Experimental Status for Leptonic and Semileptonic Charm Decays

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Topic Seminar on Frontier of Particle Physics: Charm and Charmonium Physics, 2010, Aug. 27-31, Beijing China

Outline of the lectures

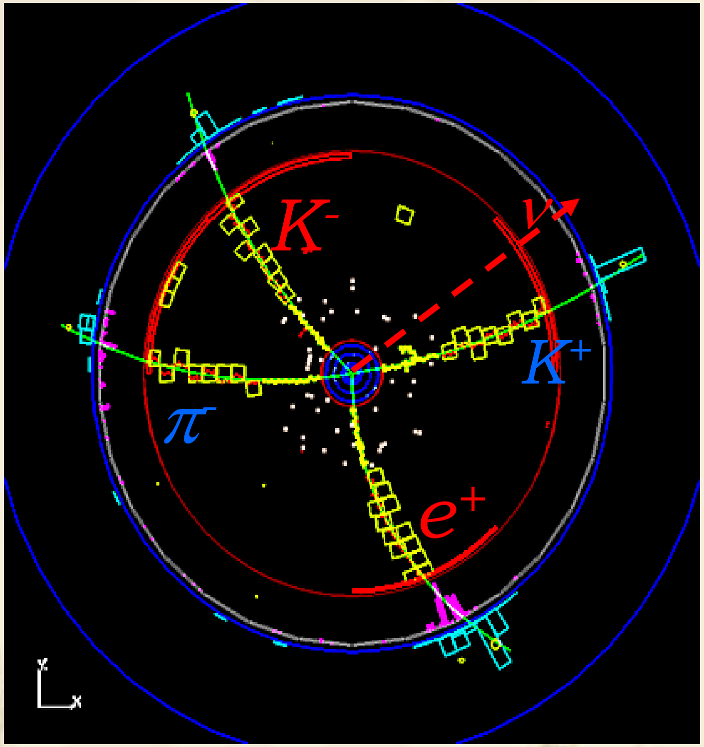
- Introduction
- Leptonic D/D_S decays and decay constants
- Semileptonic D decay and form factor
- Rare and forbidden Charm decays

Thanks to my colleagues from CLEO, BABAR and Belle:
R. Breire, S. T'Jampens, Ian Shipsey, D.M.Asner,
D. Cronin-Hennessy, R. Poling, Peter Zweber, K.M. Ecklund, S.Stone,
M. Pappagallo, D. G. Cassel and many others.

Theorists: D.N. Gao, J. F. Kamenik, Z.z.Xing, M.Z.Yang

Why Charm?

- 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?



In this lecture, I will mention the experimental techniques and systematic analysis in detail. Challenging BESIII data to reach high precision.

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

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

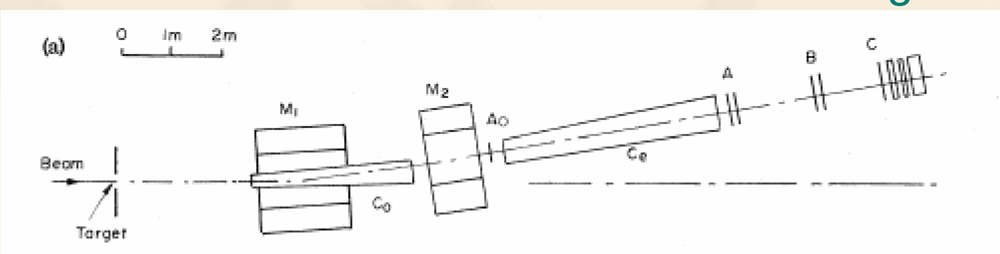
Charm in 1974:

Charm discovery at BNL in 1974

$$p + \mathrm{Be} \rightarrow e^{+} + e^{-} + x$$

measuring $m_{e^+e^-}$

Ting



J/ψ: M=3.1GeV, Γ ≤1.3MeV

Broad band probe, clean final state

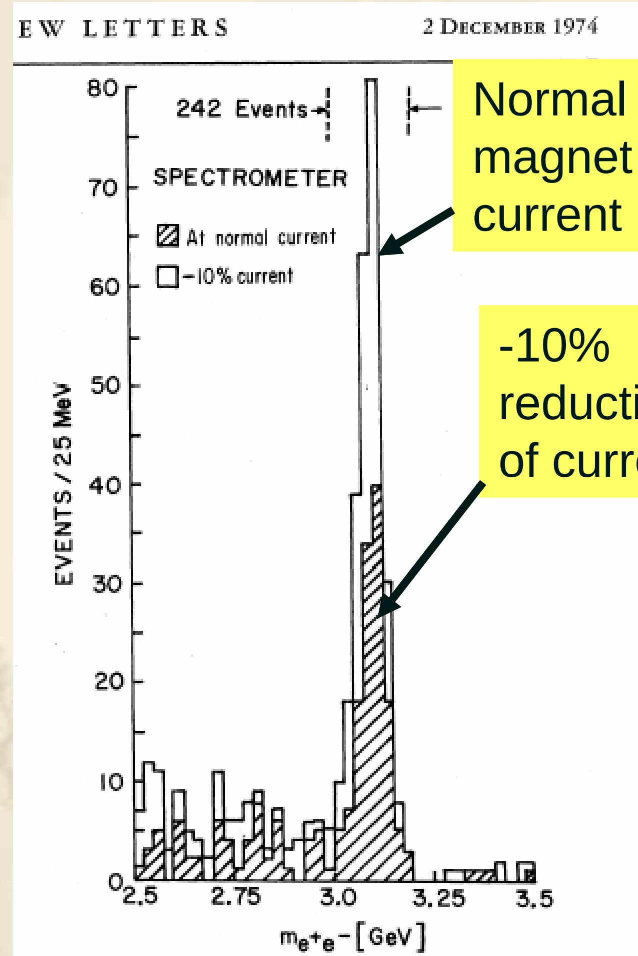


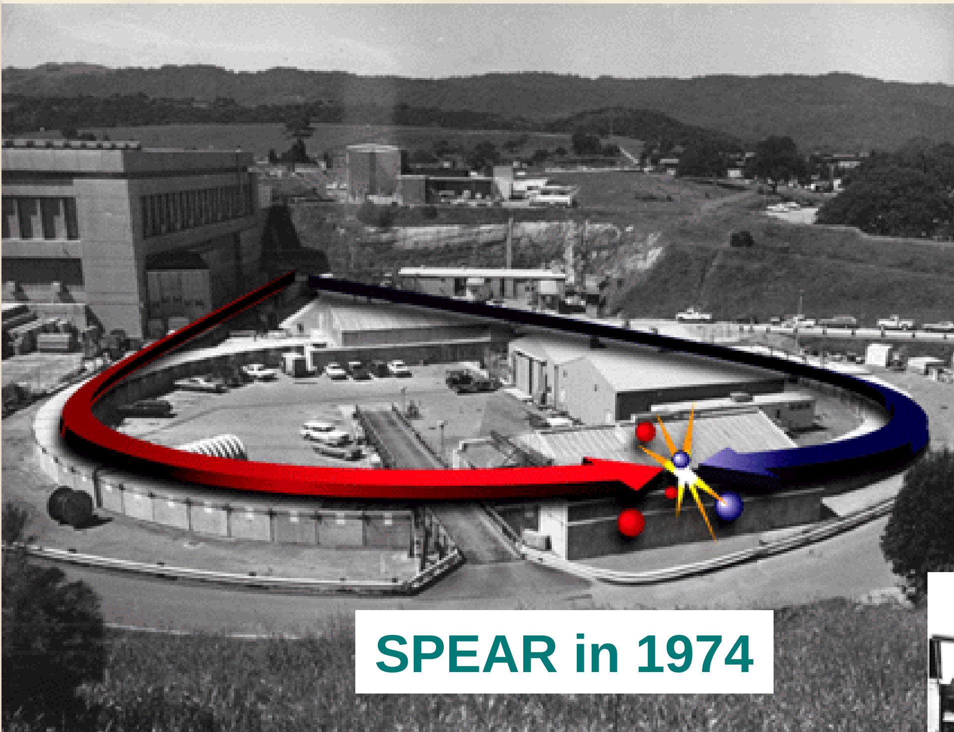
FIG. 2. Mass spectrum showing the existence of J. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

Normal magnet current

-10% reduction of current

Charm in November 1974

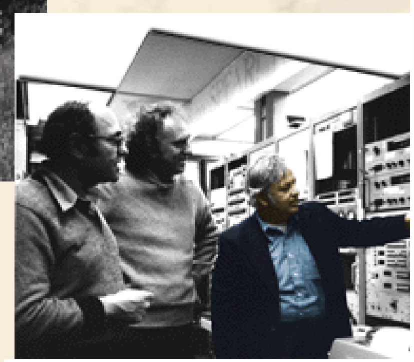
Charm discovery at SLAC in November 1974



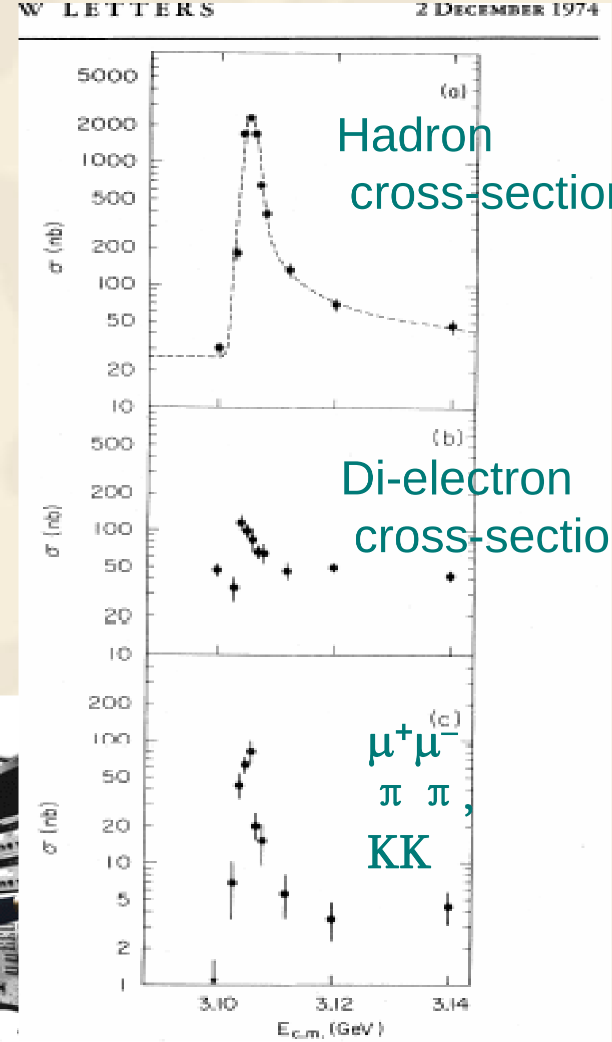
SPEAR in 1974

$$e^+ + e^- \to \text{hadrons},\ e^+e^-,\ \mu^+\mu^-, \cdots$$

J/ψ width << 2 MeV (beam width)



Goldhaber, Perl, Richter 1974



Charm in November 1974

The ADONE e+e- collider at Frascati in Italy was designed at a maximum center-of-mass energy 3.0GeV.

That was badly unfortunate, the energy was just below the edge of discovering this particle.

Immediately after receiving the news of J/ψ observation, they boosted the energy beyond design limits, …

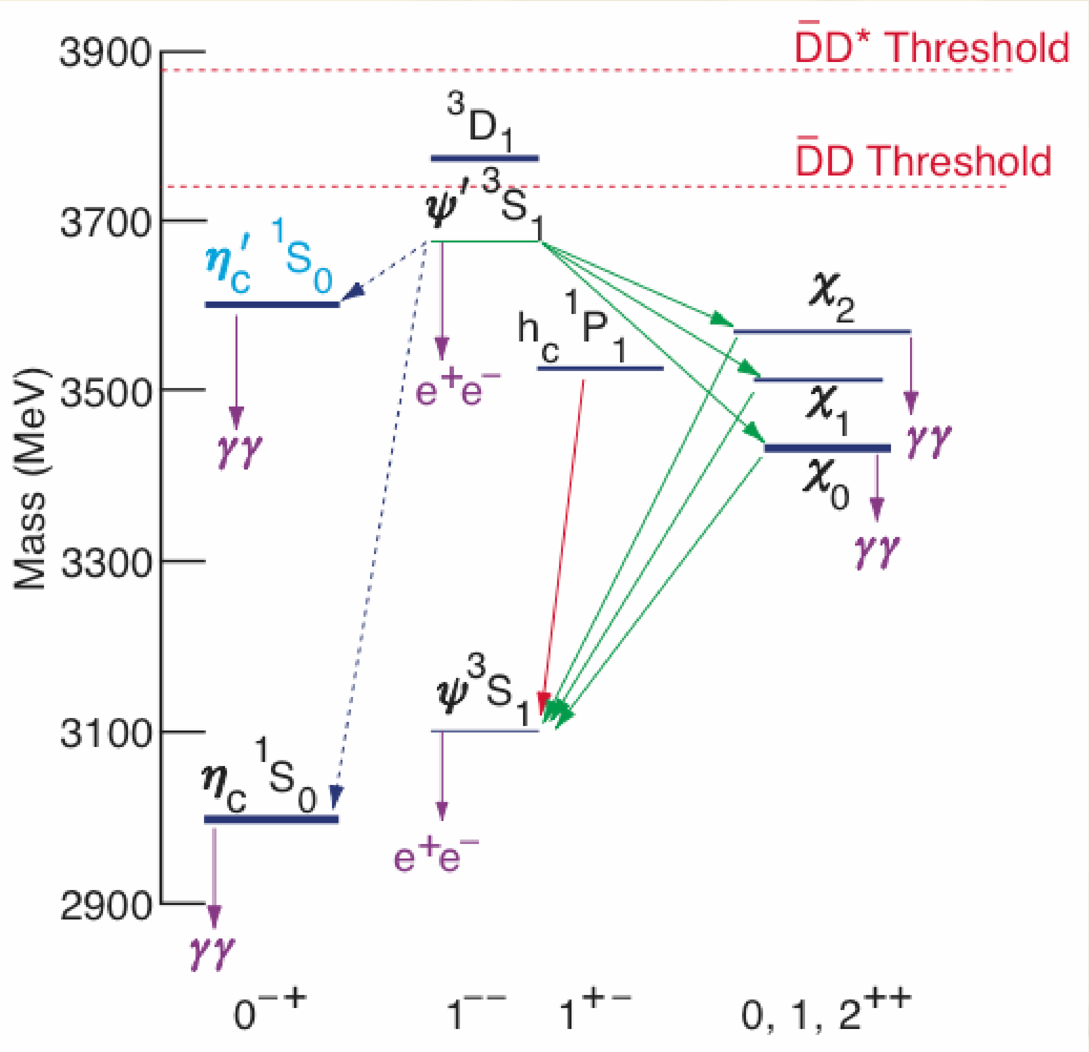
Phys. Rev. Lett. 33 (1974) 1404;
Phys. Rev. Lett. 33 (1974) 1406;
Phys. Rev. Lett. 33 (1974) 1408;

November Revolution!

Charmonium family

Open Charm

Ψ (2S) -- 3.686 GeV



L=0

L=1

D meson in 1976

$D^0\ (c\bar{u})$
$D^+\ (c\bar{d})$

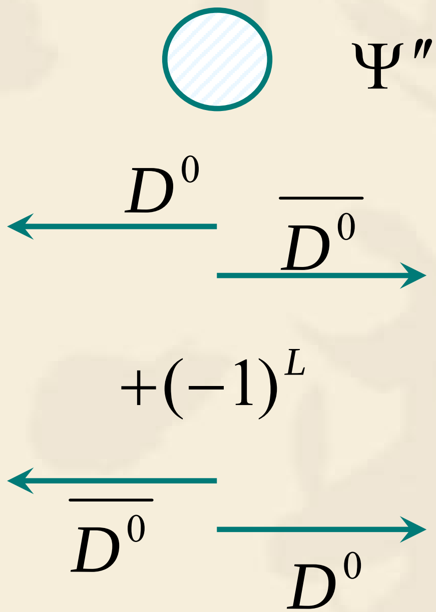
D meson discovered 1976 Goldhaber/Trilling

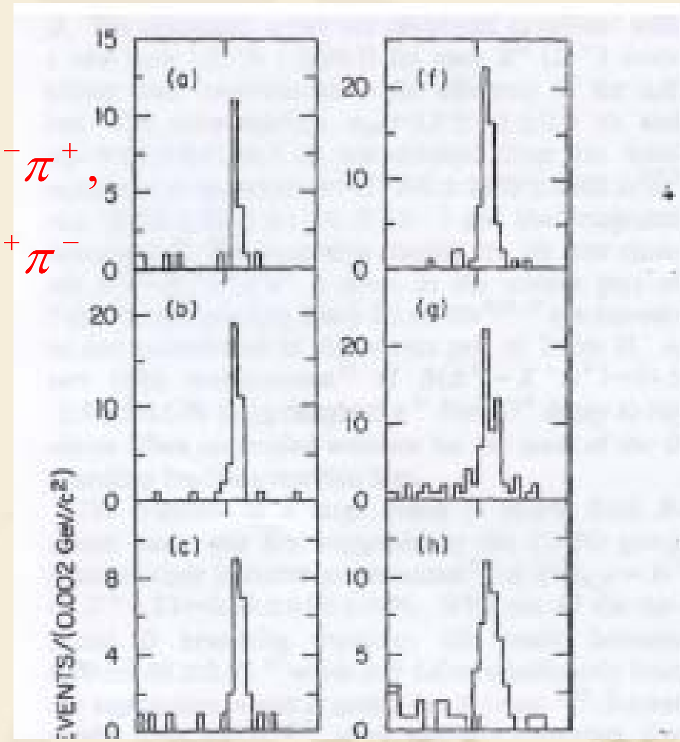
At $\Psi'' = \Psi(3S) = \Psi(3770)$

$$\Psi'' \to D^0\overline{D^0},\ D^+D^-$$

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

$$\Psi'' \to L = 1$$





PRL37(1976)255

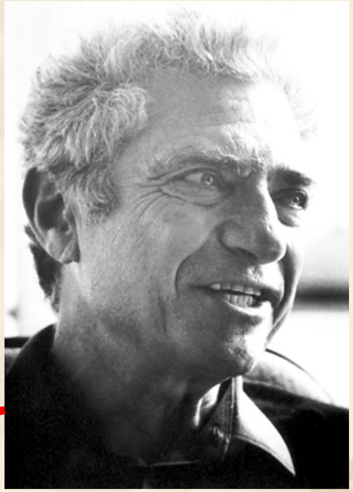
m_{D0} = 1864.84 ±0.17 MeV; m_{D+} = 1869.62±0.20 MeV

Theoretical side

From Mao-zhi Yang

Originally there are three quarks in the quark model , a theory based on the SU(3) symmetry of hadrons, in 1960s.

Jack Steinberger



$$\begin{pmatrix} u \\ d \end{pmatrix} \quad S$$

But there are at least two leptons and two neutrinos since 1962 when people knew ν_e and ν_μ are not the same.

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$

The number of quarks and leptons are unsymmetrical.

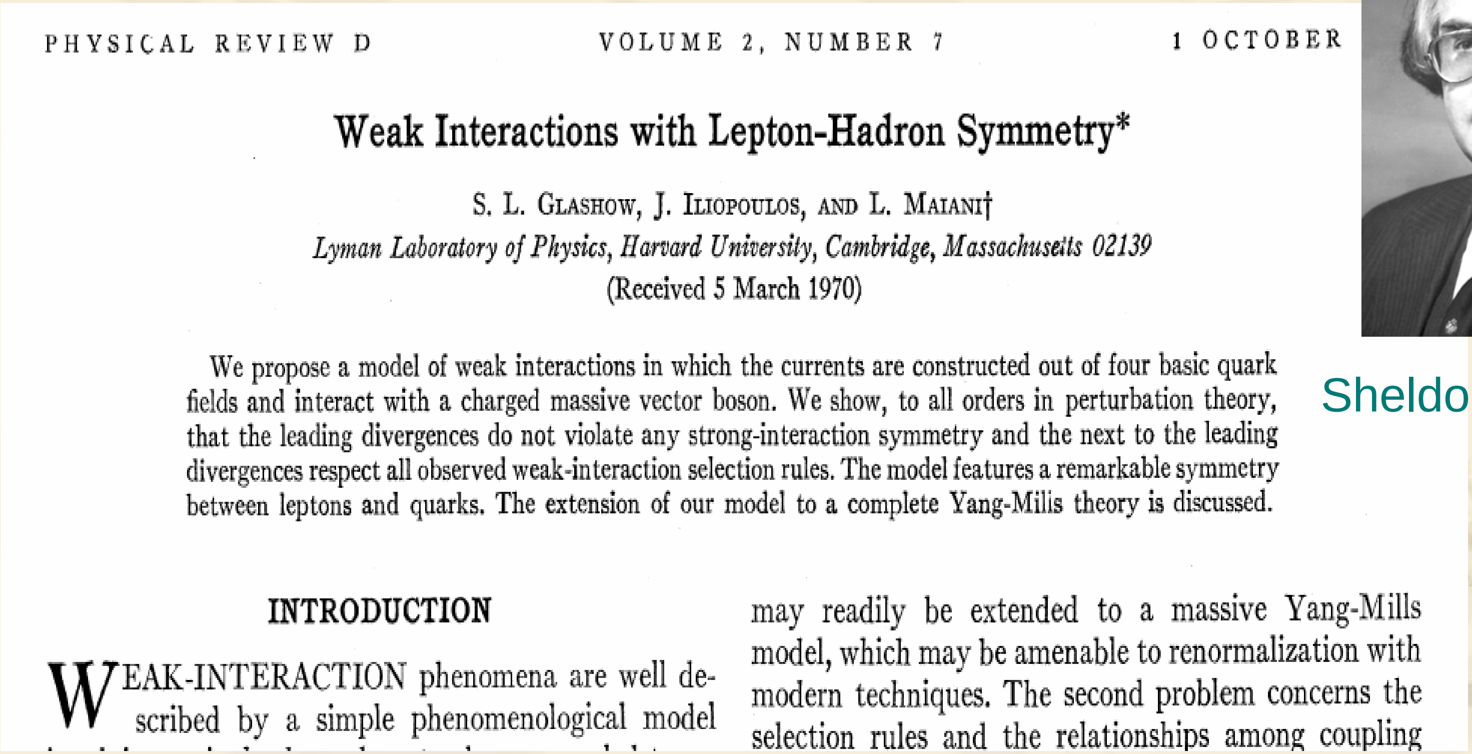
Predicted charm quark

From Mao-zhi Yang

A theory of weak interaction with four quarks was proposed by Bjorken, Glashow, Illiopoulos and Maiani in the mid-1960 and early 1970s

Phys. Lett. 11 (1964) 255;

Phys. Rev. D2 (1970) 1285



PHYSICAL REVIEW D VOLUME 2, NUMBER 7 1 OCTOBER

Weak Interactions with Lepton-Hadron Symmetry*

S. L. Glashow, J. Iliopoulos, and L. Maiani†

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139

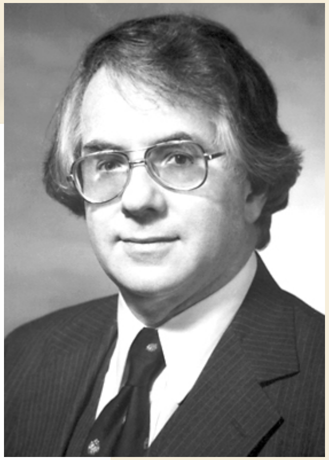
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Mills theory is discussed.

INTRODUCTION

WEAK-INTERACTION phenomena are well described by a simple phenomenological model

may readily be extended to a massive Yang-Mills model, which may be amenable to renormalization with modern techniques. The second problem concerns the selection rules and the relationships among coupling



Sheldon Glashow

The fourth quark

From Mao-zhi Yang

The fourth quark charm was introduced.

Then two families are formed due to the structure of the charged current of weak interaction of quarks.

Charge: +2/3 ; -1/3

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix}$$

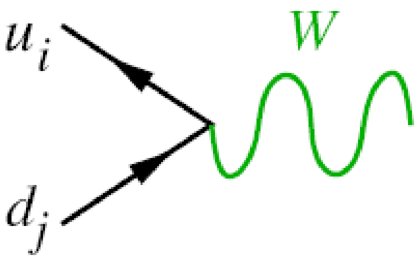
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$

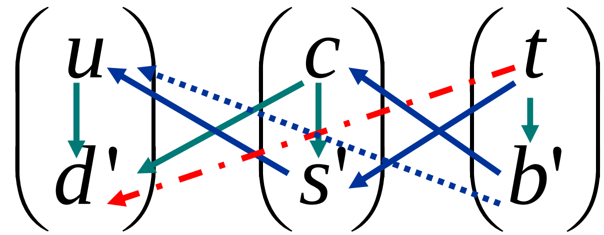
The properties of charm quark are the same as up, except for the mass.

The weak interactions of quarks and leptons are highly symmetric in this theory.

Weak interaction and CKM in Standard Model

In the quark sector of the SM, weak eigenstates $\neq$ Mass eigenstates





with the unitary Cabibbo-Kobayashi-Maskawa matrix:

小林诚

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

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

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

3 generations $\Longrightarrow$ complex phase, source of CP-violation in SM

The Wolfenstein parameterizations

L. Wolfenstein, Phys. Rev. Lett. 51, 1945 (1983)

$$s_{12} \equiv \lambda\,,\quad s_{23} \equiv A\lambda^2\,,\quad s_{13}e^{-i\delta} \equiv A\lambda^3(\rho - i\eta)$$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

λ=0.23

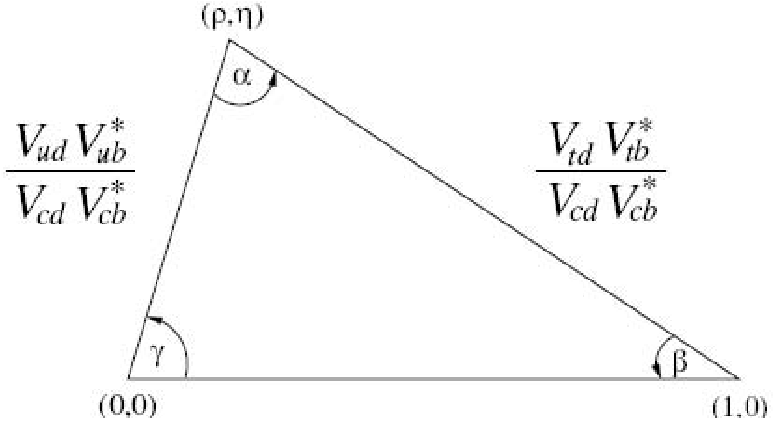
$$= \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4).$$

$$\lambda^2 = \frac{|V_{us}|^2}{|V_{ud}|^2+|V_{us}|^2},\quad A^2\lambda^4 = \frac{|V_{cb}|^2}{|V_{ud}|^2+|V_{us}|^2},\quad \bar{\rho}+i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

CKM unitarity

Unitarity of the CKM matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



B_d *triangle*

Many unitarity relations, related to four hadrons (top excluded)

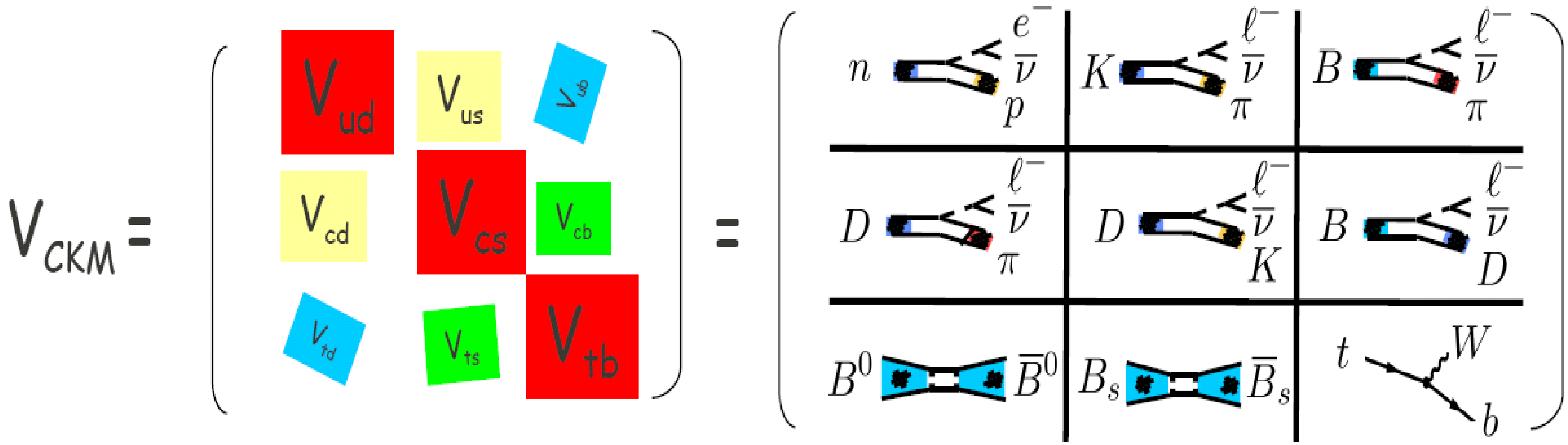
- B_d meson : $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad (\lambda^3, \lambda^3, \lambda^3)$
- B_s meson : $V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0 \quad (\lambda^4, \lambda^2, \lambda^2)$
- K meson : $V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0 \quad (\lambda, \lambda, \lambda^5)$
- D meson : $V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0 \quad (\lambda, \lambda, \lambda^5)$

CKM determination

In SM, weak-charged transitions mix quarks of different generations

↳ CKM matrix: free parameters determined experimentally

- Once we assume unitarity, the CKM matrix can be completely determined using only tree-level CC amplitudes: $\Gamma \propto |V_{ij}|^2$
- The only CKM elements we cannot access via tree-level processes are V_{ts} and V_{td}.



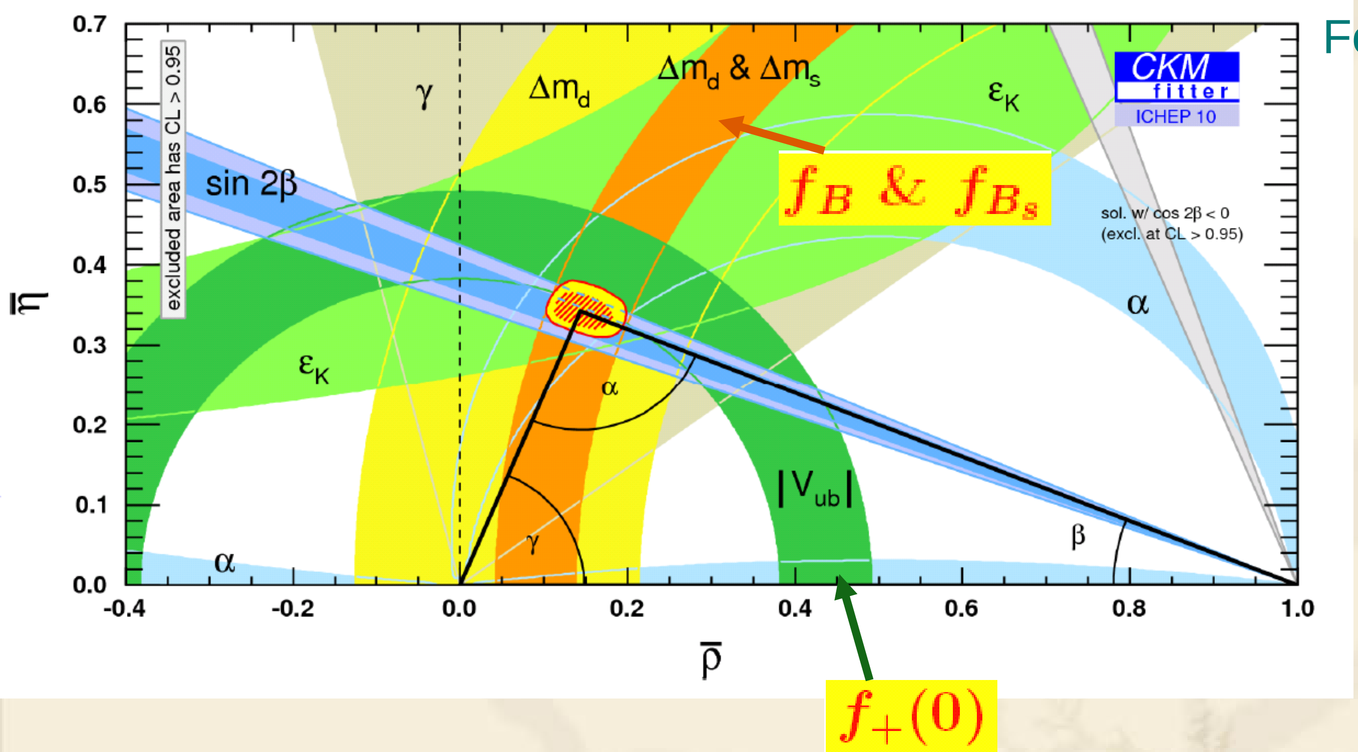
From S. T'Jampens ICHEP2010

Kobayashi & Maskawa,
Prog.Theor.Phys.49 (1973) 652

Cited 6032 times (SPIRES)

Precision theory + charm

From S. T'Jampens ICHEP2010
For CKM fitter group



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

New Physics

2017?
year

Charm Physics: The Context

This Decade

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

The Future

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

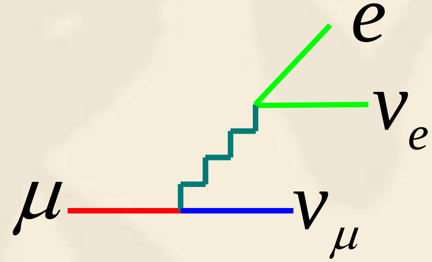
The Lattice

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

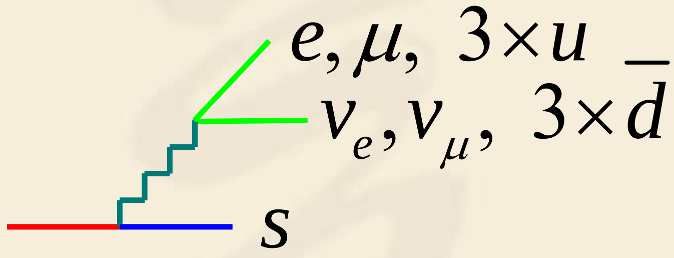


Naïve spectator model for charm

e, μ $\qquad u\bar{d}$ x 3 colors

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

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



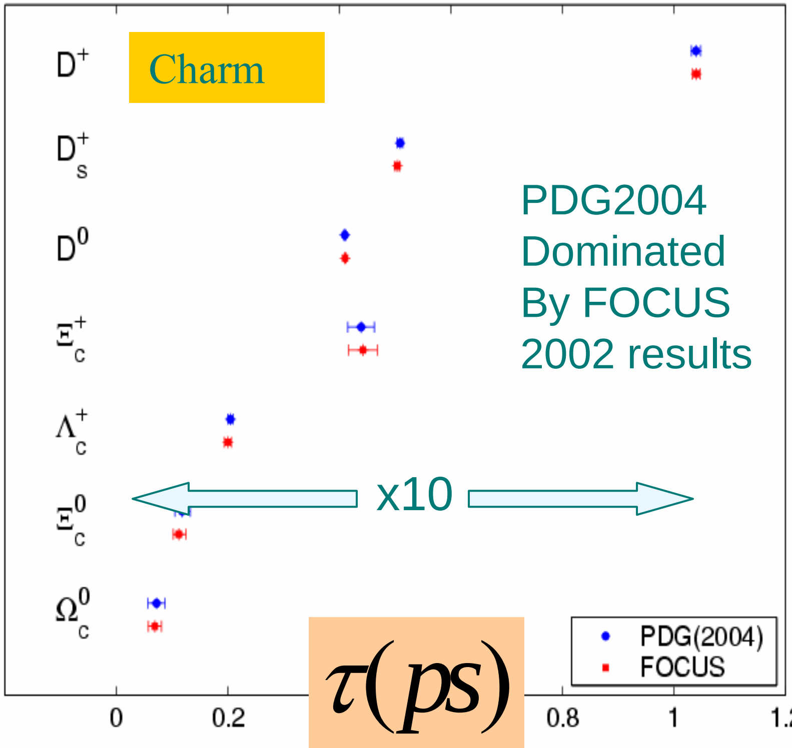
Scaling from the muon: $\tau_c = \dfrac{1}{5}\left(\dfrac{0.105}{1.5}\right)^5 2.2\times10^{-6} = 7\times10^{-13}\,s$

(700 fs)

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

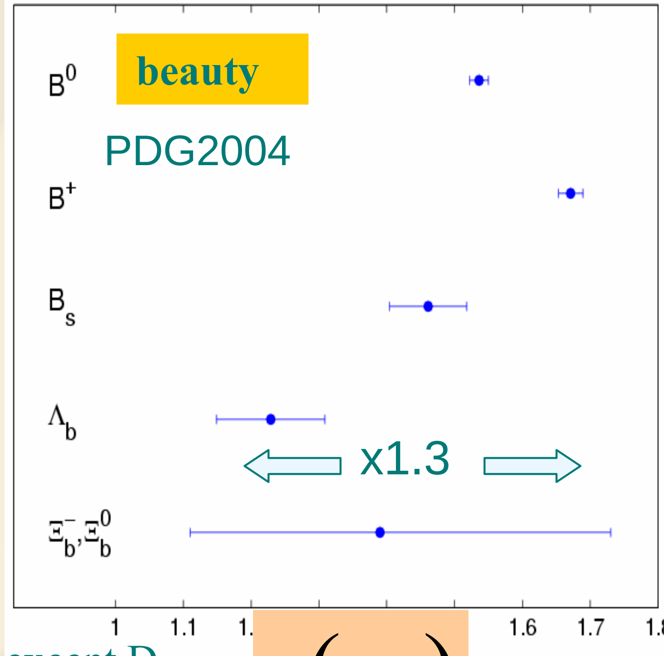
Charm Lifetimes

SELEX, FOCUS,
CLEO E791 E687



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

Lifetimes are PDG2004 except D_s which is a PDG2004 + FOCUS average.



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

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

PDG2004

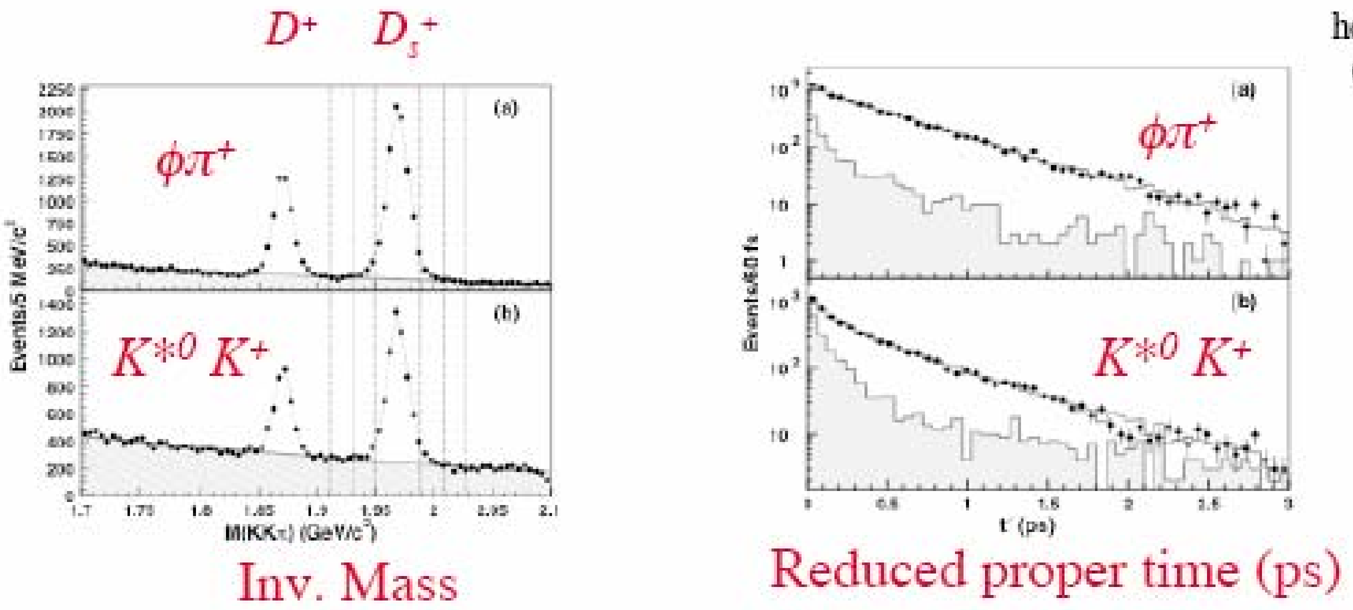
Charm quarks more influenced by hadronic environment than beauty quarks.

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

Charm meson lifetime measurements are still being improved.

D_s^+ Lifetime

hep-ex/0504056 (sub. to PRL)



New D_s lifetime: $507.4 \pm 5.5 \pm 5.1$ fs

New average

\# events

D_s^+	501 ± 6 fs	FOCUS'05 ± 8	8961

Charm baryon lifetimes, less well known new measurements from SELEX
$\tau(\Omega_c) = 69.3 \pm 14.4 \pm 8.6$ fs Nucl. Phys. A755 180 (2005)

D Nonleptonic Decays

Nonleptonic decays dominate the total rate

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

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

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

Quarks or hadrons? ….in between

Compare to kaons and B-mesons:

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

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

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

Hadrons

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

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

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

Like free quarks

Questions to you

- Why V_{ts} and V_{td} can not be accessed at tree level?
- Why b quark is less influenced by hadronic environment?
- If the forth generation of quark exists, what's the unitarity relations?

The Landscape for open charm

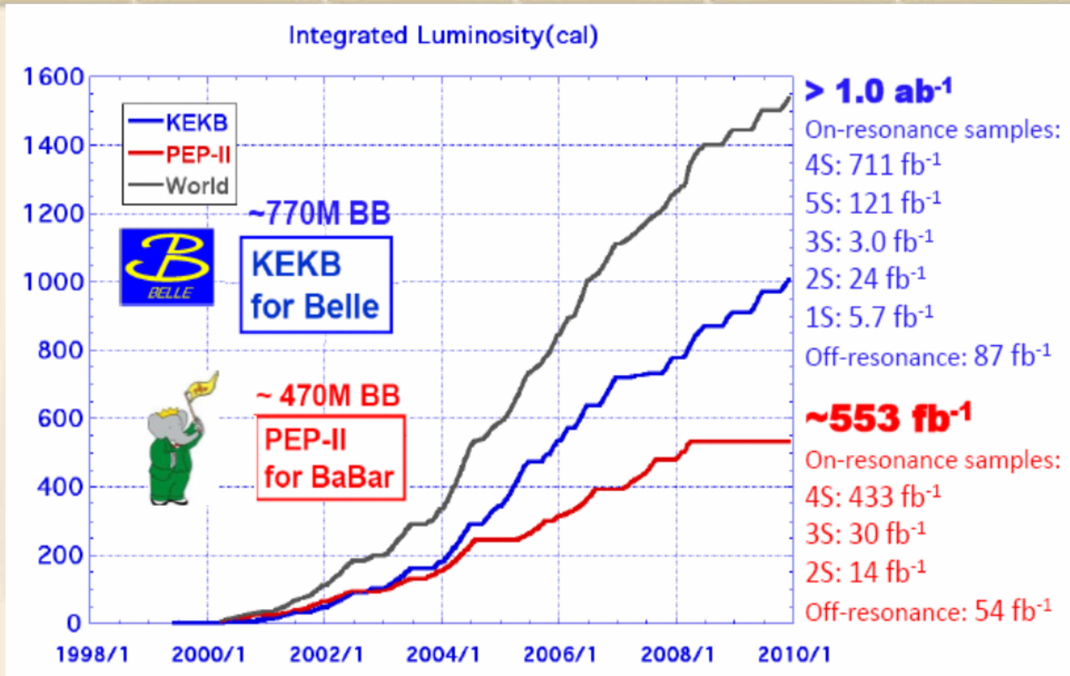
- B factories:
- --BABAR, Belle
- -- Super-B factories ?

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

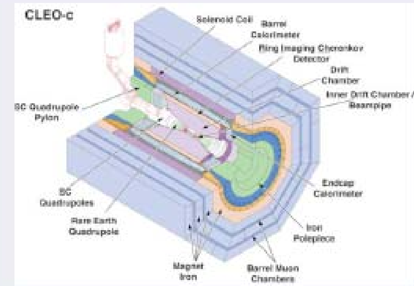
- e^+e^- Colliders@threshold:
- -- Precision results dominated by CLEO-c
- -- Quantum correlations and CP-tagging are unique

The BEPCII machine overcomes the key limit of CLEO-c: luminosity

Open charm data

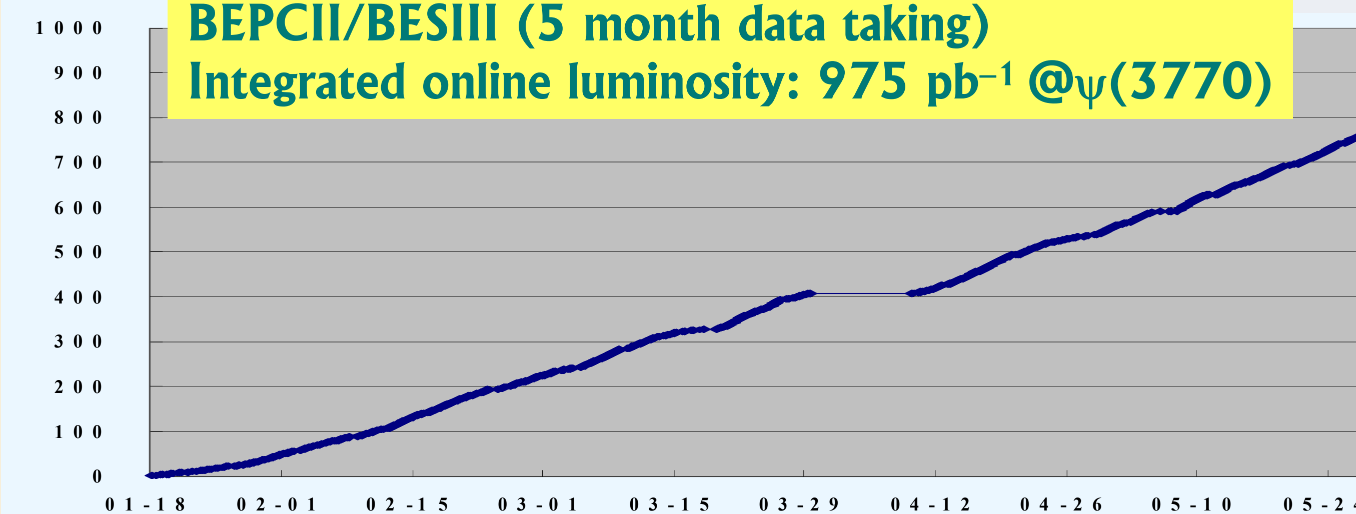


Cleo-c

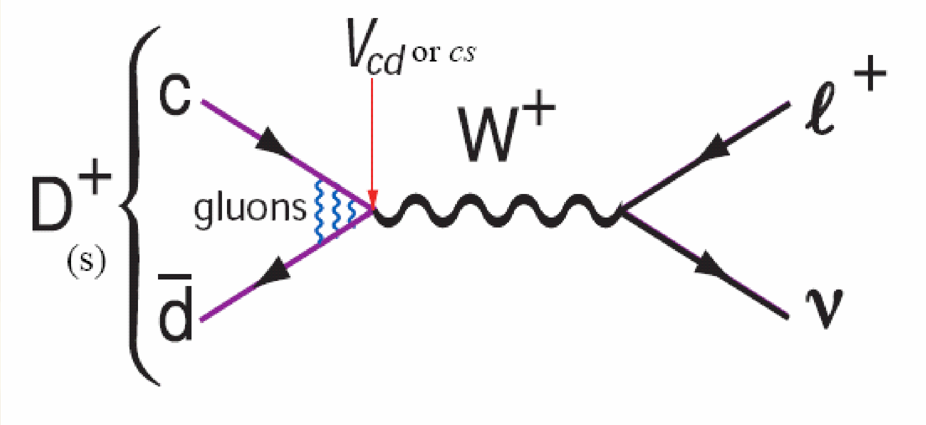


- 0.818/fb at $\psi(3770)$
  - $\star$ 2.4×10^6 D^+D^- pairs
- 0.586/fb at $\psi(4170)$
  - $\star$ 0.54×10^6 $D_s^{*\pm}D_s^{\mp}$ pairs

BEPCII/BESIII (5 month data taking)
Integrated online luminosity: 975 pb^{-1} @$\psi(3770)$

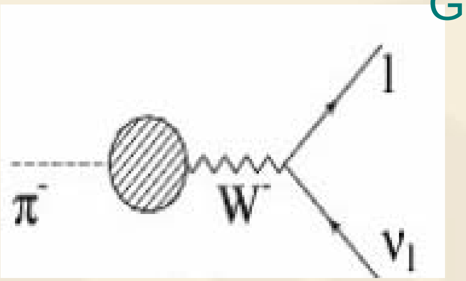


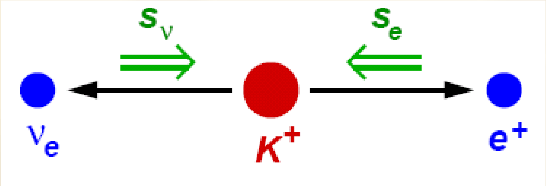
Leptonic D/D_s decays



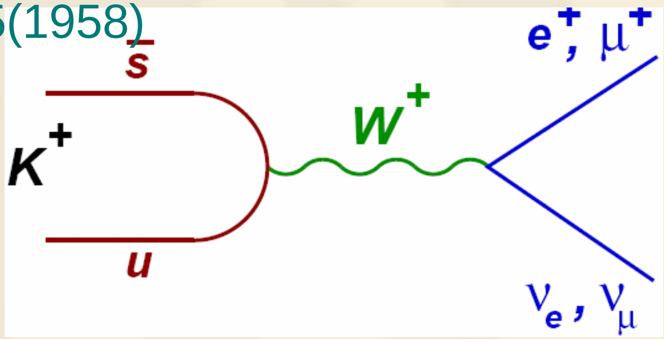
Charged Pion and Kaon leptonic decays

Gaoldhaber et al PR 109,1015(1958)





Helicity suppression



$$R^{th}_{e/\mu} = \frac{\Gamma(\pi \to e\nu + \pi \to e\nu\gamma)}{\Gamma(\pi \to \mu\nu + \pi \to \mu\nu\gamma)} = (1.2353 \pm 0.0004)x10^{-4}$$

$$R^{th}_{e/\mu} - R^{exp}_{e/\mu} = 43(37)x10^{-8}$$

PIEMU @TRIUMF in Canada

$$R_K = \frac{\Gamma(K^\pm \to e^\pm \nu)}{\Gamma(K^\pm \to \mu^\pm \nu)} = \frac{m_e^2}{m_\mu^2} \cdot \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \cdot (1 + \delta R_K^{rad.corr.})$$

$$= (2.477 \pm 0.001) \times 10^{-5}$$

(V. Cirigliano, I. Rosell, JHEP 0710:005 (2007))

$$R_K = (2.486 \pm 0.011_{stat} \pm 0.007_{syst}) \times 10^{-5}$$

$$= (2.486 \pm 0.013) \times 10^{-5}$$

0.5% precision

NA46, A. Winhart ICHEP2010

$$R_K^{th} - R_K^{exp} = -9(13) \times 10^{-8}$$

Precise test of lepton universality probe New Physics

Test physics beyond SM

2HDM (incl. SUSY) - tree level:

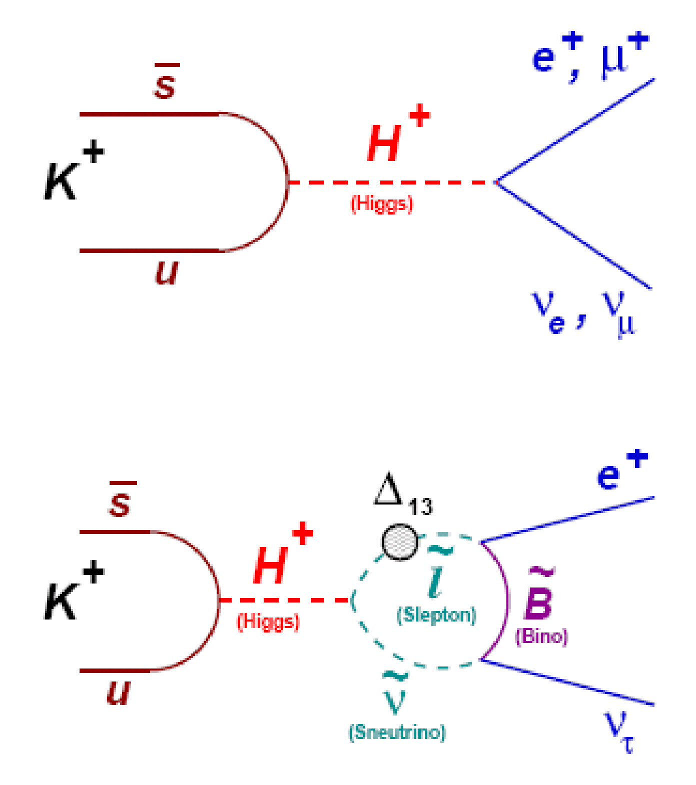
$K^+ \rightarrow l^+\nu$ can proceed via exchange of charged Higgs H^+ instead of W^+

Possible scenario, one loop level:

(Masiero, Paradisi, Petronzio, PRD 74, 2006)

'Loop effects are predicted to lead to **lepton flavour violating (LFV) couplings** $lH^+\nu_\tau$ which give dominant contribution to ΔR_K'

Up to $\sim 1\%$ effect possible in large (not extreme) $\tan\beta$ regime with relatively massive charged Higgs $\rightarrow$ experimentally accessible!

