ from DIRAC (pionium lifetime). PLB 619, 50 (2005)

Experimentally sensitive to higher-order terms in matrix element expansion

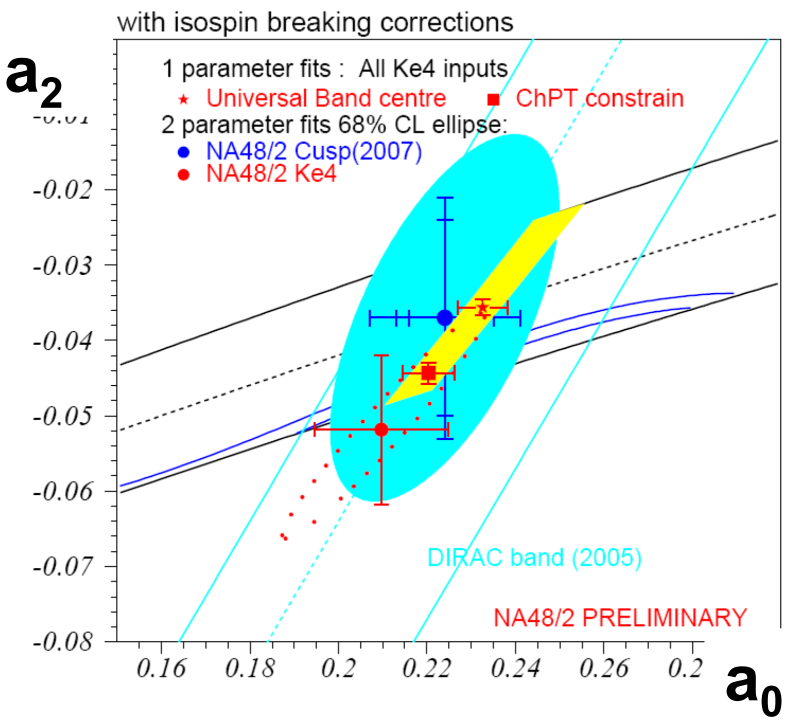
G. Lamanna, talk at this conference

$K^{+-} \rightarrow \pi^+\pi^- e^{+-}\nu$ (Ke4) results



Five independent kinematic variables, expansion in form factors with spin-dependent coefficients, model-independent determination of coefficients and phase shift btw L=0 and L=1, δ.

$\delta \Rightarrow a_0$ and a_2 via theory



NA48/2

- 677500 K^+ and K^- Ke4 decays (preliminary results on partial statistics)
- Ke4 Form factors measured with a precision within 5% to 15%

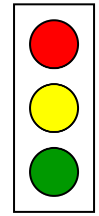
A new level of sensitivity

G. Lamanna, talk at this conference

Q=c,b

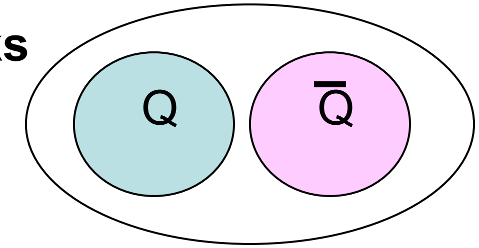
q=u,d,s

Summary



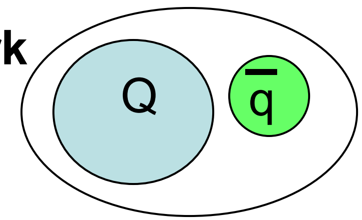
General goal:
Explore QCD phenomena at different scales

Two heavy quarks



$\psi(2S)$ width
J/ψ, χ_{cJ} decay to light q
B decay to charmonium
States above DD threshold
Charmonium-like states

One heavy quark

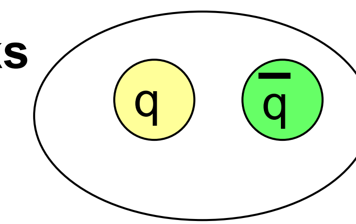


$D_{s1}(2536)^+ \rightarrow D^{*+}K^0_S$
$\Xi_c(3077)$, $\Xi_c(3123)$

Non-perturbative QCD

$a_0,f_0(980)$
η,η' mixing and glue in η'
η mass
$\eta(')$ decay
$K^{+-} \rightarrow \pi^+\pi^- e^{+-}\nu$, $\pi^{+-}\pi^0\pi^0$, $\pi^\pm\pi^0\gamma$

Zero heavy quarks

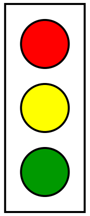


This talk: mostly mesons, but many new results on baryons as well. See list of topics at the end.

Conclusion

Many measurements on hadron spectroscopy and decay are arriving

- Examples shown of new phenomena, systematic surveys, and precision studies
- Especially overwhelming the amount of new unclassified states: Organize!!



Many thanks to my colleagues on BaBar, Belle, BES, CLEO, KLOE, NA48, …

Many more results

Bottomonium:

- CLEO bottomonium results: talk by H. Vogel at this conference
- CDF h_b search: talk by A. Gessler at this conference

Charmonium:

- psi(2S) to gamma+light survey: BES, PRL99, 011802 (2007)
- psi(2S) multibody survey: CLEO: PRL 95, 062001 (2005)
- psi(3770) non-DDbar: CLEO, PRL 96, 032003 (2006), PRD 73, 012002 (2006)
  BES, C. Jiangchuan, talk at this conference
- J/psi to light: BES, Phys. Rev. Lett. 97 (2006) 142002: gamma pipi PWA

Y(4260):

- BaBar: PRL 95, 142001 (2005),
  CLEO: PRD 74, 091104(R),
  Belle “old” prelim: hep-ex/0612006

X(3872):

- X(3872) mass: BaBar, G. Cibinetto, talk at this conference
- D0 mass: CLEO, PRL 98, 092002 (2007)

Charm mesons:

