CLEO-c Results and Prospects

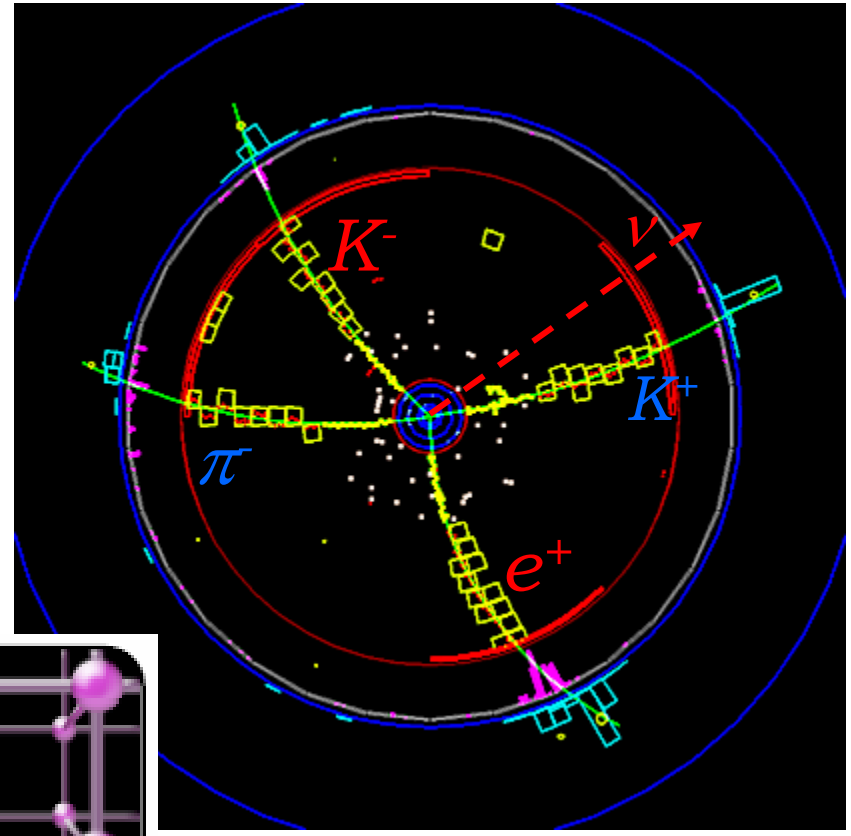
OUTLINE

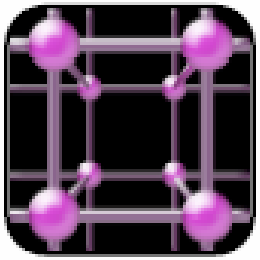
The role of charm in particle physics

Testing the Standard Model with precision quark flavor physics

Searches for Physics Beyond the Standard Model

Ian Shipsey, Purdue University
CLEO-c Collaboration





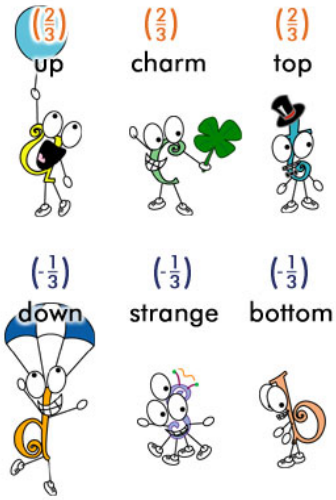
$$\psi(3770) \to D^0 \overline{D^0}$$

$$\overline{D^0} \to K^+\pi^-, D^0 \to K^-e^+\nu$$

Big Questions in Flavor Physics

Dynamics of flavor?

Why generations?
Why a hierarchy of masses & mixings?



Origin of Baryogenesis?

Sakharov's criteria: Baryon number violation
CP violation Non-equilibrium

3 examples: Universe, kaons, beauty but Standard Model CP violation too small, need additional sources of CP violation

Connection between flavor physics & electroweak symmetry breaking?

Extensions of the Standard Model (ex: SUSY) contain flavor & CP violating couplings that should show up at some level in flavor physics, but *precision* measurements and *precision* theory are required to detect the new physics

Charm: The Context

This Decade

Flavor physics is in the "sin 2β era' akin to precision Z.
Over constrain CKM matrix with precision measurements
Discovery potential is limited by systematic errors
from non-perturbative QCD

The Future

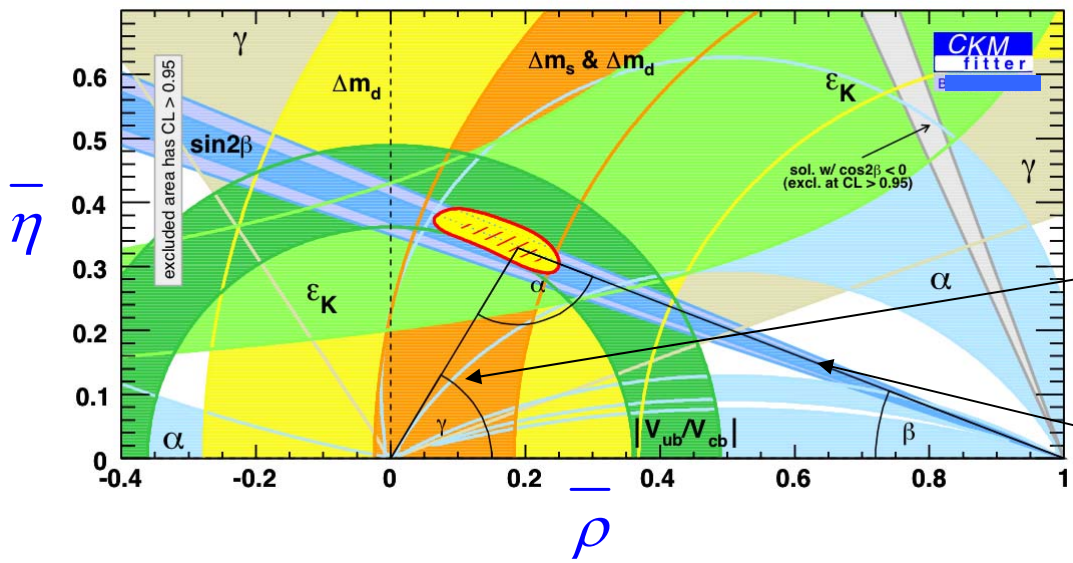
LHC may uncover strongly coupled sectors in the physics Beyond the Standard Model. The ILC will study them. Strongly coupled field theories→ an outstanding challenge to theory. Critical need: reliable theoretical techniques & detailed data to calibrate them

The Lattice

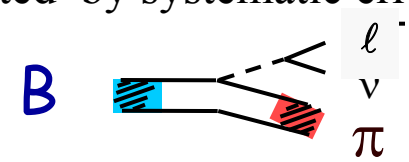
Complete definition of pert. and non-pert. QCD Goal: Calculate B, D, Y, ψ to 5% in a few years, and a few % longer term.

Charm can provide data to test & calibrate non-pert. QCD techniques such as the lattice (especially true at charm threshold)→ CLEO-c

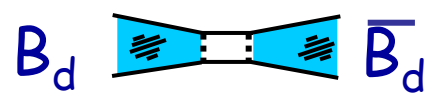
Precision Quark Flavor Physics



The discovery potential of B physics At BABAR/Belle/CDF/D0/ LHC-b is limited by systematic errors from QCD:

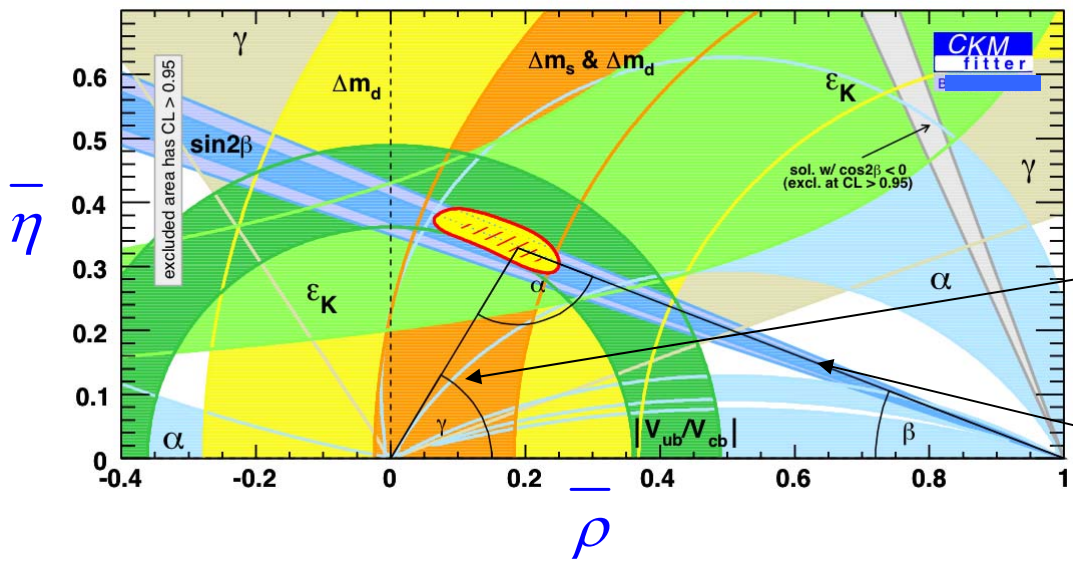


$$\propto \left[f^{B\to\pi}(q) \right]^2 |V_{ub}|^2$$



$$\propto \left[f_{Bd} \right]^2 |V_{td}|^2$$

Precision Quark Flavor Physics



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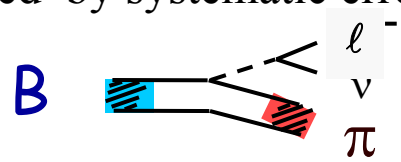

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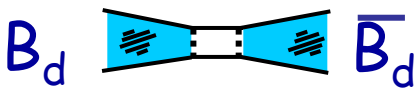
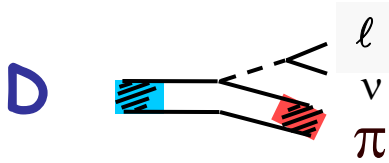
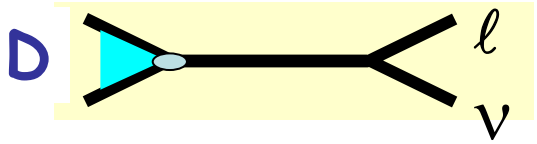


$$\propto \left[f_{Bd} \right]^2 |V_{td}|^2$$

D system- CKM elements known to <1% by unitarity



$$\propto \left[f^{D\to\pi}(q) \right]^2 |V_{cd}|^2$$

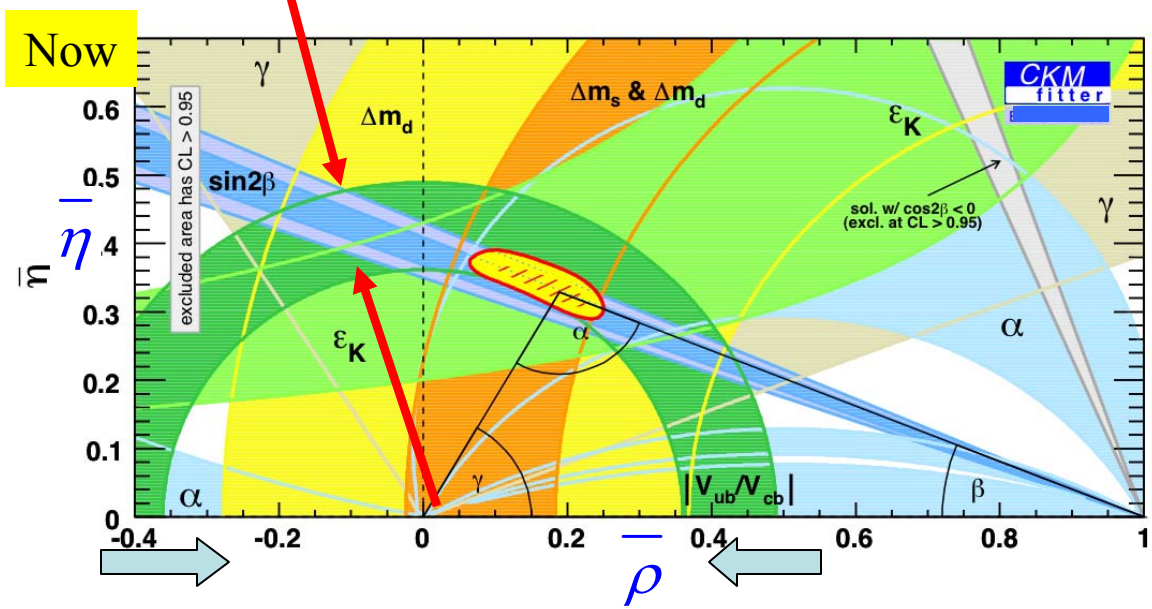


$$\propto \left[f_{D+} \right]^2 |V_{cd}|^2$$

→*measurements* of *absolute rates* for D leptonic & a wide variety of semileptonic decays yield decay constants & form factors to *test* and hone QCD techniques into *precision theory* which can then be applied to the B system.

+ Br(B→ D)~100% *absolute* D hadronic rates normalize B physics important for Vcb (scale of triangle) - also normalize D physics

Precision theory + charm = large impact



Theoretical errors dominate width of bands

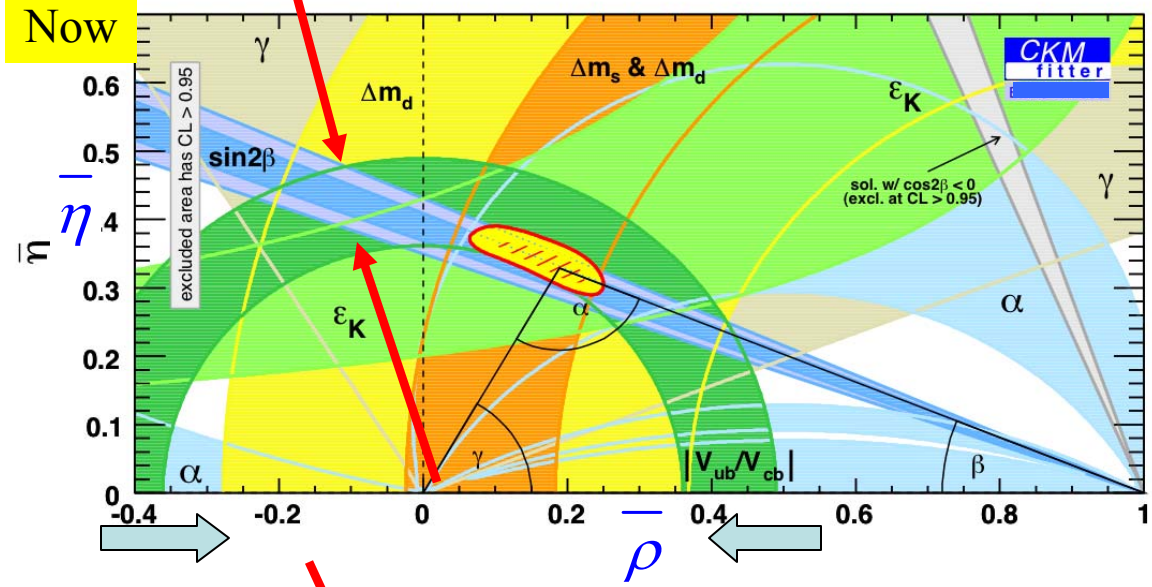
precision QCD calculations tested with *precision* charm data
➔theory errors of a few % on B system decay constants & semileptonic form factors

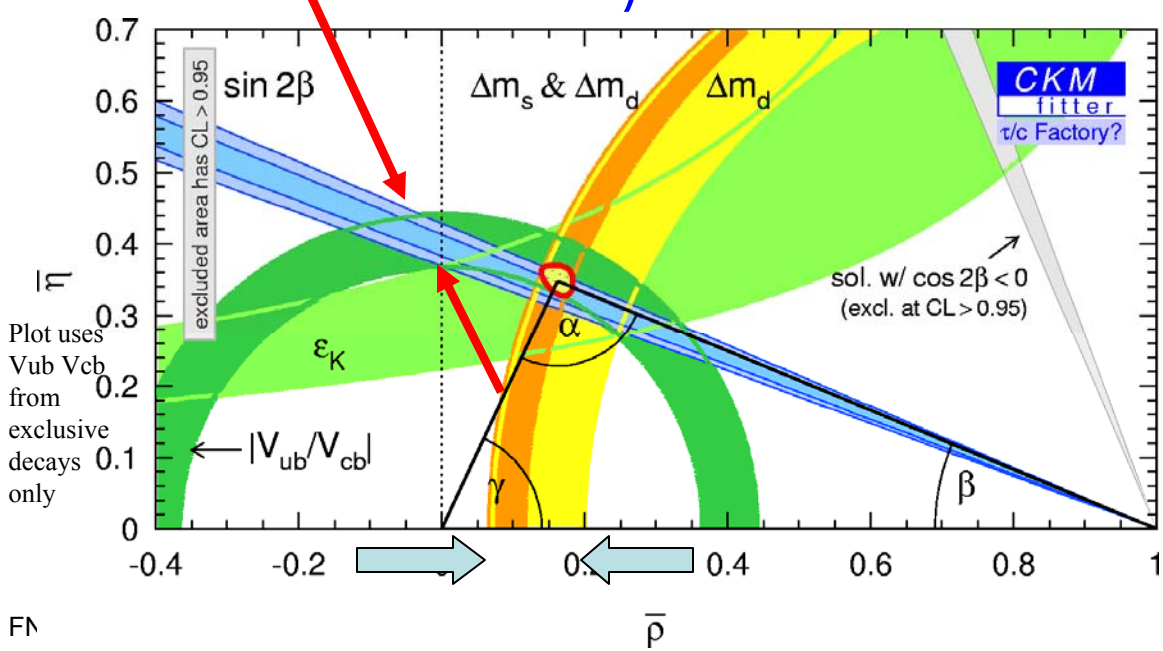
+

500 fb-1 @ BABAR/Belle

Precision theory + charm = large impact

Now





Plot uses Vub Vcb from exclusive decays only

Theoretical errors dominate width of bands

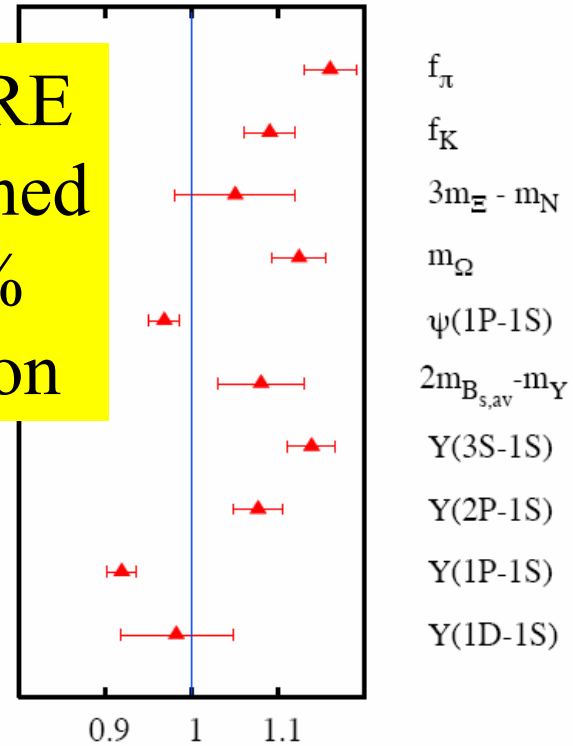
precision QCD calculations tested with *precision* charm data
➔theory errors of a few % on B system decay constants & semileptonic form factors

+

500 fb-1 @ BABAR/Belle

Precision theory? Lattice QCD

BEFORE
Quenched
10-15%
precision

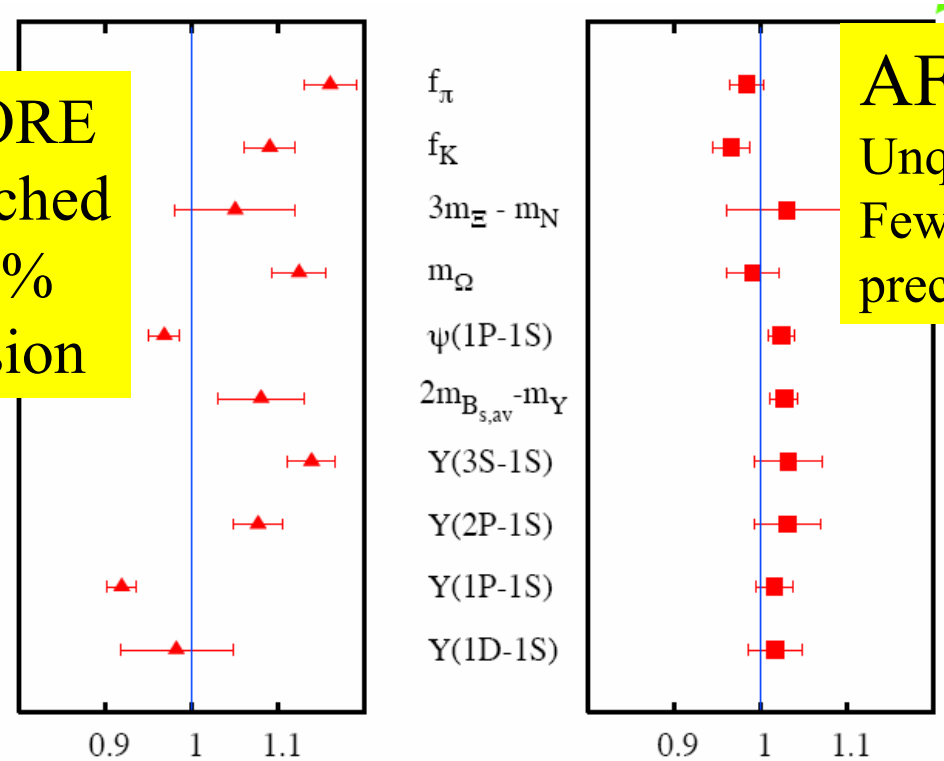


$$\frac{\text{theory-expt}}{\text{expt}}.$$

Precision theory? In 2003 a breakthrough in Lattice QCD

Recent revolutionary progress in algorithms allows inclusion of QCD vacuum polarization
LQCD demonstrated it can reproduce a wide range of mass differences & decay constants. *These were postdictions*

BEFORE
Quenched
10-15% precision



$\frac{\text{theory-expt}}{\text{expt}}$.

$\frac{\text{theory-expt}}{\text{expt}}$.

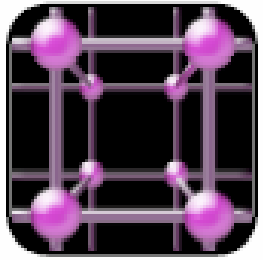
AFTER
Unquenched
Few % precision

This dramatic improvement needs validation

Charm decay constants f_{D+} & f_{Ds}

Charm semileptonic Form factors

Understanding strongly coupled systems is important beyond flavor Physics. LHC might discover new strongly interacting physics



Precision Experiment for charm?

Circa 2004 (pre-CLEO-c)

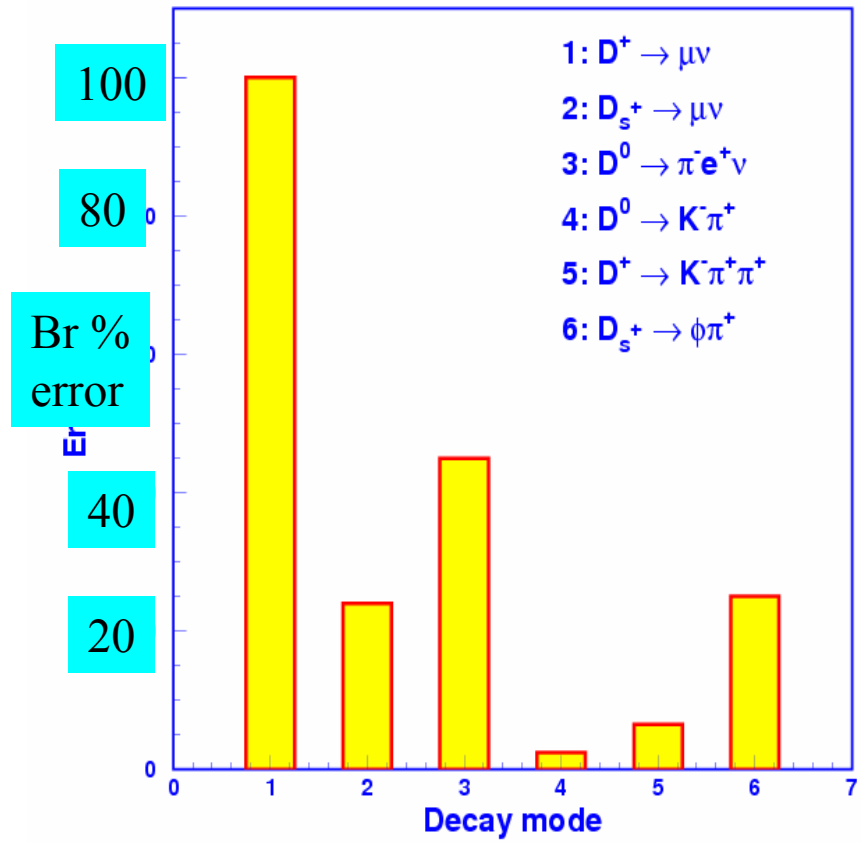
Experiment : Theory

Poorly known

$$\frac{Br}{\tau} = \Gamma$$

Measured very precisely 0.4-0.8%

Key leptonic, semileptonic & hadronic modes



at B Factories/Tevatron/ FT:

$$Br(D \to X) = \frac{\#\text{X Observed}}{\text{efficiency x \#D's produced}}$$

Backgrounds are large.

#D's produced is usually not well known.

CLEO-c data samples

CLEO-c: Oct. 2003 – Apr. 2008

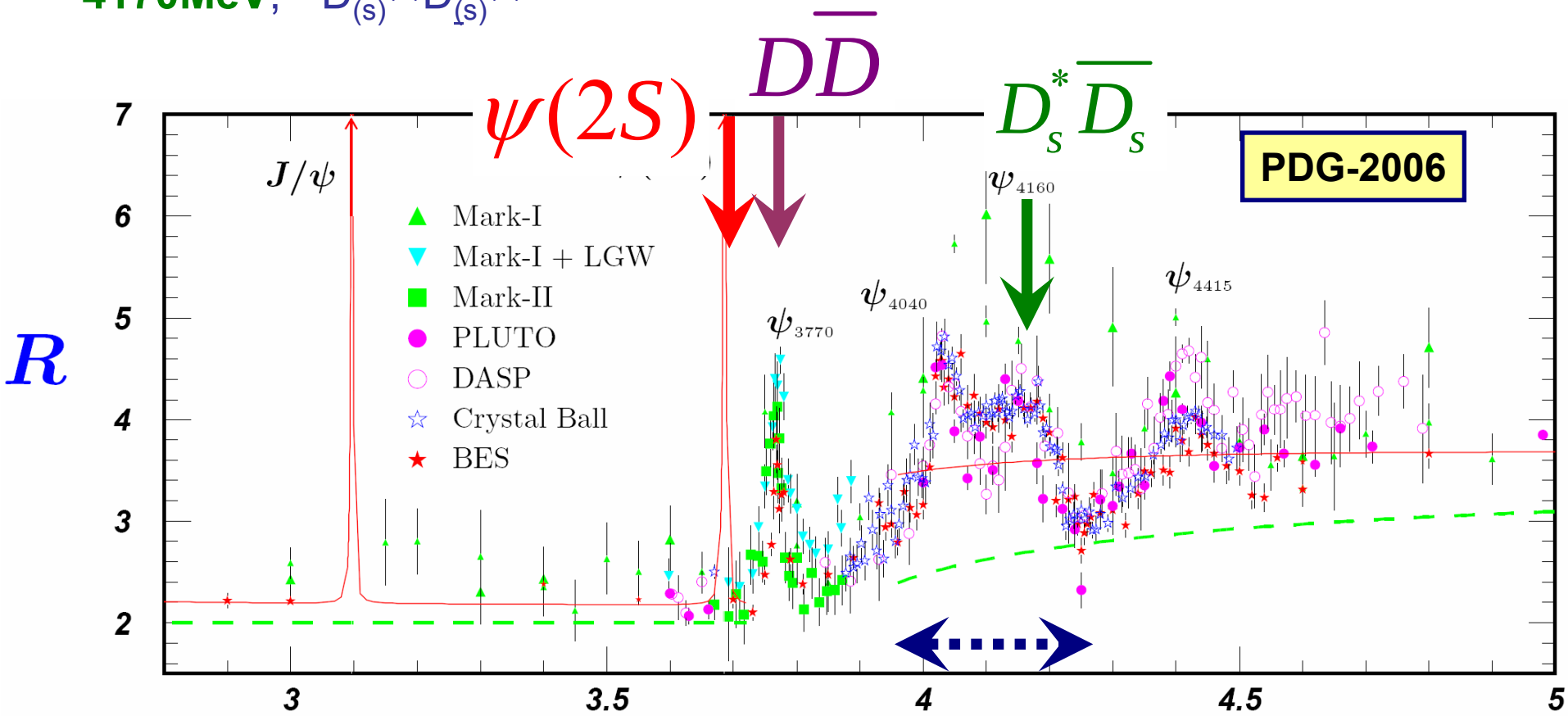
Conversion of CESR (10GeV) to CESR-c at 4GeV

Conversion CLEO III detector to CLEO-c

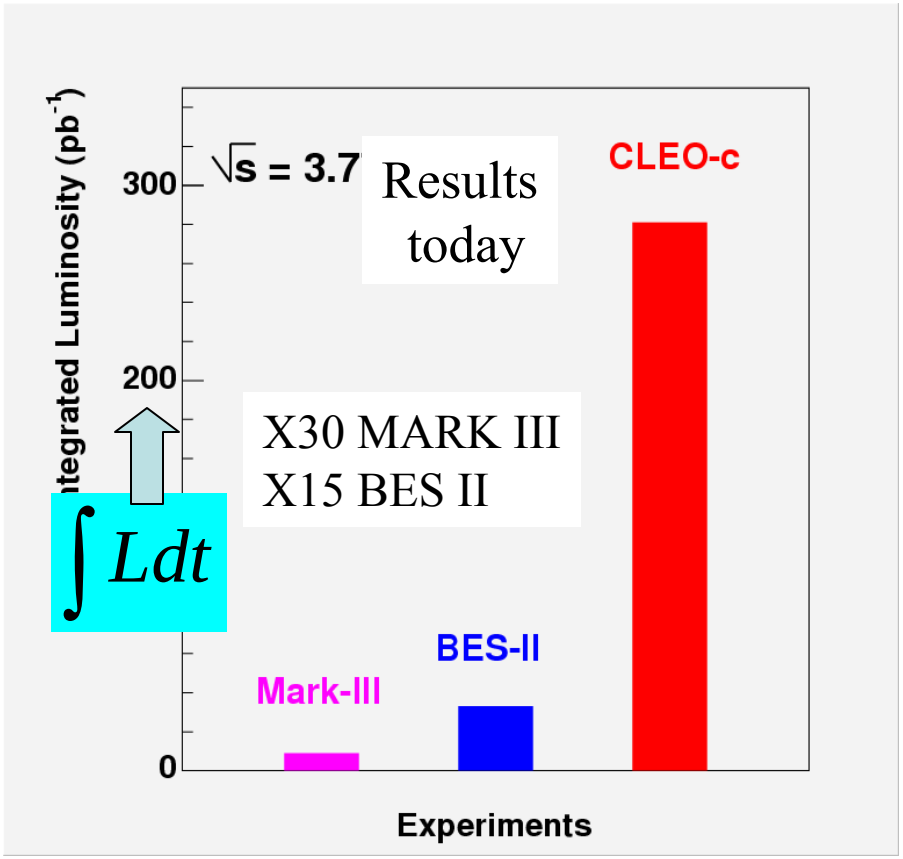
3686MeV, 54pb^{-1}, N(ψ(2S))≈27M **$e^+e^- \to \psi(2S) \to \pi\pi\, J/\psi, \gamma\chi_c$ etc.**

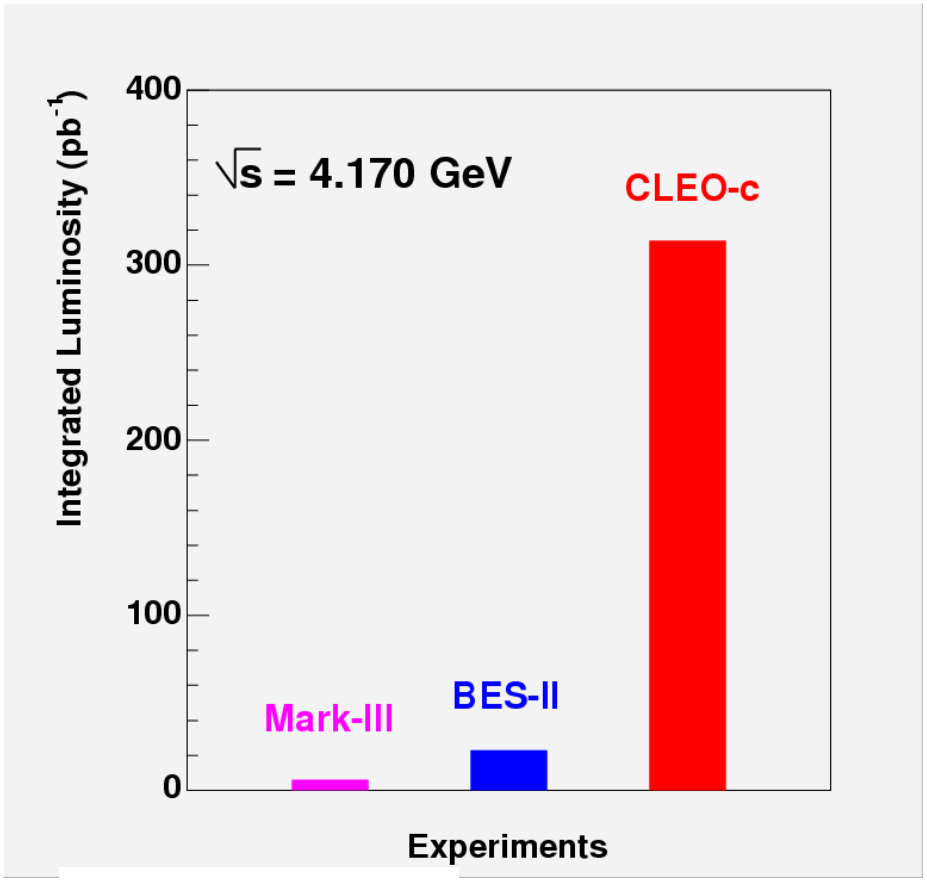
3773MeV, ψ(3770) →DD

4170MeV, $D_{(s)}^{(*)}D_{(s)}^{(*)}$



World's largest data sets at charm threshold





$\psi(3770) \rightarrow D\overline{D}$

281 pb^{-1}

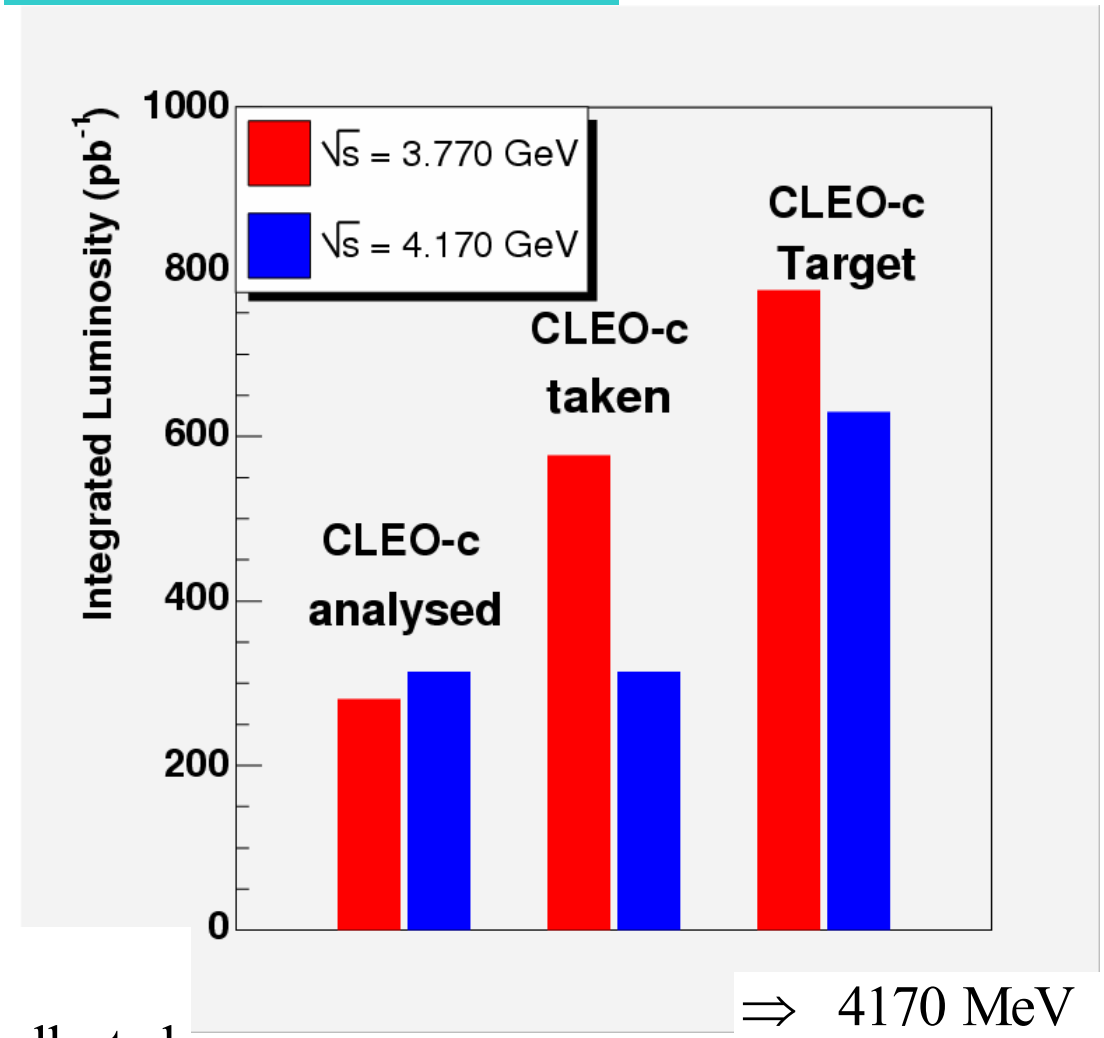
$1.8\times10^{6}\, D\overline{D}$

$4170 \rightarrow D_s^* D_S$

314 pb^{-1} Results today

$\sim 3\times10^{5}\, D_s^* D_S$

More data on the way:



$\psi(3770)$

x2 already collected

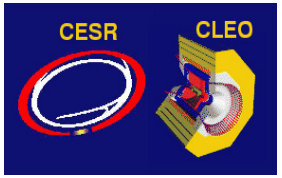
by March 31 2008 :

$\Rightarrow 800/pb$

$\Rightarrow$ 4170 MeV

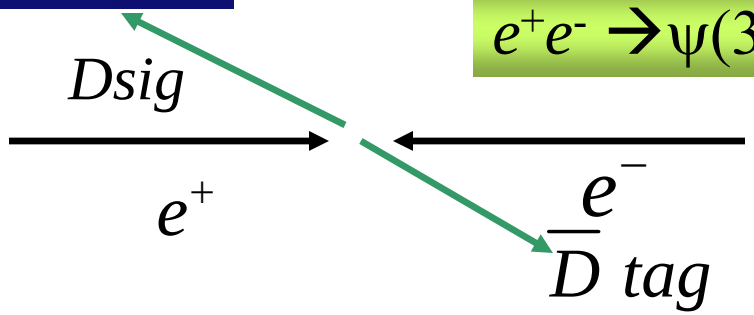
X2 current data

600/pb ($\times$130 BES)