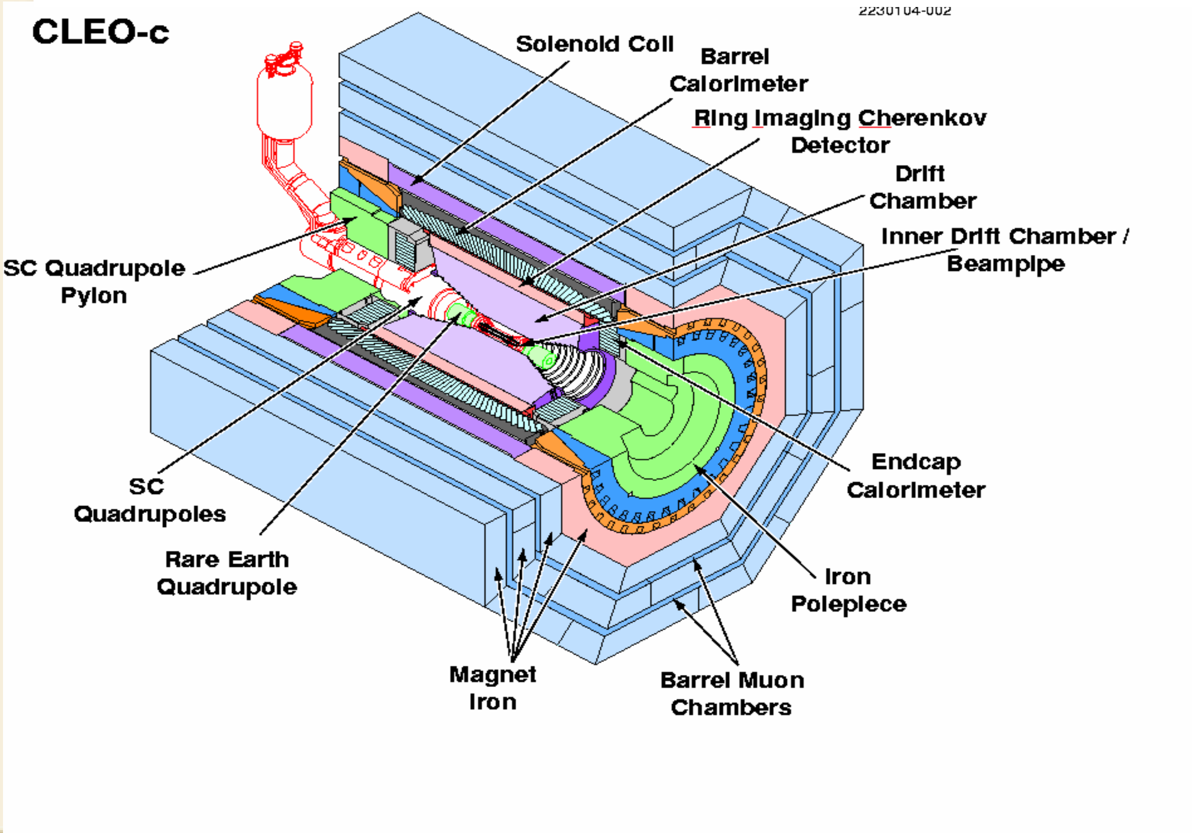


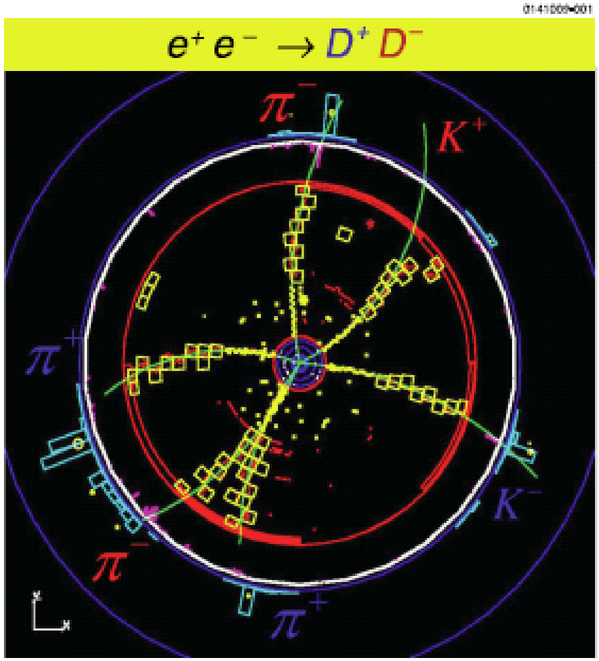
This can be also tested in $D/D_s/B^+$ leptonic decays

CLEO-c detector

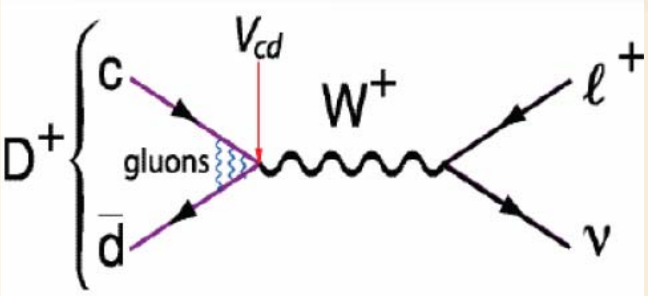
- Excellent Particle Identification (dE/dx and RICH): $0 < p < 1$ GeV/c
- Tracking Resolution: $\sigma_p/p = 0.6\%$ at $p = 1$ GeV/c
- CsI Calorimeter Resolution: $\sigma_E/E = 5\%$ at $E_\gamma = 100$ MeV and 2.2% at 1 GeV
- Hermetic Tracking and Calorimetry: 93% of 4π
- Acceptance, Resolution, and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

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





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



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

SM predicts : $(D^+ \to l^+ \nu)$ = 2.35×10^{-5} : 1 : 2.65 (l = e : μ : τ)

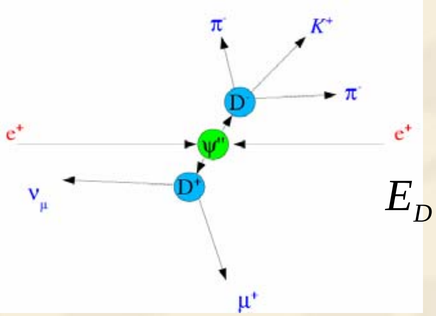
CLEO-c [PRD 78, 052003 (2008)]:
$B(D^+ \to \mu^+\nu) = (3.82 \pm 0.32 \pm 0.09) \times 10^{-4}$
$B(D^+ \to \tau^+ \nu) < 1.2\ \mathrm{x}10^{-3}$ ($\tau^+ \to \pi^+\nu$ only)
$B(D^+ \to e^+\nu) < 8.8\times10^{-6}$

Standard Model: $B(D^+ \to \tau^+ \nu) = (1.01 \pm 0.33)\ \mathrm{x}10^{-3}$
$B(D^+ \to e^+ \nu) = 1\times10^{-8}$

In the SM, decay constant can be extracted as:

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

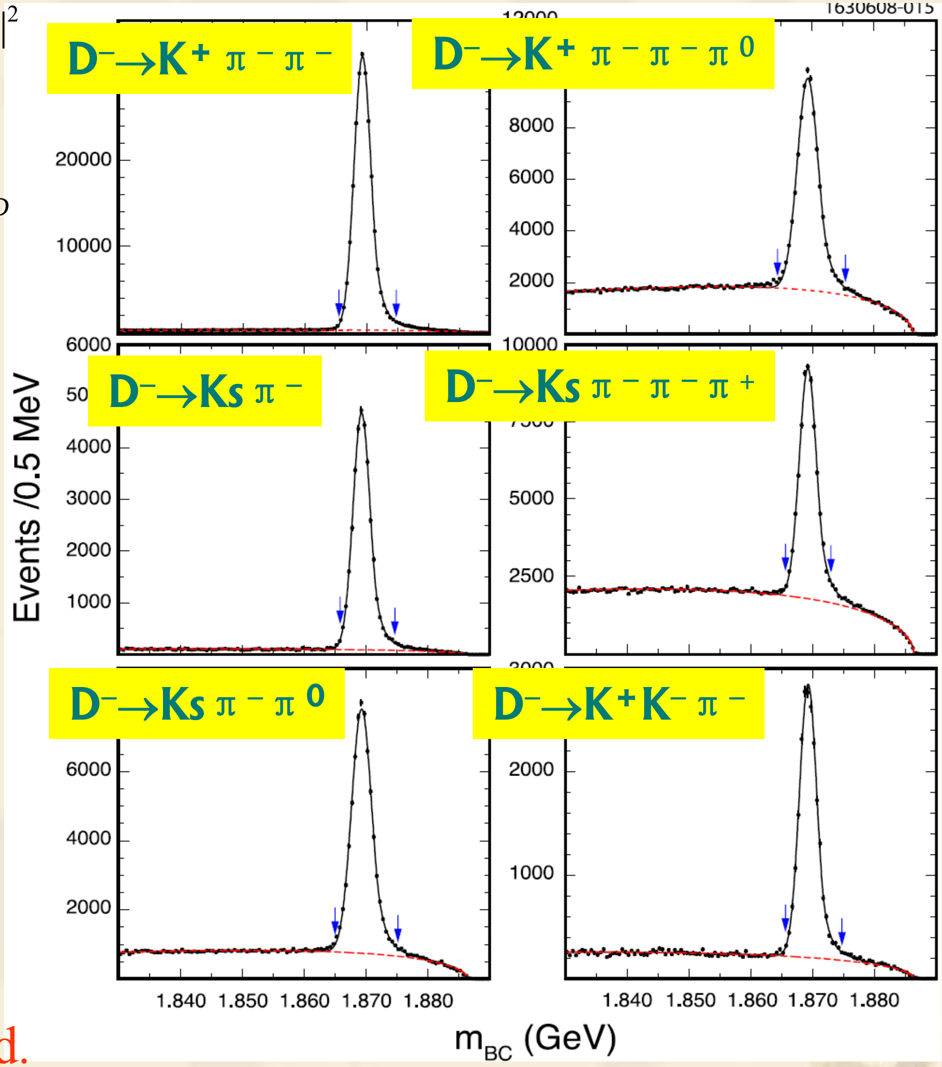
Tagging techniques at ψ(3770)



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

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

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



- 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:

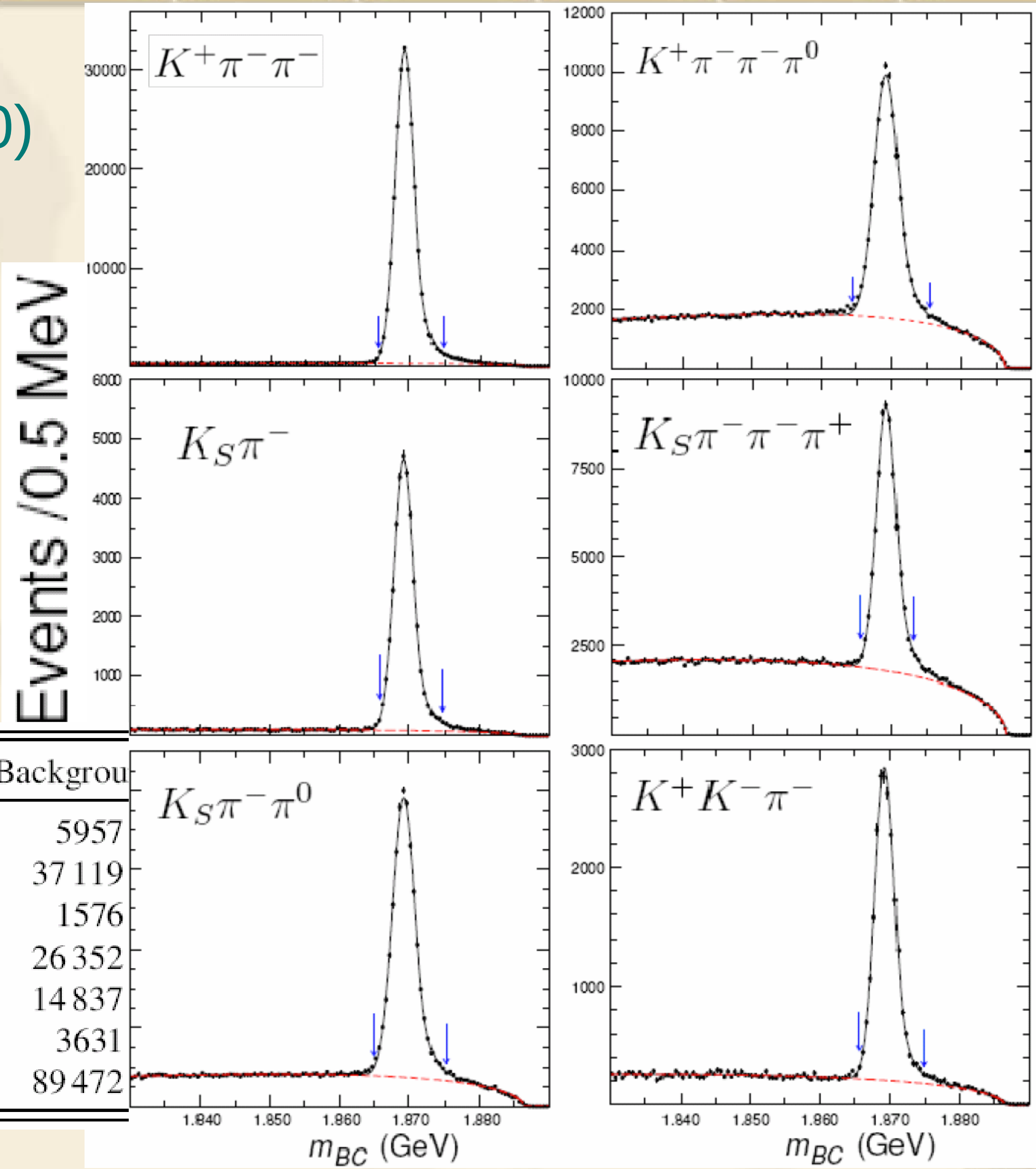
~22% of all D's produced are reconstructed.

D^- tags

- From CLEO-c at ψ(3770)
- Total of 460,000
- Background 89,400

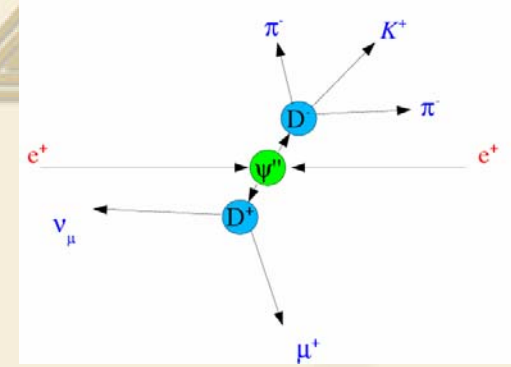
Typical tag rate per D:
15% / 10% / 5%
D^0 / D^- /Ds

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



Mode	Signal	Backgrou
$K^+\pi^-\pi^-$	24 778 ± 497	5957
$K^+\pi^-\pi^-\pi^0$	71 605 ± 359	37 119
$K_S\pi^-$	32 696 ± 189	1576
$K_S\pi^-\pi^-\pi^+$	52 554 ± 315	26 352
$K_S\pi^-\pi^0$	59 298 ± 289	14 837
$K^+K^-\pi^-$	19 124 ± 159	3631
Sum	460 055 ± 787	89 472

Missing mass squared

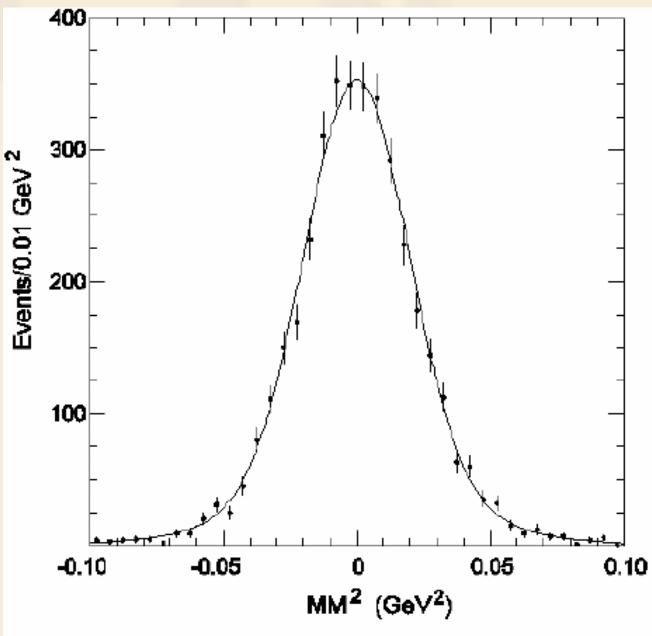


CLEO-c [PRD 78, 052003 (2008)]:

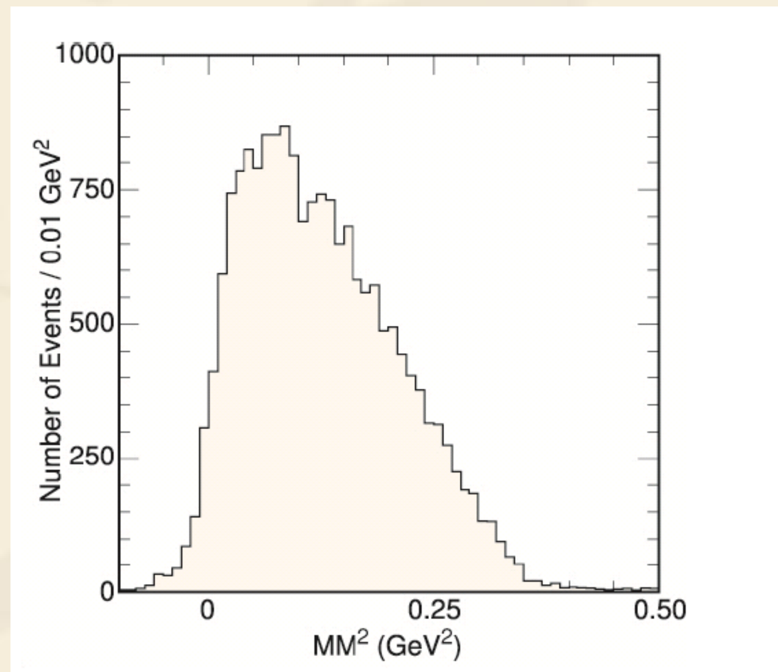
For $D^+ \to \mu^+\nu$ 1 additional track (consistent with a muon) is used to compute missing mass2:

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

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



Monte Carlo Signal $\mu\nu$



Monte Carlo Signal $\tau\nu$, $\tau \to \pi\nu$

The resolution for the MM^2

Signal lineshape from MC, and fit with double Gaussian.

The average resolution is defined as

$$\sigma = f_1\sigma_1 + (1 - f_1)\sigma_2,$$

- **Among different of tag modes, the resolution is:**

$0.0266 \pm 0.0006 \text{ GeV}^2$

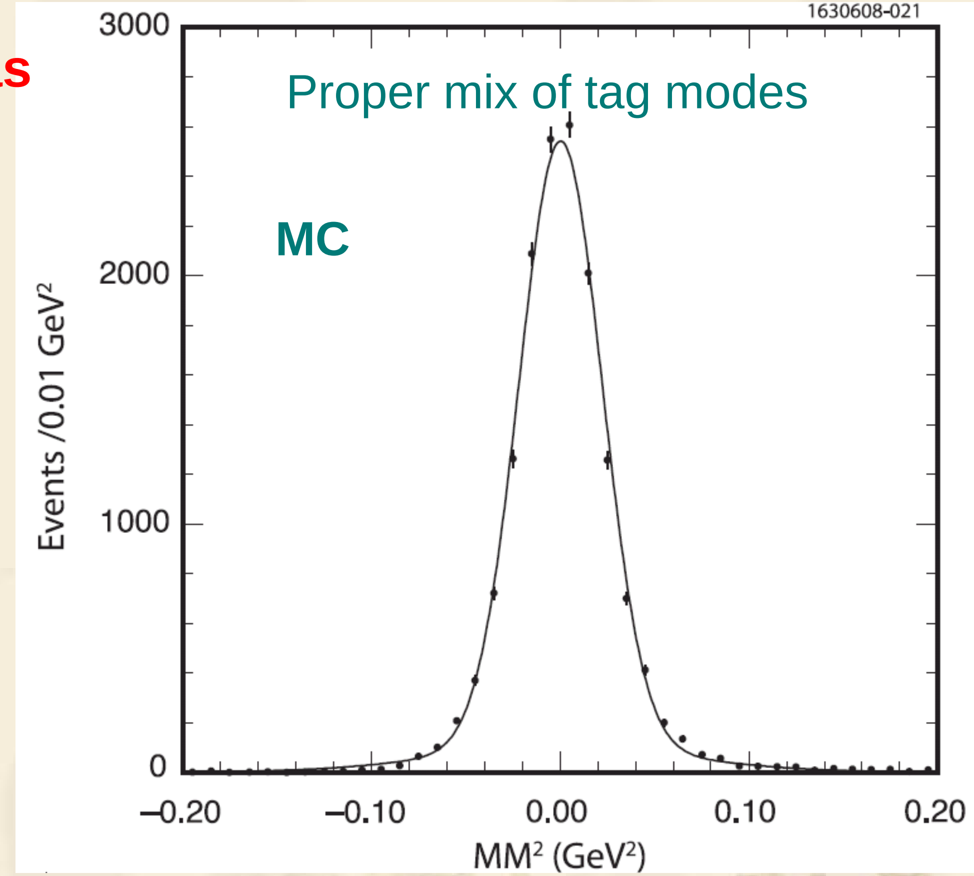
in the fitting range:

$-0.2 < \text{MM}^2 < 0.2 \text{ GeV}^2$

- **While in the fitting range of** $-0.1 < \text{MM}^2 < 0.1 \text{ GeV}^2$

the resolution is:

$0.0248 \pm 0.0006 \text{ GeV}^2$



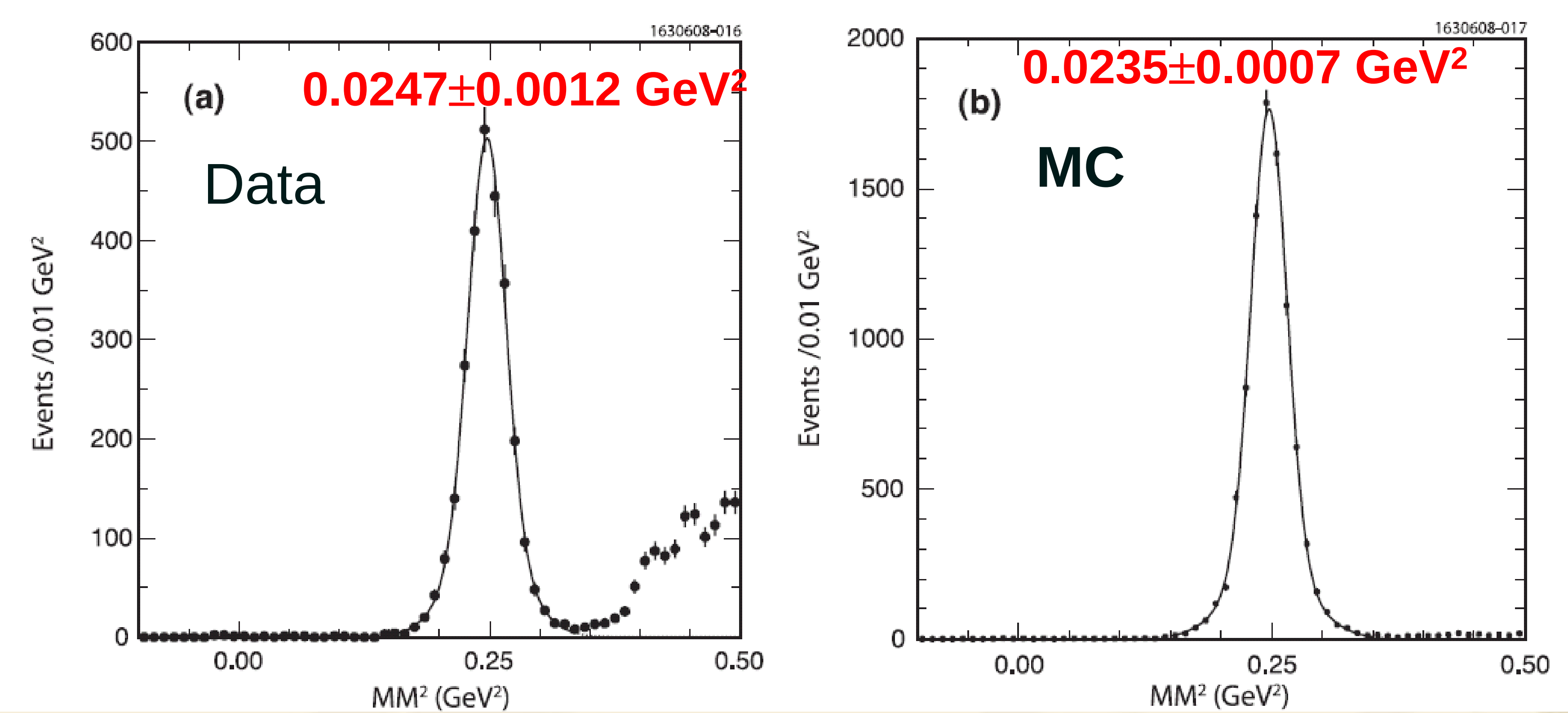
CLEO-c [PRD 78, 052003 (2008)]:

Validate of signal lineshape MM^2

Can we trust the MC simulation? CLEO-c [PRD 78, 052003 (2008)]

From the same tagged sample as $D^+ \to \mu^+ \nu$, $D^+ \to K_s \pi^+$ are selected, with requirement of on additional Ks, and the ignore the Ks, looking at the MM^2 (peak at 0.25 GeV^2):

Consistent value of resolution!



Final data

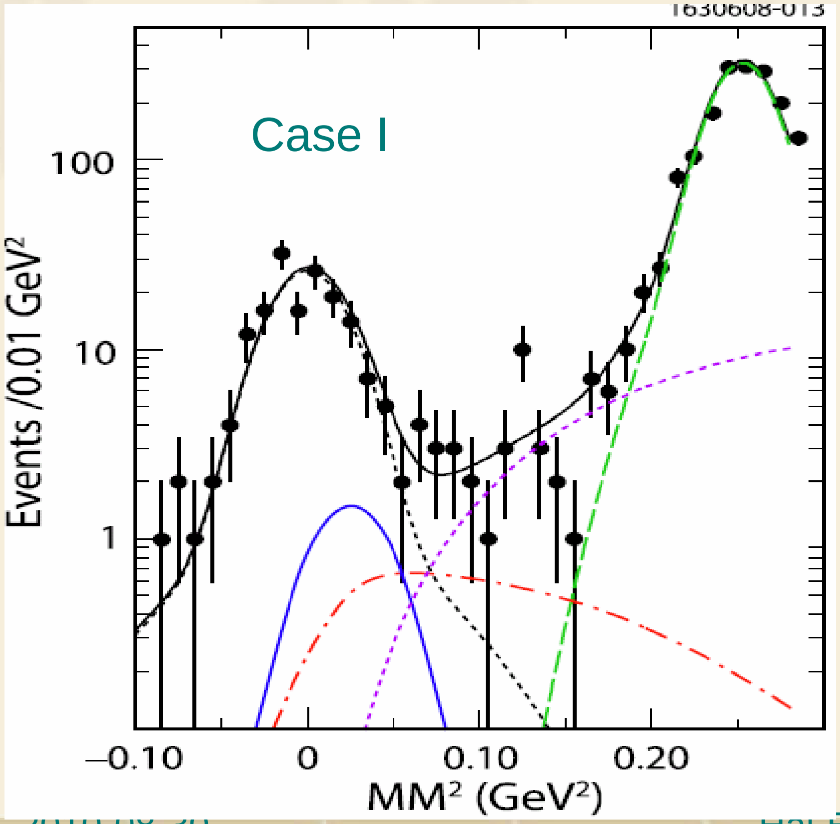
Case i: E(μ)<300MeV, reject 45% of $D^+ \to \pi^+ \pi^0$, and $D^+ \to \tau\nu$, $\tau \to \pi^+\nu$

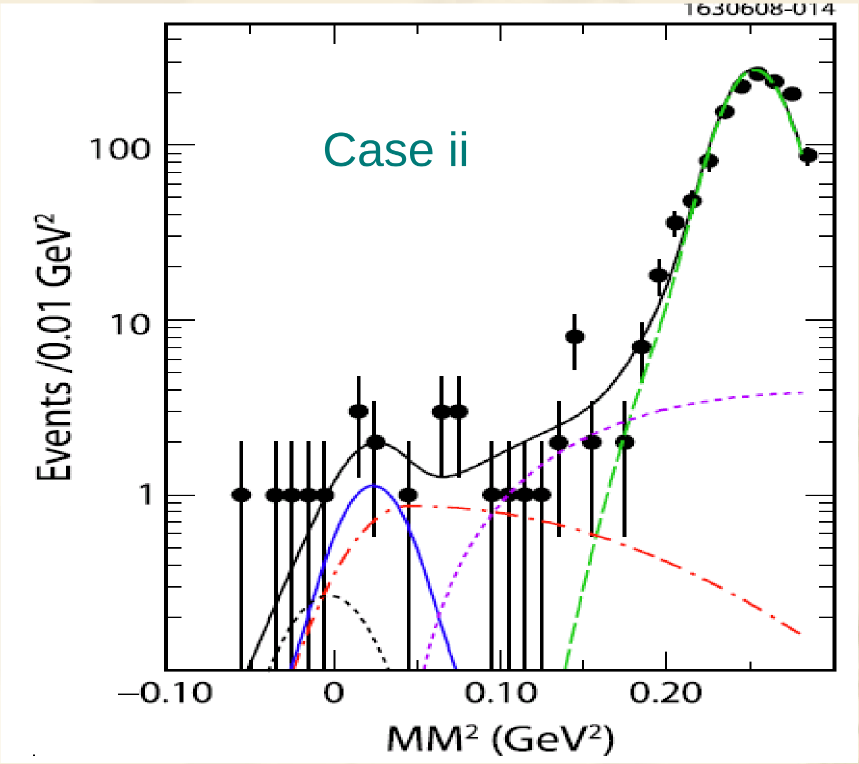
98.8% $D^+ \to \mu\nu$ left.

Case ii: E(μ) > 300MeV

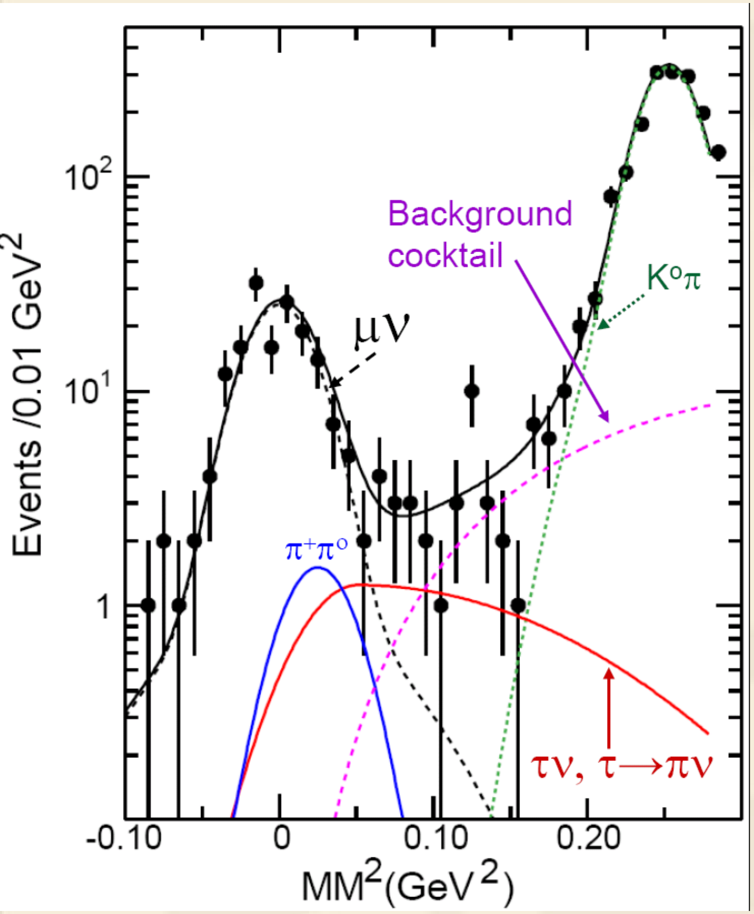
1.2% $D^+ \to \mu\nu$, 45% $D^+ \to \pi^+ \pi^0$ and $D^+ \to \tau\nu$, $\tau \to \pi^+\nu$

For both cases, no extra photon with energy > 250 MeV to reject **$D^+ \to \pi^+ \pi^0$**





Source of backgrounds



Sources of background:

1) **background from D^+ decays:**
   $D^+ \to \pi^+\pi^0$, $D^+ \to \tau^+\nu$, $\tau^+ \to \pi^+\nu\nu$
   $D^+ \to K^0\pi^+$ (far away from signal)

   $E(\mu)$<300MeV, reject 45% of $D^+ \to \pi^+\pi^0$
   no extra γ > 250 MeV, to veto π^0
   $D^+ \to \pi^+\pi^0$: expected 9.5 events

2) **background D^0D^0bar : 0.3**
3) **Background from continuum and "radiative return" $e^+e^- \to \gamma\psi(2S)$: 0.8**

In the fit, signal shapes, shapes for **$D^+ \to \pi^+\pi^0$, $D^+ \to \tau^+\nu$, $\tau^+ \to \pi^+\nu\nu$**
$D^+ \to K^0\pi^+$ are considered.

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

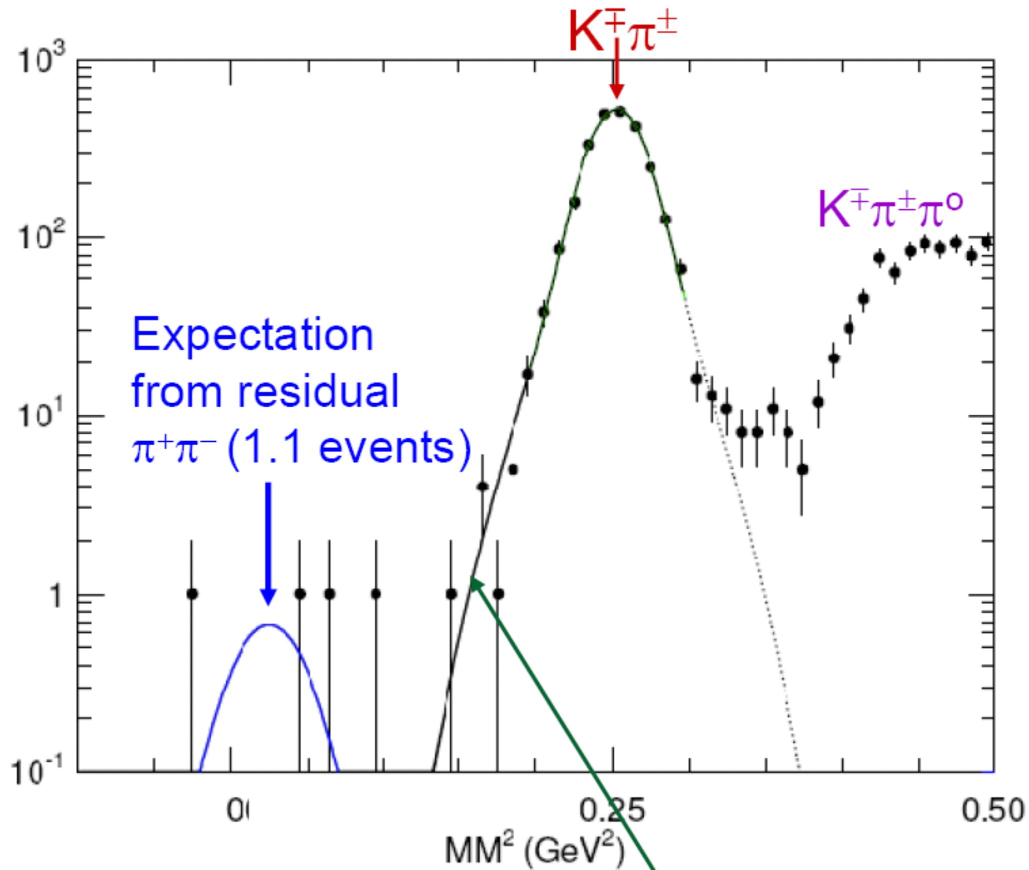
TABLE II. Backgrounds from additional sources, not contained in the fitting functions.

Mode	# of Events
Continuum	0.8 ± 0.4
$\bar{K}^0\pi^+$	1.3 ± 0.9
D^0 modes	0.3 ± 0.3
Sum	2.4 ± 1.0

Model of $K^o\pi^+$ Tail

Use double tag D^o $\bar{D}^o$ events, where both $D^o \to K^{\mp}\pi^{\pm}$

Make loose cuts on 2nd D^o so as not to bias distribution: require only 4 charged tracks in the event



CLEO-c [PRD 78, 052003 (2008)]: Computed ignoring charged kaon

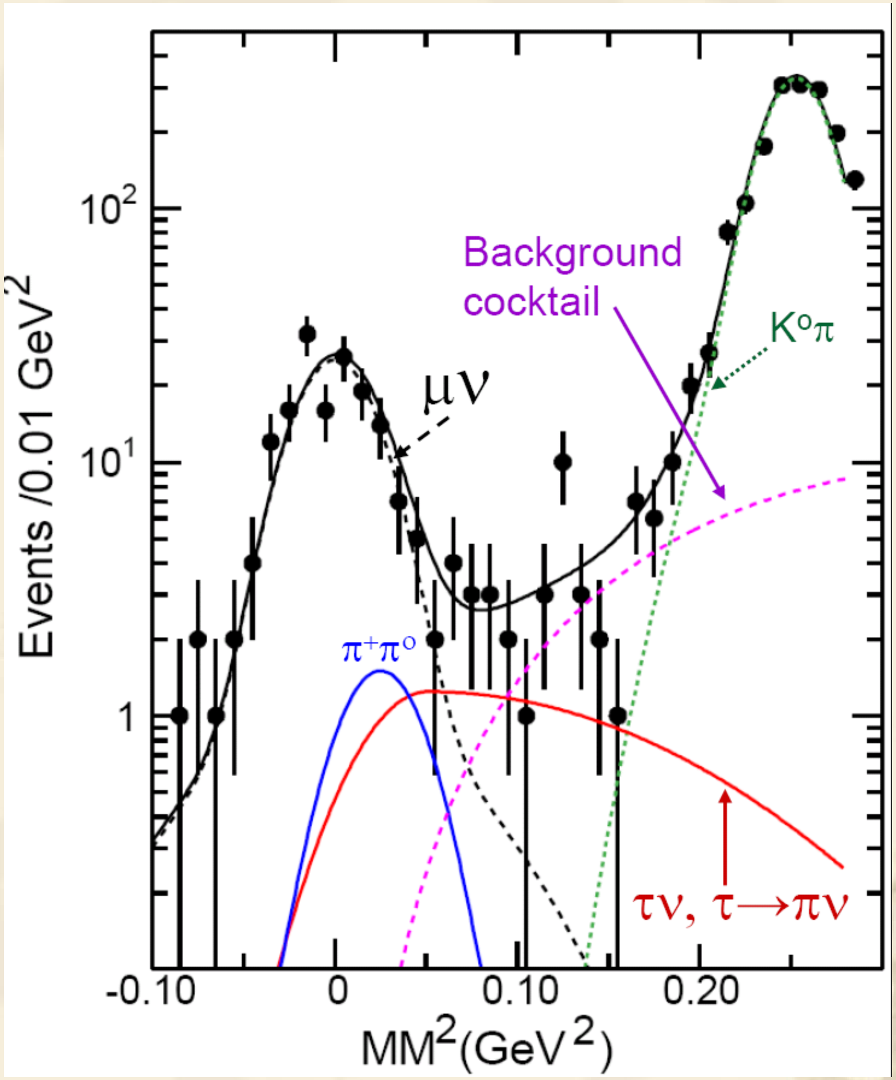
Gives an excellent description of shape of low mass tail
"Extra" 1.3 event background in signal region

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

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

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

- 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 $\tau\nu$



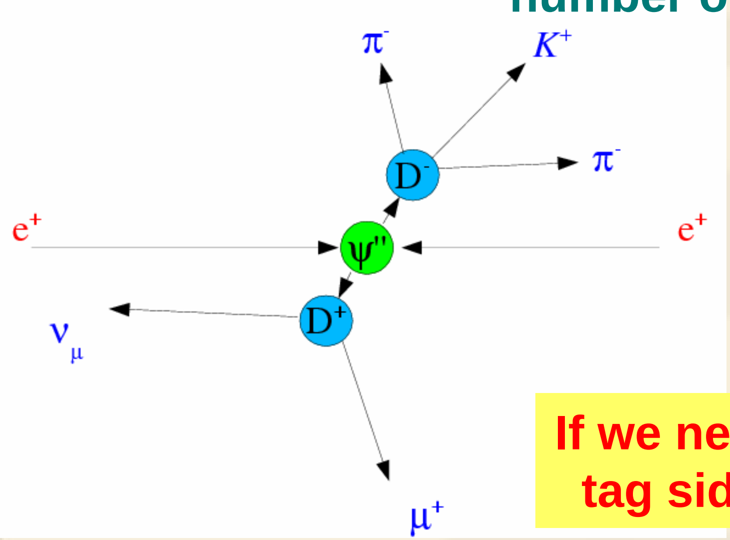
Absolute branching fraction

Absolute branching ratio:

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

$N_{tagged\text{-}D}$: the number of single tag candidates,
$\varepsilon_{D\text{->}\mu\nu}$: 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.



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

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

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

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 τ_{D+} =1.040(7)ps

818fb^{-1} from CLEO-c

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

$$\mathcal{B}(D^+\to\mu^+\nu) = (3.82\pm0.32\pm0.09)\times10^{-4}$$

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

This is best number in context of SM.

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

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

$$\mathcal{B}(D^+\to\mu^+\nu) = (3.93\pm0.35\pm0.10)\times10^{-4}$$

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

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

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

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

Fit to samples of case 1 and 2:

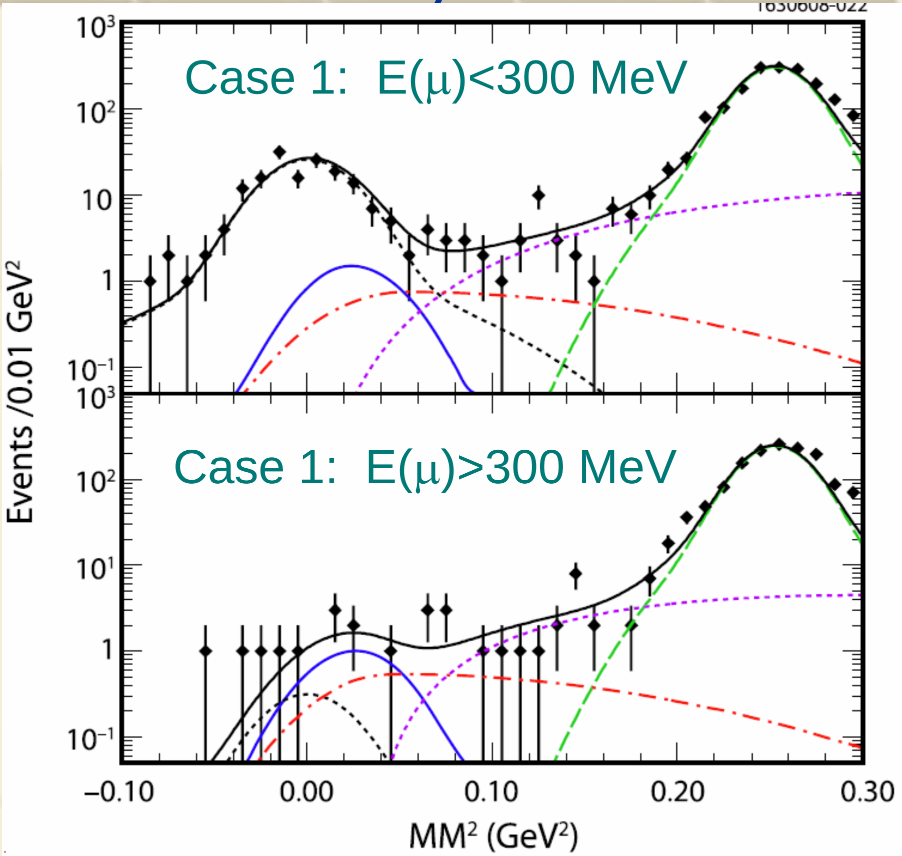
27.8±16.4 signal events.

