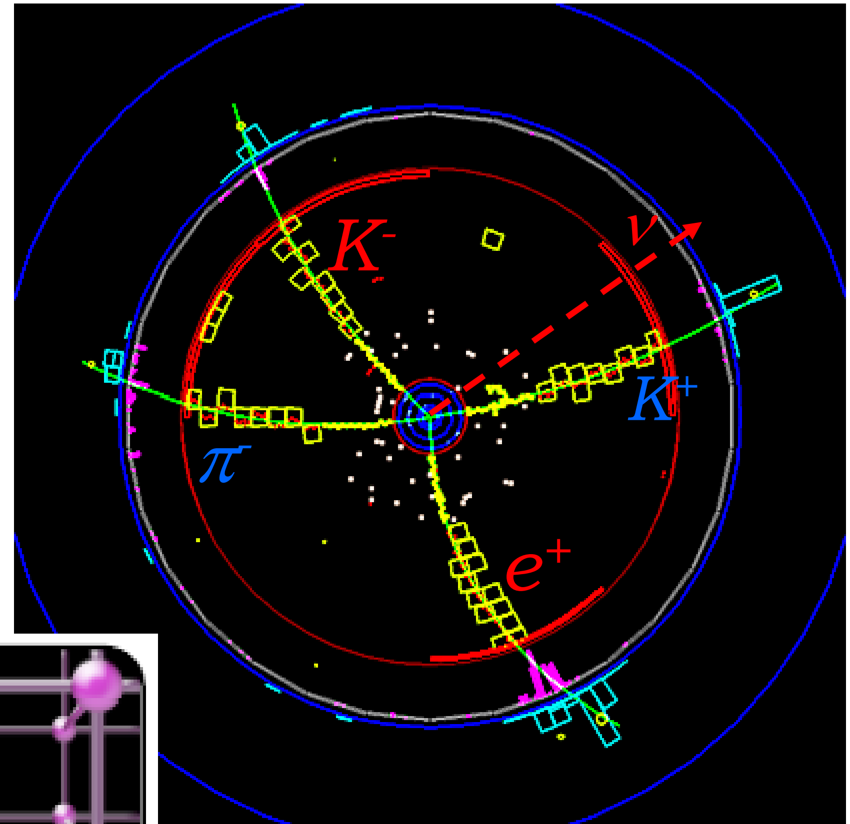
Latest CLEO-c Results

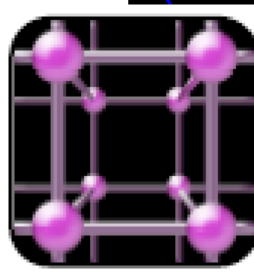
OUTLINE

Testing the Standard Model with precision quark flavor physics:

- *Decay constants*
- *Form Factors*
- *CKM matrix elements*
- *γ (CKM) & Charm mixing*

Direct Searches for Physics Beyond the Standard Model





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

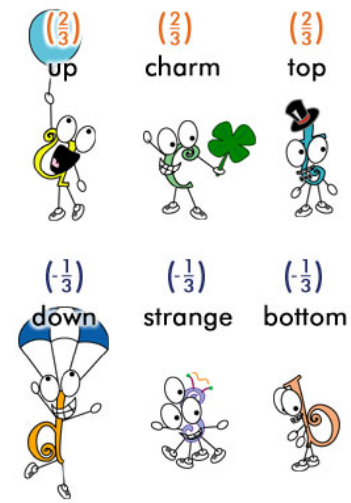
$$\overline{D^0} \to K^+\pi^-, D^0 \to K^-e^+\nu$$

Ian Shipsey, Purdue University
CLEO-c Collaboration

Big Questions in Flavor Physics

Dynamics of flavor?

Why generations?
Why a hierarchy of masses & mixings?



Origin of Baryogenesis?

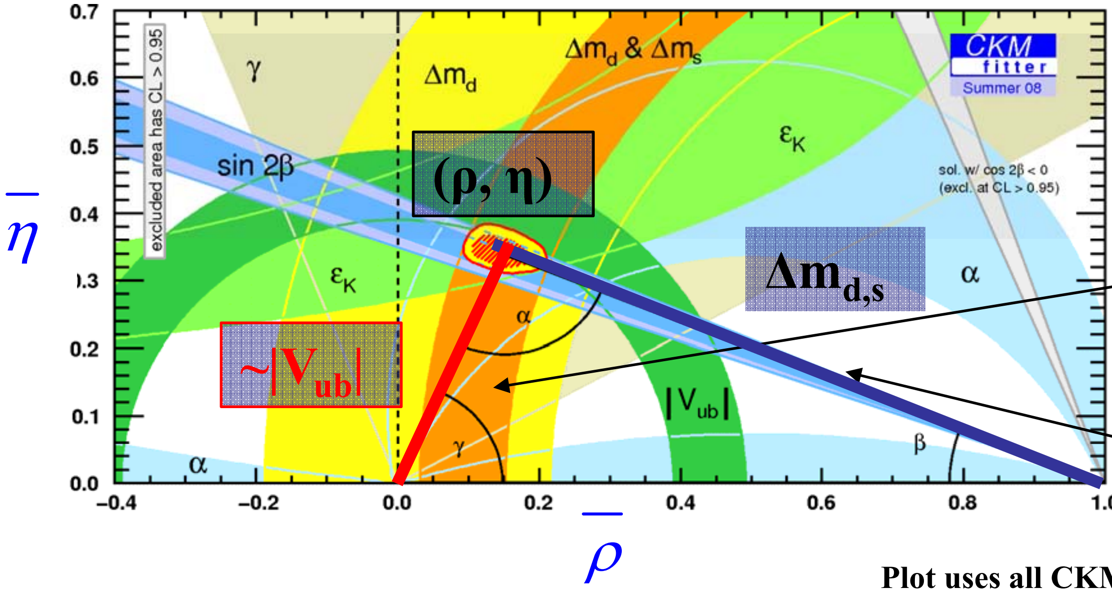
Sakharov's criteria: Baryon number violation
CP violation Non-equilibrium

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?

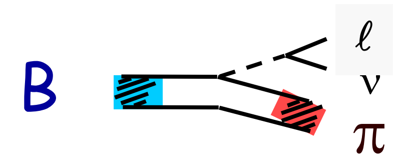
Extensions of the Standard Model (ex: SUSY) contain flavor & CP violating couplings that should show up at some level in flavor physics, but *precision* measurements and *precision* theory are required to detect the new physics

Precision Quark Flavor Physics

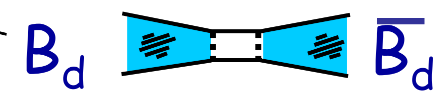


Plot uses all CKM inputs

The discovery potential of B physics is limited by systematic errors from QCD:

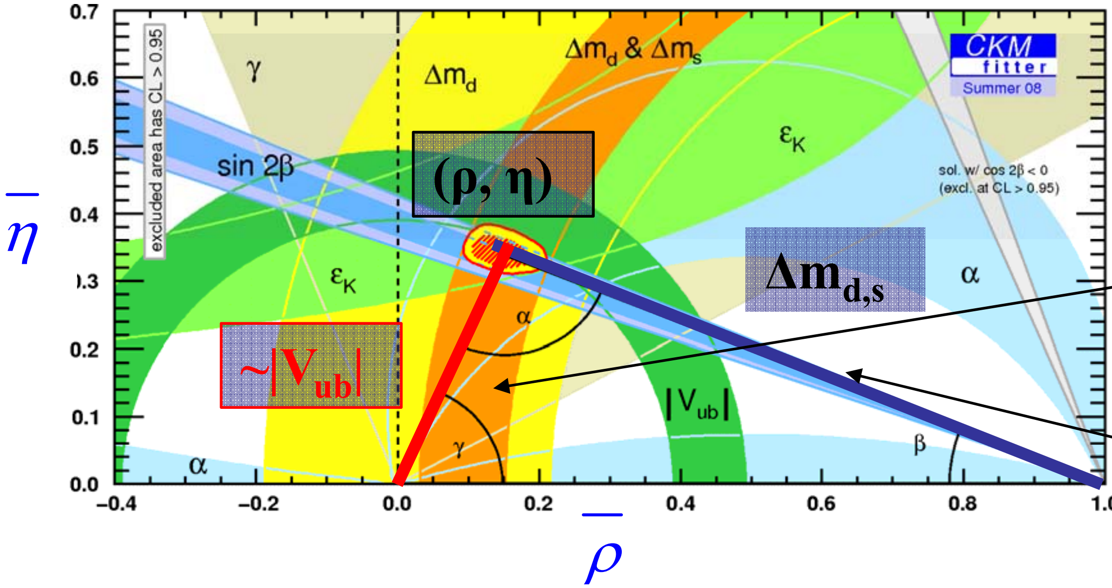


$$\propto \left[f^{B\to\pi}(q) \right]^2 \left| V_{ub} \right|^2$$



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

Precision Quark Flavor Physics



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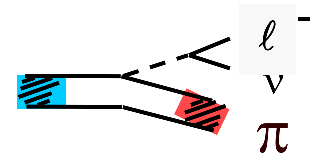
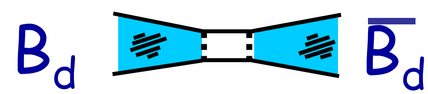
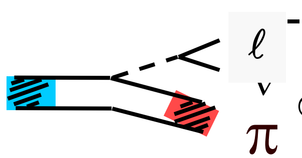


$$\propto \left[f^{B\to\pi}(q) \right]^2 |V_{ub}|^2$$

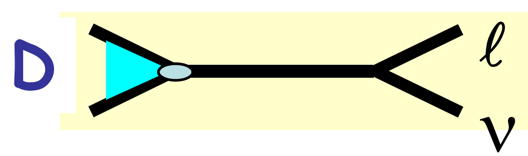


$$\propto \left[f_{Bd} \right]^2 |V_{td}|^2$$

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



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

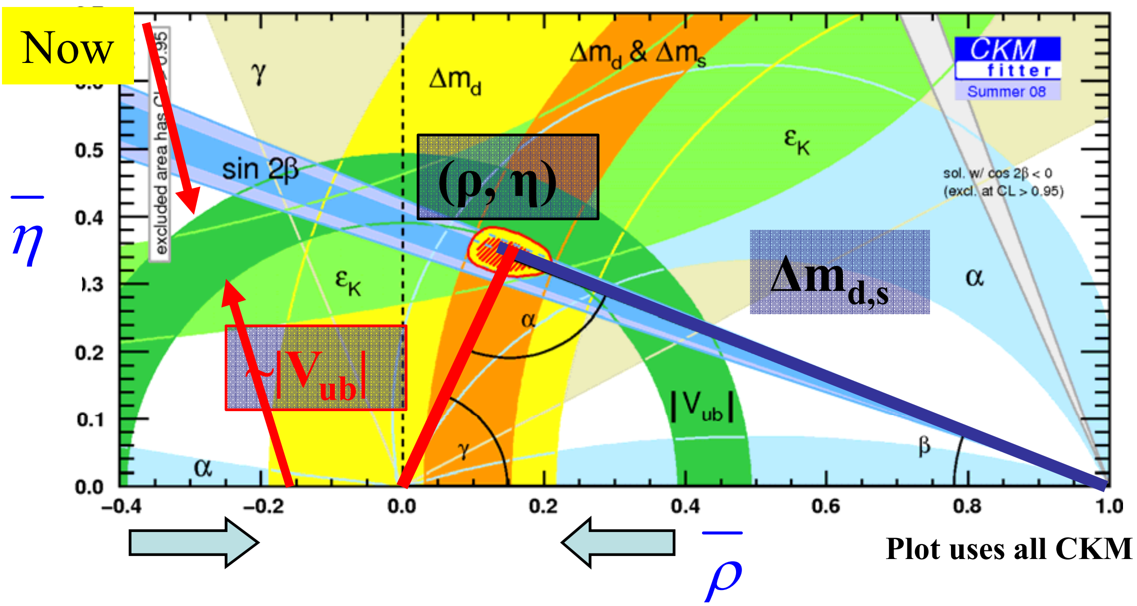


$$\propto \left[f_{D+} \right]^2 |V_{cd}|^2$$

➔ *measurements* of *absolute rates* for D semileptonic & leptonic decays yield decay constants & form factors to *test* and hone QCD techniques into *precision theory* which can be applied to the B system enabling improved determination of the apex (ρ,η)

+ Br(B➔ D)~100% *absolute* D hadronic rates normalize B physics important for V_{cb} (scale of triangle) - also normalize D physics

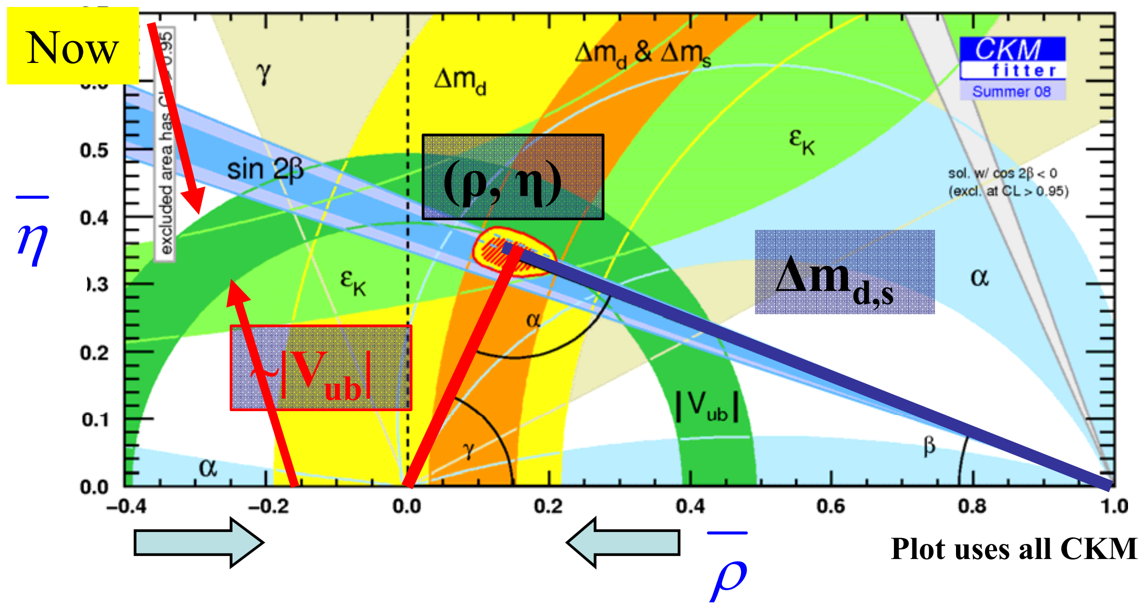
Precision theory + charm = large impact



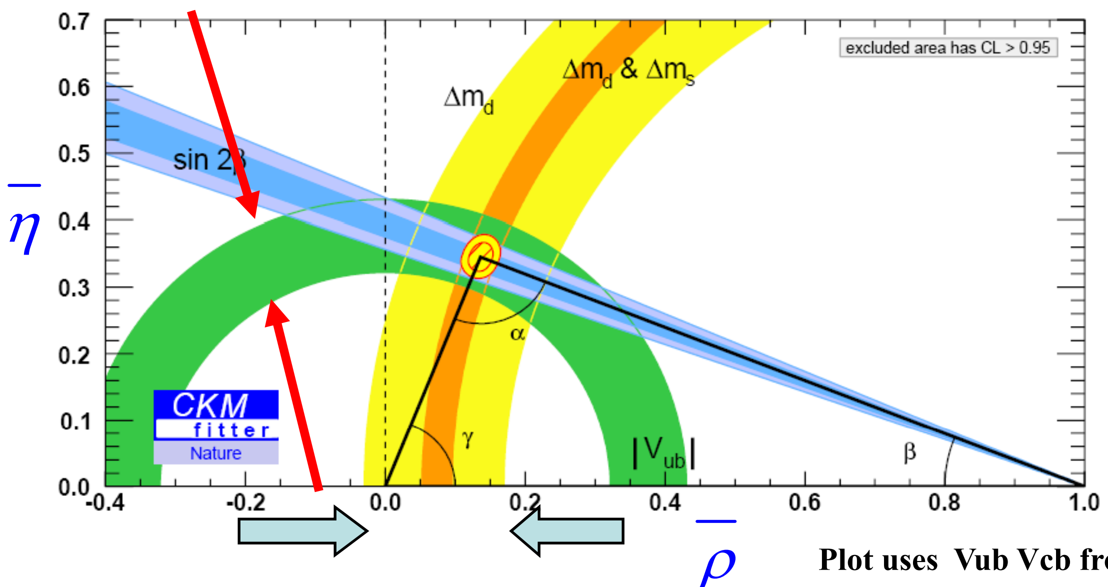
Plot uses all CKM inputs

Theoretical errors dominate width of bands

Precision theory + charm = large impact



Plot uses all CKM inputs



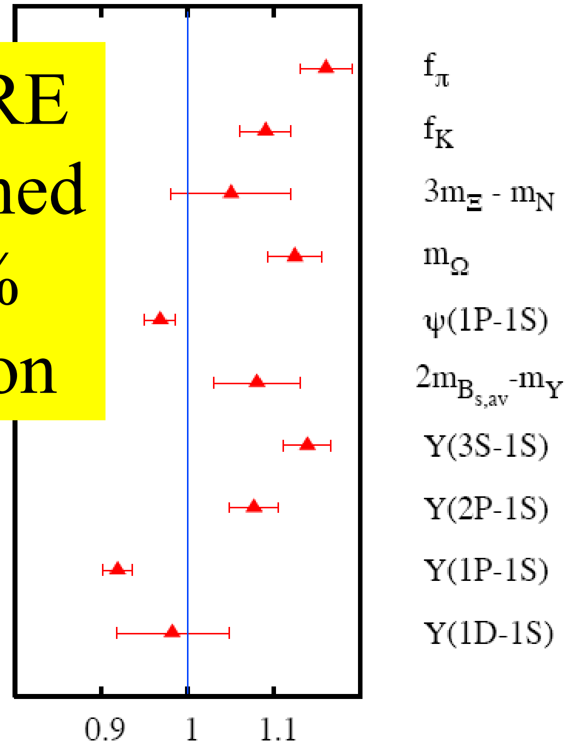
Plot uses Vub Vcb from exclusive decays
no gamma or alpha constraints

Theoretical errors dominate width of bands

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

Precision theory? Lattice QCD

BEFORE
Quenched
10-15%
precision

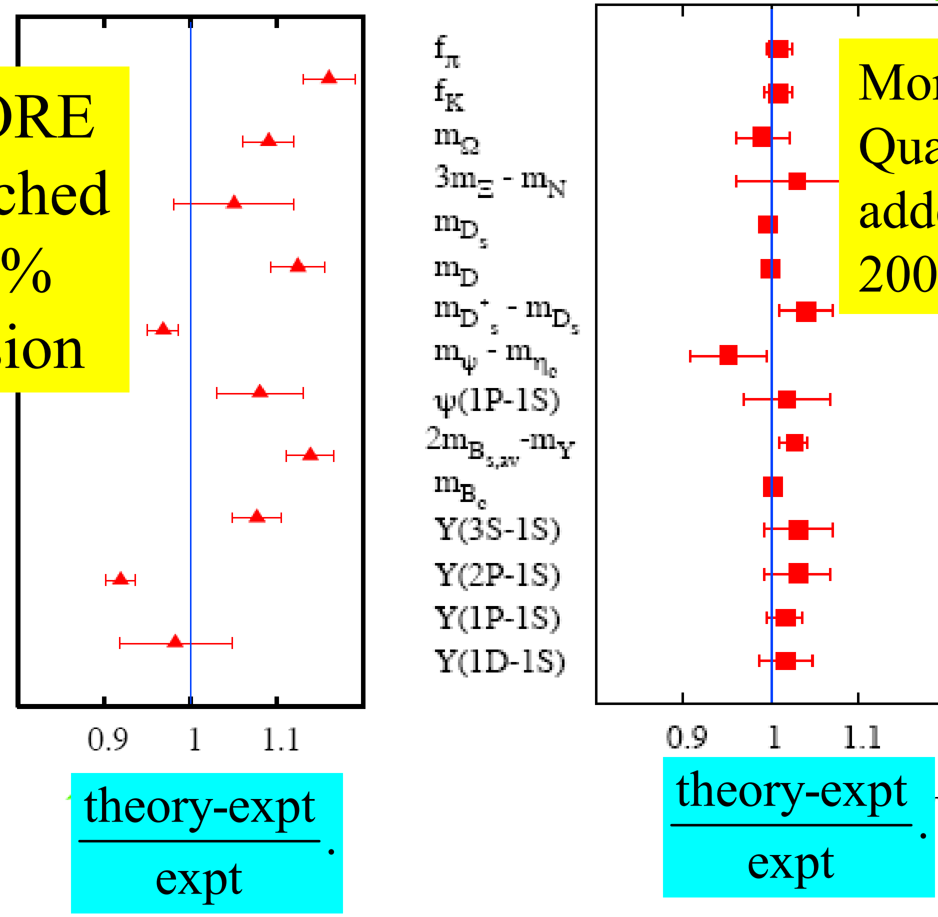


$$\frac{\text{theory-expt}}{\text{expt}}.$$

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

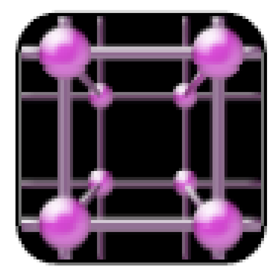


More
Quantities
added
2007

This dramatic improvement needs validation
m(Bc) prediction succesful
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)

Key leptonic, semileptonic & hadronic modes:

Experiment : Theory

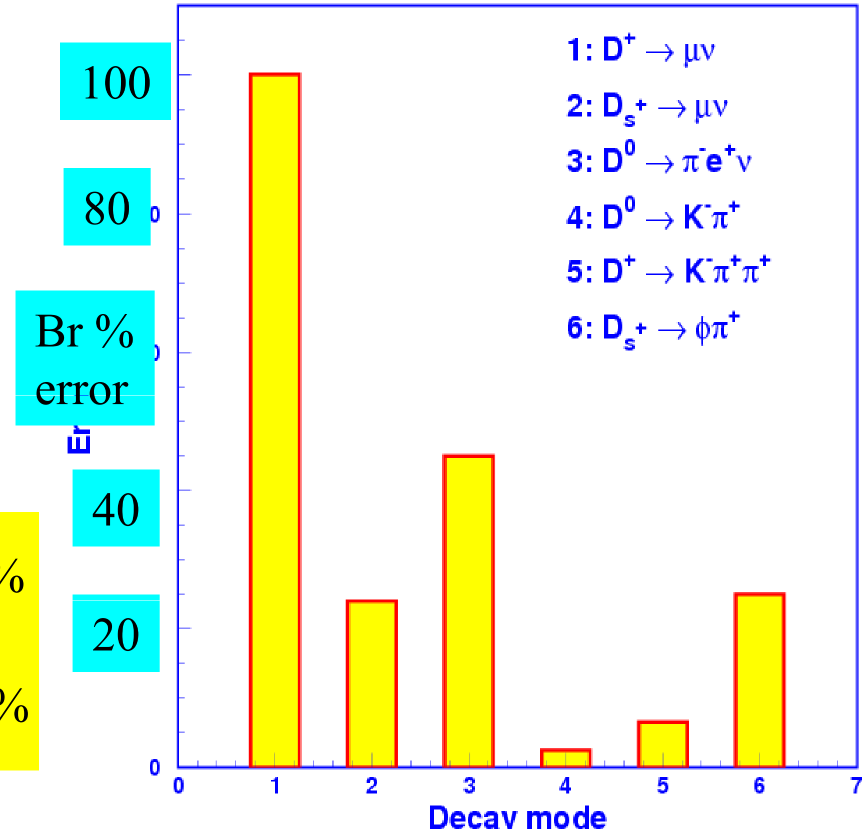
$$\frac{Br}{\tau} = \Gamma$$

Poorly known → Br

Measured very precisely 0.4-0.8% → τ

$$\frac{\delta B}{B}(D \to \pi e^{+} \upsilon) = 45\%$$

$$\frac{\delta B}{B}(D^{+} \to \mu^{+} \upsilon) = 100\%$$



Before CLEO-c precise measurements of charm decay constants and form factors did not exist, because at Tevatron/FT/ B factories:

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

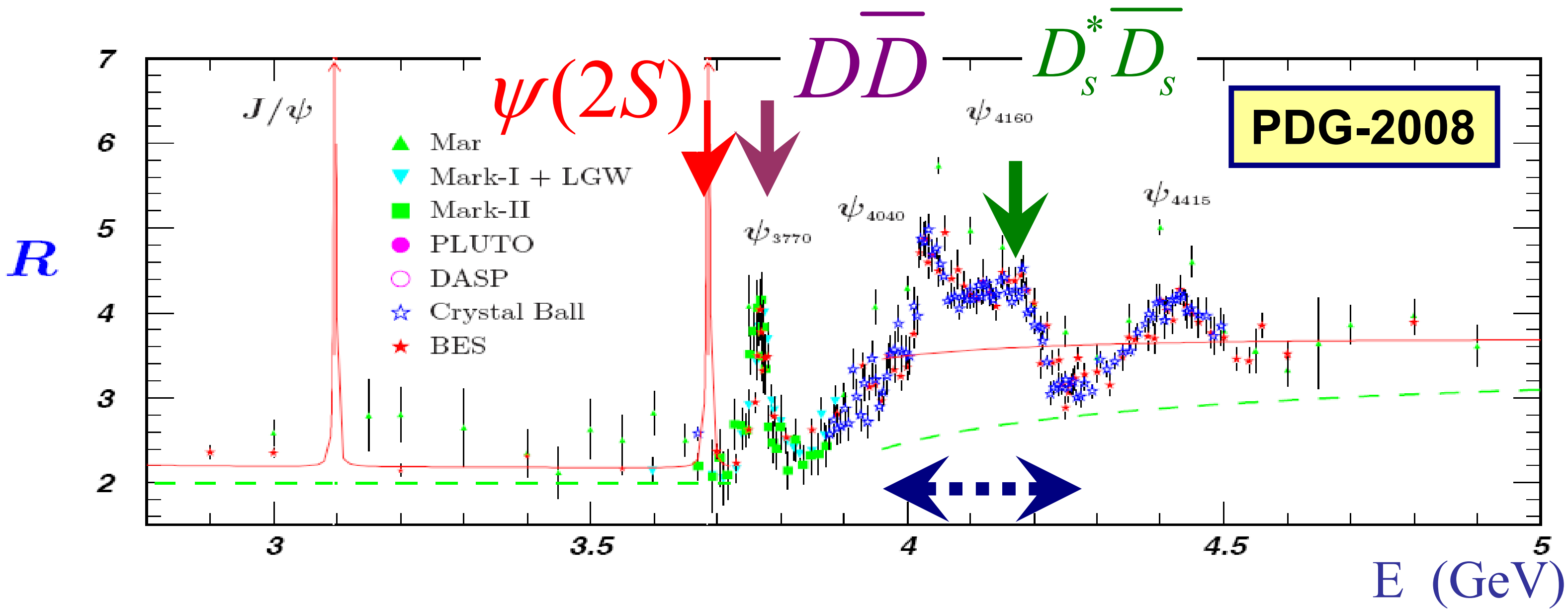
Backgrounds are large. (→ #X Observed)

#D's produced is usually not well known. (→ #D's produced)

CLEO-c: World's largest data sets at charm threshold

CLEO-c: Oct. 2003 – March 2008, **CESR (10GeV) → CESR-c at 4GeV**

CLEO III detector →CLEO-c



$\sqrt{s}$ (MeV) Ldt (pb^{-1})

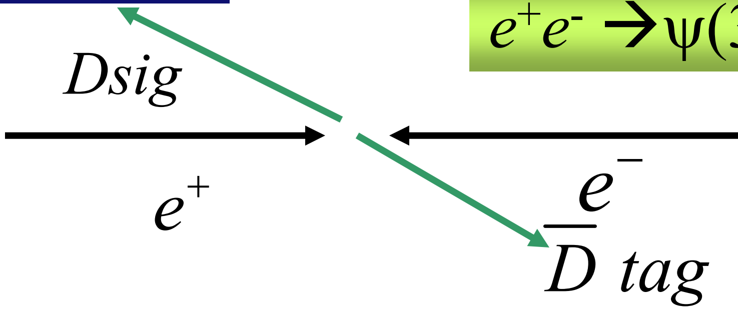
3686 54 $N(\psi(2S)) \approx 27M$

3773 818 $\psi(3770) \to D\overline{D} \approx 5\times10^6\, D\overline{D}$ ⇐ X86 MARK III, X25 BES II

4170 600 $D_{(s)}^{(*)} \overline{D_{(s)}^{(*)}} \approx 6\times10^5\, D_s^* \overline{D_s}$ ⇐ First sample at this energy

ψ(3770) Analysis Strategy

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

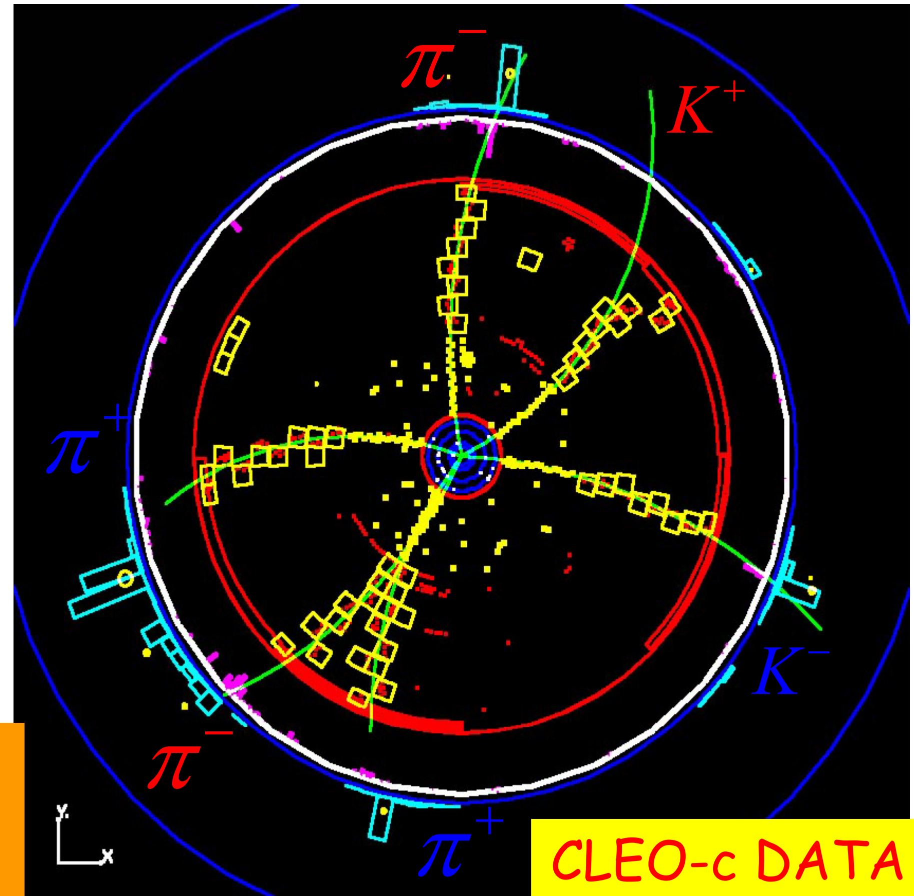


ψ(3770) is to charm what Y(4S) is to beauty

- ❑ 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 tag efficiency: ~25% of events

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



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

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

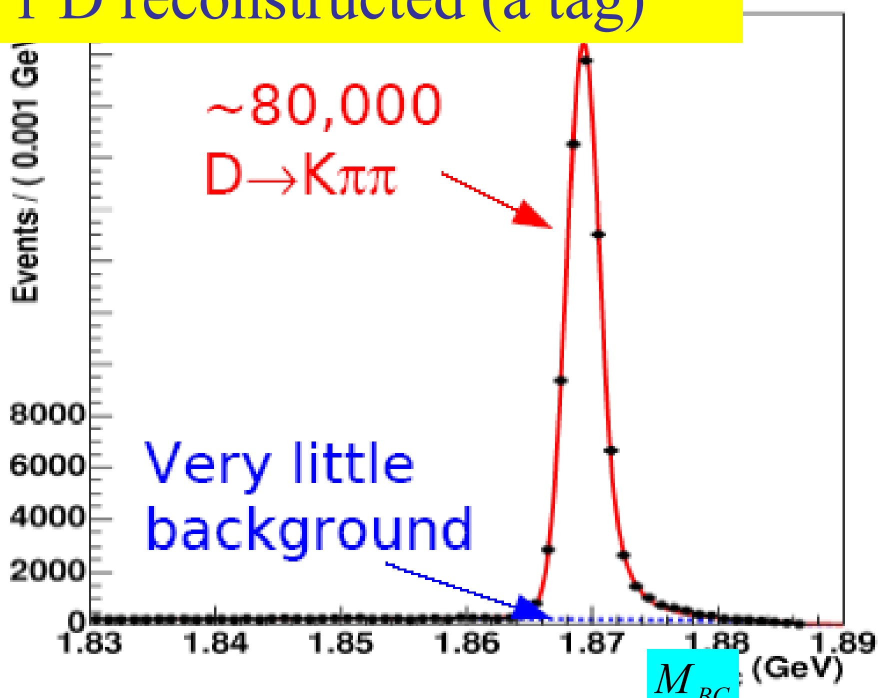
A little luminosity goes a long way:
Tagging ability:
D tags in 800 pb^{-1} @ charm factory
~ # B tags in 1300 fb^{-1} @ Y(4S)

Absolute Charm Branching Ratios at Threshold

281/pb

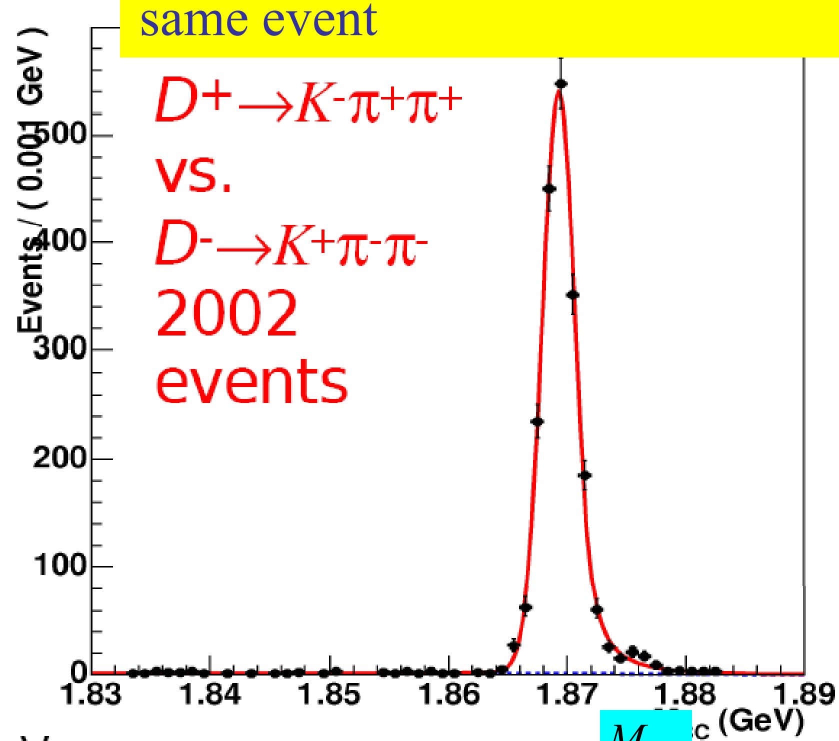
$$E_D \Rightarrow E_{beam}: \quad \Delta E = E_{beam} - E_D \qquad M_{BC} = \sqrt{E_{beam}^2 - |p_D|^2}$$

1 D reconstructed (a tag)



M_{BC}

1D⁺ & 1D⁻ reconstructed in same event



M_{BC}

Independent of L and cross section

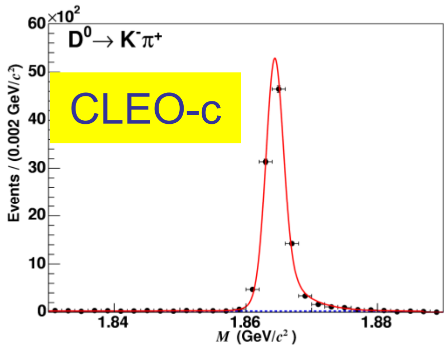
$$B(D^- \to K^+\pi^-\pi^-) = \frac{\#\,(K^+\pi^-\pi^-)\text{ Observed in tagged events}}{\text{detection efficiency for }(K^+\pi^-\pi^-)\ \bullet\ \#\text{D tags}}$$

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

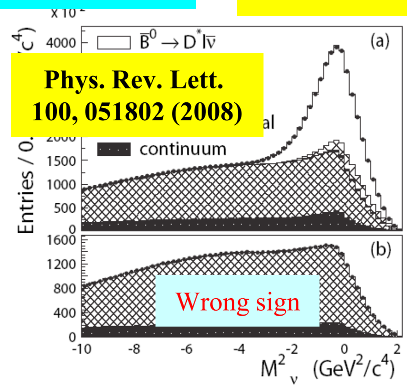
Sets scale of bd triangle

BABAR

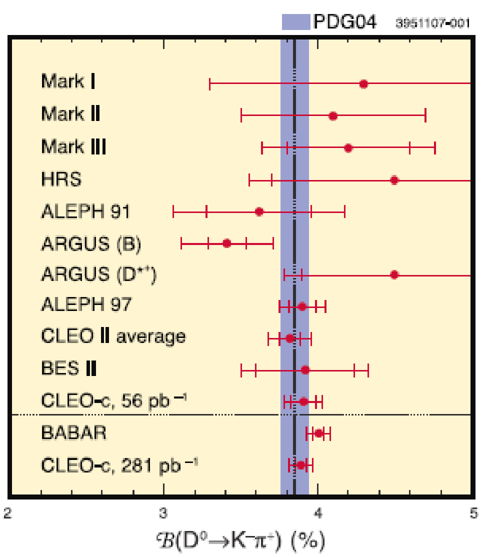
CLEO-c



Phys. Rev. Lett. 100, 051802 (2008)



$\mathcal{B}$ (%)	Error(%)	Source
3.80 ±0.09	2.4	PDG04
3.891±0.035 ±0.069	2.0	CLEO-c
4.007 ±0.037 ±0.072	2.0	BABAR



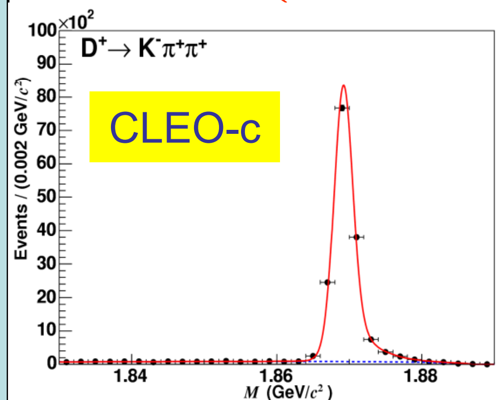
Syst. limited: 2%

CLEO-c & BABAR agree vastly superior S/N at CLEO-c

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

Previous best:

CLEO-c



measure:

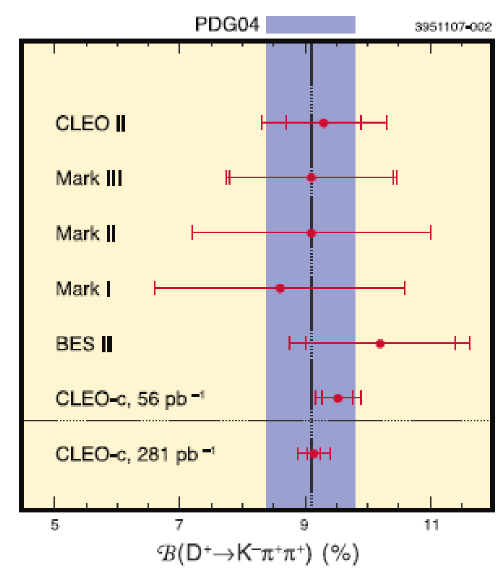
$$\frac{B(D^{*+} \to D^0\pi^+)}{B(D^{*+} \to D^+\pi^0)} \frac{B(D^0 \to K^-\pi^+)}{B(D^+ \to K^-\pi^+\pi^+)}$$

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

$\mathcal{B}$ (%)	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
9.14 ±0.10±0.17	1.9	CLEO-c

now: $B(D^+ \to K^-\pi^+\pi^+)$ *independently measured*

CLEO-c x 3.5 More precise than PDG



charm hadronic scale is finally on a SECURE FOUNDATION

Phys. Rev. D 76, 112001 (2007)

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

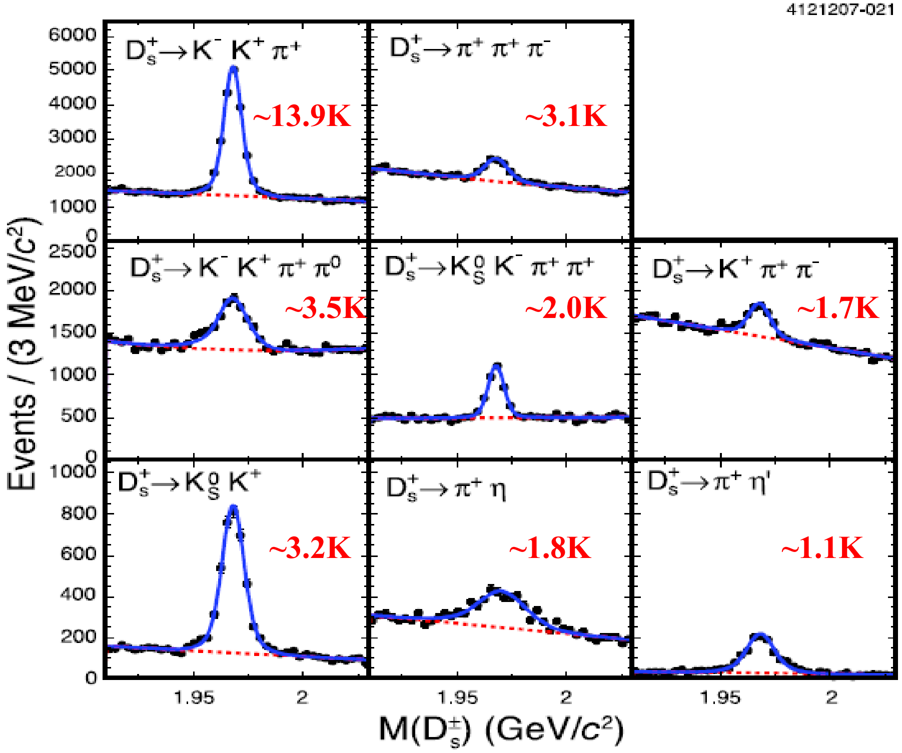
D_s hadronic BFs serve to nomalize many processes in D_s & B_s physics

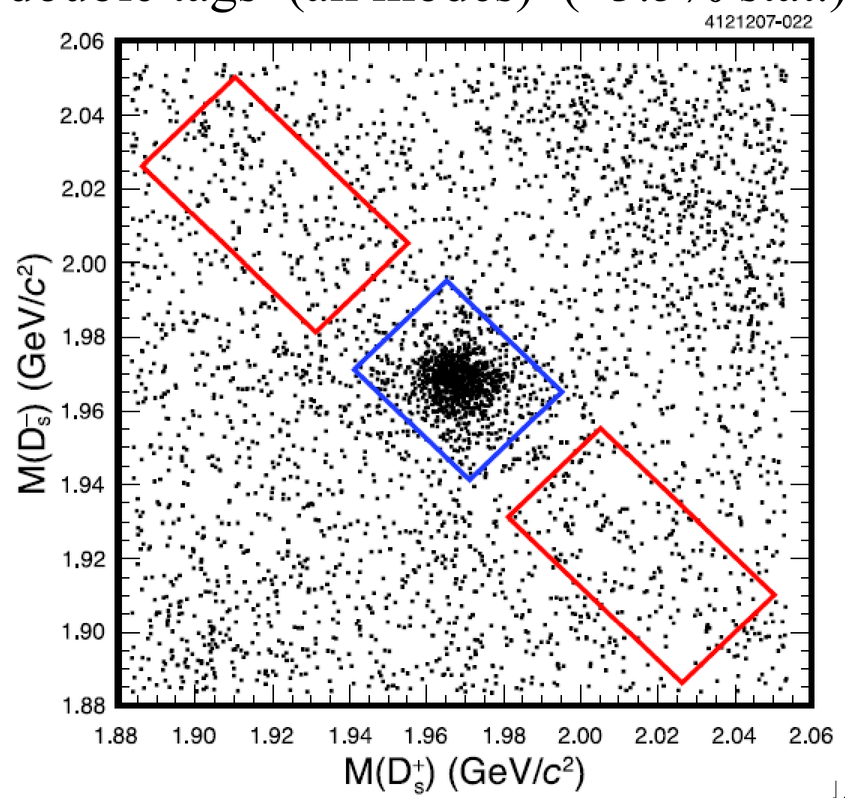
This is the 1st high statistics study @ threshold Phys. Rev. Lett. 100, 161804(2008)

E_{cm}=4170 MeV. 298/pb. Optimal energy for D_sD_s*production. Analysis technique similar to DDbar at 3770.