ψ(3770) Analysis Strategy

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

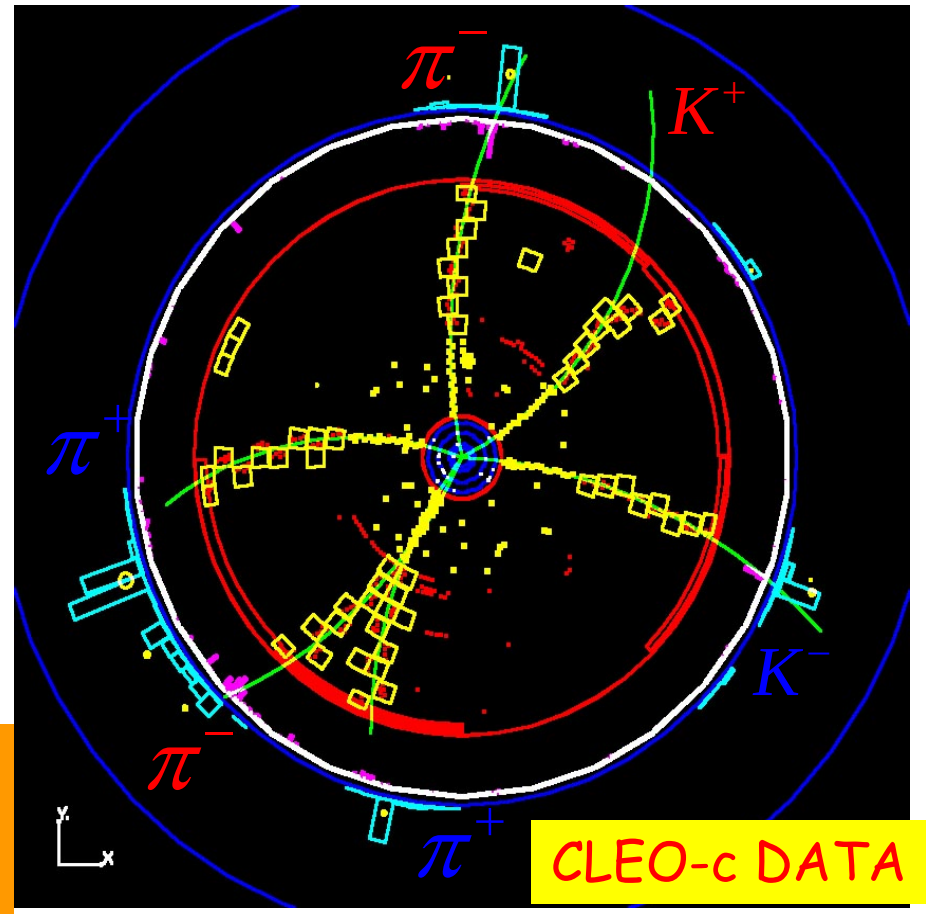


ψ(3770) is to charm what Y(4S) is to beauty

- Pure DD, no additional particles ($E_D = E_{beam}$).
- σ (DD) = 6.4 nb (Y(4S)->BB ~ 1 nb)
- Low multiplicity ~ 5-6 charged particles/event

➔ high tagging efficiency: ~22% of D's

Compared to ~0.1% of B's at the Y(4S)



$\psi(3770) \rightarrow D^+D^-$

$D^+ \rightarrow K^-\pi^+\pi^+, \; D^- \rightarrow K^+\pi^-\pi^-$

A little luminosity goes a long way:
events in 100 pb^{-1} @ charm factory with 2D's reconstructed ~
events in 500 fb^{-1} @ Y(4S) with 2B's reconstructed

Absolute Charm Branching Ratios at Threshold

281/pb

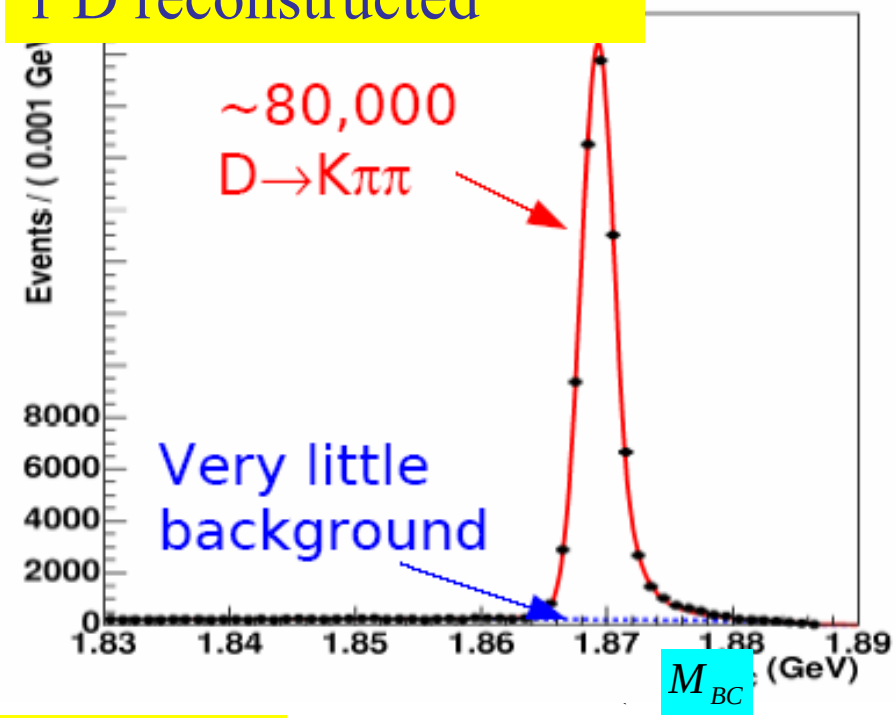
- Kinematics analogous to $\Upsilon(4S)\rightarrow BB$: identify D using

$$E_D \Rightarrow E_{beam} : \begin{array}{l} \Delta E = E_{beam} - E_D \\ M_{BC} = \sqrt{E_{beam}^2 - |p_D|^2} \end{array}$$

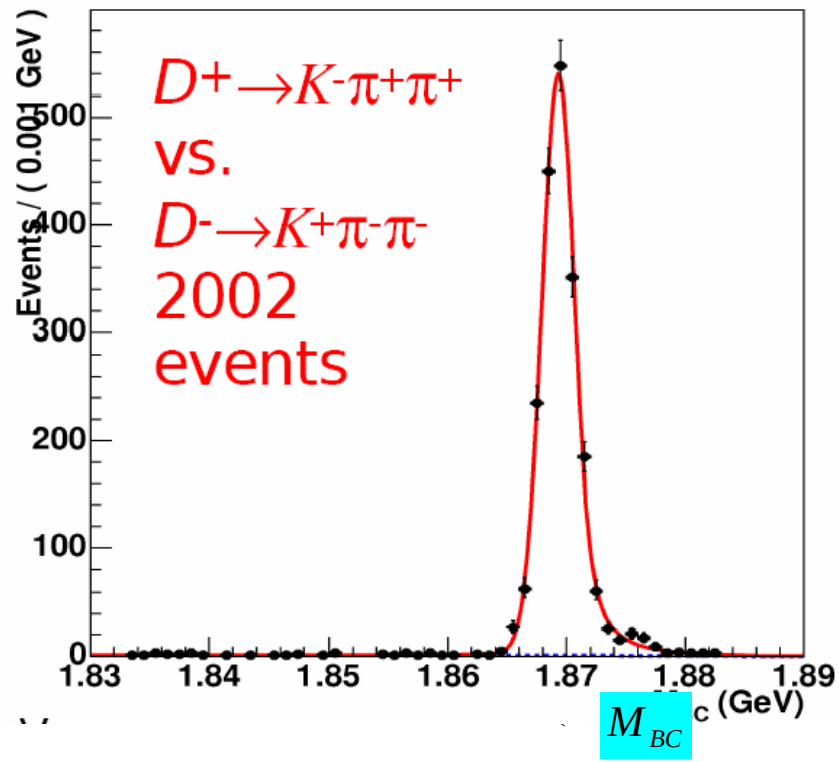
- $\sigma(M_{BC})$ ~ 1.3 MeV, x2 with π^0
- $\sigma(\Delta E)$ ~ 7—10 MeV, x2 with π^0

$$E_D \Rightarrow E_{beam} : \times 10 \downarrow \delta M_{bc} / M_{bc}$$

1 D reconstructed



1D+ & 1D- reconstructed

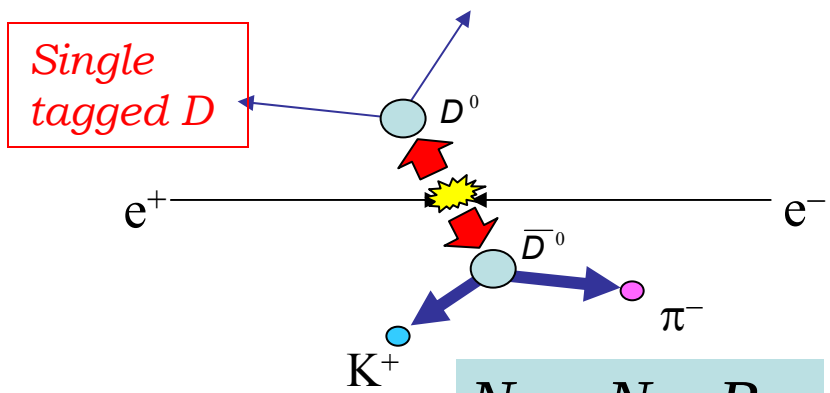


Independent of L and cross section

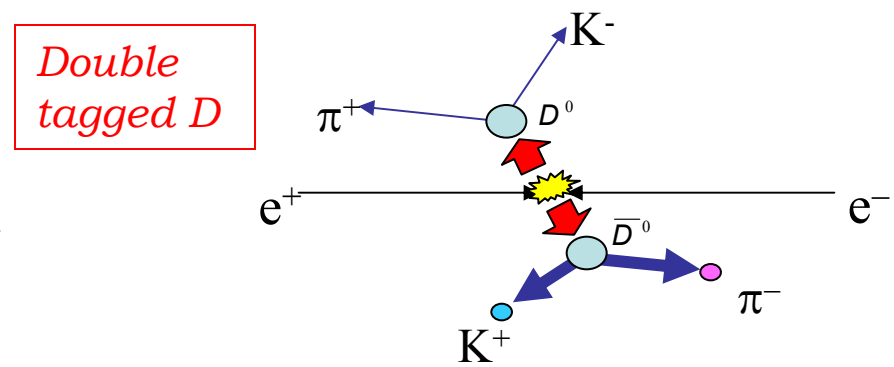
$$B(D^- \rightarrow K^+\pi^-\pi^-) = \frac{\#\,(K^+\pi^-\pi^-)\,\text{Observed in tagged events}}{\text{detection efficiency for }(K^+\pi^-\pi^-)\ \bullet\ \#\text{D tags}}$$

D^0 and D^+ absolute BF: method

Measure 3 D^0 and 6 D^+ decay modes



$$N_i = N_{D\bar{D}} B_i \varepsilon_i$$



$$N_{ij} = N_{D\bar{D}} B_i B_j \varepsilon_{ij}$$

$$B_i = \frac{N_{ij}}{N_j} \frac{\varepsilon_j}{\varepsilon_{ij}}$$

$$N_{D\bar{D}} = \frac{N_i N_j}{N_{ij}} \frac{\varepsilon_{ij}}{\varepsilon_i \varepsilon_j}$$

BF are independent of luminosity and cross section

Combine ST and DT yields for all modes in χ^2 fit to get absolute BF (and N_{DD})

Scale of statistical error is set by number of total DT yield

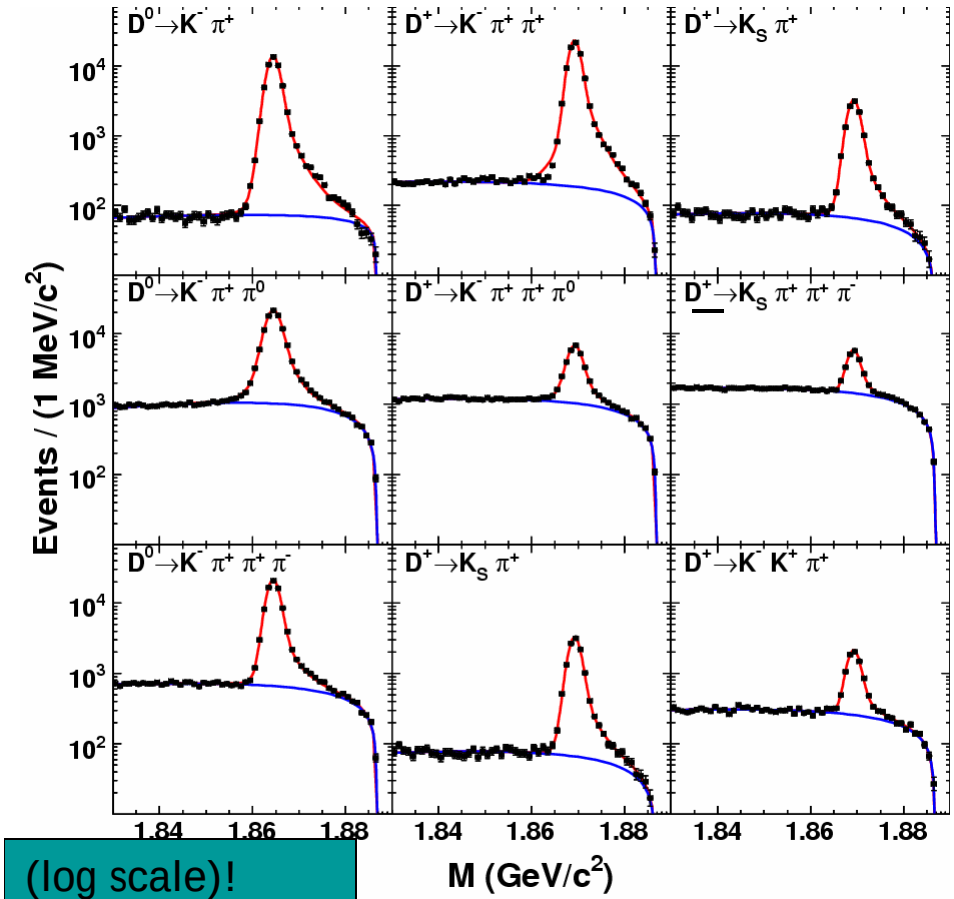
Since $\varepsilon_{ij} \approx \varepsilon_i \varepsilon_j$ to first order

B_i are independent of tag mode efficiencies (ε_j)

1 D reconstructed

3 D^0 Modes

6 D^+ Modes



(log scale)!

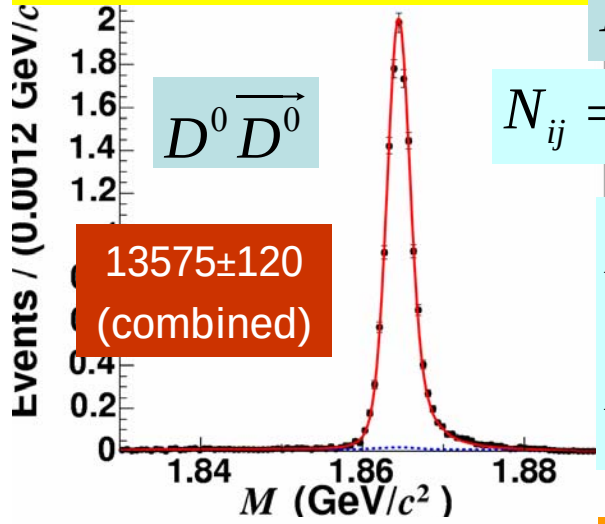
2 D's reconstructed

$$N_i = N_{D\bar{D}} B_i \varepsilon_i$$

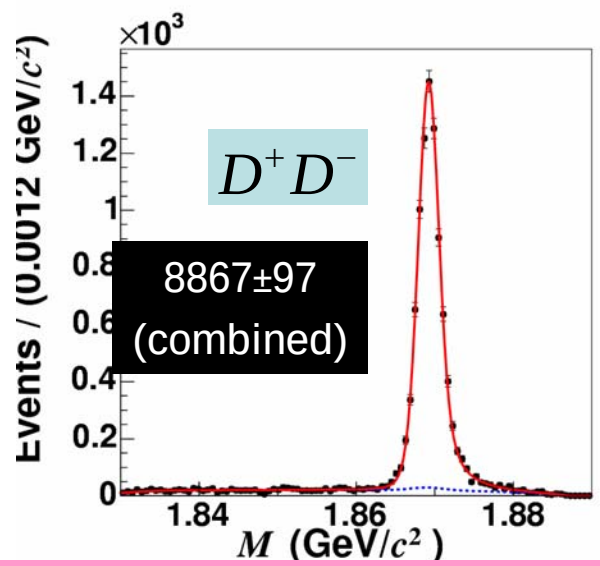
$$N_{ij} = N_{D\bar{D}} B_i B_j \varepsilon_{ij}$$

$$B_i = \frac{N_{ij}}{N_j} \frac{\varepsilon_j}{\varepsilon_{ij}}$$

$$N_{D\bar{D}} = \frac{N_i N_j}{N_{ij}} \frac{\varepsilon_{ij}}{\varepsilon_i \varepsilon_j}$$



PRELIMINARY



Signal shape: ψ(3770) line shape, ISR, beam energy spread & momentum resolution, Bgkd: ARGUS

Global fit pioneered by MARK III 2x9 = 18 single & 45= ($3^2 + 6^2$) double tag yields (χ^2 minimization technique, syst, errors included) ➔ N_{DD} & 9 B_i's

Comparison with other measurements $D^o \to K^-\pi^+$

THEN:

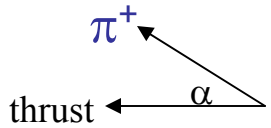
CLEO & ALEPH

$D^{*+} \to \pi^+ D^o$, $D^o \to K^-\pi^+$

compare to:

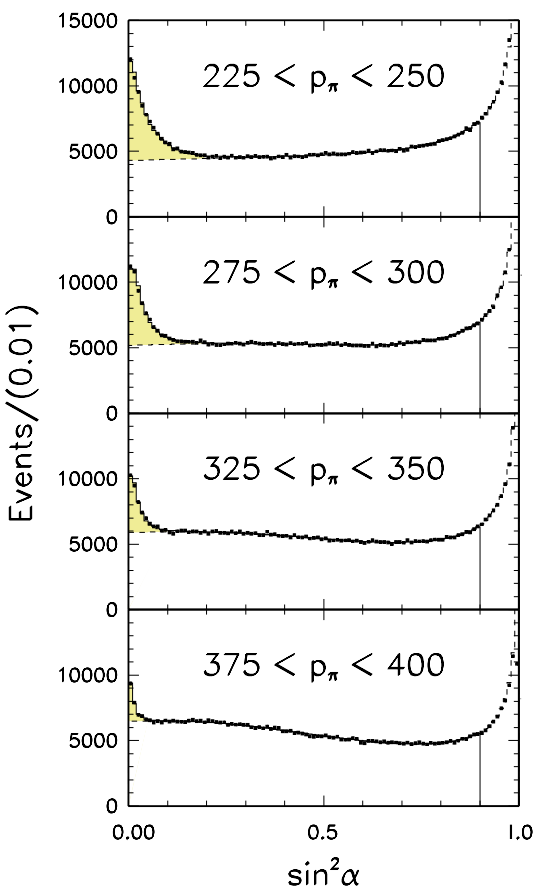
$D^{*+} \to \pi^+ D^o$, $D^o \to$ unobserved

(Q~6MeV)



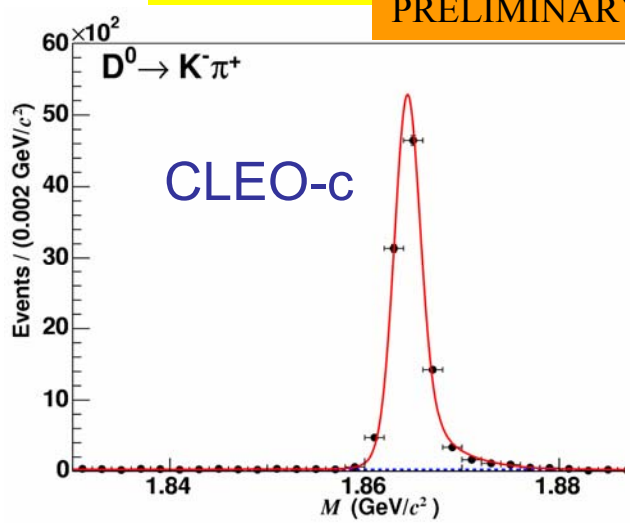
$\mathcal{B}$ (%)	Error(%)	Source
3.82±0.07±0.12	3.6	CLEO
3.90±0.09±0.12	3.8	ALEPH
3.80 ±0.09	2.4	PDG04
3.876±0.035 ±0.085	2.3	CLEO-c

Systematics limited 2%

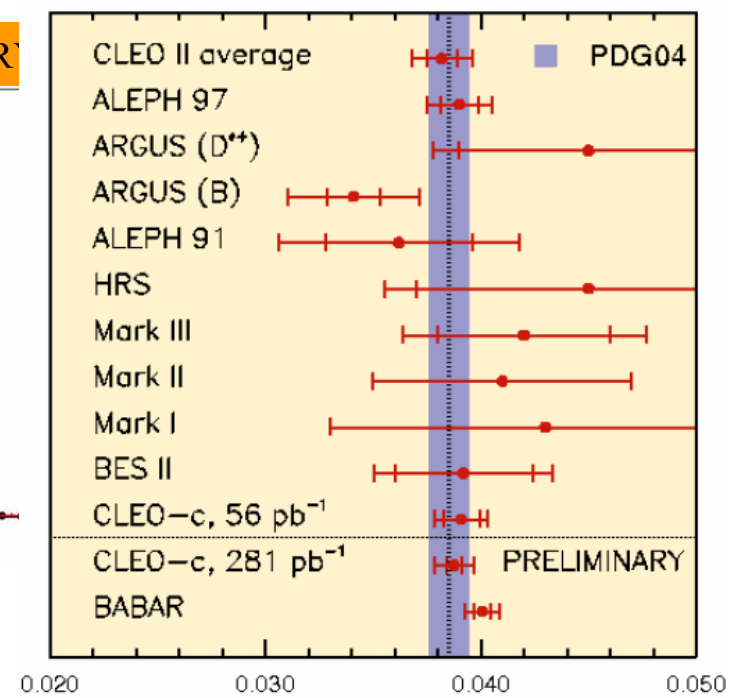


NOW:

PRELIMINARY



CLEO-c (not in PDG04 average)



Comparison with other measurements $D^0 \to K^-\pi^+$

BABAR use B partial reconstruction

$B \to D^{*+}\ell\nu,\ D^{*+} \to D^0\pi^+$

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

compare to

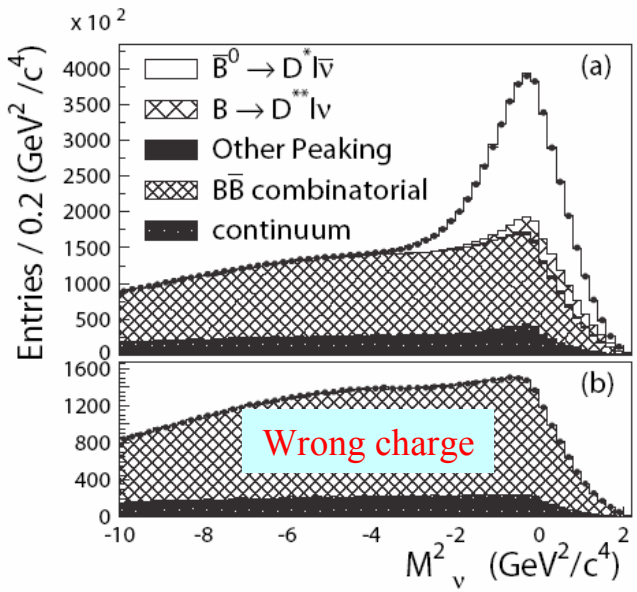
$\ell\pi^+, D^0 \to$ *unobserved*

arXiv:0704.2080

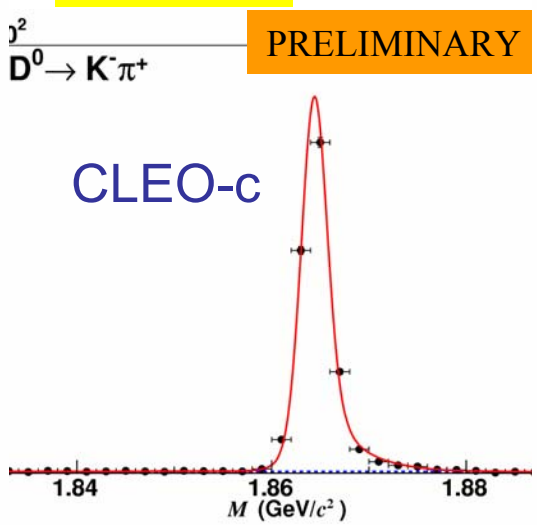
$\mathcal{B}$ (%)	Error(%)	Source
3.82±0.07±0.12	3.6	CLEO
3.90±0.09±0.12	3.8	ALEPH
3.80 ±0.09	2.4	PDG04
3.876±0.035 ±0.085	2.3	CLEO-c
4.007 ±0.037 ±0.070	2.0	BABAR

Systematics limited 2%

NOW:



BABAR must know background shapes well



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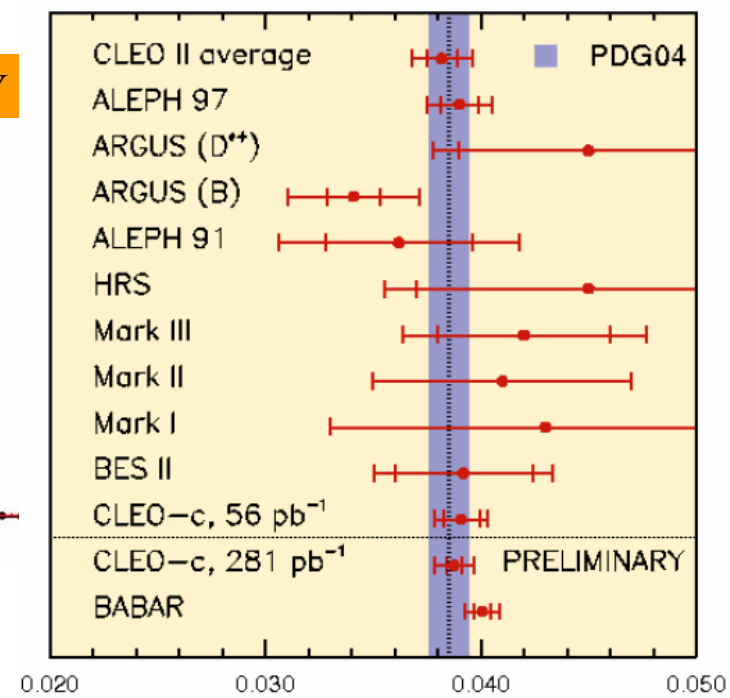
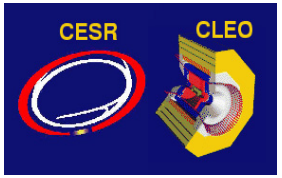
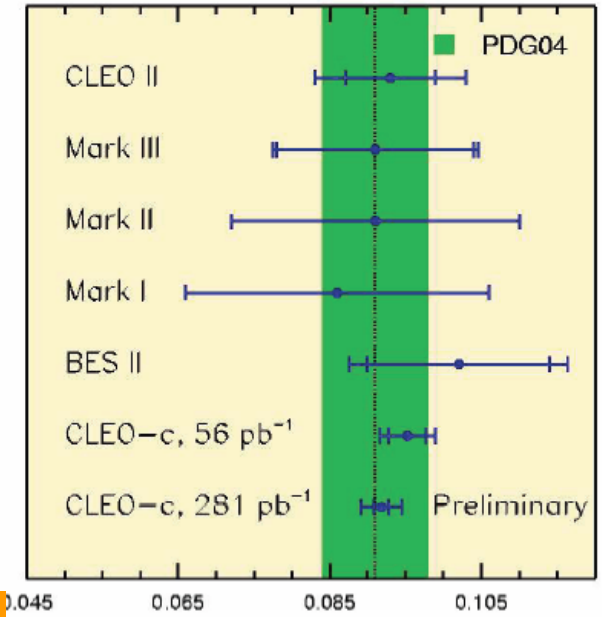




$B(D^+ \to K^- \pi^+ \pi^+)$

Three best measurements:

$\mathcal{B}$ (%)	Error(%)	Source
9.3±0.6±0.8	10.8	CLEO
9.1±1.3±0.4	14.9	MKIII
9.1±0.7	7.7	PDG04
9.18 ±0.10±0.25	2.9	CLEO-c



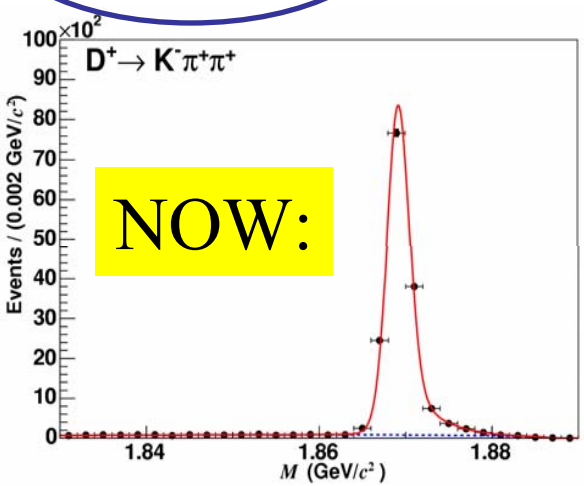
PRELIMINARY

THEN:

Method (CLEO) Bootstrap: Measure:

$$\frac{B(D^{*+} \to D^0 \pi^+)}{B(D^{*+} \to D^+ \pi^0)} \quad \frac{B(D^0 \to K^- \pi^+)}{B(D^+ \to K^- \pi^+ \pi^+)}$$

← Assume isospin



NOW:

CLEO-c X 2.5 More precise than world average

THEN: A HOUSE OF CARDS
NOW: the charm hadronic scale we have been using for last 10 years has been demonstrated to be approximately correct & is finally on a SECURE FOUNDATION

In search of the D_s at charm threshold

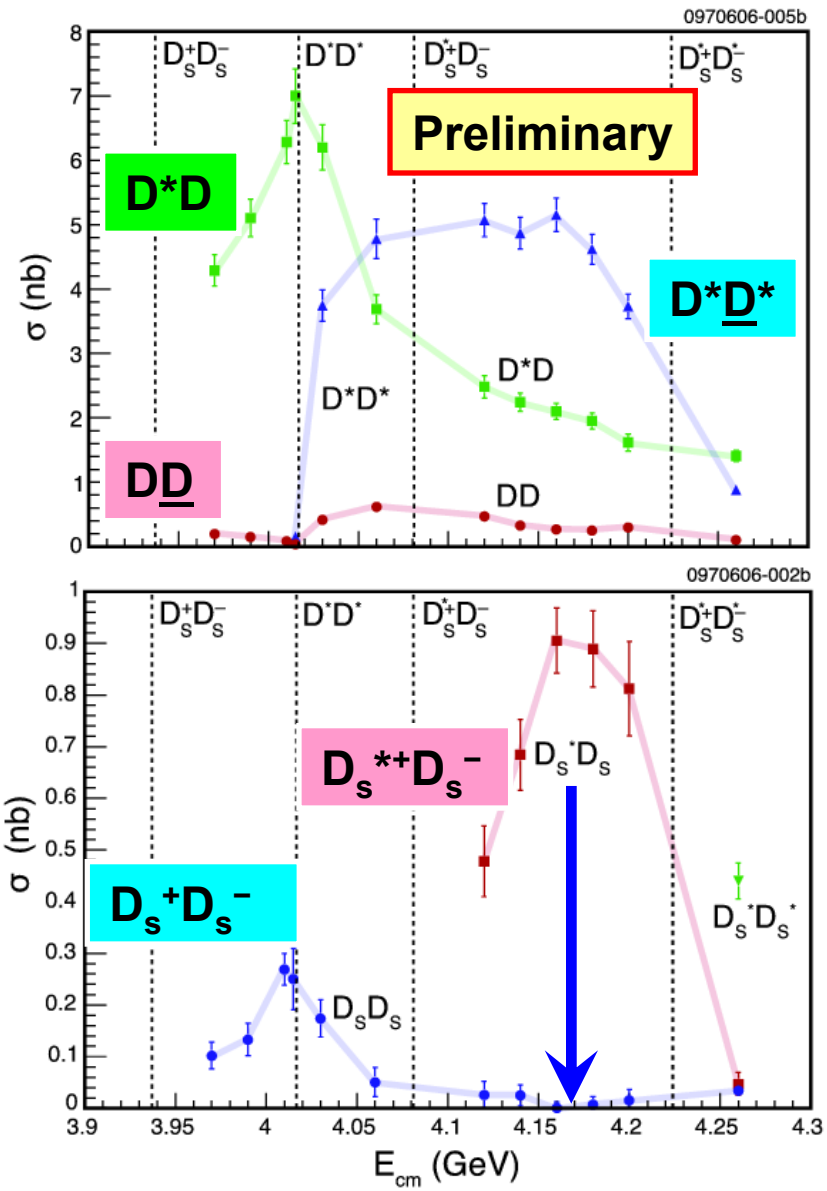
Little was known about components of $\sigma(e^+e^- \to \text{hadrons})$ @ $E_{cm} > M[\psi(3770)]$

CLEO scan ($60 pb^{-1}$) in 12 points 3.97-4.26GeV

Took large statistics at 4.17GeV, $314 pb^{-1}$

At 4.17 GeV approx cross-sections:

Light quarks	12 nb
$D^*\bar{D}^*$	5 nb
$D\bar{D}^*$	2 nb
$D\bar{D}$	0.2 nb
$D_s^*\bar{D}_s$	0.9 nb
$D_s\bar{D}_s$	0.02 nb



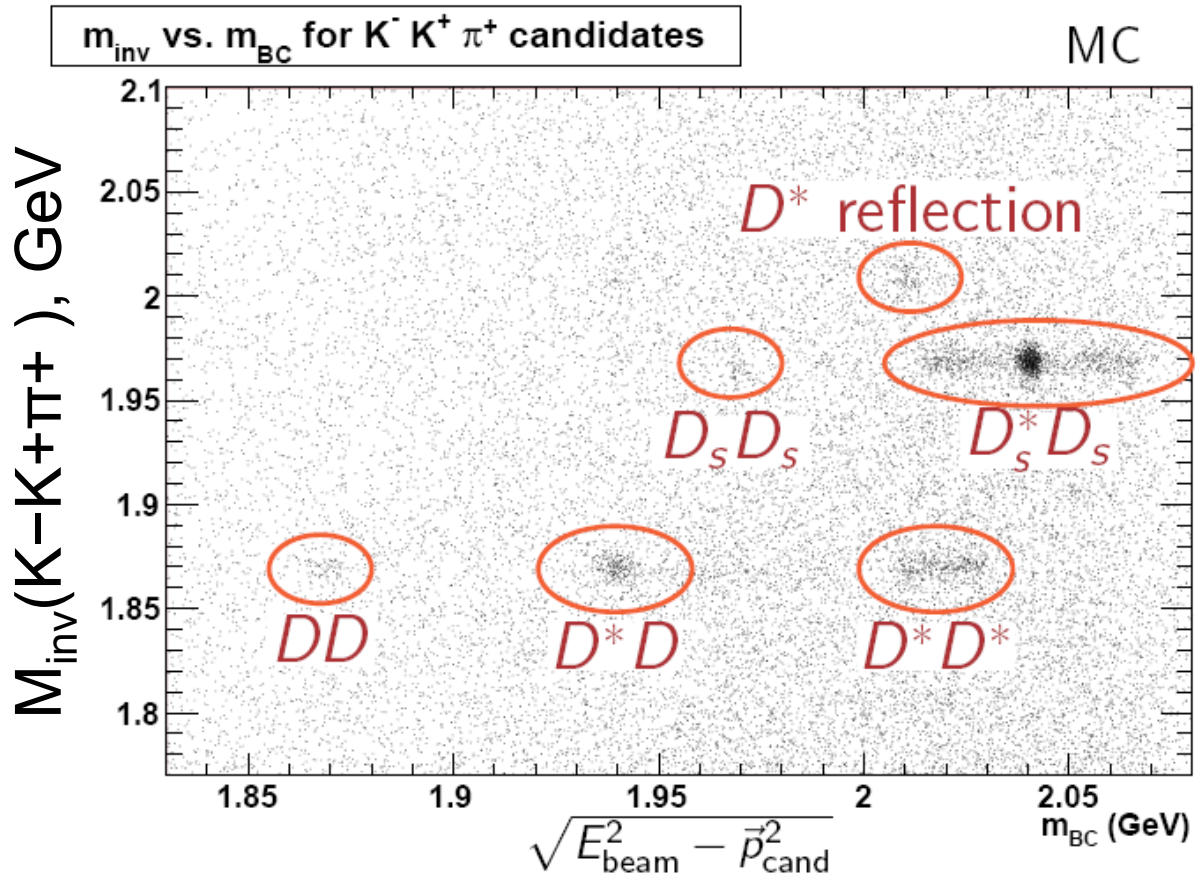
Absolute D_s hadronic $\mathcal{B}$'s: selection

$$e^+e^- \to D_s^{*\pm} D_s^{\mp}$$

$$D_s^{*\pm} \to D_s^{\pm}\gamma \text{ or } D_s^{\pm}\pi^0$$

- Ignoring γ or π^0 from D_s^*
- Select events using:

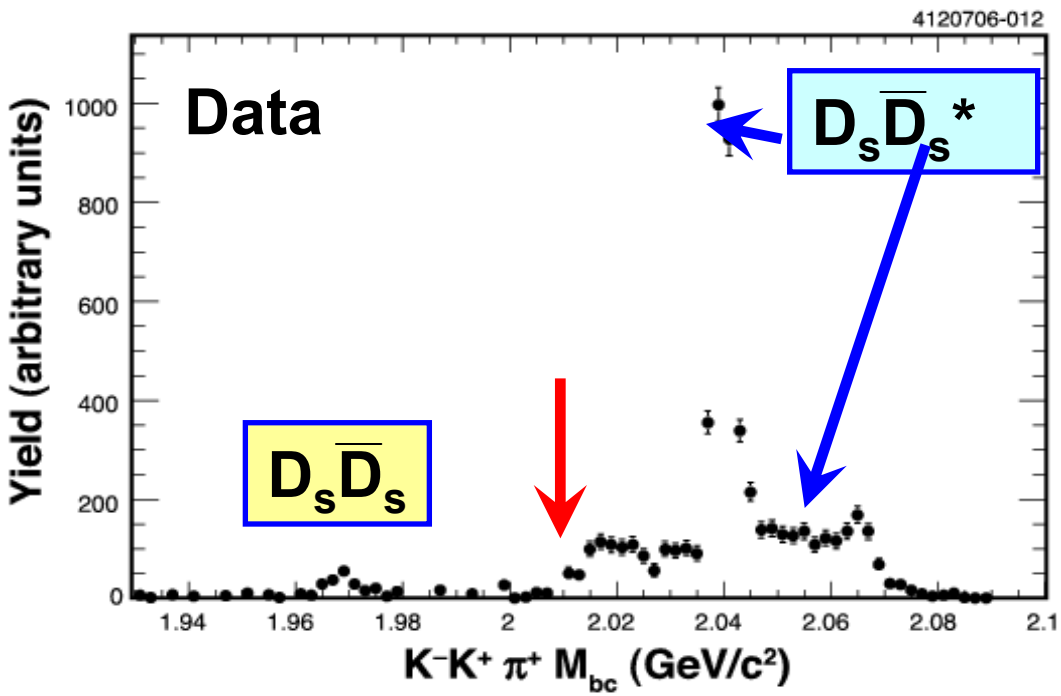
- Good kinematical separation between modes



Absolute D_s hadronic $\mathcal{B}$'s

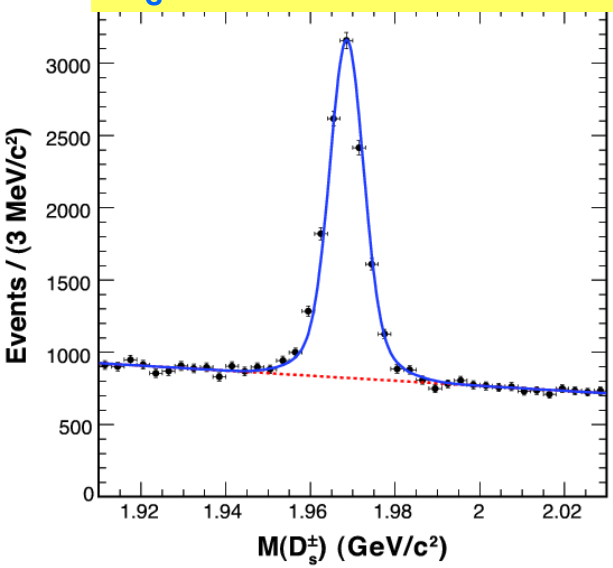
Same technique as at ψ(3770) Measure Single Tag and Double Tag yields:

– Require M_{BC}>2.01GeV to ensure $\mathbf{D_s\overline{D}_s^*}$

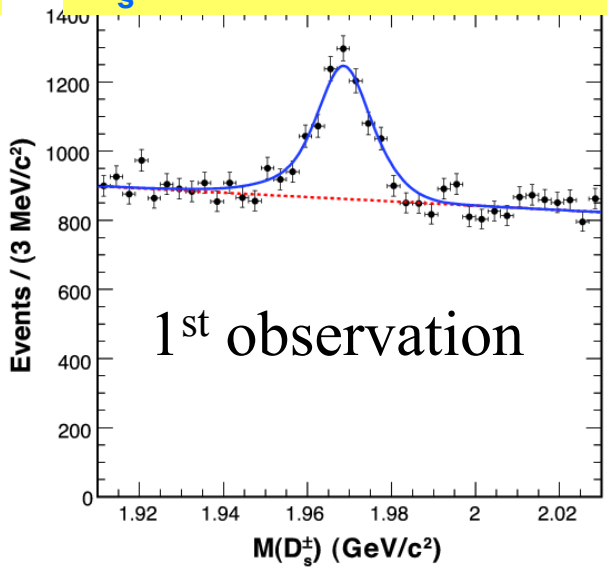


Absolute D_s hadronic $\mathcal{B}$'s, ST yields:

