Charm Physics
from experimental side of view

Hai-Bo Li

Institute of High Energy Physics

Chinese Academy of Sciences

Asia-Europe-Pacific School of High-Energy Physics
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Outline of the lectures

Lecture 1

- Introduction
- Leptonic D/D_s decays and decay constants
- Semileptonic D decay and form factor

Lecture 2

- Rare and forbidden Charm decays
- D^0-$\bar{D}^0$ mixing and CP violation

Lecture 1

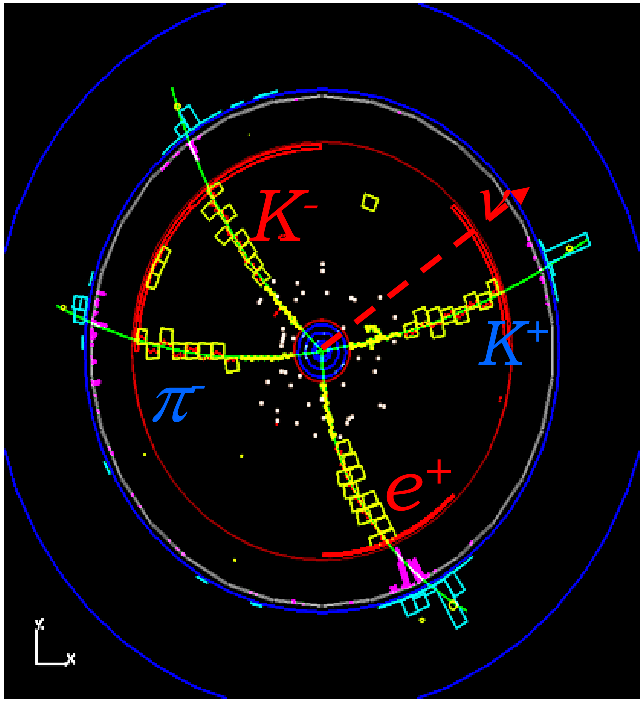
- **Introduction**
- **Leptonic D/D_s decays and decay constants**
- **Semileptonic D decay and form factor**

Introduction

Why still Charm?

Common feeling: charm physics – great past, no future!

I. Bigi at CHARM2006:
"I know she invented fire – but what she has done lately?"
"fire" = November revolution of 1974!
Charm is closed chapter?

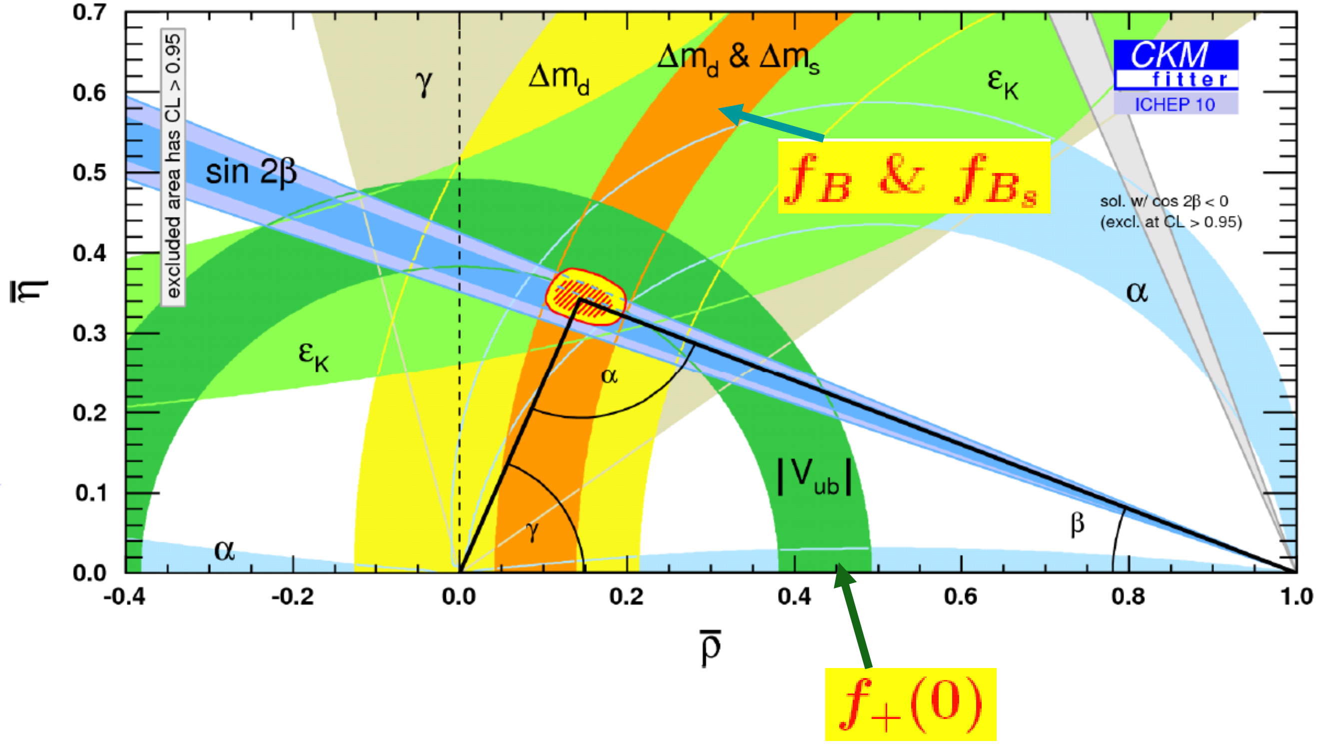


- **Why Charm is unique to test QCD in low energy?**
- **Why Charm allows us to overconstrain CKM in B decays?**
- **Why Charm can be used to probe New Physics beyond Standard Model?**

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

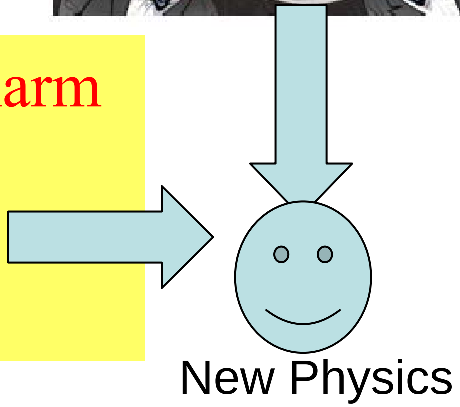
$$\overline{D^0} \to K^+\pi^-, D^0 \to K^- e^+ \nu$$

Precision theory + charm



Theoretical errors dominate width of bands

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



Charm Physics: The Context

Last 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

This Decade

LHC found Higgs candidate and may uncover the physics Beyond the Standard Model. An outstanding challenge to theory. Critical need: reliable theoretical techniques & detailed data to calibrate them

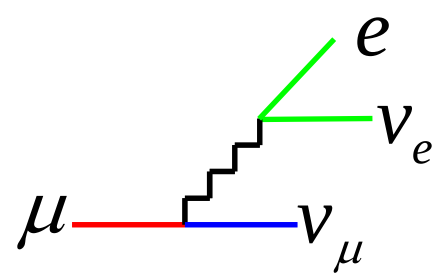
The Lattice

Complete definition of pert. and non-pert. QCD
Calculate B, D, Υ, ψ to a few % in a few years.

Charm can provide the data to test and calibrate non-pert. QCD techniques (especially true at charm threshold)

Lifetimes

Muon decay: $\Gamma_o = \frac{G_F^2 m_\mu^5}{192\pi^3}$

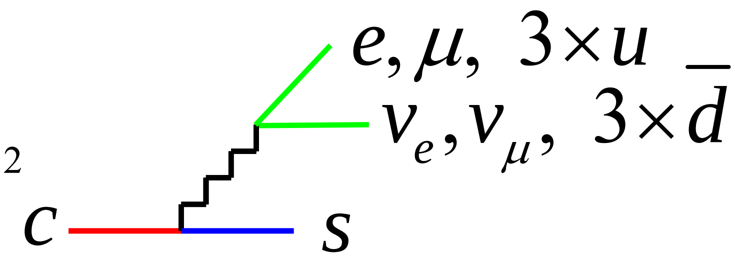


Naïve spectator model for charm

e, μ $\quad u\bar{d}$ x 3 colors

$$\Gamma_c = (2 + 3)\Gamma_0$$

$$\Gamma_o = \frac{G_F^2 m_c^5}{192\pi^3} |V_{cs}|^2$$



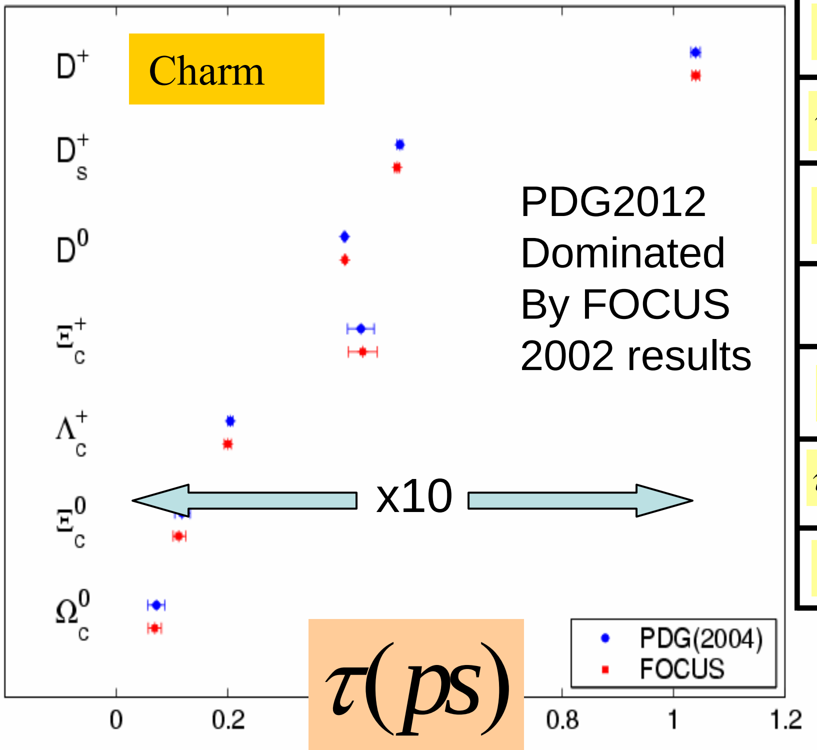
Scaling from the muon: $\tau_c = \frac{1}{5}\left(\frac{0.105}{1.5}\right)^5 2.2\times 10^{-6} = 7\times 10^{-13} s$

(700 fs)

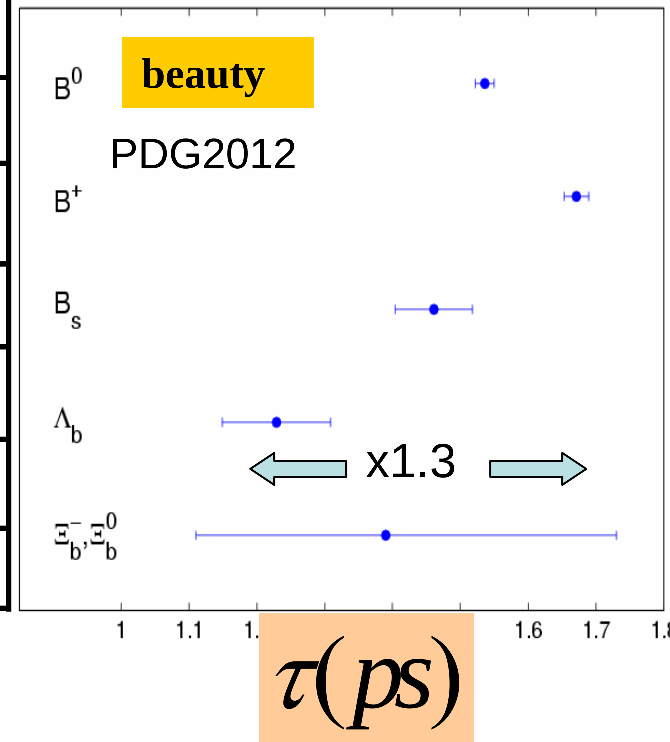
$\tau(D^+)$ ~1,000 fs τ (D^0) ~400 fs. Not too bad. Including baryons lifetimes vary between ~100 and 1000 fs,→ non-spectator processes and higher order corrections

Charm Lifetimes

SELEX, FOCUS, CLEO E791 E687



$\tau(D^+)$	$1040 \pm 7\ fs$
$\tau(D_s^+)$	$501 \pm 6\ fs$
$\tau(D^0)$	$410.3 \pm 1.5\ fs$
$\tau(\Xi^+{}_c)$	$442 \pm 26\ fs$
$\tau(\Lambda_c)$	$200 \pm 6\ fs$
$\tau(\Xi^0{}_c)$	$112^{+13}_{-10}\ fs$
$\tau(\Omega_c)$	$69 \pm 12\ fs$



D^+ 7 ‰, D^0 4 ‰, D_s 8 ‰, Λ_c 3%, Ξ^0 10%, Ξ^+_c 6 %, Ω_c 17%
some lifetimes known as precisely as kaon lifetimes.

Charm quarks more influenced by hadronic environment than beauty quarks.

$$\frac{\tau(D^+)}{\tau(D^0)} \approx 2.5 \qquad \frac{\tau(B^+)}{\tau(B^0)} \approx 1.1$$

PDG2012

Errors on lifetimes are *not* a limiting factor in the measurement of absolute rates.

D Nonleptonic Decays

Nonleptonic decays dominate the total rate

$$D^+(c\bar{d}): \tau_+ = 1042.7 \pm 6.9\ fs$$

$$D^0(c\bar{u}): \tau_0 = 410.5 \pm 1.5\ fs$$

$$\tau_+ / \tau_0 \approx 2.5$$

Quarks or hadrons? ….in between

Compare to kaons and B-mesons:

$$K^+(\bar{s}u): \tau_+ = 12390 \pm 20\ ps$$

$$K^0(\bar{s}d): \tau_0 = 178.7 \pm 0.16\ ps$$

$$\tau_+ / \tau_0 \approx 70$$

Hadrons

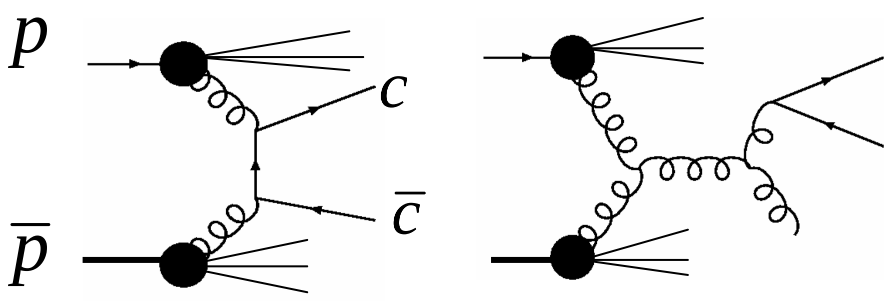
$$B^+(\bar{b}u): \tau_+ = 1643 \pm 10\quad fs$$

$$B^0(\bar{b}d): \tau_0 = 1528 \pm 9\quad fs$$

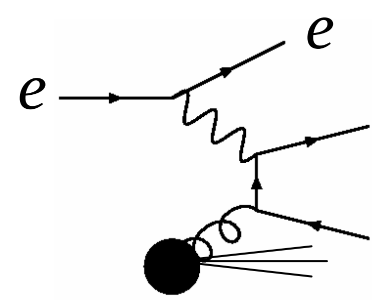
$$\tau_+ / \tau_0 = 1.08 \pm 0.008$$

Like free quarks

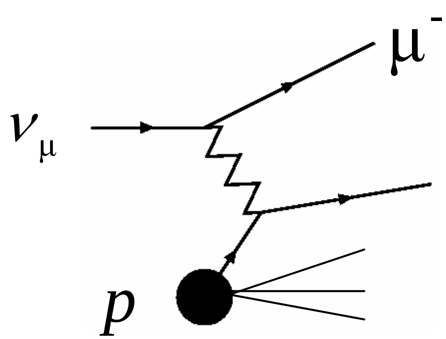
A little summary for
the production environment of D mesons



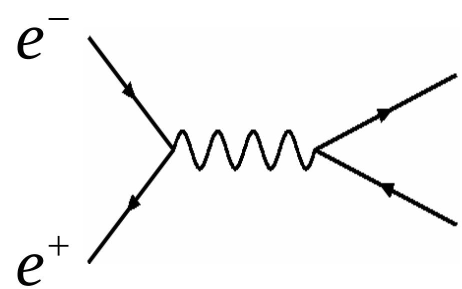
(a) Hadronproduction



(b) e^+p production



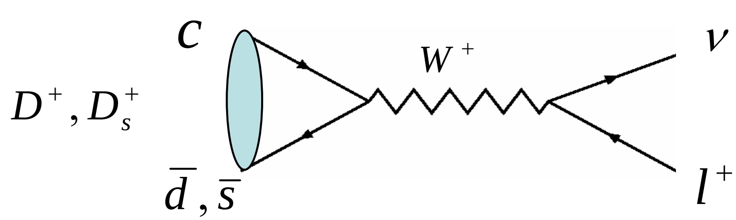
(c) Neutrino interaction



(d) electron-positron collision

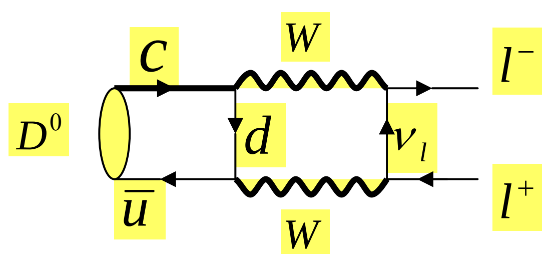
D meson decays

a) Leptonic decay

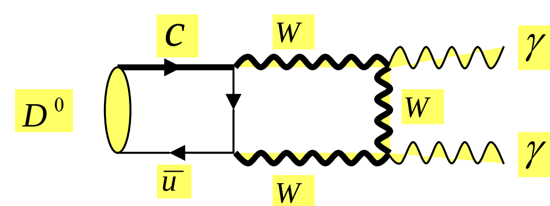


$D^+ \to e^+\nu_e,\ \mu^+\nu_\mu,\ \tau^+\nu_\tau$ $D_s^+ \to e^+\nu_e,\ \mu^+\nu_\mu,\ \tau^+\nu_\tau$

b) Rare decay

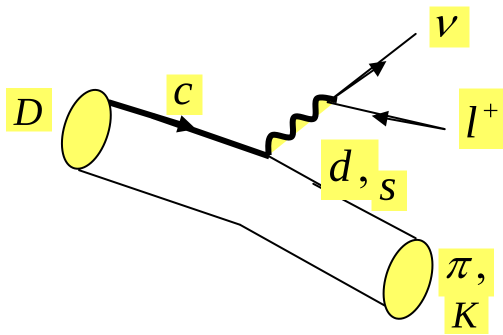


$D^0 \to l^+l^-$



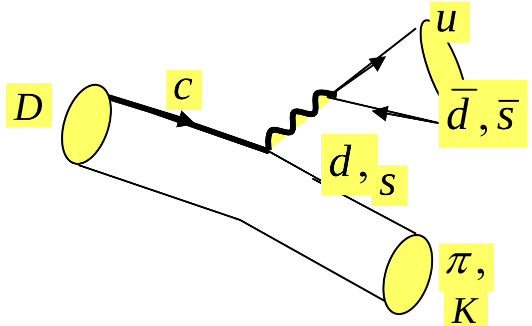
$D^0 \to \gamma\gamma$

c) Semi-leptonic decay



$$D \to \pi\ l^+\nu, \quad D \to K\ l^+\nu$$

d) Hadronic decay



$$D \to h_1 h_2$$

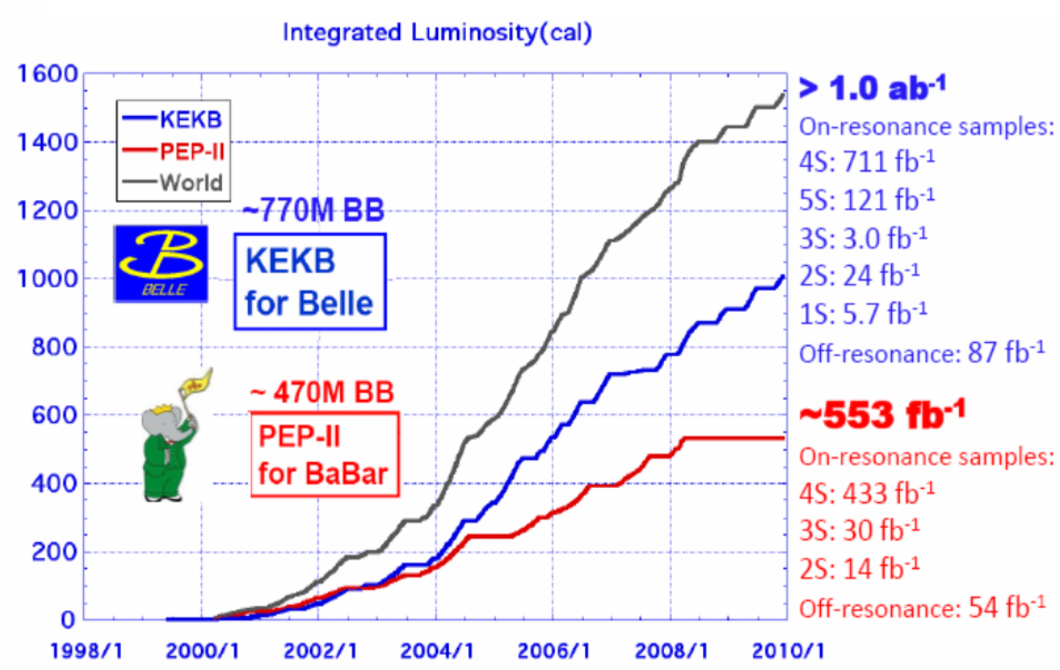
The Landscape for open charm

- B factories:
- --BABAR, Belle
- -- Super-B factories ?

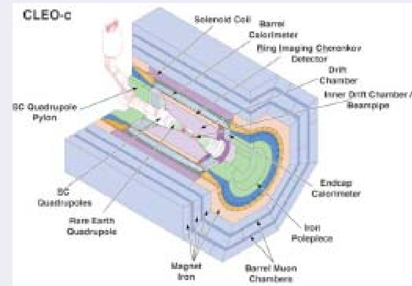
- Hadronic Production:
- --Fixed target: FOCUS dominates
- --LHCb: on-going now!
- --ATLAS and CMS

- e^+e^- Colliders@threshold:
- -- Precision results dominated by CLEO-c
- -- BESIII/BEPCII machine: higher luminosity: 10^{33} $cm^{-2}s^{-1}$
- -- Quantum correlations and CP-tagging are unique

Open charm data at e^+e^- machine

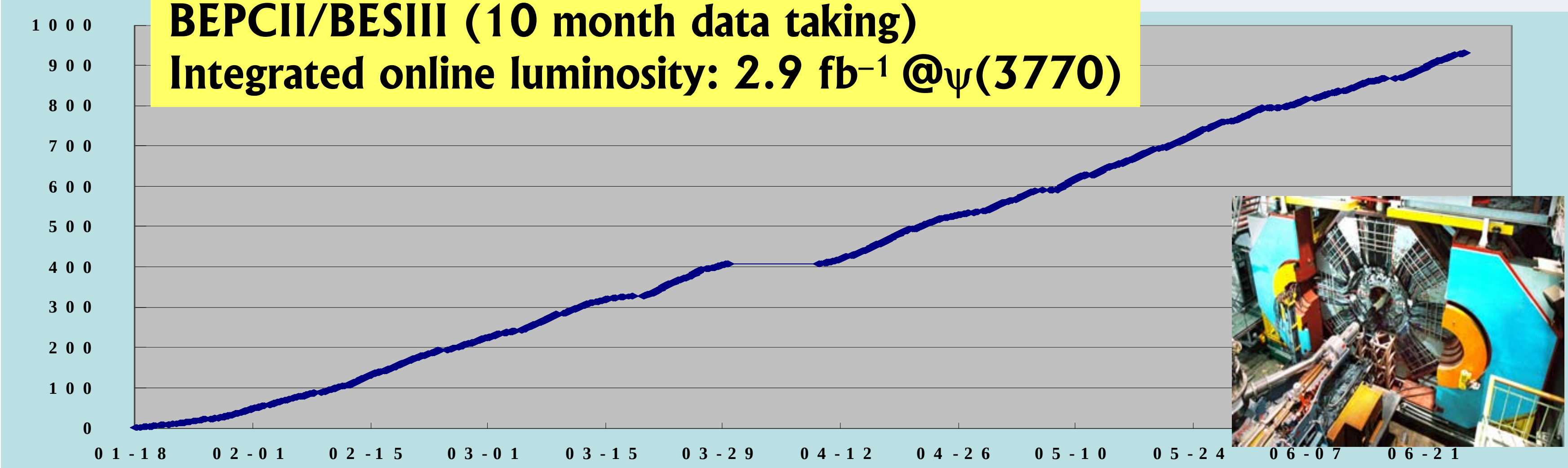


Cleo-c

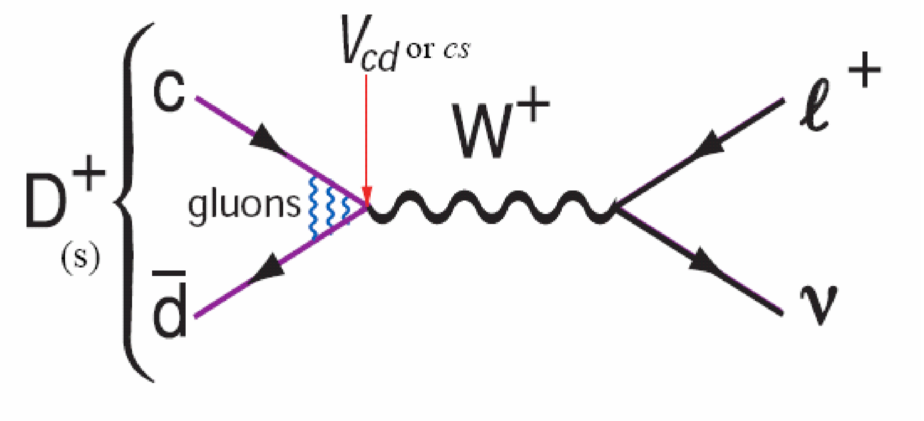


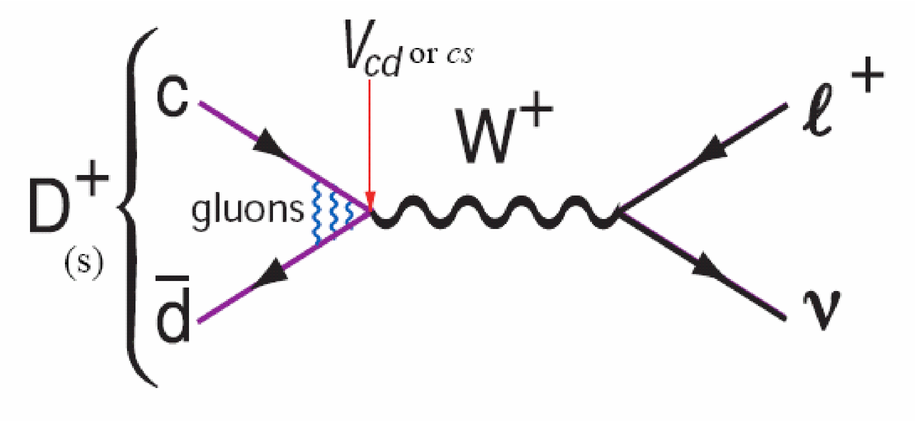
- 0.818/fb at $\psi(3770)$
  - $\star$ 2.4×10^6 D^+D^- pairs
- 0.586/fb at $\psi(4170)$
  - $\star$ 0.54×10^6 $D_s^{*\pm}D_s^{\mp}$ pairs

BEPCII/BESIII (10 month data taking)
Integrated online luminosity: 2.9 fb^{-1} @$\psi(3770)$



Leptonic D/D_s decays





The amplitude

$$T = \frac{G_F}{\sqrt{2}} f_D V_{cq}^{*} \overline{u}_{\nu}^{\lambda_1} \gamma_{\mu} (1-\gamma_5) v_l^{\lambda_2} p^{\mu}$$

Phase space factor

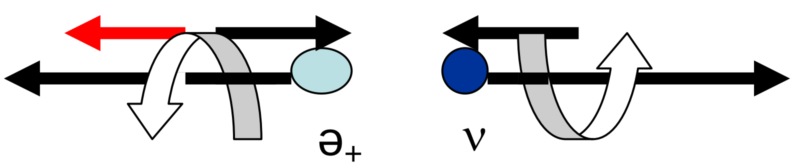
The total decay width is then given by

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

Angular momentum conservation requires helicity for positron and neutrino should be the same.

