Charm Physics at CLEO

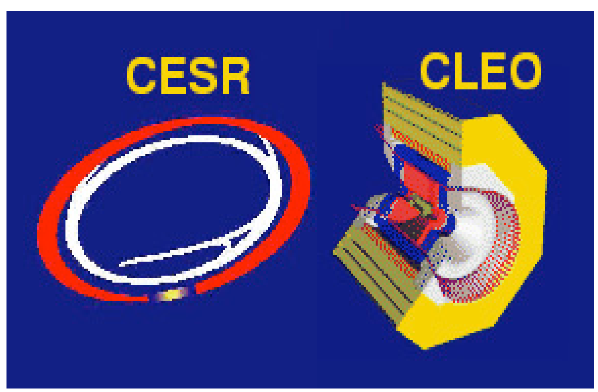
Roy A. Briere

Carnegie Mellon University

CLEO Symposium
31 May 2008

CORNELL UNIVERSITY LEPP
LABORATORY FOR ELEMENTARY-PARTICLE PHYSICS

NSF



Carnegie Mellon

Office of Science
U.S. DEPARTMENT OF ENERGY

Overview

Weak Physics at CLEO: "All notes from the same chord"

B^b D F (this is a B^b major chord)

CLEO first concentrated with B mesons
containing b quarks: B^b

After the asymmetric B factories came online,
we moved to other notes in the same chord: D F

For the younger crowd, note (sic) that the D_s was once called the "F"
(Lincoln Wolfenstein often asked me how our "F Factory" was going)

Our Distinguished Cast

Seven Weakly-Decaying Ground States:

	D^0	D^+	D_s^+	Λ_c	Ξ_c^0	Ξ_c^+	Ω_c
Modes	$K\pi$	$K\pi\pi$	$KK\pi$	$pK\pi$	$\Xi\pi$	$\Xi\pi\pi$	$\Omega\pi$

Vector mesons, other L=0 baryons states:

very common

decays are a mix of pion and photon transitions

P-wave states:

a bit less common; pion and kaon decay transitions;

HQET guidance --> some narrow states due to D-wave decays

CAVEATS & OMISSIONS

Many other people could have been chosen to give this talk.

I'm sure I will say "we" sometimes when "CLEO" is more appropriate… I've been here for "only" 13 years, after all.

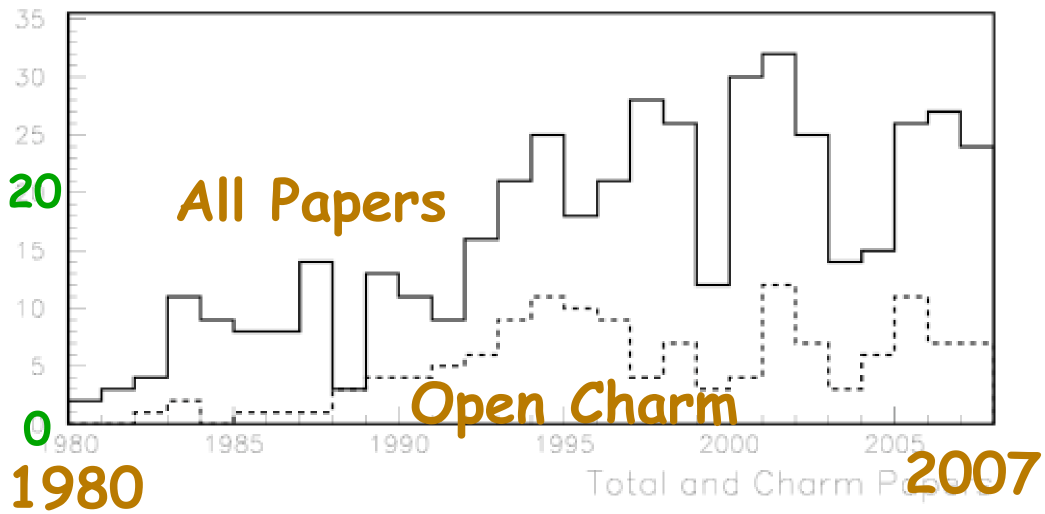
Charmonium was well-covered earlier in this Symposium…

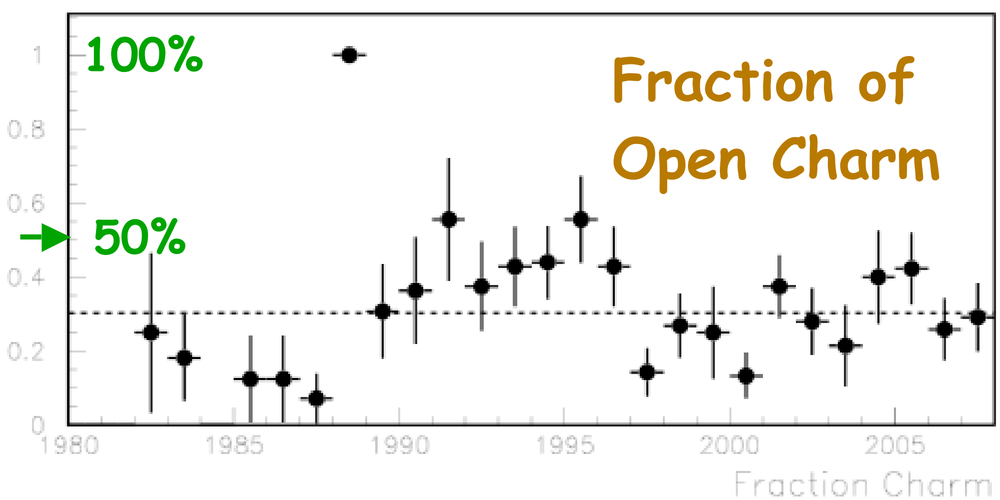
STILL about 150 open-charm papers from CLEO !!!
(>30% through 2008 submissions)

So some things will of course be missed, e.g.:
- o Mapping out decay modes is under-covered
- o CLEO-c: a bit less emphasized since it's more familiar

Finally, I only know some of the historical tales… take advantage of this gathering to talk to the Primary Sources among us !

Paper Statistics





Open Charm papers are 30% of total CLEO papers (1980 - 2007)

A bit slow at the start

Then…much interest in 1990's

-- New university groups

-- Served by multiple PTAs

SURPRISE: Open Charm does NOT dominate CLEO-c era, due to quarkonia, other topics

Organizational Themes

Historical Ordering

CESR Upgrades and Data Size (correlated)

Detector Upgrades

CLEO1.5	DR2 tracking	0.43 fb^{-1}	1987-1988
CLEOII	CsI calorimeter	4.8 fb^{-1}	1989-1995
CLEOII.V	Silicon vertexing	9.0 fb^{-1}	1995-1999
CLEOIII	RICH Particle ID	9.4 fb^{-1}	2000-2003

Techniques

- D* tags
- Vertixing
- Partial reconstruction

The CLEO-c era changed the whole landscape! 2003 - 2008

Physics

CKM, CPV, DCSD, FCNC, FSI, HQET, LQCD, D Mixing, Spectator Model, Diagramology, Spectroscopy, Dalitz Plots, Fragmentation, …

Act I:
Charm Arrives at CLEO

Interest in Charm?
First D* Mesons Appear in CBX Land
Charm Fragmentation Papers
Earning an "F" Grade
First Lifetimes from CLEO
Tagging, 1988-style

CLEO1.5 on D_s Decays and Charm Baryons

1981: Interest in Charm?

CBX 81-22
19 March 1981
Analysis Committee

Analysis Effort - February 1981

During February, members of the Analysis Committee studied the analysis effort at their own institutions, and prepared the reports that follow. The gain from putting together an integrated report did not seem worth the delay it would entail. We list here topics that appear in 2 or more reports.

$K^{\pm}$ identification (Har, Syr, Van)
e identification (Cor, Roc, Rut, Van)
$p,\bar{p}$ identification (Har, Syr)
K^0 detection (Cor, Har, Van)
π^0 detection (Rut, Syr)
D reconstruction (Cor, Har, Roc, Van)
B reconstruction (Cor, Roc, Van)
Hard photons (Cor, Roc)

Not clear that much interest is in charm itself; likely more in charm from B…

CBX 81-20
E. H. Thorndike
March 10, 1981

Physics Objectives Survey

56% response rate

Points system:

10,5,2,3,1 for 1st-5th choice

Results:

B Physics	512.1	
Upsilon	121.5	
Other	103.4	
New States	26.6	
Continuum	38.6	**
Misc…	8.5	
Higgs!	8.0	
'Unexpected'	21.7	

** 5.0 ccbar

** 2.0 charm baryons

Charm at CLEO:

A Slow but Steady Start

First 10 CLEO papers:

-- 4 Upsilon, 5 B meson, and… *1 on D* fragmentation*

Only 4 of first 37 CLEO papers from 1980-1985 are on charm

-- 3 on fragmentation plus the discovery of the F (now D_s)

13 of 75 total journal papers 1980-89 are on charm (17%)

-- 4 on D fragmentation (including 1 on the Λ_c)

-- 4 on Charm Baryons (note: 3 of the 4 from 1989 !)

-- 3 on $D_{(s)}$ decays (2 w/ observations, 1 w/ FCNC limits)

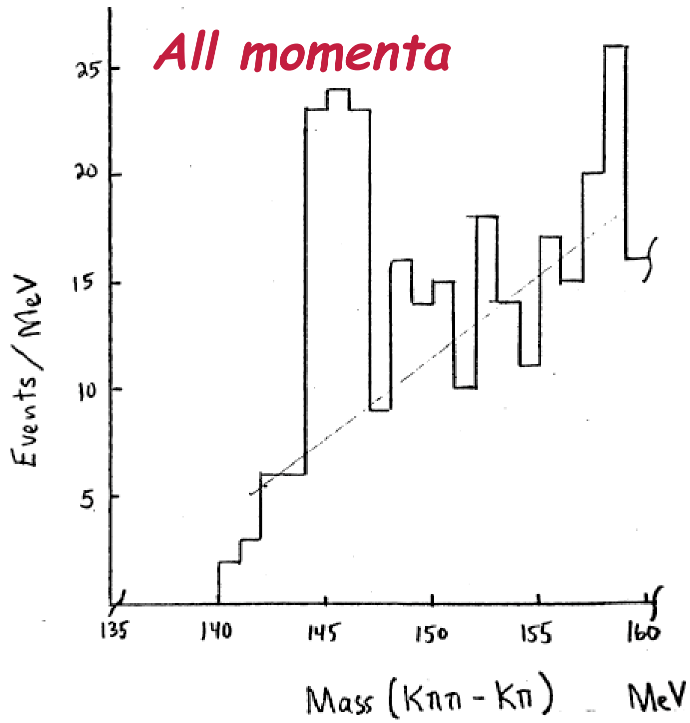
best: $B(c \rightarrow Xe^+e^-) < 2.2\ 10^{-3}$

-- 1 on the $D^0/D^+/D_s$ meson lifetimes

-- 1 on the discovery of the F (= D_s) 2nd charm paper!

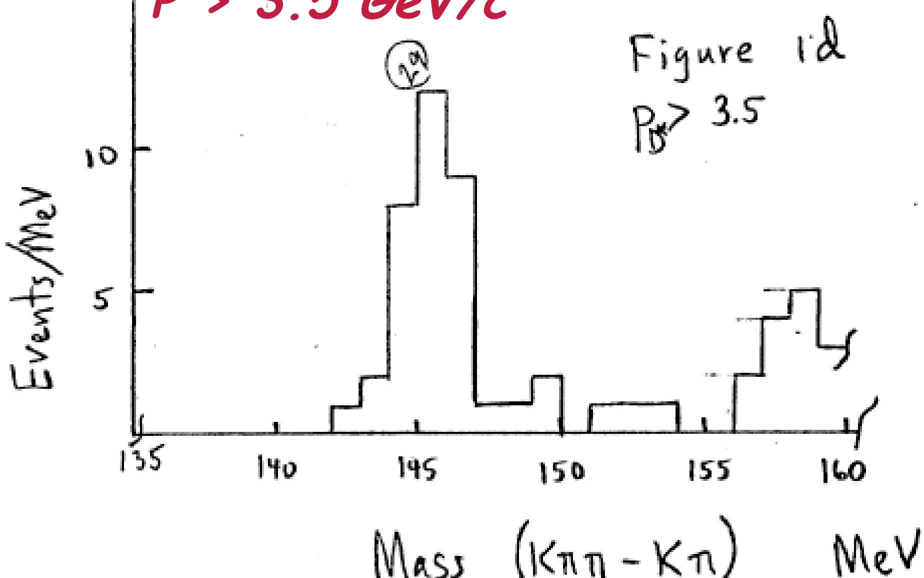
First D* at CLEO

All momenta



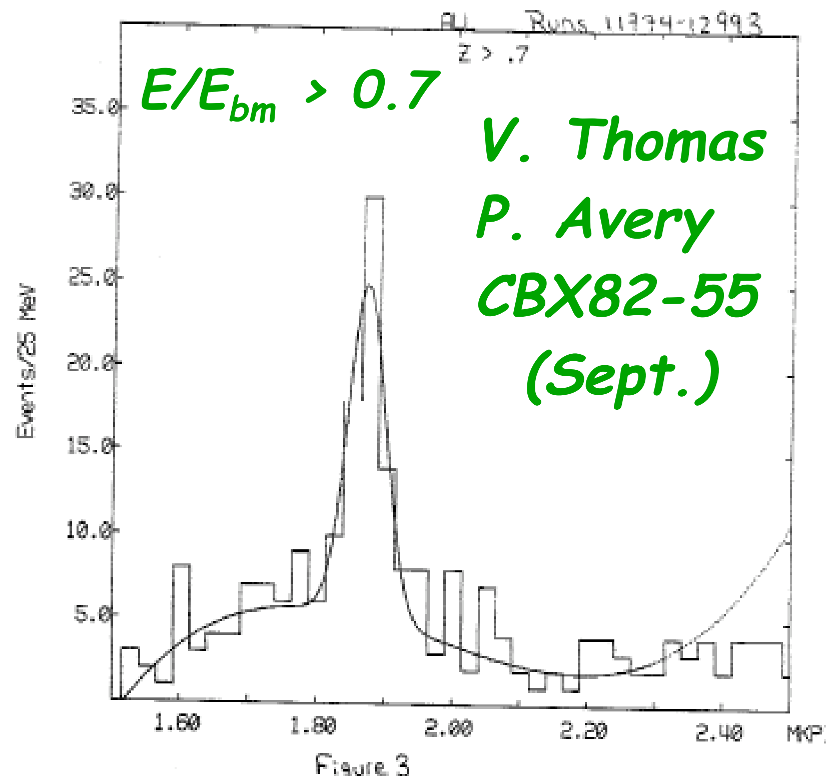
J. Rohlf
CBX82-19
(Feb.)

P > 3.5 GeV/c



Note: I'm skipping the work on D^0, D^+ from the $\Upsilon(4S)$

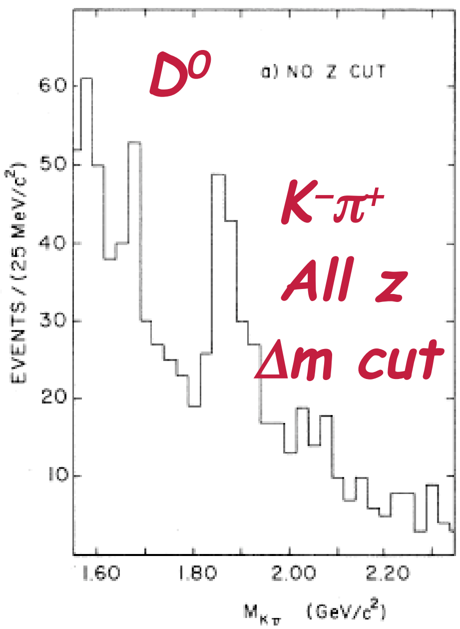
$E/E_{bm} > 0.7$

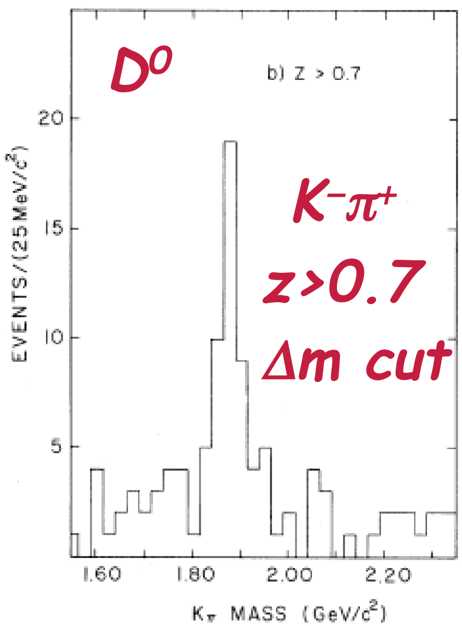


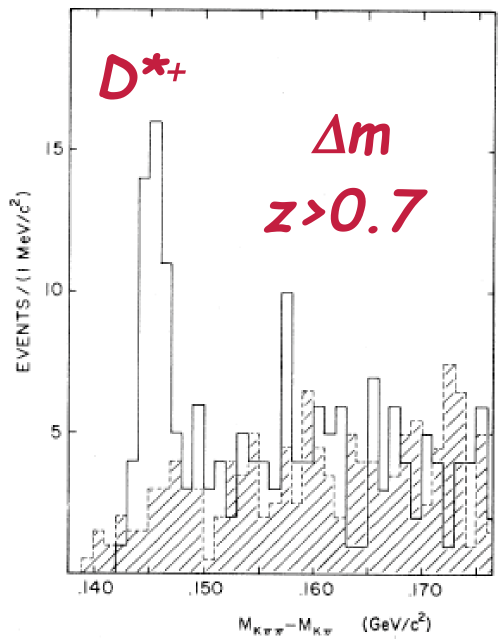
V. Thomas
P. Avery
CBX82-55
(Sept.)

First Fragmentation Papers

PRD 49, 610
1982 23 pb^{-1}

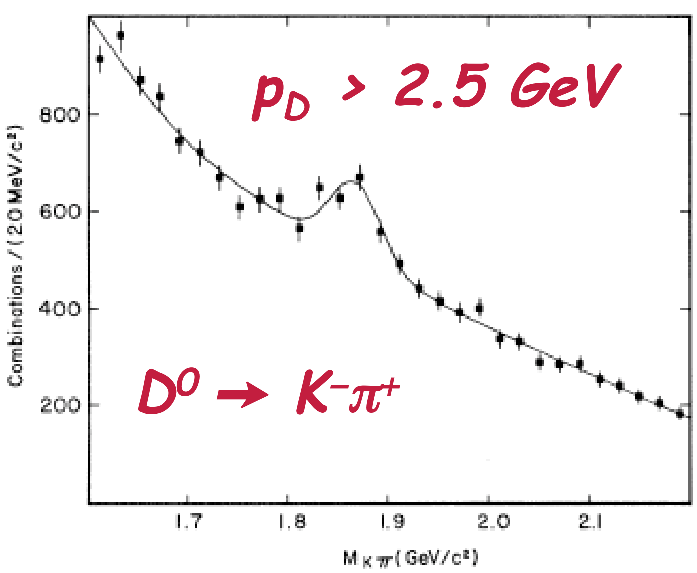


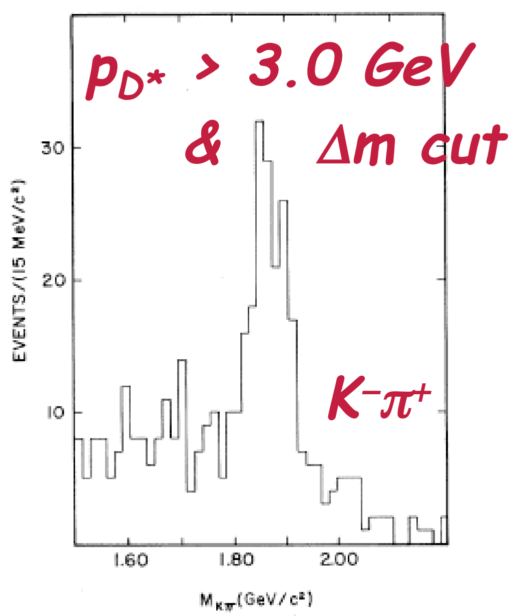


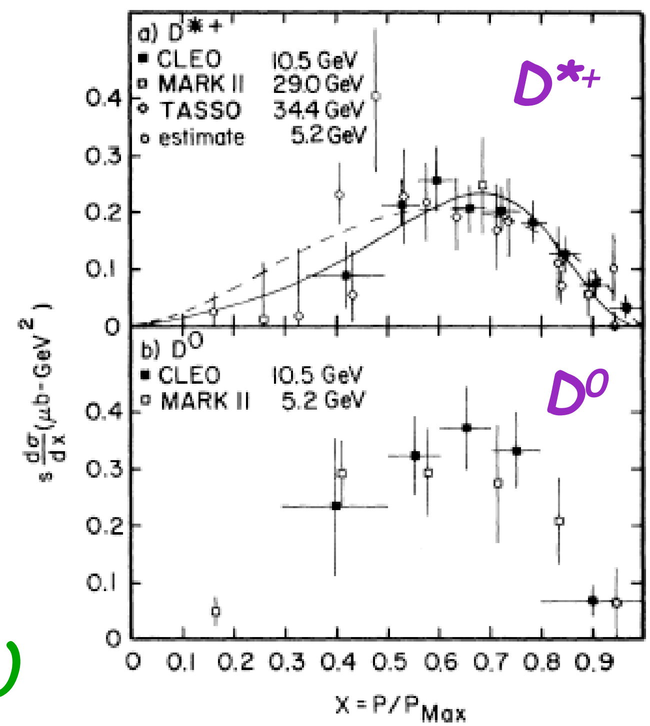


Plot vs.
$Z = 2E/W$
(scaled E)

see hard fragmentation







PRL 51,1139
1983 59 pb^{-1}

Switched to: $x = P/P_{max}$ (scaled p)

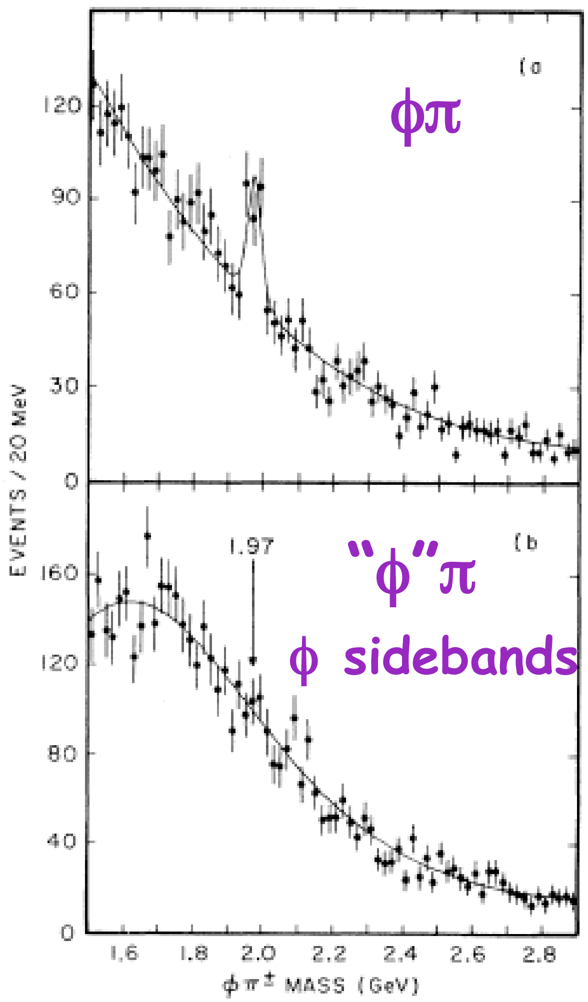
CLEO Earns an F

(that's really an A^+)

PRL 51, 634 (1983)
* 58 pb^{-1} *

VOLUME 51, NUMBER 8 — PHYSICAL REVIEW LETTERS — 22 AUGUST 1983

Evidence for the *F* Meson at 1970 MeV



Signal: 104 ± 19 Events
Mass: (1970 ± 5 ± 5) MeV
(calibrate w/ $K \rightarrow \pi\pi$ $D \rightarrow K\pi$)

Paper's "crude estimate" that:
$B(D_s \Rightarrow \phi\pi) \sim 4.4\%$,
is actually remarkably good !

Really a "discovery"? Yes, this seems fair !
Previous F discovery claims were "pathological"
See S. Stone, arXiv:hep-ph/00100295 for details

Early CLEO D Lifetimes

PL B191,318
1987 110 pb^{-1}

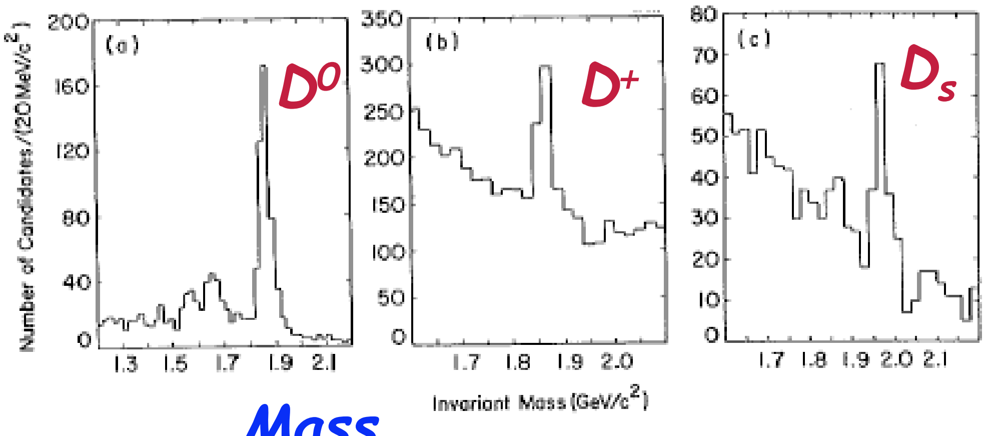
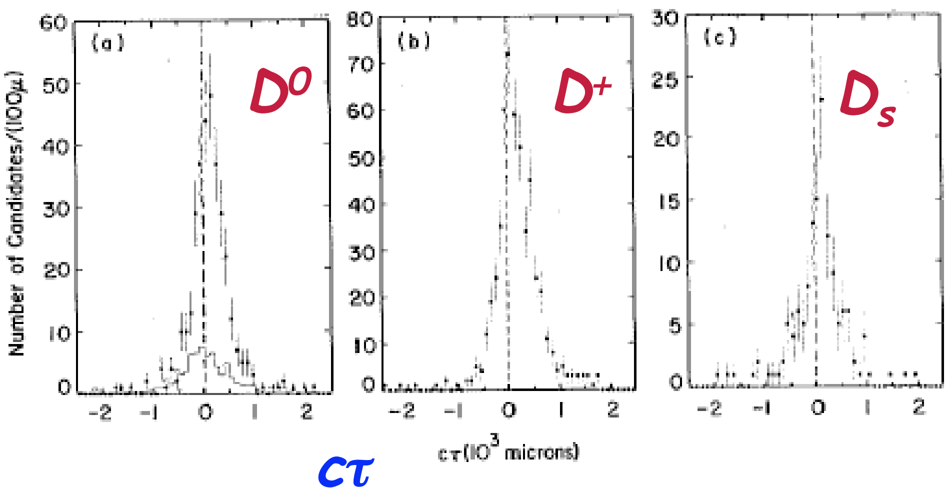


Fig. 1. Invariant mass distributions for (a)D^0, (b)D^+, and (c)D_s^+ candidates.



Connects BF (experiment)
to Γ_i (theory)

Spectator model violations?

Precision: ~15% (50% D_s)
Competitive at the time

Also firms up unequal lifetimes:
$\tau(D^+)/\tau(D^0)$ = 2.3 ± 0.5
(quotes new world ave.
as 2.3 ± 0.3)

	# Candidates	$(c\tau)_m$ (μm)	f_b (%)	$(c\tau)_b$ (μm)	Lifetime (x10^{-13} s) decay vertex	impact parameter
D^0	345	138±19	8±2	14±39	5.0±0.7±0.4	4.1±1.0±0.4
D^+	526	173±20	53±3	22± 8	11.4±1.6±0.7	10.6±1.9±0.6
D_s^+	141	93±37	39±3	19±34	4.7±2.2±0.5	4.5±3.2±0.5

Continuum Tags

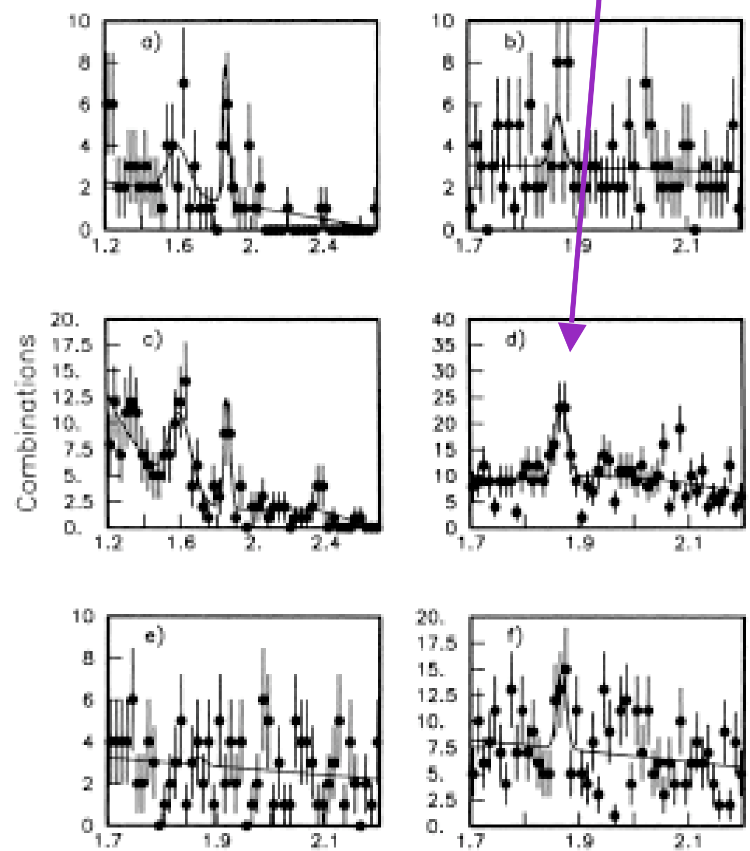
PRD 38, 2679
1988 113 pb^{-1}

Paper measures ΔR_{had} from charm, in two ways.