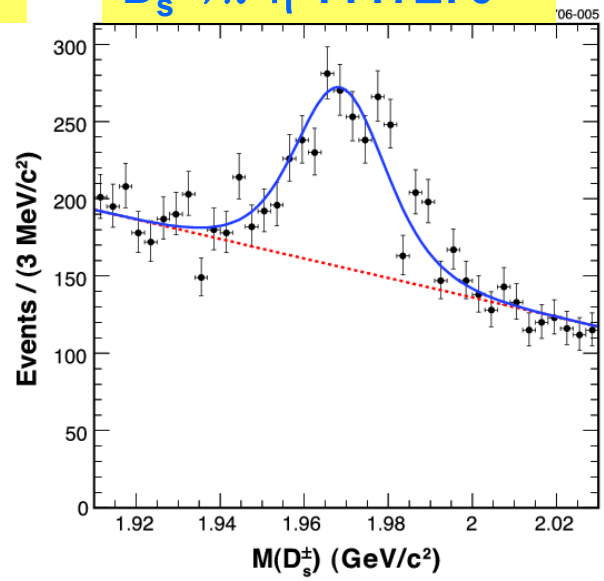
$D_s \to K^+K^-\pi^+$ 8665±126



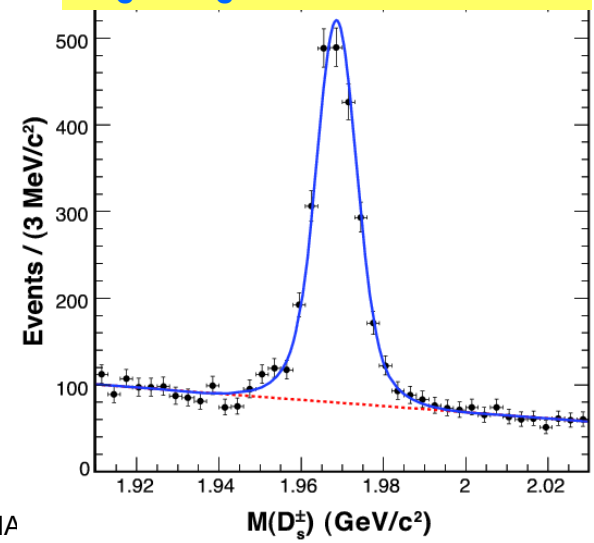
$D_s \to K^+K^-\pi^0\pi^+$ 2410±119



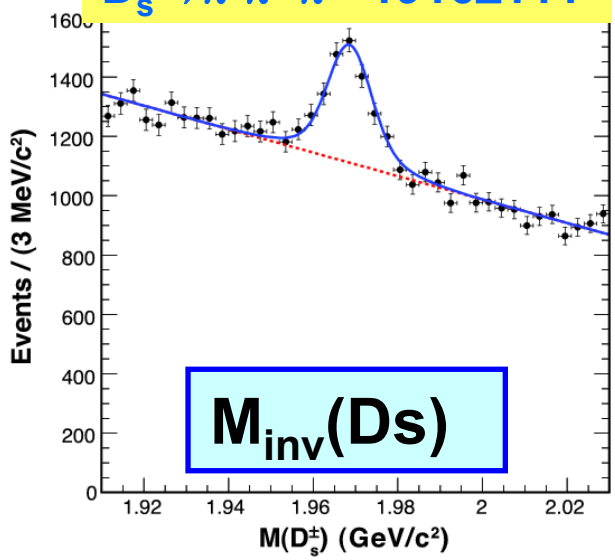
$D_s \to \pi^+\eta$ 1117±70



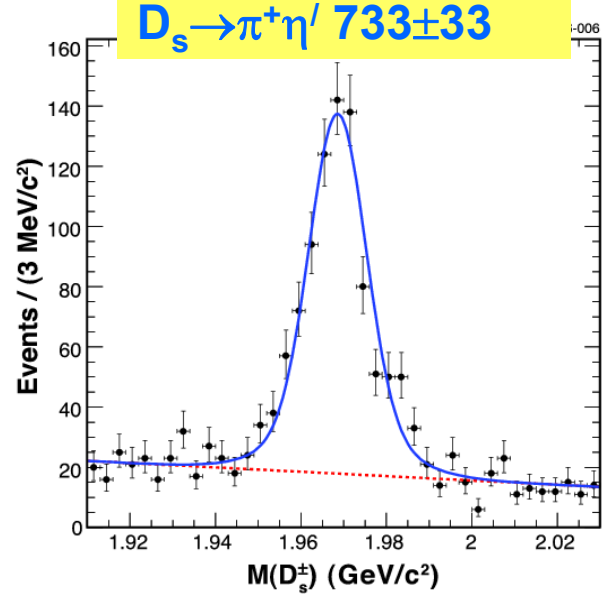
$D_s \to K_sK^-\pi^0$ 1983±54



$D_s \to \pi^-\pi^+\pi^0$ 1916±111

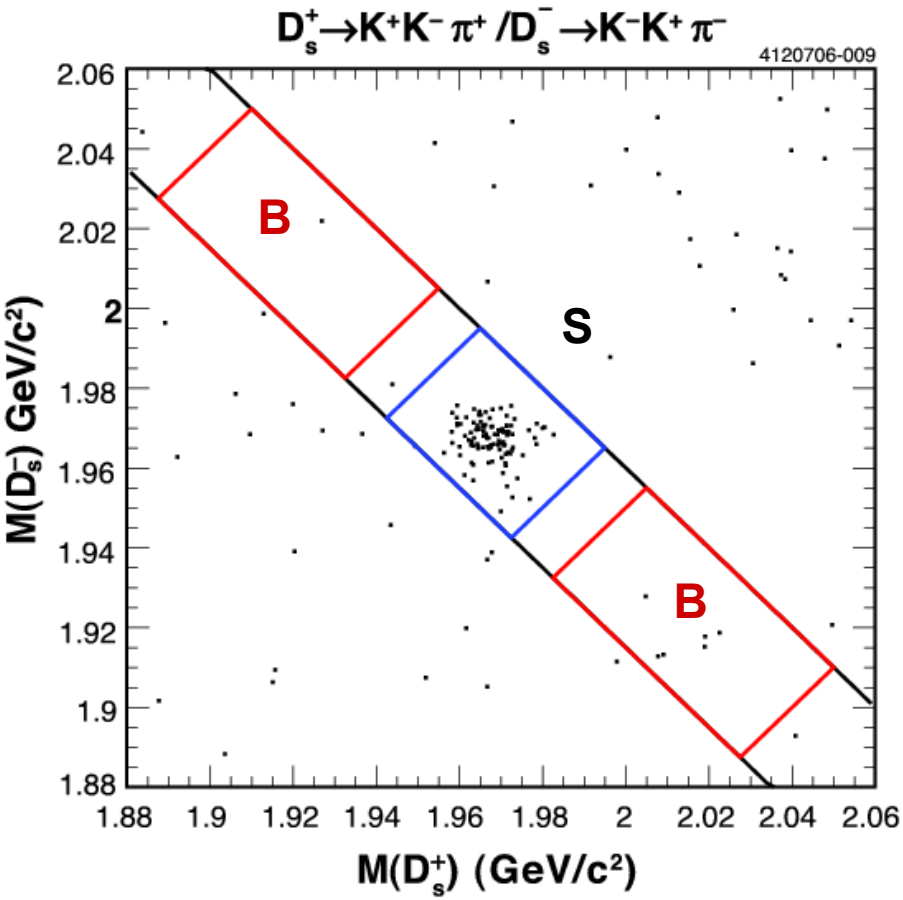


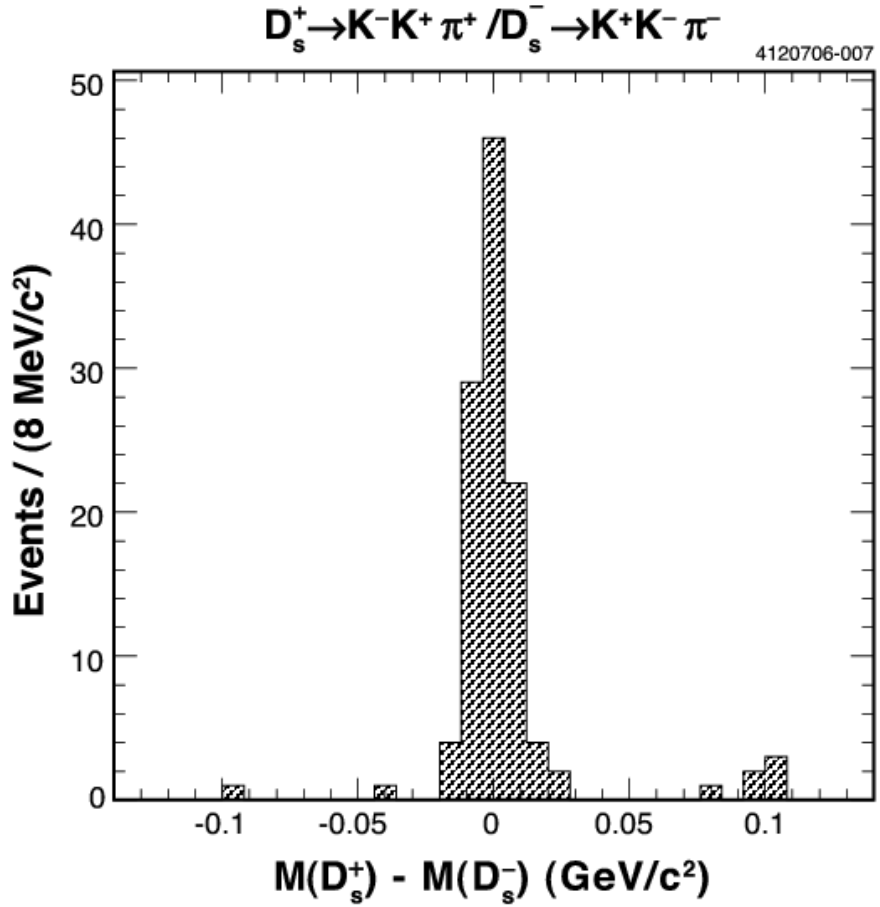
$D_s \to \pi^+\eta'$ 733±33



D_s Double Tag Yields

PRELIMINARY 195 pb^{-1}





Double tag yields:

Cut and count in $M(D_s^+)$ vs $M(D_s^-)$

Absolute D_s hadronic $\mathcal{B}$'s

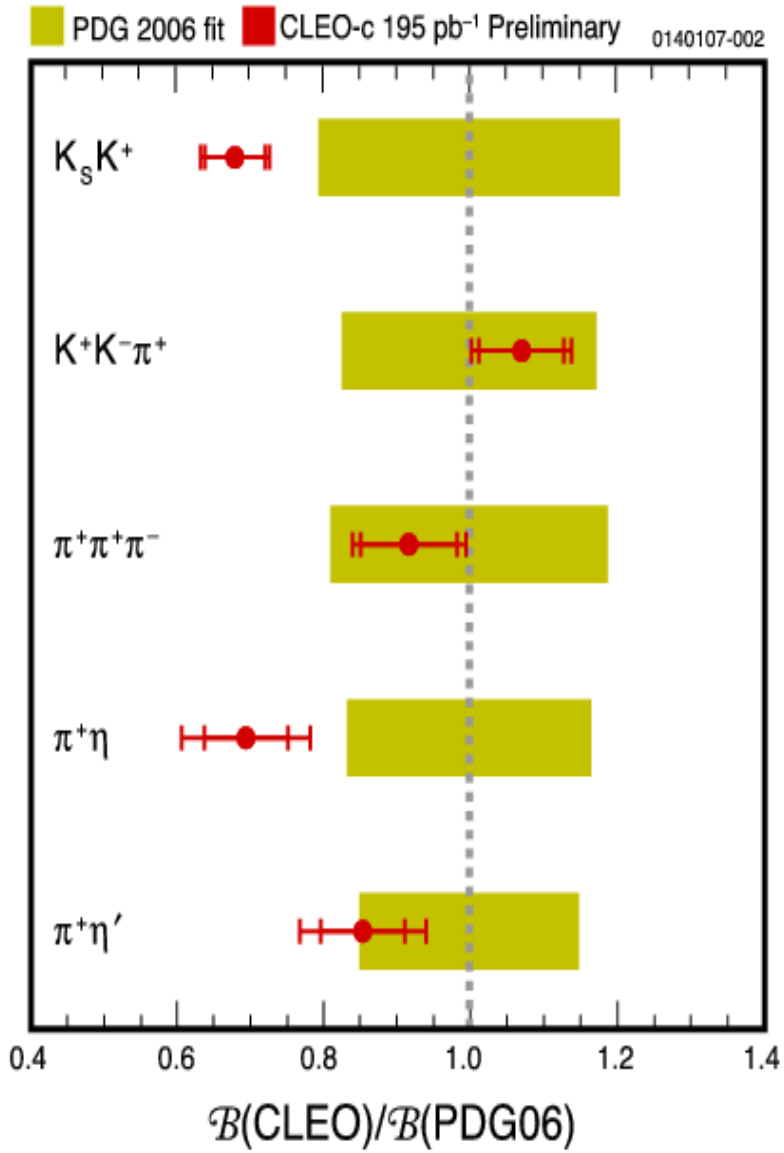
Errors already << PDG

CLEO-c, 4170MeV, 195pb^{-1}

Preliminary

D_s^+ Mode	$\mathcal{B}$ (%)
$K_S K^+$	$1.50 \pm 0.09 \pm 0.05$
$K^- K^+ \pi^+$	$5.57 \pm 0.30 \pm 0.19$
$K^- K^+ \pi^+ \pi^0$	$5.62 \pm 0.33 \pm 0.51$
$\pi^+ \pi^+ \pi^-$	$1.12 \pm 0.08 \pm 0.05$
$\pi^+ \eta$	$1.47 \pm 0.12 \pm 0.14$
$\pi^+ \eta'$	$4.02 \pm 0.27 \pm 0.30$

Stat. limited precision 6%➔ 4%
with full data sample



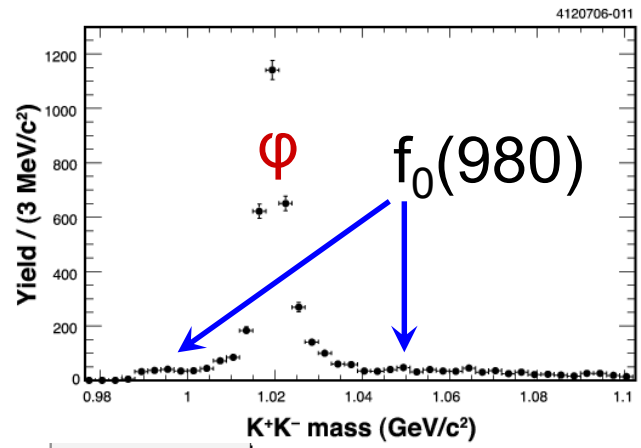
The $\varphi\pi^+$ problem in $D_s \to K^-K^+\pi^+$

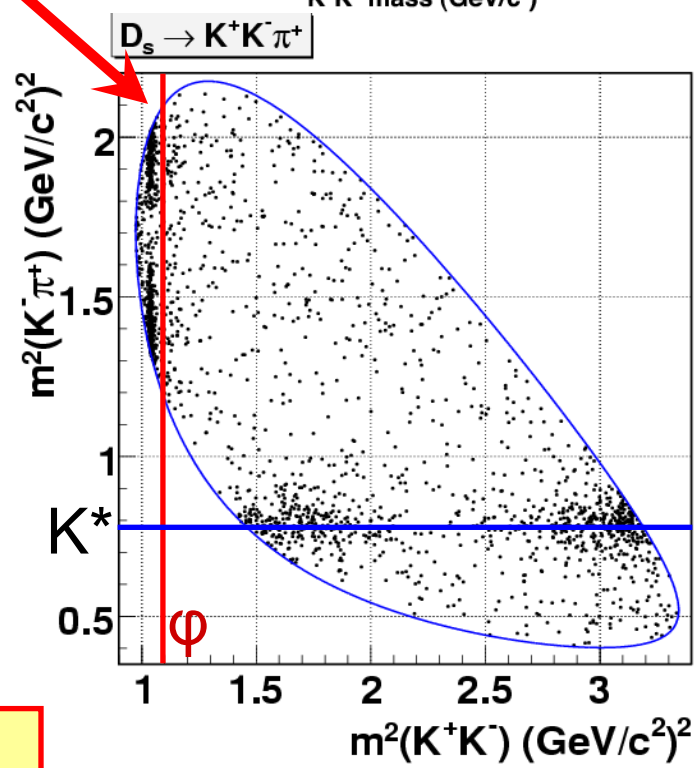
- Historically $D_s \to \varphi\pi^+$ used for normalization
- The process $f_0(980) \to K^-K^+$ contributes to any $\varphi \to K^-K^+$ mass region
- Correction depends on experiment's mass window, resolution, angular distribution requirements
- We produce partial $K^-K^+\pi^+$ branching for 10 and 20 MeV mass windows on each side of the φ mass:

BF	Result (%)
$\mathcal{B}_{10}$	$1.98 \pm 0.12 \pm 0.09$
$\mathcal{B}_{20}$	$2.25 \pm 0.13 \pm 0.12$

  – 14% difference

- Amplitude analysis is most appropriate to disentangle this problem…



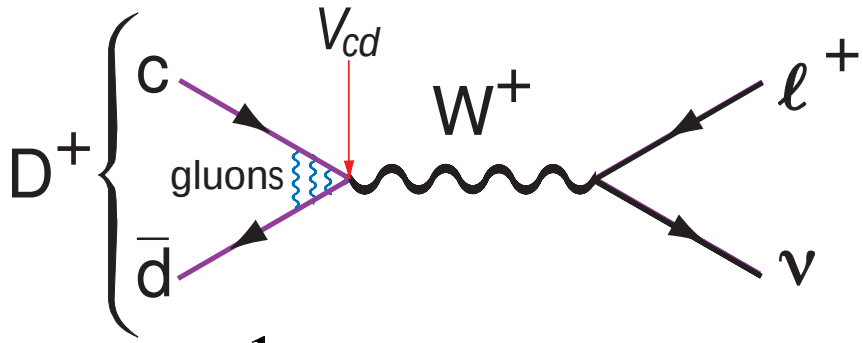


Preliminary

$D_{(s)}$ Leptonic Decays

In $D_{(s)} \to \ell^+\nu$ decay, c and q annihilate, probability is $\propto$ to wave function overlap

Example :

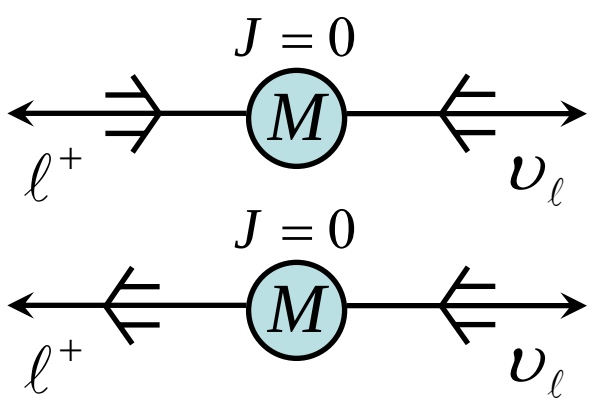


$$\Gamma(D^+ \to l^+\nu) = \frac{1}{8\pi} G_F^2 \boxed{f_D^2} m_l^2 M_D (1 - \frac{m_l^2}{M_D^2})^2 \boxed{|V_{cd}|}^2$$

- Standard Model:

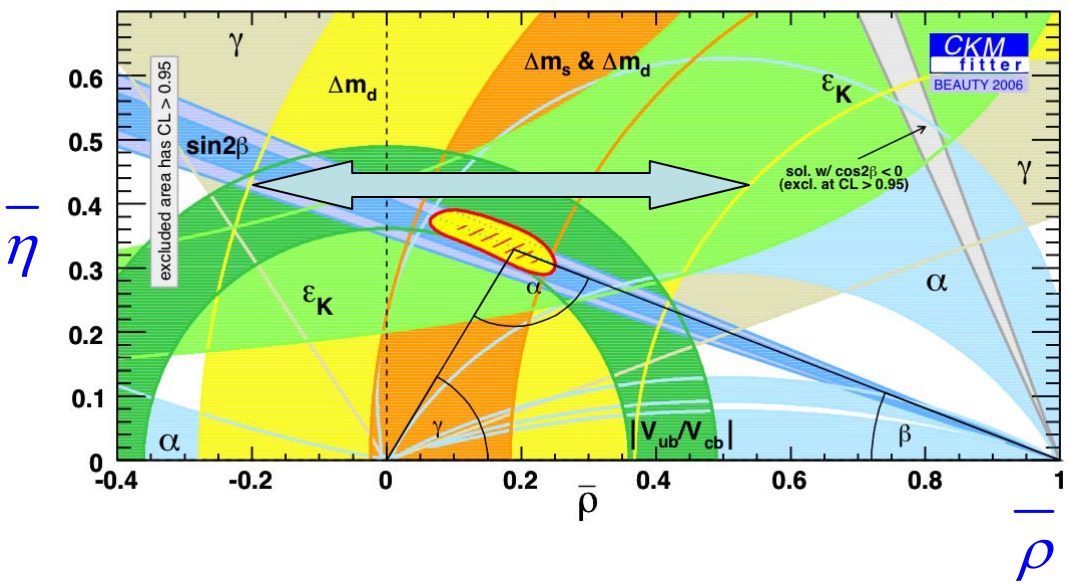
$$D^+ \;\; \Gamma(e^+\nu):\Gamma(\mu^+\nu):\Gamma(\tau^+\nu) = 2.3\times10^{-5} : 1.0 : 2.7$$

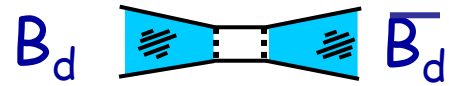
$$D_S \;\; \Gamma(e^+\nu):\Gamma(\mu^+\nu):\Gamma(\tau^+\nu) = 2.5\times10^{-5} : 1.0 : 9.7$$



- Use V_{cd} and V_{cs} from unitarity to extract f_D and f_{Ds},

Importance of measuring *absolute* charm leptonic branching ratios: f_D & f_{Ds} → V_{td} & V_{ts}





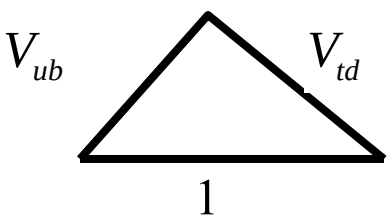
$$rate = (const.)\left[f_{Bd} \right]^2 |V_{td}|^2 |V_{tb}|^2$$

0.8% (expt) HFAG

~10% (HPQCD) PRL95 212001 (2005)

~12%

if f_{Bd} was known to 3%
$|V_{td}||V_{tb}|$ would be known to ~5%



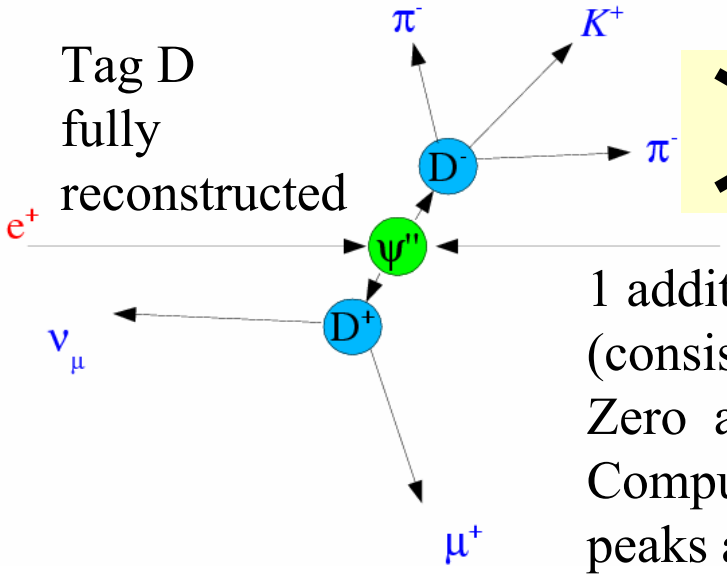
f_{Bd} f_{Bs} inaccessible, $B \to \tau\nu \propto f_{B+} V_{ub}$
if V_{ub} known well (it's not) get f_{B+}
f_{D+} f_{Ds+} accessible

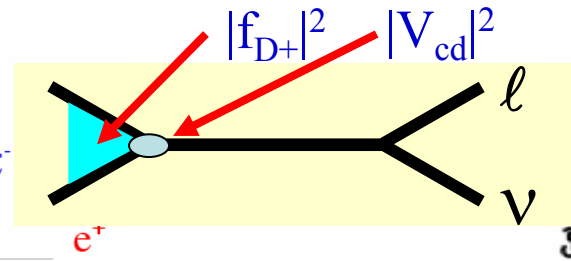
$$\frac{\delta f_{D_c}}{f_{D_c}} \sim 100\%$$
PDG04

Lattice predicts f_B/f_D with a small error
If a precision measurement of f_D existed (it did not)
→Precision Lattice estimate of f_B → precision determination of V_{td}
Similarly f_D/f_{Ds} checks f_B/f_{Bs} → precise $|V_{td}|/|V_{ts}|$ from B_s mixing

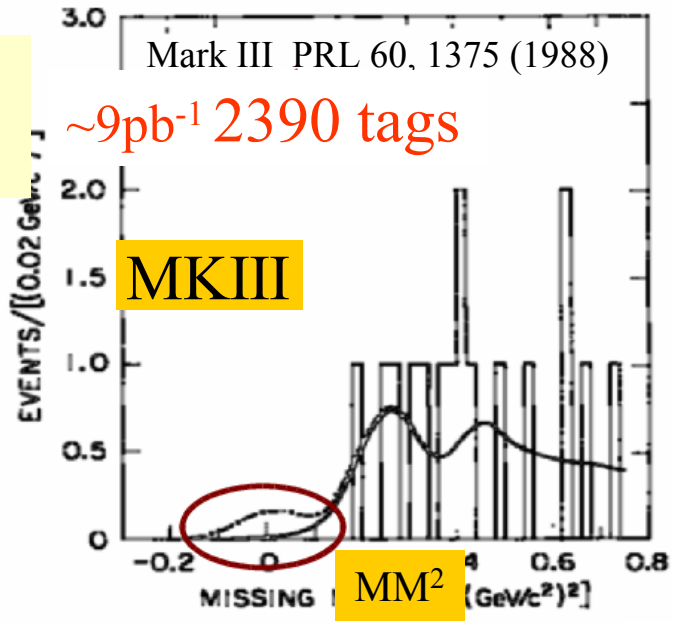
f_{D+} from Absolute $Br(D^+ \to \mu^+\nu)$ @ψ(3770) CLEO-c

Tag D fully reconstructed



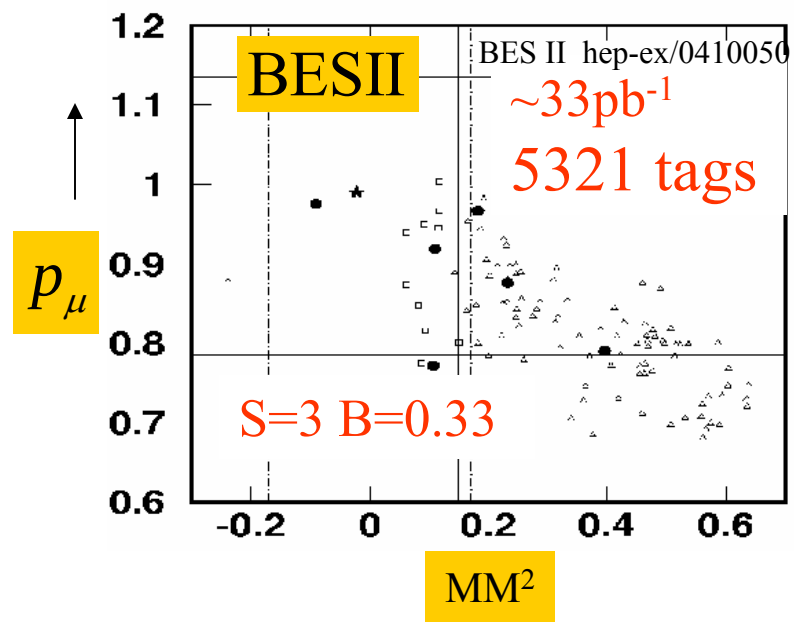


1 additional track (consistent with a muon)
Zero additional photons
Compute missing mass²: peaks at 0 for signal



$$MM^2 = (E_D - E_\mu)^2 - (\overrightarrow{P_D} - \overrightarrow{P_\mu})^2$$

where $E_D = E_{beam}$, $\overrightarrow{P_D} = -\overrightarrow{P_{D\,tag}}$



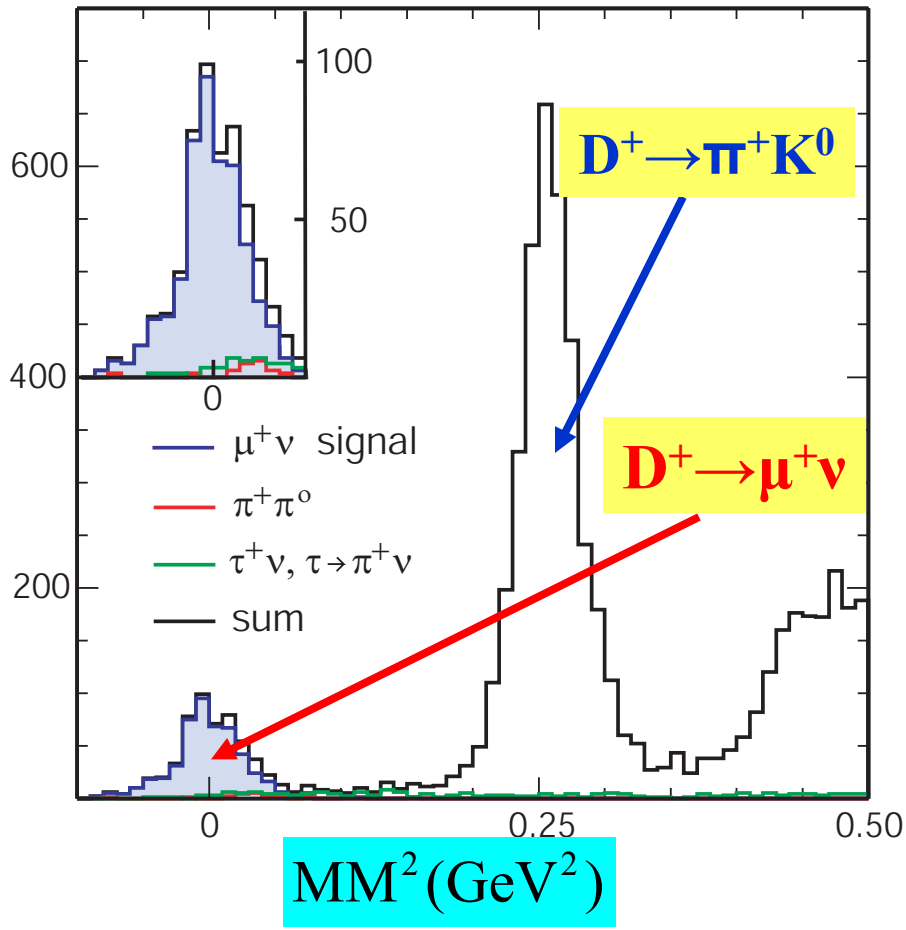
	$B(D^+ \to \mu\nu)\times 10^{-4}$	f_D MeV
MkIII	< 7.2	< 290
BESII	$12.2^{11.1}_{-53} \pm 0.11$	$371^{+129}_{-119} \pm 25$

f_{D+} from Absolute $Br(D^+ \to \mu^+\nu)$

$$MM^2 = (E_{beam} - E_\mu)^2 - (-\vec{P}_{D\,tag} - \vec{P}_\mu)^2$$

$$\delta MM^2 \sim M^2_{\pi 0}$$

- **MC 1.7 fb^{-1}, 6 x data**



CLEO-c analysis was to be unveiled at LP05

2 days before LP05

1st full unquenched lattice calc.

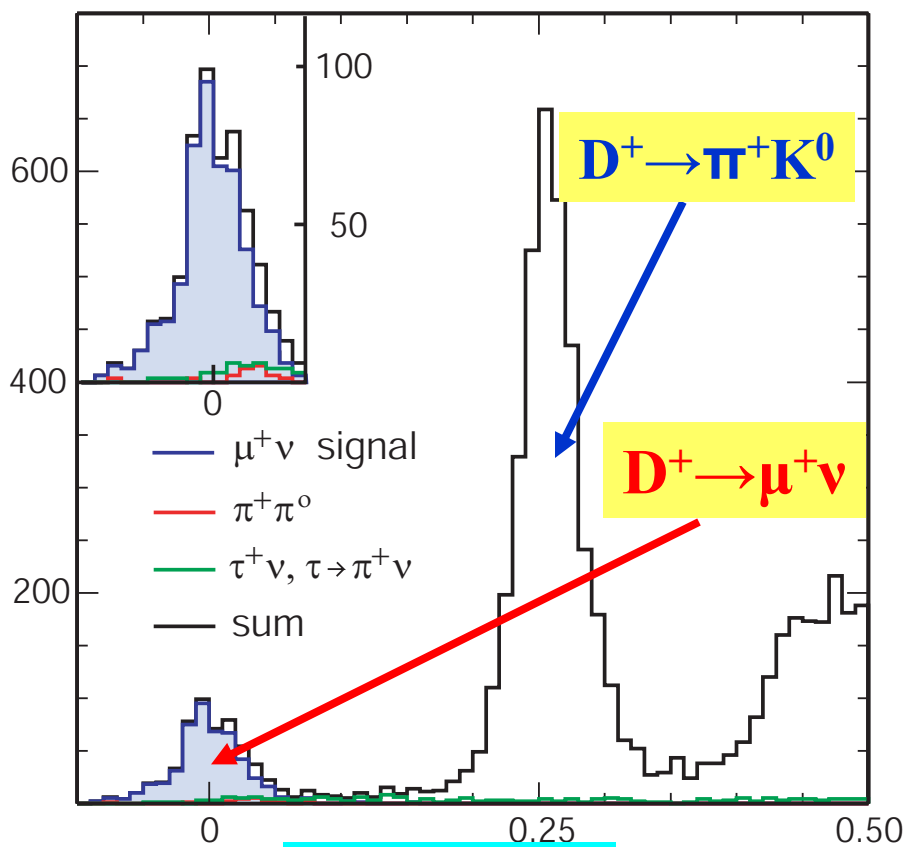
a prediction

$$f_{D^+} = (201 \pm 3 \pm 17)\ \text{MeV}$$

f_{D+} from Absolute $Br(D^+ \to \mu^+\nu)$

$$MM^2 = (E_{beam} - E_\mu)^2 - (-\vec{P}_{D\,tag} - \vec{P}_\mu)^2$$

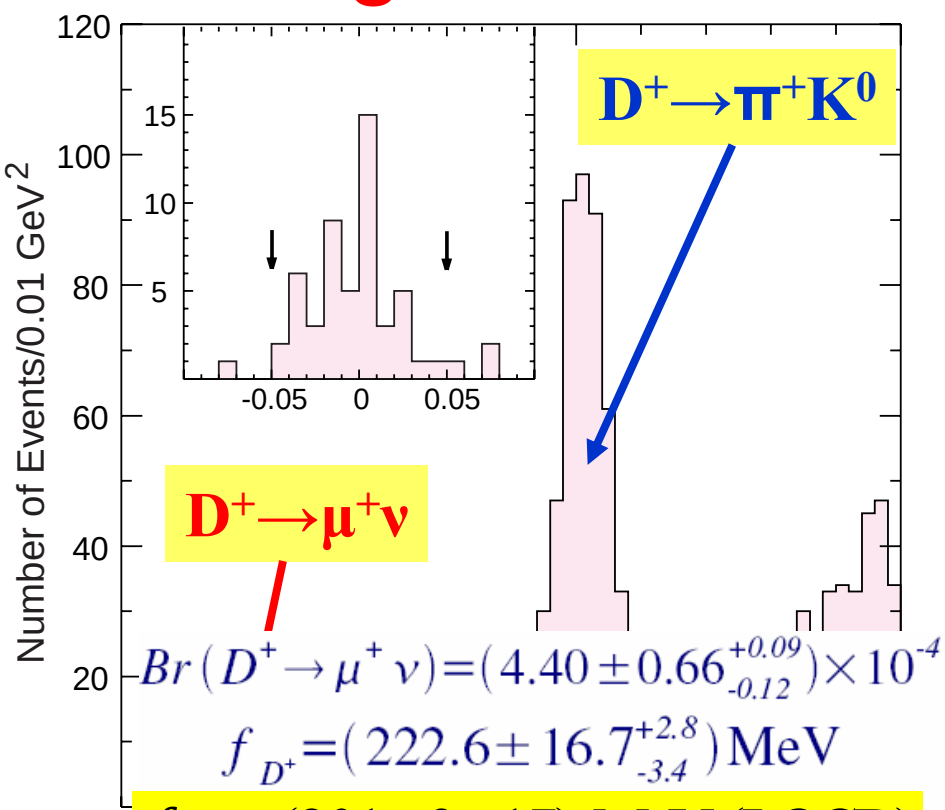
- **MC 1.7 fb^{-1}, 6 x data**



$$\delta MM^2 \sim M^2_{\pi 0}$$

281 pb^{-1} at $\psi(3770)$

50 signal events



$$Br(D^+ \to \mu^+\nu) = (4.40 \pm 0.66^{+0.09}_{-0.12}) \times 10^{-4}$$

$$f_{D^+} = (222.6 \pm 16.7^{+2.8}_{-3.4})\,\text{MeV}$$

$$f_{D^+} = (201 \pm 3 \pm 17)\ \text{MeV (LQCD)}$$

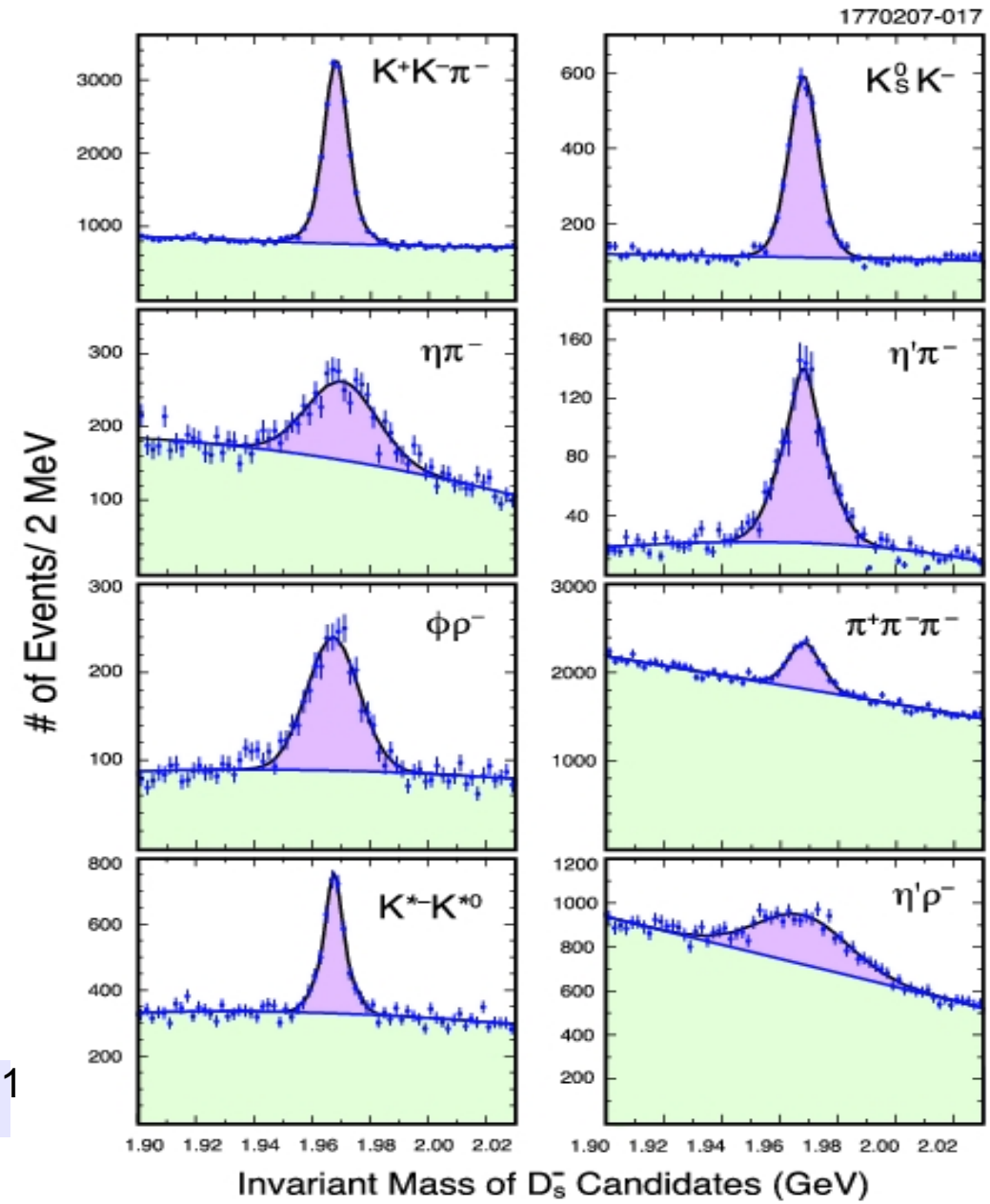
Expt/Theory agree ~ to 10%

fD_s^+ from $D_s \to \mu^+\nu$ and $\tau^+(\pi^+\nu)\nu$

arXiv:0704.0437
arXiv0704.0629
supercedes ICHEP06
analysis which used a
smaller data sample