Helicity suppressed

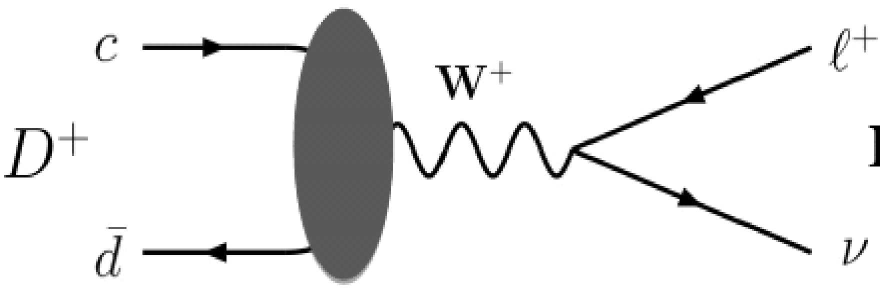
$m_{e+} \to 0$
Helicity: +1



m_ν =0
Helicity: –1

antiparticle

Leptonic Decay



$$\Gamma\left(D^{+}\to \ell^{+}\nu_{\ell}\right)=f_{D}^{2}\left|V_{cd}\right|^{2}\frac{G_{F}^{2}}{8\pi}m_{D}m_{\ell}^{2}\left(1-\frac{m_{\ell}^{2}}{m_{D}^{2}}\right)^{2}$$

- Decay constant f_D incorporates the strong interaction effects (wave function at the origin)
- Use charm leptonic decays to validate theory (LQCD) and apply to B mixing, which requires f_B
- Multiple tests with charm: f_D, f_{Ds} (esp. ratios)
- Sensitivity to New Physics

D^+ leptonic decays and decay constant f_{D^+}

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

SM predicts : $(D^+ \to l^+ \nu)$ = $2.35\times10^{-5} : 1 : 2.65$ ($l = e : \mu : \tau$)

CLEO-c [PRD 78, 052003 (2008)]:
$B(D^+ \to \mu^+\nu) = (3.82 \pm 0.32 \pm 0.09) \times 10^{-4}$
$B(D^+ \to \tau^+ \nu) < 1.2 \times 10^{-3}$ ($\tau^+ \to \pi^+\nu$ only)
$B(D^+ \to e^+\nu) < 8.8\times10^{-6}$

Standard Model: $B(D^+ \to \tau^+ \nu) = (1.01 \pm 0.09) \times 10^{-3}$
$B(D^+ \to e^+ \nu) = 1\times10^{-8}$

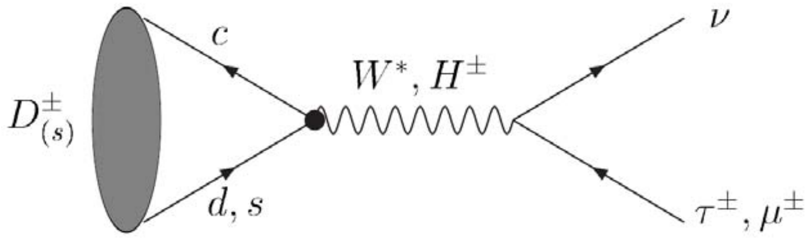
In the SM, decay constant can be extracted as:

$$f_{D^+} = \frac{1}{G_F |V_{cd}| m_l \left(1 - \frac{m_l^2}{m_{D^+}^2}\right)} \sqrt{\frac{8\pi \mathcal{B}(D^+ \to l^+\nu)}{m_{D^+}\tau_{D^+}}}$$

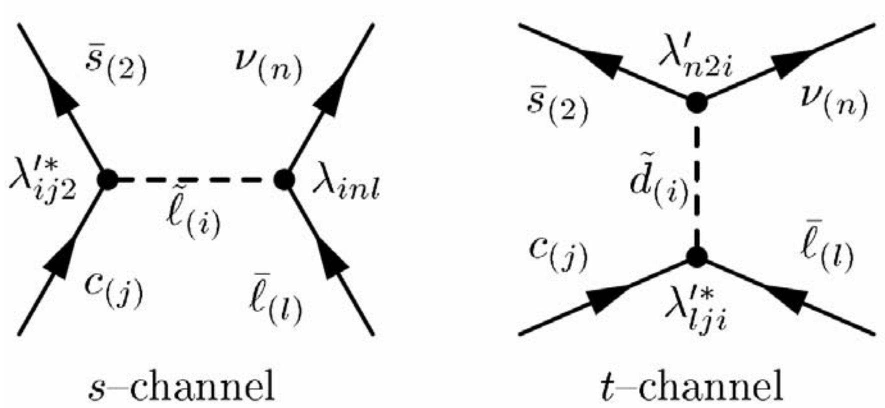
Test physics beyond SM

hep-ph/0308260

2HDM(incl. SUSY) – tree level:
$D^+ \to l^+\nu$ can proceed via exchange of **charged Higgs H^+** **instead of only W^+.**



Possible scenario in simple R parity violating coupling: correlation with charged lepton flavor violation (cLFV).



hep-ph/0210376

Up to 10% effect possible in large $\tan\beta$ regime with relatively massive charged Higgs $\to$ experimentally accessible!

Possible new physics can be probed in D/Ds leptonic decays.

Experimental status of $D_{(s)} \to \mu\nu$

- **CLEO-c**

$D^+ \to \mu\nu$	[PRD78,052003(2008)]
$D^+ \to \tau\nu$; $\tau \to \pi\nu$	[PRD78,052003(2008)]
Ds $\to \mu\nu$	[PRD79,052001(2009)]
Ds $\to \tau\nu$; $\tau \to \pi\nu$	[PRD79,052001(2009)]
Ds $\to \tau\nu$; $\tau \to e\nu\nu$	[PRD79,052002(2009)]
Ds $\to \tau\nu$; $\tau \to \rho\nu$	[PRD80,112004(2009)]

- **BESIII** — CHARM2012 conference
  - **$D^+ \to \mu\nu$**

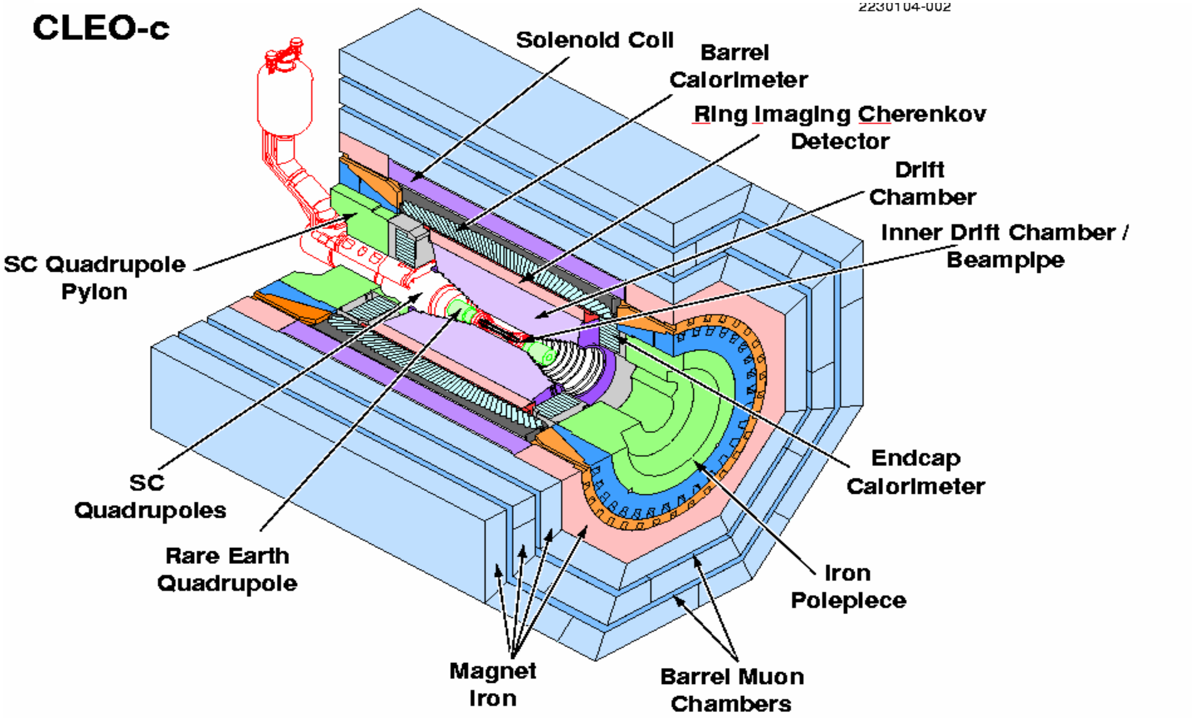
- **Belle** — FPCP2012 conference
  - **Ds $\to \mu\nu$**
  - **Ds $\to \tau\nu$; $\tau \to e\nu\nu$, $\mu\nu\nu$, $\pi\nu$**

- **BABAR** — [PRD82, 091103(2010)]
  - **Ds $\to \mu\nu$**
  - **Ds $\to \tau\nu$; $\tau \to e\nu\nu$, $\mu\nu\nu$,**

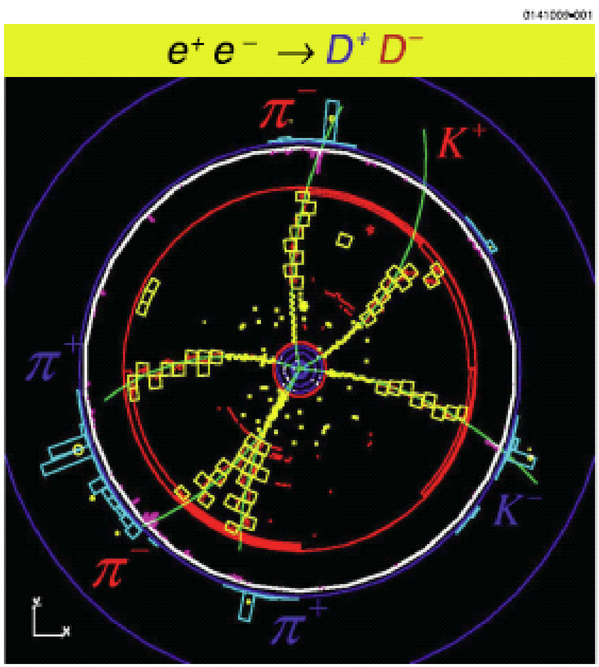
CLEO-c detector

- Excellent Particle Identification (dE/dx and RICH): $0 < p < 1$ GeV/c
- Tracking Resolution: $\sigma_p/p = 0.6\%$ at $p = 1$ GeV/c
- CsI Calorimeter Resolution: $\sigma_E/E = 5\%$ at $E_\gamma = 100$ MeV and 2.2% at 1 GeV
- Hermetic Tracking and Calorimetry: 93% of 4π
- Acceptance, Resolution, and Particle Identification: Well-Understood

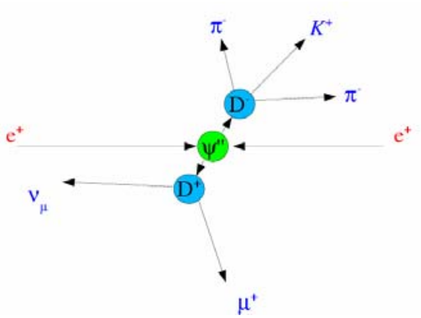
These qualities enable accurate reconstruction of missing νs in semileptonic decays!



Very Clean Events



Tagging techniques at $\psi(3770)$



$E_D \Rightarrow E_{beam}$:

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

$$\Delta E = E_{beam} - E_D$$

- Pure DD, no additional particles ($E_D = E_{beam}$).
- Low multiplicity ~ 5-6 charged particles/event
- Good coverage: ν reconstruction
- Pure $J^{PC} = 1^{--}$ (mixing, CP, strong phase)

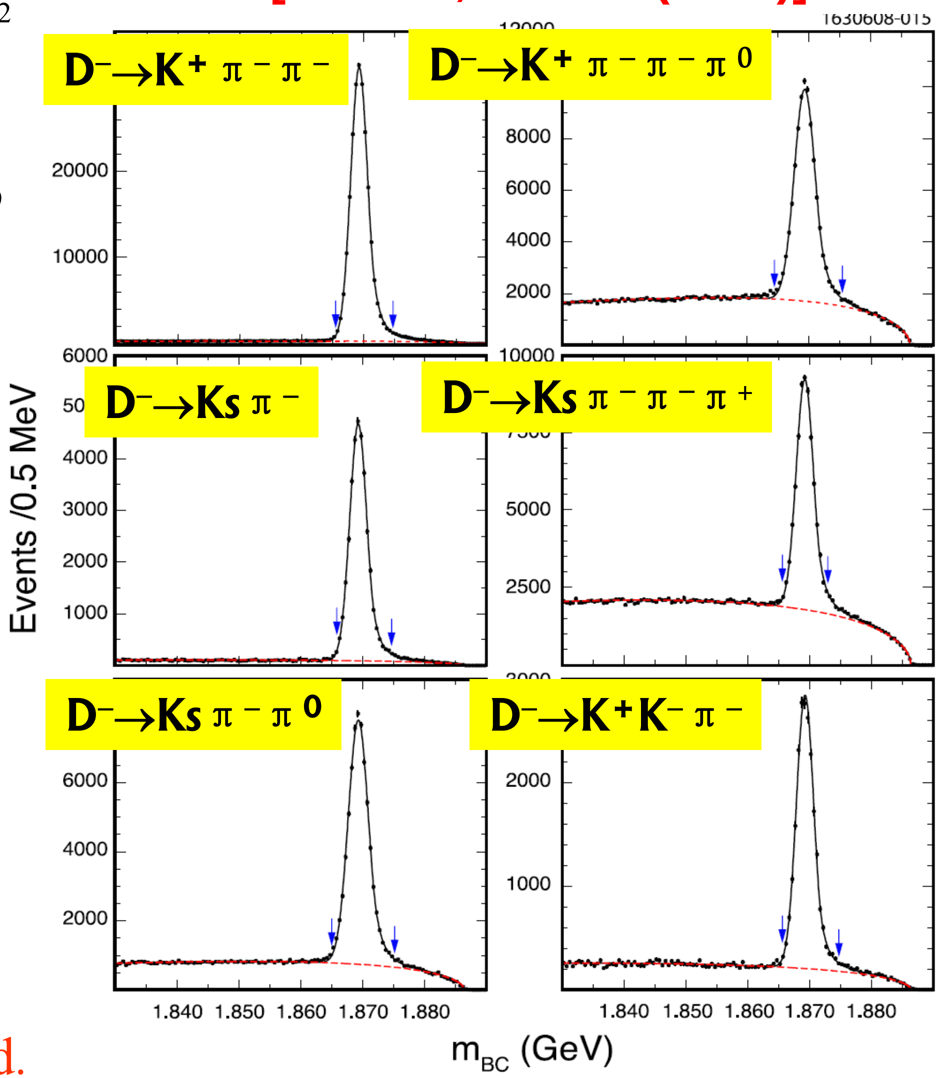
• Common to all analyses, fully reconstruct one D as "the tag" then analyze decay of 2nd D to extract exclusive or inclusive properties

Tagging creates a single D beam of known 4-momentum

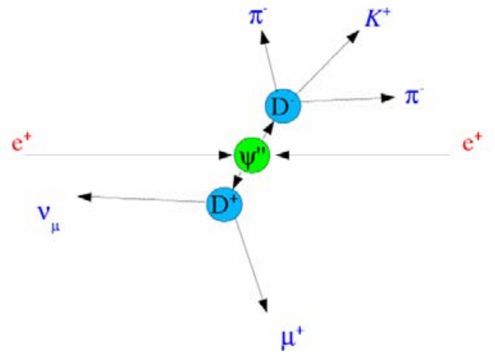
Unique to charm: high tagging efficiency:

~25% of all D's produced are reconstructed.

CLEO-c [PRD 78, 052003 (2008)]:



Missing mass squared

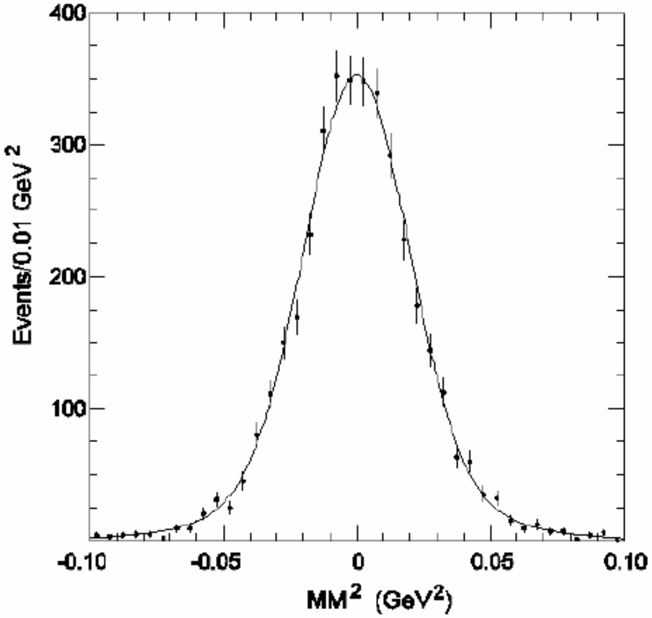


CLEO-c [PRD 78, 052003 (2008)]:

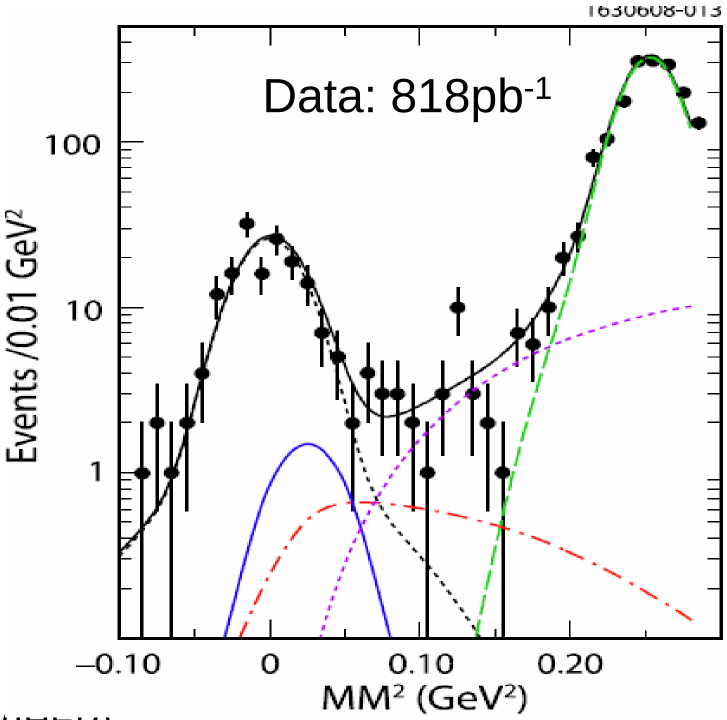
For $D^+ \to \mu^+\nu$ 1 additional track (consistent with a muon) is used to compute missing mass2:

$$MM^2 = (E_{beam} - E_\mu)^2 - (-\overrightarrow{P_{Dtag^+}} - \overrightarrow{P_\mu})^2$$

If close to zero then almost certainly we have a missing ν



Monte Carlo Signal $\mu\nu$

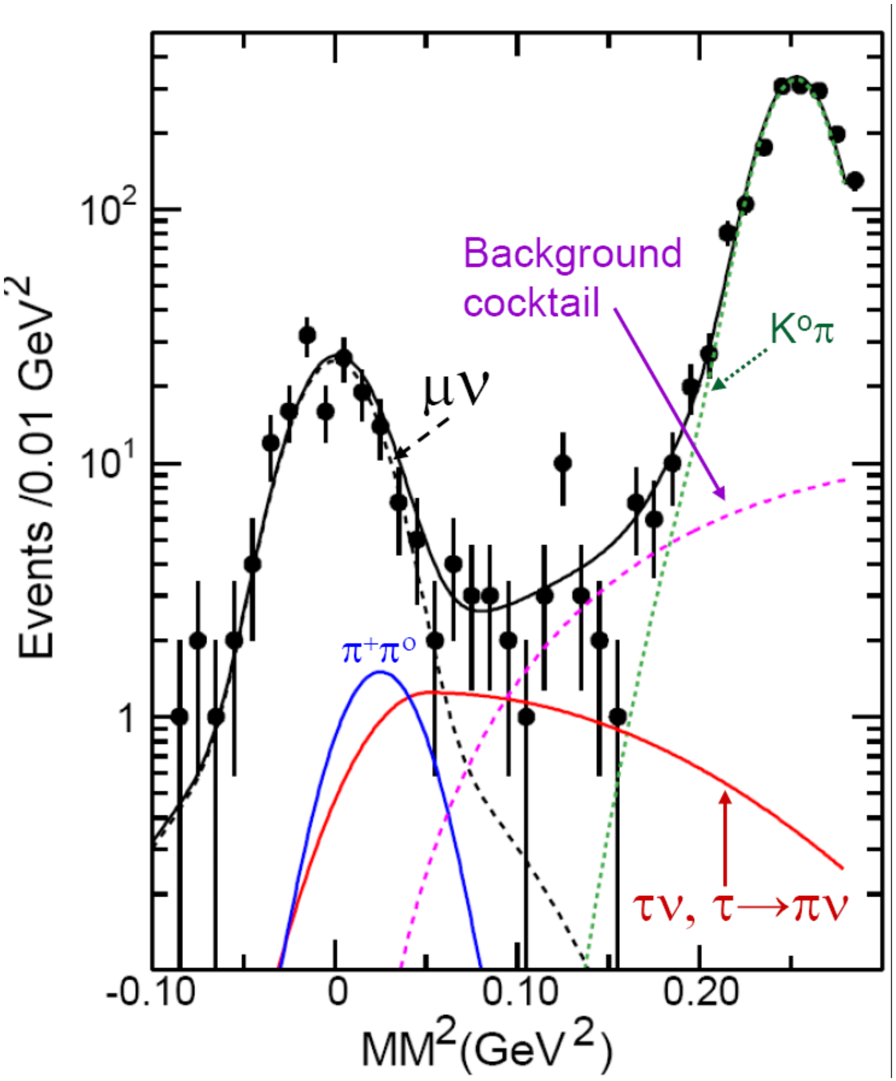


Measurement of $D^+ \to \mu^+ \nu$

CLEO-c [PRD 78, 052003 (2008)]:

- Require E_{cal} <300 MeV for candidate; no extra γ > 250 MeV
- $\tau^+\nu/\mu^+\nu$ is **fixed** to SM ratio
  - 149.7±12.0 $\mu\nu$
  - 28.5 $\tau\nu$
- $\tau^+\nu/\mu^+\nu$ is allowed to **float**
  - 153.9±13.5 $\mu\nu$
  - 13.5±15.3 $\tau\nu$

818fb^{-1} from CLEO-c

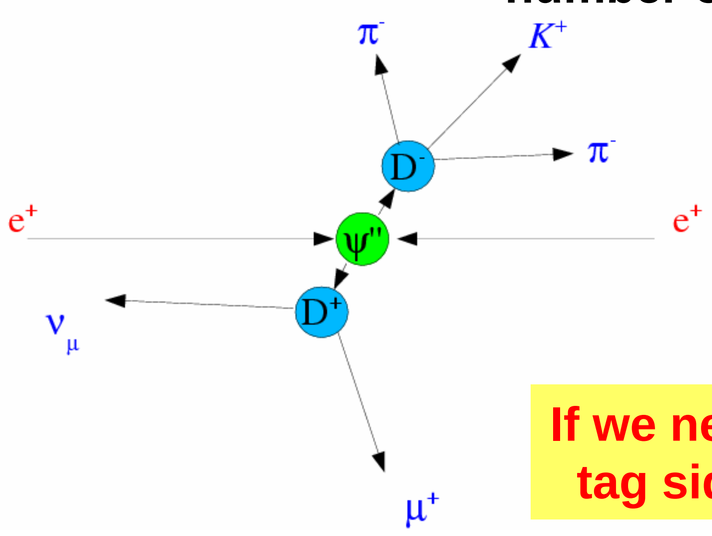


Absolute branching fraction

Absolute branching ratio: $$Br(D^+ \to \mu^+ \nu_\mu) = \frac{N^{observed}_{D\to\mu\nu}}{\varepsilon_{D\to\mu\nu} \times N_{tagged-D}}$$

$N_{tagged-D}$: the number of single tag candidates,
$\varepsilon_{D->\mu\nu}$: the selection efficiency for signal D decay to $\mu\nu$.
$N^{observed}$: the number of signal observed from tagged D.

This branching ratio does not depend on the total number of D mesons.



$$n_i = 2N_{D\overline{D}} B_i \varepsilon_i$$

$$n_{ij} = 2N_{D\overline{D}} B_i B_j \varepsilon_{ij}, i \neq j$$

$$B_i = \frac{n_{ij}\varepsilon_j}{n_i \varepsilon_{ij}} = \frac{n_{ij}}{n_i \varepsilon_j}, i \neq j$$

If we neglect the correlation between tag side and signal side

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

BR($D^+ \to \mu^+ \nu$) and f_{D+} from CLEO-c

$|V_{cd}|=|V_{cs}|=0.2245(12)$ and $\tau_{D+}=1.040(7)$ps

$818 fb^{-1}$ from CLEO-c

- Fix $\tau\nu/\mu\nu$ at SM ratio of 2.65

$$\mathcal{B}(D^+ \to \mu^+ \nu) = (3.82 \pm 0.32 \pm 0.09) \times 10^{-4}$$

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

This is best number in context of SM.

- Float $\tau\nu/\mu\upsilon$

CLEO-c [PRD 78, 052003 (2008)]

$$\mathcal{B}(D^+ \to \mu^+ \nu) = (3.93 \pm 0.35 \pm 0.10) \times 10^{-4}$$

$$f_{D^+} = (207.6 \pm 9.3 \pm 2.5)\ \mathrm{MeV}$$

These are final number from CLEO-c with 818 fb^{-1}
The error is still dominated by statistical error (4.3%).

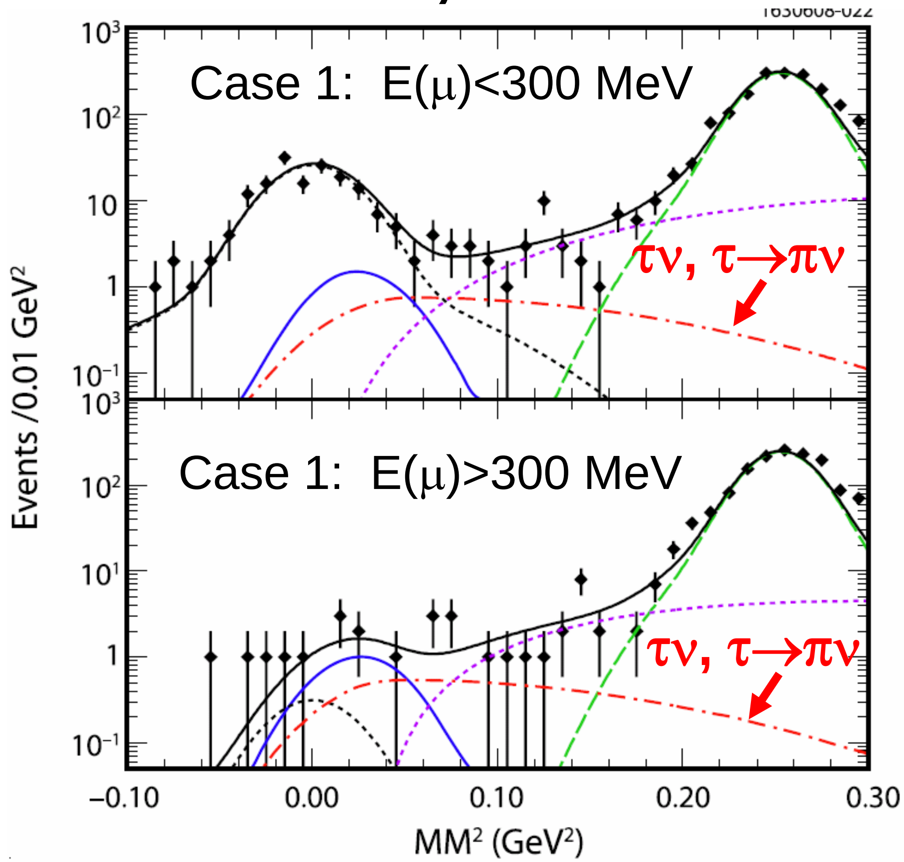
Measurement of $D^+ \to \tau^+\nu$, $\pi^+ \nu$

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

Fit to samples of case 1 and 2:
27.8±16.4 signal events.
give branching fraction
@90% C.L.:

$$\mathcal{B}(D^+ \to \tau^+\nu) < 1.2 \times 10^{-3}$$

$$\frac{\Gamma(D^+ \to \tau^+\nu)}{2.65 \cdot \Gamma(D^+ \to \mu^+\nu)} < 1.2$$



Requiring the track as electron using energy deposit in EMC and dE/dx information:

818fb^{-1} from CLEO-c

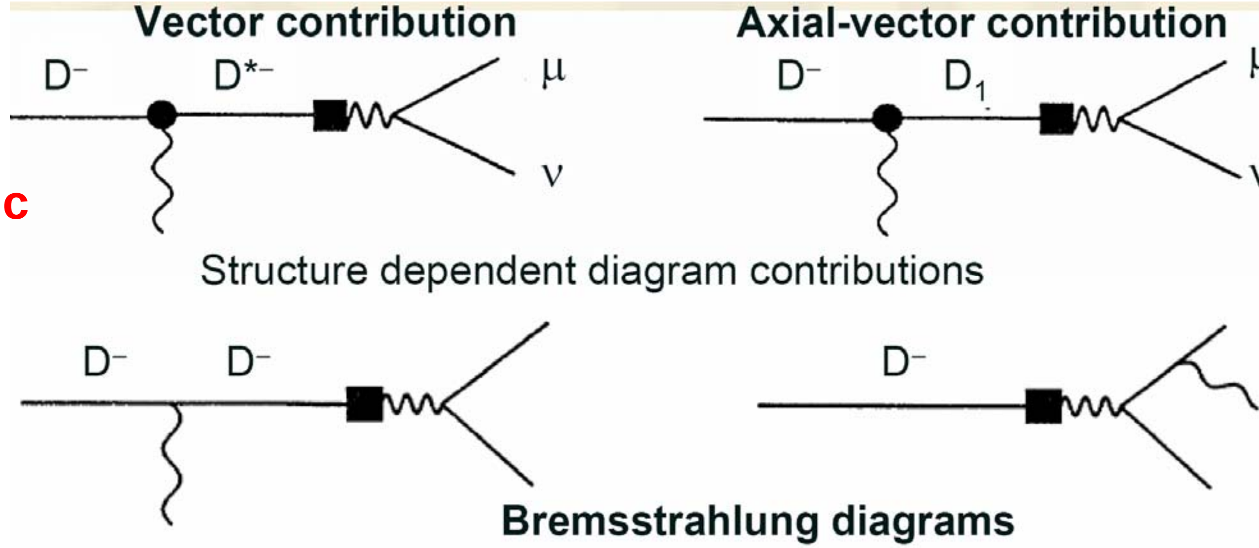
$$\mathcal{B}(D^+ \to e^+\nu) < 8.8 \times 10^{-6} \quad \text{at } 90\%\text{c.l.,}$$

Standard Model predictions:
$B(D^+ \to \tau^+ \nu) = (1.01 \pm 0.09) \times 10^{-3}$
$B(D^+ \to e^+ \nu) = 1 \times 10^{-8}$

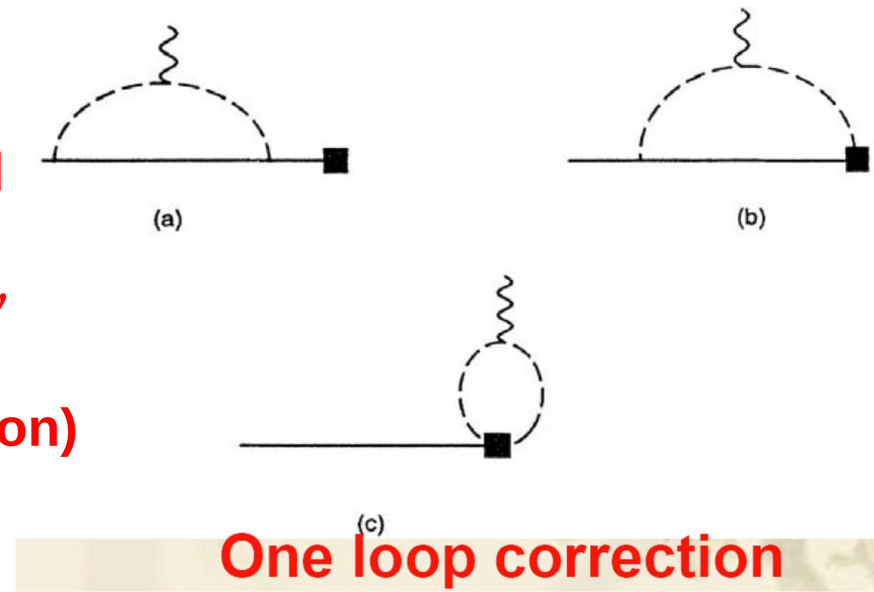
CLEO-c [PRD 78, 052003 (2008)]

Radiative correction – $D^- \to \mu^- \nu \gamma$

For $D^+ \to \tau^+ \nu$, no sizable suppression since τ only acquires 9.3 MeV of kinetic energy. So the radiative correction is too small.

