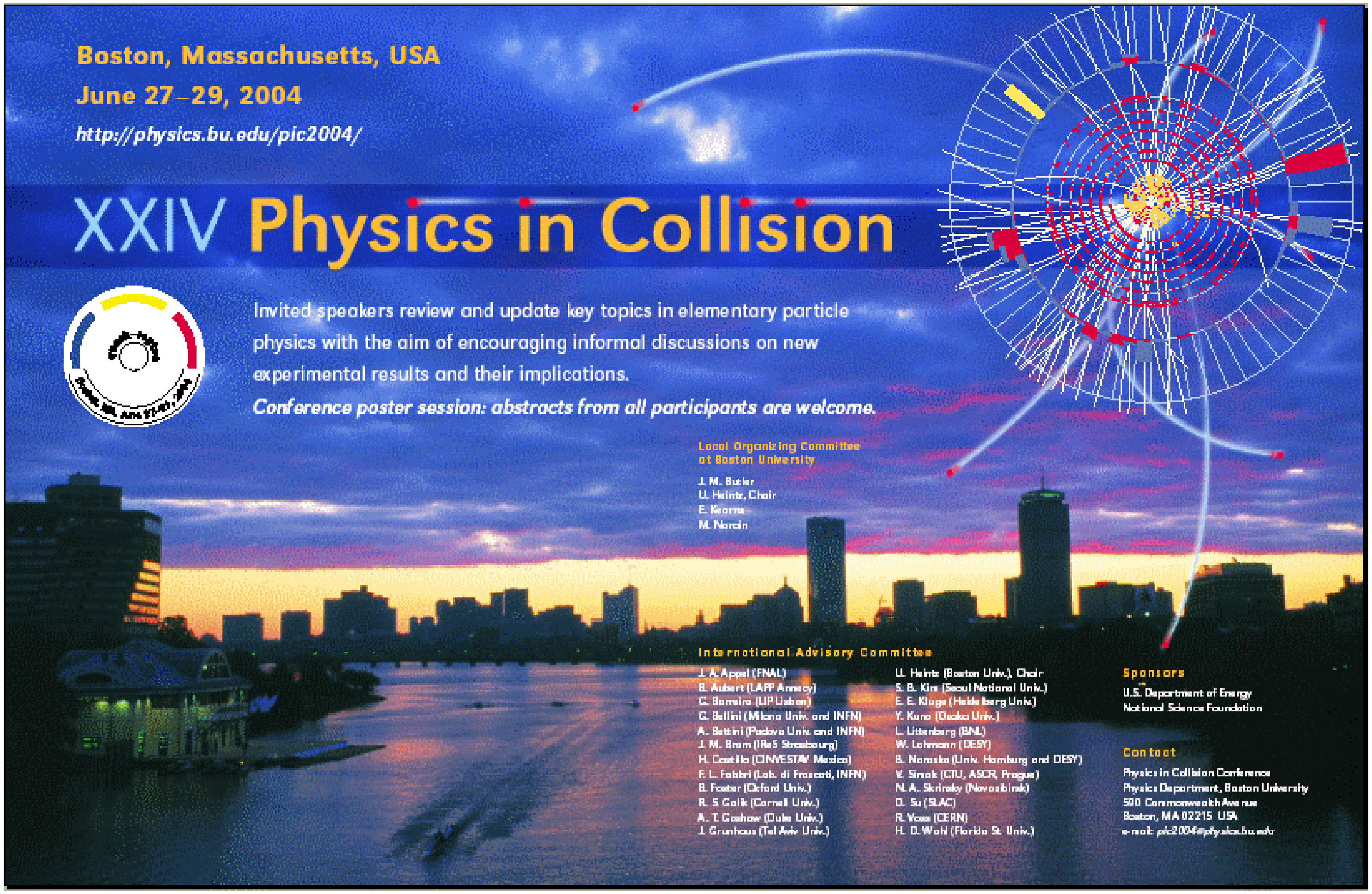


Charm decays

Daniele Pedrini

(INFN-Milano)

Outline

- High impact physics
- D^0 - $\bar{D}^0$ mixing, CP asymmetry and rare decays
- Charm lifetimes
- Semileptonic decays
- Hadronic decays

} unexpected surprises !

- DsJ system — **BIG SURPRISE!!!**
- Conclusions

High impact Physics

One of the misteries of the Standard Model is the existence of multiple fermion generations. This mystery appears to originate at high mass scales ⟶ can only be studied indirectly.

CP violation, mixing and rare decays ⟶ may investigate the physics at these new scales!!

Why charm?

Because in the charm sector the SM contributions to these effects are small ⟶ can provide unique information

High impact Physics

In addition charm is the unique probe of Up-type quark sector

but how small is small ?

- CP asymmetry ~ 10^{-3}
- D^0 - $\overline{D}^0$ mixing ~ 10^{-6} -- 10^{-10}
- Rare decays ~ 10^{-9} -- 10^{-19}

High statistics instead of High Energy

Large window to search for new physics

Mixing review

- Neutral charm mesons:

$$D^0 = c\bar{u}, \bar{D}^0 = \bar{c}u$$

- If $\boldsymbol{H_{12}, H_{21} \neq 0}$, they are not eigenstates.

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0 \\ \bar{D}^0 \end{pmatrix} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix}\begin{pmatrix} D^0 \\ \bar{D}^0 \end{pmatrix}$$

where $\boldsymbol{H_{ij} = M_{ij} - i\Gamma_{ij}/2}$.

- If CP is conserved,

$$D_{1,2} = \left(D^0 \pm \bar{D}^0\right)/\sqrt{2}$$

with mass and lifetime as

$$M_{1,2} = M \pm \Re[H_{12}H_{21}]^{1/2} = M \pm 1/2\,\Delta M$$
$$\Gamma_{1,2} = \Gamma \mp 2\Im[H_{12}H_{21}]^{1/2} = \Gamma \mp \Delta\Gamma$$

- For charm mesons, experimental limits state that $\Delta M, \Delta\Gamma \ll \Gamma$.

$$x = \frac{\Delta M}{\Gamma}, y = \frac{\Delta\Gamma}{2\Gamma}$$

- Methods to see x or y:

– wrong sign final decays

– comparing lifetime of CP eigenstates

nice review: Burdman and Shipsey, Ann.Rev.Nucl.Part.Sci.53:431,2003

Methods to see x,y

- In hadronic D^0 decays, wrong sign final: mixing, double Cabbibo suppressed or interference (strong phase δ). $\rightarrow$ D^0 charge tagged by D^{*+} Time evolution study finds x', y'.

$$K^-\pi^+ \xleftarrow{\text{CF}} D^0 \xrightarrow[\text{DCS}]{\overline{D}^0\ \text{mixing}} K^+\pi^-$$

$$\frac{dN_{ws}}{dt} \approx e^{-\Gamma t}\left\{\left(\frac{x^2+y^2}{2}\right)\frac{\Gamma^2 t^2}{2} + D_{DCS}{}^2 + D_{DCS}(-x\sin\delta + y\cos\delta)\Gamma t\right\}$$

- $D_{DCS} = \mathbf{0}$ in semileptonic decays. $\rightarrow$ Cleaner analysis but less sensitivity.

- Direct comparison of CP final state lifetime finds y_{CP}

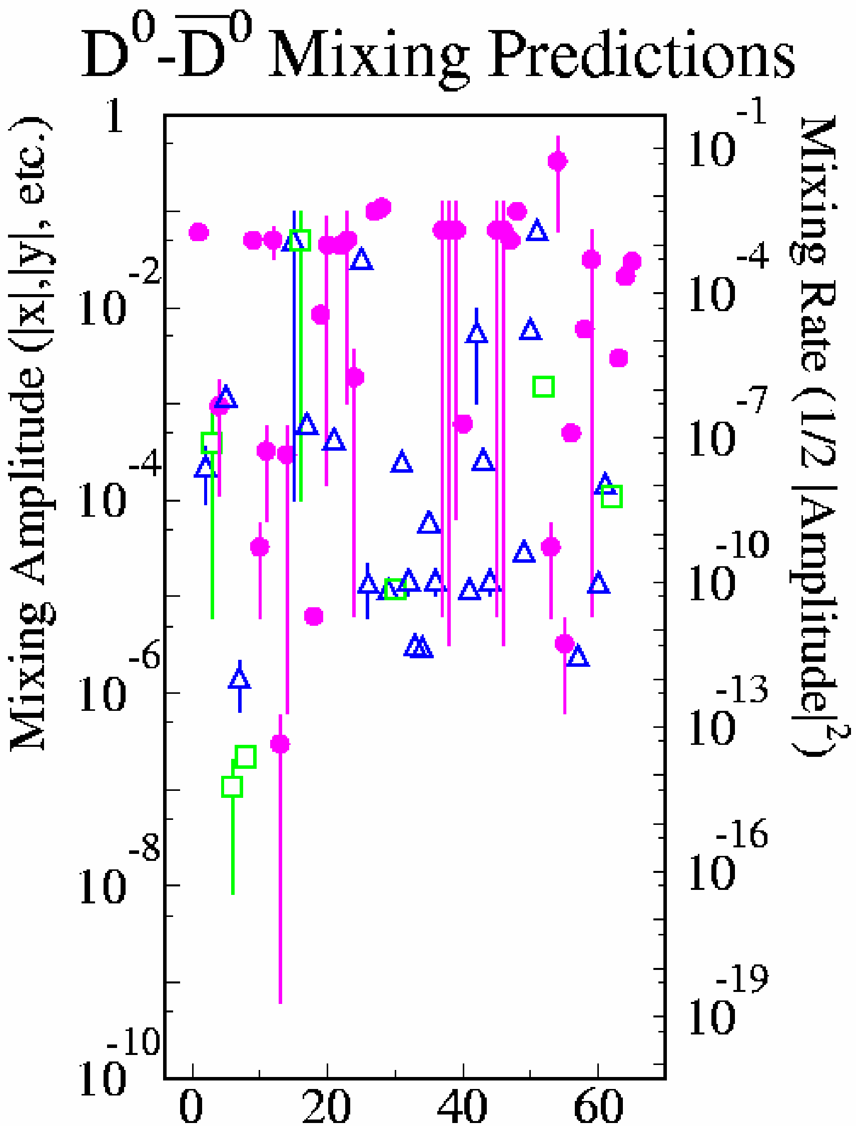
$D^0 \rightarrow K^+K^-$ (CP-even) $\rightarrow \Gamma_+$

$D^0 \rightarrow K^-\pi^+$ (CP-even, CP-odd)

$\rightarrow \Gamma(K^-\pi^+) = (\Gamma_+ + \Gamma_-)/2$

$$y_{CP} = \frac{\tau(D \rightarrow K\pi)}{\tau(D \rightarrow KK)} - 1$$

Theoretical "guidance"



From compilation of H.N.Nelson hep-ex/9908021

Triangles are SM x

Squares are SM y

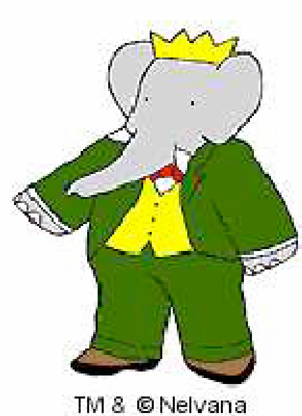
Circles are NSM x

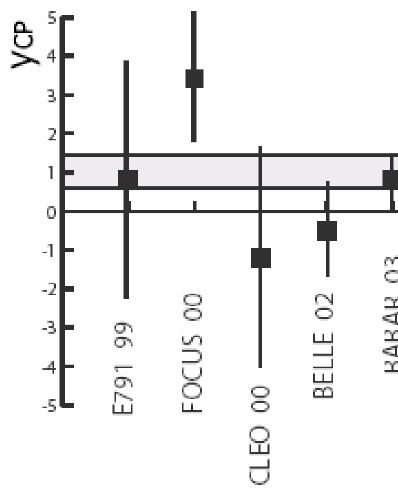
Predictions encompass **15 orders magnitude** for R_{mix}

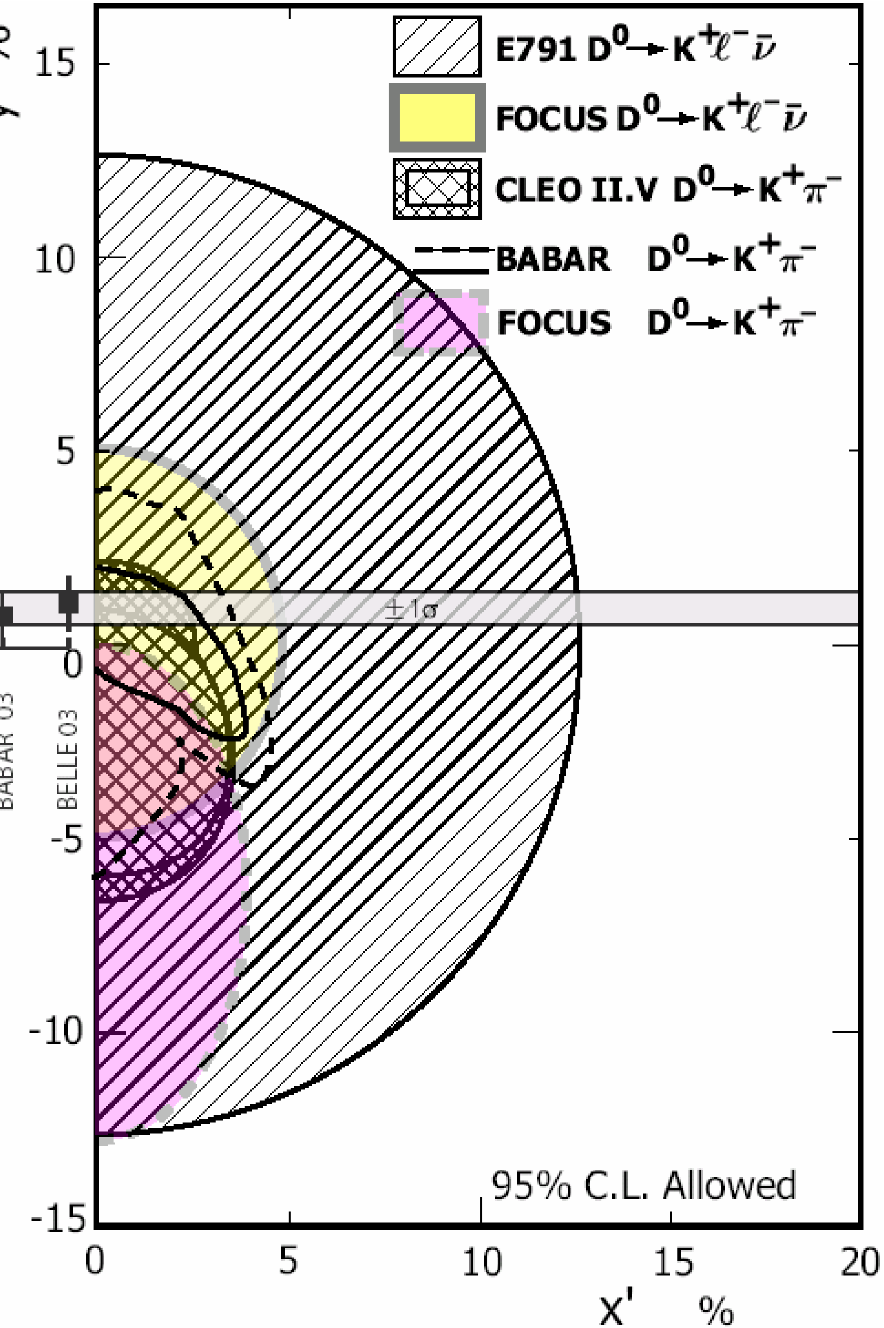
(but only 7 orders of x or y!)

Mixing review

It will be interesting to see if mixing does occur at the percent level.