8 D_s single tag modes

~1000 double tags (all modes) (~3.5% stat.)





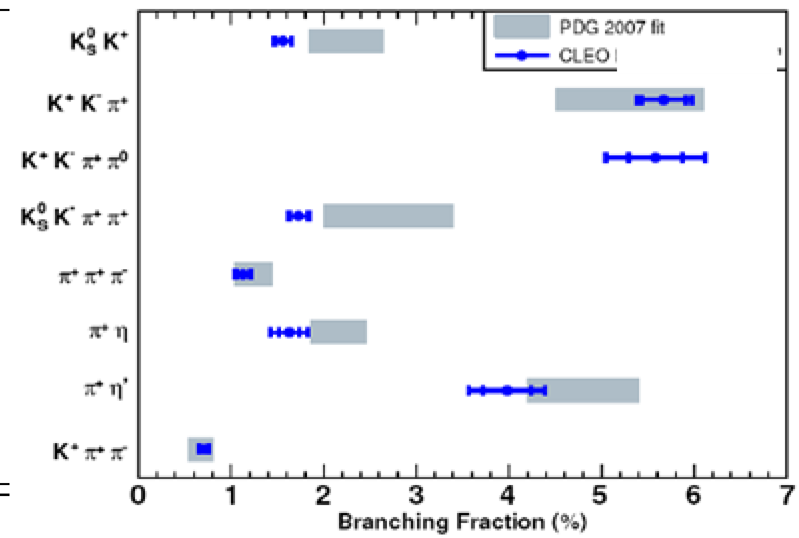
Absolute D_s hadronic $\mathcal{B}$'s

Phys. Rev. Lett. 100, 161804(2008)

CLEO-c, 4170MeV, 298pb^{-1}

Errors already << PDG

Mode	This result $\mathcal{B}$ (%)	PDG 2007 fit $\mathcal{B}$ (%)
$K_S^0 K^+$	$1.49 \pm 0.07 \pm 0.05$	2.2 ± 0.4
$K^- K^+ \pi^+$	$5.50 \pm 0.23 \pm 0.16$	5.3 ± 0.8
$K^- K^+ \pi^+ \pi^0$	$5.65 \pm 0.29 \pm 0.40$	…
$K_S^0 K^- \pi^+ \pi^+$	$1.64 \pm 0.10 \pm 0.07$	2.7 ± 0.7
$\pi^+ \pi^+ \pi^-$	$1.11 \pm 0.07 \pm 0.04$	1.24 ± 0.20
$\pi^+ \eta$	$1.58 \pm 0.11 \pm 0.18$	2.16 ± 0.30
$\pi^+ \eta'$	$3.77 \pm 0.25 \pm 0.30$	4.8 ± 0.6
$K^+ \pi^+ \pi^-$	$0.69 \pm 0.05 \pm 0.03$	0.67 ± 0.13

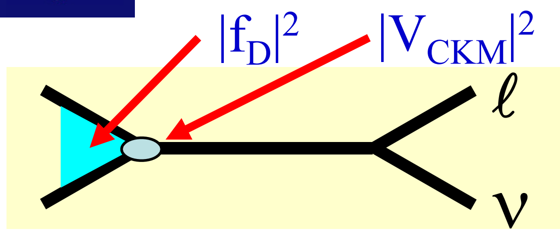


The important normalizing mode $K^+K^+\pi^+$ is in good agreement with PDG

By tagging and counting D and Dbar separately a search for CP Violation was made – new physics if found in a Cabibbo allowed D decay - results were null.

Update to full data set in progress

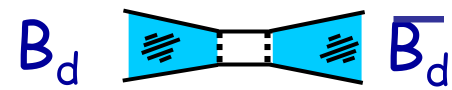
Importance of *absolute* charm leptonic branching ratios

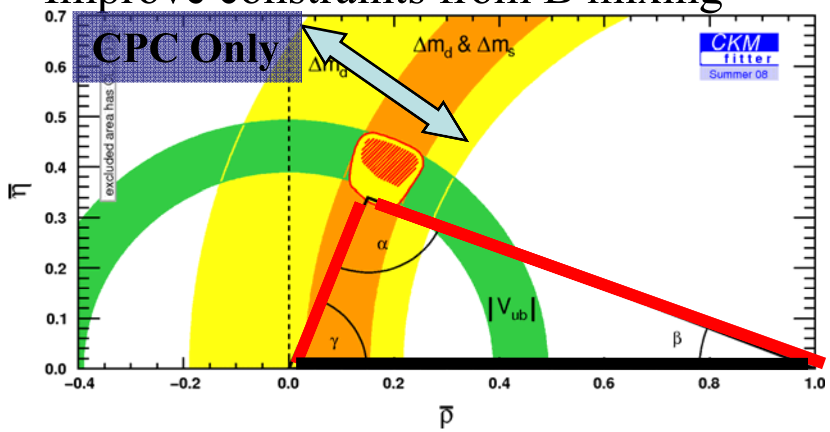


$$\Gamma(D_q^+ \to l\,\upsilon) = \frac{1}{8\pi} G_F^2 M_{D_q^+} m_l^2 \left(1 - \frac{m_l^2}{M_{D+}^2}\right) f_{D+}^2 |V_{cq}|^2$$

1 Check lattice calculations of decay constants

2 Improve constraints from B mixing





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

0.8% (expt) HFAG

~10% (HPQCD) PRL95 212001 (2005)

~ 12%

if f_{Bd} to 3% → $|V_{td}||V_{tb}|$ to ~5%

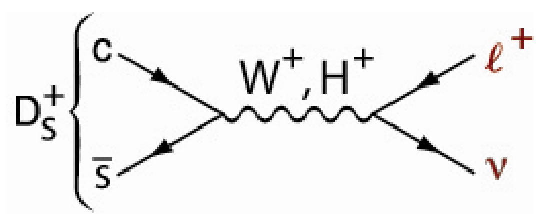
$B \to \tau\nu \propto f_{B+} V_{ub}$ but rate low & V_{ub} not well known

$f_{D\ CLEO\text{-}c}$ and $(f_B/f_D)_{lattice}$ → f_B
(And f_D/f_{Ds} CLEO-c checks f_B/f_{Bs})lattice

precise $|V_{td}|$

important for $|V_{td}|/|V_{ts}|$

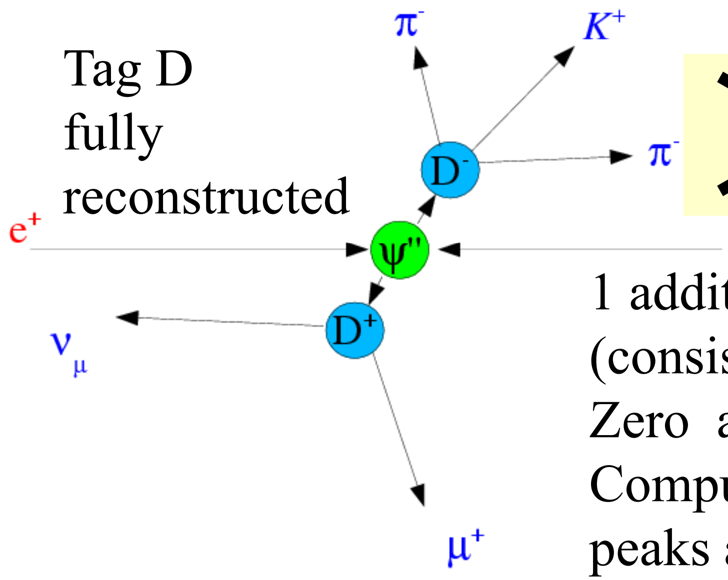
3 Sensitive to new physics

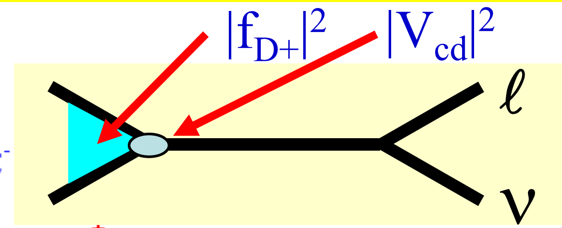


H+ W prime , leptoquarks
In 2HDM effect is largest for Ds

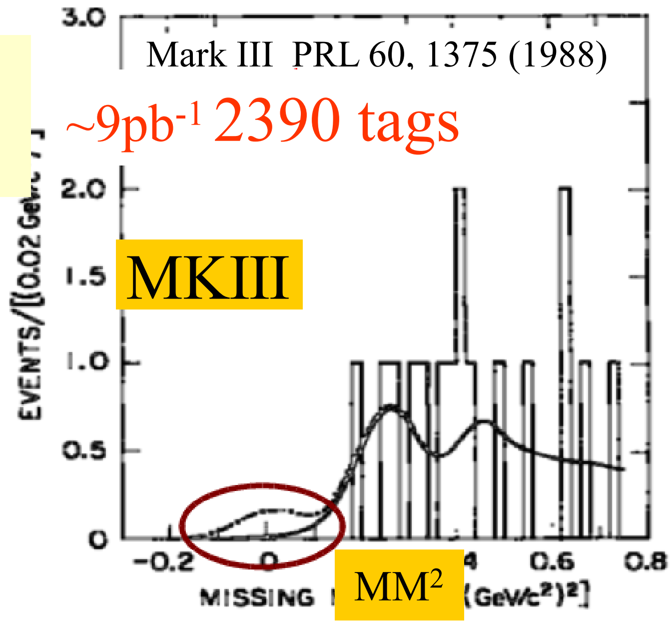
f_{D^+} from Absolute Br($D^+ \rightarrow \mu^+\nu$) at $\psi(3770)$

Tag D fully reconstructed



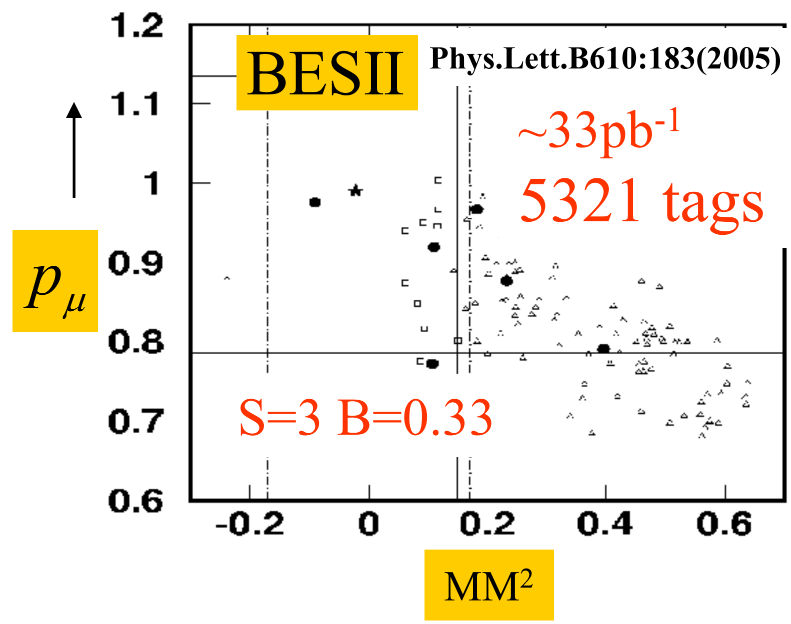


1 additional track (consistent with a muon)
Zero additional photons
Compute missing mass^2:
peaks at 0 for signal



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

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



	$B(D^+ \rightarrow \mu\nu)\times 10^{-4}$	f_D MeV
MkIII	< 7.2	< 290
BESII	$12.2^{11.1}_{-5.3} \pm 0.11$	$371^{+129}_{-119} \pm 25$

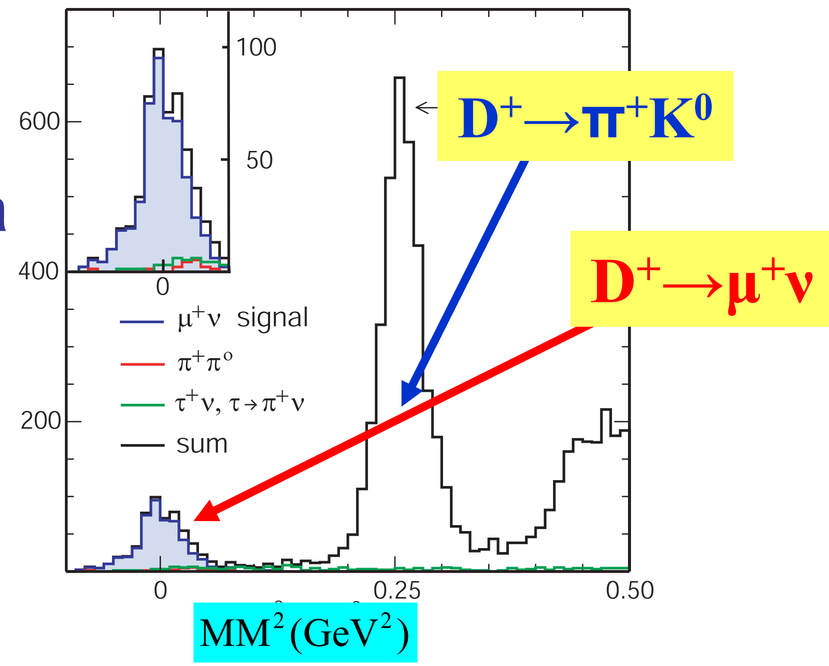
f_{D+} from Absolute Br($D^+ \to \mu^+\nu$)

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

MC

2 x

data



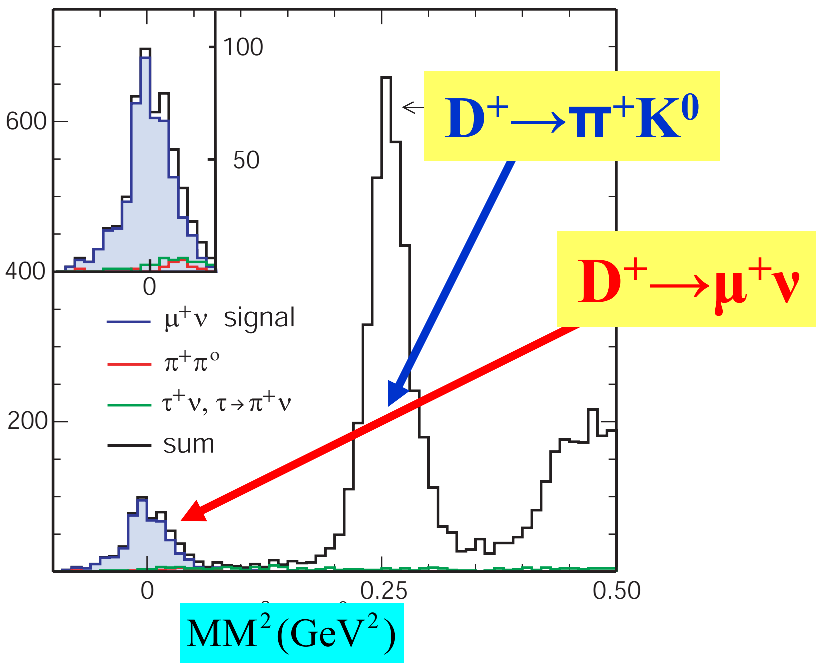
f_{D+} from Absolute Br($D^+ \to \mu^+\nu$)

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

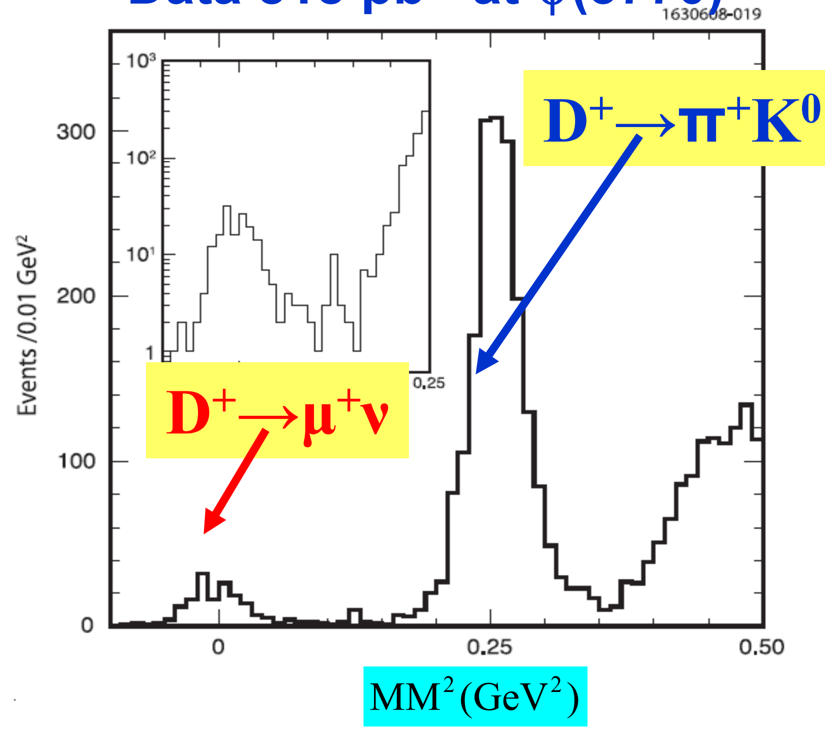
MC

2 x

data



Data 818 pb⁻¹ at ψ(3770)



PRD 78,052003 (2008)

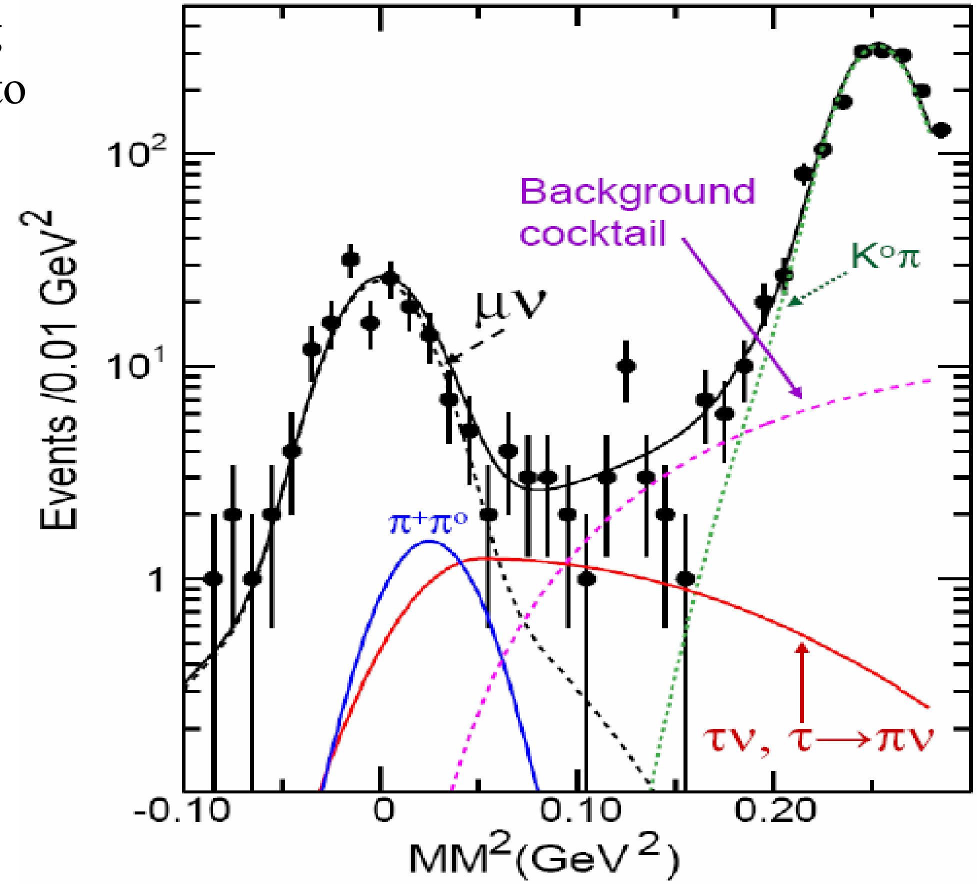
Next: count the number of events in the peak

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

PRD 78,052003 (2008)

- In practice we fit:
  - $\mu\nu$, $\tau\nu$ (signal) : from MC
  - $K^0\pi^+$: from data using double tag DD events where both D decays to charged $K\pi$
  - $\pi^+\pi^0$ and Other bkg: from MC

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



When $\tau^+\nu/\mu^+\nu$ is fixed to SM ratio

149.7 ± 12.0 $\mu^+\nu$; 25.8 $\tau^+\nu$

BF($D\to\mu\nu$) =(3.82±0.32±0.09)x10^{-4}

f_{D+} = (205.8±8.5±2.5) MeV

When $\tau^+\nu/\mu^+\nu$ is allowed to float

153.9 ± 13.5 $\mu^+\nu$; 13.5 ± 15.3 $\tau^+\nu$

BF($D\to\mu\nu$) =(3.93±0.35±0.10)x10^{-4}

f_{D+} = (207.6±9.3±2.5) MeV

Measurements are statistics limited

$f_{D^+} = (208 \pm 4)$ MeV (LQCD)

Expt/Theory agree

LQCD (2%) more precise than experiment (5%)

→ Experimental validation of LQCD is at 5% level

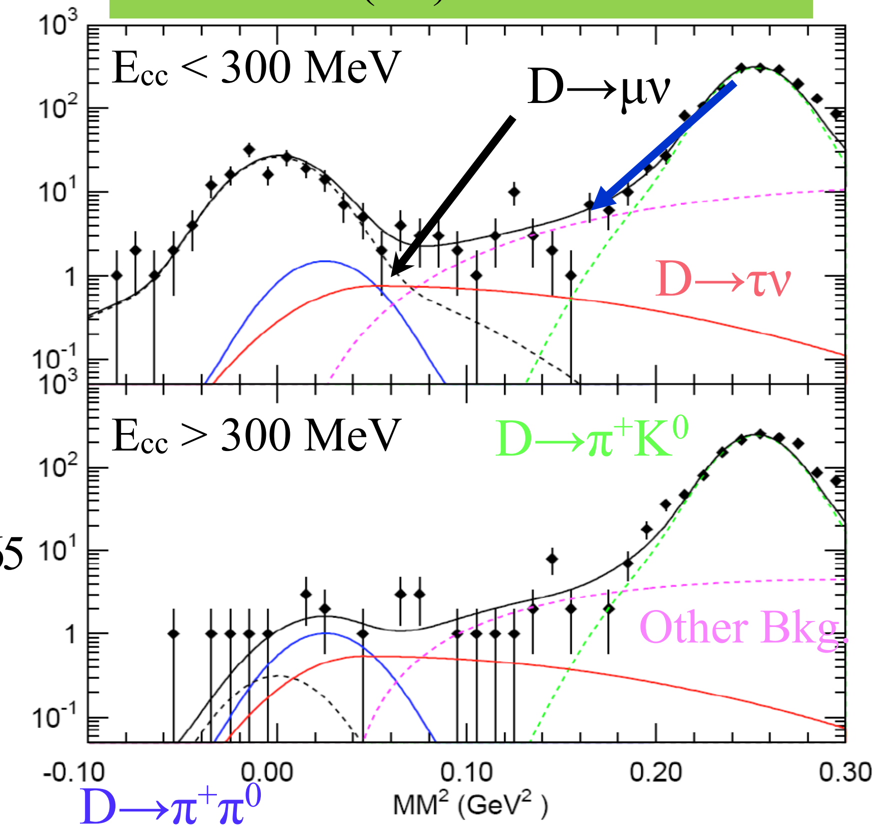
$D^+ \to \tau^+\nu, \tau^+ \to \pi^+\nu$

Two samples mu-like and pi-like based on signal track energy in calorimeter (E_{cc})

A test of lepton universality

- Simultaneous fit to both samples constrain the relative τν yield to the pion acceptance ratio 55:45.
- No significant signal seen:

$B(D^+ \to \tau^+ \nu_\tau) < 1.2 \times 10^{-3}$ @ 90% C.L.