Method 1 uses tags:

- Uses inclusive reconstruction of a given charm mode
- Compares to same, with another anti-charm "tag"
- Get cross-section independent of BF
  - (similar to CLEO-c, but with
  - some assumptions & approximations)
  - ΔR_{had} = 1.13 +0.17-0.13 ± 0.09

D^{*-} vs. D^0
(both $K3\pi$)

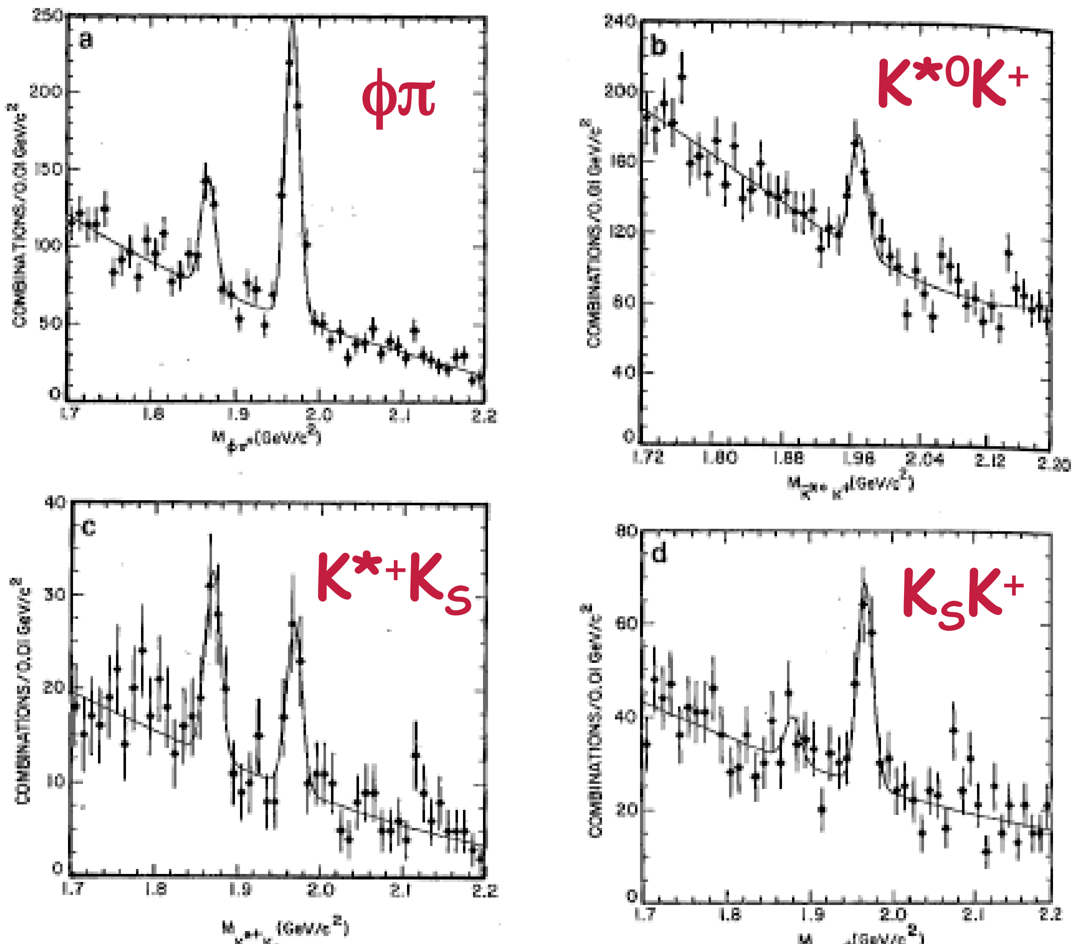


Method 2 uses inclusive electrons:

- Get cross-section for eX
- Estimate production rates and
  - semileptonic BFs to get charm x-section
- ΔR_{had} = 2.07 ± 0.12 ± 0.26

Some D_s Decay Modes

PLB 226,192
1989 0.43 fb^{-1}



note D^{+} peaks to left...

Still in "early days", investigate role of:

- o color suppression
- o W-exchange
- o W annihilation
- o FSI

Mode	# of events	Efficiency [%]	$B\cdot\sigma$(pb), $x_r \geqslant 0.5$	$B/B(D_s^+ \to \phi\pi^+)$
$D_s^+ \to \phi\pi^+$	405 ± 27	14.3 ± 0.3	6.5 ± 0.5 ± 0.3	1.0
$D_s^+ \to \overline{K^{0*}}K^+$	149 ± 25	5.1 ± 0.4	6.8 ± 1.1 ± 0.7	1.05 ± 0.17 ± 0.12
$D_s^+ \to K^{*+}\overline{K^0}$	40 ± 7	1.2 ± 0.1	7.8 ± 1.4 ± 0.8	1.20 ± 0.21 ± 0.13
$D_s^+ \to \overline{K^0}K^+$	110 ± 19	4.0 ± 0.3	6.4 ± 1.1 ± 0.6	0.99 ± 0.17 ± 0.10

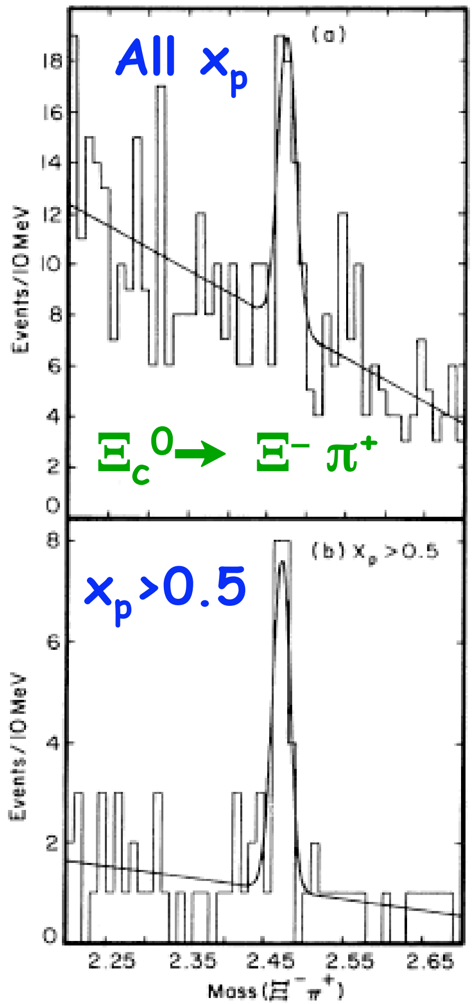
PRL 62,863
1989 0.43 fb^{-1}

Charm Baryons Discoveries

PRL 62,1240
1989 0.57 fb^{-1}

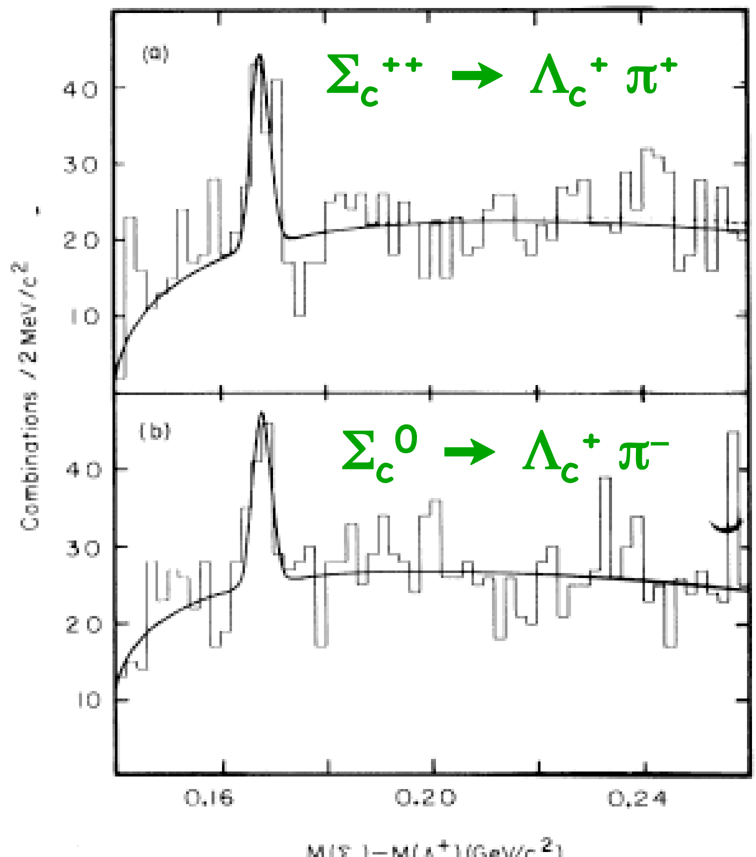
The story begins in 1989:

Discovery of the Ξ_c^0



$M(\Xi^- \pi^+)$

Confirmation of the Σ_c^{++} & Σ_c^0



$M(\Sigma_c) - M(\Lambda_c)$

Act II:
Hitting Our Stride

The CLEOII Datasets:

Too many topics to be worth listing…

Two Popular Sample sizes:

- Early Results

  ~1.6-1.9 fb^{-1}

- Full Statistics

  4.7 fb^{-1}

René would be proud:

It is not enough to have a good ~~mind~~ *detector*.
The main thing is to use it well.

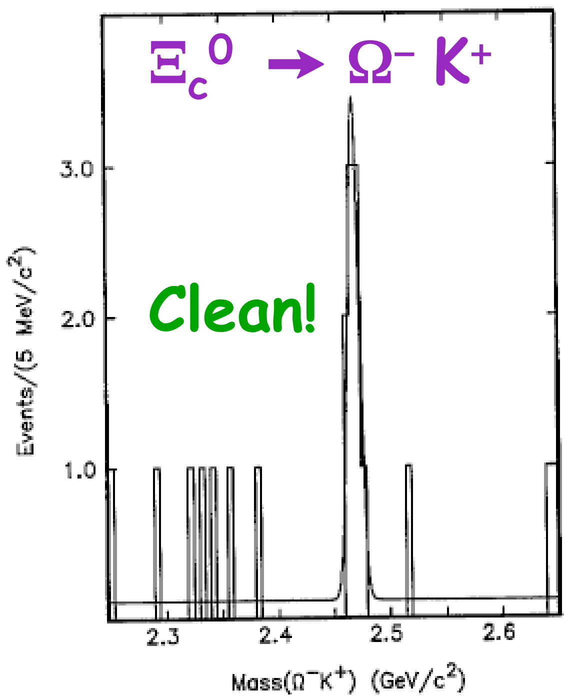
-- René Descartes in *Discours de la Méthode*

PLB 283,161
1992 0.43 fb^{-1}

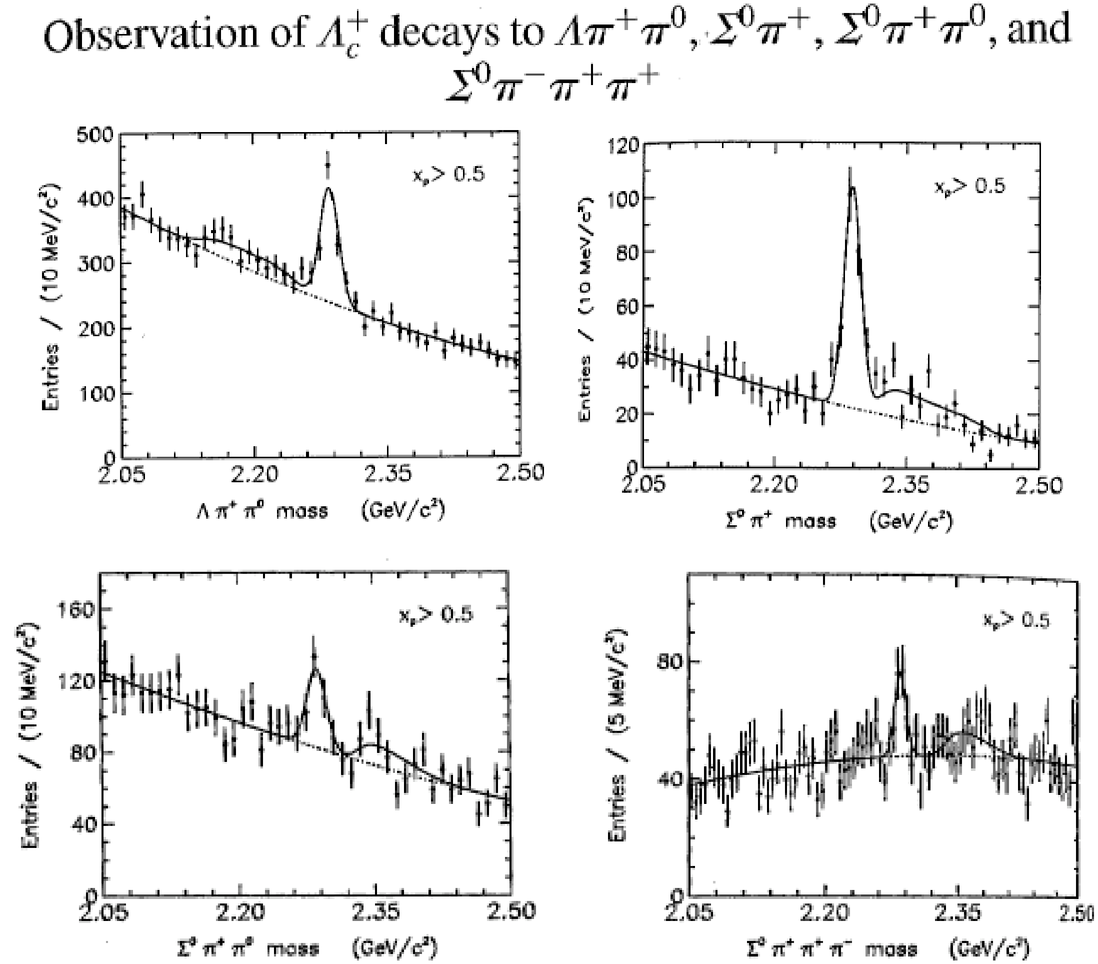
Charm Baryon Decays

PLB 325,257
1994 1.9 fb^{-1}

Good at charged modes… & also with neutrals !



CLEOI.5 tracking



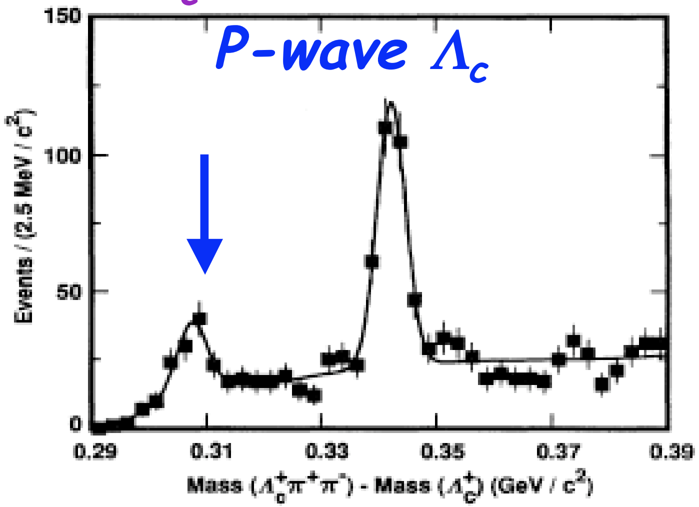
CLEOII CsI

PRL 74,3331
1995 3 fb^{-1}

More Charm Baryons

PRL 78,2304
1997 4.8 fb^{-1}

$\Lambda_c^+\pi^+\pi^-$ final state



$M(\Lambda_c^+\pi^+\pi^-) - M(\Lambda_c^+)$

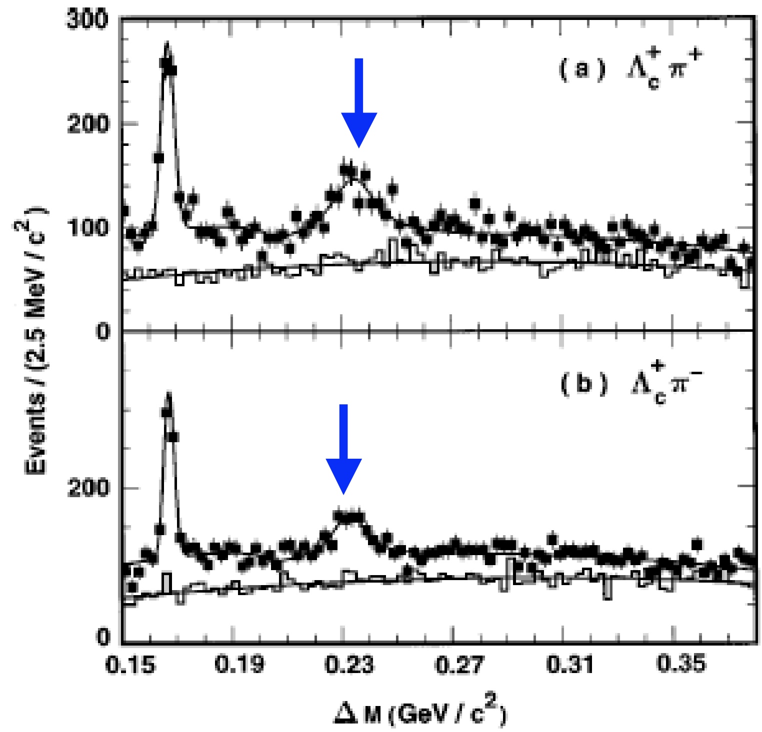
Higher peak seen by ARGUS;
lower peak is NEW

Still four more excited states from CLEO in 2001 :
PRL 86,4243 & 4479 (2001)

At CLEO's peak dominance:
9 of first 10 Ξ
7 of first 11 Σ & Λ

$\Lambda_c^+\pi^+$ & $\Lambda_c^+\pi^-$ final states

spin-3/2 Σ_c^{*++} & Σ_c^{*0}



Lower peaks are spin-1/2

Masses useful to study hyperfine splittings…

Charmed Baryons from a 1998 Talk

Scoreboard: CLEO = 10.5 Rest of World = 6.5

(later paper references added)

Charmed Baryons

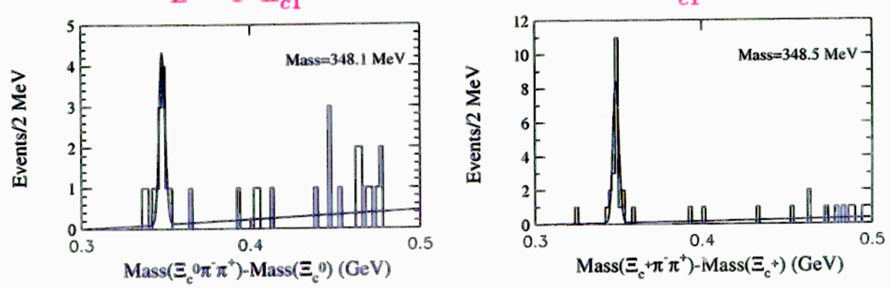
Eight new states discovered since 1996 PDG!

Newest are:

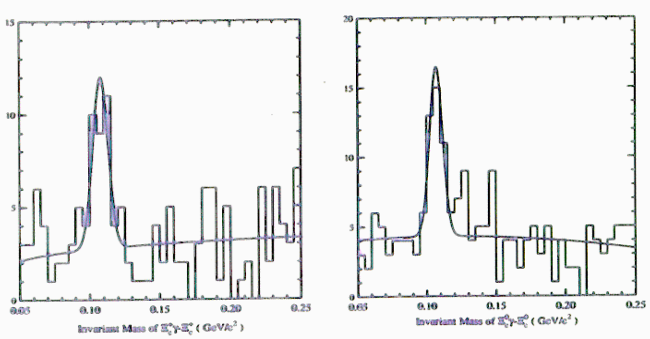
- First $L = 1$ Ξ_c states [top plots] CLEO CONF 98-10; 5 fb^{-1}
- Ξ_c' states [lower plots]

→ PRL 83,4390 (1999)

$L = 1$ Ξ^0_{c1} $L = 1$ Ξ^+_{c1}



$\Xi^{+\prime}_c$ $\Xi^{0\prime}_c$



→ PRL 82,492 (1999)

(RAB @ 1998 SLAC Summer Institute)

Charmed Baryons

RED = CLEO discoveries 10.5

GREEN = not yet seen 2 $L = 0 + ???$

BLACK = All other experiments 6.5

$C = 1, L = 0$ States:

$J^P = 1/2^+$

Ω^0_c

Ξ^0_c Ξ^+_c $\Xi^{0\prime}_c$ $\Xi^{+\prime}_c$

Λ^+_c Σ^0_c Σ^+_c Σ^{++}_c

$J^P = 3/2^+$

Ω^{0*}_c

Ξ^{*0}_c Ξ^{*+}_c

Σ^{*0}_c Σ^{*+}_c Σ^{*++}_c

$C = 1, L = 1$ States:

$\Lambda_c(2593)$, $\Lambda_c(2625)$, $\Xi^+_c(\sim 2815)$, $\Xi^0_c(\sim 2820)$

Λ_c Semileptonic

PLB 323,219
1994 1.6 fb^{-1}
PRL 75,624
1995 3.0 fb^{-1}

1.6 fb^{-1} PLB:

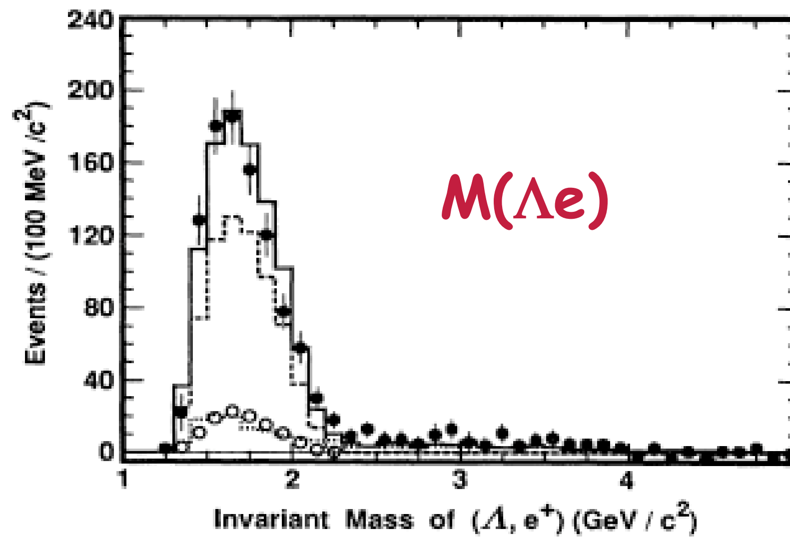
- $\Lambda_c \rightarrow \Lambda l \nu$ ~350 events
- Measure $\sigma \cdot B$
- no significant of $\Lambda_c \rightarrow \Lambda X l \nu$
- Asymmetry parameter
- Some info on $pK\pi$ BF

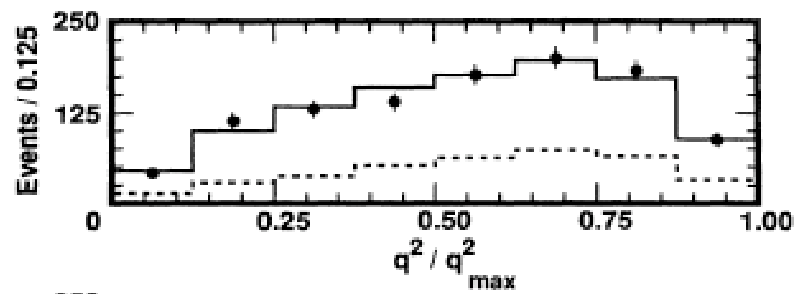
3.0 fb^{-1} PRL:

- $\Lambda_c \rightarrow \Lambda e \nu$ ~700 events
- Concentrate on Form Factor

  $R = f_2/f_1 = -0.25 \pm 0.14 \pm 0.08$
- Redo asymmetry parameter

PRL Plots



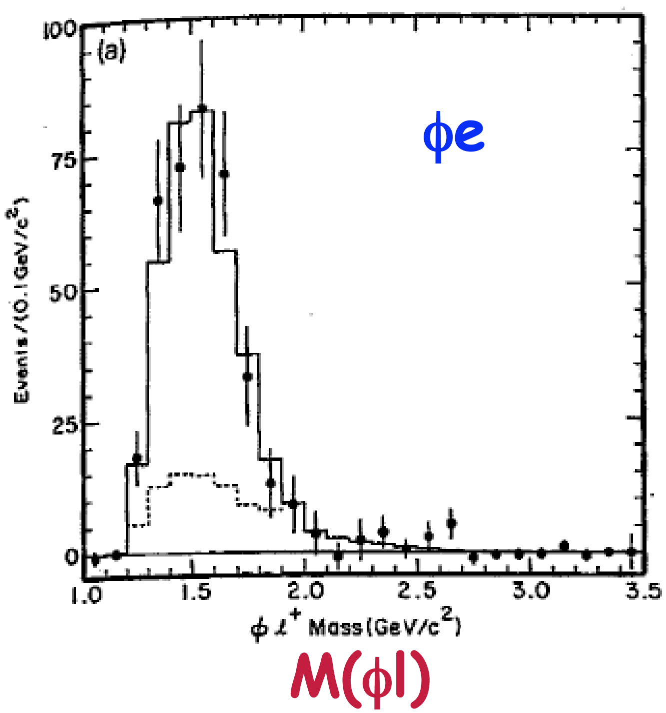


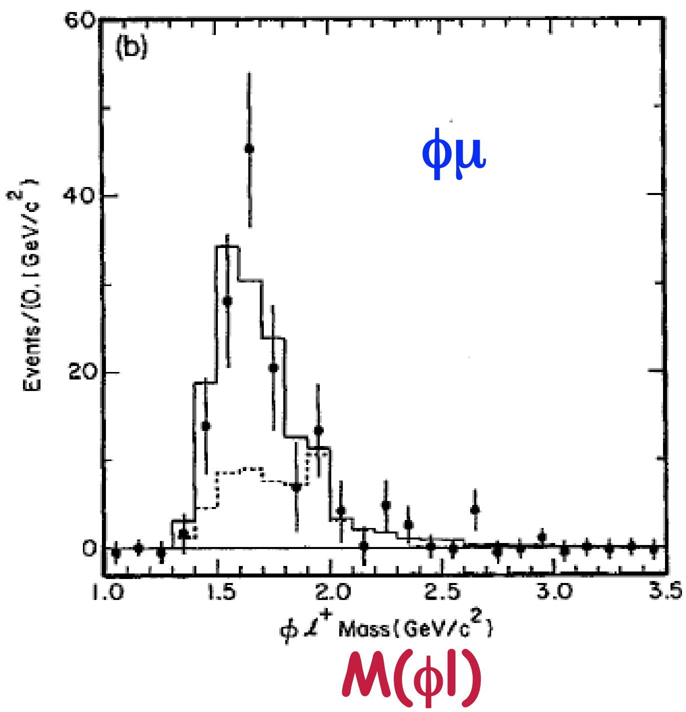
$D_s \to \phi l \nu$ & $D_s \to \phi \pi$

PRL 65, 1531
1990 0.43 fb^{-1}
PLB 324,255
1994 1.71 fb^{-1}

First, a CLEOI.5, then CLEOII analysis

Use theory for $\Gamma(D_s \to \phi l \nu) / \Gamma(D \to K^* l \nu)$ to get $B(D_s \to \phi l \nu)$





Each point from a ϕ mass fit

CLEOII result:

$B(D_s \to \phi e \nu) / B(D_s \to \phi \pi) = 0.54 \pm 0.05 \pm 0.04$

Extract: $B(D_s \to \phi \pi) = 5.1 \pm 0.4 \pm 0.4 \pm 0.7$

$B(D_s \to \phi\pi)$ using B Decays

PLB 378, 364
1996 2.5 fb^{-1}

All candidates →

Partial reconstruction of:

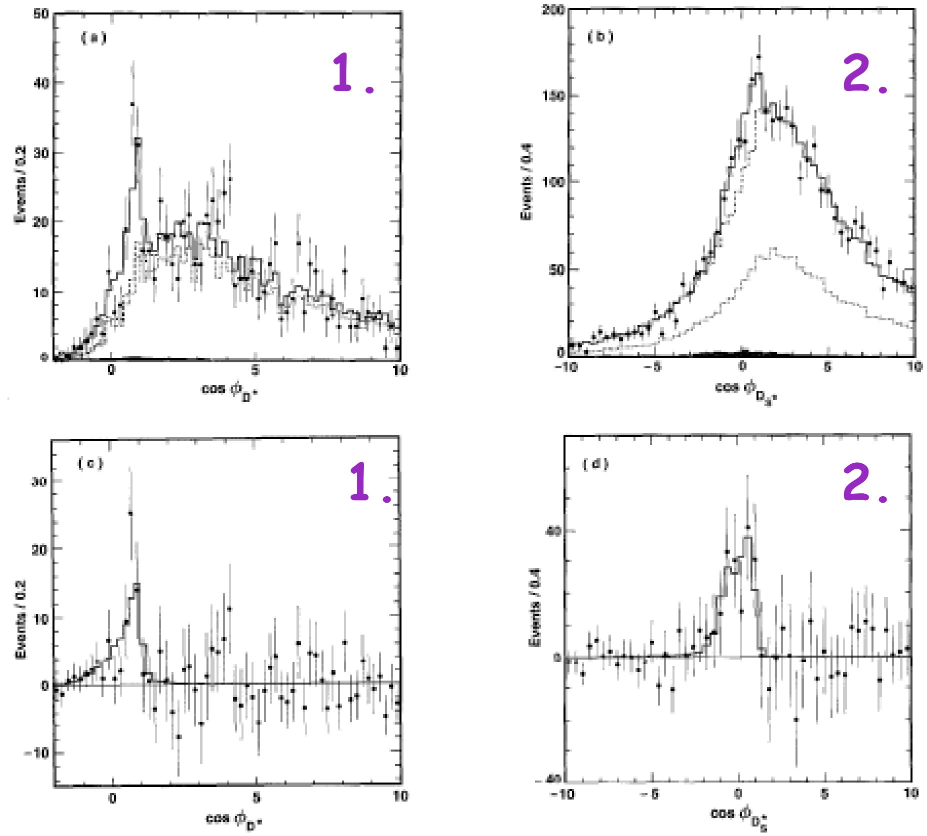
B^0bar → D^{*+} D_s^{*-}

Compare:

1. partial D^{*+} & full D_s^{*-}
2. full D^{*+} & partial D_s^{*-}

Kinematics give "intersecting cones" characterized by an angle ϕ

Background-subtracted →



cos ϕ

Measure $B(D_s \to \phi\pi)$ / $B(D^0 \to K^-\pi^+)$

Extract: $B(D_s \to \phi\pi)$ = 3.59 ± 0.77 ± 0.48

DCSD First Observed

PRL 72,1406
1994 1.8 fb^{-1}

$B(D^0 \to K^+\pi^-) / B(D^0 \to K^-\pi^+)$
$= (0.77 \pm 0.25 \pm 0.25)\%$

~large re: $\tan^4\theta_C$ & current PDG,
but well within errors!