- BaBar: T. Schroeder, talk at this conference
- Belle: B0bar -> D**+ pi-; (observation of D_0*) hep-ex/0611054 (acc by PRD)

Open charm production:

- Belle: e+e- -> D(*)D* cross-section (at sqrt(s) from threshold to ~5 GeV), PRL98, 092001 (2007)

Baryons:

- Belle, Λ_c(2880) J^P and Λ_c(2940) -> Σ_c π; PRL 98, 262001 (2007)
- Belle, Observation of Ξ_c(2980), Ξ_c(3077); PRL 97, 162001 (2006)
- BaBar: T. Schroeder, talk at this conference
- D0: Λ_b lifetime, Ξ_b discovery: E. De La Cruz Burelo, talk at this conference

Light scalars:

- KLOE: $a_0 \rightarrow$ eta pi^0, $f_0 \rightarrow pi^0 pi^0$ shown at winter conferences

Light resonances:

- E. Fadeeva, talk at this conference

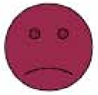
NA48

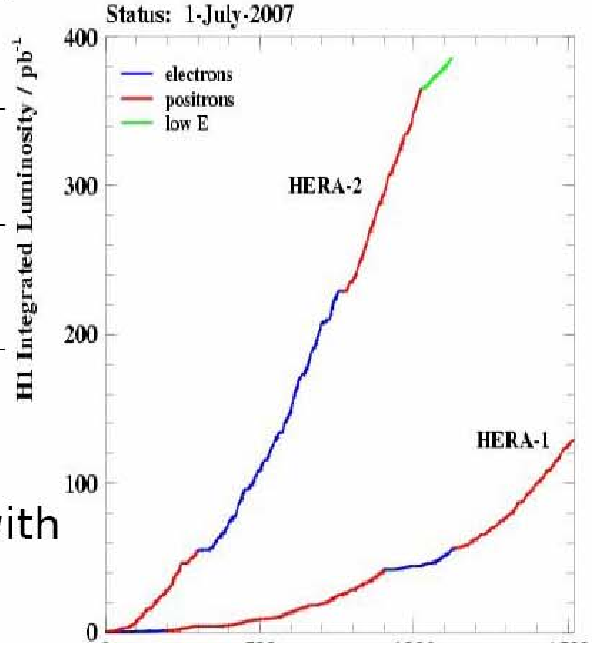
- Radiative decays: M. Piccini, talk at this conference

Pentaquarks

Summary

• Complete HERA I data was analysed with the following results from H1 & ZEUS:

	H1	ZEUS
strange pentaquark ($K^0_s p$)		
double strange pentaquark ($\Xi\ \pi$)		
charm pentaquark ($D^* p$)		



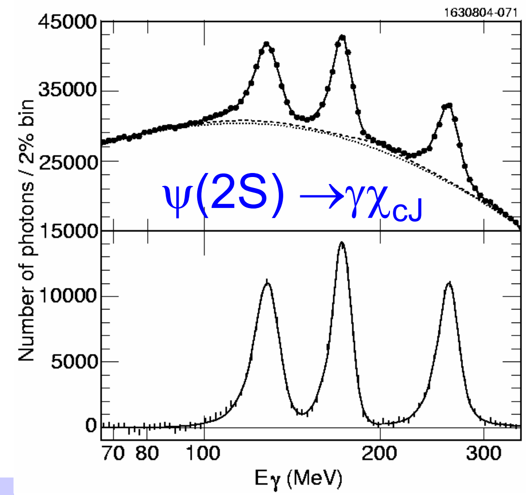
This controversial situation will be possible to resolve with high statistics HERA II data

Charmonium States

$\eta_c(2S)$:
mass recently remeasured,
width a moving target,
M1 rates not measured,
only one decay mode seen

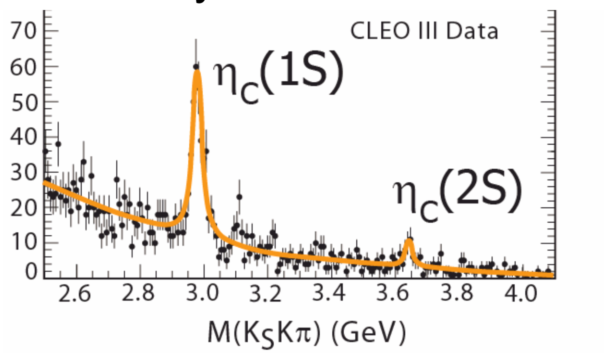
2^1S_0 2^3S_1

χ_{cJ}: masses, width, dominant decay modes reasonably well measured. Beginning to study substructure.

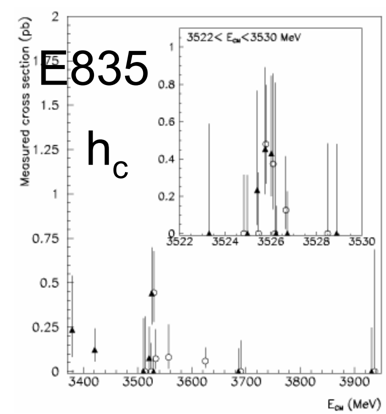


1^1P_1 1^3P_J

h_c χ_c



h_c: Newest member of the family, seen in $\psi(2S) \to \pi^0 h_c \to \gamma\eta_c$ and in $p\bar{p}$ production, product BR measured. That's it!



$\eta_c(1S)$: mass and width known to MeV's, most urgent project: M1 transition rate $J/\psi \to \gamma\eta_c$

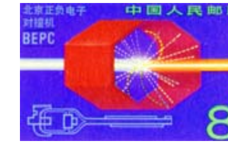
1^1S_0 1^3S_1

η_c ψ

$\psi(2S), J/\psi$: accessible in e^+e^-. Masses, total width, dominant decay modes well measured. Studying BR's in the range of <0.01%, and substructure.

