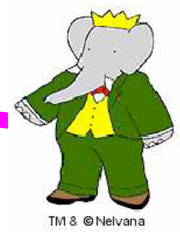
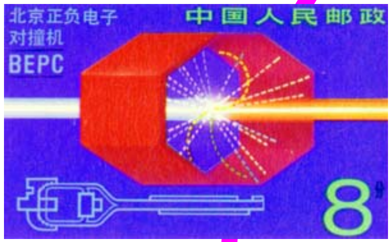
BELLE

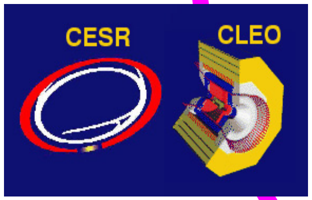




Charm

Hanna Mahlke
Cornell University

lapp ANNECY



Physics In Collision
June 26-29, 2007
LAPP, Annecy, France

FERMILAB E835
CHARMONIUM

E831
FOCUS

charm

Pronunciation: 'chärm

Function: *noun*

Etymology: Middle English *charme,* from Anglo-French, from Latin *carmen* song, from *canere* to sing -- more at CHANT

1 a : the chanting or reciting of a magic spell **:** INCANTATION

b : a practice or expression believed to have magic power

2 : something worn about the person to ward off evil or ensure good fortune **:** AMULET

3 a : a trait that fascinates, allures, or delights

b : a physical grace or attraction -- used in plural <her feminine *charms*>

c : compelling attractiveness <the island possessed great *charm*>

4 : a small ornament worn on a bracelet or chain

5 : a fundamental quark that has an electric charge of + 2/3 and a measured energy of approximately 1.5 GeV; *also* **:** the flavor characterizing this particle

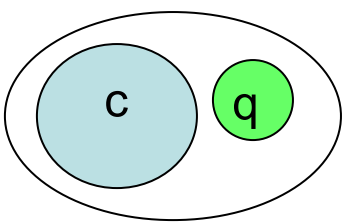
The role of charm for QCD

Why charm: heavy enough for theory to have an easier time (m_c ~1.5GeV), large data samples available.

Study of charm provides important testing ground for theory, to apply in heavier systems.

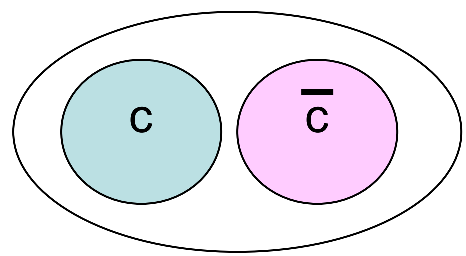
Charm decay provides the opportunity to study properties of lighter particles

Two scenarios:



Charm+light

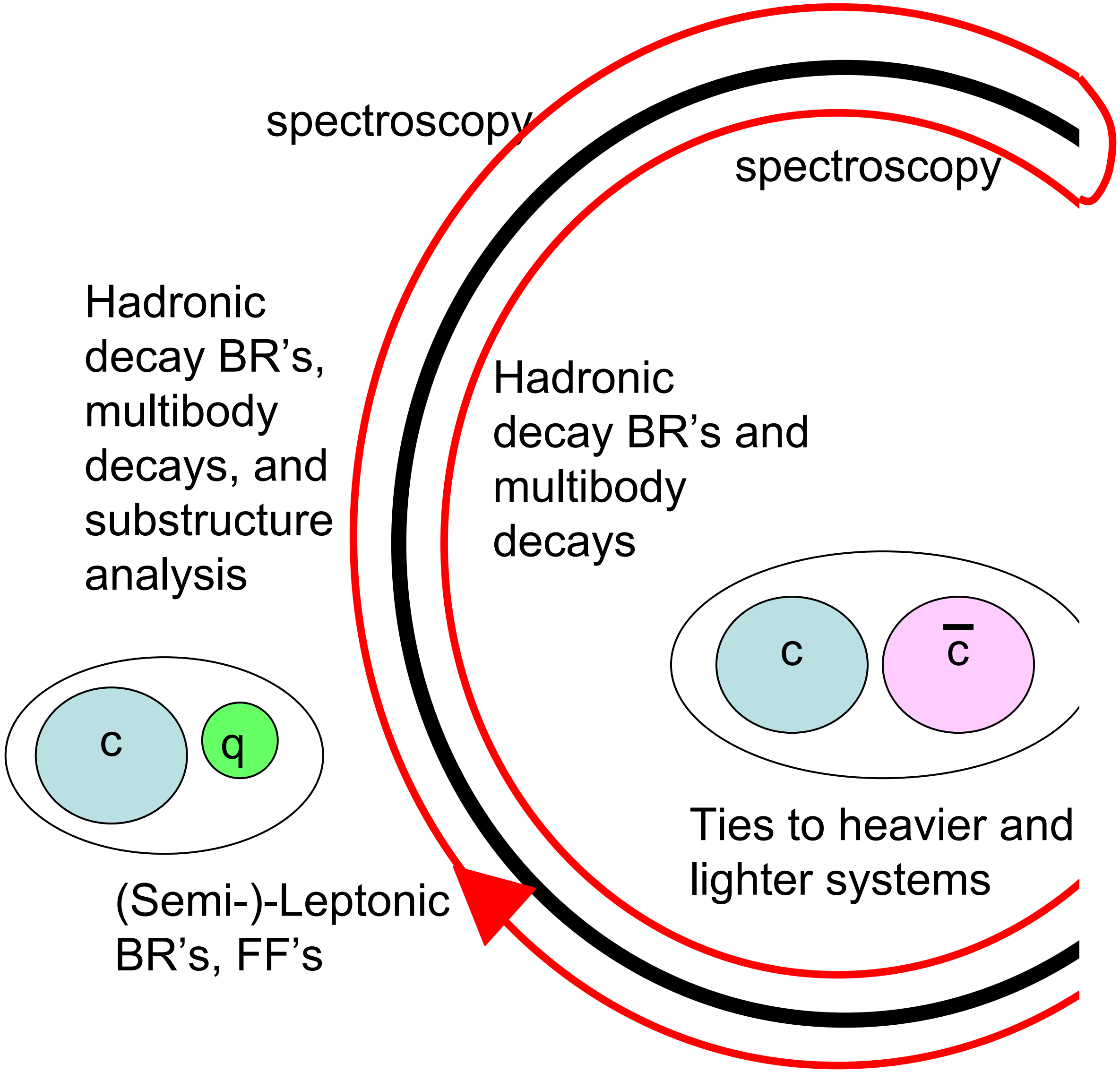
$D_{(s)}^{(*)-}$mesons, “open charm”



$c\bar{c}$ bound state

“charmonium”

Overview



Overall mission: Improve our understanding of the strong interaction.

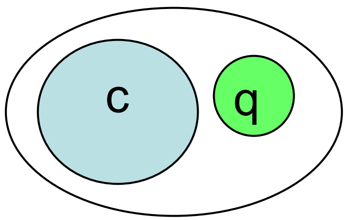
Goals:

Study charm for charm's sake

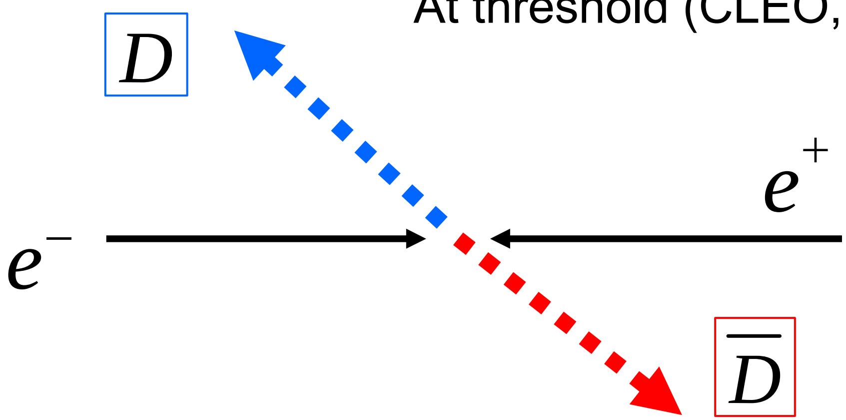
Calibration playground for heavier systems

Production site for lighter states

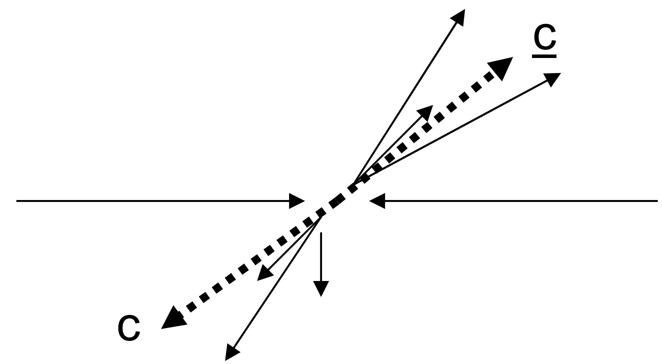
Open Charm Decays



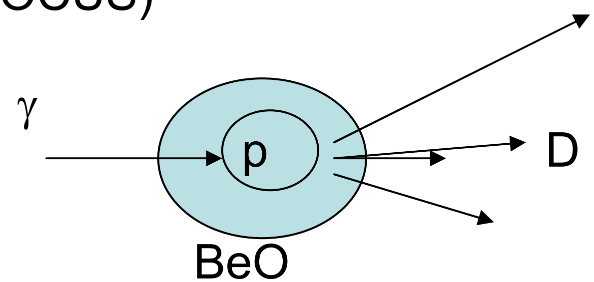
At threshold (CLEO, BES)

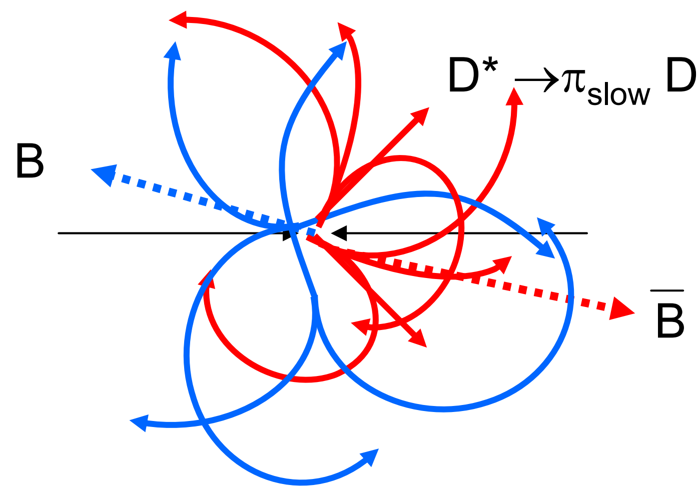


At ~10GeV (BaBar, Belle)



In photoproduction
(FOCUS)





OPEN CHARM

Leptonic and semileptonic decays

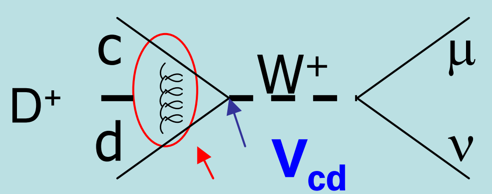
Motivation: study QCD effects in a weak decay
Goal: Determine form factors and decay constants

Precision experiments meet precision theory predictions
Verify calculations in the D system to apply in the B system

Overview: (Semi-)Leptonic Decays

Examples:

Leptonic:

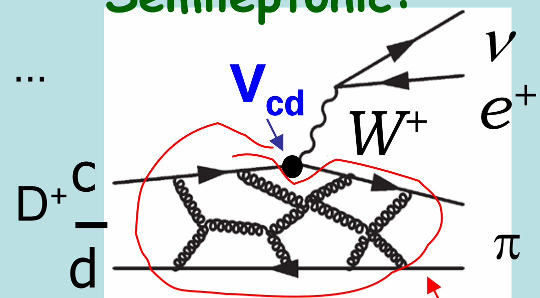


Decay constant f_D

Similar for D_s, B, B_s, …

Challenge: understand QCD portion in a "simple" weak process

Semileptonic:



q^2: momentum transfer or $m(W^*)$

Form factor $f_+(q^2)$

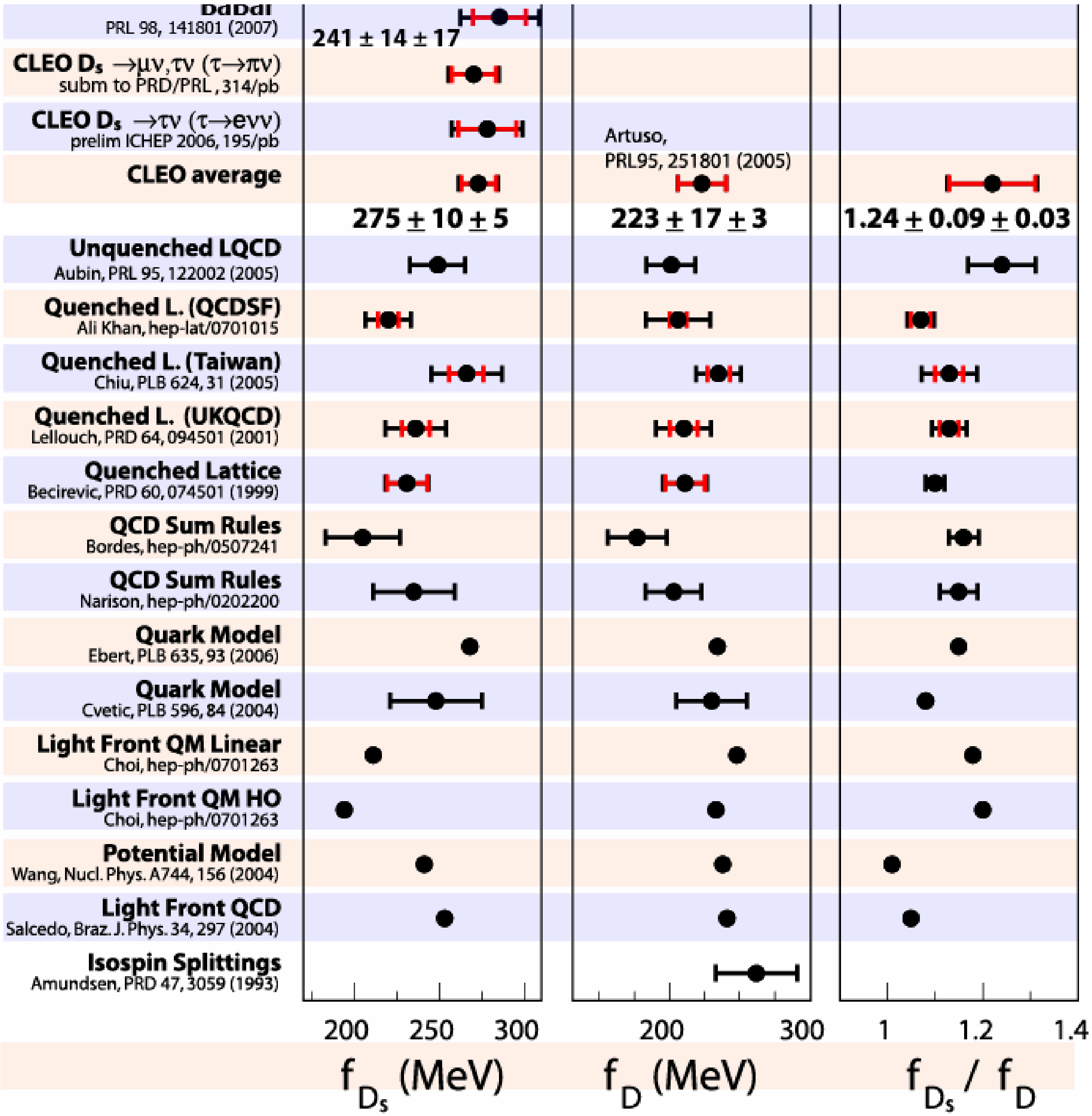
$$\Gamma(D^+ \to \ell^+ \nu) = \frac{1}{8\pi} G_F^2 f_D^2 m_\ell^2 M_D \left(1 - \frac{m_\ell^2}{M_D^2}\right)^2 |V_{cq}|^2$$

$$\frac{d\Gamma}{dq^2}(D \to P\ell\nu) \propto \left|f_+^P(q^2)\right|^2 p_P^3 |V_{cd}|^2$$

* BR measurements
$\Rightarrow$ Decay constants

* BR measurements
* Form factors

Decay Constants, Status



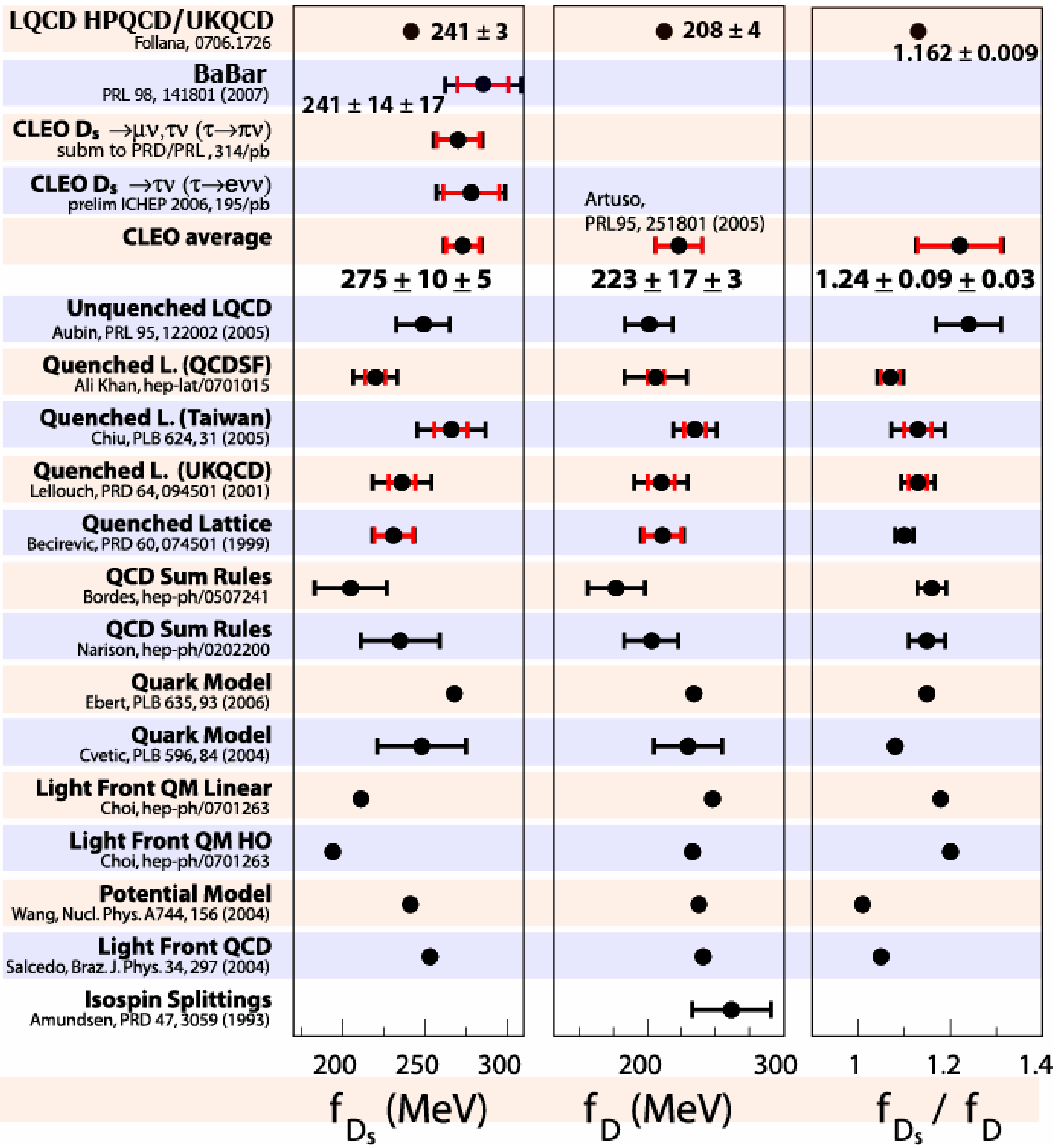
Leptonic charm decays:

$D \to \mu\nu$: fairly precise measurement of f_D (8%)

$D_s \to \mu\nu, \tau\nu$: two nice new measurements of f_{Ds} (5% CLEO, 8% BaBar)

Dominant experimental errors are statistical (BaBar also normalization) $\Rightarrow$ error reduction "easy"