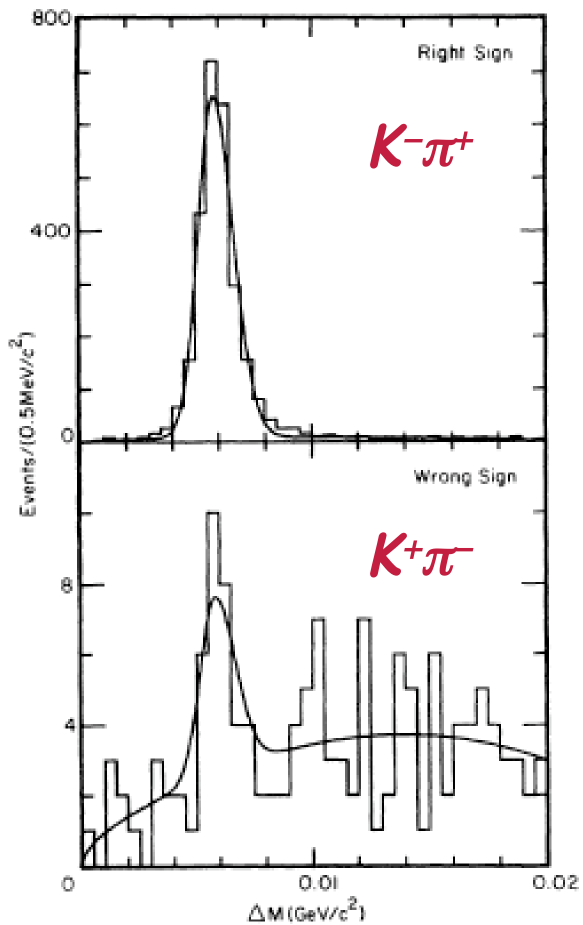


FIG. 1. Mass difference in the D^0 mass signal region for right sign and wrong sign. The solid lines are the fitted results.

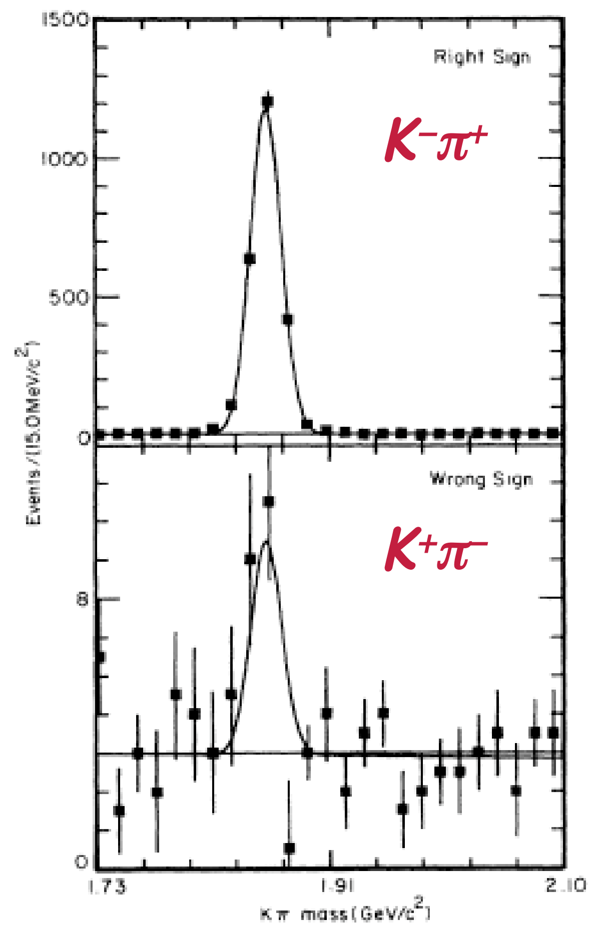
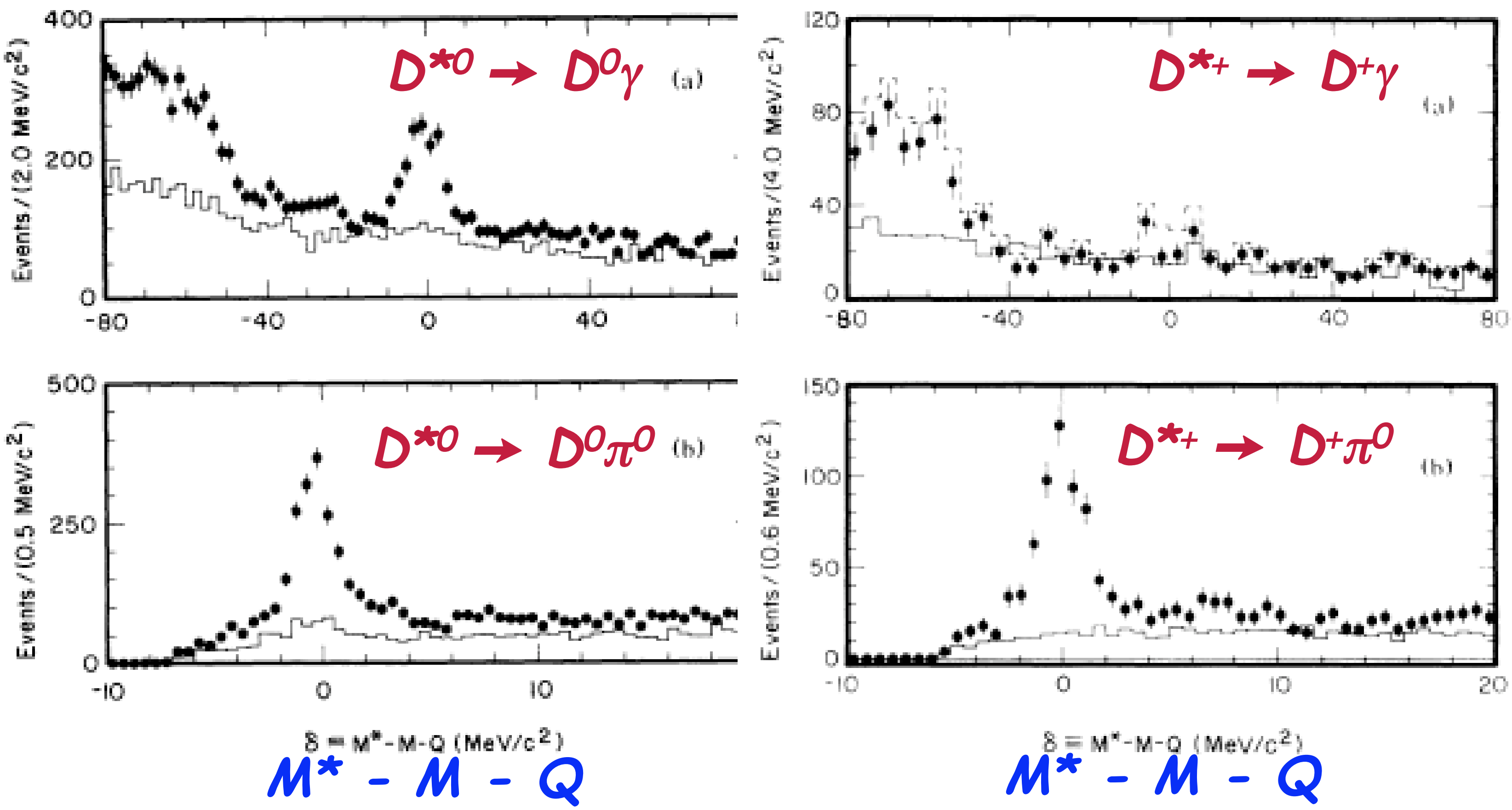


FIG. 2. The D^0 mass in ΔM signal region after ΔM sideband subtraction for right sign and wrong sign. The solid lines are the fitted results.

D* Branching Fractions

PRD 69,2041
1992 0.78 fb^{-1}



Dominated PDG averages & led to significant shifts for D^{*+}

$D^{*+} \rightarrow D^+\gamma$ was a limit here, later observed later by CLEO;
& also high-statistics updates of other D^{*+} BFs

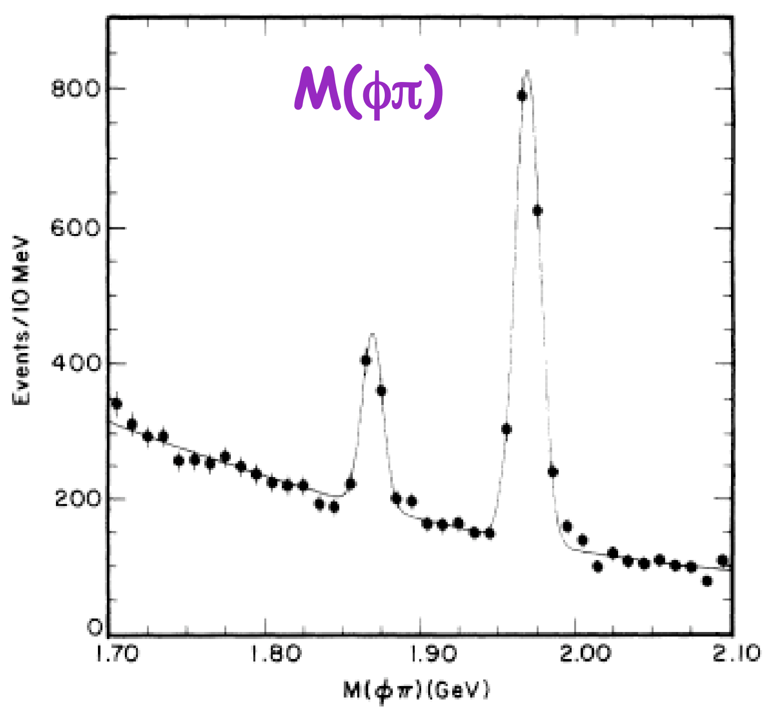
PRL 80,3919
1998 4.7 fb^{-1}

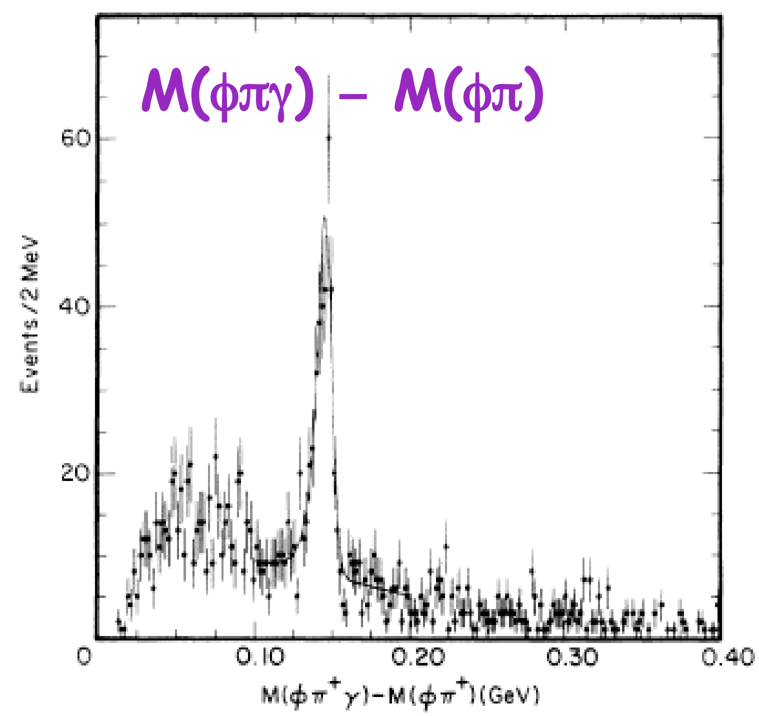
Precision D_s^* - D_s Mass

PRD 50,1884
1994 1.7 fb^{-1}

Calibration:

Use $D^{*0} \rightarrow D^0 \gamma$ decay:
compare to CLEO's precise $D^{*0} \rightarrow D^0 \pi^0$ result!
(low-Q decay; π^0 mass well-known)





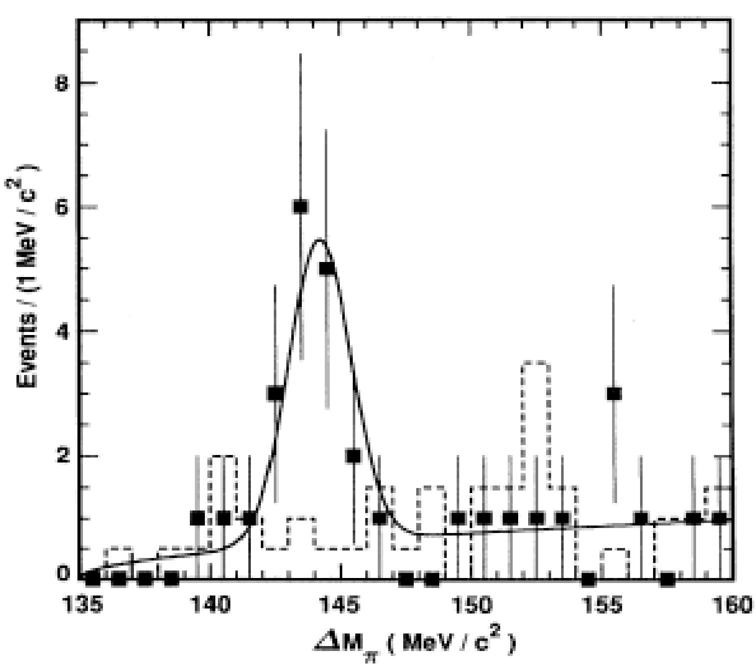
$M(D_s^*) - M(D_s) = 144.22 \pm 0.47 \pm 0.37$

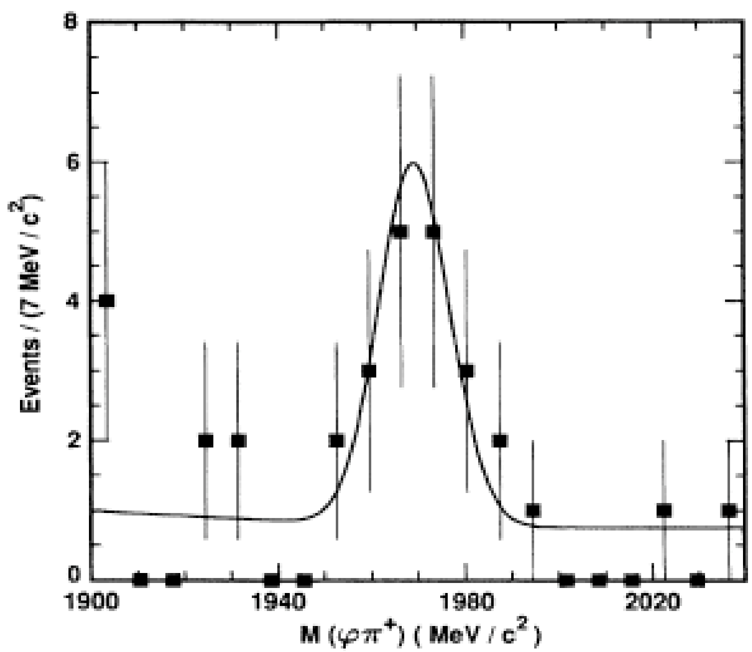
Previous World Ave.: 142.4 ± 1.7

Observation of $D_s^* \rightarrow D_s\pi^0$

PRL 75,3232
1995 3.75 fb^{-1}

Interest: isospin-violating decay
Competes with dominant EM decay





$\Gamma(D_s^* \rightarrow D_s\pi^0)/\Gamma(D_s^* \rightarrow D_s\gamma) =$

$0.062 \ {}^{+0.020}_{-0.018} \pm 0.022$

Discovery of $D_{s2}^*(2573)$

PRL 72,1972
1994 2.16 fb^{-1}

2nd narrow P-wave D_s state
(& the last narrow one, right??? Sigh…)

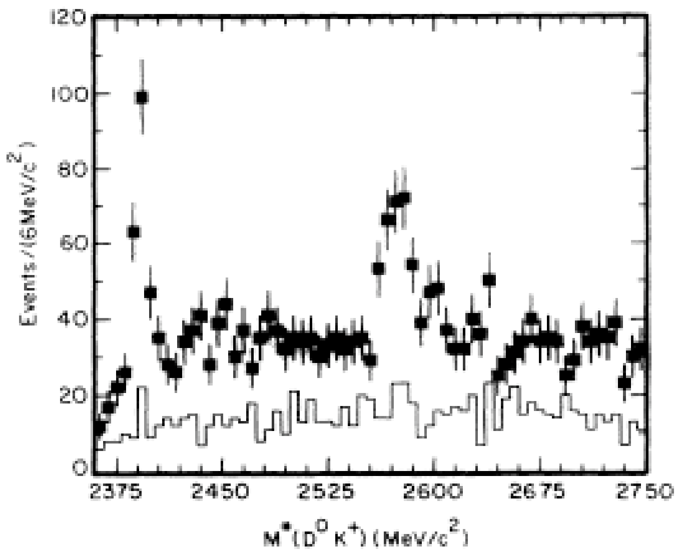


FIG. 1. M^*, "corrected" invariant mass, of $(K^-\pi^+[\pi^0])K^+$ combinations. Data points are for $K^-\pi^+[\pi^0]$ combinations in the D^0 signal region; the histogram shows M^* for $(K^-\pi^+[\pi^0])K^+$ combinations where the $K^-\pi^+[\pi^0]$ combinations were chosen in D^0 sidebands.

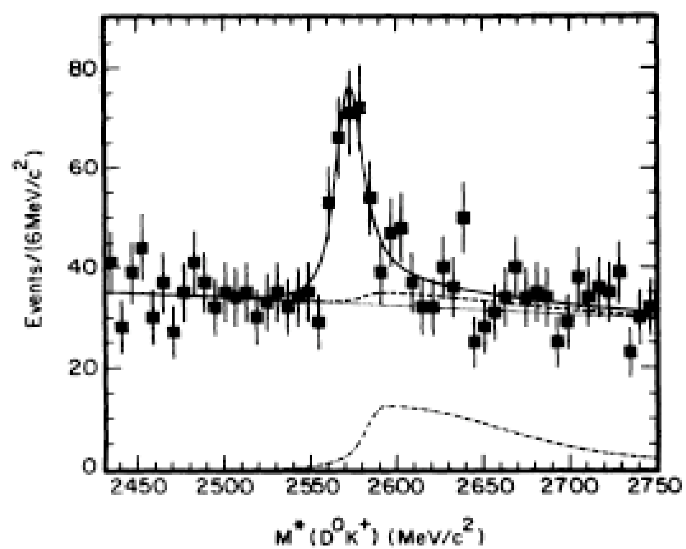


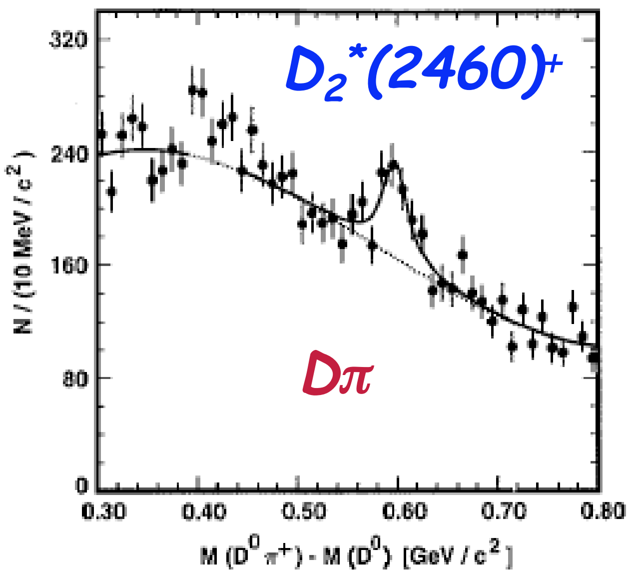
FIG. 2. Histogram of $M^*(D^0K^+)$, with fit. The solid line shows the complete signal and background fitting functions. The sum of the background functions is shown by the dashed line. The dotted line shows just the polynomial used to represent the combinatoric background. The shape of the $D_J^*(2470)^+$ background function is shown at the bottom by the dash-dotted line, with the area scaled up by a factor of 5.

Note: known narrow J=1 state cannot decay to DK (spin-parity)

P-Wave D^+ Mesons

PLB 340,194
1994 2.37 fb^{-1}

D_1 forbidden here

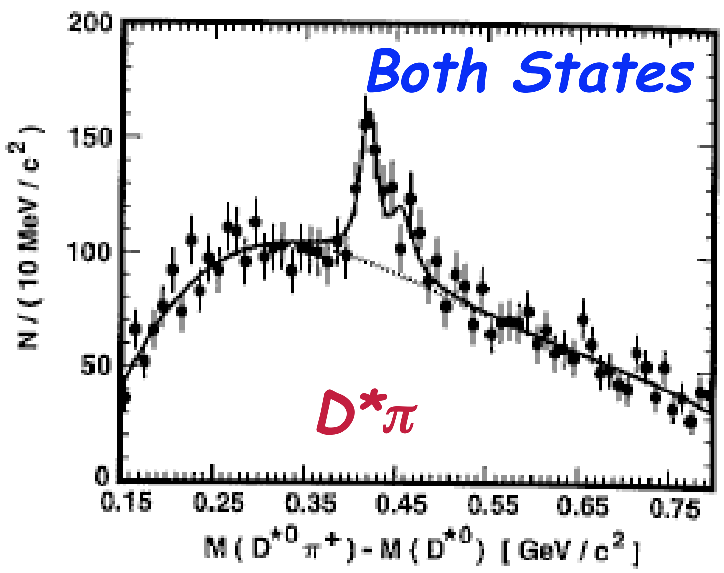


Neutral D better known

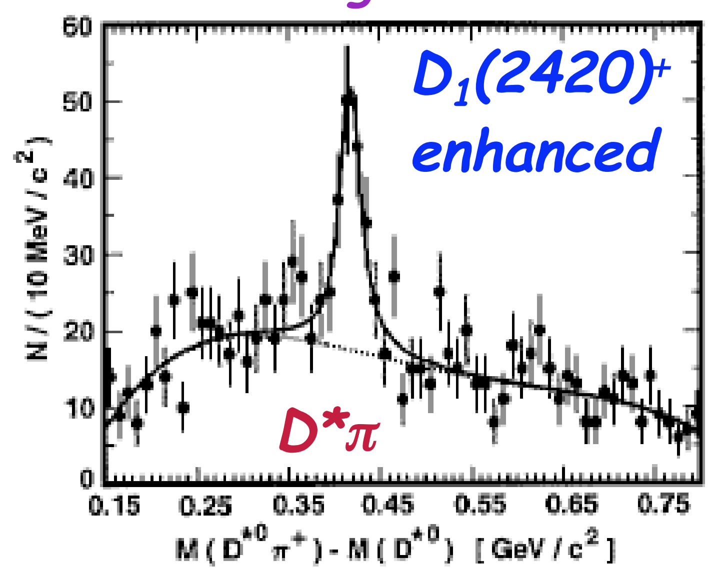
Study charged D here:

-- First full recon. of $D_1(2420)^+$

-- First obs'n of $D^*\pi$ mode of $D_2^*(2460)^+$



Use angular cut:

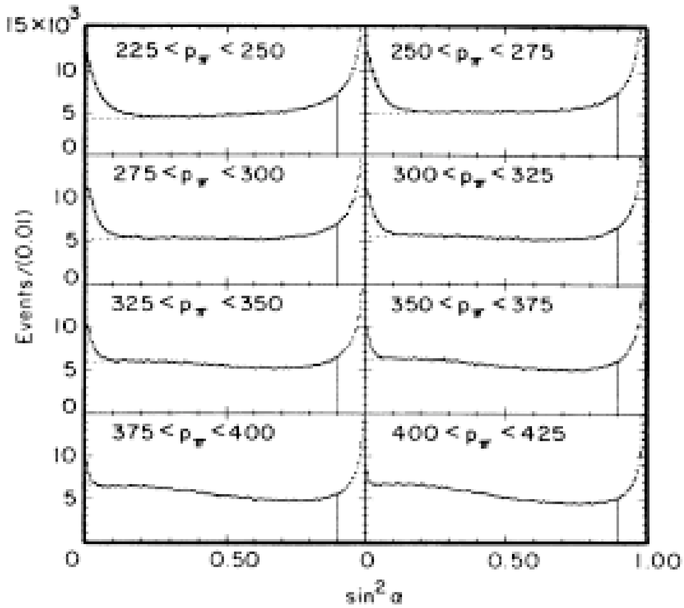


$B(D^0 \to K^-\pi^+)$

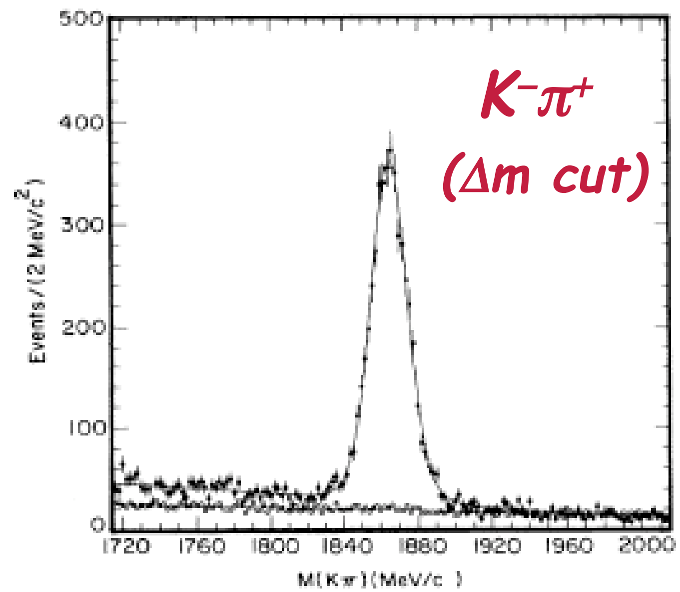
PRL 71,3070
1993 1.79 fb^{-1}

$D^{*+} \to D^0 \pi^+$

Analyze $\sin^2\alpha$: α is the angle between thrust axis and slow pion



$\sin^2\alpha$ (in p_π bins)



$M(K^-\pi^+)$

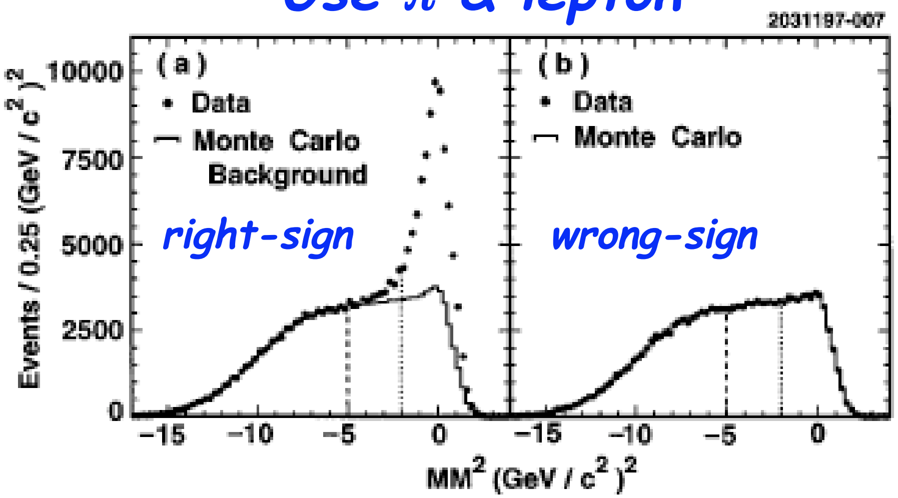
$B(D^0 \to K^-\pi^+) = (3.95 \pm 0.08 \pm 0.17)\%$

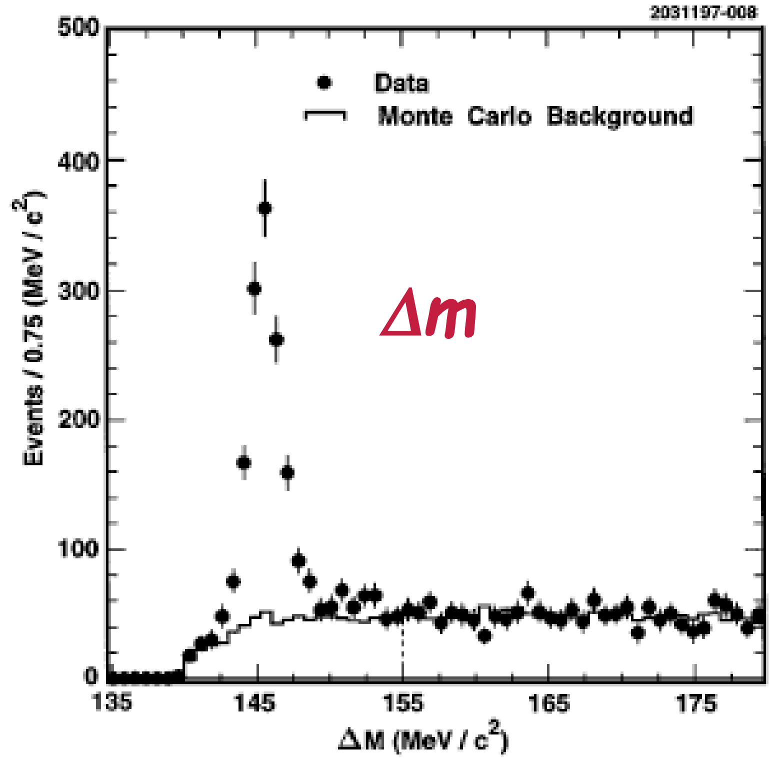
$B(D^0 \to K^-\pi^+)$

PRL 80,3193
1998 3.1 fb^{-1}

Partial reconstruction of: $\bar{B} \to D^{*+}Xl\nu$

Use π & lepton





$B(D^0 \to K^-\pi^+) = (3.81 \pm 0.15 \pm 0.16)\%$

A tagged $b \to c,\bar{c}$ paper also obtained a BR: PRL 80,1150 (1998)
$B(D^0 \to K^-\pi^+) = (3.69 \pm 0.11 \pm 0.16)\%$

New CLEO Average (All three results):
$B(D^0 \to K^-\pi^+) = (3.82 \pm 0.07 \pm 0.12)\%$