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

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

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

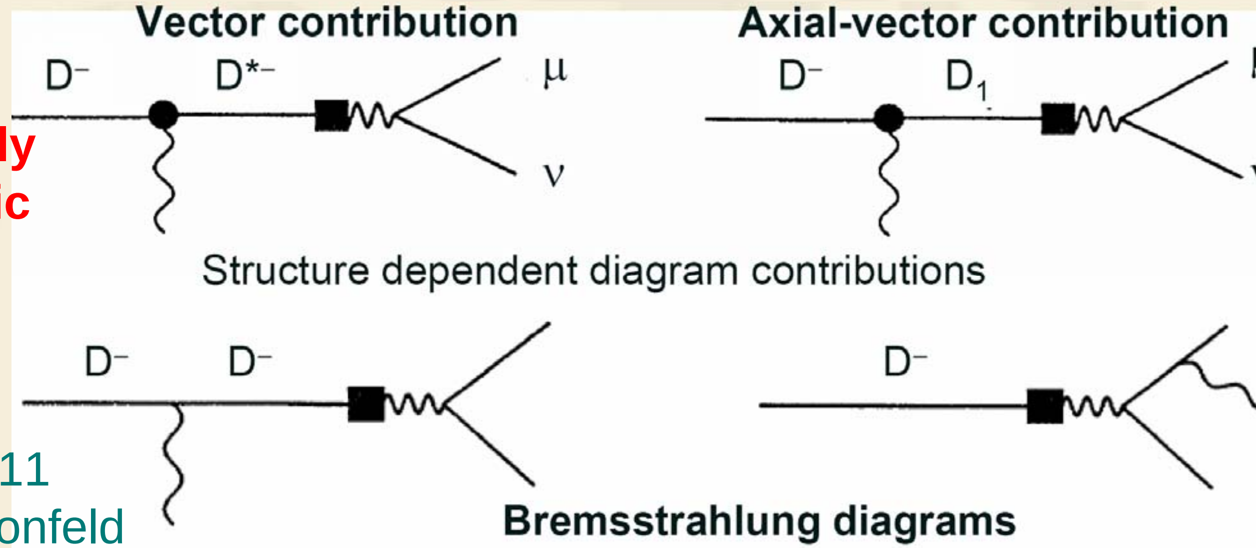
Standard Model predictions:

$B(D^+ \to \tau^+ \nu) = (1.01 \pm 0.33) \times 10^{-3}$

$B(D^+ \to e^+ \nu) = 1 \times 10^{-8}$

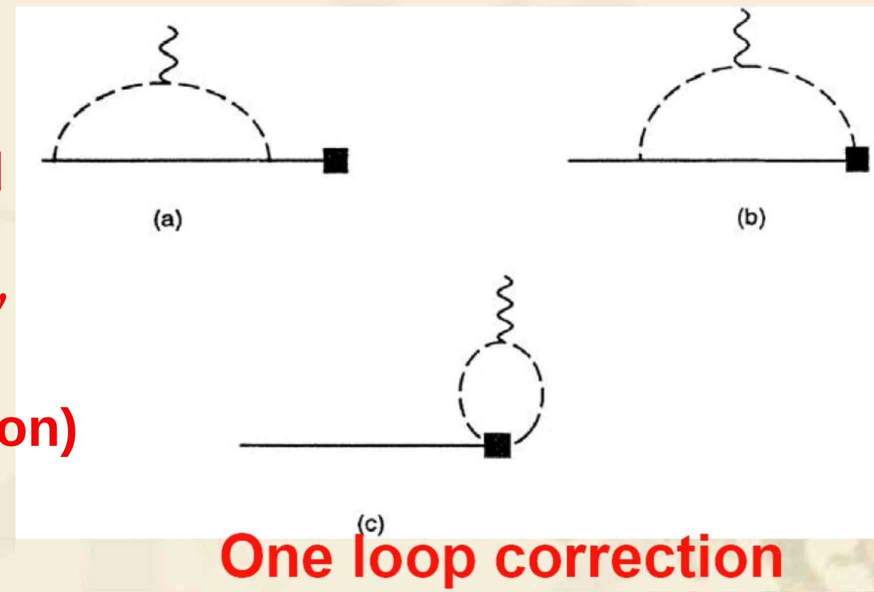
Radiative correction – $D^- \to \mu^- \nu \gamma$

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



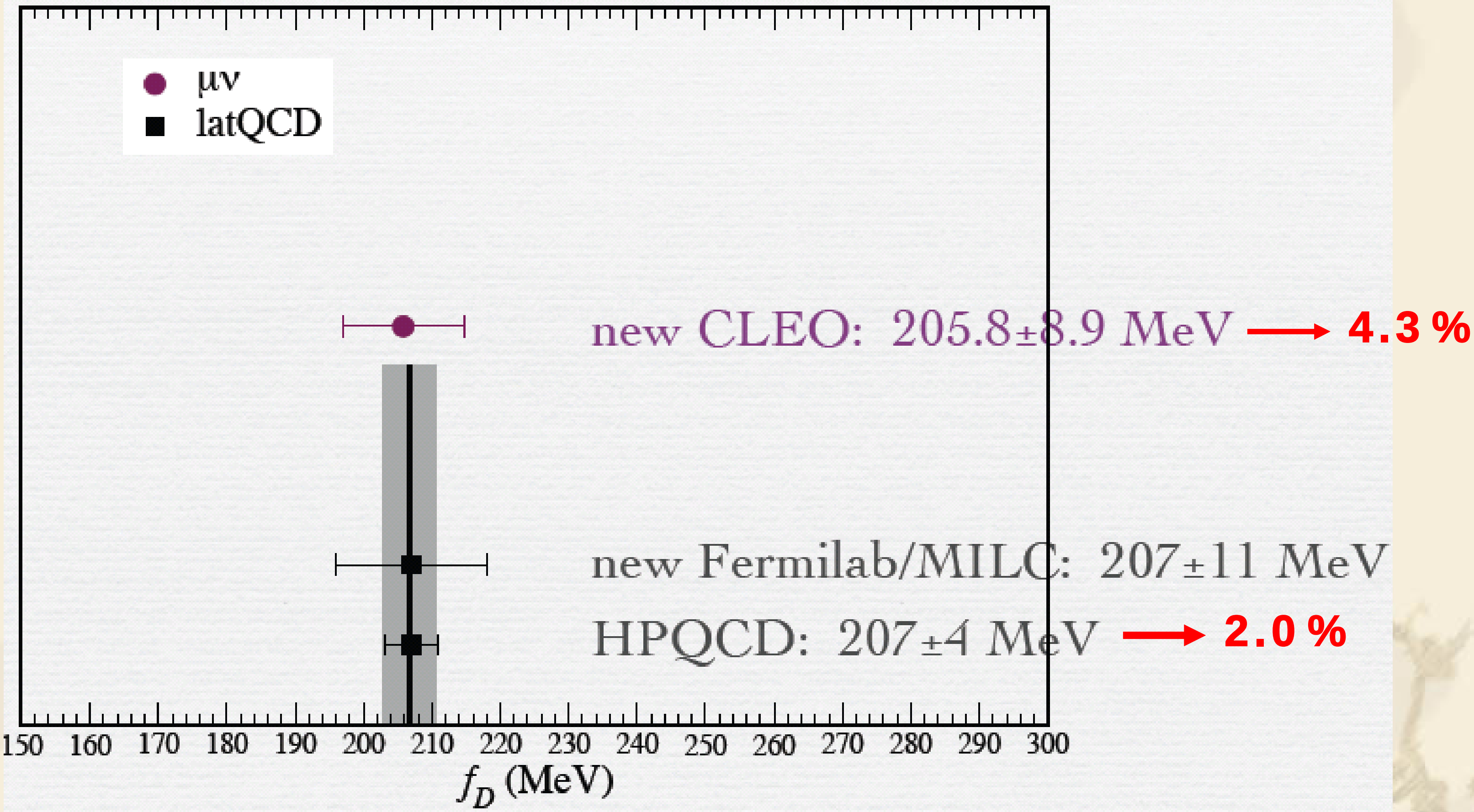
G.Burdman et al PRD51,111
B.A. Dobrescu and A.S. Kronfeld PRL100, 241802

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)



A precision test of QCD

The f_D^+ can be precisely calculated in the Lattice QCD!



It is BESIII's job to reduce the statistical and systematic errors, 1.0 fb^{-1}@ ψ(3770) is just a start point.

CP Violation

818fb^{-1} from CLEO-c

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

- D^+ tags 228,945±551
- D^- tags 231,107±552
- $\mu^-\nu$ events 64.8±8.1
- $\mu^+\nu$ events 76.0±8.6

$$A_{CP} \equiv \frac{\Gamma(D^+ \to \mu^+\nu) - \Gamma(D^- \to \mu^-\nu)}{\Gamma(D^+ \to \mu^+\nu) + \Gamma(D^- \to \mu^-\nu)} = 0.08 \pm 0.08$$

- $-0.05 < A_{CP} < 0.21$ @ 90% c. l.

Prospect for f_{D+} at BESIII

- D^+ decay constant can be only measured at $\psi(3770)$ peak with high precision
- The final number from CLEO-c with statistical error 4.3% **818fb^{-1} from CLEO-c**
- With 3 fb^{-1} to 5fb^{-1} at BESIII, the error can be reached 2.3% or less
- The accuracy of best LQCD prediction is 2.0% now.

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: $B(D^+ \to \tau^+ \nu) = (1.01 \pm 0.33)\ \mathrm{x}10^{-3}$

$\tau^+ \to X$	$\mathcal{B}(\tau^+ \to X)$	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 $e^+e^- \to D_s D_s^*$ 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:

$\sigma(DsDs) = 0.269 \pm 0.030 \pm 0.015$ nb @ 4010 MeV

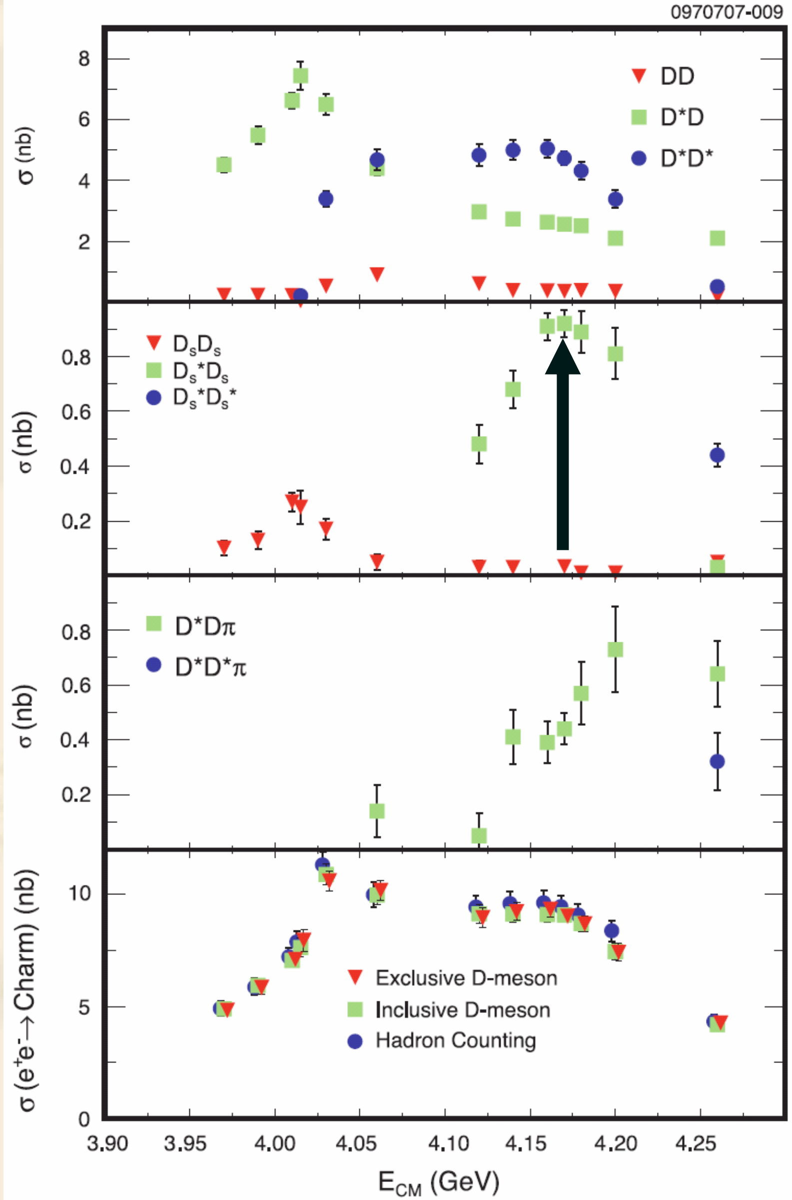
$\sigma(DsDs^*) = 0.916 \pm 0.011 \pm 0.049$ nb @ 4170 MeV

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

Data@4170 MeV

$e^+e^- \to Ds^+Ds^{*-}$, $Ds^{-*} \to \gamma Ds^+$

on top of uds *plus* other* charm continuum (DDbar, DD*bar, D*D*bar)



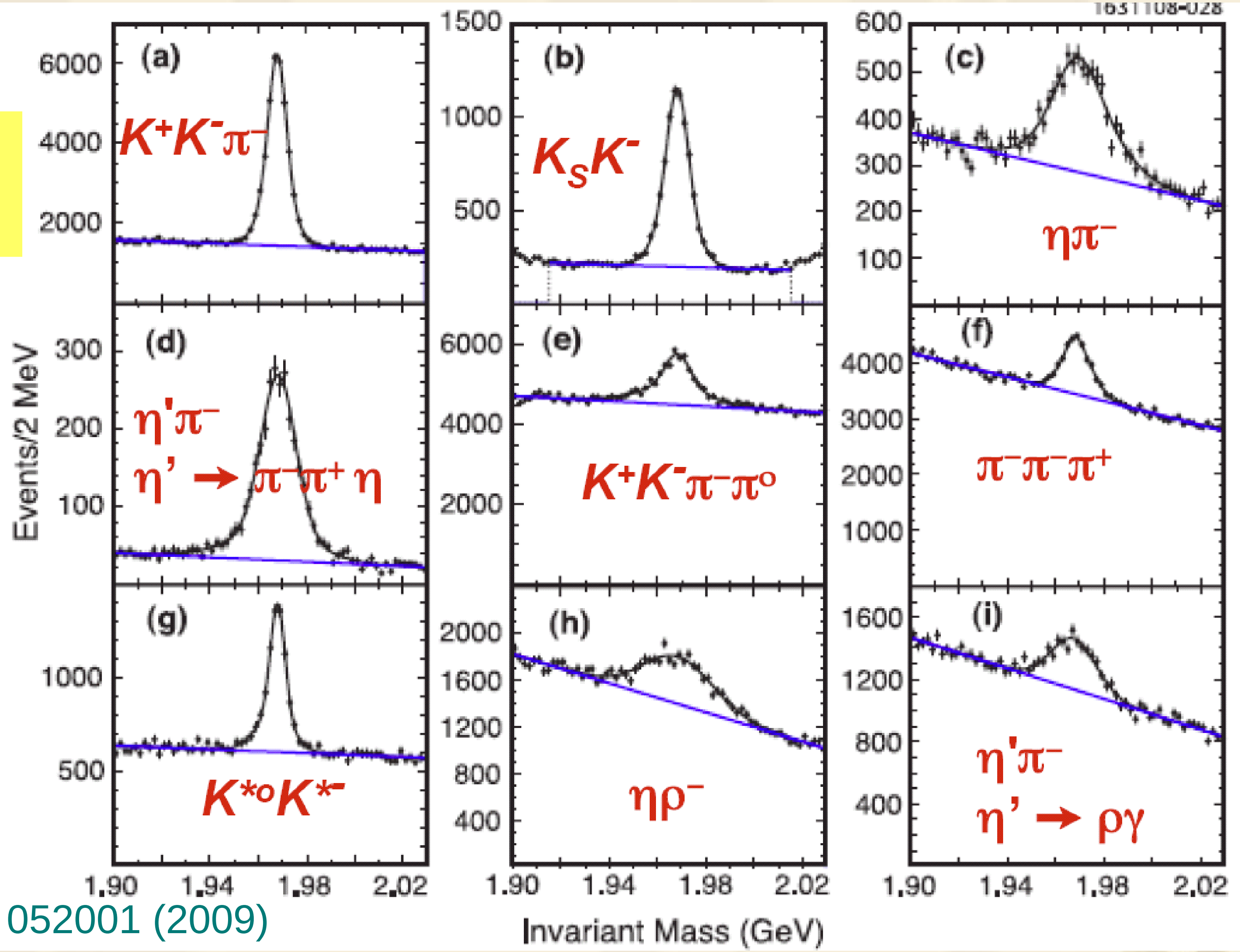
CLEO-c PRD 80, 072001 (2009)

Ds tag modes

Fully reconstruct Ds γ, to look for another Ds.

Invariant mass of 9 tag modes

In the fit:
Signal: Double Gaussian center at zero;
Bakgrd: linear Poly.



CLEO: PRD 79, 052001 (2009)

Combined Ds tag

In the fit:
Signal: Double
Gaussian center
at zero;
Bakgrd:
linear Poly.

CLEO: PRD 79, 052001 (2009)

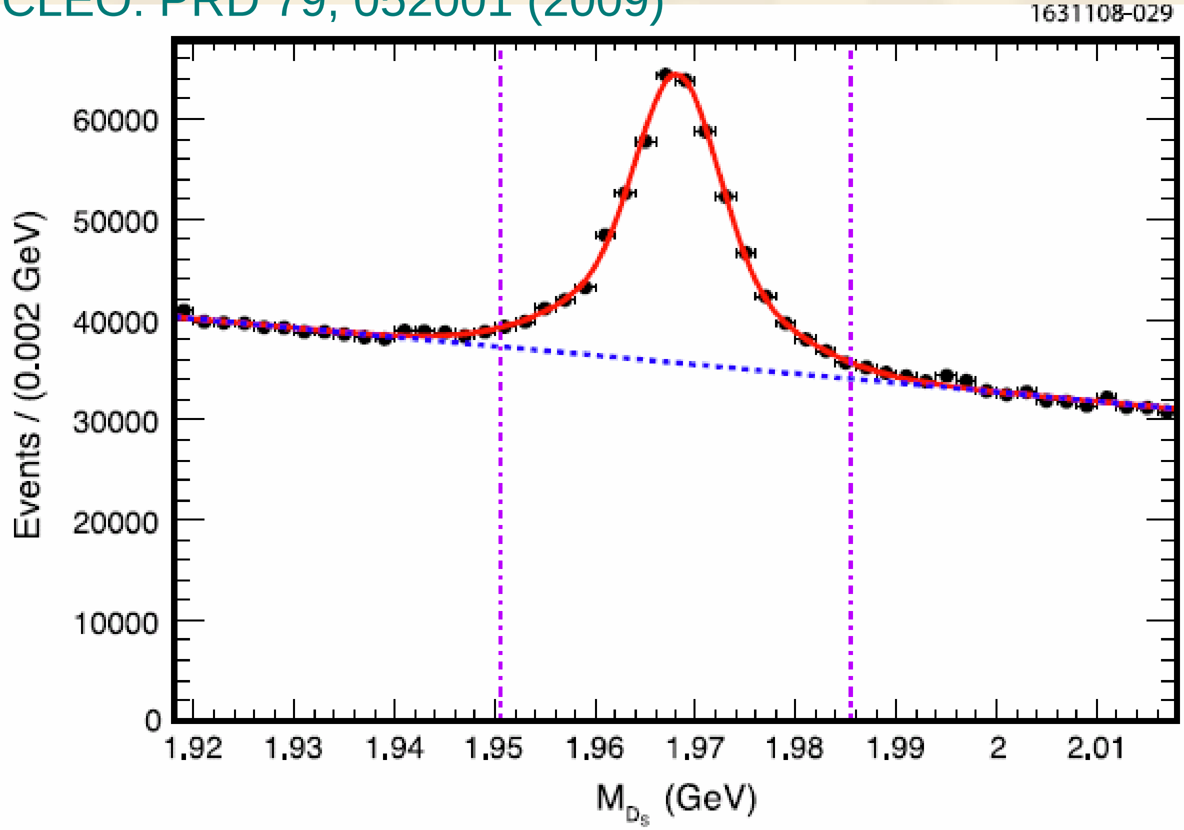


FIG. 4 (color online). Invariant mass of D_s^- candidates summed over all decay modes and fit to a two-Gaussian signal shape plus a straight line for the background. The vertical dot-dashed lines indicate the ±17.5 MeV definition of the signal region.

Missing-mass*^{2} against Ds+γ system – Ds γ tag

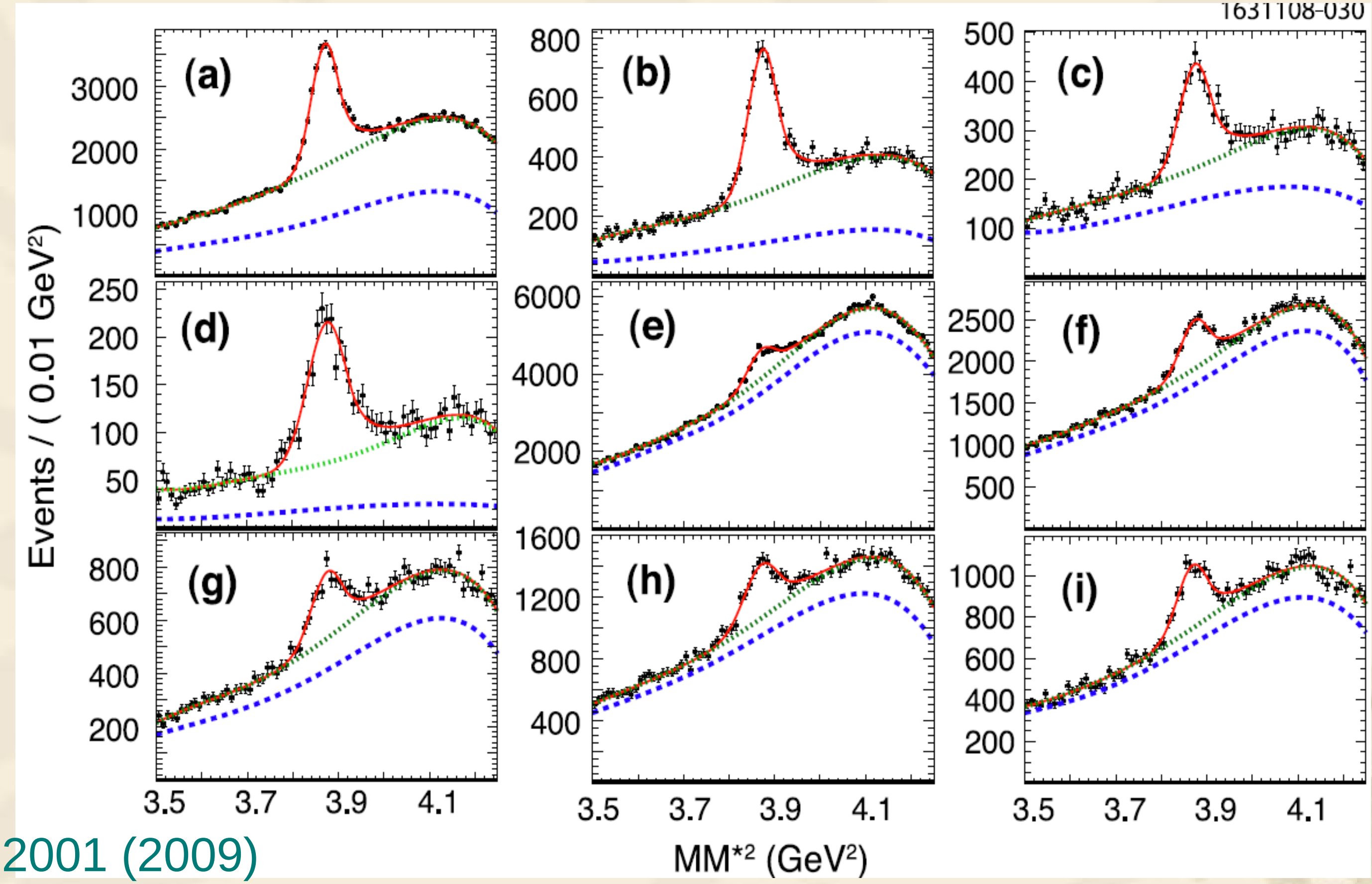
Look at missing mass after adding photon (from Ds*→Dsγ)
Plot missing-mass^2 against Ds γ system.

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

Peak at $(M_{Ds})^2$

Need photon to fully constrain the other Ds….

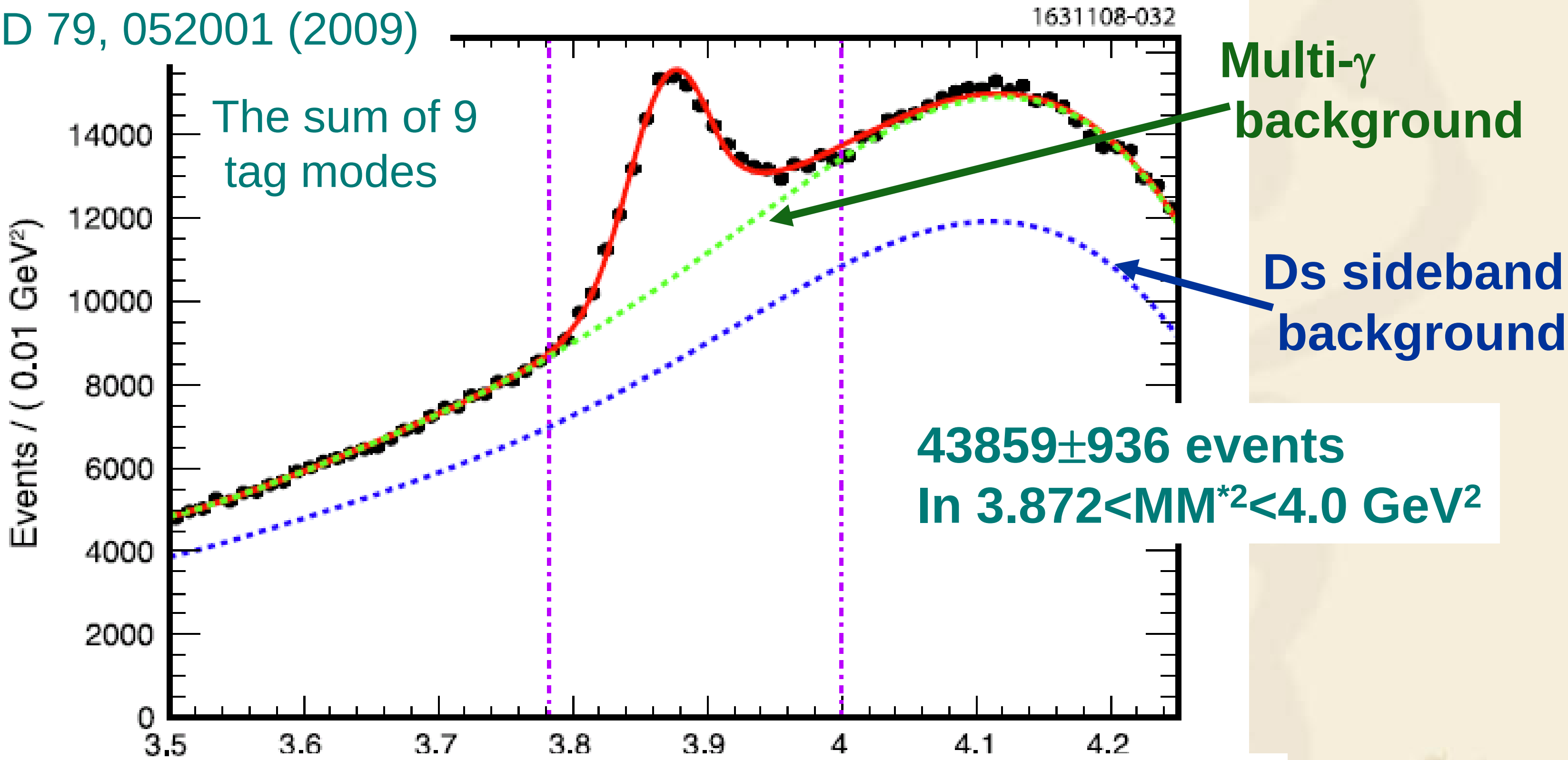
Signal: CB function
Backg: Chebychev Poly.;



CLEO: PRD 79, 052001 (2009)

Combined Ds *plus* γ tag

CLEO: PRD 79, 052001 (2009)



43859±936 events
In 3.872<MM^{*2}<4.0 GeV^2

Peak at $(M_{Ds})^2$

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

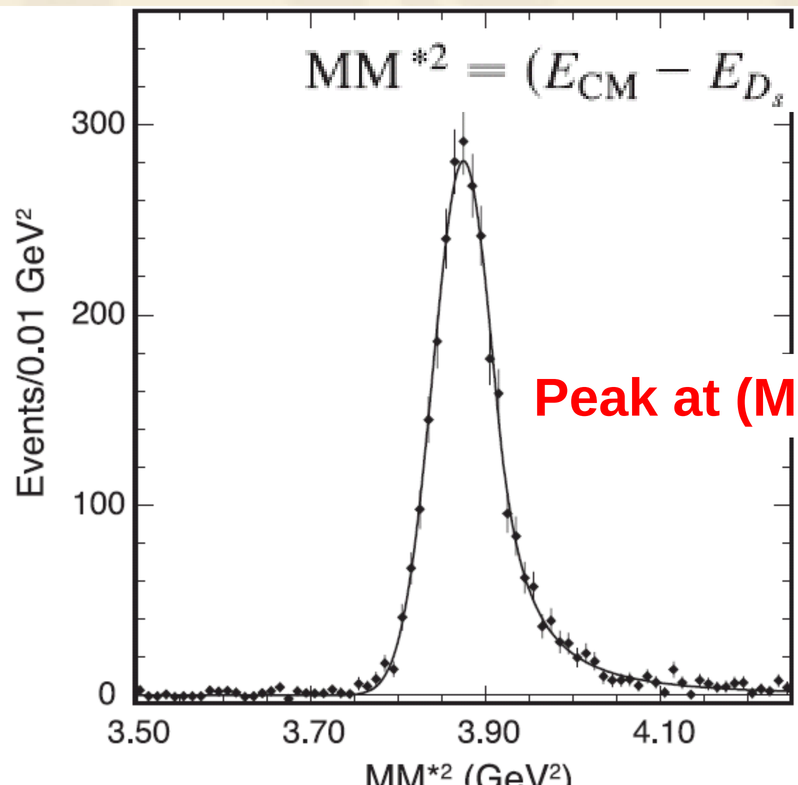
FIG. 7 (color online). The MM^2 distribution summed over all modes. The curves are fits to the number of signal events using the Crystal-Ball function and two 5th order Chebychev background functions (see text). The vertical lines show the region of events selected for further analysis.

Clean double tag – control sample

From data:

- **Fully reconstruct both sides for "zero" background**
- **Ignore one Ds to see resolution of MM^{*2}**
- **To see the signal lineshape in the fit to MM^{*2} in previous slides**
- **Tail is mostly independent of tag mode (depends on ISR, photon detection, beam spread)**

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



Peak at $(M_{Ds})^2$

$e^+e^- \to Ds^{*-}Ds^+$ +c.c. → $Ds^+Ds^-\gamma$ both Ds' are fully reconstructed.

Crystal ball function for signal;
Resolution from data:
0.035 ± 0.001 GeV²

Ds tag samples

Mode	Invariant Mass		MM^{*2}	
	Signal	Background	Signal	Background
$K^+K^-\pi^-$	26 534 ± 274	25 122	16 087 ± 373	39 563
K_SK^-	6383 ± 121	3501	4215 ± 228	6297
$\eta\pi^-$; $\eta \to \gamma\gamma$	2993 ± 156	5050	2005 ± 145	5016
$\eta'\pi^-$; $\eta' \to \pi^+\pi^-\eta$, $\eta \to \gamma\gamma$	2293 ± 82	531	1647 ± 131	1565
$K^+K^-\pi^-\pi^0$	11 649 ± 754	78588	6441 ± 471	89 284
$\pi^+\pi^-\pi^-$	7374 ± 303	60 321	5014 ± 402	43 286
$K^{*-}K^{*0}$; $K^{*-} \to K^0_S\pi^-$, $K^{*0} \to K^+\pi^-$	4037 ± 160	10 568	2352 ± 176	12 088
$\eta\rho^-$; $\eta \to \gamma\gamma$, $\rho^- \to \pi^-\pi^0$	5700 ± 281	24 444	3295 ± 425	24 114
$\eta'\pi^-$; $\eta' \to \rho^0\gamma$,	3551 ± 202	19 841	2802 ± 227	17 006
Sum	70 514 ± 963	227 966	43 859 ± 936	238 218

CLEO: PRD 79, 052001 (2009)

Reconstruction of signal $D_s \to \mu\nu$

One additional charged track, μ, is reconstructed and the missing mass is calculated by consider the Ds, γ, and μ, the signal should be peak at zero for the single missing neutrino:

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

CLEO: PRD 79, 052001 (2009)

Kinematical constraint fits:

$$\mathbf{p}_{D_s} + \mathbf{p}_{D_s^*} = 0, \qquad E_{\mathrm{CM}} = E_{D_s} + E_{D_s^*},$$
$$E_{D_s^*} = \frac{E_{\mathrm{CM}}}{2} + \frac{M_{D_s^*}^2 - M_{D_s}^2}{2E_{\mathrm{CM}}} \quad \text{or } E_{D_s} = \frac{E_{\mathrm{CM}}}{2} - \frac{M_{D_s^*}^2 - M_{D_s}^2}{2E_{\mathrm{CM}}},$$
$$M_{D_s^*} - M_{D_s} = 143.8 \text{ MeV}. \qquad (7)$$

Double Gaussian center at zero for signal:

$$\sigma \equiv f_1\sigma_1 + (1 - f_1)\sigma_2,$$

Resolution of MM^2 from MC:

$$\sigma = 0.0346 \pm 0.0002 \text{ GeV}^2$$

PHYSICAL REVIEW D **79,** 052001 (2009)

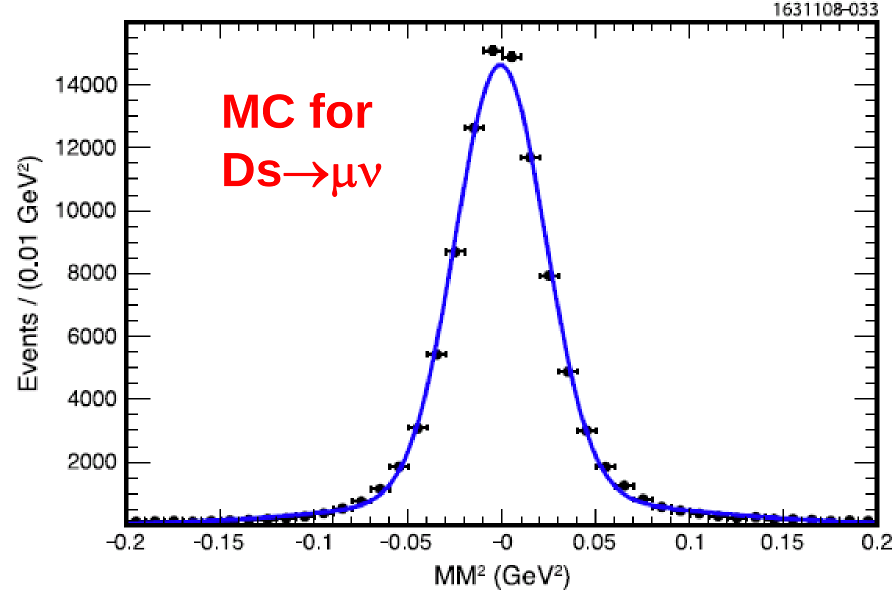


FIG. 8 (color online). The MM^2 resolution from Monte Carlo simulation for $D_s^+ \to \mu^+\nu$. The curve is the sum of two-Gaussians with means constrained to be the same.

Signal MM^2 Line Shape

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

Can we trust MC ?

Check with data !

Mostly $D_s \to K^0 K^-$
Find track,
ignore neutral K

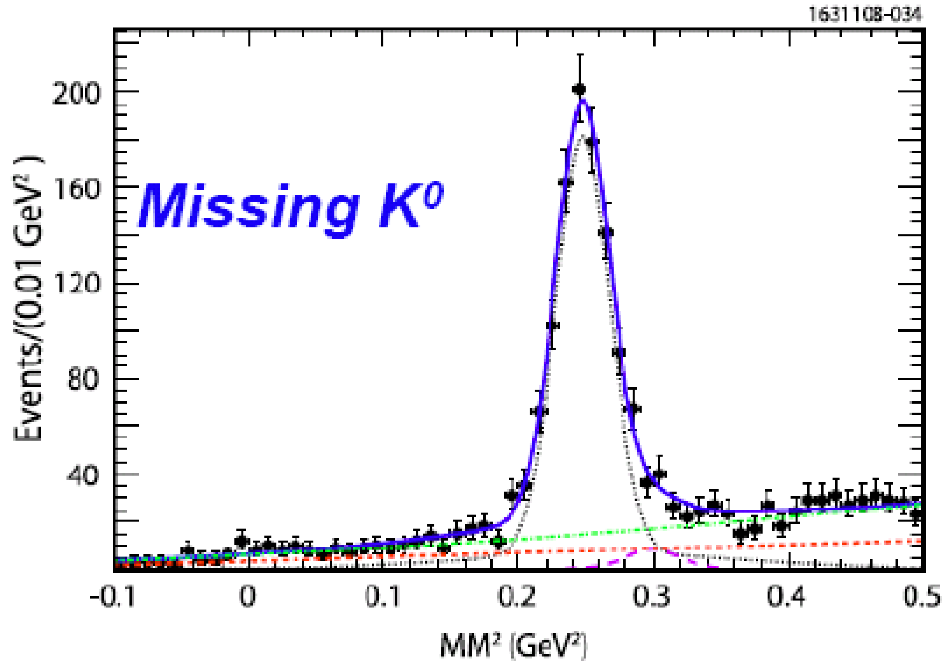


FIG. 9 (color online). The MM^2 distribution for events with an identified K^+ track. The kinematic fit has been applied. The data are shown as points with error bars. The long-dashed curve shows the calculated yield of ηK^+ events. The solid curve shows the results of a fit to the data, where the dotted curve is the sum of two-Gaussians centered at the square of the K^0 mass, and the dashed and dot-dashed lines refer to the sideband, and combinatoric backgrounds, respectively.

Resolution from data:

$$\sigma = 0.0338 \pm 0.0014 \text{ GeV}^2$$

From MC:
$\sigma = 0.0344 \pm 0.0003 \text{ GeV}^2$

Final dataset

Three cases datasets:

For the signal track deposits in CsI:

case i: E <300 MeV;

dominated by Ds→$\mu\nu$

98.8% muons,

55% pions (Ds→ π^++X)

but ½ Ds→ $\tau\nu$ ($\tau\to\pi\nu$)

case ii: E> 300 MeV;

1.2% muons, 45% pions

dominated by another ½

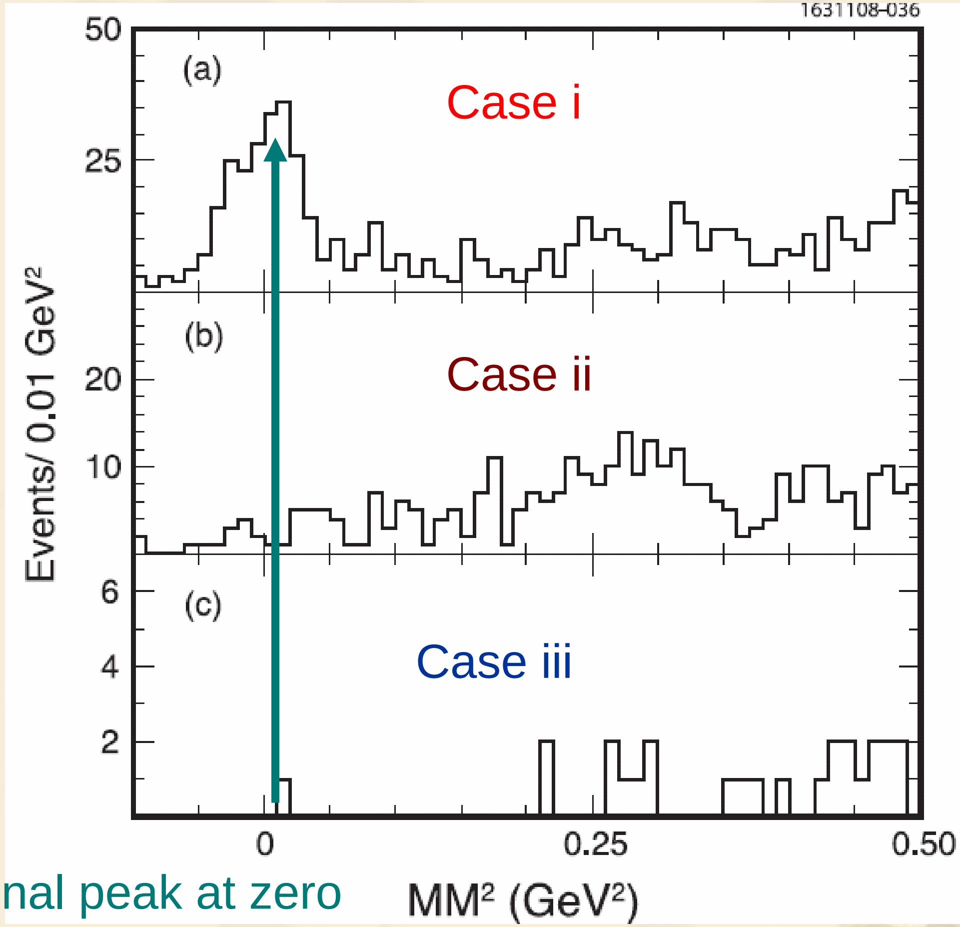
Ds→ $\tau\nu$ ($\tau\to\pi\nu$)

(very little Ds→$\mu\nu$)

If the signal track is identified as electron:

case iii: Ds→ e ν measurement.

CLEO: PRD 79, 052001 (2009)



Signal peak at zero

$D_s \to \mu^+\upsilon$ & $\tau^+\upsilon$

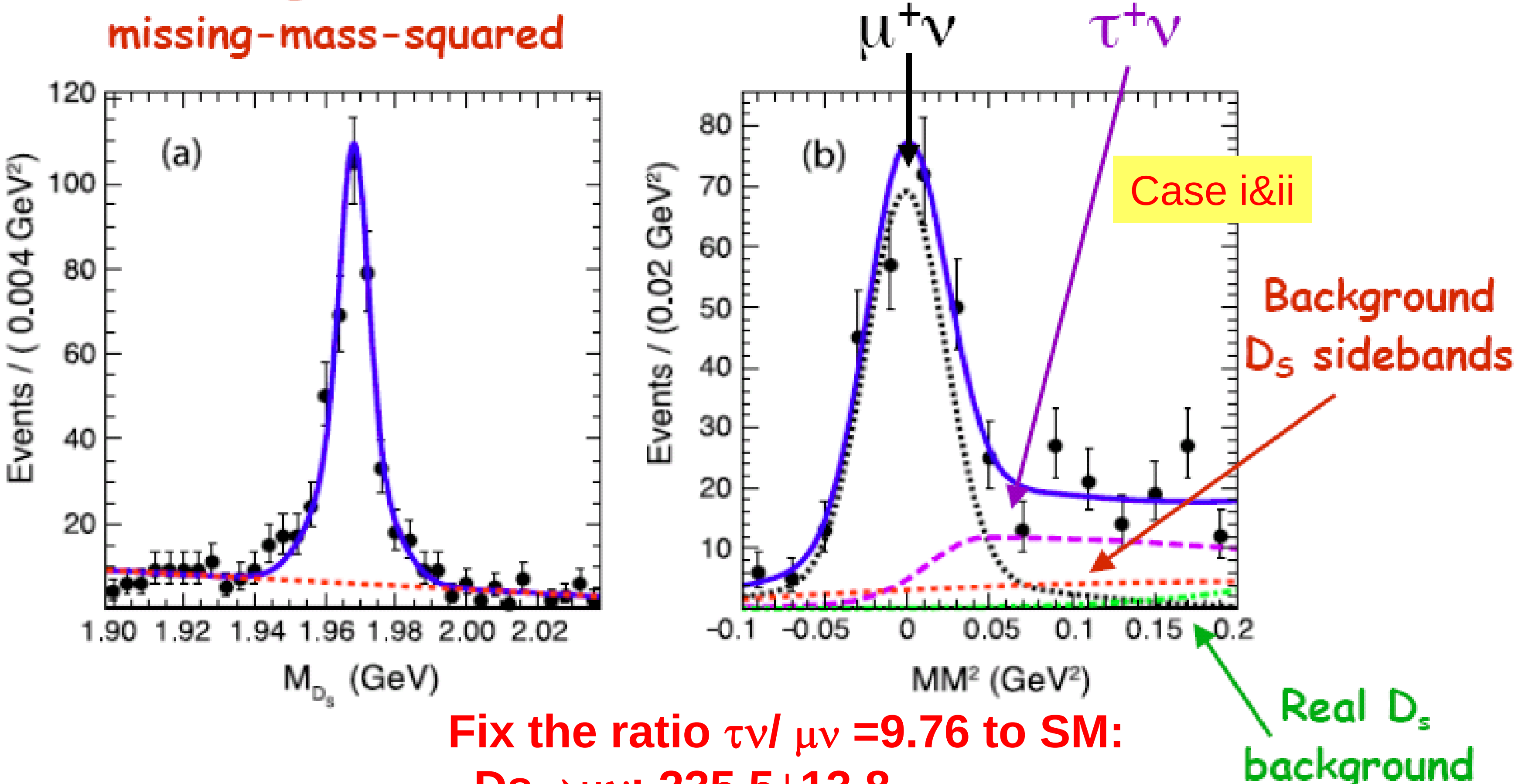
($\tau^+ \to \pi\,\upsilon$)

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

Combined case i and case ii data:

2-dimensional fit to D_s Tag mass and missing-mass-squared

Two signal modes



Fix the ratio $\tau\nu/\mu\nu$ =9.76 to SM:

$D_s \to \mu\nu$: 235.5±13.8

Backgrounds

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

TABLE II. Background estimates for the data in the signal region $-0.1 < MM^2 < 0.2$ GeV^2. (We assume $\mathcal{B}(D_s^+ \to \tau^+ \nu) = 6.2 \pm 0.7\%$.)

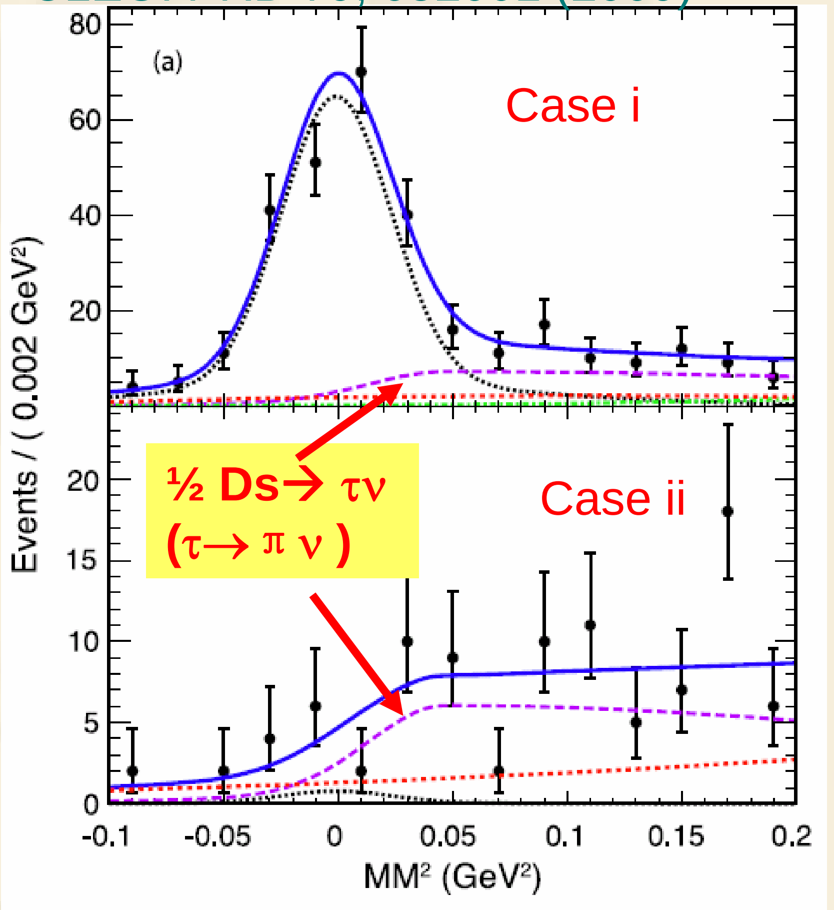
Final State	$\mathcal{B}$ (%)	# of events case(i)	# of events case (ii)
$\tau^+ \to \pi^+ \pi^0 \bar{\nu}$	1.6 ± 0.2	2.06 ± 0.34	1.43 ± 0.36
$\tau^+ \to \mu^+ \nu \bar{\nu}$	1.1 ± 0.1	1.60 ± 0.24	0
$D_s^+ \to \pi^+ \pi^0 \pi^0$	1.1 (estimate)	0.12	0.12
$D_s^+ \to K^0 \pi^+$	0.24 ± 0.03	1.3 ± 0.3	1.1 ± 0.3
$D_s^+ \to \eta \pi^+$	1.5 ± 0.2	1.1 ± 0.3	0.9 ± 0.3
Sum		6.2 ± 0.7	3.5 ± 0.6

Rates are for full range of signal plots I've shown…

For reference, $\mu^+\upsilon$ signal is 235.5 ± 13.8 events

Ds→μν & Ds→τν (π ν): case i&ii

CLEO: PRD 79, 052001 (2009)



Absolute branching fraction:

$$Br(D_S \to l^+ \nu_\mu) = \frac{N^{observed}_{D_S \to l\nu}}{\varepsilon_{D_S \to l\nu} \times N_{tagged-D_S}}$$

Fix τν/ μν at SM ratio of 9.76 :

$$\mathcal{B}^{\rm eff}(D_s^+ \to \mu^+ \nu) = (0.591 \pm 0.037 \pm 0.018)\%.$$

Float τν/ μν :

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

$$\mathcal{B}(D_s^+ \to \tau^+ \nu) = (6.42 \pm 0.81 \pm 0.18)\%.$$

$$\mathcal{B}(D_s^+ \to e^+ \nu) < 1.2 \times 10^{-4}$$ @90% C.L.

$$R \equiv \frac{\Gamma(D_s^+ \to \tau^+ \nu)}{\Gamma(D_s^+ \to \mu^+ \nu)} = 11.4 \pm 1.7 \pm 0.2.$$

→ **SM prediction: 9.76**

Systematic Errors

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

Error on f_{D_s} 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!)