Decay Constants, Status



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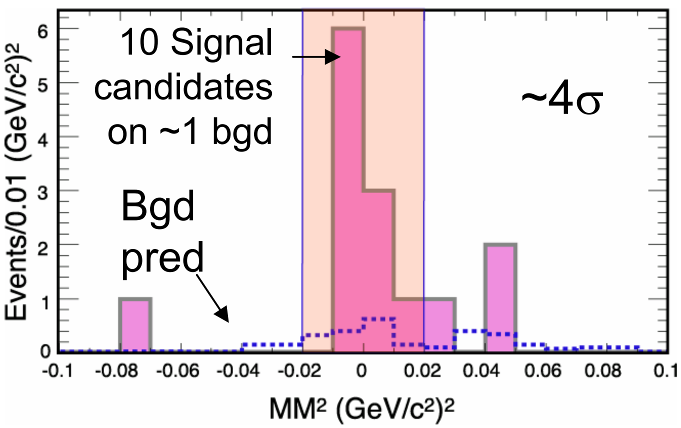
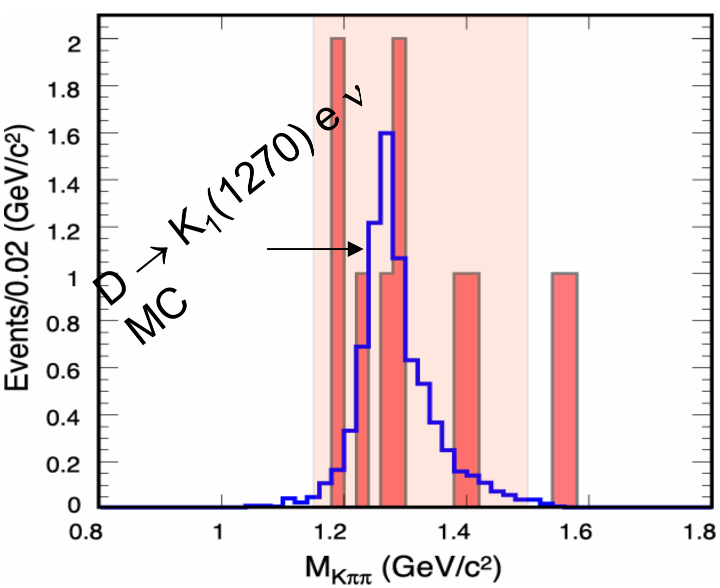
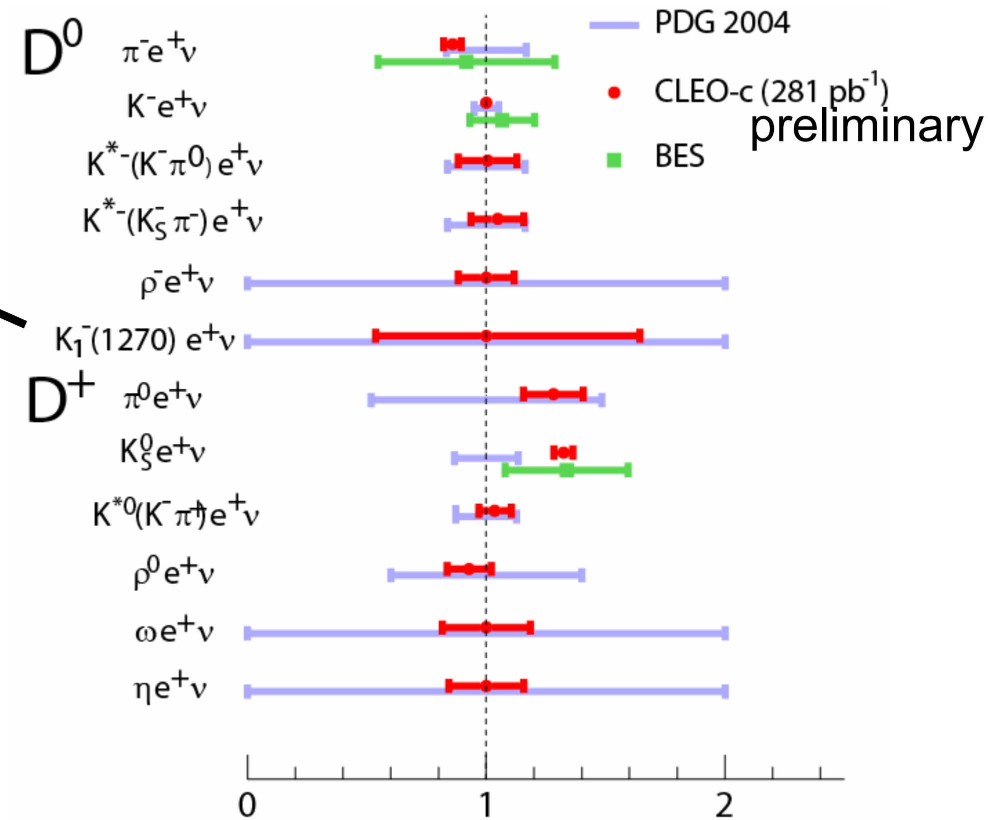
Dominant experimental errors are statistical (BaBar also normalization) $\Rightarrow$ error reduction “easy” arXiv:0705.4276 [hep-ex], subm to PRL

CLEO **semi**leptonic BR measurements

$D^0 \to K^-\pi^+\pi^- + e^+ \nu$, 281/pb:





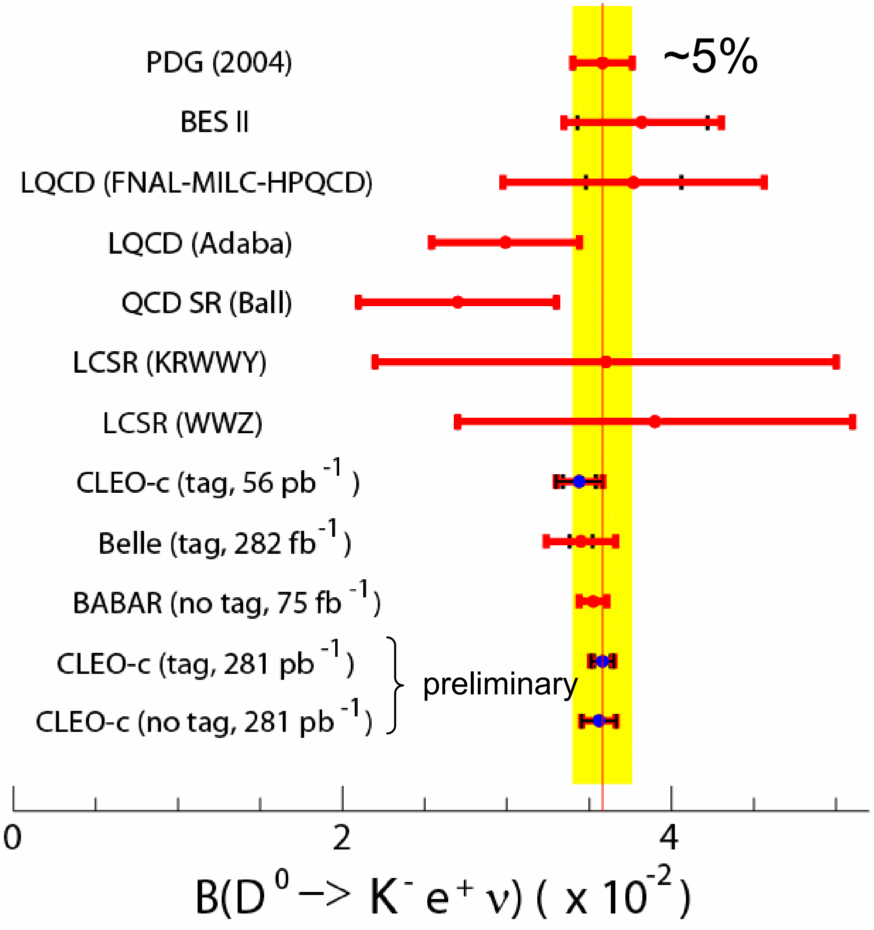


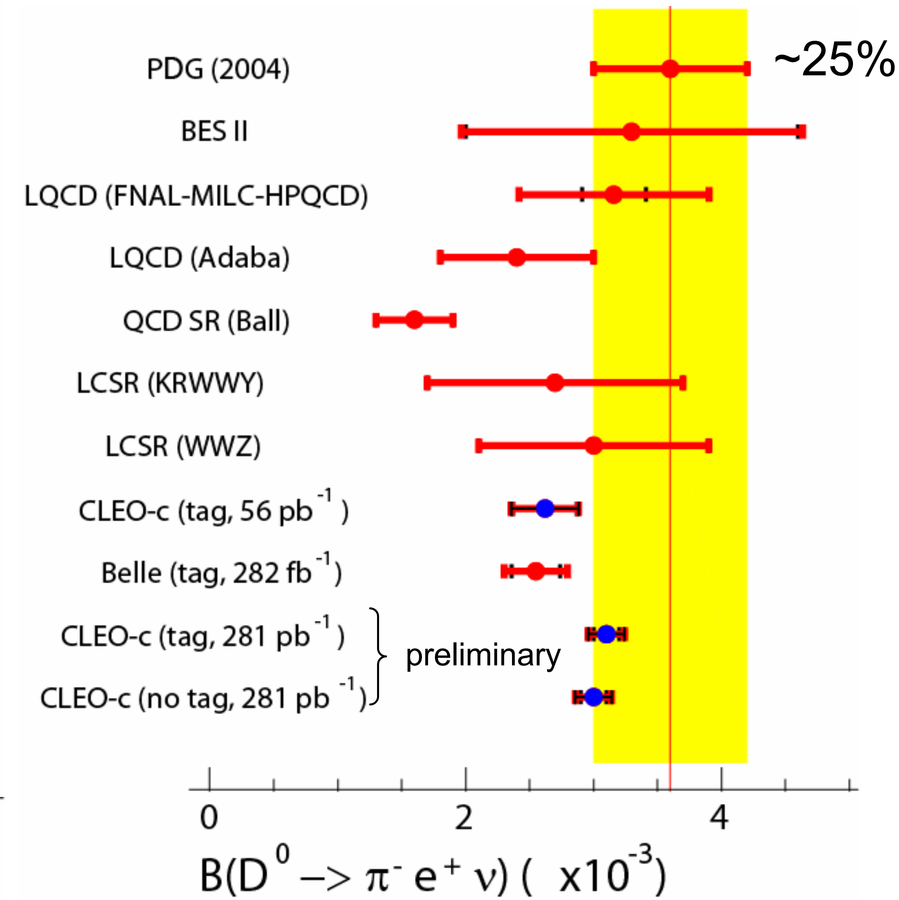
Substantial improvement over PDG04.

$$\mathcal{B}(D^0 \to K^-\pi^+\pi^-e^+\nu_e) = [2.8^{+1.4}_{-1.1}(\text{stat}) \pm 0.3(\text{syst})] \times 10^{-4}$$

$$\mathcal{B}(D^0 \to K_1^-(1270)\ e^+\nu_e) = [7.6^{+4.1}_{-3.0}\ (\text{stat}) \pm 0.6\ (\text{syst}) \pm 0.7] \times 10^{-4}$$

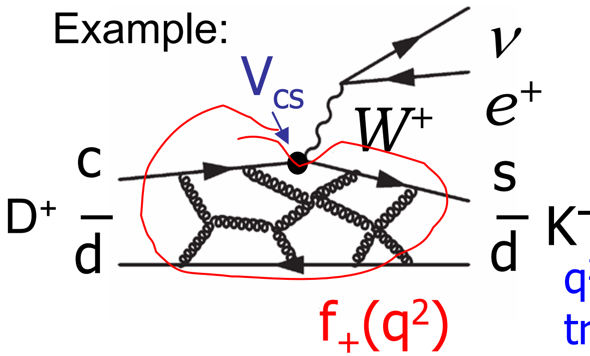
$D \to \pi, K \ell \nu$ branching fractions





Form factors

Example:



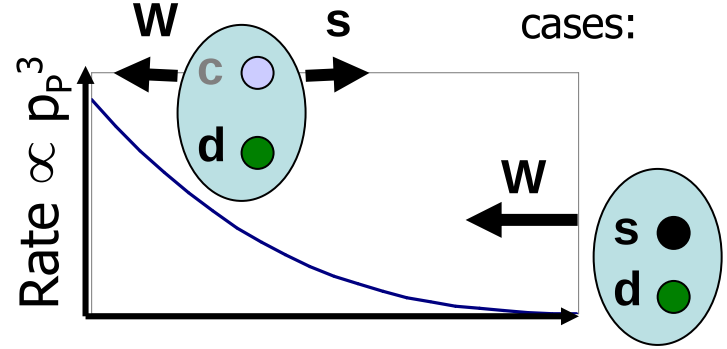
$$\frac{d\Gamma}{dq^2}(D \to \pi \ell \nu)$$

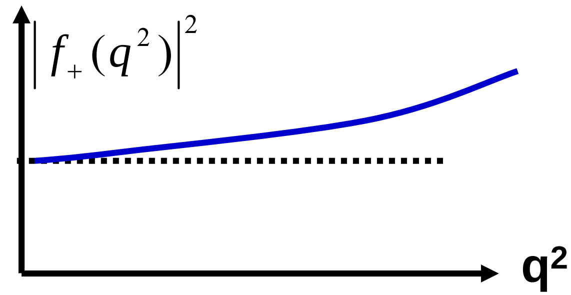
$$\propto \left| f_+^{\pi}(q^2) \right|^2 p_\pi^3 |V_{cd}|^2$$

$q^2 = m_{W*}$: momentum transfer to the W^*

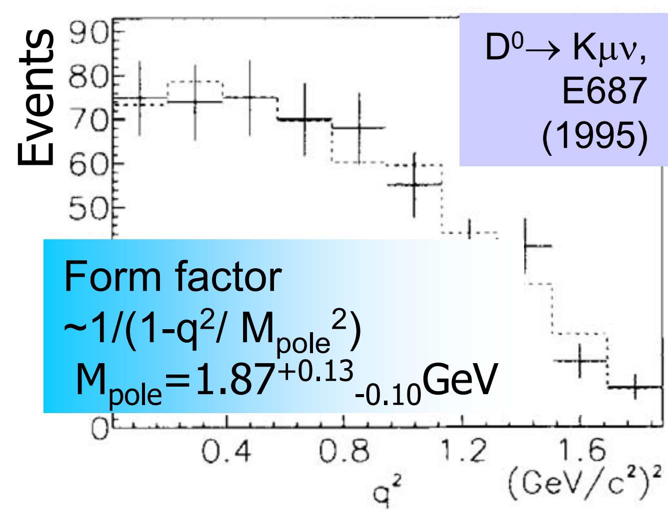
$f_+(q^2)$: form factor function

2 special cases:



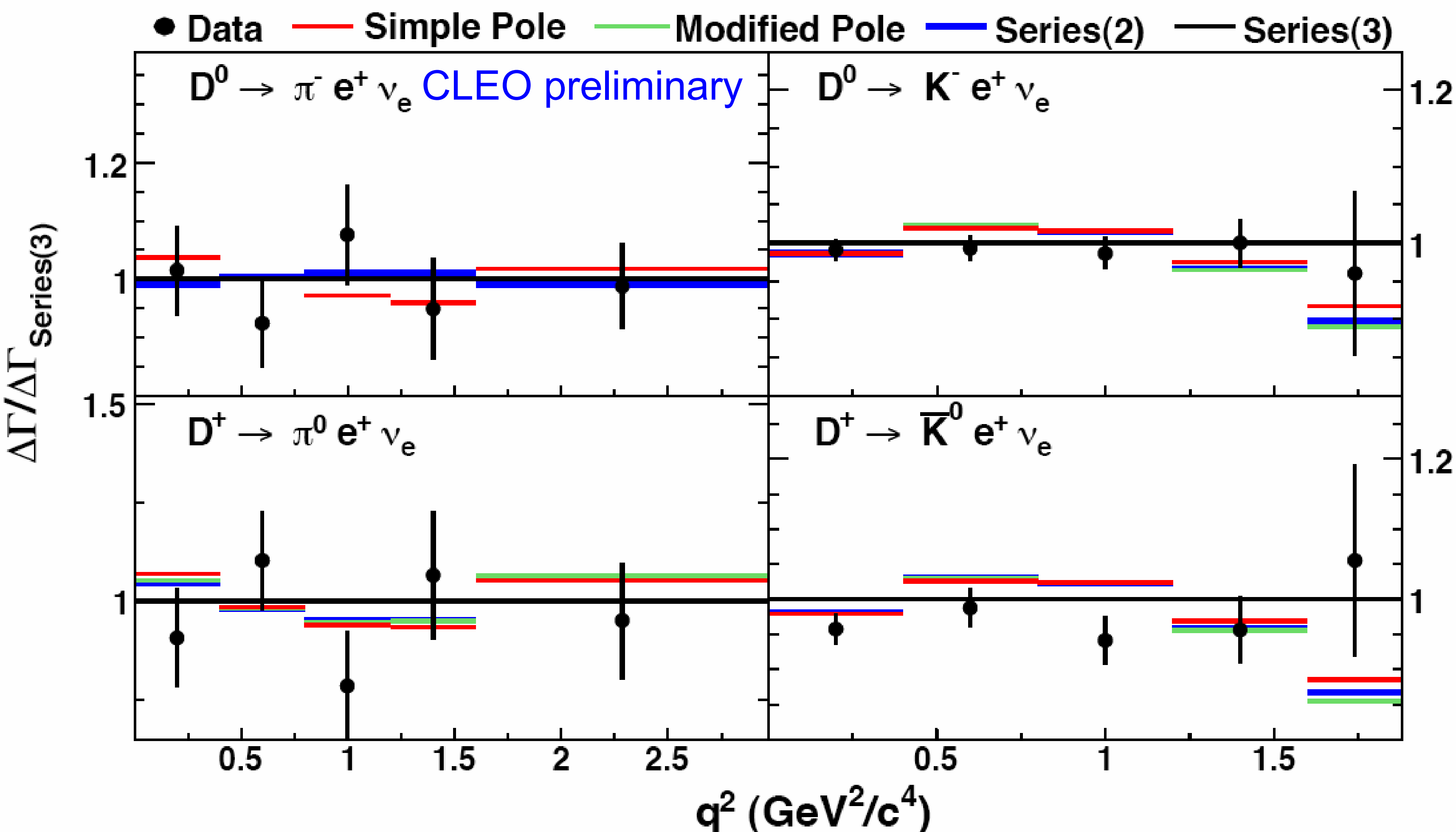


- Cannot calculate from first principles
- Many different parametrizations on the market
- Quantities of interest:
  shape *and* normalization
- Experiment can determine $|V_{cq} \times f_+(0)|^2$
- Unitarity constrains V_{cq}, hence
  stringent tests possible
- HQET links D and B decay



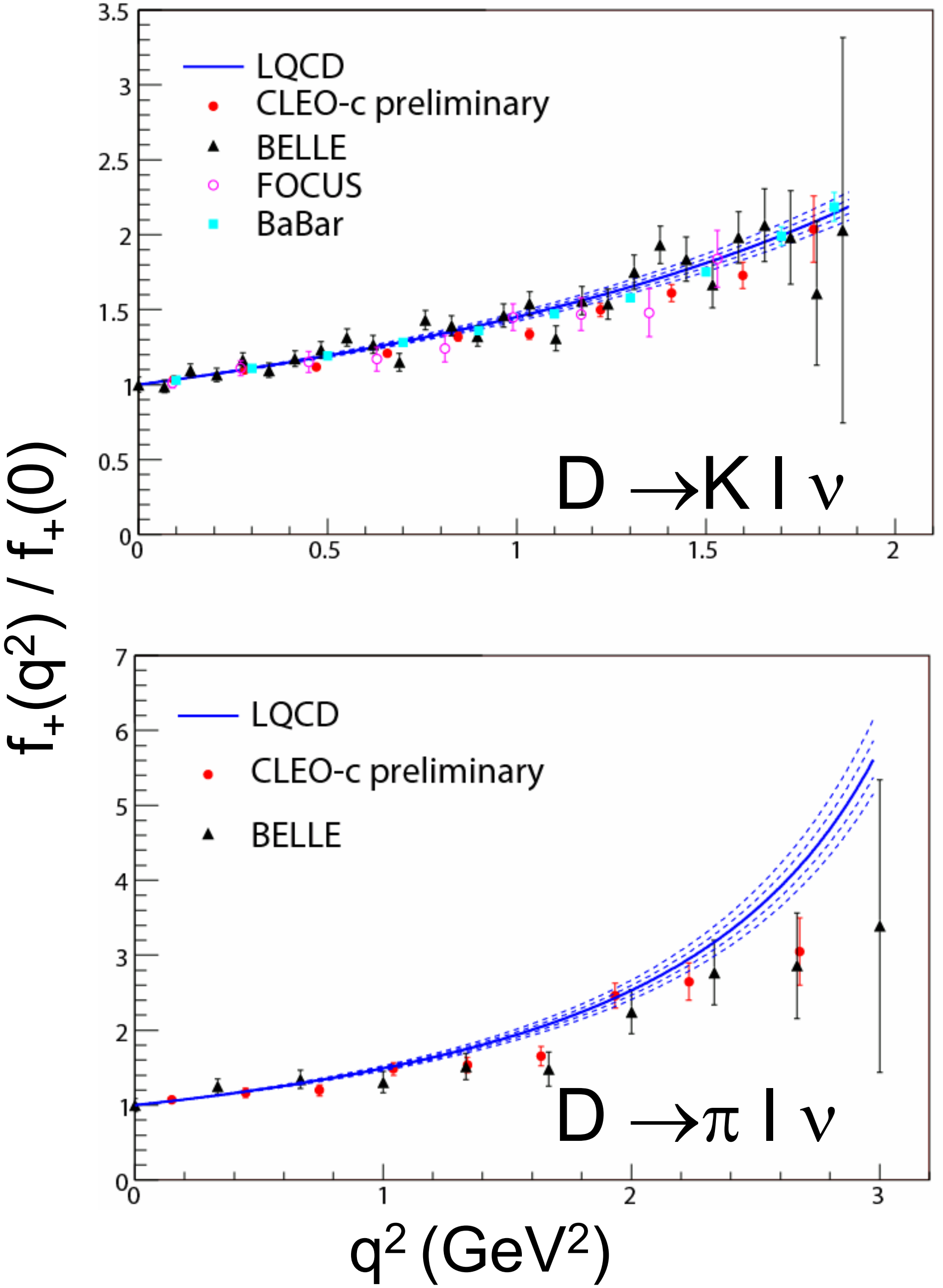
E687, PLB 364, 127 (1995)

$D \to \pi/Ke\nu$: Which Form Factor Parameterization?



Data: CLEO preliminary (untagged)

All these models describe the data pretty well (except when forcing pole mass to nominal value in pole model).