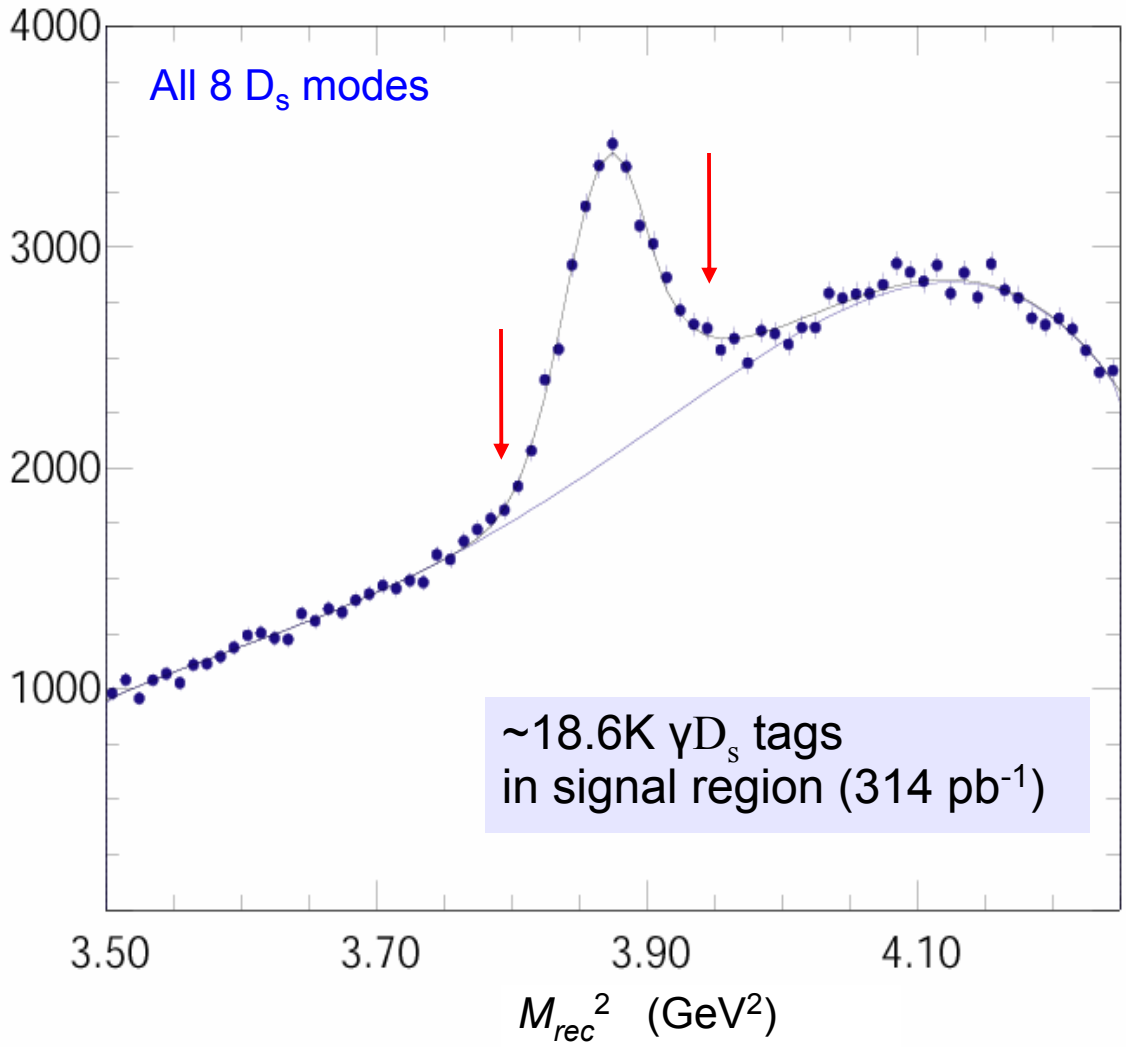
Tagging
Reconstruct
one D_s
decaying
into each of
8 hadronic
modes

~31.3K D_s tags in 314 pb^{-1}



$D_s \to \mu^+\nu$ and $\tau^+(\pi^+\nu)\nu$

Require additional photon calculate recoil mass against the $\gamma D_{s\text{-tag}}$ (Kinematic constraints to improve Resolutions & remove multiple combinations)

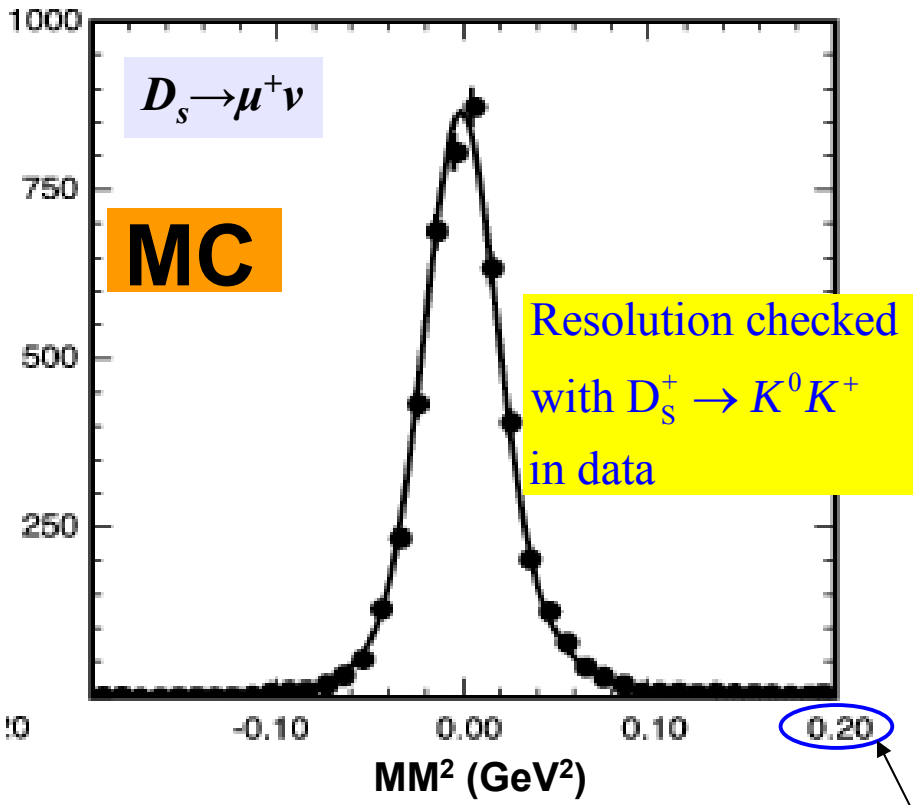


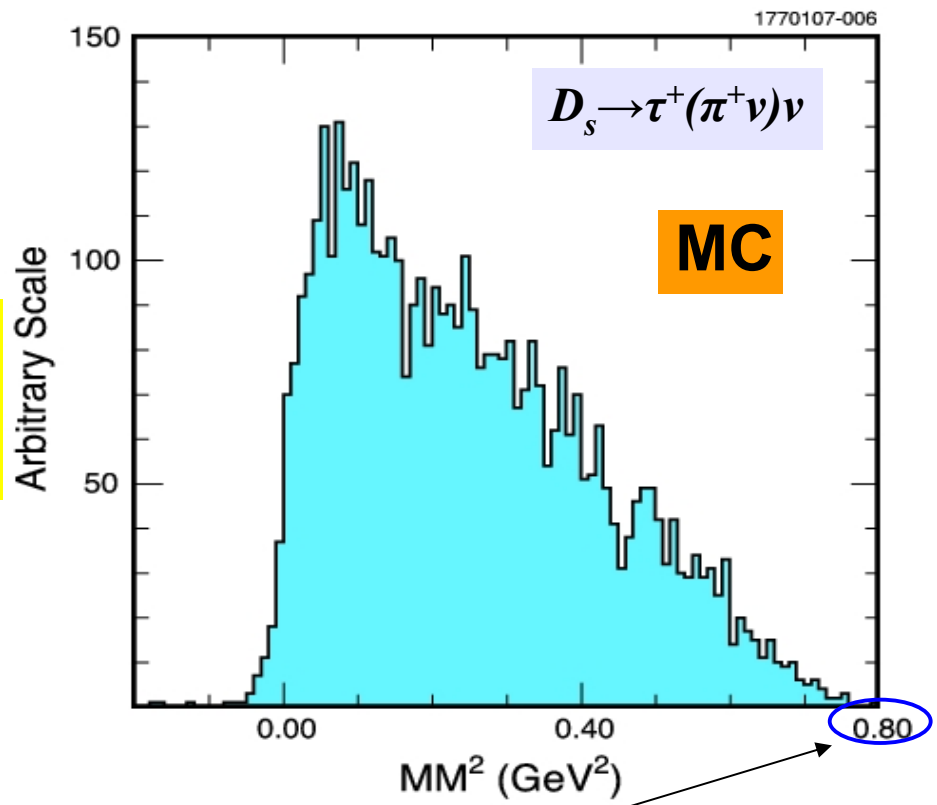
$$M_{rec}^2 = (E_{CM} - E_{D_S-tag} - E_\gamma)^2 - (-\vec{p}_{D_S-tag} - \vec{p}_\gamma)^2 \approx M_{D_S}^2$$

$D_s \to \mu^+\nu$ and $\tau^+(\pi^+\nu)\nu$

- Require one additional track and no extra shower in calorimeter with > 300 MeV
- Calculate missing mass in the event to infer the neutrino(s):

$$MM^2 = (E_{CM} - E_{D_S-tag} - E_\gamma - E_{\mu(\pi)})^2 - (-\vec{p}_{D_S-tag} - \vec{p}_\gamma - \vec{p}_\mu)^2$$





Note different scale

$D_s \to \mu^+\nu$ and $\tau^+(\pi^+\nu)\nu$

- Three cases depending on particle type:

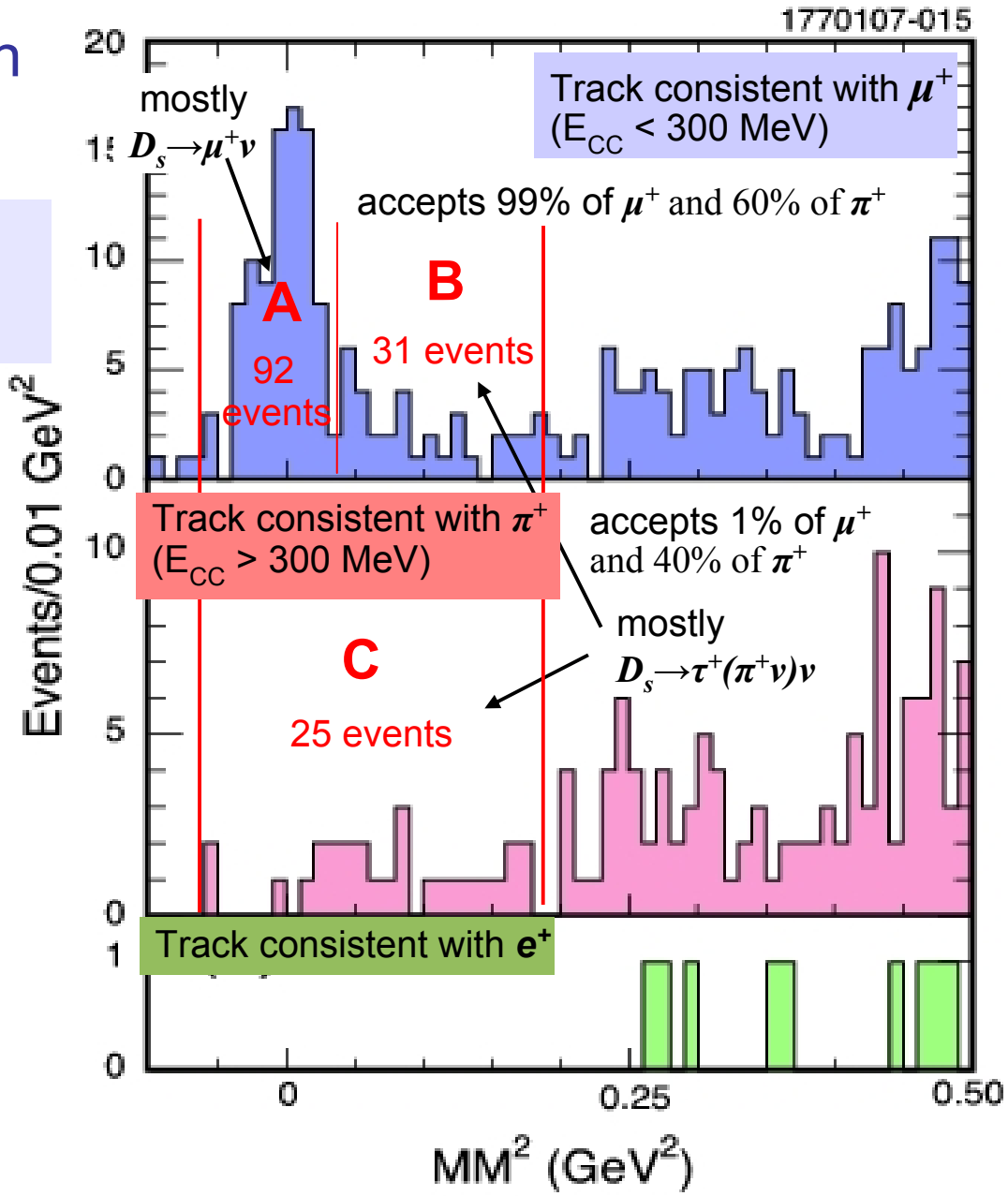
A 92 events (3.5 backg+7.4 $\tau^+(\pi^+\nu)\nu$)
using SM τ/μ ratio
$B(D_s \to \mu^+\nu)$ = **(0.594 ± 0.066 ± 0.031)%**

B+C: 31+25 events (3.5+5 backg)
$B(D_s \to \tau^+\nu)$ = **(8.0 ± 1.3 ± 0.4)%**

A+B+C: 148 events (10.7 background)
using SM τ/μ ratio
$B^{eff}(D_s \to \mu^+\nu)$ = ***(0.621 ± 0.058 ± 0.032)%***

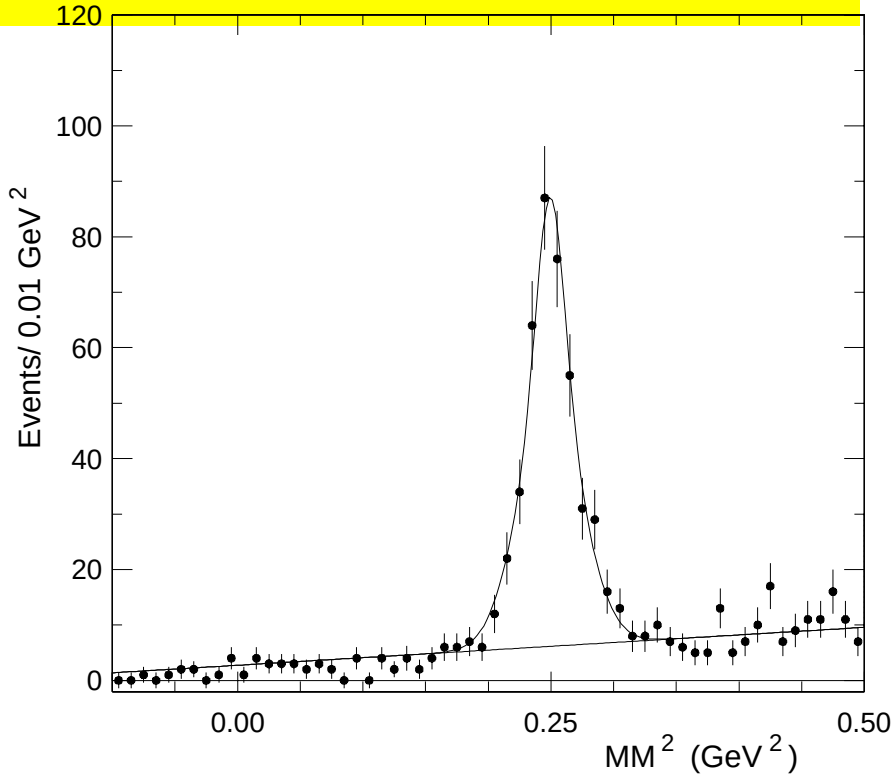
f_{D_s} = (270 ± 13 ± 7) MeV

$B(D_s \to e^+\nu)$ < **1.3x10^{-4}**



Check of procedure: $\mathcal{B}(D_S^+ \to K^+ K^o)$

Ds tag + γ
consider MM^2
recoiling against
an identified K^+
Allow extra charged
tracks and showers to
not veto K^o decays or
interactions in EM calorimeter



- Signal verifies expected MM^2 resolution
- Find
- $\mathcal{B}(D_S^+ \to K^+ K^o) = (2.90 \pm 0.19 \pm 0.18)\%$,

  $\mathcal{B}(D_S^+ \to K^+ K^o) = (3.00 \pm 0.19 \pm 0.10)\%$ (Double tag CLEO-c)

Good agreement

Comparison with Previous Experiments

Exp.	Mode	$\mathcal{B}$	$\mathcal{B}_{\phi\pi}$ (%)	$f_{D_s^+}$ (MeV)
CLEO-c	$\mu^+\nu$	$(5.93 \pm 0.66 \pm 0.31) \cdot 10^{-3}$		$264 \pm 15 \pm 7$
CLEO-c	$\tau^+\nu$	$(8.0 \pm 1.3 \pm 0.4) \cdot 10^{-2}$		$310 \pm 25 \pm 8$
CLEO-c	combined	-		$270 \pm 13 \pm 7$
CLEO [32]	$\mu^+\nu$	$(6.2 \pm 0.8 \pm 1.3 \pm 1.6) \cdot 10^{-3}$	3.6 ± 0.9	$273 \pm 19 \pm 27 \pm 33$
BEATRICE [33]	$\mu^+\nu$	$(8.3 \pm 2.3 \pm 0.6 \pm 2.1) \cdot 10^{-3}$	3.6 ± 0.9	$312 \pm 43 \pm 12 \pm 39$
ALEPH [34]	$\mu^+\nu$	$(6.8 \pm 1.1 \pm 1.8) \cdot 10^{-3}$	3.6 ± 0.9	$282 \pm 19 \pm 40$
ALEPH [34]	$\tau^+\nu$	$(5.8 \pm 0.8 \pm 1.8) \cdot 10^{-2}$		
L3 [35]	$\tau^+\nu$	$(7.4 \pm 2.8 \pm 1.6 \pm 1.8) \cdot 10^{-2}$		$299 \pm 57 \pm 32 \pm 37$
OPAL [36]	$\tau^+\nu$	$(7.0 \pm 2.1 \pm 2.0) \cdot 10^{-2}$		$283 \pm 44 \pm 41$
BaBar [38]	$\mu^+\nu$	$(6.74 \pm 0.83 \pm 0.26 \pm 0.66) \cdot 10^{-3}$	4.71 ± 0.46	$283 \pm 17 \pm 7 \pm 14$

- CLEO-c is most precise result to date for f_{Ds} (& f_{D+})
- The CLEO-c result is an absolute measurement, specifically it *does not depend* on an external normalizing mode i.e B(Ds→Φπ)

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

ICHEP06 analysis update in process preliminary

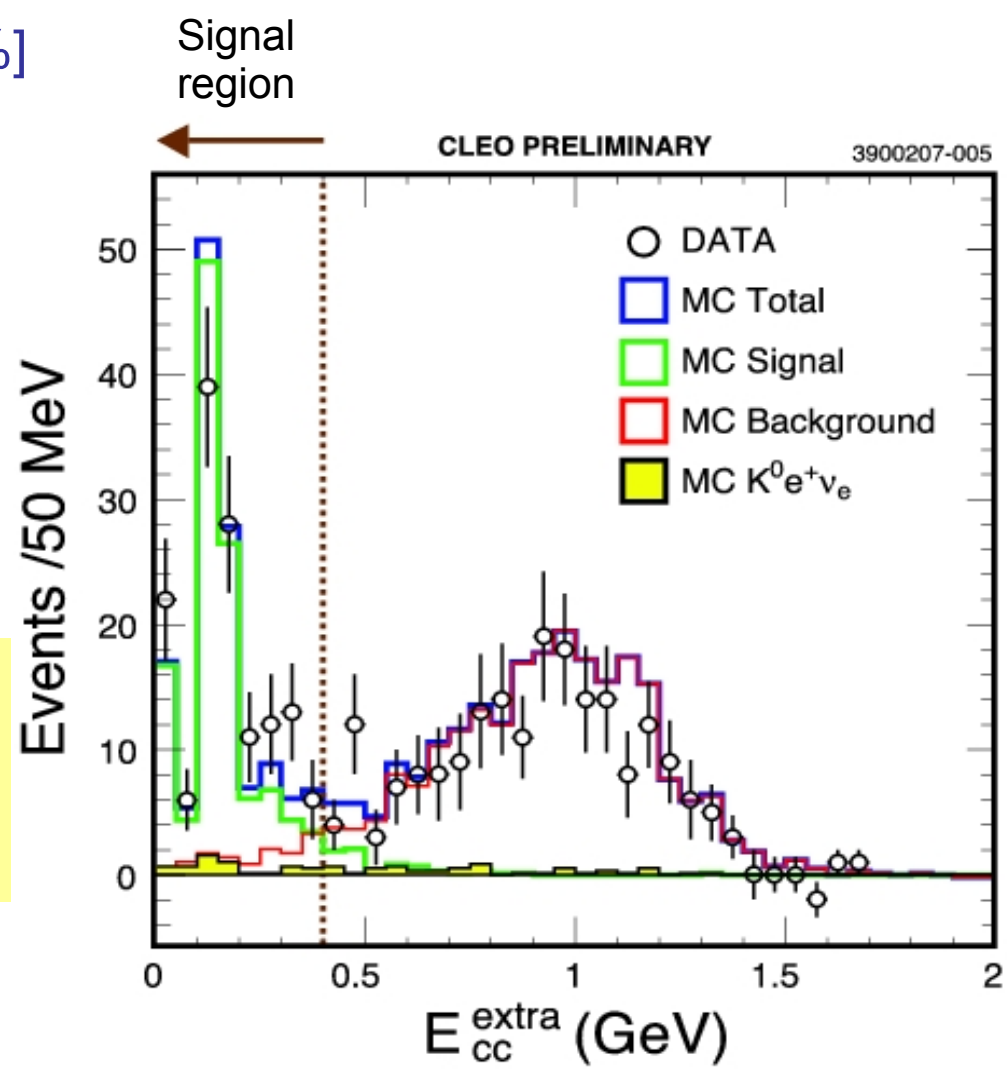
- Complimentary analysis using $D_s \to \tau^+\nu$, $\tau^+ \to e^+\nu\nu$

  $B(D_s \to \tau^+\nu)B(\tau^+ \to e^+\nu\nu) \approx 1.3\%$ significant

  [compare to $B(D_s \to Xe^+\nu) \approx 8\%$]

Analysis technique:

- Find D_s^- tag and e^+ (no need to find γ from D_s^*)
- No extra track
- Extra energy in calorimeter < 400 MeV



Results:

$B(D_s \to \tau^+\nu)$ = **(6.29 ± 0.78 ± 0.52)%**

[PDG06: $B(D_s \to \tau^+\nu)$ = (6.4 ± 1.5)%]

f_{Ds} = **(278 ± 17 ± 12) MeV**

f_D and f_{Ds} : comparison with theory

Summary of CLEO-c results:

f_D = (223 ± 17 ± 3) MeV

f_{Ds} = (273 ± 10 ± 5) MeV

(f_{Ds} weighted average of the two methods 4%!)

f_{Ds}/f_D = 1.22 ± 0.09 ± 0.03

Consistent with most models

Statistically limited – more data is on the way!

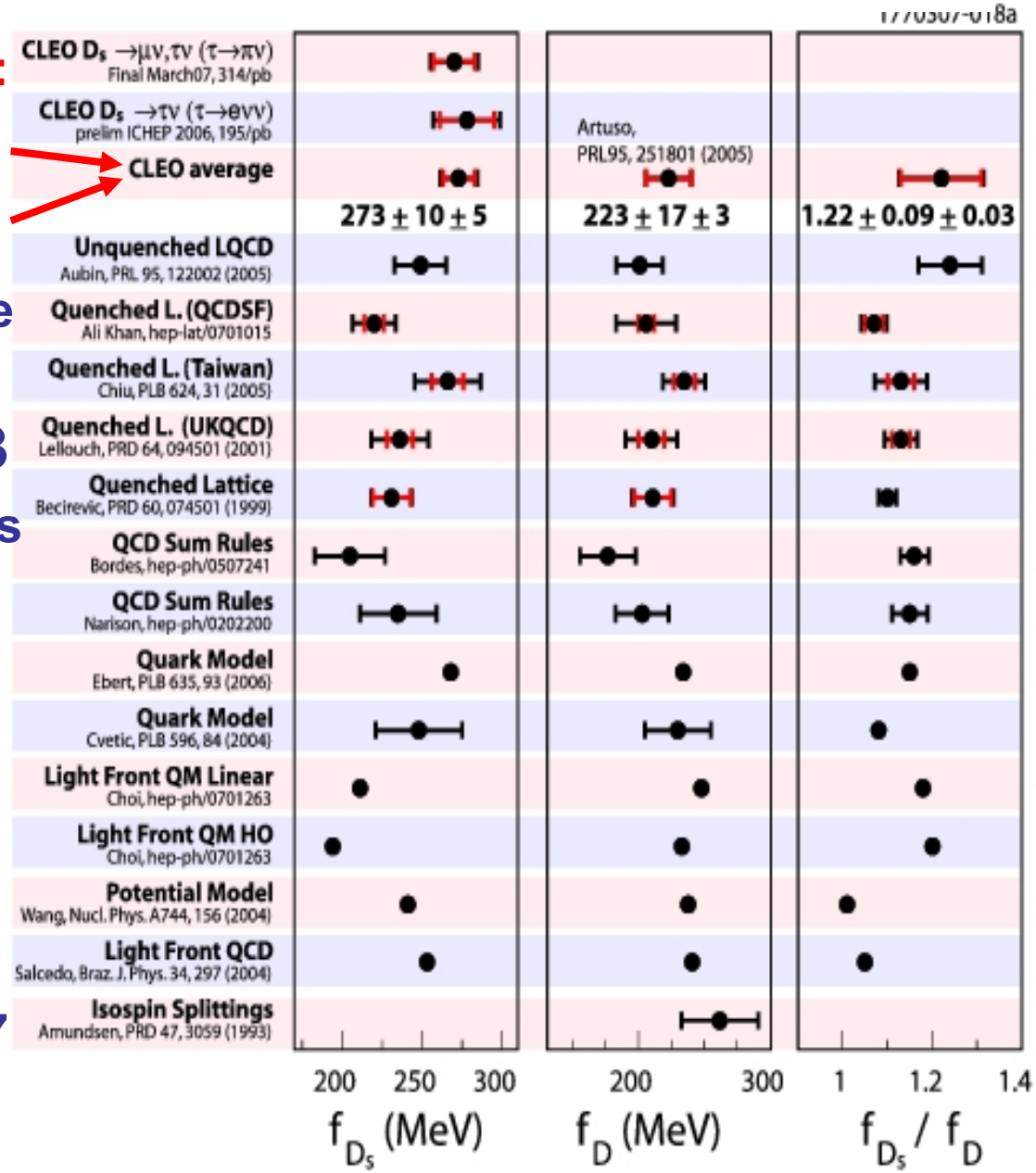
Lattice QCD (unquenched) PRL 95, 122002 (2005):

f_D = (201 ± 3 ± 17) MeV

f_{Ds} = (249 ± 3 ± 16) MeV

f_{Ds}/f_D = 1.24 ± 0.01 ± 0.07

systematics limited!



Summary & Outlook: Decay Constants

- f_{Bs}/f_B is key ingredient in V_{ts}/V_{td}

with $0.75 fb^{-1}$: f_{D+} ~4%

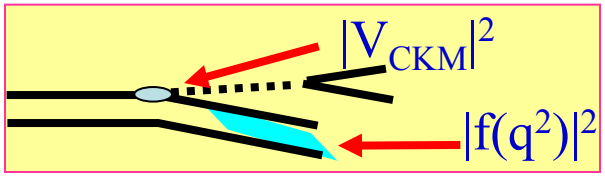
f_{Ds} to ~3% @ $\sqrt{s} \sim 4170 MeV$

- f_D, f_{Ds} & f_{Ds}/f_D statistics limited *after* CLEO-c. I expect:

Exp't	3.77 GeV	4.17 GeV	$\sigma(f_{Ds}/f_D)$
CLEO-c	281 pb^{-1}	310 pb^{-1}	9%
CLEO-c	750 pb^{-1}	750 pb^{-1}	5%
BESIII	20 fb^{-1}	12 fb-1	<2%
SuperB	~150 fb^{-1}	~200 fb^{-1}	<1%

Need LQCD predictions
for f_{D+} & f_{Ds} 3-4% by 2008 and a few % ~2010
& for the ratio f_{D+}/f_{Ds} to match above table

Importance of *Absolute* Charm Semileptonic Decay Rates



1 Charm semileptonic decays determine Vcs and Vcd

$$\frac{d\Gamma}{dq^2} \propto |V_{cd}|^2 |f_+^{D\to\pi}(q^2)|^2$$

2 *Test theoretical calculations of form factors* $|V_{cd}|$ & $|V_{cs}|$ known from unitarity to 1%

3 Useful input to Vub from exclusive B semileptonic decays

$Br(B \to \pi l \nu)$ 6% precision

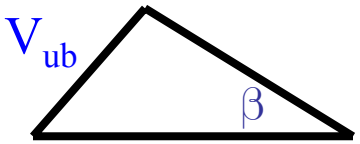
BABAR / Belle / CLEO

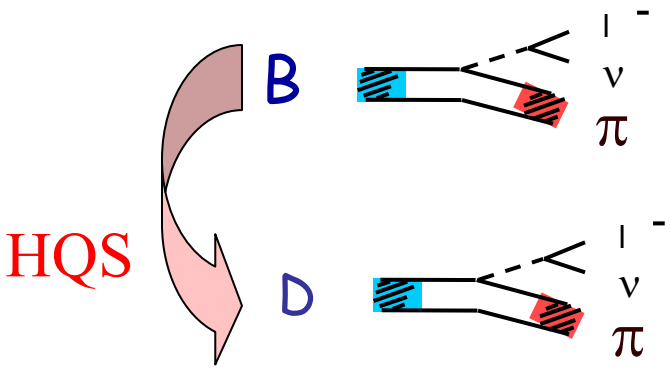
(HFAG (2006)

$$|V_{ub}| = (3.60 \pm 0.10 \pm 0.50) \times 10^{-3}$$
$$\pm \exp \pm \mathrm{LQCD}$$

Expt. 3%

14% average over HFAG FF calc.s





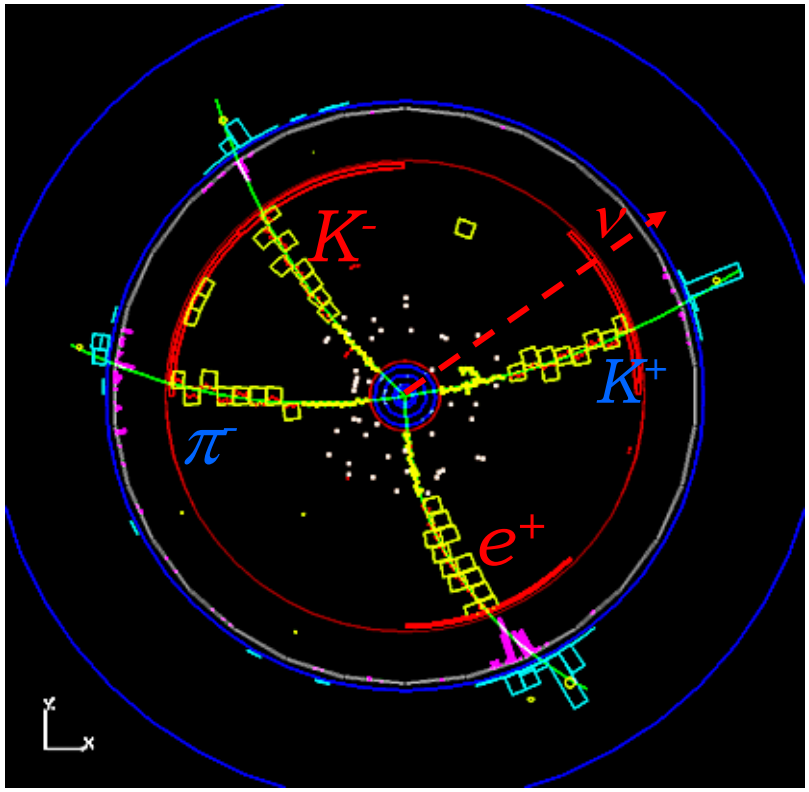
$$\propto \left[f^{B\to\pi}(q) \right]^2 |V_{ub}|^2$$

$$\propto \left[f^{D\to\pi}(q) \right]^2 |V_{cd}|^2$$

Vub is a SM benchmark it tests the sin2β value based on CP asymmetries in b→ ccs & b→sss penguin decays which currently differ

Absolute BFs of Semileptonic Decays CLEO-c

The neutrino direction is determined to 1^0



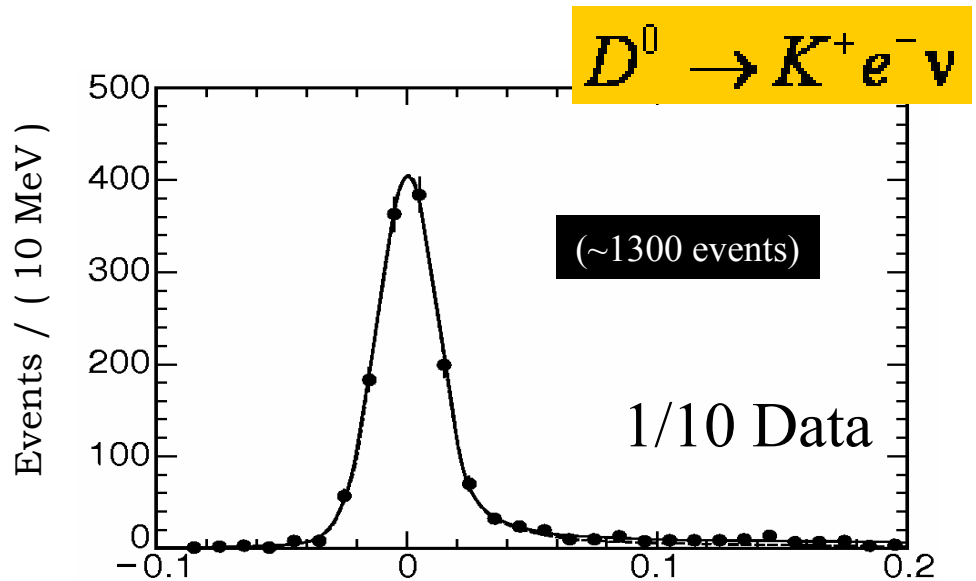
Semileptonic decays are reconstructed with *no* kinematic ambiguity

$$U \equiv E_{miss} - \left|\vec{p}_{miss}\right| = 0$$

$$\psi(3770) \rightarrow D^0 \overline{D^0}$$

$$\overline{D^0} \rightarrow K^+\pi^-, D^0 \rightarrow K^-e^+\nu$$

Tagging creates a single D beam of known 4-momentum

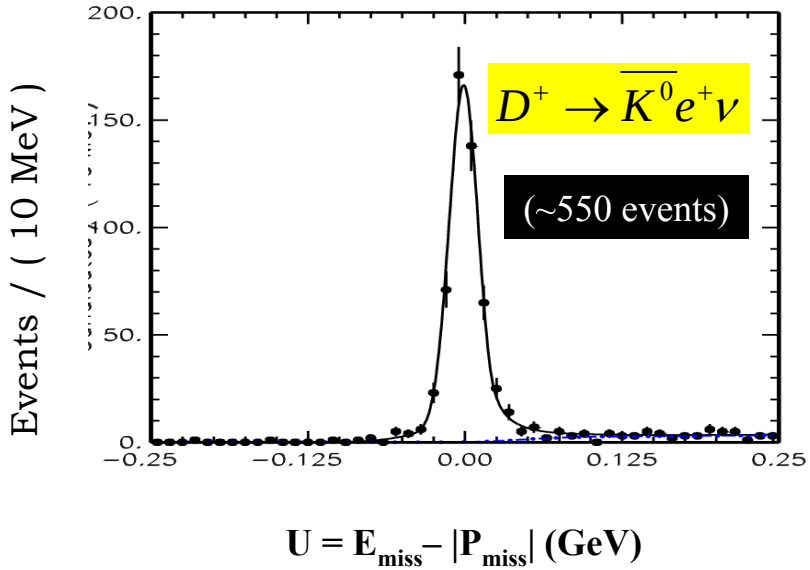


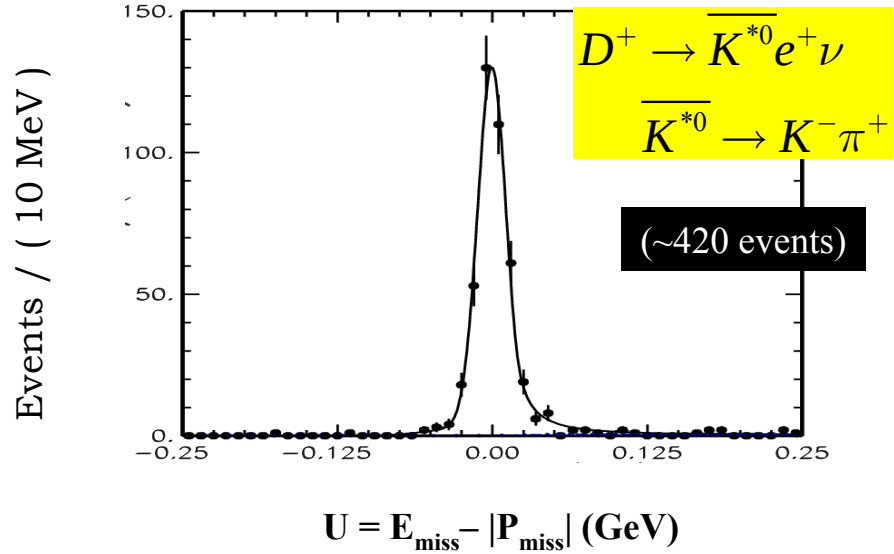
U = E_{miss} – |P_{miss}| (GeV)

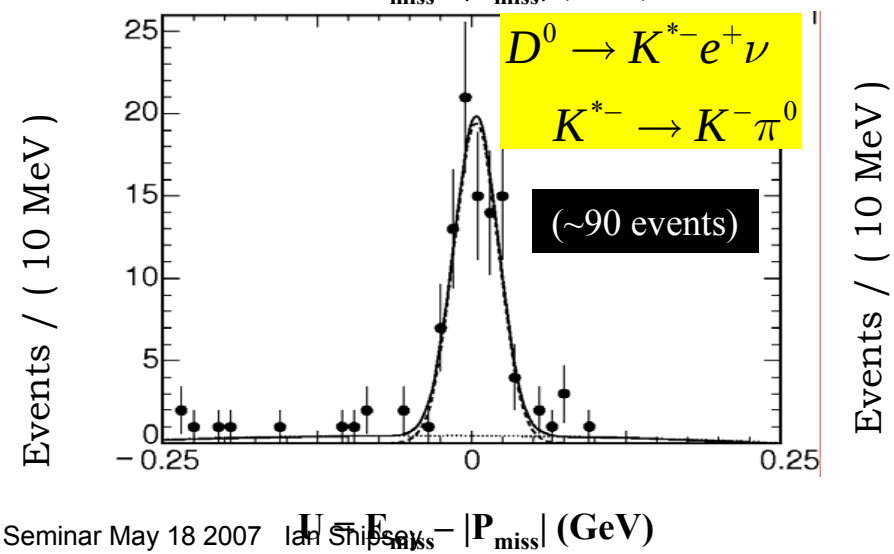
More Cabibbo allowed modes

1/10 Data

$c \rightarrow s$ Cabibbo Favored

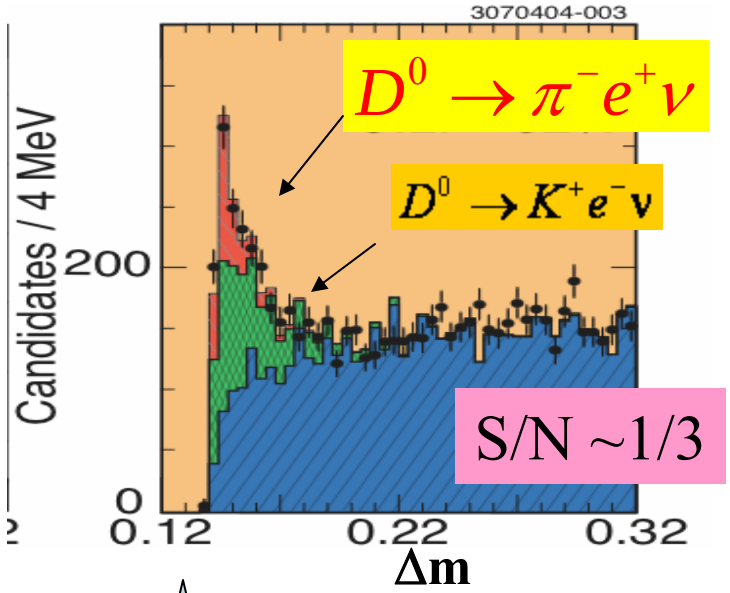






Historically Cabibbo allowed modes: provide a significant background to Cabibbo suppressed modes, making the latter particularly challenging…..