In SM:

$$R = \frac{\Gamma(D^+ \to \tau^+\nu)}{\Gamma(D^+ \to \mu^+\nu)} = m_\tau^2 \left(1 - \frac{m_\tau^2}{M_{D^+}^2}\right)^2 \Big/ m_\mu^2 \left(1 - \frac{m_\mu^2}{M_{D^+}^2}\right)^2 = 2.65$$

combine with CLEO-c $B(D^+ \to \mu^+\nu)$:

$$R_{CLEO} / R_{SM} < 1.2 \text{ at } 90\% \text{ CL}$$

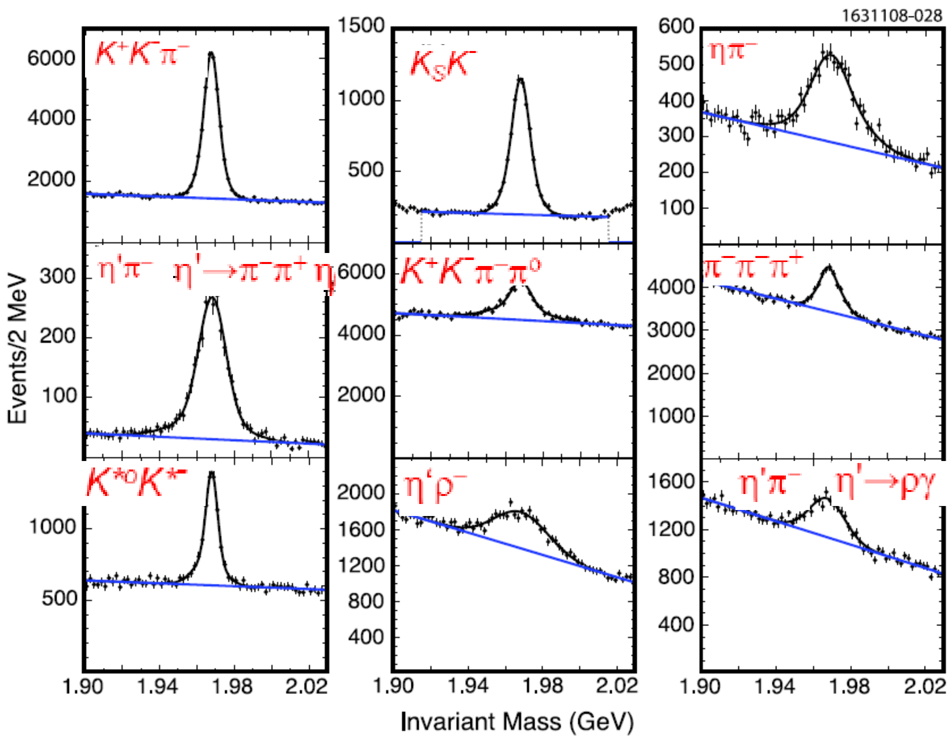
➔ lepton universality in purely leptonic *D+* decays is satisfied at the level of current experimental precision.

PRD 78,052003 (2008)

Method 1: $D_s \to \mu^+\nu, D_s \to \tau^+\nu, \tau^+ \to \pi^+\nu$ & f_{Ds}

D_s (tag) 8 modes:
D_s tags 70514+963

Cabibbo favored decay compensates for smaller cross section @ 4170 MeV

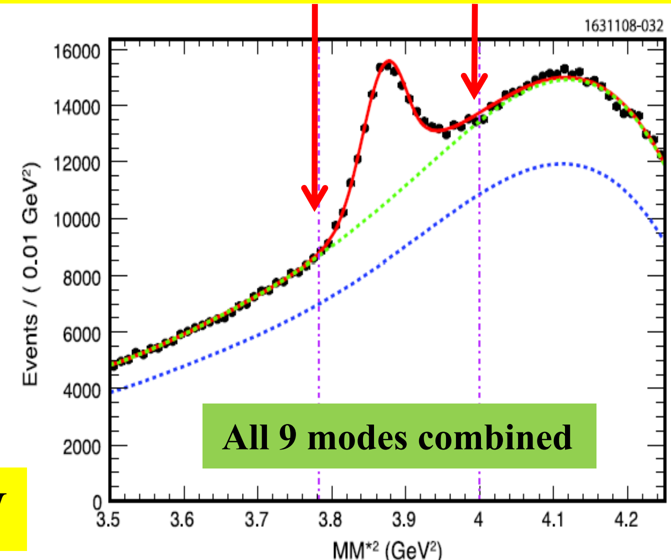


@4170 $D_s D_s^*$, $D_s^* \to D_s\gamma$

Calculate MM^2 for D_s tag plus photon.

Peaks at D_s mass. N(tag+γ)=43859±936

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



We search simultaneously for $D_s \to \mu\nu$ & $D_s \to \tau\nu$

* For the signal: require one additional track and no unassociated extra energy
* Calculate missing mass (next slide)

NEW

arXiv:0901:1216 (Submitted to PRD Jan 12 2009)

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

NEW

arXiv:0901:1216

Three cases depending on particle type:

Fit mu & pi like distributions simultaneously

Using SM $\tau^+\nu/\mu^+\nu$ ratio

$B^{eff}(D_s \to \mu^+\nu)$ = **(0.591 ± 0.037 ± 0.018)%**

f_{D_s} **= (263.3 ± 8.2 ± 3.9) MeV**

Fit muon-like distribution

Not constraining $\tau^+\nu/\mu^+\nu$ ratio

$B(D_s \to \mu^+\nu)$ = **(0.565 ± 0.045 ± 0.017)%**

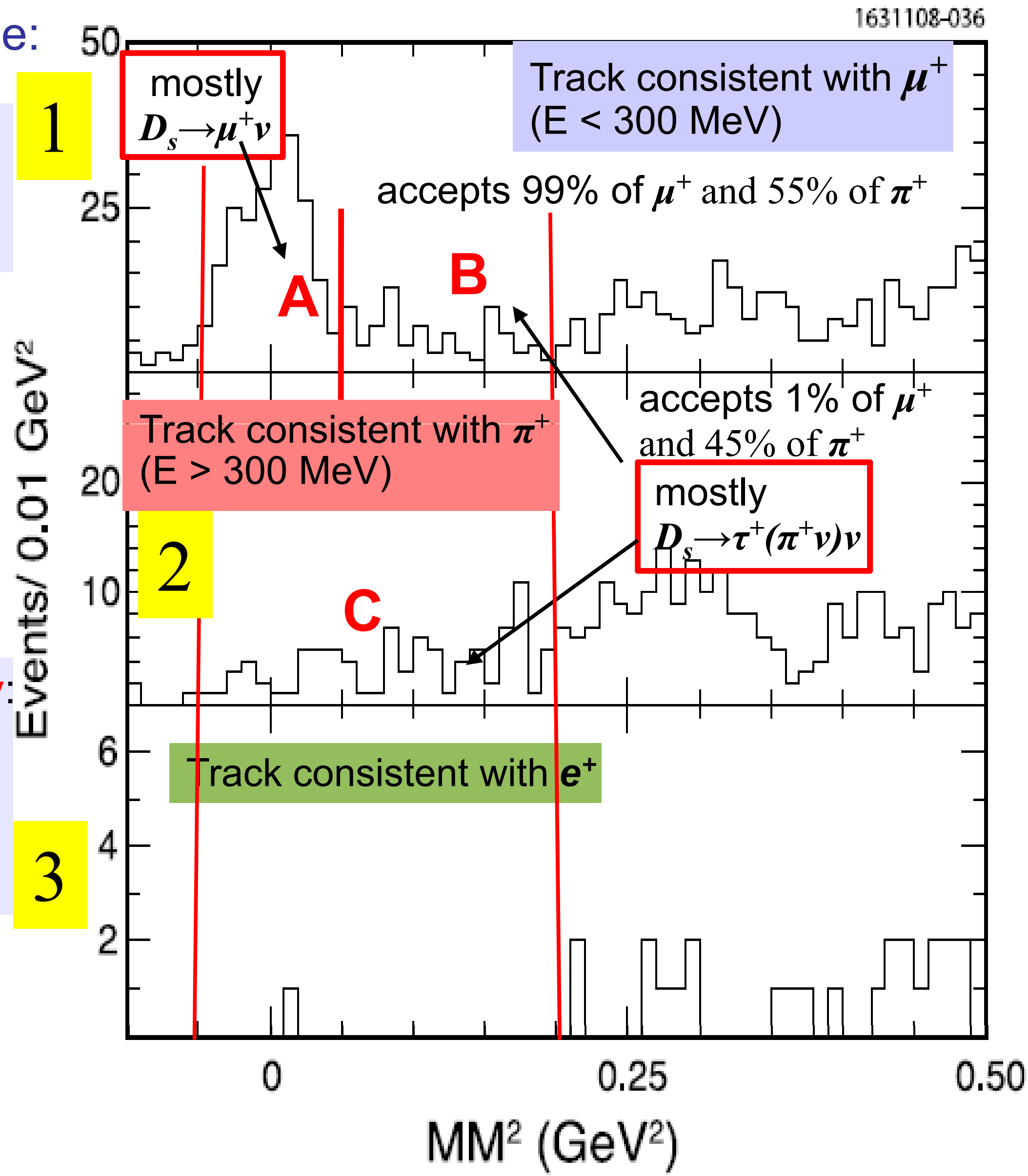
Fit mu & pi-like distributions simultaneously:

Constraining

ratio of $\mu^+\nu$ events to be 98.8:1.2

ratio of $\tau^+\nu$ events to be 55:45

$B(D_s \to \tau^+\nu)$ = ***(6.42 ± 0.81 ± 0.18)%***



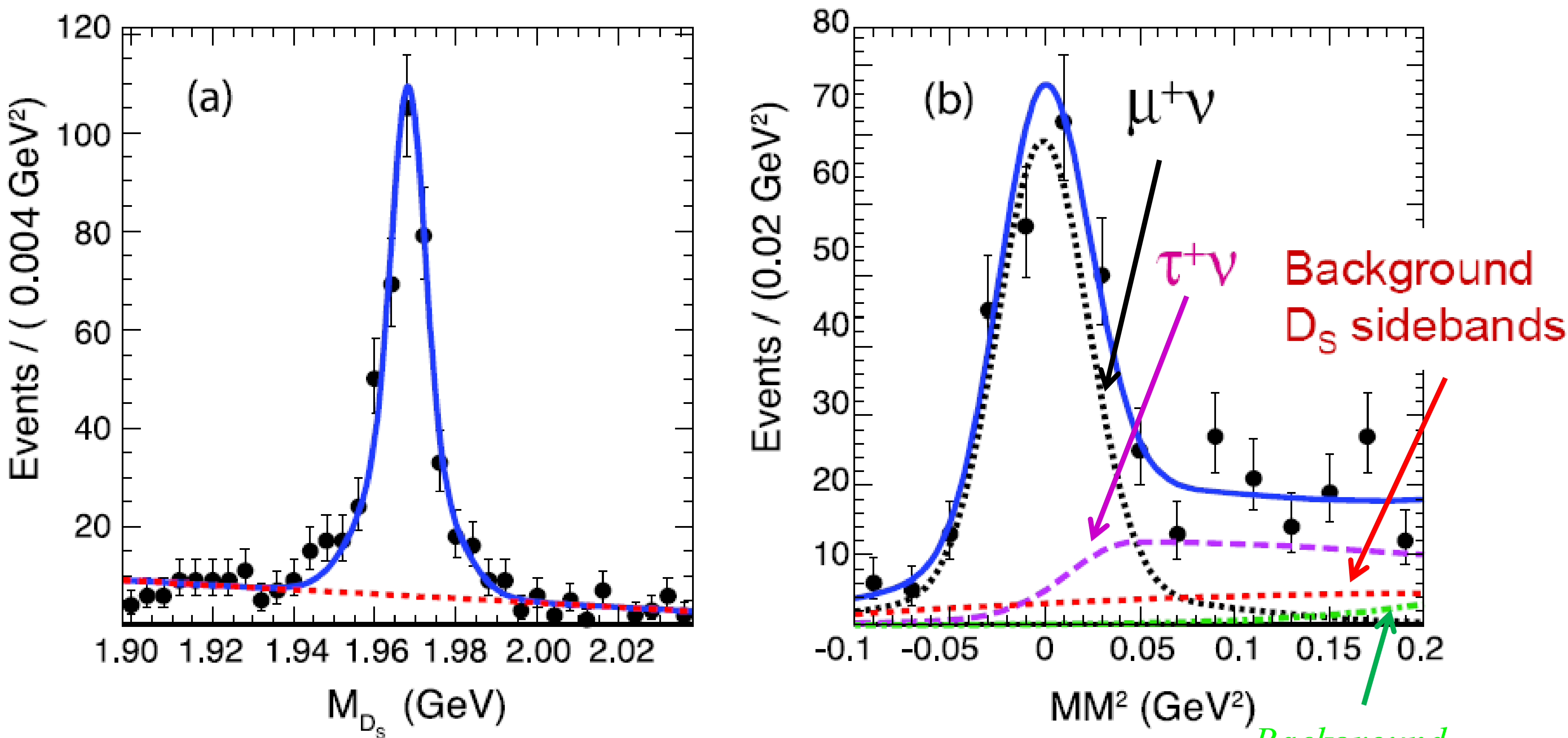
$B(D_s \to e^+\nu)$ **< 1.2x10⁻⁴**

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

arXiv:0901:1216

NEW

2-D fit to sum of muon-like and pion -like distributions



Using SM $\tau^+ \nu / \mu^+ \nu$ ratio

$B^{eff}(D_s \to \mu^+\nu)$ = **(0.591 ± 0.037 ± 0.018)%**

f_{D_s} = (263.3 ± 8.2 ± 3.9) MeV

Statistics limited

	events
$D_s \to \mu\nu$	235 ± 13.8
Bkgd	9.7±0.9
S/N>20/1	

Method 2: $D_s \to \tau^+\nu, \tau^+ \to e^+\nu\nu$ & f_{Ds}

NEW

arXiv:0901.1147

(Sub. to PRD Jan 12 2009)

600/pb @4170 MeV

Require D_s tag

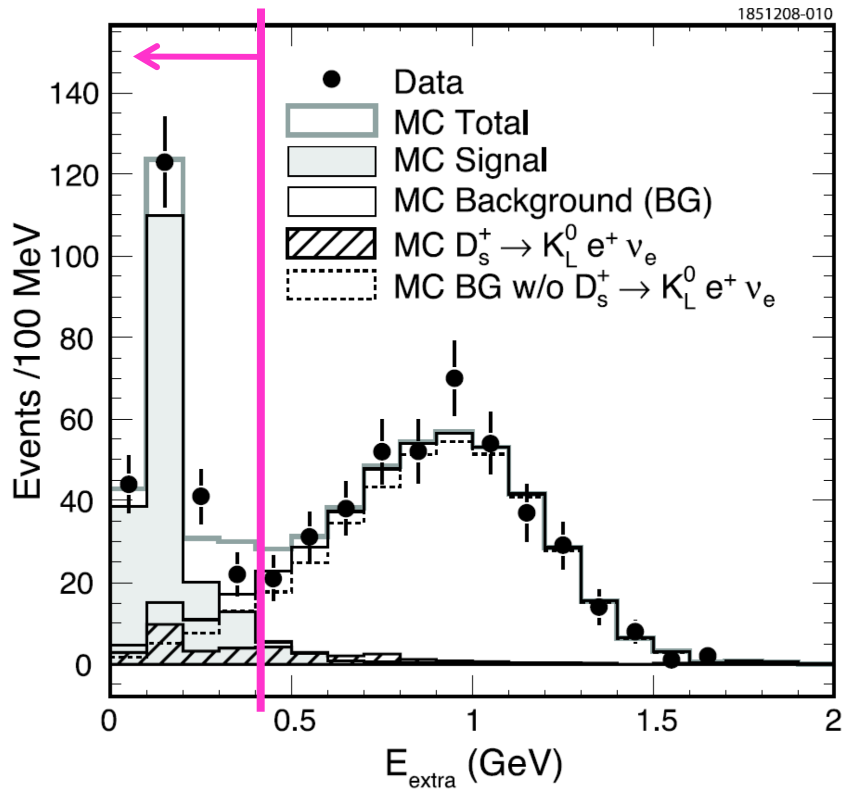
Require 1 electron and no other tracks

Primary bkgd D_s (tag) + $D_s \to X e \nu$.

Suppress X by requiring low amount of extra energy in calorimeter. Shown on right.

Signal region E_{cc}(extra)< 0.4 GeV.

MC describes data well



	events
$D_s \to \tau\nu$	180.6 ± 15.9
Bkgd	49.4 ± 1.8
S/N>3/1	

Results:

$B(D_s \to \tau^+ \nu)$ = **(5.30 ± 0.47 ± 0.22)%**

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

f_{Ds} = **(252.5 ± 11.1 ± 5.2) MeV**

This is the most precise determination of $B(D_s \to \tau^+ \nu)$

f_{Ds} & f_{Ds}/f_{D^+}

Combining method 1 $D_s \to \mu\nu$ & $D_s \to \tau\nu, \tau \to \pi\nu$

& method 2 $D_s \to \tau\nu, \tau \to e\nu$

weighted average: $f_{Ds} = (259.5 \pm 6.6 \pm 3.1)$ MeV

(syst. uncertainties are mostly uncorrelated between methods)

combine with $f_{D^+} = (205.8 \pm 8.5 \pm 2.5)$ MeV (CLEO)

$$f_{Ds}/f_{D^+} = 1.26 \pm 0.06 \pm 0.02$$

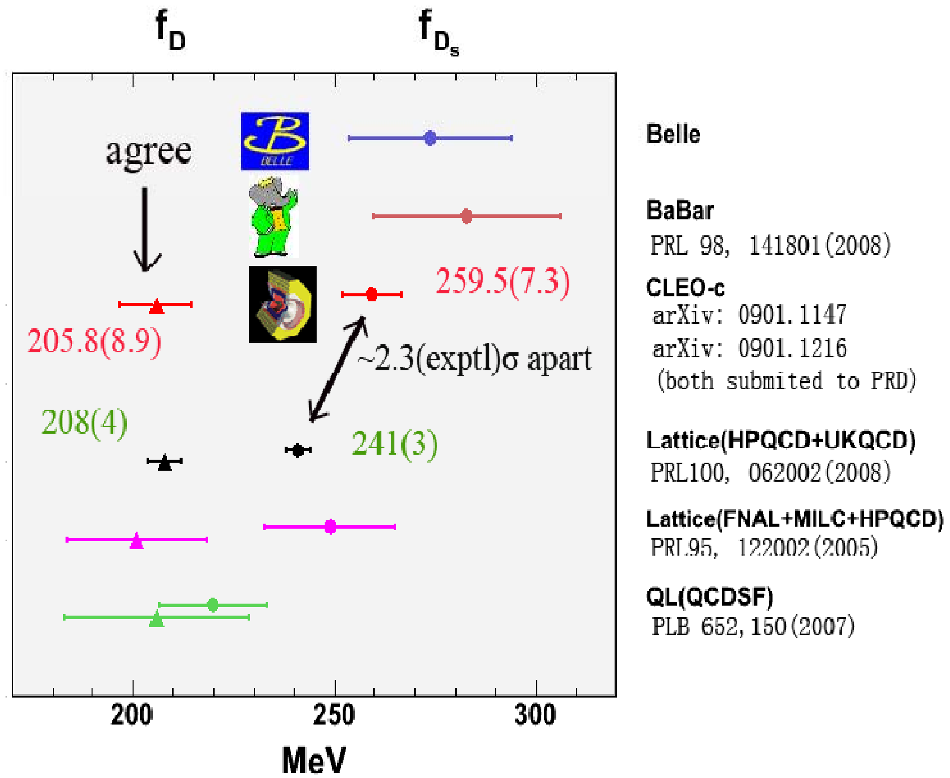
$$R_{CLEO} = \frac{\Gamma(D_s^+ \to \tau^+\nu)}{\Gamma(D_s^+ \to \mu^+\nu)} = 10.1 \pm 0.9 \pm 0.3$$

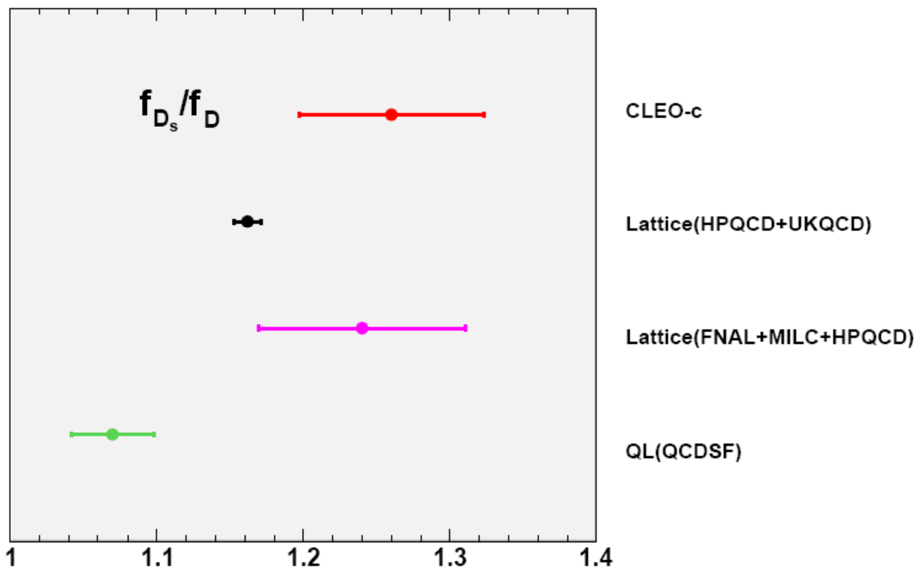
compared to:

$$R_{SM} = \frac{\Gamma(D_s^+ \to \tau^+\nu)}{\Gamma(D_s^+ \to \mu^+\nu)} = 9.76 \quad \text{(Standard Model)}$$

➔ lepton universality in purely leptonic D_s decays is satisfied at the level of current experimental precision.