PRL99, 011802 (2007)

$\psi(2S) \to \gamma$ + light hadrons



$\psi(2S)$ to light hadrons, PDG07:

$\gamma \pi^0$
$\gamma \eta'(958)$
$\gamma f_2(1270)$
$\gamma f_0(1710)$
  $\gamma f_0(1710) \to \gamma \pi \pi$
  $\gamma f_0(1710) \to \gamma K \overline{K}$
$\gamma \gamma$
$\gamma \eta$
$\gamma \eta \pi^+ \pi^-$
$\gamma \eta(1405)$
  $\gamma \eta(1405) \to \gamma K \overline{K} \pi$
  $\gamma \eta(1405) \to \eta \pi^+ \pi^-$
$\gamma \eta(1475)$
  $\gamma \eta(1475) \to K \overline{K} \pi$
  $\gamma \eta(1475) \to \eta \pi^+ \pi^-$

All limits or meas'ts at $10^{-4..5}$

The corresponding list for the J/ψ is almost 50 entries long…

$BR(\psi(2S) \to ggg + \gamma gg)$
$= 1 - \pi\pi, \eta, \pi^0 J/\psi - \Sigma M1, E1 = \sim 20\%$

J/ψ: $\gamma gg/\ ggg$ ~6%

$BR(\psi(2S) \to \gamma gg)$ ~ 1%
Where are they?

BES: survey of $\gamma + n(\pi^+\pi^-) + m(K^+K^-)$

Mode	N^{Tot}	N^{Bg}	N^{Sig}	$\epsilon(\%)$	$\mathcal{B}(\times 10^{-5})$
$\gamma p\bar{p}$	329	187	142 ± 18	35.3	$2.9\pm0.4\pm0.4$
$\gamma 2(\pi^+\pi^-)$	1697	1114	583 ± 41	10.4	$39.6\pm2.8\pm5.0$
$\gamma K^0_S K^+\pi^- + c.c.$	–	–	115 ± 16	4.83	$25.6\pm3.6\pm3.6$
$\gamma K^+K^-\pi^+\pi^-$	361	229	132 ± 19	4.94	$19.1\pm2.7\pm4.3$
$\gamma K^{*0}K^+\pi^- + c.c.$	–	–	237 ± 39	6.86	$37.0\pm6.1\pm7.2$
$\gamma K^{*0}\bar{K}^{*0}$	58	17	41 ± 8	2.75	$24.0\pm4.5\pm5.0$
$\gamma \pi^+\pi^- p\bar{p}$	55	38	17 ± 7	4.47	$2.8\pm1.2\pm0.5$
$\gamma K^+K^-K^+K^-$	15	8	< 14	2.93	< 4.0
$\gamma 3(\pi^+\pi^-)$	118	95	< 45	1.97	< 17
$\gamma 2(\pi^+\pi^-)K^+K^-$	17	13	< 15.5	0.69	< 22