Cabibbo suppressed modes



Tag with $D^{*+} \to D^0 \pi_s$

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

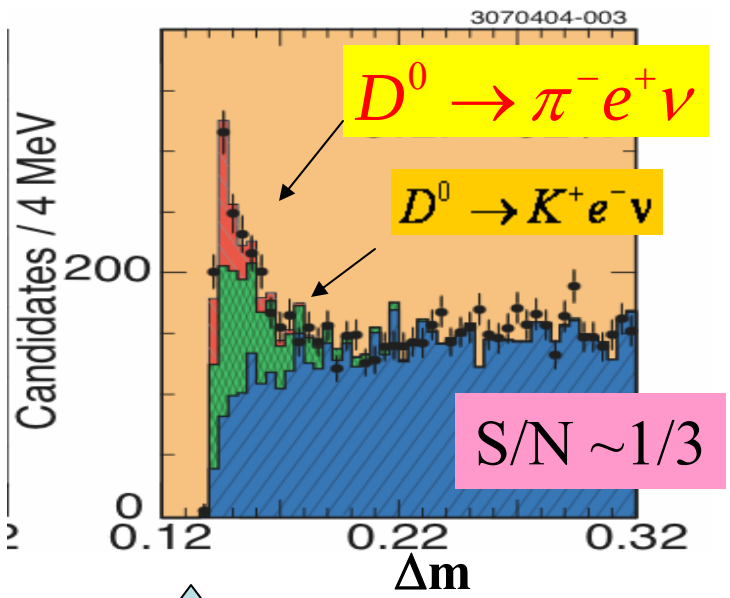
observable:

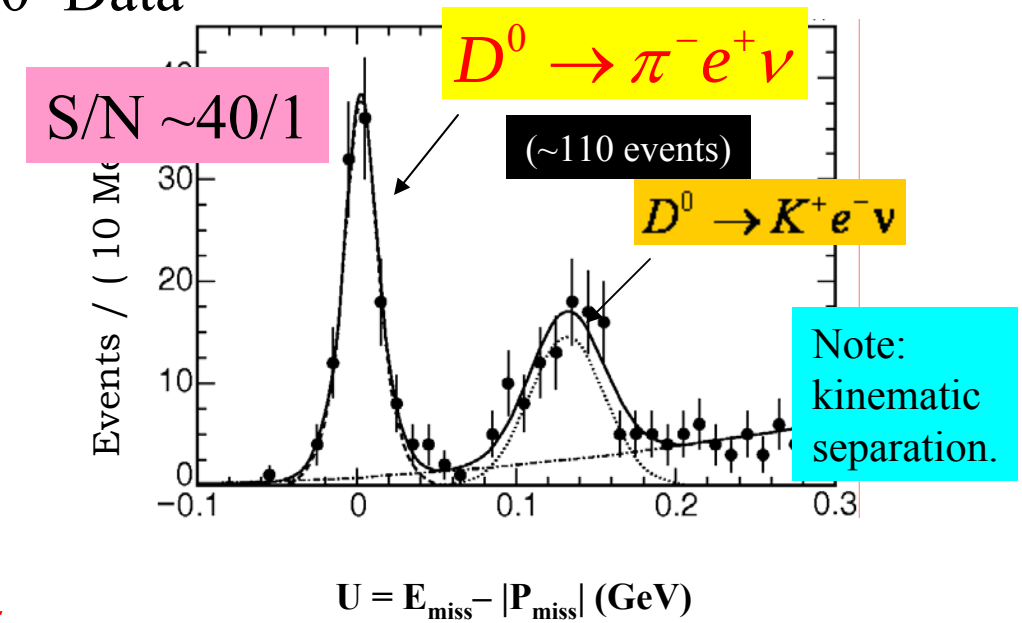
$\Delta m = m(\pi_s \pi \ell) - m(\pi \ell)$

state of the
art measurement
at 10 GeV (CLEO III)
PRL 94, 11802

Cabibbo suppressed modes

1/10 Data





Tag with $D^{*+} \to D^0 \pi_s$

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

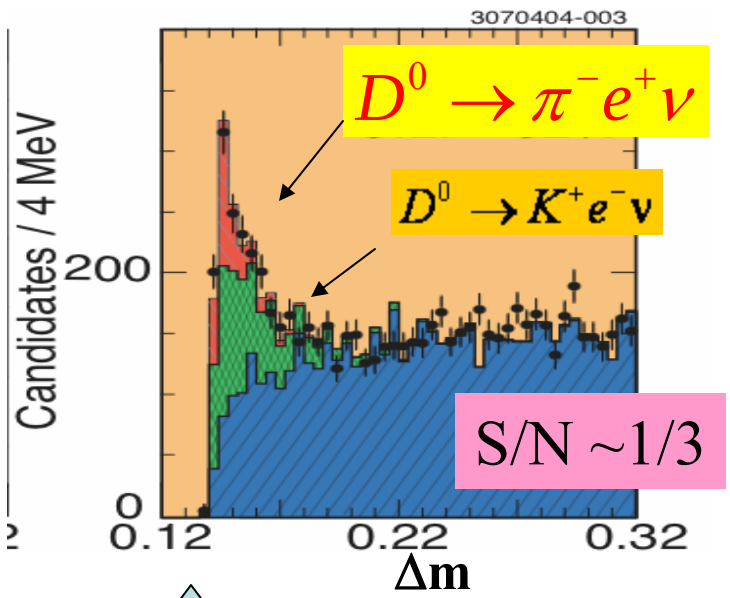
observable:

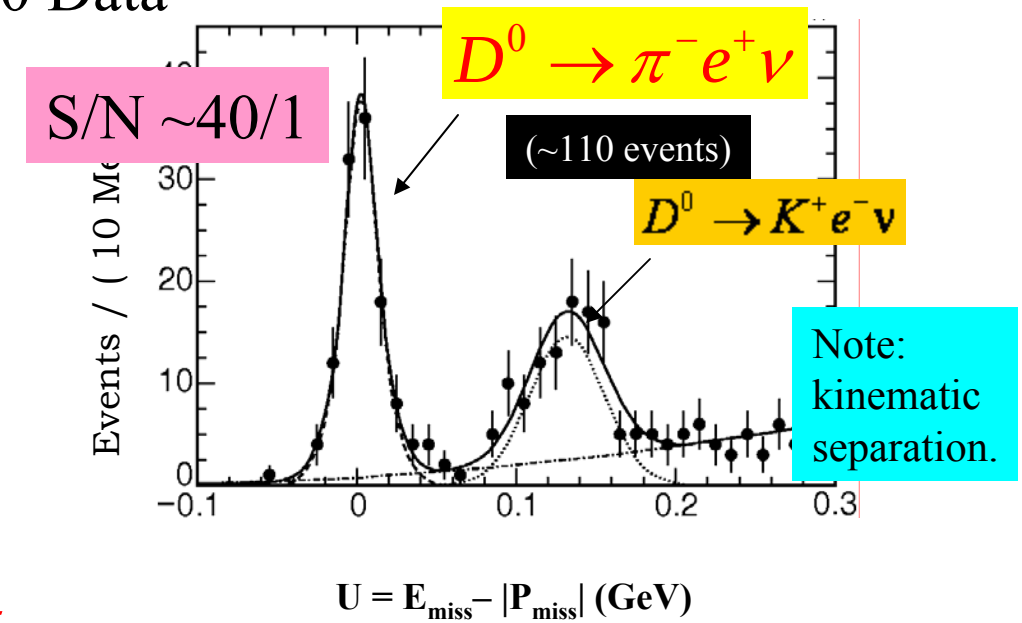
$\Delta m = m(\pi_s \pi \ell) - m(\pi \ell)$

Compare to: state of the art measurement at 10 GeV (CLEO III) PRL 94, 11802

Cabibbo suppressed modes

1/10 Data





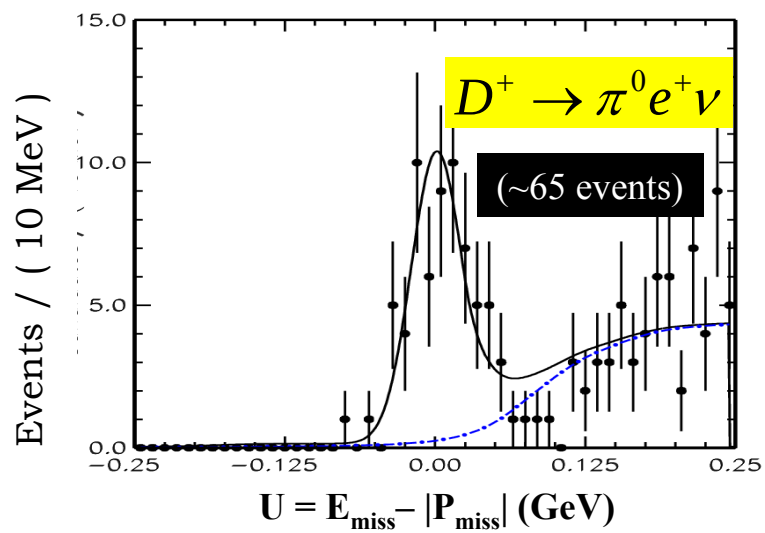
Compare to: state of the art measurement at 10 GeV (CLEO III) PRL 94, 11802

Tag with $D^{*+} \to D^0 \pi_s$

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

observable:

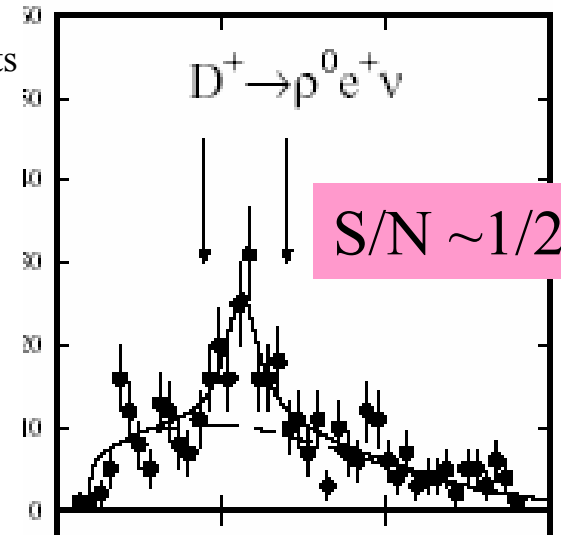
$\Delta m = m(\pi_s \pi \ell) - m(\pi \ell)$



More Cabibbo supressed modes

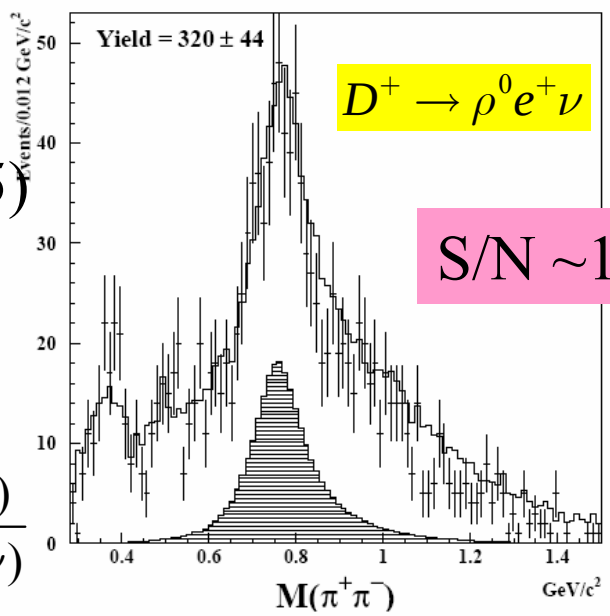
Only measurements untl now

E791
PLB 397
325
(1997)



S/N ~1/2

FOCUS
Hep-ex
/0511022
(Nov 2005)



S/N ~1/2

Relative
Rate:

$$\frac{\Gamma(D^+ \to \rho^0 e^+ \nu)}{\Gamma(D^+ \to K^{*0} e^+ \nu)}$$

More Cabibbo supressed modes 1/10 Data

Only measurements untl now

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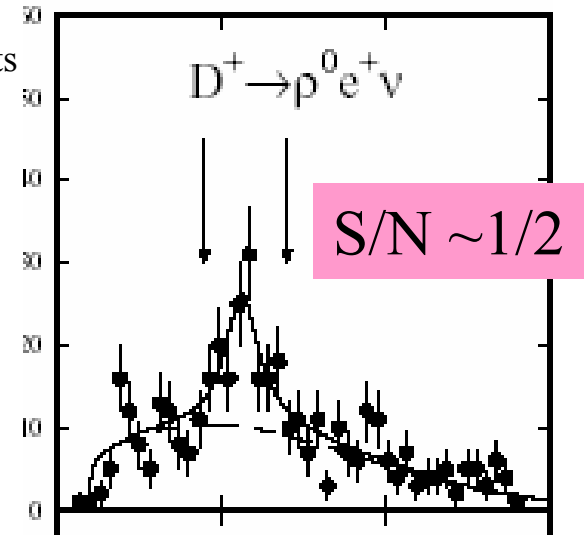
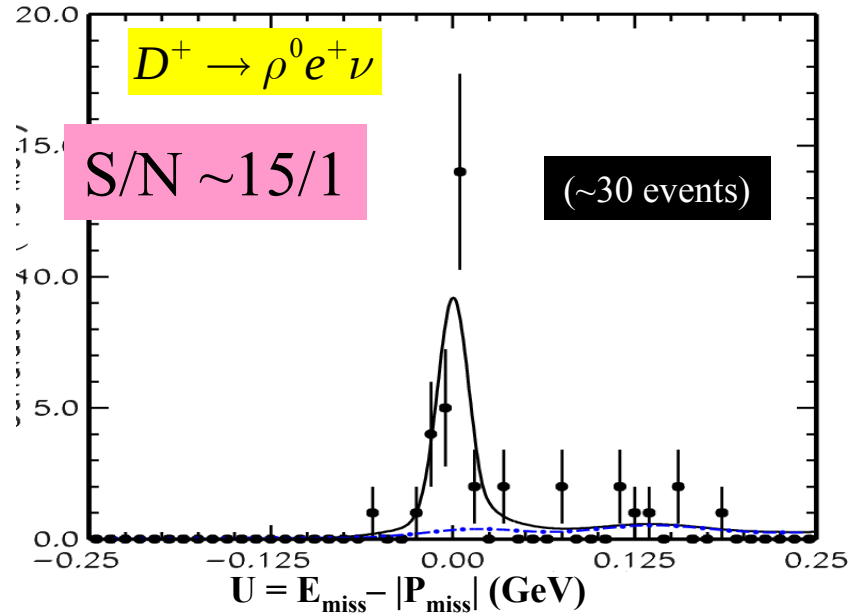
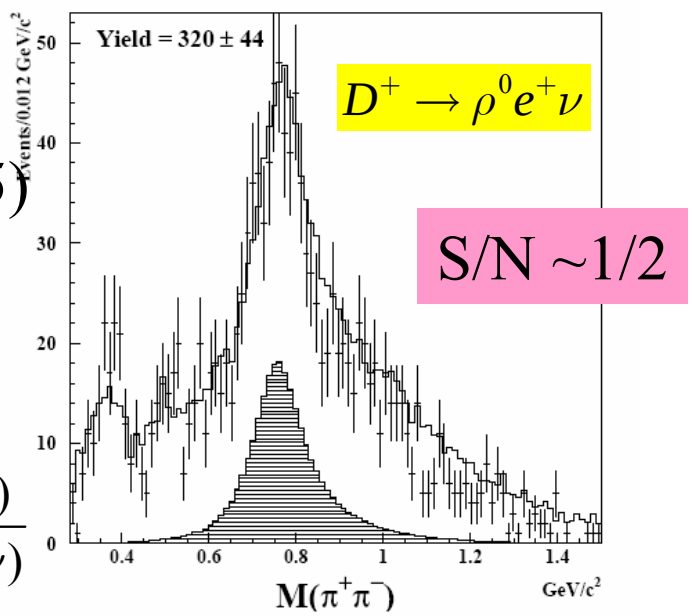
(1997)





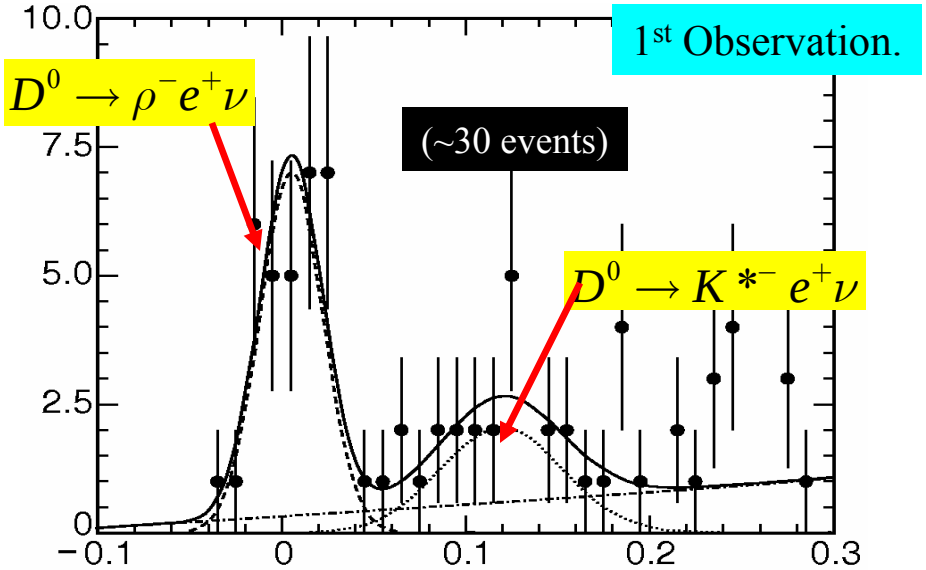
FOCUS
Hep-ex
/0511022
(Nov 2005)

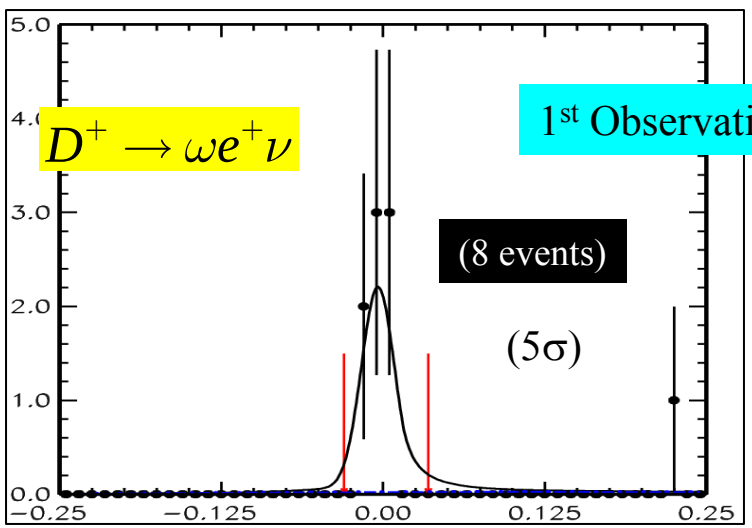


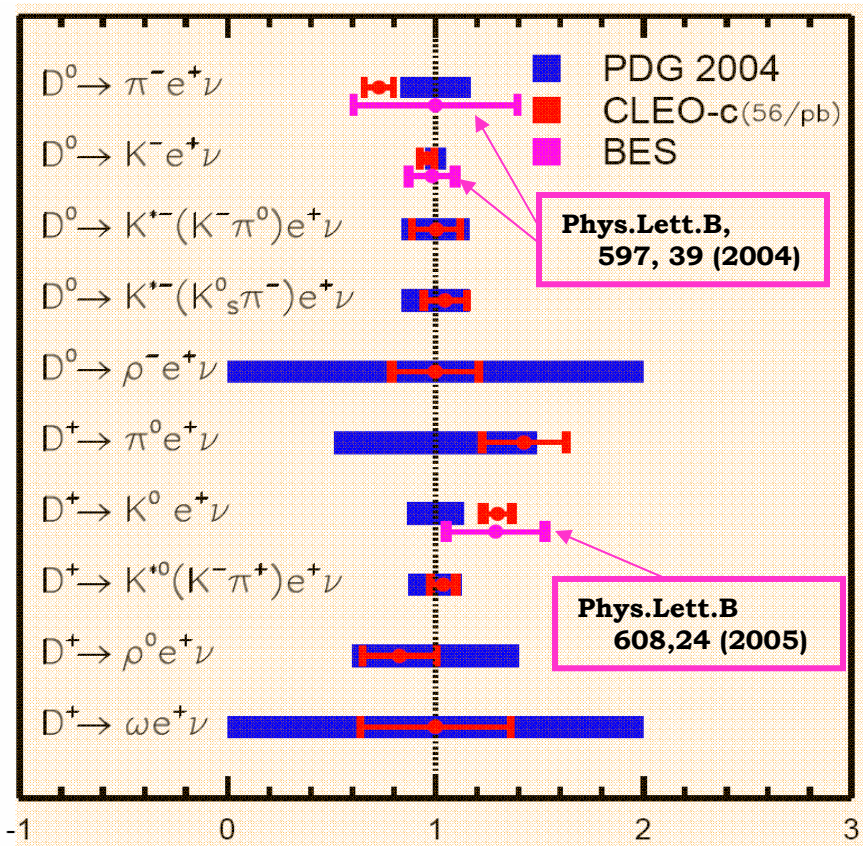
Relative Rate:

$$\frac{\Gamma(D^+ \to \rho^0 e^+ \nu)}{\Gamma(D^+ \to K^{*0} e^+ \nu)}$$

Absolute BF for *D* semileptonic decays with 1/10th data set





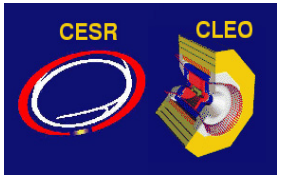


Normalized to PDG

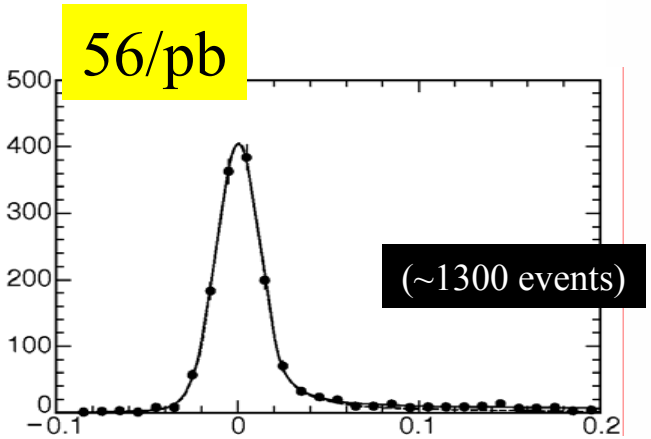
CLEO-c the most precise BF for ALL modes

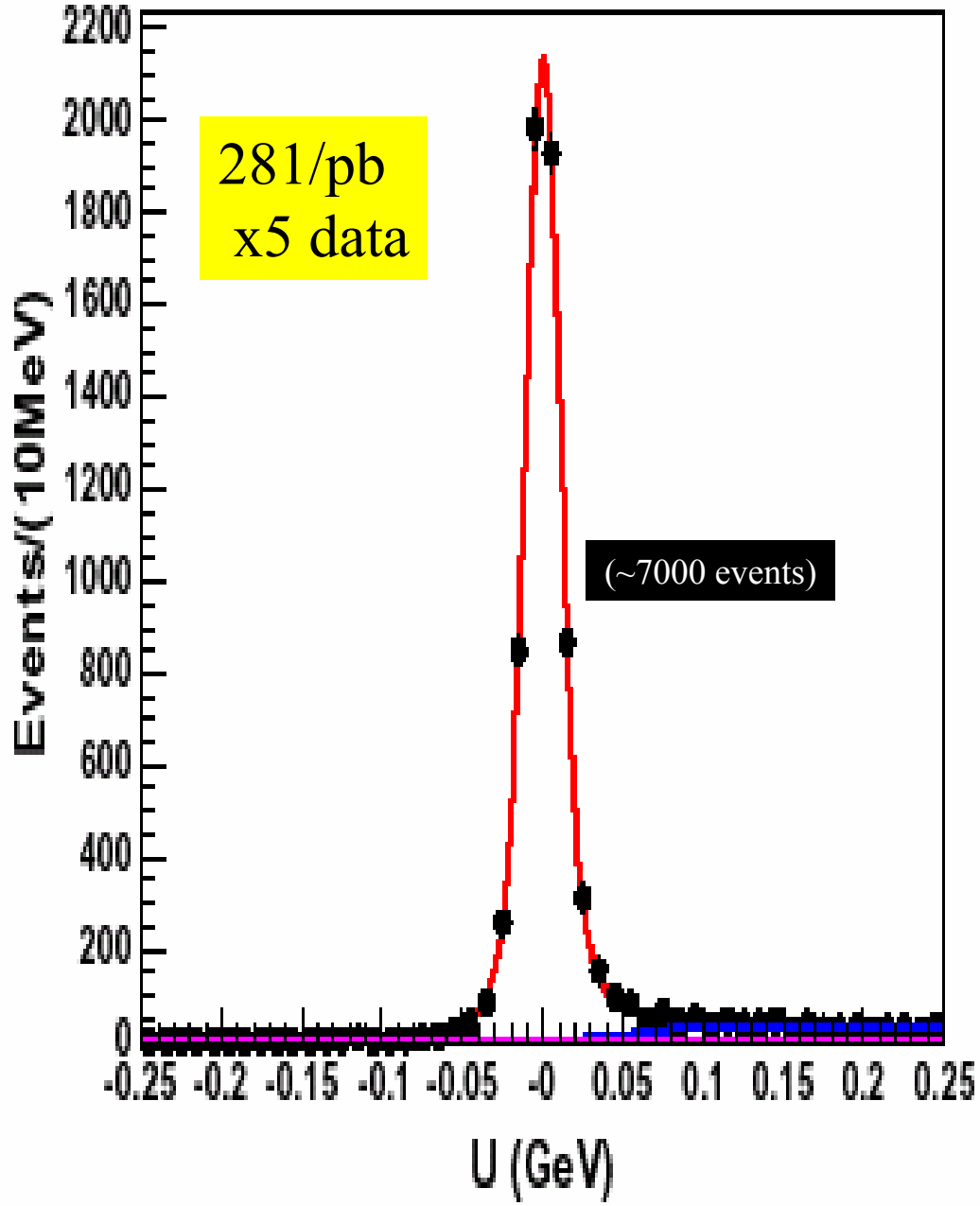
References:
PRL 95, 181801 (2005);
PRL 95, 181802 (2005)

With x5 data BF's i.e. counting → detailed dynamical studies



$$D^0 \rightarrow K^- e^+ \nu$$

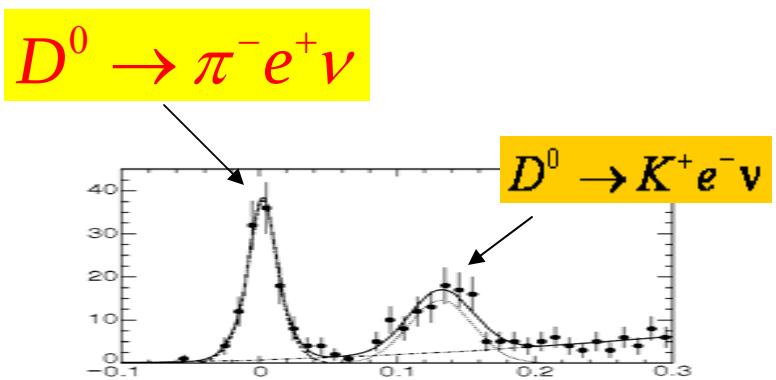


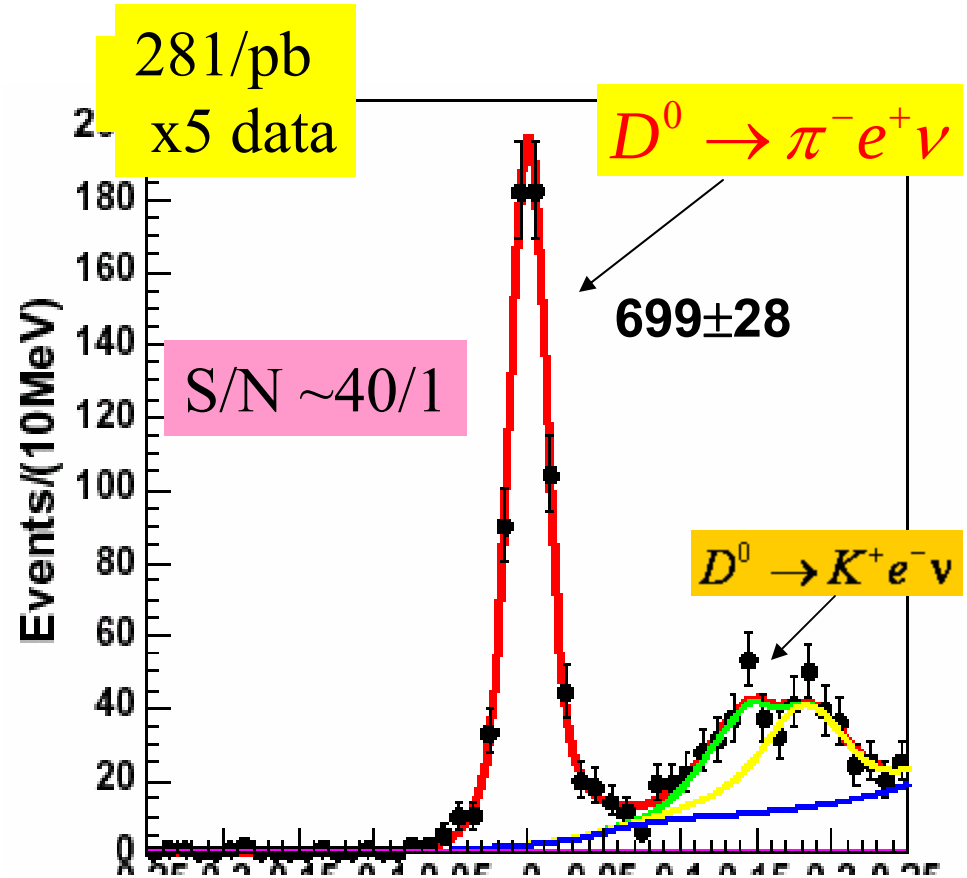


With x5 data BF's i.e. counting → detailed dynamical studies

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

56/pb





$U = E_{miss} - |P_{miss}|$ (GeV)

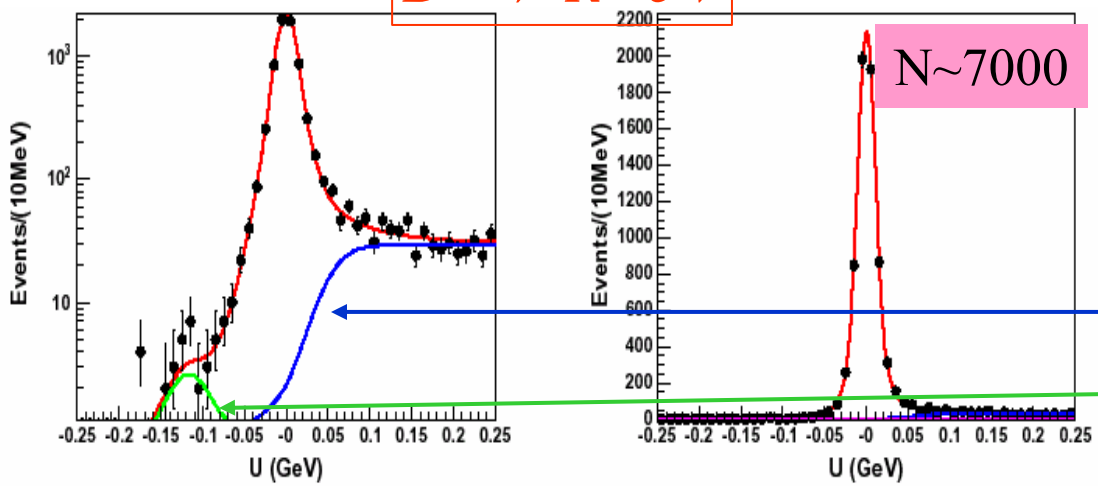
With x5 data BF's i.e. counting → detailed dynamical studies

Example of Fits to U $D^0 \to K^- / \pi^- e^+ \nu$

Log

Linear

$D^0 \to K^- e^+ \nu$

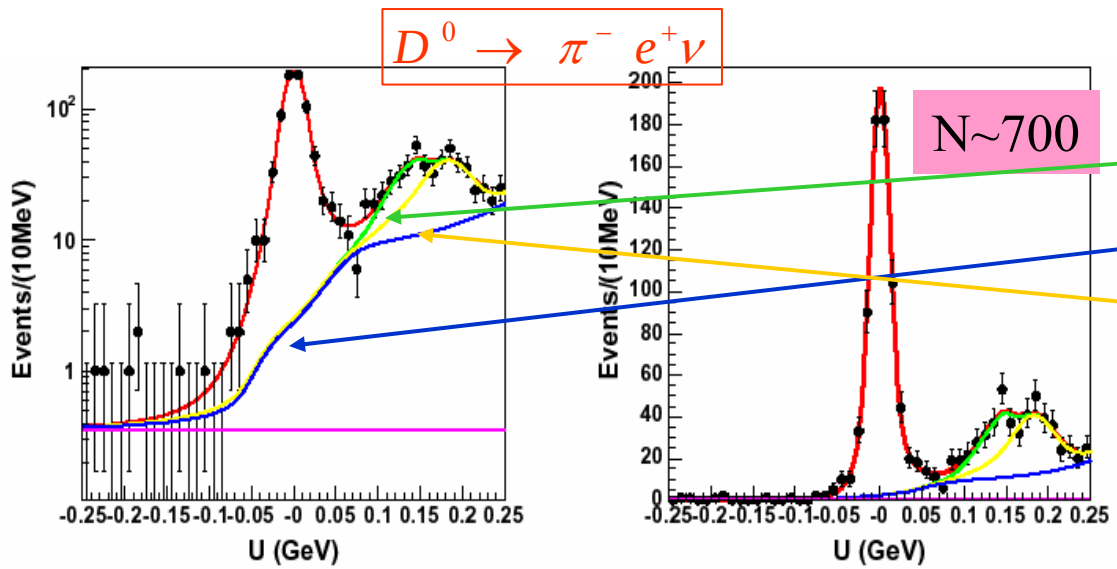


$$U = E_{miss} - \left| \vec{P}_{miss} \right|$$

Main backgrounds for $D^0 \to K^- e^+ \nu$

- $D^0 \to K^{*-}(K^-\pi^0)e^+\nu$
- $D^0 \to \pi^- e^+ \nu$

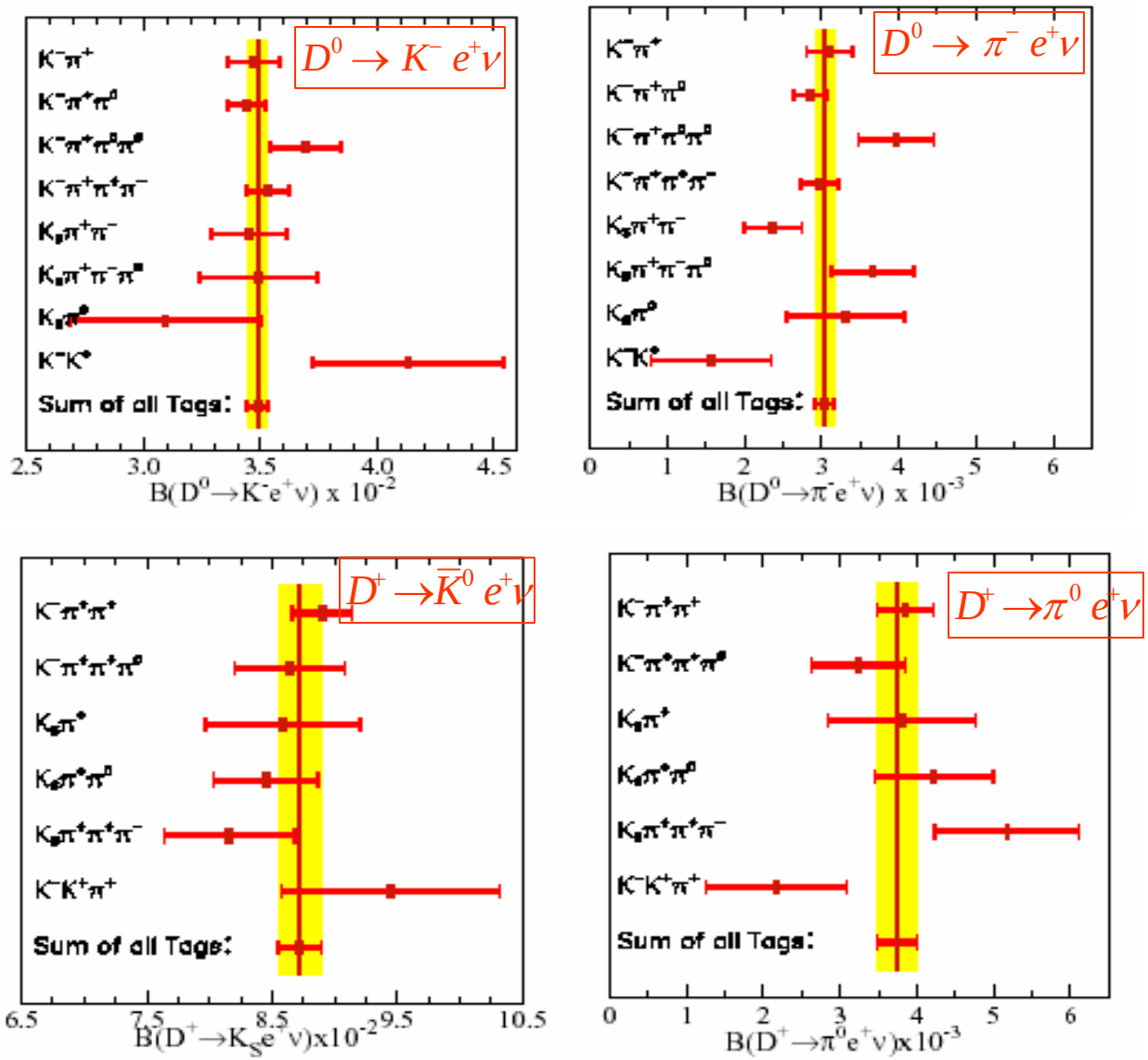
$D^0 \to \pi^- e^+ \nu$

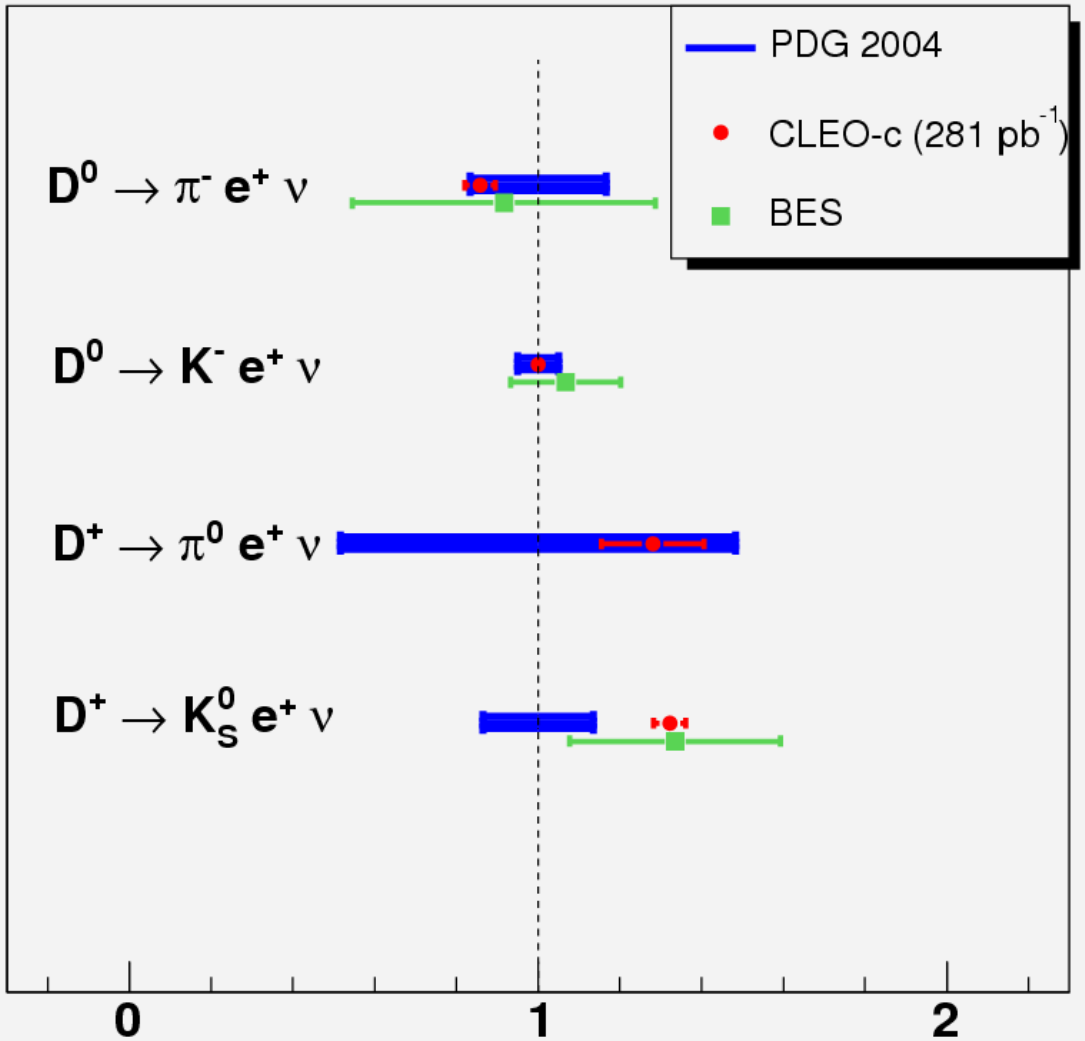


Main backgrounds for $D^0 \to \pi^- e^+ \nu$

- $D^0 \to K^- e^+ \nu$
- $D^0 \to \rho^-(\pi^-\pi^0)e^+\nu$
- Kaon fakes positron in D→ Kpipi0 or Kpi