Comparison to LQCD





CLEO f_D consistent with calculations

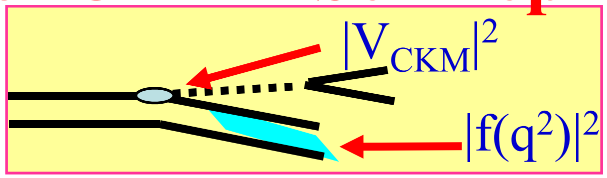
CLEO f_{Ds} (and Belle & BABAR) higher than most theoretical expectations

CLEO f_{Ds} is ~2.3σ above the most recent & precise LQCD calculation (HPQCD+UKQCD).

Ds leptonic decay width could be modified by new physics ex: Dobrescu and Kronfeld arXiv:0803.0512

The difference between expt & HPQCD+UKQCD could be due to new physics, unlikely statistical fluctuations in experiment of lattice calculations or systematic uncertainties which are not understood in the lattice calculation or experiment. BES III measurements are eagerly awaited.

Importance of Charm Semileptonic Decays

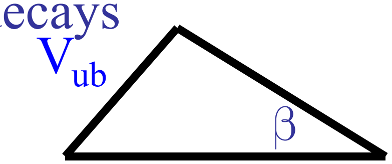


$$\frac{d\Gamma}{dq^2} \propto |V_{cs(d)}|^2 |f_+^{D\to(K)\pi}(q^2)|^2$$

1 Assuming th ff⇒V_{cs} and V_{cd}

2 Assuming V_{cs} and V_{cd} known, we can check theoretical calculations of the form factors

3 *Potentially* useful input to Vub from exclusive B semileptonic decays



$Br(B\to\pi l\nu)\sim$ 6% precision
BABAR/Belle/CLEO(HFAG)

(summer 2008)

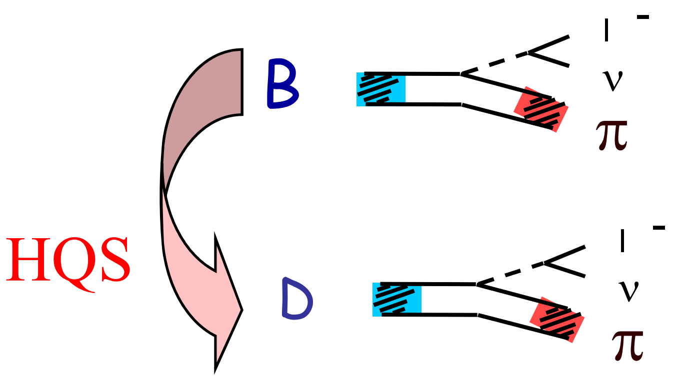
$$|V_{ub}| = (3.62 \pm 0.22 \pm^{+0.63}_{-0.41}) \times 10^{-3}$$
$\pm$ exp $\pm$ LQCD

Expt. 5%
$q^2 > 16\, GeV^2$

~11- 17% e.g.
HPQCD &FNAL

ASK update this morning

$$|V_{ub}| = (3.38 \pm 0.36) \times 10^{-3}$$
11%

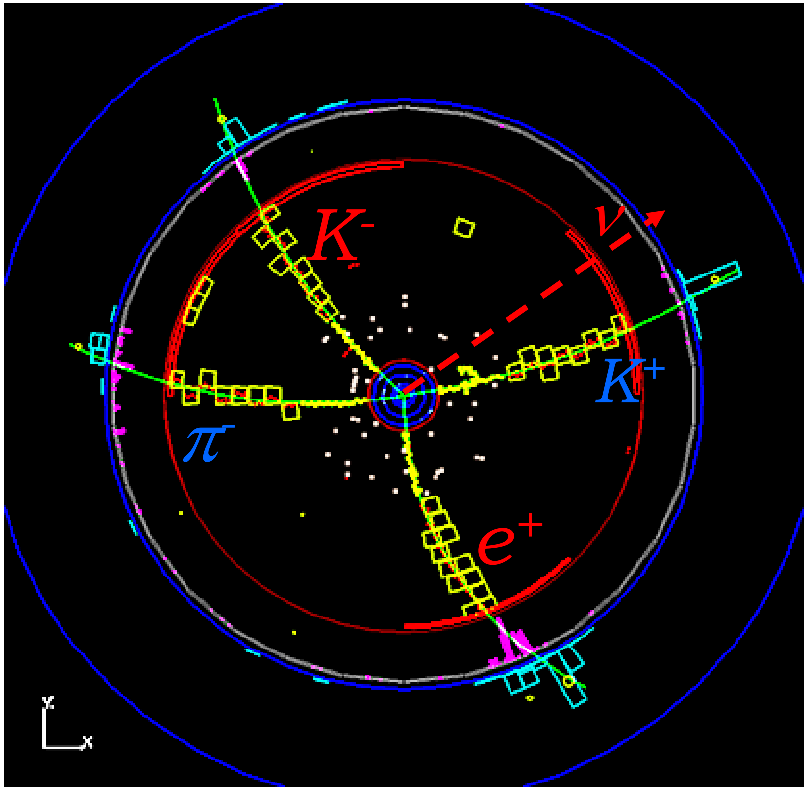


$$\propto \left[f^{B\to\pi}(q) \right]^2 |V_{ub}|^2$$

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

Related at same invariant 4 velocity

Absolute Semileptonic Branching Fractions



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

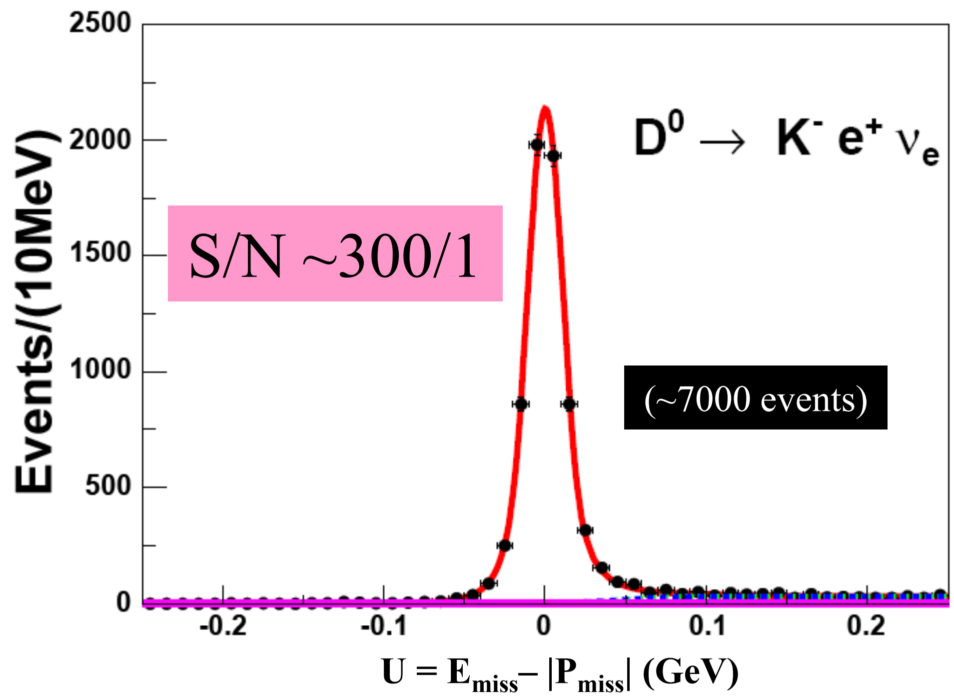
$$\overline{D}^0 \rightarrow K^+\pi^-, D^0 \rightarrow K^-e^+\nu$$

Tagging creates a single D beam of known 4-momentum

The neutrino direction is determined to 1^0

no kinematics ambiguity

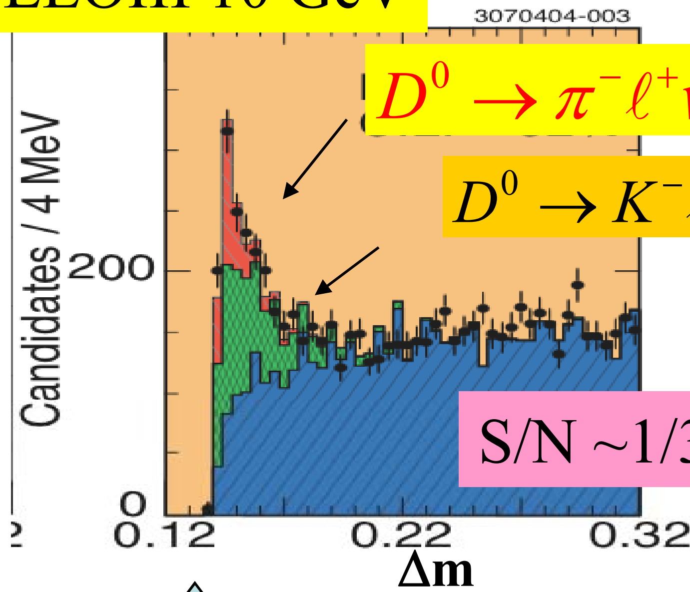
$$U \equiv E_{miss} - |\vec{p}_{miss}| = 0$$



arXiv:0810.3878 (accepted PRD)
Feb 3 2009

$$\mathcal{B}(D \rightarrow Ke\nu) = \frac{N(D \rightarrow Ke\nu)}{\text{Efficiency} \times N_{\text{tags}}}$$

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



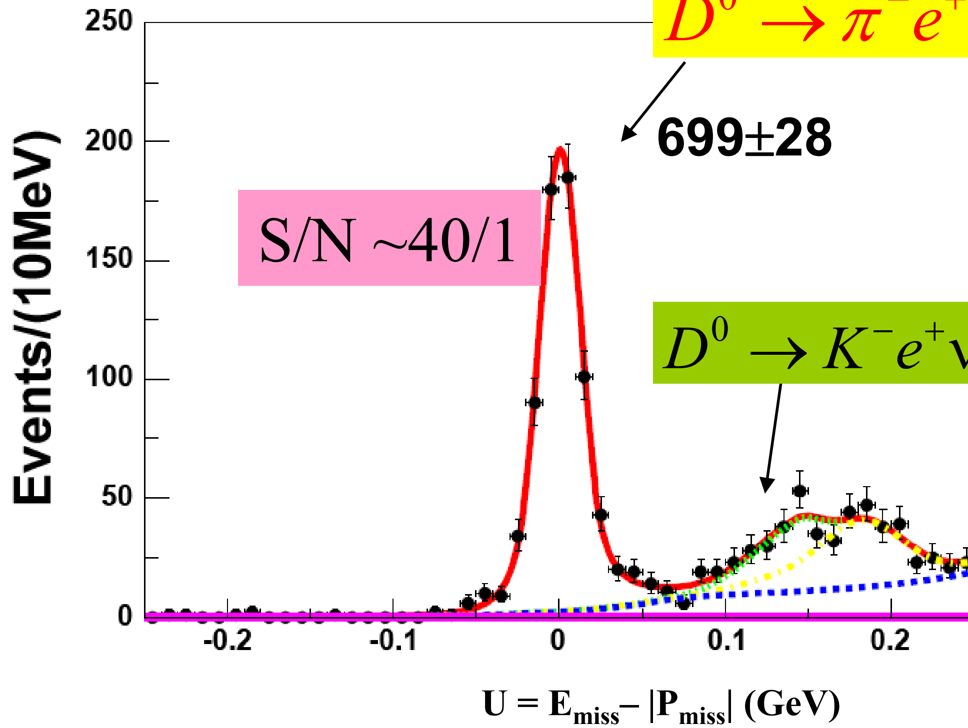
CLEOIII 10 GeV

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

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

S/N ~1/3

CLEO-c



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

699±28

S/N ~40/1

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

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

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

observable:

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

Compare to:
state of the
art measurement
at 10 GeV (CLEO III)
PRL 94, 11802 (2004)

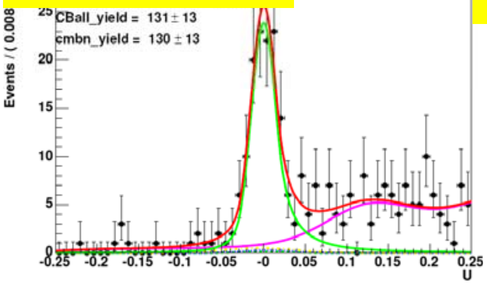
Note:
kinematic
separation.

Only other high statistics measurement is from Belle
282/fb (x1,000 CLEOc) 222± 17 events S/N 4/1

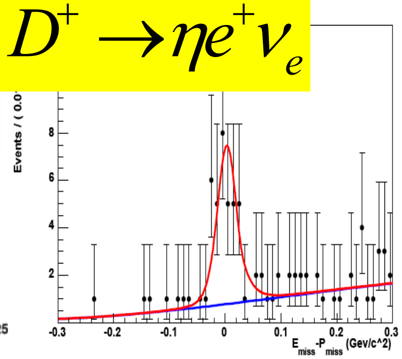
CLEO-c semileptonic tagging analysis technique: big impact

1st Observations:

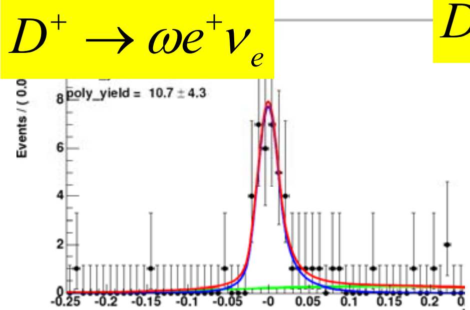
$D^0 \to \rho^- e^+ \nu_e$



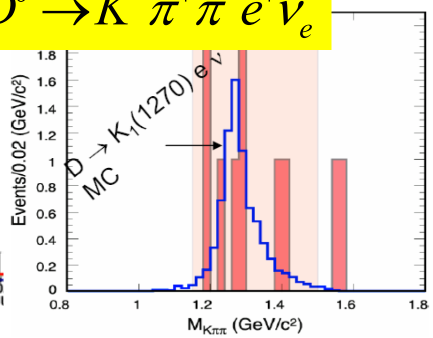
$D^+ \to \eta e^+ \nu_e$



$D^+ \to \omega e^+ \nu_e$



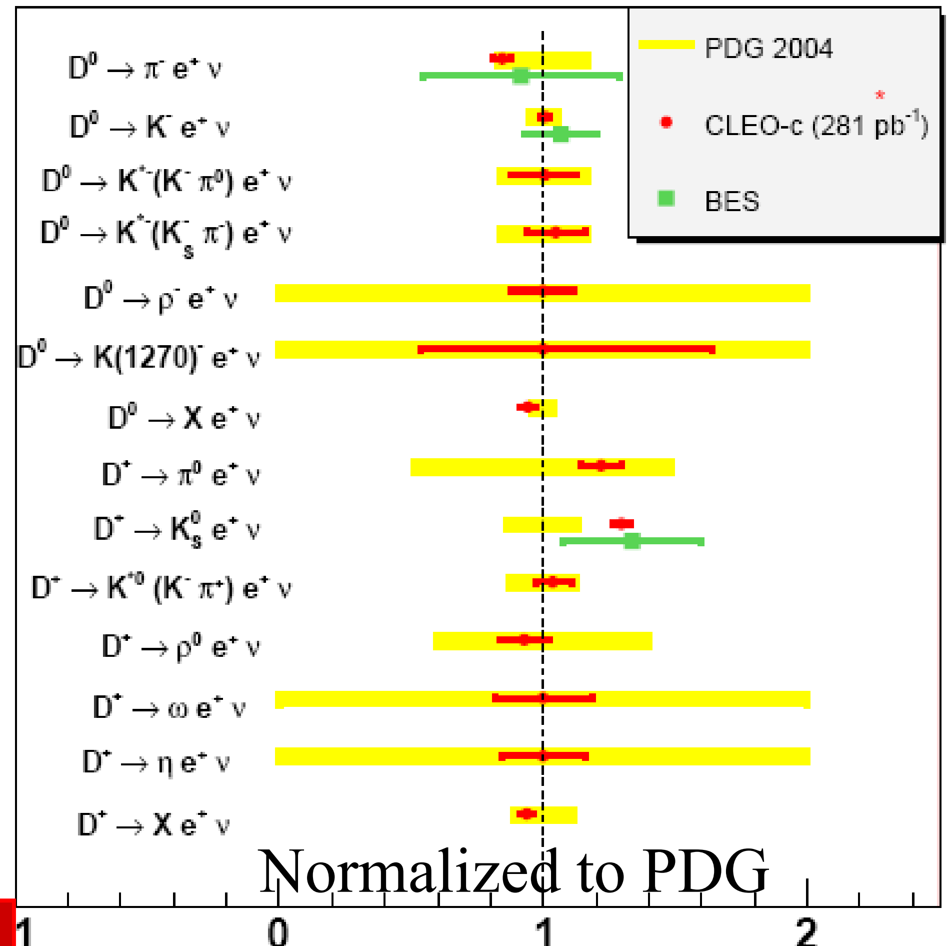
$D^0 \to K^- \pi^+ \pi^- e^+ \nu_e$



+ $D^+ / D^0 \to X e^+ \nu_e$

$D \to K^* e^+ \nu_e$ form factors

Precision Measurements:



$D \to K^* e^+ \nu$ branching fractions are for 56/pb

Note: use PDG2004, as PDG2006 & PDG2008 are dominated by CLEO-c measurements

PRL. 97, 251801 (2006);
arXiv:0810.3878 (accepted PRD);
PRL, 100, 251802(2008);
PRD, 77, 112005(2008);
PRD. 74, 052001(2006);
arXiv:0802.4222 (accepted PRL);
PRL. 99, 191801 (2007);

CLEO's measurements most precise for ALL modes; *4 modes* observed for the first time

$D \to K/\pi e^+ \nu$ without tagging

Phys.Rev.Lett.100:251802,2008.
Phys.Rev.D77:112005,2008

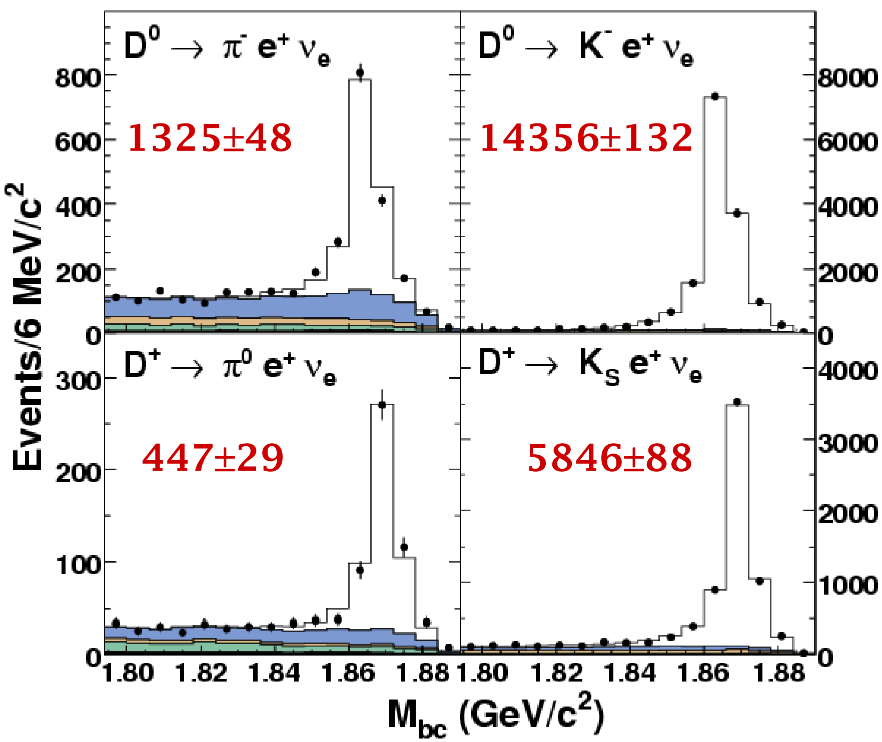
[analogous to neutrino reconstruction @ Υ(4S)]

Uses neutrino reconstruction:
Identify semileptonic decay.