World data on π/Klν form factors

Generally good agreement between experiments

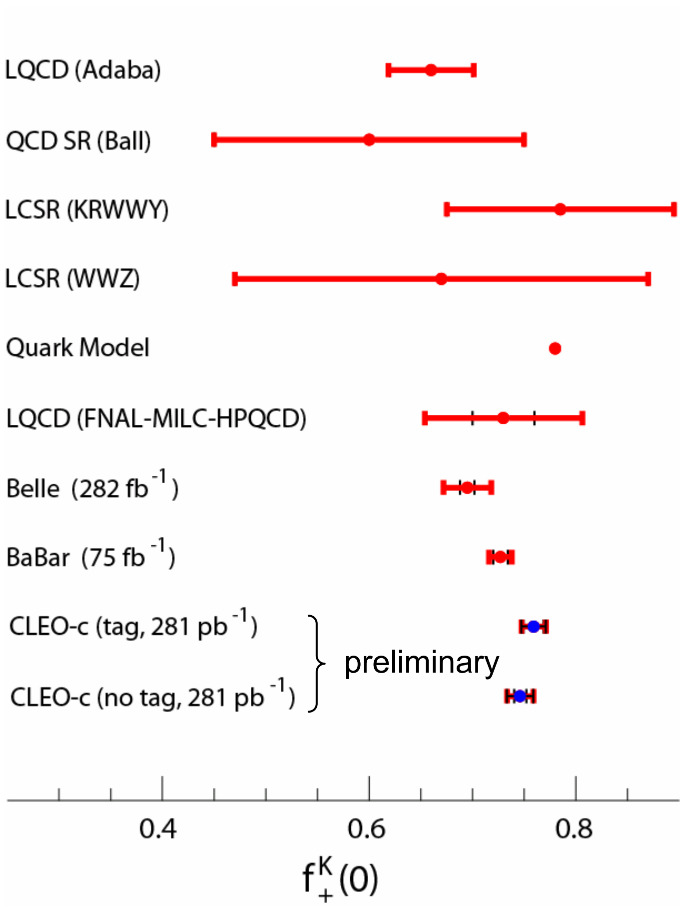
LQCD πeν points a bit high

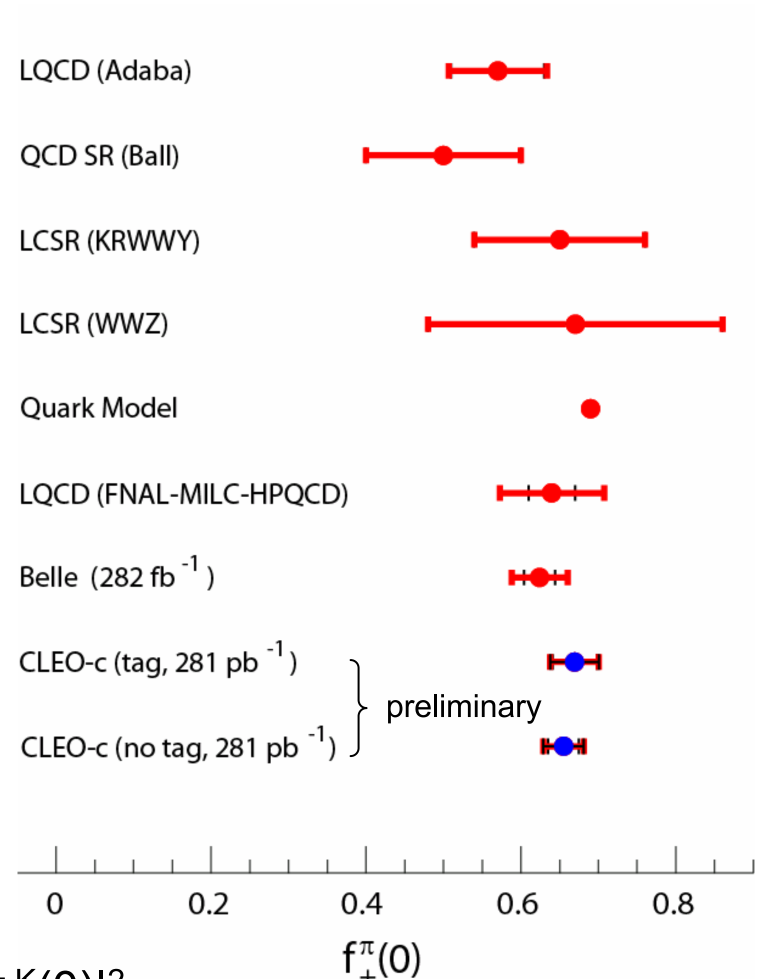
Theory prediction more precise than experiment

BELLE: PRL 97, 061804 (2006) [hep-ex/0604049]
BaBar: hep-ex/0607077
FOCUS: PLB607, 233 (2005) [hep-ex/0410037]
CLEO preliminary

LQCD unquenched: FNAL/MILC/HPQCD, PRL 94, 011601 (2005)

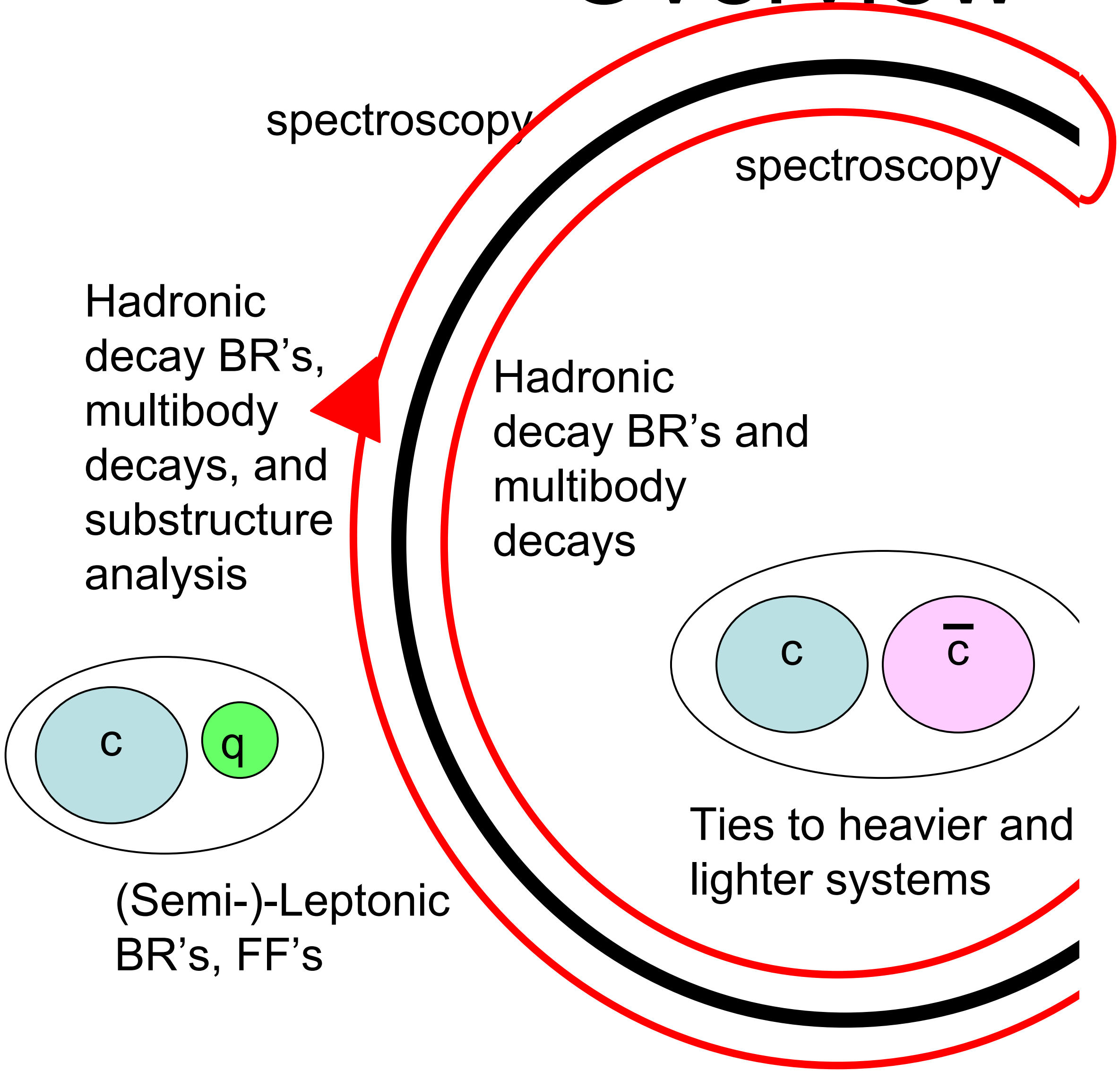
Comparison between form factor normalization determinations





Recall BR is $\propto |V_{cq}|^2 \times |f_+^{\pi,K}(0)|^2$ ...

Overview



Overall mission: Improve our understanding of the strong interaction.

Goals:

Study charm for charm's sake

Calibration playground for heavier systems

Production site for lighter states

OPEN CHARM

Hadronic Branching Fractions

Normalizing modes – need precision

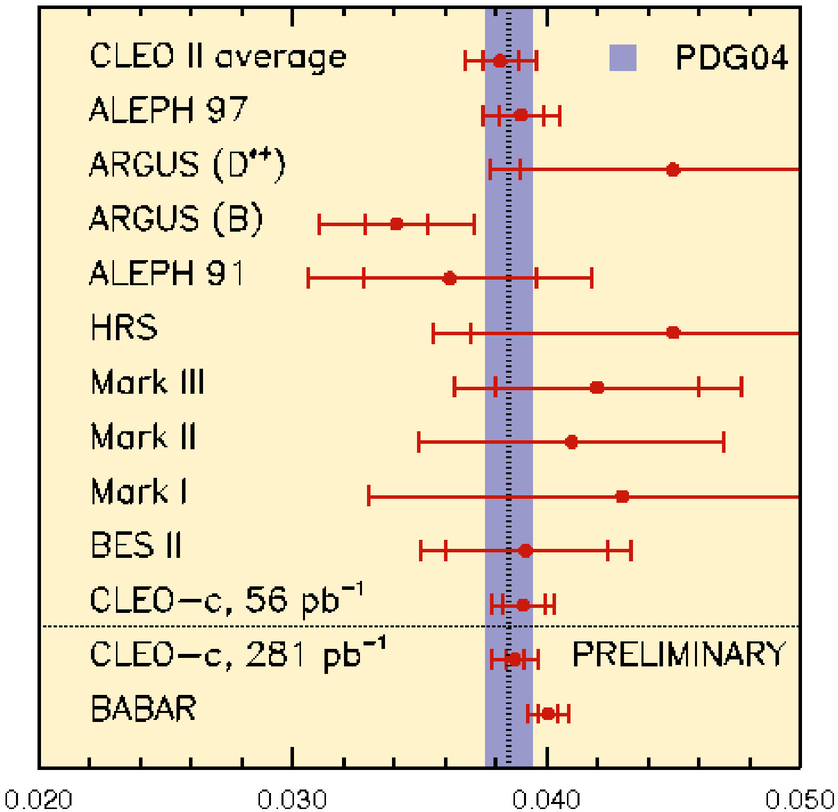
Suppressed modes: assess level of suppression in 2-body and 3-body systems

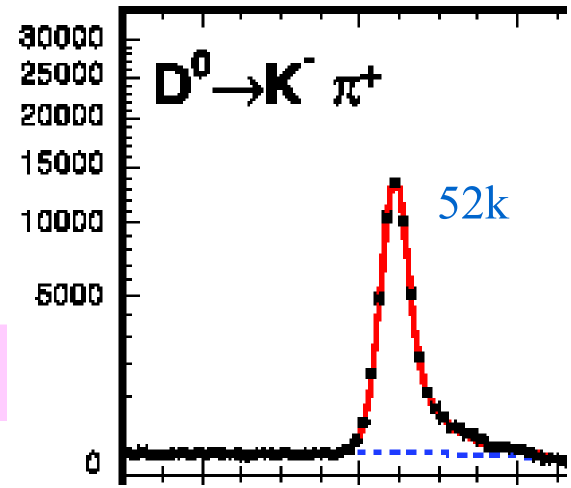
Compare D and D_s

Multibody decays

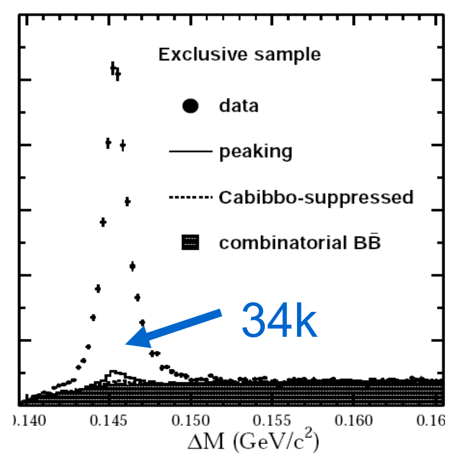
understand decay dynamics

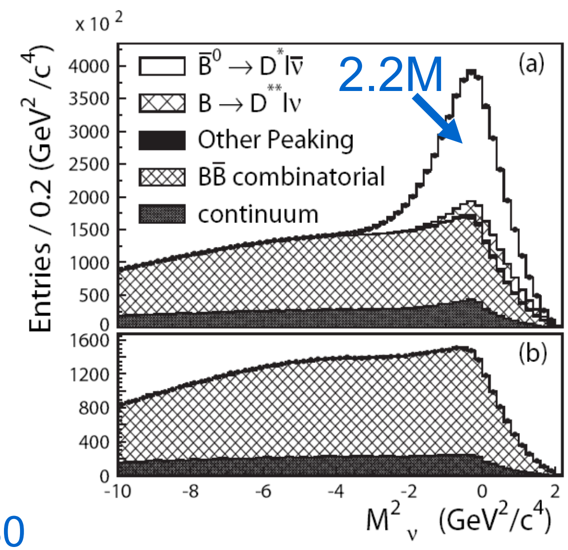
Absolute D hadronic BR measurements





$D^0 \to K^- \pi^+$





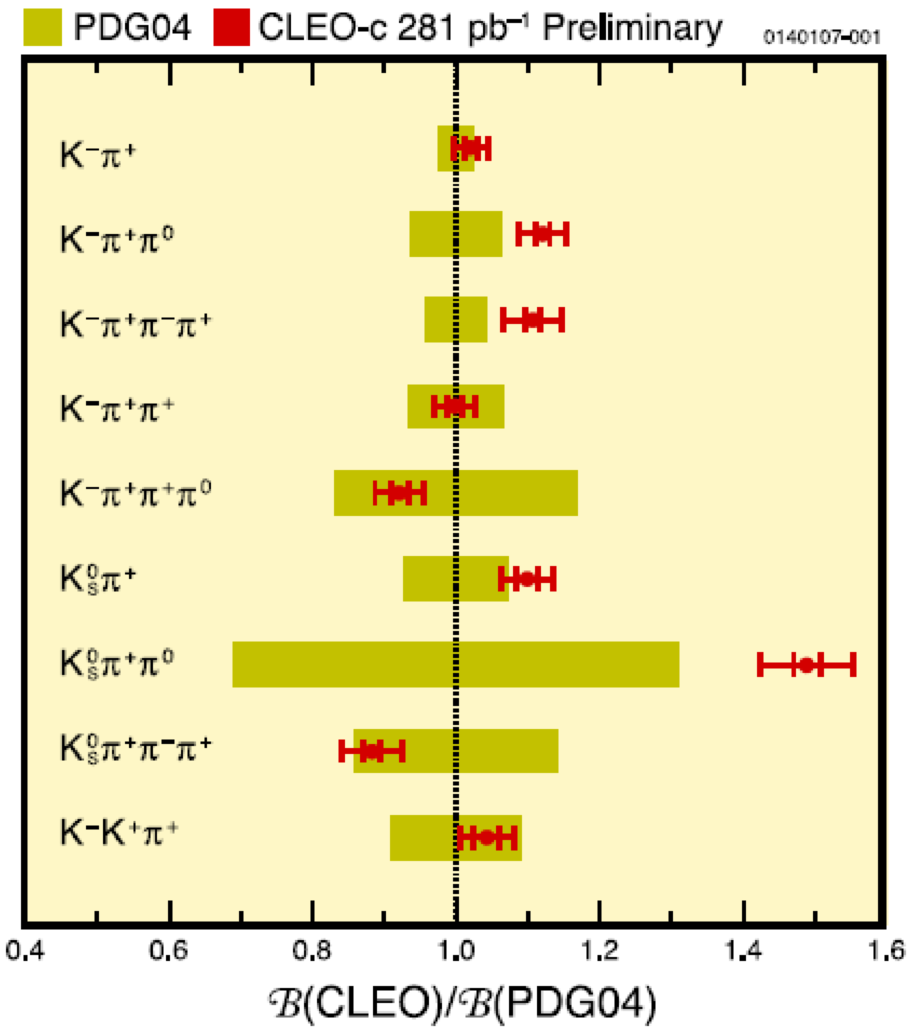
BaBar, 0704.2080

Absolute hadronic D^+ and D^0 BR's

CLEO preliminary

Mode	$\mathcal{B}$ (%)
$D^0 \to K^-\pi^+$	$3.87 \pm 0.04 \pm 0.08$
$D^0 \to K^-\pi^+\pi^0$	$14.6 \pm 0.1 \pm 0.4$
$D^0 \to K^-\pi^+\pi^-\pi^+$	$8.3 \pm 0.1 \pm 0.3$
$D^+ \to K^-\pi^+\pi^+$	$9.2 \pm 0.1 \pm 0.2$
$D^+ \to K^-\pi^+\pi^+\pi^0$	$6.0 \pm 0.1 \pm 0.2$
$D^+ \to K^0_S\pi^+$	$1.55 \pm 0.02 \pm 0.05$
$D^+ \to K^0_S\pi^+\pi^0$	$7.2 \pm 0.1 \pm 0.3$
$D^+ \to K^0_S\pi^+\pi^+\pi^-$	$3.13 \pm 0.05 \pm 0.14$
$D^+ \to K^+K^-\pi^+$	$0.93 \pm 0.02 \pm 0.03$

CLEO, hep-ex/0702021



$D^0 \to \pi^-\pi^+\pi^0, K^-K^+\pi^0 / K^-\pi^+\pi^0$

Starting point: PDG 06

- CF: $D^0 \to K^-\pi^+$: 3.80 ± 0.07 %
- CS: $D^0 \to K^+K^-$: 0.384 ± 0.010 %
- CS: $D^0 \to \pi^+\pi^-$: 0.1364 ± 0.0032 %

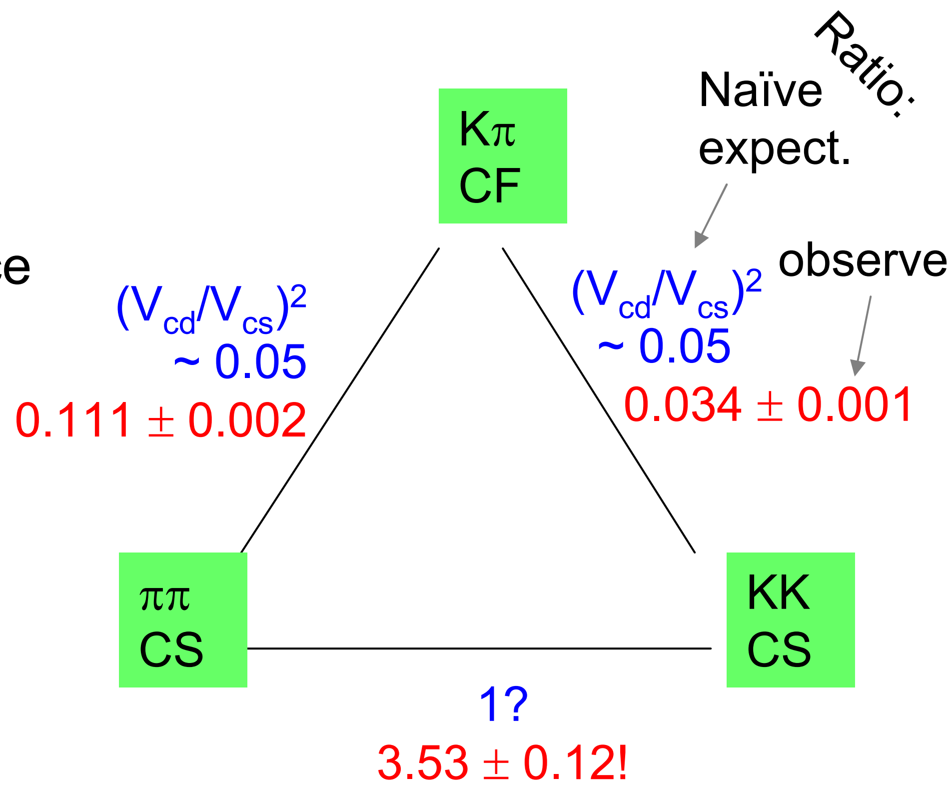
Compare rates, adjust for phase space

Surprisingly small $\pi^+\pi^-$ rate.

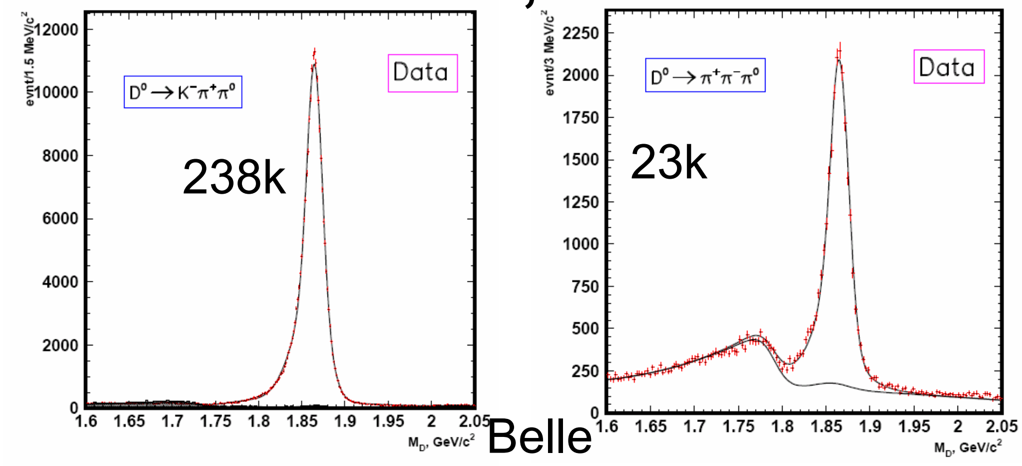
❖ Check 3body decays: add a π^0

Branching ratios:

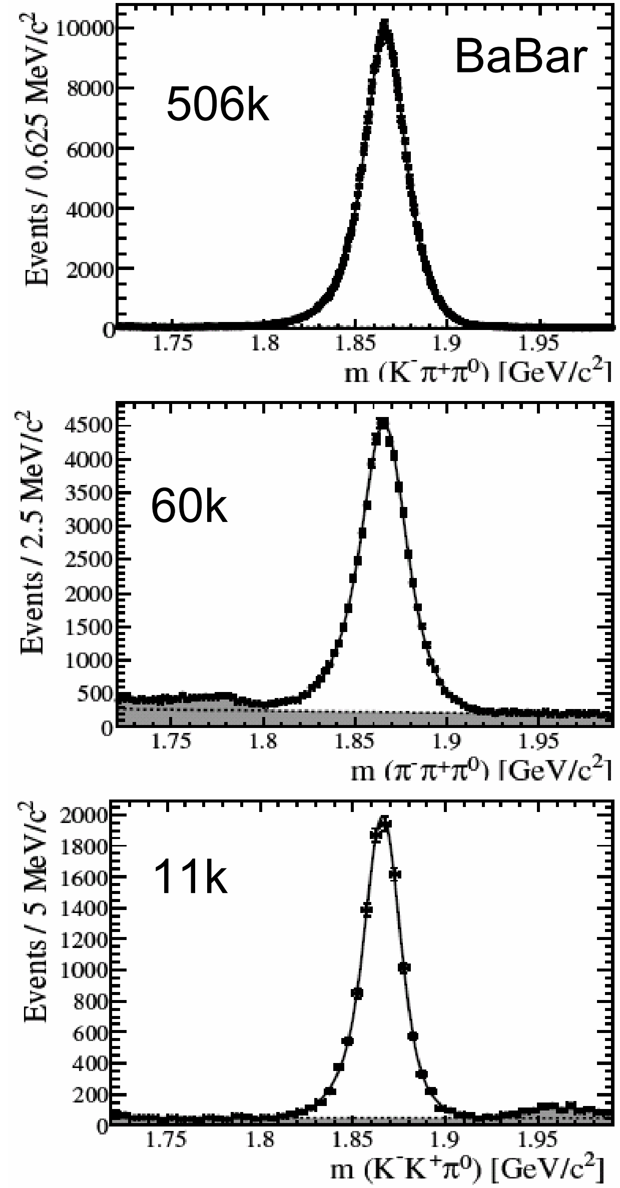
- $K^-\pi^+\pi^0$: 14% (CF),
  $\pi^-\pi^+\pi^0$ ~1.3% (CS),
  $K^-K^+\pi^0$ ~0.13% (CS)



$D^0 \to \pi^-\pi^+\pi^0, K^-K^+\pi^0 / K^-\pi^+\pi^0$



		Branching ratio (10^{-2})			ME ratio	==?
$\pi^-\pi^+\pi^0 / K^-\pi^+\pi^0$	BaBar	10.59	±	0.14	0.07	0.05
	Belle	9.71	±	0.31	0.06	0.05
$K^-K^+\pi^0/K^-\pi^+\pi^0$	BaBar	2.37	±	0.05	0.05	0.05
$K^-K^+\pi^0/\pi^-\pi^+\pi^0$	BaBar				0.68	1



Naïve picture – suppression is an effect of Cabibbo-suppression at the quark level.