CP violation

"CP studies in charm transitions represent an almost zero background search for New Physics"
(from "CP violation" by Bigi and Sanda)

- In the Standard Model no direct CP asymmetry can arise in Cabibbo allowed or DCS modes since they are driven by a single weak amplitude

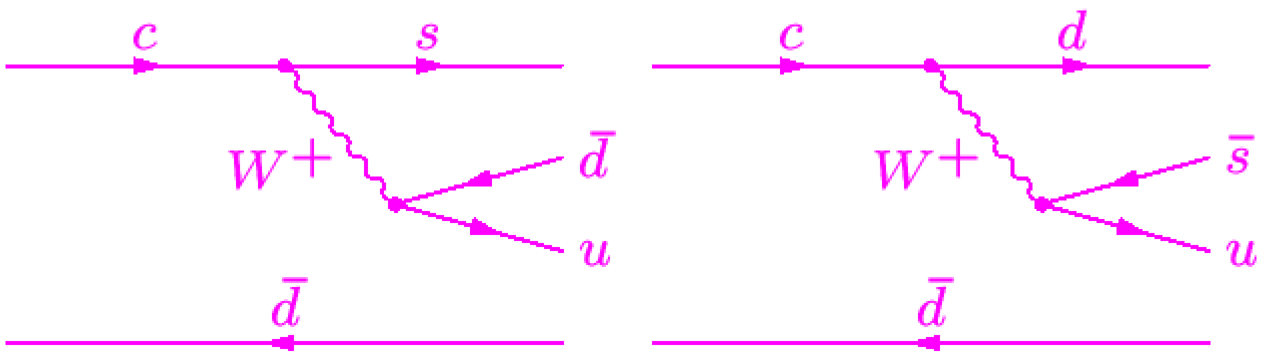
- For D^0 decays there is the possibility of indirect CP violation due to mixing

CP violation

However in $D \longrightarrow K_s \pi$ CP asymmetries can arise in two different ways:

a) through the CP impurity in Ks

b) through interference of two weak amplitudes



because one cannot differentiate between a K^0 and a $\overline{K^0}$ in the final state

- if New Physics intervenes through DCSD, then it would have the cleanest impact on $D^+ \longrightarrow K_{S,L}\ \pi^+$ (Bigi and Sanda)

CP Asymmetries

results:

Cabibbo-suppressed decays of D^0

Cabibbo suppressed D^0 decays seen in mass plot.

$\Gamma(D^0 \to KK)/\Gamma(D^0 \to K\pi) = 9.96 \pm 0.11 \pm 0.12\%$

$\Gamma(D^0 \to \pi\pi)/\Gamma(D^0 \to K\pi) = 3.608 \pm 0.054 \pm 0.040\%$

compare with FOCUS (2003)

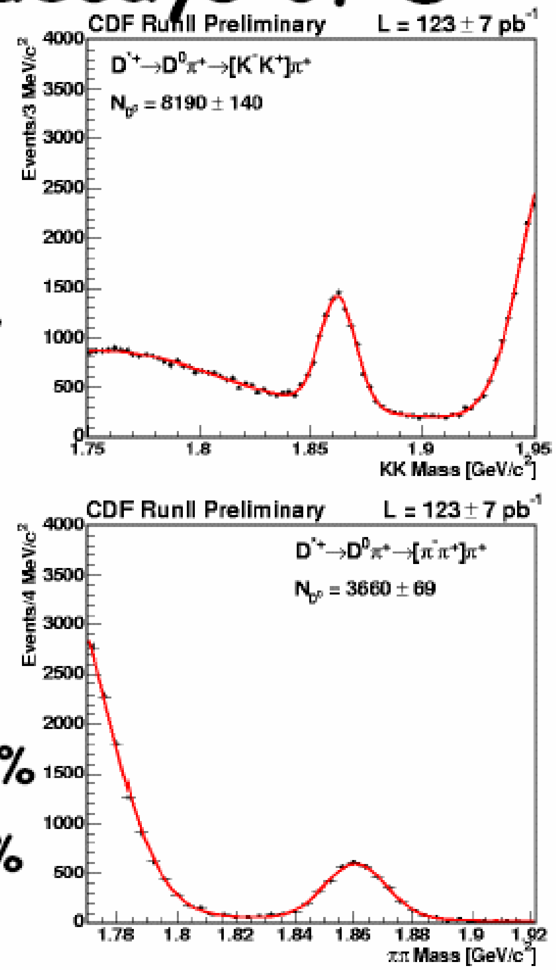
$\Gamma(D^0 \to KK)/\Gamma(D^0 \to K\pi) = 9.93 \pm 0.14 \pm 0.14\%$

$\Gamma(D^0 \to \pi\pi)/\Gamma(D^0 \to K\pi) = 3.53 \pm 0.12 \pm 0.06\%$

CP asymmetry: tagging the soft π with D^* decays.

$A(D^0 \to KK) = 2.0 \pm 1.2(stat) \pm 0.6(syst)\ \%$

$A(D^0 \to \pi\pi) = 3.0 \pm 1.3(stat) \pm 0.6(syst)\ \%$



Summary of CP asymmetry measurements

Decay mode	E791	CLEO	FOCUS	CDF
$D^0 \to K^-K^+$	$-0.010 \pm 0.049 \pm 0.012$	$+0.000 \pm 0.022 \pm 0.008$	$-0.001 \pm 0.022 \pm 0.015$	$0.020 \pm 0.012 \pm 0.006$
$D^0 \to \pi^-\pi^+$	$-0.049 \pm 0.078 \pm 0.030$	$+0.030 \pm 0.032 \pm 0.008$	$+0.048 \pm 0.039 \pm 0.025$	$0.030 \pm 0.013 \pm 0.006$
$D^0 \to K_S K_S$		-0.23 ± 0.19		
$D^0 \to K_S \pi^0$		$+0.001 \pm 0.013$		
$D^0 \to \pi^0\pi^0$		$+0.001 \pm 0.048$		
$D^+ \to K^-K^+\pi^+$	-0.014 ± 0.029		$+0.006 \pm 0.011 \pm 0.005$	
$D^+ \to \pi^-\pi^+\pi^+$	-0.017 ± 0.042			
$D^+ \to K_S\pi^+$			$-0.016 \pm 0.015 \pm 0.009$	
$D^+ \to K_S K^+$			$+0.071 \pm 0.061 \pm 0.012$	

- 1% level reached for some decay modes
- measured CP asymmetries are consistent with zero within errors
- no evidence of CP violation

T-odd correlation (triple product)

From I.I.Bigi 'Charm physics - Like Botticelli in the Sistine Chapel'

(hep-ph/0107102 v1 (2001))

" Consider,e.g., $D^0 \to K^- K^+ \pi^- \pi^+$,where one can form a T-odd correlation with the momenta:

$$C_T = \langle p_{K^+} \circ (p_{\pi^+} \times p_{\pi^-}) \rangle$$

Under time reversal T one has $C_T \to - C_T$ hence the name 'T-odd'.

Yet $C_T \neq 0$ does not necessarily establishes T violation.

Since time reversal is implemented by an antiunitary operator, $C_T \neq 0$ can be induced by FSI. While in contrast to the situation with partial width differences FSI are not required to produce an effect, they can act as an 'imposter' here, id est induce a T-odd correlation with T-invariant dynamics.

This ambiguity can unequivocally be resolved by measuring in $D^0 \to K^- K^+ \pi^- \pi^+$.

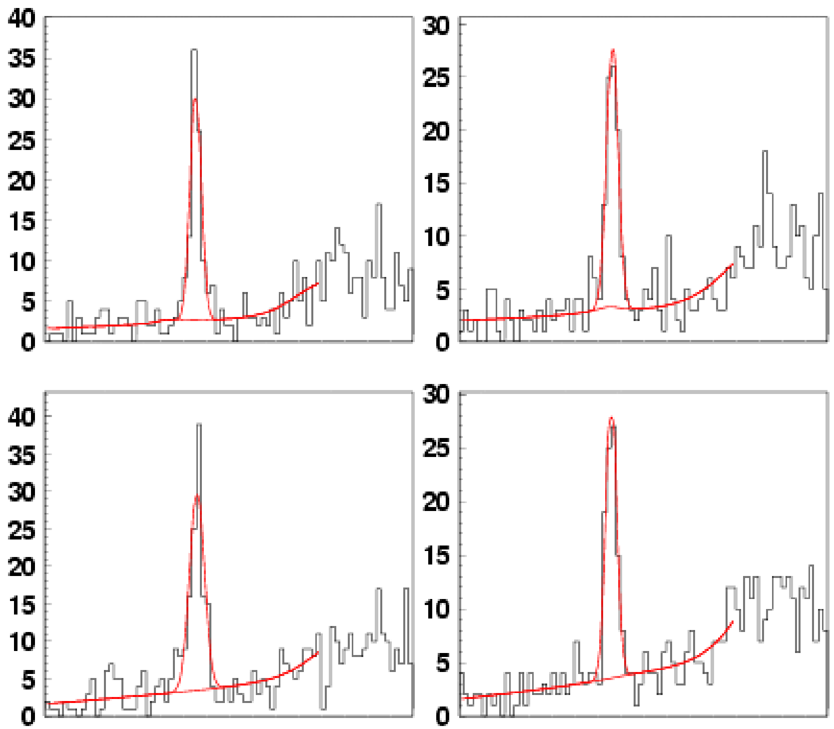
$$\overline{C}_T = \langle p_{K^-} \circ (p_{\pi^-} \times p_{\pi^+}) \rangle$$

Finding $C_T \neq - \overline{C}_T$ establishes CP violation without further ado."

T-odd correlation (triple product)

FOCUS $D^0 \to K^+K^-\pi^+\pi^-$: Preliminary

- Use $D^{*+} \to D^0\pi^+$ decays to distinguish D^0 from $\overline{D}^0$



- Yield: D^0: $C_T > 0$: 88 ± 10, $C_T < 0$: 82 ± 10
- Yield: $\overline{D}^0$: $\overline{C}_T < 0$: 80 ± 10, $\overline{C}_T > 0$: 101 ± 11
- No evidence for T violation

Rare decays and forbidden decays

3 categories:

1) FCNC: $D^+ \to h^+\mu^+\mu^-$, $D^0 \to l^+l^-$, ...
Flavor Changing Neutral Current

2) LFNV: $D^+ \to h^+ l_1^+ l^-_2$, ...
Lepton Family Number Violating

3) LNV: $D^+ \to h^- l_1^+ l^+_{1,2}$, ...
Lepton Number Violating

- Rare decays usually means a process which proceeds via an internal quark loop in the Standard Model (forbidden at the tree level)

- Forbidden decays are NOT allowed in the Standard Model

Rare decays

CDF, Phys.Rev.D68 (2003) 091101

result:

FCNC with $D^0 \to \mu\mu$ decays

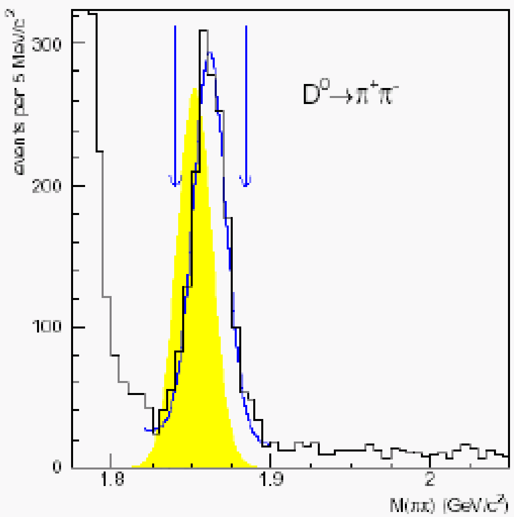
SM BR is 3×10^{-13}, can grow by 10^7 in R-violating SUSY

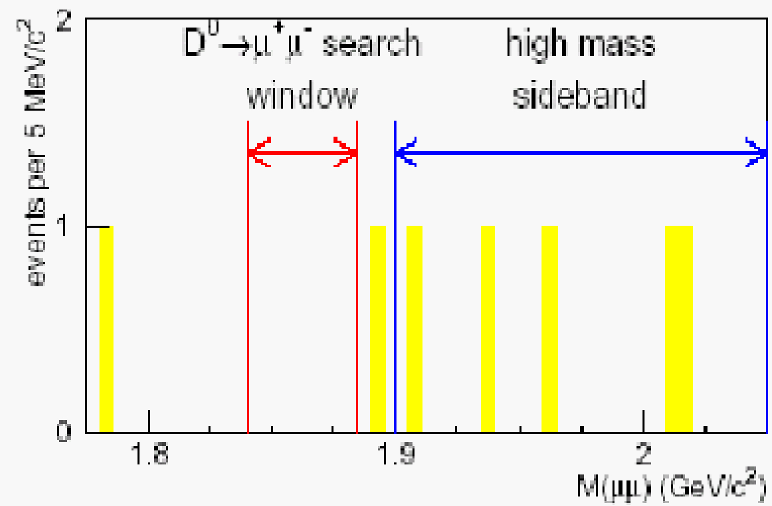
$D0 \to \pi\pi$ used as reference sample

0 events observed, 1.6 ± 0.7 estimated from BG

$BR(D^0 \to \mu\mu) < 2.5\ (3.3) \times 10^{-6}$ at 90% (95%) CL

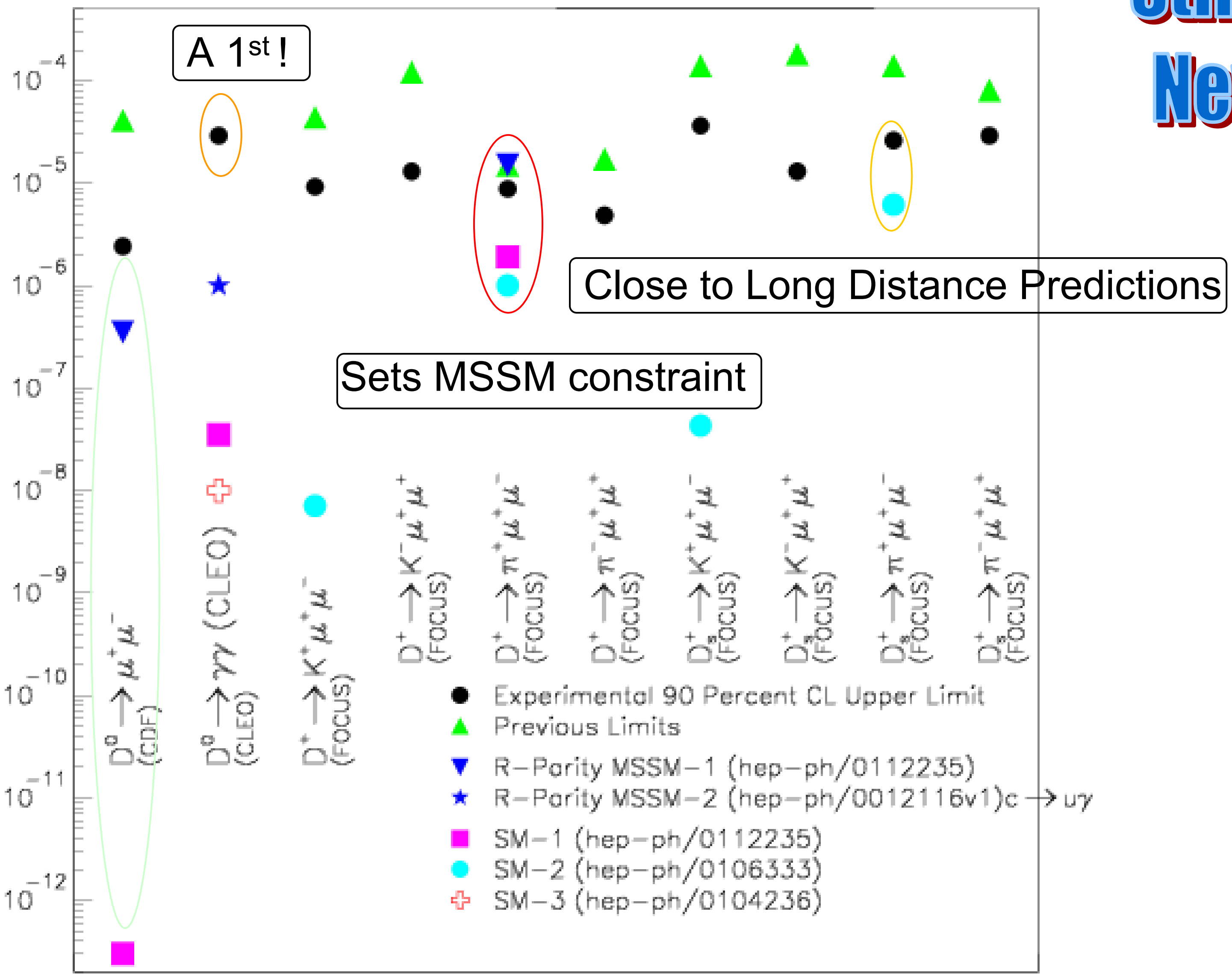
(improves PDG by a factor 2)