Reconstruct neutrino 4-momentum from all measured energy in the event.

Use K(π), e, and missing 4-momentum and require consistency in energy and beam-energy constrained mass.

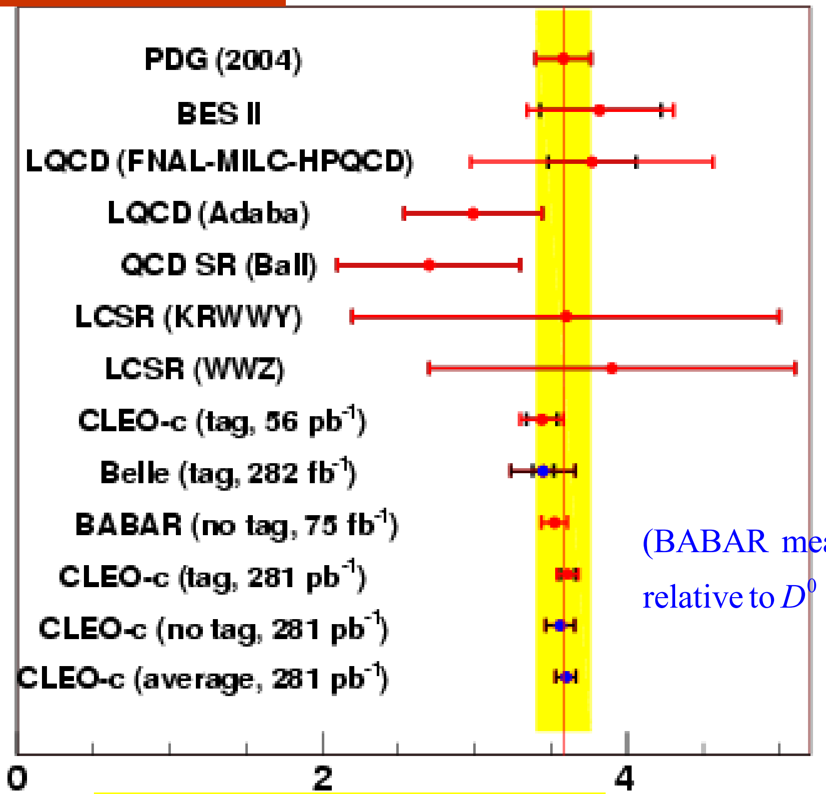
Higher efficiency than tagging but larger backgrounds



M_{bc} distributions fitted simultaneously in 5 q^2 bins to obtain $d(BF)/dq^2$. Integrate to get branching fractions and fit to get form factors

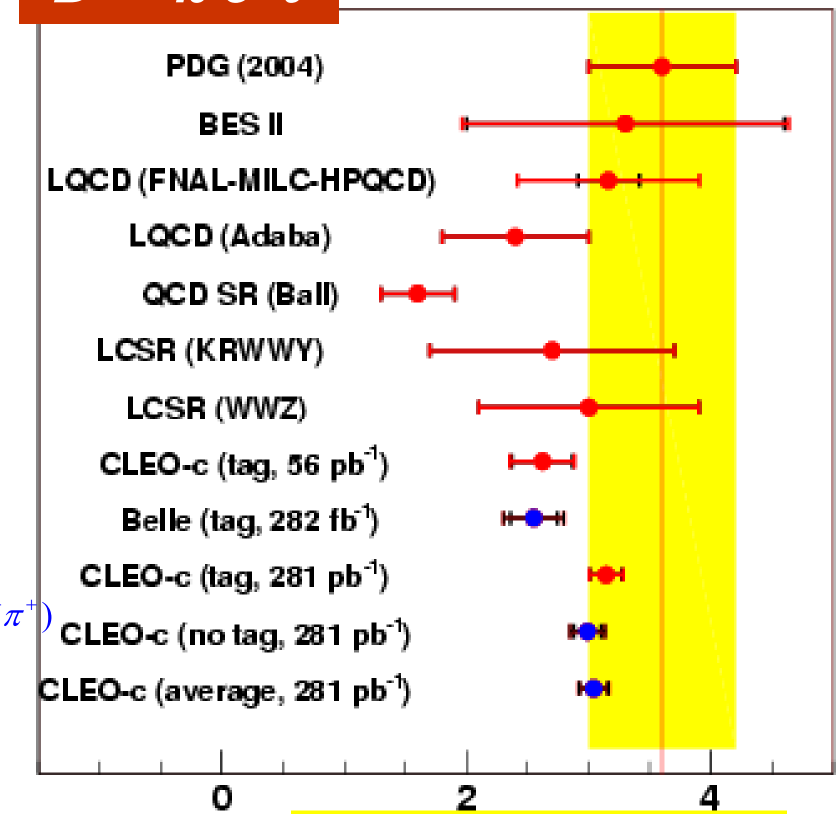
D →K, π eν Branching Fractions

$D \to K e^+ \nu$



(BABAR measures relative to $D^0 \to K^- \pi^+$)

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



$\mathrm{B}(D^0 \to K^- e^+ \nu) \times 10^{-2}$
3.60(3)(6) %
(CLEO-c average)

$\sigma(B(Ke\nu))/B(Ke\nu) \sim 2\%$
$\sigma(B(\pi e\nu))/B(\pi e\nu) \sim 4\%$

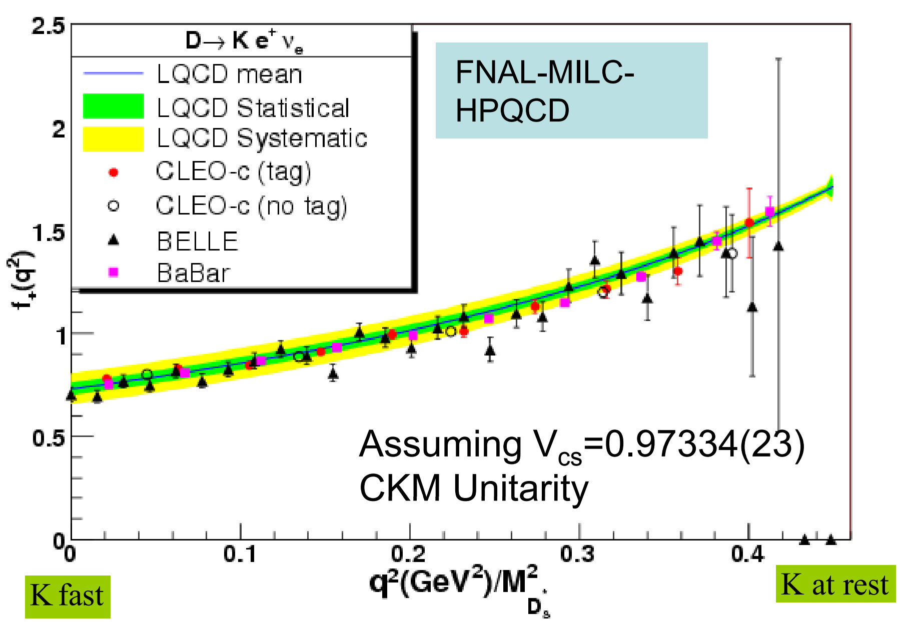
$\mathrm{B}(D^0 \to \pi^- e^+ \nu) \times 10^{-3}$
0.304(11)(5)%
(CLEO-c average)

Precision measurements from BABAR/Belle/CLEO-c.
CLEO-c most precise. Theoretical precision lags experiment.

$D^0 \to K e^+ \nu$ Form Factor: test of LQCD

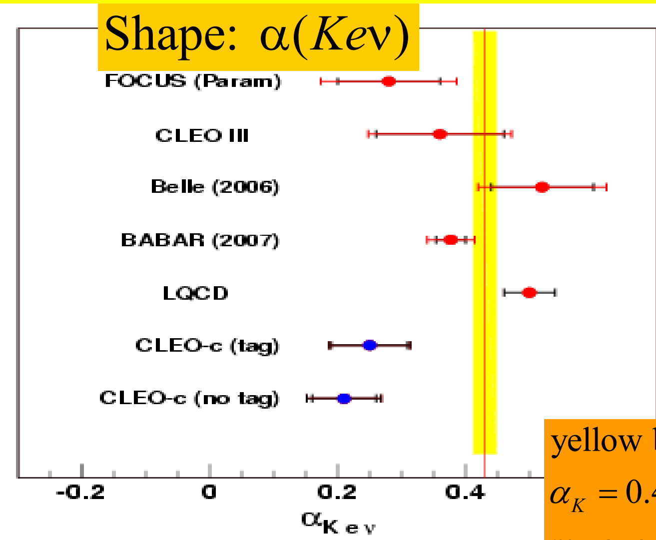
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} P_K^3 \left| f_+(q^2) \right|^2 \left| V_{cs} \right|^2$$

Form factor measures probability hadron will be formed



Modified pole model used as example

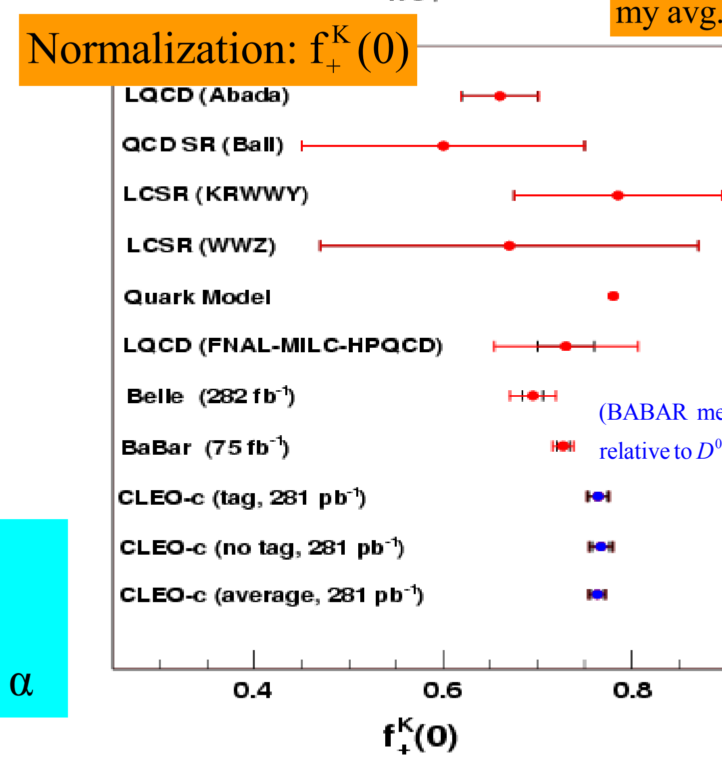
$$f_+(q^2) = \frac{f_+(0)}{\left(1 - q^2/m_{pole}^2\right)\left(1 - \alpha\, q^2/m_{pole}^2\right)}$$



yellow band

$\alpha_K = 0.40(2)$

my avg.

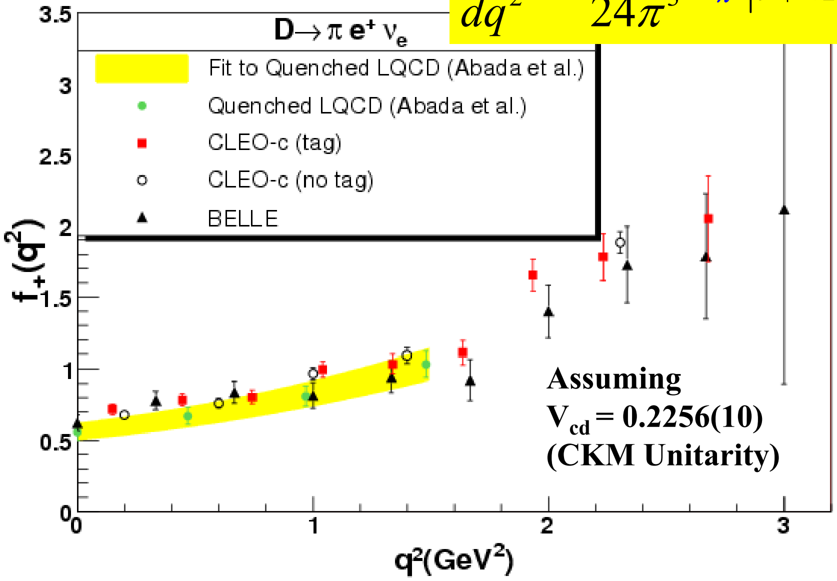


(BABAR measures relative to $D^0 \to K^- \pi^+$)

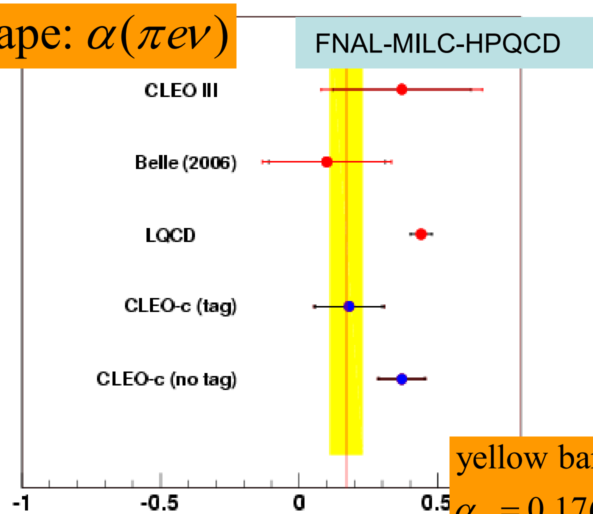
Normalization: experiments (1.2%) consistent with LQCD (10%). *Theoretical precision lags.*
CLEO-c prefers smaller value for shape parameter, α

$D^0 \to \pi^- e^+ \nu$ Form Factor: test of LQCD

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

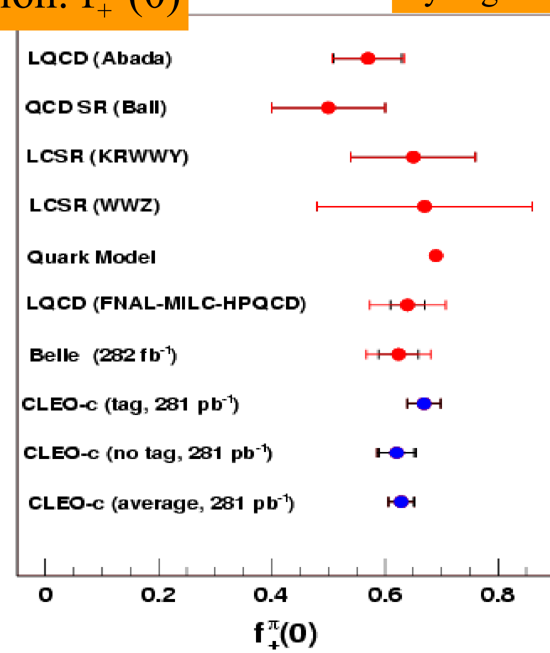


shape: $\alpha(\pi e \nu)$



yellow band
$\alpha_\pi = 0.17(6)$
my avg.

Normalization: $f_+^K(0)$



Modified pole model used as example

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

Normalization experiments (2%) consistent with LQCD (10%). CLEO-c is most precise. *Theoretical precision lags.*

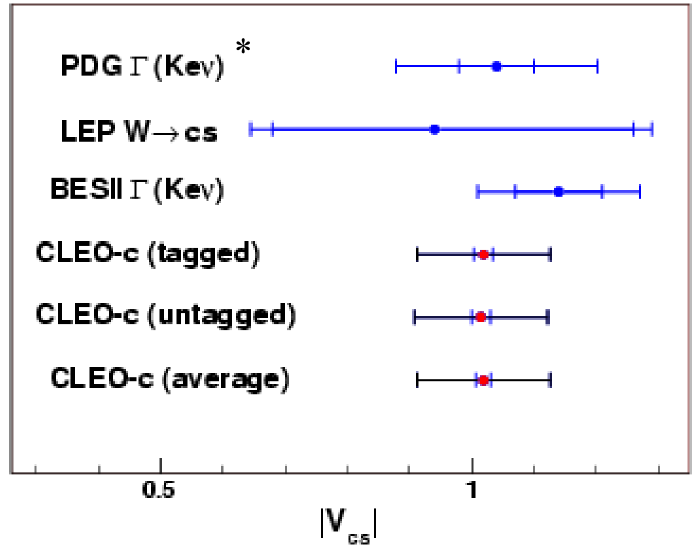
The data determines $|V_{cd}|f_+(q^2)$. To extract $|V_{cd}|$ we fit to $|V_{cd}|f_+(q^2)$ using Becher-Hill z -expansion to determine $|V_{cd}|f_+(0)$ & use $f_+(0)$ from theory (FNAL-MILC-HPQCD.) Same for $|V_{cs}|$

$|V_{cs}|$ & $|V_{cd}|$ Results

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

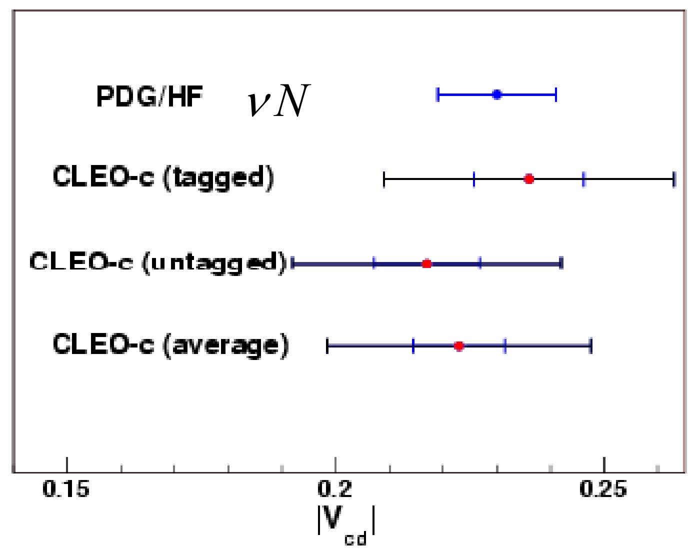
$$\sigma(|V_{cs}|)/|V_{cs}| \sim 1.3\%(\text{expt}) \oplus 10\%(\text{theory})$$

$CLEO-c$	V_{cs}
(average)	$1.018 \pm 0.010 \pm 0.008 \pm 0.106$
	stat syst theory



CLEO-c: $\sigma(|V_{cd}|)/|V_{cd}| \sim 3.8\%(\text{expt}) \oplus 10\%(\text{theory})$
νN remains most precise determination *(for now)*

$CLEO-c$	V_{cd}
(average)	$0.222 \pm 0.008 \pm 0.003 \pm 0.023$
	stat syst theory



Averaged values represent final results from CLEO-c 281/pb data set. Analysis of the full data set (x3 this study) is almost complete.

* PDG2002

Fits use Becher-Hill z-expansion

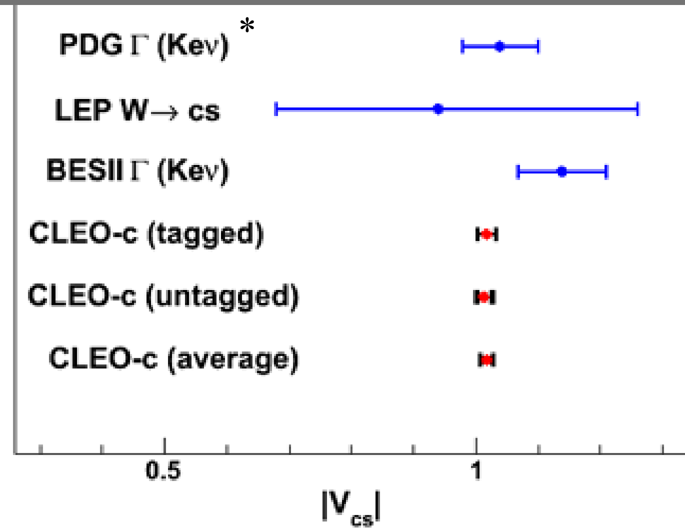
$|V_{cs}|$ & $|V_{cd}|$ Results

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

$$\sigma(|V_{cs}|)/|V_{cs}| \sim 1.3\%(\text{expt}) \oplus 10\%(\text{theory})$$

CLEO − c	V_{cs}		
(average)	$1.018 \pm 0.010 \pm 0.008 \pm 0.106$		
	stat	syst	theory

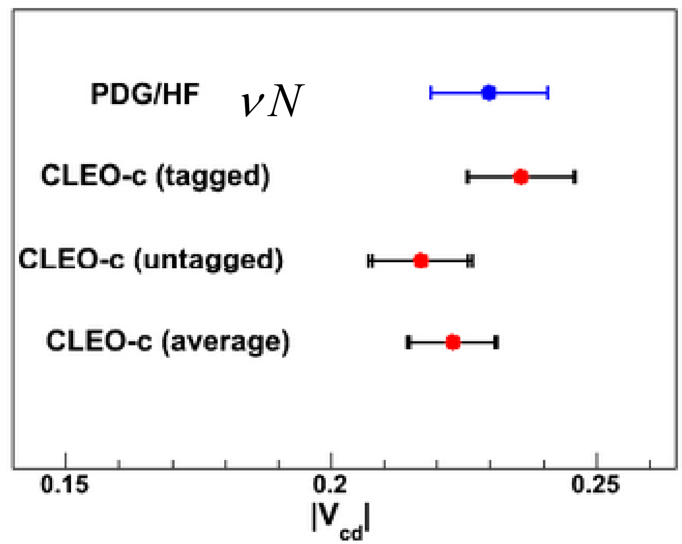
THEORY UNCERTAINITY REMOVED



CLEO-c: $\sigma(|V_{cd}|)/|V_{cd}| \sim 3.8\%(\text{expt}) \oplus 10\%(\text{theory})$

νN remains most precise determination (*for now)*

CLEO − c	V_{cd}		
(average)	$0.222 \pm 0.008 \pm 0.003 \pm 0.023$		
	stat	syst	theory



Averaged values represent final results from CLEO-c 281/pb data set. Analysis of the full data set (x3 this study) is almost complete.

* PDG2002

Unitarity Test: Compatibility of charm & beauty sectors of CKM matrix?