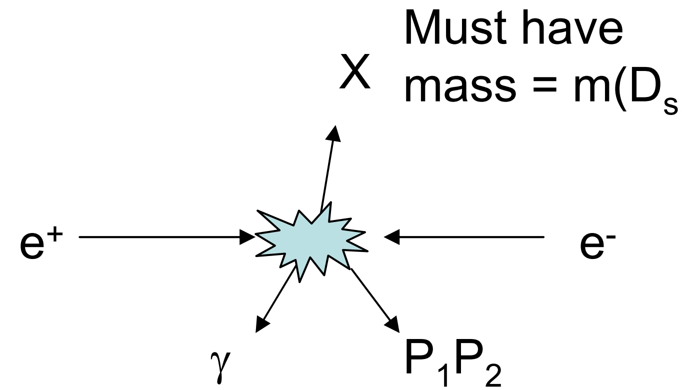
Results support this at the level of 30%.

Doesn't solve puzzle of corresponding 2-body decays…

BaBar 232/fb,
PRD 74, 091102 (2006)R

Belle prelim, 357/fb,
hep-ex/0610062

D_s decay to two pseudo-scalars



Cabibbo Suppressed:

$\pi^0 K^+$

$K^+\eta$

$K^+\eta'$

$K^0\pi^+$

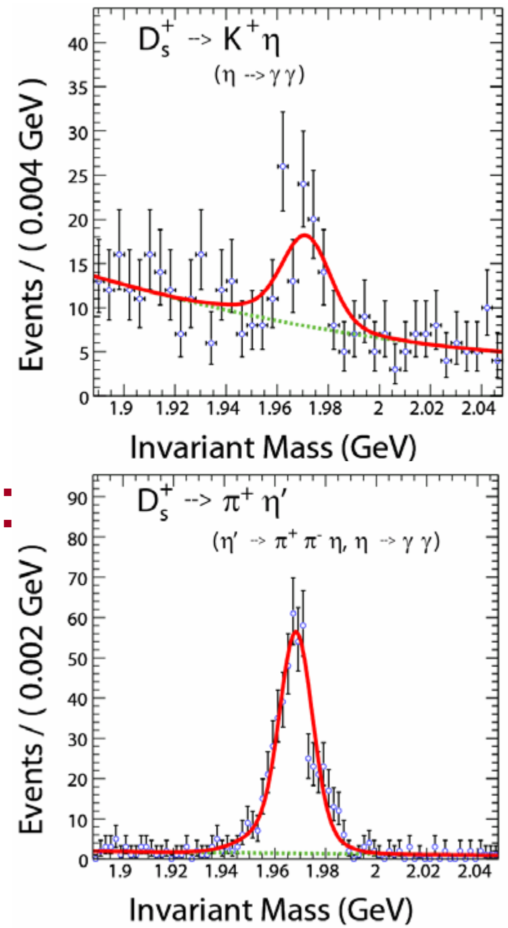
$\pi^+ \pi^0$ Forbidden

Cabibbo Favored:

$\pi^+\eta$

$\pi^+\eta'$

K^+K^0



Single tag analysis
(double tags give consistent results, but costly in statistics)

Goal:
complete survey of all accessible modes.
Compare ratio CS:CF with naïve expectation, 0.05.

Results CLEO Preliminary

Suppressed / favored:

$(D_s \to K^+\eta)/(D_s \to \pi^+\eta) = 0.080 \pm 0.015$

$(D_s \to K^+\eta')/(D_s \to \pi^+\eta') = 0.039 \pm 0.013$

$(D_s \to K^0\pi^+)/(D_s \to K^+K^0) = 0.083 \pm 0.009$

$(D_s \to K^+\pi^0)/(D_s \to K^+K^0) = 0.042 \pm 0.012$

$(D_s \to \pi^+ \pi^0)/(D_s \to K^+K^0) < 0.04$

Compare with $(V_{cd}/V_{cs})^2$ of 1/20

Statistics limited – more data to come

Substructure analysis of multibody decays

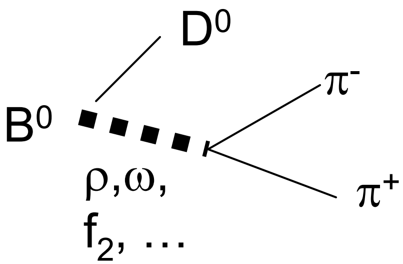
Goal – learn about intermediate states and decay dynamics

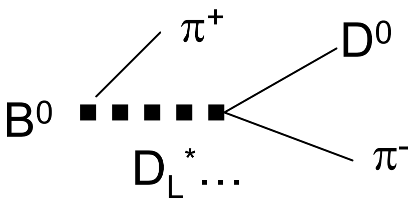
Modern data samples afford the opportunity to study these decays in detail
(many x10^3 well-reconstructed events)

Need to find a way to parametrize the intermediate states

Industry of formalisms:

Breit-Wigner resonance shapes,
K-Matrix formalism,
projective weighting technique,
…

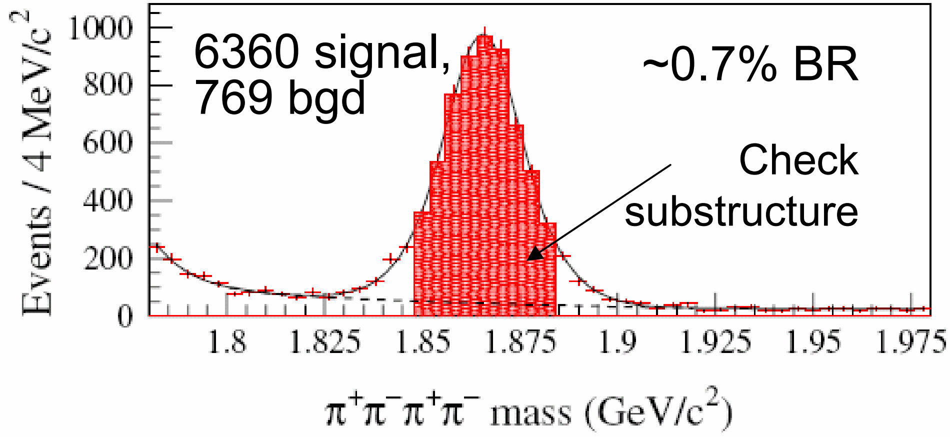


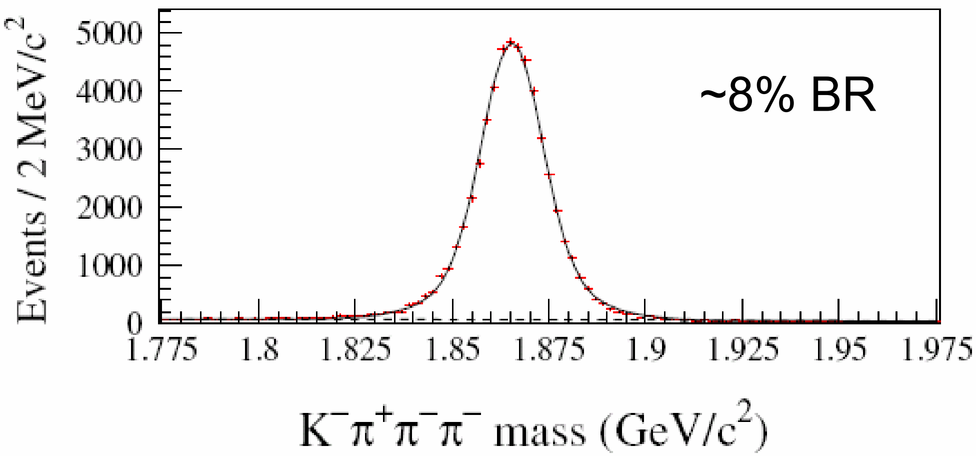


Issues:
- Quality control
- Theoretical basis
- Knowledge of intermediate states, esp. consistency with scattering experimens
- Final state interactions

FOCUS, PRD 75, 052003 (2007)

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





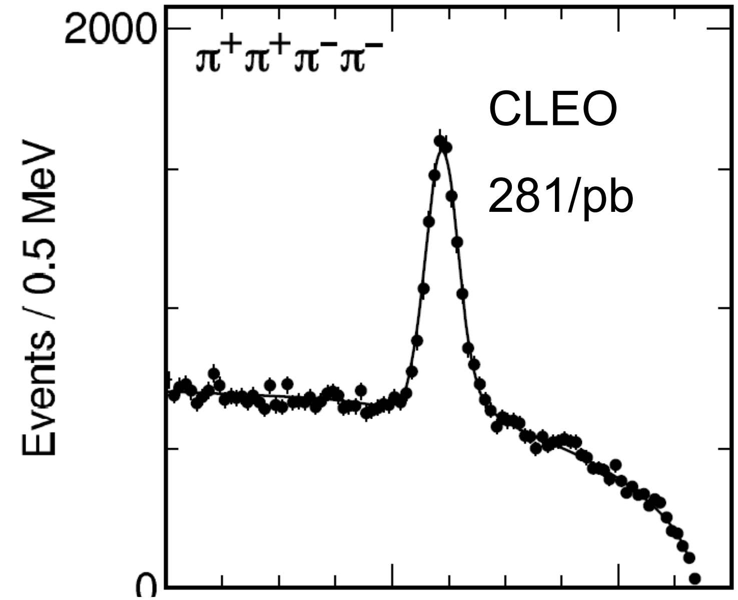
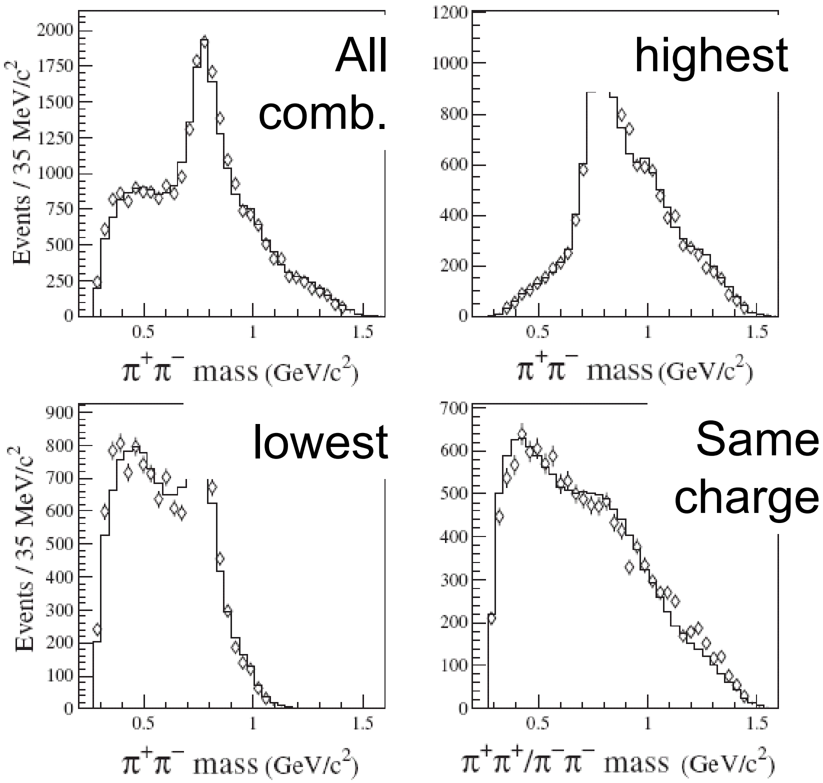


TABLE II. Comparison with other experiments.

Experiment	$\Gamma(D^0 \to \pi^-\pi^+\pi^-\pi^+)/\Gamma(D^0 \to K^-\pi^+\pi^-\pi^+)$	Events
FOCUS (this result)	$0.0914 \pm 0.0018 \pm 0.0022$	6360 ± 115
CLEO-c [20]	$0.097 \pm 0.002 \pm 0.003$	7331 ± 130
BES [21]	$0.079 \pm 0.018 \pm 0.005$	162 ± 20
E687 [22]	$0.095 \pm 0.007 \pm 0.002$	814 ± 26

FOCUS, PRD 75, 052003 (2007)

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



Amplitude analysis, 1st time:

Motivation:

- Just because,
- to study FSI,
- to gain experience with $4\pi^\pm$ structure and in particular $a_1(1260)$ lineshape and decays → B^0 to $4\pi^\pm$

Model, 10 baseline components:

- 3: $D^0 \to a_1(1260)^+ \pi^-$, $a_1^+ \to \rho^0\pi^-$ (S and D) and $\sigma\pi^+$
- 3: $D^0 \to \rho^0\rho^0$ in three helicity states
- 4: $D^0 \to \pi^+\pi^- + \mathcal{R}$, $\mathcal{R} = \sigma, \rho^0, f_0(980), f_2(1270)$

Fit result, dominant contributions:

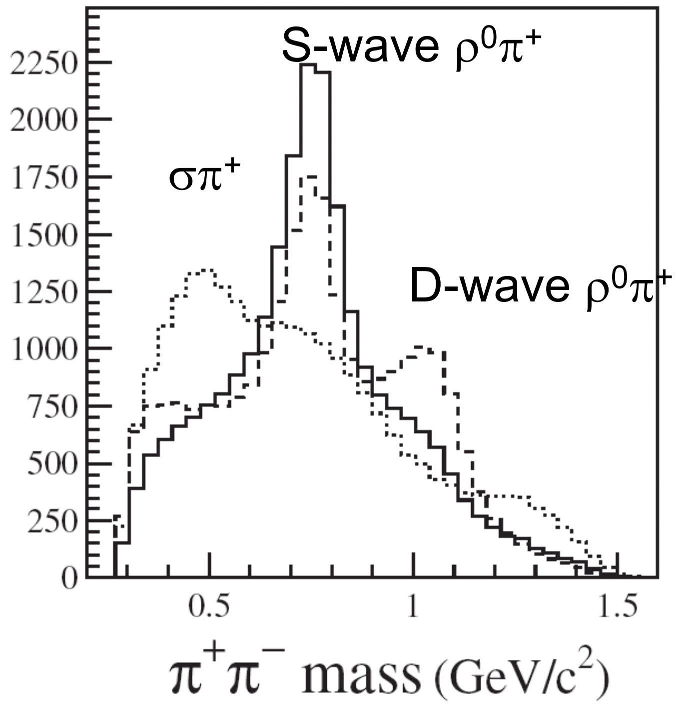
- $a_1(1260)$ – 60%, $a_1(1260)$ dominance also seen in $K^+\pi^+\pi^-\pi^+$ and $K^0\pi^+\pi^-\pi^+$
- $\rho^0\rho^0$ – 25%, $D^0 \to V_1V_2$ also not uncommon
- $\pi^+\pi^-$ + resonance – 11%

Simplified model gets gross features right, but CL is low.

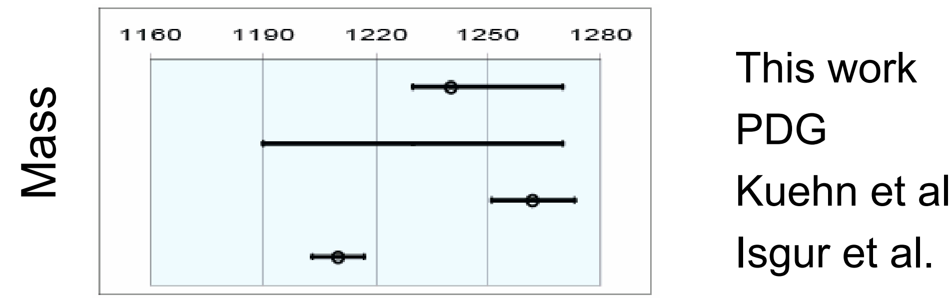
"It is very unlikely that the poor CL is caused by problems with the representation of signal amplitudes." – model too simplistic? FSI?

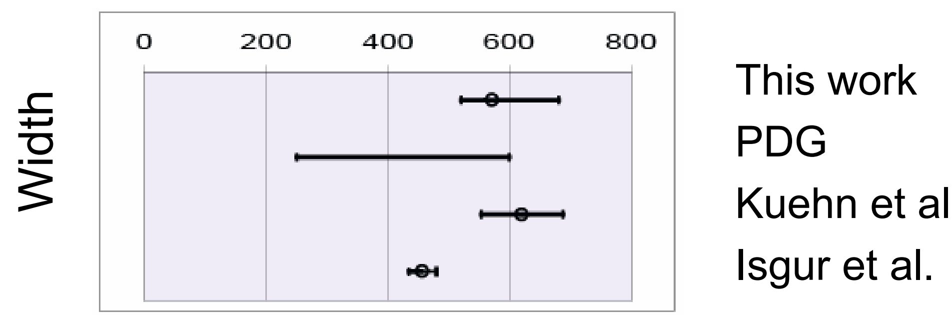
FOCUS, PRD 75, 052003 (2007)

Information on $a_1(1260)$



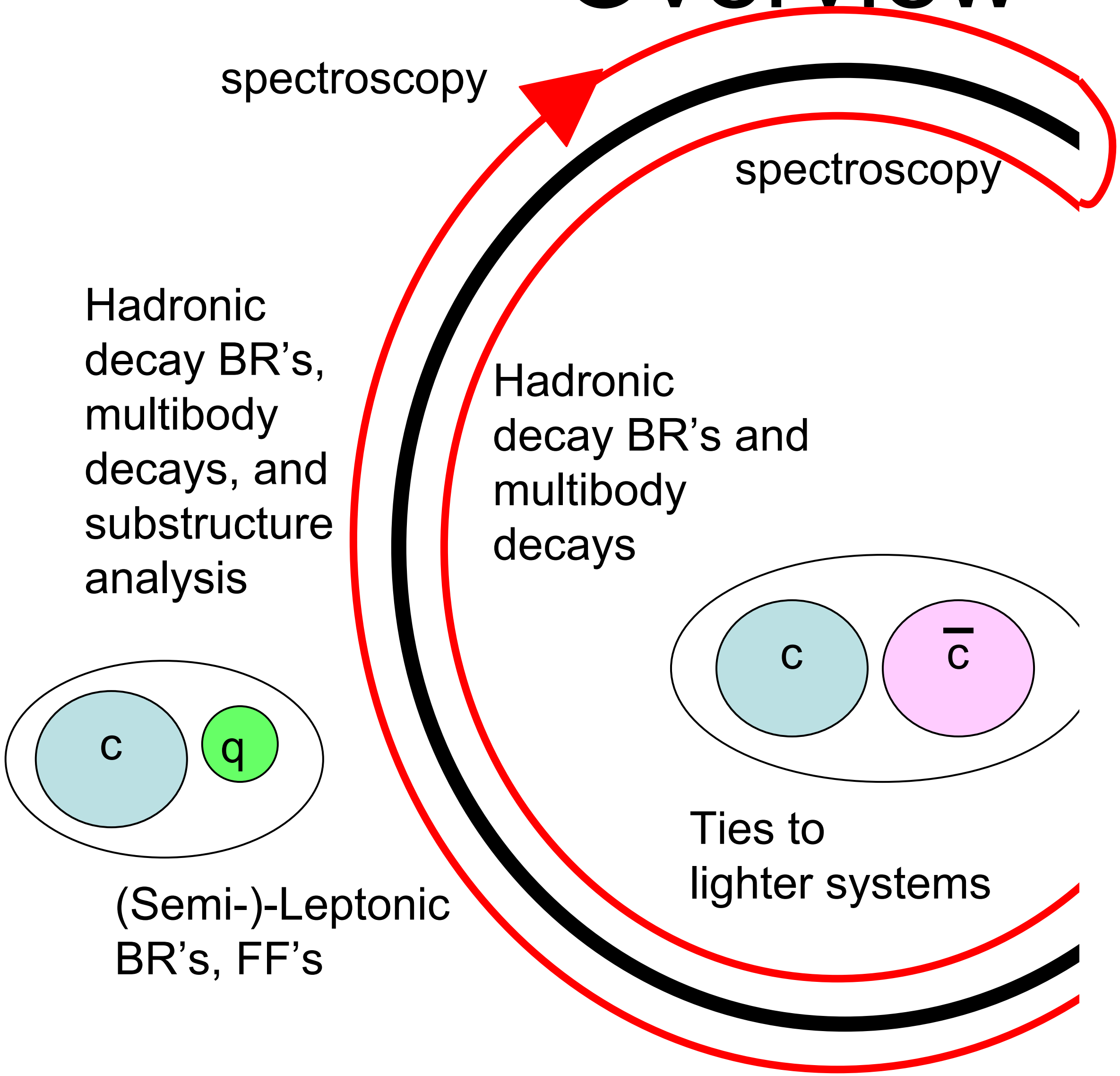
Compare $a_1(1260)$ decay:
here – 3 decays are enough,
tau $\rightarrow \nu 3\pi$ – 7 amplitudes were needed (CLEO),
but still, dominant features were like found here.