Rare Decay Round-Up

Still Room for New Physics



Charm lifetimes

- lifetime determination allows conversion of relative BRs to partial decay rates

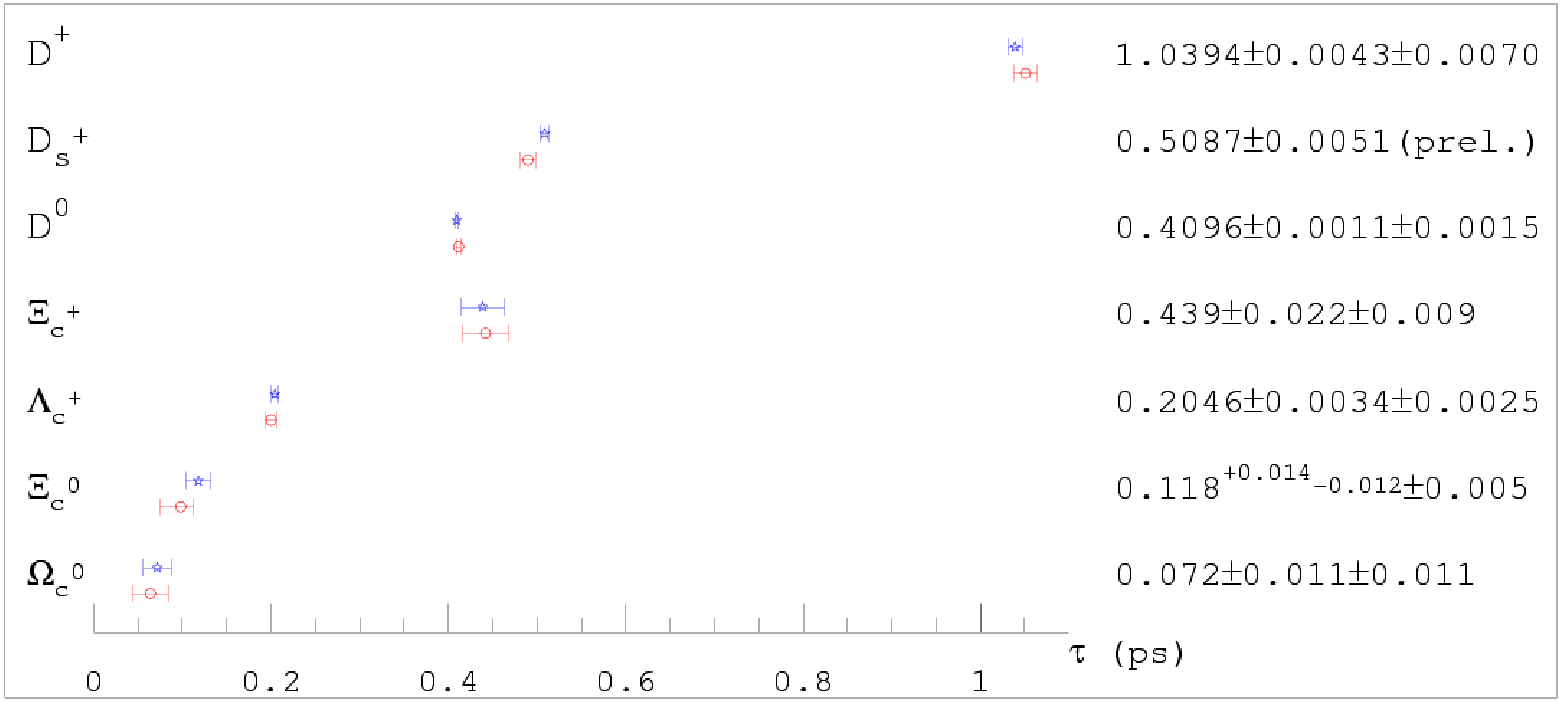
- increasingly precise measurements of the heavy quarks lifetimes have stimulated the development of theoretical models able to predict this rich pattern (more than one order of magnitude from D^+ to Ω_c)

- charm lifetime hierarchy established

- crucial for meaningful measurements of lifetime difference

Charm lifetimes

Charm lifetimes



FOCUS (*) produced new lifetimes results with precision better than the previous world average (○), PDG 2002

(most of the systematic errors cancel out in the ratio of lifetimes)

Charm lifetimes

Theory and experiments comparison

- HQE description (implemented through OPE)

	$1/m_c$ expect. [240]	theory comments	data
$\frac{\tau(D^+)}{\tau(D^0)}$	$\sim 1 + \left(\frac{f_D}{200\ \mathrm{MeV}}\right)^2 \sim 2.4$	PI dominant	2.54 ± 0.01
$\frac{\tau(D_s^+)}{\tau(D^0)}$	1.0 - 1.07 0.9 - 1.3	*without* WA [256] *with* WA [256]	1.22 ± 0.02
$\frac{\tau(\Lambda_c^+)}{\tau(D^0)}$	~ 0.5	quark model matrix elements	0.49 ± 0.01
$\frac{\tau(\Xi_c^+)}{\tau(\Lambda_c^+)}$	$\sim 1.3 \div 1.7$	ditto	2.2 ± 0.1
$\frac{\tau(\Lambda_c^+)}{\tau(\Xi_c^0)}$	$\sim 1.6 \div 2.2$	ditto	2.0 ± 0.4
$\frac{\tau(\Xi_c^+)}{\tau(\Xi_c^0)}$	~ 2.8	ditto	4.5 ± 0.9
$\frac{\tau(\Xi_c^+)}{\tau(\Omega_c)}$	~ 4	ditto	5.8 ± 0.9
$\frac{\tau(\Xi_c^0)}{\tau(\Omega_c)}$	~ 1.4	ditto	1.42 ± 0.14

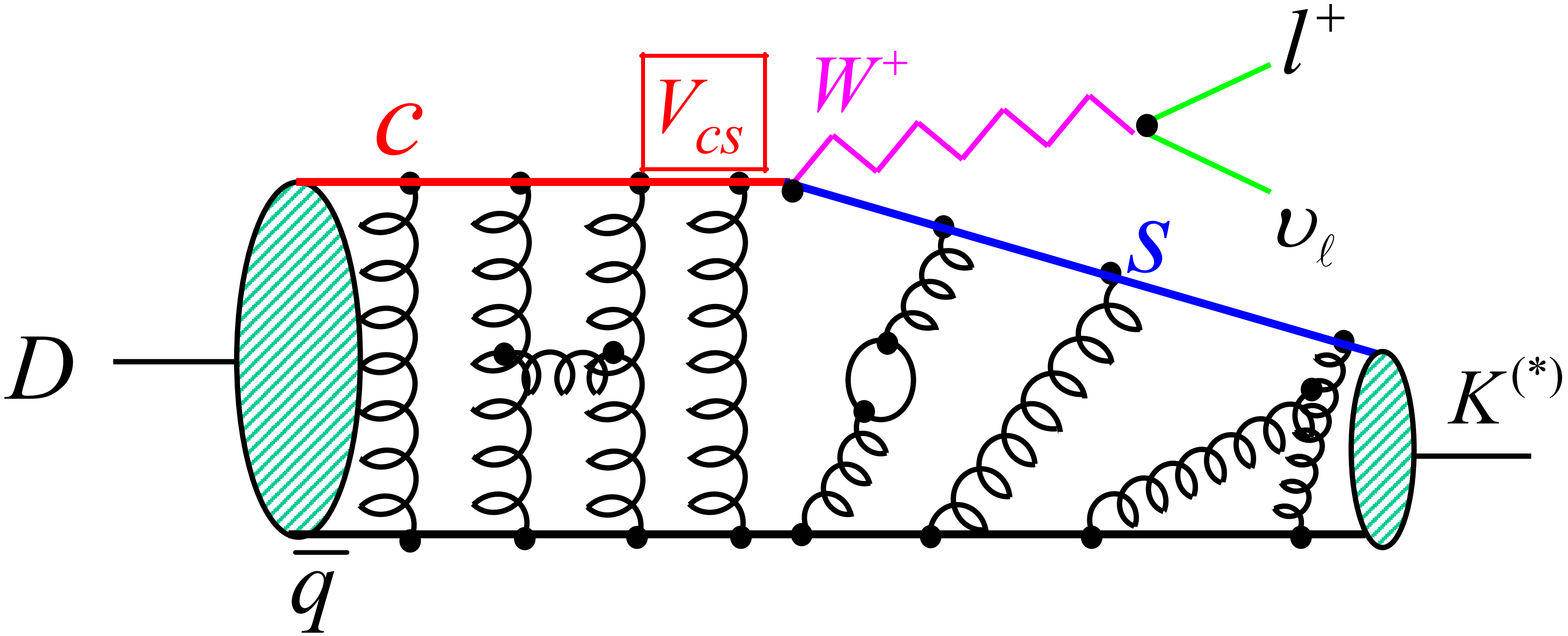
TABLE VI. – *Lifetime ratios in the charm sector*

Bigi et al., Riv.Nuovo Cim.26N7-8 (2003),1

- Guberina et al. (1986): $\tau(\Omega_c) \sim \tau(\Xi^0{}_c) < \tau(\Lambda_c) < \tau(\Xi^+{}_c)$
- Voloshin et al. (1986): $\tau(\Omega_c) < \tau(\Xi^0{}_c) < \tau(\Lambda_c) \sim \tau(\Xi^+{}_c)$

Charm semileptonic decays

Apart from form factors, these decays can be computed using perturbation theory and are first order in CKM elements

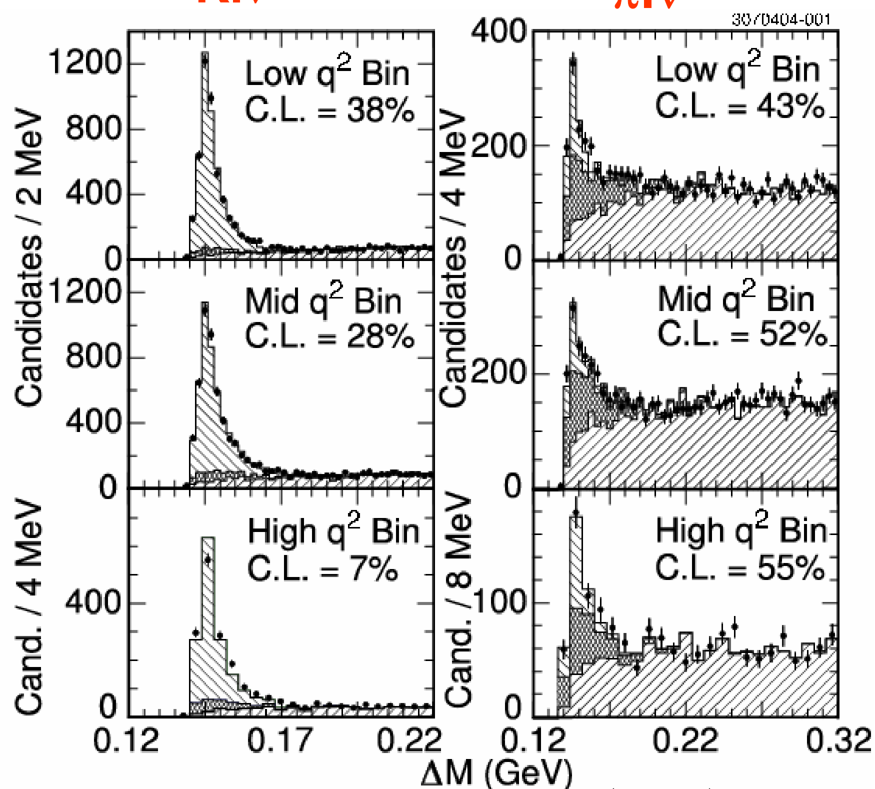


The form factors incorporate hadronic complications and can be calculated via non-perturbative Lattice QCD.

Charm SL decays provide a high quality lattice calibration crucial to reduce future systematic error in the Unitarity Triangle. The same techniques validated in charm can be applied to beauty.

$D \to \pi e \nu / K e \nu$

- Look for $D^* \to D$ decays. The "signal" is in the Δm plot.
- 3 bins in q^2 to get form factor info.
- Include peaking and non peaking backgrounds

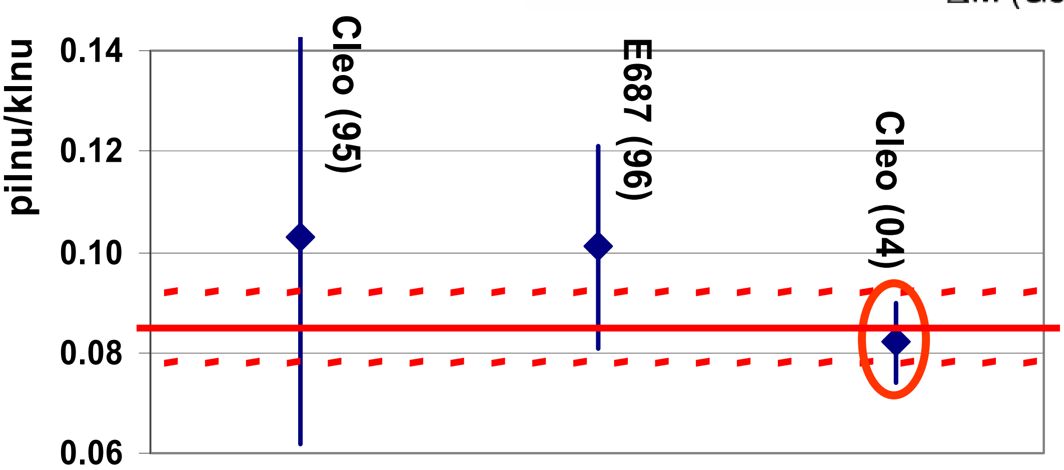


$$\frac{d\Gamma(D \to P \ell \nu)}{dq^2} = \frac{G_F^2 |V_{cq}|^2 P_P^3}{24\pi^3} |f_+(q^2)|^2$$

$$\frac{\Gamma(\pi e \nu)}{\Gamma(K e \nu)} = 0.082 \pm .006 \pm 0.005 \text{ CLEO}$$

$$\frac{|f_+^\pi(0)|^2 |V_{cd}|^2}{|f_+^K(0)|^2 |V_{cs}|^2} = 0.038^{+0.006+0.005}_{-0.007-0.003}$$

$$\frac{|f_+^\pi(0)|}{|f_+^K(0)|} = 0.86 \pm 0.07 \pm 0.05 \pm 0.01$$



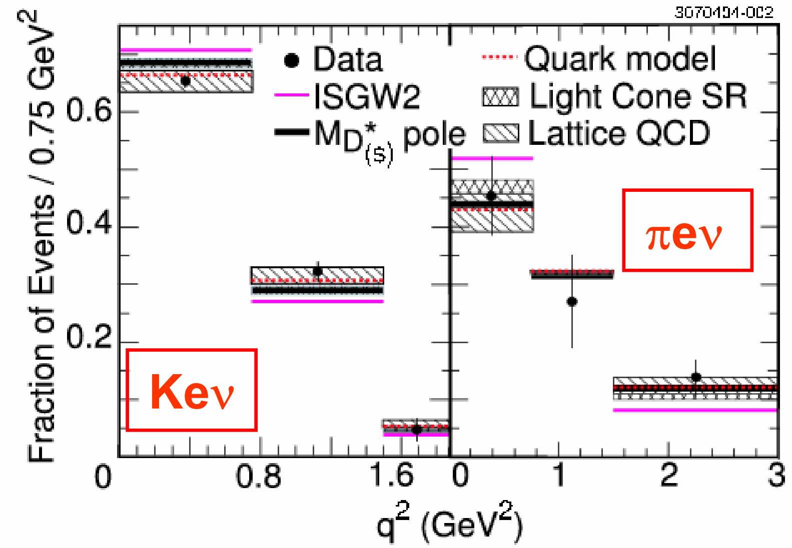
A big advance in precision!