CLEO-c full data set + 3-4% theory uncertainties

$|V_{cd}| \& |V_{cs}|$ indirect

1) K & nucleon

$|V_{ud}| \simeq |V_{cs}| \ \& \ |V_{cd}| \simeq |V_{us}|$

2) B physics

Indirect= global CKM fit = 1+2

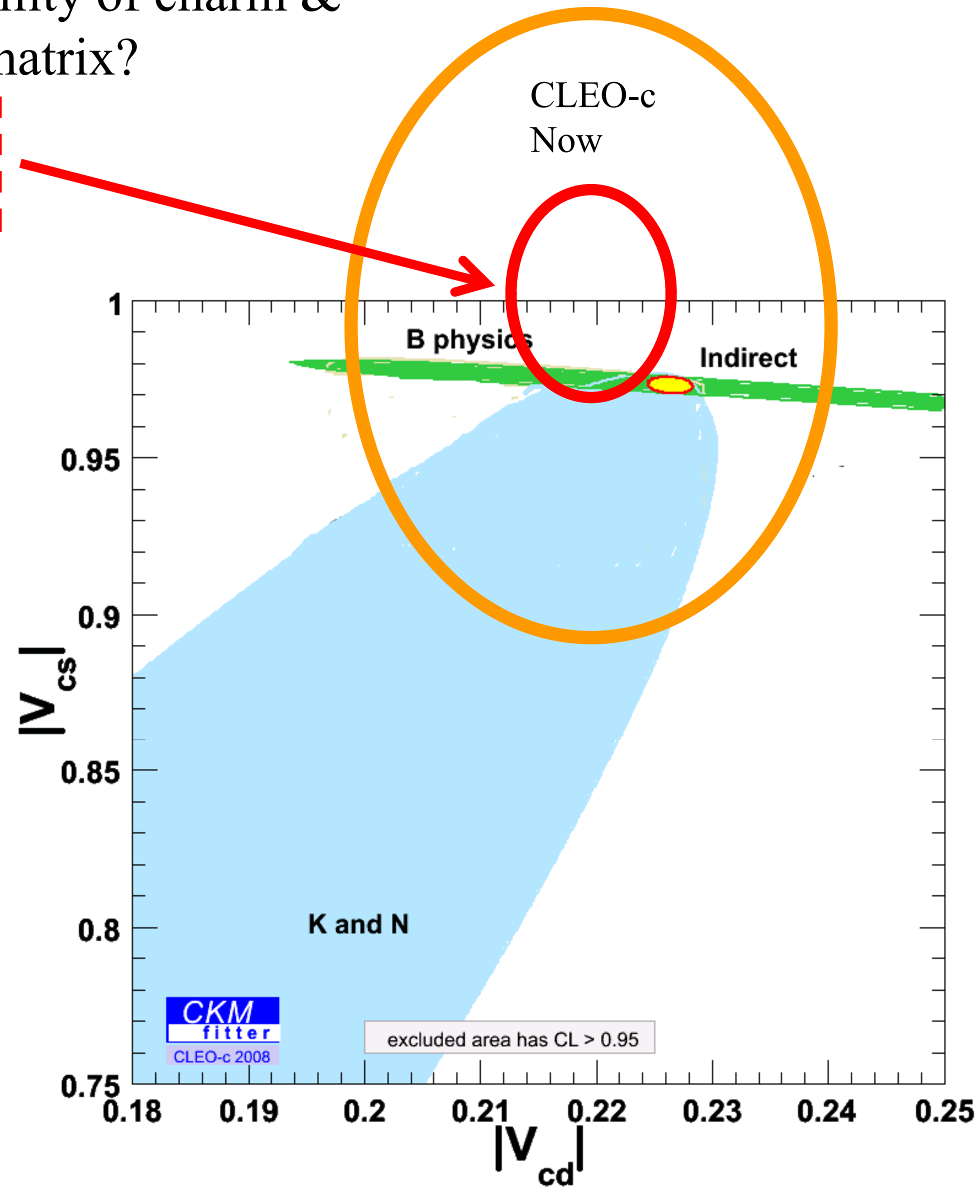
$|V_{cd}| \& |V_{cs}|$ direct

(D semileptonic decays CLEO)

Projections to full data set

$\sigma(|V_{cd}|)/|V_{cd}| \sim 2.7\% \oplus \text{theory}$

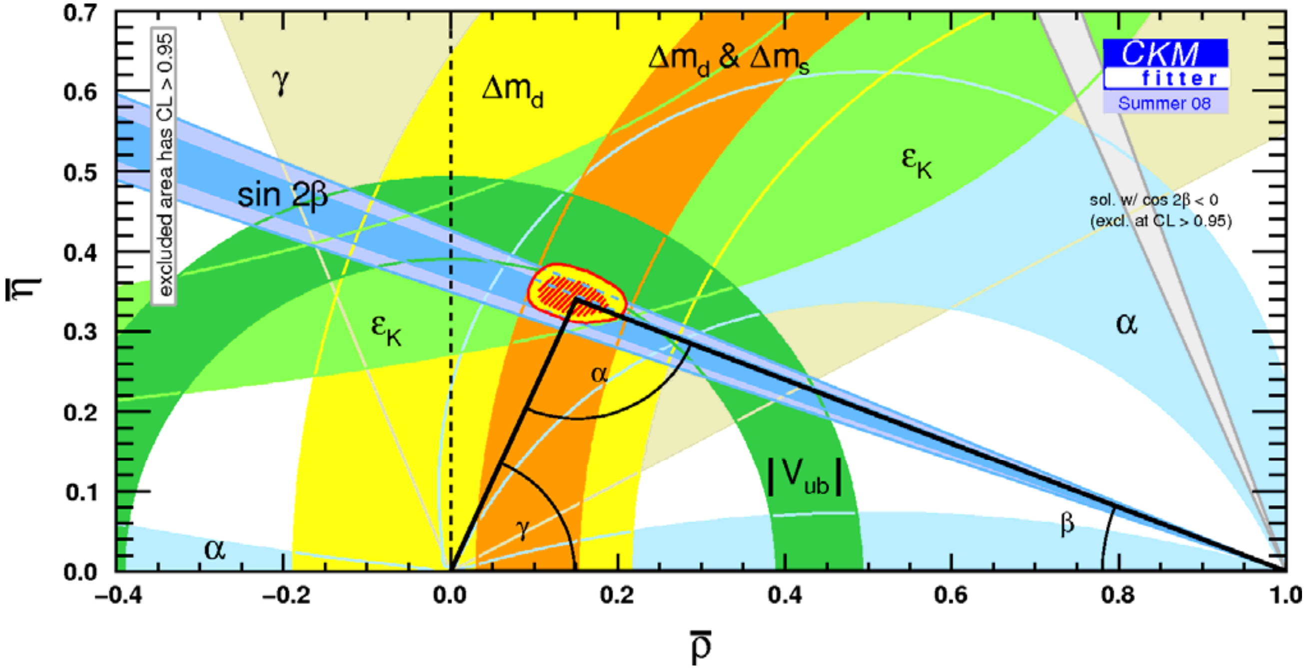
$\sigma(|V_{cs}|)/|V_{cs}| \sim 1.1\% \oplus \text{theory}$



D semileptonic decays with comparable theory and experimental uncertainty may lead to interesting competition between direct and indirect constraints

Plots by Sebastien Descortes-Genon & Ian Shipsey
See also talk by Descotres-Genon at joint BABAR-Belle-BESIII-CLEO-c Workshop 11/07, Beijing

CLEO-c & Direct Determination of γ



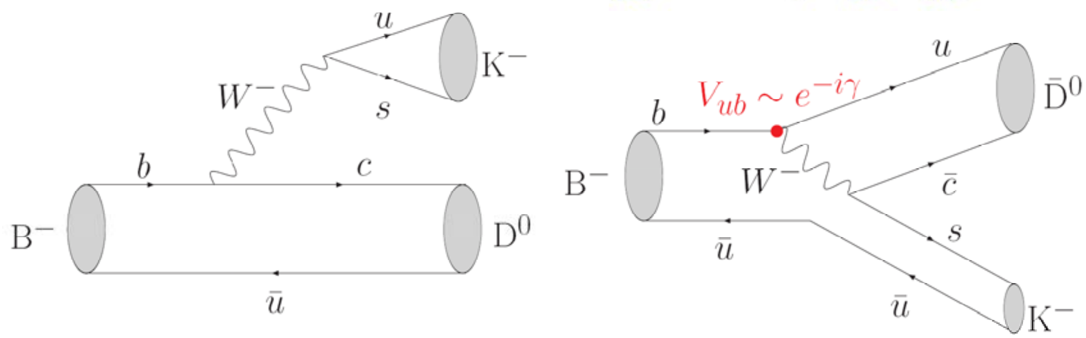
- γ is the least well determined angle of the unitarity triangle with an uncertainty of ~30° from direct measurements
  - $\sigma_\beta = 1°$

- Comparison of measurements of γ in tree and loop processes sensitive to new physics

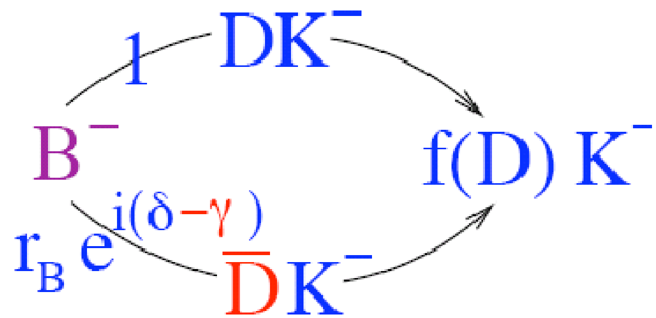
γ from $B^\pm \to DK^\pm$

Color/CKM suppressed – r_B~0.1

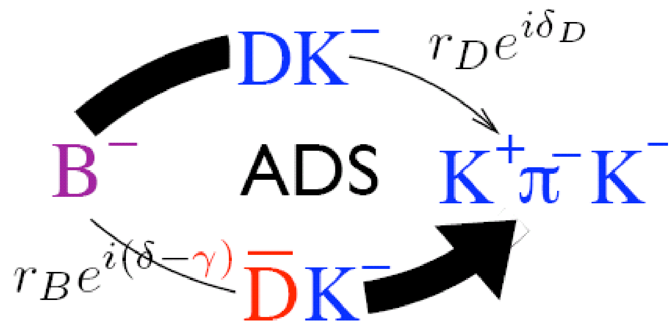
$$B^- \longrightarrow D^0K^- \qquad B^- \longrightarrow \overline{D}^0K^-$$



$$\frac{< B^- \longrightarrow \overline{D}^0K^- >}{< B^- \longrightarrow D^0K^- >} = r_B e^{i(\delta_B - \gamma)}$$



- Extraction through interference between $b \to c$ and $b \to u$ transitions
- Require decay of D^0 and $\overline{D^0}$ to a common final state, f(D)
- A theoretically clean determination of γ **SM 'standard candle'**



ADS Method f(D) = non-CP Eigenstate (e.g. $K^+\pi^-$)

PRL 78, 3257 (1997)

$$\frac{< D^0 \longrightarrow K^+\pi^- >}{< \overline{D}^0 \longrightarrow K^+\pi^- >} = r_D e^{i\delta_D}$$

~0.06

Doublle CKM suppression r_D~.06

δ_D unknown.

Measurement of δ_D useful for γ (also for Dmixing in $K\pi$)

Quantum Coherence @ ψ(3770)

At the ψ"(3770)

$e^+e^- \to \psi'' \to D^0\bar{D}^0$

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

$$CP(f_1 f_2) = CP(f_1)\,CP(f_2)\,(-1)^l = CP+$$

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

Example:
Two CP eigenstates of opposite sign

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

- CP eigenstate tag X flavor mode

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

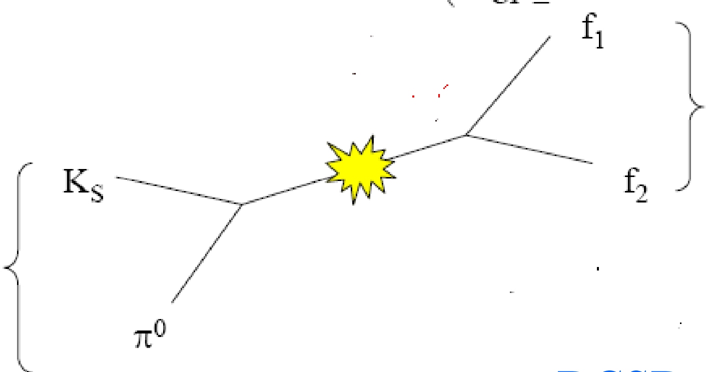
Principle of Measurement of Strong Phase δ

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

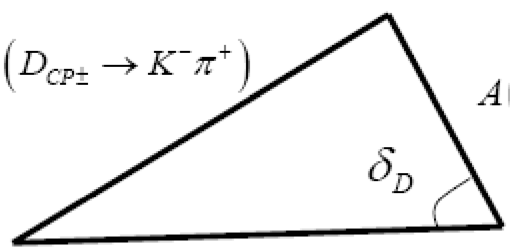
$$|D_{CP\pm}\rangle = \frac{1}{\sqrt{2}}\left[|D^0\rangle \pm |\overline{D^0}\rangle\right]$$

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

CF DCSD



$$D_{CP(+)} \to f_1 f_2$$



In the limit of CP-invariance

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

But method is limited by CP tag statistics at CLEO-c. Fortunately, the method can be extended to a global fit to a combination of CP and flavor tags

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

as r_D is well measured

Coherent vs. Incoherent Decay

- Measure yields for single tags (ST) & double tags (DT)
  - Analysis similar to previous D hadronic BF analysis

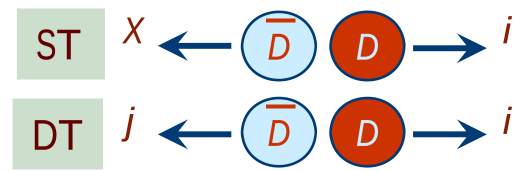
D. Asner and W. Sun, Phys. Rev. D73, 034024 (2006)

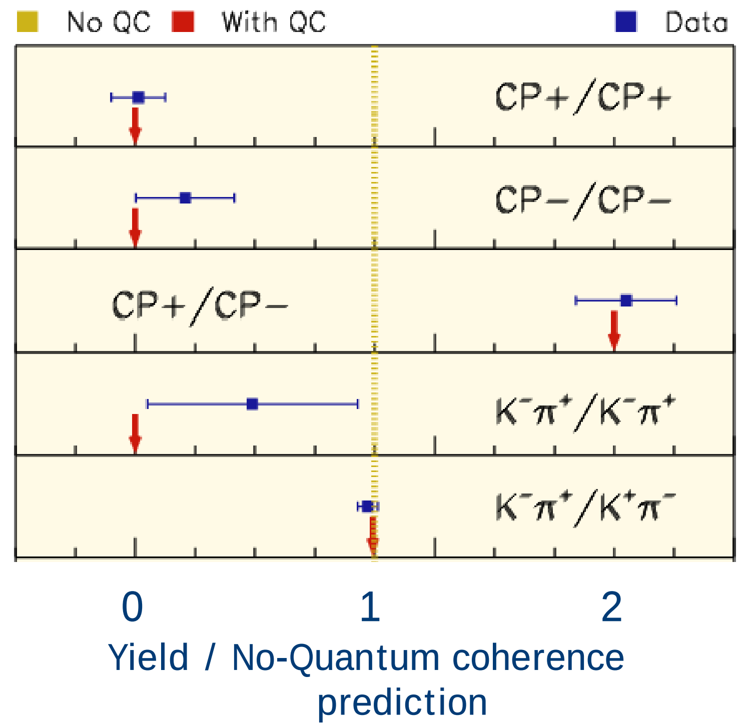
DT	$K^-\pi^+$	e^+	$CP+$	$CP-$
$K^-\pi^+$	R_M / R_{WS}	$\frac{\text{QC rate}}{\text{incoherent rate}}$		
$K^+\pi^-$	$1 + 2R_{WS} - 4r\cos\delta\,(r\cos\delta + y)$			
e^-	$1 - r\,(y\cos\delta + x\sin\delta)$	1		
$CP+$	$1 + (2r\cos\delta + y) / (1 + R_{WS})$	$1 + y$	0	
$CP-$	$1 - (2r\cos\delta + y) / (1 + R_{WS})$	$1 - y$	2	0
ST	1	1	1	1

$R_M = (x^2 + y^2)/2$ and $R_{WS} = r^2 + ry' + R_M$

where x and y are D mixing parameters

and $y' = y\cos\delta - x\sin\delta$





Quantum correlations are seen

- Compare coherent/incoherent BFs
- Sources of incoherent BFs:
  - Externally measured BFs
  - Single tags at $\psi(3770)$

Yield measurements in 281 pb^{-1}

PRL 100, 221801 (2008)
PRD 78, 012001 (2008)

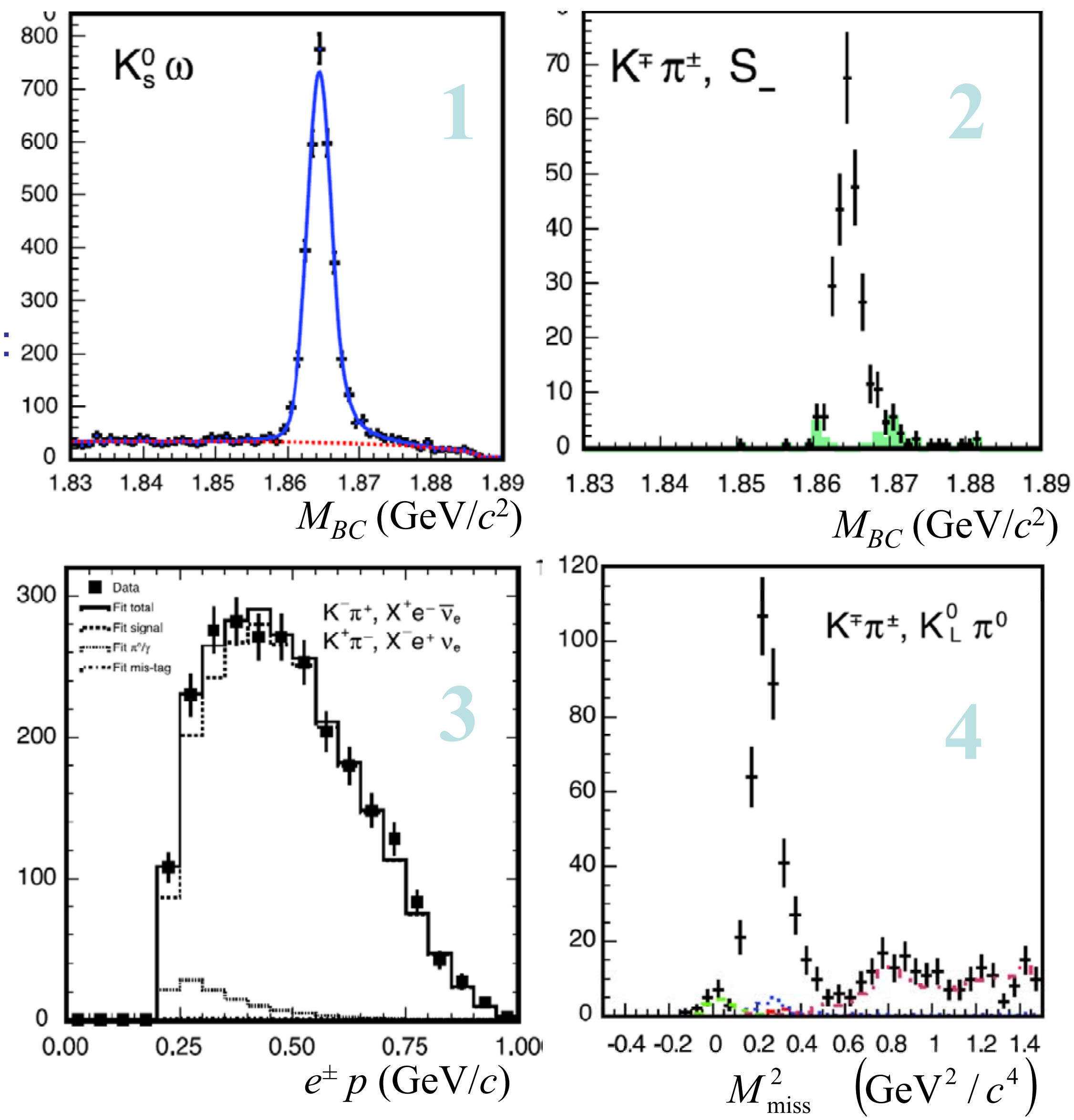
1. Fully-reconstructed single tags:
   – Fit beam-constrained mass distribution

$$M_{BC} = \sqrt{E_{beam}^2 - |p_D|^2}$$

2. Fully-reconstructed double tags:
   – Two fully-reconstructed STs

3. Inclusive semileptonic DTs:
   – One fully-reconstructed ST
   – Plus one electron candidate
   – Fit $e^{\pm}$ momentum spectrum

4. $K^0{}_L\pi^0$ double tags:
   – One fully-reconstructed ST
   – Plus one π^0 candidate
   – Compute missing mass^2
      • Signal peaks at $M^2(K^0)$.