MC simulation of the $\pi^+\pi^-$ mass distribution for the $a_1(1260)^+$ decay modes used in the FOCUS fit

Overview



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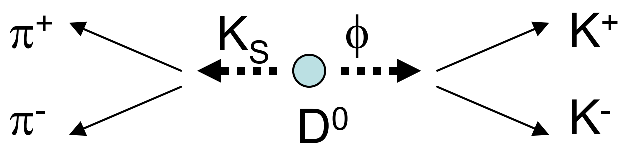
Production site for lighter states

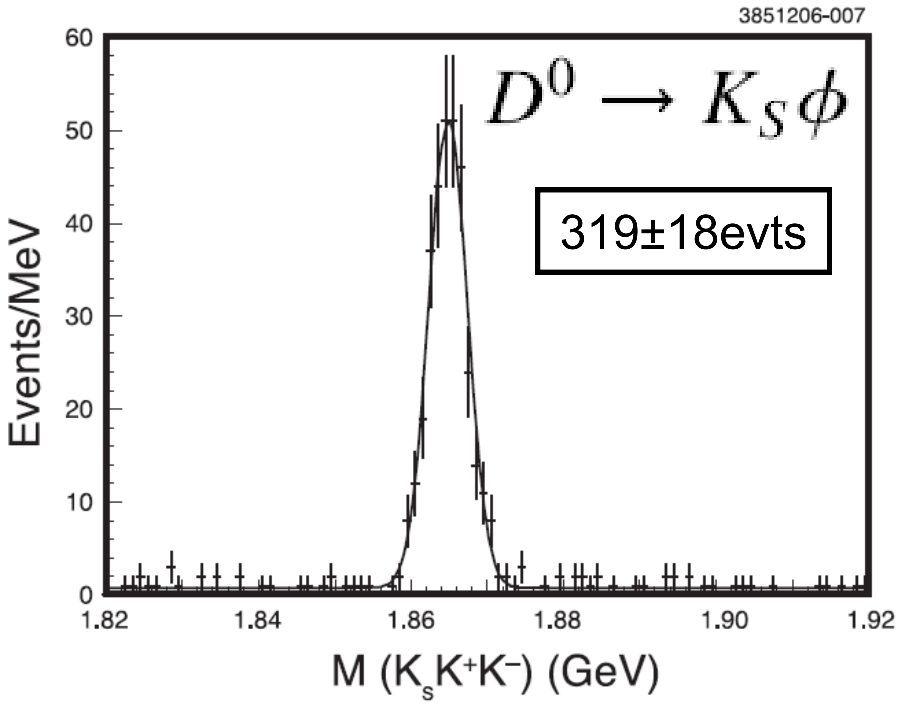
CLEO PRL 98, 092002 (2007)

D^0 mass measurement

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

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





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

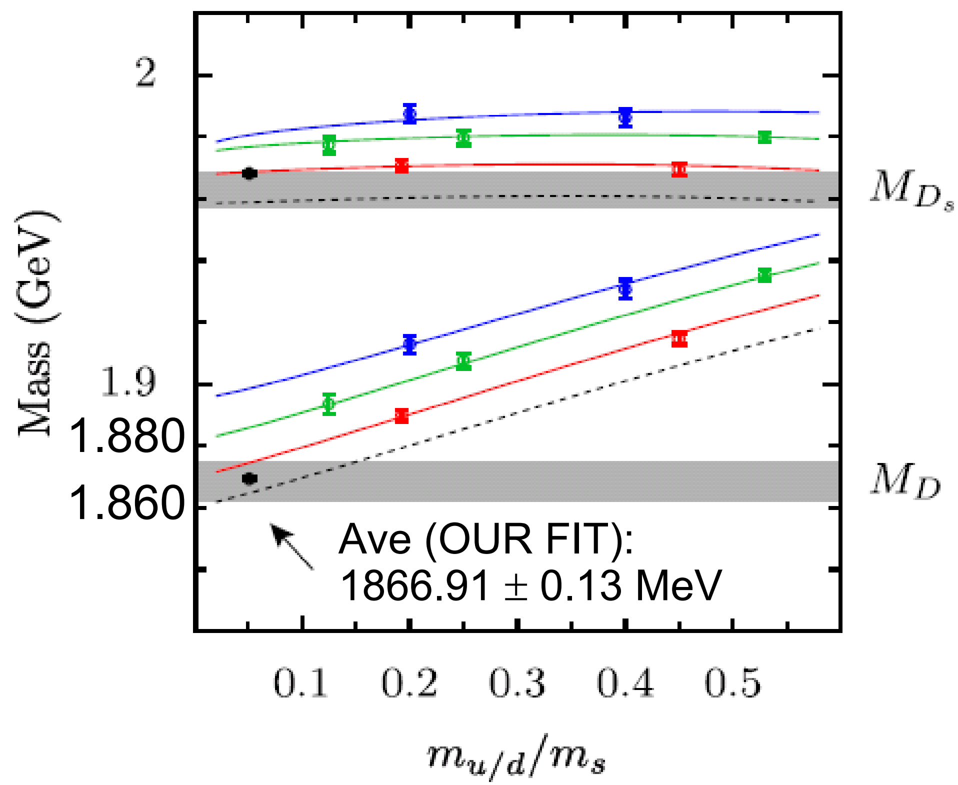
LQCD D mass calculation

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)

OPEN CHARM

Production

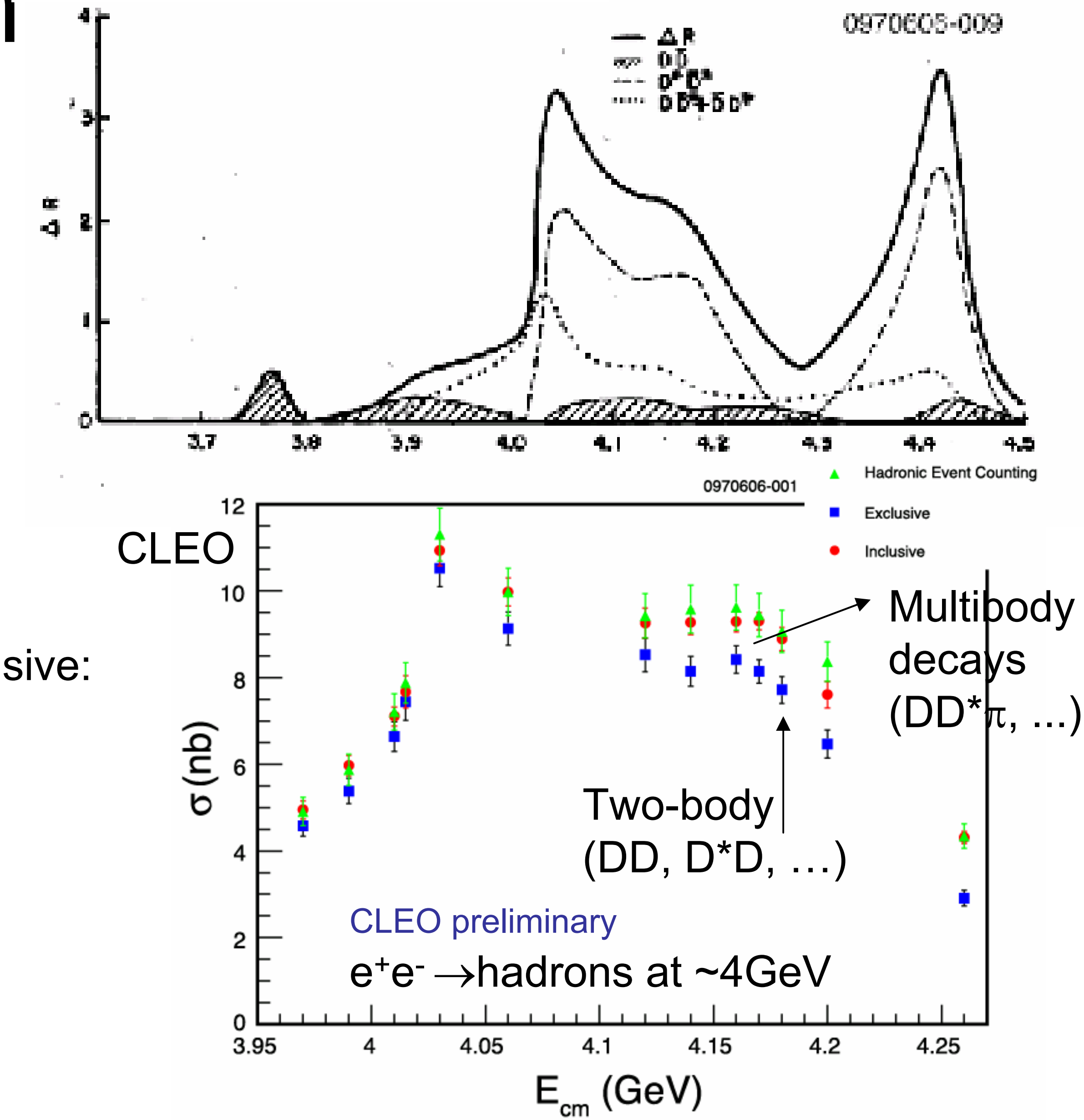
Issues: measure rate as function of center-of-mass energies for inclusive hadron production as well as exclusive D-pair combinations

Determine charmonium resonance parameters

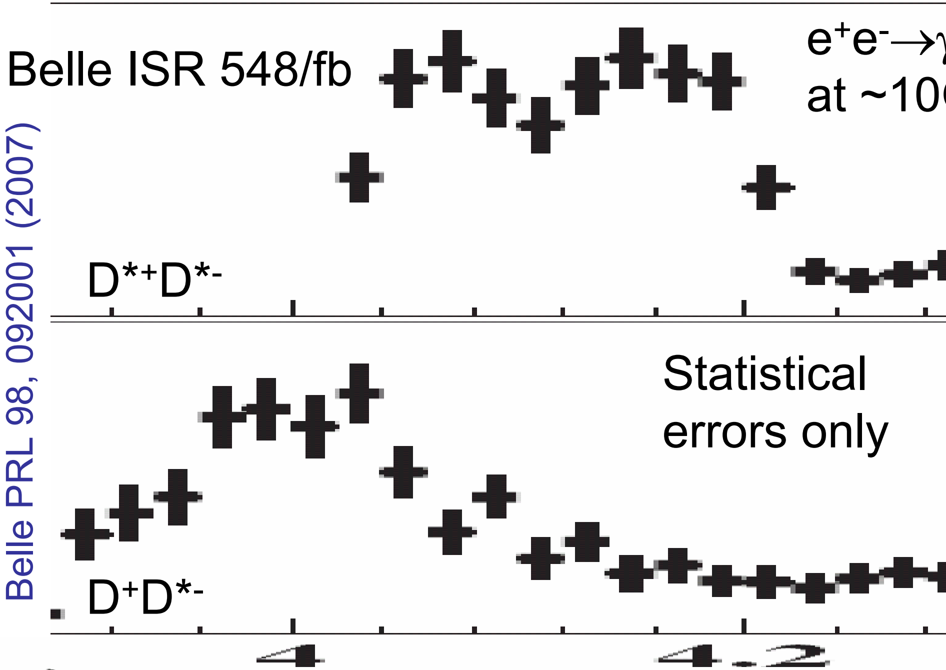
Study dependence of production rate on center-of-mass energy

Open charm production in e^+e^-

Eichten et al, PRD 21, 208 (1980)

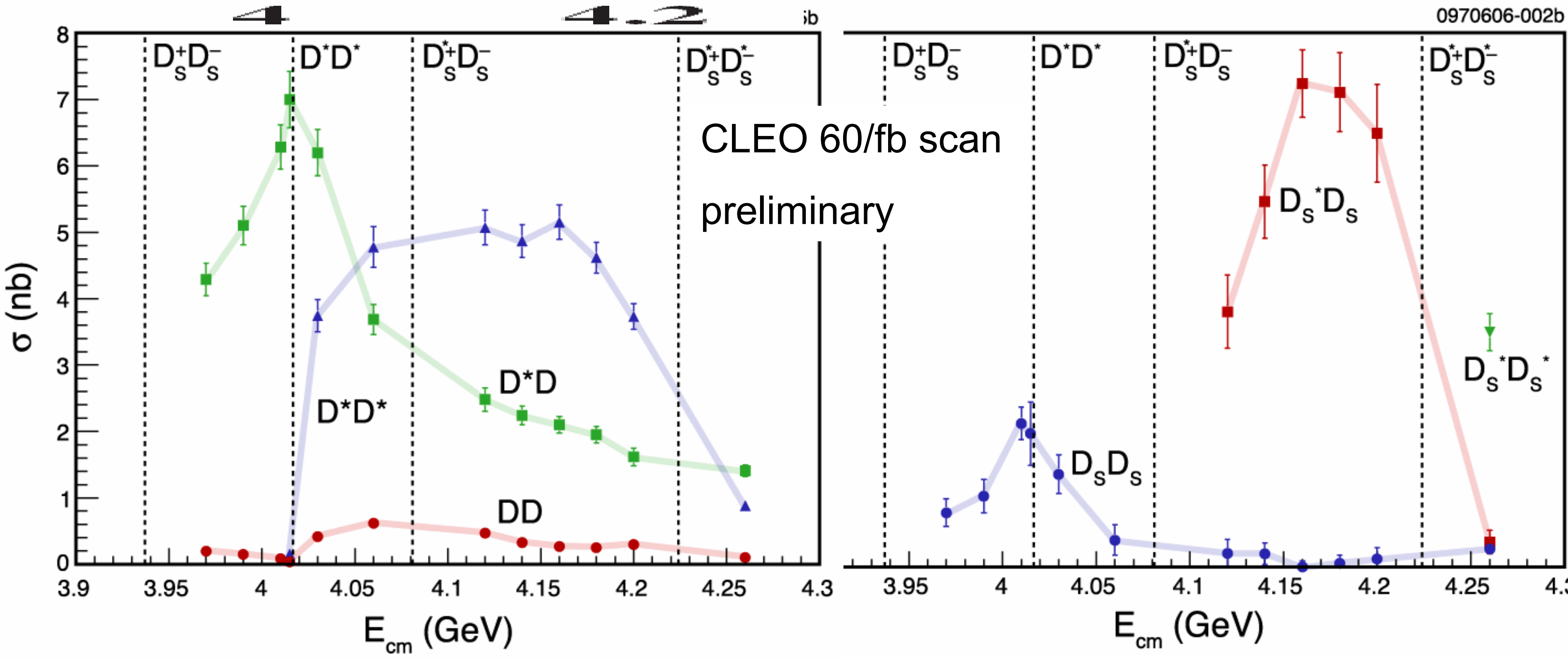


inclusive:

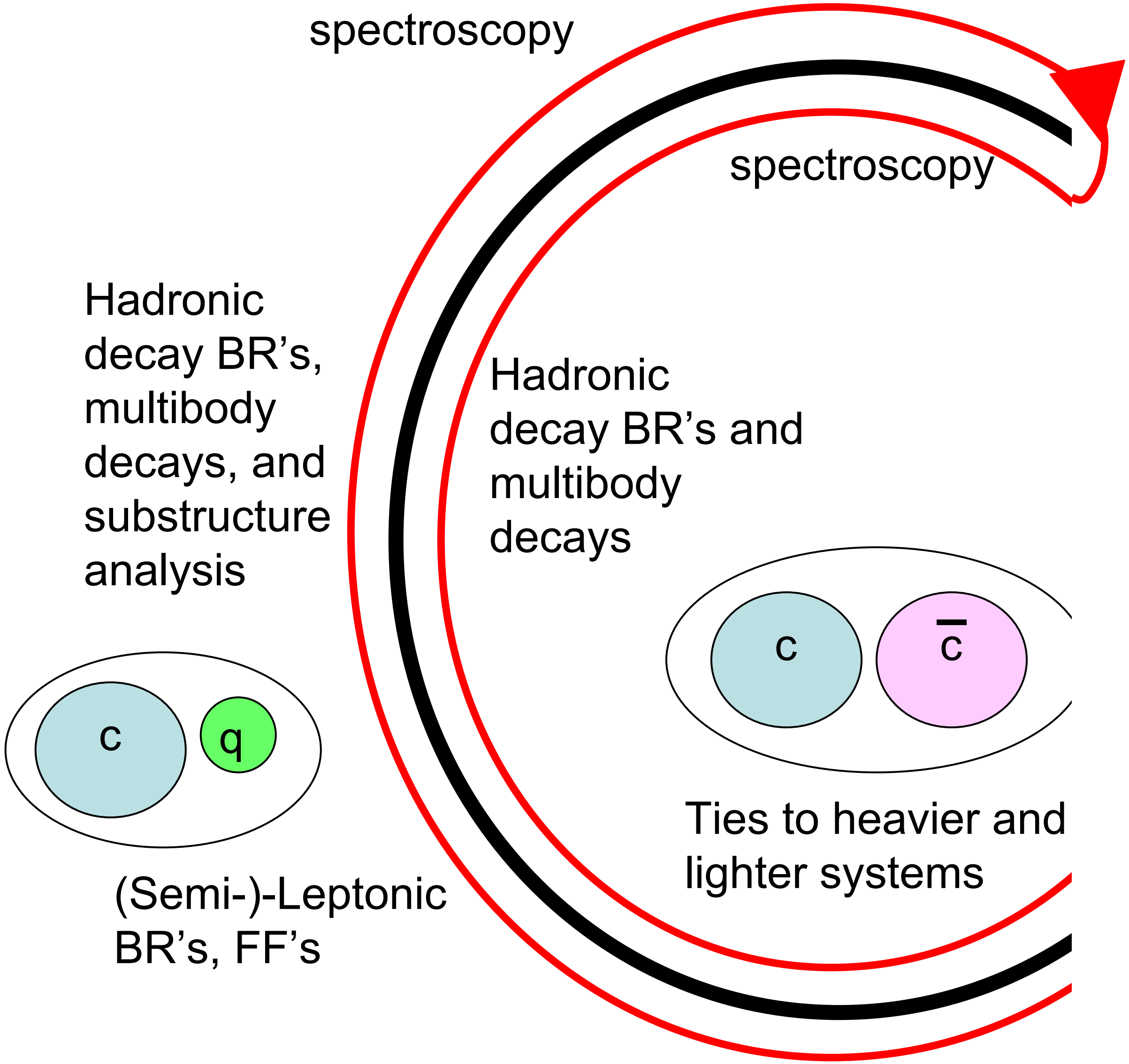


Rough features agree between CLEO and Belle measurements.

Interpretation of the rates as charmonium resonances next…



Overview



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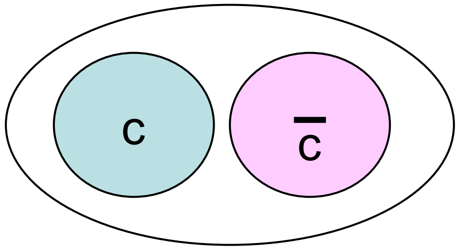
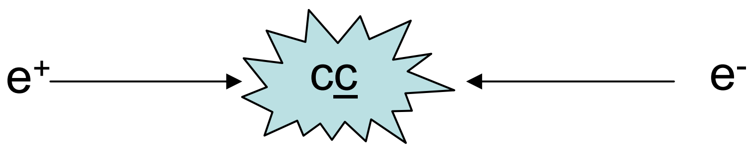


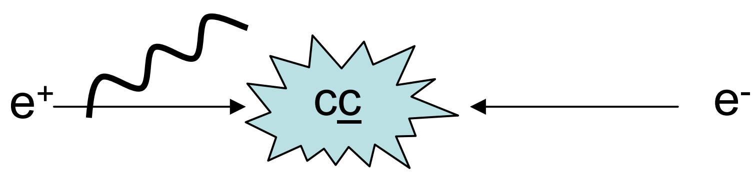
Charmonium

$J^{PC} = 1^{--}$

At threshold (CLEO, BES)

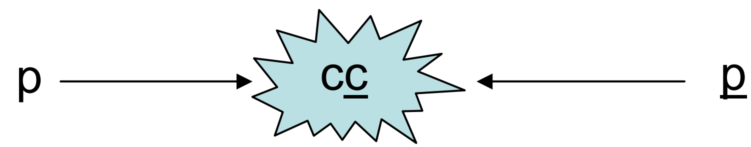


At ~10GeV (BaBar, Belle)

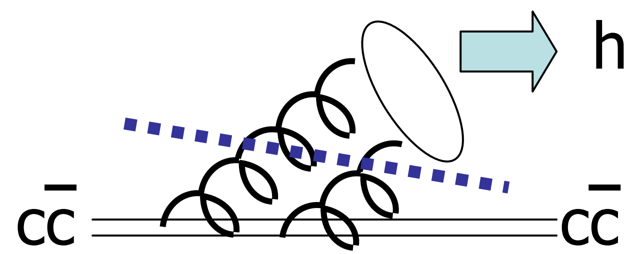


More quantum numbers:

In $p\bar{p}$ (E835, PANDA)



Anywhere:



and other transitions

- Transitions: low energy release (<1GeV)
- Decay: perturbative methods apply
- Spectrum of bound states an important test for models

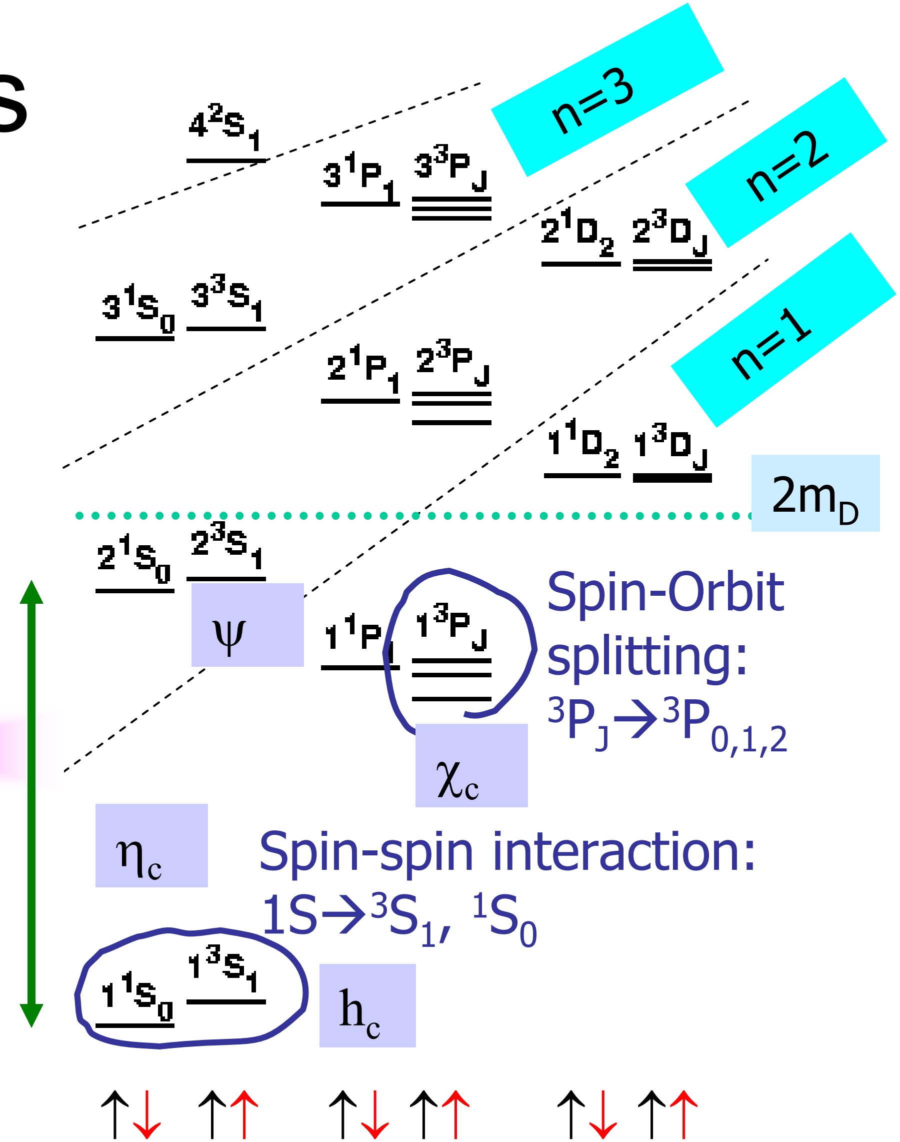
Charmonium States

? **Masses**
? **Widths**
? **Production and decay dynamics**

Charm system is very similar to bottom system, $(v/c)^2$ for charm is 0.25, 0.08 for bottom