q^2 information in $D \to \pi e \nu / K e \nu$

Two forms are used to parameterize $f_+(q^2)$:

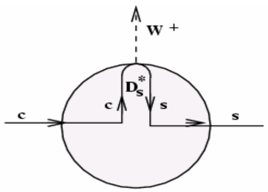
pole $\quad f_+ \propto \frac{1}{q^2 - m_{pole}^2}$

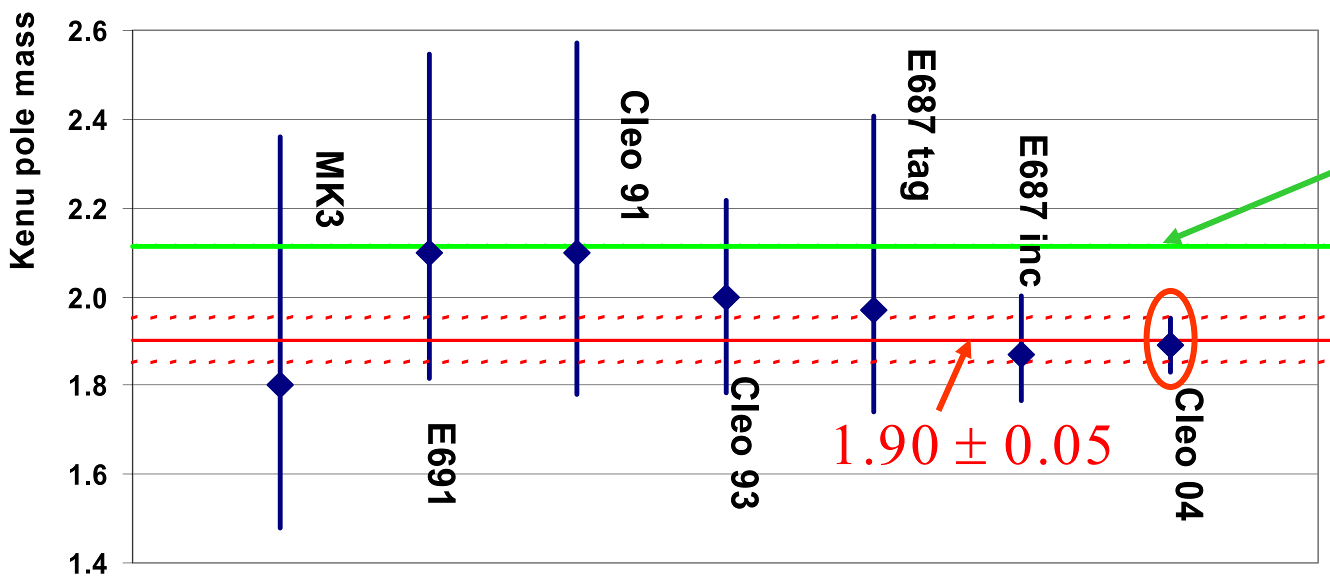
ISGW $\quad f_+ \propto \exp\left(\alpha q^2\right)$



After correcting for smearing Cleo reports these corrected q^2 fractions

Disfavors ISGW2 form by ~4.2σ





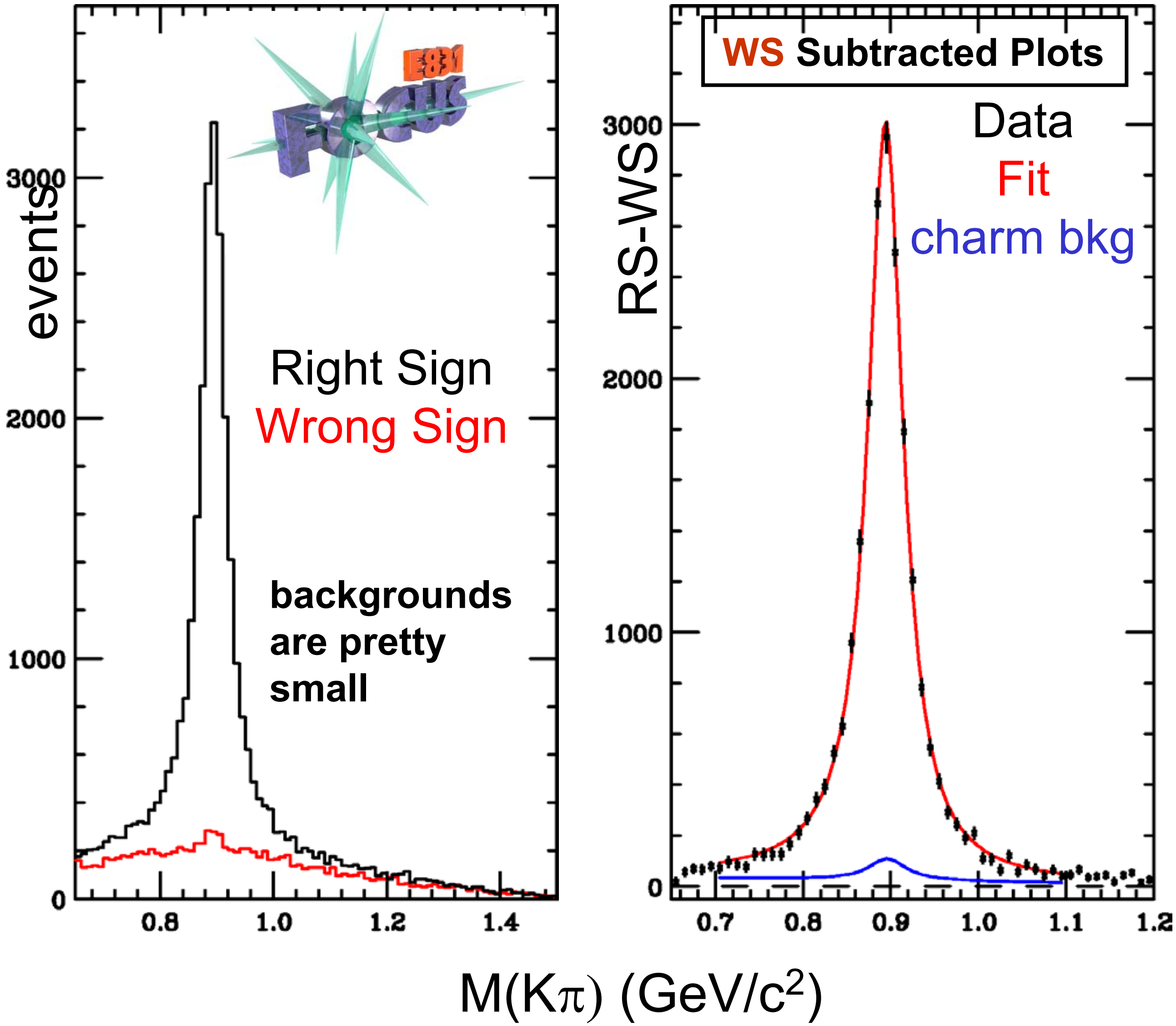
Clearly the data does not favor the simple Ds* pole

The Cleo 04 $\pi e \nu$ pole mass is

$1.86^{+0.10+0.07}_{-0.06-0.03}$ GeV

Semileptonic decays: $D^+ \to K\pi\mu\nu$ events

FOCUS, PLB 535 (2002) 43

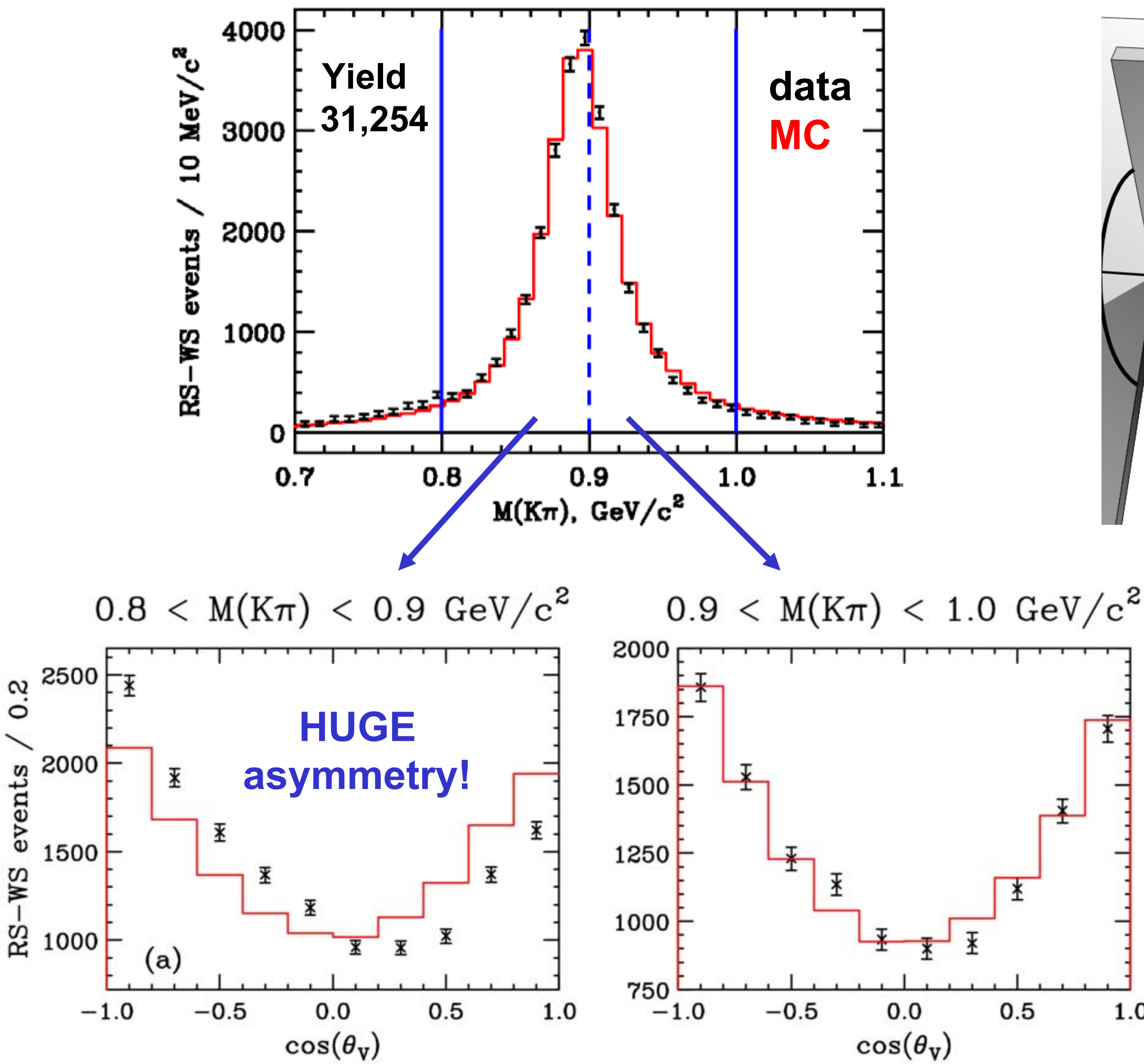


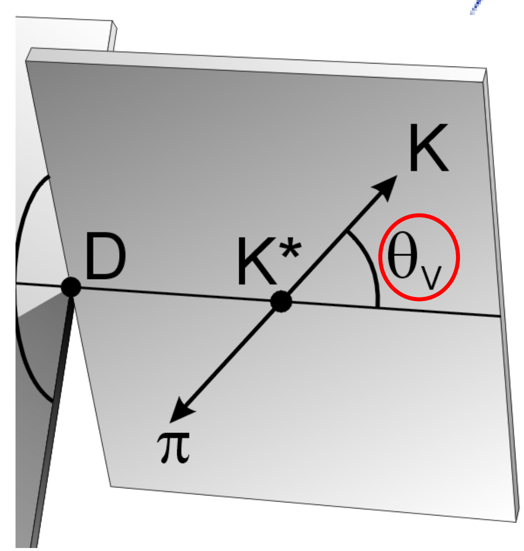
$K\pi$ spectrum looks like everyone else's, 100% K*(890), with much more data.

This has been so for last 20 years.

But *strange things* happen when one tried to measure form factors.

An unexpected asymmetry in the K* decay





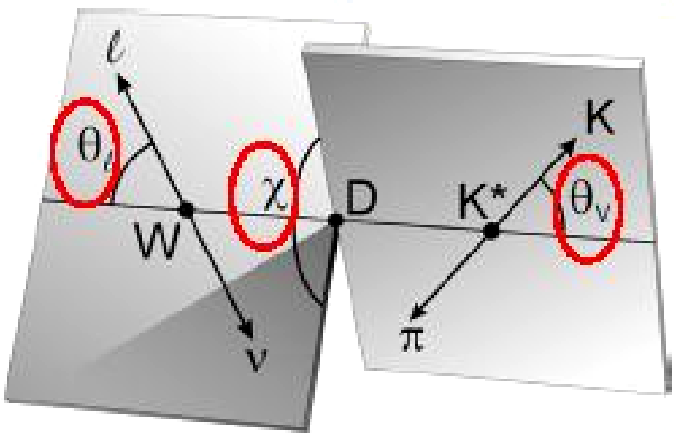
FOCUS noticed a forward-backward asymmetry in $\cos\theta_V$ below the K* pole, but almost none above the pole. → QM interference?

$$\frac{d\Gamma}{d\Omega} \propto 1 + \alpha \cos^2 \theta_V$$

Simplest approach — Try an interfering spin-0 amplitude

A 4-body decay requires 5 kinematic variables:

- $M_{K\pi}$
- $M_W^2 = q^2 = t$



$$|M|^2 \propto (t - m_\mu^2) \left| \begin{array}{l} \frac{(1+\cos\theta_l)}{2} \frac{\sin\theta_V}{\sqrt{2}} e^{i\chi} B H_+ \\ + \frac{(1-\cos\theta_l)}{2} \frac{-\sin\theta_V}{\sqrt{2}} e^{-i\chi} B H_- \\ + \frac{-\sin\theta_l}{\sqrt{2}} (\cos\theta_V B + A e^{i\delta}) H_0 \end{array} \right|^2$$

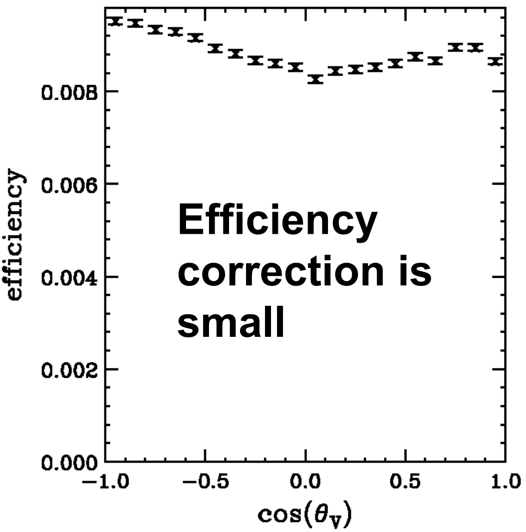
+ muon mass terms

A exp(iδ) will produce 3 interference terms

where $B \equiv \frac{\sqrt{m_o \Gamma}}{m^2 - m_0^2 + i m_0 \Gamma}$

We simply add a new constant amplitude : A exp(iδ) in the place where the K* couples to an m=0 W^+ with amplitude H_0. This assumes the q^2 dependence of the anomaly s-wave coupling is the same as the K* (could be challenged)