Semileptonic D Decays

PLB 317,647
1993 1.68 fb^{-1}

All four Cabibbo-allowed $K^{(*)}l\nu$

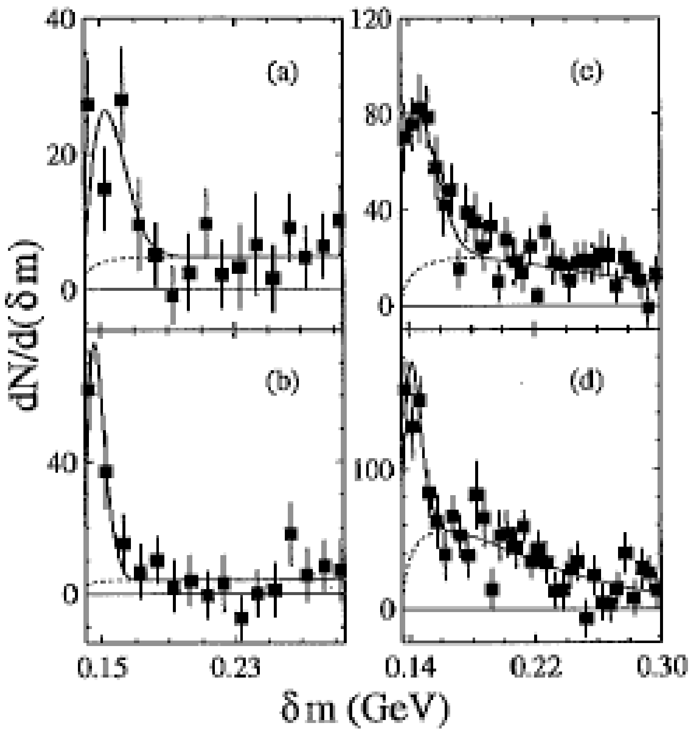
Use δm: like Δm,
but w/o neutrino

$$\frac{\Gamma(D \to K^{*} e\nu)}{\Gamma(D \to K e\nu)} = 0.62 \pm 0.08$$

$K^{*-}l\nu$ $K^{*0}l\nu$

low $M(Kl)$

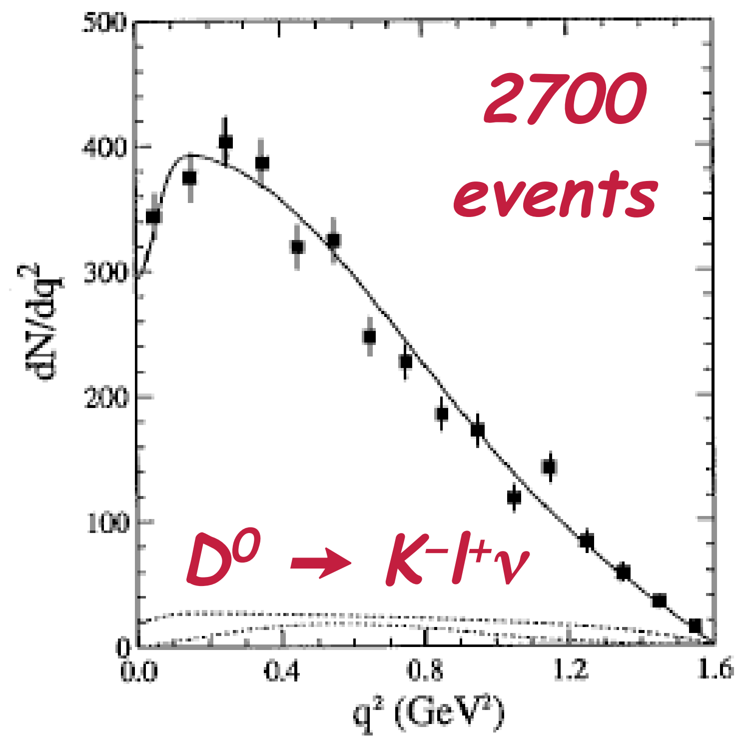
high $M(Kl)$



δm

Note: K modes are higher Statistics than K* shown…

can look at form-factor

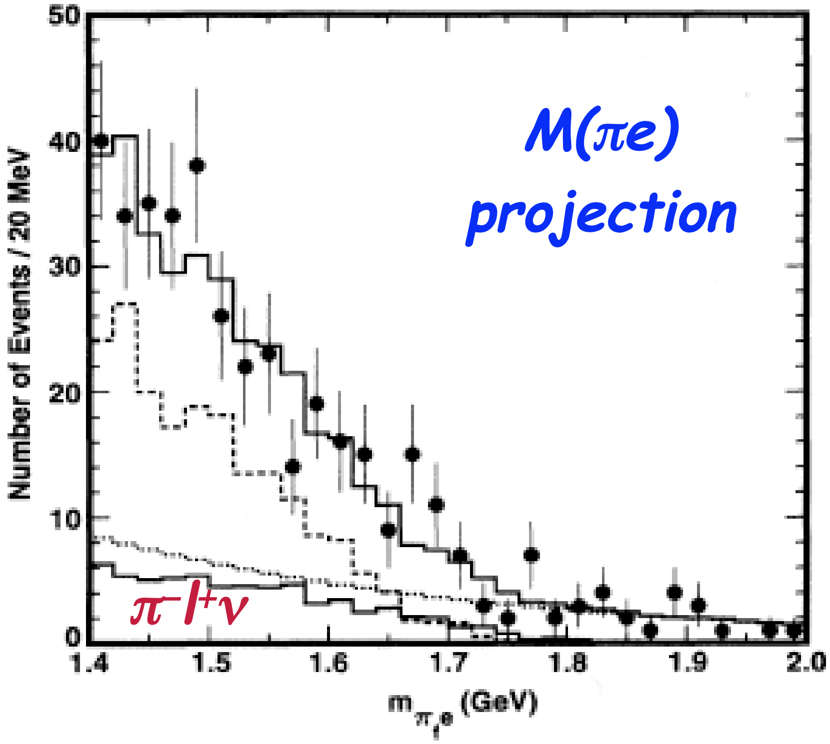


$B(D^0 \to \pi^- l^+ \nu)$ / $B(D^0 \to K^- l^+ \nu)$

PRD 52,2656
1995 3.0 fb^{-1}

Cabibbo-suppressed

Use D^{*+} tag
2-D fit to δm $M(\pi e)$



dashed line: $K^- l^+ \nu$
dotted line: other background
solid line: $\pi^- l^+ \nu$

$B(D^0 \to \pi^- l^+ \nu)$ / $B(D^0 \to K^- l^+ \nu)$
$= (10.3 \pm 3.9 \pm 1.3)\%$

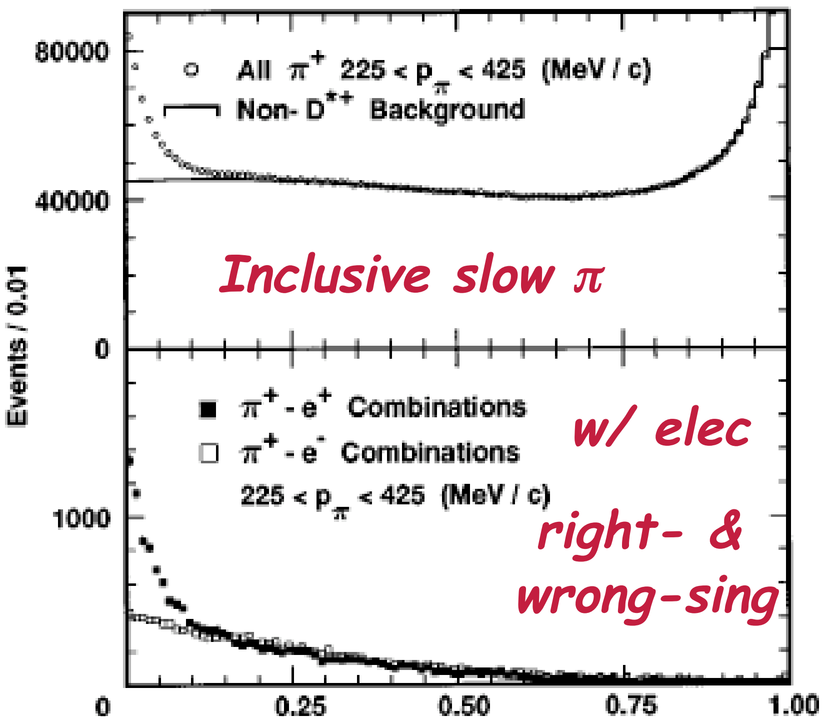
or $< 15.6\%$ 90%CL

Later improvements will come from:
- *o RICH PID*
- *o CLEO-c kinematics*

D^0: Inclusive Electrons

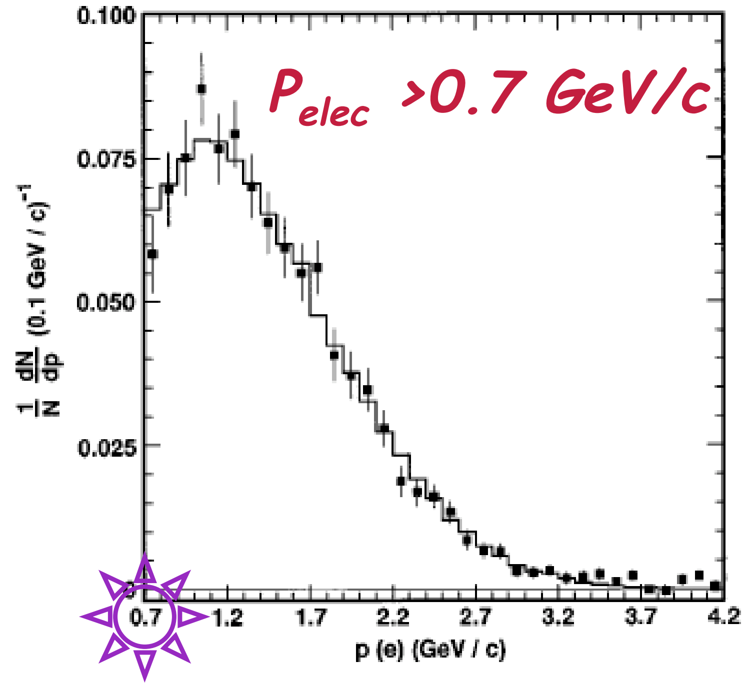
PRD 54,02994
1996 1.7 fb^{-1}

Use slow π from D^{*+} tag



$\sin^2\alpha$

Analyze $\sin^2\alpha$: α is the angle between thrust axis and slow pion



Electron Spectrum

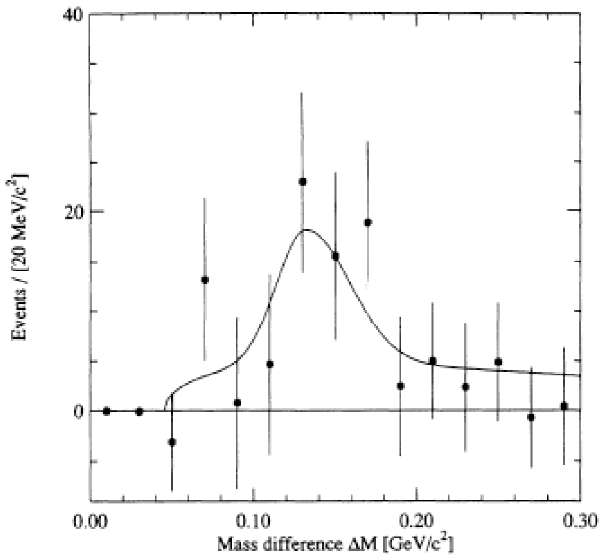
$B(D^0 \to Xe\nu)$ =
6.64 ± 0.18 ± 0.29

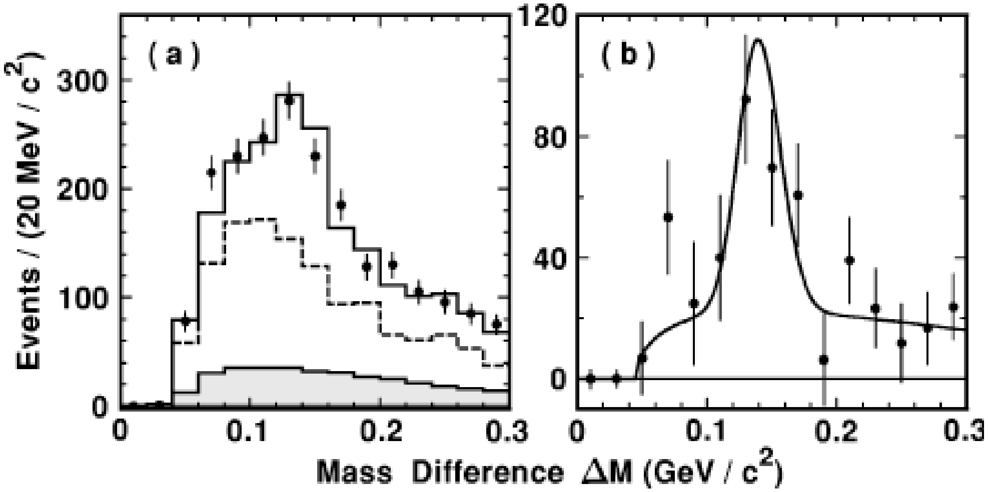
Prev. World Ave.:
7.01 ± 0.62

PRD 49,5690
1994 2.13 fb^{-1}

D_s Decay Constant

PRD 58,032002
1998 4.79 fb^{-1}





$B(D_s \to \mu\nu) / B(D_s \to \phi\pi) =$
$0.245 \pm 0.052 \pm 0.074$

$B(D_s \to \mu\nu) / B(D_s \to \phi\pi) =$
$0.173 \pm 0.023 \pm 0.035$

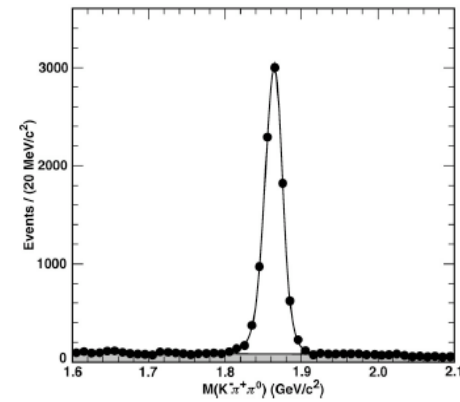
$f_{Ds} = (280 \pm 19 \pm 28 \pm 34)$ MeV
most accurate

Clever use of electrons for background, plus e-mu differences

State-of-the-art for quite some time…

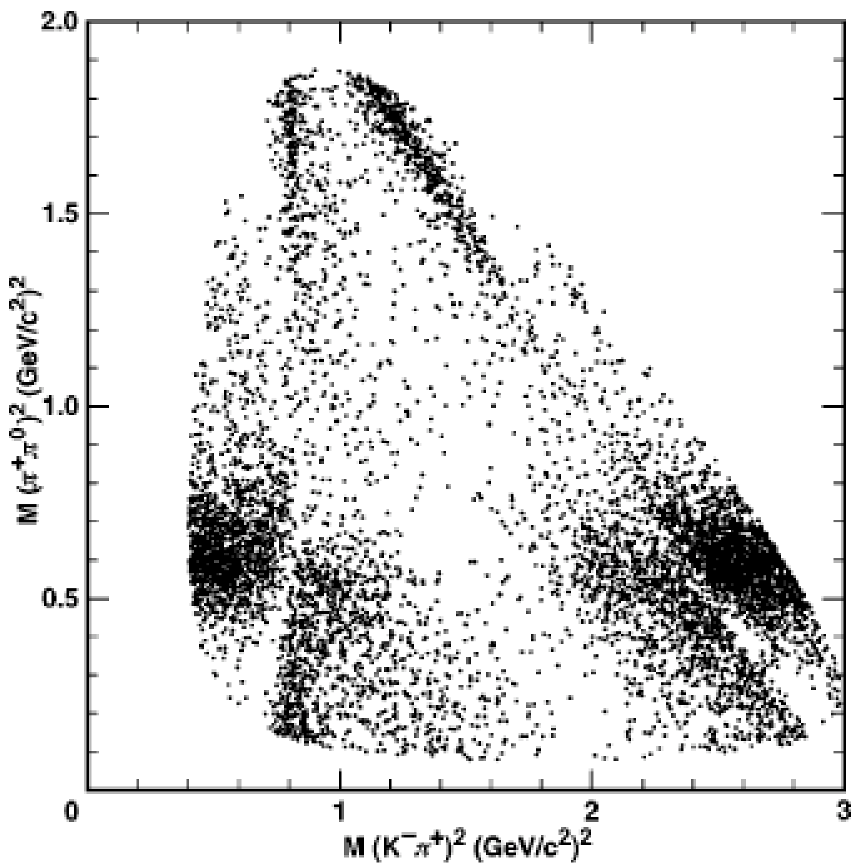
$D^0 \to K\pi\pi^0$ Dalitz Plot

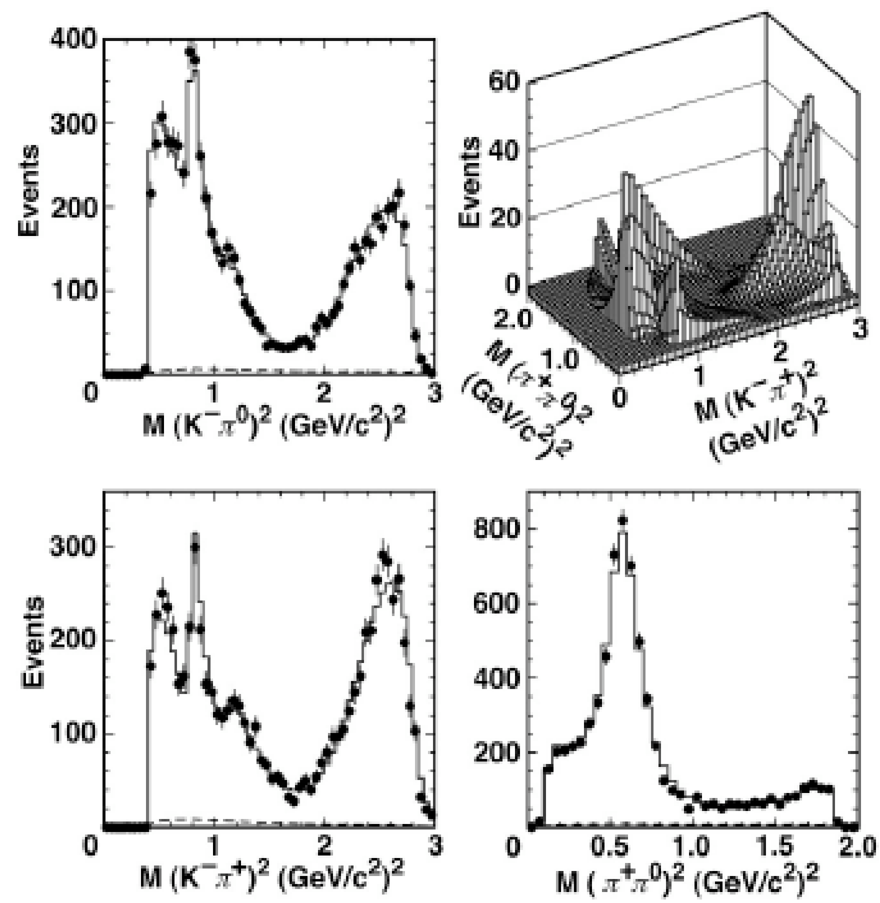
PRD 63,092001
2001 4.7 fb^{-1}



Previous 4 experiments: <1000 events
CLEOII: 7070 events 97% signal

Classic structure:
3 bands with long. Polarization
but lots more detailed structure!





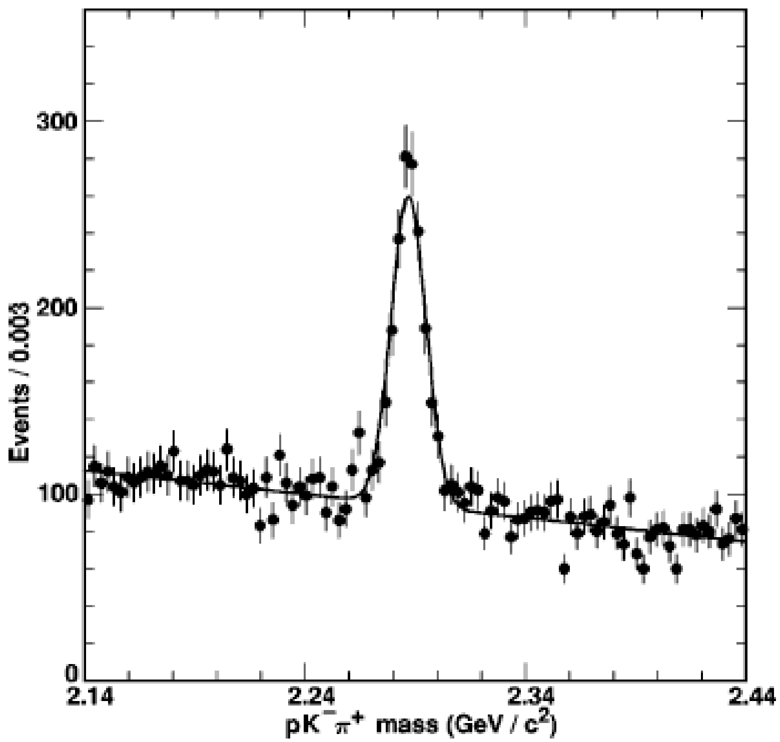
$B(\Lambda_c \to pK\pi)$

PRD 62, 072005
2000 4.7 fb^{-1}

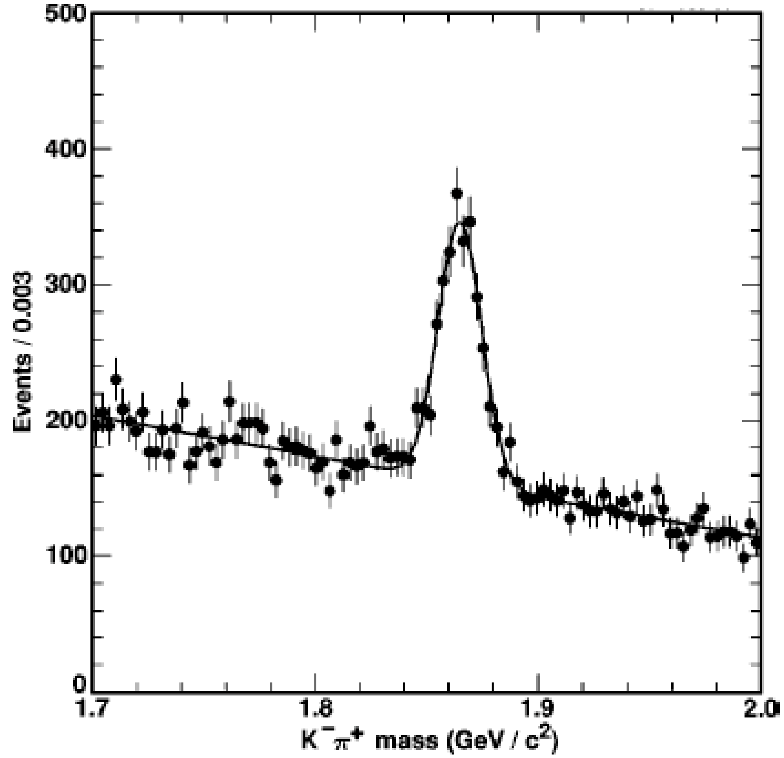
Tag: anti-proton and anti-D

(D: slow π from D, electrons, $K\pi$)*

Reconstruct Λ_c opposite this tag



$M(pK\pi)$



$M(K\pi)$

Result: (5.0 ± 0.5 ± 1.2) %

Act II.V:

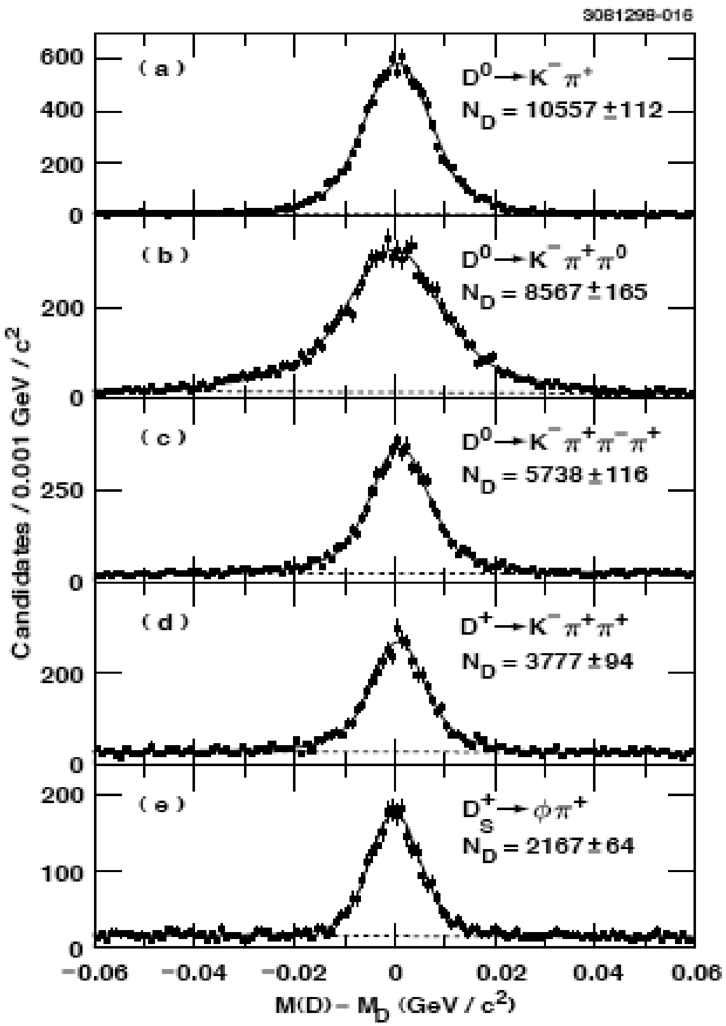
Silicon arrives at the 4S

Lifetimes & D^{*+} Width
DCSD & D mixing?
Charm Baryon Work
Fragmentation
More Narrow D_{sJ} !?!

D Meson Lifetimes

PRL 82, 4586
1999 3.7 fb^{-1}

Partial II.V statistics



Note nice fits for t<0 :
good resolution modeling

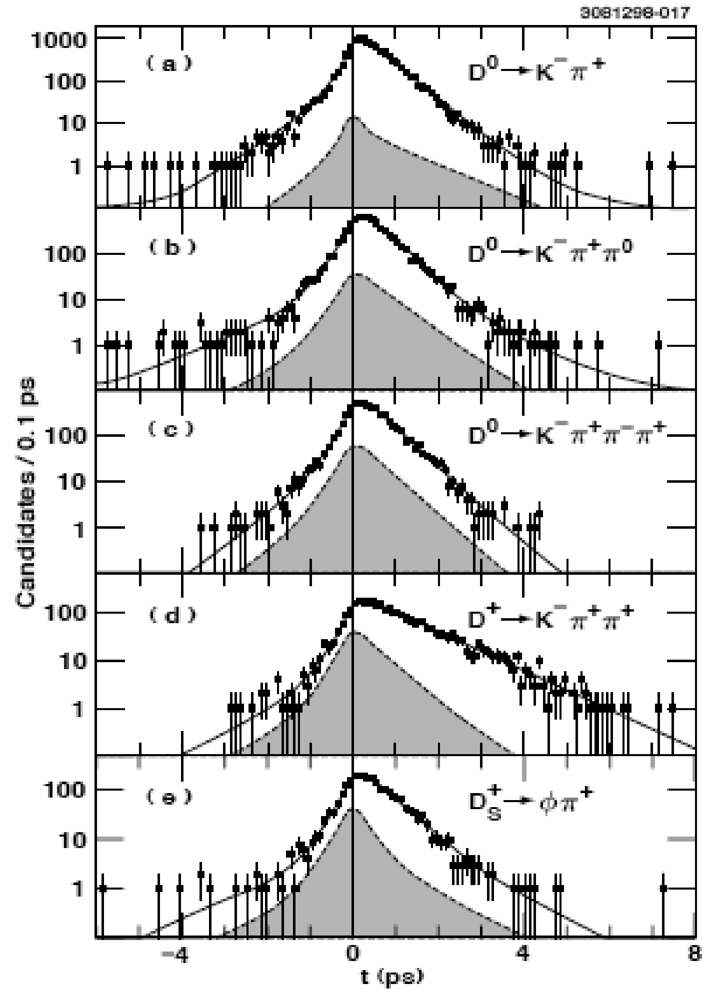
D^0

D^0

D^0

D^+

D_s^+

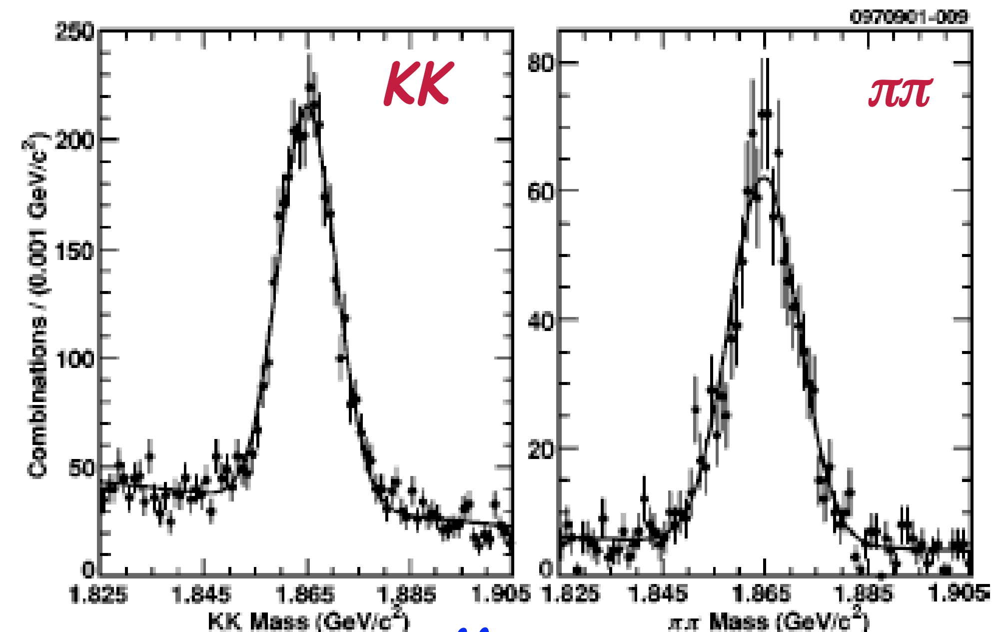


Different systematics than fixed target, very competitive

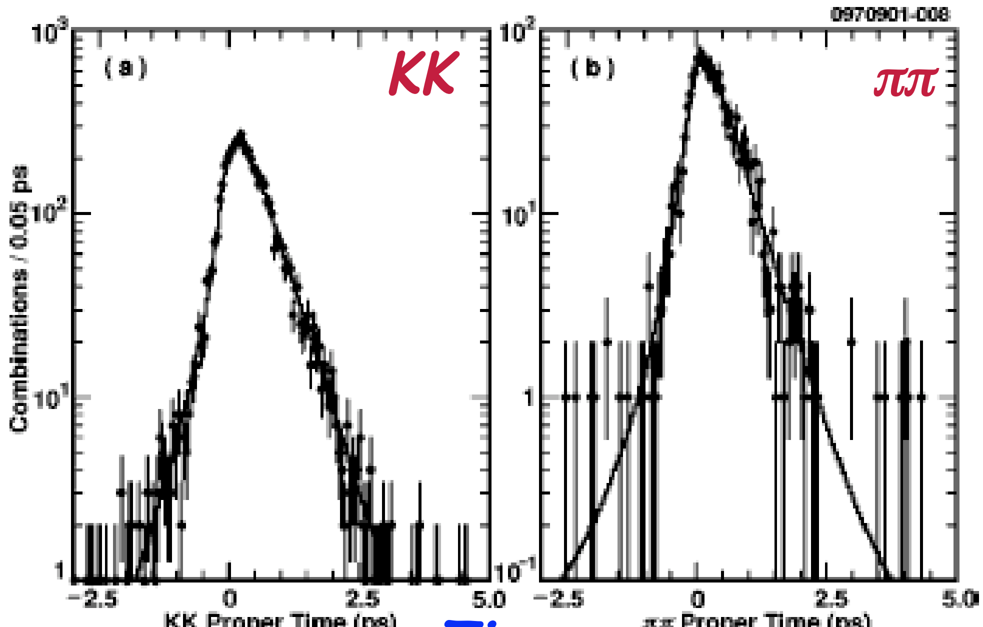
D^0, D^+, and D_s^+ mesons are $408.5 \pm 4.1^{+3.5}_{-3.4}$ fs, $1033.6 \pm 22.1^{+9.9}_{-12.7}$ fs, and $486.3 \pm 15.0^{+4.9}_{-5.1}$ fs.