CP violation

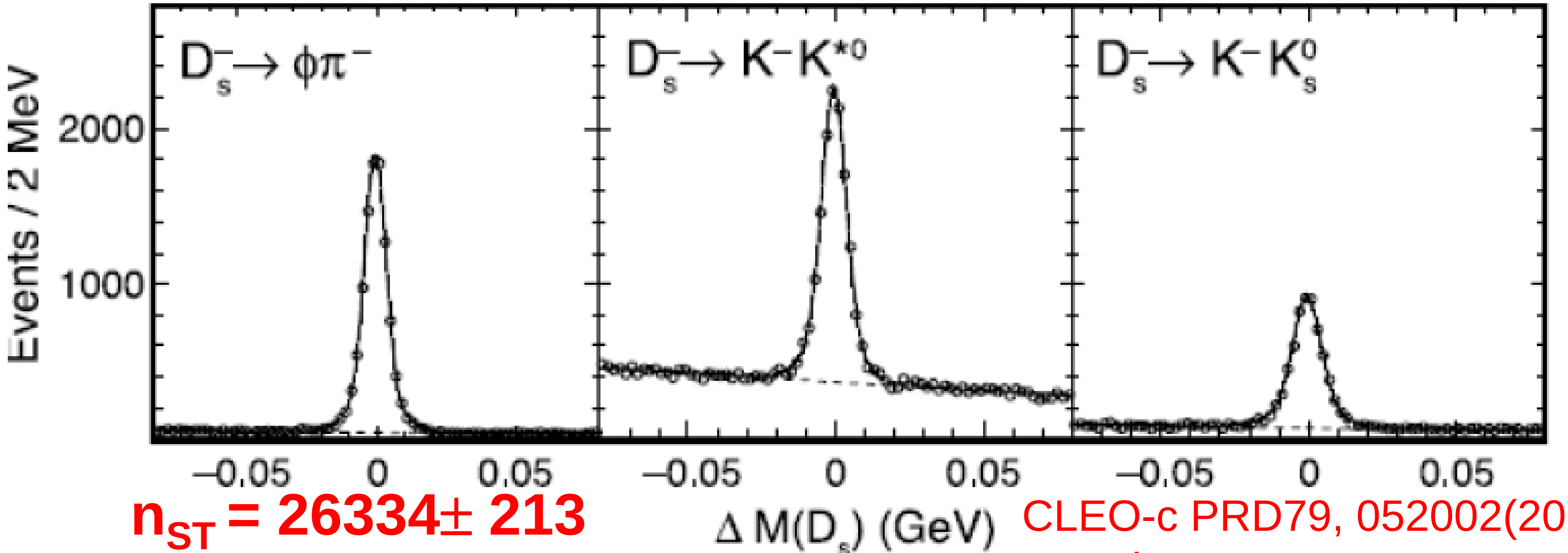
- **Ds– tag: 21807± 581**
- **Ds+ tag: 21370± 581**
- **μ–ν events: 124 ±9.9**
- **μ+ν events: 110.8 ±9.6**

$$\frac{\Gamma(D_s^+ \to \mu^+ \nu) - \Gamma(D_s^- \to \mu^- \bar{\nu})}{\Gamma(D_s^+ \to \mu^+ \nu) + \Gamma(D_s^- \to \mu^- \bar{\nu})} = 0.048 \pm 0.061,$$

CLEO: PRD 79, 052001 (2009)

CLEO: $D_S^+ \to \tau^+\nu$, $\tau^+ \to e^+\nu\nu$

- $\mathcal{B}(D_S^+ \to \tau^+\nu) \bullet \mathcal{B}(\tau^+ \to e^+\nu\nu) \sim 1.3\%$ is "large" compared with expected $\mathcal{B}(D_S^+ \to X e^+\nu) \sim 8\%$
- We will be searching for events opposite a tag with one electron and not much other energy
- Opt to use only a subset of the cleanest tags



n_{ST} = 26334± 213

CLEO-c PRD79, 052002(2009)
600pb-1

Another method E_{extra} $Ds \to \tau\nu, \tau \to e\nu_e\nu_\tau$

Always have >1 neutrino! Abandon use of MM^2

Technique is to find single tag candidates with an electron with momentum >200 MeV & no other tracks, with extra energy in calorimeter: E_{extra} <400 MeV (we get our DT sample).

Extra energy is sum of neutral shower energy (>30 MeV) in EMC, these showers must not be associated with any of the ST decay tracks, or the signal electron.

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

No need to find γ from Ds* decays:
$e^+e^- \to D^*_sD_s \to D_s^+D_s^-\gamma$: only one Ds is fully reconstructed and look at the other Ds in signal side.

CLEO-c PRD79, 052002(2009)
600pb-1

Plot of E_{extra}

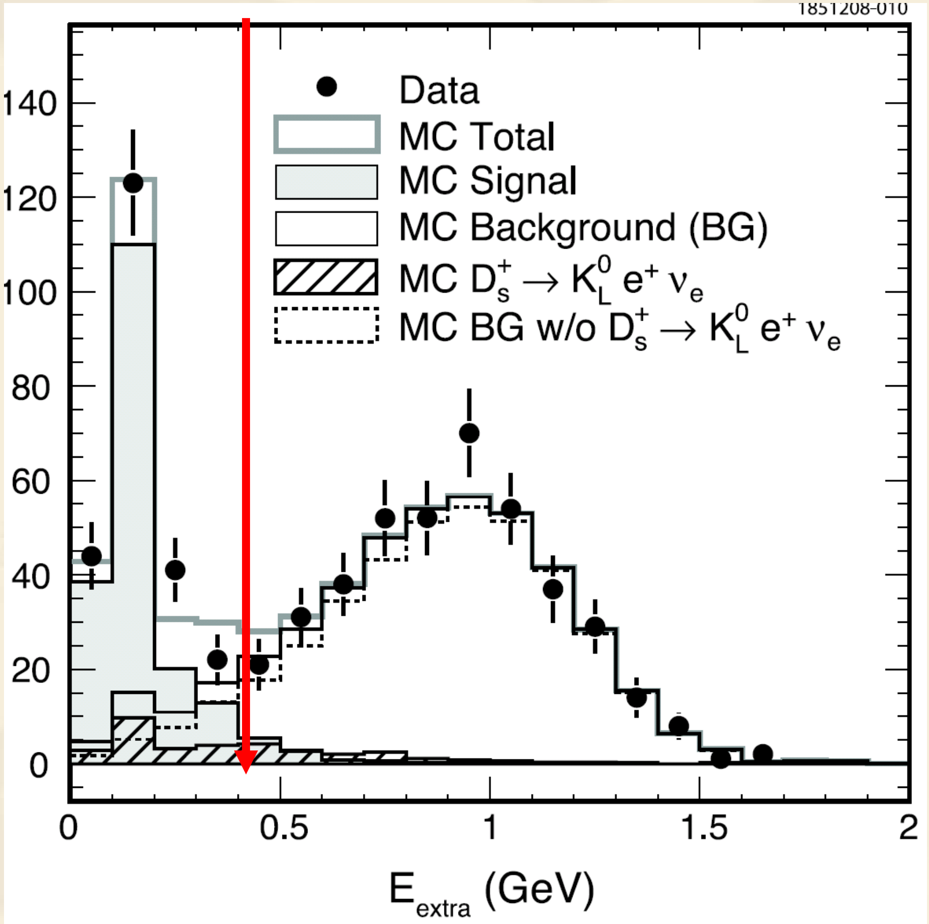
CLEO-c PRD79, 052002(2009)
600pb-1

Signal region: <400 MeV

Extra energy peaks away from zero
E_{extra} can include γ from Ds* decay

Ds→ $\tau\nu\gamma$ is also included as signal however, this is expected to be very small, as the kinetic energy of τ in the Ds rest frame is only 9.3 MeV.

The peaking background
Ds →K_L eν which can be simulated and determined by using expected number from MC simulation.
Normalized to the measured:
Br(Ds →Ks eν) = (0.19±0.05±0.01)%



Measurement of $D_s \to \tau\nu, \tau \to e\nu_e\nu_\tau$ @CLEO-c

CLEO-c PRD79, 052002(2009)
600pb^{-1}

Summary of DT yield in each tag mode:

Tag mode	n_{DT}^{S}	n_{DT}^{B}	s	b	n_{DT}
$D_s^- \to \phi\pi^-$	79	1	0.980	19.4 ± 1.1	58.6 ± 9.0
$D_s^- \to K^-K^{*0}$	110	6	1.000	20.9 ± 1.3	83.1 ± 10.8
$D_s^- \to K^-K_S^0$	50	2	0.999	9.1 ± 0.7	38.9 ± 7.2
Total				49.4 ± 1.8	180.6 ± 15.9

Average efficiency ε, and tag bias, b_{tag}

Tag mode	w	$\epsilon \equiv \epsilon_{DT}/\epsilon_{ST}$	$b_{tag} = \epsilon'_{ST}/\epsilon_{ST}$
$D_s^- \to \phi\pi^-$	0.3671	0.6964 ± 0.0046	1.0089 ± 0.0058
$D_s^- \to K^-K^{*0}$	0.4154	0.7337 ± 0.0049	1.0061 ± 0.0060
$D_s^- \to K^-K_S^0$	0.2175	0.7536 ± 0.0054	1.0032 ± 0.0065
Average		0.7244 ± 0.0029	1.0065 ± 0.0036

A few word on efficiencies in ST and DT

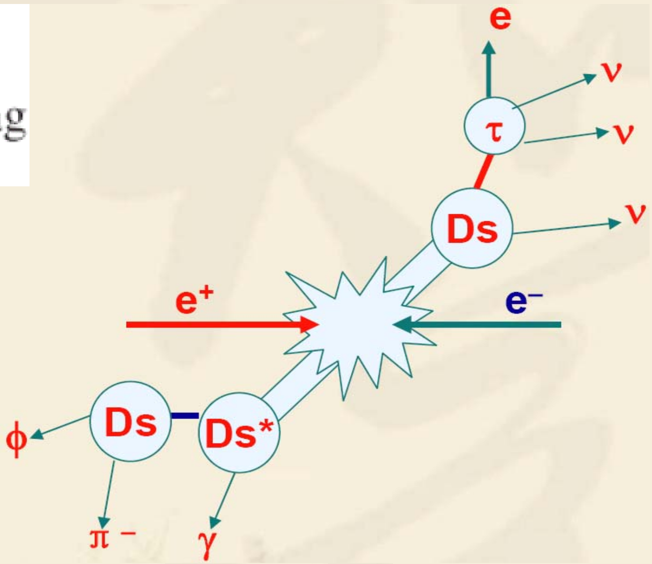
CLEO-c PRD79, 052002(2009)
600pb-1

$$\mathcal{B}_{\mathrm{L}} = \frac{n_{\mathrm{DT}}}{n_{\mathrm{ST}}} \frac{\epsilon_{\mathrm{ST}}}{\epsilon_{\mathrm{DT}}} = \frac{n_{\mathrm{DT}}/\epsilon}{n_{\mathrm{ST}}}, \qquad (4)$$

where $\epsilon (\equiv \epsilon_{\mathrm{DT}}/\epsilon_{\mathrm{ST}})$ is the effective signal efficiency. Because of the large solid angle acceptance with high segmentation of the CLEO-c detector and the low multiplicity of the events with which we are concerned, $\epsilon_{\mathrm{DT}} \approx \epsilon_{\mathrm{ST}}\epsilon_{\mathrm{L}}$, where ϵ_{L} is the leptonic decay efficiency. Hence, the ratio $\epsilon_{\mathrm{DT}}/\epsilon_{\mathrm{ST}}$ is insensitive to most systematic effects associated with the ST, and the signal branching fraction $\mathcal{B}_{\mathrm{L}}$ obtained using this procedure is nearly independent of the efficiency of the tagging mode.

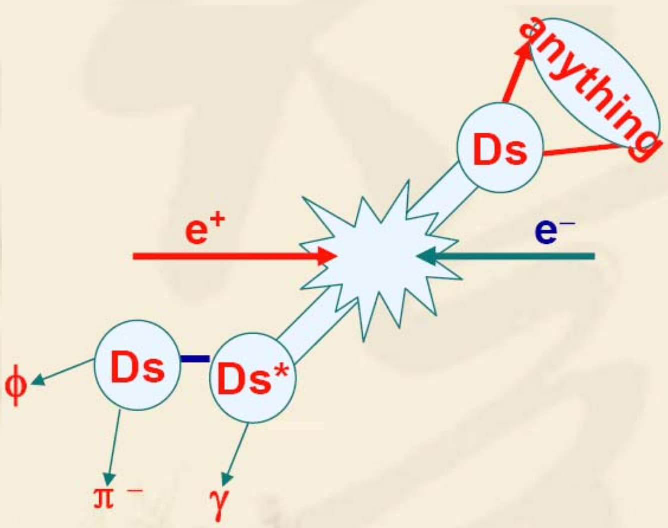
Tag bias due to the correlation between tag side and signal side reconstructions

$$\epsilon = \frac{\epsilon_{\rm DT}}{\epsilon_{\rm ST}} = \frac{\epsilon_{\rm DT}}{\epsilon'_{\rm ST}}\frac{\epsilon'_{\rm ST}}{\epsilon_{\rm ST}} = \frac{\epsilon_{\rm L}\epsilon'_{\rm ST}}{\epsilon'_{\rm ST}}\frac{\epsilon'_{\rm ST}}{\epsilon_{\rm ST}} = \epsilon_{\rm L} b_{\rm tag}$$



ε'_{ST} Single tag efficiency: the recoiling system is signal leptonic decay in the other side of tag mode.

ε_{ST} Single tag efficiency: the recoiling system is Ds decay to anything.



Sizable tag bias could be introduced if the multiplicity of the tag mode were high, or tag mode were include neutral particles in the final state.

$$\varepsilon'_{ST} < \varepsilon_{ST}$$

Tag bias due to the correction between tag side and signal side reconstruction

TABLE III. Summary of the signal efficiency determined by MC simulation. Average efficiency ϵ and the tag bias $b_{\rm tag}$ are obtained by using the weighting factor w determined from single-tag yields in data.

Tag mode	w	$\epsilon \equiv \epsilon_{\rm DT}/\epsilon_{\rm ST}$	$b_{\rm tag} = \epsilon'_{\rm ST}/\epsilon_{\rm ST}$
$D_s^- \to \phi\pi^-$	0.3671	0.6964 ± 0.0046	1.0089 ± 0.0058
$D_s^- \to K^- K^{*0}$	0.4154	0.7337 ± 0.0049	1.0061 ± 0.0060
$D_s^- \to K^- K_S^0$	0.2175	0.7536 ± 0.0054	1.0032 ± 0.0065
Average		0.7244 ± 0.0029	1.0065 ± 0.0036

btag is almost equal to 1.0, and the tag mode selected is clean and tag bias is small.

CLEO-c PRD79, 052002(2009)
600pb-1

Branching fraction from Ds→τν, τ→eνν

The decay constant f_{D_s} can be computed using Eq. (1) with known values [3] $G_F = 1.166\,37(1) \times 10^{-5}$ GeV^{-2}, $m_{D_s} = 1968.49(34)$ MeV, $m_\tau = 1776.84(17)$ MeV, and $\tau_{D_s} = 500(7) \times 10^{-15}$ s. We assume $|V_{cs}| = |V_{ud}|$ and use the value 0.974 18(26) given in Ref. [27]. We obtain

$$\Gamma(P_{Q\bar{q}} \to \ell^+ \nu_\ell) = \frac{G_F^2 |V_{Qq}|^2 f_P^2}{8\pi} m_P m_\ell^2 \left(1 - \frac{m_\ell^2}{m_P^2}\right)^2, \quad (1)$$

$$f_{D_s} = (252.5 \pm 11.1 \pm 5.2)\ \text{MeV}. \quad (9)$$

Note: rad. corr. is small,

since tau has only 9 MeV kin. E

$$\mathcal{B}(D_s^+ \to \tau^+ \nu_\tau) = (5.30 \pm 0.47 \pm 0.22)\%,$$

Source	Effect on $\mathcal{B}$ (%)
Background (nonpeaking)	0.7
$D_s^+ \to K_L^0 e^+ \nu_e$ (peaking)	3.2
Extra shower	1.1
Extra track	1.1
$Q_{\text{net}} = 0$	1.1
Non electron	0.1
Secondary electron	0.3
Number of tag	0.4
Tag bias	0.2
Tracking	0.3
Electron identification	1.0
FSR	1.0
Total	4.1

CLEO-c PRD79, 052002(2009)
600pb-1

Source of systematic error

$D_s^+ \to \tau^+ \nu$, $\tau^+ \to \rho^+ \nu$

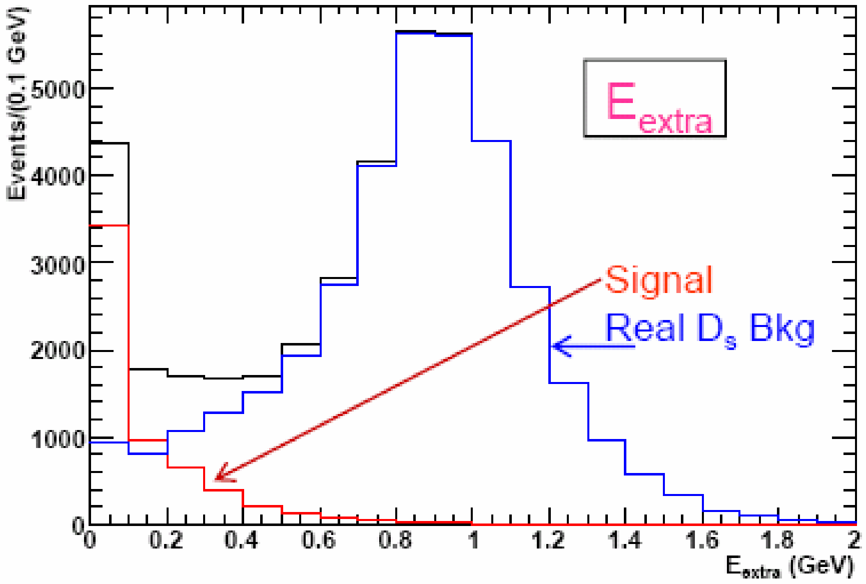
CLEO, PRD 80, 112004(2009)

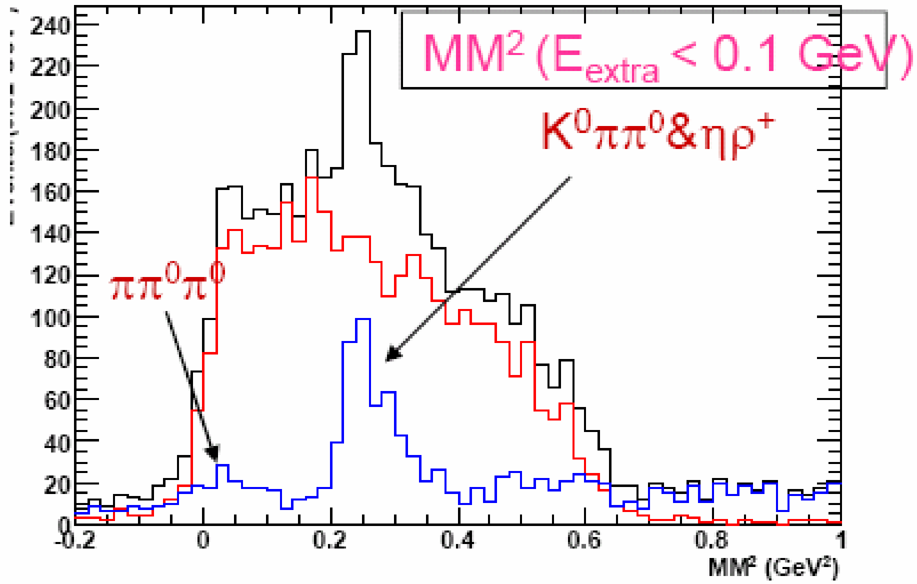
- Because of the two neutrinos, the signal does not peak in MM^2, but the most important backgrounds do
- Use E_{extra} as an important discriminant

Analysis for Ds→τν, τ→ρ+ν

CLEO, PRD 80, 112004(2009)

- Signal and MC predicted backgrounds





- Measure the $\mathcal{B}$ of the 3 indicated peaking modes. Use same set of D_S^- tags. Find:

$$\mathcal{B}(D_s^+ \to K^0\pi^+\pi^0) = (1.00 \pm 0.18 \pm 0.04)\%,$$
$$\mathcal{B}(D_s^+ \to \pi^+\pi^0\pi^0) = (0.65 \pm 0.13 \pm 0.03)\%,$$
$$\mathcal{B}(D_s^+ \to \eta\rho^+) = (8.9 \pm 0.6 \pm 0.5)\%.$$

Analysis for $Ds \to \tau\nu$, $\tau \to \rho + \nu$

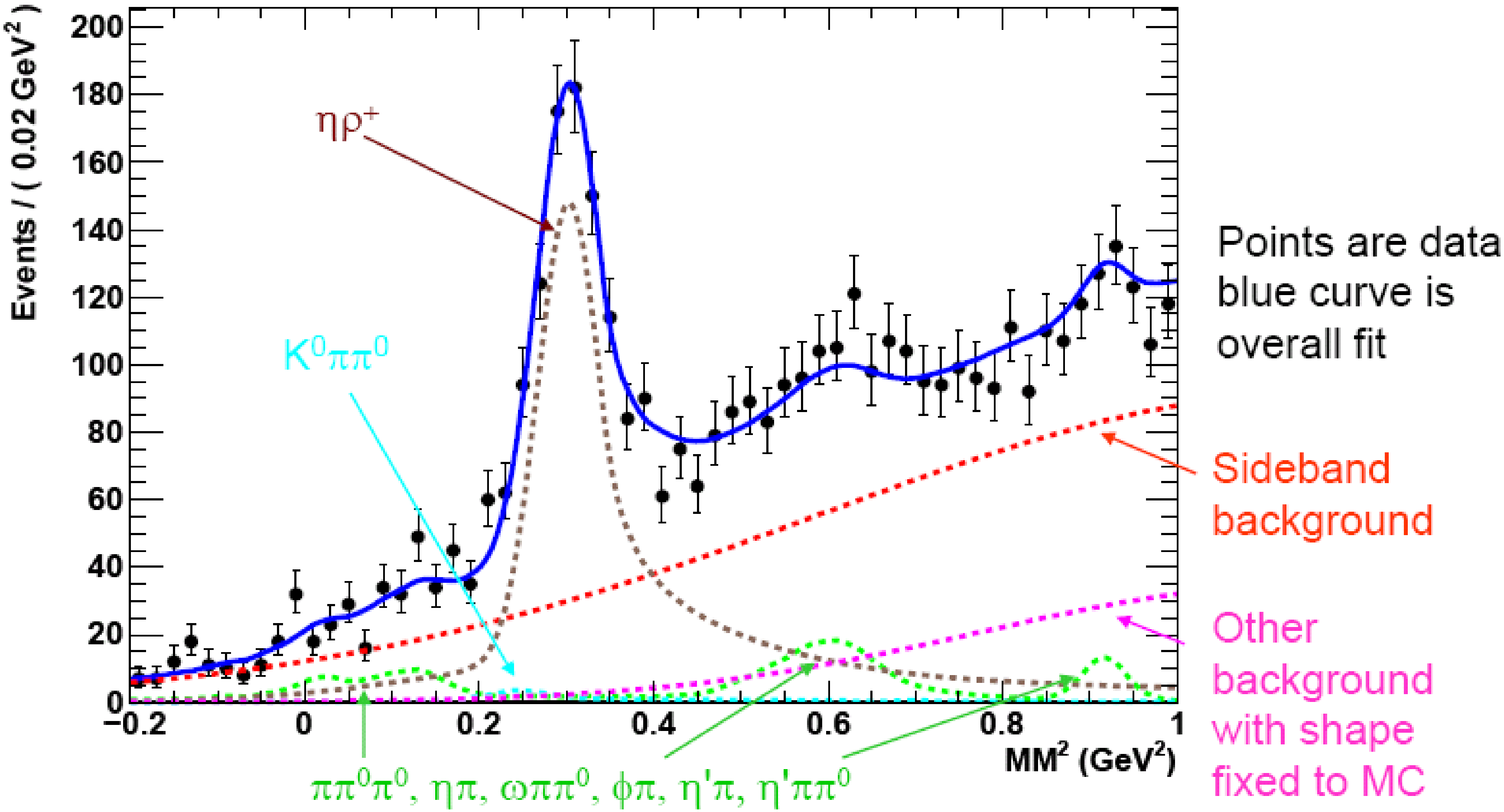
CLEO, PRD 80, 112004(2009)

- We will fit simultaneously the invariant tag mass & the MM^2 distributions, separately in three E_{extra} intervals, <0.1 GeV where signal dominates, (0.1, 0.2) GeV where S & B are equivalent, and >0.8 GeV for checking of understanding background, where signal is absent.
- In the fits, we put Gaussian constraints on the bkgrnd yields using known branching fractions and their errors. For the remaining sum of small modes we use the MC estimated rate with a rather large error. Thus the uncertainties in the background will be taken care of in the statistical error.

Fit to E_{extra} > 0.8 GeV

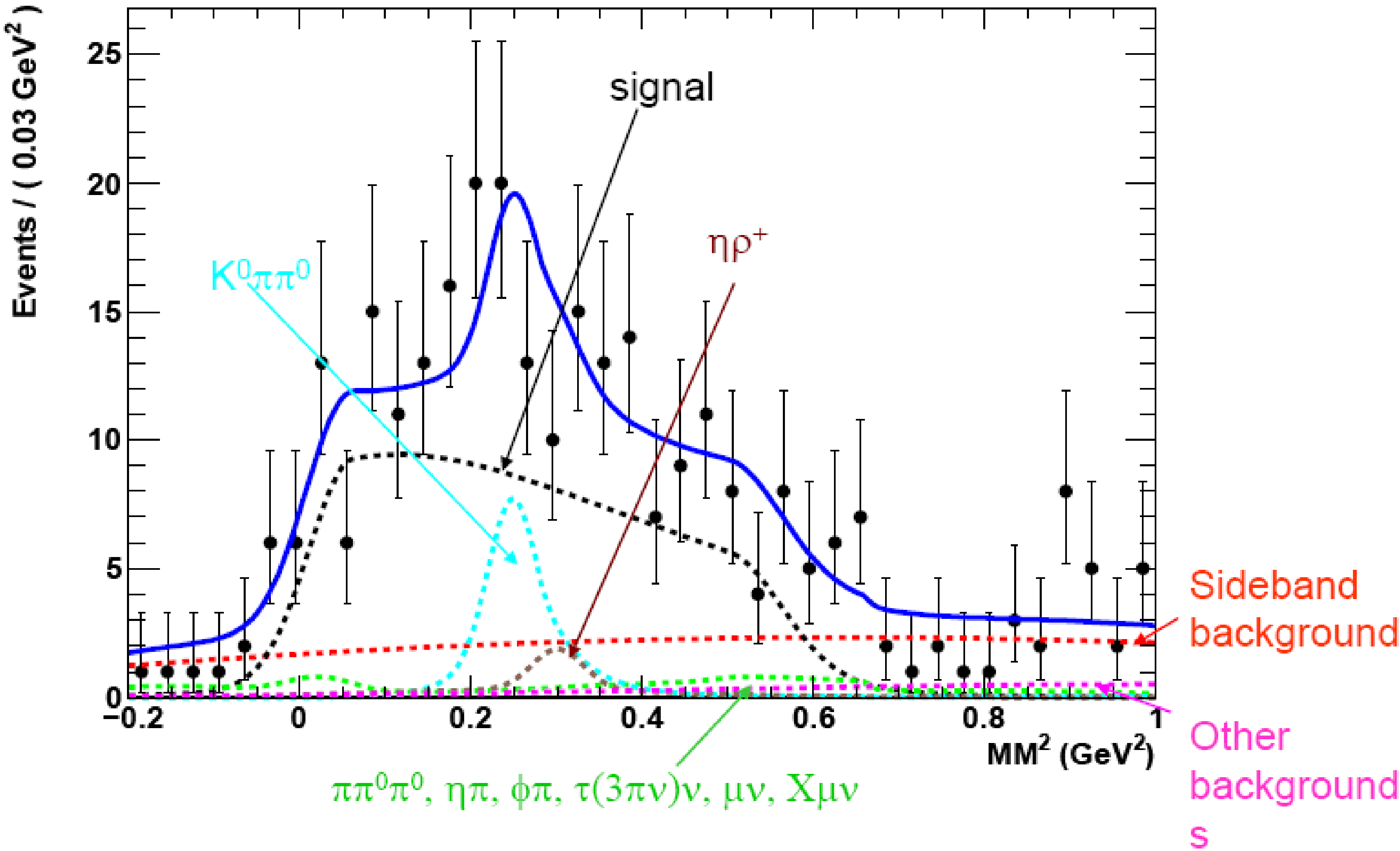
CLEO, PRD 80, 112004(2009)

No signal, fit consistent with bkgrnd expectations



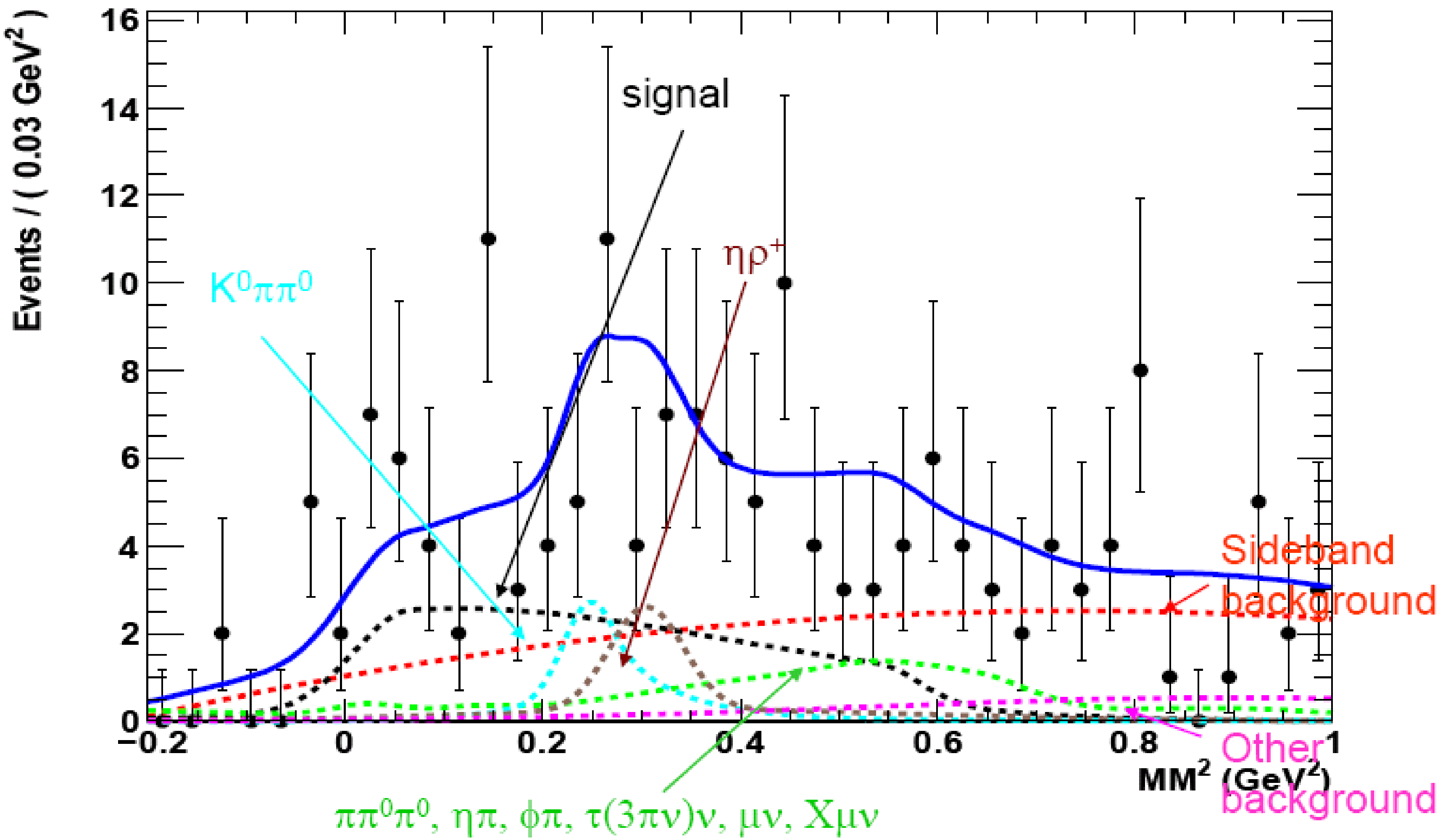
Signal Region I: E_{extra}<0.1 GeV

CLEO, PRD 80, 112004(2009)



Signal Region II: $0.1<E_{extra}<0.2$ GeV

CLEO, PRD 80, 112004(2009)



Branching fraction from $D_s \to \tau\nu$, $\tau \to \rho + \nu$

CLEO, PRD 80, 112004(2009)

$E_{extra} \in$	Signal yields	Efficiency	$\mathcal{B}(D_s^+ \to \tau^+\nu)$
[0,100] MeV	155.2 ± 16.5	25.3%	**$(5.48 \pm 0.59)\%$**
[100,200] MeV	43.7 ± 11.3	6.9%	**$(5.65 \pm 1.47)\%$**
[0,200] MeV	198.8 ± 20.0*	32.2%	**$(5.52 \pm 0.57 \pm 0.21)\%$**

- *Sum of the above two

- $f_{Ds} = (257.8 \pm 13.3 \pm 5.2)$ MeV

Summery on f_{D_s} from CLEO-c

CLEO, PRD 80, 112004(2009) 600 pb-1 @4170MeV

TABLE IV. Recent absolute measurements of f_{D_s} from CLEO-c.

Experiment	Mode	$\mathcal{B}$ (%)	f_{D_s} (MeV)
	$\tau^+\nu\ (\rho^+\bar{\nu})$	$(5.52 \pm 0.57 \pm 0.21)$	$257.8 \pm 13.3 \pm 5.2$
	$\tau^+\nu\ (\pi^+\bar{\nu})$	$(6.42 \pm 0.81 \pm 0.18)$	$278.0 \pm 17.5 \pm 4.4$
	$\tau^+\nu\ (e^+\nu\bar{\nu})$	$(5.30 \pm 0.47 \pm 0.22)$	$252.6 \pm 11.2 \pm 5.6$
Average	$\tau^+\nu$	$(5.58 \pm 0.33 \pm 0.13)$	$259.7 \pm 7.8 \pm 3.4$
CLEO-c [9]	$\mu^+\nu$	$(0.565 \pm 0.045 \pm 0.017)$	$257.6 \pm 10.3 \pm 4.3$
Average	$\tau^+\nu + \mu^+\nu$		$259.0 \pm 6.2 \pm 3.0$

(3.4%±1.2%)

HPQCD+UKQCD: 241±3 MeV,
2.4 sigma deviation from CLEO-c measurements

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

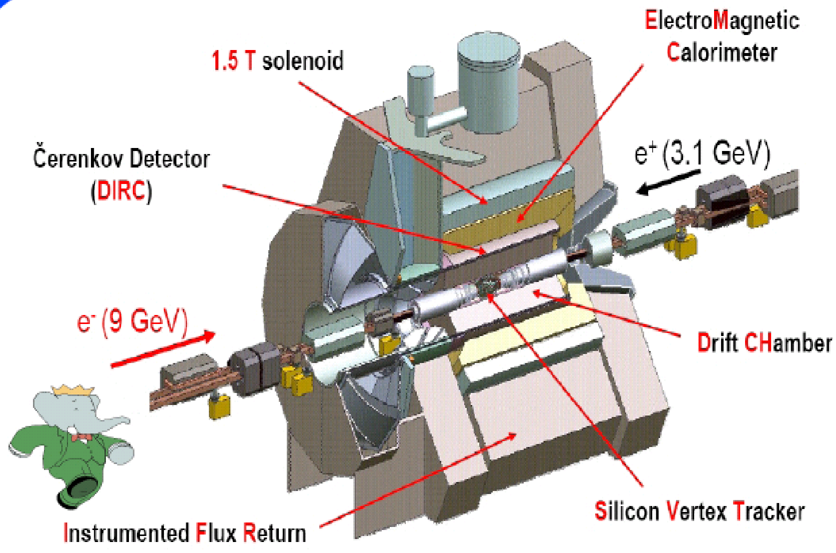
Consistent with the lepton universality

Theoretical prediction for f_{Ds} and f_{D+}

TABLE VI. Theoretical predictions of $f_{D_s^+}$, f_{D^+}, and $f_{D_s^+}/f_{D^+}$. QL indicates quenched lattice calculations. (This table adopted from Table II of ref. [7].)

Model	$f_{D_s^+}$ (MeV)	f_{D^+} (MeV)	$f_{D_s^+}/f_{D^+}$
Lattice (HPQCD+UKQCD) [6]	241 ± 3	208 ± 4	1.162 ± 0.009
Lattice (FNAL+MILC+HPQCD) [5]	$249 \pm 3 \pm 16$	$201 \pm 3 \pm 17$	$1.24 \pm 0.01 \pm 0.07$
QL (QCDSF) [36]	$220 \pm 6 \pm 5 \pm 11$	$206 \pm 6 \pm 3 \pm 22$	$1.07 \pm 0.02 \pm 0.02$
QL (Taiwan) [37]	$266 \pm 10 \pm 18$	$235 \pm 8 \pm 14$	$1.13 \pm 0.03 \pm 0.05$
QL (UKQCD) [38]	$236 \pm 8^{+17}_{-14}$	$210 \pm 10^{+17}_{-16}$	$1.13 \pm 0.02^{+0.04}_{-0.02}$
QL [39]	$231 \pm 12^{+6}_{-1}$	$211 \pm 14^{+2}_{-12}$	1.10 ± 0.02
QCD Sum Rules [40]	205 ± 22	177 ± 21	$1.16 \pm 0.01 \pm 0.03$
QCD Sum Rules [41]	235 ± 24	203 ± 20	1.15 ± 0.04
Field Correlators [42]	210 ± 10	260 ± 10	1.24 ± 0.03
Quark Model [43]	268	234	1.15
Quark Model [44]	248 ± 27	230 ± 25	1.08 ± 0.01
LFQM (Linear) [45]	211	248	1.18
LFQM (HO) [45]	194	233	1.20
LF-QCD [46]	253	241	1.05
Potential Model [47]	241	238	1.01
Isospin Splittings [48]		262 ± 29	

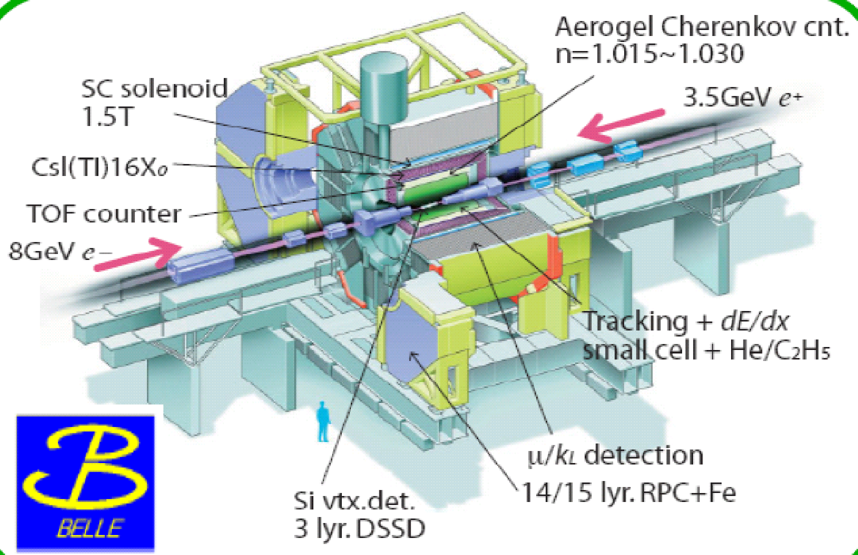
B factories experiments



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: $D_s \to \mu^+ \upsilon$

PRL 100, 241801 (2008) 548 fb^{-1}

Use "Continuum tagging":

$e^+e^- \to D^{\pm,0} K^{\pm,0} X D_s^*$,

"X" = $n\pi$ -or- $n\pi\ \gamma$ (fragmentation)

about 25% of D BF used

Use recoil mass:

against DKXγ counts total D_s

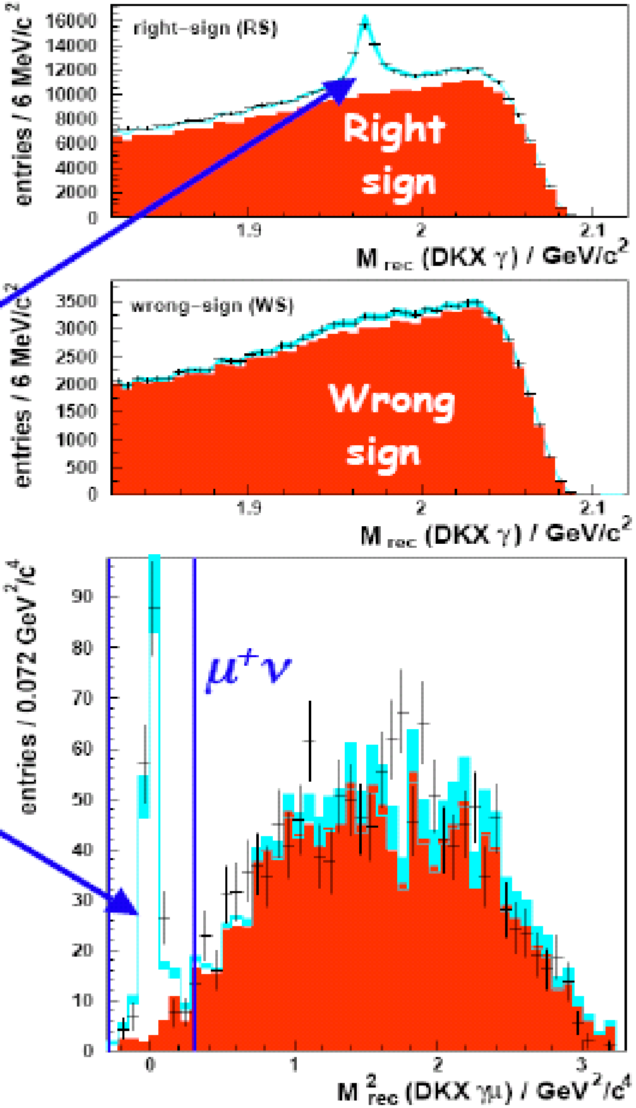
against DKX$\gamma\mu$ counts $D_s \to \mu^+\upsilon$

$\mathcal{B}(D_s^+ \to \mu^+\nu)$ = (0.644 ± 0.076 ± 0.057)%

f_{D_s} = 274 ± 16 ± 12 MeV *

[± 5.8% ± 4.4%]

* including radiative correction of -1% in BR



Belle: $D_s \to \mu^+\upsilon$

PRL 100, 241801 (2008) 548 fb^{-1}

Systematic error totals 4.4% on f_D

- 3.2% MC statistics
- 2.2% background
- 1.5% Tag simulation
- 1.4% Muon ID

Many checks with careful attention paid to tags:

simulation accuracy, stability of result, …

Super B Factory: 3.2 ab^{-1} = final CLEO-c stat error

- Need to control systematics 3x better to match CLEO-c
- That may not be crazy, but may be hard to push far beyond ?
- Still would be a nice independent cross-check

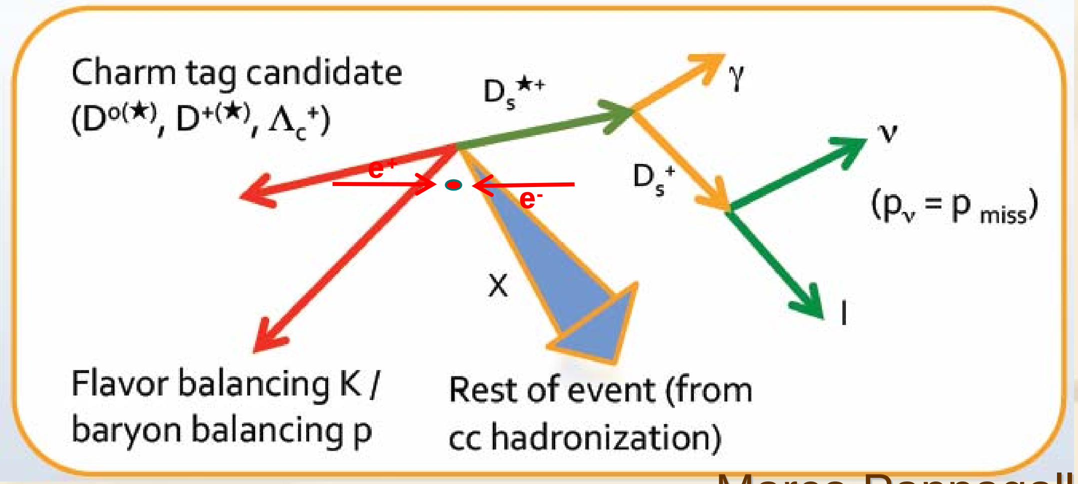
Analysis strategy from BABAR

$$e^+e^- \to c\bar{c} \to DKXD_s^{*-}, \text{ where } D_s^{*-} \to D_s^-\gamma$$

- **Inclusive D_s candidates**
  - **The signal consists of D_s^* candidates decaying to $D_s\ \gamma$**
  - **The D_s candidate is reconstructed from the four-momentum recoiling against the DKX γ ($D = D^{0(*)}, D^{+(*)}, \Lambda_c^+$; $K = K_s, K^+$,(p); $X = \pi^+, \pi^0$)**
- **Within this sample, the $D_s^+ \to \ell^+ \nu_\ell$ ($\ell = e, \mu, \tau$) events are selected**
  - **One more track, identified as e/μ, is required**

Yields corrected by efficiency to obtain the branching fractions:

$$B(D_s^+ \to l\nu) = \frac{N(D_s^+ \to l\nu)}{N(D_s^+)\varepsilon_{l\nu}}$$



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D candidate reconstruction

We reconstruct D candidates using the following 15 modes: $D^0 \to K^-\pi^+(\pi^0)$, $K^-\pi^+\pi^-\pi^+(\pi^0)$, or $K_S^0\pi^+\pi^-(\pi^0)$; $D^+ \to K^-\pi^+\pi^+(\pi^0)$, $K_S^0\pi^+(\pi^0)$, or $K_S^0\pi^+\pi^-\pi^+$; and $\Lambda_c^+ \to pK^-\pi^+(\pi^0)$, pK_S^0, or $pK_S^0\pi^-\pi^+$.

If the D candidate is Λc additional proton is required in X list, to ensure the baryon balance

To identify D mesons originating from D^* decays we reconstruct the following decays: $D^{*+} \to D^0\pi^+$, $D^{*0} \to D^0\pi^0$, $D^{*+} \to D^+\pi^0$, and $D^{*0} \to D^0\gamma$.

For all D^* decays, the mass difference $m(D^*) - m(D)$ is required to be within 2.5 sigma of the peak value.

Fully Inclusive D_s Sample

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521 fb^{-1}

Most Relevant Selection criteria:

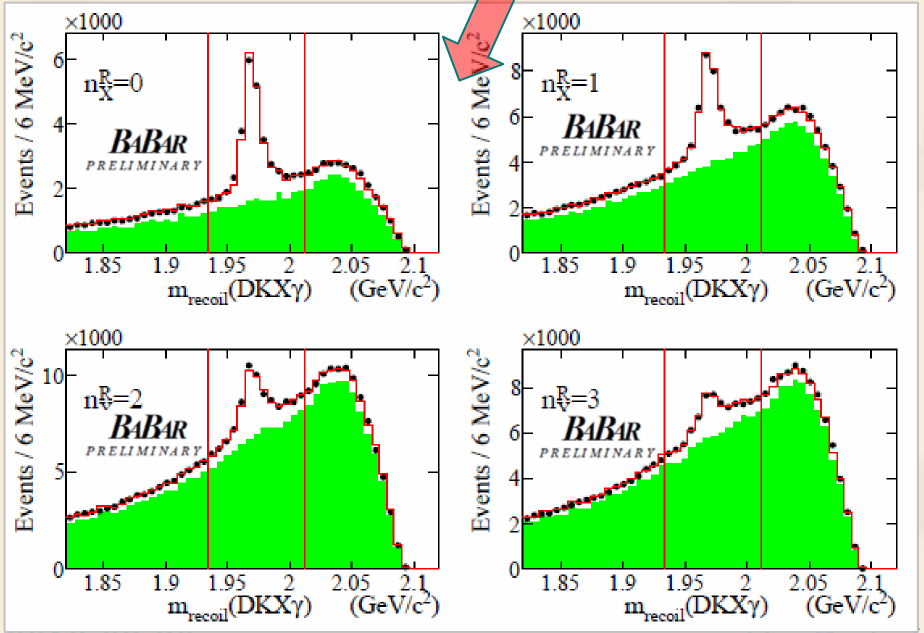
- $p^*(D_s) > 3.0$ GeV/c
- $m_{recoil}(DKX)$ within ~2.5 σ of the D_s^* PDG mass value
- $E_\gamma > 120$ MeV + π^0 and η vetoes

N.B.