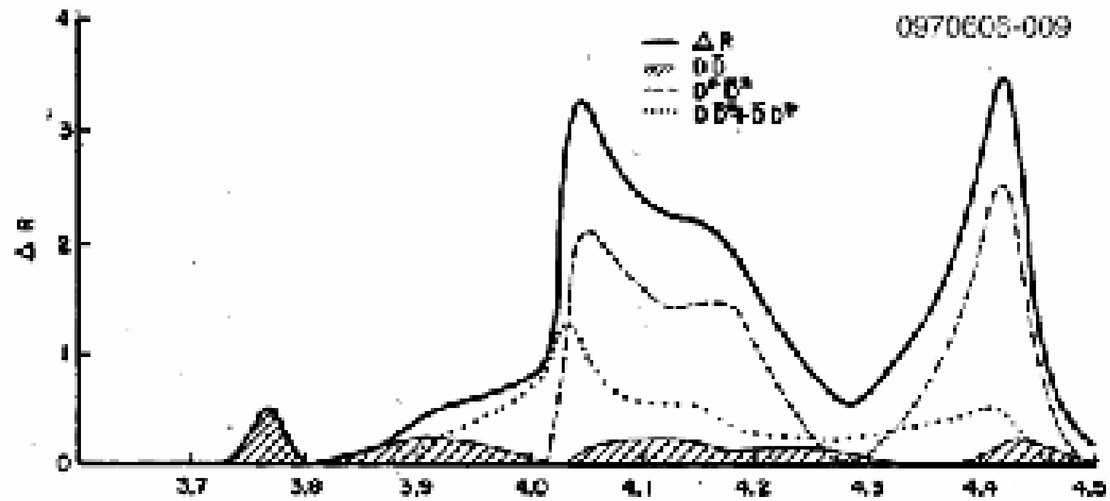
Sum nowhere near 1%…

Also included $\pi^0 + 2(\pi^+\pi^-)$[and K^+K^-], rich resonant substructure

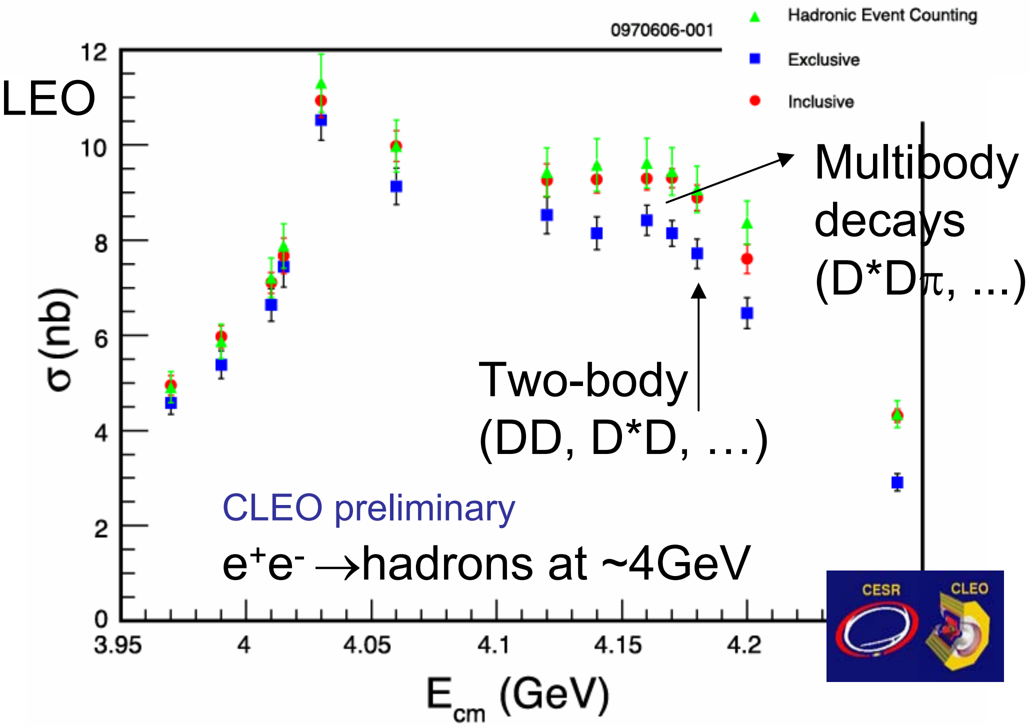
Study dependence of production rate on center-of-mass energy

Open charm production in e^+e^-

Eichten et al, PRD 21, 208 (1980)



CLEO inclusive:



Decomposition of this cross-section?

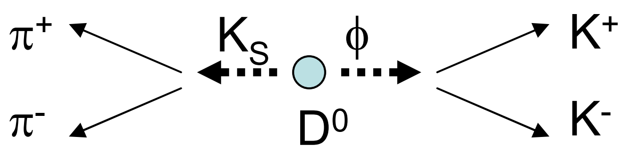
Measure yield of $D/D^*/D_S/\ldots$ combinations as function of E_{cm}

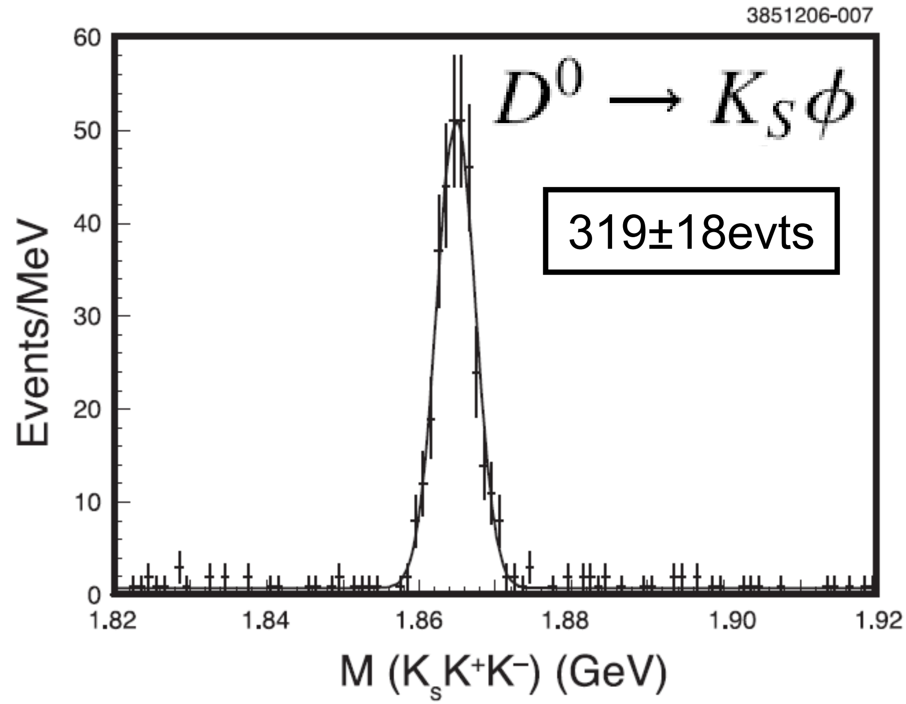
CLEO PRL 98, 092002 (2007)

D^0 mass measurement

PDG: $M(D^0)$=1864.5±0.4MeV
- average of LGW, MARK II, NA32
- Measured in $D^0 \rightarrow K\pi$, $K\pi\pi\pi$

CLEO-c, 281pb^{-1}, use $D^0 \rightarrow K_S\varphi$:
- $M(D^0)-M(\varphi)-M(K_S)$=347MeV
- p(K), p(π) <600MeV range
- Cross-check: $M(\psi(2S) \rightarrow \pi^+\pi^- J/\psi)$