CP-Eigenstate Lifetimes

PRD 65, 092001
2002 9.0 fb^{-1}



Mass



Time

Natural Extension of other
D lifetime work…
Full CLEOII.V statistics

$B(KK)/B(\pi\pi)$ =
2.96 ± 0.16 ± 0.15

CP asymmetries limited

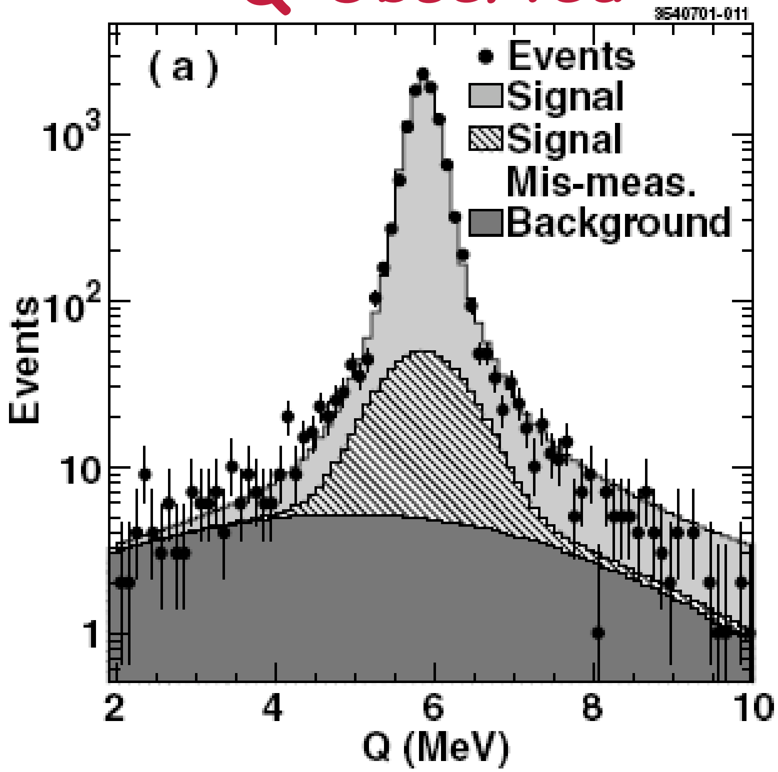
Mixing parameter, w/ no CPV:
y_{CP} = -0.012 ± 0.025 ± 0.044

D^{*+} Total Width

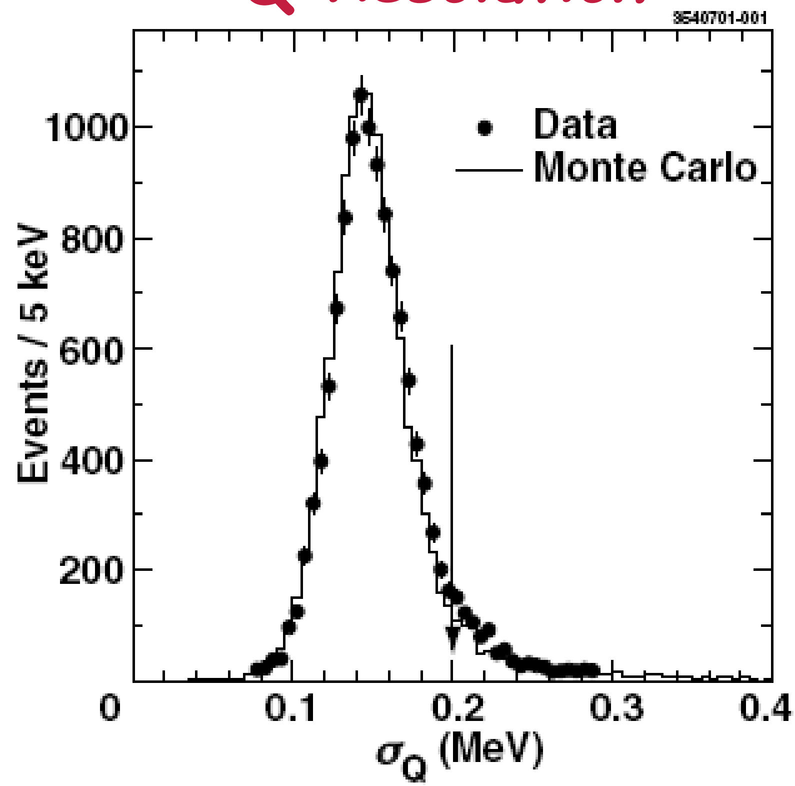
PRL 87, 251801
PRD 65, 032003
2001/2 9.0 fb^{-1}

Study Q = energy release
Good MC & careful cross-checks

Q Observed



Q Resolution

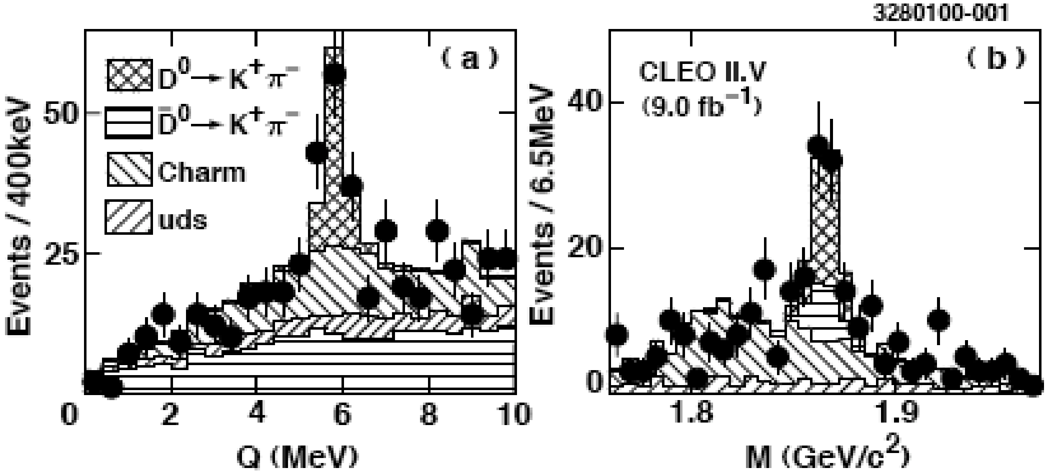


$$\Gamma(D^{*+}) = 96 \pm 4 \pm 22 \text{ keV}$$

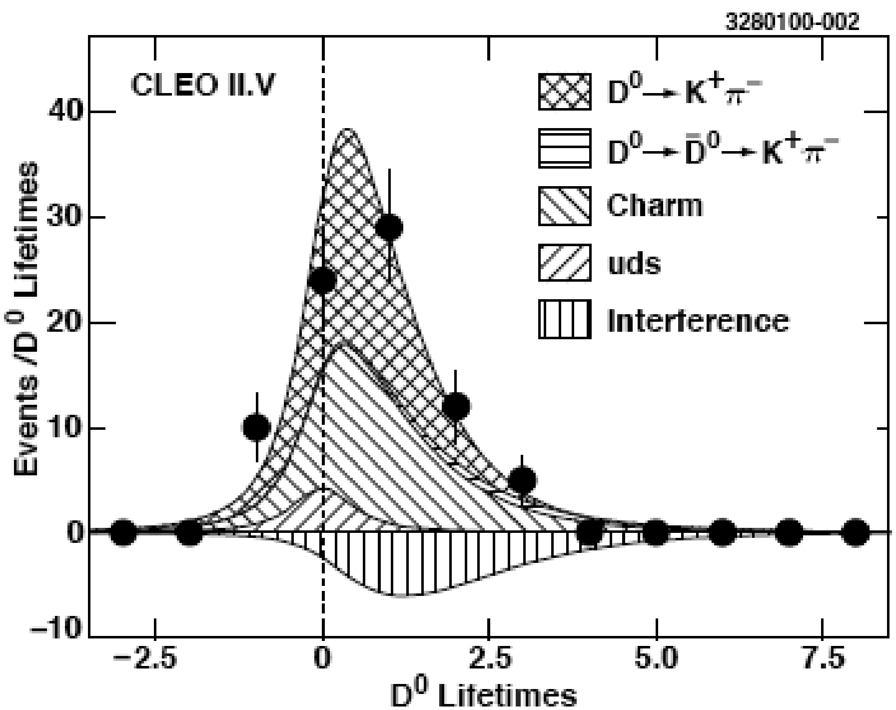
$$M(D^{*+}) - M(D^0) = 145.412 \pm 0.002 \pm 0.012 \text{ MeV}$$

DCSD & D Mixing Work

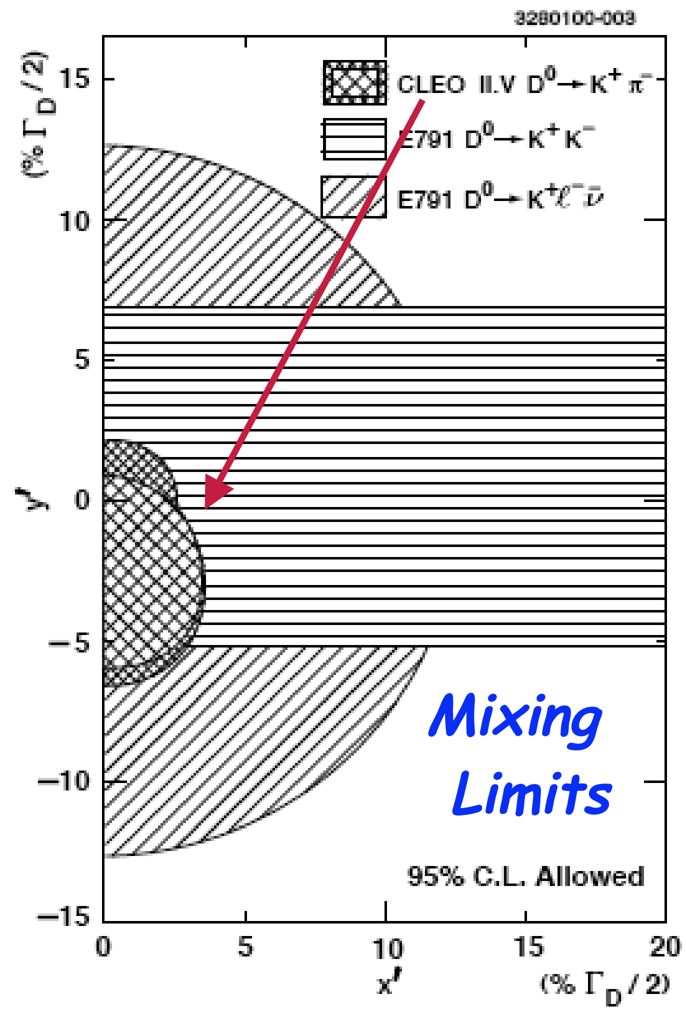
PRL 84, 5038
2000 9.0 fb^{-1}



Wrong-sign Kπ



y'



Mixing Limits

x'

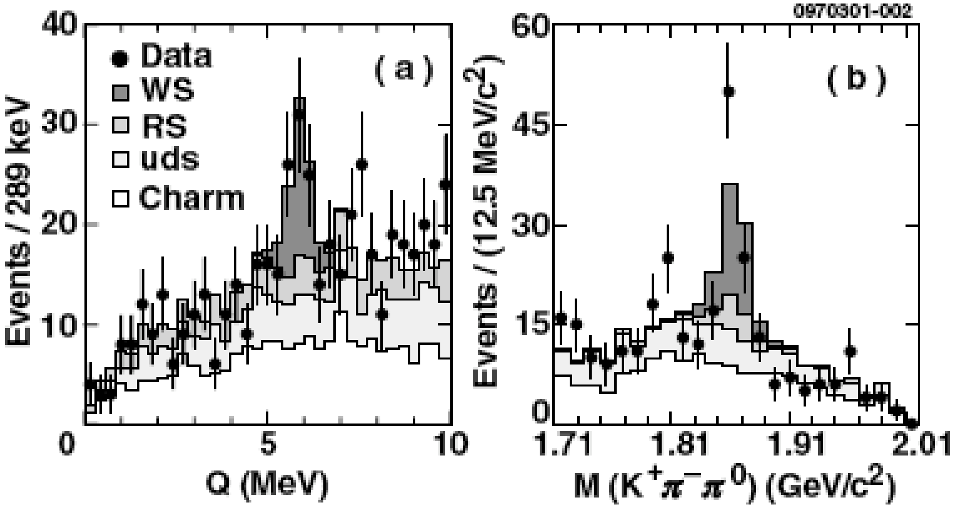
Note: Analysis also spawned new dE/dx calibration ideas…

PRL 87, 251802
2001 9.0 fb^{-1}

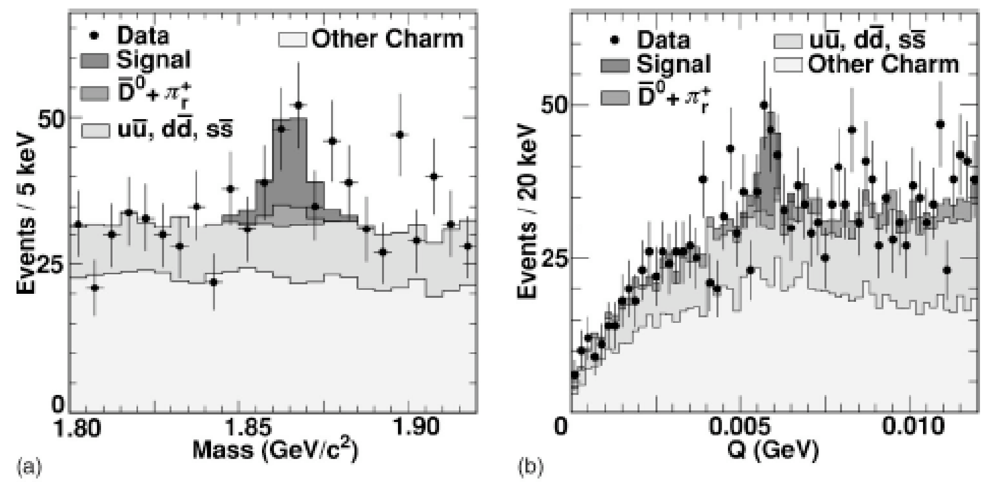
More D^0 DCSD Modes

PRD 64, 111101
2001 9.0fb^{-1}

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



$K^+\pi^-\pi^-\pi^+$



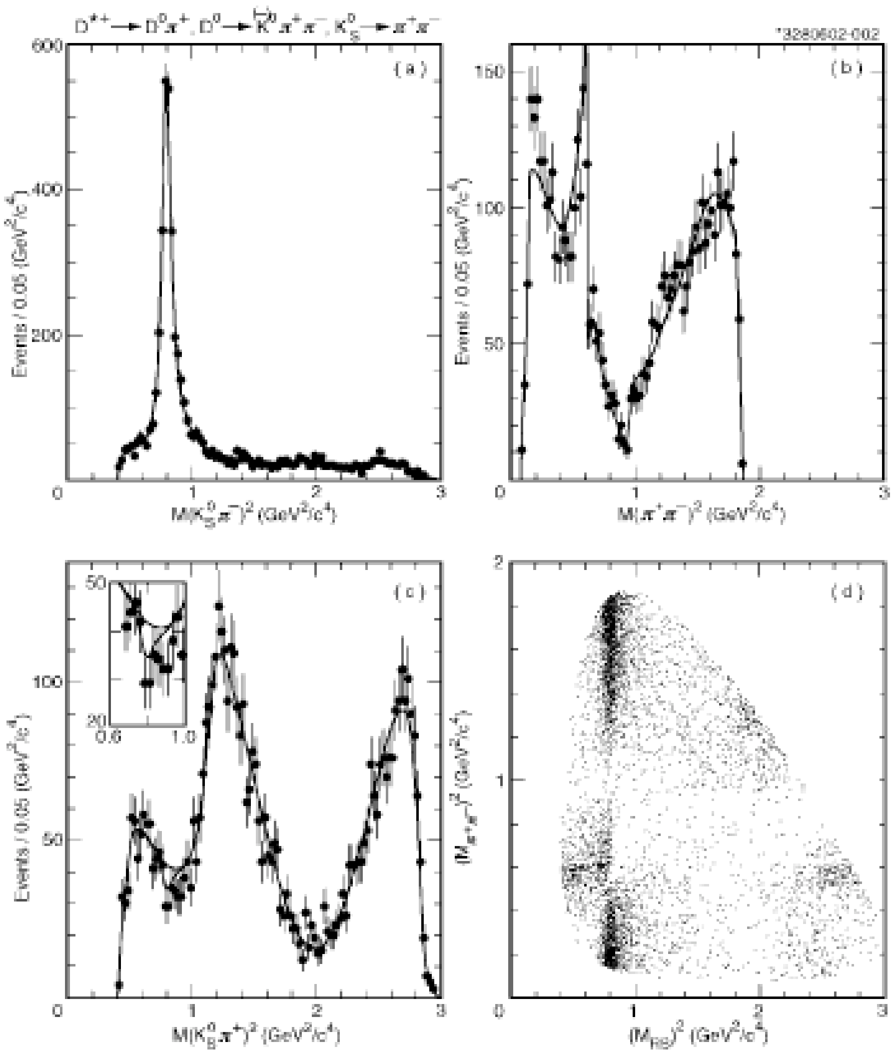
DCSD/Cabibbo-allowed ratios:

R = 0.0043 +0.0011–0.0010 ± 0.0007

R = 0.0041 +0.0012–0.0011 ± 0.0004
(x a phase-space factor)

$D^0 \rightarrow K_s\pi^0\pi^0$ Dalitz Plot

PRL 89, 251802
2002 9.0 fb^{-1}



5299 events
~98% signal

10 components in fit
See $K^{*+}\pi^-$ component:
DCSD and/or mixing

First paper of set:
followed by searches
for CP-violation
and D mixing:

PRD 70, 091101
2004 9.0 fb^{-1}

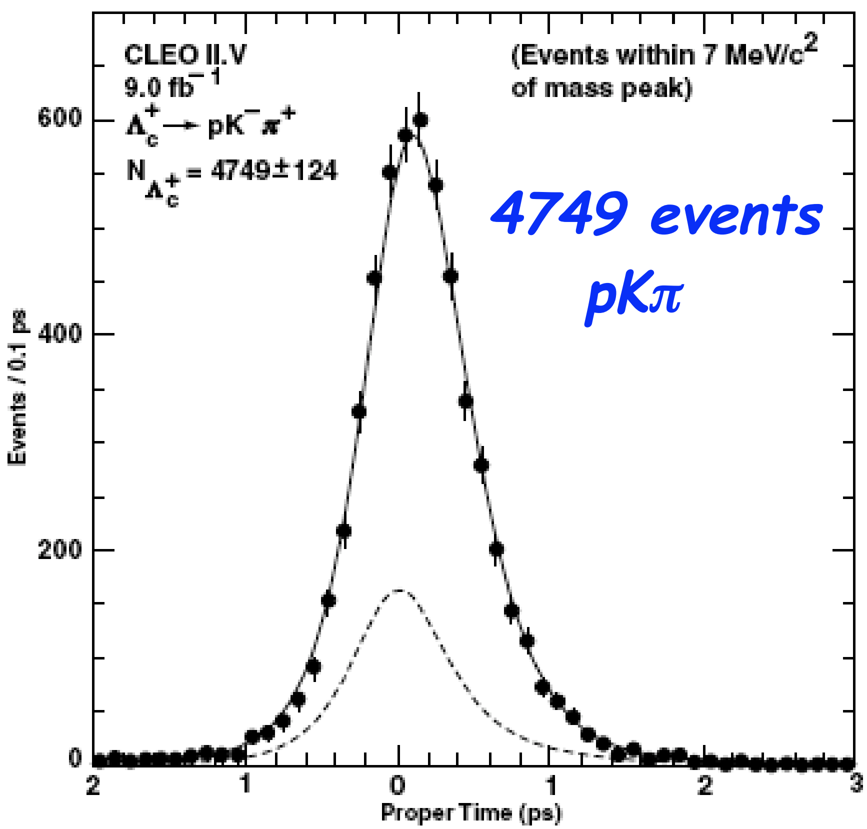
PRD 72, 012001
2005 9.0 fb^{-1}

PRL 86, 2232
2001 9.0 fb^{-1}

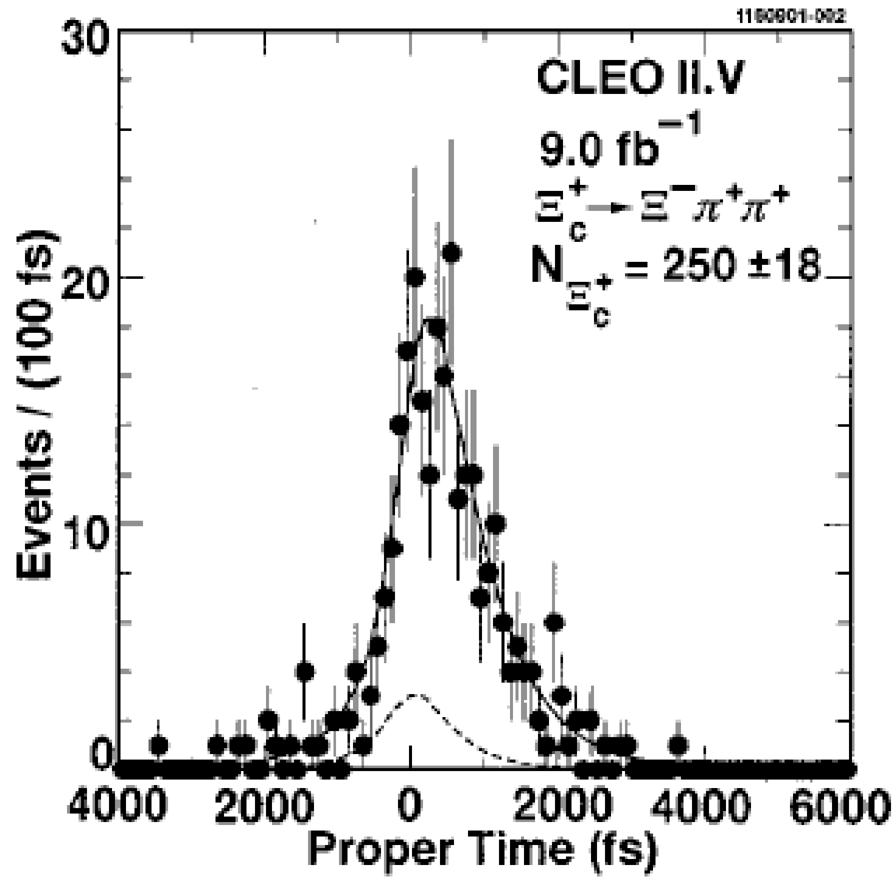
Λ_c & Ξ_c^+ Lifetime

PRD 65, 031102
2002 9.0 fb^{-1}

Λ_c: Short lifetime !



Ξ_c^+



Result: 179.6 ± 6.9 ± 4.4 fs

World average of 200 ± 6 fs

Result: 503 ± 47 ± 18 fs

World average of 442 ± 26 fs

PRL 86, 3730
2001 13.7 fb^{-1}

Ω_c: Finding & Beta Decay

PRL 89,171803
2002 13.7 fb^{-1}

Both use all II + II.V data

Establish Ω_c at CLEO:
5 hadronic modes summed

40.4 +- 9.0 events

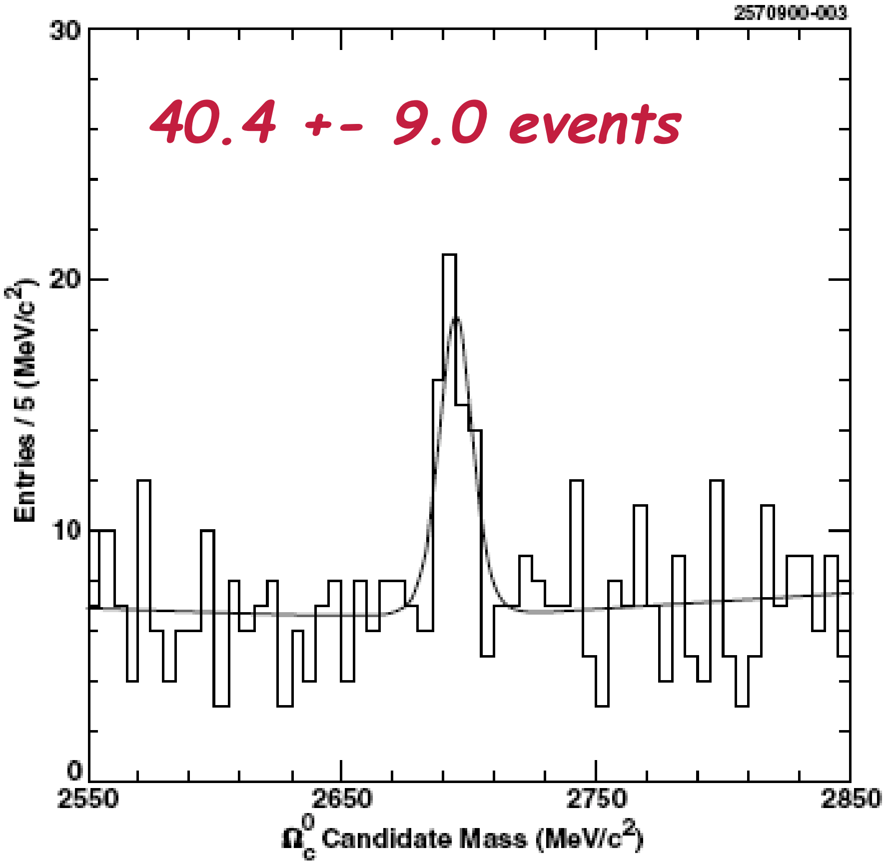
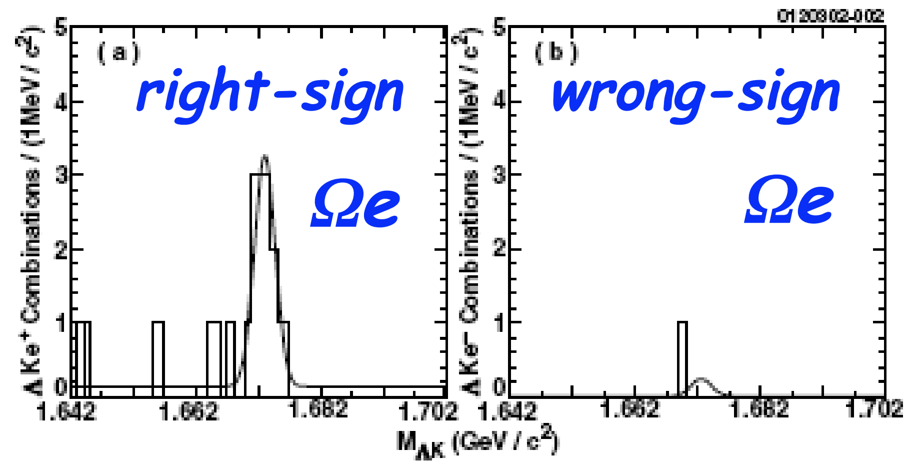


FIG. 2. The invariant mass distribution for the sum of $\Omega^-\pi^+$, $\Omega^-\pi^+\pi^0$, $\Omega^-\pi^+\pi^+\pi^-$, $\Xi^0 K^-\pi^+$, and $\Xi^- K^-\pi^+\pi^+$ combinations. The fit function is a sum of the fit functions from Fig. 1.