Results

First Determination (281 pb^{-1})

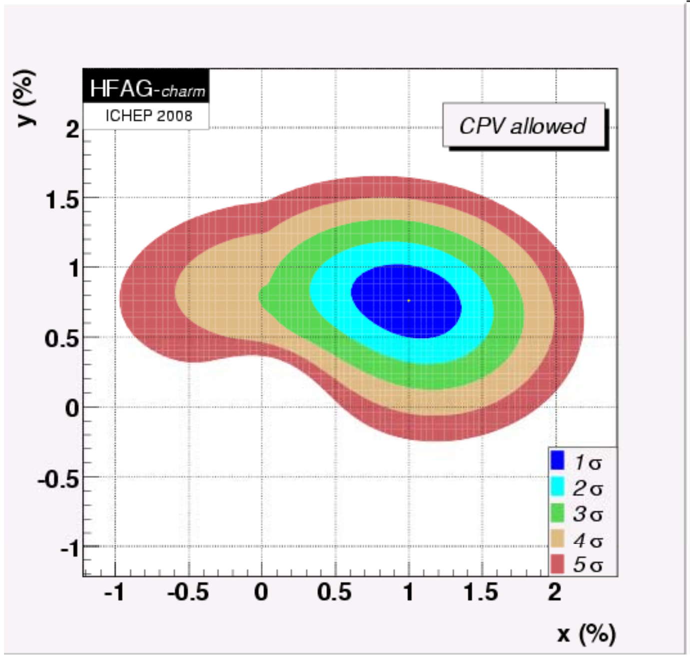
PRL 100, 221801 (2008)
PRD 78, 012001 (2008)

Parameter	Standard Fit	Extended Fit
$y\ (10^{-3})$	$-45 \pm 59 \pm 15$	$6.5 \pm 0.2 \pm 2.1$
$r^2\ (10^{-3})$	$8.0 \pm 6.8 \pm 1.9$	$3.44 \pm 0.01 \pm 0.09$
$\cos\delta$	$1.03 \pm 0.19 \pm 0.06$	$1.10 \pm 0.35 \pm 0.07$
$x^2\ (10^{-3})$	$-1.5 \pm 3.6 \pm 4.2$	$0.06 \pm 0.01 \pm 0.05$
$x \sin\delta\ (10^{-3})$	0 (fixed)	$4.4 \pm 2.4 \pm 2.9$
$\chi^2_{\rm fit}/{\rm ndof}$	$30.1/46$	$55.3/57$

- Standard fit result important component in average of charm mixing
- Extended fit leads to measurement of:

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

From likelihood scan of physically allowed region



- *Next: full data set + C-even 4170 MeV*

Charm Factory INPUTS TO CKM ANGLE ϕ_3 /γ

Dalitz plot Method

– $B^- \to DK^-$, $D \to K_s\pi^+\pi^-$

currently most accessible method experimentally.

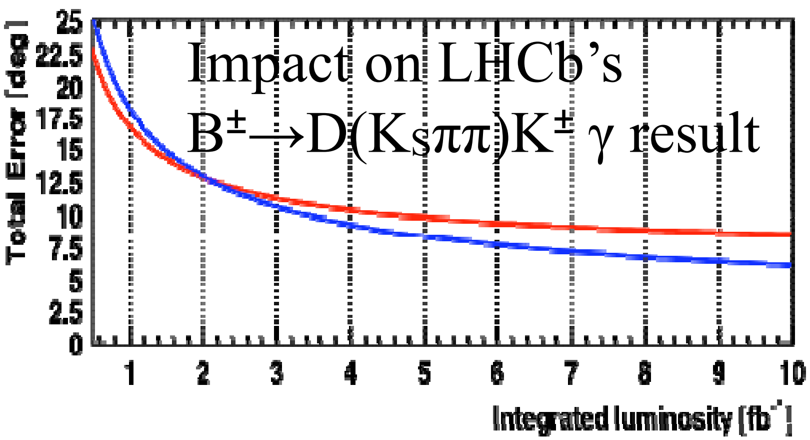
($D \to K_{S/L}\pi\pi$ is Cabibbo favored)

Model uncertainty can be reduced to ~2° by analyzing CP & flavor tagged Dalitz plots at CLEO-c

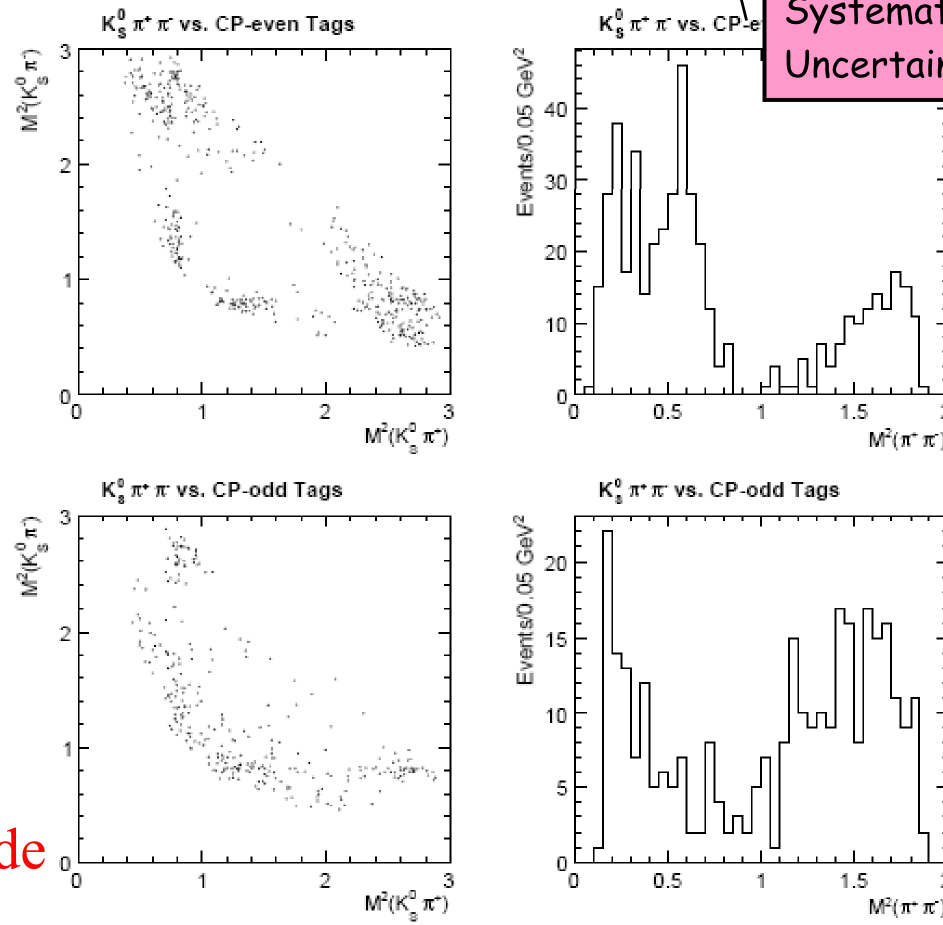
$$\text{BABAR } (K_sKK\ K_s\pi\pi)\ \gamma = (76^{+23}_{-24} \pm 5 \pm 5)^0$$

$$\text{Belle } (K_s\pi\pi)\quad \gamma = (76^{+12}_{-13} \pm 4 \pm 9)^0$$

D Decay Model Systematic Uncertainty



Total Error (10 fb^{-1}): 8.5°(amplitude model); 6°(binned, with CLEO-c)



Analysis about to be submitted to arXiV

Search for a non-SM-like pseudoscalar Higgs

Dermisek, Gunion, and McElrath propose adding to the MSSM a non-SM-like pseudoscalar Higgs a_1 with $m_{a_1} < 2m_b$: "NMSSM" PRD 76 051105(R) (2007)

"natural", avoids fine tuning

evades the LEP limit $M_h > 100$ GeV since $h \to a_1 a_1$, but $a_1 \not\to bb$ and LEP sought b jets

$a_1 \to \tau^+\tau^-$ should predominate if $m_{a_1} > 2m_\tau$

should be visible in $\Upsilon \to \gamma a_1$

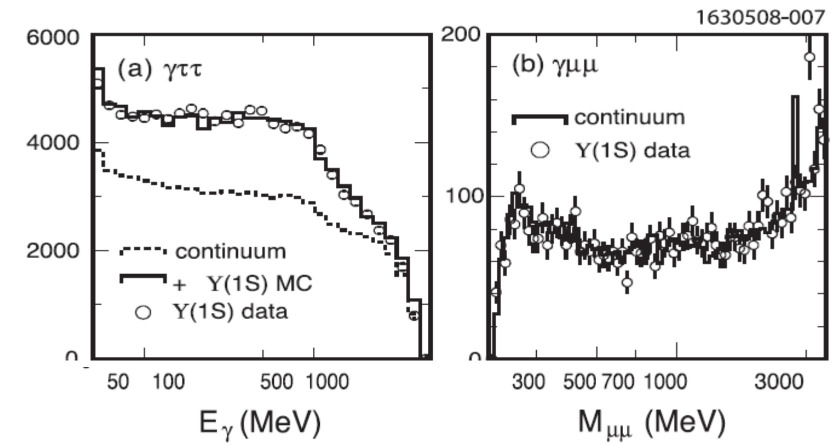
HyperCP observed 3 $\Sigma^+ \to p\mu^+\mu^-$ events, with m $(\mu^+\mu^-)$= 214.3±0.5 MeV.
He, Tandean and Valencia [PRL 98, 081802 (2007)] interpret this as evidence for **a_1** at 214.3 MeV

CLEO search for the **a_1** in radiative Upsilon decays, ***$Y(1S) \to \gamma\, a_1$***
Signature monochromatic peak in the γ energy distribution:

- ❑ For the $a_1 \to \tau^+\tau^-$ search : events with missing energy & one identified μ or e
- ❑ For the $a_1 \to \mu^+\mu^-$ search: events with NO missing energy & two identified $\mu^\pm$

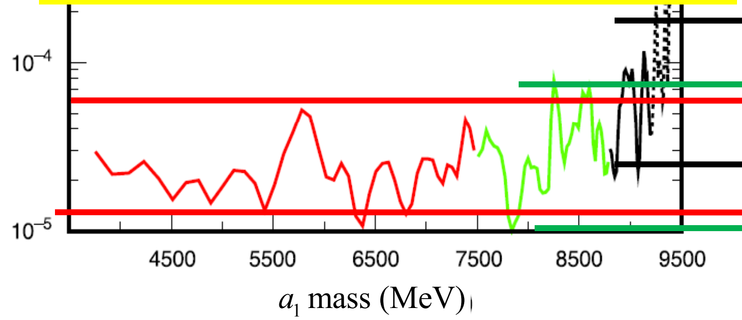
PRL 101, 151802(2008)

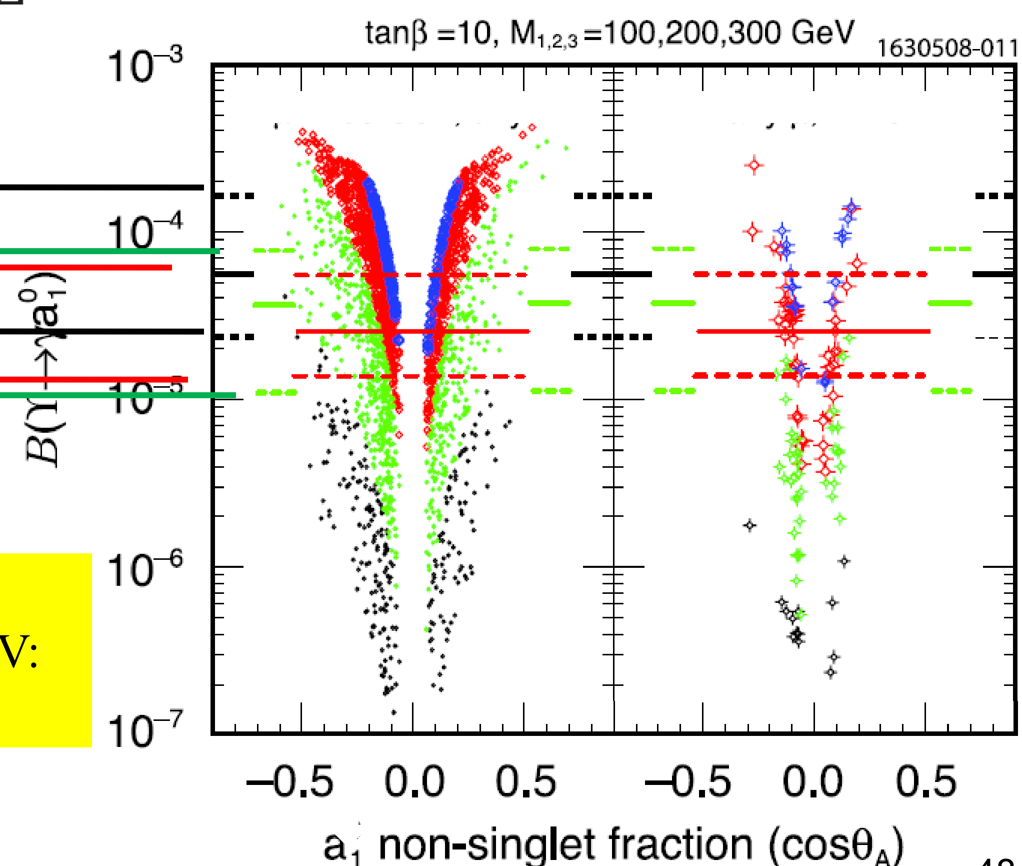
Search for a non-SM-like pseudoscalar Higgs



- limits on
  $B(\Upsilon(1S) \rightarrow \gamma a_1) * B(a_1 \rightarrow \tau^+\tau^-)$ and
  $B(\Upsilon(1S) \rightarrow \gamma a_1) * B(a_1 \rightarrow \mu^+\mu^-)$
- Using $\gamma\tau^+\tau^-$ we eliminate a large portion of previously unconstrained parameter space in the NMSSM model

90% U.L. on $B(\Upsilon(1S) \rightarrow \gamma a_1) * B(a_1 \rightarrow \tau^+\tau^-)$



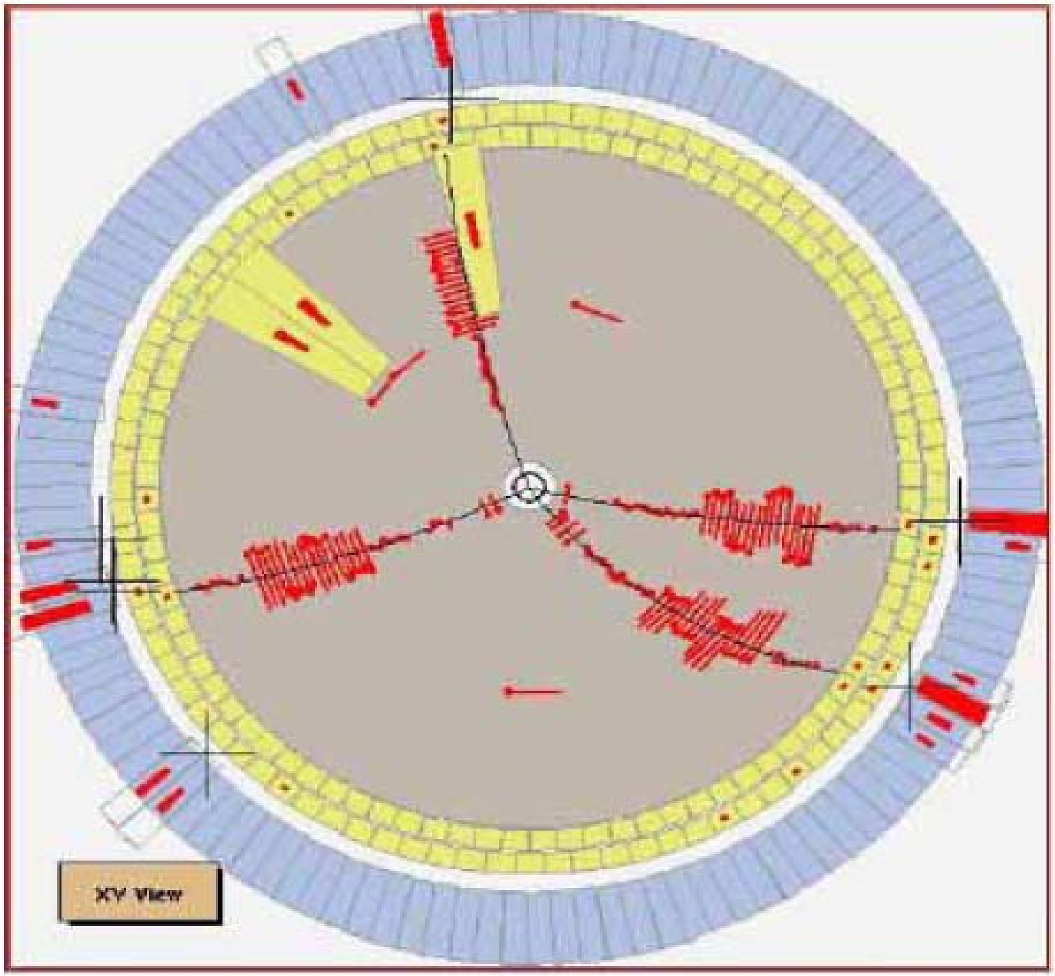


There is no evidence for a CP-odd Higgs decaying to $\mu^+\mu^-$ with a mass of 214.3 MeV: $B(\Upsilon(1S) \rightarrow \gamma a_1) < 2.3 \times 10^{-6}$ @ 90% C.L.

PRL 101, 151802(2008)

charm factory mantle now passing to BES III

First hadron event observed in BESIII 7/19/08



- beam current has reached >1/2 of design.
- World record luminosity $1\times10^{32}cm^{-2}s^{-1}$@1.84GeV
- Detector performs @ design

Ψ(2S), ψ(3770) scan and extensive beam tuning planned for 2009

Summary Slide

CLEO-c hadronic D^0, D^+ and D_s branching fractions more precise than PDG averages: (for D^0, D^+ 2% precision is syst.limited) CLEO establishes charm hadronic scale

most precise: $f_{D^+} = (205.8 \pm 8.5 \pm 2.5)$ MeV consistent with LQCD $\rightarrow$ 1% (2 MeV) full data

Most precise: $f_{D_s} = (259.5 \pm 6.6 \pm 3.1)$ MeV $\sim 2.3\sigma$ higher than LQCD.
To interpret as "prosaic" or "exciting": requires more data (BES III)

lepton universality in D, D_s decays is satisfied

most precise $|V_{cs}| = 1.018 \pm 0.010 \pm 0.008 \pm 0.106_{\text{theory}}$

$|V_{cd}| = 0.222 \pm 0.008 \pm 0.003 \pm 0.023_{\text{theory}}$
most precise determination from semileptonic decay

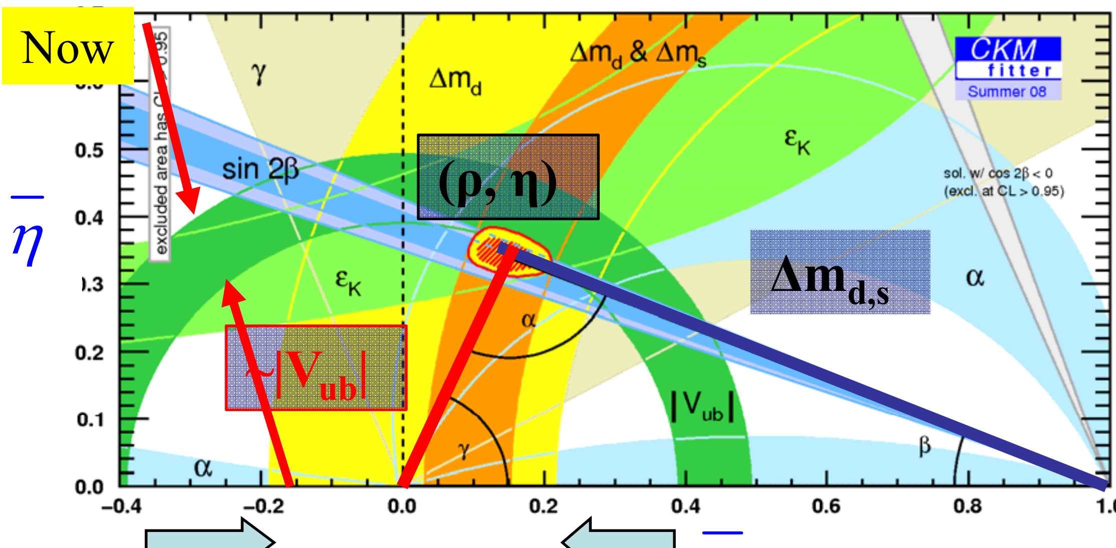
Projections to full data set
$\sigma(|V_{cd}|)/|V_{cd}| \sim 2.7\% \oplus$ theory
$\sigma(|V_{cs}|)/|V_{cs}| \sim 1.1\% \oplus$ theory

CLEO-c data vital for γ extraction strategies with $B^{\pm} \rightarrow DK^{\pm}$
First determination of strong phase difference for $D \rightarrow K\pi$

Best limits for a non-SM-like pseudoscalar Higgs

CLEO-c has a few more analyses in the pipeline
Notably: D→ K/πeν f+(0),shape,Vcs & Vcd and further input to γ
Longer term the charm factory mantle passes to BES III.

Precision theory + charm = large impact

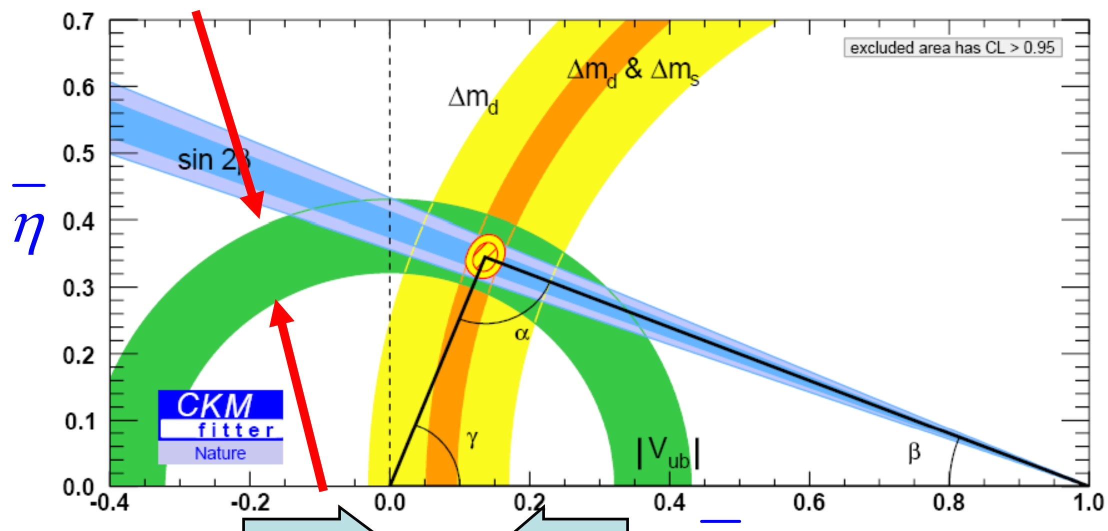


Plot uses all CKM inputs

* Cleo-c: a major contribution to the goal the lower plot represents,
* LQCD has been validated at the 5% level (fd+)
* A triumph for theory & experiment!

More precise LQCD form factor Calculations needed

more data ➔ BESIII



Plot uses Vub Vcb from exclusive decays
no gamma or alpha constraints

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