Cross Check: Consistency of Branching Fractions by Tag Mode



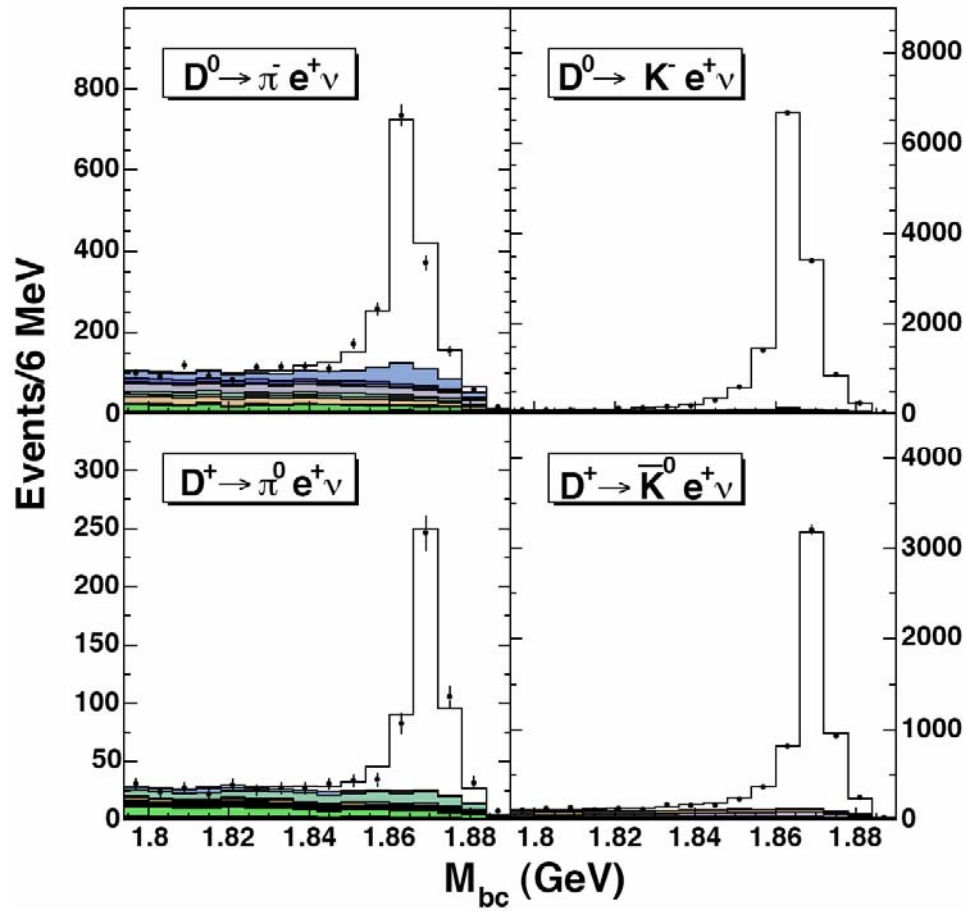


D Decay	Tag Br. Fra
$D^0 \to K^- e^+ \nu$	3.58±0.05±0.05
$D^0 \to \pi^- e^+ \nu$	0.309±0.012±0.006
$D^+ \to \bar{K}^0 e^+ \nu$	8.86±0.17±0.20
$D^+ \to \pi^0 e^+ \nu$	0.397±0.027±0.028

Dominant systematic uncertainties:
electron ID, track finding,
FSR, number of tags

CLEO-c results untagged analysis

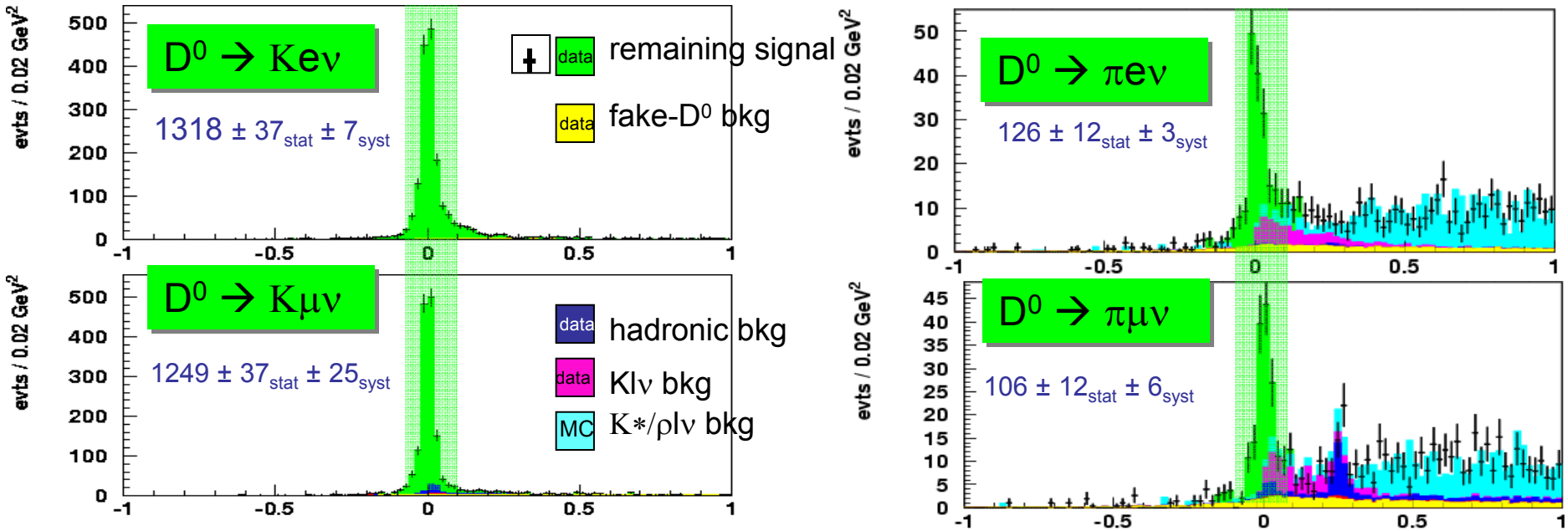
- Unspecified other side D decay, collect other showers and tracks
- Use neutrino reconstruction like $B \to \pi/\rho\, \ell\nu$ at Y(4S)
- Higher statistical accuracy, larger systematic uncertainty
- Tag and untag samples overlap



$D^0 \to K/\pi\ e/\mu\nu$ Belle (282 fb^{-1})

Fully re-contruct $e^+e^- \to \bar{c}c$ at 10 GeV

A first!

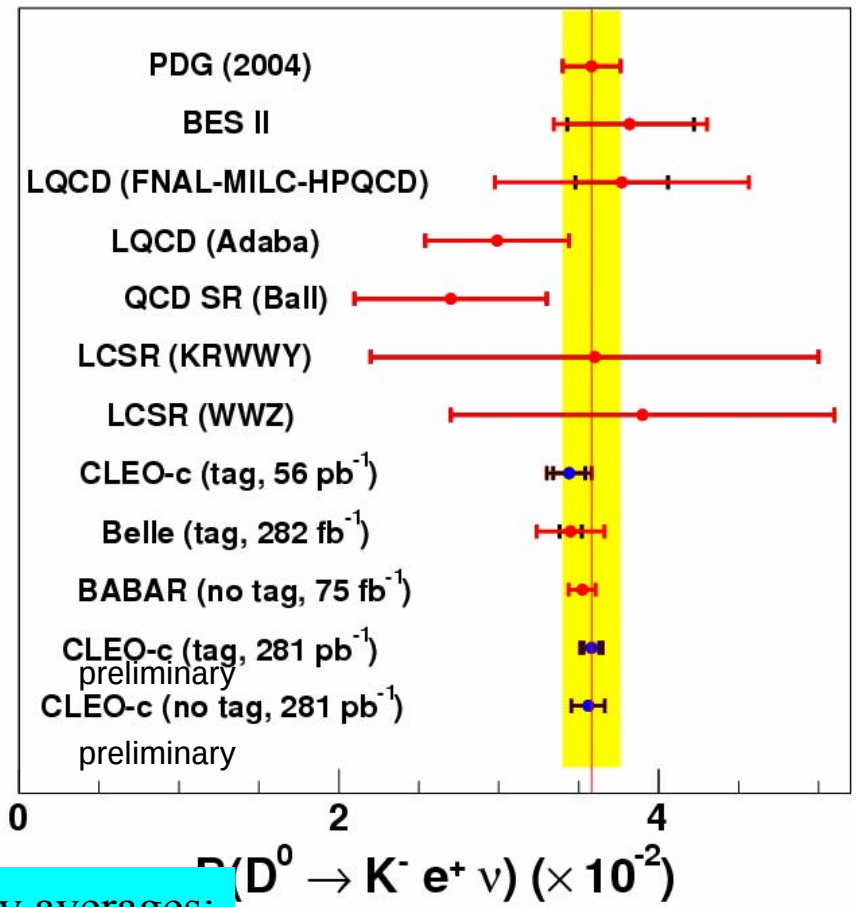


- Tagged $e^+ e^- \to D^{(*)}_{tag} D^{*-} X$ events (about 56×10^3 tags)
- Similar to the CLEO-c tagged analysis- an *absolute* measurement

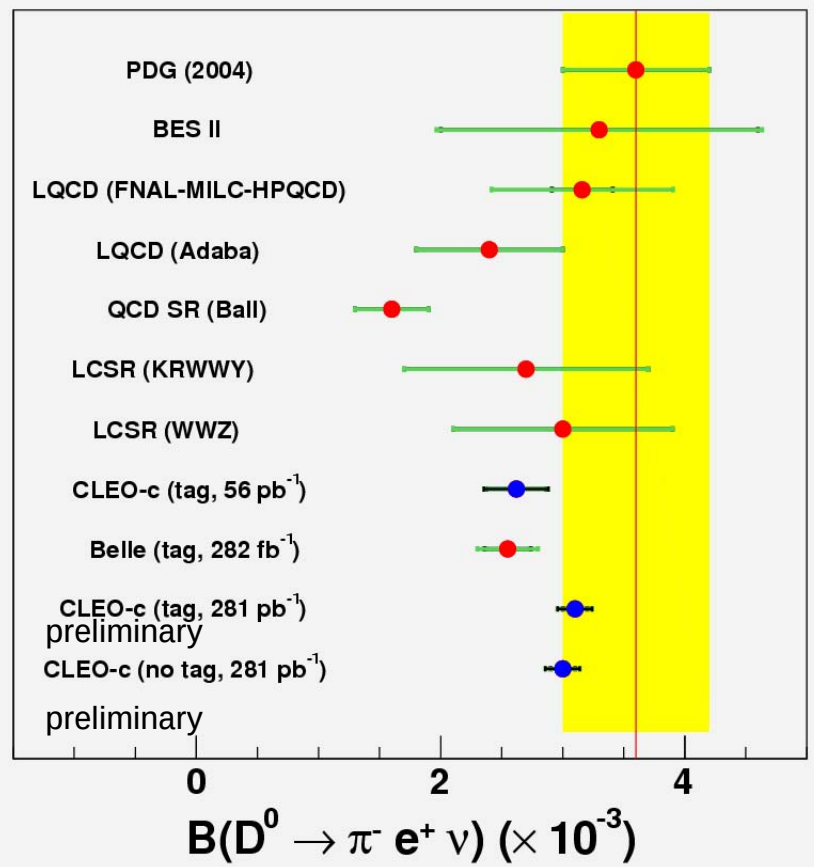
1/7 statistics of CLEO-c with 1000x Luminosity

D →K, π eν Branching Fractions

$D \to K\, e^+ \nu$



$D \to \pi\, e^+ \nu$



My averages:

$$B(D \to K^- e\nu) = (3.555 \pm 0.050)\%$$

$$B(D^0 \to \pi^- l^+ \nu) = (2.99 \pm 0.12) \times 10^{-3}$$

Significant recent increase in precision.
Good consistency between measurements
Theoretical precision lags experiment

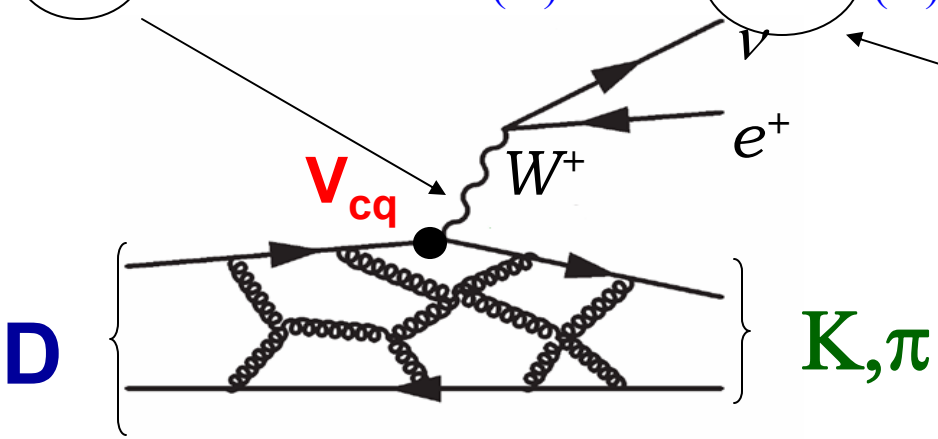
Semileptonic Decay Form Factors

$$M(D^0 \to \pi^- l^+ \nu) = -i \frac{G_{Fermi}}{\sqrt{2}} V_{cd}\, L_\mu\, H^\mu$$

$$q^2 = m_D^2 + m_{K(\pi)}^2 - 2 m_D E_{K(\pi)}$$

Squared 4-momentum transfer

In D rest frame



Matrix element expressed as form-factors (for D→Pseudoscalar $\ell^+\nu$)

simplest case for expt. and theory

$$H^\mu = \left\langle P(P_D) \middle| J_\mu \middle| D(P_{K,\pi}) \right\rangle = f_+(q^2)(P_{K,\pi} + P_D)_\mu + f_-(q^2)(P_{K,\pi} - P_D)_\mu$$

For ℓ = e, $f_-(q^2) \to 0$:

$$\frac{d\Gamma\left(D^+ \to K,\pi e \nu\right)}{dq^2} = \frac{G_F^2}{24\pi^3} P_{K,\pi}^3 \left| f_+(q^2) \right|^2 \left| V_{cs,d} \right|^2$$

form factor measures probability final state hadron will be formed

"Form factors are the most fundamental dynamical quantities for describing the inner properties of a composite particle.." -- *CERN Courier*, April 2006

Form Factor Parameterizations

Measure: $$\frac{d\Gamma\left(D^+ \to Ke\nu\right)}{dq^2} = \frac{G_F^2}{24\pi^3} P_{K,\pi}^3 \left| f_+(q^2) \right|^2 \left| V_{cs} \right|^2$$

Models

- Single pole $$f_+(q^2) = \frac{f_+(0)}{\left(1 - q^2/m_{pole}^2\right)} \qquad m_{pole} = m(D_S^*)$$
- Modified Pole $$f_+(q^2) = \frac{f_+(0)}{\left(1 - q^2/m_{pole}^2\right)\left(1 - \alpha\, q^2/m_{pole}^2\right)}$$

(Allows for additional poles)

Model independent

- Series Expansion *Hill & Becher, Phys. Lett. B 633, 61 (2006)*

the function $z(q^2, t_0) = \dfrac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$ $\quad t \equiv q^2 = (P_D - P_K)^2 \quad t_\pm \equiv \left(M_D \pm m_K\right)^2,$

z small, converges rapidly → linear or quadratic sufficient

maps the physical q^2 region into $0<z<0.1$: $D \to Ke\nu$

form factors can be written as: $$f_+(q^2) = \frac{1}{P(q^2)\phi(q^2)} \sum_{k=0}^{\infty} a_k(t_0)[z(q^2, t_0)]^k$$

accounts for D_S^* pole

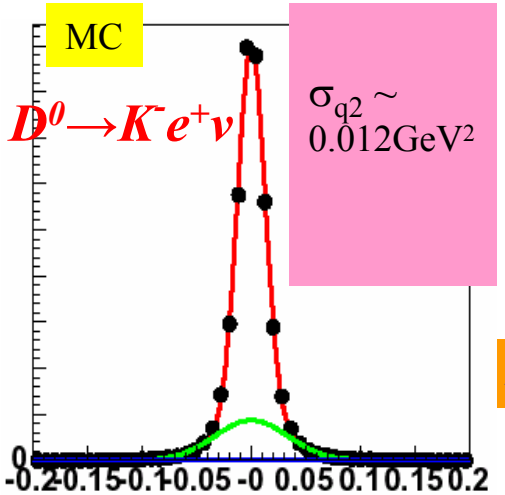
calculable function to make a_K's look simple

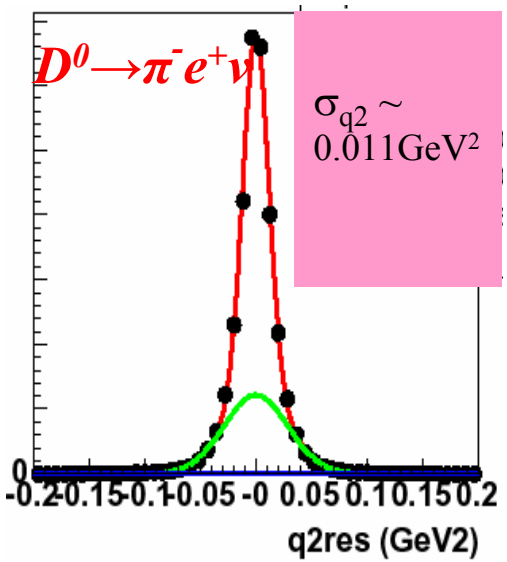
q^2 reconstrruction

Tagged analysis

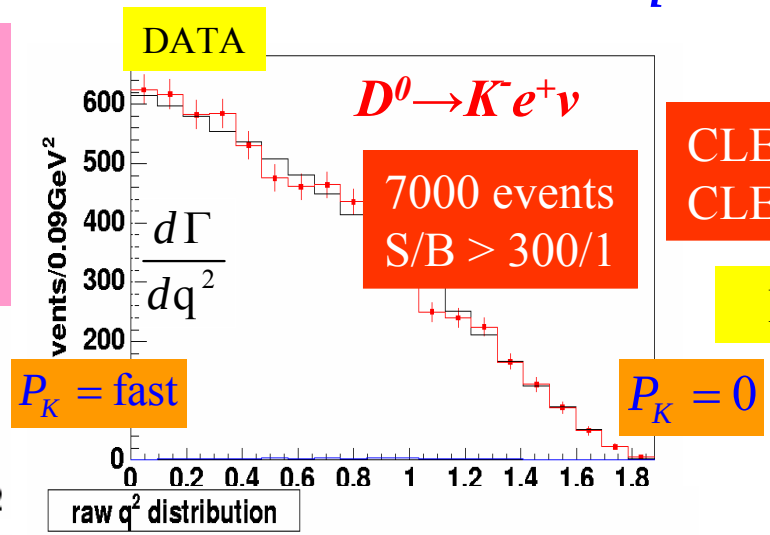
$$q^2 = m_D^2 + m_{K(\pi)}^2 - 2m_D E_{K(\pi)}$$

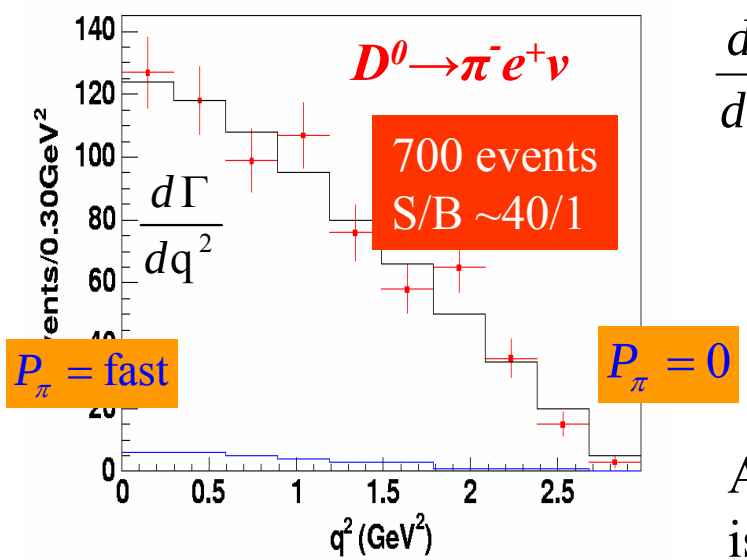
q^2 resolution





Raw q^2 distribution





CLEOIII(Y(4S): $\delta q^2 \sim 0.4$ GeV^2
CLEO-c(ψ(3770)): $\delta q^2 \sim 0.012$GeV^2

Belle$\sigma(q^2)$ = 0.0145 GeV²/c²

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} P_{K,\pi}^3 \left| f_+(q^2) \right|^2 \left| V_{cs} \right|^2$$

$0^- \to 0^-1$ *i.e.* P-wave

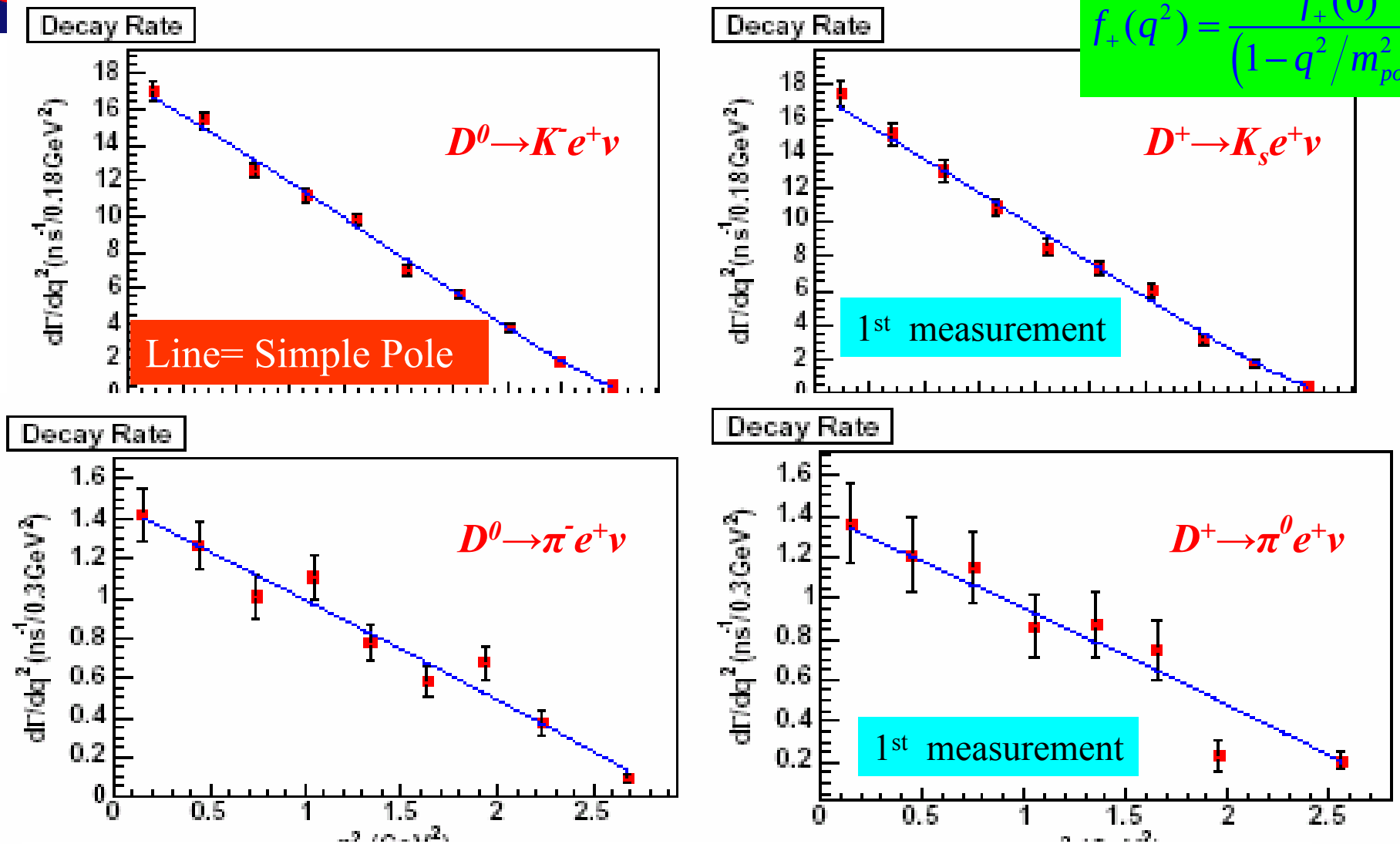
A de-convolution matrix is used to correct data for resolution and efficiency→

background in blue

PRELIMINARY

Absolute $d\Gamma / dq^2$ distributions

$$f_+(q^2) = \frac{f_+(0)}{\left(1 - q^2 / m^2_{pole}\right)}$$

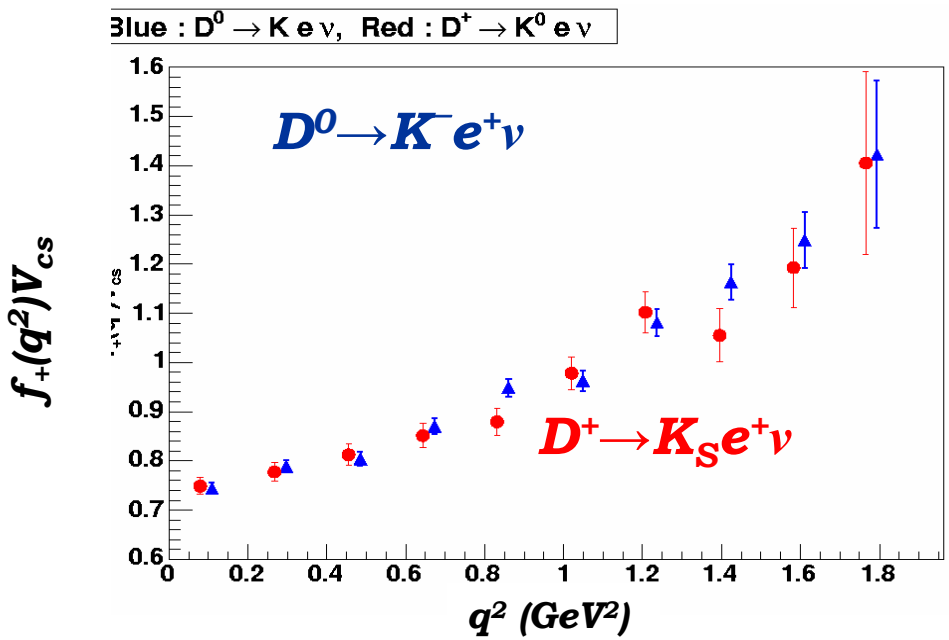


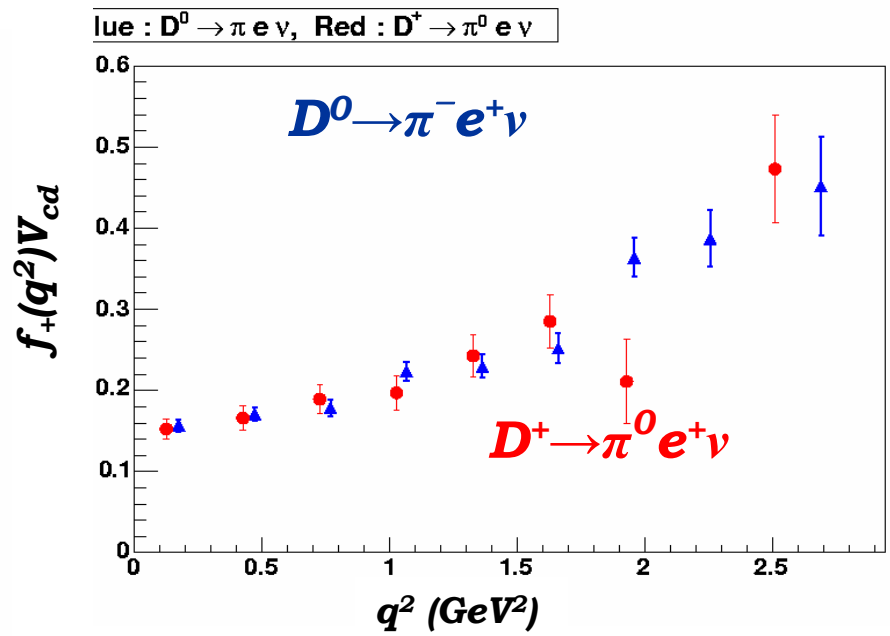
Background subtracted efficiency corrected absolute $d\Gamma / dq^2$ distributions. are simultaneously fit for sospin conjugate pairs

$$\left|V_{cs(cd)}\right|\left|f_+(q^2)\right|$$

Removing the kinematic terms reveals the form factor (which varies by only a factor ~2 (~3) across phase space for Keν ($\pi e\nu$))

$$\left|V_{cs(cd)}\right|\left|f_+(q^2)\right| \sim \left[\frac{\Delta\Gamma_i(D\to K(\pi)e\nu)}{\Delta q_i^2} / P^3_{K(\pi)i}\right]^{1/2}$$

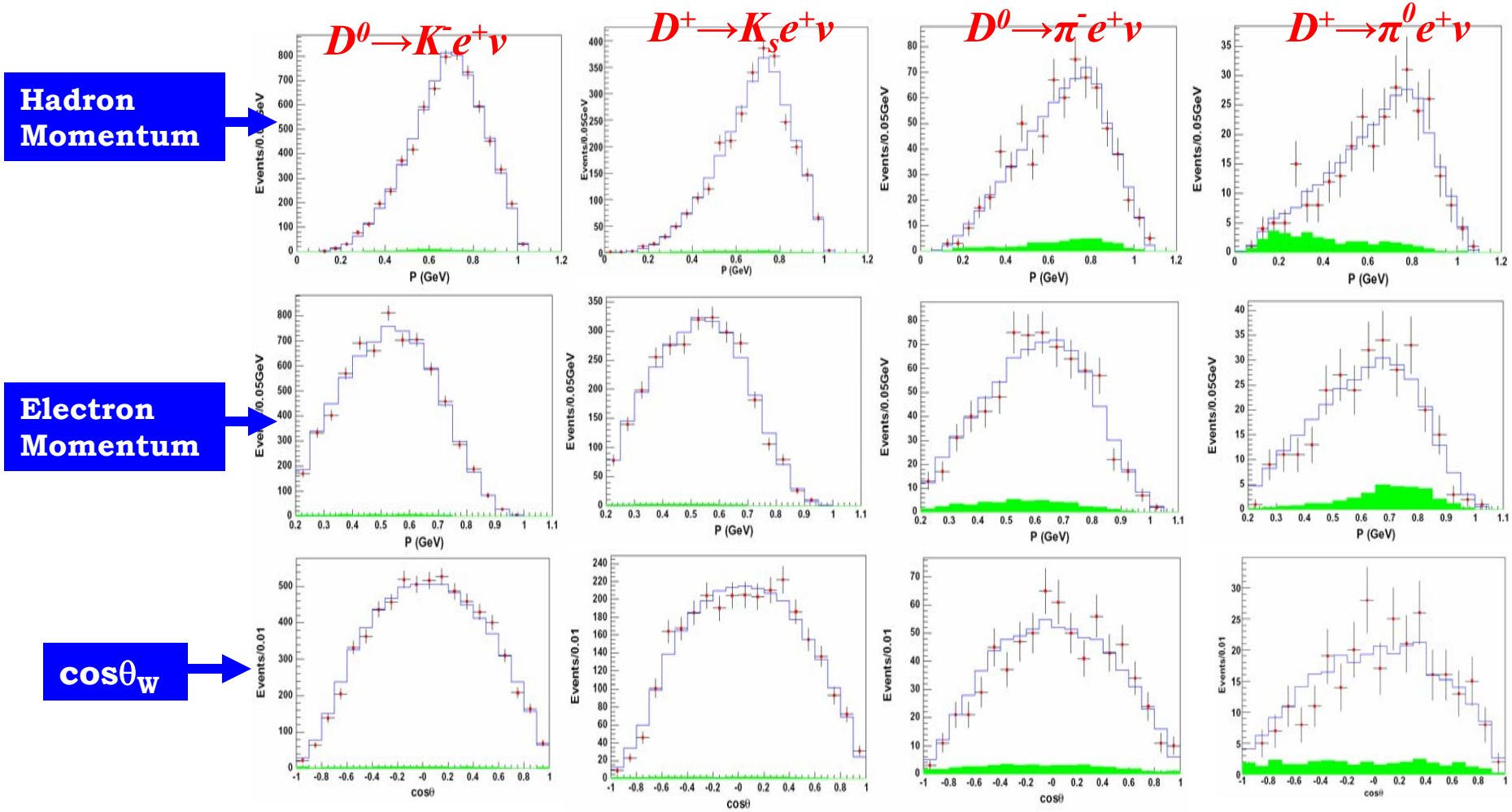




The q^2 spectra for isospin conjugate modes are consistent which provides a *unique* and powerful cross check

Data Cross Check: Other Observables

- Other observables not constrained in the fit are in good agreement with the MC

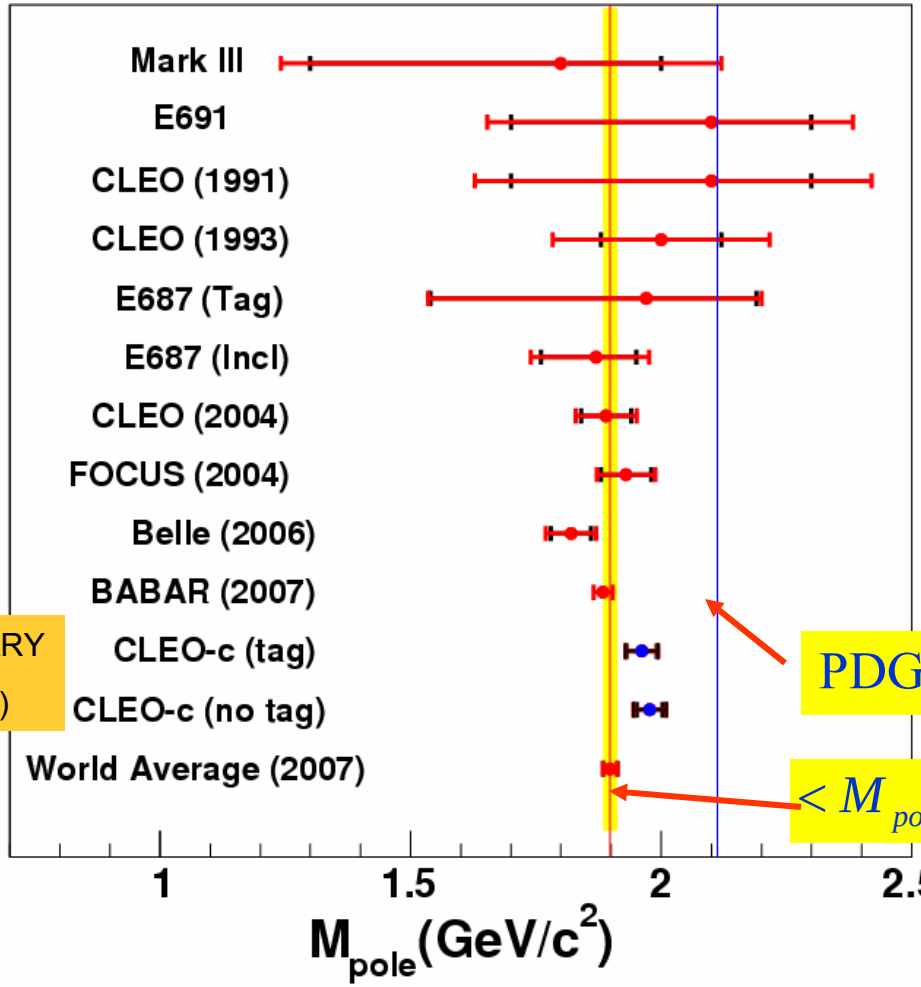


Background in green

$D \to K e^+ \nu$

M_{pole}

$$f_+(q^2) = \frac{f_+(0)}{\left(1 - q^2/m_{pole}^2\right)}$$



PRELIMINARY
(isospin avg)

pole model describes $D \to Ke\nu$ but not when the pole mass is the spectrocopic pole $M(D_S^*)$

$$\text{PDG}: M(D_S^*) = (2112.0 \pm 0.6)\text{MeV}$$

$$< M_{pole} = (1898 \pm 15)\text{MeV} >$$

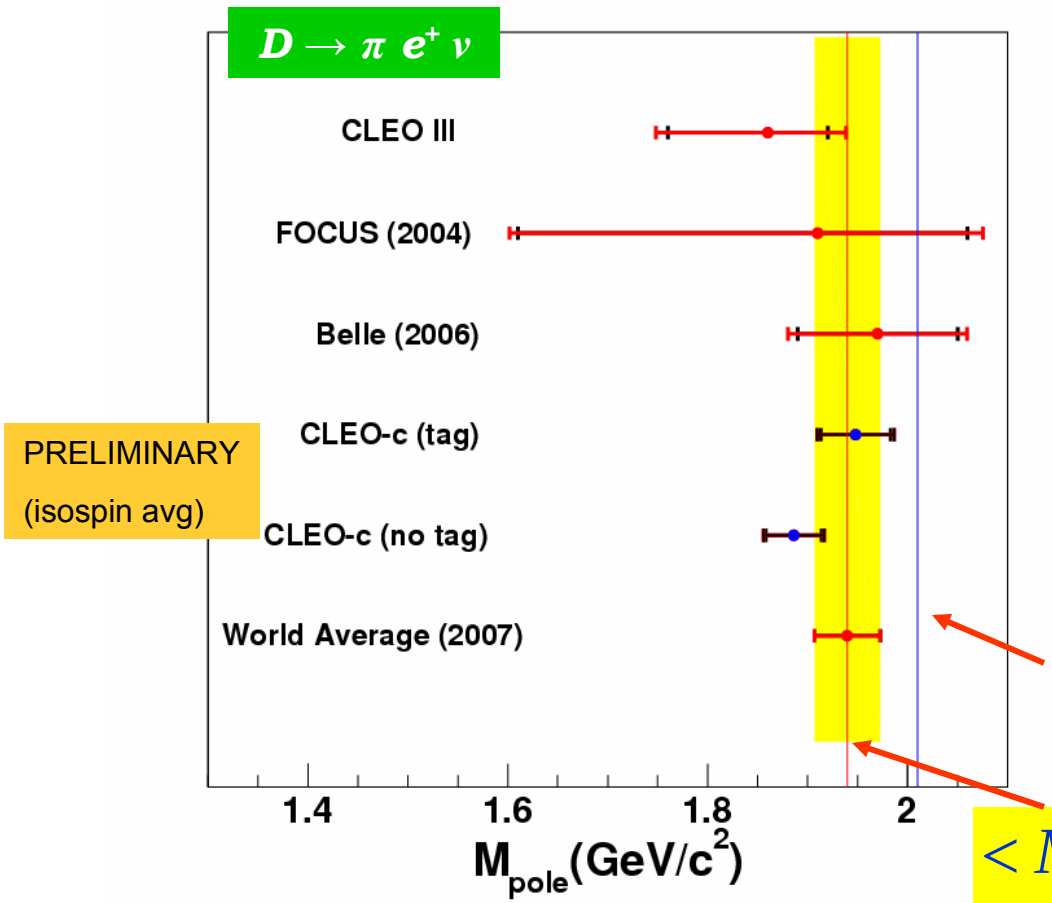
$\sim 14\sigma$ discrepancy

- CLEO-c 1st measurements of Mpole forr D^+ important consistency check
- BABAR most precise $D \to Ke^+\nu$

[CLEO-c tag used in world average]

M_{pole}

$$f_+(q^2) = \frac{f_+(0)}{\left(1 - q^2/m_{pole}^2\right)}$$



PRELIMINARY
(isospin avg)

pole model describes $D \to \pi e \nu$
all measurements of pole mass
lower than spectrocopic pole $M(D^*)$
but limited statistics $\to$ more data