$m_{recoil}(DKX) \equiv m(D_s^*)$

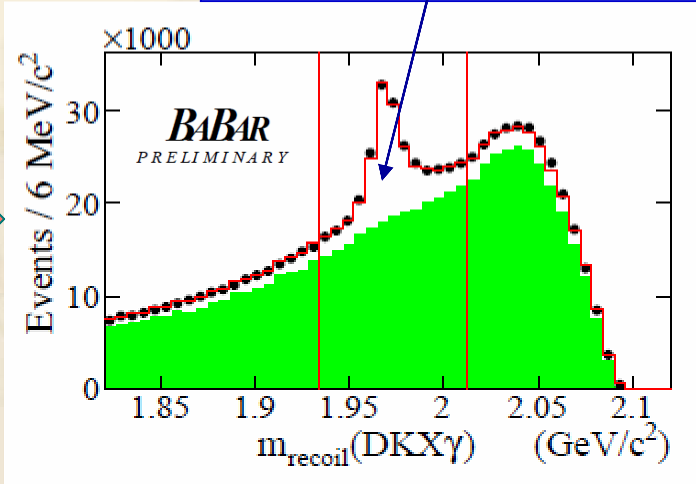
$m_{recoil}(DKX\gamma) \equiv m(D_s)$

Result of 2D fit $m_{recoil}(DKX\gamma)$ vs. n^R_X (n^R_X = Number of reconstructed pions in X system)



Total

(67.2±1.5)x10³ events



Results from BABAR

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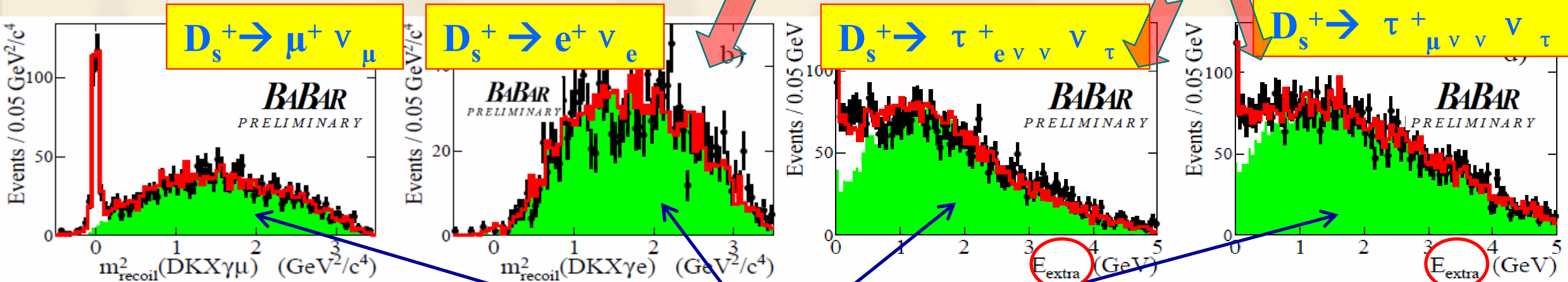
arXiv:1008.4080[hep-ex]

521 fb^{-1}

Helicity Suppressed

PHSP Suppressed



Background

Extra neutral energy in the event

Decay	Signal Yield	$\mathcal{B}(D_s^+ \to \ell^+ \nu_\ell)$	f_{D_s} (MeV)
$D_s^+ \to e^+ \nu_e$	$6.1 \pm 2.2 \pm 5.2$	$< 2.3 \times 10^{-4}$ at 90% C.L.	
$D_s^+ \to \mu^+ \nu_\mu$	275 ± 17	$(6.02 \pm 0.38 \pm 0.34) \times 10^{-3}$	$265.7 \pm 8.4 \pm 7.7$
$D_s^+ \to \tau^+_{e\nu\nu} \nu_\tau$	408 ± 42	$(5.07 \pm 0.52 \pm 0.68) \times 10^{-2}$	$247 \pm 13 \pm 17$
$D_s^+ \to \tau^+_{\mu\nu\nu} \nu_\tau$	340 ± 32	$(4.91 \pm 0.47 \pm 0.54) \times 10^{-2}$	$243 \pm 12 \pm 14$

Normalization mode of many D_s decays!

The hadronic $D_s^+ \to K^+K^-\pi^+$ used to cross-check the method

$$\mathcal{B}(D_s^+ \to K^+K^-\pi^+) = (5.78 \pm 0.20(\text{stat}) \pm 0.30(\text{syst}))\%$$

$$f_{D_S} = (258.6 \pm 6.4(\text{stat}) \pm 7.5(\text{syst}))\ \text{MeV}$$

(2.5% ±3.0%)

Very Competitive Measurements!

Most recent summary of f_{Ds}

Experiment	Mode	$\mathcal{B}$	$f_{D_s^+}$ (MeV)
CLEO-c [12]	$\mu^+\nu$	$(5.65 \pm 0.45 \pm 0.17) \times 10^{-3}$	$257.6 \pm 10.3 \pm 4.3$
Belle [13]	$\mu^+\nu$	$(6.38 \pm 0.76 \pm 0.57) \times 10^{-3}$	$274 \pm 16 \pm 12$
Average	$\mu^+\nu$	$(5.80 \pm 0.43) \times 10^{-3}$	261.5 ± 9.7
CLEO-c [12]	$\tau^+\nu$ $(\pi^+\overline{\nu})$	$(6.42 \pm 0.81 \pm 0.18) \times 10^{-2}$	$278.0 \pm 17.5 \pm 3.8$
CLEO-c [14]	$\tau^+\nu$ $(\rho^+\overline{\nu})$	$(5.52 \pm 0.57 \pm 0.21) \times 10^{-2}$	$257.8 \pm 13.3 \pm 5.2$
CLEO-c [15]	$\tau^+\nu$ $(e^+\nu\overline{\nu})$	$(5.30 \pm 0.47 \pm 0.22) \times 10^{-2}$	$252.6 \pm 11.2 \pm 5.6$
BaBar [16]	$\tau^+\nu$ $(e^+\nu\overline{\nu})$	$(4.54 \pm 0.53 \pm 0.40 \pm 0.28) \times 10^{-2}$	$233.8 \pm 13.7 \pm 12.6$
Average	$\tau^+\nu$	$(5.58 \pm 0.35) \times 10^{-2}$	255.5 ± 7.5
Average	$\mu^+\nu + \tau^+\nu$		257.5 ± 6.1

From Rosner & Stone, use $|V_{cs}|=|V_{ud}|-|V_{cb}|^2/2$ =0.97345, τ_{Ds}=0.500(7) ps [arXiv:1002.1655]

$f_{Ds}(\tau\nu)/f_{Ds}(\mu\nu)$ = 0.98 ± 0.05 **f_{Ds}/f_{D^+} = 1.25 ± 0.06**

These results are very important to guide theory, useful to calculate f_{B+}/f_{Bs+}!

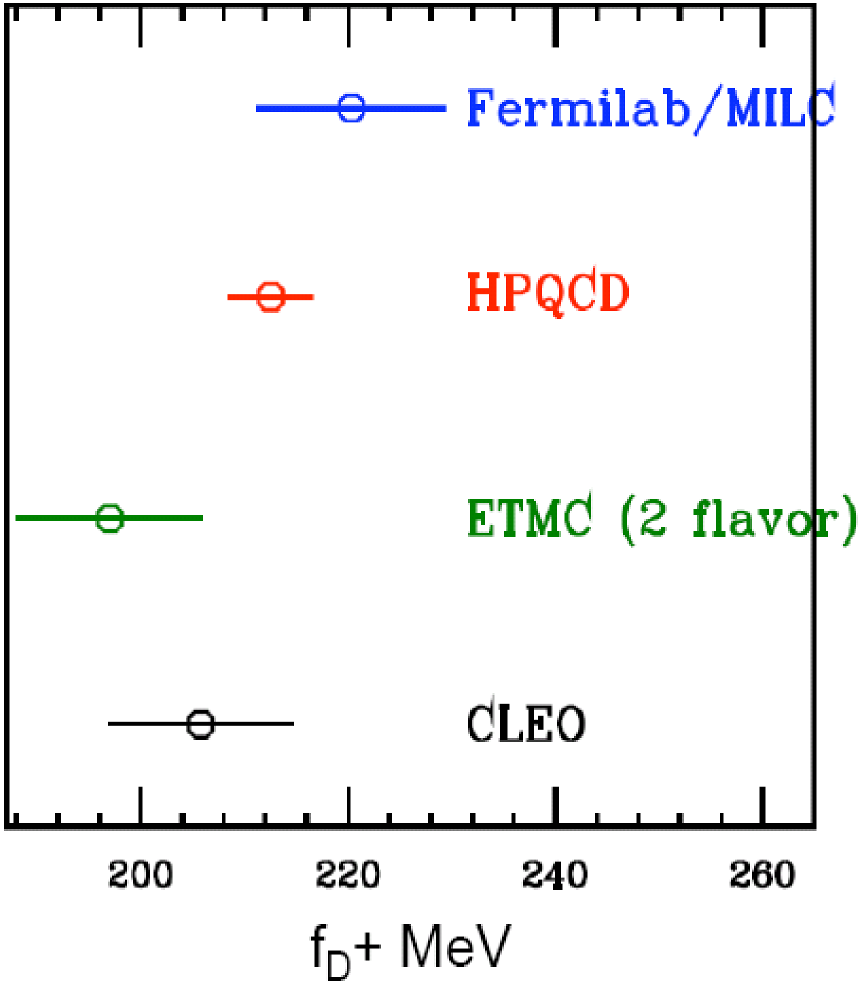
Theoretical predictions & postdictions

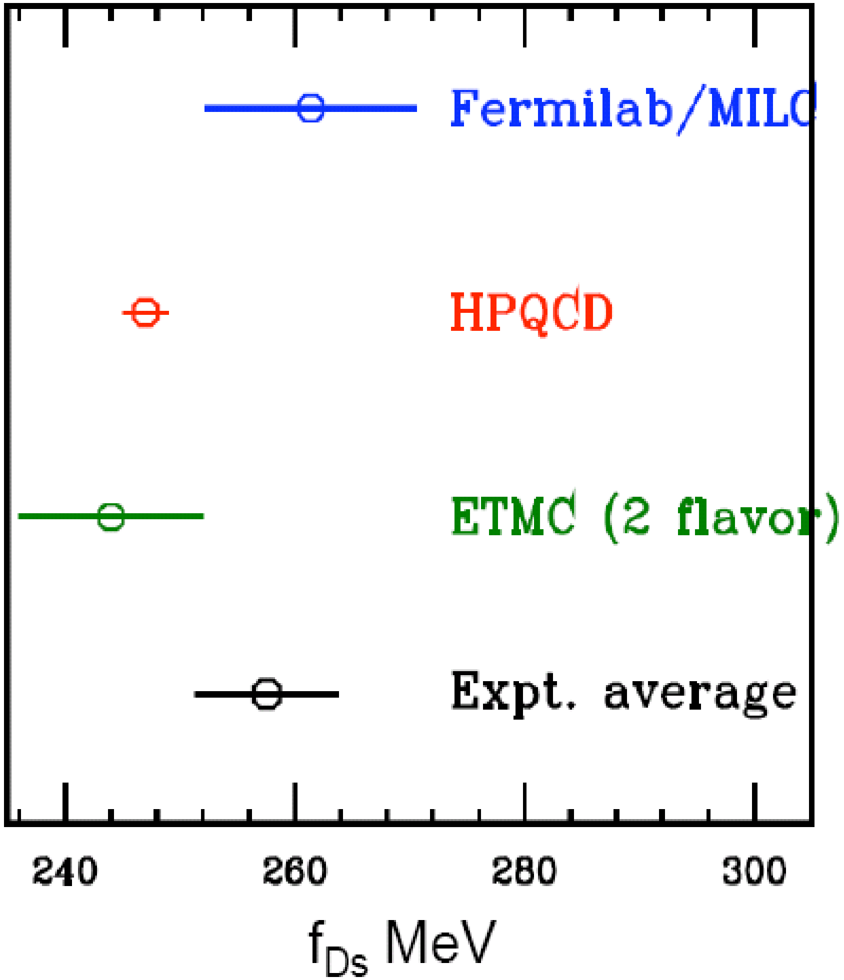
- Quote only unquenched Lattice results (MeV)

	Data	Fermi-Milc (2005)	Fermi-Milc (2010)	HPQCD (2007)	HPQCD (2010)	ETMC (2 flavors of sea q)
f_{D^+}	206.7±8.9	207±3±17	220.3±8.0±4.8	207±4		197±9
f_{Ds}	257.5±6.1	249±3±16	261.4±7.7±5.0	241±3	247±2	244±8

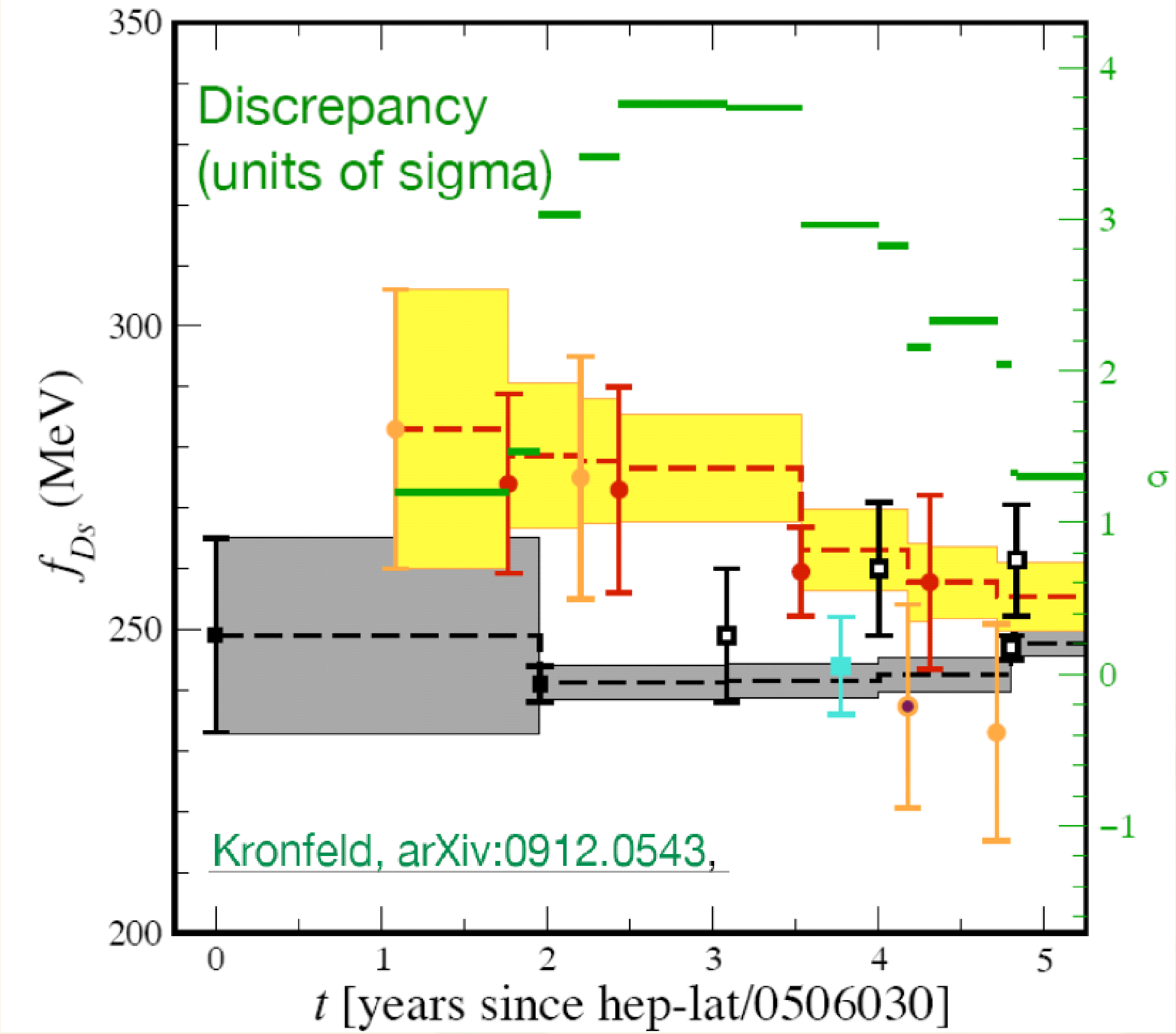
- HPQCD extrapolation from C. Bernard at Lattice QCD Meets Experiment Workshop, Fermilab April 26-27, 2010

Latest LQCD


Fermilab/MILC
HPQCD
ETMC (2 flavor)
CLEO
200
220
240
260
f_D+ MeV


Fermilab/MILC
HPQCD
ETMC (2 flavor)
Expt. average
240
260
280
300
f_{Ds} MeV

From Kronfeld and his updates



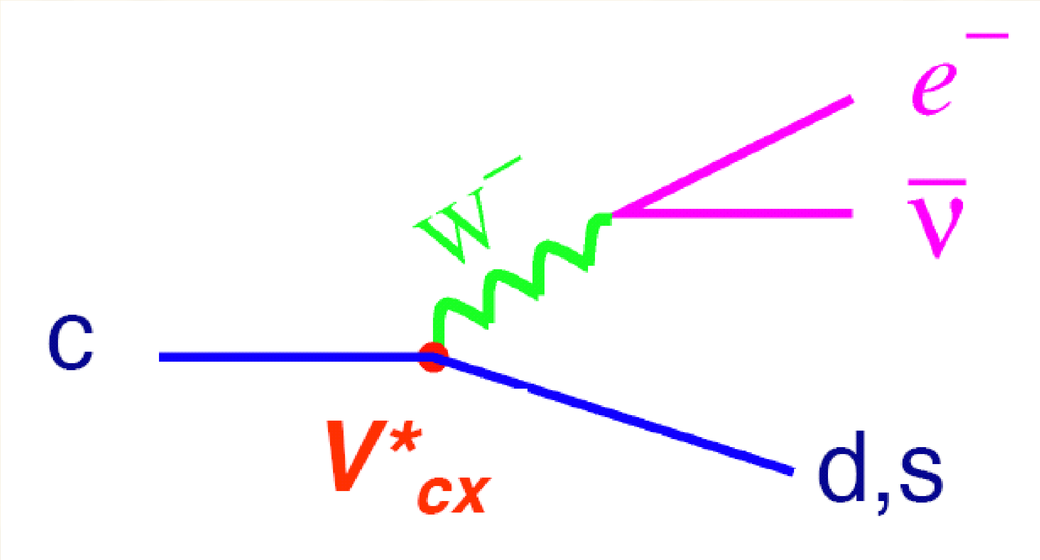
- **Yellow**: expt. average
- **Gray**: lattice average
- Circles: expts.:
  - orange: $\Upsilon(4S)$
  - red: $D_s^{(*)} D_s^{(*)}$ threshold
- Squares: lattice
  - filled: published
  - open: prelim or conference proc.
  - cyan: 2 flavors

The "puzzle" disappeared, no exciting!

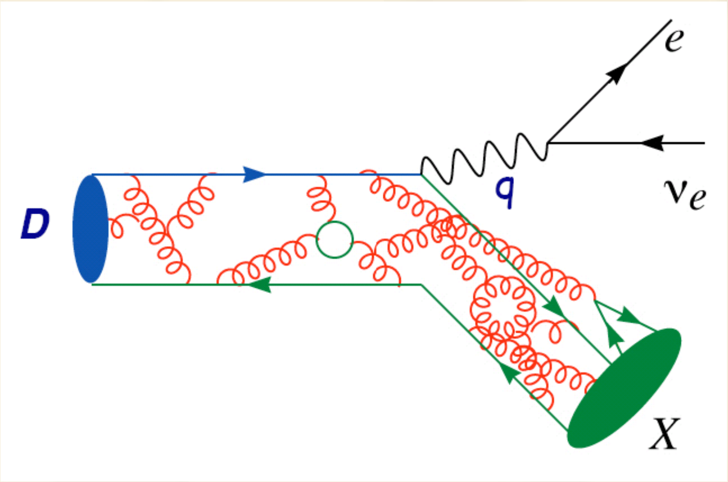
Questions for you

- **At $\psi(3770)$, the D mass can be constrained by beam energy, why this technique will provide us clean single tag sample without peaking background?**
- **At 4030 MeV, the $D_s^+D_s^-$ can be produced in pair, while at 4170 MeV, $D_s^+D_s^{*-}$ will be produced, for the measurement of f_{Ds}, in which energy point, the systematic error can be controlled?**
- **Can f_{D^+} be measured at B factories by using data at Y(4S)?**
- **Why f_{Ds} can be made at B factories?**
- **Why tau(B^+) $\cong$ tau(B^0), while it is not true for D^0 and D^+?**

Semileptonic 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

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

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

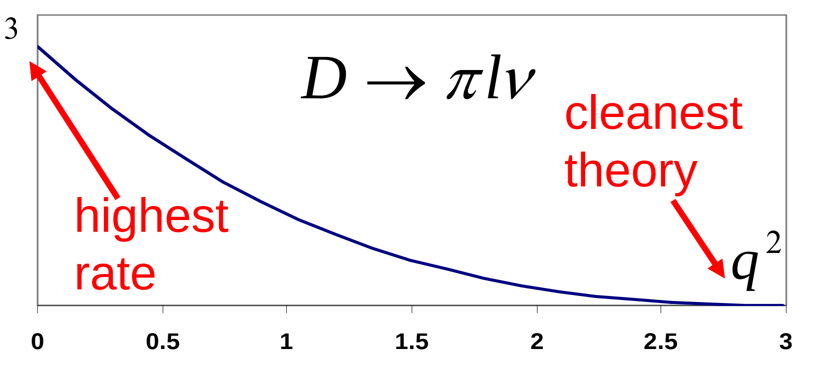
Precise measurements of D→ π /K $\ell\nu$ can calibrate Lattice QCD and allow a precise extraction of CKM elements in B/D meson decays.

Two Key Kinematic Configurations

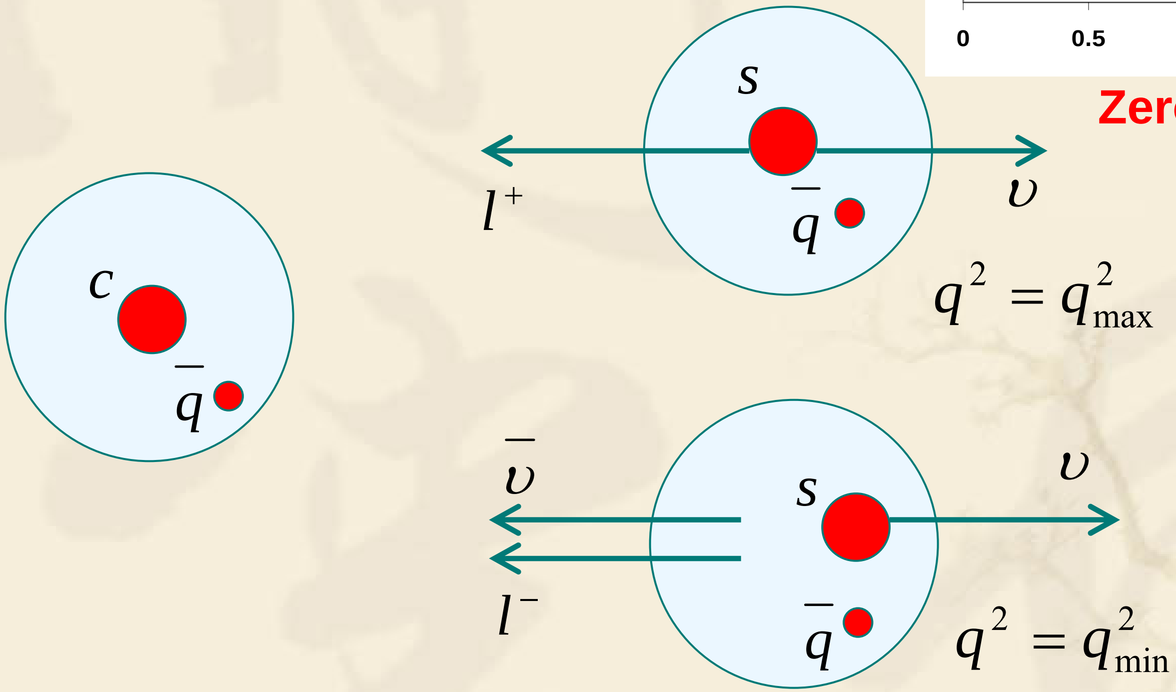
J. Richman, Rev. of Mod. Phys. 67, 893(1995)

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

P^3



Zero recoil

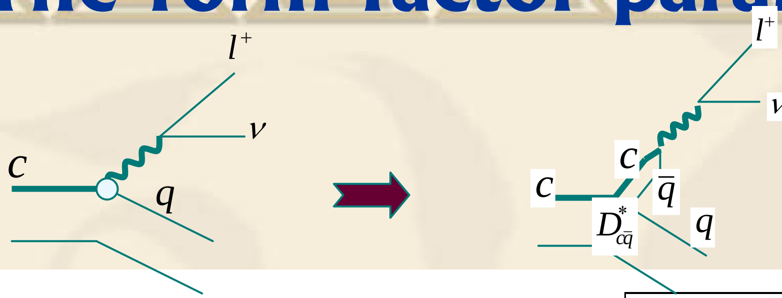


Form factor maximum, easy to form meson

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

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

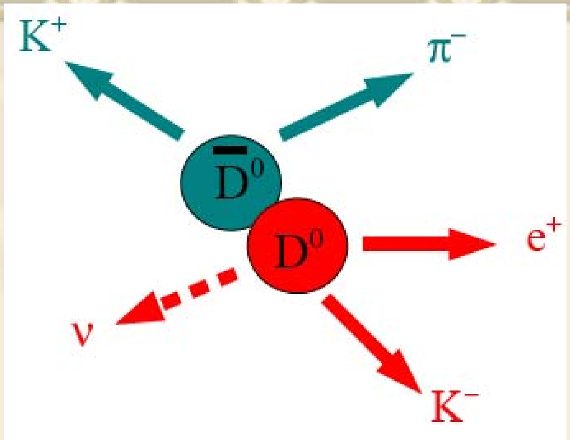
$$t_\pm = (m_D \pm m_X)^2$$

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

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

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

Selecting D Tags

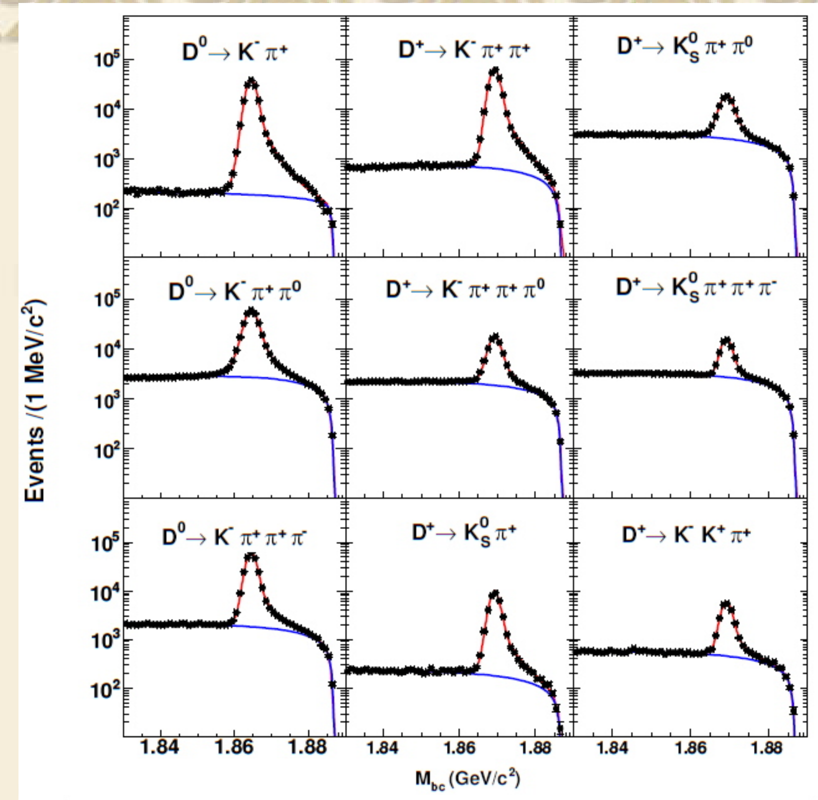
CLEO PRD80, 032005(2009)
818 pb-1

- Standard selection criteria implemented in D tag code
  - Track quality (good fit, fiducial, vtx cuts, hit fraction)
  - Hadron identification
    - Positively ID'ed $\pi^{\pm}$ and $K^{\pm}$ by dE/dx and RICH (if available); accept as π if PID info not available
    - π^0 kinematically fitted from good, photon-like, showers, with $3\ \sigma$ mass cut; resolve multiple candidates based on mass
    - K_S reconstructed from vertex-constrained tracks, $3\ \sigma$ mass cut; resolve multiple candidates based on mass
- D tags selected with standard cuts, then subjected to tighter M_{bc} and ΔE cuts, optimized mode by mode
  - Multiple tag candidates in an event: choose one per tag mode per flavor based on ΔE

Counting D Tags

- Unbinned likelihood fit
  - Signal line shape developed for and parameters fixed by D hadronic (double-tag vs. single-tag) BF analysis
    - $\psi(3770)$ natural shape, beam-energy resolution, ISR, p resolution
- Fit data for yields and MC for tagging efficiency
  - Lots of MC!

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
$D^- \to K_S^0\pi^-$	33870 ± 194	51.10
$D^- \to K_S^0\pi^-\pi^0$	74842 ± 357	28.74
$D^- \to K_S^0\pi^-\pi^-\pi^+$	49117 ± 323	43.58
$D^- \to K^+K^-\pi^-$	19926 ± 171	42.07

Selecting Semileptonic Decays

CLEO PRD80, 032005(2009)
818 pb-1

- Standard electron ID requirements
  - E/p + dE/dx + RICH $\rightarrow$ combined likelihood
    $p > 200$ MeV and $|\cos\theta| < 0.9$
- Bremsstrahlung recovery
  - Add good non-track-matched showers with $E > 30$ MeV if they are within 5° of an electron track – reduces systematic uncertainty due to FSR simulation
- Meson selection: same track and PID cuts as D tags. Demand proper charge correlation
  - D^0 – electron and meson oppositely charged
  - D^+ – electron and tag D oppositely charged

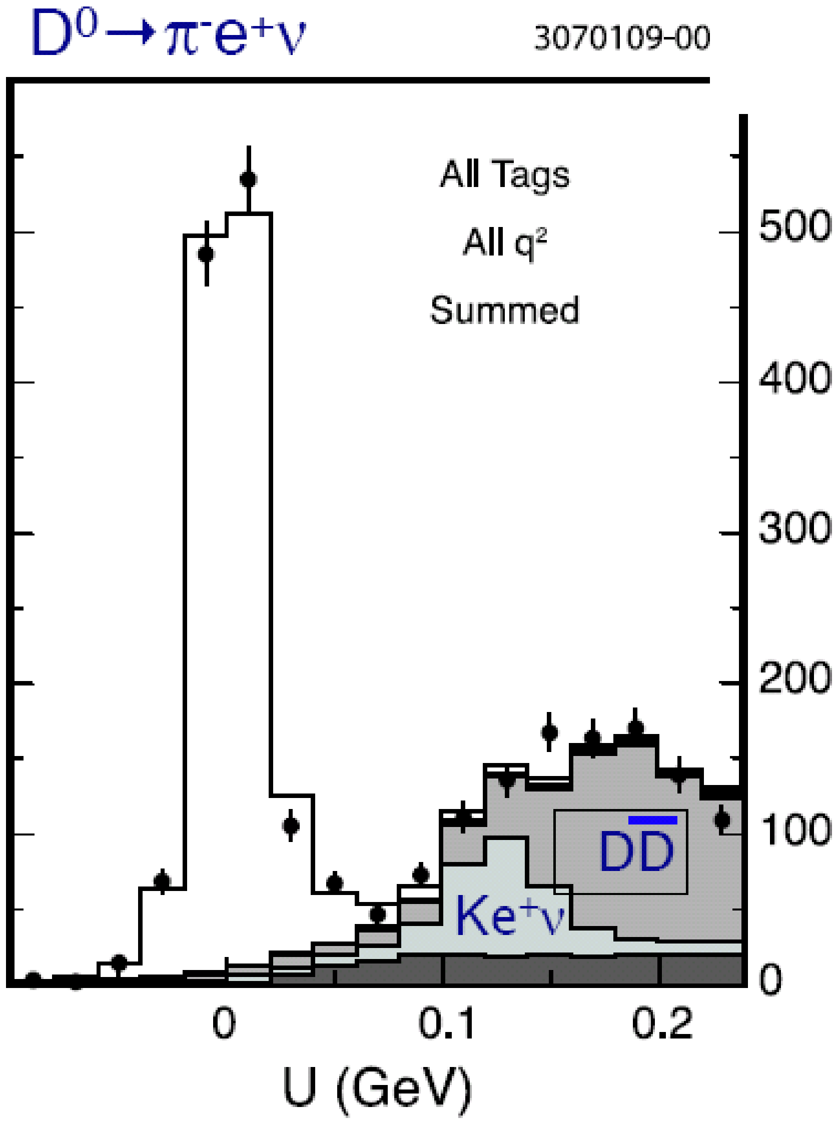
PRD 80 032005 (2009)
CLEO-c 818 pb^{-1}

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)
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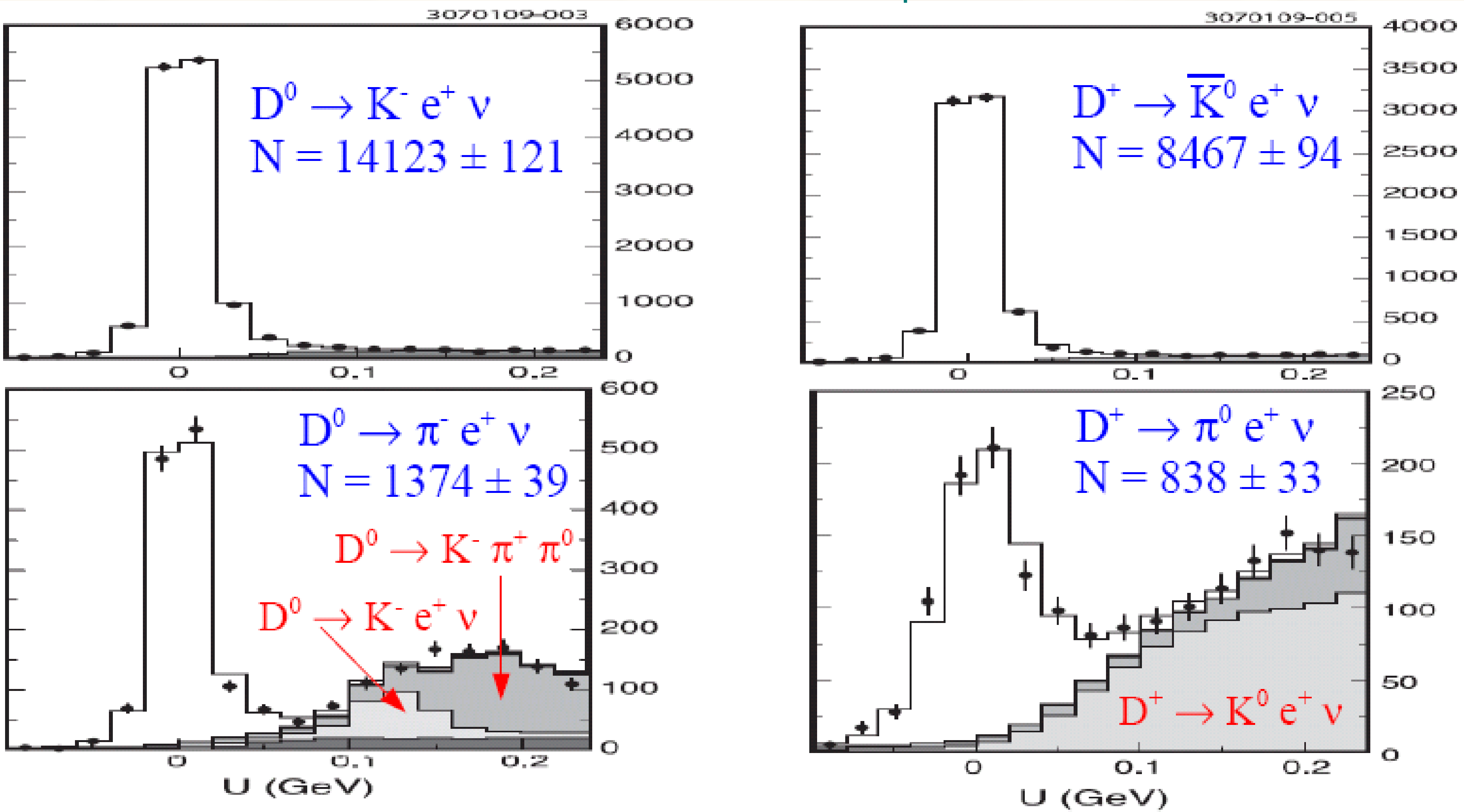

$$U = E_{miss} - c|\mathbf{P}_{miss}|$$

Branching Fraction Results

CLEO PRD80, 032005(2009

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

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

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

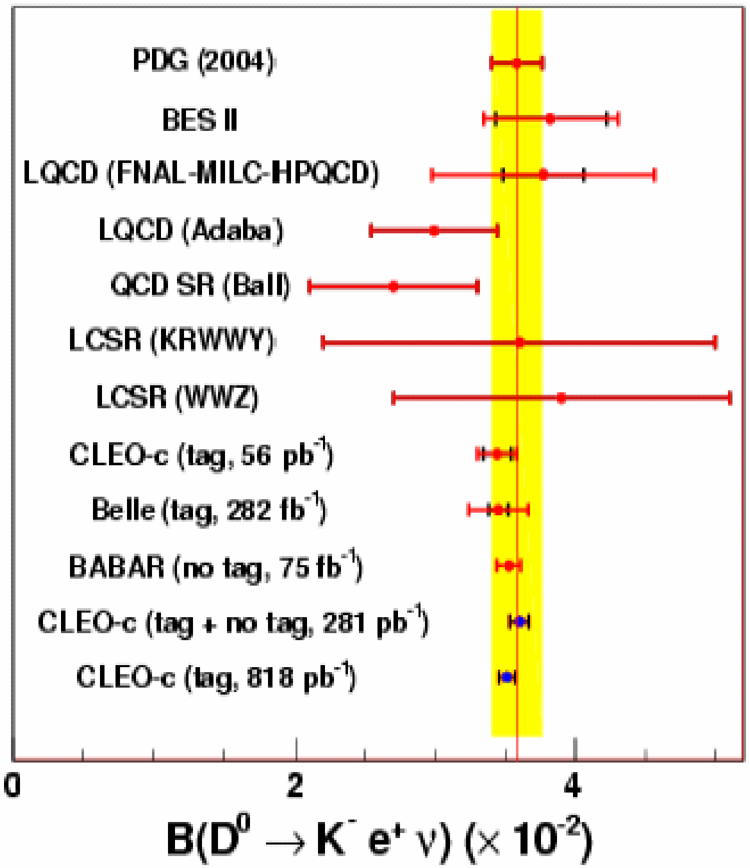
$$\mathcal{B}\left(D^+ \to \bar{K}^0 e^+ \nu_e\right) = (8.83 \pm 0.10 \pm 0.20)\%.$$

Kaon modes are systematics limited

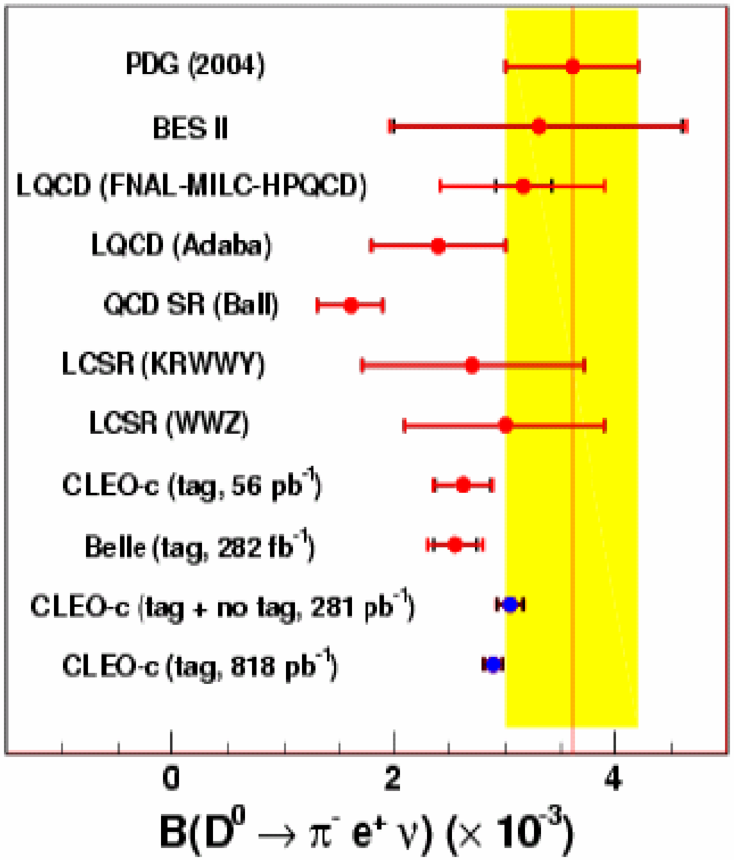
Pion modes are statistics-limited. Without improvement, they become systematics limited at ~6 fb^{-1}

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

Branching Fractions of $D^0 \to K^-/\pi^- e^+ \nu$



$(3.50 \pm 0.03 \pm 0.04)\%$



$(2.88 \pm 0.08 \pm 0.03) \times 10^{-3}$

Most precise measurements of branching fractions

- 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 $D \to K e \nu$

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

Inverted Signal Efficiency Matrix

Signal Yields

Tag Yield

Tagging Efficiency

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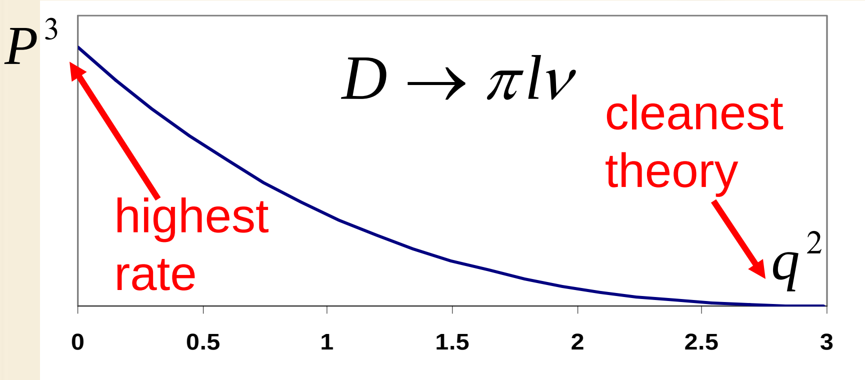
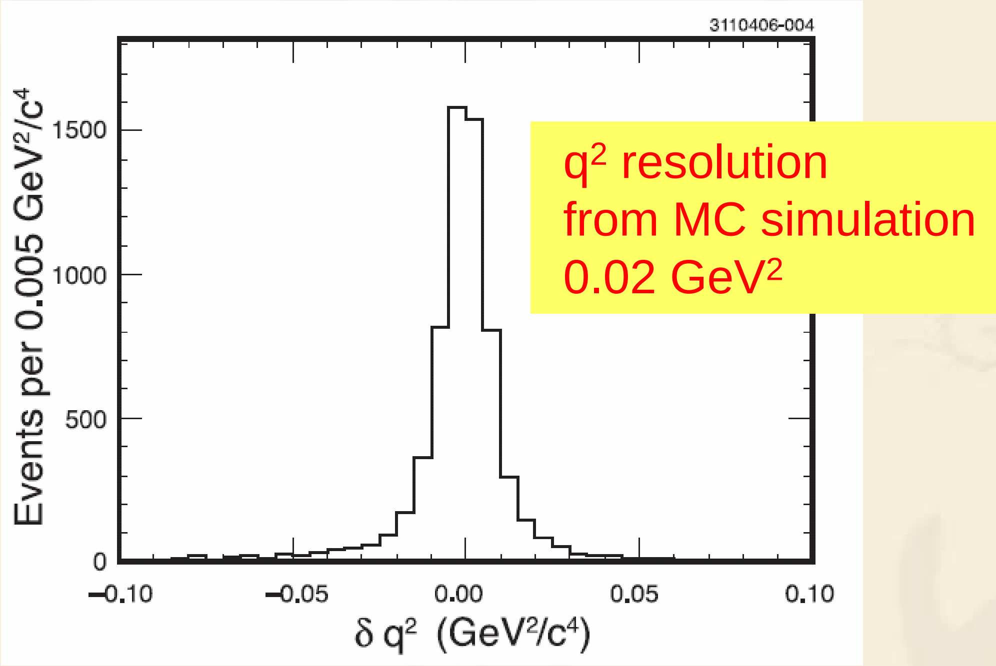
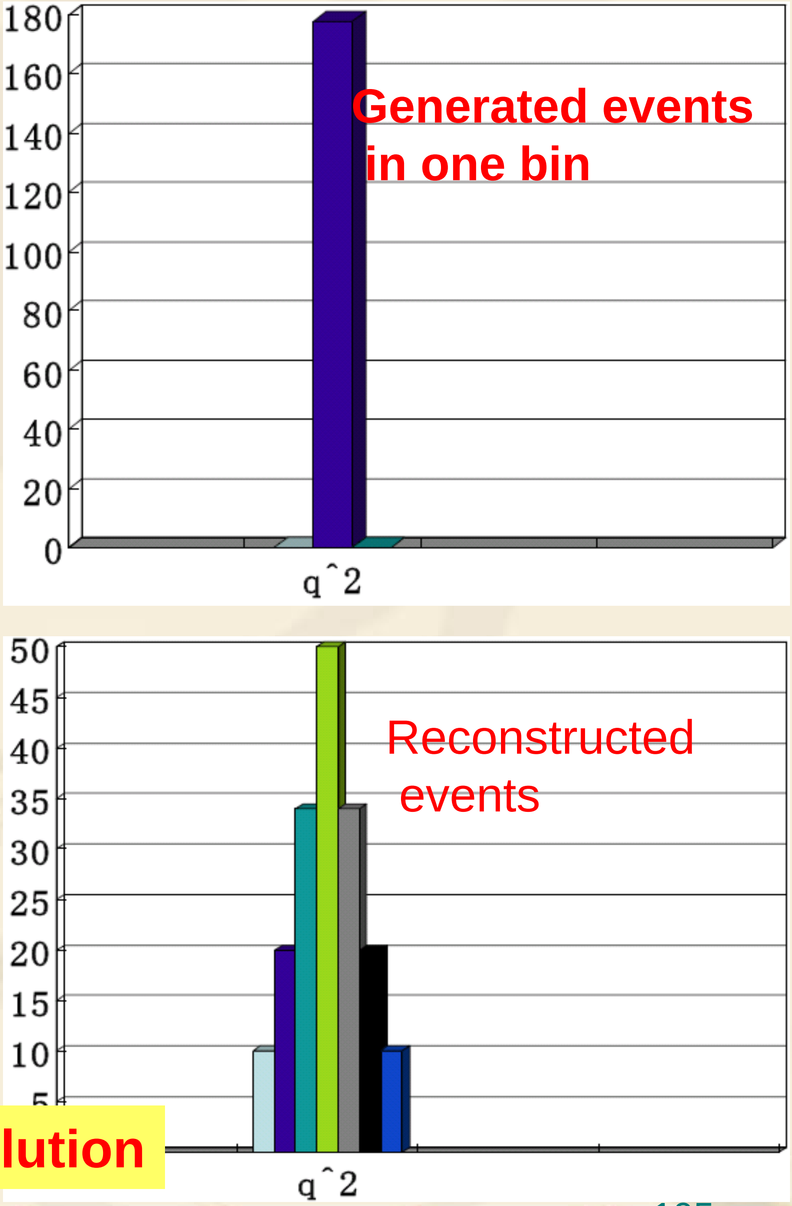
- Integrate for total width (BF) and fit for FF parameters