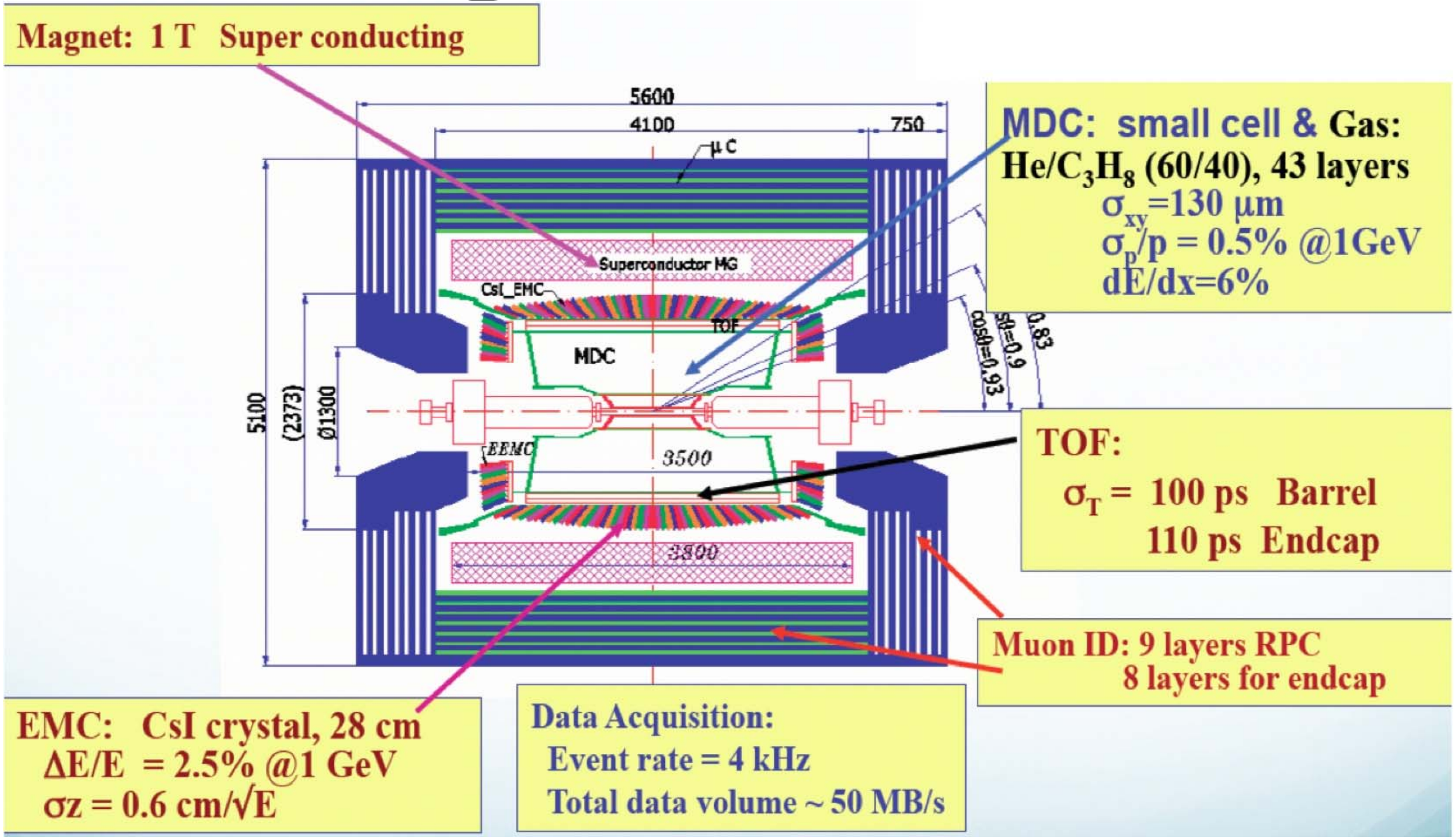


G.Burdman et al
PRD51,111 (1995)



For $D^+ \to \mu^+ \nu$, radiative correction could play a role due to the process of $D^+ \to \gamma D^{*+} \to \gamma \mu^+ \nu$. The transition $D^{*+} \to \mu^+ \nu$ is not helicity-suppressed:
this indicates a 1% correction (reduction)

BESIII detector



- Comparable capabilities to CLEO-c, plus muon ID
- The big advantage: BEPCII is a two-ring machine designed for charm
  - Design (achieved) luminosity at $\psi(3770)$: 1 (0.65) x 10^{33}

BESIII data set and future plans

- 2009: 106M $\psi(2S)$
  225M J/ψ
- 2010-2011: 2.9fb^{-1} @ $\psi(3770)$ 3.5 ×CLEO-c
- 2011: 470pb^{-1} @ 4010MeV
- 2012: τ mass scan, R scan [2.0 3.65] GeV
  0.4 billion $\psi(2S)$ and 1 billion J/ψ

Tentative future running plans:

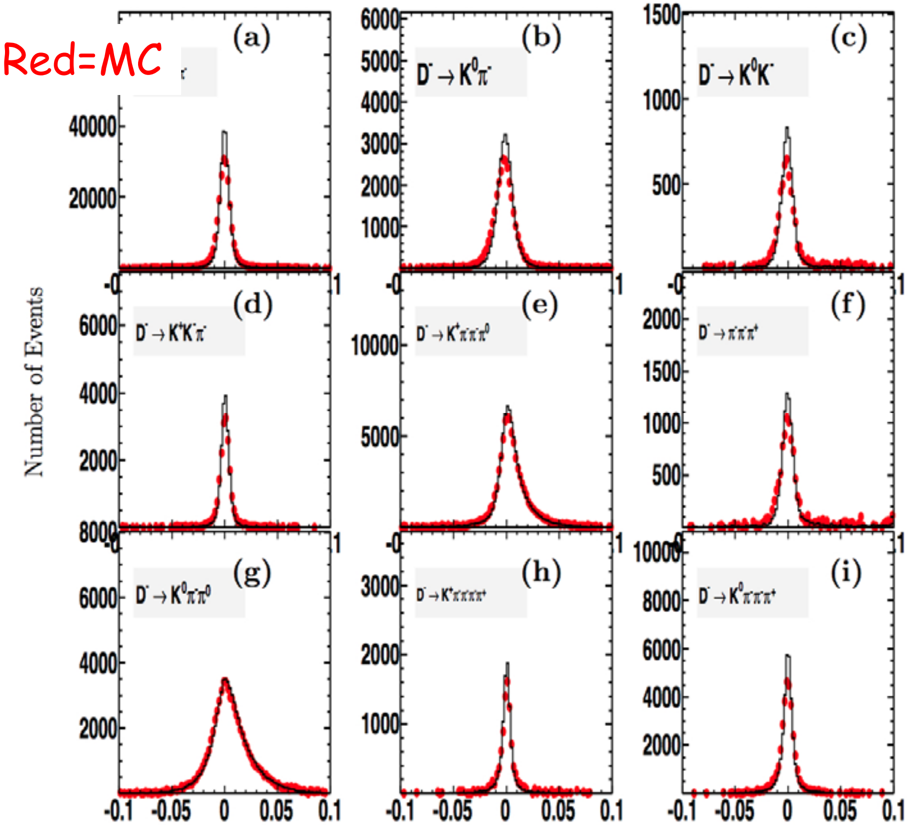
2013: E_{CM}=4260 and 4360 MeV:
For "XYZ" studies (0.5 fb^{-1} each point)
2014: E_{CM}=4170 MeV for Ds (~2.4 fb^{-1})
2015: TBD → additional $\psi(3770)$ data

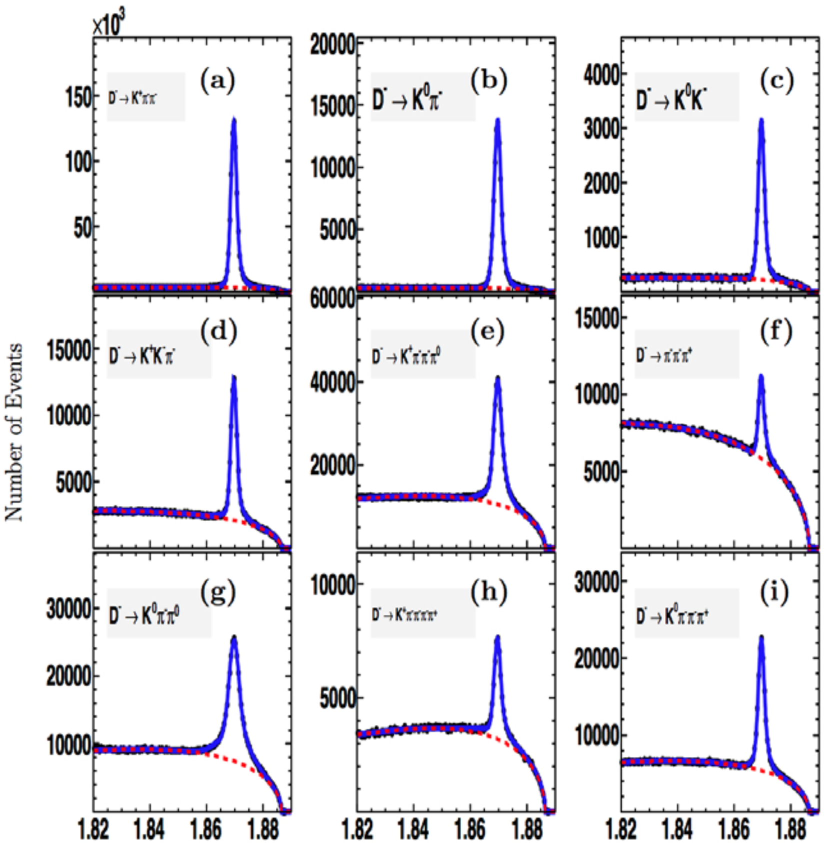
D^+ Leptonic Decays – Tag Selection

- Nine D^- tag modes

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

Red=MC

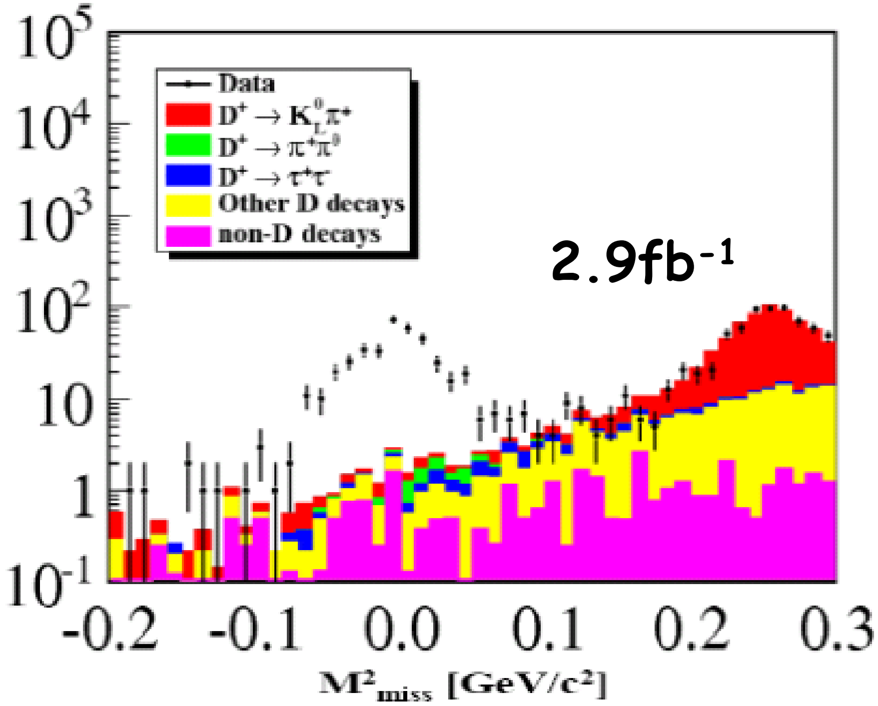




$$N_{D^-}^{tag} = (1.566 \pm 0.002) \times 10^6 \text{ in } 2.9 \text{ fb}^{-1}$$

BESIII Preliminary

D^+ Leptonic Decays



BESIII Preliminary

$$N\left(D^+ \to \mu^+\nu\right) = 377.3 \pm 20.6$$

$$\mathcal{B}\left(D^+ \to \mu^+\nu\right) = \left(3.74 \pm 0.21 \pm 0.06\right) \times 10^{-4}$$

$$f_{D+} = (203.91 \pm 5.72 \pm 1.97)\ \text{MeV}$$

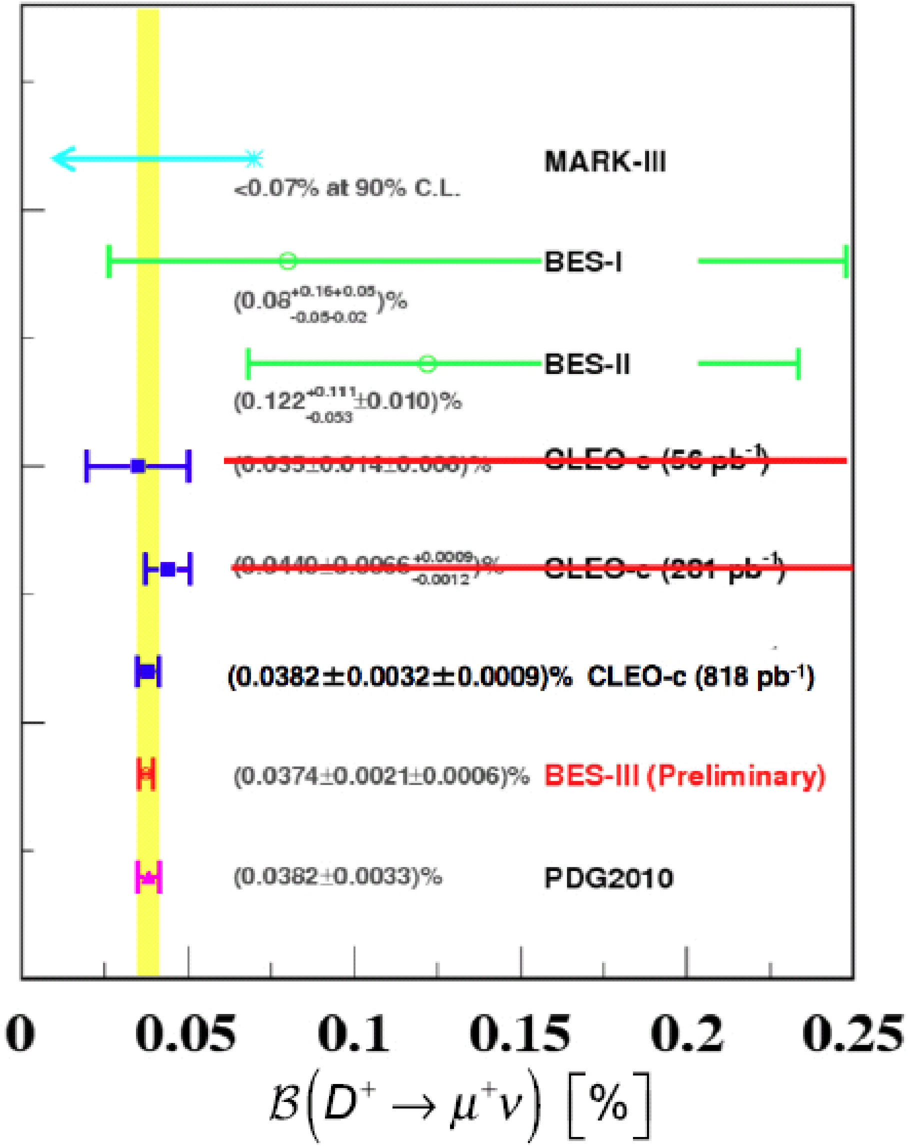
Consistent with CLEO-c

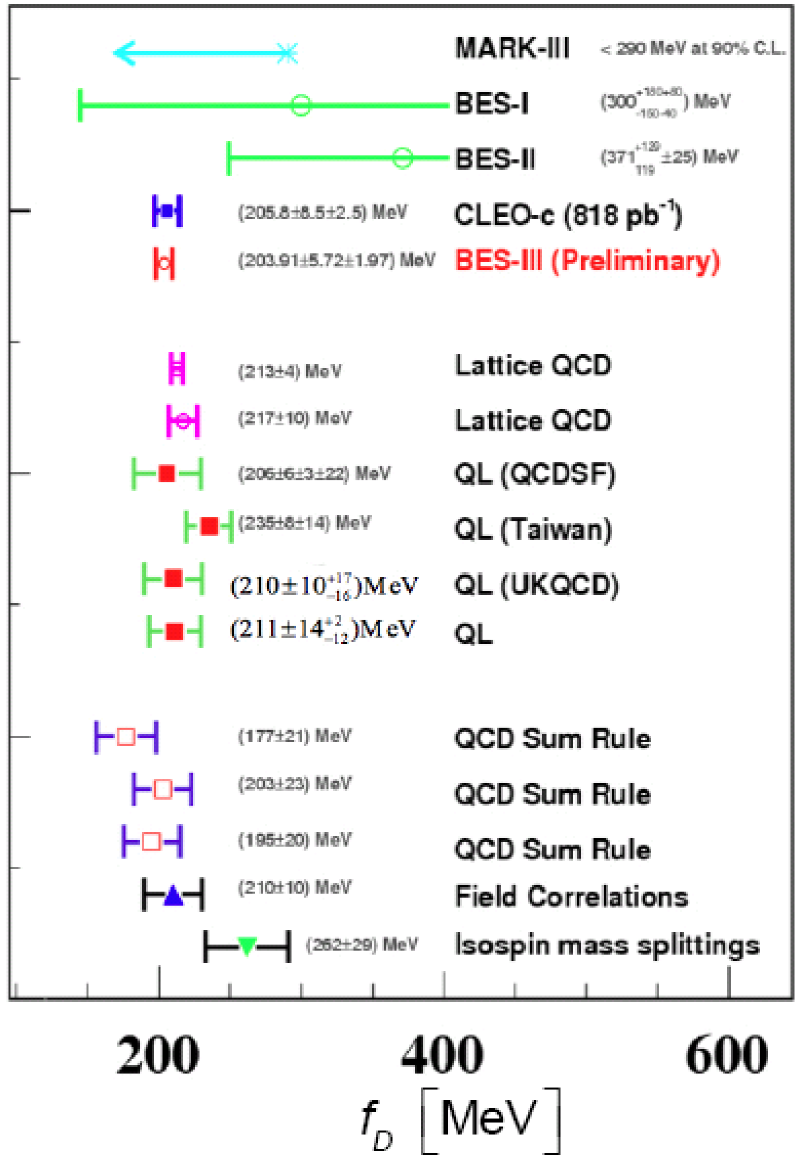
Still statistics limited – need more data!

Experiment	$\mathcal{B}(D \to \mu\nu)$	f_d
BES III (preliminary)	$(3.74 \pm 0.21 \pm 0.06) \times 10^{-4}$	$(203.91 \pm 5.72 \pm 1.97)$ MeV
CLEO-c	$(3.82 \pm 0.32 \pm 0.09) \times 10^{-4}$	$(205.8 \pm 8.5 \pm 2.5)$ MeV
Average	$(3.76 \pm 0.18) \times 10^{-4}$	(204.5 ± 5.0) MeV

The error is still dominated by statistics, more data at threshold is needed.

D^+ Leptonic Decays – Comparisons





 G. Rong CHARM2012

Prospect for $D^+ \to \tau^+ \nu$ at BESIII

$$\mathcal{B}(D^+ \to l^+\nu) = \frac{G_F^2\, m_{D^+} \tau_{D^+}}{8\pi}\, m_l^2 \left(1 - \frac{m_{l^+}^2}{m_{D^+}^2}\right) f_{D^+}^2\, |V_{cd}|^2$$

SM predicts : $(D^+ \to l^+ \nu) = 2.35\times10^{-5} : 1 : 2.65 \ (l = e : \mu : \tau)$

CLEO-c [PRD 78, 052003 (2008)]:
$B(D^+ \to \mu^+ \nu) = (3.82 \pm 0.32 \pm 0.09)\mathrm{x}10^{-4}$

$B(D^+ \to \tau^+ \nu) < 1.2\ \mathrm{x}10^{-3}$ ($\tau^+ \to \pi^+\nu$ only)

SM: $B(D^+ \to \tau^+ \nu) = (1.01 \pm 0.09)\ \mathrm{x}10^{-3}$

$\tau^+ \to X$	$\mathcal{B}(\tau^+ \to X)$	N_{prod}/fb^{-1}
$\pi^+\overline{\nu}$	0.1091	61
$\pi^+\pi^0\overline{\nu}$	0.2552	143
$\pi^+\pi^-\pi^+\overline{\nu}$	0.0932	52
Sum	0.4575	256

* Sensitive to measuring radiative lepton decays

	$\mathcal{B}$(Predicted) $[10^{-6}]$
$D^+ \to \mu^+ \overline{\nu} \gamma$	1 - 25
$D^+ \to e^+ \overline{\nu} \gamma$	1 - 82

f_{Ds} measurements

CLEO: Use $e^+e^- \to D_s\bar{D}_s^*$ at 4170 MeV

Belle & BaBar: $e^+e^- \to c\,\bar{c}$ at Y(4S)

$$f_{D_S^+} = \frac{1}{G_F |V_{cs}| m_l \left(1 - \frac{m_l^2}{m_{D_S^+}^2}\right)} \sqrt{\frac{8\pi \mathrm{B}(D_S^+ \to l^+ \nu)}{m_{D_S^+} \tau_{D_S^+}}}$$

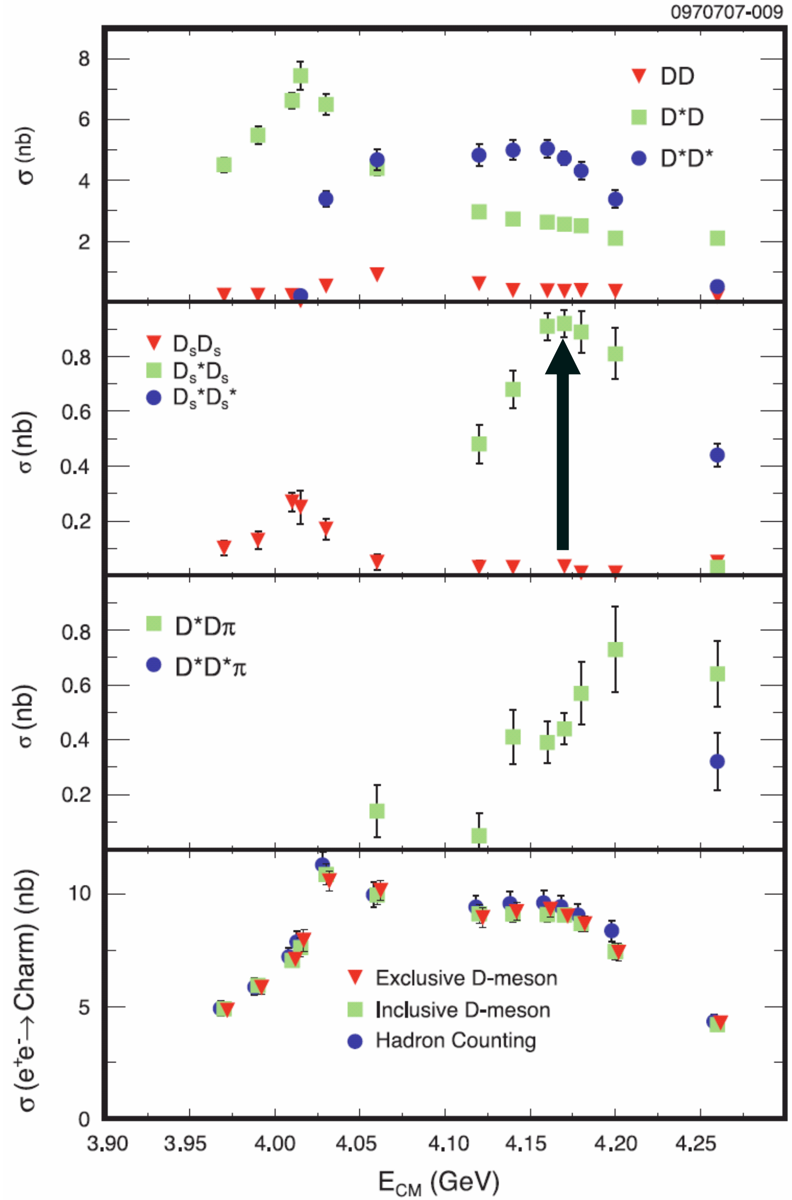
Production cross sections for DsDs$^{(*)}$

Maximum production rates:

σ(DsDs) = 0.269±0.030±0.015 nb @ 4010 MeV

σ(DsDs*) = 0.916±0.011±0.049 nb @ 4170 MeV

CLEO-c took 600 pb^{-1}data @ 4170MeV



Data@4170 MeV

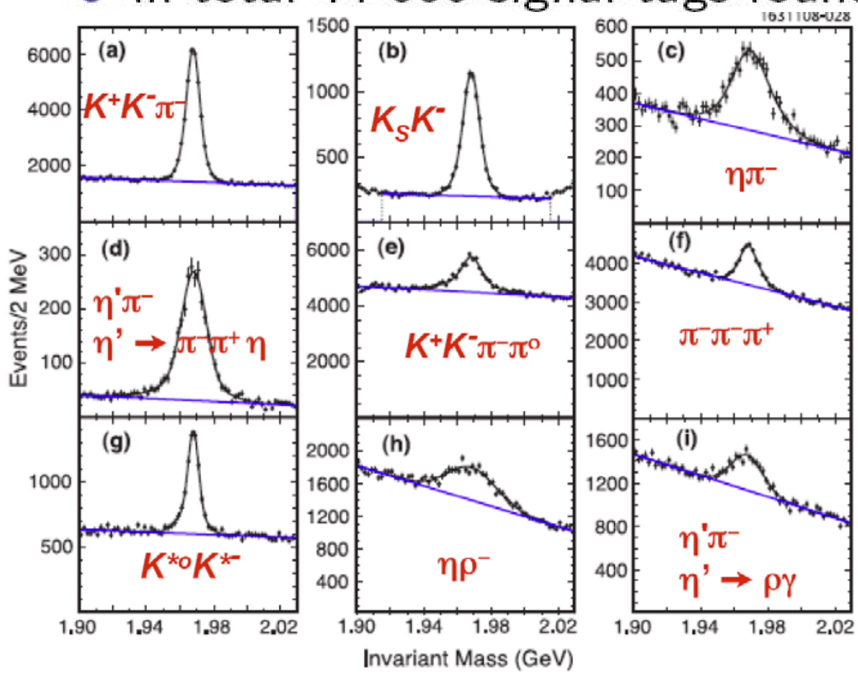
$e^+e^- \rightarrow Ds^+Ds^{*-}$, $Ds^{-*} \rightarrow \gamma Ds^+$
on top of uds *plus* other* charm continuum (DDbar, DD*bar, D*D*bar)