$$M(D^0) = 1864.847 \pm 0.150(\text{stat}) \pm 0.095(\text{syst})\ \text{MeV}$$

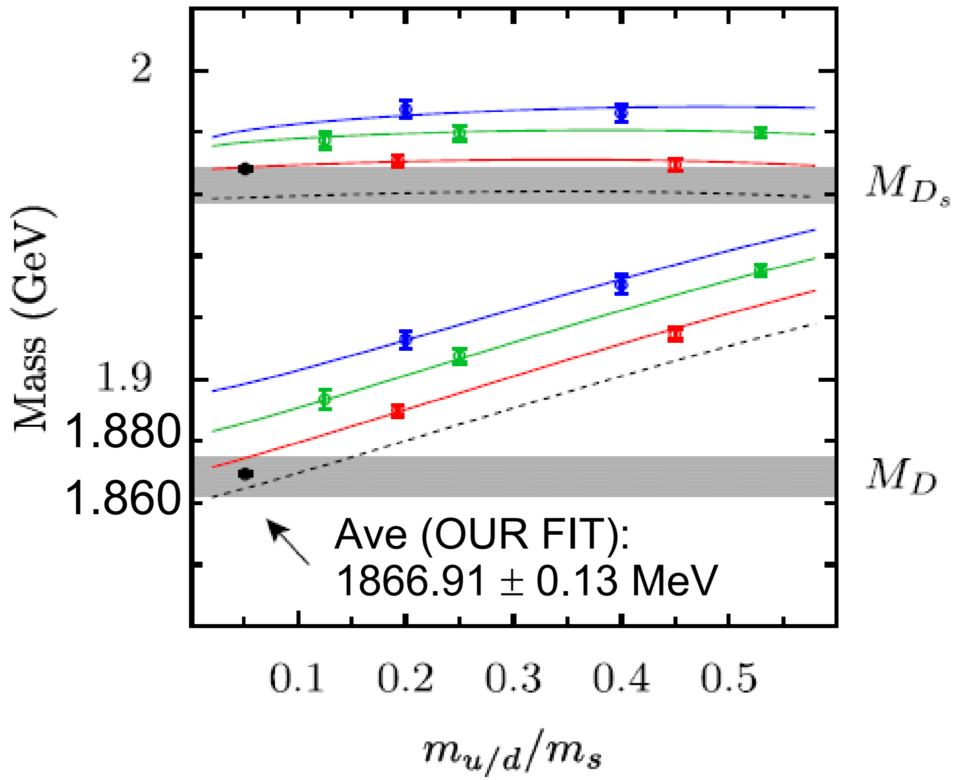
LQCD D mass calculation

D^+

1869.62 ± 0.20	**OUR FIT**	Error includes scale factor of 1.1.					
1869.5 ± 0.5	**OUR AVERAGE**						
1870.0 ± 0.5 ± 1.0		317	BARLAG	90C	ACCM	π^- Cu 230 GeV
1869.4 ± 0.6			[1] TRILLING	81	RVUE	$e^+ e^-$ 3.77 GeV

D^0

1864.84 ± 0.17	**OUR FIT**	Error includes scale factor of 1.1.		
1864.84 ± 0.18	**OUR AVERAGE**			
1864.847 ± 0.150 ± 0.095		319 ± 18	CAWLFIELD	07



LQCD arXiv:0706.1726 (hep-lat)

η,η': mixing and gluonium

The η , η' mesons wave function can be decomposed in the strangeness non strangeness base.

$$|\eta'> = X_{\eta'}|q\bar{q}> + Y_{\eta'}|s\bar{s}> + Z_{\eta'}|gluon>$$
$$|\eta> \;=\; cos(\varphi_p)|q\bar{q}> - sin(\varphi_p)|s\bar{s}>$$

$$X_{\eta'} = \cos\phi_G \sin\varphi_P$$
$$Y_{\eta'} = \cos\phi_G \cos\varphi_P$$
$$Z_{\eta'} = \sin\phi_G$$

$$\frac{Br(\phi\to\eta'\gamma)}{Br(\phi\to\eta\gamma)} = R_\phi = \cot^2\phi_P \cdot \cos^2\phi_G \left(1 - \frac{m_s}{\bar{m}} \cdot \tan\frac{\phi_V}{\sin 2\phi_P}\right)^2 \cdot \left(\frac{p_{\eta'}}{p_\eta}\right)^3$$

Comparing with other decay rates using SU(3) relations:

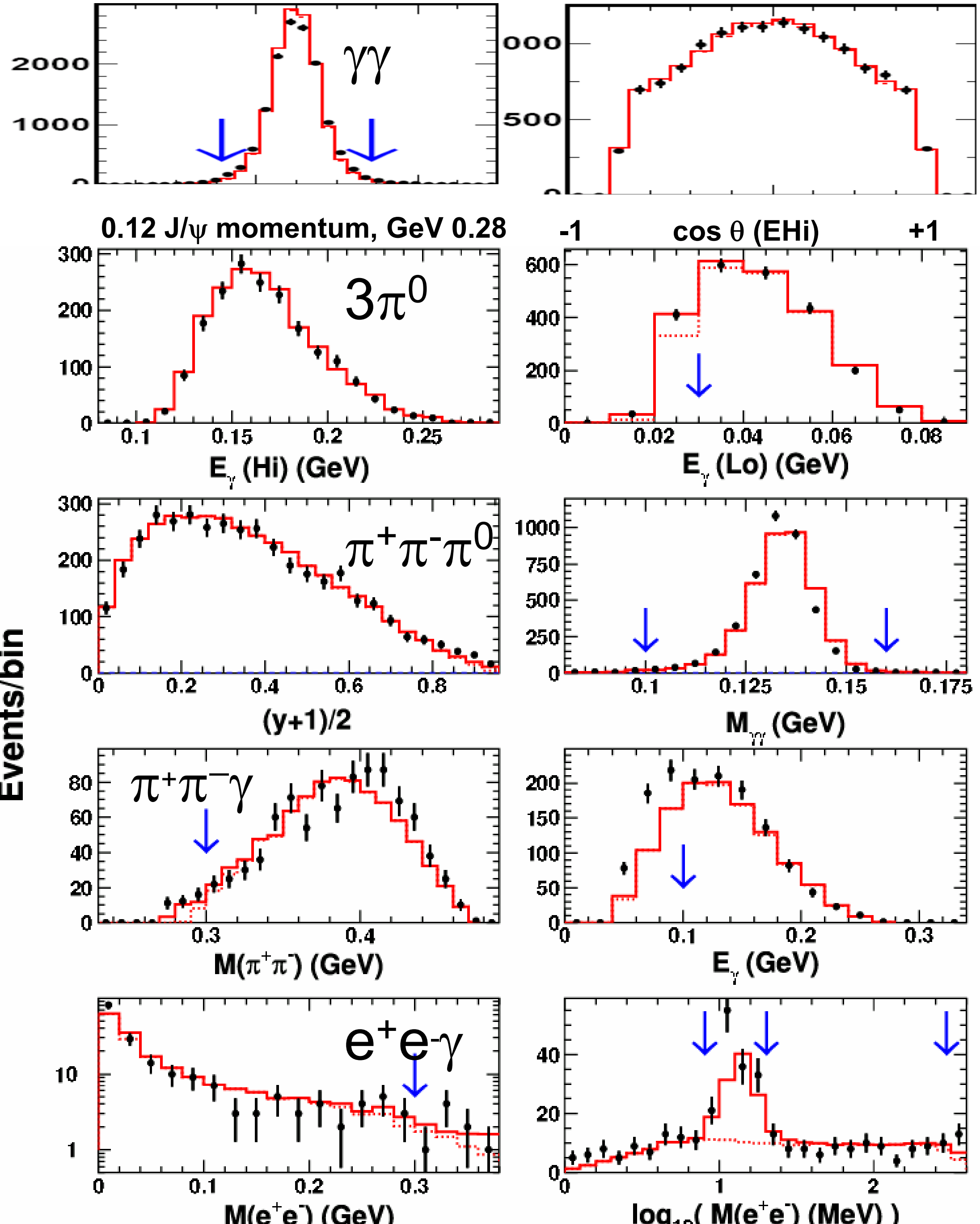
$$\Gamma(\eta'\to\gamma\gamma)/\Gamma(\pi^0\to\gamma\gamma) = \frac{1}{9}\left(\frac{m_{\eta'}}{m_\pi}\right)^3 \left(5\cos\phi_G\sin\varphi_P + \sqrt{2}\frac{f_q}{f_s}\cos\phi_G\cos\varphi_P\right)^2$$