Semileptonic
$\Omega_c \rightarrow \Omega e \nu$

11.4 +- 3.8 events



First baryonic beta-decay
w/o u,d quarks at vertex

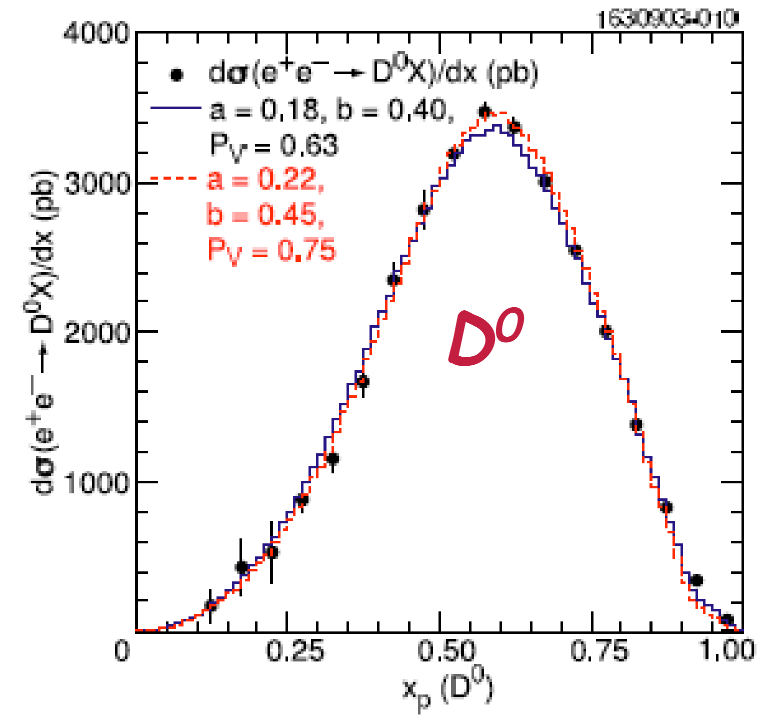
$D^{(*)}$ Fragmentation

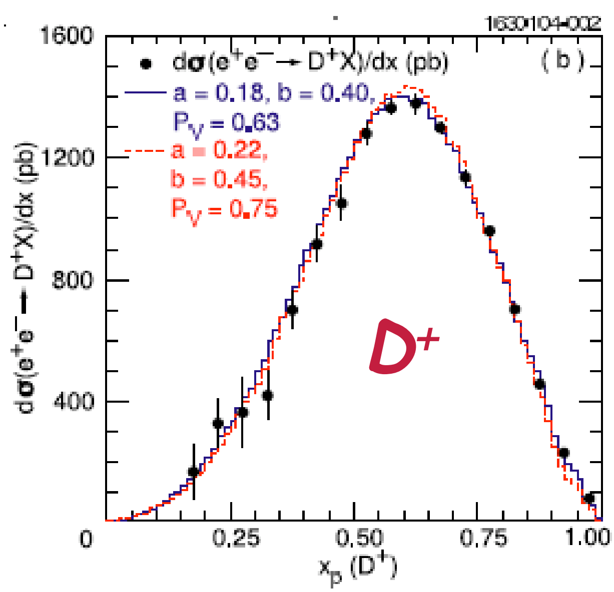
PRD 70,112001
2004 13.4 fb^{-1}

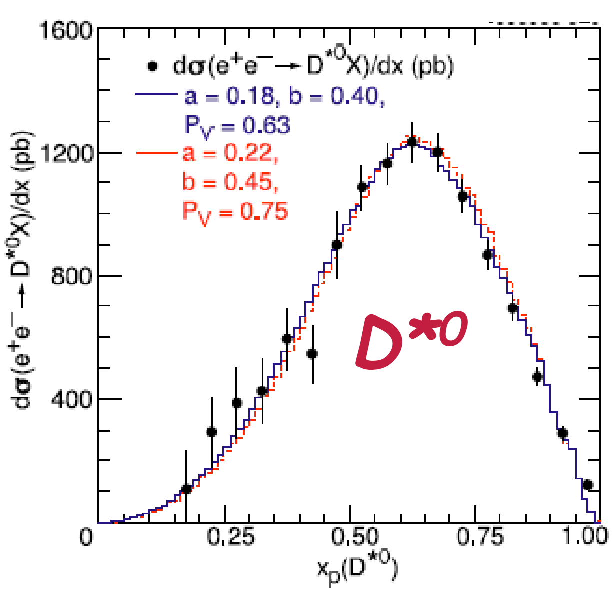
CLEO's definitive result

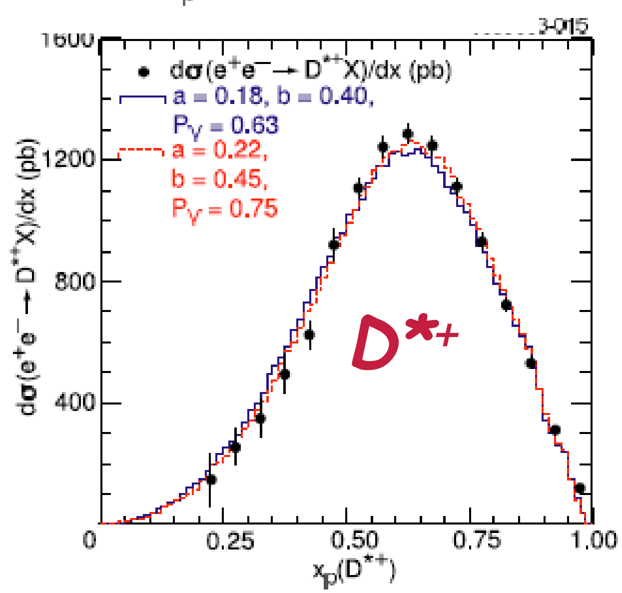
Full II+II.V data

Great care w/ efficiency & yield systematics









CLEO Pre-History:
Tail of the the D_{sJ} (2460)

CBX 96-4
1996 3.75 fb^{-1}

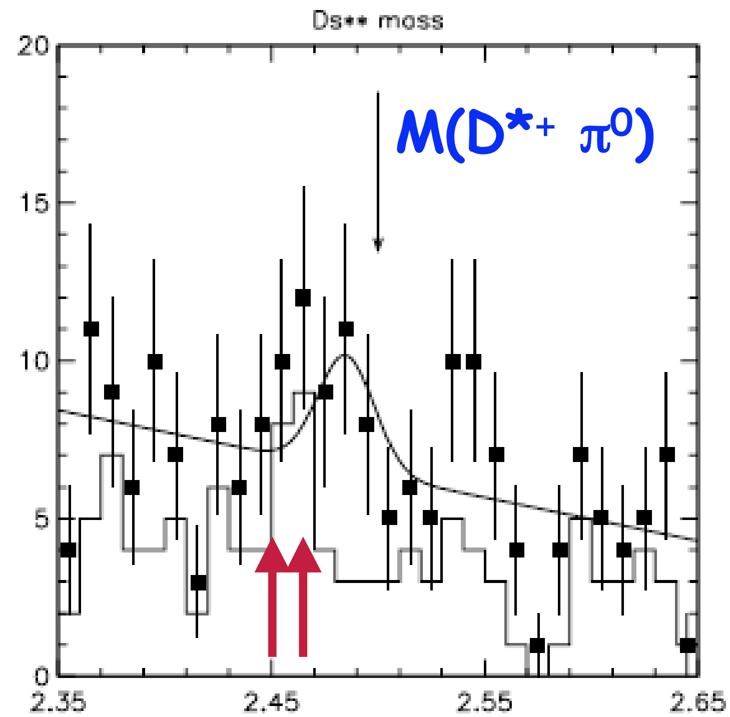
Follow-up to $D_s\ \pi^0$ …
1996

CBX 96-4
January 16, 1996

Search for a Narrow Charmed Strange Meson Near D^*K Threshold

J. Bartelt
Vanderbilt University, Nashville, Tennessee 37235

A search has been carried out for a narrow state decaying to $D_s^+\pi^+\pi^-$ or $D_s^{*+}\pi^0$. It has been suggested that the "broad" 1^+ D_s^{**+} state, if below D^*K threshold, might be narrow and might decay to these modes. No evidence is found for such a state. Upper limits are also set on the decays of the $D_{s1}(2536)^+$ and $D_{s2}^*(2573)^+$ to these modes.



Dots: $x>0.6$
Histogram: $x>0.7$

Real 2460 peak in latter?
But fit to former…

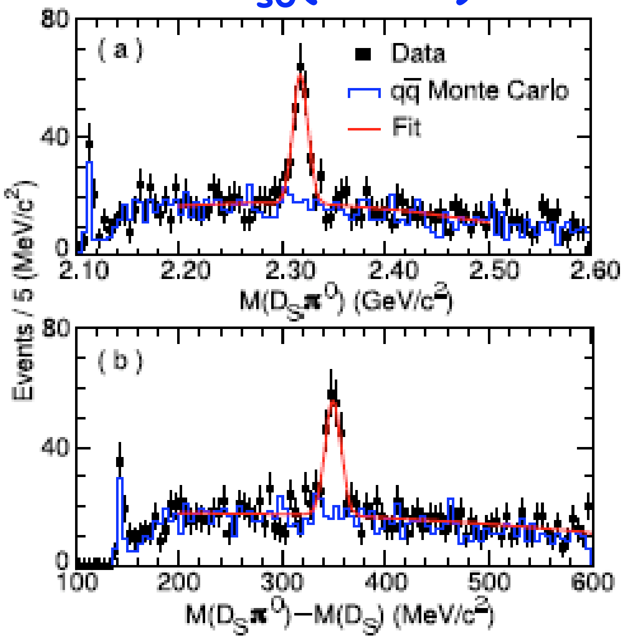
Rapid Response Team: Snagging the D_{sJ} (2460)

PRD 68, 032002
2003 13.5 fb^{-1}

BaBar finds an unexpected (huge) D_{sJ}(2317),
and sees a "structure" at 2460 MeV as well:
but it is clearly partly feed-across.

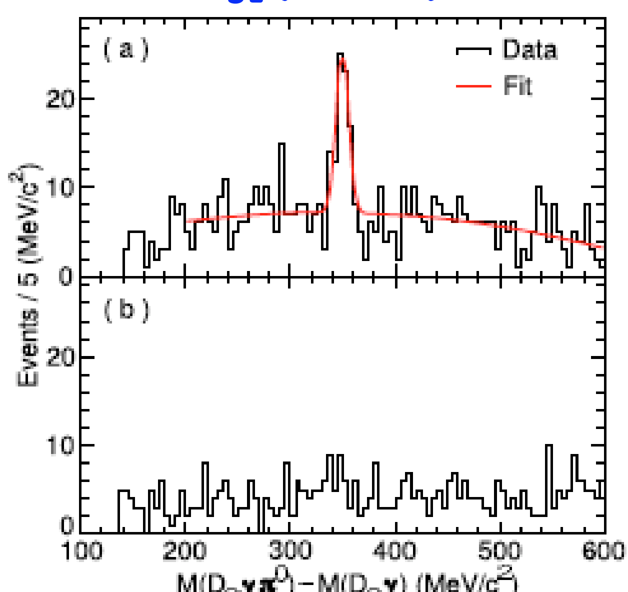
Various CLEOns believe the 2460 may be real, and prove it!
Leverages our very well-understood detector & well-tuned MC

$D^*_{s0}(2317)$



$M(D_s\pi^0) - M(D_s)$

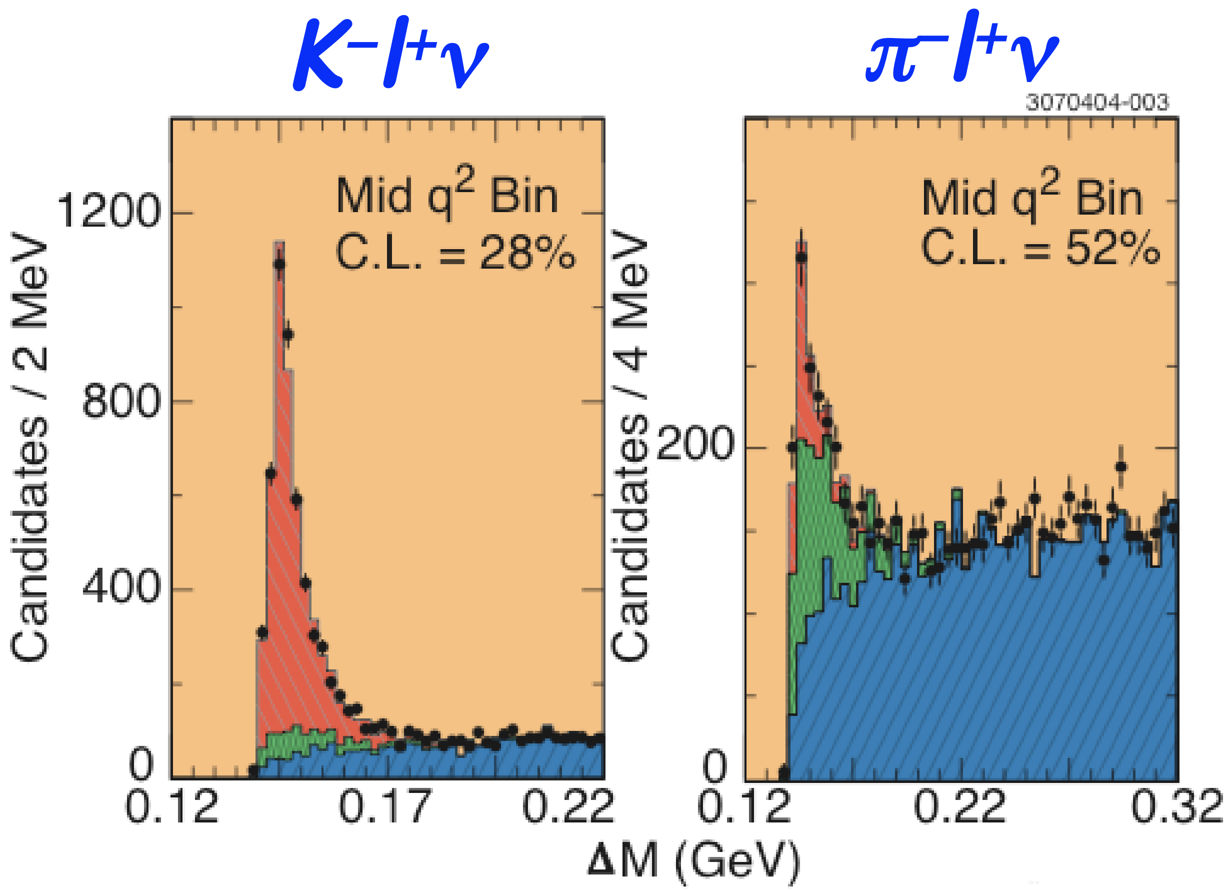
$D_{s1}(2460)$



$M(D_s\gamma\pi^0) - M(D_s\gamma)$

CLEOIII $D^0 \to \pi^- l^+ \nu$, $K^- l^+ \nu$

PRL 94, 011802 (2005) 6.7/8.0 fb^{-1}



World's best when done…

But note Kaons under pion peak ! (even w/ RICH…)

Decays with K are 10x more common than π : Separation via "particle ID" alone is hard !

Soon, CLEO-c: has excellent kinematic separation

Act IV:
The CLEO-c Era

The Three Pillars of CLEO-c

- o Letponic modes and Decay Constants
- o Semileptonic modes and Form Factors
- o Hadronic modes and Golden-Mode BFs

Quantum Coherence & other fun modes

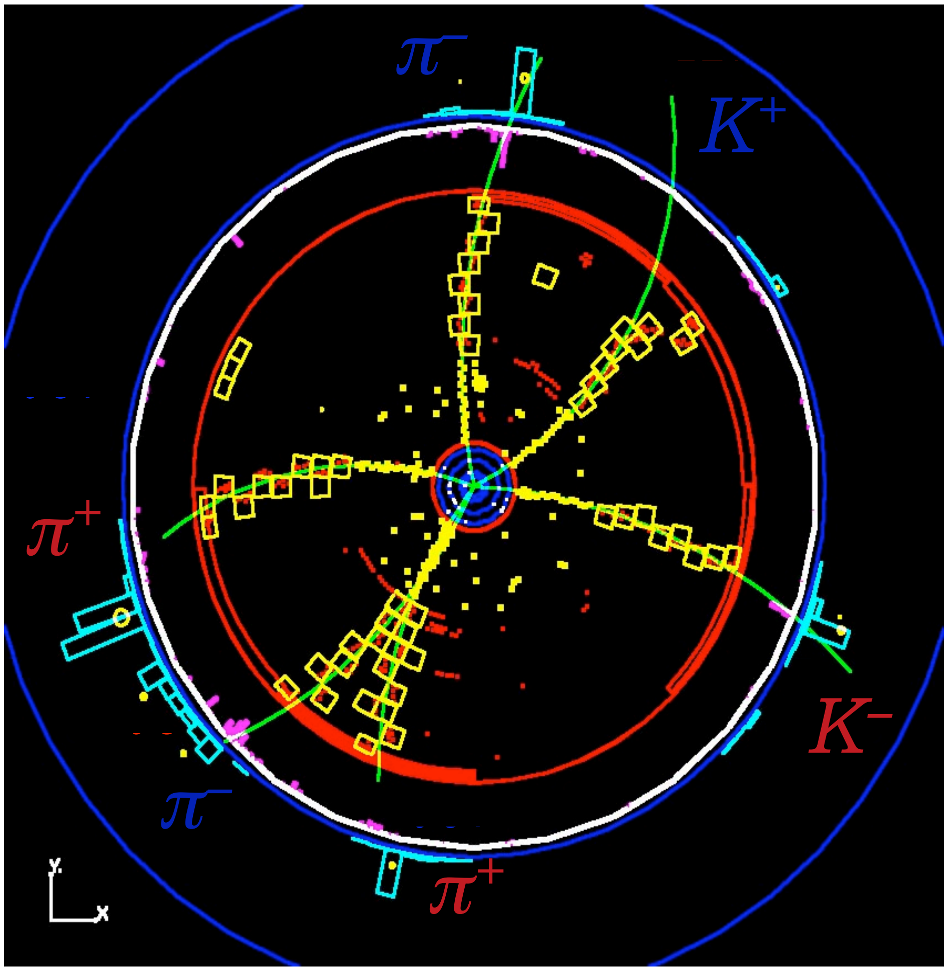
This history is still being written...

God grant me the Serenity to accept
the things I cannot change,
the Courage to change the things I can,
and the Wisdom to know the difference.
-- attributed to St. Francis of Assisi

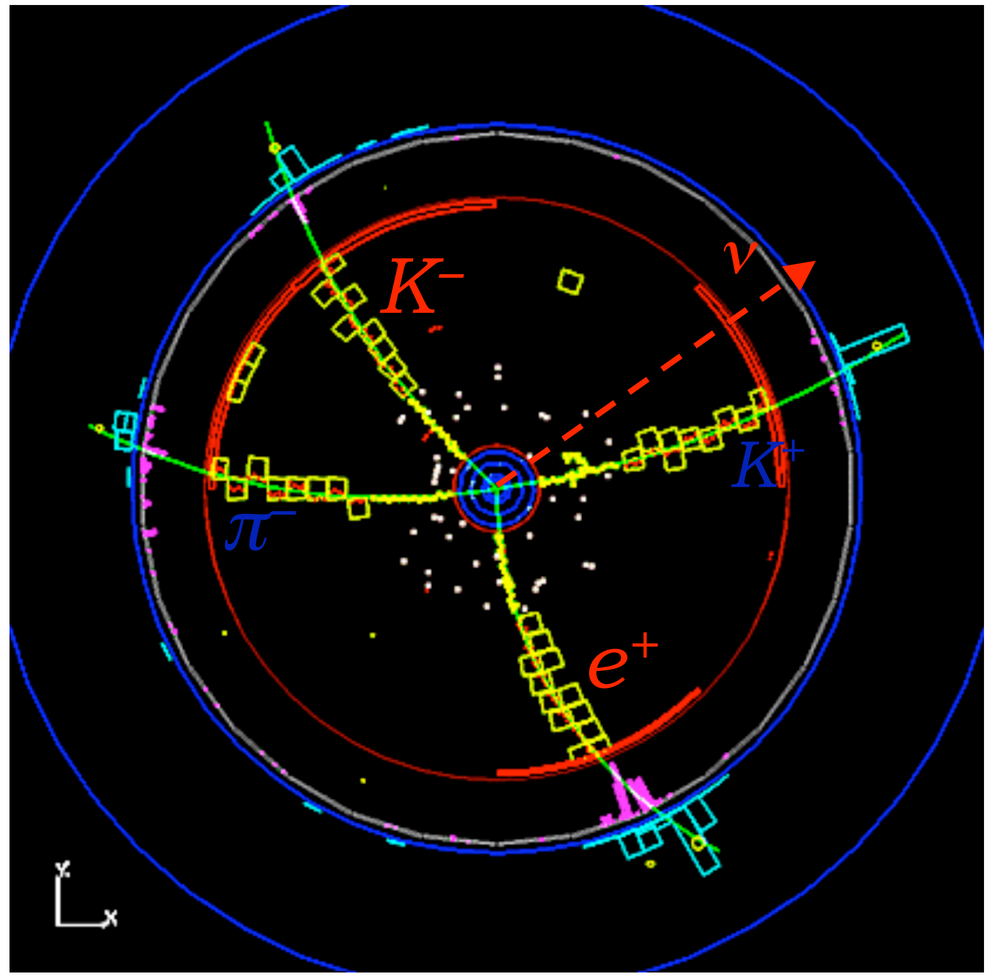
D Tagging at CLEO-c

Clean: high-efficiency for full reconstruction & low background

Don't forget the use of data for efficiency & resolution systematics !



$K^- \pi^+ \pi^+$ vs. $K^+ \pi^- \pi^-$



$K^- e^+ \nu$ vs. $K^+ \pi^-$

Note: coarse yellow boxes are trigger cells, not for track reconstruction !

Tagging Techniques

CLEO-c uses Tagging:

$\psi(3770) \rightarrow D^0\bar{D}^0,\ D^+D^-$

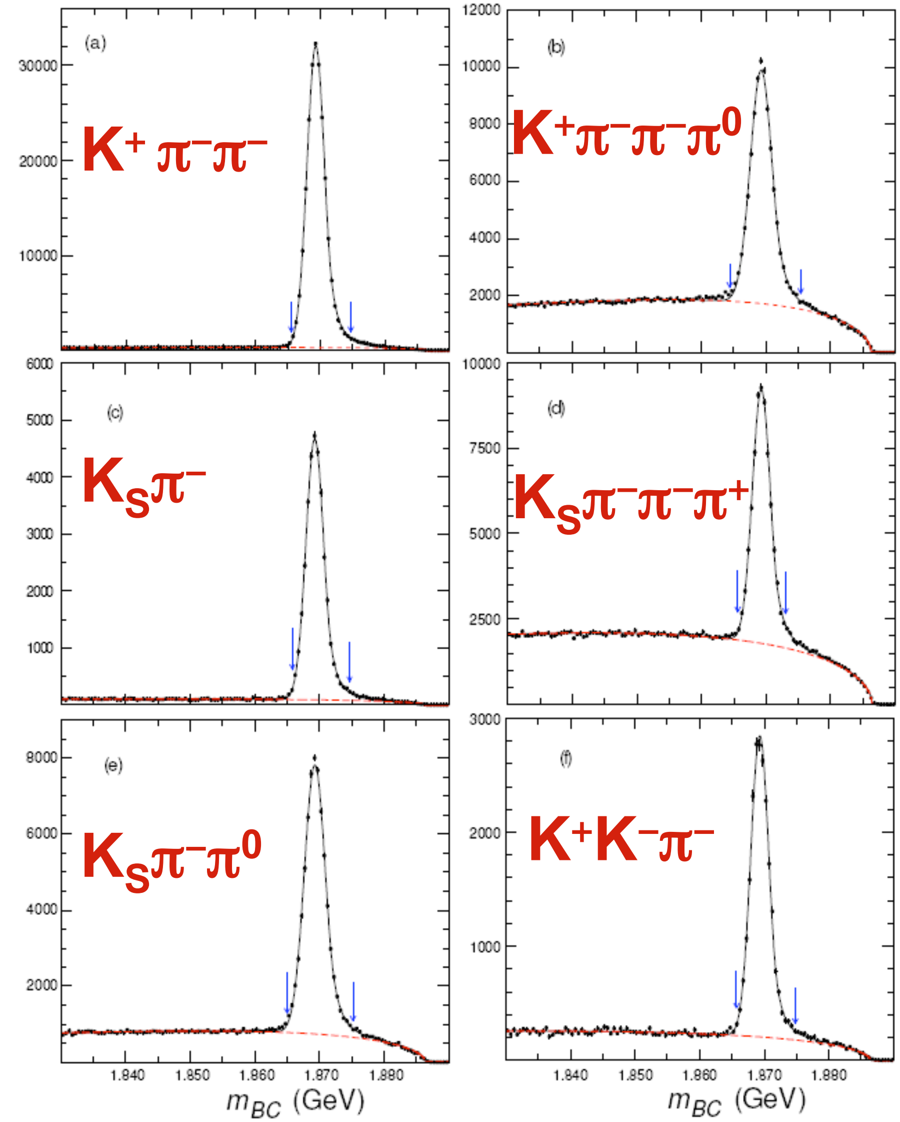
@4170 MeV: $D_s^+D_s^{*-}$ + c.c.

creates ONLY D pairs

Fully reconstruct one $D_{(s)}$

- Can then infer neutrinos (constrained kinematics)
- or get absolute hadronic BFs (algebra eliminates #D's)

CLEO-c D^- Tags (used for f_D)



The Three Pillars of CLEO-c

The core open-charm program at CLEO-c features:

Leptonic Decays $D_{(s)} \Rightarrow \mu\nu$,
to extract decay constants

$D \Rightarrow Kl\nu$, $\pi l\nu$:,
to measure form factors

Testbeds for modern Lattice QCD

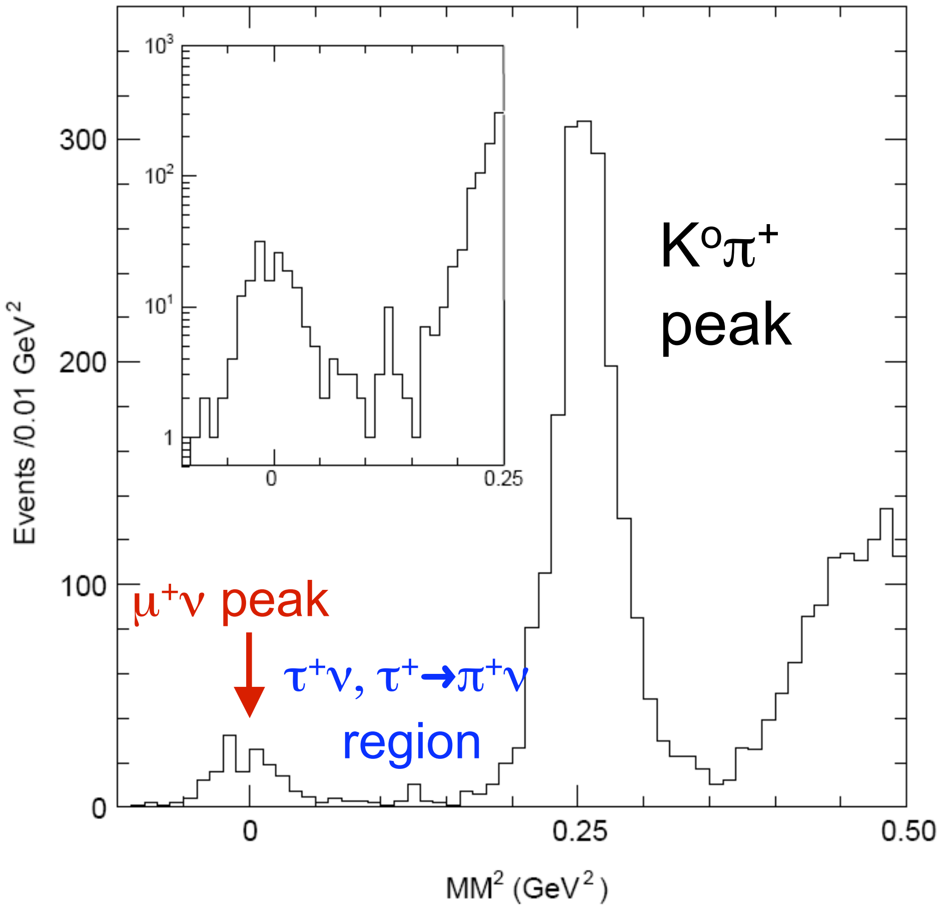
$D0 \Rightarrow K\pi$ $D+ \Rightarrow K\pi\pi$ $Ds \Rightarrow KK\pi$,
to provide golden-mode branching rations

…and many other nice open-charm topics

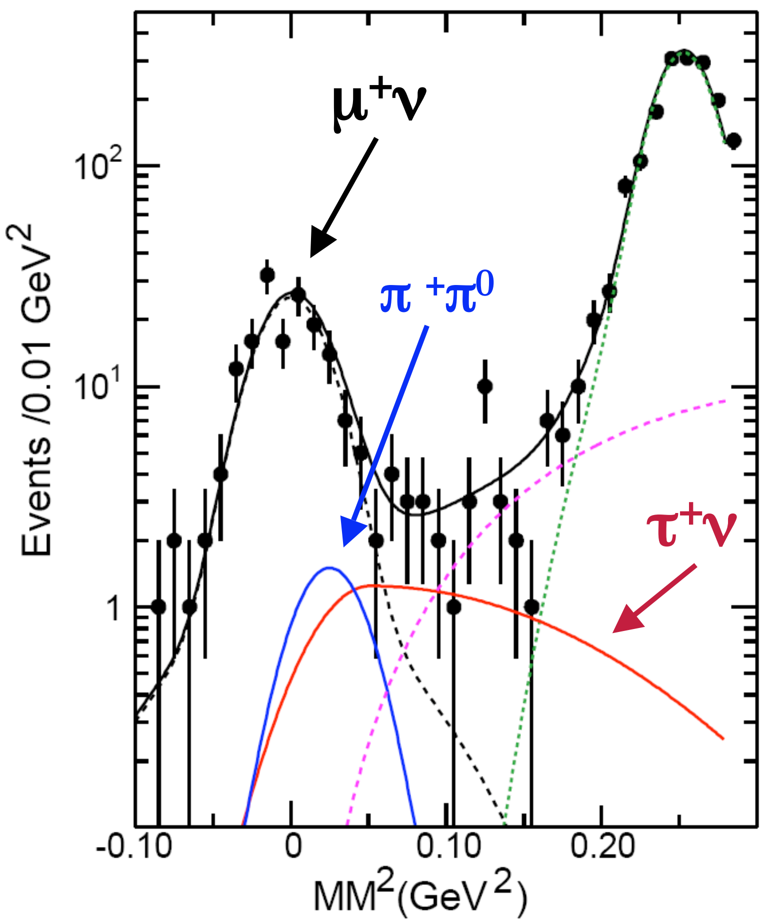
$D^+ \Rightarrow \mu^+\nu$

PRELIMINARY
FPCP2008
818 pb^{-1}

Clean, isolated signal peak: Power of D-tagging:
Recall that the signal is one track + neutrino !