Studies of the acoplanarity-averaged interference



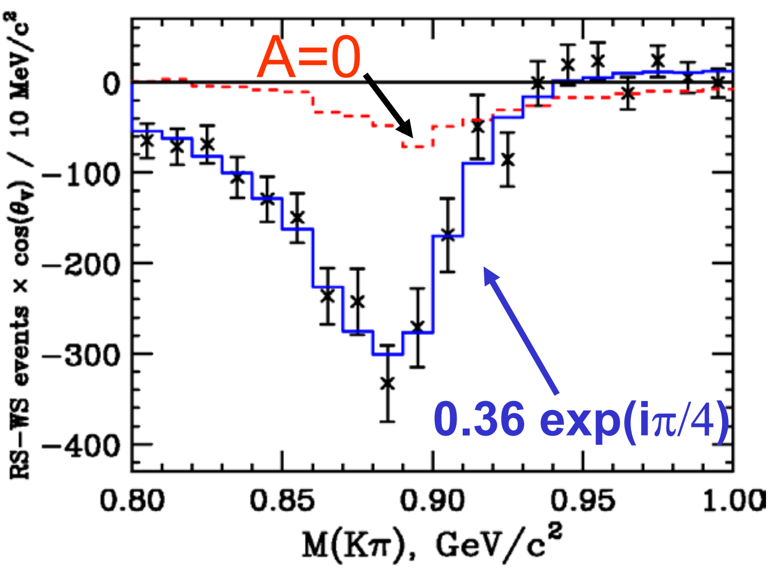
$$+8\cos\theta_V \sin^2\theta_l A\, \mathrm{Re}(e^{-i\delta} B_{K^*}) H_0^2$$

Extract this interference term by weighting data by $\cos\theta_V$,

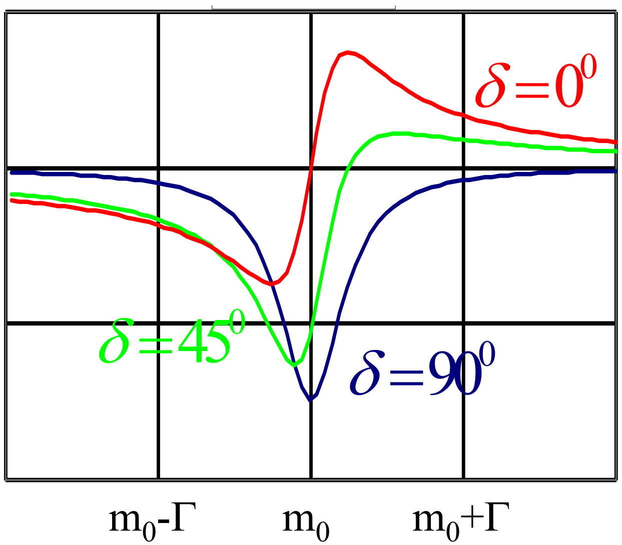
Since all other χ-averaged terms in the decay intensity are constant or $\cos^2\theta_V$.

We begin with the mass dependence: $\mathrm{Re}(e^{-i\delta} B_{K^*})$

Our weighted mass distribution..



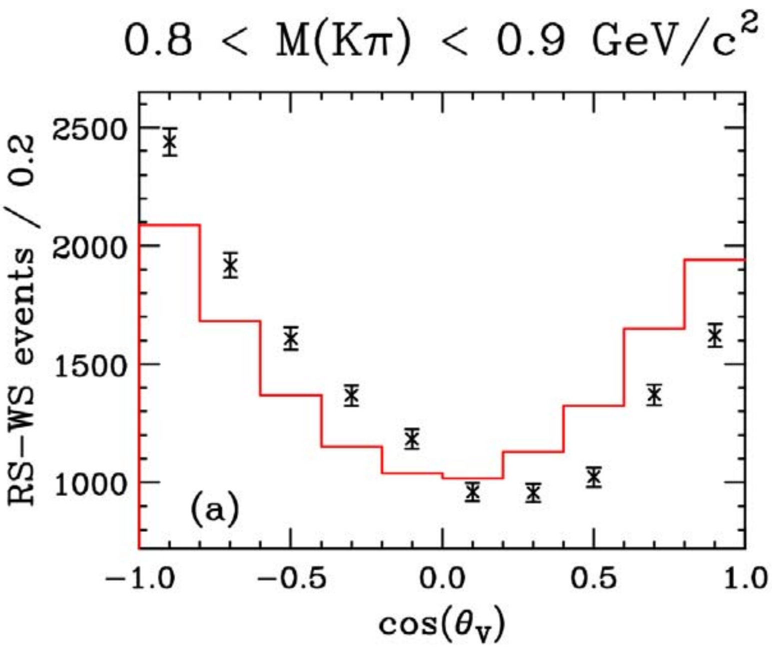
..looks just like the calculation..

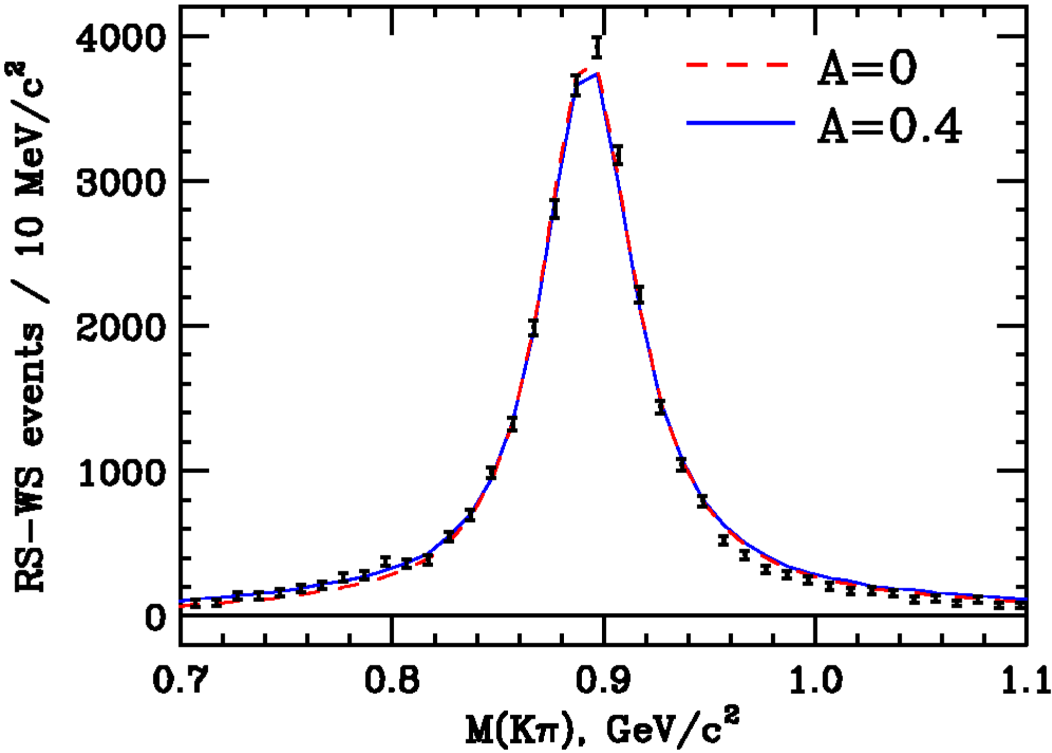


A constant 45^0 phase works great…

…other options also possible.

But surely an effect this large must have been observed before?





Although the interference *significantly* distorts the decay intensity....

...the interference is nearly invisible in the Kπ mass plot.

Results on BR($D^+ \to K^*\mu\nu/K2\pi$)

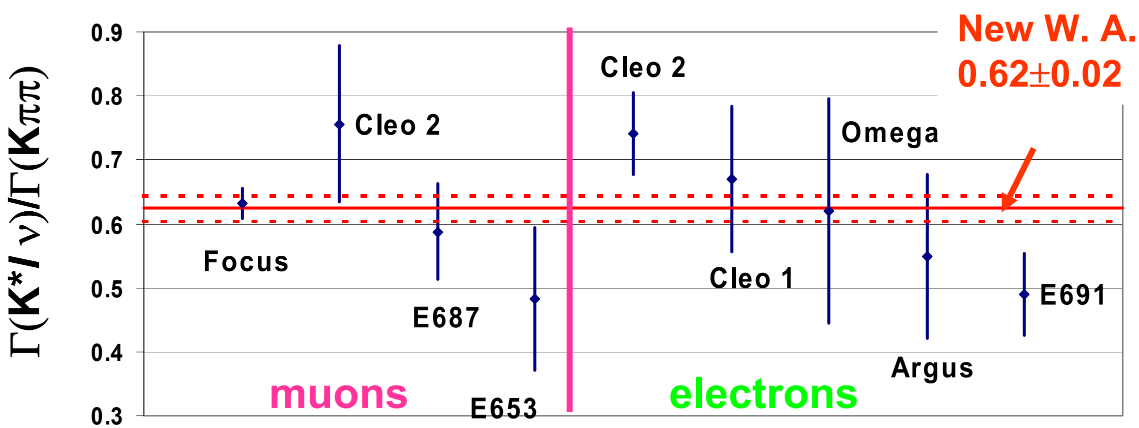
11,698 events

$$\frac{\Gamma(D^+ \to \overline{K}^{*0}\mu^+\nu)}{\Gamma(D^+ \to K^-\pi^+\pi^+)} = 0.602 \pm 0.010\ (\mathrm{stat}) \pm 0.021\ (\mathrm{sys})$$

65,421 events

With the correction factor applied,

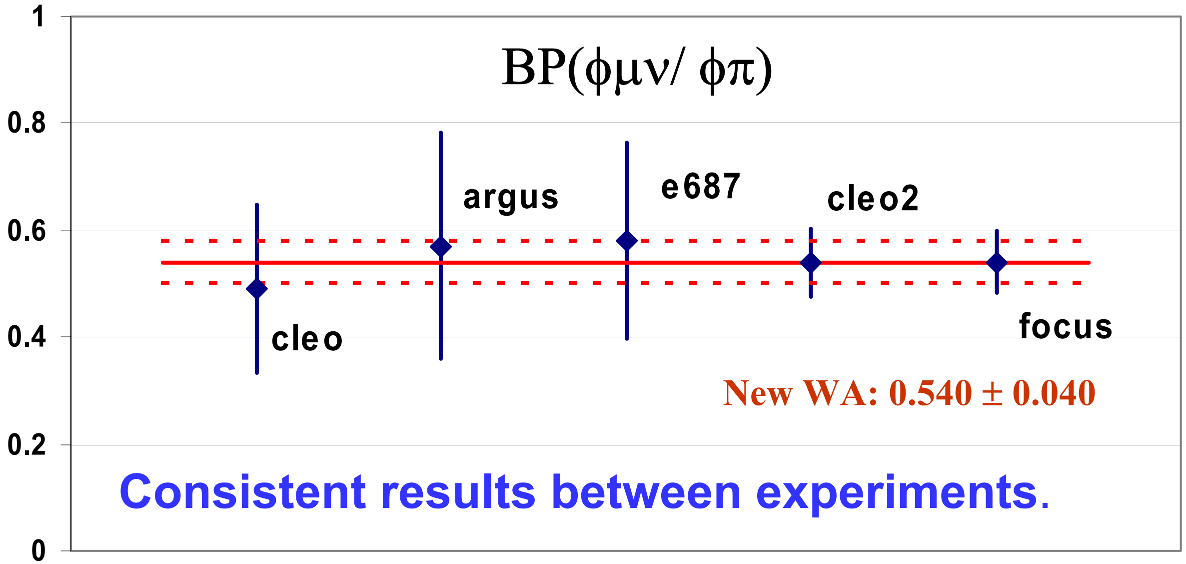
$$f_{K*} \equiv \frac{\int dLIPS\ |\mathcal{M}(r_v, r_2, A=0)|^2}{\int dLIPS\ |\mathcal{M}(r_v, r_2, A=0.36)|^2} = 0.945$$



All muon results multiplied by 1.05 to be compared to electron results

The FOCUS number is the only one to consider an s-wave contribution explicitly

Results on $BR(D_s^+ \to \phi\mu\nu/\phi\pi)$

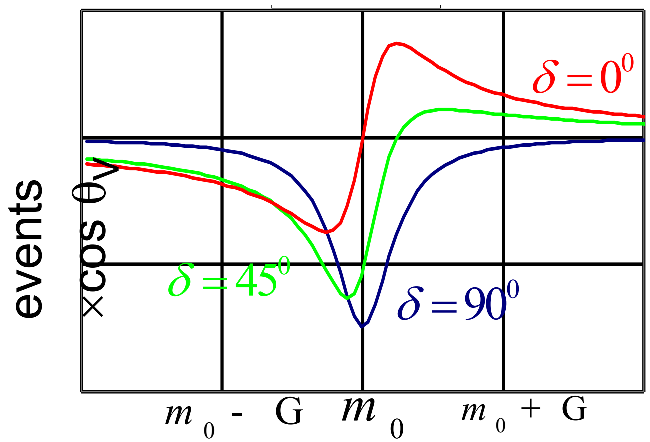


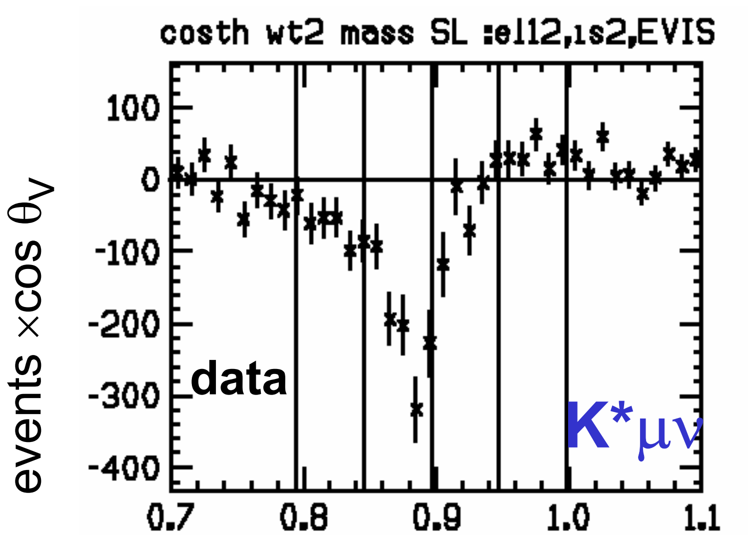
	br	stat	sys	stat+sys
cleo	0.49	0.1	0.12	0.156
argus	0.57	0.15	0.15	0.212
e687	0.58	0.17	0.07	0.184
cleo2	0.54	0.05	0.04	0.064
focus	0.540	0.033	0.048	0.058

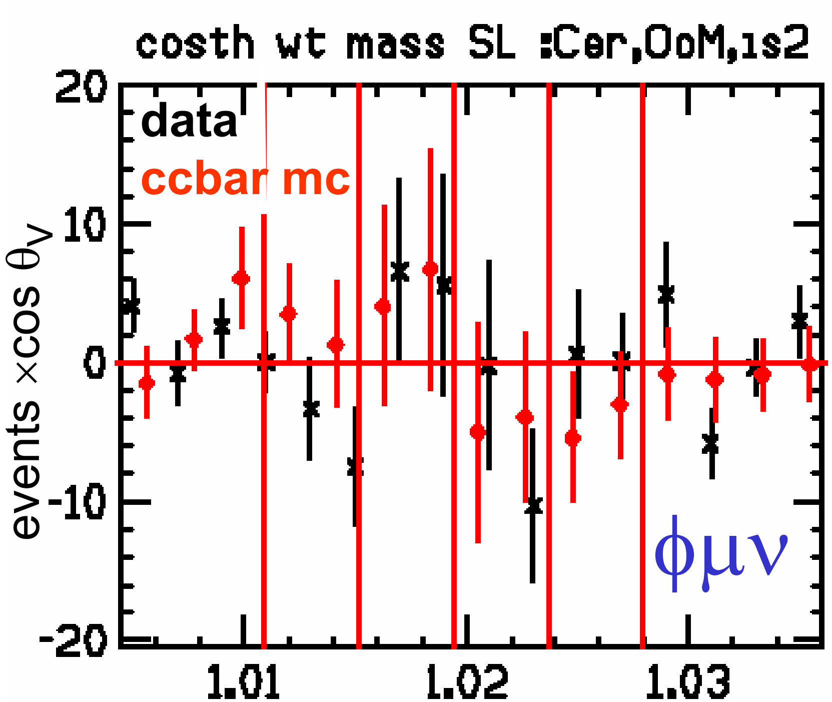
This branching ratio is traditionally used to set the scale for D_s^+ branching fractions by assumptions such as:

$$\Gamma(\phi\mu\nu) = (0.8 \to 1.0) \times \Gamma(\overline{K}^{*}\mu\nu)$$

S-wave interference in $\phi\mu\nu$?