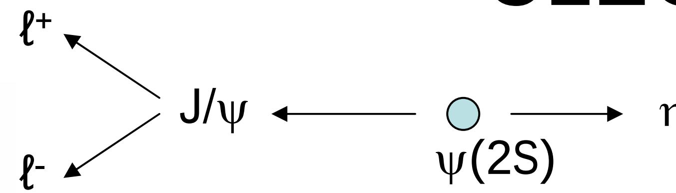
$$\Gamma(\eta'\to\rho\gamma)/\Gamma(\omega\to\pi^0\gamma) = \frac{C_{NS}}{\cos\varphi_V}\cdot 3\left(\frac{m^2_{\eta'} - m^2_\rho}{m^2_\omega - m^2_\pi}\frac{m_\omega}{m_{\eta'}}\right)^3 \cos^2\phi_G \sin^2\varphi_P$$

$$\Gamma(\eta'\to\omega\gamma)/\Gamma(\omega\to\pi^0\gamma) = \frac{1}{3}\left(\frac{m^2_{\eta'} - m^2_\omega}{m^2_\omega - m^2_\pi}\frac{m_\omega}{m_{\eta'}}\right)^3 [C_{NS}\cdot\cos\phi_G\sin\varphi_P + 2\frac{m_s}{\bar{m}}C_S\cdot\tan\varphi_V\cdot\cos\phi_G\cos\varphi_P]^2$$

The gluonium coupling is neglected.

η branching ratios, CLEO





27M ψ(2S),
B(ψ(2S)→ηJ/ψ) = 3.1%,
B(J/ψ→l+l-) = 12%,

Fully reconstruct five final states:
$\gamma\gamma + 3\pi^0 + \pi^+\pi^-\pi^0 + \pi^+\pi^-\gamma + e^+e^-\gamma$

Constrain ℓ^+, ℓ^- ⇒J/ψ,
constrain J/ψ, η products ⇒ ψ(2S)

Excellent data/MC agreement

Measurement of ratios allow cancellation of systematics

Follow PDG procedure: sum of the above five modes is ~ 100%
⇒ build absolute Br's from ratios

Results and systematics

KLOE

The result is dependent from the knowledge of the sqrt(s). It is calibrated using the resonance curve of the $\phi \to K_S K_L$.

$m(\phi) = 1019.483 \pm 0.011 \pm 0.025$ MeV/c^2

CMD-2 Phys. Lett. B578, 285

Systematic table err./(tot. err)

Calorimeter calibration	**1%**
Calorimeter linearity	**1 %**
Vertex position	**1 %**
Azimuthal dependence	**18 %**
Polar dependence	**8 %**
Dalitz plot cut + corr.	**67 %**

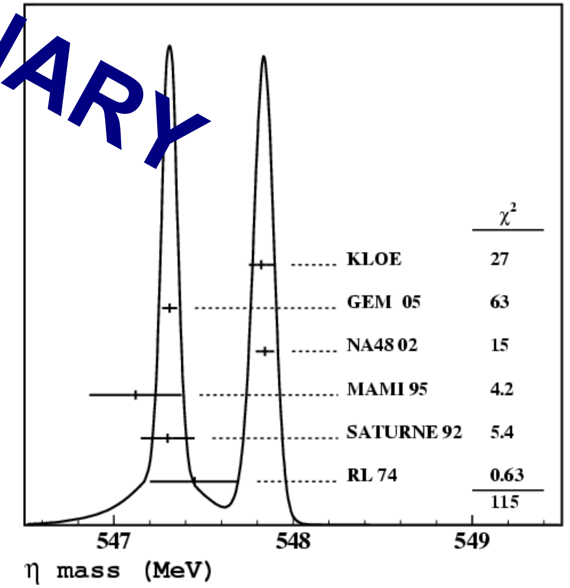
PRELIMINARY

$M(\pi^0) = (134990 \pm 6_{stat} \pm 30_{syst})$ keV

$M(\pi^0)_{\Pi\Delta\Gamma} = (134976.6 \pm 0.6)$ keV

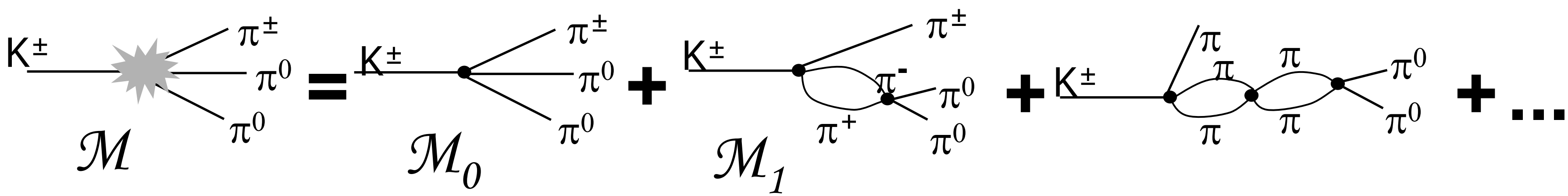
$M(\eta) = (547822 \pm 5_{stat} \pm 69_{syst})$ keV