589MeV

Non-perturbative regime

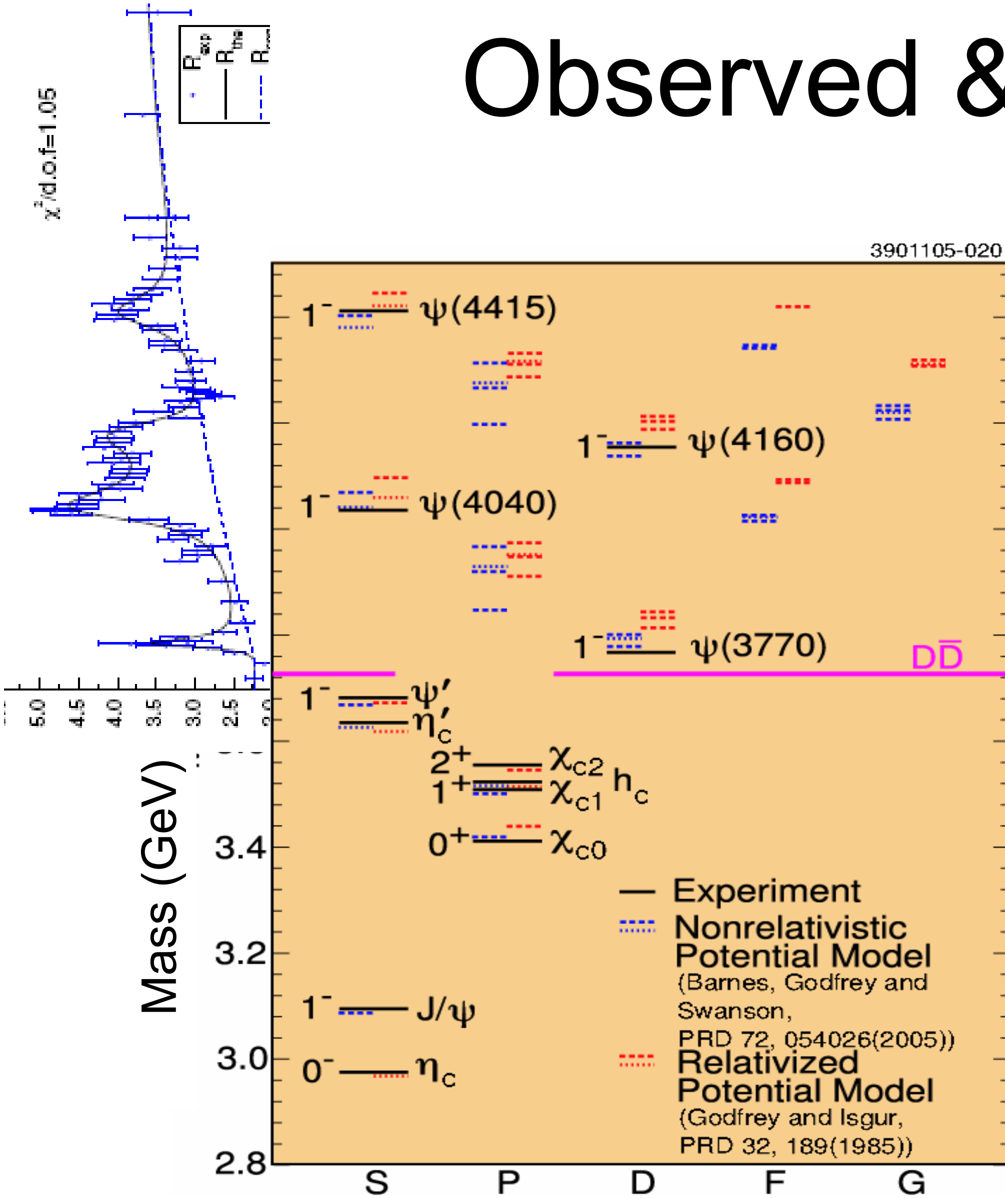


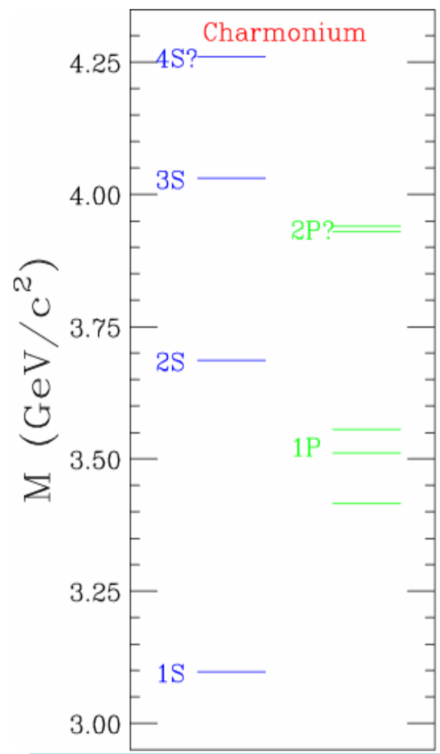
Notation: $n^{2S+1}L_J$, $\vec{J} = \vec{L} + \vec{S}$

Partly discovery, partly precision measurements

Above DD threshold:

Observed & Predicted States



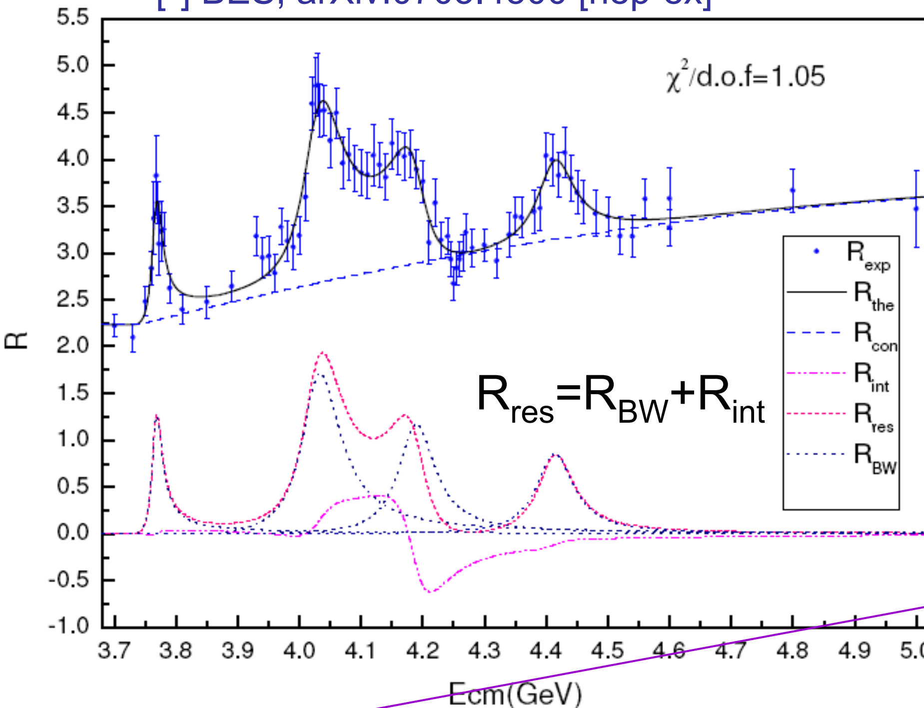


V(r)~log r
Rosner & Quigg, PLB71,153 (1977)

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.

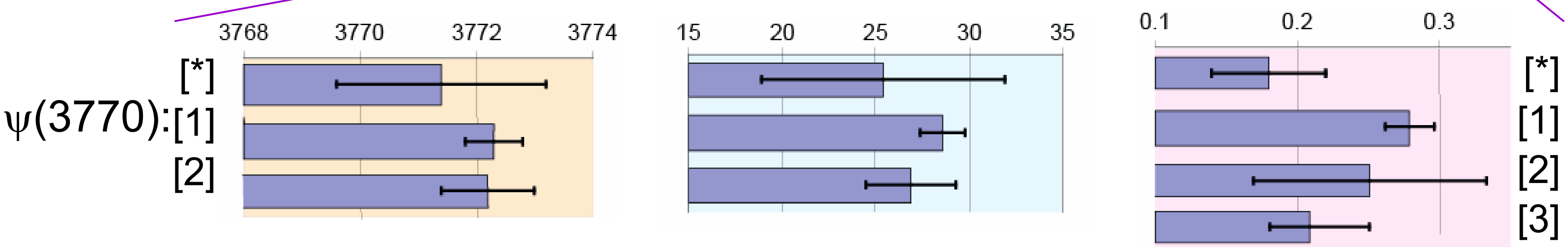
Re-analysis of BES R data and extraction of charmonium resonance parameters

[*] BES, arXiv:0705.4500 [hep-ex]



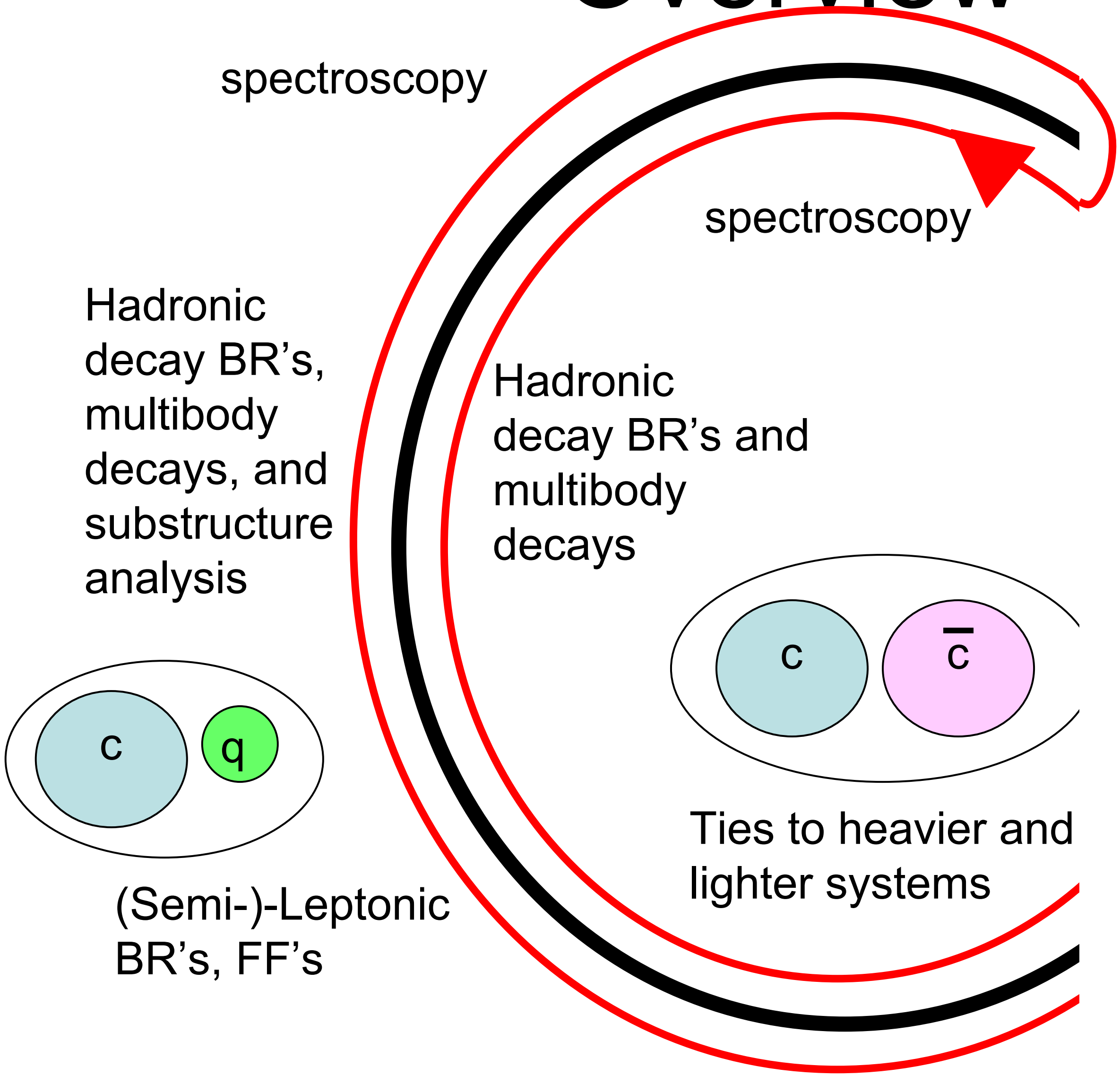
		$\psi(3770)$	$\psi(4040)$	$\psi(4160)$	$\psi(4415)$
M (MeV/c^2)	PDG2004	3769.9±2.5	4040±10	4159±20	4415±6
	PDG2006	3771.1±2.4	4039±1.0	4153±3	4421±4
	CB (Seth)	-	4037±2	4151±4	4425±6
	BES (Seth)	-	4040±1	4155±5	4455±6
	BES (this work)	3771.4±1.8	4038.5±4.6	4191.6±6.0	4415.2±7.5
Γ_{tot} (MeV)	PDG2004	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

[1]: BES, hep-ex/0612056 (68 scan points)
[2]: BES, PRL 97, 121801 (49 scan points)
[3]: CLEO, PRL 96, 092002 (2006)



Mass (GeV) Γ_{tot} (MeV) Γ_{ee} (MeV)

Overview



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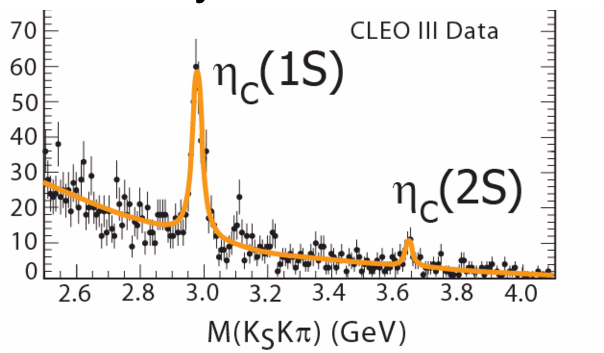
Below-threshold Charmonium

SPECTROSCOPY

Goal:
describe the observed spectrum of states
and study their properties

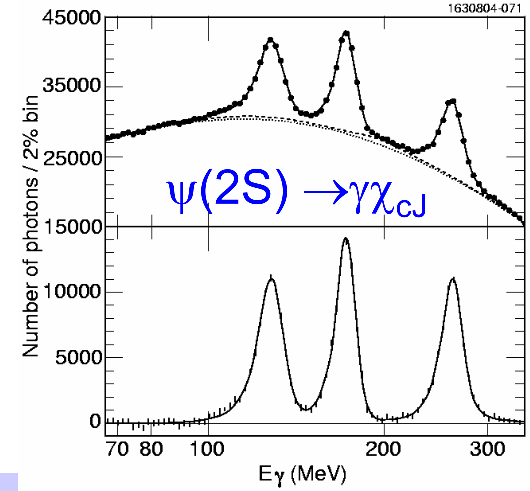
Charmonium States

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



2^1S_0 2^3S_1

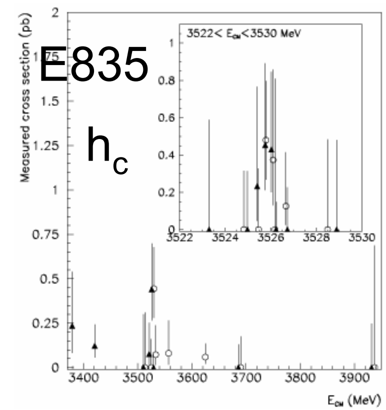
χ_{cJ}: masses, width, dominant decay modes reasonably well measured. Beginning to study substructure.



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!



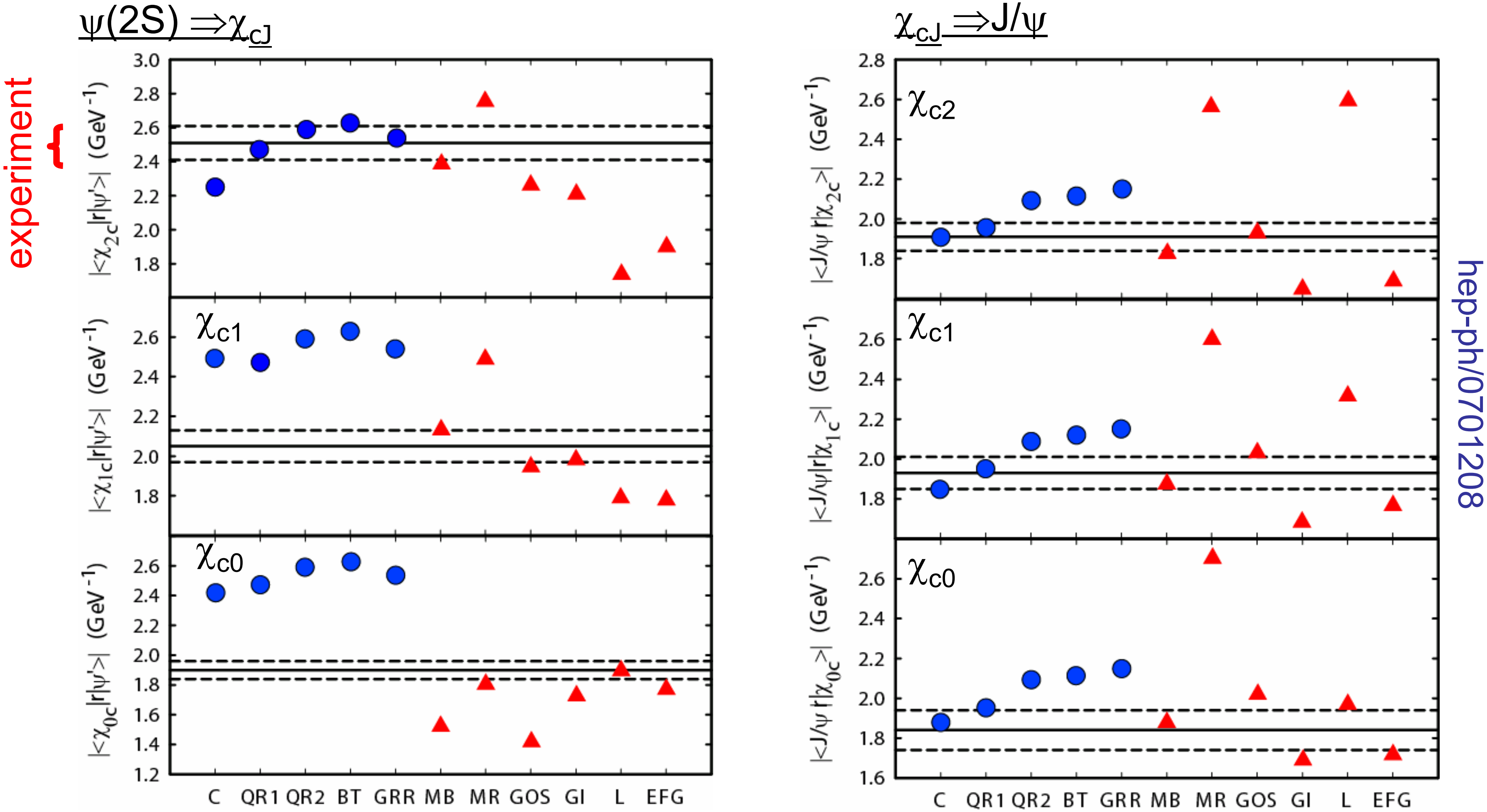
$\eta_c(1S)$: mass and width known to MeV's, most urgent project: M1 transition rate $J/\psi \to \gamma\eta_c$

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.

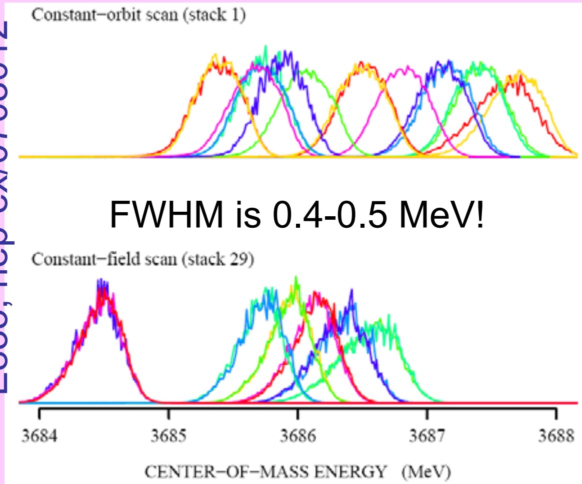
E1 rates, theory vs experiment



Potential model calculations: ● non-relativistic ▲ relativistic

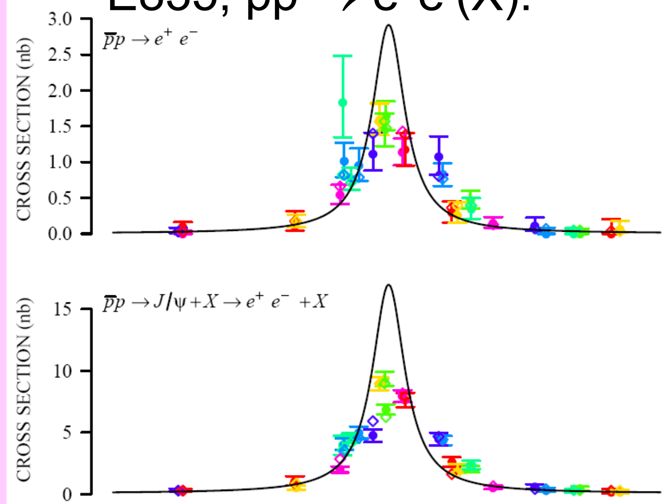
$\psi(2S)$ width measurements

E835, hep-ex/0703012

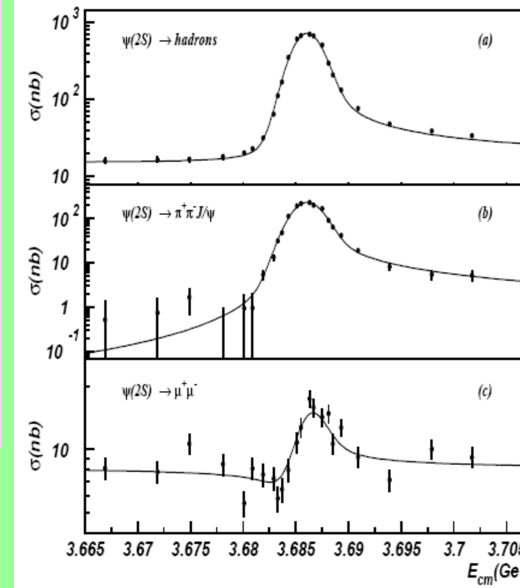


FWHM is 0.4-0.5 MeV!