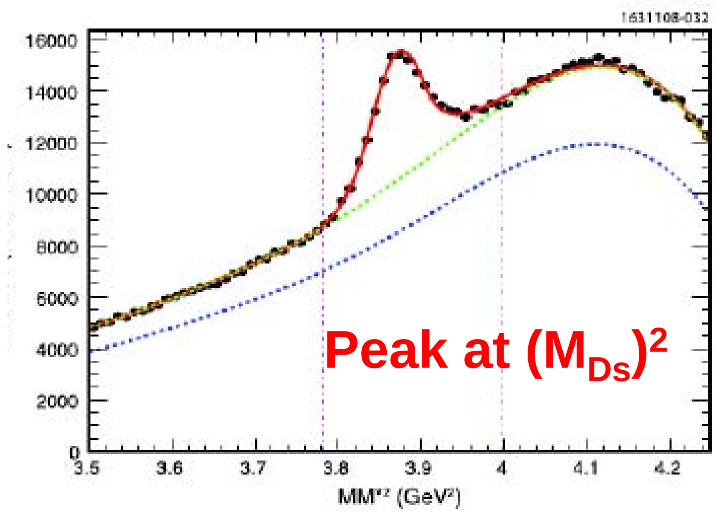
CLEO-c PRD 80, 072001 (2009)

CLEO-c: Ds tag modes (600 fb^{-1} at 4170 MeV)

PRD 79, 052001 (2009); PRD 80, 112004 (2009); PRD 79, 052002 (2009)

- Use $e^+e^- \rightarrow D_s^+ D_s^{*-}$, $D_s^{*-} \rightarrow \gamma D_s^-$ at 4170 MeV
- Tag side:
  - Fully reconstruct $D_s\gamma$ to look for another D_s
  - D_s reconstructed in nine decay modes
  - tags selected in missing mass recoiling against $D_s\gamma$
    $\longrightarrow$ for $D_s D_s^*$ events this always peaks at M_{D_s}
  - in total 44 000 signal tags found in missing mass spectrum





$$\mathrm{MM}^{*2} = (E_{\mathrm{CM}} - E_{D_s} - E_\gamma)^2 - (\mathbf{p}_{\mathrm{CM}} - \mathbf{p}_{D_s} - \mathbf{p}_\gamma)^2$$

CLEO-c: $D_s \to \mu\nu$ & $D_s \to \tau(\pi, \rho)\nu$

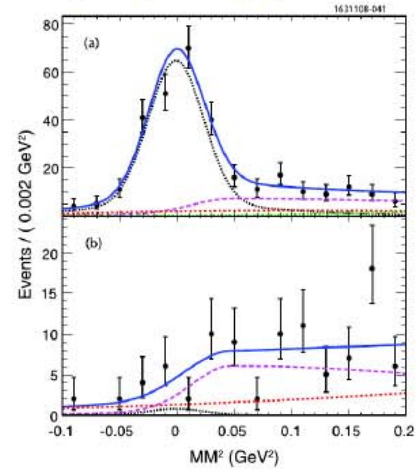
$\mathbf{D_s \to \mu\nu}$ & $\mathbf{D_s \to \tau(\pi)\nu}$

- single extra track with opposite charge to tag, not being identified as electron or kaon, with
  (a) $E_{\rm cal} < 300$ MeV (99% μ, 55% π) or
  (b) $E_{\rm cal} > 300$ MeV (1% μ, 45% π)
- 2D fit to D_s-tag mass and MM^2 to extract signal yields
- cases (a) and (b) fitted simultaneously
- find 235.5 ± 13.8 $\mu\nu$ events
  and 125.6 ± 15.7 $\tau\nu(\tau \to \pi\nu)$ events
- backgrounds: about 10 events in total

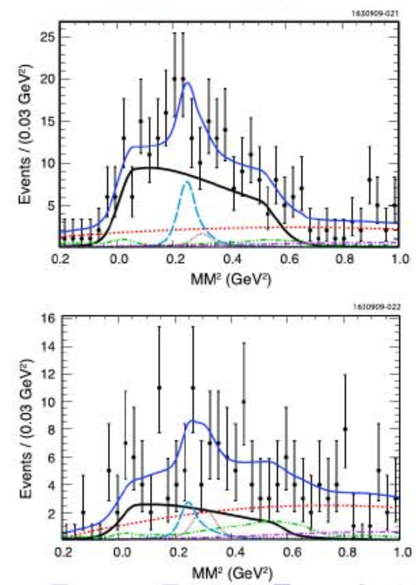
$\mathbf{D_s \to \tau(\rho)\nu}$

- event with exactly one charged pion forming $\rho^+ \to \pi^+\pi^0$
- fit MM^2 distribution in the first two $E_{\rm extra}$ bins
- signal yields:
  155.2 ± 16.5, $E_{\rm extra} < 0.1$ GeV
  43.7 ± 11.3, $0.1 < E_{\rm extra} < 0.2$ GeV

$D_s \to \mu\nu$, $\tau(\pi)\nu$



$D_s \to \tau(\rho)\nu$



Systematic Errors

PRD 79, 052001
(2009) 600 pb^{-1}

Error on f_{Ds} is 1/2 on this

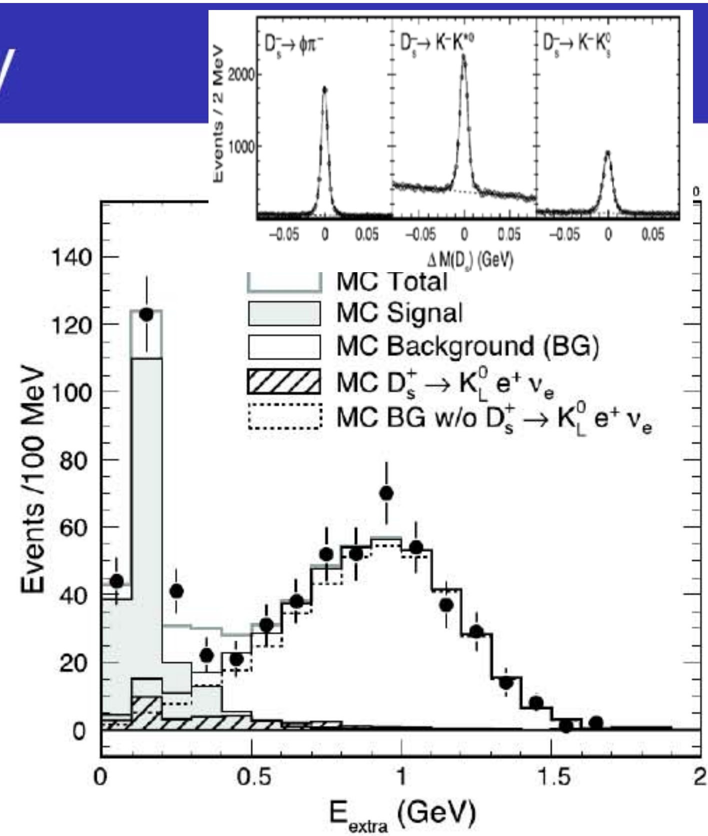
TABLE III. Systematic errors on determination of the $D_s^+ \to \mu^+ \nu$ branching fraction.

Error Source	Size (%)
Track finding	0.7
Particle identification of μ^+	1.0
MM^2 width	0.2
Photon veto	0.4
Background	1.0
Number of tags	2.0
Tag bias	1.0
Radiative Correction	1.0
Total	3.0

Largest single error
is # tags:
might be better at
4030 MeV, with no D_s^*
(but only 30%
of cross-section!)

CLEO-c: $D_s \to \tau(e)\nu$ and Summary

- Tag side:
  - similar to $D_s^+ \to \mu^+\nu$
  - only cleanest modes used ($D_s^- \to \phi\pi^-$, $D_s^- \to K^-K^{*0}$, $D_s^- \to K^-K_s^0$)
- Signal side:
  - event with exactly one electron
  - estimate $D_s^+ \to K_L^0 e^+\nu$ peaking bkg. from MC
  - signal yield: $\mathbf{180.6 \pm 15.9}$



Extra deposited energy in the Calorimeter.

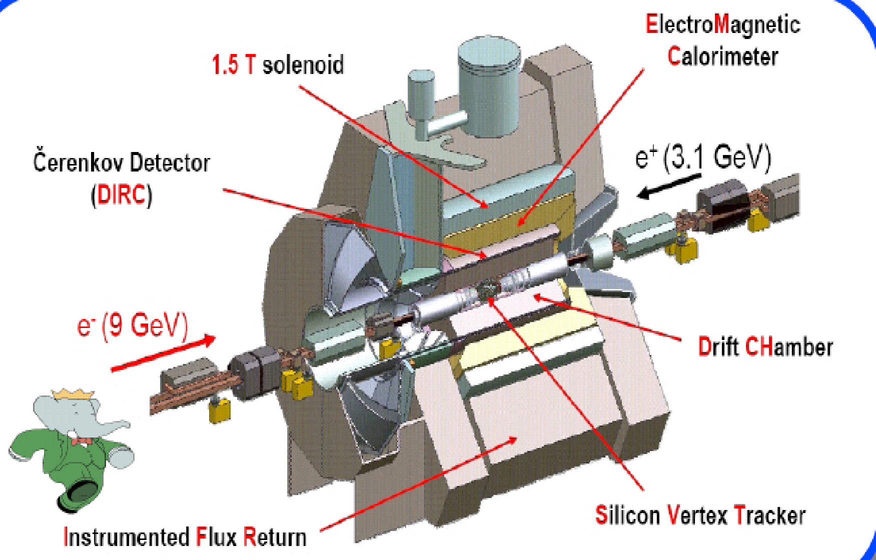
CLEO-c averages:

$$\mathcal{B}(D_s^+ \to \mu^+\nu) = (0.565 \pm 0.045 \pm 0.017)\%$$

$$\mathcal{B}(D_s^+ \to \tau^+\nu) = (5.58 \pm 0.33 \pm 0.13)\%$$

$$f_{D_s} = (259.0 \pm 6.2 \pm 3.0)\ \text{MeV}$$

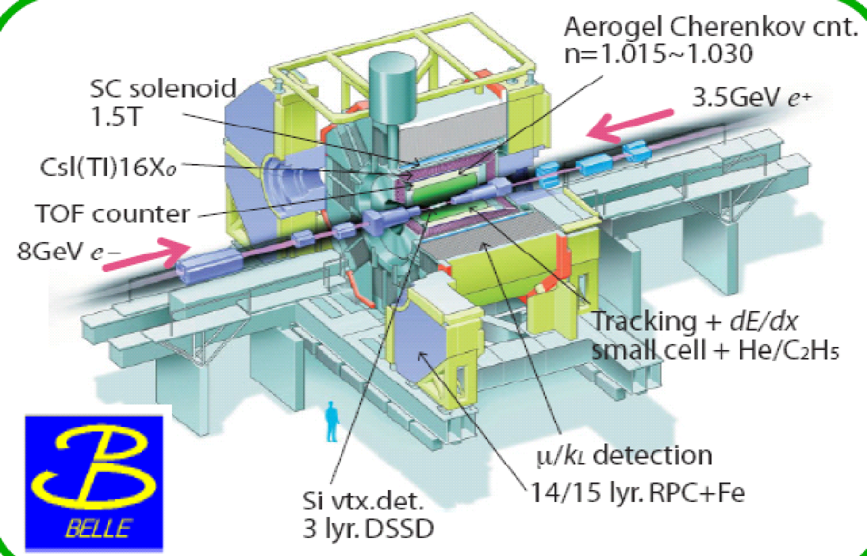
B factories experiments



BaBar operated at PEP-II at SLAC National Accelerator Laboratory until April 2008.

Belle operated at KEKB at Tsukuba

Asymmetric e^+e^- colliders with $\sqrt{s}$~10.6 GeV



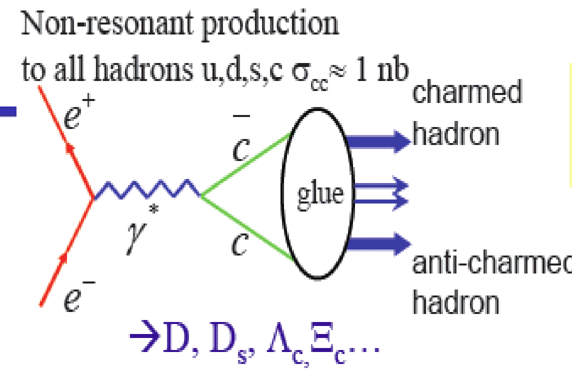
Integrated luminosity:

BaBar ~530 fb^{-1} Belle ~1000 fb^{-1}

BaBar also collected world-largest samples at Υ(2S) and Υ(3S)

Belle also collected samples at Υ(1S) and Υ(5S)

Belle: $D_s \to \mu\nu$ (913 fb^{-1} @10.6 GeV)



- Recoil method in charm events

$$e^+e^- \to c\overline{c} \to \overline{D}_{\text{tag}} K X_{\text{frag}} D_s^{*+}$$

At B-factories $\sqrt{s} = 10.58$ GeV therefore all charmed hadron pairs are possible and additional light mesons (X_{frag}) can be produced in fragmentation process.

2 step reconstruction:

1. Inclusive reconstruction of D_s mesons for normalization
   - Reconstruct $D_{\text{tag}} K X_{\text{frag}}$ and γ from $D_s^* \to D_s\gamma$ decay and identify D_s in missing mass spectrum (without any requirements upon D_s decay products)

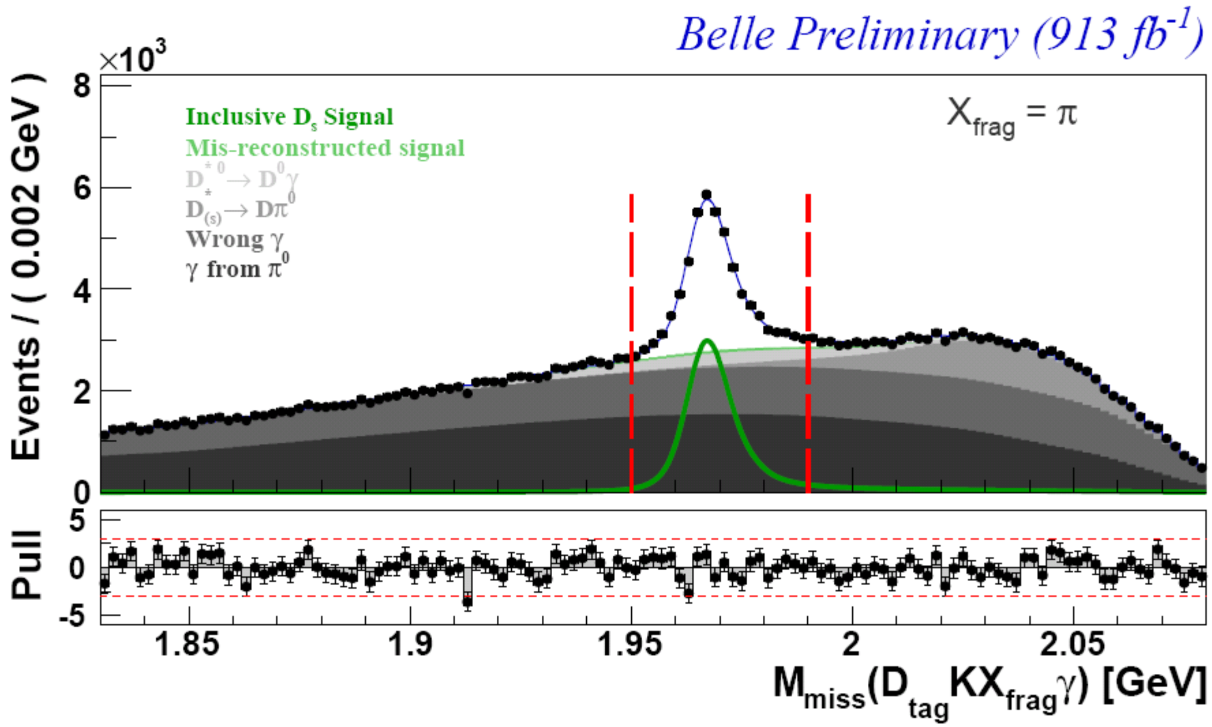
$$M_{\text{miss}}(\overline{D}_{\text{tag}} K X_{\text{frag}} \gamma) = |p_{e^+e^-} - p_{D_{\text{tag}}} - p_K - p_{X_{\text{frag}}} - p_\gamma|^2$$

2. Within the inclusive D_s sample search for $D_s \to f$ decays
   - $D_s \to \mu\nu$: peak at $m_\nu^2 = 0$ in $M_{\text{miss}}^2(D_{\text{tag}} K X_{\text{frag}} \gamma\mu)$
   - $D_s \to \tau\nu$: peak towards 0 in extra energy in calorimeter

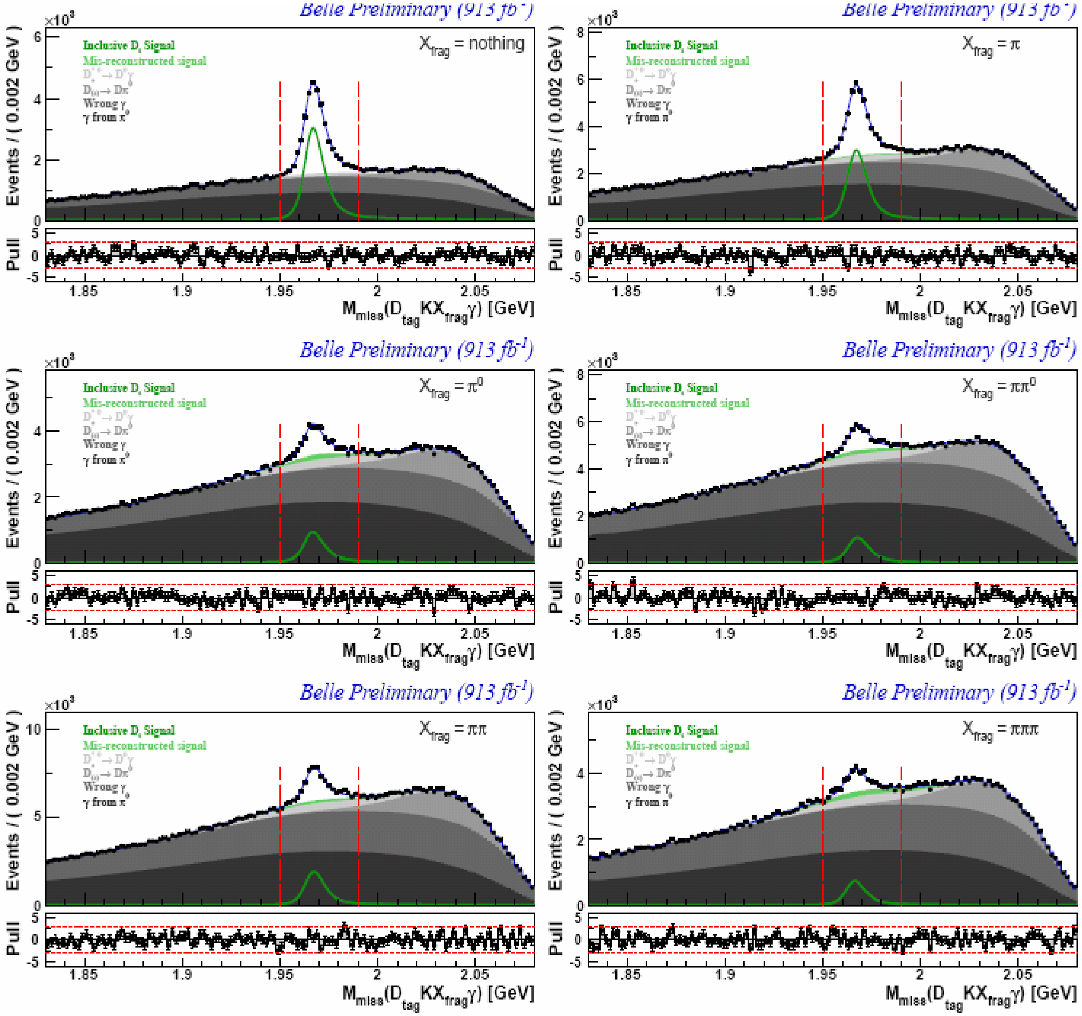
Belle: $D_s \to \mu\nu$: method overview

$$e^+e^- \to c\bar{c} \to \overline{D}_{\rm tag} K X_{\rm frag} D_s^{*+}$$

- γ from $D_s^* \to D_s\gamma$
  - $E_\gamma > 0.12$ GeV, in opposite hemisphere wrt. $D_{\rm tag}$
- **Inclusive D_s**
  - $p_{\rm miss}(D_{\rm tag} K X_{\rm frag}\gamma) > 2.8$ GeV
  - only one candidate per event is allowed (selection based on γ properties only)



Belle: Ds → μν , method overview



Fit to $M_{\rm miss}(D_{\rm tag}KX_{\rm frag}\gamma)$ for each $X_{\rm frag}$:

- Histogram MC templates (6 categories)
- Peak resolution calibrated using real data
- Good description of the observed distributions achieved

Belle preliminary @ 913 fb^{-1}

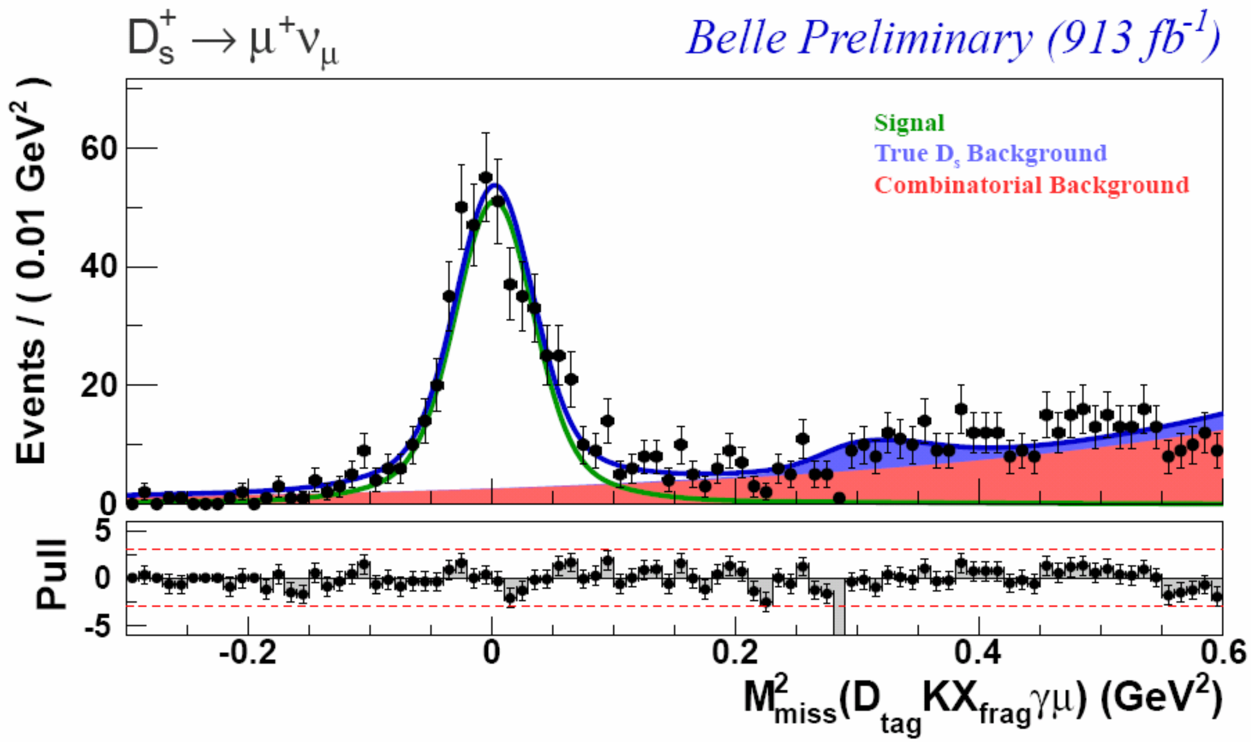
$$\mathbf{N^{incl}_{D_s} = 94400 \pm 1300(stat.) \pm 1400(syst.)}$$

Belle: $D_s \to \mu\nu$ (913 fb^{-1} @10.6 GeV)

Fit to the missing mass squared – $M^2_{\rm miss}(D_{\rm tag}KX_{\rm frag}\gamma\mu^\pm)$

Selection:

- $M_{\rm miss}(D_{\rm tag}KX_{\rm frag}\gamma)$ signal region
- 1 charged track pointing to the IP
- passing muon PID requirements



$$N^{\rm excl}_{D_s\to\mu\nu} = 489 \pm 26$$

Belle preliminary @ 913 fb^{-1}

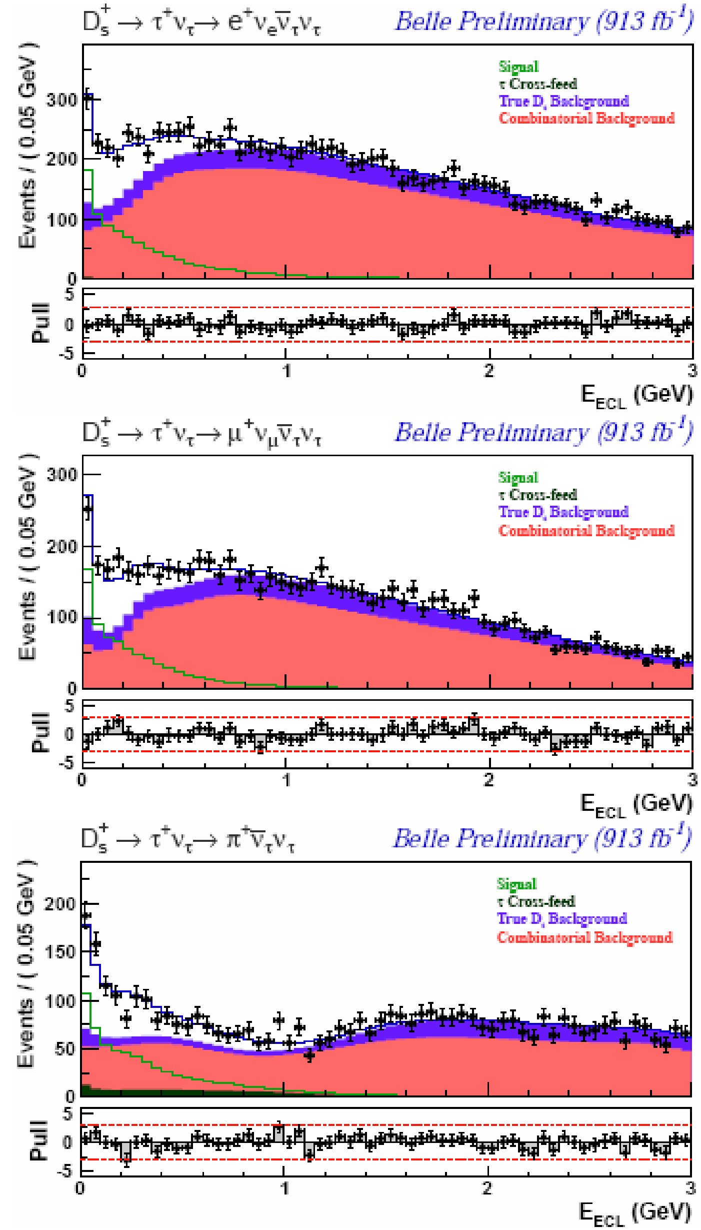
$$\boxed{\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (0.528 \pm 0.028({\rm stat.}) \pm 0.019({\rm syst.}))\%}$$

Most precise measurement up to date.