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

q^2 resolution



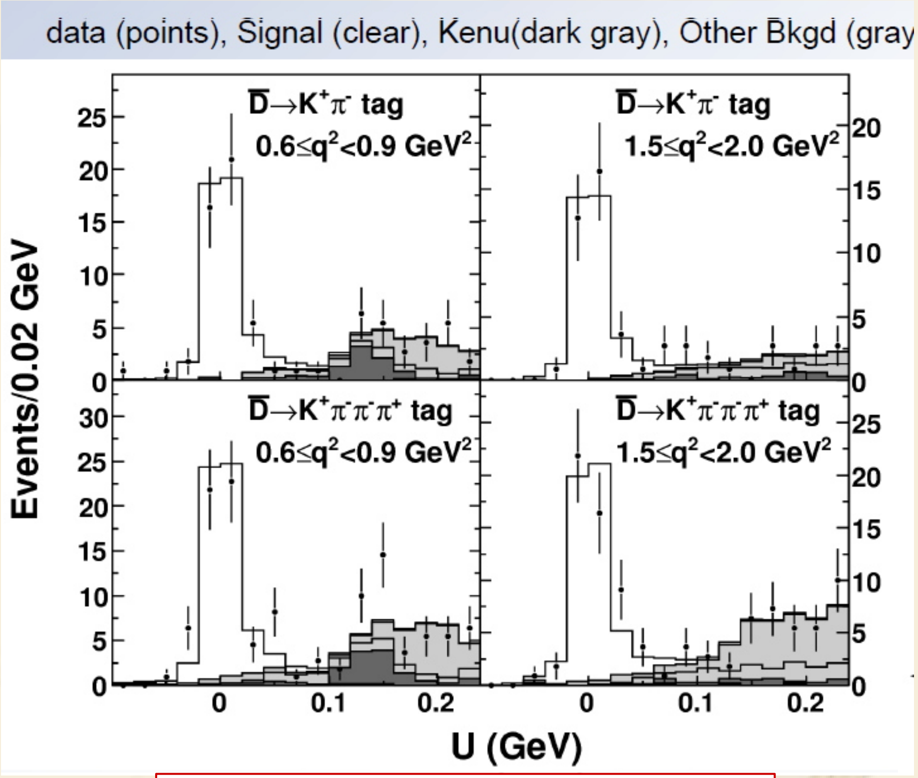




The selected bin size is larger than the resolution

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 (columns) ; Reconstructed Bin (rows)

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

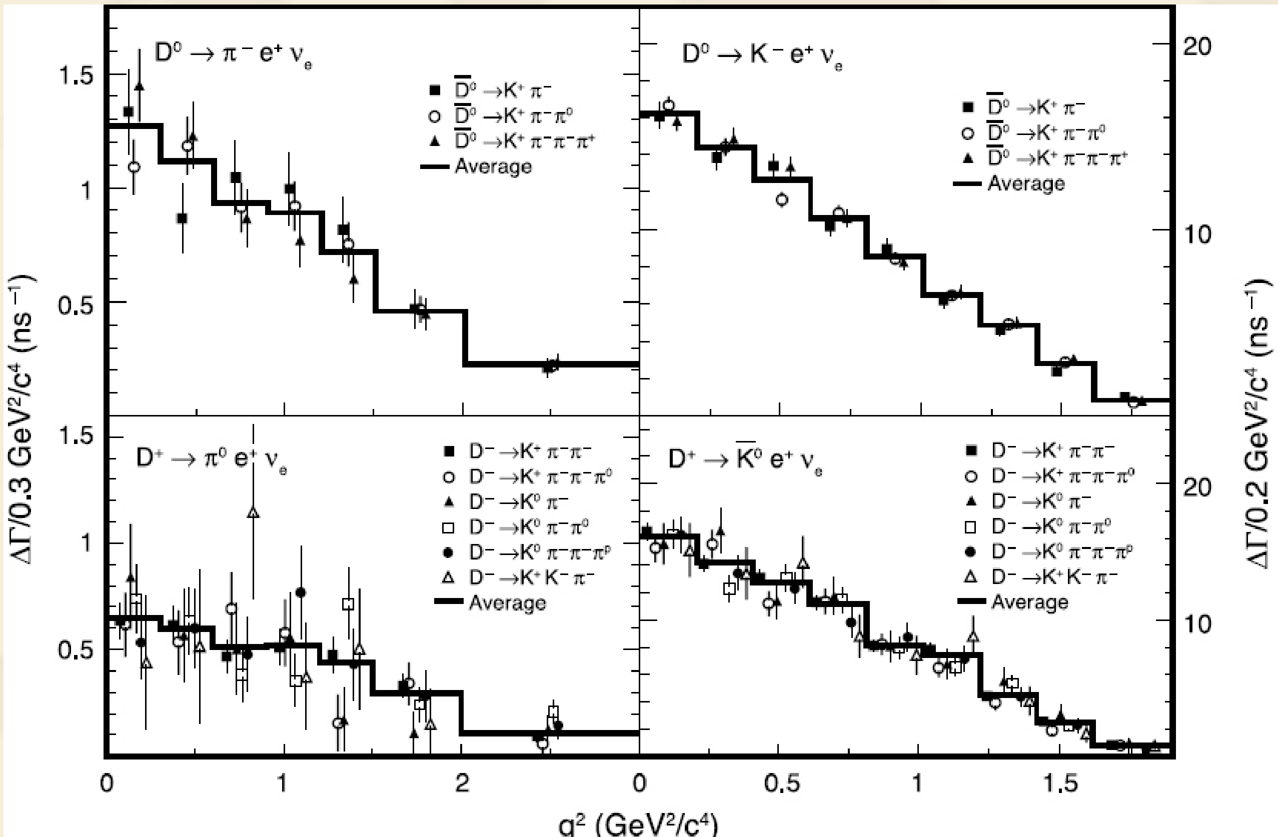
Partial Rate Results

CLEO PRD80, 032005(2009)
818 pb-1

Inverted Signal Efficiency Matrix — Signal Yields

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

Tag Yield — Tagging Efficiency

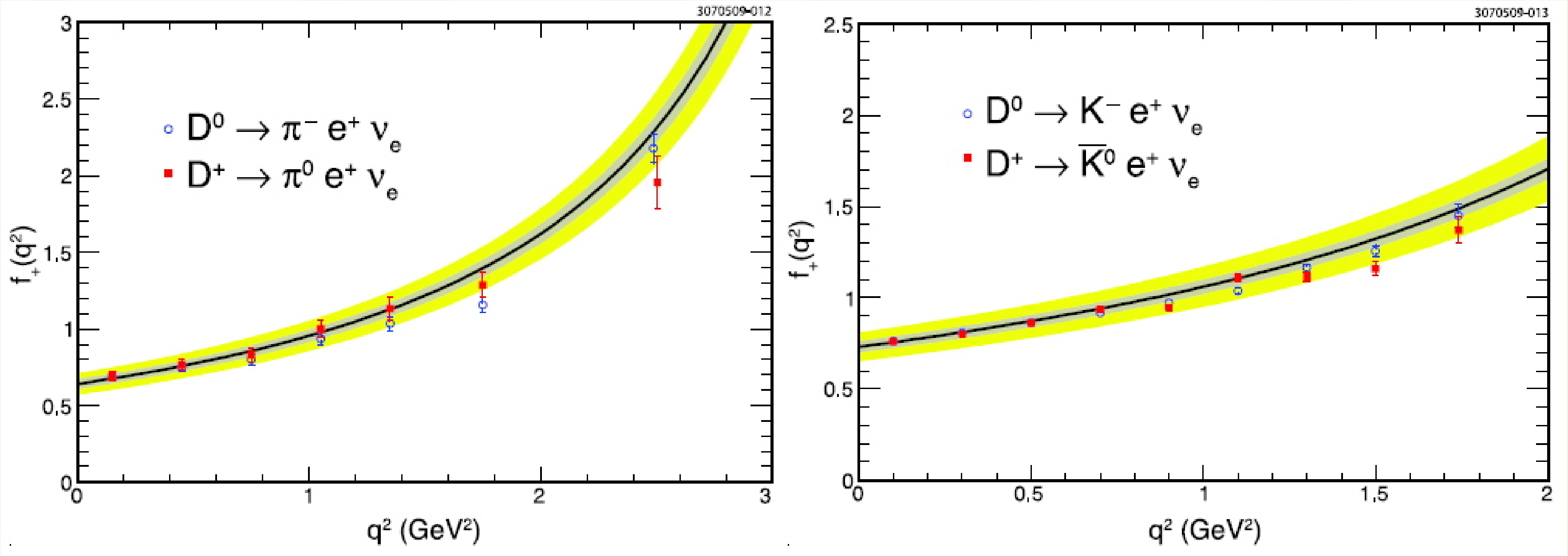


- Averaged over tag modes; verified to be consistent
- Consistent with isospin symmetry

Form Factor Tests

CLEO PRD80, 032005(2009)
818 pb-1

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



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

Systematics

CLEO PRD80, 032005(2009)
818 pb-1

	$\sigma(\Delta\Gamma_1)$	$\sigma(\Delta\Gamma_2)$	$\sigma(\Delta\Gamma_3)$	$\sigma(\Delta\Gamma_4)$	$\sigma(\Delta\Gamma_5)$	$\sigma(\Delta\Gamma_6)$	$\sigma(\Delta\Gamma_7)$	$\sigma(\Delta\Gamma_8)$	$\sigma(\Delta\Gamma_9)$
$D^+ \to \bar{K}^0 e^+ \nu_e$									
Tag line shape	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Tag fakes	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70
Tracking efficiency	0.76	0.77	0.78	0.79	0.81	0.83	0.87	0.91	0.96
K^0 ID	2.00	1.96	1.90	1.83	1.71	1.51	1.25	1.35	1.89
$e^\pm$ ID	0.42	0.43	0.43	0.45	0.48	0.48	0.44	0.33	0.20
FSR	0.17	0.13	0.08	0.01	-0.11	-0.16	-0.23	-0.24	-0.28
Signal shape	0.20	0.22	0.17	0.20	0.23	0.26	0.38	0.26	0.47
Backgrounds	0.13	0.13	0.11	0.11	0.14	0.15	0.27	0.23	1.46
MC form factor	0.03	-0.02	-0.02	-0.02	-0.02	-0.01	0.01	0.02	0.08
q^2 smearing	0.63	-0.24	-0.02	0.29	-1.06	0.75	-0.67	-0.78	-1.11
D Lifetime	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
All systematic	2.52	2.42	2.36	2.33	2.47	2.23	2.08	2.16	3.03
Statistical	2.63	2.90	3.04	3.23	3.82	3.98	5.04	6.88	10.63

Evaluation of systematic uncertainties includes determination of systematic correlations across q^2 construction of the full covariance matrix for incorporation into FF fits

Note that contributions from tracking and charged hadron/π^0/K_S ID are significant – and reducible with large data sets

Comments on Systematic Studies

- Tracking efficiency
  - Missing mass technique: fully reconstruct

    $\psi(3770) \to D\bar{D},\ \psi(2S) \to \pi^+\pi^- J/\psi$ or $\psi(2S) \to \pi^0\pi^0 J/\psi$

    leaving out one particle. When MM says we should find $\pi^\pm (e^\pm)$ or $K^\pm$, determine how often we do as function of momentum. Data and MC agree well – no correction
  - Alternative procedure to evaluate uncertainty based on understanding of tracking failures (dominated by decays in flight)

    0.2% - 0.3% for $\pi^\pm$ 0.4% - 1.4% for $K^\pm$
- π^0 detection efficiency
  - 6% lower in data than MC – apply correction. Systematic 1.0%-2.1%
- K_S detection efficiency
  - Data/MC consistent, no correction. Systematic 0.8%

Comments on Systematic Studies

- $\pi^\pm/K^\pm$ PID efficiency
  - Use $D^0 \to K_S^0\pi^+\pi^-$ $D^+ \to K^-\pi^+\pi^+$
    or exclusive $\psi(2S)$ decays
  - Select w/o PID on one track and determine efficiency – correction required
    $\pi^\pm$ - shift $0.34\% \pm 0.11\%$ $K^\pm$ - shift $0.83\% \pm 0.15\%$
- Electron ID
  - Two sources of uncertainty: physics/understanding of e detection and complexity of real event environment
  - Study as function of momentum with $ee\gamma$ and $eeee$ events
  - Embed these into hadronic events using the same tools as MC noise embedding. Do it both in data and MC.
  - Data 1.5% below MC – corrected. Get covariance matrices by varying correction by its uncertainty and remeasuring partial widths
- Mismodeling of q^2 resolution estimated based on data/MC differences in U resolution – smear MC and remeasure

$D \rightarrow K/\pi\ e\nu$ 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)

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

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

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

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

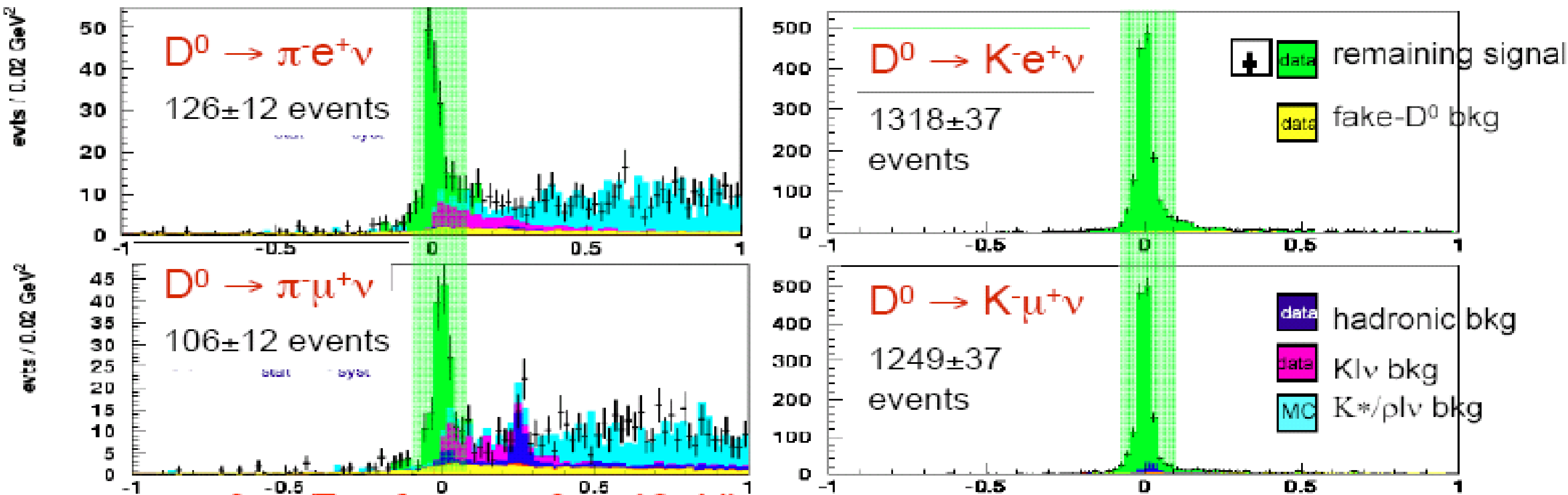
Use "Continuum tagging" again: $e^+e^- \to D^{(*)}_{tag}\ D^*_{signal}\ X$.

Reconstruct all particles (except for neutrino)

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

Cabibbo suppressed

Cabibbo favored



$m_{miss}^2 = E_{miss}^2 - p_{miss}^2$ (GeV) $m_{miss}^2 = E_{miss}^2 - p_{miss}^2$ (GeV)

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

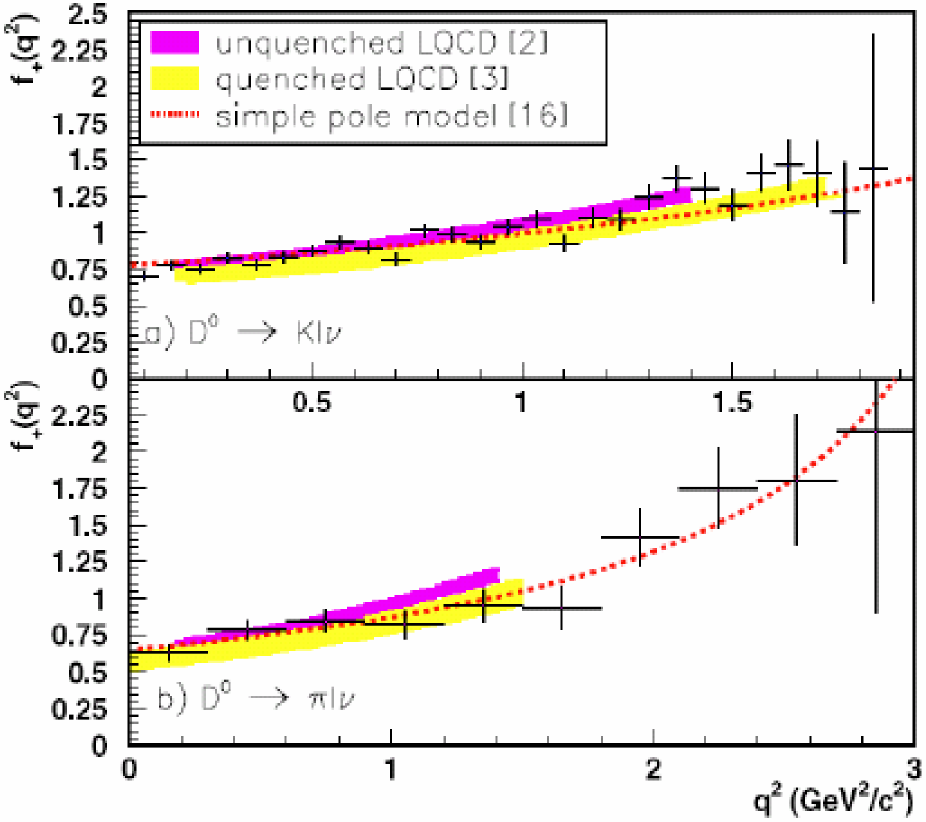
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cx}|^2 p_X^3 |f_+(q^2)|^2$$

Compare to

LQCD Form Factor

Simple Pole parameterization

Modified Pole Model



Lattice Form Factors

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

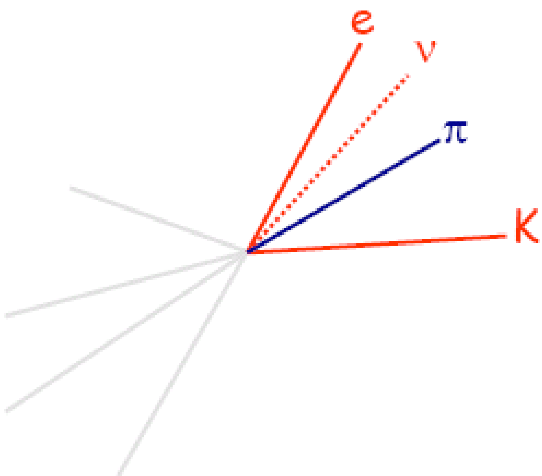
[3]Abada et al. Nucl. Phys. B619, 565 (2001)

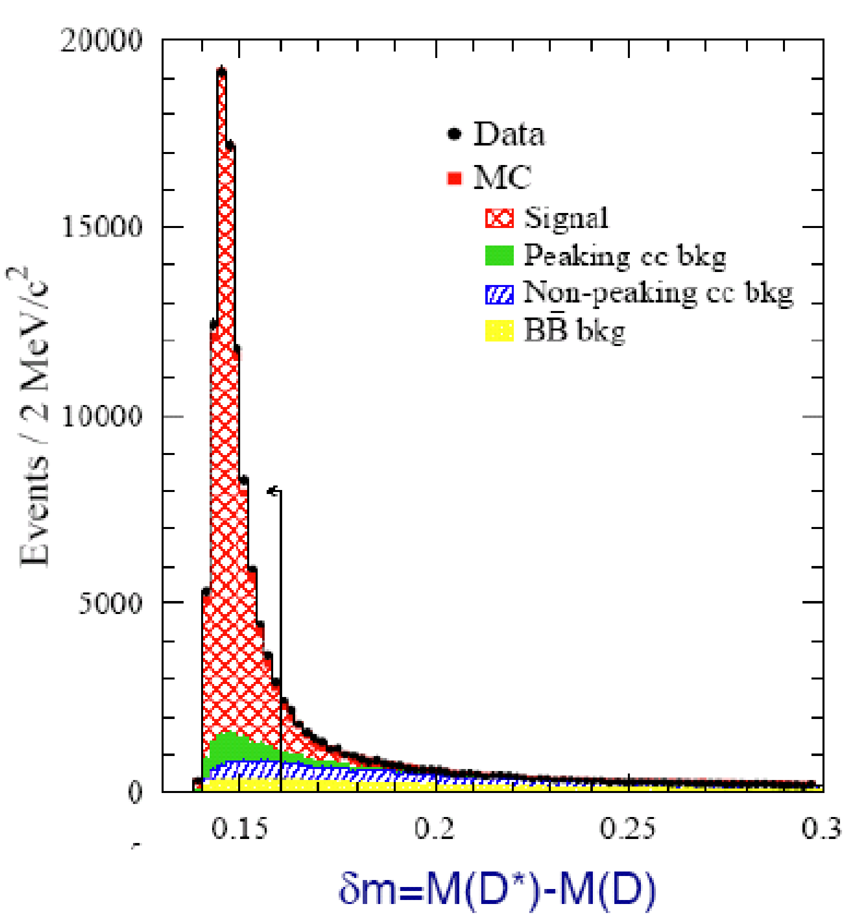
PRD 76 052005 (2007)
75 fb^{-1}

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 $D^0 \to K e \nu$
- Estimate p_D and E_ν with remaining event & kinematic fits
- Use Neural Nets to suppress backgrounds

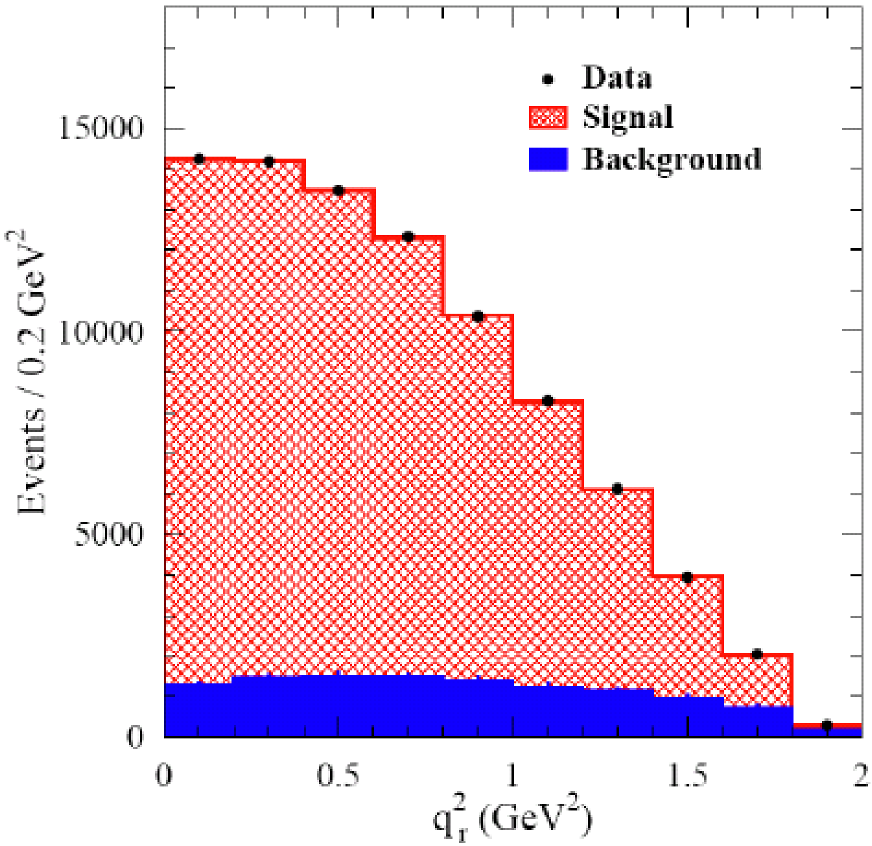


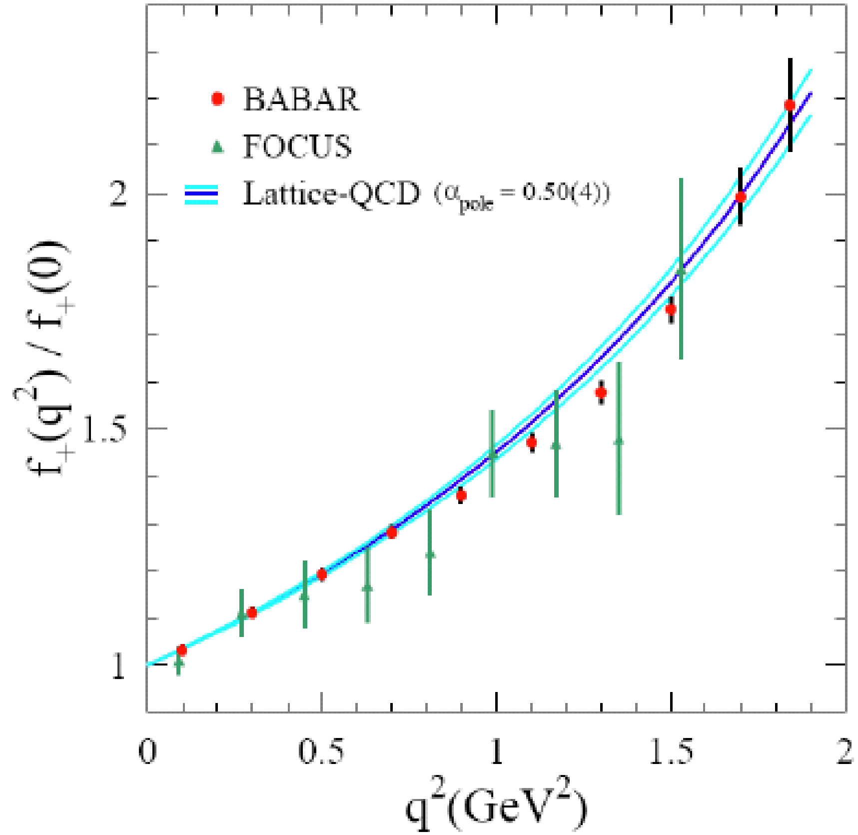


- high statistics: ~74,000
- good S/N

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

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





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

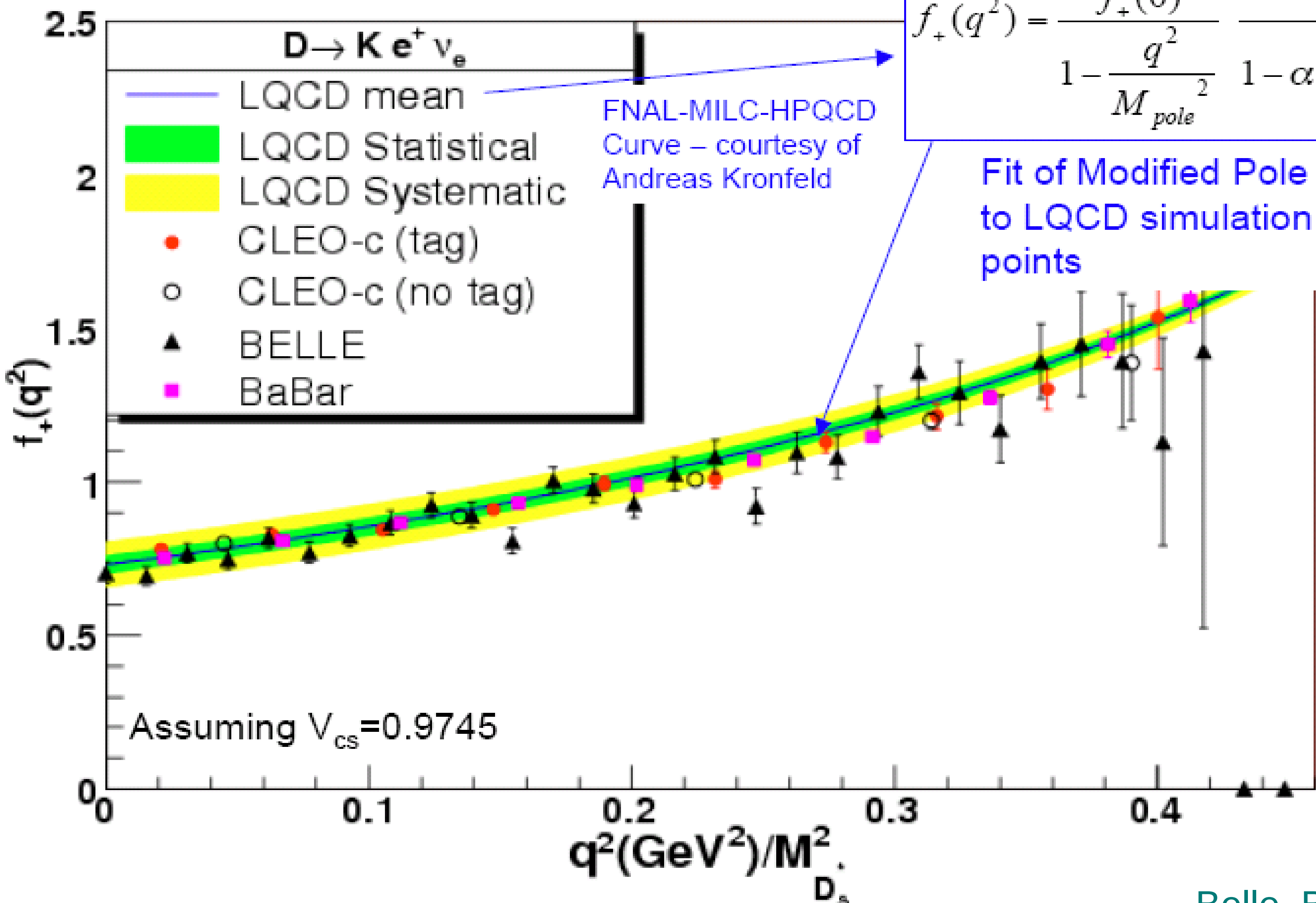
85k signal/11k background

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

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

[2] PLB607, 233 (2005)

$D \to K e \nu$ Form Factor vs. LQCD



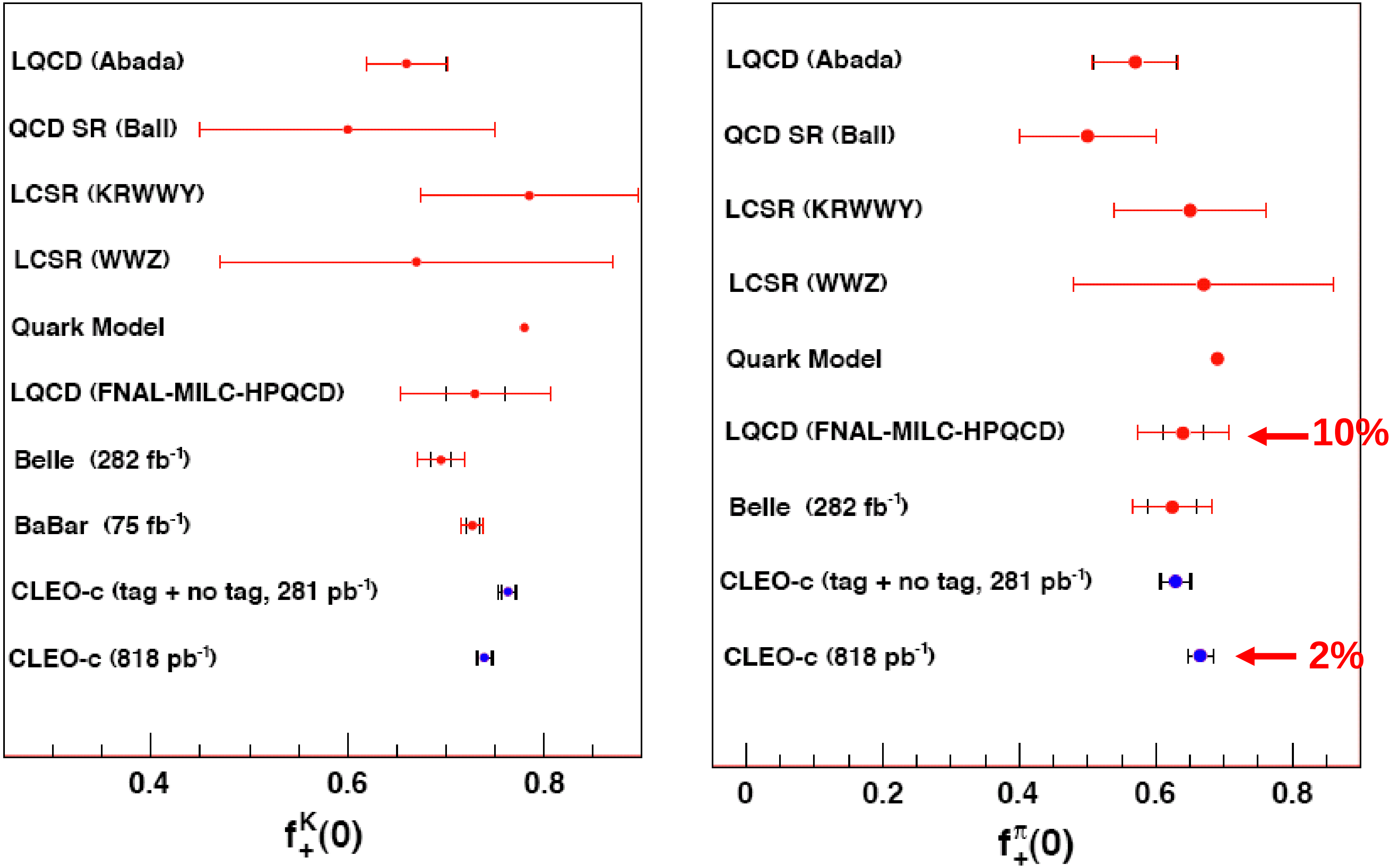
$$f_+(q^2) = \frac{f_+(0)}{1-\frac{q^2}{M_{pole}^2}} \frac{1}{1-\alpha\frac{q^2}{M_{pole}^2}}$$

Fit of Modified Pole Model to LQCD simulation points

Belle, BABAR

$f_+(0)$ for D^0 and D^+ Semileptonic Decays

Results averaged over isospins



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

CLEO, PRL 102, 081801(2009)

Alternative technique:
General Reconstruction (GR)

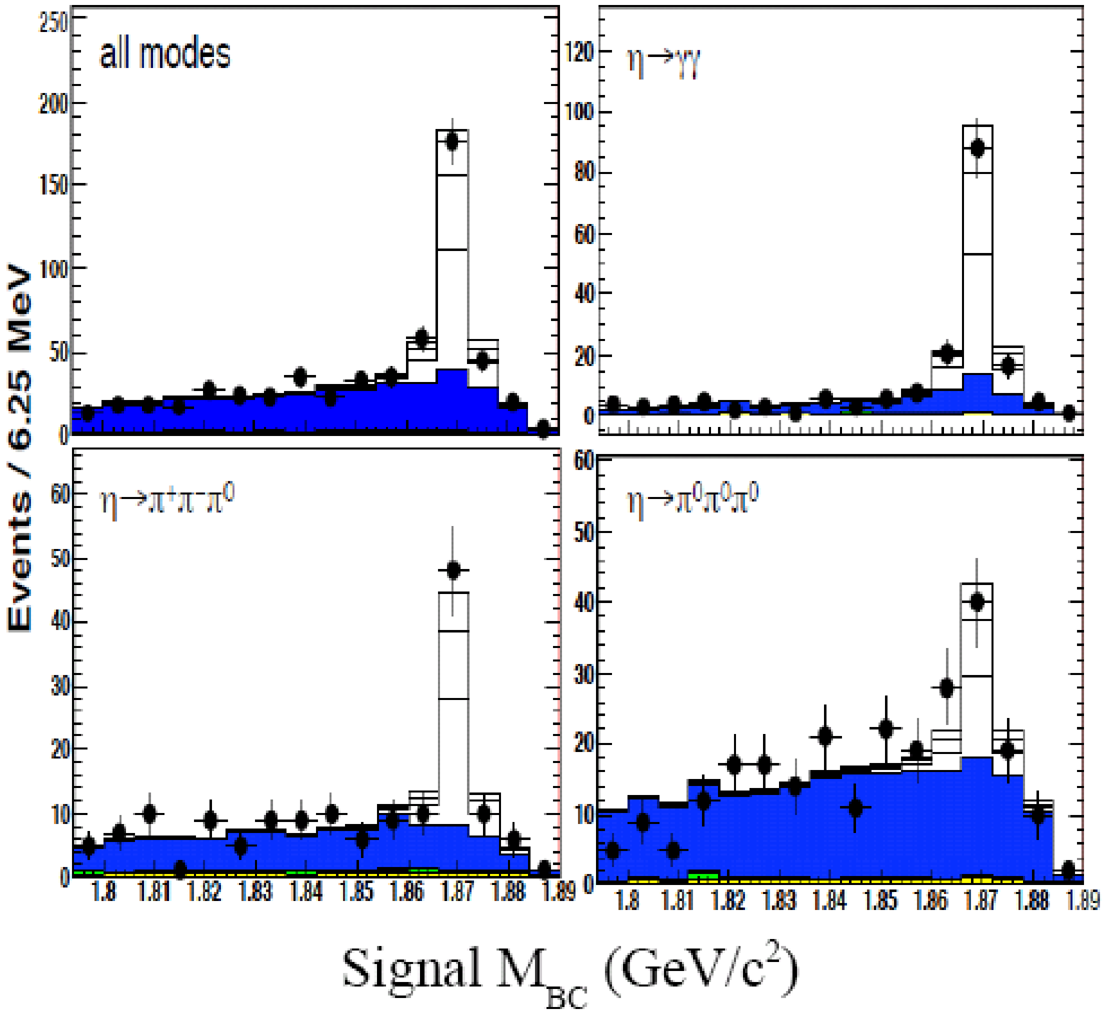
Reconstruct signal mode (e.g., η and e^+)

Look for $\pi^\pm$; $K^\pm$; K_S;
π^0, $\eta \to \gamma\gamma$ in other side D

Infer neutrino from all observed particles in event, results normalized to $K^-\pi^+\pi^+$

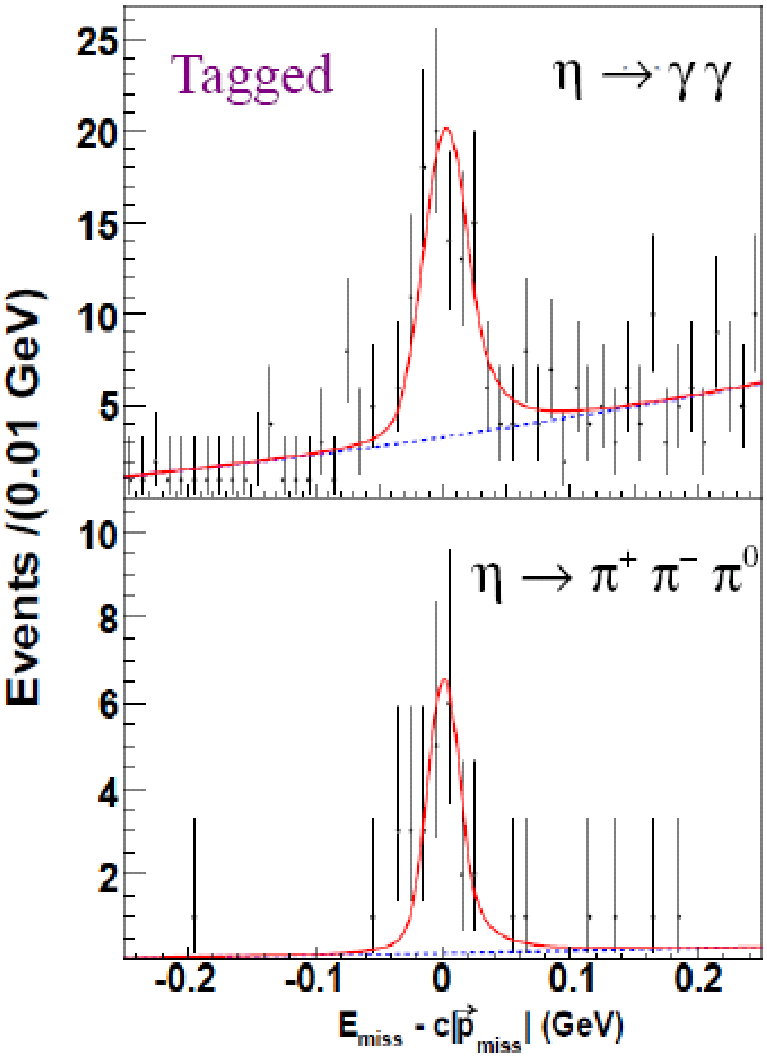
Byproduct: Observed 28 other side D^+ hadronic decays (13 not reported in PDG),
Tagged: 6 D^+ hadronic decays

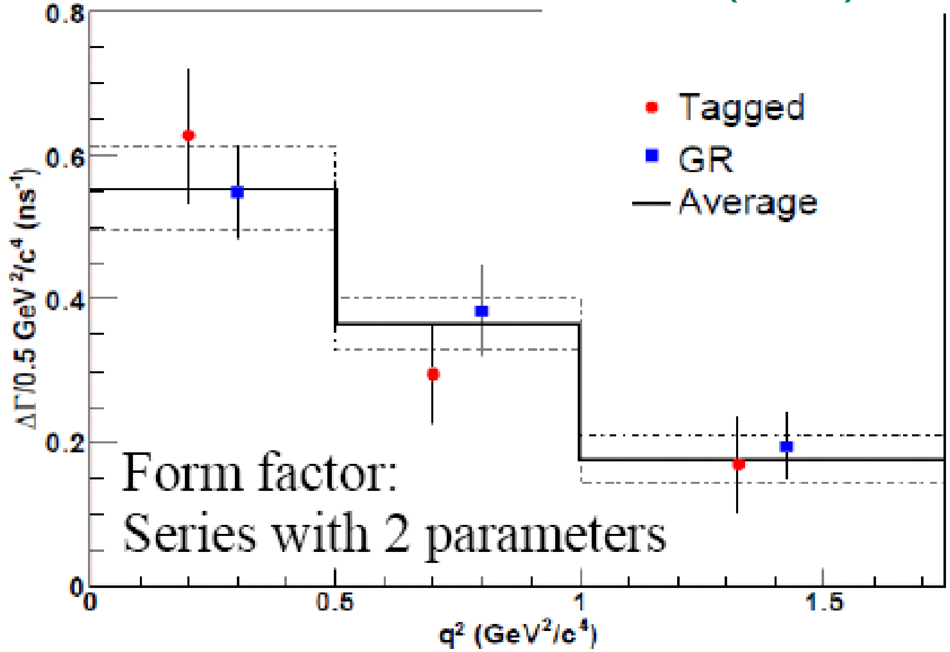
Full ψ(3770) sample



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

CLEO, PRL 102, 081801(2009)





First form factor measurement of $D^+ \to \eta\, e^+ \nu$

$B(D^+ \to \eta\, e^+ \nu) = (11.4 \pm 0.9 \pm 0.4)\text{x}10^{-4}$

[average of both methods]

Full $\psi(3770)$ sample

$D^+ \to \eta', \varphi\, e^+ \nu$

From Peter Zweber
phipsi 2009

PRELIMINARY

Full $\psi(3770)$ sample

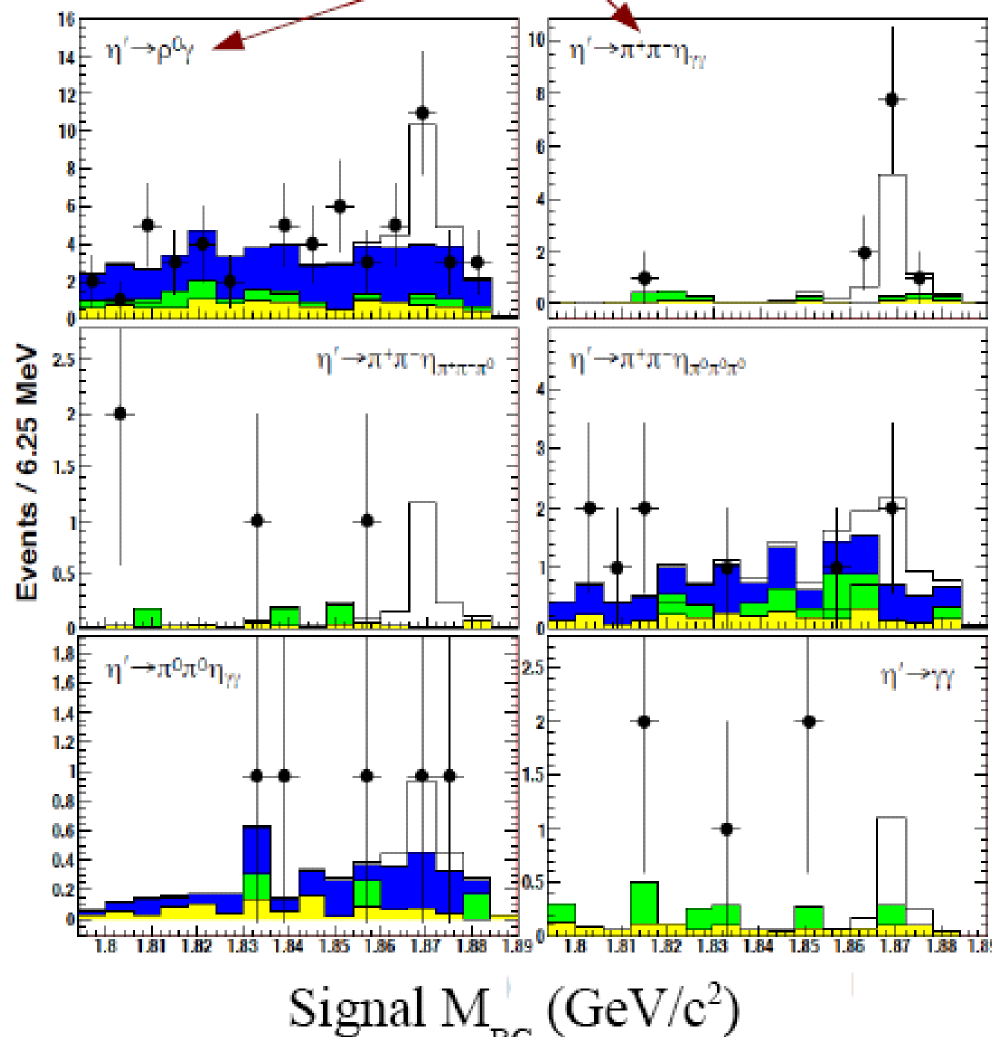
GR: $B(D^+ \to \eta' e^+ \nu)$
$= (2.16 \pm 0.53 \pm 0.05 \pm 0.05) \times 10^{-4}$
stat syst $K\pi\pi$

Tagged: 5 observed events with
0.04 ± 0.03 background events
⇒ 5.6 statistical significance

First observation of $D^+ \to \eta' e^+ \nu$

Tagged: $B(D^+ \to \phi\, e^+ \nu) < 0.9 \times 10^{-4}$
(90% C.L.)

Dominant modes



Exclusive D_s decays

From Peter Zweber
phipsi 2009

PRD 80, 052007 (2009)

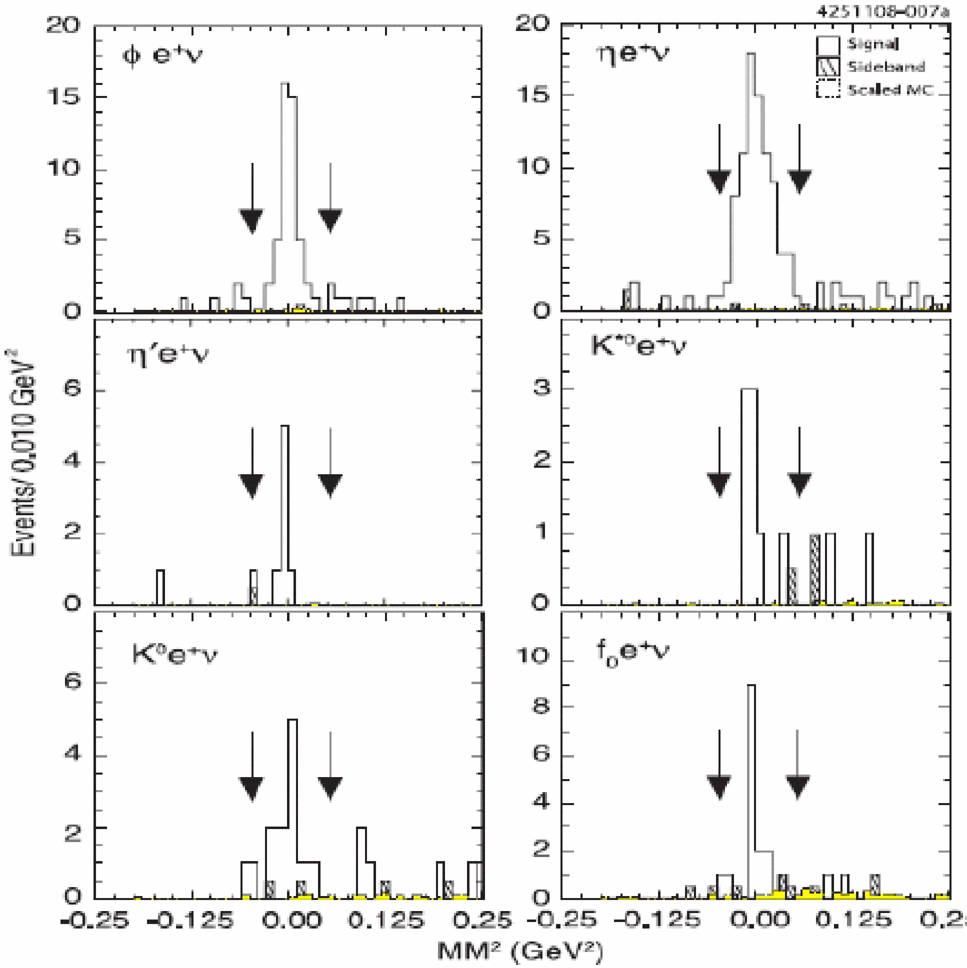
300 pb^{-1} @ 4170 MeV
(half of full sample)

Mode	$\mathcal{B}(D_S^+ \to X)$ (%)
$\phi\ e^+\nu_e$	$2.29 \pm 0.37 \pm 0.11$
$\eta\ e^+\nu_e$	$2.48 \pm 0.29 \pm 0.13$
$\eta'\ e^+\nu_e$	$0.91 \pm 0.33 \pm 0.05$
$K^0\ e^+\nu_e$	$0.37 \pm 0.10 \pm 0.02$
$K^{*0}\ e^+\nu_e$	$0.18 \pm 0.07 \pm 0.01$
$f_0(\pi^+\pi^-)\ e^+\nu_e$	$0.13 \pm 0.04 \pm 0.01$

$B(D_S^+ \to f_0 e^+ \nu) B(f_0 \to \pi^+\pi^-)$

First absolute branching fraction measurements of these decay modes.