Fit components

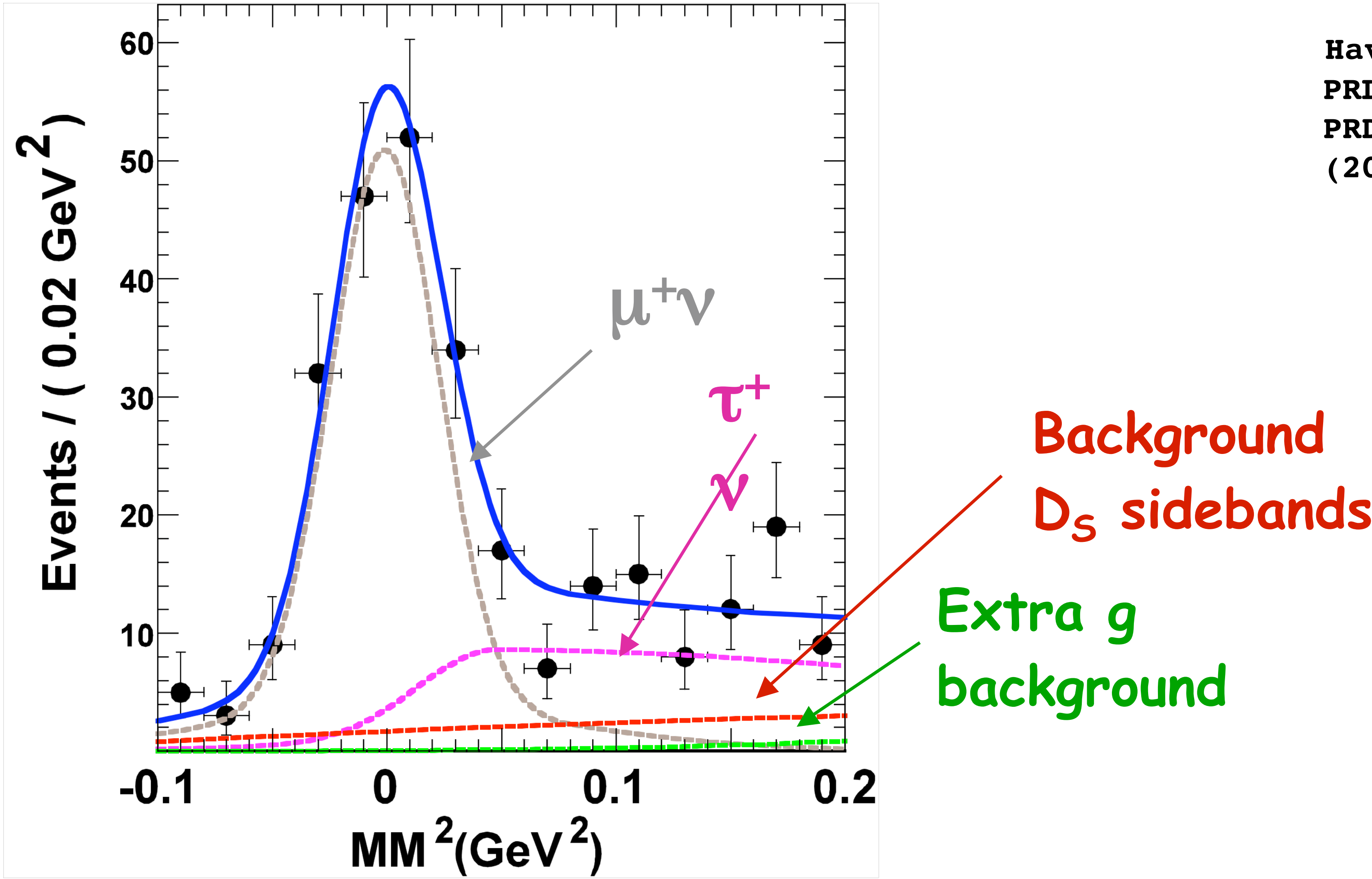


f_{D^+} = (206.7 ± 8.5 ± 2.5) MeV

Good agreement w/ LQCD
(207 ± 4) MeV

$D_s \Rightarrow \mu^+\upsilon$ & $\tau^+\upsilon$ ($\tau^+ \Rightarrow \pi\,\upsilon$)

PRELIMINARY
FPCP2008
~400 pb^{-1}



Have published:
PRL99, 071802
PRD76, 072002
(2007) 314 pb^{-1}

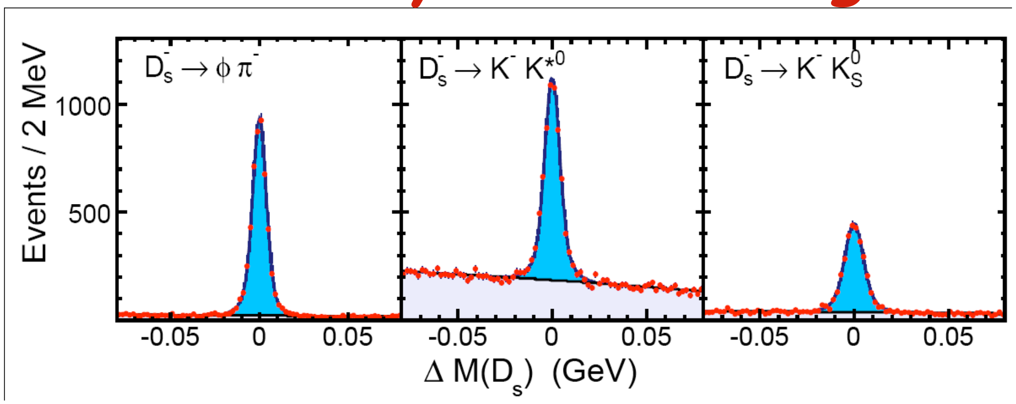
f_D = (268.2 ± 9.6 ± 4.4) MeV

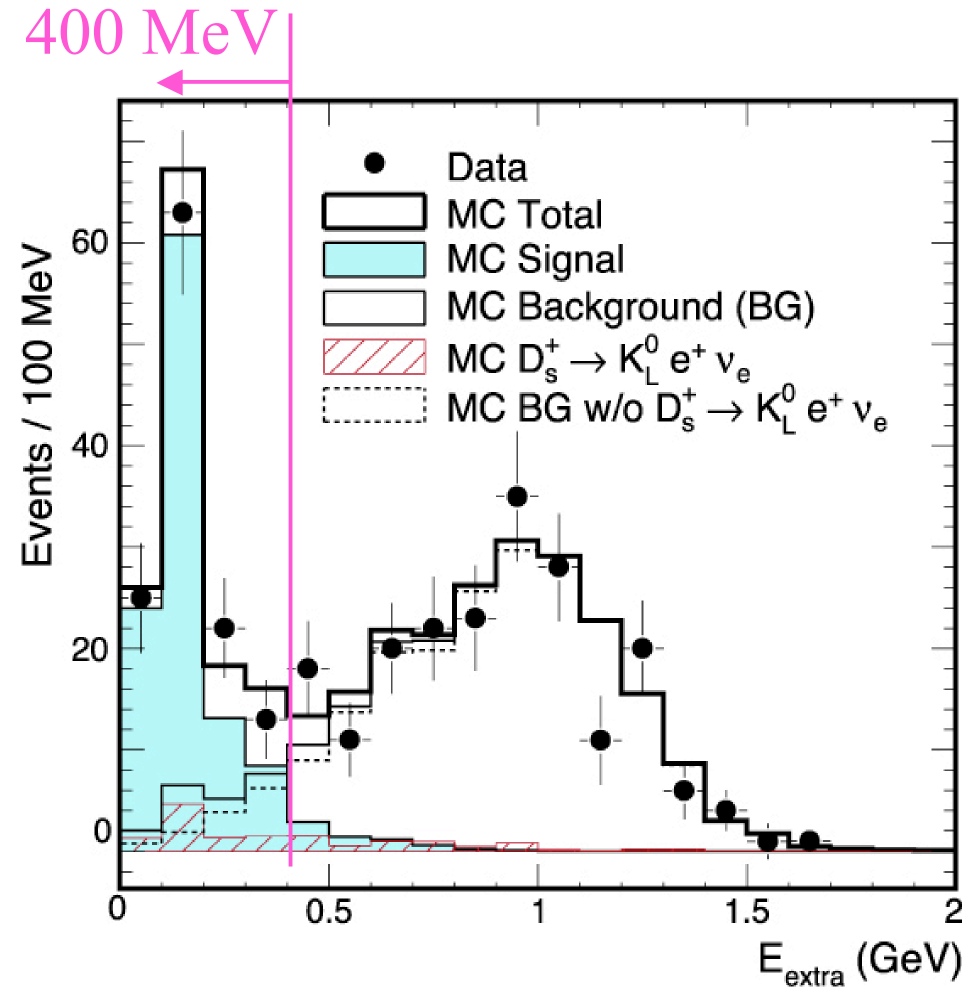
Higher then recent LQCD ?!?
(241 ± 3) MeV

$D_s \to \tau^+\nu$ ($\tau^+ \to e^+\nu\nu$)

PRL100, 161801 (2007) 298 pb^{-1}

Uses only cleanest tags





Can't use MM^2 with >1 neutrino…

Semileptonic events tend to have hadronic Energy in CsI (but careful re: K_L !)

Plot E_{extra} in Calorimeter (Extra = not tag D or e)

E_{extra} can include γ from D_s^* decay

f_{Ds} = (273 ± 16 ± 8) MeV

Consistent w/ other CLEO result

Inclusive Semileptonic

PRL 97, 251801
2006 281 pb^{-1}

Results for $\mathcal{B}$(D ⇒ Xeυ):

D^+ : $\mathcal{B}$ = (16.13 ± 0.20 ± 0.33)%
D^0 : $\mathcal{B}$ = (6.46 ± 0.17 ± 0.13)%

Better than prior PDG *world averages*:

D^+ $\mathcal{B}$ = (17.2 ± 1.9)% (electrons)
D^0 $\mathcal{B}$ = (6.87 ± 0.28)% (electrons)
D^0 $\mathcal{B}$ = (6.5 ± 0.8)% (muons)

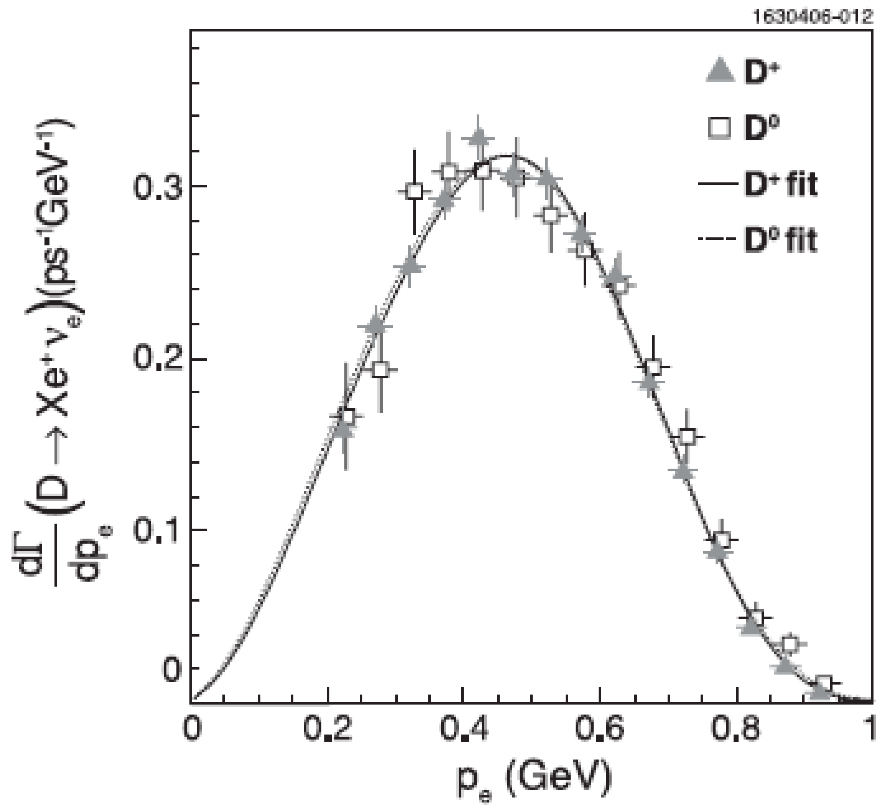
Most exclusives known **(use CLEO-c BF's):**

$\Sigma \mathcal{B}(D^+ \Rightarrow Xe\upsilon)_{excl} = (15.1 \pm 0.5 \pm 0.5)\%$
$\Sigma \mathcal{B}(D^0 \Rightarrow Xe\upsilon)_{excl} = (\ 6.1 \pm 0.2 \pm 0.2)\%$

Combine with lifetimes:

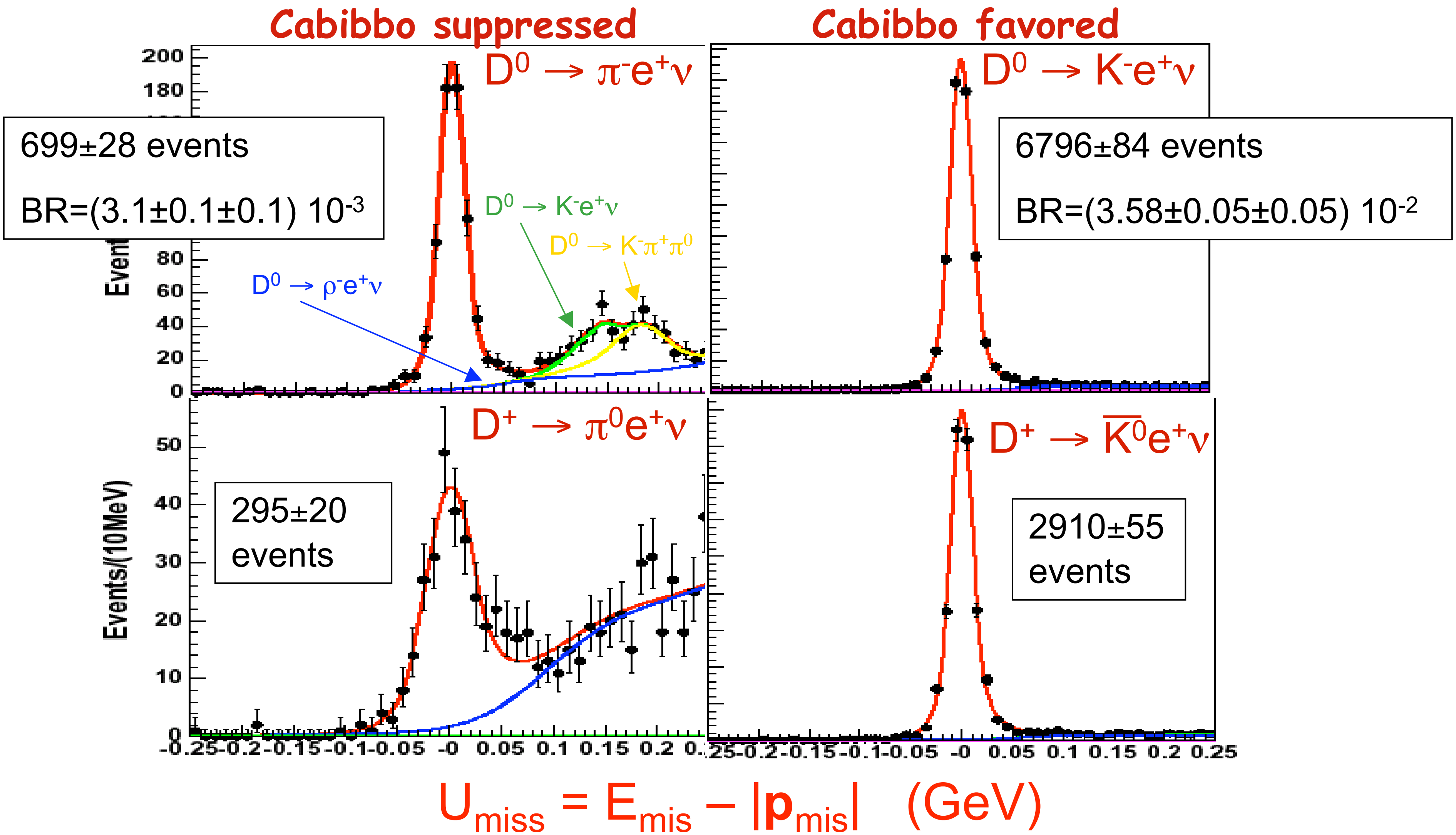
D^+ $\Gamma_{SL} = 0.1551 \pm 0.0020 \pm 0.0031\ ps^{-1}$
D^0 $\Gamma_{SL} = 0.1574 \pm 0.0041 \pm 0.0032\ ps^{-1}$
$\Gamma_{SL}(D^+) / \Gamma_{SL}(D^0) = 0.985 \pm 0.28 \pm 0.15$

Only "golden" tags:
$D^+ \Rightarrow K^-\pi^+\pi^+$ & $D^0 \Rightarrow K^-\pi^+$



Tagged $\pi e \upsilon$, $K e \upsilon$

281 pb^{-1}
Preliminary

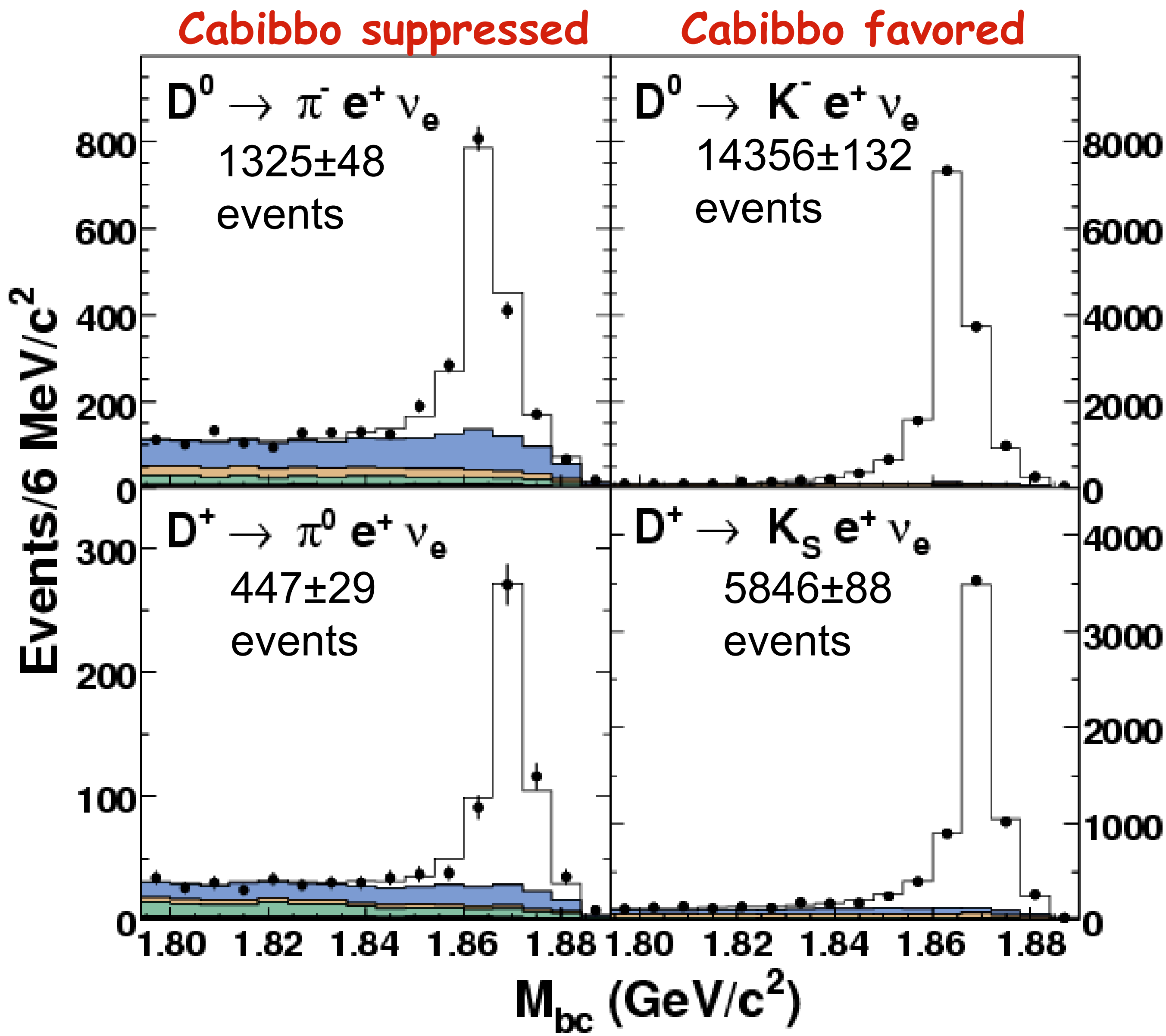


Excellent background suppression

Small K-π feed-across due to threshold kinematics

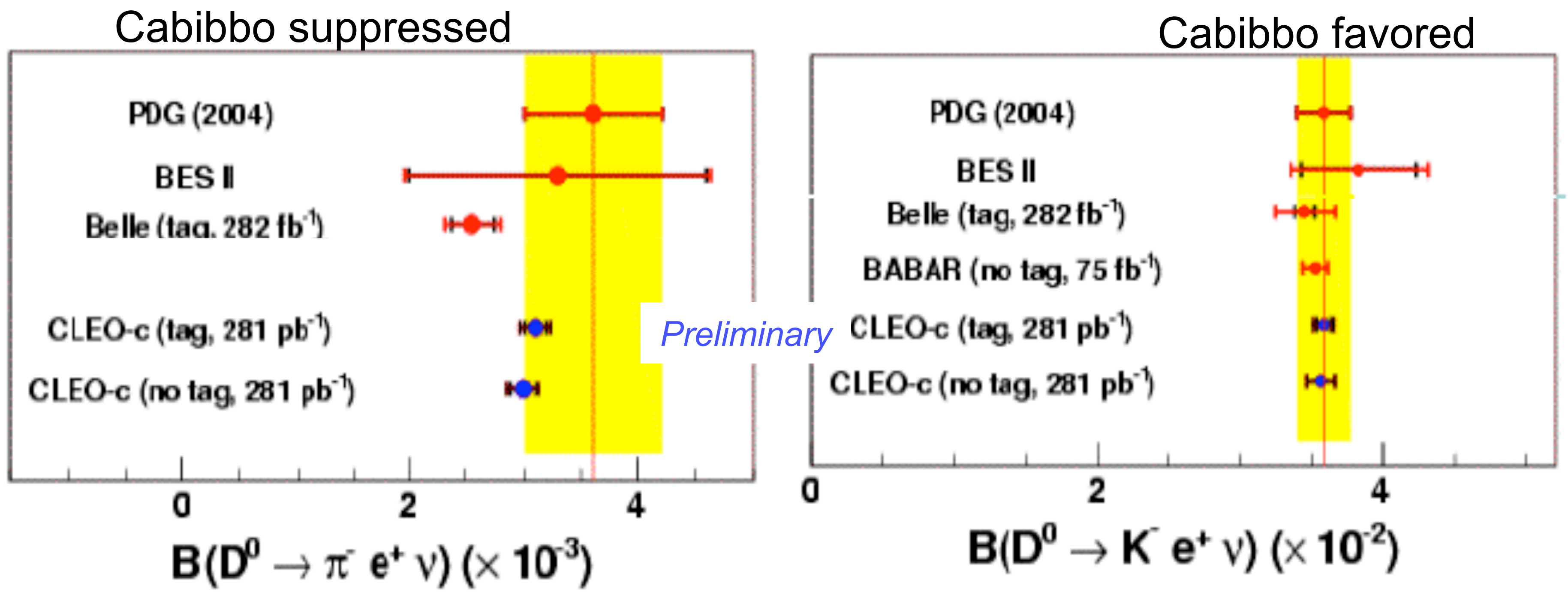
Tagged $\pi e \upsilon$, $K e \upsilon$

arXiv:0712.1012
arXiv:0712.0998
(accepted by PRD)
281 pb^{-1}



Factor ~2 increase in the signal statistics compared to the tagged analysis

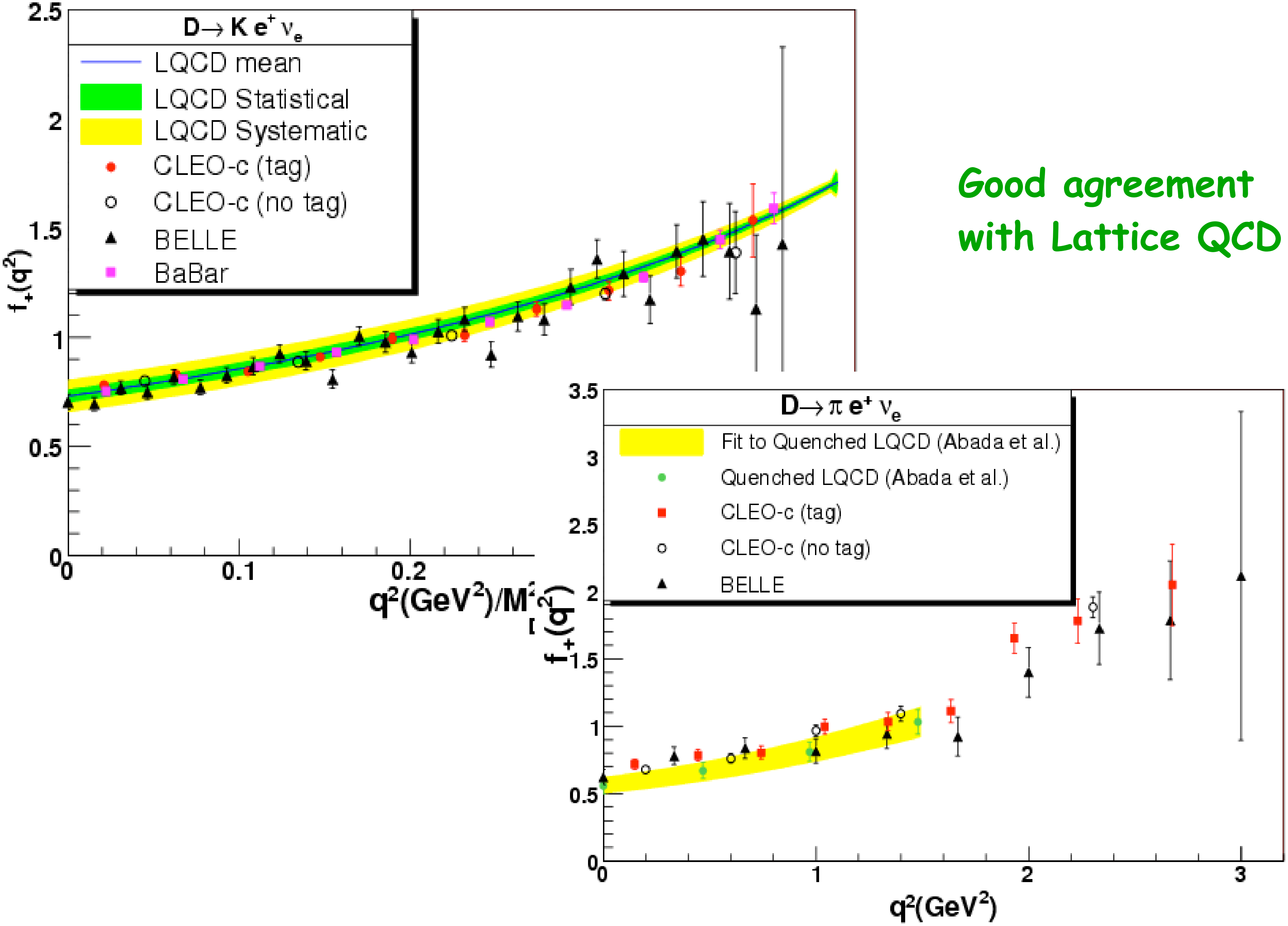
Branching Ratios



Significant improvement in precision by recent measurements

(CLEO-c most precise)

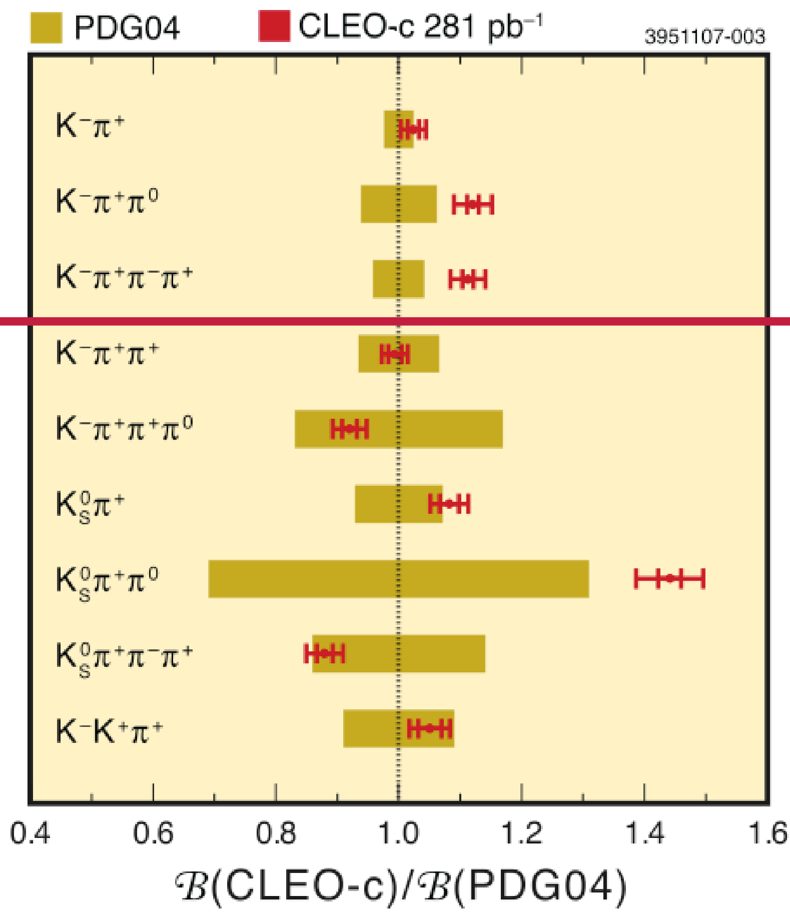
Pseudoscalar Form Factors



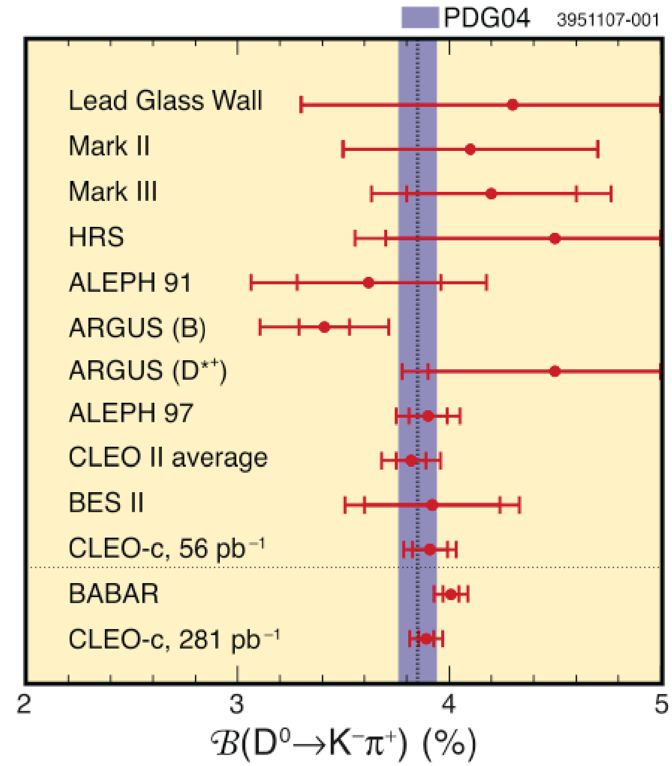
Good agreement with Lattice QCD

D^0 & D^+: Some Comparisons

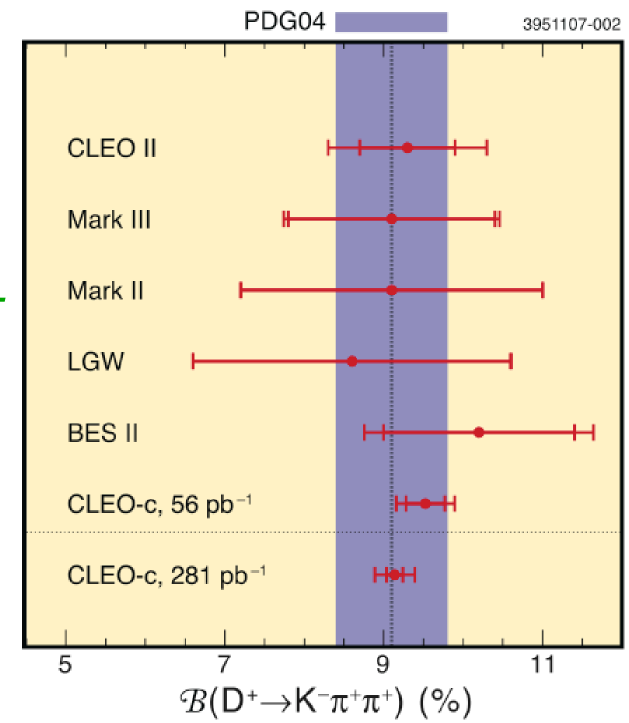
"Golden Modes" are now systematics limited