$D_s \to \tau\nu$ (Belle: 913 fb^{-1})

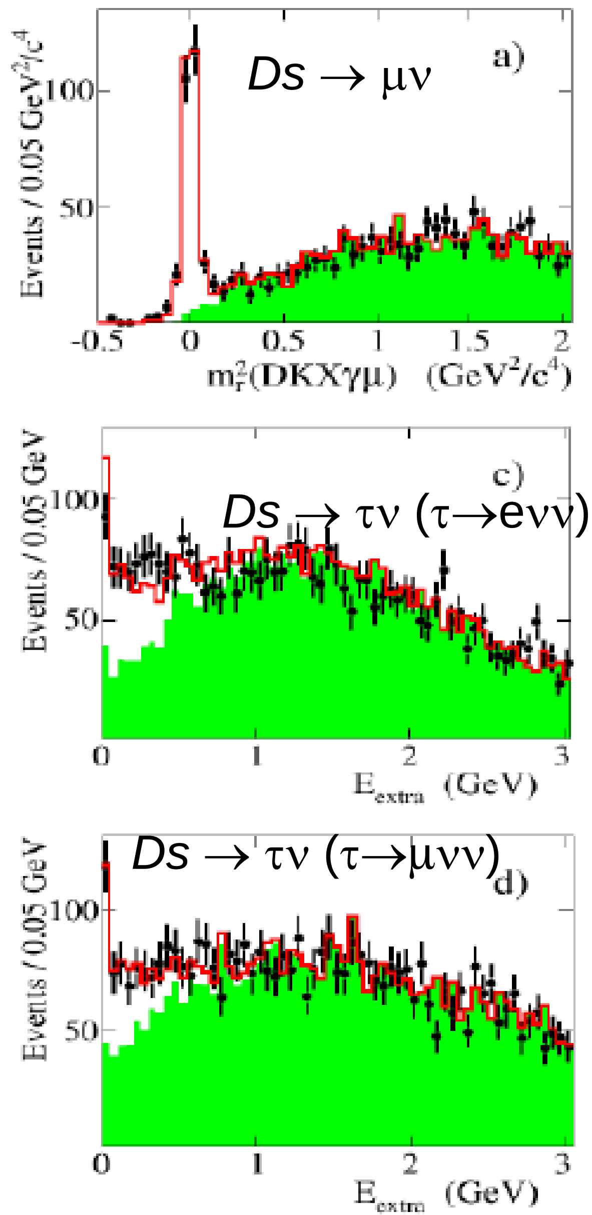
- Tag side ($D_{tag}KX_{frag}\gamma$)
  - Same as $D_s \to \mu\nu$ mode
- Signal side ($D_s \to \tau\nu$)
  - 3 τ decay modes: $\tau \to e\nu\nu$, $\mu\nu\nu$, $\pi\nu$
  - Kinematic variable: Extra energy in calorimeter (E_{ECL})

τ decay mode	$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)$ $[\times 10^{-2}]$
$e\nu\nu$	$5.37 \pm 0.33^{+0.35}_{-0.30}$
$\mu\nu\nu$	$5.88 \pm 0.37^{+0.34}_{-0.58}$
$\pi\nu$	$5.96 \pm 0.42^{+0.45}_{-0.39}$
Combination	$5.70 \pm 0.21^{+0.31}_{-0.30}$



BABAR: $D_s \to \mu\nu, \tau\nu$ (521 fb^{-1} @10.6 GeV)

- PRD82, 091103(R)(2010)
- Recon. Method: Similar to Belle
- Tag side
  - 4 decay modes ($X \to n\pi$, n=0 - 3)
  - Background model: wrong flavor candidates (charge of not consistent with D_s)
  - # of tags: 67200±1500
- Signal side
  - $D_s \to \mu\nu$
    - Br($D_s \to \mu\nu$)=(0.602±0.038±0.034)%
  - $D_s \to \tau\nu$ ($\tau \to e\nu\nu$, $\mu\nu\nu$)
    - Br($D_s \to \tau\nu$)=(5.00±0.35±0.49)%
- Decay constant: f_{Ds} = (258.6 ± 6.4 ± 7.5)



Experimental averages : f_{Ds}

Experiment	Mode	$\mathcal{B}$	f_{Ds} (MeV)
CLEO-c	$\mu^+\nu$	$(5.65 \pm 0.45 \pm 0.17) \times 10^{-3}$	$257.6 \pm 10.3 \pm 4.3$
BaBar	$\mu^+\nu$	$(6.02 \pm 0.38 \pm 0.34) \times 10^{-3}$	$265.9 \pm 8.4 \pm 7.7$
Belle	$\mu^+\nu$	$(5.28 \pm 0.28 \pm 0.19) \times 10^{-3}$	$249.0 \pm 6.6 \pm 4.9$
Average	$\mu^+\nu$	$(5.54 \pm 0.24) \times 10^{-3}$	255.1 ± 5.5
CLEO-c	$\tau^+\nu$	$(5.58 \pm 0.33 \pm 0.13) \times 10^{-2}$	$259.1 \pm 7.7 \pm 3.5$
BaBar	$\tau^+\nu$	$(5.00 \pm 0.35 \pm 0.49) \times 10^{-2}$	$245.3 \pm 8.6 \pm 12.2$
Belle	$\tau^+\nu$	$(5.70 \pm 0.21 \pm 0.31) \times 10^{-2}$	$261.9 \pm 4.9 \pm 7.2$
Average	$\tau^+\nu$	$(5.54 \pm 0.24) \times 10^{-2}$	258.2 ± 5.6
Experimental Average	$\mu^+\nu + \tau^+\nu$		257.2 ± 4.5
Lattice HPQCD			248.0 ± 2.5

Test of lepton universality:

$$R^{\rm SM}_{\tau/\mu} \equiv \frac{\mathcal{B}(D_s \to \tau\nu)}{\mathcal{B}(D_s \to \mu\nu)} = \frac{m_\tau^2 \left(1 - \frac{m_\tau^2}{M_{D_s}^2}\right)}{m_\mu^2 \left(1 - \frac{m_\mu^2}{M_{D_s}^2}\right)} = 9.76 \quad \text{vs.} \quad R^{\rm exp}_{\tau/\mu} = 10.0 \pm 0.6$$

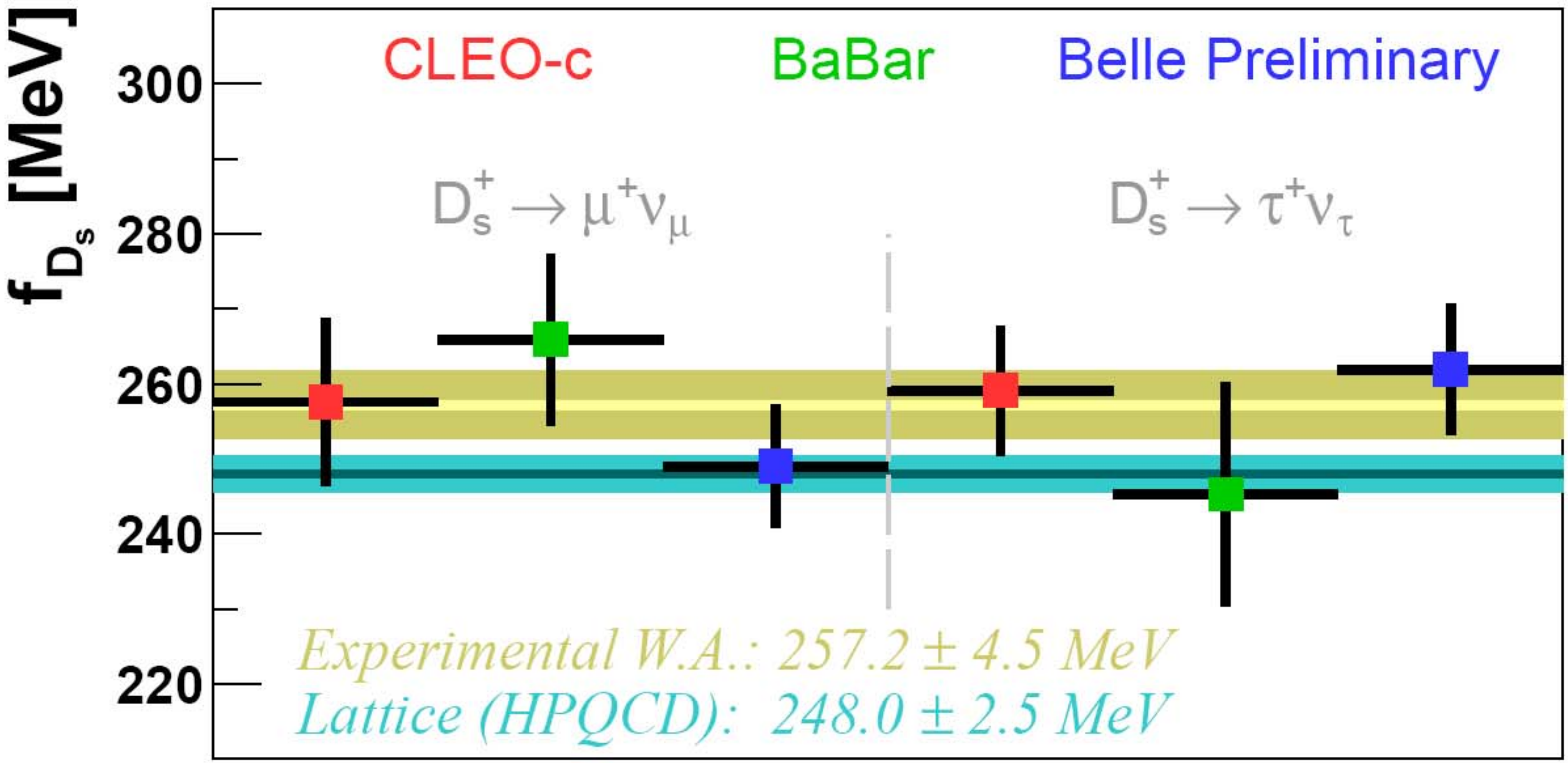
$D_{(s)}$ meson decay constants ratio:

$$\frac{f_{D_s}(D_s^+ \to \tau^+\nu)}{f_{D_s}(D_s^+ \to \mu^+\nu)} = 1.01 \pm 0.05,$$

$$f_{D_s}/f_D = 1.250 \pm 0.022(f_{D_s}) \pm 0.054(f_D)$$

f_{D_s} Comparison

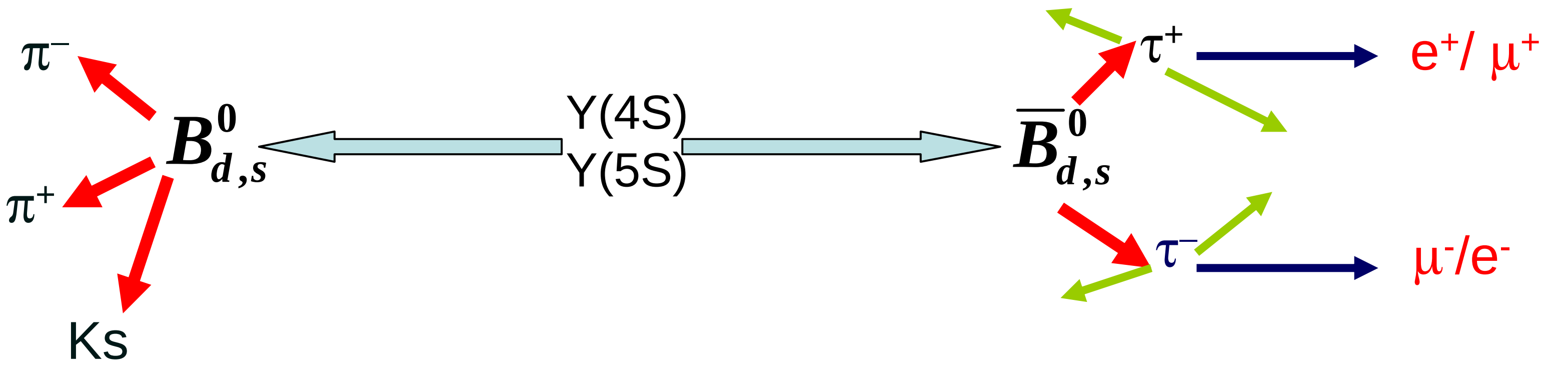
Average of CLEO-c [PRD80,112004(2009)], BaBar [PRD82,091103(2010)] and Belle Preliminary.



Average of experimental determinations is consistent within 1.8σ with most precise lattice QCD calculation by HPQCD.

Need further lattice QCD results with comparable precision to confirm the calculation by HPQCD.

Exercise: how to look for $B_{d,s} \rightarrow \tau^+\tau^-$ at super-B



Step 1: Fully reconstruct one B with hadronic tag

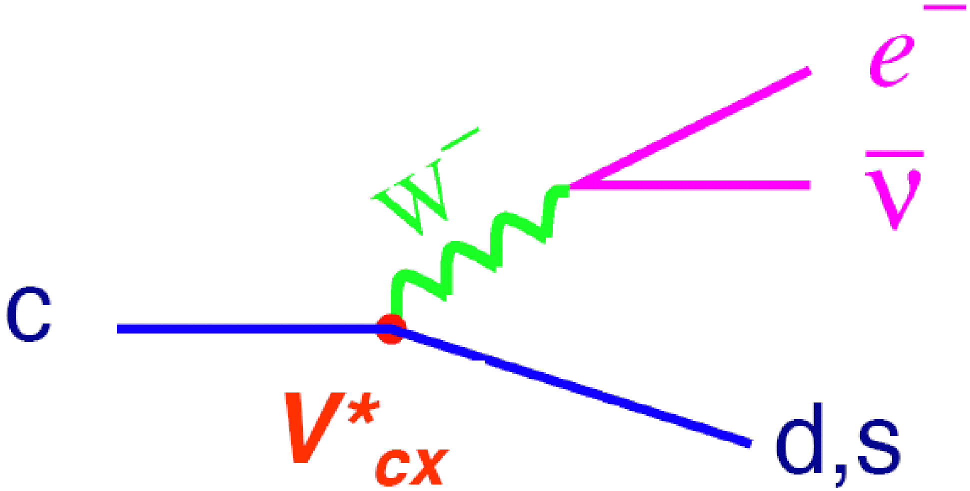
Step 2: missing mass of the tagged B → inclusive reconstruct the other B

Step 3: require μ^+e^- or $e^+\mu^-$ in the signal side ($\tau^+ \rightarrow e^+ \nu\nu$, $\tau^- \rightarrow \mu^-\nu\nu$)

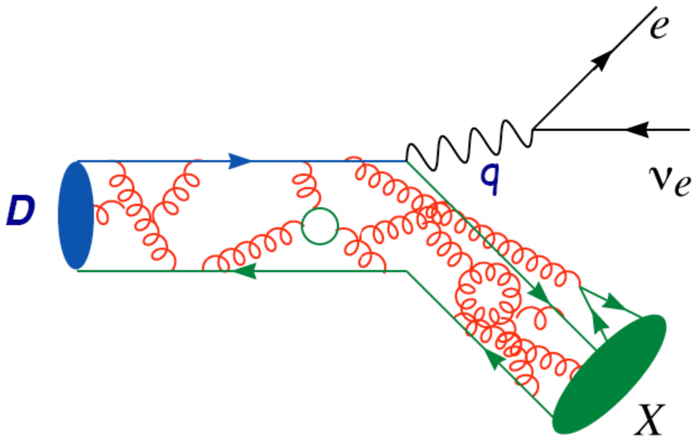
Step 4: look for missing mass of tagged B and extra energy, and perform fits simultaneously.

Then you may access $\mathbf{B_{d,s}} \rightarrow \tau^+\tau^-$ at Super-B factories.

Semileptonic D/Ds decays



Semileptonic D decay



- Decay rate depends on kinematics and V_{CKM}
- Form factor encapsulates QCD bound-state effects
- Consider Pseudoscalar final states: K, π

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cx}|^2 \, p_X^3 \, |f_+(q^2)|^2$$

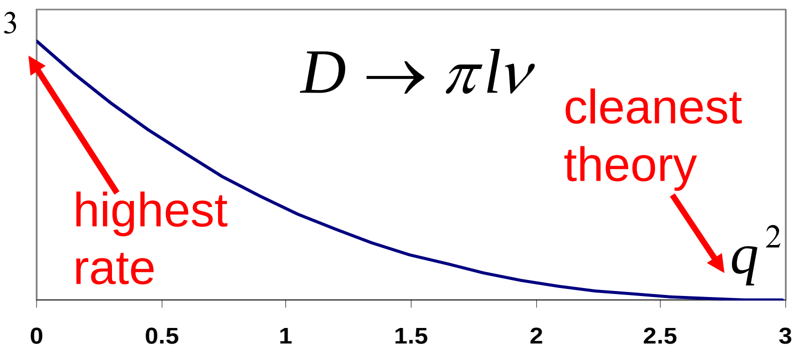
$$q^2 = (p_D - p_X)^2$$
$$= M_D^2 + M_X^2 - 2E_X M_D + 2\vec{p}_D \cdot \vec{p}_X$$

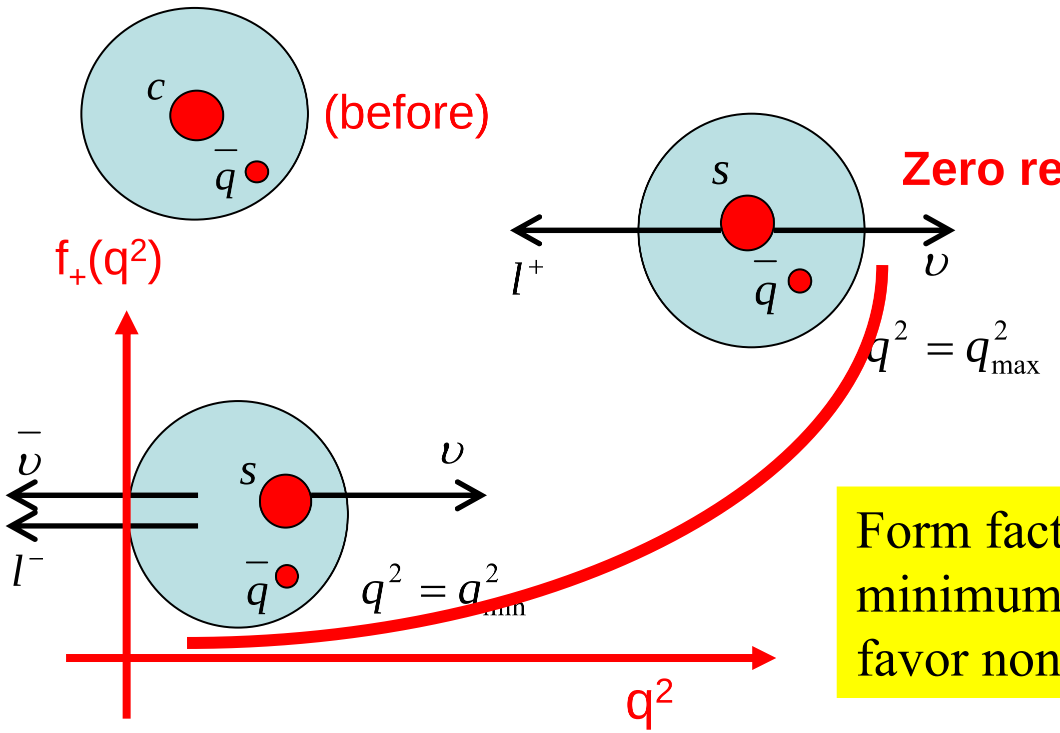
Precise measurement of $|V_{cx}|^2 \times f_+(q^2)$, get Vcx from CKM unitarity to extract form factor as test of Lattice QCD- or reverse the logic and test of CKM unitarity.

Two Key Kinematic Configurations

J. Richman and Burchat , Rev. of Mod. Phys. 67, 893-976(1995)

$$\frac{d\Gamma}{dq^2}(D \to Pl^+\nu) = \frac{G_F^2}{24\pi^3}|V_{cq}|^2 P_X^3 |F_+(q^2)|^2$$



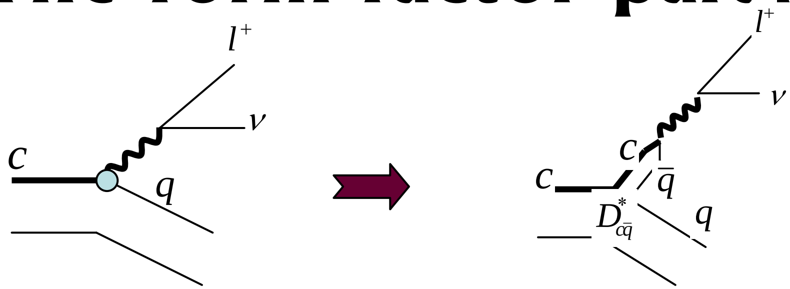


Form factor maximum, easy to form meson

Form factor minimum, favor nonresonant

Form factor describes the probability to form a meson in the final state.

The form factor parameterizations



- Pole ansatz:

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

  - dominated by lowest lying vector meson H* with correct flavor
  - e.g. D* for D→π
  - D_s^* for D→K
- Modified pole:

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

Becirevic & Kaidalov PLB 478, 417 (2000)

- Analyticity expansions:

Becher & Hill PLB 633, 61 (2006)

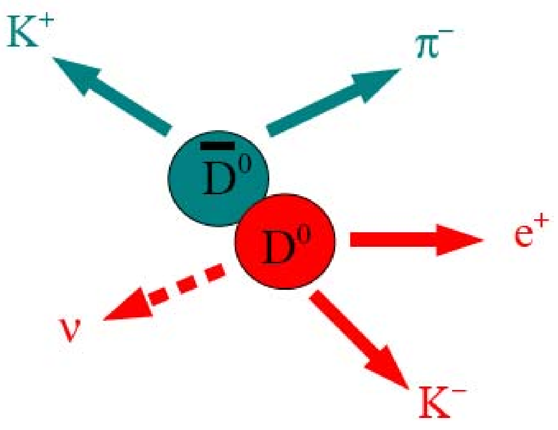
$$f_+(q^2)=\frac{1}{P(q^2)\phi(q^2,t_0)}\sum_{k=0}^{\infty}a_k(t_0)\left[z(q^2,t_0)\right]^k$$

  - expand in z around t_0
  - better convergence
  - 2 or 3 parameters

$$z(q^2,t_0)=\frac{\sqrt{t_+-q^2}-\sqrt{t_+-t_0}}{\sqrt{t_+-q^2}+\sqrt{t_+-t_0}}$$

$$t_\pm=(m_D\pm m_X)^2$$

Analysis Overview



- Tag hadronic $\bar{D}$ decay in "golden" modes :

$\bar{D}^0 \to K^+\pi^-$
$\bar{D}^0 \to K^+\pi^-\pi^0$
$\bar{D}^0 \to K^+\pi^-\pi^-\pi^+$

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

$$\Delta E = E_{\rm tag} - E_{\rm beam}$$

$$M_{\rm bc} = \sqrt{E_{\rm beam}^2 - p_{\rm tag}^2}$$

- Cut on ΔE and fit $M_{\rm bc}$ to extract tag yield $N_{\rm tag}$

- Identify semileptonic D decay with

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

- Fit U to extract signal yield N

$$E_{miss} = E_{beam} - E_K - E_e$$

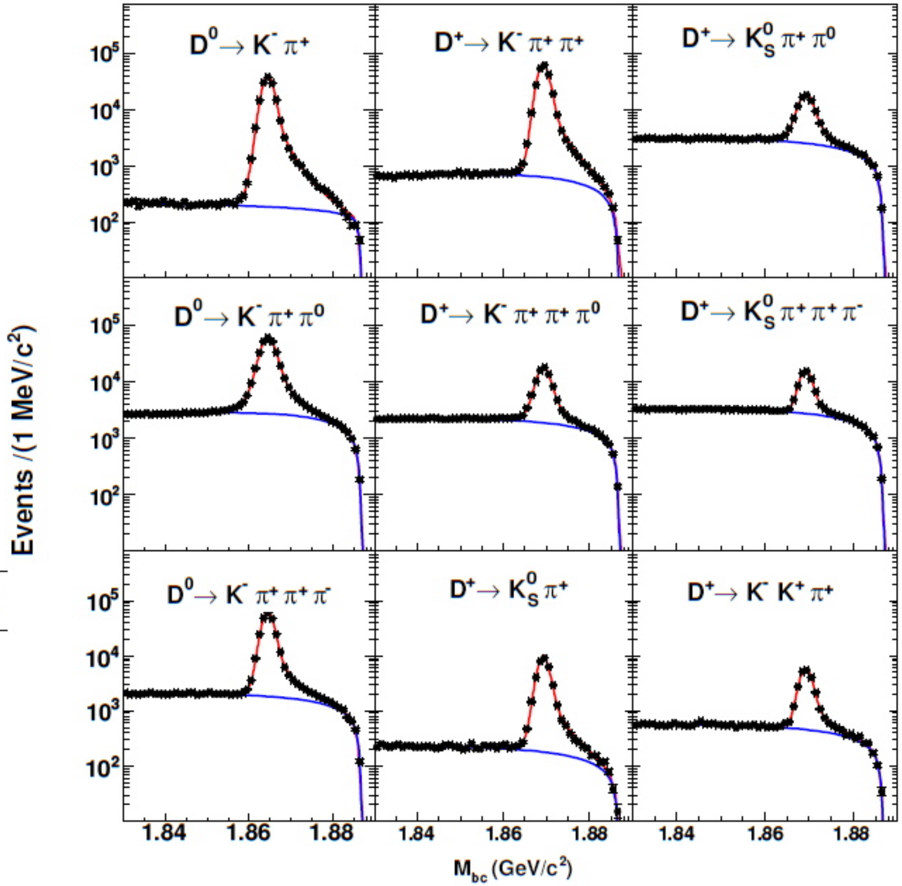
$$\vec{p}_{miss} = -\sqrt{E_{beam}^2 - m_D^2}\,\hat{p}_D - \vec{p}_K - \vec{p}_e$$

Counting *D* Tags

- Unbinned likelihood fit to data for D tag yields and MC for tagging efficiencies.

CLEO PRD80, 032005(2009)
818 pb-1

Mode	Yield	Efficiency(%)
$\bar{D}^0 \to K^+\pi^-$	149616 ± 392	65.32
$\bar{D}^0 \to K^+\pi^-\pi^0$	284617 ± 589	35.15
$\bar{D}^0 \to K^+\pi^-\pi^-\pi^+$	227536 ± 517	45.55
$D^- \to K^+\pi^-\pi^-$	233670 ± 497	55.42
$D^- \to K^+\pi^-\pi^-\pi^0$	69798 ± 330	27.39
$D^- \to K^0_S\pi^-$	33870 ± 194	51.10
$D^- \to K^0_S\pi^-\pi^0$	74842 ± 357	28.74
$D^- \to K^0_S\pi^-\pi^-\pi^+$	49117 ± 323	43.58
$D^- \to K^+K^-\pi^-$	19926 ± 171	42.07



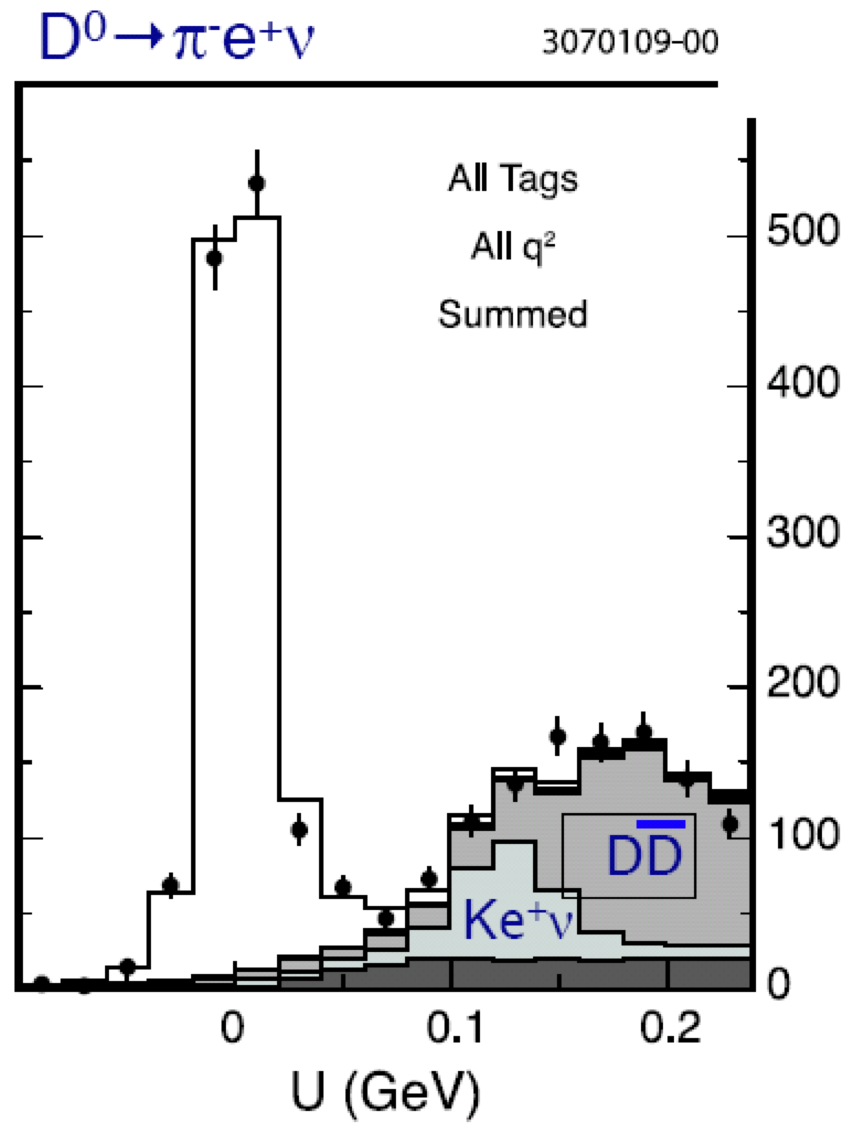
PRD 80 032005 (2009)
CLEO-c 818 pb^{-1}

Signal Side Reconstruction

- Against the tagged D
  - pion candidate
    - with dE/dx and RICH
  - positron candidate
- Fit U for signal

$$U \equiv E_{miss} - |\mathbf{p}_{miss}|$$

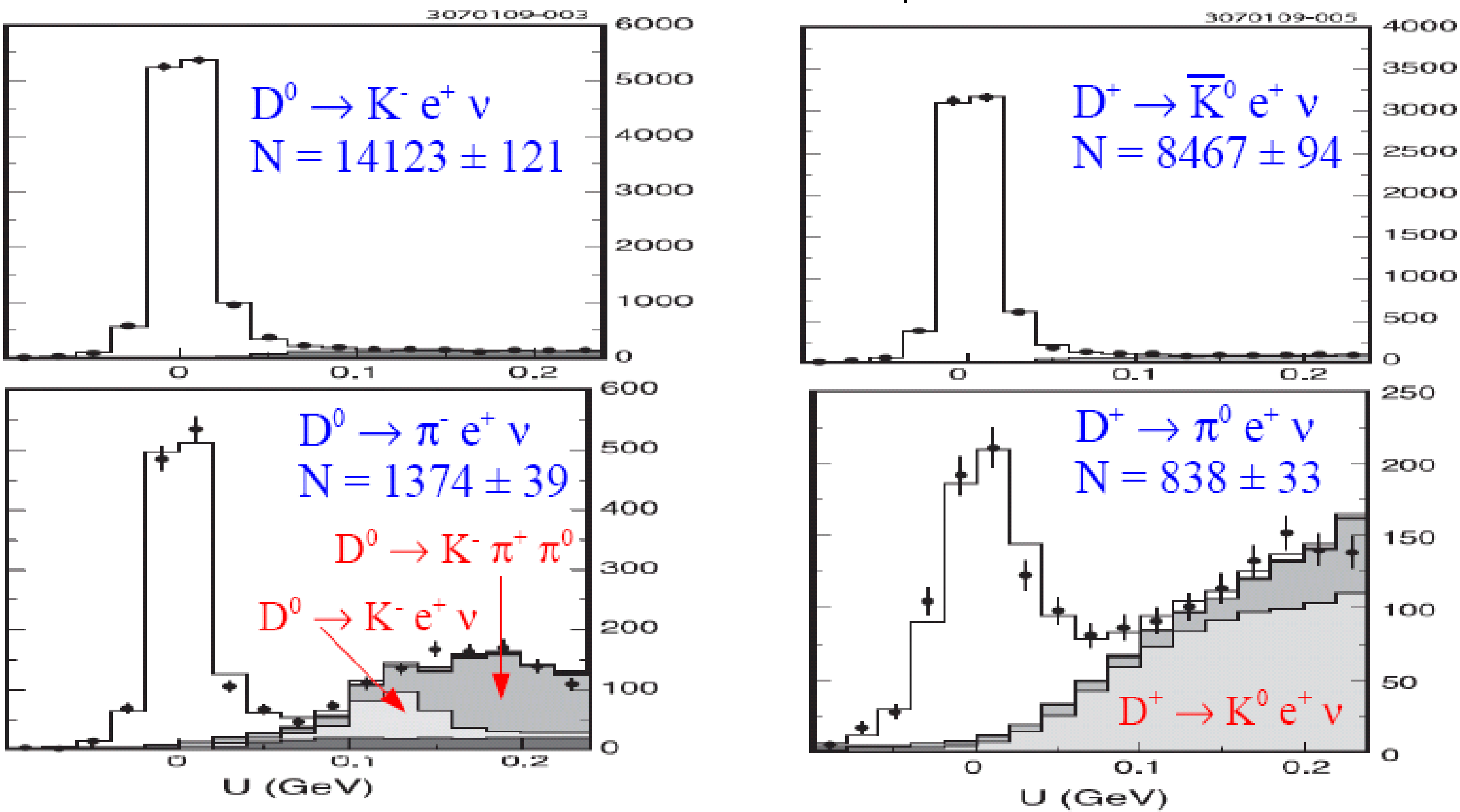
- Peaks at 0 for signal
  - kinematic separation for backgrounds
    - $Ke^+\nu$ cross feed to $\pi e^+\nu$
    - $\rho e^+\nu$ from known BF
- Fit four modes in q^2 bins