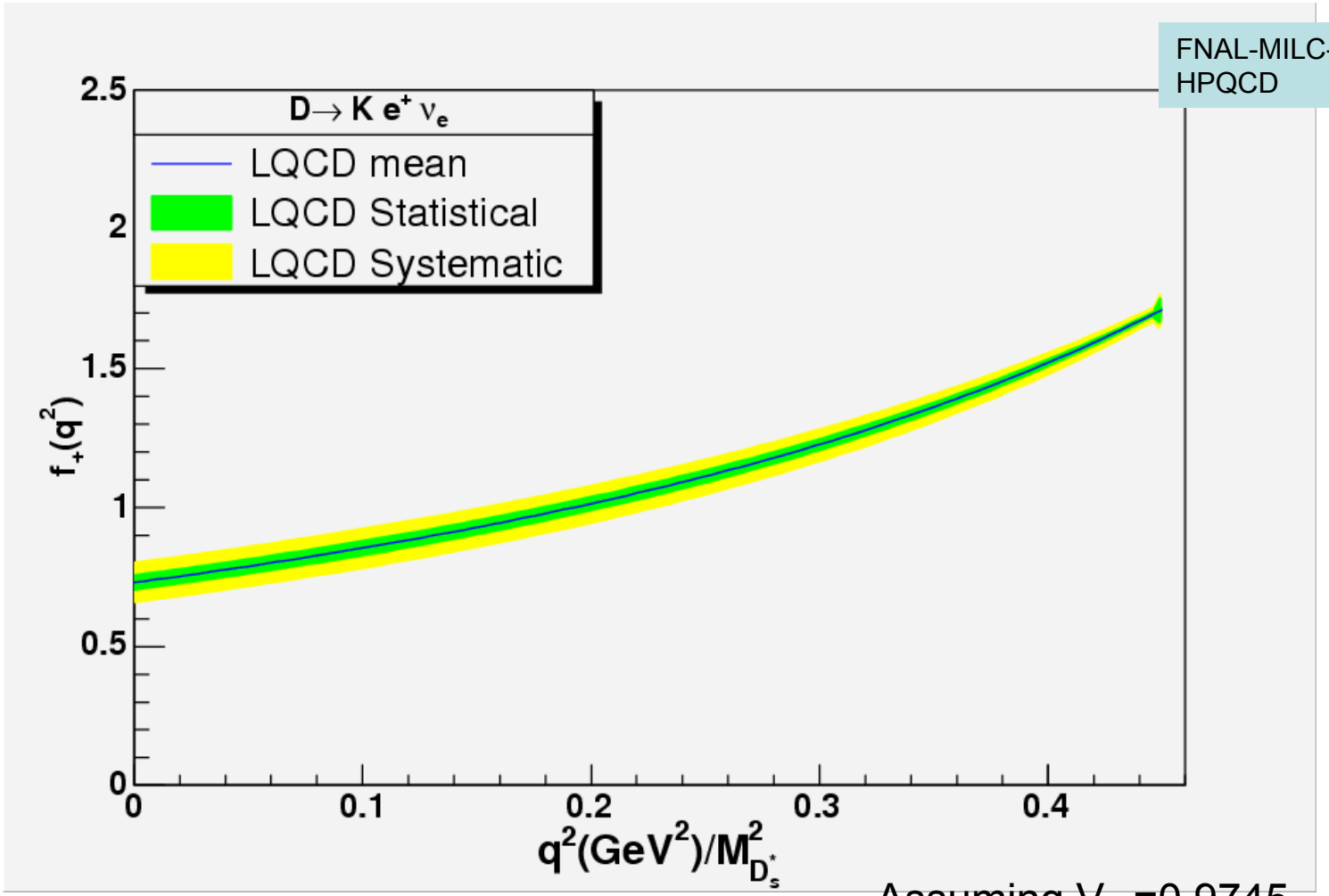
$$\text{PDG}: M(D^*) = (2010.0 \pm 0.4)\text{MeV}$$

$$< M_{pole} = (1940 \pm 33)\text{MeV} >$$

- CLEO-c 1st measurements of Mpole D^+
- CLEO-c is most precise $D \to \pi e^+ \nu$

[CLEO-c tag used in world average]

Lattice Prediction shape *and* absolute normalization

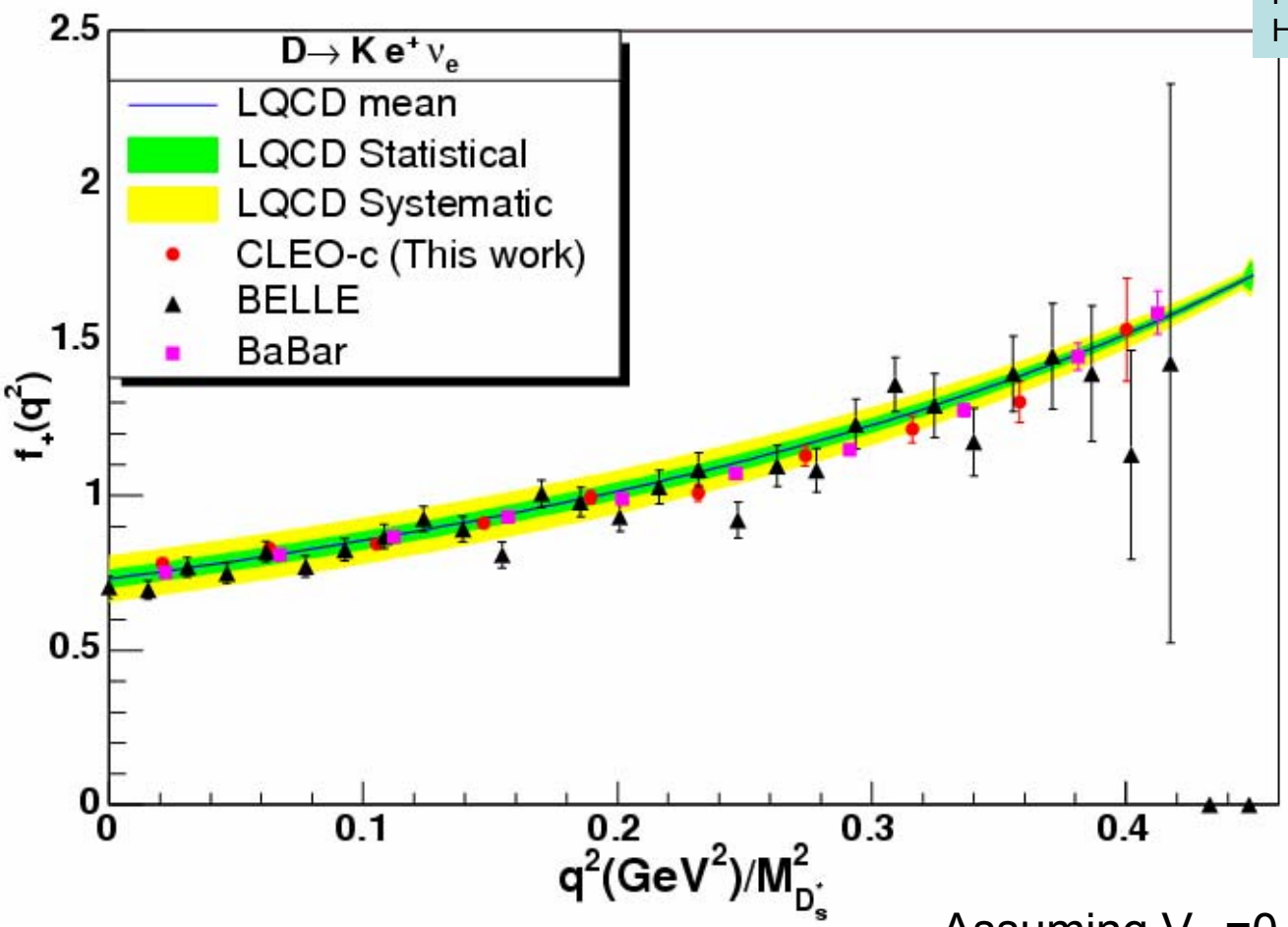


Assuming V_{cs}=0.9745

Curve courtesy Andreaas Kronfeld

Lattice Prediction shape *and* absolute normalization $f_+(q^2)$

FNAL-MILC-HPQCD



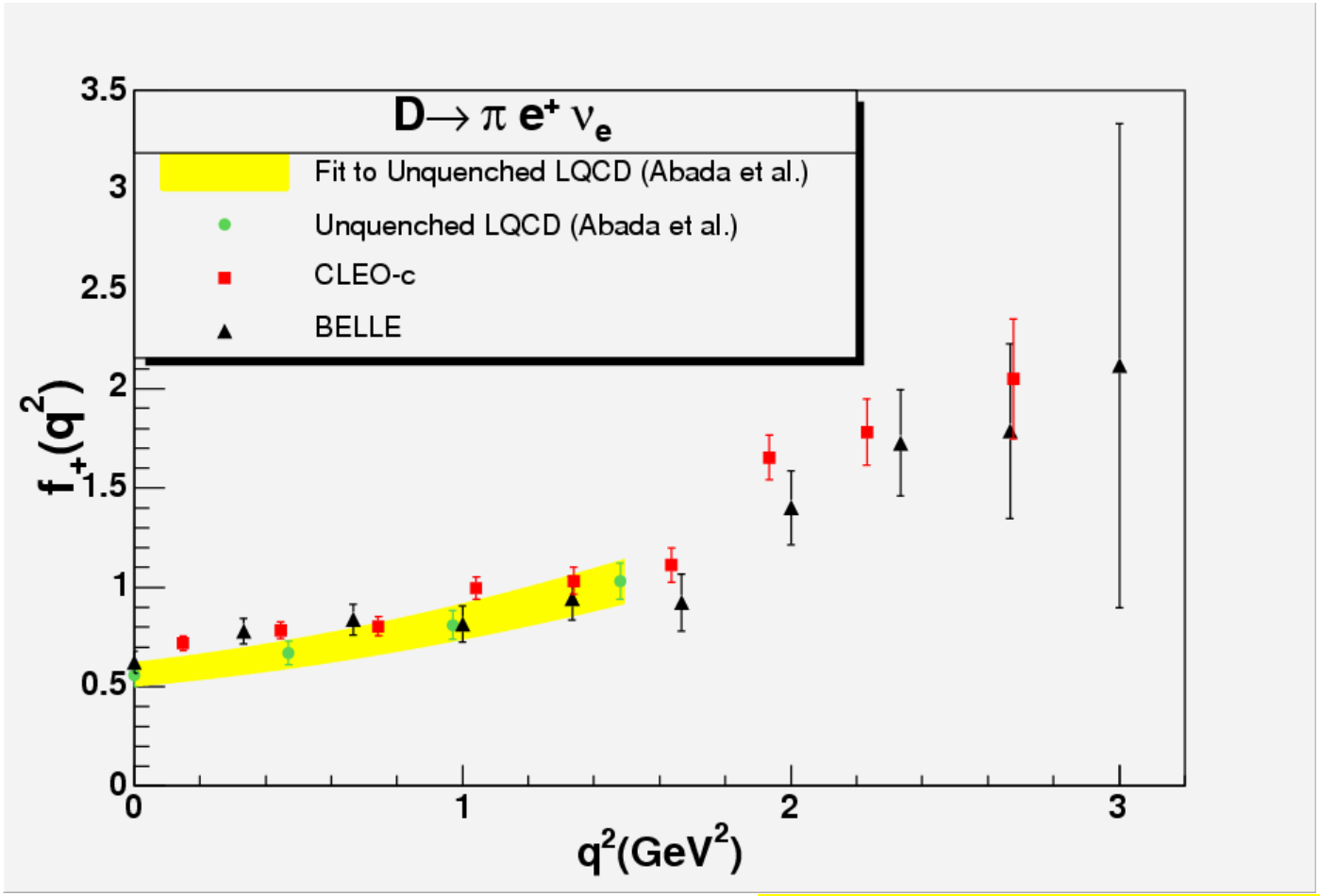
Assuming V_{cs}=0.9745

Curve courtesy Andreaas Kronfeld

Absolute shape and normalization validation

Normalization Precision: experiment 2% Lattice 10%

Lattice Prediction shape *and* absolute normalization $f_+(q^2)$

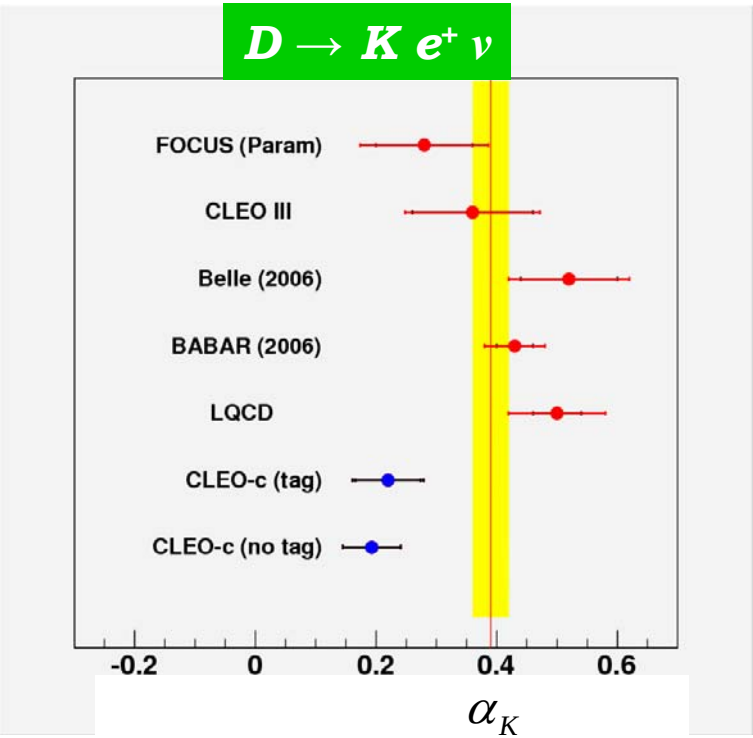


Assuming V_{cd} = 0.2238±0.0029

Absolute normalization validation

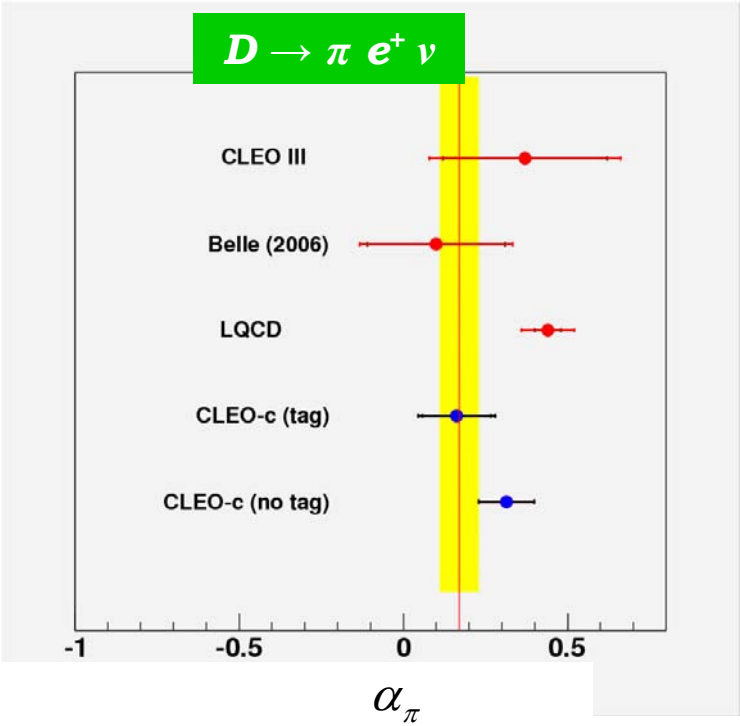
Precision: experiment 4% Lattice 10%

Test of LQCD FNAL-MILC-HPQCD *shape* predictions



LQCD $0.50 \pm 0.04 \pm$ syst.

world avg 0.40 ± 0.02



LQCD $0.44 \pm 0.04 \pm$ syst.

world avg 0.17 ± 0.06

FNAL-MILC-HPQCD uses mod. pole model To fit for form factor from "calculated"points at fixed q^2

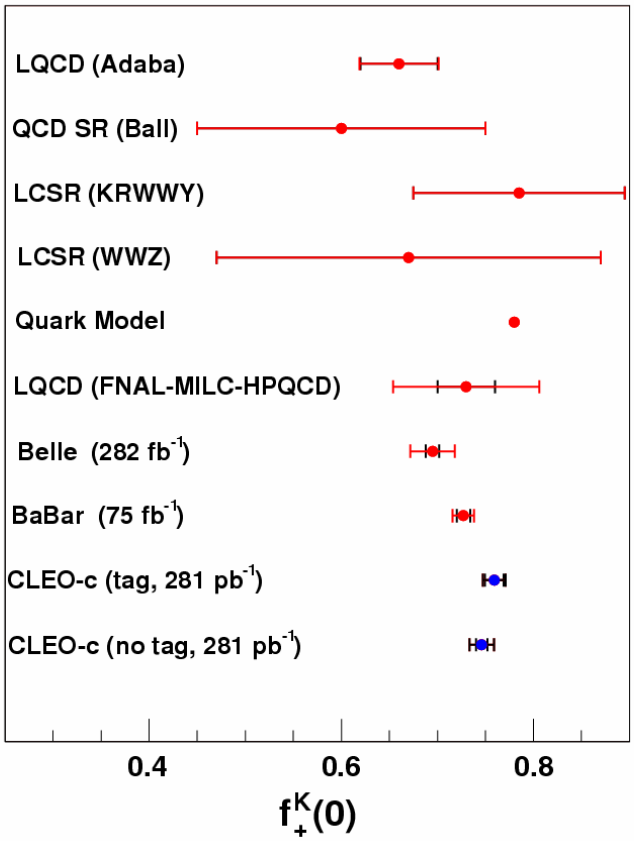
CLEO-c low compared to LQCD (Kev) but world average is consistent with LQCD

my world avg from fit to all expt $f_+(q^2)$ distributions

Validation of lattice shape prediction to ~10% for $Ke\nu$, $\pi e \nu$ ~30% → need more data

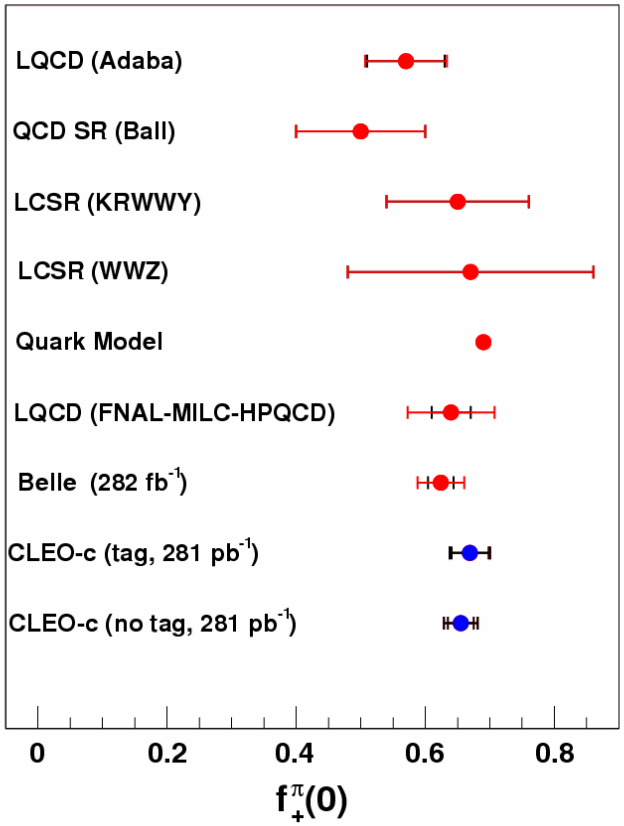
Tests of Theory/LQCD Form Factor *Normalization*

$$D^0 \to K^- e^+ \nu$$



Assuming V_{cs}=0.9745

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



Assuming V_{cd} = 0.2238

Excellent consistency
between measurements & Theory

Theoretical precision lags.

Becher-Hill Parameterization

PRELIMINARY

Hill & Becher, Phys. Lett. B 633, 61 (2006)

*Advantages include: model independent,

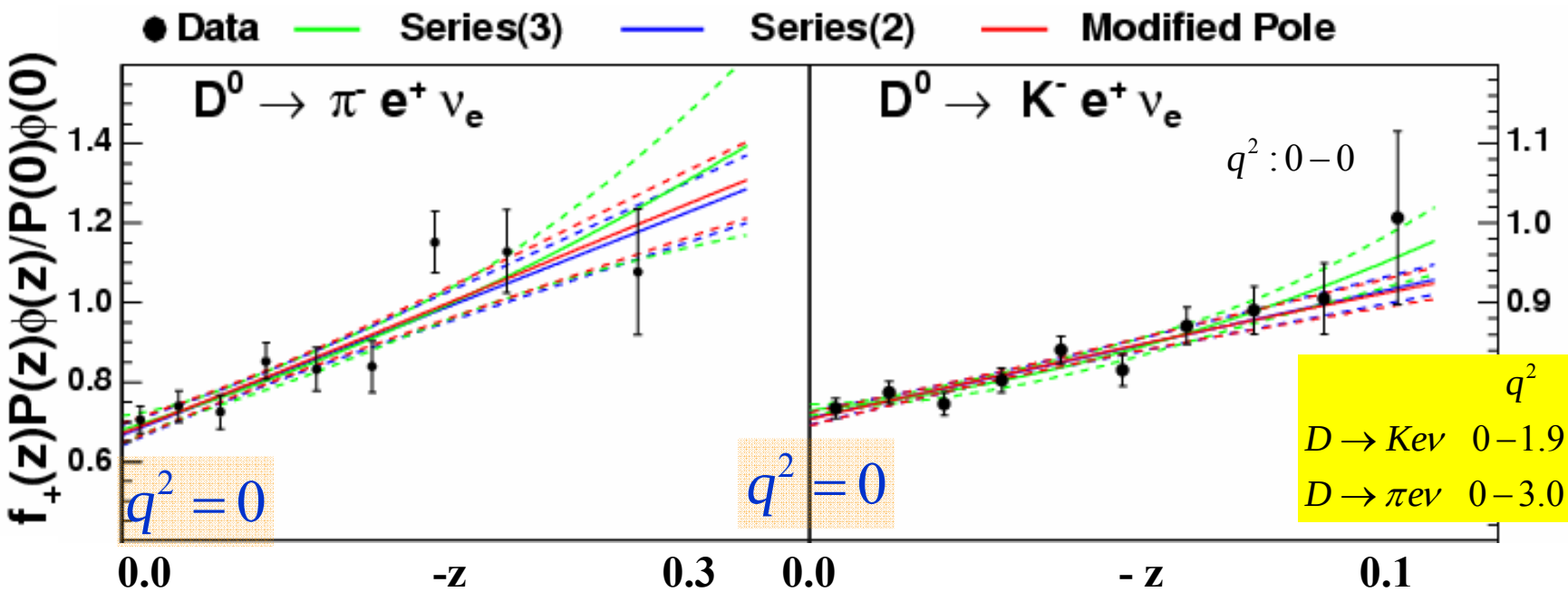
*shape variable "physically meaningful" slope at $q^2=0$

(1) Facilitates: future expt. test of LQCD (FNAL-MILC-HPCQD now using it) .

(2) D/B Measurements: the a_i in D→π constrain class of form factors needed to fit B→π hence improve determination of Vub

(3) In HQET direct relations between a_i in D and B

$$f_+(z) \propto f_+(0)[1+\frac{a_1}{a_0}z+\frac{a_2}{a_0}z^2]$$



	q^2	z
$D \to Ke\nu$	$0-1.9$	$0-0.1$
$D \to \pi e\nu$	$0-3.0$	$0-0.33$

Parameterization describes data well Linear "Series(2)" consistent with modified pole. Quadratic "Series(3)" a_2 not well- determined with current statistics.

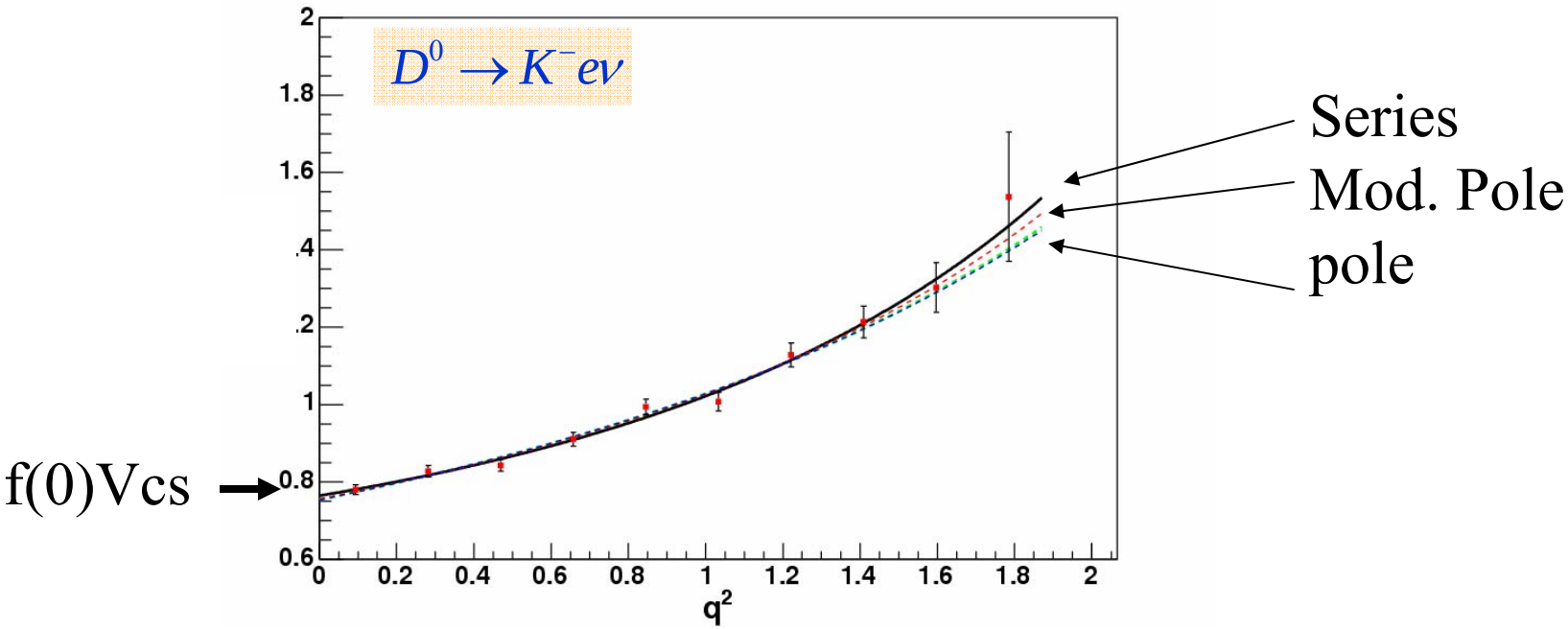
Prior V_{cs} Determination

	V_{cs}	Uncertainty (%) exp.	thy.	tot.
1)$PDG\,\Gamma(Kev)$	1.04 ± 0.16	6	14.2	15.4
2)$BESII\,\Gamma(Kev)$	$1.14 \pm 0.07 \pm 0.11$	6.5	10.4	12.8
3)$W \rightarrow cs$	$0.94^{+0.32}_{-0.26} \pm 0.14$			31

- 1) Kev total rate before CLEO-c (PDG02)
- 2) Kev total rate BESII
- 3) DELPHI tagged $W^+ \rightarrow c\bar{s}$
- *Note PDG 06 cites Vcs using CLEO-c Kev total rate based on smaller CLEO-c data. Result presented here which is a fit, supercedes it.*

D → π/Keν determination of Vcs & Vcd

Need to select one parameterization to measure intercept & determine f(0)Vcs then use theory value of f(0) to obtain Vcs

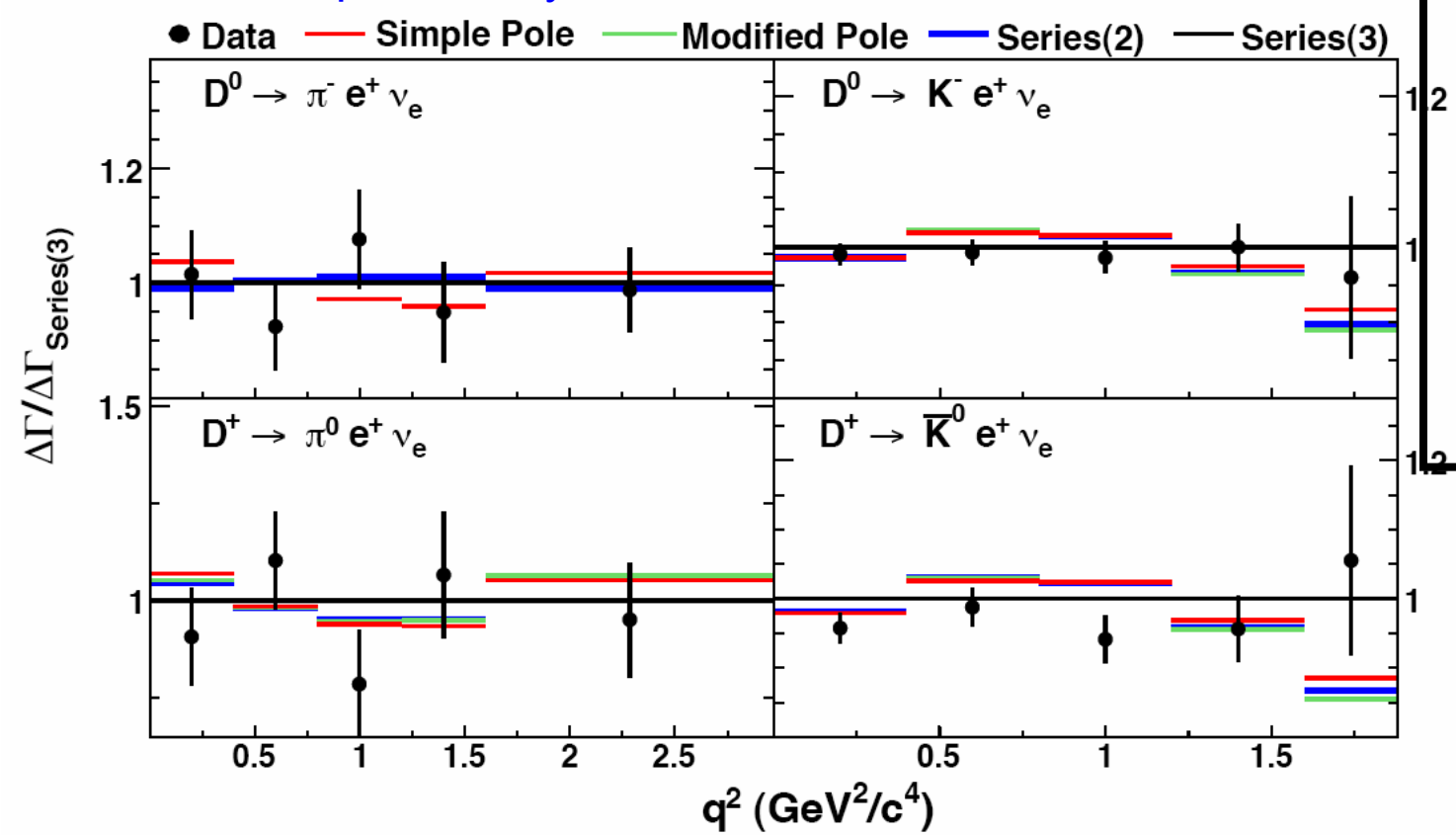


All parameterizations describe the data

$D \to \pi/K e\nu$ Which Form Factor Parameterization?

PRELIMINARY

CLEO preliminary

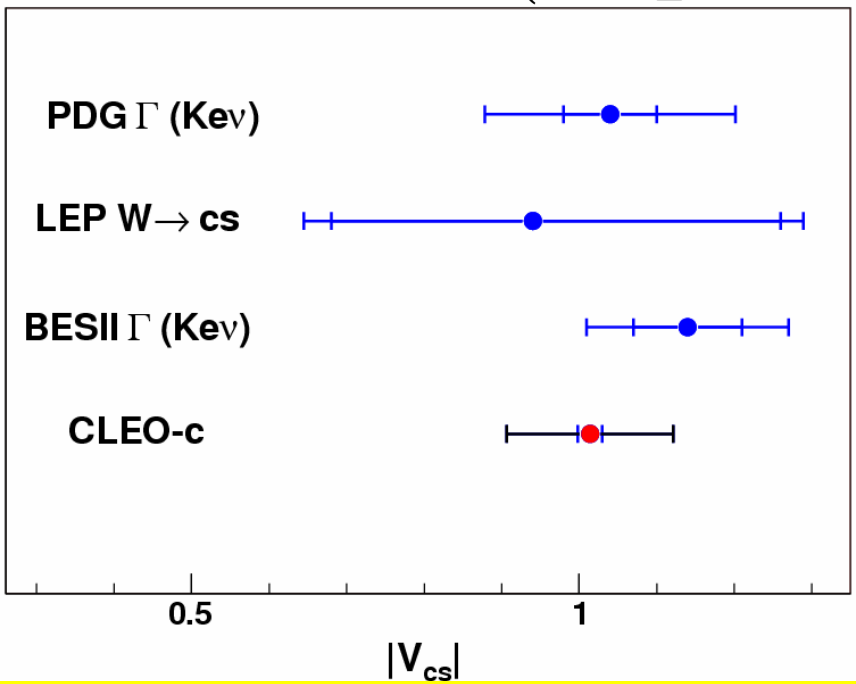


Form factor fits to partial branching fraction results in five q^2 ranges normalized to Hill series parameterization (Untagged shown)

- The confidence levels for all parameterizations are good
- use *model independent* Becher-ill series parameterization

V_{cs} Result

Combine measured $|V_{cx}|f_+(0)$ values using Becher-Hill parameterization *with (FNAL_MILC-HPQCD) for* $f_+(0)$



$CLEO-c$	V_{cs}
$(tagged)$	$1.014 \pm 0.013 \pm 0.009 \pm 0.106$
$(untagged)$	$0.996 \pm 0.008 \pm 0.015 \pm 0.104$
	stat syst theory

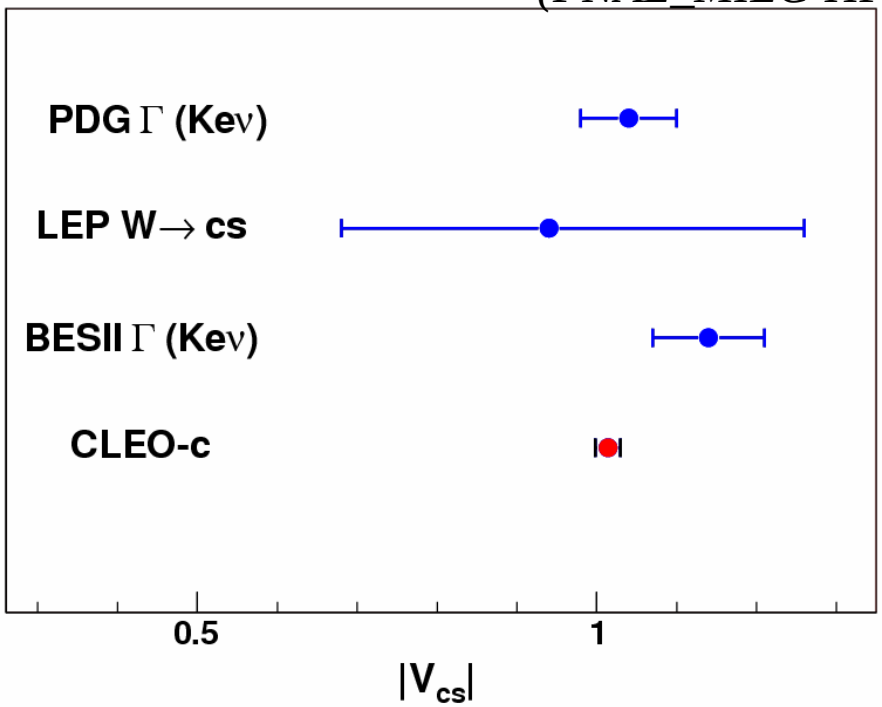
Tagged/untagged consistent, 40% overlap DO NOT AVERAGE

	V_{cs}	Uncertainty (%) exp.	thy.	tot.
$PDG\,\Gamma(Ke\nu)$	1.04 ± 0.16	6	14.2	15.4
$W \to cs$	$0.94^{+0.32}_{-0.26} \pm 0.14$			31
$BESII\,\Gamma(Ke\nu)$	$1.14 \pm 0.07 \pm 0.11$	6.5	10.4	12.8
$CLEO-c$	$1.014 \pm 0.016 \pm 0.106$	1.6	10.4	10.5

CLEO-c: the most precise *direct* determination of V_{cs} dominant uncertainty LQCD

V_{cs} Result (if zero theory uncertainty)

Combine measured $|V_{cx}|f_+(0)$ values using Becher-Hill parameterization *with (FNAL_MILC-HPQCD) for* $f_+(0)$



Expt. uncertainty Vcs <2%
(Theory 10%)

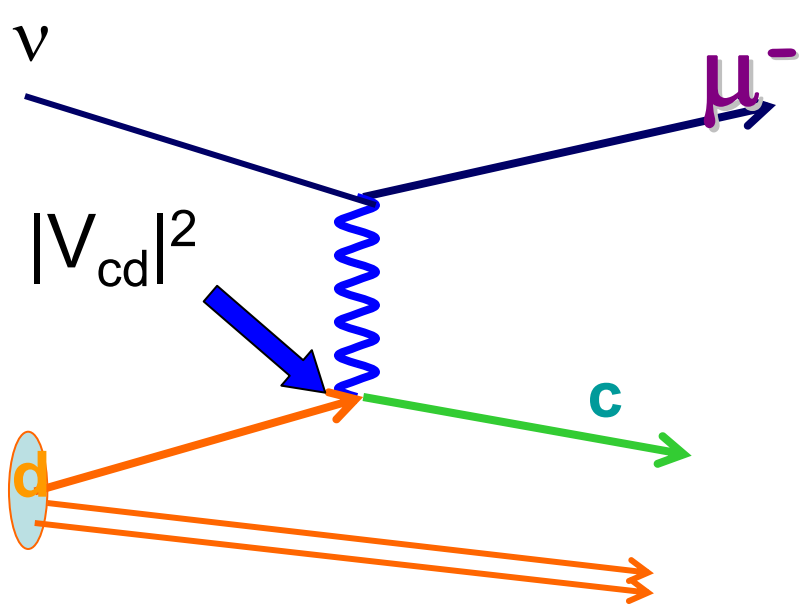
Removing the dominant theoretical uncertainty stresses the experimental precision and underlines how eagerly we are awaiting new result from LQCD at FNAL

Full CLEO-c data set Vcs will be experimentally systematics limited

$$D \to Ke^+\upsilon \quad \frac{\delta Vcs}{Vcs} = 0.8\% \oplus \frac{\delta Theory}{Theory}$$

Prior determination of V_{cd}

- Method: $\nu + d \rightarrow c + \mu \propto |V_{cd}|^2 \mathcal{B}_\mu$ [average semileptonic branching ratio of charm]



$\langle |Vcd|^2 \mathcal{B}_\mu \rangle = (0.463 \pm 0.034) \times 10^{-2}$

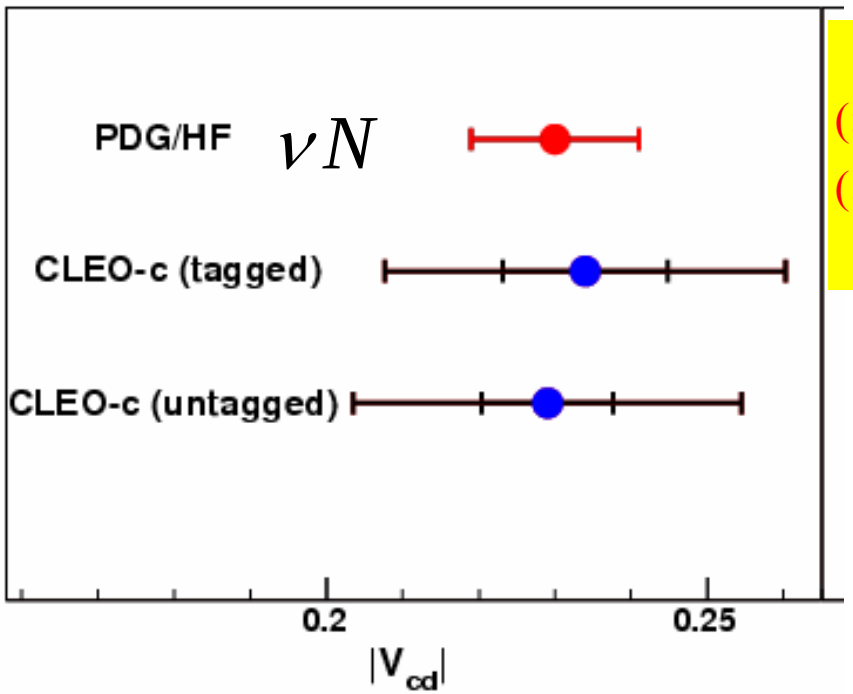
$\mathcal{B}_\mu = 0.0873 \pm 0.0052$

[pdg 2006]

$|V_{cd}| = 0.230 \pm 0.011$
(5% accuracy)

V_{cd} Result

Combine measured $|V_{cx}|f_+(0)$ values using Becher-Hill parameterization *with (FNAL_MILC-HPQCD) for* $f_+(0)$



$CLEO-c$	V_{cd}
$(tagged)$	$0.234 \pm 0.010 \pm 0.004 \pm 0.024$
$(untagged)$	$0.229 \pm 0.007 \pm 0.005 \pm 0.024$
	stat syst theory

Tagged/untagged consistent, 40% overlap
DO NOT AVERAGE

CLEO-c & PDG consistent

	V_{cd}	Uncertainty (%)
$PDG\ \nu d \to cu$	0.22 ± 0.011	5%
$CLEO-c$	$0.229 \pm 0.08 \pm 0.024$	$3.5\% \oplus 10.5\%$

Full CLEO-c data set
Vcd stat. limited

$$D \to \pi e^+ \upsilon \quad \frac{\delta Vcd}{Vcd} = 1.6\% \oplus \frac{\delta Theory}{Theory}$$

CLEO-c: dominant uncertainty LQCD
Neutrino interactions remain most precise determination (for now)

CKM independent test of FNAL-MILC-HPQCD amplitudes

Independent of VCKM

$$R_{\ell sl} \equiv \sqrt{\frac{\Gamma(D^+ \to \mu\upsilon)}{\Gamma(D \to \pi\ell\upsilon)}} \propto \frac{f_D}{f_+^{\pi}(0)} \frac{\cancel{V_{cd}}}{\cancel{V_{cd}}}$$

- .

$$R_{\ell sl}^{th} = 0.212 \pm 0.028$$

$$R_{\ell sl}^{\exp} = 0.236 \pm 0.019$$

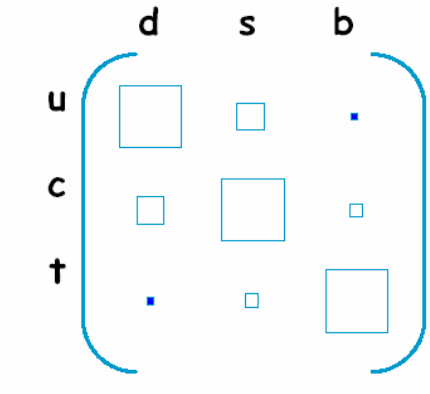
Data and theory are consistent within the considerable (~10%) uncertainties

Full CLEO-c data set → 5%

BES III (20/fb) will provide 1% test

Unitarity Tests Using Charm

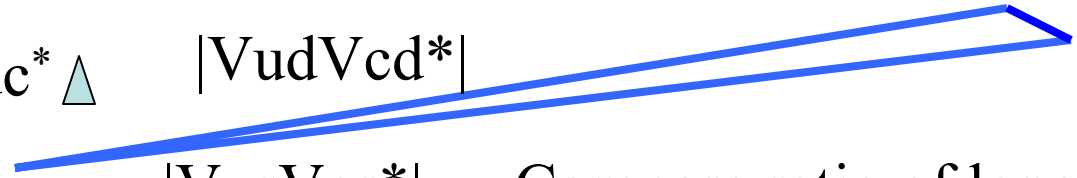
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



$uc^*=0$

☆ 2nd row: $|Vcd|^2 + |Vcs|^2 + |Vcb|^2 = 1$?? (can only be tested with *direct* determination of each element)
CLEO-c & νN: $|1- \{|Vcd|^2 + |Vcs|^2 + |Vcb|^2\} = 0.012 \pm 0.18$
Could be tested *now* to few% (if theory was good to few %)
As Vcd precision improves 1st column:
$|Vud|^2 + |Vcd|^2 + |Vtd|^2 = 1$?? similar precision to 1st row

☆ uc^* △



Compare ratio of long sides to few %

Charm As a Probe of Physics Beyond the Standard Model

Can we find violations of the Standard Model at low energies?
Natural β Decay ➔ missing energy ➔ W (100 GeV) from experiments @ MeV scale.