Analysis on full 600 pb^{-1} data sample in progress.



$$MM^2 = (E_{CM} - E_{D_S} - E_\gamma - E_e - E_{had})^2 - (\mathbf{p}_{CM} - \mathbf{p}_{D_S} - \mathbf{p}_\gamma - \mathbf{p}_e - \mathbf{p}_{had})^2$$

$D_s \to \phi, f_0(980)\ e\ \nu$

From Peter Zweber phipsi 2009

PRD 80, 052009 (2009)

600 pb^{-1} @ 4170 MeV (full data sample)

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)

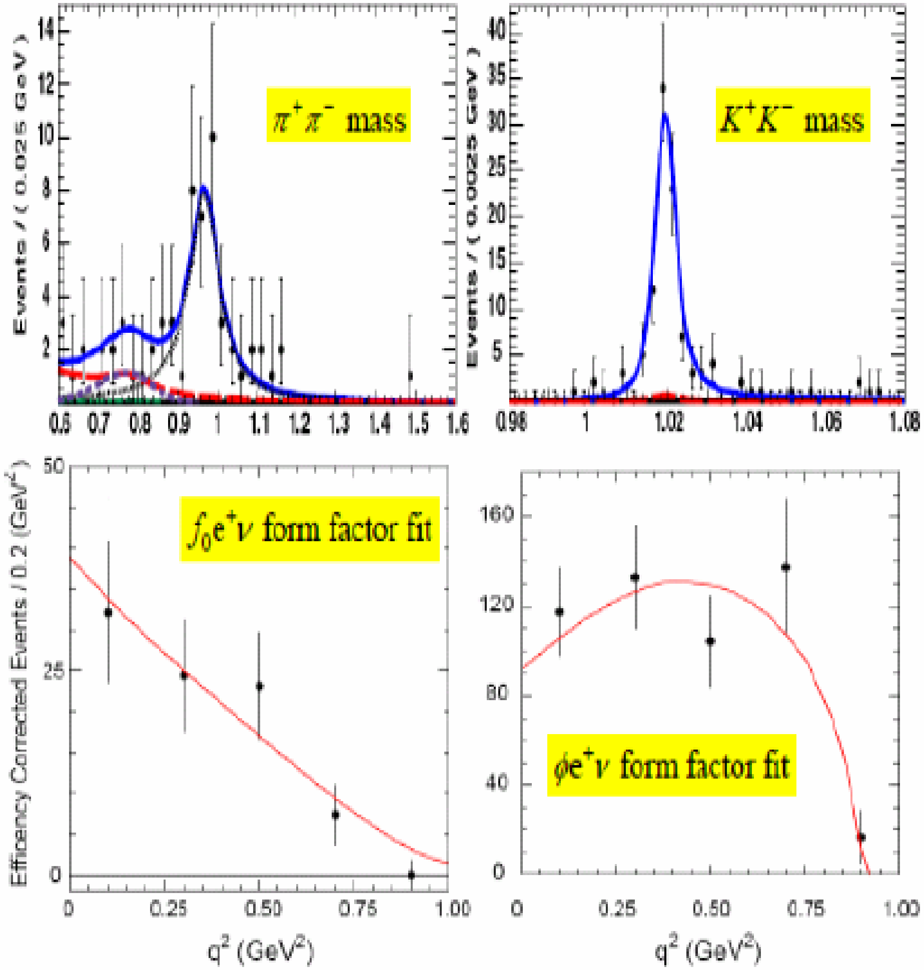
Stone & Zhang [PRD 79, 074024 (2008)]

$$\left.\frac{\Gamma(D_s^+ \to f_0(980)e^+\nu, f_0 \to \pi^+\pi^-)}{\Gamma(D_s^+ \to \phi e^+\nu, \phi \to K^+K^-)}\right|_{q^2=0} = (42\pm11)\%$$

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

$B(D_s^+ \to f_0(\pi^+\pi^-)\ e^+\ \nu) = [0.20(3)(1)]\%$

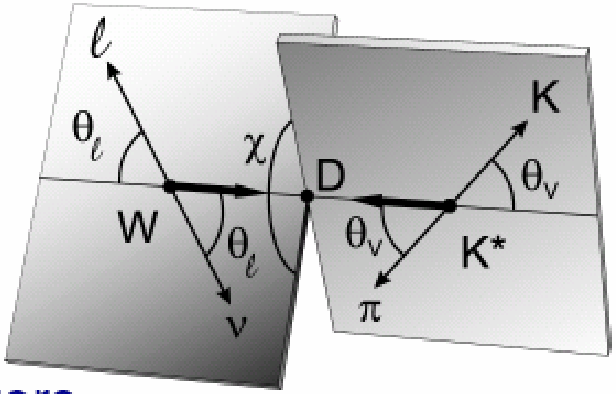
$B(D_s^+ \to \phi\ e^+\ \nu) = [2.36(23)(13)]\%$



arXiv:1004.1954 to appear PRD
CLEO-c 818 pb^{-1}

Study of $D^+ \to K^- \pi^+ \ell^+ \nu$

- Full CLEO-c $\psi(3770)$ dataset
  - Using hadronic D decay tags to fully reconstruct $D\bar{D}$ event
    - excellent resolution on ν from E, p conservation
- Detailed study including resonant K* and non-resonant $K\pi$
  - All 5 kinematic variables used to study 4 helicity amplitudes completely free of model dependence
    - invariant masses: $m(K\pi)$, $q^2=m^2(\ell\nu)$
    - θ_V & θ_ℓ helicity angles in K* & W rest frames
    - angle χ between decay planes



  - projective weighting technique
    - model independent measurement of form factors
    - pioneered by FOCUS: PLB 633, 183 (2006)
    - exploit the fine kinematic resolution possible at charm threshold

arXiv:1004.1954 to appear PRD
CLEO-c 818 pb^{-1}

BF($D^+ \to K^- \pi^+ \ell^+ \nu$)

- Six hadronic tag modes:
  - $D^- \to K^+\pi^-\pi^-$, $K^+\pi^-\pi^-\pi^0$, $K_S\pi^-$, $K_S\pi^-\pi^0$, $K_S\pi^-\pi^-\pi^+$, $K^+K^-\pi^-$
- Signal selected with cut on $\left| E_{\rm miss} - |\mathbf{p}_{\rm miss}| \right| < 20\,\mathrm{MeV}$
- Both muons and electrons used (novel for CLEO-c)
  - μ's give sensitivity to mass-suppressed form factors

	$\mathcal{L}_{\rm int}$ (pb^{-1})	B_e (%)
CLEO-c	818	5.52±0.07±0.13
CLEO-c	56	5.56±0.27±0.23
World Average	PDG 2008	5.49±0.31
		B_μ (%)
CLEO-c	818	5.27±0.07±0.14
World Average	PDG 2008	5.40±0.40

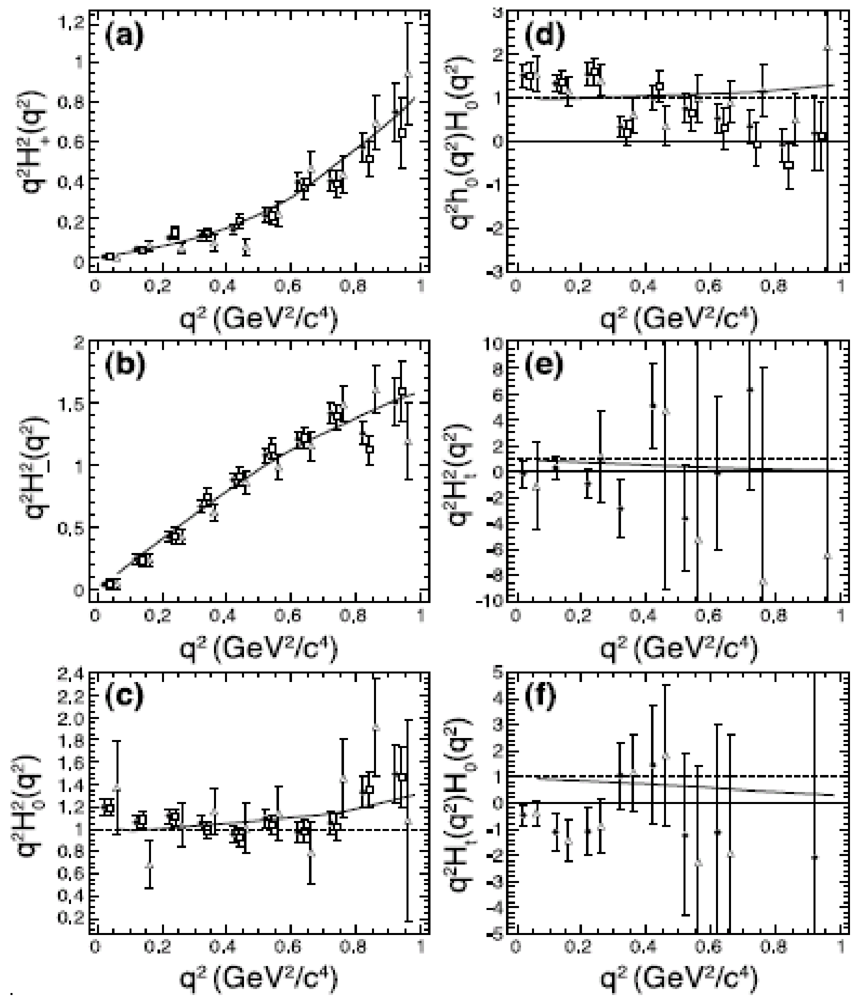
Branching Fraction Results
- full range of m(Kπ)

  - BF reduced by phase space factor $B_\mu / B_e = 0.9598 \pm 0.0193 \pm 0.0130$
  - Most precise results, consistent with previous measurements

arXiv:1004.1954 to appear PRD
CLEO-c 818 pb^{-1}

$D^+ \to K^- \pi^+ \ell^+ \nu$ Form Factors

- Analyze 6 helicity FF
- Plot products vs q^2:
  - $H_+^2(q^2)$, $H_-^2(q^2)$, $H_0^2(q^2)$
  - $H_t^2(q^2)$, $H_t H_0(q^2)$, $h_0 H_0(q^2)$
- General agreement with spectroscopic pole-dominated model (curve)
  - (a)-(c) dominant H_0 H_+ H_-
- Confirmed NR s-wave interference with K* (d)
  - no evidence for d- or f-wave
- (e),(f) suggest smaller H_t than expected from LQCD

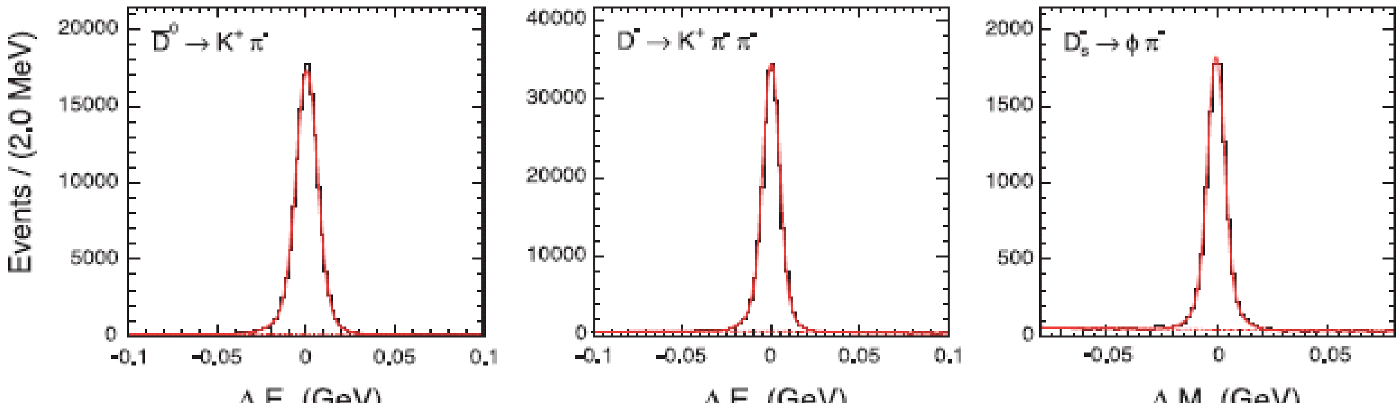


Curves: pole-dominance model
points: data (□e, △μ, ●combined)

PRD 81 052007 (2010)
CLEO-c 818+602 pb^{-1}

Inclusive D and D_s SL decays

- Full CLEO-c open charm samples:
  - 818 pb^{-1} $\psi(3770)$ for $D^0\overline{D}^0$ and D^+D^-
  - 602 pb^{-1} $\sqrt{s}$=4.17 GeV for $D_s\overline{D}^*_s$
- Use hadronic $D_{(s)}$ decay on one side as a tag
  - 3 cleanest tags: $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D_s^+ \to \phi\pi^+$

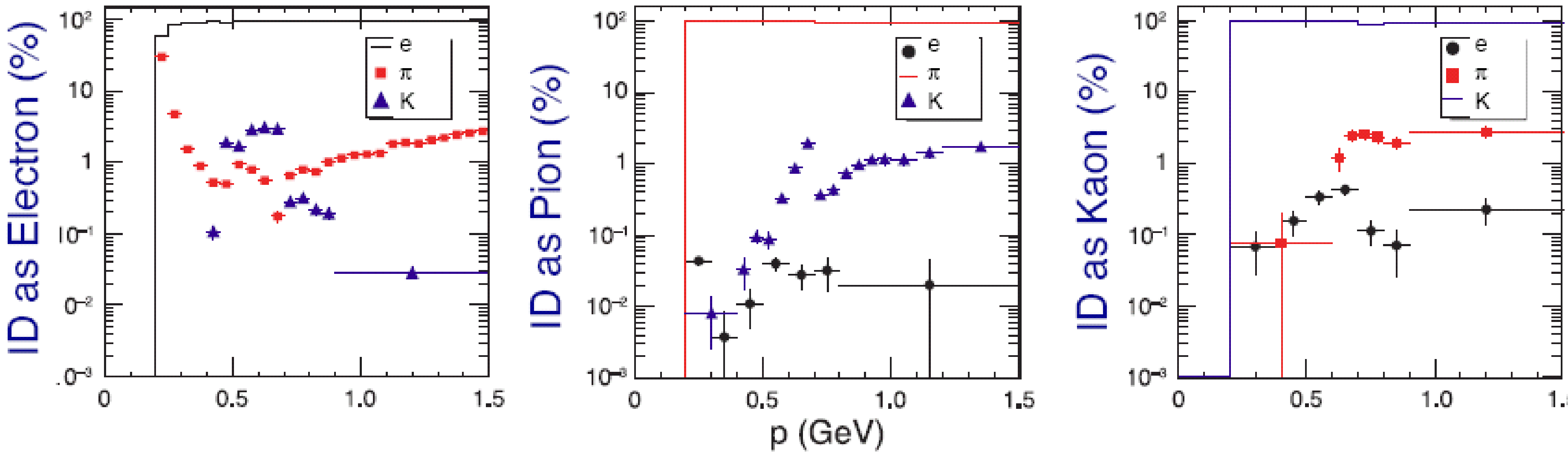


- Accompanying electron spectrum gives inclusive S.L. branching fraction
  - fit spectrum to extrapolate below p = 200 MeV/c

PRD 81 052007 (2010)
CLEO-c 818+602 pb^{-1}

Electron Identification

- Tracks above 200 MeV/c and $|\cos\theta|<0.8$
  - electrons identified with dE/dx, E/p and RICH
  - efficiency and fake rates measured using data
    - π from $K_S \to \pi\pi$;
    - K from reconstructed $D^+ \to K^-\pi^+\pi^+$ decays
    - electrons from radiative Bhabha events embedded in data

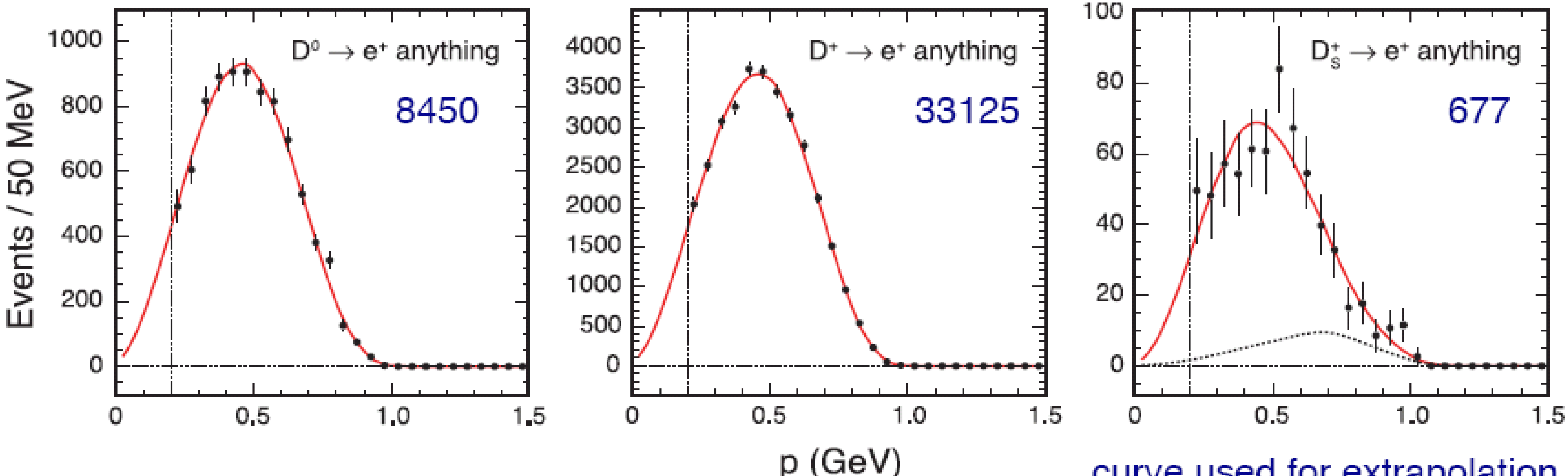


  - High efficiency and low fake rates

PRD 81 052007 (2010)
CLEO-c 818+602 pb^{-1}

Electron Spectra

- Unfold true electron spectrum from π, K & e spectra using PID efficiency matrix binned in momentum
  - Matrix accounts for smearing from finite momentum resolution
- Subtract backgrounds ($\gamma \rightarrow ee$, $\pi^0 \rightarrow \gamma ee$) using wrong sign candidates (9% correction for D^0)



curve used for extrapolation
dashed = $D_s \rightarrow \tau\nu, \tau \rightarrow e\nu\nu$

BRs for Inclusive D and Ds

	$\mathcal{B}(D^0 \to Xe^+\nu)$	$\mathcal{B}(D^+ \to Xe^+\nu)$	$\mathcal{B}(D_S^+ \to Xe^+\nu)$	
Inclusive (%)	$6.55 \pm 0.10 \pm 0.09$	$16.36 \pm 0.11 \pm 0.29$	$6.49 \pm 0.40 \pm 0.18$	CLEO
Σ Exclusive (%)	6.34 ± 0.18	14.8 ± 0.4	6.5 ± 0.6	PDG

$$\frac{\Gamma(D^+ \to Xe^+\nu)}{\Gamma(D^0 \to Xe^+\nu)} = 0.985 \pm 0.016 \pm 0.024$$

(Consistent with isospin)

$$\frac{\Gamma(D_S^+ \to Xe^+\nu)}{\Gamma(D^0 \to Xe^+\nu)} = 0.813 \pm 0.052 \pm 0.028$$

(SU(3): Ds ⟷ D)

Voloshin suggests difference between D^0 and D_s may be non-factorizable terms, similar effect in $B^0, B^\pm \to X_u l\nu$ and determination of V_{ub} [PLB 515, 74 (2001)]

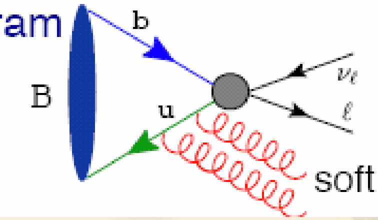
PRD 81 052007 (2010)
CLEO-c 818+602 pb^{-1}

Interpretation

- Compare decay rates under
  - Isospin $D^0 \leftrightarrow D^+$ $$\frac{\Gamma(D^+ \to Xe^+\nu)}{\Gamma(D^0 \to Xe^+\nu)} = 0.985 \pm 0.015 \pm 0.024$$
    - consistent with unity as expected
  - SU(3) ($D_s \leftrightarrow D^+$) $$\frac{\Gamma(D_s^+ \to Xe^+\nu)}{\Gamma(D^0 \to Xe^+\nu)} = 0.828 \pm 0.051 \pm 0.025$$
    - Rate not expected to be equal under SU(3)
    - May shed light on heavy quark SL decays in Heavy Quark expansion
    - Weak Annihilation* contributions impact extraction of V_{ub} from inclusive $b \to u\ell\nu$, estimated ~3% of the total rate concentrated at q^2_{max}
    - Voloshin suggested $\frac{\Gamma(D_s^+ \to Xe^+\nu)}{\Gamma(D^0 \to Xe^+\nu)}$ can constrain B^+ & B^0 differences in the kinematic regions used to measure $b \to u\ell\nu$ and V_{ub}
    - Expectations for WA in D_s are larger by $\sim(m_b/m_c)^3$
    - CLEO-c measurement suggests the WA contribution to B decays is smaller than 3%, perhaps < 1%
      - Recent analysis in Ligeti et al. arXiv:1003.1351 Gambino& Kamenik arXiv:1004.0114 presentation tomorrow

Voloshin PLB 515, 74 (2001)

* "WA" diagram



Summary & Outlook for Charm SL

- Full CLEO-c statistics are partially analyzed
  - Form factors and BF in $D \to K e \nu$, $D \to \pi e \nu$, $D^+ \to K^- \pi^+ \ell^+ \nu$
    - $D \to \pi e \nu$ gives a challenge for LQCD FF needed for V_{ub} from $B \to \pi e \nu$
    - V_{cs} and V_{cd} consistent with CKM unitarity (leading uncertainty from LQCD FF)
  - Inclusive D^0, D^+, D_s branching fraction & electron spectrum
    - provides some constraints on weak annihilation in V_{ub} extraction
- Additional analysis underway at CLEO-c
  - $D \to \rho e \nu, \eta e \nu, \omega e \nu$ with full statistics
  - D_s exclusive decays: $\phi e \nu, \eta e \nu, \eta' e \nu, K_S e \nu, K^{*0} e \nu, f_0 e \nu$
    - (not shown: 310 pb^{-1} published PRD 80, 052007 (2009); 600 pb^{-1} on tape)
- B factories have potential to add here
  - not shown: preliminary $D^+ \to K^- \pi^+ \ell \nu$ form factors from BaBar
- BES III is now running at $\psi(3770)$ with upgraded detector

Precise test of CKM and QCD in D decays at BESIII

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

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

In reality, about 5pb-1 data will be collected @ BESIII in the next four years. the sensitivity will be 2% or less.

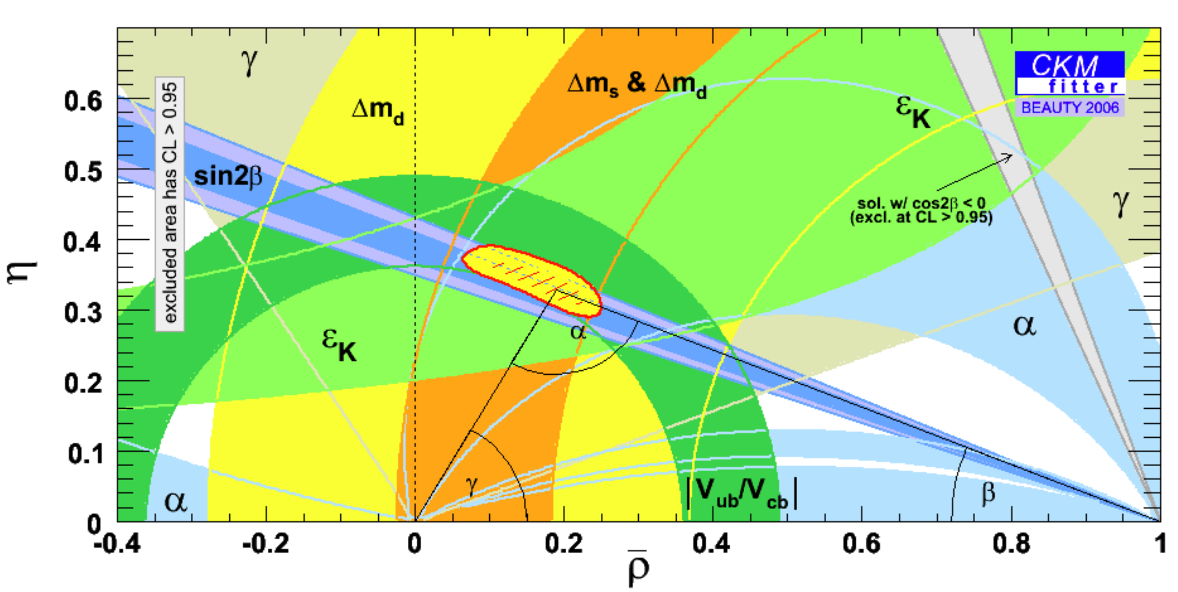
Impact on CKM from LQCD and charm data

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

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)

Charm role in flavor physics



$|V_{ub}|$ from $B \to \pi \ell \nu$:

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

Form factor $f(q^2)$:
- Hard to calculate
- Limits $|V_{ub}|$ precision
- Lattice QCD can do from first principles

Heavy flavor physics:
- over-constrain V_{CKM};
- Inconsistency → New Physics

Unitarity Triangle Constraints
- sin(2β) is clean
- Vub is "dirty"
- B mixing is diluted by hadronic uncertainties.

Charm decay measurements
- decay constants
- form factors
- V_{CKM} clean extraction
- validate QCD
- extract clean weak physics parameters

Questions for you

- $D^0 \to Xe^- \nu$ (or $\bar{D}^0 \to Xe^+ \nu$) is allowed? Why the form factors only depend on q^2 ?
- What's the physical meaning of the FF?
- Can all of semileptonic decays of D/B be used to extract CKM matrix elements?
- Why the weak annihilation processes dilute the extraction of Vub in $B \to X_u e \nu$ inclusive decay.

Z. Ligeti, M.Luke and A.V.Manohar arXiv:1003.1351[hep-ph]

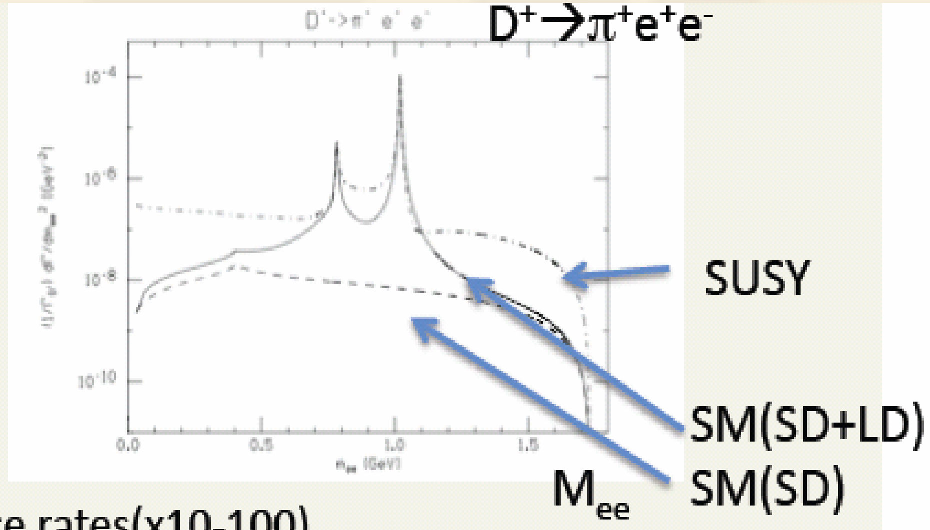
Rare & forbidden charm decays

What's the rare?

- Suppressed or Forbidden by SM
  - FCNC (c→u) GIM suppressed:
    - $D^+ \to \pi^+ e^+ e^-$, $D \to X \gamma$
  - LNV/LFV:
    - $D^+ \to \pi^- e^+ e^+$, $D^+ \to \pi^+ e^+ \mu^-$
  - BNV:
    - $D \to X\, p$
- Not so exotic but interesting (BESIII targets)
  - $D \to \tau\nu$ (SM consistency)
  - $D \to l\nu\gamma$ (Validate radiative contributions, $\times 10^{-5}$)
- Small Deviations rather than small rates (BESIII target)
  - Lepton Universality ($D \to Xe\nu$ versus $D \to X\mu\nu$)
- D-mixing and CPV
  - Covered in other talks today.

Expected rate

- Standard Model SD contributions
  - Range
    - $D^+ \to X_u e^+e^-$: 10^{-8}
    - $D^0 \to e^+e^-$: 10^{-24}
    - $D^0 \to e\mu$: =0
- Exotic contributions
  - NSM contributions can significantly enhance rates(x10-100).
  - $D^+ \to \pi^+e^+e^-$ (at high M_{ee})
- SM LD contributions:
  - Enhancement in rate due to vector resonances (x100).



G. Burdman, I. Shipsey,
Ann.Rev.Nucl.Part.Sci.53:431-499,2003

Expected Rate in SM

Decay Mode	$Br_{S.D.}$	$Br_{L.D.}$
$D^+ \to X_u^+ e^+ e^-$	2×10^{-8}	
$D^+ \to \pi^+ e^+ e^-$		2×10^{-6}
$D^+ \to \pi^+ \mu^+ \mu^-$		1.9×10^{-6}
$D^+ \to \rho^+ e^+ e^-$		4.5×10^{-6}
$D^0 \to X_u^0 + e^+ e^-$	0.8×10^{-8}	
$D^0 \to \pi^0 e^+ e^-$		0.8×10^{-6}
$D^0 \to \rho^0 e^+ e^-$		1.8×10^{-6}
$D^0 \to \rho^0 \mu^+ \mu^-$		1.8×10^{-6}
$D^+ \to X_u^+ \nu\bar{\nu}$	1.2×10^{-15}	
$D^+ \to \pi^+ \nu\bar{\nu}$		5×10^{-16}
$D^0 \to \bar{K}^0 \nu\bar{\nu}$		2.4×10^{-16}
$D_s \to \pi^+ \nu\bar{\nu}$		8×10^{-15}
$D^0 \to \gamma\gamma$	4×10^{-10}	few $\times 10^{-8}$
$D^0 \to \mu^+ \mu^-$	1.3×10^{-19}	few $\times 10^{-13}$
$D^0 \to e^+ e^-$	$(2.3 - 4.7) \times 10^{-24}$	
$D^0 \to \mu^\pm e^\mp$	0	0
$D^+ \to \pi^+ \mu^\pm e^\mp$	0	0
$D^0 \to \rho^0 \mu^\pm e^\mp$	0	0

Burdman et. al., PRD66(2002) 014009

Physics at BESIII Int. J. Of Mod. Phys. A 24 Supp. 1 Page 679 Edited by K.T.Chao Y.F.Wang

Experimental limits

Mode	Reference Experiment	Best Upper limits(10^{-6})
$\pi^+e^+e^-$	CLEO-c [436]	7.4
$\pi^+\mu^+\mu^-$	FOCUS [437]	8.8
$\pi^+\mu^+e^-$	E791 [438]	34
$\pi^-e^+e^+$	CLEO-c [436]	3.6
$\pi^-\mu^+\mu^+$	FOCUS [437]	4.8
$\pi^-\mu^+e^+$	E791 [438]	50
$K^+e^+e^-$	CLEO-c [436]	6.2
$K^+\mu^+\mu^-$	FOCUS [437]	9.2
$K^+\mu^+e^-$	E791 [438]	68
$K^-e^+e^+$	CLEO-c [436]	4.5
$K^-\mu^+\mu^+$	FOCUS [437]	13
$K^-\mu^+e^+$	E687 [439]	130

Mode	Reference Experiment	Best Upper limits(10^{-6})
$\gamma\gamma$	CLEO [442]	28
$\mu^+\mu^-$	D0 [444]	2.4
μ^+e^-	E791 [438]	8.1
e^+e^-	E791 [438]	6.2
$\pi^0\mu^+\mu^-$	E653 [445]	180
$\pi^0\mu^+e^+$	CLEO [443]	86
$\pi^0e^+e^-$	CLEO [443]	45
$K_S\mu^+\mu^-$	E653 [445]	260
$K_S\mu^+e^-$	CLEO [443]	100
$K_Se^+e^-$	CLEO [443]	110
$\eta\mu^+\mu^-$	CLEO [443]	530
$\eta\mu^+e^-$	CLEO [443]	100
ηe^+e^-	CLEO [443]	110

What's the rare program?

I

Current Exp Limits

BESIII Reach } NP

SM (LD+SD)

BR

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

$D \rightarrow \gamma\gamma$

II

Current Exp Limits

BESIII Reach } SM

LD

BR

$D \rightarrow V\gamma$

III

Current Exp Limits

BESIII Reach } SM

SD

BR

$D \rightarrow \tau\nu$

IV: Forbidden($Xe\mu$, $X l^+ l^+$)

CLEO-c for $D \to Xe^+e^-$ ($281 pb^{-1}$)

CLEO
PRL 95 (2005) 221802

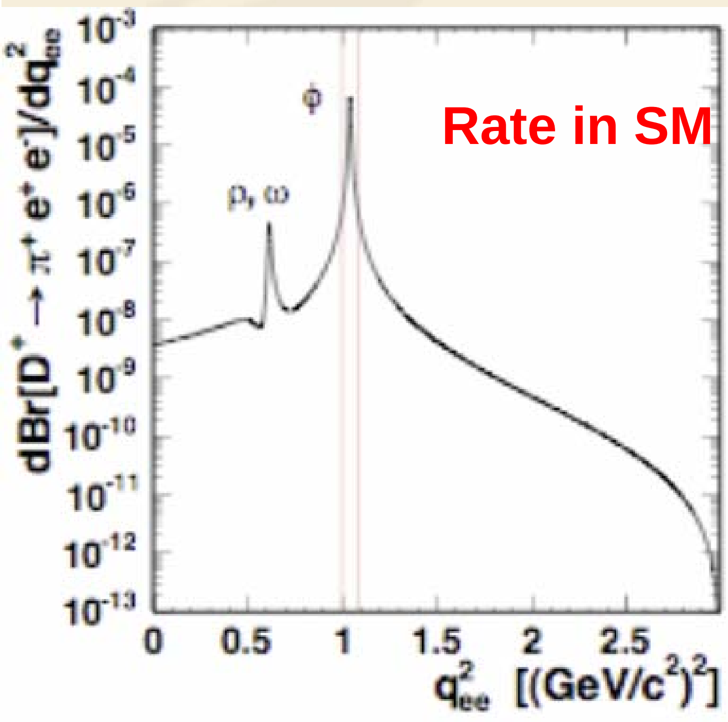
Branching-fraction UL values are all at 90% C.L.

Mode	ϵ (%)	N	n	σ_{syst} (%)	$\mathcal{B}$ (10^{-6})
$\pi^+e^+e^-$	36.41	1.99	2	8.7	<7.4
$\pi^-e^+e^+$	43.85	0.48	0	7.1	<3.6
$K^+e^+e^-$	26.18	1.47	0	10.0	<6.2
$K^-e^+e^+$	35.44	0.50	0	7.2	<4.5
$\pi^+\phi(e^+e^-)$	46.22	0.04	2	7.4	$2.7^{+3.6}_{-1.8} \pm 0.2$

First observation of $D \to Xee$ type decay.
Rate consistent with expectations.

Efficiency and resolution are very good:
$\sigma_{\Delta E}$ ~ 6 MeV
σ_{Mbc} ~1.5 MeV

Backgrounds:
double-semileptonic, conversions, Dalitz, QED
*Suppressed with other side energy requirement.
*Reject low Mee



What is special about doing a rare analysis

Experimental perspective

- Blind analyses should be the rule.
- Unusual backgrounds require extensive care.
  - Anomalous detector problems must be anticipated.
  - MC may not reproduce detector anomalies.
  - May required nonstandard background samples from MC.
  - Control samples from data can help identify and quantify MC performance.
- Extensive statistical optimization required.
  - Systematics are often not driving the data selection criteria.
  - Creativity in developing novel selection should be encouraged.
- The time scale for receiving a meaningful data sample is long.
  - Preparation should still start now for BESIII.
  - Mock data challenges should be planned.
- $D \to V\gamma$ and $\gamma\gamma$ provide excellent examples.
  - First observations are possible at BESIII.
  - Will provide next level of precision on observed modes.
  - Photon resolution and broad resonances are handled well in our clean environment.
  - Novel analysis techniques can enhance reach significantly.
  - Provides a reality check on our “hopes”.

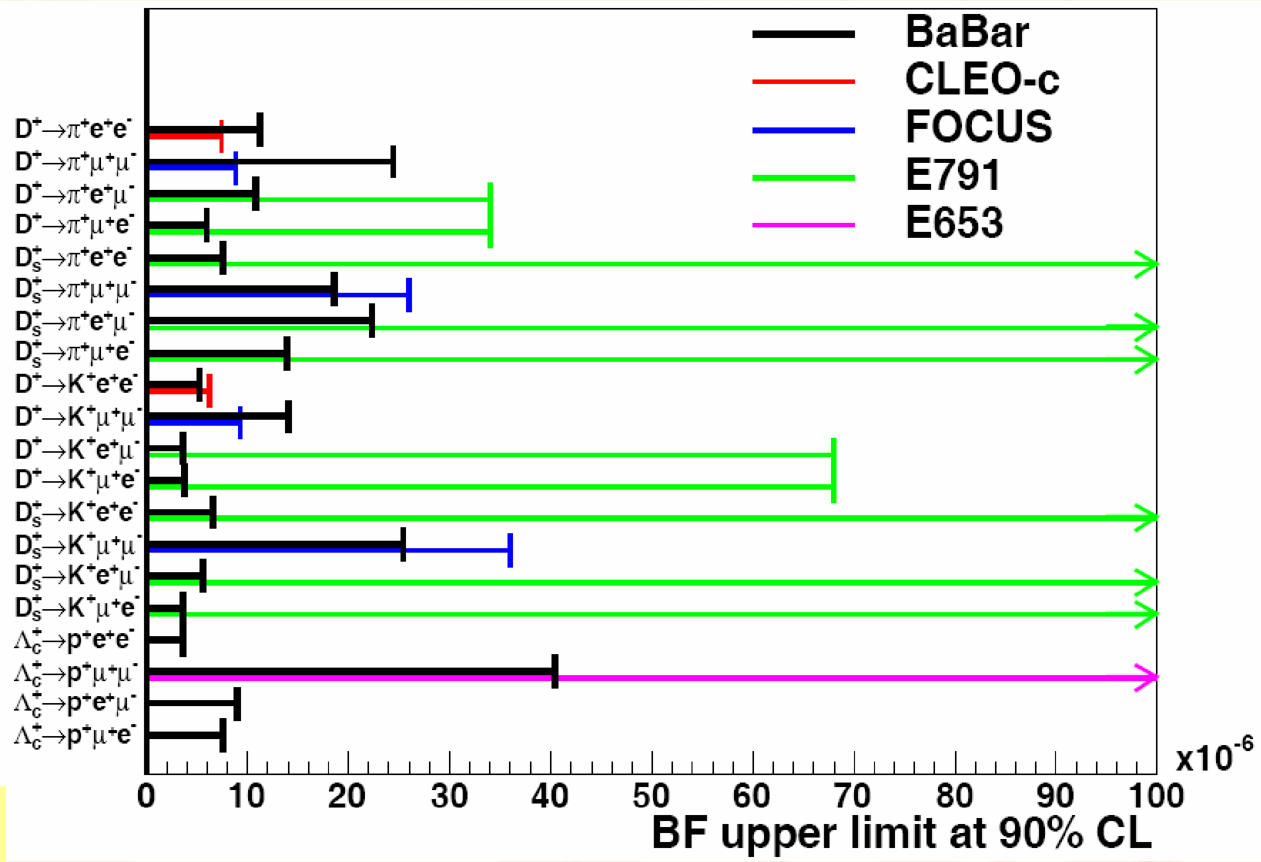
$D \to h l^+ l^-$ Like Rare Decays

BaBar Input
ICHEP06
288 fb^{-1} @$\Upsilon(4S)$

CLEO-c
0.8 M (0.281 fb^{-1})

$$\frac{L_{BaBar}}{L_{CLEO-c}} = \frac{288}{0.3} = 960$$

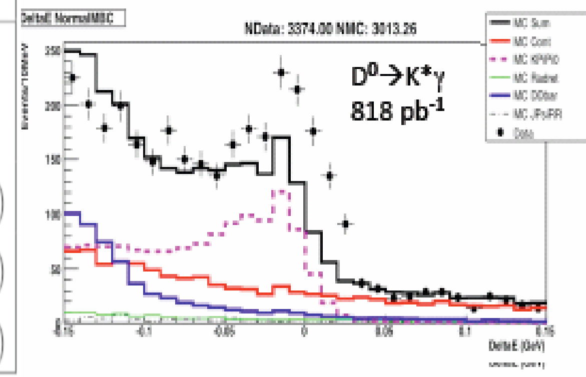
Background free at a tau charm factory @3770 peak!

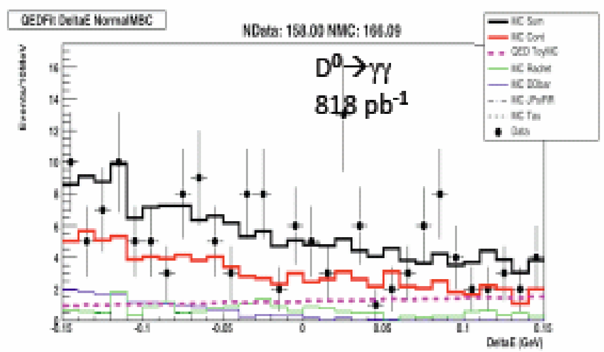


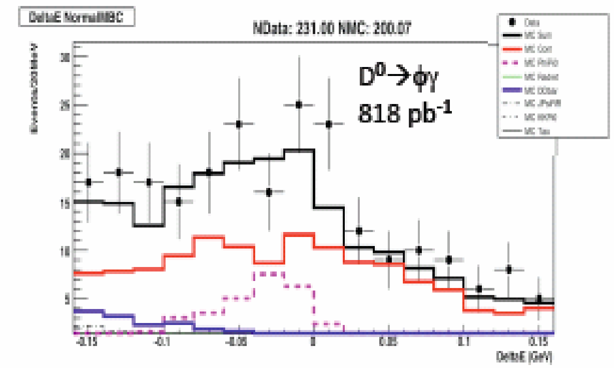
D→Vγ with CLEO-c full dataset

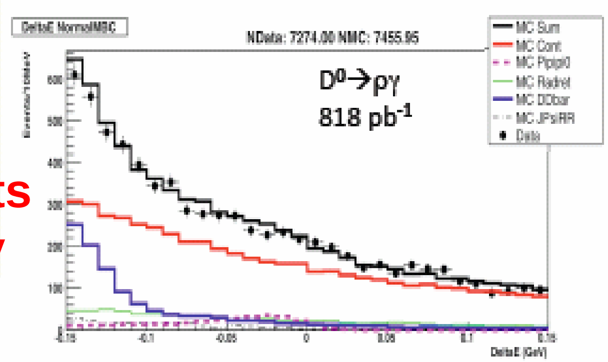
- Modes: $D^0 \to K^*\gamma$, $D^0 \to \phi\gamma$, $D^0 \to \rho\gamma$, $D^0 \to \omega\gamma$, $D^0 \to \gamma\gamma$
- Luminosity: 818 pb^{-1}
- Comprehensive: Modes with low measurement resolution and broad resonances are not measured by B-factories.
- Easy to compare ratios (remove LD physics) and look for NP contributions
- Improved upper limits
- Confirm: K^*, ϕ observations

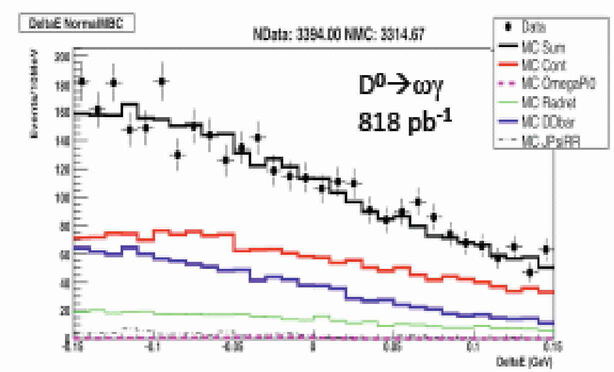
Channel	$\epsilon[\%]$	N_{Bknd}	$N_{observed}$	$\mathcal{B}$
$D \to \bar{K}^*\gamma$	12.29	355.79 ± 2.55	677	$[4.37 \pm 0.37 \pm 0.52] \times 10^{-4}$
$D \to \phi\gamma$	11.61	28.66 ± 1.08	44	$[2.21 \pm 0.95 \pm 0.29] \times 10^{-5}$
$D \to \gamma\gamma$	19.90	15.79 ± 0.81	17	$< 8.63 \times 10^{-6}$ (UL @90% CL)
$D \to \rho\gamma$	23.41	615.4 ± 4.9	625	$< 3.63 \times 10^{-5}$ (UL @90% CL)
$D \to \omega\gamma$	11.37	247.8 ± 4.5	235	$< 3.00 \times 10^{-5}$ (UL @90% CL)











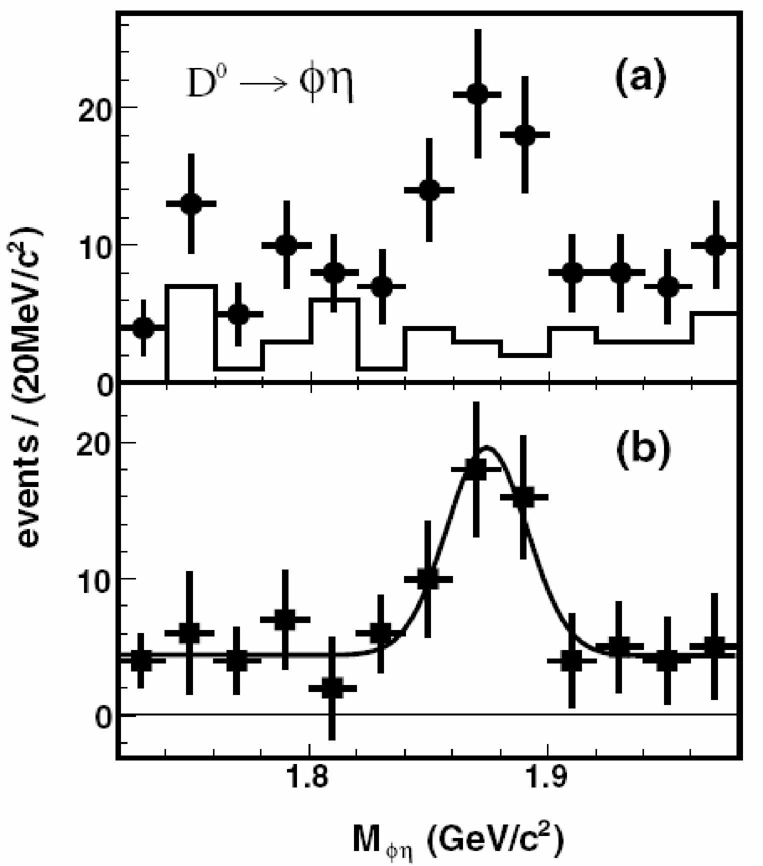
CLEO-c preliminary results from D. Cronin-Hennessy

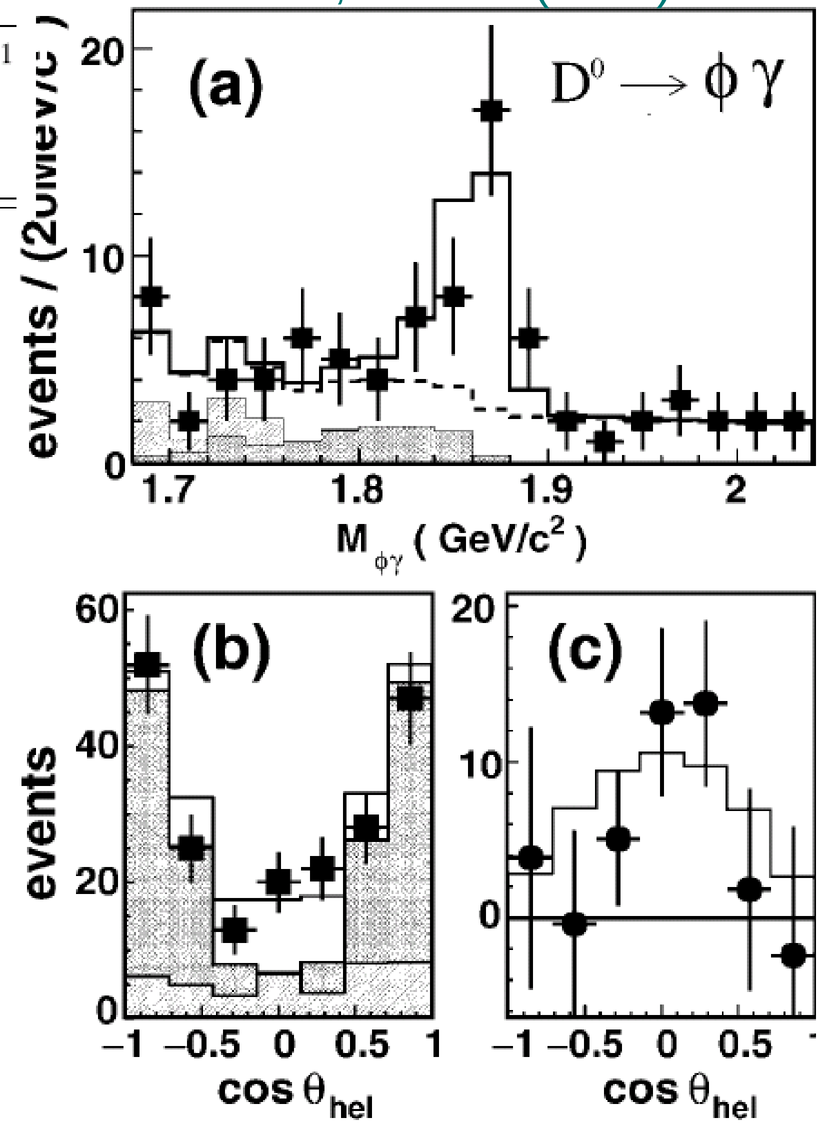
D→φγ from Belle 78fb^{-1}

Mode	$\mathcal{B}_f/\mathcal{B}_{K^+K^-}$	$\mathcal{B}_f$ ($\times 10^{-4}$)
$\phi\gamma$	$[6.31^{+1.70}_{-1.48}\,^{+0.30}_{-0.36}] \times 10^{-3}$	$[2.60^{+0.70}_{-0.61}\,^{+0.15}_{-0.17}] \times 10^{-1}$
$\phi\pi^0$	$[1.94 \pm 0.06 \pm 0.09] \times 10^{-1}$	$8.01 \pm 0.26 \pm 0.47$
$\phi\eta$	$[3.59 \pm 1.14 \pm 0.18] \times 10^{-2}$	$1.48 \pm 0.47 \pm 0.09$

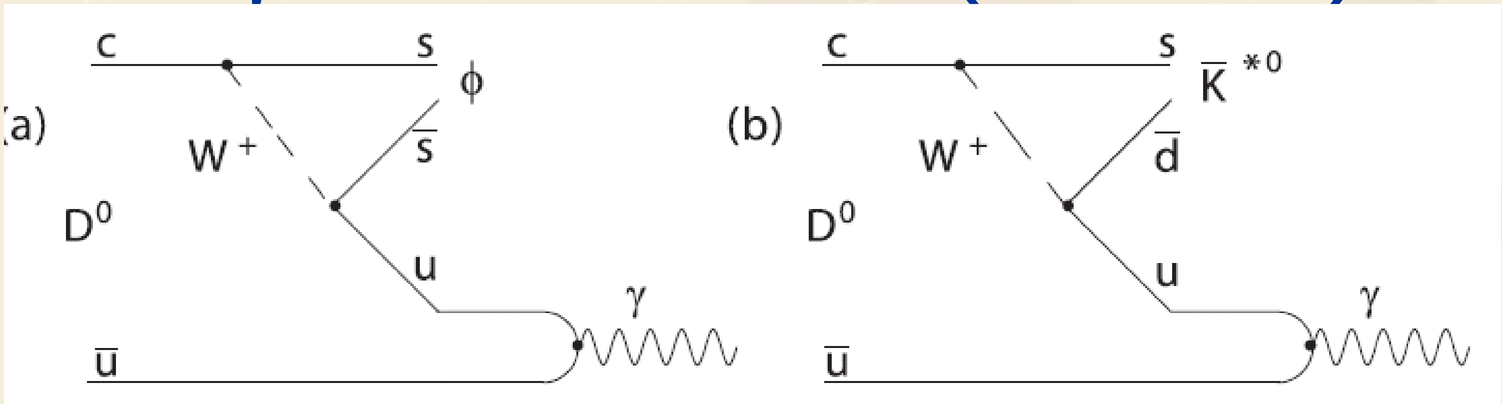
PRL92, 101803 (2004)

Belle observed the D→φγ for the first time!