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

Signal yields from Double tag

CLEO PRD80, 032005(2009)
818 pb-1



$$U = E_{miss} - c|\mathbf{P}_{miss}|$$

Branching Fraction Results

CLEO PRD80, 032005(2009
818 pb-1

$$\mathcal{B}\left(D^0 \to \pi^- e^+ \nu_e\right) = (0.288 \pm 0.008 \pm 0.003)\%,$$

$$\mathcal{B}\left(D^0 \to K^- e^+ \nu_e\right) = (3.50 \pm 0.03 \pm 0.04)\%,$$

$$\mathcal{B}\left(D^+ \to \pi^0 e^+ \nu_e\right) = (0.405 \pm 0.016 \pm 0.009)\%,$$

$$\mathcal{B}\left(D^+ \to \bar{K}^0 e^+ \nu_e\right) = (8.83 \pm 0.10 \pm 0.20)\%.$$

Kaon modes are systematics limited

Pion modes are statistics-limited. Without improvement, they become systematics limited at ~6 fb^{-1}

But, this is the integral and we'll need more statistics to nail the detailed shape of the distribution

- Make these yield measurements and determine partial widths $\Delta\Gamma_i$ in bins of $q^2 = \left(E_\nu + E_e\right)^2 - \left|\vec{p}_\nu + \vec{p}_e\right|^2$
  - 7 q^2 bins for $D \to \pi e \nu$ and 9 for $D \to K e \nu$

Inverted Signal Efficiency Matrix

Signal Yields

$$\Delta\Gamma_i = \int_{q^2_{low,i}}^{q^2_{high,i}} \frac{d\Gamma(D \to Pe\nu)}{dq^2} dq^2 = \frac{\sum_j \epsilon_{ij}^{-1} N_j}{\tau_D N_{tag}/\epsilon_{tag}}$$

Tag Yield

Tagging Efficiency

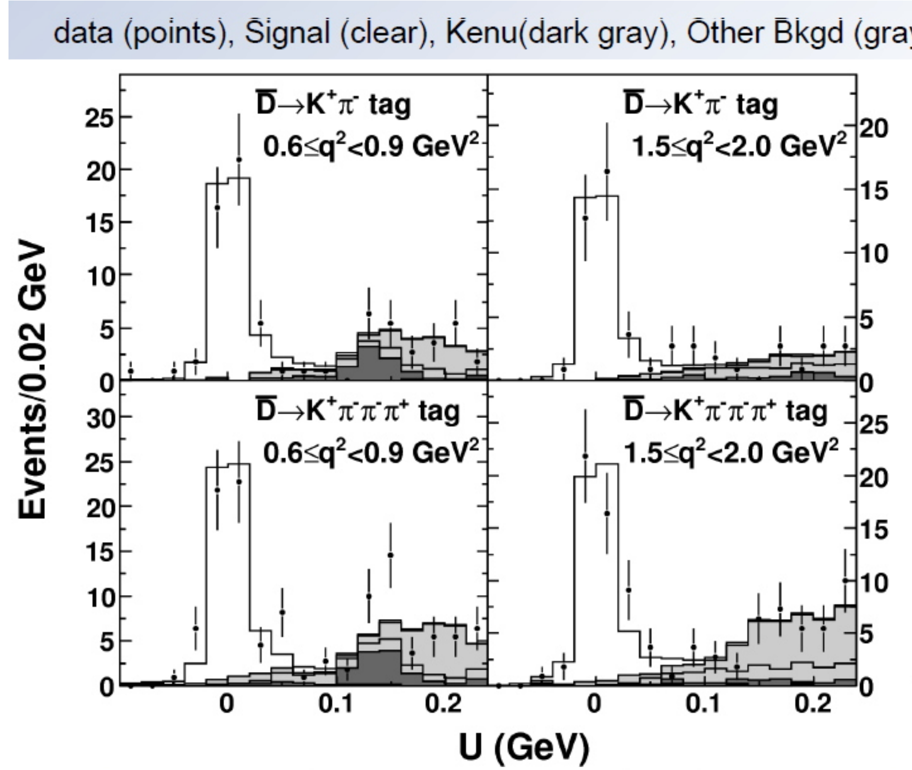
CLEO PRD80, 032005(2009)
818 pb-1

- Integrate for total width (BF) and fit for FF parameters

$$\frac{d\Gamma\left(D \to Pe\nu\right)}{dq^2} = \frac{G_F^2 p^3}{24\pi^3} \left|V_{cq}\right|^2 \left|f_+\left(q^2\right)\right|^2$$

Counting Semileptonic Decays in each q^2 bin

- Unbinned likelihood fit of U distributions separately by q^2 bin and tag mode.
  - Signal (smeared by 5-13 MeV Gaussian to match data) and BG shapes from MC
  - Free parameters for signal normalization and $D\bar{D}$ BG. Non- $D\bar{D}$ fixed by luminosity



$D^0 \to \pi^+ e\nu$ - 4 of 21 fits

CLEO PRD80, 032005(2009)
818 pb-1

Signal Efficiencies

$$\Delta\Gamma_i = \int_{q^2_{low,i}}^{q^2_{high,i}} \frac{d\Gamma(D\to Pe\nu)}{dq^2}\, dq^2 = \frac{\sum_j \epsilon_{ij}^{-1} N_j}{\tau_D N_{tag}/\epsilon_{tag}}$$

Inverted Signal Efficiency Matrix

Signal Yields

Tag Yield

Tagging Efficiency

$$e_{ij} = \frac{N(\text{Reconstructed in } i, \text{ Generated in } j)}{N(\text{Generated in } j)}$$

CLEO PRD80, 032005(2009)
818 pb-1

Generated Bin →
Reconstructed Bin ↓

0.420	0.012	0.000	0.000	0.000	0.000	0.000
0.007	0.430	0.015	0.000	0.000	0.000	0.000
0.001	0.008	0.448	0.014	0.000	0.000	0.000
0.000	0.001	0.012	0.457	0.014	0.000	0.000
0.000	0.001	0.001	0.012	0.464	0.009	0.000
0.000	0.000	0.001	0.001	0.011	0.469	0.007
0.000	0.000	0.000	0.000	0.000	0.007	0.469

πeν/Kπ Signal Efficiency Matrix

- Nonzero off-diagonal elements ⇒ correlation across q^2 in $\Delta\Gamma_I$ measurements

Partial Rate Results

CLEO PRD80, 032005(2009)
818 pb-1

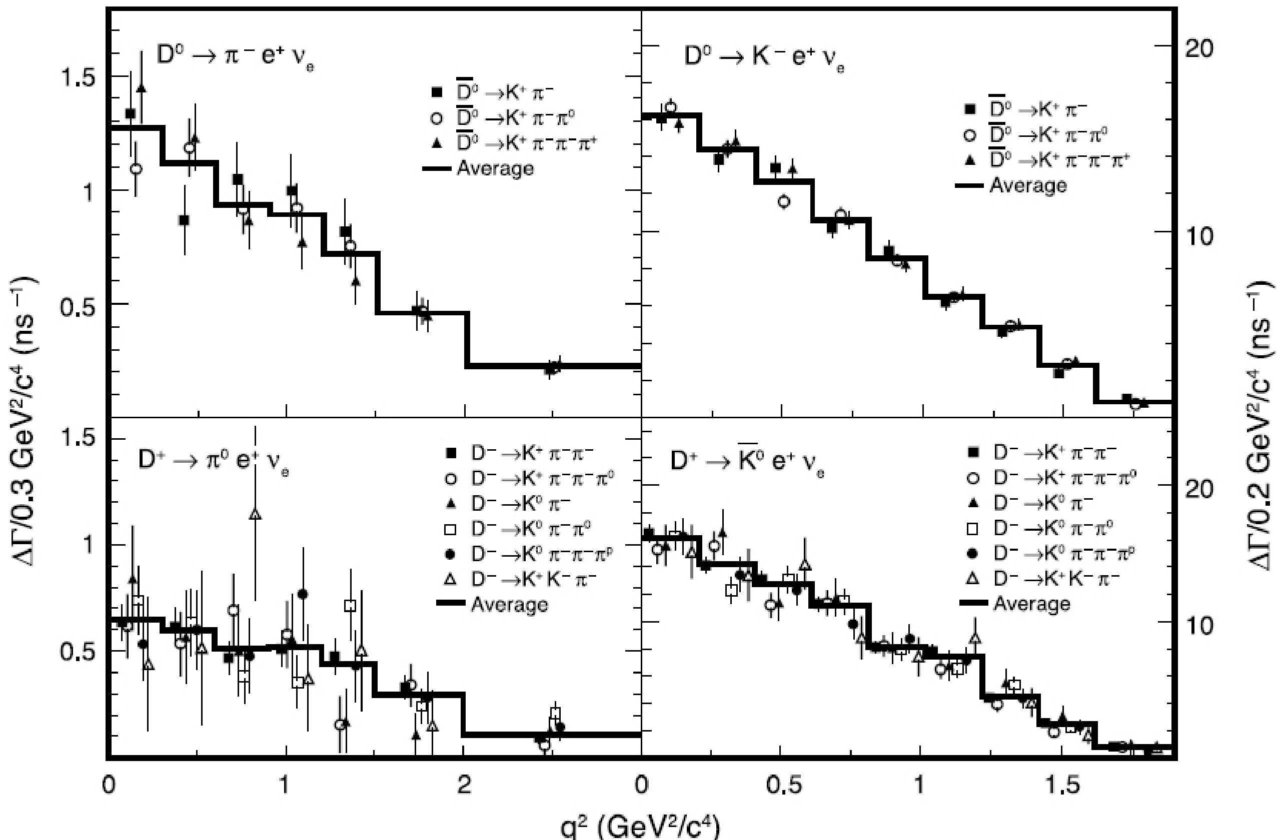
Inverted Signal Efficiency Matrix

Signal Yields

$$\Delta\Gamma_i = \int_{q^2_{low,i}}^{q^2_{high,i}} \frac{d\Gamma(D\to P e\nu)}{dq^2}dq^2 = \frac{\sum_j \epsilon_{ij}^{-1} N_j}{\tau_D N_{tag}/\epsilon_{tag}}$$

Tag Yield

Tagging Efficiency

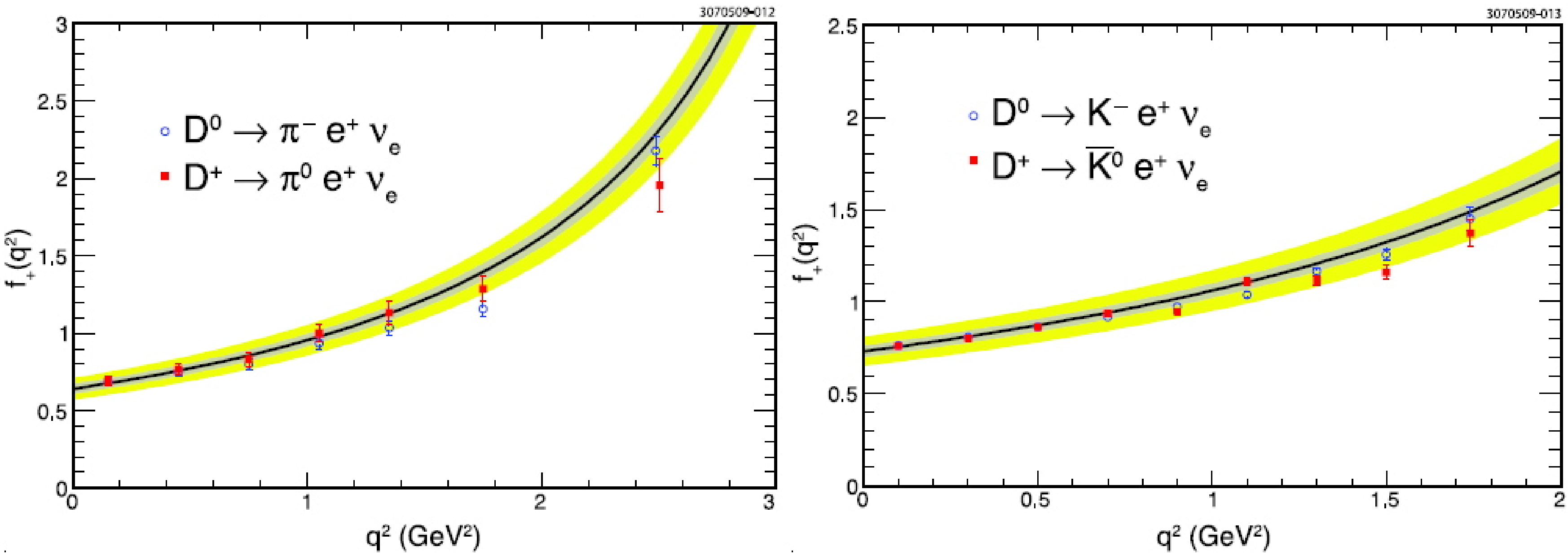


- Averaged over tag modes; verified to be consistent
- Consistent with isospin symmetry

Form Factor Tests

CLEO PRD80, 032005(2009)
818 pb-1

$$\frac{d\Gamma\left(D\to Pev\right)}{dq^2}=\frac{G_F^2 p^3}{24\pi^3}\left|V_{cq}\right|^2\left|f_+\left(q^2\right)\right|^2$$



- More data, better understood data, can have significant impact on these tests, especially at high q^2
- At BESIII, 2.9 fb^{-1} is just the start (but a good start)

$D \to K/\pi e\nu$ results from CLEO-c

PRD 80, 032005 (2009)

With 818 pb^{-1} $\psi(3770)$ data, CLEO has measured

$$f_+^{\pi}(0)\,|V_{cd}| = 0.150 \pm 0.004\ (\text{stat}) \pm 0.001\ (\text{syst})$$

$$f_+^{K}(0)\,|V_{cs}| = 0.719 \pm 0.006\ (\text{stat}) \pm 0.005\ (\text{syst})$$

using the series parameterization form factor model with three parameters

Using LQCD: $f_+^{\pi}(0) = 0.64(3)(6)$ $f_+^{K}(0) = 0.73(3)(7)$

$$|V_{cd}| = 0.234 \pm 0.007 \pm 0.002 \pm 0.025$$

$$|V_{cs}| = 0.985 \pm 0.009 \pm 0.006 \pm 0.103$$

stat syst LQCD

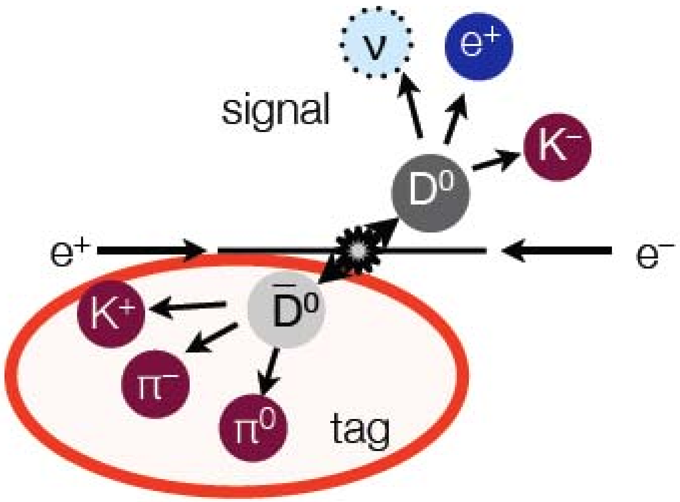
PDG: $|V_{cd}| = 0.230 \pm 0.011$ (neutrino beam)

$|V_{cs}| = 1.04 \pm 0.06$ $(D_S^+ \to \mu^+, \tau^+ \nu;\ D \to K\, \ell^+ \nu)$

Most precise measurements of $|V_{cd}|$ & $|V_{cs}|$ using semileptonic decays

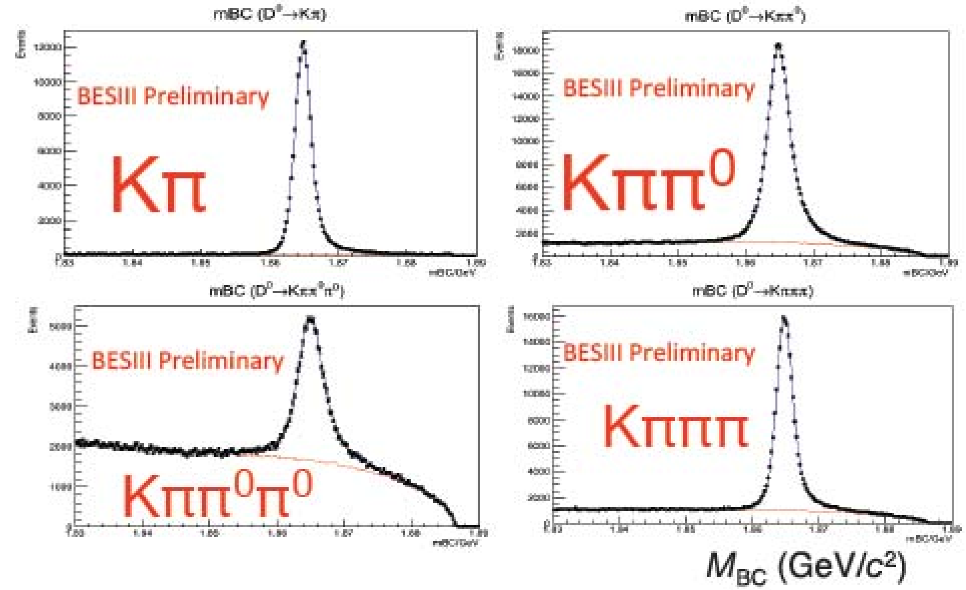
$D^0 \to \{K,\pi\}\, e^+ \nu$ new BES III result

BES III 2012 (prelim)



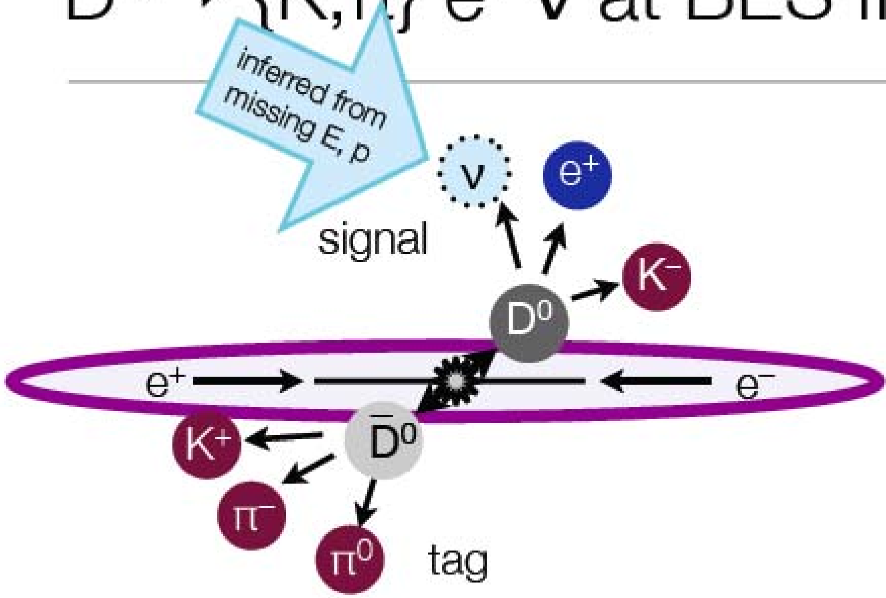
- Step 1: Reconstruct ~3/4 M tag D (provides normalisation)

beam-constrained mass of tag D

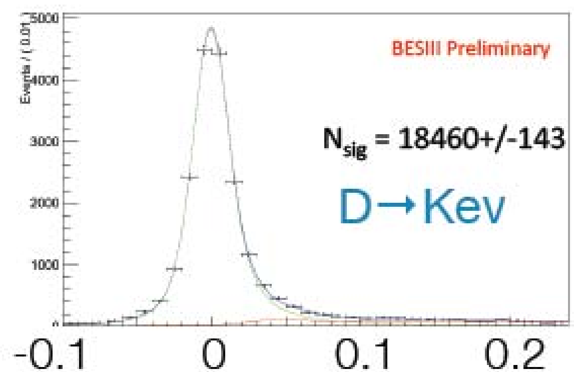


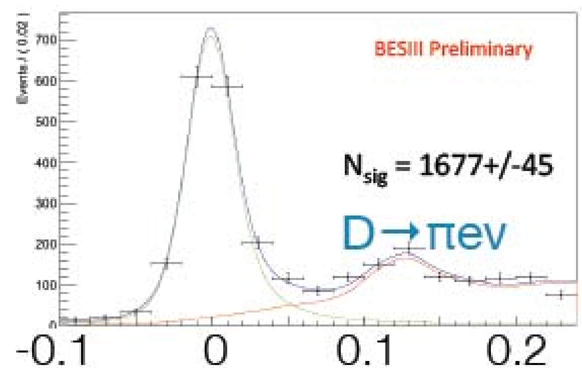
BES III: CHARM 2012 by Chunlei Liu

$D^0 \to \{K,\pi\}\, e^+ \nu$ at BES III



$$U \equiv E_{\rm miss} - |\vec{p}_{\rm miss}| \;\; \text{(GeV)}$$





- Step 1: Reconstruct Tag D
- Step 2: Find U (~ missing mass) from beam constraint and e and η, η', φ.

BES III: CHARM 2012 by Chunlei Liu

$D^0 \rightarrow \{K,\pi\}\ e^+ \nu$ Branching Fractions

BES III 2012 (prelim)

BESIII Preliminary

BES III prelim (0.9/fb)

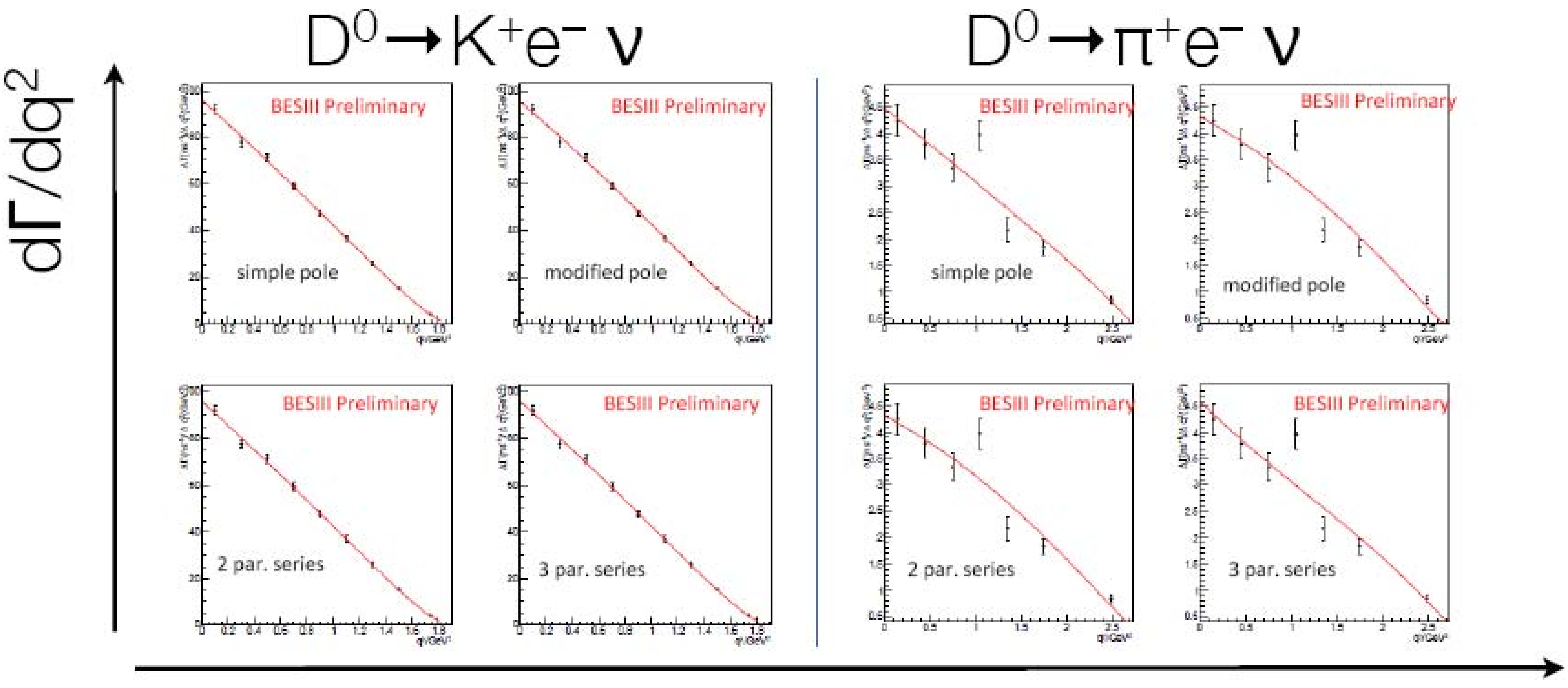
Mode	measured branching fraction(%)	PDG	CLEOc
$\bar{D}^0 \rightarrow K^+ e^- \bar{\nu}$	3.542 ±0.030±0.067	3.55 ±0.04	3.50 ±0.03 ±0.04
$\bar{D}^0 \rightarrow \pi^+ e^- \bar{\nu}$	0.288 ±0.008±0.005	0.289 ±0.008	0.288 ±0.008±0.003

BES III: CHARM 2012 by Chunlei Liu

$D^0 \to \{K,\pi\}\, e^+ \nu$ fits to decay rates

BES III 2012 (prelim)

$d\Gamma/dq^2$: BES III data with fits using different form factor models



q^2/GeV^2

BES III: CHARM 2012 by Chunlei Liu

BES III form factor fit results

BES III 2012 (prelim)

BESIII Preliminary

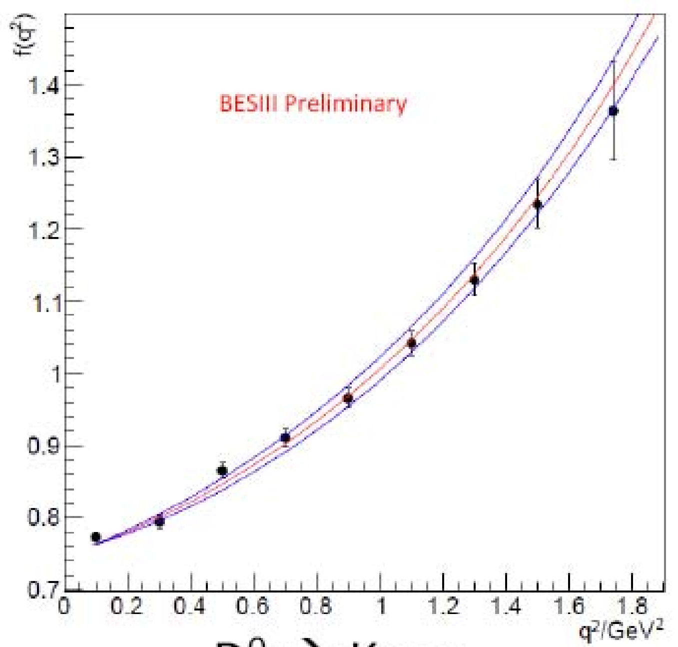
Simple Pole	$f_+(0)\|V_{cd(s)}\|$	m_{pole}	
$D^0 \to Ke\nu$	$0.729\pm0.005\pm0.007$	$1.943\pm0.025\pm0.003$	
$D^0 \to \pi e\nu$	$0.142\pm0.003\pm0.001$	$1.876\pm0.023\pm0.004$	
Modified Pole	$f_+(0)\|V_{cd(s)}\|$	α	
$D^0 \to Ke\nu$	$0.725\pm0.006\pm0.007$	$0.265\pm0.045\pm0.006$	
$D^0 \to \pi e\nu$	$0.140\pm0.003\pm0.002$	$0.315\pm0.071\pm0.012$	
2 par. series	$f_+(0)\|V_{cd(s)}\|$	r_1	
$D^0 \to Ke\nu$	$0.726\pm0.006\pm0.007$	$-2.034\pm0.196\pm0.022$	
$D^0 \to \pi e\nu$	$0.140\pm0.004\pm0.002$	$-2.117\pm0.163\pm0.027$	
3 par. series	$f_+(0)\|V_{cd(s)}\|$	r_1	r_2
$D^0 \to Ke\nu$	$0.729\pm0.008\pm0.007$	$-2.179\pm0.355\pm0.053$	$4.539\pm8.927\pm1.103$
$D^0 \to \pi e\nu$	$0.144\pm0.005\pm0.002$	$-2.728\pm0.482\pm0.076$	$4.194\pm3.122\pm0.448$

BES III: CHARM 2012 by Chunlei Liu

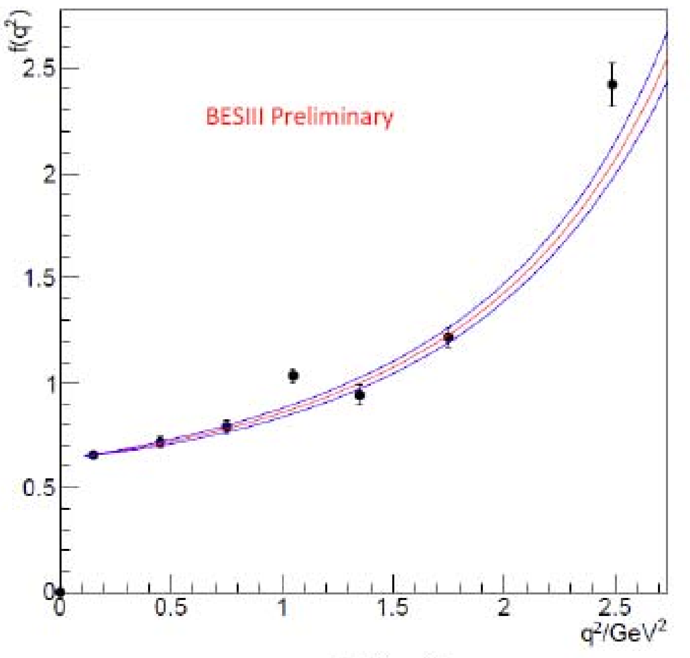
Form factor shapes: BES III / LQCD

BES III 2012 (prelim)
Fermilab/The Lattice/MILC 2011

note: these compare shape-only, no absolute scale.