The existence of multiple fermion generations may originate at high mass scales ➔ can only be studied indirectly.

CP violation, mixing and rare decays ➔ may investigate the physics at these new scales through intermediate particles entering loops.

Why charm? in the charm sector the SM contributions to these effects are small ➔ large window to search for new physics

CP asymmetry $\leq 10^{-3}$

Rare decays $\leq 10^{-6}$

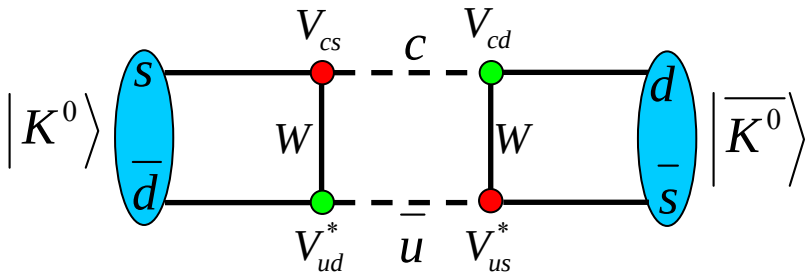
$D^0 - \bar{D}^0$ mixing

charm is the *unique* probe of the up-type quark sector (down quarks in the loop).

High statistics instead of High Energy

D Mixing

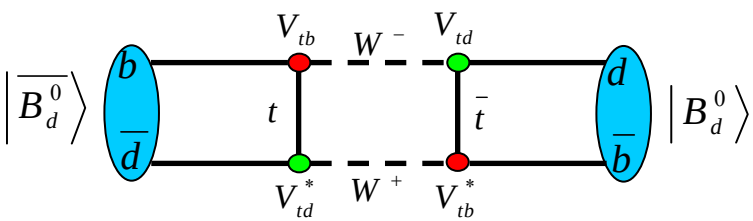
Mixing has been fertile ground for discoveries:



Mixing rate ≈1

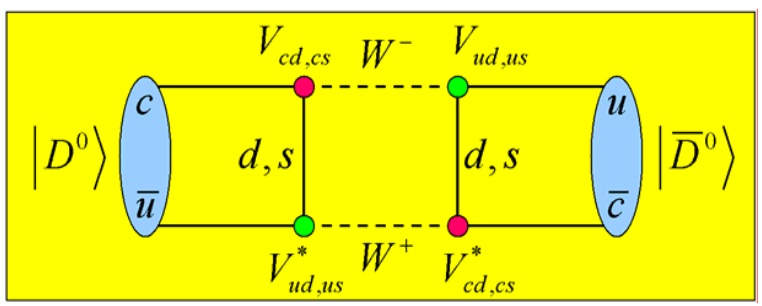
Mixing rate (1958) used to bound c quark mass → discovery(1974).

CPV part of transition , ε_K (1964), was a crucial clue top quark existed → discovery (1994).



Mixing rate ≈1

Mixing rate → early indication m_{top} large
Crucial ingredient for B CP violation (sin2β)

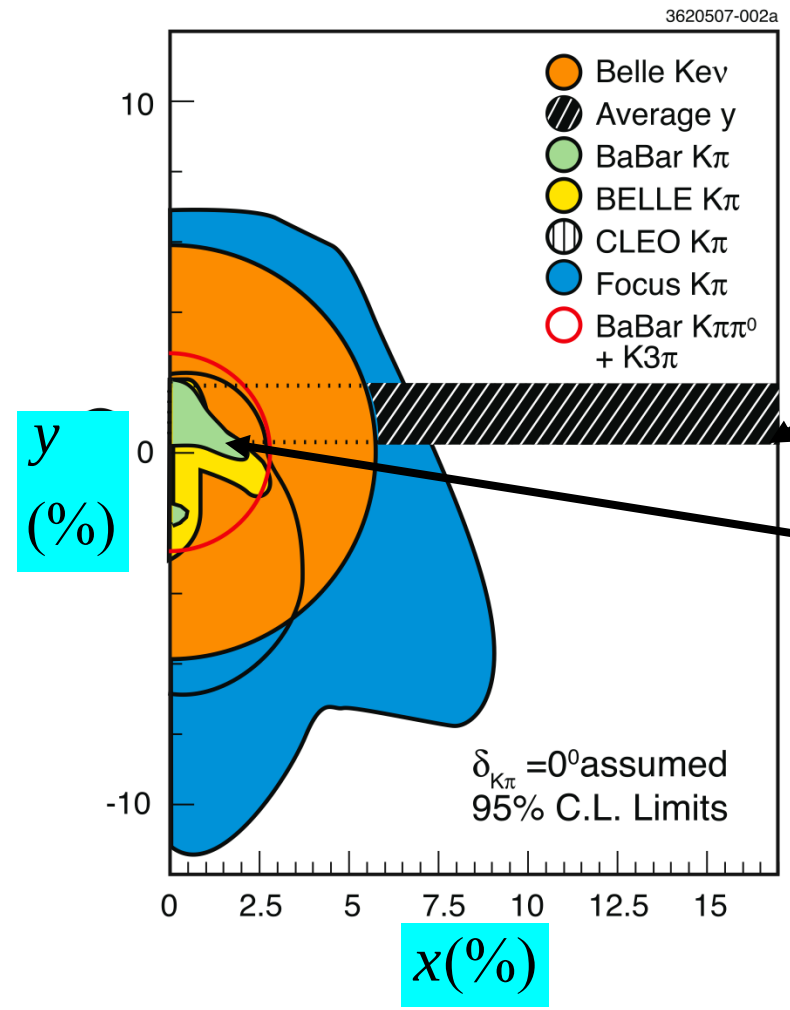


Mixing rate ?

expected to be no larger than $<10^{-3} - 10^{-2}$

CP violation in mixing → new physics

D^0-D^{0bar} Mixing After Moriond '07



Mixing paramters $x = \Delta m/\Gamma \quad y = \Delta\Gamma/2\Gamma$

NO MIXING (x,y)=(0,0) excluded:

Belle $y_{CP} = (1.31 \pm 0.32 \pm 0.25)\%$

$\langle y \rangle = (1.12 \pm 0.32)\%$

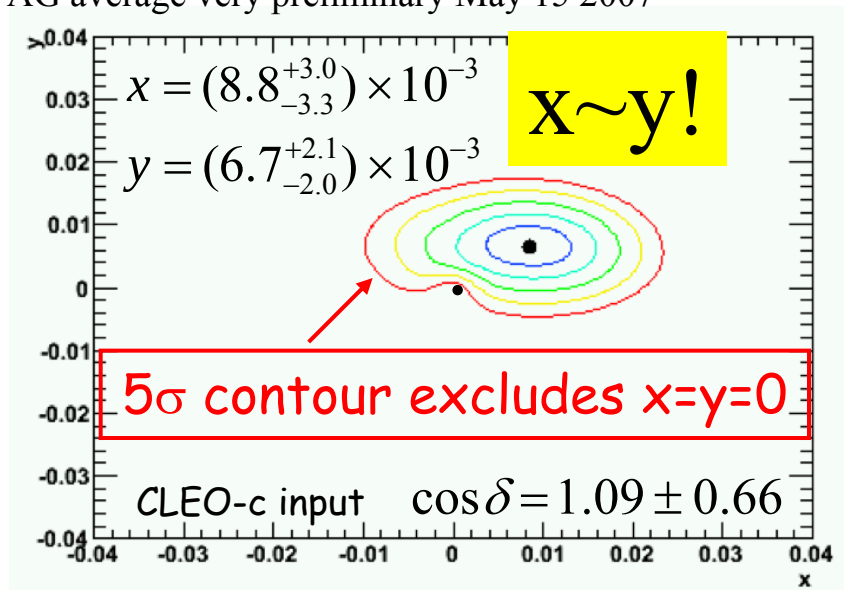
~3.5σ Average y

$x'^2 = (-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$

$y' = (9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$

~3.9σ BABAR $D^0 \to K\pi$ (no CPV)

HFAG average very preliminary May 15 2007



Standard Model x≤y

Short distance 10^{-6} - 10^{-3}

Long distance 10^{-3} - 10^{-2}

Projected Mixing Sensitivity

Exp't 1 σ sensitivity	y_{CP} (10^{-3})	y' (10^{-3})	x'^{2} (10^{-4})	cosδ
B-factories (2ab^{-1})	2-3	2-3	1-2	-
SuperB (50 ab^{-1})	0.5	0.7	0.3	-
CLEO-c (750 pb^{-1})	10	-	2-3	0.1-0.2
BESIII (20 fb^{-1})	4	-	0.5-1	0.05
SuperB - 4 GeV (0.2 ab^{-1})	1-2	-	<0.2	<0.05

- BABAR/Belle 5σ signal in both y_{CP} & $D^0 \to K\pi$ possible with 2ab^{-1} @Υ(4S)
- LHCb can confirm signal in $D^0 \to K\pi$ - y_{cp} study in progress
- Super B precision mixing measurement *& 5-10% limits on CPV in mixing*

Charm factories:

Mixing: $\psi(3770) \to D\overline{D}$ (C= - 1)

Coherence simplifies study (no DCSD)

unmixed: $D^0 \to K^-\pi^+ \ \overline{D^0} \to K^+\pi^-$

mixed: $D^0 \to K^-\pi^+ \ \overline{D^0} \to D^0 \to K^-\pi^+$

A Global approach fits single/double CP/flavor tag yields @ψ(3770) &4170 $\propto B_i\ x^2$, y, & δ.

CLEO-c may glimpse
BES III 4 σ confirm
SuperB @ 4GeV
confirm SuperB @10GeV

CP Eigenstates @ ψ(3770) & strong phases δ

At the ψ"(3770)

$e^+e^- \to \psi'' \to D^0D^0$

$J^{PC} = 1^{--}$ i.e. CP+

A D^0 is observed to decay to a CP eigenstate f_1 which is CP even:
Then in the limit of CP conservation, the state recoiling against the tag has a definite CP as well and it must be of opposite sign :

$$CP(f_1 f_2) = \underbrace{CP(f_1)\, CP(f_2)}_{-}\, \underbrace{(-1)^l}_{-\ (\text{since } l = 1)} = CP+$$

Example
Two CP eigenstates of opposite sign

$$(\pi^+\pi^-)(K_s^0\pi^0)(-1)^\ell = CP+$$

$+ \quad - \quad -$

- CP eigenstate tag X flavor mode

$$K^+K^- \leftarrow D_{CP} \leftarrow \psi(3770) \to D_{CP} \to K^-\pi^+ (-1)^l$$

$+ \quad - \quad - \quad = CP+$

Charm factories measure δ by using CP tagging (δ needed to interpret charm mixing in Kπ and other hadronic states at B Factories/Tevatron)

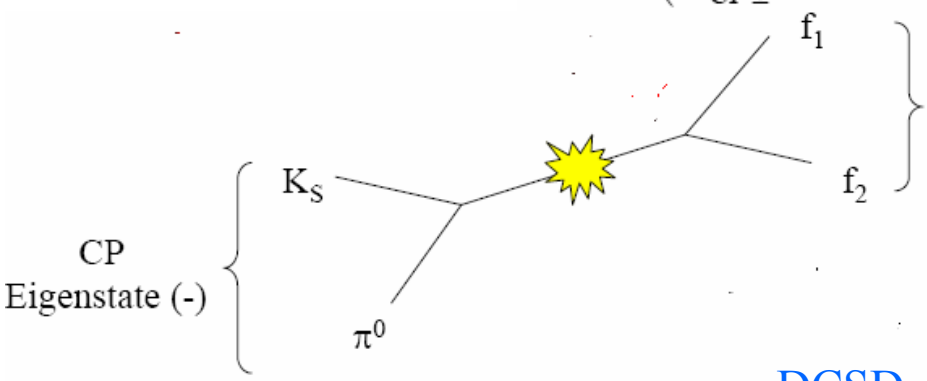
Basic Measurement of a Strong Phase δ

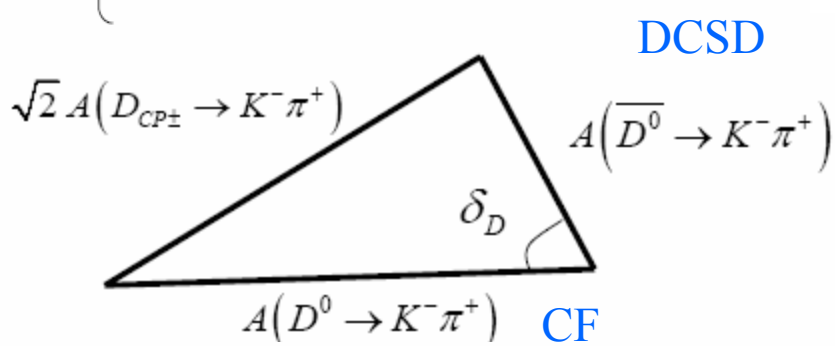
- If CP violation in charm is neglected: mass eigenstates = CP eigenstates

$$\left|D_{CP\pm}\right\rangle = \frac{1}{\sqrt{2}}\left[\left|D^0\right\rangle \pm \left|\overline{D^0}\right\rangle\right]$$

$$\sqrt{2}\,A\left(D_{CP\pm} \to K^-\pi^+\right) = A\left(D^0 \to K^-\pi^+\right) \pm A\left(\overline{D^0} \to K^-\pi^+\right)$$

CF DCSD





In the limit of CP-invariance

$$A\left(D^0 \to K^+\pi^-\right) = A\left(\overline{D^0} \to K^-\pi^+\right)$$

Method limited CP tag statistics

Extend to global approach with

@ 3770 & 4170 Currently

cos $\delta_{D=}$ ±0.66 0.75/fb

cos δ_D ~ ±0.13 BESIII 10/fb

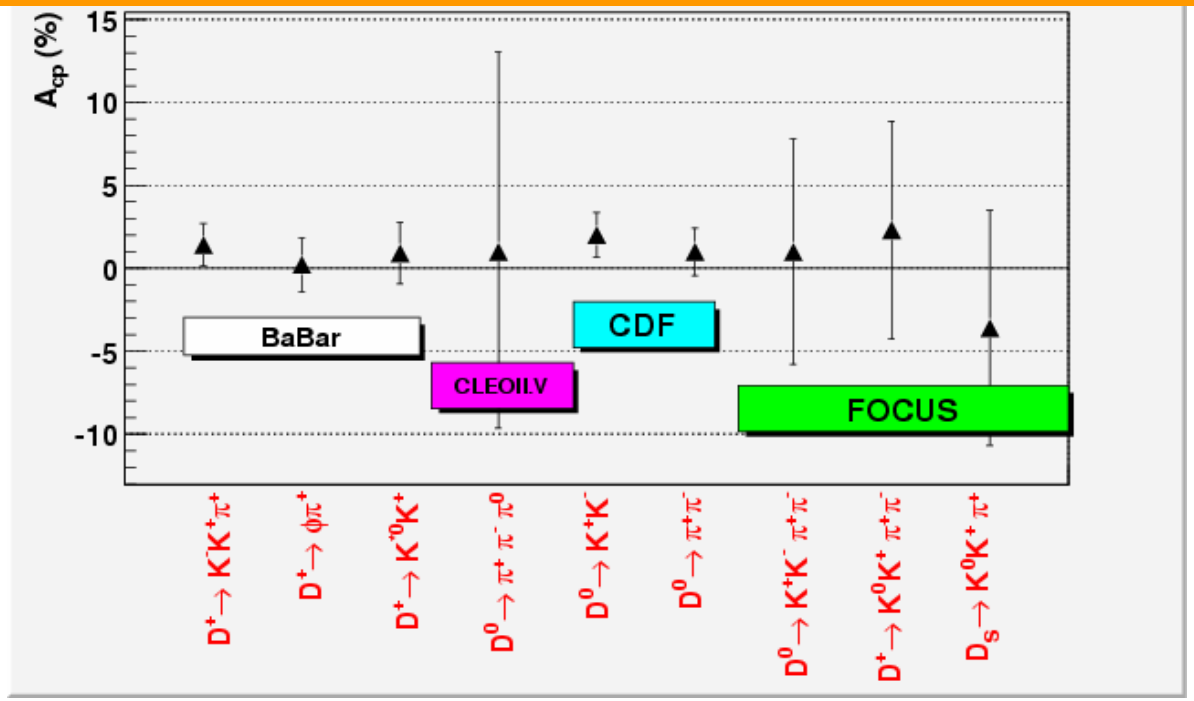
@3770 & 4160 cos δ_D ~ ±0.05

$$\cos\delta_D = \frac{Br\left(D_{CP+} \to K^-\pi^+\right) - Br\left(D_{CP-} \to K^-\pi^+\right)}{2\sqrt{r_D}\,Br\left(D^0 \to K^-\pi^+\right)}$$

as r_D is well measured $r_D = (3.76 \pm 0.09)\times 10^{-3}$

Searches for CP violation in D decays

3 types (1) mixing, (2) decay amplitude (direct) or interference between (1) & (2) Small D mixing ➔ best bet direct CP violation
In SM only possible in singly Cabibbo suppressed decays.
(A_{CP} ~0.001 SM, larger NP). Direst CPV so time independent: event counting. Many limits from CDF/FOCUS/CLEOII/BABAR/BELLE some of the recent ones are shown here typical limits A_{CP} <~1%)



Note: if CP violation seen in Doubly Cabibbo suppressed or Cabibbo favored D decays it would be a clear indication of new physics

CP Violation at ψ(3770)

@ 3770
Unique search strategy
Complementary to other expts.

$e^+e^- \rightarrow \psi'' \rightarrow D^0D^0$ $\quad J^{PC} = 1^{--}$ $\quad$ i.e. CP+

$$CP(f_1 f_2) = \underbrace{CP(f_1)\, CP(f_2)}_{-}\, \underbrace{(-1)^l}_{-\ (\text{since } l = 1)} = CP+$$

CP conserving

- CP violating asymmetries can be measured by searching for events with two CP odd or two CP even final states ex:

$$(\pi^+\pi^-)(\pi^+\pi^-) \qquad (-1)^l$$

$$+ \qquad + \qquad - \quad = CP-$$

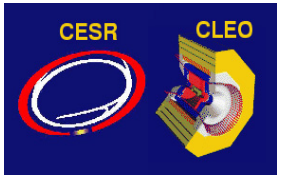
CP violating

K-K+ $A_{cp} < 0.08$ (CLEO-c) , $<4 \times 10^{-3}$ (BESIII), 6×10^{-5} (superflavour/10^7s)
(1.4×10^{-4} (stat) LHCb/yr)

2nd method D (flavor) D (CP)

- $A_{cp} < 0.025$ (CLEO-c) , $<6 \times 10^{-3}$ (BESIII), 7×10^{-4} (superflavour)

Many other strategies exist to search for CP violation
Ex: CP tagged Dalitz plots. are particularly interesting as they are sensitive to amplitudes, rather than rates



$D \to X l^+ l^-$

D Rare decays

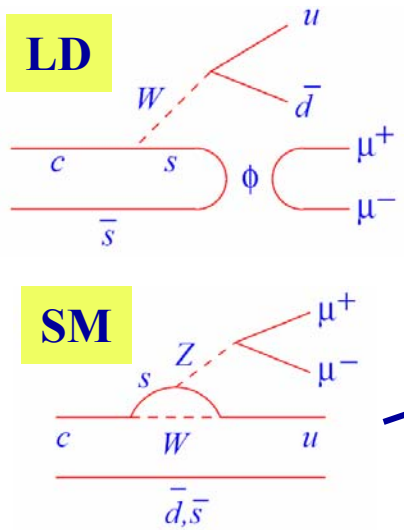
No FCNC in kaons → charm,

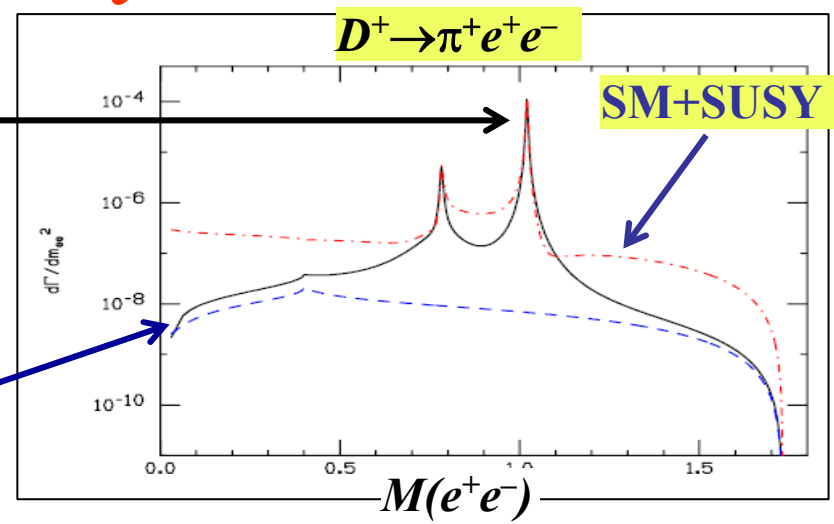
If new particles are to appear

on-shell at LHC

they must appear in virtual loops

and affect amplitudes





In the SM

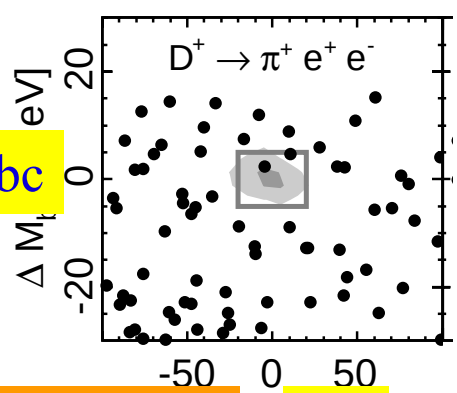
$\mathcal{B}(D^+ \Rightarrow \pi^+e^+e^-)$
$\sim 2 \times 10^{-6}$

R-parity violating SUSY:

$\mathcal{B}(D^+ \Rightarrow \pi^+e^+e^-)$
$\sim 2.4 \times 10^{-6}$

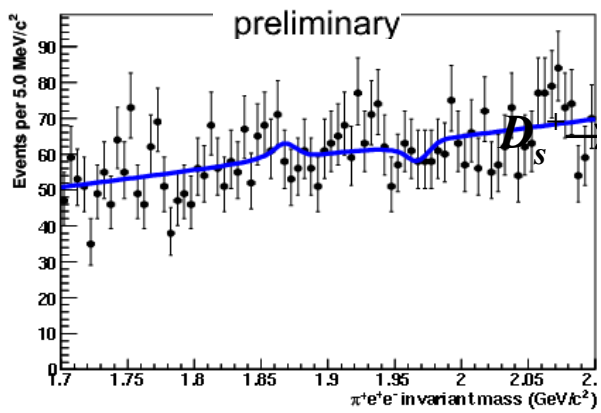
$D^+ \to \pi^+ e^+ e^-$

CLEO-c



Statistics limited

BABAR



Bkgd limited

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

Results: x 10^{-6} (90% CL)	CLEO-c 0.28/fb	BABAR 288/fb
$\mathcal{B}(D^+ \Rightarrow \pi^+e^+e^-)$ (prev. 45)	7.4	11.2
	(stat, limited)	(background limited)

$B(D^+ \to \pi^+\mu^+\mu^-) < 4.7\times10^{-6}$ @90% CL Best Limit (1/fb)

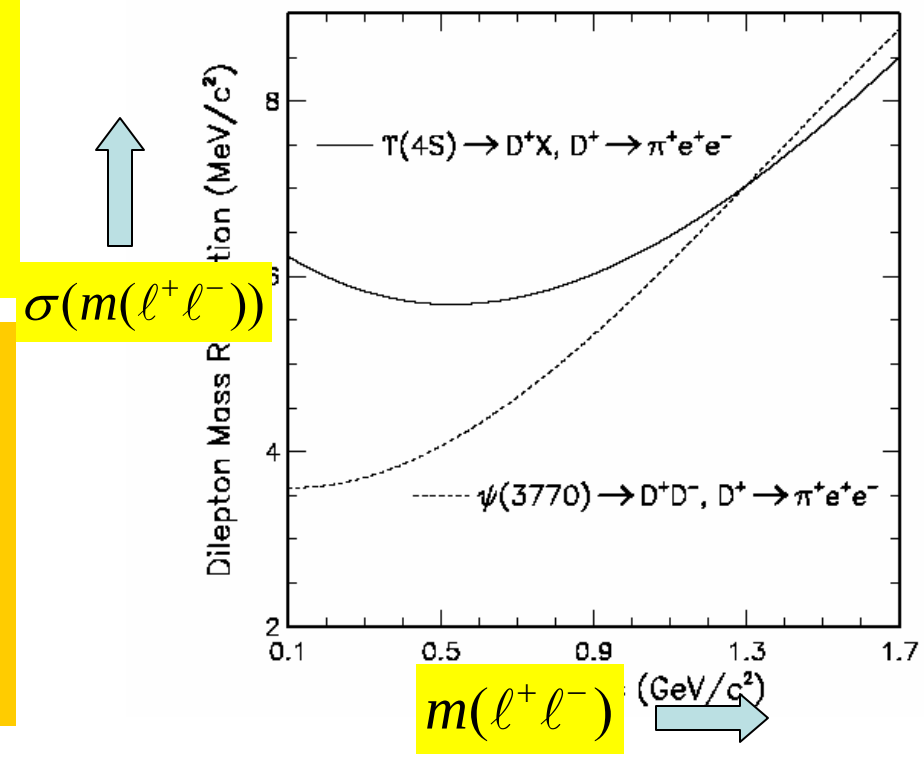
$B(D^+ \to \pi^+\phi \to \pi^+\mu^+\mu^-) < (1.75 \pm 0.7 \pm 0.5)\times10^{-6}$(long distance seen)

Limits are ~x4 above SM rates

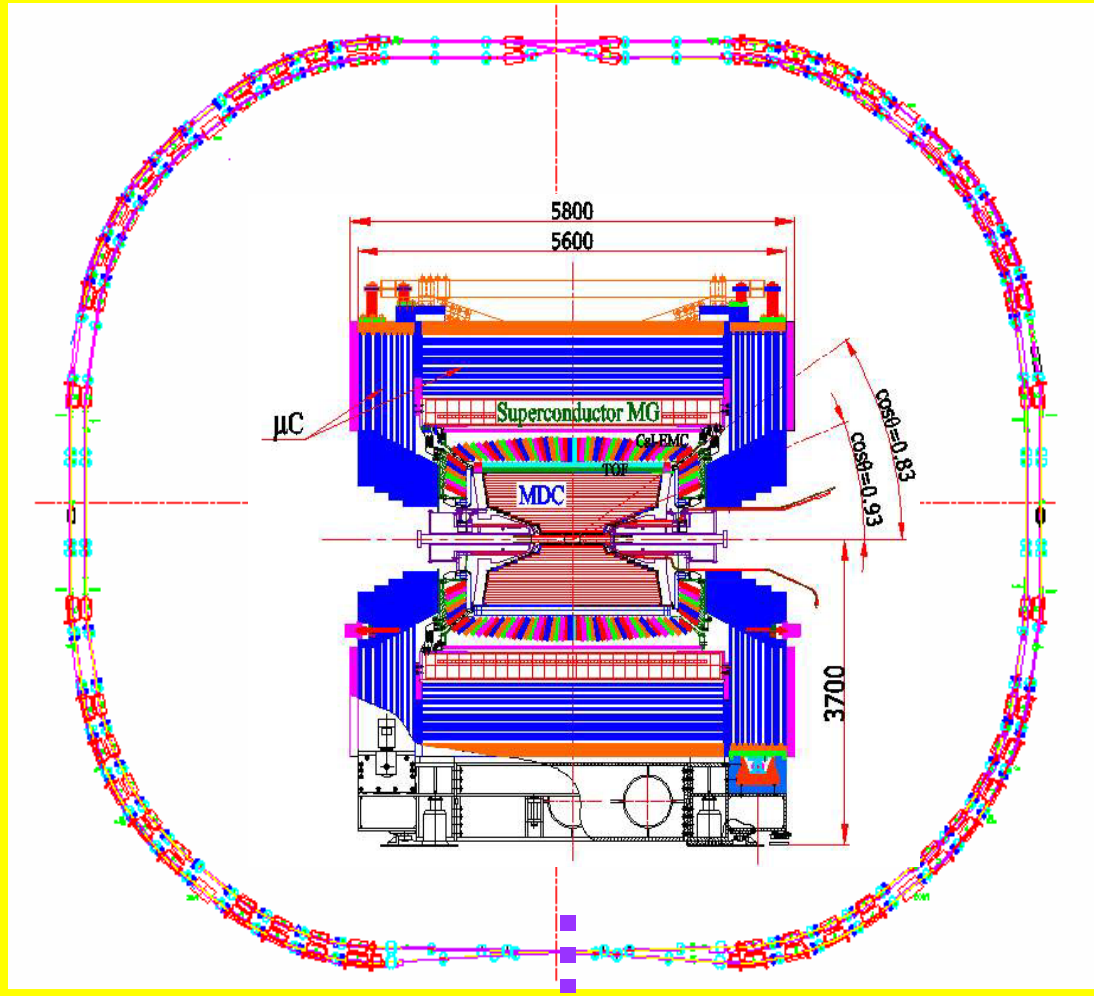
BESIII: If $D^+ \Rightarrow \pi^+e^+e^-$ is @ SM level ➔~2 evt/fb
$D^+ \Rightarrow \pi^+e^+e^-/\mu\mu$,$D^0 \Rightarrow \pi^0e^+e/\mu\mu$
$\Rightarrow$~50 events
If events cluster well away from φ/ρ/ω!
Smoking gun for new physics!

Superflavour facility @ 10GeV large backgrounds BUT @ψ(3770)
$D^+ \Rightarrow \pi^+e^+e^-$ ~3000 events (low bkgd)
also $D^0 \Rightarrow \pi^0e^+e^-$ accessible.
e+e- is unique probe of the rare decay frontier

G. Burdman and I. Shipsey
Ann. Rev. Nucl. Part. Sci. **53** 431 (2003) arXivhep-ph/0310076



The very near future: BEPCII/BESIII Project



run plan not decided: example 5/fb/yr 15/fb/3yrs

10 billion J/ψ

3 yrs @ 3770 30M $D\bar{D}$/yr =90M$D\bar{D}$ $\sim\times 20$ full CLEO-c

3 yrs @4170 3M $Ds\bar{D}s$/yr $= 9M Ds\bar{D}s$ $\sim\times 20$ full CLEO-c

Design

- Two ring machine
- 93 bunches each
- Luminosity

X5 CESR-c design

10^{33} cm^{-2} s^{-1} @1.89GeV DD

6×10^{32} cm^{-2} s^{-1} @1.55GeV J/ψ

6×10^{32} cm^{-2} s^{-1} @ 2.1GeV DsDs

- New BESIII

Status and Schedule

- Linac installed 2005
- Ring installed 2006
- BESIII in place and Commissioning 2008

BEPCII/BESIII data taking & great physics thereafter

CKM Impact of Charm Measurements

f_D : before CLEO unmeasured
Now CLEO-c ~8% eventually 4-5%
BESIII expect ~1-2%

- Leptonic Charm Decays
  $D^+ \to \mu^+\nu$, $D_s^+ \to \mu^+\nu, \tau^+\nu$
  - Measure decay constants f_D, f_{Ds}
  - Improved f_B possible from f_D measurement + LQCD
  - Important for $|V_{td}|$ and $|V_{ts}|$
- Semileptonic Charm Decays
  - Measurements of $|V_{cs}|$ and $|V_{cd}|$
  - Test theoretical form factor models
  - Impacts prediction of form factors for B meson decays
  - Important for $|V_{ub}|$ and $|V_{cb}|$
- Hadronic Charm Decays
  $D^0 \to K\pi$, $D^+ \to K\pi\pi$, $D_s^+ \to \phi\pi$
  - Important for $|V_{cb}|$
- Multibody Charm Decays
  $D^0 \to K_{S,L}\pi\pi$,
  - Important for γ/ϕ_3

1st absolute measurement of f_{Ds}: CLEO-c ~4% (300/pb)
Expect 3%
BESIII expect ~1-2%

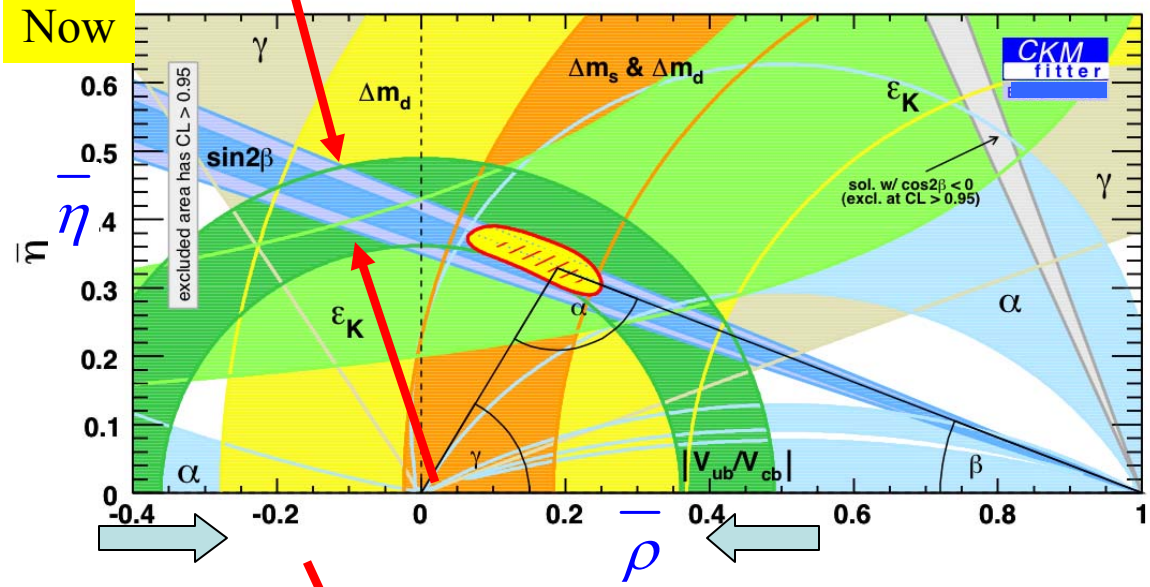
D→ Kev before CLEO-c 6% now 2%
Vcs <2% (expt. uncertainty only) Best direct measurement, expect 1%,
D→ πev before CLEO-c 45% now 4%
Vcd <4%,(most precise determination with a semileptonic decay) expect 2%
BESIII improvement depends on sys err.
B-factories contribute to Klν, πlν FF

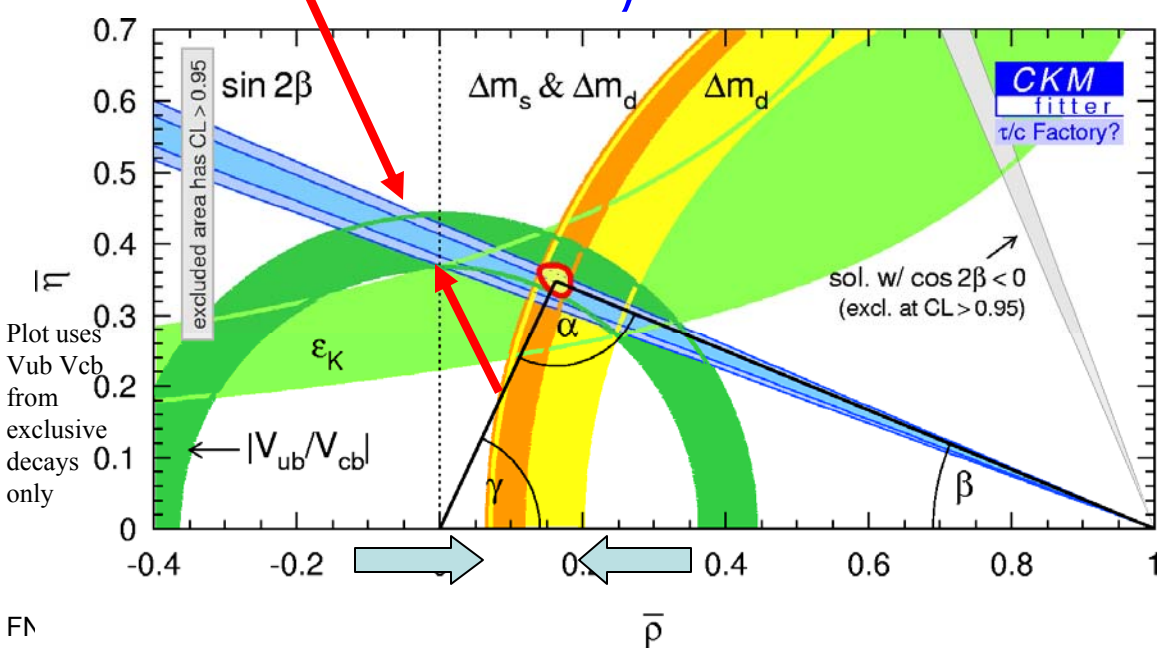
CLEO-c 1-2% D,D+ BF
CLEO-c 6% → 4% Ds BF
Cosδ -0.1-0.2 (previously unmeasured)

CP tagged $K_S\pi\pi$ + $K_L\pi\pi$: improve γ/ϕ_3 ~ <4° at CLEO-c (750/pb)

Precision theory + charm = large impact

Now





Plot uses Vub Vcb from exclusive decays only

* Cleo-c: a major contribution to the goal the lower plot represents, more data needed.
* LQCD has been validated at the 10% level.
* A triumph for theory & experiment!
* A significant further reduction in LQCD uncertainties is needed

precision QCD calculations tested with *precision* charm data
➔theory errors of a few % on B system decay constants & semileptonic form factors

+

500 fb-1 @ BABAR/Belle