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

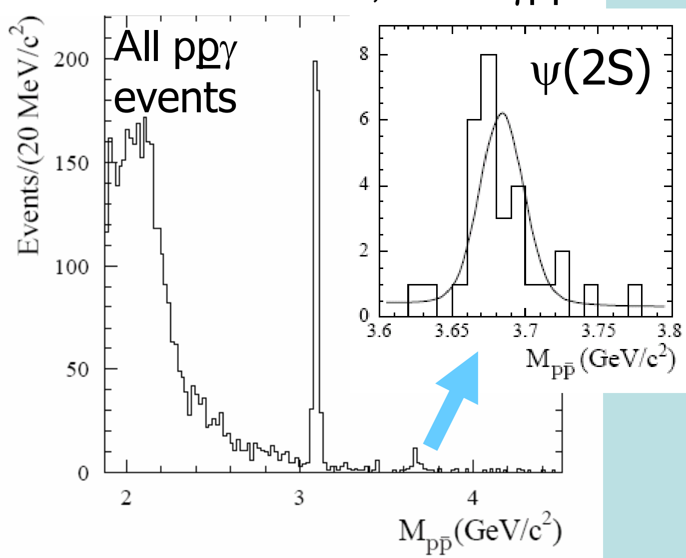


BES scan:



BES, PLB 550, 24 (2002)

BaBar ISR 232/fb, $e^+e^- \to \gamma p\bar{p}$:



BaBar, PRD73, 012005 (2006)

1

$\Gamma_{ee} \times \mathbf{B}_{pp}$:

E835:

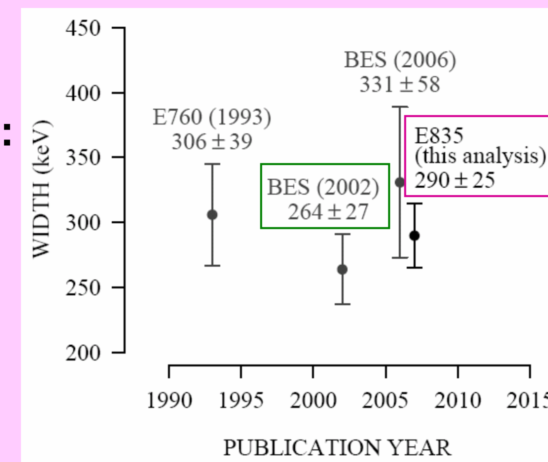
579±38±6 meV

BaBar:

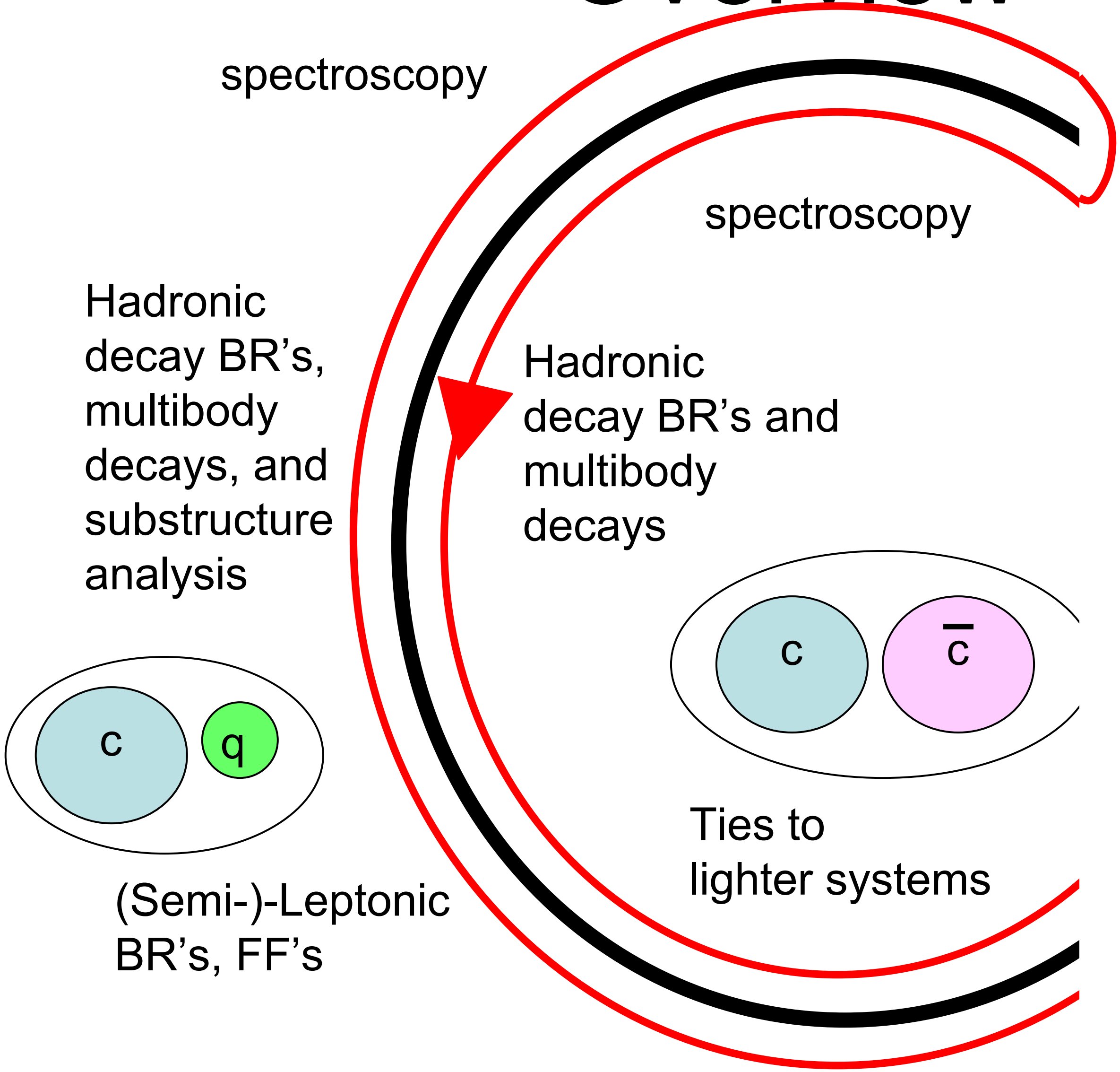
0.70±0.17±0.03 eV

2

Γ_{total}:



Overview



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Charmonium

DECAY

Many channels have been discovered for the “easy to produce” charmonia. We are down to levels of 10^{-5} in finding new ones.

We are moving from mere branching fraction measurements to investigating resonant substructure, in particular for $\psi(2S)$ and χ_{cJ}. Two examples:

a) Radiative multibody decays of $\psi(2S)$

b) Multibody decays of χ_{cJ}

$\psi(2S) \to \gamma$ + 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 meast's at $10^{-4..5}$

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

BR($\psi(2S) \to ggg + \gamma gg$)
= 1– $\pi\pi,\eta,\pi^0 J/\psi$– ΣM1,E1 = ~ 20%

J/ψ: γgg/ ggg ~6%

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

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

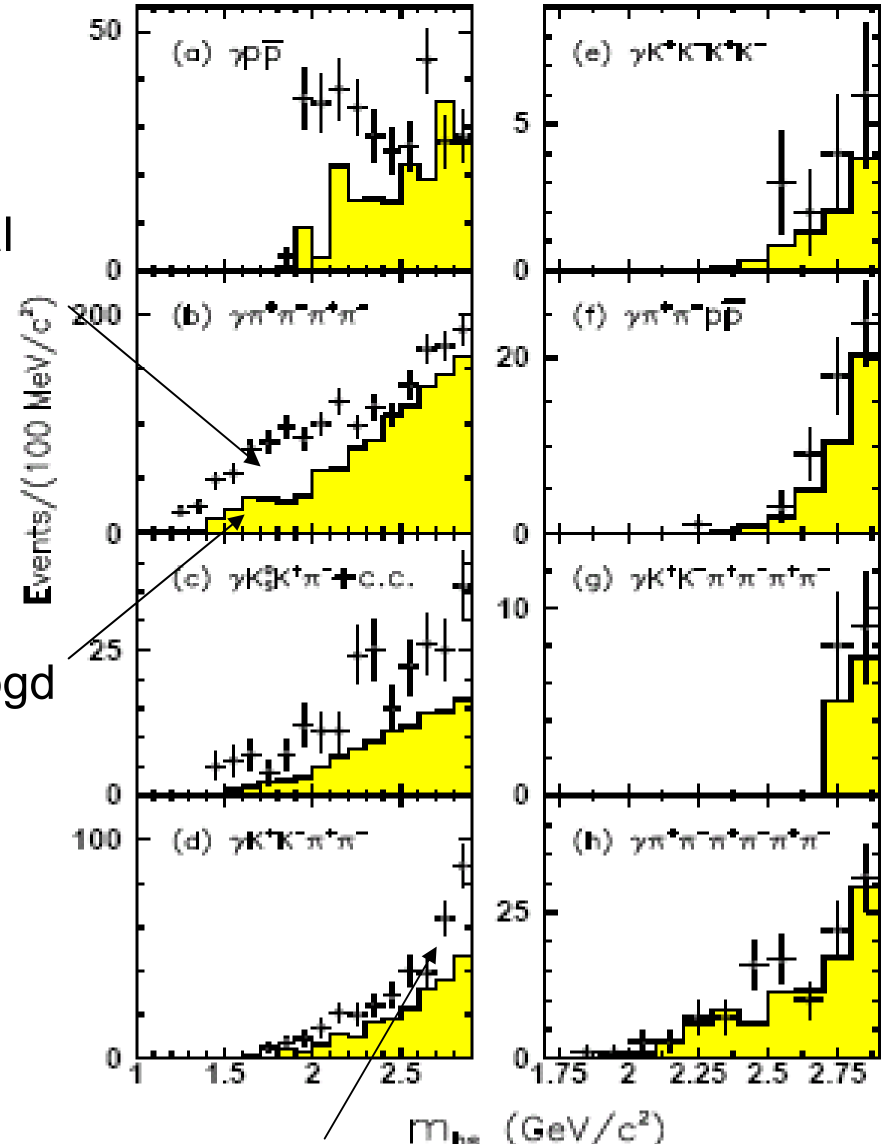
Mode	N^{Tot}	N^{Bg}	N^{Sig}	$\epsilon(\%)$	$\mathcal{B}(\times 10^{-5})$
$\gamma p\bar{p}$	329	187	142 ± 18	35.3	$2.9\pm0.4\pm0.4$
$\gamma 2(\pi^+\pi^-)$	1697	1114	583 ± 41	10.4	$39.6\pm2.8\pm5.0$
$\gamma K^0_S K^+\pi^- + c.c.$	–	–	115 ± 16	4.83	$25.6\pm3.6\pm3.6$
$\gamma K^+K^-\pi^+\pi^-$	361	229	132 ± 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

Raw event yield

signal



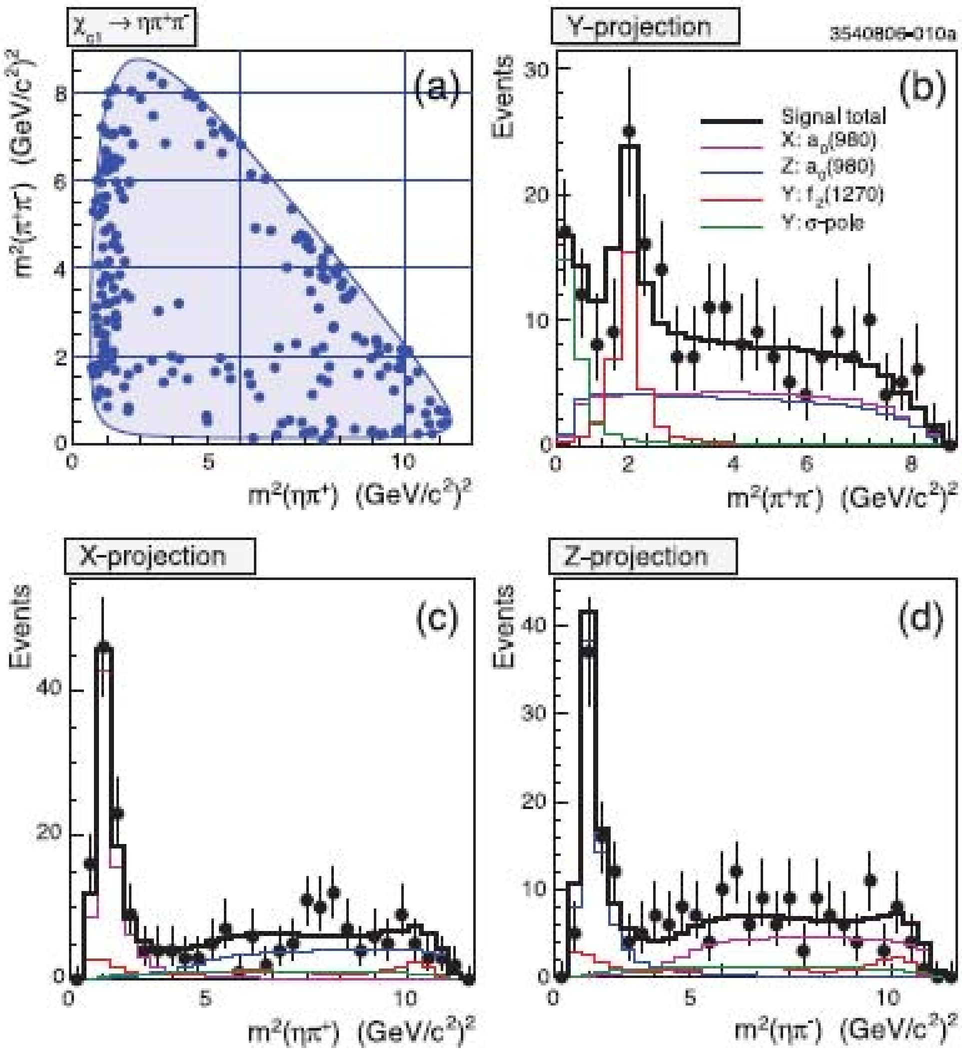
bgd

Also determine how much of this is K*Kπ and K*K*

BES, hep-ex/0612016

$\chi_c \rightarrow h^+h^-h^0 \quad (\pi^+\pi^-\eta)$

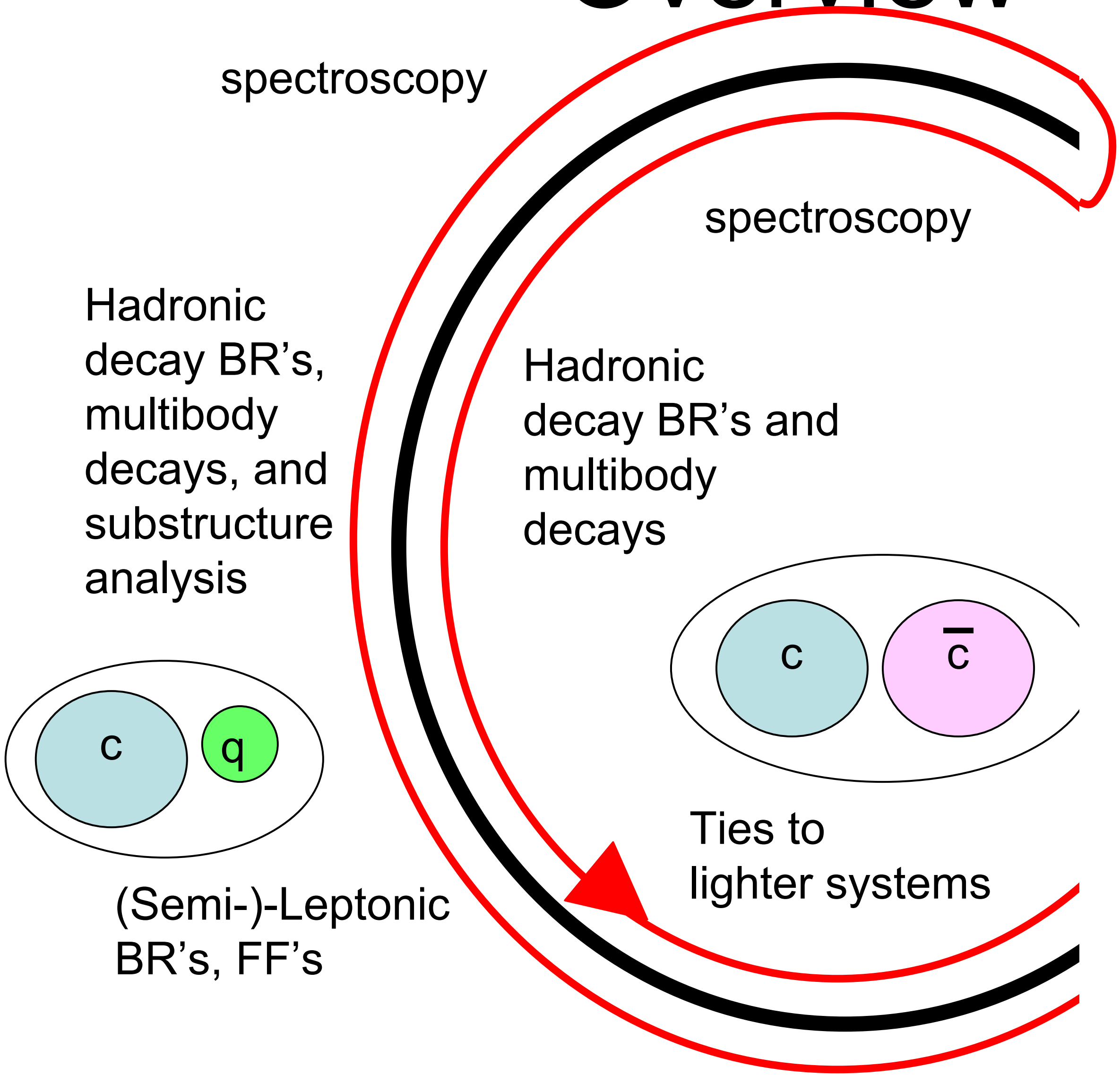
PRD 75, 032002 (2007)



Substructure in $\chi_{c1} \rightarrow \pi^+\pi^-\eta$

- Use a simple model of non-interfering resonances coming from a spin-1 parent. *(this describes the dominant structure, but will be refined with more statistics).*
- Find significant contributions from $a_0\pi$, $f_2\eta$, and $\sigma\eta$.
- No exotic structures apparent.

Overview



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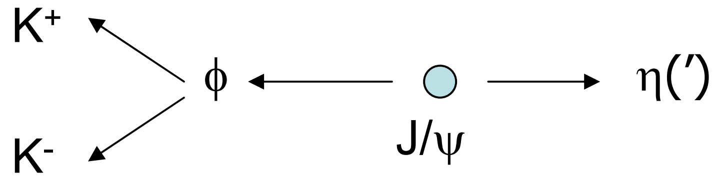
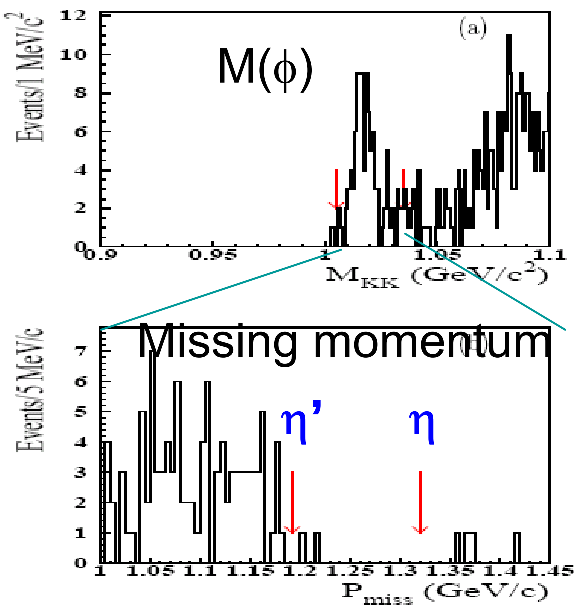
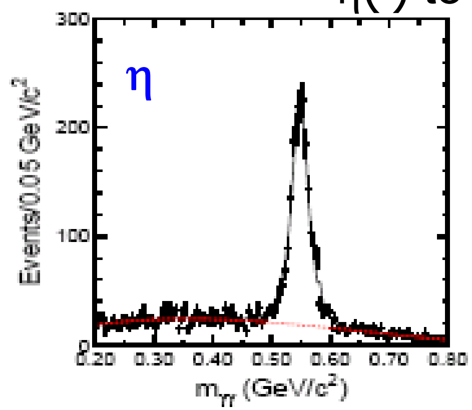
$\eta(')$ Branching Ratios

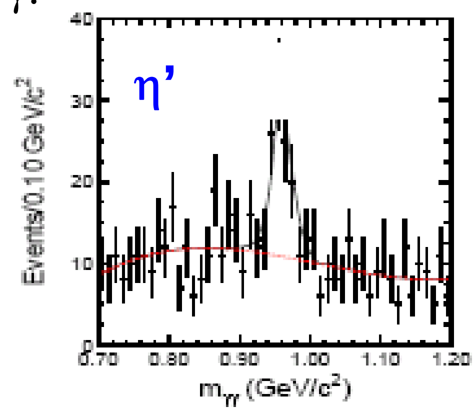


η to undetectable final states:



$\eta(')$ to $\gamma\gamma$:





1760±49 72±13

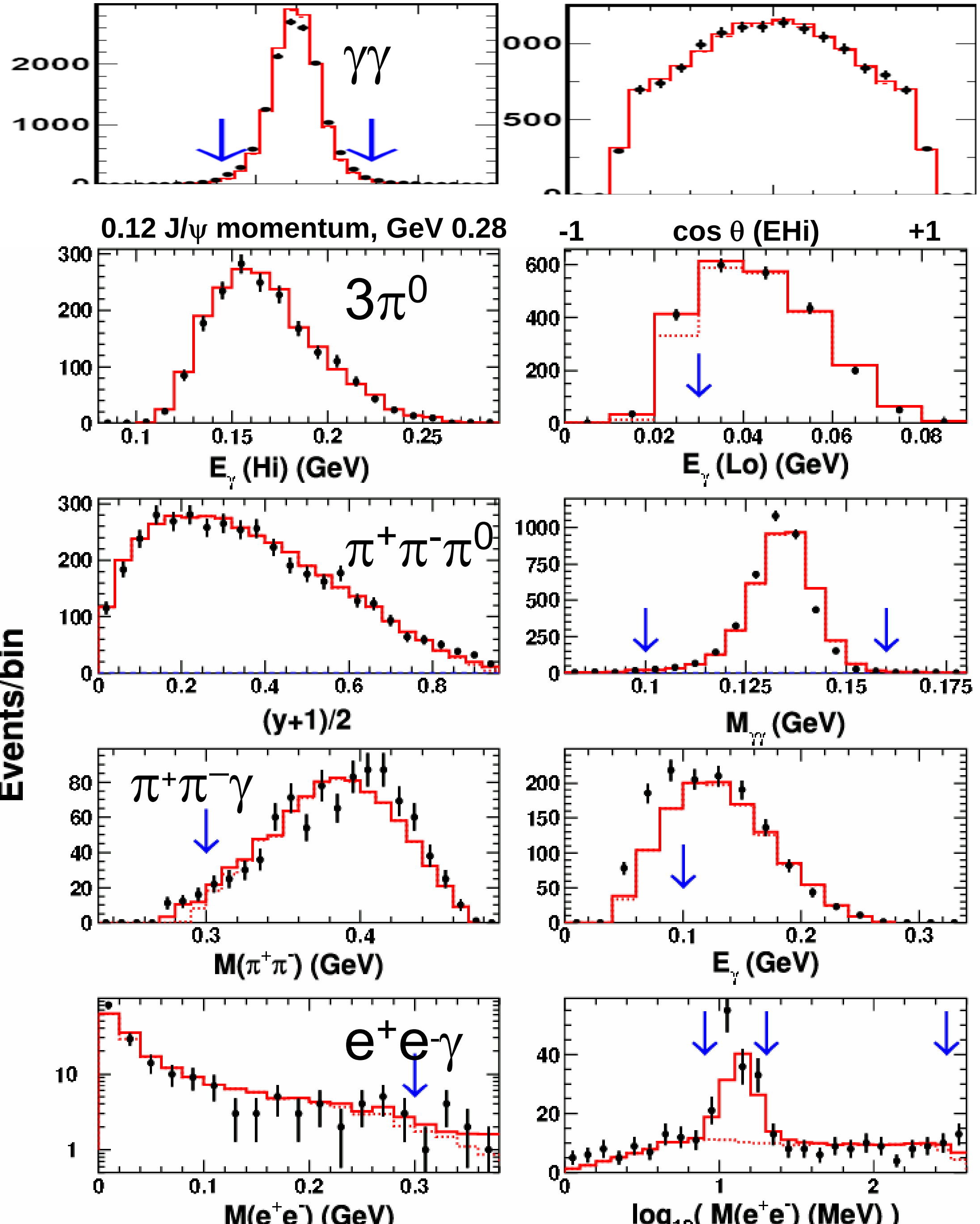
$$\frac{B(\eta \to \text{invisible})}{B(\eta \to \gamma\gamma)} < 1.65 \times 10^{-3}$$

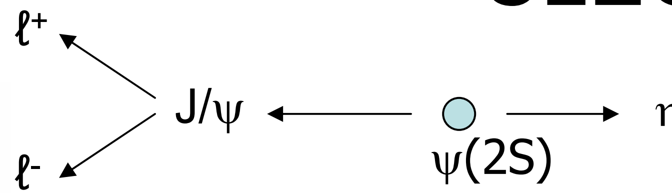
$$\frac{B(\eta' \to \text{invisible})}{B(\eta' \to \gamma\gamma)} < 6.69 \times 10^{-3}$$

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)

η branching ratios, CLEO





27M $\psi(2S)$,
$B(\psi(2S)\to\eta J/\psi) = 3.1\%$,
$B(J/\psi\to l^+l^-) = 12\%$,

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

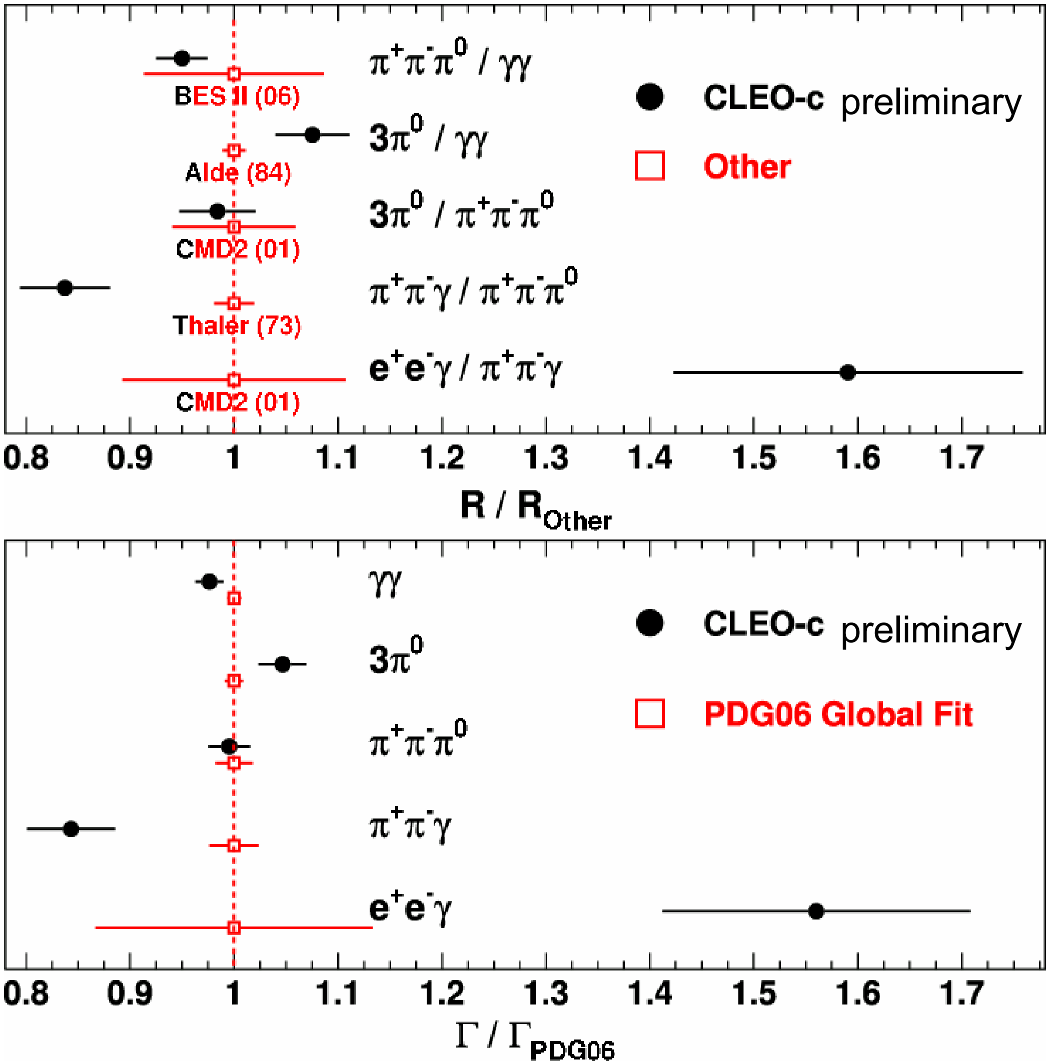
Constrain ℓ^+, ℓ^- $\Rightarrow J/\psi$,
constrain J/ψ, η products $\Rightarrow \psi(2S)$

Excellent data/MC agreement

Measurement of ratios allow cancellation of systematics

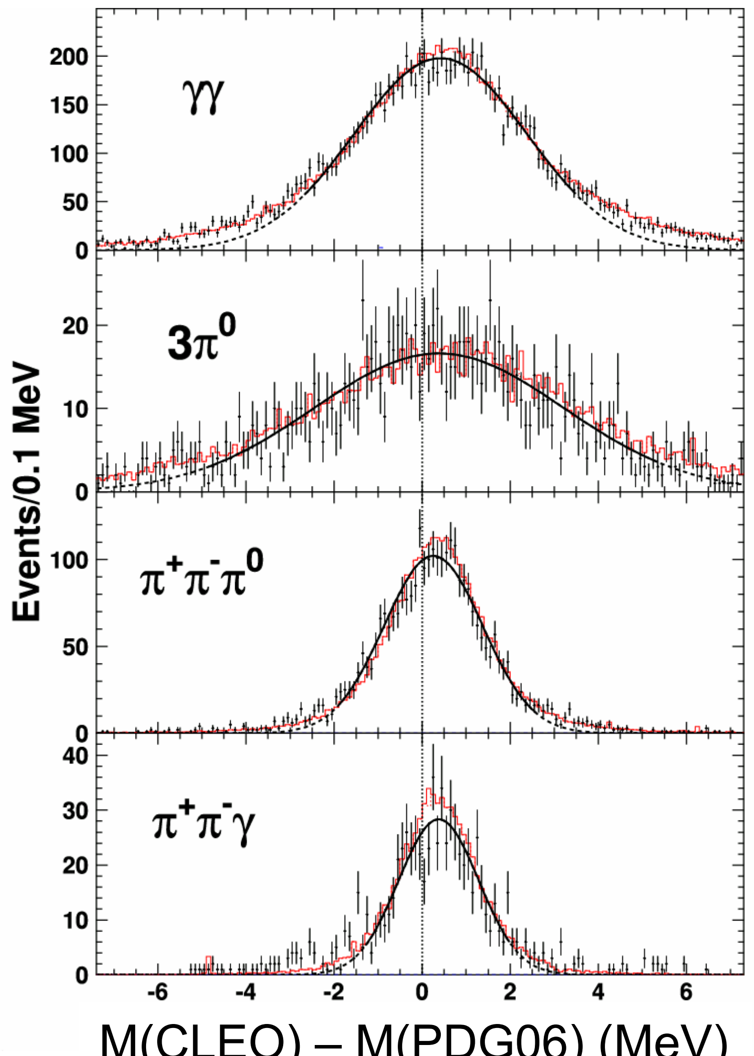
Follow PDG procedure: sum of the above five modes is ~ 100%
$\Rightarrow$ build absolute Br's from ratios

CLEO η branching fractions



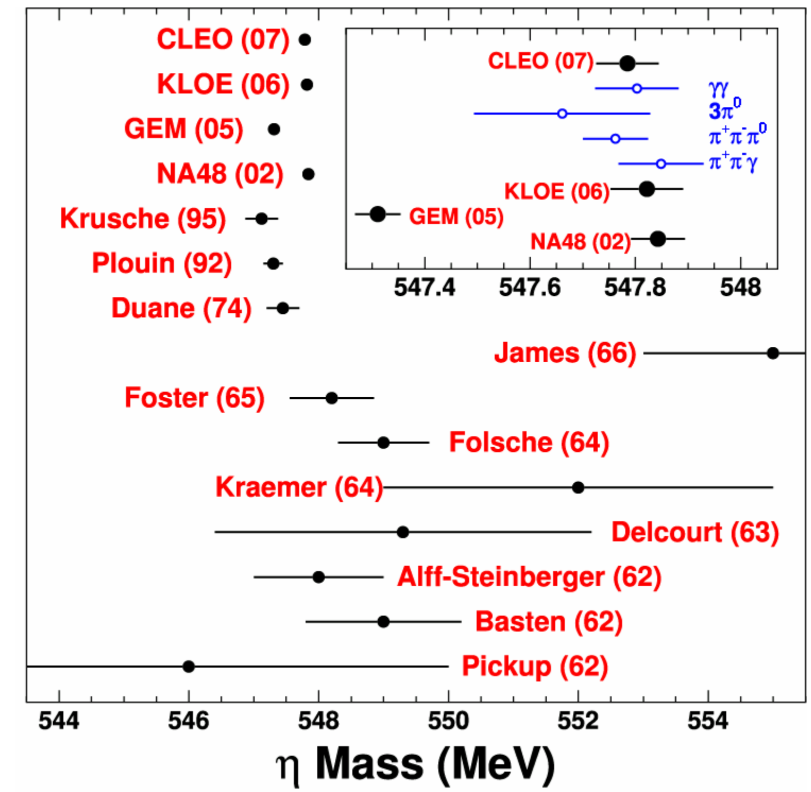
CLEO η Mass Measurement

Invariant mass of η decay products:

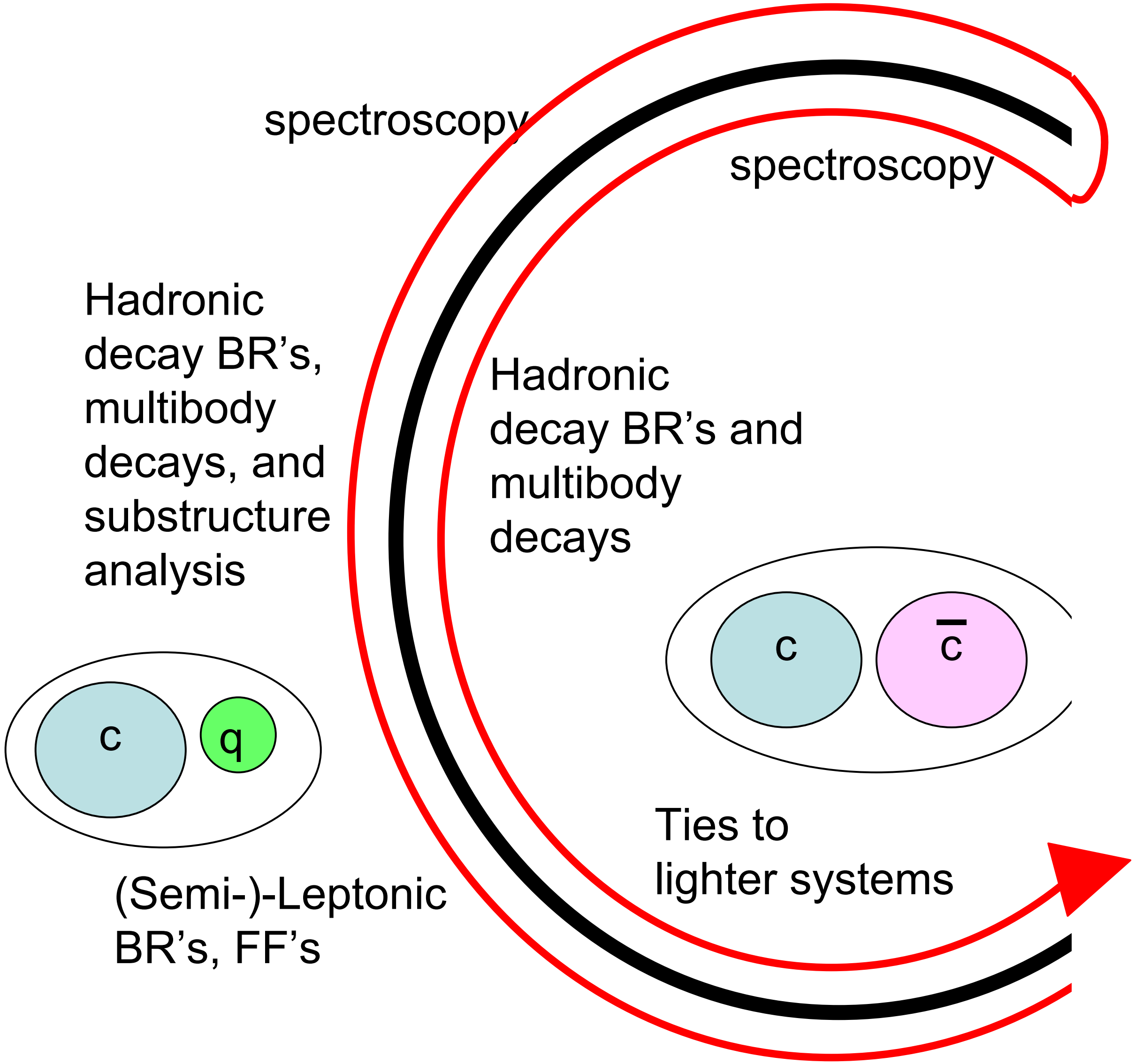


$M(\eta) = 547.785 \pm 0.017 \pm 0.057$ MeV

CLEO preliminary



Summary



Overall mission: Improve our understanding of the strong interaction.

Goals:

Study charm for charm's sake

Calibration playground for heavier systems

Production site for lighter states

Looking forward to a rich "charming" future!

Recommended Reading

Leptonic D decays:
Belle, $D^0 \to \pi^-, K^- l^+ \nu$, PRL 97, 061804 (2006)
BaBar, $D^0 \to K^- l^+ \nu$, 0704.0020v1
BES, $D^+ \to K^0 \mu^+\nu$ and $\Gamma(D^0 \to K^-\mu^+\nu)/\Gamma(D^+ \to K^{0bar}\mu^+\nu)$, PLB 644, 20 (2007)
CLEO, f_{Ds}, 0704.0629 and 0704.0437
CLEO, f_D, PRL 95, 251801 (2005)
BaBar, f_{Ds}, PRL 98, 141801 (2007)

Hadronic D decays:
BaBar, BR $D^0 \to \pi^-\pi^+\pi^0, K^-K^+\pi^0 / K^-\pi^+\pi^0$, PRD74, 091102(R) (2006)
Belle, BR $D^0 \to \pi^-\pi^+\pi^0$ / $K^-\pi^+\pi^0$ hep-ex/0610062
BaBar, BR $D^0 \to K^-\pi^+$, arXiv:0704.2080
CLEO, D absolute hadronic BR's, hep-ex/0702021
BES, BR $D^{+,0} \to K(*)+X$,PLB643, 246 (2006)

Dalitz analyses:
CLEO, $D^0 \to \pi^-\pi^+\pi^0$, PRD 76, 012001 (2007)
FOCUS, $D^+ \to K^-\pi^+\pi^+$ K-matrix, 0705.2248
FOCUS, $D^+ \to K^-K^+\pi^+$ non-parametric, hep-ex/0612032
CLEO, $D^0 \to \pi^-\pi^+\pi^+\pi^-$, PRD 75, 052003 (2007)

Open-charm and charmonium spectroscopy:
CLEO, $D^=$ mass, PRL 98, 092002 (2007)
Belle, $\Lambda_c(2880)$ J^P and $\Lambda_c(2940) \to \Sigma_c\pi$, hep-ex/0608043
Belle, $\Xi_c(2980)$, $\Xi_c(3077)$, PRL 97, 162001 (2006)
BaBar, Ω_c^0 prod/decay, PRL 97, 232001 (2006)
BaBar, Ω_c^* to $\Omega_c^0\gamma$, PRL 97, 232001 (2006)
Seth, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$ parameters, PRD 72, 017501 (2005)
BES, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$ parameters, 0705.4500
BES, $\psi(2S)$ and $\psi(3770)$ scan, PRL 97, 121801 (2006)
Belle, $e^+e^- \to D(*)D^*$ cross-section (at sqrt(s) from threshold to ~5 GeV), PRL98, 092001 (2007)
Belle, $B^{0bar} \to D^{**+}\pi^-$; (observation of D_0^*), hep-ex/0611054
Belle, Y(4260) in ISR, hep-ex/0612006
E835, $\psi(2S)$ width, hep-ex/0703012

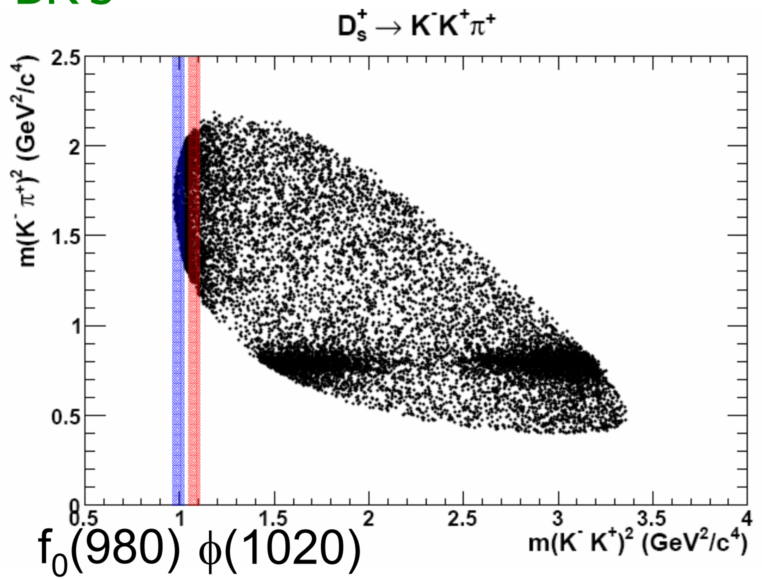
$\psi(2S)$ decay:
BES, radiative multibody, hep-ex/0612016
CLEO, χ_{cJ} multibody decays and substructure analysis, PRD 75, 032002 (2007)

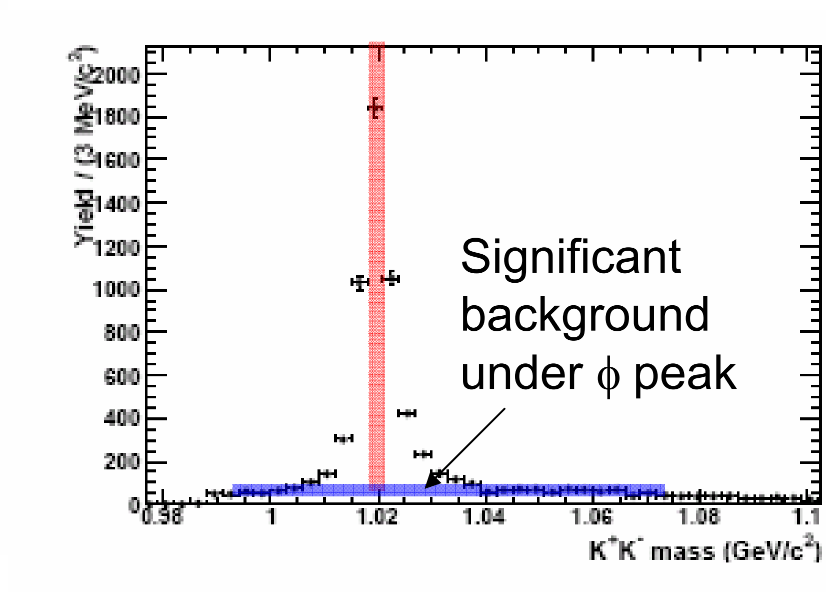
Light meson properties:
BES, σ in $\pi^+\pi^-J/\psi$, PLB 45, 19 (2007)
BES, η(') to invisible, PRL 97, 202002 (2007)

$D_s^+ \to \phi\pi^+$

Popular normalizing mode for D_s decays, easy to identify, substantial BR

- In practice, "ϕ" is K^+K^- with $\Delta m = m(KK) - m(\phi) = X$ – this is not purely ϕ!
- Measuring $D_s^+ \to \phi\pi^+$ in a partial wave analysis is fine, but it's still not the relevant number for relative BR measurements: they need partial BR's





CLEO partial $D_s^+ \to K^+K^-\pi^+$ BR's: Δm= 10 [20] MeV: 1.98 $\pm$ 0.15 % [2.25 $\pm$ 0.18 %] ,
BaBar $D_s^+ \to \phi\pi^+$: 4.62 $\pm$ 0.62 % $\Rightarrow$ Accuracy of normalizing mode BR: sub-10%.