$D^0 \rightarrow K e \nu$



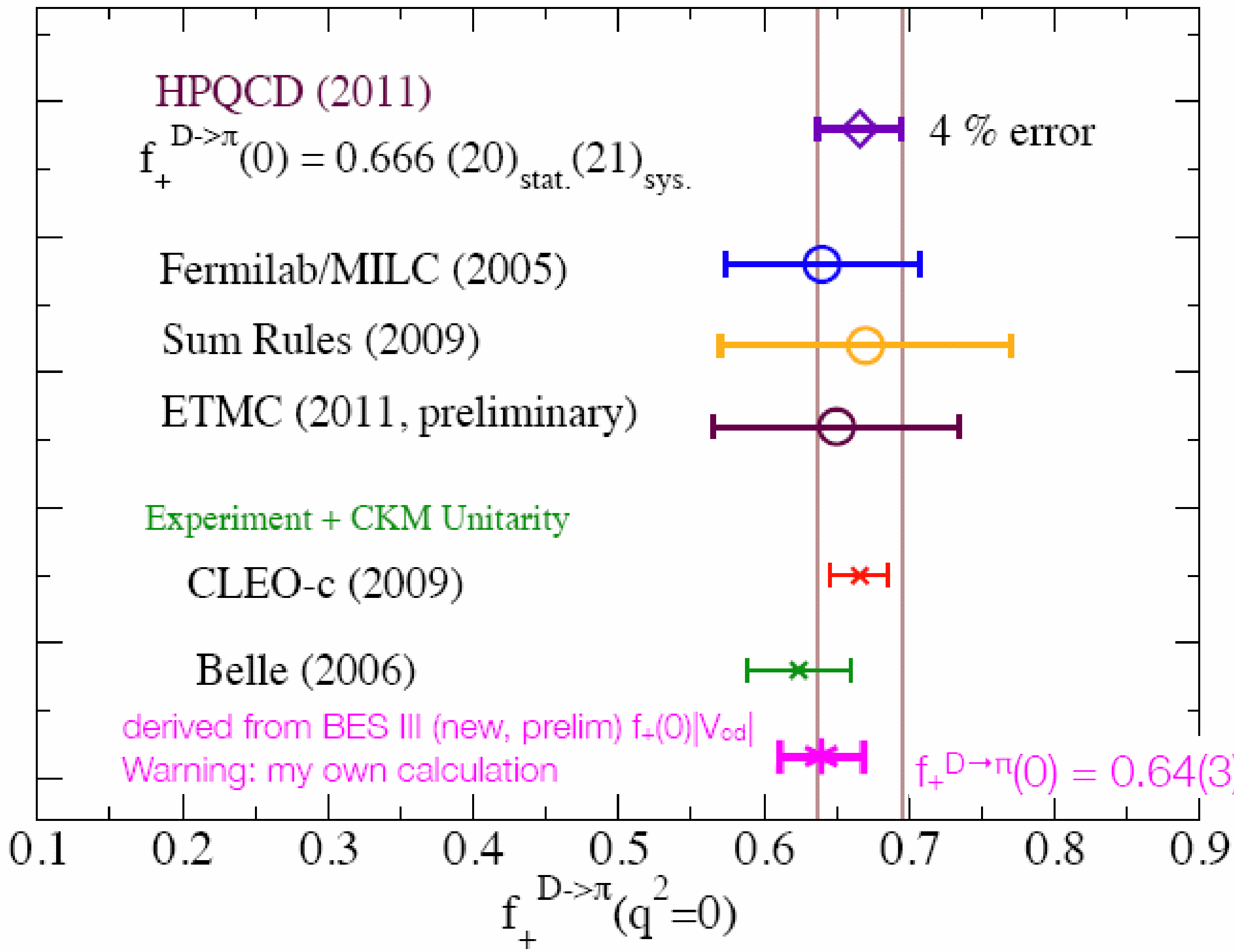
$D^0 \rightarrow \pi e \nu$

Points: BES III preliminary with stat errors
Curves: Fermilab/The Lattice/MILC with 1σ stat error band, arXiv:1111.5471 (Nov 2011)

BES III: CHARM 2012 by Chunlei Liu

$f_+^{D\to\pi}(0)$ from experiment and theory

Taken from Na, Davies, Follana, Koponen, Lepage and Shigemitsu, Phys.Rev. D84 (2011) 114505 and modified (added BES III)

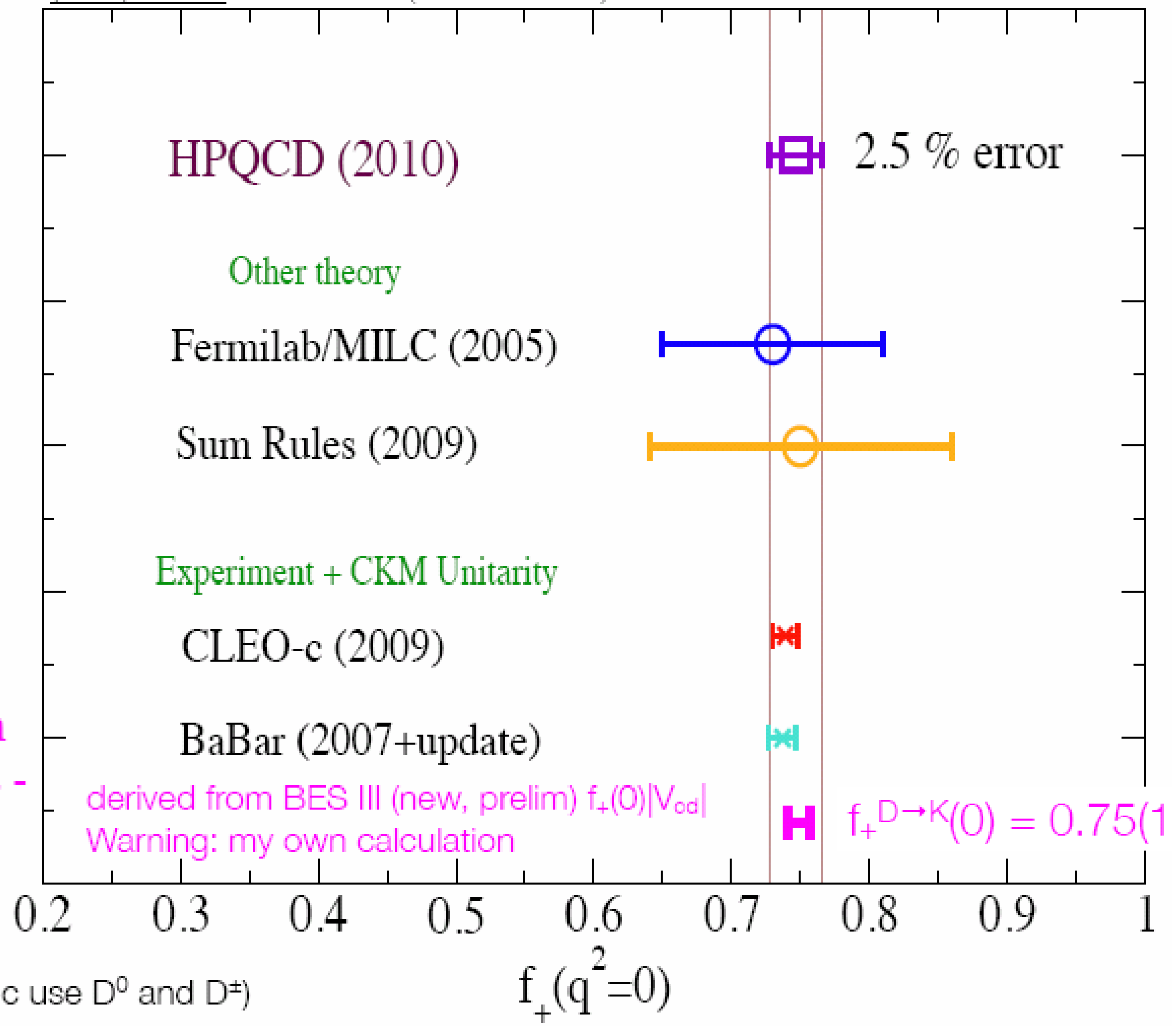


With $|V_{cd}| = 0.2252 \pm 0.0007$, I get from BES III new result (3 par series - as used by CLEO-c):

(note: BES III result from D^0 only, CLEO-c use D^0 and $D^\pm$)

$f_+^{D\to K}(0)$ from experiment and theory

Taken from Na, Davies, Follana, Koponen, Lepage and Shigemitsu, Phys.Rev. D82 (2010) 114506 and modified (added BES III)



With $|V_{cs}| = 0.97345$, I get from BES III new result (3 par series - as used by CLEO-c):

(note: BES III result from D^0 only, CLEO-c use D^0 and $D^\pm$)

$D^0 \to \pi l \nu,\ K l \nu$

PRL 97, 061804 (2006) 282 fb^{-1}

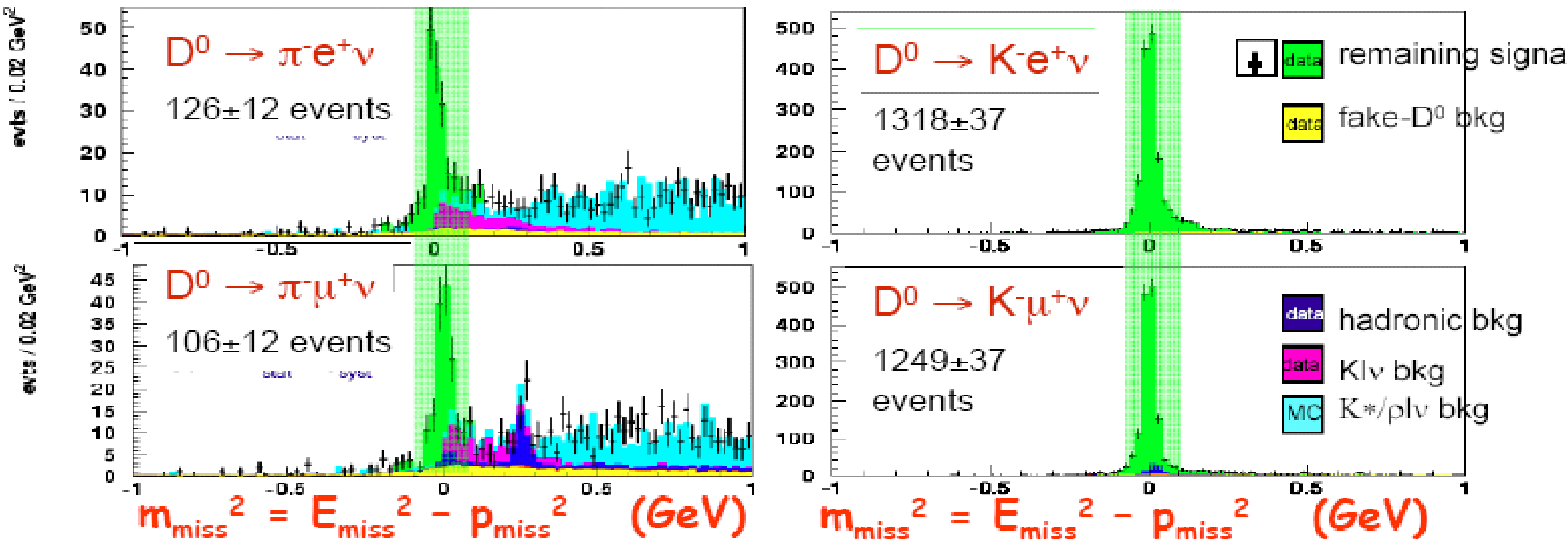
Use "Continuum tagging" again: $e^+e^- \to D^{(*)}_{tag}\ D^*_{signal}\ X$.

Reconstruct all particles (except for neutrino)

Tagging provides absolute normalization ~56,000 tagged D^0

Cabibbo suppressed

Cabibbo favored



Impressive results in difficult production environment

Both e and m measured, but only D^0

vs. CLEO-c: 1000x lumi, but ~3x less signal events & ~10x worse signal/noise

Belle $D^0 \to \pi^- \ell^+ \nu$ & $D^0 \to K^- \ell^+ \nu$

Excellent q^2 resolution:

$\sigma(q^2)=0.017\ GeV^2$

Measure rate directly in q^2 bins

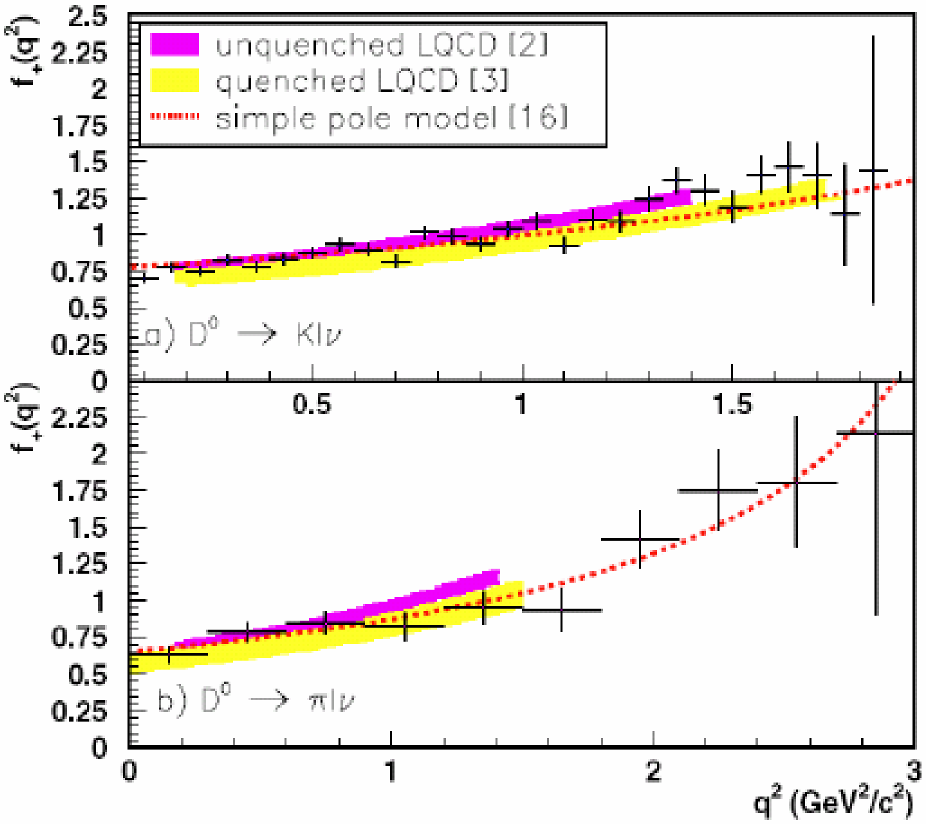
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cx}|^2 p_X^3 |f_+(q^2)|^2$$

Compare to

LQCD Form Factor

Simple Pole parameterization

Modified Pole Model



Lattice Form Factors

[2]Aubin et al. PRL 94, 011601 (2005)

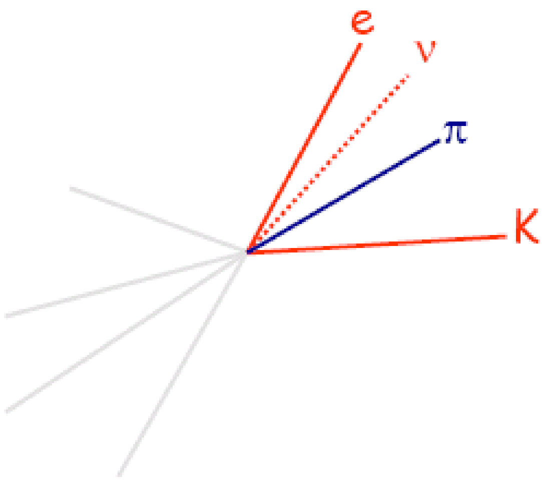
[3]Abada et al. Nucl. Phys. B619, 565 (2001)

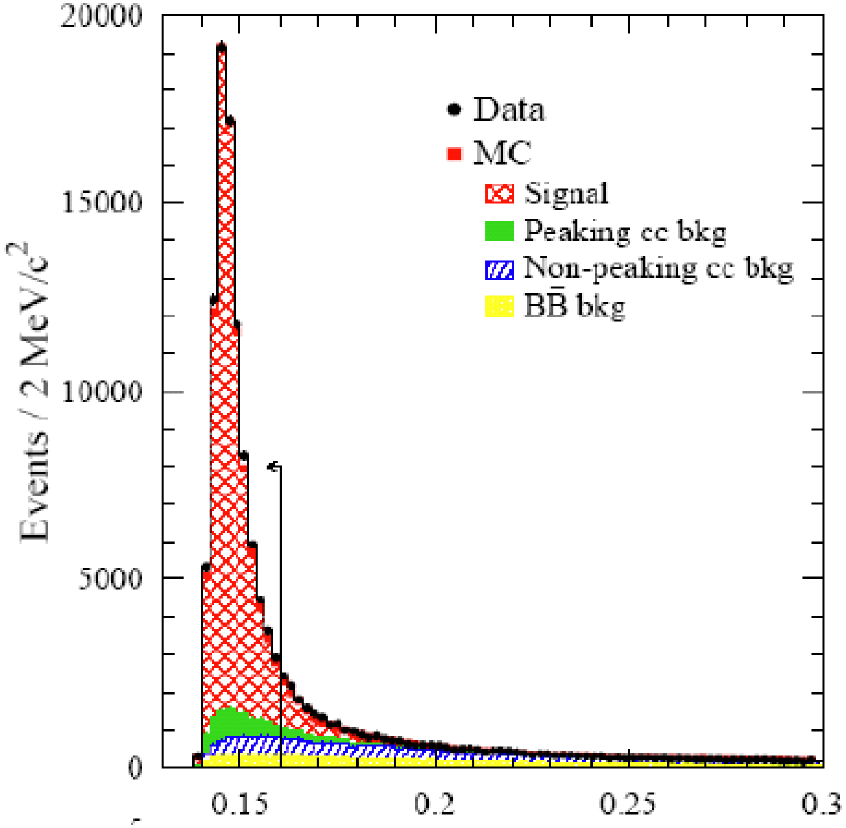
PRD 76 052005 (2007)
75 fb^{-1}

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

$e^+e^- \to c\bar{c}$ at $\sqrt{s}$=10.6 GeV

- Reconstruct $D^{*+} \to \pi^+ D^0$ and signal $D^0 \to Ke\nu$
- Estimate p_D and E_ν with remaining event & kinematic fits
- Use Neural Nets to suppress backgrounds



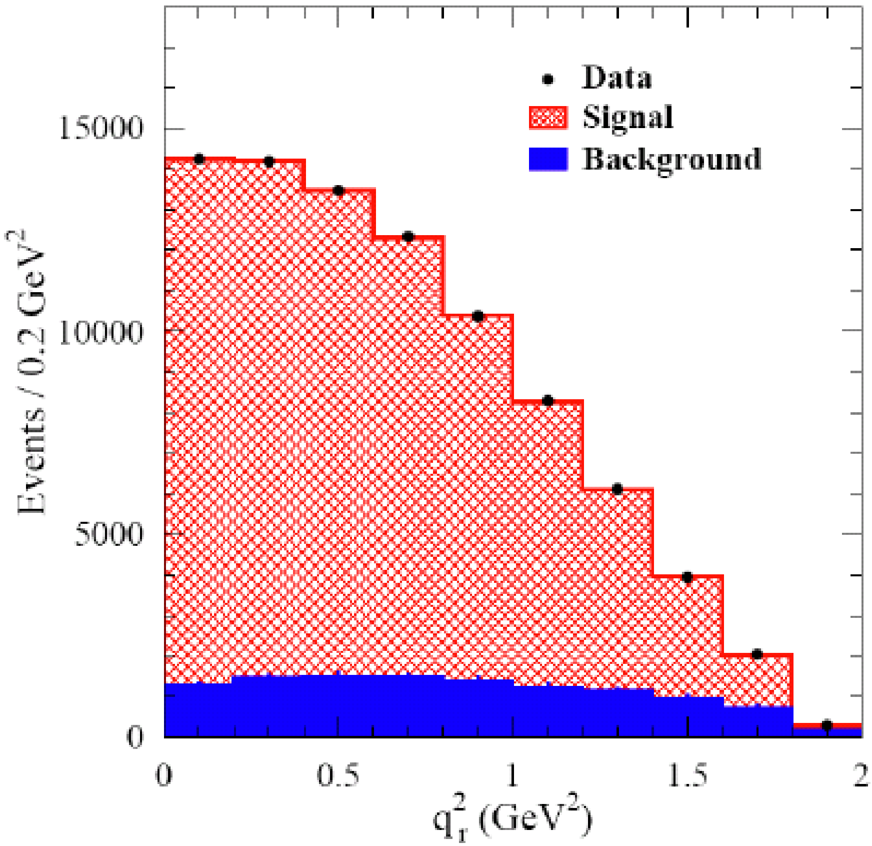


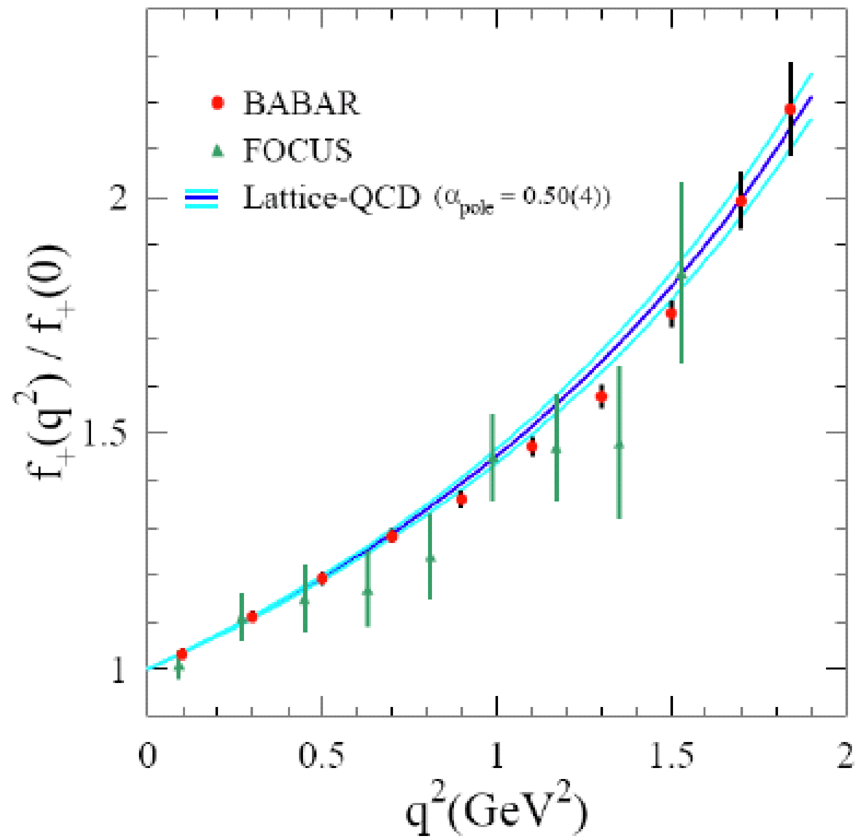
δm=M(D*)-M(D)

- high statistics: ~74,000
- good S/N

PRD 76 052005 (2007)
75 fb[-1]

BaBar $f_+(q^2)$ $D^0 \to K^- e^+ \nu$





$$q^2 = (p_D - p_X)^2$$

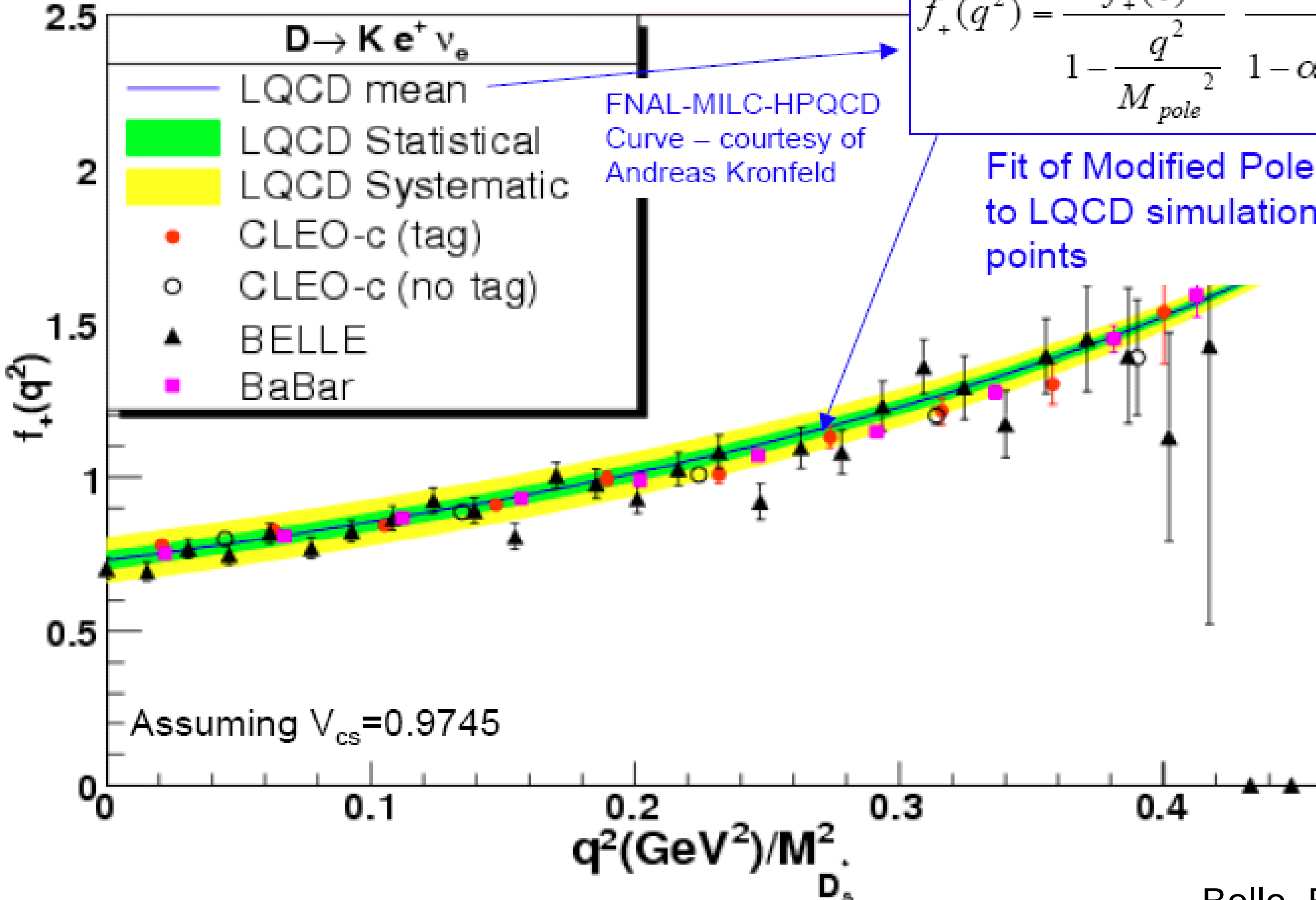
85k signal/11k background

- Corrected spectrum compared to LQCD[1], FOCUS[2]

[1] Aubin et al. PRL 94, 011601 (2005)

[2] PLB607, 233 (2005)

D → Kev Form Factor vs. LQCD



$$f_+(q^2) = \frac{f_+(0)}{1-\dfrac{q^2}{M_{pole}^2}} \; \frac{1}{1-\alpha\dfrac{q^2}{M_{pole}^2}}$$

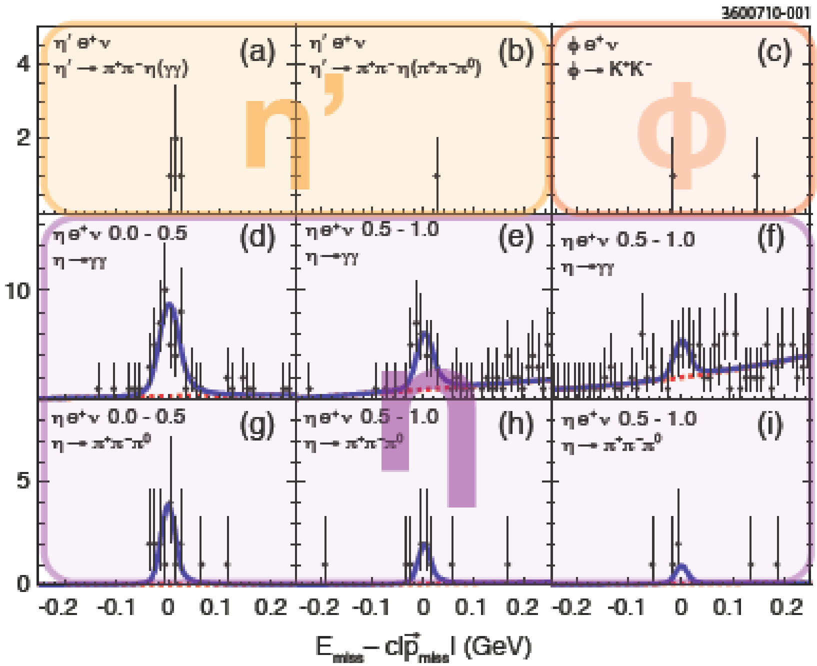
Fit of Modified Pole Model to LQCD simulation points

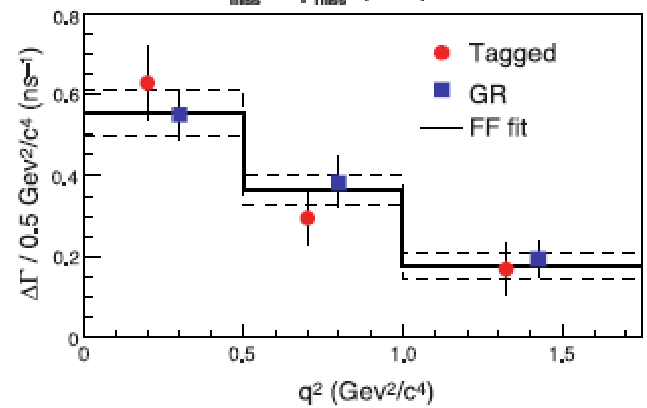
Belle, BABAR

$D \to \{\eta, \eta' \text{ or } \phi\}\, e\nu$, (CLEO-c: 818 pb^{-1})

- CLEO: Phys.Rev. D84 (2011) 032001
- Tag side
  - Fully reconstructed D
  - 6 decay modes
  - # of tags: 481K
- Signal side
  - Kinematic variable: $\mathbf{U}_{\mathbf{miss}}$
- Generic reconstruction method
  - No full reconstruction on Tag side
  - Adds up all momenta & energies in the event to identify ν
  - Fully reconstruct η, π^0 and Ks $\Rightarrow$ suppress background
- Combined results (Dorminated by "Generic recon method")
  - Br($D \to \eta' e\nu$)=(2.16±0.53±0.07) x10^{-4} (First observation, 5.8σ)
  - Br($D \to \eta e\nu$)=(11.4±0.9±0.4) x10^{-4}
  - Br($D \to \phi e\nu$)< 0.9x10^{-4} (@90% C.L.)