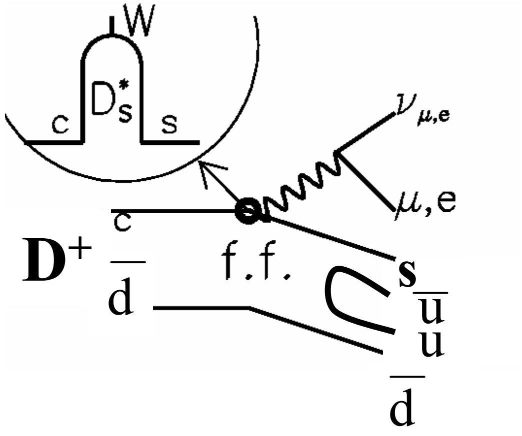
NO evidence for s-wave interference in Ds $\rightarrow\phi\mu\nu$

...and form factors

$$\frac{d^5\Gamma}{dm_{K\pi}dq^2d\cos\theta_V d\cos\theta_\ell d\chi} \propto f(H_\pm, H_0, H_t)$$

$$H_{\pm,0,t}(q^2) = g\left[A_{1,2,3}(q^2), V(q^2))\right]$$

The vector and axial form factors are generally parametrized by a pole dominance form



$$A_i(q^2) = \frac{A_i(0)}{1-q^2/M^2{}_A} \quad V(q^2) = \frac{V(0)}{1-q^2/M^2{}_V}$$

$$r_v \equiv V(0)/A_1(0) \quad r_2 \equiv A_2(0)/A_1(0)$$

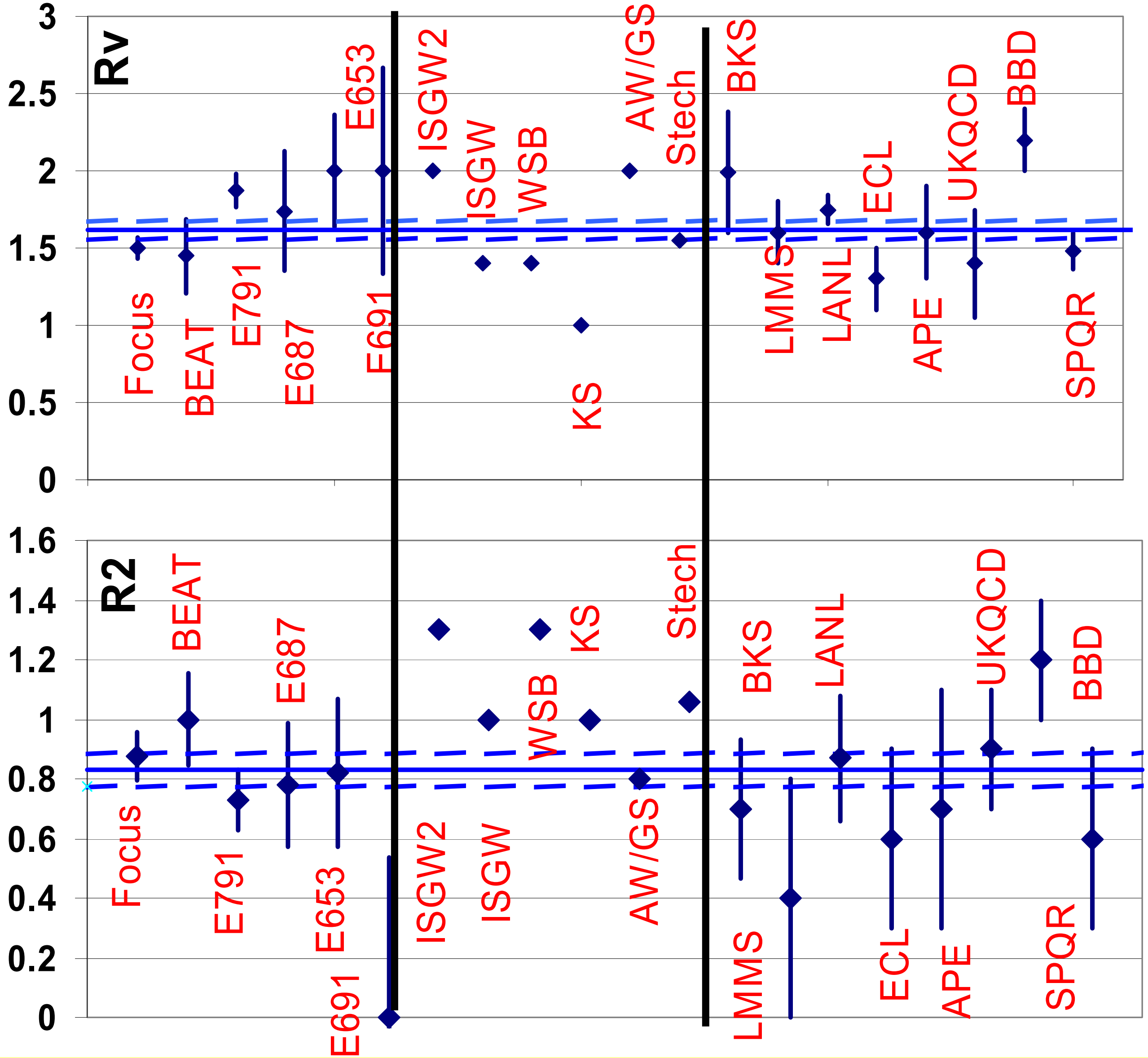
$$r_3 \equiv A_3(0)/A_1(0)$$

$M_A = 2.5 \quad GeV/c^2$

$M_V = 2.1 \quad GeV/c^2$

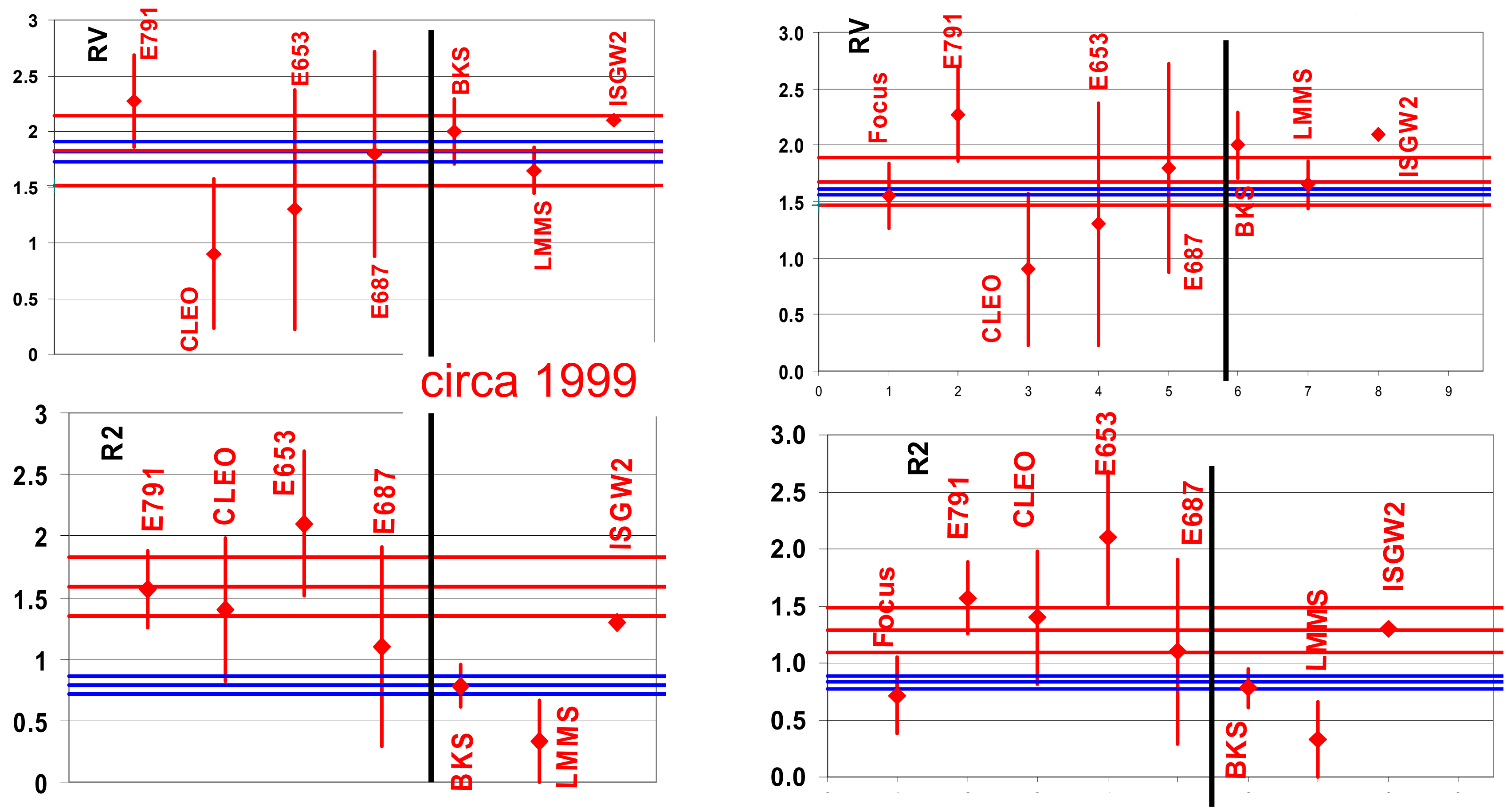
Nominal spectroscopic pole masses

$D^+ \to K^*\mu\nu$ form factors



Results are getting very precise and more calculations are needed.

$D_s \to \phi\mu\nu$ form factors



Theoretically the **$D_s \to \phi l \nu$** form factor should be within 10% of **$D \to K^* l \nu$** . The rV values were consistent but r2 for **$D_s \to \phi l \nu$** was ≈ 2⊗ higher than **$D \to K^* l \nu$** .

But the (2004) FOCUS measurement has consistent r2 values as well!

Semileptonic decays

Will there be similar effects (interference) in other charm semileptonic or beauty semileptonic channels?

Good question!

Hadronic decays

- the correct interpretation of the hadronic decays is complicated
- FSI play a central role (in the B decays they are supposed to be small, is it true?)
- amplitude analysis (Dalitz plot) is the correct tool to determine the resonant substructure
- first application of the *K-matrix* approach in the charm sector

FSI, an example the BR($D^0 \to K^- K^+$)/($D^0 \to \pi^- \pi^+$)

Elastic FSI - rotation in Isospin space

$\pi^- \pi^+ \xrightarrow[\text{FSI}]{\text{Elastic}} \pi^0 \pi^0$ $\quad K^- K^+ \xrightarrow[\text{FSI}]{\text{Elastic}} K^0 \bar{K}^0$

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(BR and Isospin analysis)

$$\frac{\Gamma(D^0 \to K^- K^+)}{\Gamma(D^0 \to \pi^- \pi^+)} = 2.81 \pm 0.12$$

Large SU(3) breaking

$$\frac{\Gamma(D^0 \to K^+ K^-) + \Gamma(D^0 \to K^0 \bar{K}^0)}{\Gamma(D^0 \to \pi^- \pi^+) + \Gamma(D^0 \to \pi^0 \pi^0)} = 2.06 \pm 0.24$$

Not affected by elastic FSI

SU(3) breaking is reduced

Conclusions:

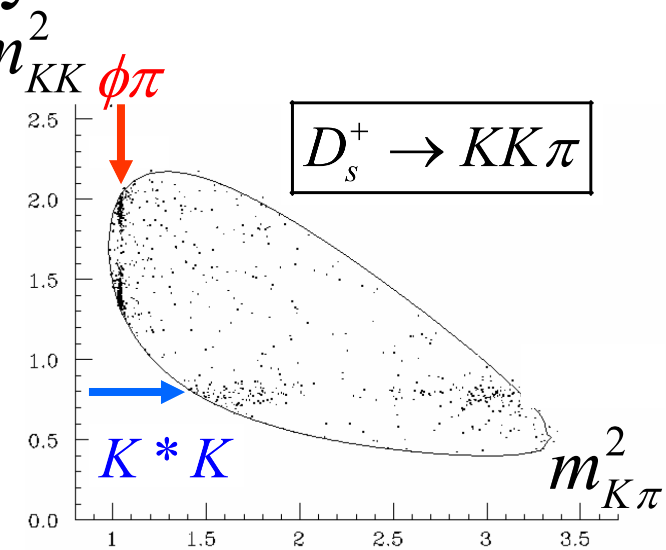
- Summing over Isospin rotated channels, SU(3) breaking is reduced.
- The effect of elastic FSI on BR ($K^- K^+$) /($\pi^- \pi^+$) is significant, but is unable to explain the discrepancy between experimental results and theoretical predictions ($\Gamma(K^- K^+)/\Gamma(\pi^- \pi^+) \leq 1.4$)

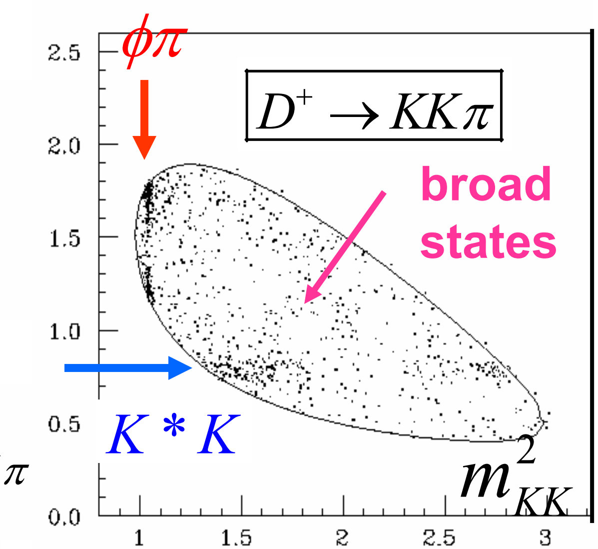
→ **Most reasonable explanation : inelastic FSI**

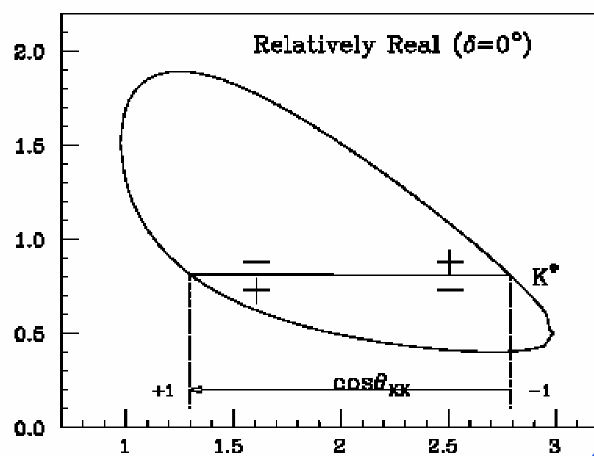
What do you learn from Dalitz plots?