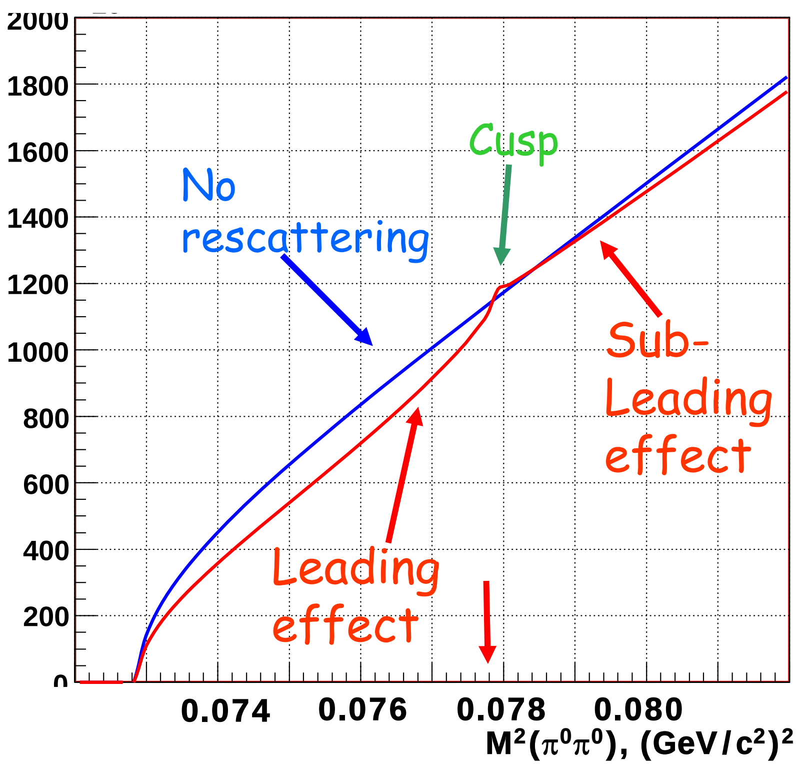
- NA48 compatibility: 0.24 σ
- Independent measurement with the $\eta \to \pi^+\pi^-\pi^0$ decay mode in progress: $m_\eta = 547.95 \pm 0.15$ MeV/c^2 (very preliminary fully in agreement with the $\gamma\gamma$ channel)



KLOE

Cusp: two loops





Cabibbo, Isidori JHEP 0503 (2005) 21

- Including 2-loops diagrams other terms appear in the amplitude
- All the S-wave amplitudes (5 terms) can be expressed as linear combination of a0 and a2
- The isosping breaking effect is taking in to account
- The radiative correction (most relevant near threshold) are still missing
- A deviation from the no rescattering amplitude behaviour appears also above threshold

$K^{\pm} \rightarrow \pi^{\pm}\pi^{0}\gamma$: First measurement of direct emission contribution

NA48/2

$$\frac{d\Gamma^{\pm}}{dW} \simeq \left(\frac{d\Gamma^{\pm}}{dW}\right)_{IB}\left[1 + 2\left(\frac{m_\pi}{m_K}\right)^2 W^2|E|cos((\delta_1-\delta_0)\pm\phi) + \left(\frac{m_\pi}{m_K}\right)^4 W^4(|E|^2+|M|^2)\right]$$

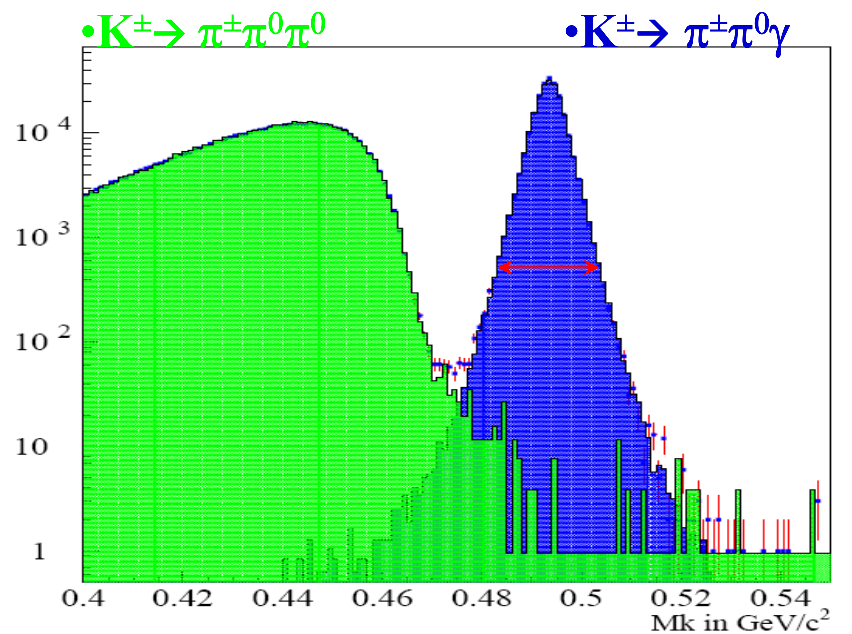
IB — INT — DE

Sensitive variable:

$$W^2 = \frac{(P_K^* \cdot P_\gamma^*)(P_\pi^* \cdot P_\gamma^*)}{(m_k m_\pi)^2}$$