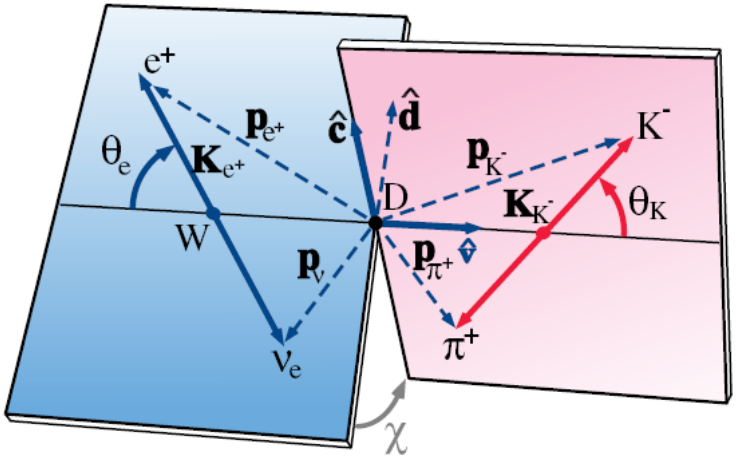
$$U \equiv E_{\rm miss} - |\vec{p}_{\rm miss}|$$





$$f_+(0)\,|V_{cd}| = 0.086\,(6)_{\rm (stat)}(1)_{\rm (sys)}$$

$D \to V\, l\, \nu$



- Kinematics ($K^* \to K\pi$ as Vector decay example): 5 degree of freedom (m^2 in K^* system, q^2 in $l\nu$ system, $\cos(\theta_K)$, $\cos(\theta_e)$ and χ
- For massless l (e: good approximation), need 3 form factors: 2 axial and 1 vector. Usually parameterized with simple pole.
- Usually measure $\mathbf{r_V}$ **and** $\mathbf{r_A}$
- Combined with $D \to \rho e\nu$, $D \to K^* e\nu$ and $B \to V\, l^+ l^-$, to extract $|V_{ub}|$ from $B \to \rho e\nu$ (PRD 70, 114005 (2004))
- Measure $D \to \{K\pi$ -S wave$\}e\nu$ component (first observed by FOCUS, PLB535 (2002) 43-51)

Simple pole parameterization:

$$V(q^2) = \frac{V(0)}{1 - \frac{q^2}{m_V^2}},$$

$$A_1(q^2) = \frac{A_1(0)}{1 - \frac{q^2}{m_A^2}},$$

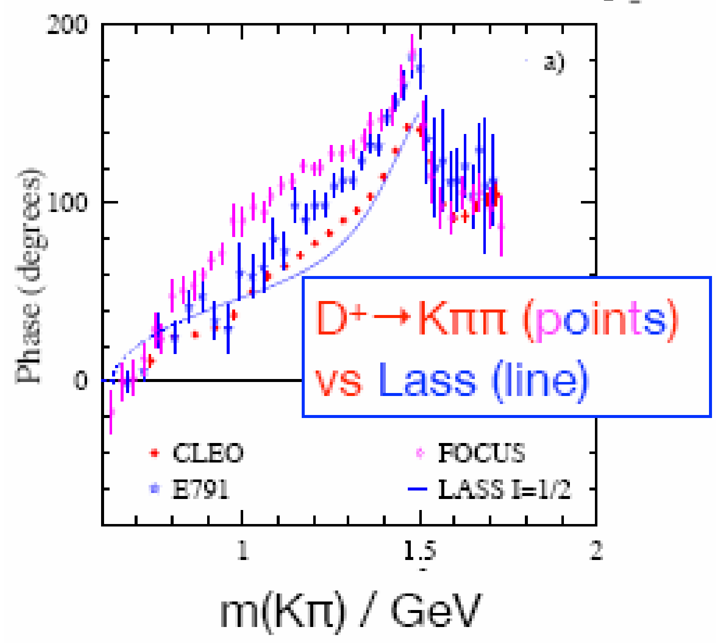
$$A_2(q^2) = \frac{A_2(0)}{1 - \frac{q^2}{m_A^2}},$$

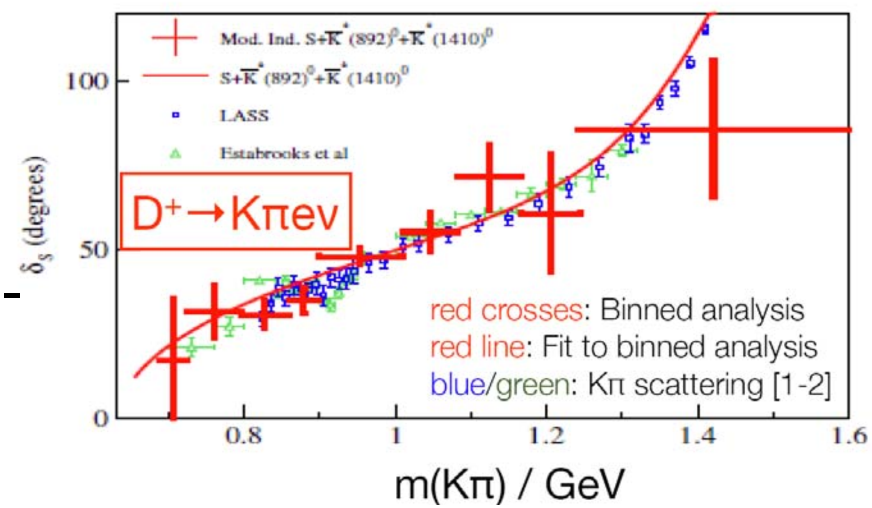
$$r_V \equiv \frac{V(0)}{A_1(0)}$$

$$r_A \equiv \frac{A_2(0)}{A_1(0)}$$

$D \to K^*(K\pi)e\nu$, (BaBar: 348 fb^{-1})

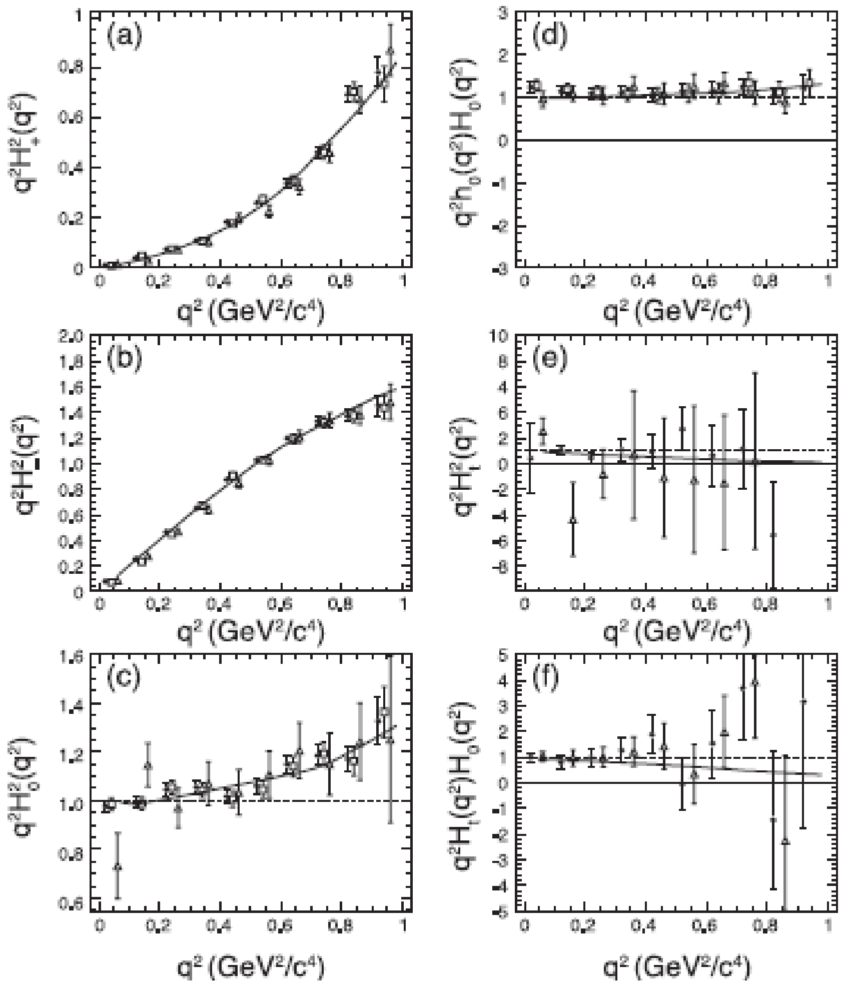
- Phys.Rev. D83 (2011) 072001
- Using 1/4 M tagged $D\to K\pi e\nu$ events, form factors of $D\to K^*e\nu$ were measured
  - m_A=2.63±0.10±0.13 GeV
    r_V=1.463±0.017±0.031
    r_A=0.801±0.020±0.020
- Performed detailed analysis of $K\pi$ S-wave ⇒ magnitude and phase δ_S
  - S-wave component was confirmed
- δ_S measurement (model-independent) agrees with scattering data (Lass and Estabrooks et al) better than the S-wave contributions measured in $D\to K\pi\pi$





$D \to K\pi\ e/\mu\ \nu$ (CLEO-c: 818 pb^{-1})

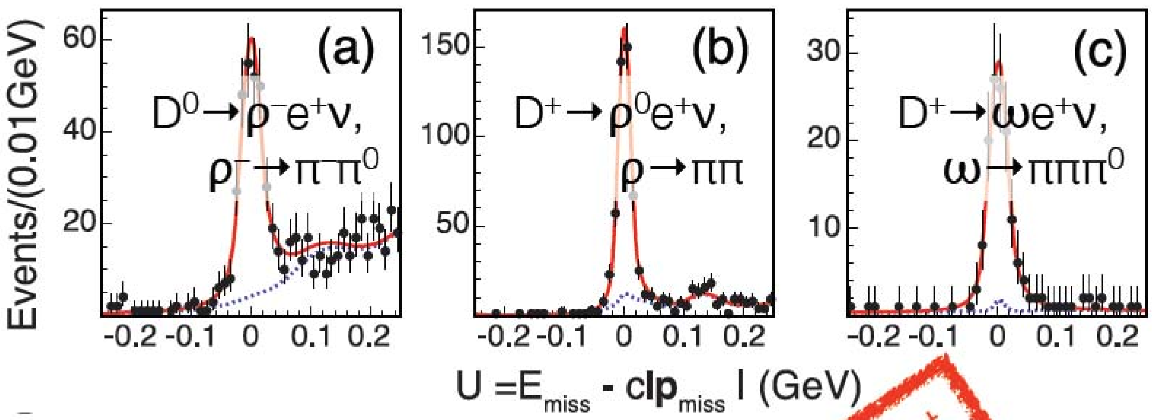
- Plots on left compare model-independent measurements with simple pole model - generally good agreement.
- Confirms evidence for S-wave.
- Cleo-c's analysis consideres highly-suppressed amplitudes with right-handed e/μ (adds a helicity, H_T, and a form factor, A_3)
- $H_T H_0$ interference less than LQCD prediction.

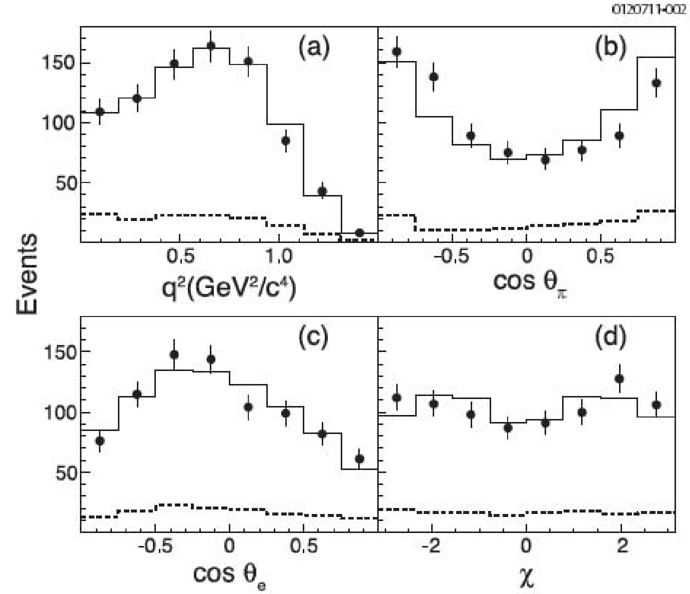


CLEO: Phys.Rev. D81 (2010) 112001

Form factors for $D^0 \to \rho^- e^+ \nu$, $D^+ \to \rho^0 e^+ \nu$

CLEO-c 2011





$$A_1(0) = 0.56 \pm 0.01^{+0.02}_{-0.03}$$

$$A_2(0) = 0.47 \pm 0.06 \pm 0.04$$

$$V(0) = 0.84 \pm 0.09^{+0.05}_{-0.06}.$$

First measurement.

Decay Mode	ϵ (%)	$N_{\text{tag, SL}}$	$\mathcal{B}_{\text{SL}}$	$\mathcal{B}_{\text{SL}}$(prev)	$\mathcal{B}_{\text{SL}}$(ISGW2)	$\mathcal{B}_{\text{SL}}$(FK)
$D^0 \to \rho^- e^+ \nu_e$	26.03 ± 0.02	304.6 ± 20.9	$1.77 \pm 0.12 \pm 0.10$	$1.94 \pm 0.39 \pm 0.13$	1.0	2.0
$D^+ \to \rho^0 e^+ \nu_e$	42.84 ± 0.03	447.4 ± 24.5	$2.17 \pm 0.12^{+0.12}_{-0.22}$	$2.1 \pm 0.4 \pm 0.1$	1.3	2.5
$D^+ \to \omega e^+ \nu_e$	14.67 ± 0.03	128.5 ± 12.6	$1.82 \pm 0.18 \pm 0.07$	$1.6^{+0.7}_{-0.6} \pm 0.1$	1.3	2.5

$$\frac{\Gamma(D^0 \to \rho^- e^+ \nu_e)}{2\Gamma(D^+ \to \rho^0 e^+ \nu_e)} = 1.03 \pm 0.09^{+0.08}_{-0.02}$$

CLEO: arXiv:1112.2884 [hep-ex] (Dec 2011)

CLEO-c: $D_s \to \phi e \nu$ and $f_0(980) e\nu$

CLEO-c performed a full form-factor analysis for $D_s \to \phi e\nu$ and $f_0(980)e\nu$ with $f_0(980) \to \pi^+\pi^-$ and $\phi \to K^+K^-$.

Suggestion that $B_s \to J/\psi\, f_0$ can be an alternative to $B_s \to J/\psi\, \phi$ to measure CP violation in the B_s system

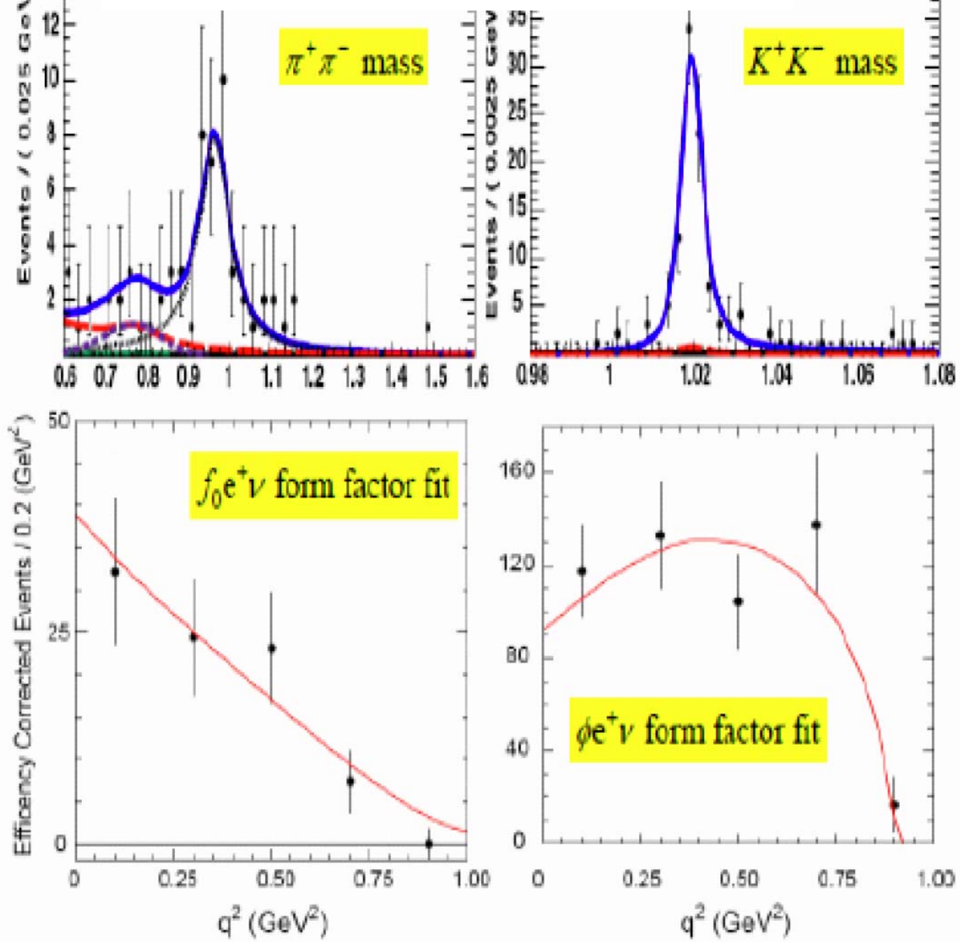
($J/\psi\, f_0$ is CP-state, no angular analysis)

Stone & Zhang [PRD 79, 074024 (2008)]

$$\left.\frac{\Gamma(D_s^+ \to f_0(980)e^+\nu, f_0 \to \pi^+\pi^-)}{\Gamma(D_s^+ \to \phi e^+\nu, \phi \to K^+K^-)}\right|_{q^2=0} = (42 \pm 11)\%$$

$$\left[\text{Predicted to equal } \frac{\Gamma(B_s \to J/\Psi f_0(980), f_0 \to \pi^+\pi^-)}{\Gamma(B_s \to J/\Psi \phi, \phi \to K^+K^-)}\right]$$

CLEO" PRD 80, 052009(2009)



LHC-b results:

$$\frac{\mathcal{B}\left(\overline{B}_s^0 \to J/\psi\pi^+\pi^-\right)}{\mathcal{B}\left(\overline{B}_s^0 \to J/\psi\phi\right)} = (21.28 \pm 0.51 \pm 0.56)\%$$

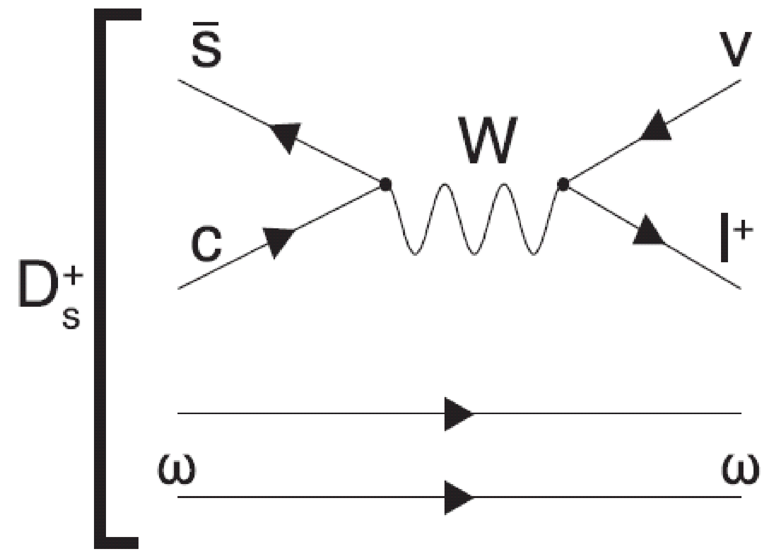
LHCb: arXiv:1204.5643 [hep-ex] (2012)

CLEO-c search for $D_s \to \omega e \nu$

CLEO-c 2011

- Highly suppressed. Potential processes (Gronau & Rosner Phys.Rev. D79 (2009) 074006):
  - Via ω-ϕ mixing (ω has $s\bar{s}$ component)? $BR < 2 \cdot 10^{-4}$
  - Via weak annihilation (radiate an ω in a non-perturbative process before annihilating)? $BR \sim (0.13 \pm 0.05)\%$
- Anything larger might hint at a **four-quark content** of the D_s (4-quark systems have been suggested to explain several exotic charmonium states).

$D_s \to \omega e \nu$ as a probe for a 4-quark contribution to the D_s



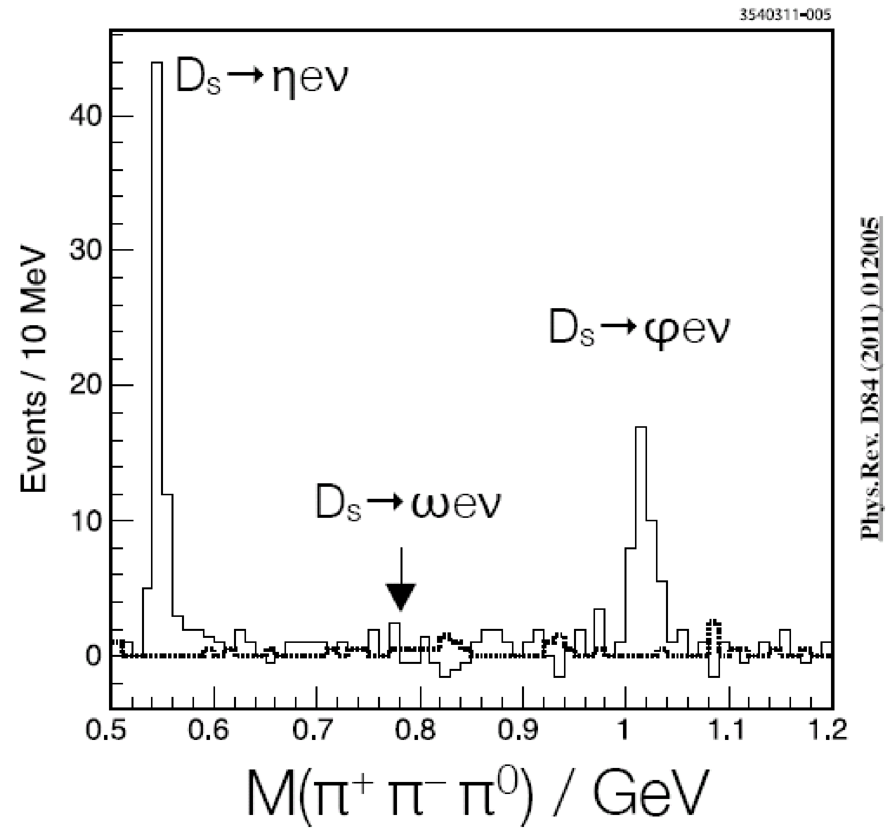
CLEO-c search for $D_s \to \omega e \nu$

CLEO-c 2011

- Analysis makes careful use of control channels $D_s \to \eta e \nu$ and $D_s \to \phi e \nu$.
- No evidence for $D_s \to \omega e \nu$.
- At 90% CL:

  $\mathcal{B}(D_s^+ \to \omega e^+ \nu) < 0.20\%$

  (compatible with Gronau & Rosner's estimate of (0.13 ± 0.05)%, no evidence of 4-quark content of D_s.)



(background subtracted)

CLEO: Phys.Rev. D84 (2011) 012005

Precise test of CKM and QCD in D decays at BESIII

Observable	CKM	QCD	Lattice	Exp meas	Exp err
$Br(D \to \ell\nu)$	$\|V_{cd}\|$	f_D	2%	$f_D\|V_{cd}\|$	1.1%
$Br(D_s \to \ell\nu)$	$\|V_{cs}\|$	f_{Ds}	1.5%	$f_{Ds}\|V_{cs}\|$	0.7%
$\frac{Br(D_s\to\ell\nu)}{Br(D\to\ell\nu)}$	$\left\|\frac{V_{cs}}{V_{cd}}\right\|$	$\frac{f_{Ds}}{f_D}$	1%	$\left\|\frac{V_{cs} f_{Ds}}{V_{cd} f_D}\right\|$	0.8%
$d\Gamma(D^0 \to \pi^-)$	$\|V_{cd}\|$	$F_{D\to\pi}(0)$	4%	$\|V_{cd}\|F_{D\to\pi}(0)$	0.6%
$d\Gamma(D^0 \to K^-)$	$\|V_{cs}\|$	$F_{D\to K}(0)$	3%	$\|V_{cs}\|F_{D\to K}(0)$	0.5%
$d\Gamma(D_s \to K)$	$\|V_{cd}\|$	$F_{D_s\to K}(0)$	2%	$\|V_{cd}\|F_{D_s\to K}(0)$	1.2%
$d\Gamma(D_s \to \phi)$	$\|V_{cs}\|$	$F_{D_s\to\phi}(0)$	1%	$\|V_{cs}\|F_{D_s\to\phi}(0)$	0.8%

The LQCD impact (in per cent) on the precision of CKM matrix elements. $20 fb^{-1}$ at BES-III.

In reality, about $10 pb^{-1}$ data will be collected @ BESIII in the next four years. the sensitivity will be 2% or less.

Impact on CKM from LQCD and charm data

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ \pi \to l\nu & K \to l\nu & B \to \pi l\nu \\ & K \to \pi l\nu & \\ V_{cd} & V_{cs} & V_{cb} \\ D \to l\nu & D_s \to l\nu & B \to Dl\nu \\ D \to \pi l\nu & D \to K l\nu & \\ V_{td} & V_{ts} & V_{tb} \\ \langle B_d|\overline{B}_d\rangle & \langle B_s|\overline{B}_s\rangle & \end{pmatrix}$$

Gold-plated LQCD processes that bear on CKM matrix elements: HPQCD, UKQCD, MILC Collaboration:
PRL, 92, 022001 (2004)
PRL, 95, 122002 (2005)
PRL, 94, 011601 (2005)

I. Shipsey International J. of Mod. Phys A V27 5381(2006)

Summary for Lecture 1

In charm's role as a natural and clean testing ground for QCD techniques there has been solid progress.

The precision with which the charm decay constant f_{D+} (f_{Ds}) is known has already improved to ~4.3% (2.4%). And the D→K semileptonic form factor has be checked to 2-4%. A reduction in errors for decay constants and form factors to the 1% level is promised.

Recent breakthroughs in precision lattice QCD need detailed data to test against. Charm provides that data. If the lattice passes the charm test it can be used with increased confidence by:
SuperB/LHC-b/ATLAS/CMS to achieve precision determinations of the CKM matrix elements Vub, Vcb, Vts, and Vtd, thereby maximizing the sensitivity of heavy quark flavor physics to physics beyond the Standard Model.