D^0 → $K^-\pi^+$



D^+ → $K^-\pi^+\pi^+$



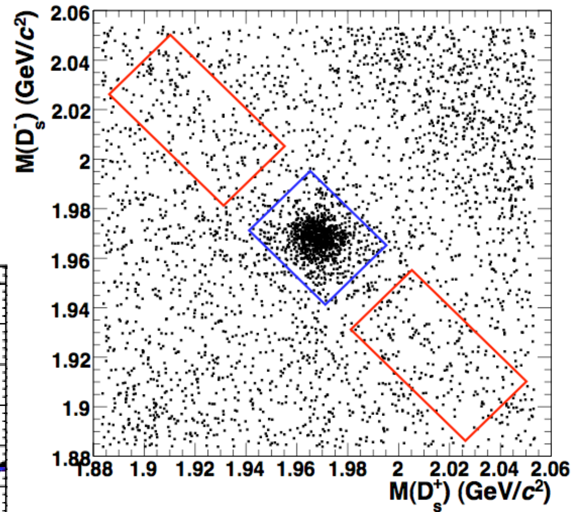
PRD 76, 112001 (2007) 281 pb^{-1}

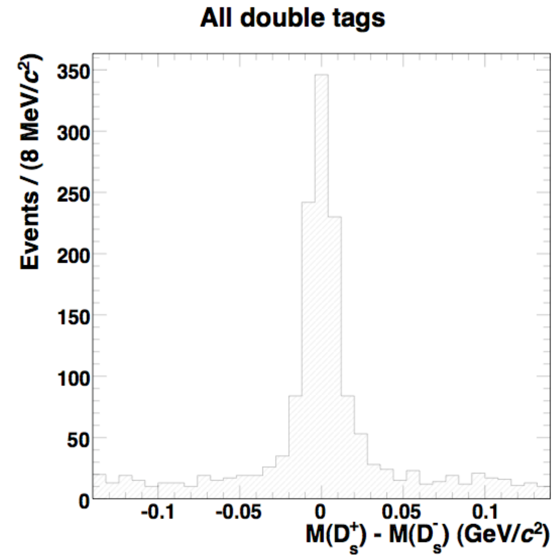
Use PDG04 since PDG06 included 56 pb^{-1} CLEO-c

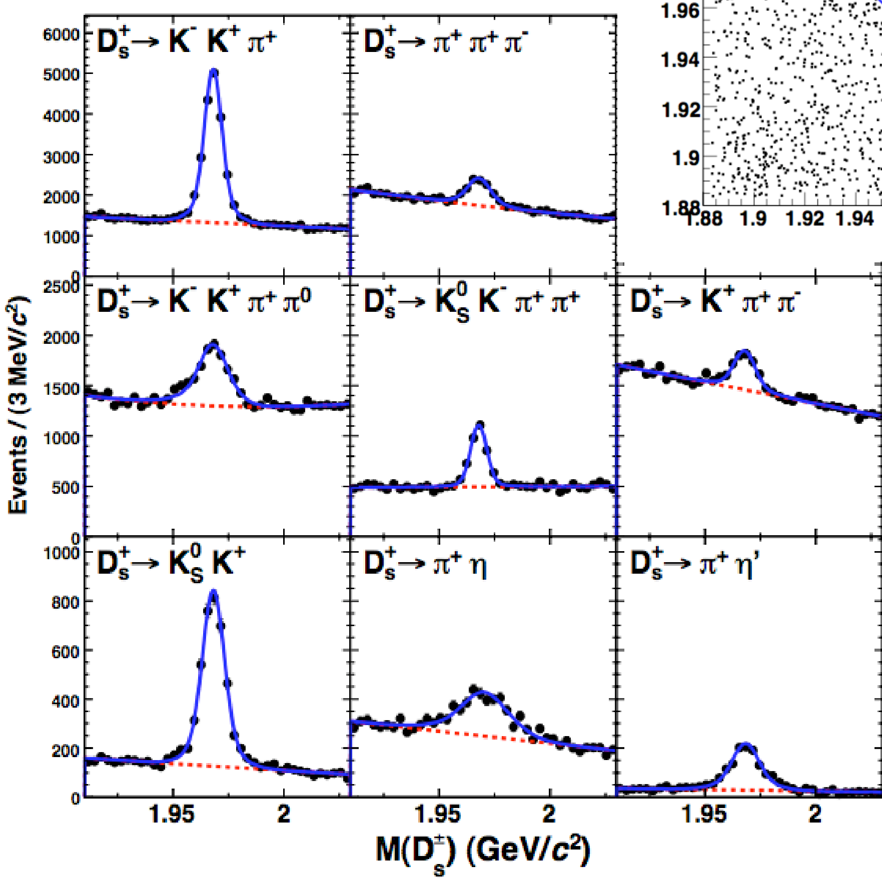
D_s Branching Ratios

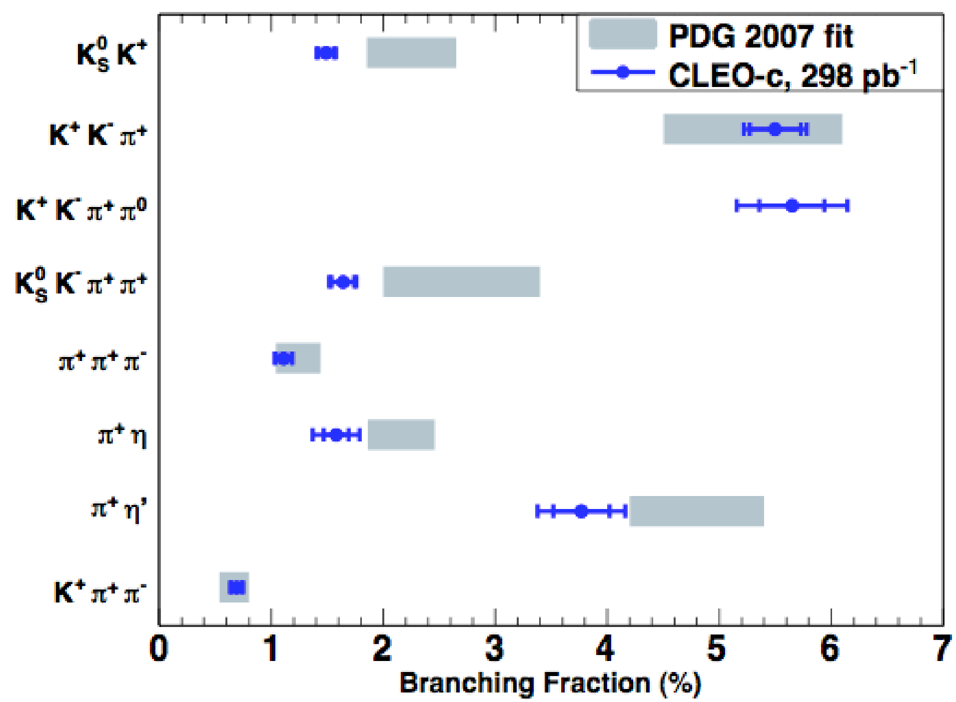
PRL 100, 161804 (2008) 298 pb^{-1}

Tougher than D
But solid results









$K\pi$ Strong Phase

arXiv:0802.2264
arXiv:0802.2268
281 pb^{-1}

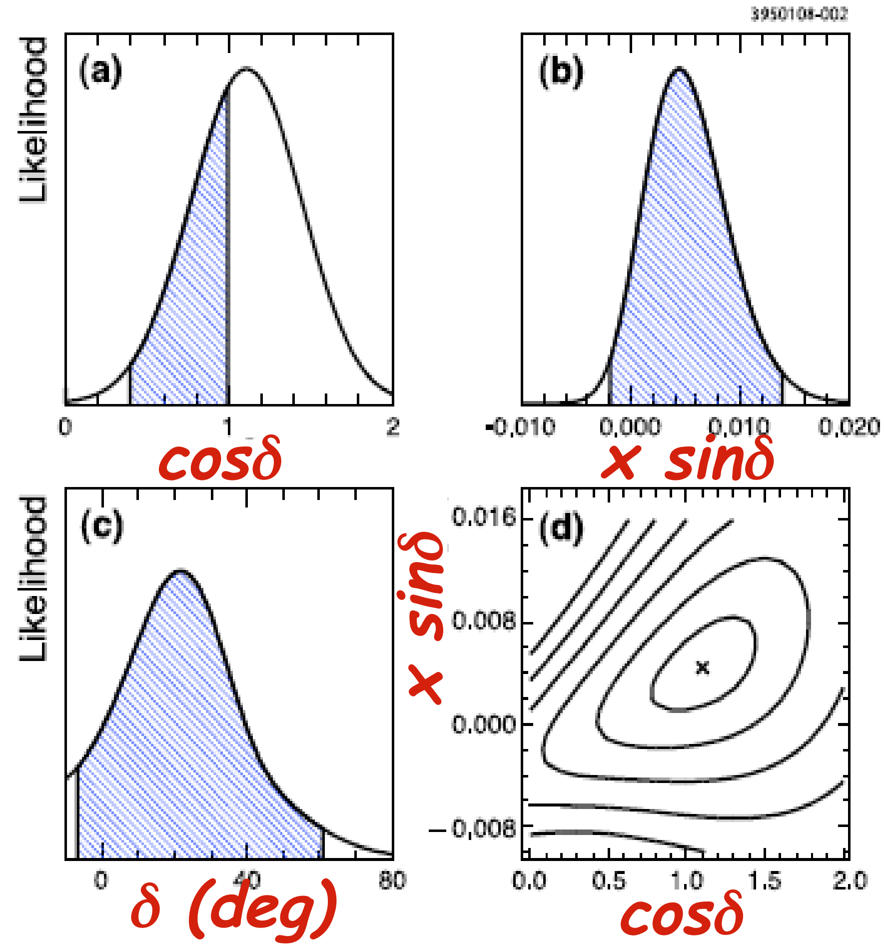
Correlated D pairs are produced
at the $\psi(3770)$:

Allows a measurement of
strong $K\pi$ FSI phase,
of great interest for
D mixing results !

Simultaneous fit to many
hadronic & semileptonic modes
& some external input

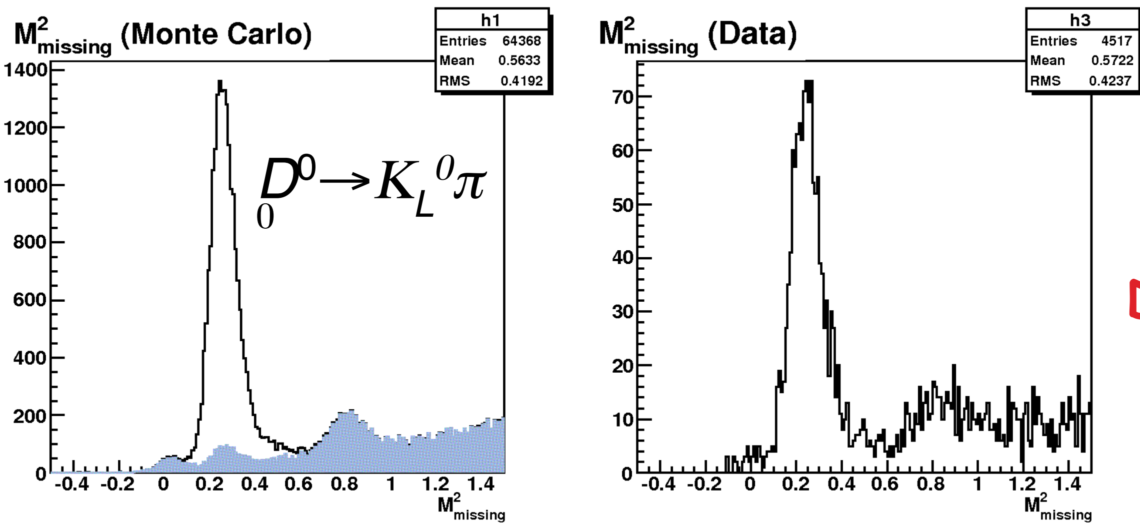
$\cos\delta = 1.10 \pm 0.35 \pm 0.07$

$\delta = (22^{+11}_{-12}\ {}^{+9}_{-11})^{o}$



$K_L\pi$, $K_S\pi$ & Interference

arXiv:0607068
281 pb^{-1}

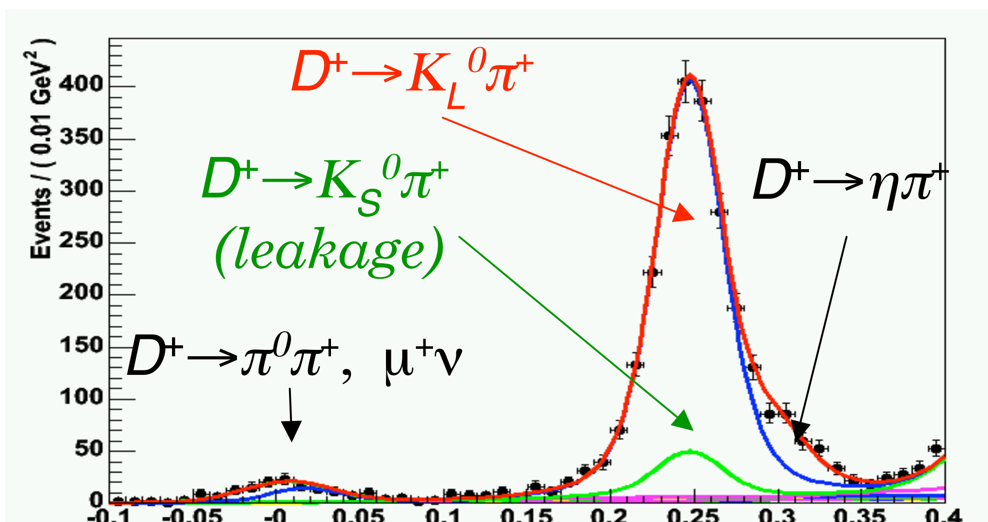


Missing Mass Squared

R_D = [$B(D \rightarrow K_S\pi) - B(D \rightarrow K_L\pi)$] / [$B(D \rightarrow K_S\pi) + B(D \rightarrow K_L\pi)$]

D^0: $R_D = 0.122 \pm 0.024 \pm 0.030$

(consistent with $2\tan^2\theta_C$)



Missing Mass Squared

D^+: $R_D = 0.030 \pm 0.023 \pm 0.025$

Dao-Neng Gao predicts:

$R(D^+) = 0.035$ to 0.044

(arXiv:hep-ph/0610389v2)

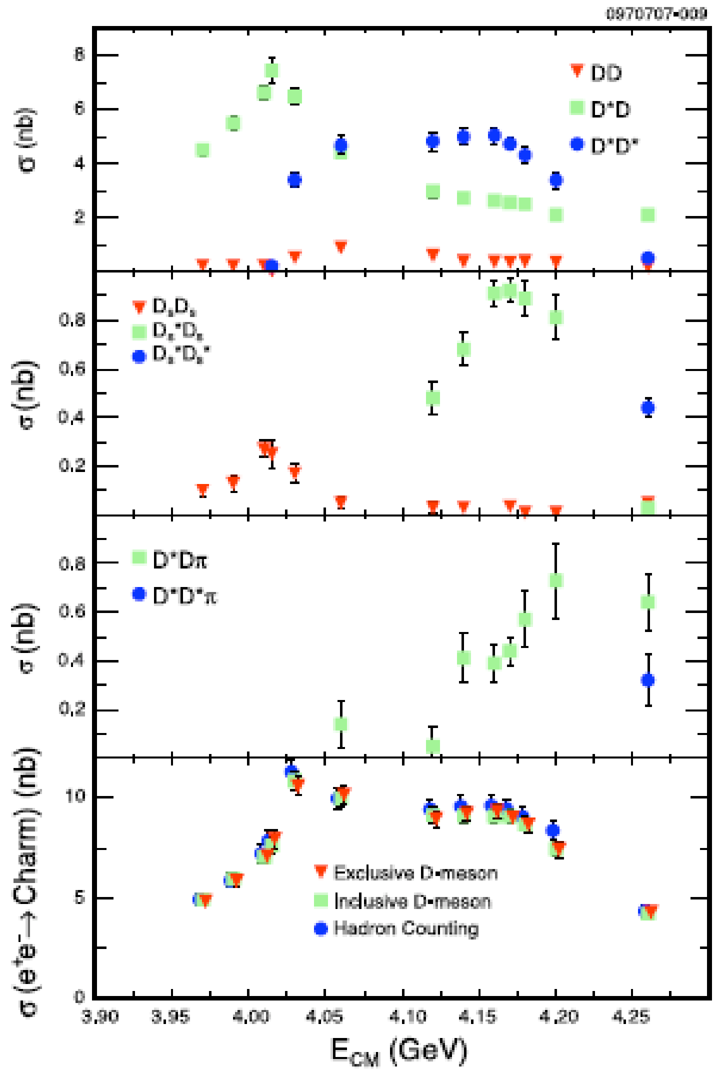
J. Rosner, CHARM2007:

$R(D^+) = 0.067 \pm 0.007$

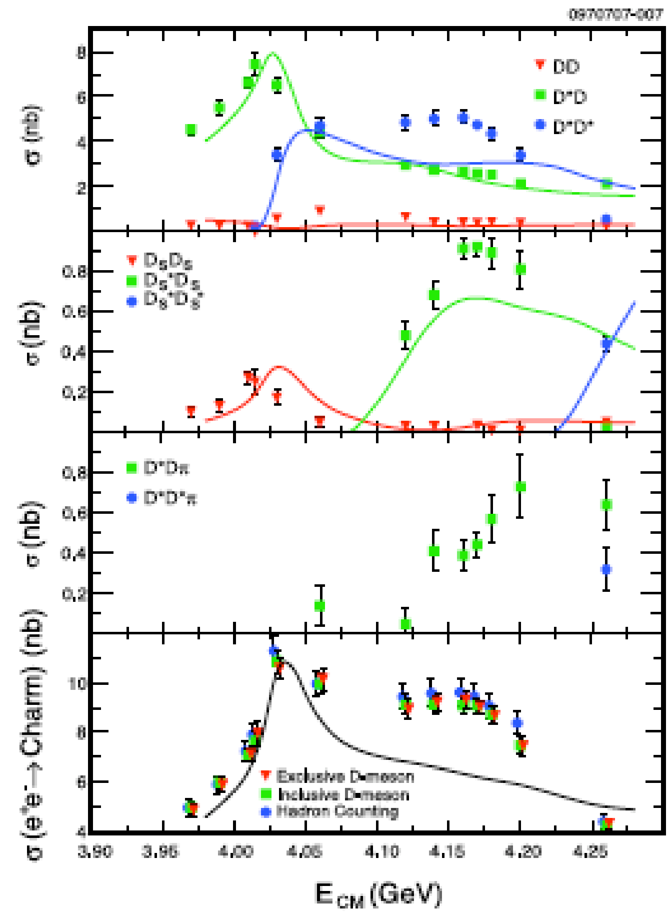
"D_s Scan" Cross-Sections

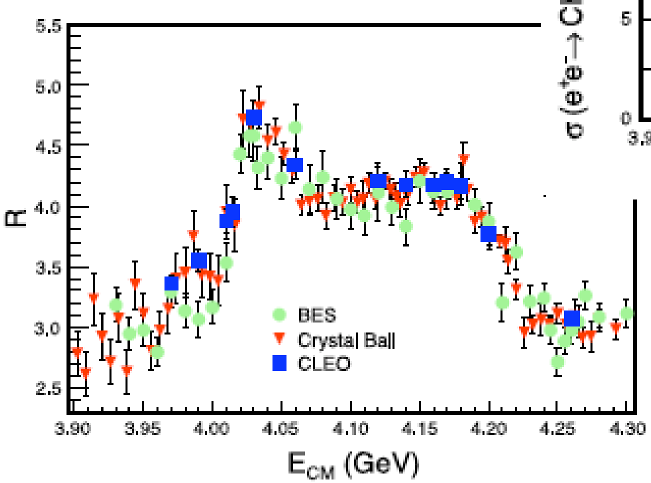
arXiv:0801.3418
2008 60.0 pb^{-1}

Spin-off from energy scan used to find Ds running point…



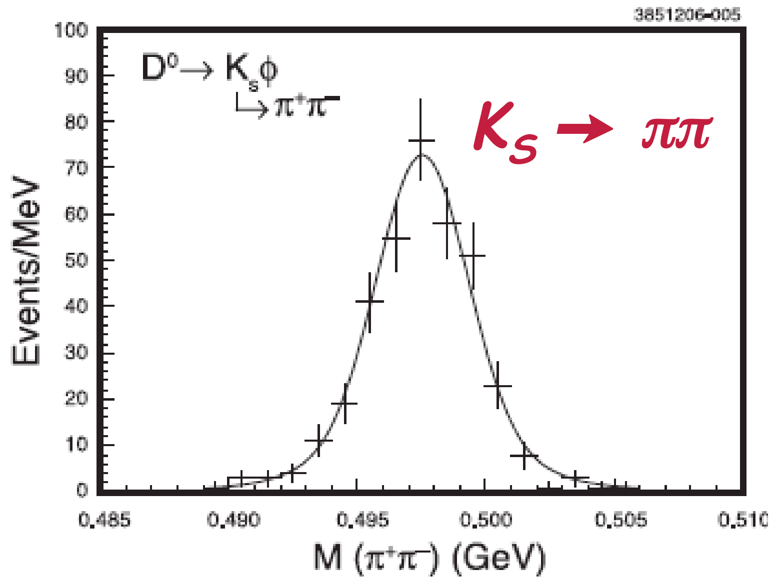
MUCH more detailed than all previous measurements…

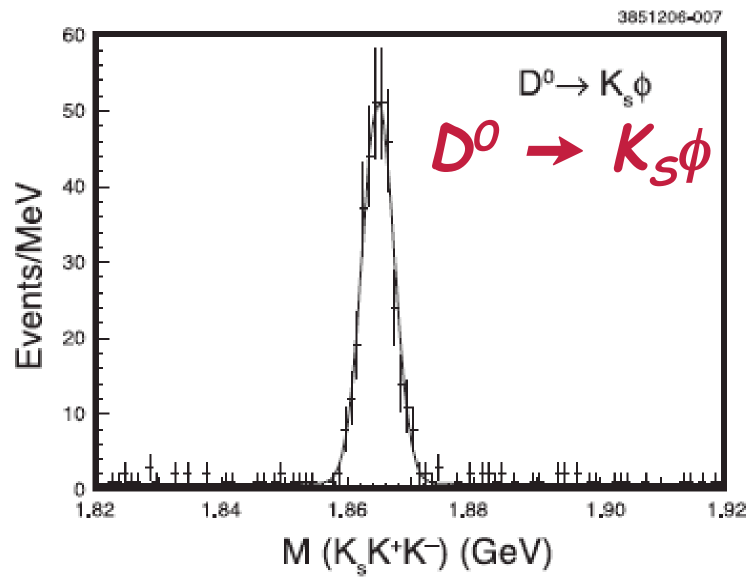


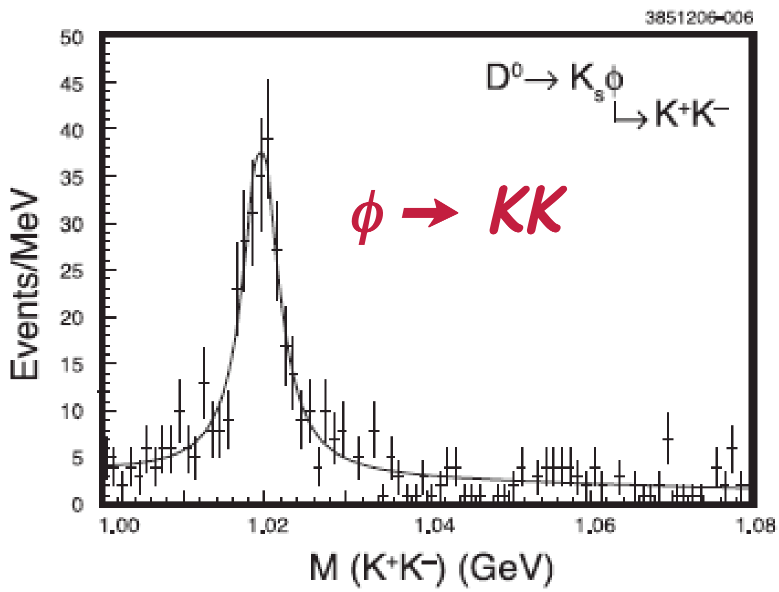


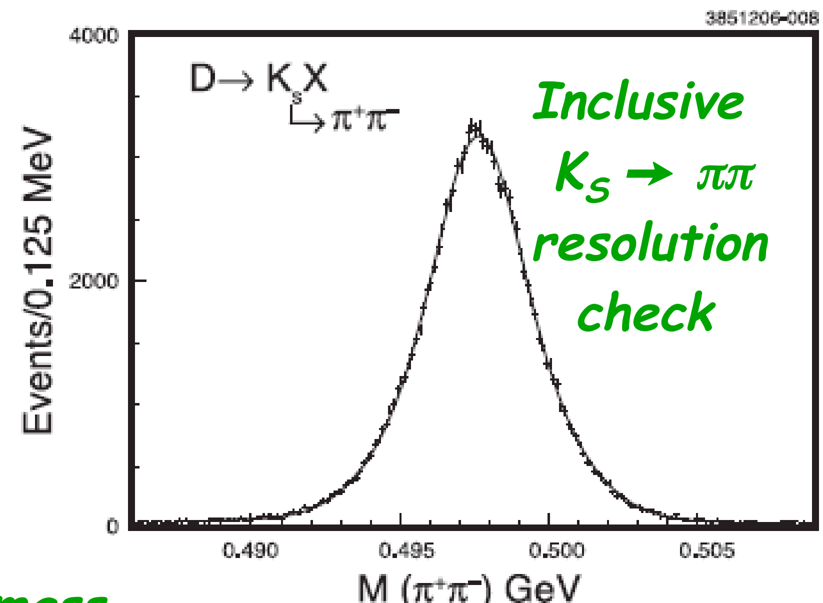
Precision D^0 Mass

PRL 98, 092002
2007 281 pb^{-1}









Final state: all charged & large rest-mass

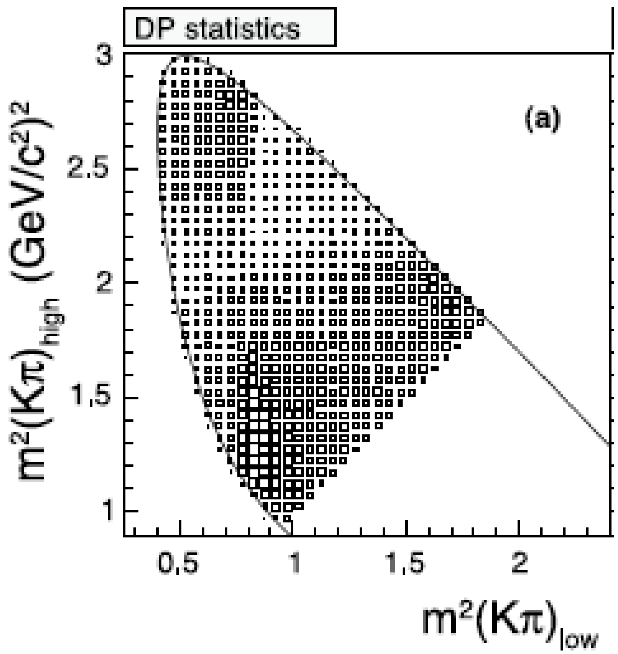
$M(D^0) = 1864.847 \pm 0.150 \pm 0.095$ *(very precise for absol. mass!)*

$D^+ \to K^-\pi^+\pi^+$ Dalitz Plot

arXiv:0802.4214
2001 572 fb^{-1}

141K events 99% signal !

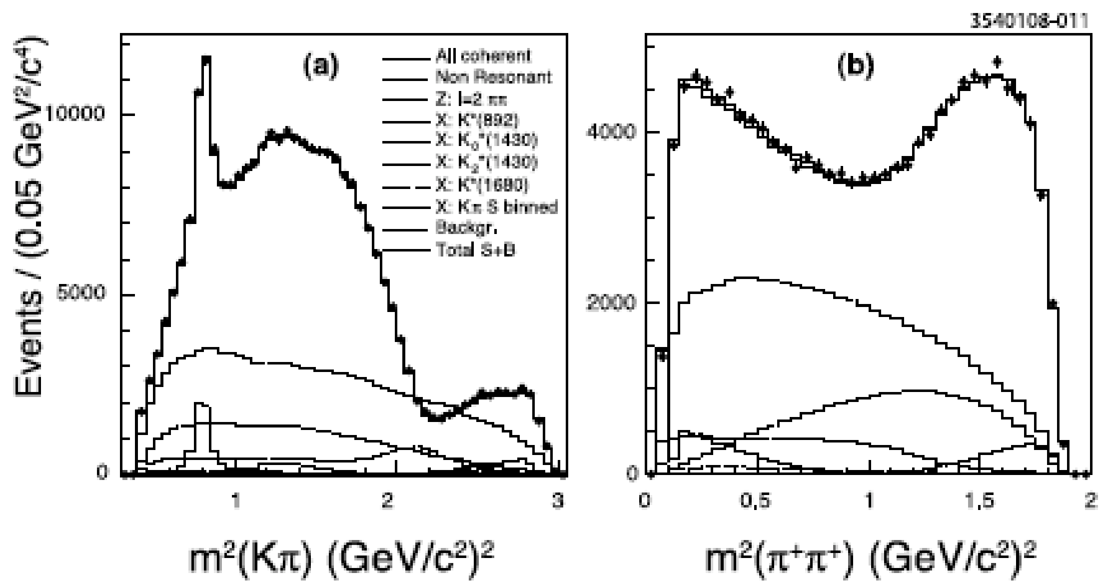
(9x E791 sample)



Isobar models, and also:

o improve some isobars

o use a "quasi-model-ind't" partial-wave analysis



Conclusions

Both the "CLEO-b" and CLEO-c phases made HUGE contributions to the world's knowledge of open charm physics.

CLEO also pioneered many techniques, even while borrowing and extending others.

The physics results are of course very important, but perhaps even more so are the physicists trained here that have continued onward with both the knowledge and spirit of CLEO Physics !

Some Charm Reviews

Predictions:

Gaillard, Lee, & Rosner

Rev. Mod. Phys. 47, 277 (1975)

Selected Reviews:

Morrison & Witherall — **D Mesons**

Ann. Rev. Nucl. Part. Sci. 39, 183 (1989)

Richman & Burchat — **D & B LSL Decays**

Rev. Mod. Phys 67, 893 (1995)

Browder, Honscheid, & Pedrini — **D & B non-Lept Decays and Lifetime**

Ann. Rev. Nucl. Part. Sci. 46, 395 (1996)

Burdman & Shipsey — **D Mixing and Rare Decays**

Ann. Rev. Nucl. Part. Sci. 53, 431 (2003)

Bianco, Fabbri, Benson, & Bigi — **A "Cicerone" for Charm**

Nuovo Cim. 26N7, 1 (2003)

Forthcoming:

Artuso, Meadows, & Petrov — **Charm Meson Decays**

Ann. Rev. Nucl. Part. Sci. 58, (2008) *available as arXiv:0802.2934*

Asking *me* questions is fine, but…

Better to use the collective historical and physics knowledge of the audience!

so…

? Comments & Discussion ?