P^*_K = 4-momentum of the $K^{\pm}$
P^*_π = 4-momentum of the $\pi^{\pm}$
P^*_γ = 4-momentum of the γ

~124K events from 2003 data



Preliminary result:

$Frac(DE)_{0<T^*_\pi<80\ MeV}$ = $(3.35 \pm 0.35 \pm 0.25)\%$

$Frac(INT)_{0<T^*_\pi<80\ MeV}$ = $(-2.67 \pm 0.81 \pm 0.73)\%$

Correlation=-92%

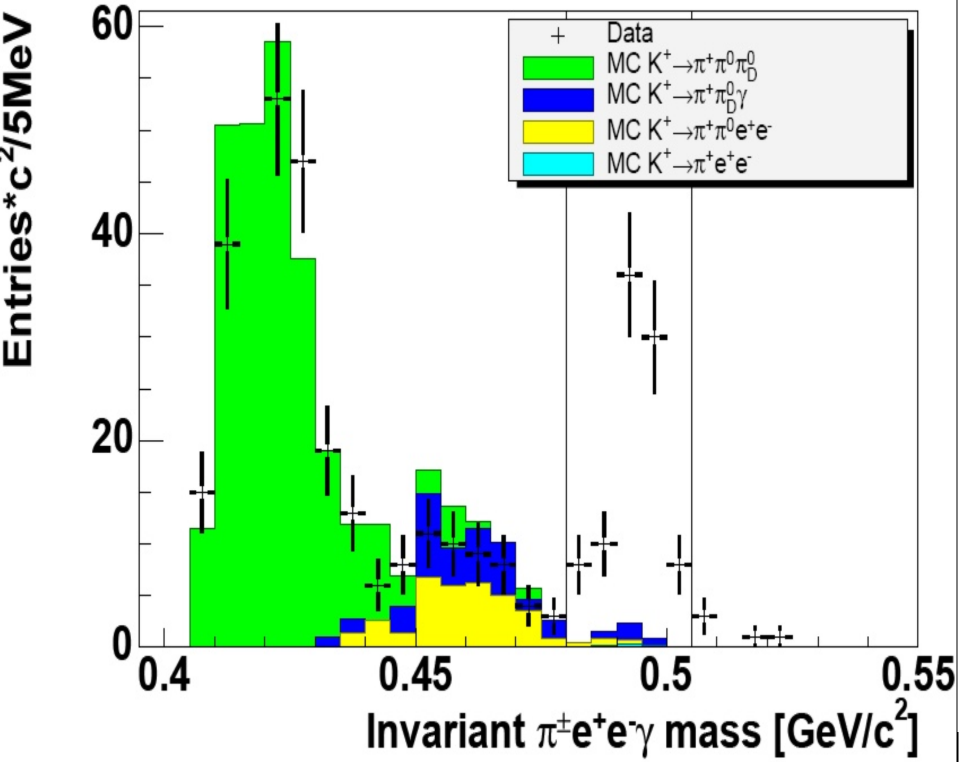
2004 data set: x4 # events and lower systematic due to trigger (analysis ongoing)

Weak radiative decay
NA48/2

$K^{\pm}\rightarrow\pi^{\pm}e^{+}e^{-}\gamma$

$\Xi^{0}\rightarrow\Lambda^{0}e^{+}e^{-}$

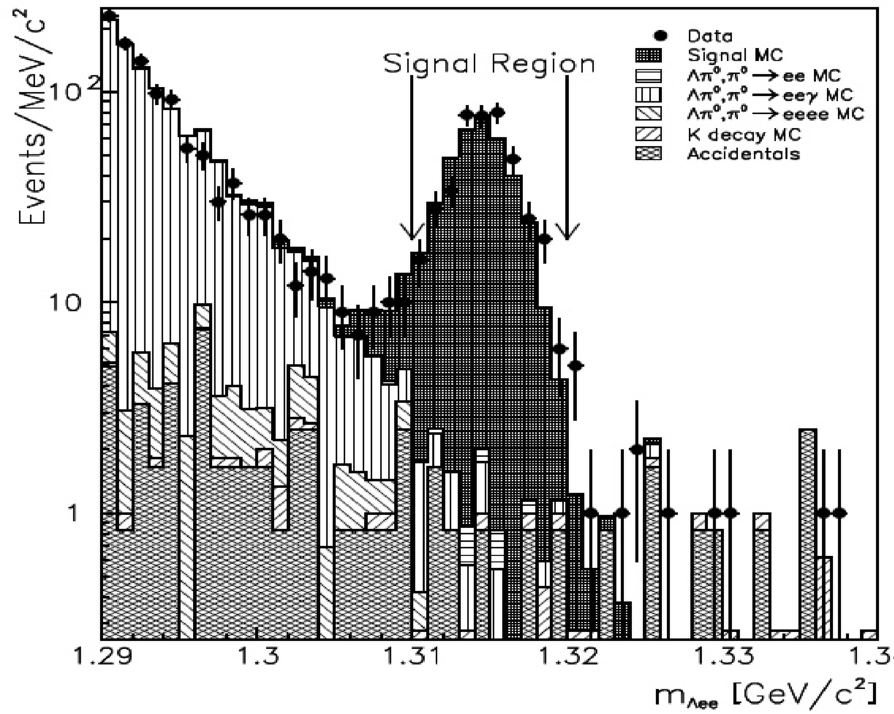
First evidence from 2003 data



Preliminary result:

$BR=(1.27\pm0.14_{stat}\pm0.05_{sys})\cdot10^{-8}$

First evidence from 2002 data



Final result (**Phys.Lett.B650:1-8,2007**):

$BR(\Xi\rightarrow\Lambda ee) =$
$7.7\pm0.5stat\pm0.4syst\cdot10^{-6}$
$\alpha(\Xi\rightarrow\Lambda ee)= -0.8 \pm 0.2$