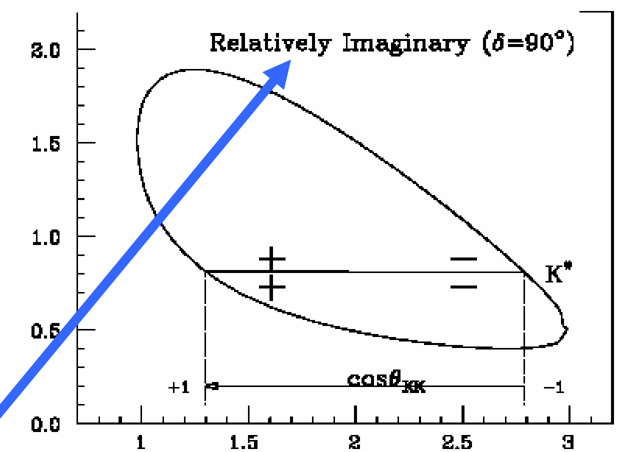
- Bands indicate resonance contributions
- For spinless parents, the number of nodes in the band give you the resonance spin
    - Look at the ϕ band
- Interference pattern gives relative phases and amplitudes
    - Look at the D+ K* band, we have a pattern of asymmetry

this could be the effect of the interference between K* and a broad large resonance









Final State Interactions

Amplitude analysis

• In the amplitude analysis of charm one has to face the problem of dealing with light scalar particles populating the hadronic decays such as **D→πππ, D →Kππ**

↓

complication for Dalitz plot analysis

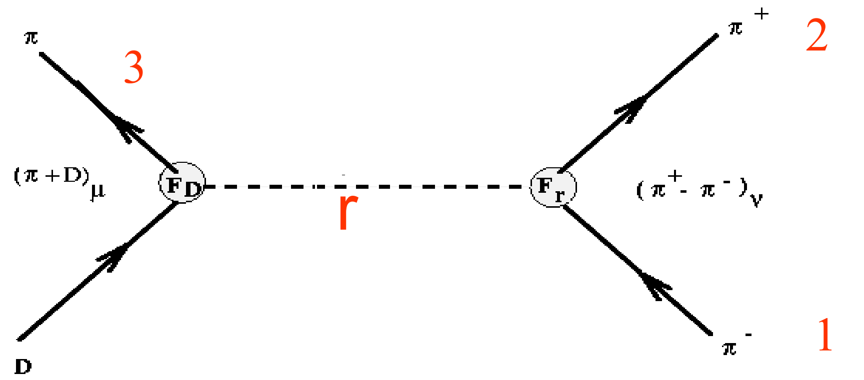
• Require understanding of light-quark hadronic physics including the riddle of

σ(600) and **κ(900)**

(i.e, ππ and Kπ states produced close to threshold), whose **existence** and **nature** is still **controversial**

How can we write the matrix element ?

$$D \longrightarrow r + 3$$
$$\quad \hookrightarrow 1 + 2$$



The problem is to write the propagator for the resonance r

For a **well-defined wave** with specific isospin and spin *(IJ)* characterized by **narrow and well-isolated** resonances, we know how:

the propagator is of the simple **BW type**

$$A = F_D F_r \times \left|\vec{p}_1\right|^J \left|\vec{p}_3\right|^J P_J(\cos \vartheta_{13}^r) \times \frac{1}{m_r^2 - m_{12}^{\ 2} - i m_r \Gamma_r}$$

The isobar model

$$A = F_D F_r \times \left|\vec{p}_1\right|^J \left|\vec{p}_3\right|^J P_J(\cos\vartheta_{13}^r) \times BW(m_{12}^2)$$

Where

$$F = 1 \quad \text{Spin 0} \quad P_J = 1$$

$$F = (1 + R^2 p^2)^{-½} \quad \text{Spin 1} \quad P_J = (-2\vec{p}_3 \cdot \vec{p}_1)$$

$$F = (9 + 3R^2 p^2 + 3R^4 p^4)^{-½} \quad \text{Spin 2} \quad P_J = 2(p_3 p_1)^2 (3\cos^2\vartheta_{13} - 1)$$

and

$$BW(12 \mid r) = \frac{1}{M_r^2 - m_{12}^2 - i\Gamma M_r} \qquad \Gamma = \Gamma_r \left[\frac{p}{p_0}\right]^{2j+1} \frac{M_r}{m_{12}} \frac{F_r^2(p)}{F_r^2(p_0)}$$

Dalitz total amplitude

$$\mathrm{M} = \sum_j a_j e^{i\delta_j} \mathrm{A}_j$$

fit parameters (a_j, δ_j)

fit fraction

$$\mathrm{f}_\mathrm{r} = \frac{\int \left| a_\mathrm{r} e^{i\delta_\mathrm{r}} \mathrm{A}_\mathrm{r} \right|^2 \mathrm{d}m_{12}^2 \mathrm{d}m_{13}^2}{\int \left| \sum_\mathrm{j} a_\mathrm{j} e^{i\delta_\mathrm{j}} \mathrm{A}_\mathrm{j} \right|^2 \mathrm{d}m_{12}^2 \mathrm{d}m_{13}^2}$$

Nearly all charm analyses use the isobar model

In contrast

when the specific *IJ*–wave is characterized by large and heavily overlapping resonances (just as the scalars!), the problem is not that simple.

Indeed, it is very easy to realize that the propagation is no longer dominated by a single resonance but is the result of a complicated interplay among resonances.

In this case, it can be demonstrated on very general grounds that the propagator may be written in the context of the K-matrix approach as

$$(I - iK \cdot \rho)^{-1}$$

where K is the matrix for the scattering of particles 1 and 2.

⇩

i.e., to write down the propagator we need the scattering matrix

K-matrix formalism

E.P.Wigner,
Phys. Rev. 70 (1946) 15
S.U.Chung et al.,
Ann.Phys. 4 (1995) 404

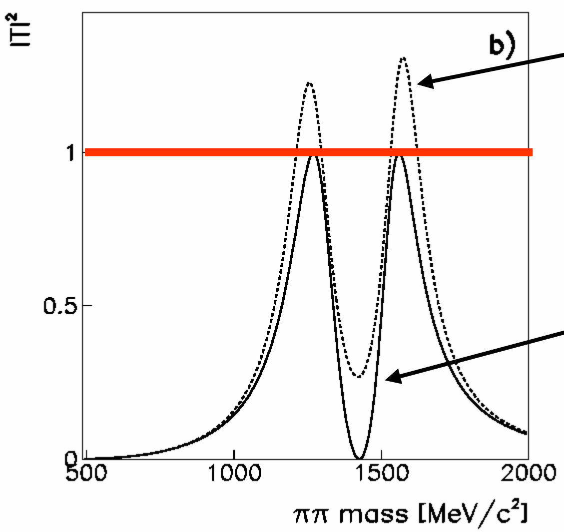
$$S = I + 2i\rho^{1/2} T \rho^{1/2}$$

T transition matrix

K-matrix is defined as: $K^{-1} = T^{-1} + i\rho$ i. e. $T = (I - iK\rho)^{-1} K$

real & symmetric

ρ = phase space diagonal matrix

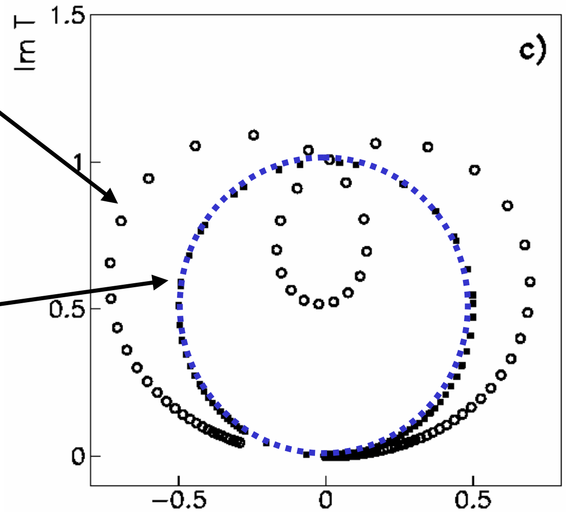


Add two BW ala Isobar model

Adding BW violates unitarity

Add two K matrices

Adding K matrices respects unitarity



The Unitarity circle

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

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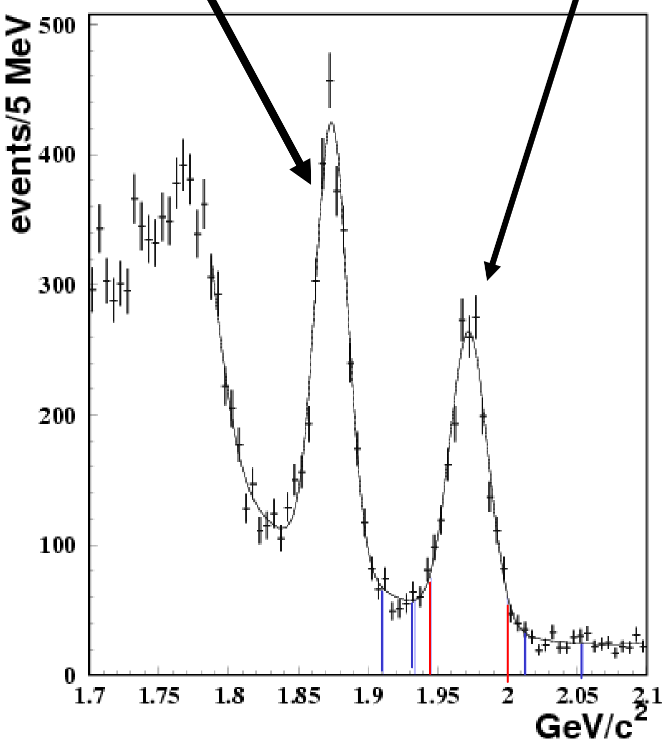
Yield D^+ = 1527 ±51

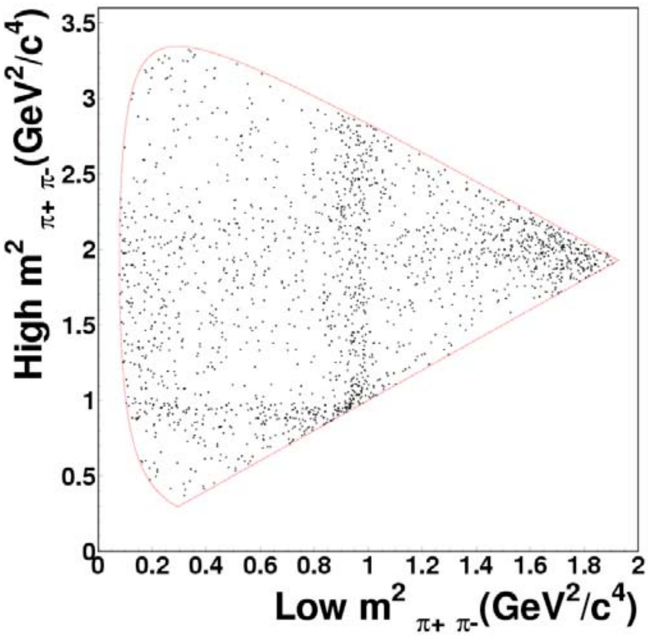
S/N D^+ = 3.64

Yield D_s^+ = 1475 ±50

S/N D_s^+ = 3.41

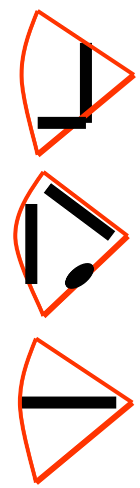


$D_s^+ \to \pi^+\pi^+\pi^-$



Observe:

- $f_0(980)$
- $f_2(1270)$
- $f_0(1500)$



Several broad and overlapping resonances contribute

Can they fit it using K- matrix based on fits to other data??

K-matrix picture

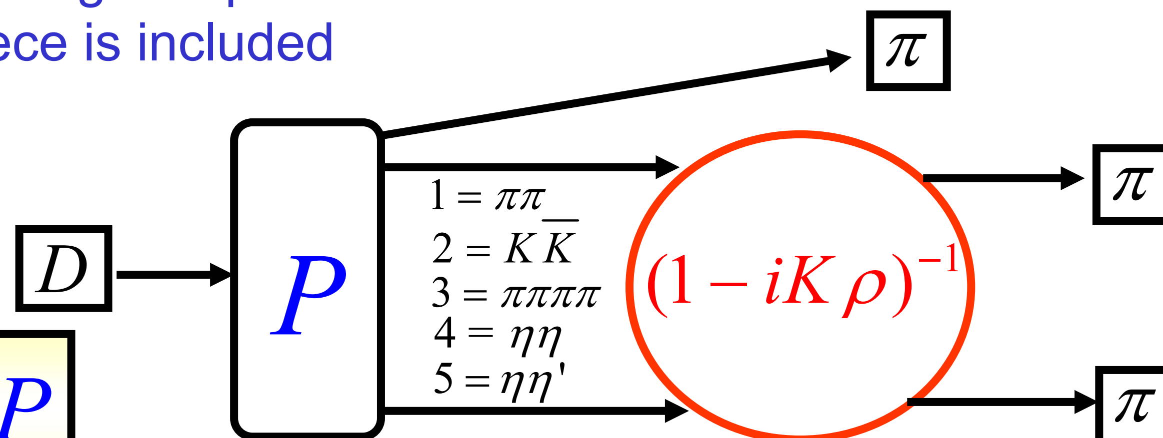
FOCUS, PLB585 (2004) 200

- The FOCUS amplitude was written as a sum

$$A(D) = a_0 e^{i\delta_0} + F + \sum_{i}^{J>0} a_i e^{i\delta_i} BW$$

vector and tensor contributions

- F term models S-wave using five virtual states ππ, KK, ηη, ηη’, 4π
- An isobar BW sum represents higher spin resonances
- A coherent non –resonant piece is included



$$F = (I - iK \cdot \rho)^{-1} P$$

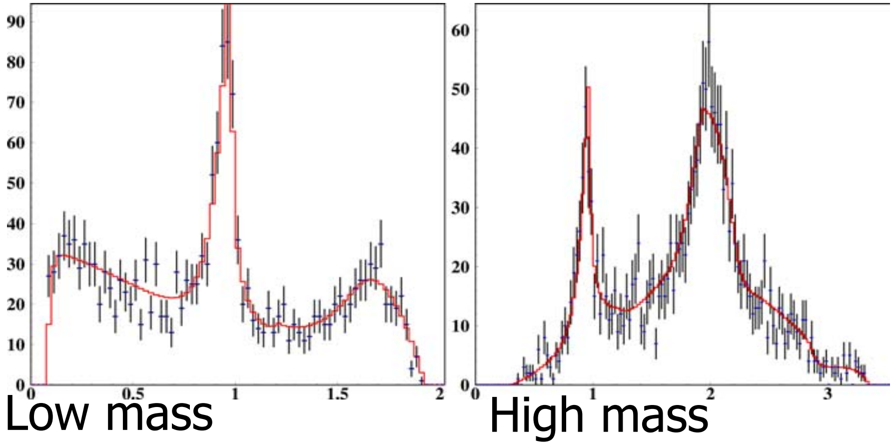
describes coupling of resonances to D

known from scattering data!

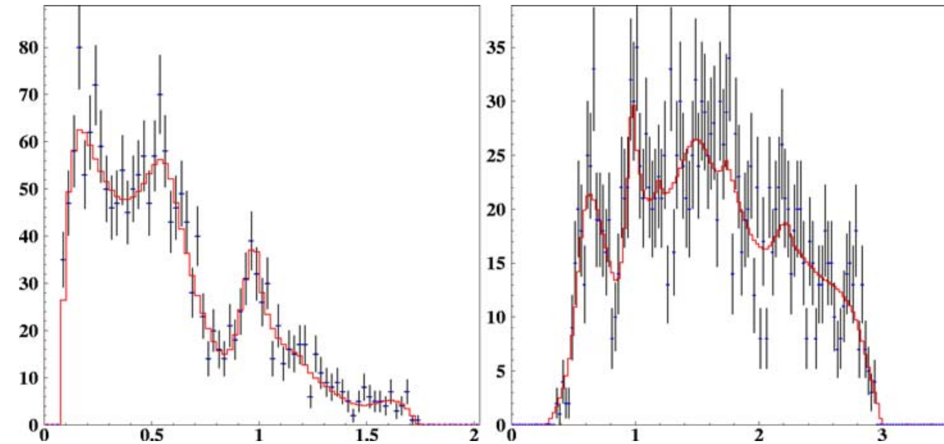
“K-matrix analysis of the 00++-wave in the mass region below 1900 MeV” V.V Anisovich and A.V.Sarantsev Eur.Phys.J.A16 (2003) 229

First K matrix fits to charm Dalitz plots

$D_s^+ \rightarrow \pi^+\pi^-\pi^+$



$D^+ \rightarrow \pi^+\pi^-\pi^+$



s-wave dominates

decay channel	fit fractions (%)	phase (deg)
$(S-wave)\pi^+$	$87.04 \pm 5.60 \pm 4.17$	$0(fixed)$
$f_2(1270)\pi^+$	$9.74 \pm 4.49 \pm 2.63$	$168.0 \pm 18.7 \pm 2.5$
$\rho^0(1450)\pi^+$	$6.56 \pm 3.43 \pm 3.31$	$234.9 \pm 19.5 \pm 13.3$

decay channel	fit fractions (%)	phase (deg)
$(S-wave)\pi^+$	$56.00 \pm 3.24 \pm 2.08$	$0(fixed)$
$f_2(1270)\pi^+$	$11.74 \pm 1.90 \pm 0.23$	$-47.5 \pm 18.7 \pm 11.7$
$\rho^0(770)\pi^+$	$30.82 \pm 3.14 \pm 2.29$	$-139.4 \pm 16.5 \pm 9.9$

Reasonable fits with <u>no retuning</u> of the A&S K-matrix and no need to invoke new resonances (such as σ(600)) and <u>no</u> NR term

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E831 FOCUS

Dalitz plot analysis : new probes of charm CP violation

- Main advantage: complete information not only the BR

→ DETERMINATION OF AMPLITUDE COEFFICIENTS AND PHASES

CP violating phase

$$\delta_i = \sigma_i + \omega_i$$

CP conserving phase

under CP conjugation :

$$\bar{\delta}_i = \sigma_i - \omega_i$$

- in general a difference between δ_i and $\bar{\delta}_i$ hints that CP is violated

Dalitz plot analysis: new probes of charm CP violation

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

CLEO, hep-ex/0311033

$$\mathcal{M} = a_0 e^{i\delta_0} + \sum_j a_j e^{i(\delta_j + \phi_j)} (1 + \frac{b_j}{a_j}) \mathcal{A}_j$$

$$\overline{\mathcal{M}} = a_0 e^{i\delta_0} + \sum_j a_j e^{i(\delta_j - \phi_j)} (1 - \frac{b_j}{a_j}) \mathcal{A}_j$$

TABLE II: *CP* Violating Parameters. Errors are statistical, experimental systematic and modeling systematic, respectively. The fit fraction is computed from Eq. 1 following the prescription described in the text and includes statistical and systematic effects.

Component	Amplitude (b_j/a_j)	Phase (ϕ_j)	Fit Fraction (95% Upper Limit)
$K^*(892)^+\pi^- \times B(K^*(892)^+ \to K^0\pi^+)$	$-.12\pm0.20^{+0.06+0.10}_{-0.15-0.04}$	$4\pm20^{+1+4}_{-3-27}$	$< 7.8 \times 10^{-4}$
$\overline{K}^0\rho^0$	$0.00\pm0.02^{+0.02+0.00}_{-0.06-0.04}$	$-3\pm16^{+0+6}_{-2-18}$	$< 4.5 \times 10^{-4}$
$\overline{K}^0\omega \times B(\omega \to \pi^+\pi^-)$	$-.09\pm0.10^{+0.07+0.01}_{-0.00-0.06}$	$-8\pm17^{+2+6}_{-3-20}$	$< 7.8 \times 10^{-4}$
$K^*(892)^-\pi^+ \times B(K^*(892)^- \to \overline{K}^0\pi^-)$	$0.00\pm0.02^{+0.01+0.01}_{-0.06-0.05}$	$-5\pm15^{+0+5}_{-1-19}$	$< 5.2 \times 10^{-4}$
$\overline{K}^0 f_0(980) \times B(f_0(980) \to \pi^+\pi^-)$	$-.03\pm0.05^{+0.04+0.04}_{-0.06-0.06}$	$7\pm15^{+1+4}_{-1-19}$	$< 5.5 \times 10^{-4}$
$\overline{K}^0 f_2(1270) \times B(f_2(1270) \to \pi^+\pi^-)$	$0.15\pm0.23^{+0.14+0.13}_{-0.19-0.10}$	$21\pm18^{+2\ +28}_{-15-27}$	$< 12.5 \times 10^{-4}$
$\overline{K}^0 f_0(1370) \times B(f_0(1370) \to \pi^+\pi^-)$	$0.08\pm0.05^{+0.05+0.15}_{-0.15-0.05}$	$7\pm14^{+1+12}_{-3-15}$	$< 24.2 \times 10^{-4}$
$K_0^*(1430)^-\pi^+ \times B(K_0^*(1430)^- \to \overline{K}^0\pi^-)$	$-.02\pm0.05^{+0.07+0.06}_{-0.06-0.06}$	$-5\pm16^{+1+8}_{-3-20}$	$< 8.6 \times 10^{-4}$
$K_2^*(1430)^-\pi^+ \times B(K_2^*(1430)^- \to \overline{K}^0\pi^-)$	$-.06\pm0.11^{+0.03+0.11}_{-0.11-0.04}$	$1\pm16^{+2+10}_{-2-16}$	$< 7.2 \times 10^{-4}$
$K^*(1680)^-\pi^+ \times B(K^*(1680)^- \to \overline{K}^0\pi^-)$	$-.20\pm0.09^{+0.11+0.12}_{-0.04-0.24}$	$-6\pm16^{+17+14}_{-0\ -14}$	$< 29.0 \times 10^{-4}$

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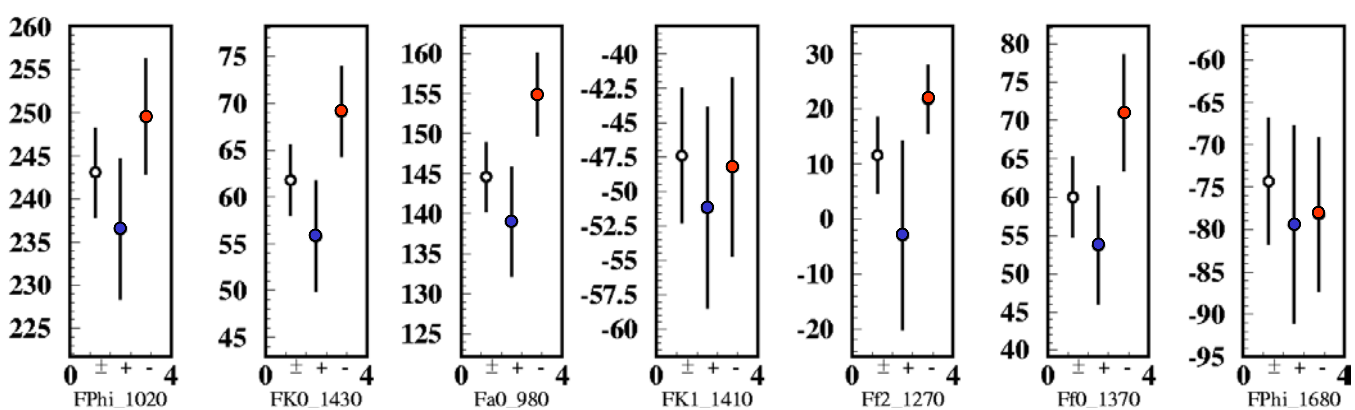
SCD $D^+ \to K^- K^+ \pi^+$

(ICHEP 2002)

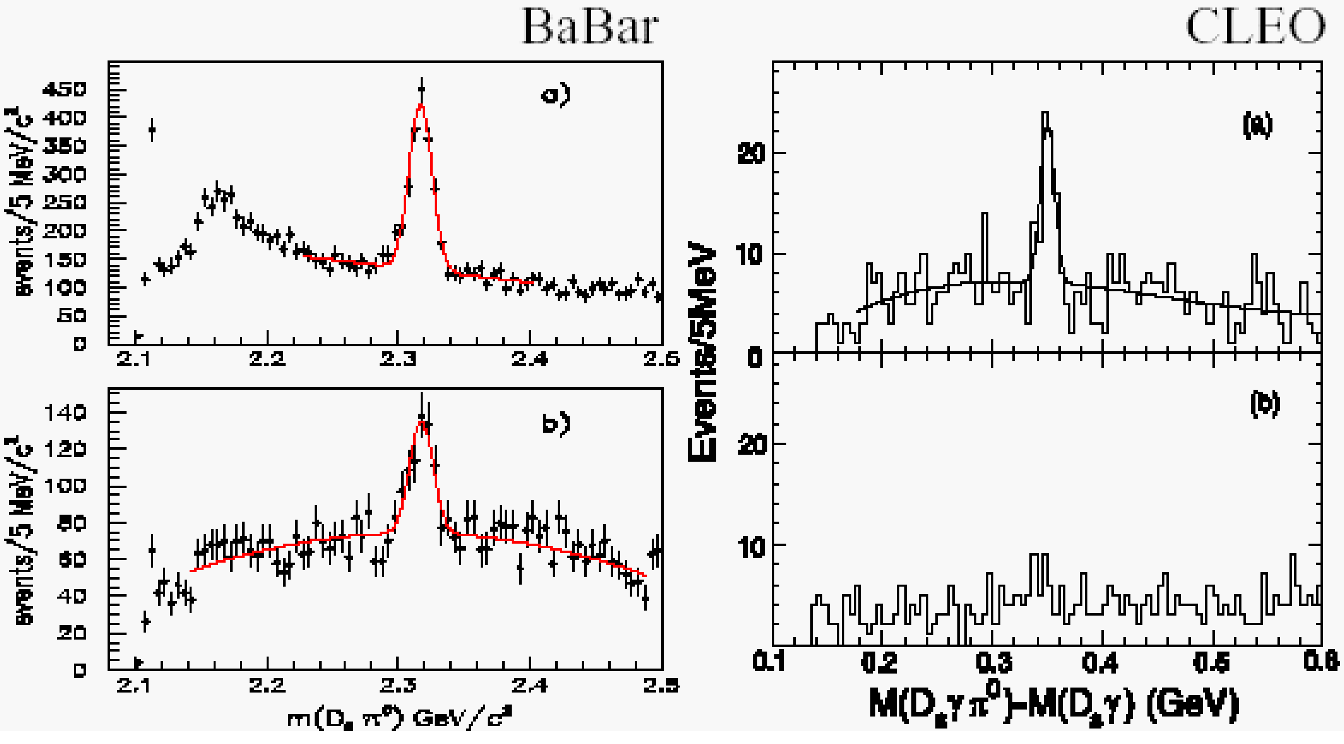
Phases: $D^\pm$, D^+, D^-



D_{sJ} states

D_{sJ} observations

- BaBar (PRL **90**, 242001) reported observation of a new resonance at 2317 MeV in $D_s^+\pi^0$ final state
- CLEO (hep-ex/0305017 → PRD) observed resonance at 2459 MeV in $D_s^{*+}\pi^0$ final state



D_{sJ} states

Strange property of these states is their surprisingly low mass compared to the potential model expectations, their masses are practically equal to those of similar states in $c\bar{u}$ system:

$c\bar{s}$	$D_{sJ}(2317)$	$D_{sJ}(2458)$
$c\bar{u}$	$D^{*}{}_{0}{}^{0}(2308)$	$D'{}_{1}{}^{0}(2427)$

D_{sJ} states

BABAR slide

SPIN-PARITY

$D^{*}_{sJ}(2317)^{+}$

- Decay to $J^P=0^-$ mesons → only natural spin-parity allowed $[0^+,1^-,2^+,\ldots]$
- $J^P=0^+$ suggested by: 1) low mass compared to $D_{s1}(2535)$ & $D_{sJ}^*(2573)$
  2) absence of decay to $D_s^+\gamma$ (not allowed if $J^P=0^+$)
  3) absence of decay to $D_s^+\pi^+\pi^-$ (not allowed if $J^P=0^+$)

$D_{sJ}(2458)^{+}$

- Un-natural spin-parity more likely (lack of decays to DK)
- $D_{sJ}(2458)^{+} \to D_s^+\gamma$[by Belle] $\Rightarrow J \neq 0$
- Belle helicity analysis from B-decays favours J=1
- Decay to $D_s\pi^+\pi^-$ (by Belle) allowed by $J^P=1^+$

EXPERIMENTAL SUMMARY

Two narrow states observed, in the inclusive $D_s\pi^0$ & $D_s{}^*\pi^0$ invariant mass distributions, near $2.317 GeV/c^2$ & $2.458 GeV/c^2$.
The widths $[\Gamma<10 MeV]$ are consistent with experimental resolution.
The most likely assignment for their spin-parity is 0^+ & 1^+.

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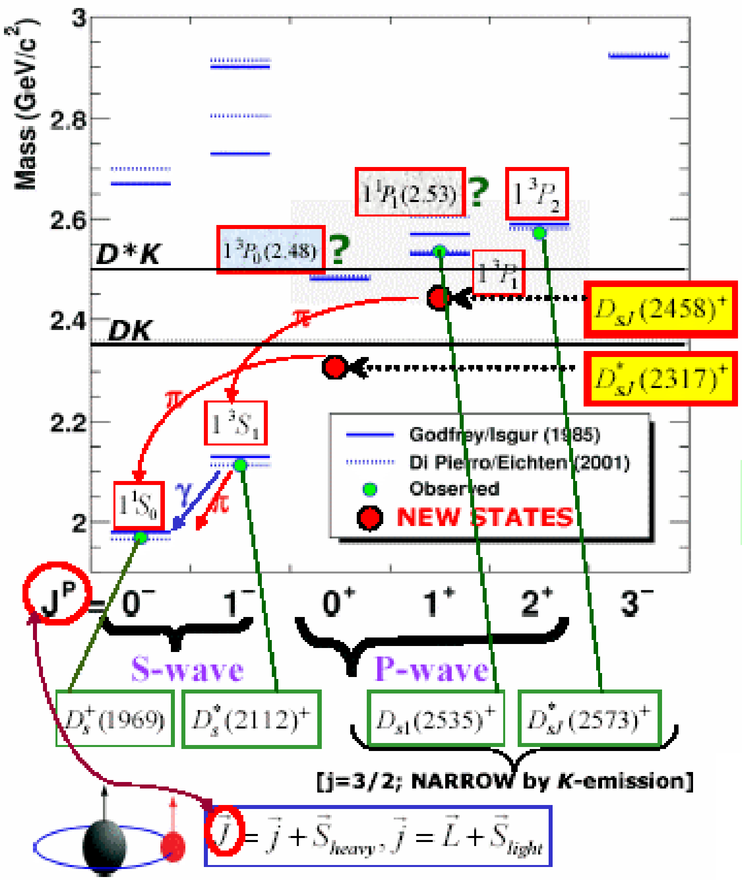
D_{sJ} states

BABAR slide

Spectroscopy of $c\bar{s}$ states (before & after)

Potential models of [heavy-quark | light-quark] mesons: so far **reasonable success** for spectroscopy of D, D_s, B, B_s systems



New states **do not fit well**: masses **below** the $DK[D^*K]$ threshold.

IF interpreted as ordinary $c\bar{s}$ states, they decay mainly by **isospin-violating π-emission** thus having **widths quite narrow**.

A possible decay mechanism is **through a virtual η followed by η-π⁰ mixing** [Cho-Wise, PRD49].

$$m[D^*_{sJ}(2317)] - m[D_s(1969)] \cong$$
$$\cong m[D_{sJ}(2458)] - m[D^*_s(2112)]$$

…as predicted by models based on HQET & chiral symmetry [*Bardeen et al.,…*] **if new states are 0^+ & 1^+**

40(!) papers by theorists:
Exotic (4-quark, molecule, …)
VS
Ordinary explanations (HQET+chiral symmetry, …)

Conclusions

- At 30 years from the discovery of the *c* quark the analysis of the decay modes of the first *heavy* quark has reached a complete maturity
- With the large statistics now available in the charm sector, we start to see strange effects which complicate the explanation of the decay processes

- FSI play a crucial role
- *Light* hadron physics is important in charm decays (*K*-matrix approach has been applied to charm decays for the first time)

- Lessons for the *b* sector?

Conclusions

- Exciting new states D_{sJ} found !!

- Charm decays:

  - Present: BABAR, BELLE, CLEO-c and CDF

  - Future: BTeV and LHC-b