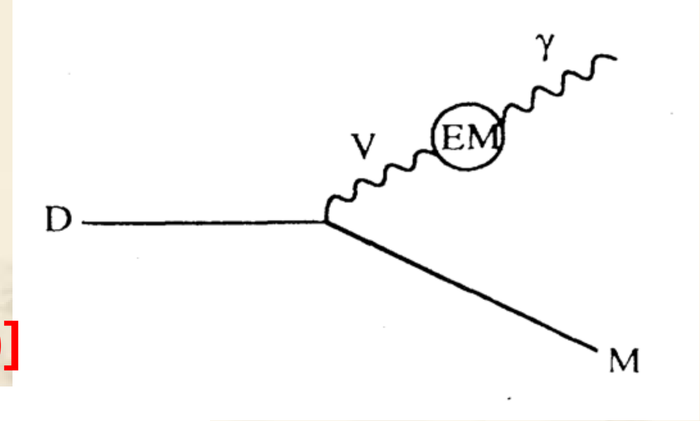
D→Vγ from BABAR (387fb^{-1})



$$\mathcal{B}(D^0 \to \phi\gamma) = (2.78 \pm 0.30 \pm 0.27) \times 10^{-5},$$

$$\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma) = (3.28 \pm 0.20 \pm 0.27) \times 10^{-4}.$$

BABAR, PRD78,071101(R)(2008)



In VDM, the largest contribution to radiative D decays is expected to come from a virtual ρ coupling to single photon [PRD52, 6383(1995)]

$$\frac{\mathcal{B}(D^0 \to \phi\gamma)}{\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma)} = (8.48 \pm 1.07 \pm 1.08) \times 10^{-2},$$

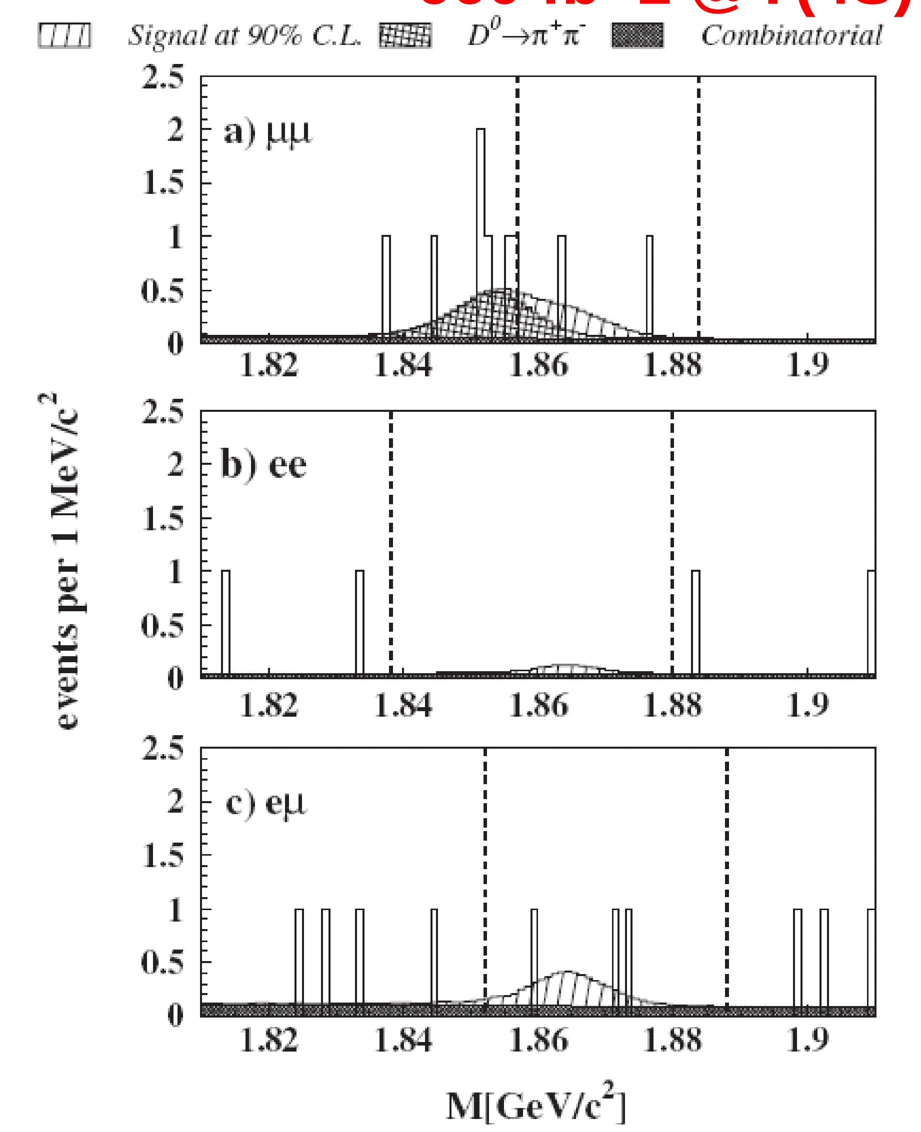
$$\frac{\mathcal{B}(D^0 \to \phi\rho^0)}{\mathcal{B}(D^0 \to \bar{K}^{*0}\rho^0)} = (9.15 \pm 2.17) \times 10^{-2}$$

D Dileptonic decay from Belle

Belle PRD81, 091102 (R) (2010)

660 fb–1 @Y(4S)

$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 1.4 \times 10^{-7},$$
$$\mathcal{B}(D^0 \to e^+e^-) < 7.9 \times 10^{-8},$$
$$\mathcal{B}(D^0 \to e^\pm\mu^\mp) < 2.6 \times 10^{-7}.$$



Outlook for rare decays at BESIII

- Assuming 10 fb^{-1} we have a viable rare decay program
  - **NP**: Will improve UL on FCNC and Forbidden decays.
  - **LD**: May have first observations in $V\gamma$ modes.

    Will improve precision of observed modes with better control of systematics
  - **SD**: $D \to \tau \nu$ may be established.
- Some lessons from CLEO-c
  - Backgrounds are indeed low for lepton analyses (untagged analysis is optimal).
  - Photon modes are hard. Innovative techniques are required to exploit the full potential of the data.
  - Well designed control samples of data are useful in uncovering deficiencies of MC.
  - MC physics needs to be checked.
  - We should encourage creative approaches to data selection (we are not required to use standard selection).
  - Expect the unexpected.

Sensitivities for rare charm decay at BESIII

- **$D \to V\gamma$ will be reached at 10^{-7}**
  $D^0 \to \phi\gamma$, $K^*\gamma$ will be confirmed and improved
  $D^0 \to \rho\gamma$, $\omega\gamma$ will be improved or found

- **$D^0 \to \gamma\gamma$ can be measured with tag or without tag**
  the sensitivity will be 10^{-7}

- **$D \to X l^+ l^-$ can be reached at 10^{-7}**
  BESIII will reach contribution from long distance

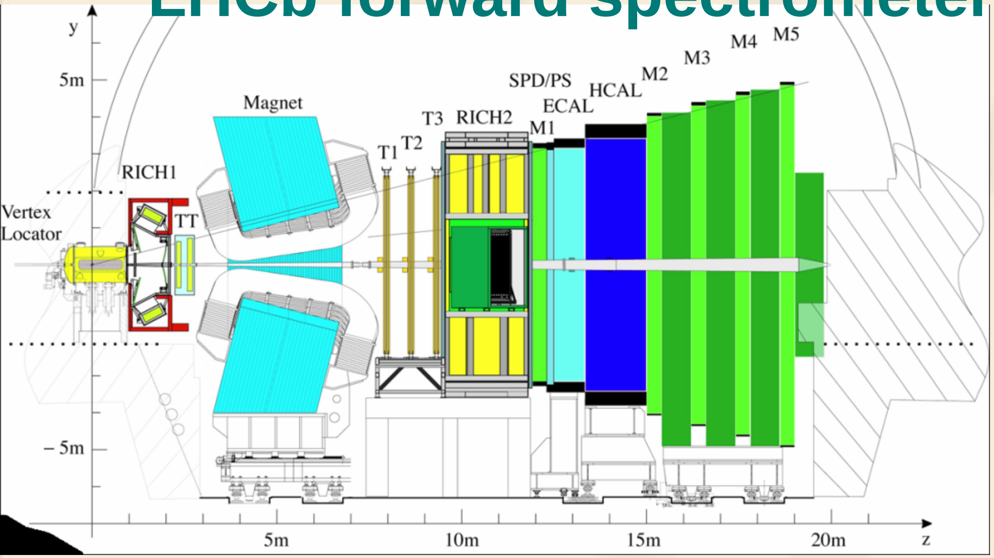
- **$D^0 \to l^+ l^-$ will be reached at 10^{-7}**

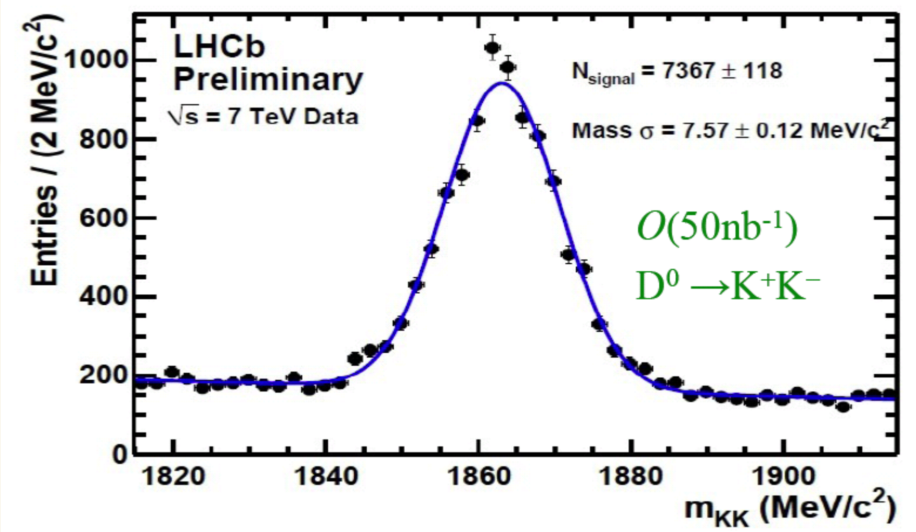
Questions for you

- **Why $D^+ \to \mu\nu$, $e\nu$ are helicity suppressed, while $D^+ \to \gamma\mu\nu$, $\gamma e\nu$ are not?**
- **To measure $D^0 \to \gamma\gamma$, double or single tag, which method is better at $\psi(3770)$ peak?**
- **Can we measure $D^0 \to \nu\nu$, or $\gamma\nu\nu$, the sensitivity with 10fb^{-1} @$\psi(3770)$? What's the main backgrounds?**
- **Can we measure $D^0 \to K/\pi\ \nu\nu$? What's the main backgrounds? @BESIII!**
- **What's GIM mechanism? How it works in charm rare decays?**

Charm flavor physics in the future

LHCb forward spectrometer

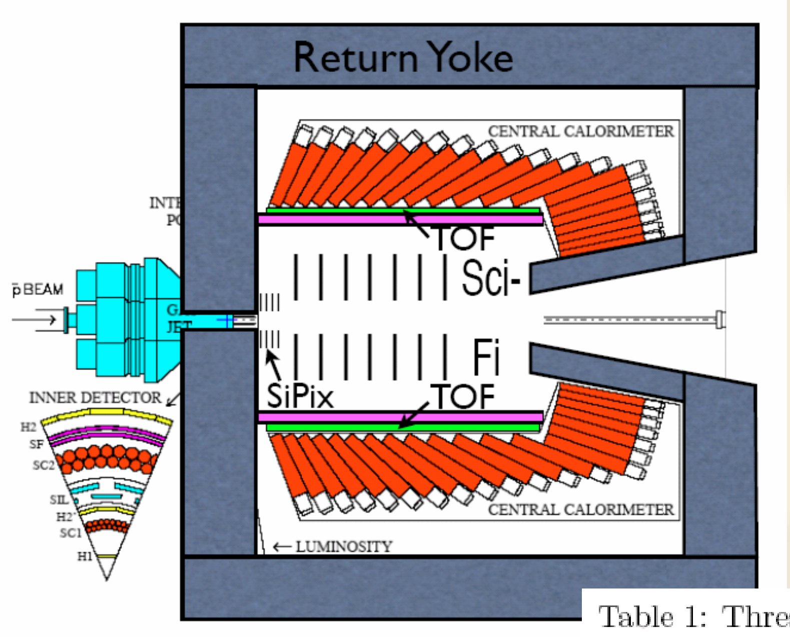


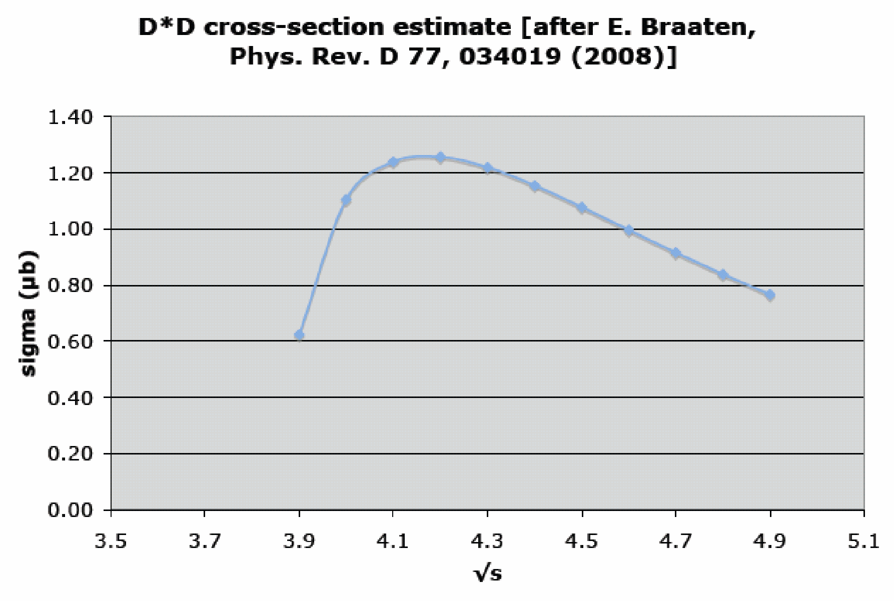


Rare charm decays, CPV, D mixing.
For example: $D^0 \to \mu\mu$: the reach is 10^{-9} with $1fb^{-1}$

Charm flavor physics in the future

Upgraded E835 at Fermilab for charm physics





10^9 charm meson /year

Rare charm decays,
New charmonium states
Charmed baryons

Table 1: Thresholds for some processes of interest and lab-frame $\overline{p}$ momentum for $\overline{p}p$ fixed-target.

Hyperon pairs	Threshold $\sqrt{s}$ (GeV)	Threshold $p_{\overline{p}}$ (GeV/c)	"Charmonium"	Threshold $\sqrt{s}$ (GeV)	Threshold $p_{\overline{p}}$ (GeV/c)
$\overline{p}p \to \overline{\Lambda}\Lambda$	2.231	1.437	$\overline{p}p \to \eta_c$	2.980	3.678
$\overline{p}p \to \overline{\Sigma}^-\Sigma^+$	2.379	1.854	$\overline{p}p \to \psi(3770)$	3.771	6.572
$\overline{p}p \to \overline{\Xi}^+\Xi^-$	2.642	2.620	$\overline{p}p \to X(3872)$	3.871	6.991
$\overline{p}p \to \overline{\Omega}^+\Omega^-$	3.345	4.938	$\overline{p}p \to X$ or $Y(3940)$	3.940	7.277
			$\overline{p}p \to Y(4260)$	4.260	8.685

Charm at Super-flavor factories

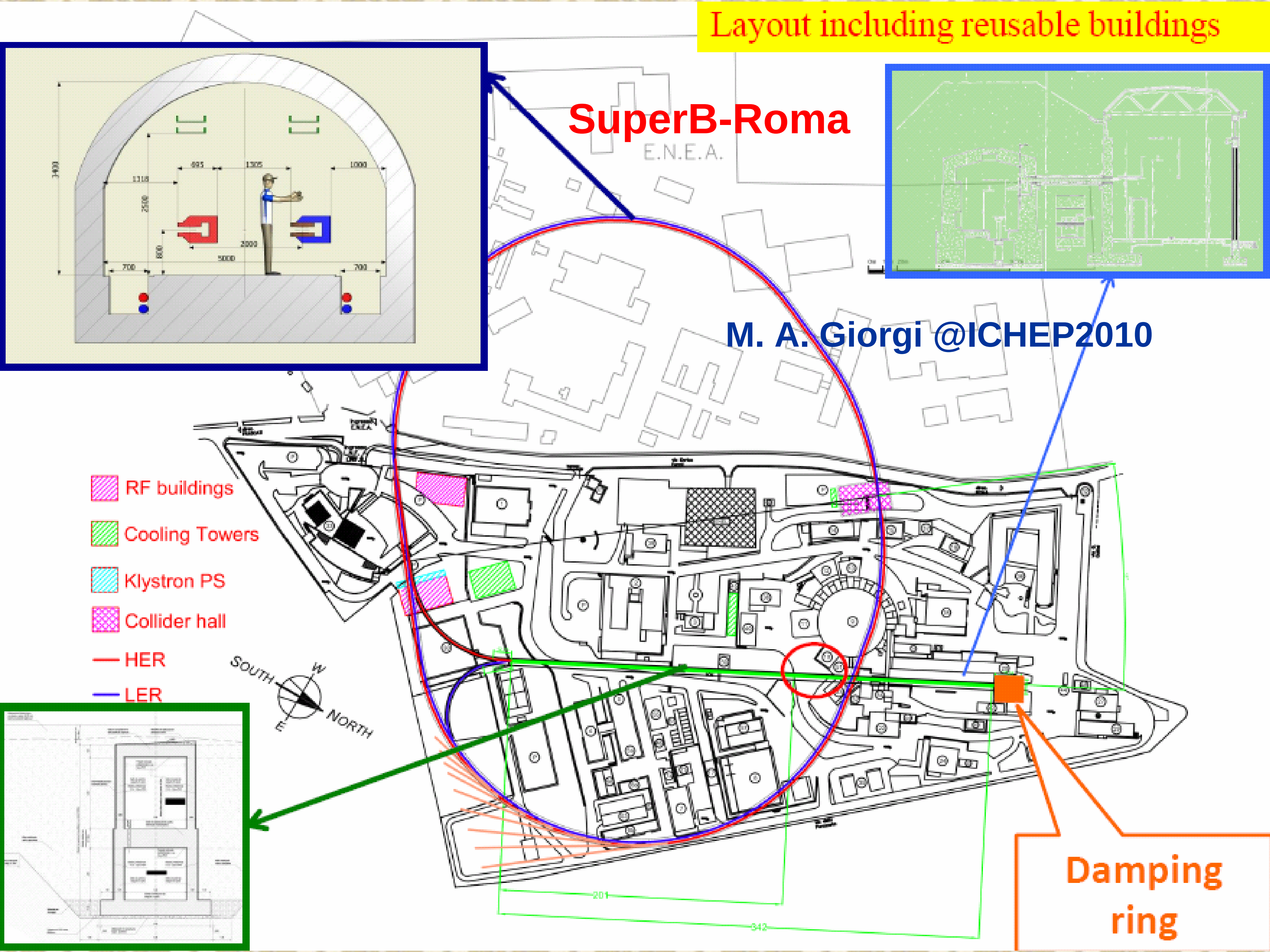
Machine project	Cms Energy (GeV)	Mode	Polarization of e^- beam >80% for τ	Lumi. (cm^{-2} s^{-1})
Super c-τ BINP (Russia)	$3.0 \div 4.5$	Symmetric	Yes	$1 \div 2$ 10^{35}
SuperKEKB (Japan)	10.58	Asymmetric	No	$2 \div 8$ 10^{35}
Super*B*-Roma	10.58 4.0	Asymmetric	Yes	$1 \div 4$ 10^{36} 1 10^{35}

500-1000 fb^{-1} /year at $\psi(3770)$ from SuperB-Roma

500--1000 times larger data than the designed Lumi. @BEPCII

Marcello A. Giorgi @ICHEP2010

Layout including reusable buildings



KEKB to SuperKEKB How to upgrade

What's the next in China?

BESIII: successful Charmonium and charm program in the next 5 years

What's our next?

You are our future!

Summary

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 semileptonoc form factor has be checked to 2-3%. 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.

New Physics searches in D mixing, D CP violation and in rare decays by CLEO-c, BABAR, Belle and CDF have become considerably more sensitive in the past year, BES III will undertake complementary studies.

BESIII maximizes the sensitivity of the worldwide heavy quark flavor physics program to new physics.

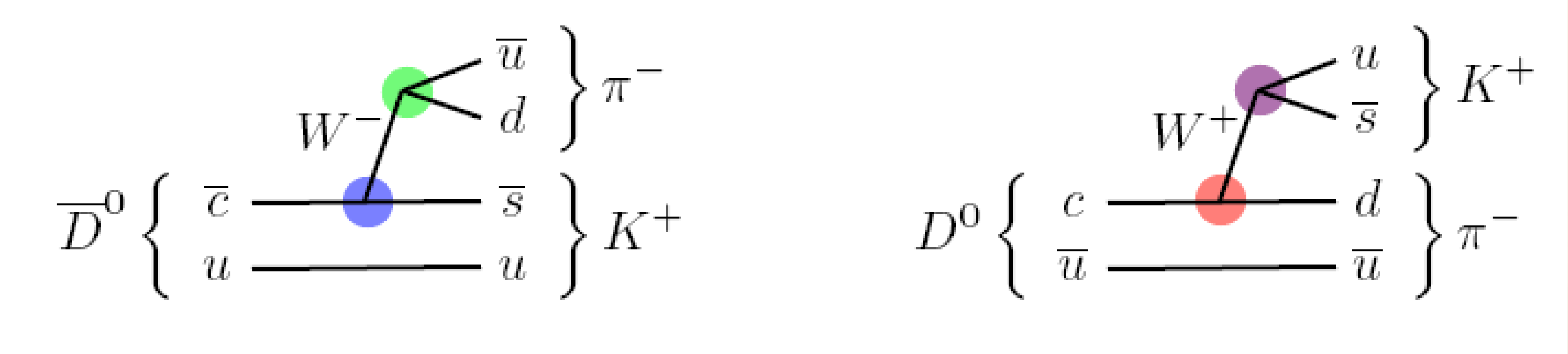
"人是人的未来"。

谢谢！

Jean Paul Sartre
(1905—1980)
French philosopher.
哲学家、作家，
他曾拒绝1964年
诺贝尔文学奖。

Back up slides

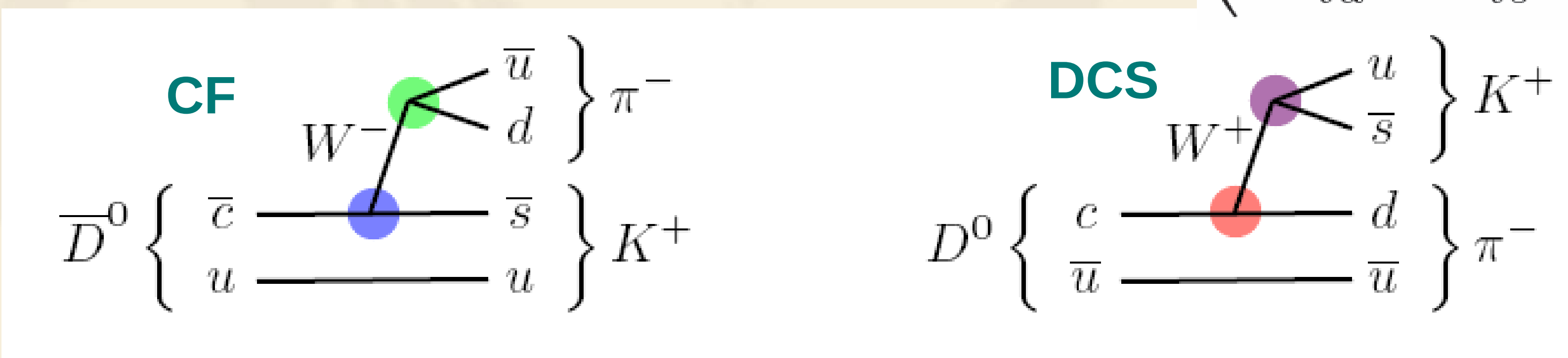
Hadronic D decays

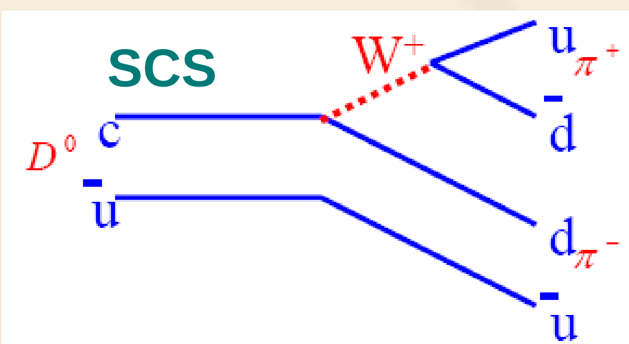


D hadronic decays

D hadronic decay can occur by through
Cabibbo favored (CF),
Doubly Cabibbo suppressed(DCS) and
Singly Cabibbo suppressed (SCS) :

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



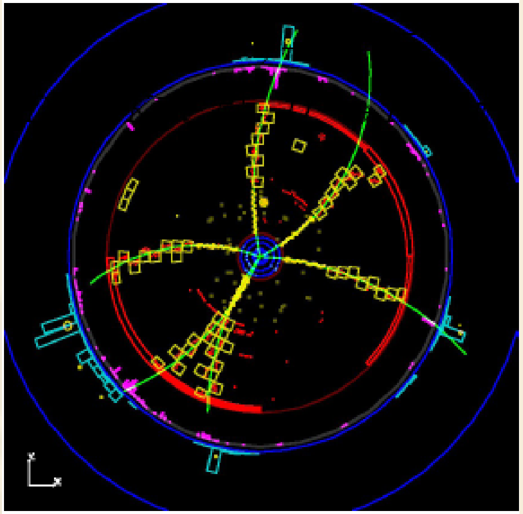


CF:SCS:DCS = 1: λ: λ²

λ=tan(θc) = 0.2317
θc is Cabibbo angle

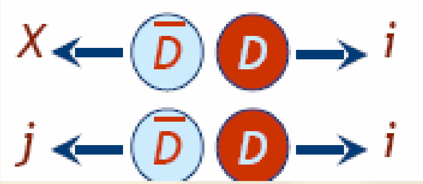
Absolute branching fractions

$e^+e^- \to \psi(3770) \to D\overline{D}$



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

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

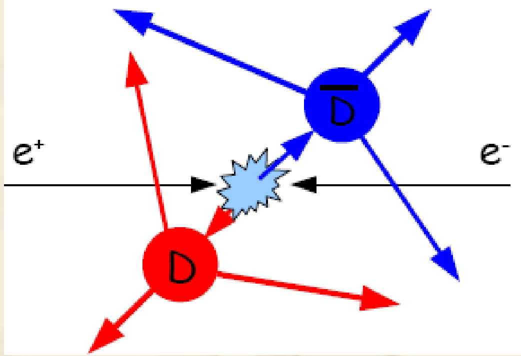


$$B_i = \frac{n_{ij}\varepsilon_j}{n_i \varepsilon_{ij}}, i \neq j$$

$$N_{D\overline{D}} = \frac{1}{2} \times \frac{n_i n_j}{n_{ij}} \times \frac{\varepsilon_{ij}}{\varepsilon_i \times \varepsilon_j}, i \neq j$$

Branching fraction is independent of the luminosity

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



The signal can be extracted by fitting the following variables:

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

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

$\sigma(\Delta E) \sim 7\text{—}10$ MeV, ×2 with π^0

$\sigma(M_{BC}) \sim 1.3$ MeV, ×2 with π^0

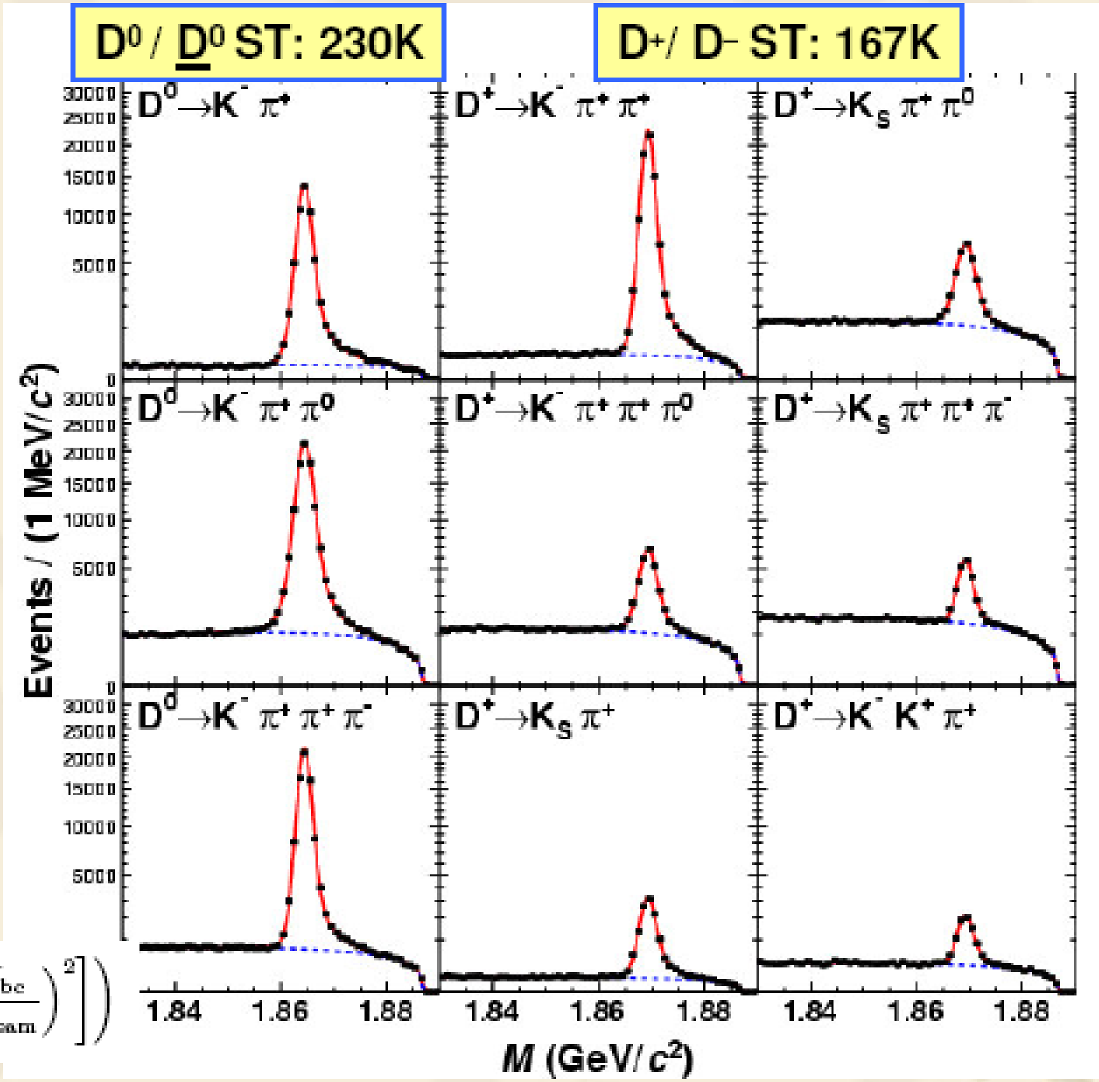
$$\delta M_{bc} = \frac{E_{beam}}{M_{bc}} \delta E_{beam} \oplus \frac{p_D}{M_{bc}} \delta p_D$$

CLEO-c single tag

- Single Tag yields
- Fit to:
  - ARGUS for bkg.
  - "First principles" for signal:
    - M_{BC} resolution
    - ISR
    - ψ(3770) BW

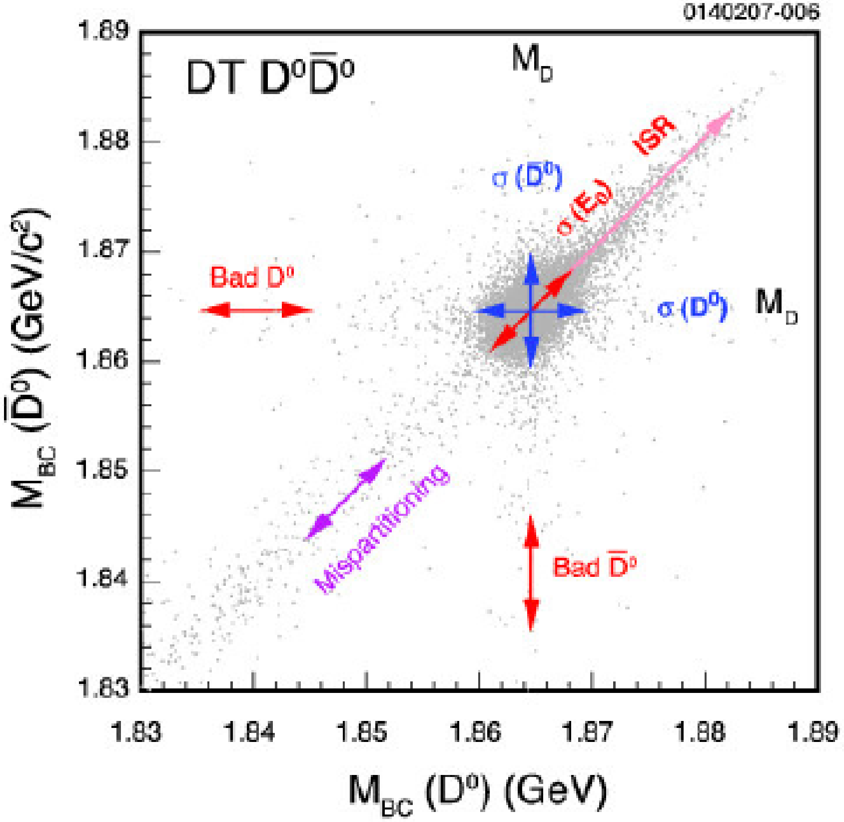
$$M_{BC} = \sqrt{E_{beam}^2 - p_D^{\ 2}}$$

$$\mathcal{B}(M_{bc}) = M_{bc}\left[1-\left(\frac{M_{bc}}{E_{beam}}\right)^2\right]^p \cdot \exp\left(c\left[1-\left(\frac{M_{bc}}{E_{beam}}\right)^2\right]\right)$$



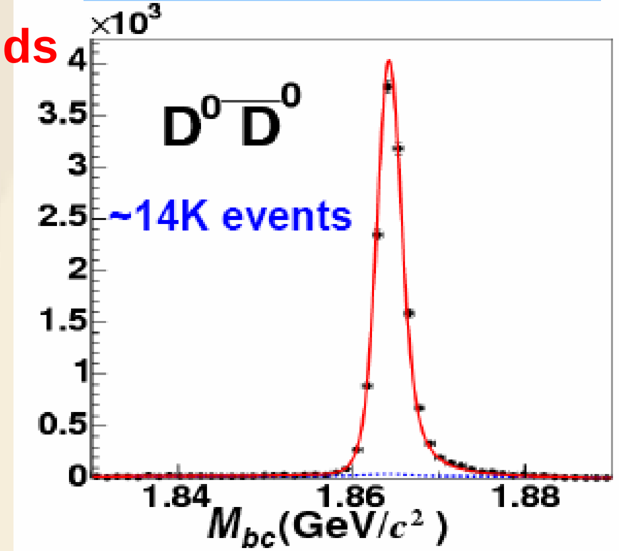
Absolute BRs

- Double Tag yields from 2D, $M_{BC}(D)$ vs $M_{BC}(\underline{D})$ fit:

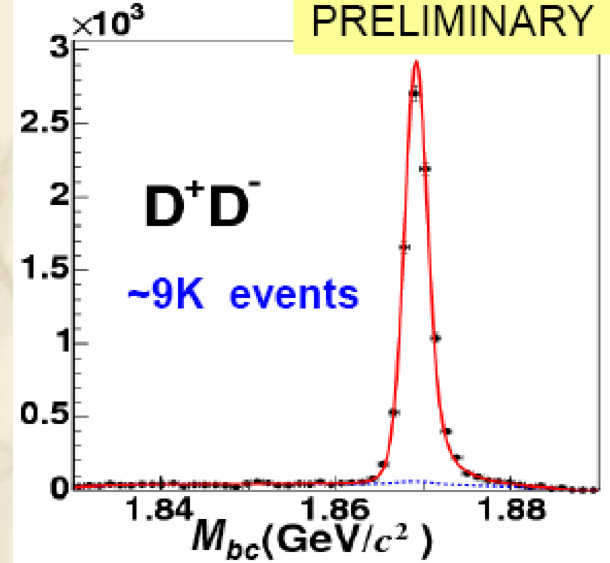


Zero backgrounds

Double tags in 281 pb^{-1}



PRELIMINARY



Absolute BRs for D/Ds→PP

CLEO-c, full data set

PhysRevD.81.052013 (2009)

818/pb at ψ(3770)

$3 \cdot 10^6$ D^oD^o

$2.4 \cdot 10^6$ D^+D^-

586/pb at

√s=4170 MeV

$5.4 \cdot 10^5$ $Ds^+ Ds^-$

TABLE II: Ratios of branching fractions to the corresponding normalization modes $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, and $D_s^+ \to K_S^0K^+$, branching fractions results from this analysis, and charge asymmetries $\mathcal{A}_{CP}$. Uncertainties are statistical error, systematic error, and the error from the input branching fractions of normalization modes.

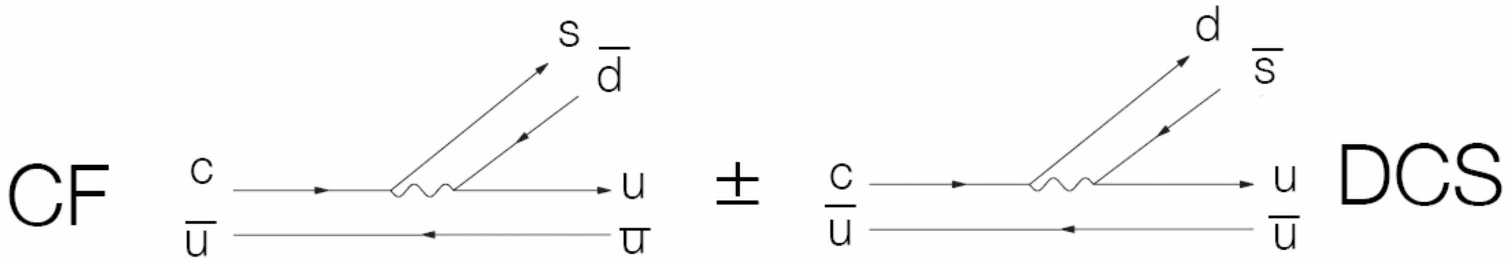
Mode	$\mathcal{B}_{\rm mode}/\mathcal{B}_{\rm Normalization}$ (%)	This result $\mathcal{B}$ (%)	$\mathcal{A}_{CP}$ (%)
$D^0 \to K^+K^-$	$10.4138 \pm 0.1064 \pm 0.1128$	$0.4052 \pm 0.0041 \pm 0.0044 \pm 0.0080$	
$D^0 \to K_S^0K_S^0$	$0.4095 \pm 0.0432 \pm 0.0214$	$0.0159 \pm 0.0017 \pm 0.0008 \pm 0.0003$	
$D^0 \to \pi^+\pi^-$	$3.7023 \pm 0.0561 \pm 0.0893$	$0.1441 \pm 0.0022 \pm 0.0035 \pm 0.0029$	
$D^0 \to \pi^0\pi^0$	$2.1491 \pm 0.0740 \pm 0.0758$	$0.0836 \pm 0.0029 \pm 0.0030 \pm 0.0017$	
$D^0 \to K^-\pi^+$	100	3.8910 external input [2]	$0.5 \pm 0.4 \pm 0.9$
$D^0 \to K_S^0\pi^0$	$31.0495 \pm 0.2964 \pm 0.7467$	$1.2081 \pm 0.0115 \pm 0.0291 \pm 0.0239$	
$D^0 \to K_S^0\eta$	$12.2575 \pm 0.2872 \pm 0.6677$	$0.4769 \pm 0.0112 \pm 0.0260 \pm 0.0094$	
$D^0 \to \pi^0\eta$	$1.7714 \pm 0.1481 \pm 0.1047$	$0.0689 \pm 0.0058 \pm 0.0041 \pm 0.0014$	
$D^0 \to K_S^0\eta'$	$24.7307 \pm 0.8154 \pm 1.1433$	$0.9623 \pm 0.0317 \pm 0.0445 \pm 0.0190$	
$D^0 \to \pi^0\eta'$	$2.4084 \pm 0.2874 \pm 0.1519$	$0.0937 \pm 0.0112 \pm 0.0059 \pm 0.0019$	
$D^0 \to \eta\eta$	$4.2495 \pm 0.2838 \pm 0.3522$	$0.1653 \pm 0.0110 \pm 0.0137 \pm 0.0033$	
$D^0 \to \eta\eta'$	$2.7318 \pm 0.6235 \pm 0.2500$	$0.1063 \pm 0.0243 \pm 0.0097 \pm 0.0021$	
$D^+ \to K^-\pi^+\pi^+$	100	9.1400 external input [2]	$-0.1 \pm 0.4 \pm 0.9$
$D^+ \to K_S^0K^+$	$3.3502 \pm 0.0573 \pm 0.0720$	$0.3062 \pm 0.0052 \pm 0.0066 \pm 0.0066$	$-0.2 \pm 1.5 \pm 0.9$
$D^+ \to \pi^+\pi^0$	$1.3208 \pm 0.0382 \pm 0.0443$	$0.1207 \pm 0.0035 \pm 0.0041 \pm 0.0026$	$2.9 \pm 2.9 \pm 0.3$
$D^+ \to K_S^0\pi^+$	$16.8160 \pm 0.1239 \pm 0.3679$	$1.5370 \pm 0.0113 \pm 0.0336 \pm 0.0331$	$-1.3 \pm 0.7 \pm 0.3$
$D^+ \to K^+\pi^0$	$0.1923 \pm 0.0206 \pm 0.0063$	$0.0176 \pm 0.0019 \pm 0.0006 \pm 0.0004$	$-3.5 \pm 10.7 \pm 0.9$
$D^+ \to K^+\eta$	< 0.1442 (90% C.L.)	< 0.0132 (90% C.L.)	
$D^+ \to \pi^+\eta$	$3.8538 \pm 0.0895 \pm 0.1916$	$0.3522 \pm 0.0082 \pm 0.0175 \pm 0.0076$	$-2.0 \pm 2.3 \pm 0.3$
$D^+ \to K^+\eta'$	< 0.2032 (90% C.L.)	< 0.0187 (90% C.L.)	
$D^+ \to \pi^+\eta'$	$5.2061 \pm 0.1762 \pm 0.2565$	$0.4758 \pm 0.0161 \pm 0.0234 \pm 0.0103$	$-4.0 \pm 3.4 \pm 0.6$
$D_s^+ \to K_S^0K^+$	100	1.4900 external input [3]	$4.7 \pm 1.8 \pm 0.9$
$D_s^+ \to \pi^+\pi^0$	< 2.3492 (90% C.L.)	< 0.0376 (90% C.L.)	
$D_s^+ \to K_S^0\pi^+$	$8.4766 \pm 0.7147 \pm 0.1778$	$0.1263 \pm 0.0106 \pm 0.0026 \pm 0.0073$	$16.3 \pm 7.3 \pm 0.3$
$D_s^+ \to K^+\pi^0$	$4.2383 \pm 1.4756 \pm 0.2304$	$0.0632 \pm 0.0220 \pm 0.0034 \pm 0.0036$	$-26.6 \pm 23.8 \pm 0.9$
$D_s^+ \to K^+\eta$	$11.7933 \pm 2.1753 \pm 0.5888$	$0.1757 \pm 0.0324 \pm 0.0088 \pm 0.0101$	$9.3 \pm 15.2 \pm 0.9$
$D_s^+ \to \pi^+\eta$	$123.1123 \pm 4.2907 \pm 6.2133$	$1.8344 \pm 0.0639 \pm 0.0926 \pm 0.1059$	$-4.6 \pm 2.9 \pm 0.3$
$D_s^+ \to K^+\eta'$	$11.9866 \pm 3.6840 \pm 0.6158$	$0.1786 \pm 0.0549 \pm 0.0092 \pm 0.0103$	$6.0 \pm 18.9 \pm 0.9$
$D_s^+ \to \pi^+\eta'$	$269.8080 \pm 8.9375 \pm 14.0957$	$4.0201 \pm 0.1332 \pm 0.2100 \pm 0.2320$	$-6.1 \pm 3.0 \pm 0.6$

Some results I'll show later use only part the data set.

U-spin test in $D^0 \to K_{S,L}\ \pi^0$

*U-spin: swap d↔s quarks, important e.g. for extracting γ from $B_S \to KK$, $B_d \to \pi\pi$

- $\Gamma(D^o \to K_S\pi^o) \neq \Gamma(D^o \to K_L\pi^o)$
- $\sqrt{2}\, A(D^o \to K_{S,L}\pi^o) = \quad A(D \to K^o\pi^o) \quad \pm \quad A(D \to \overline{K^o}\pi^o)$



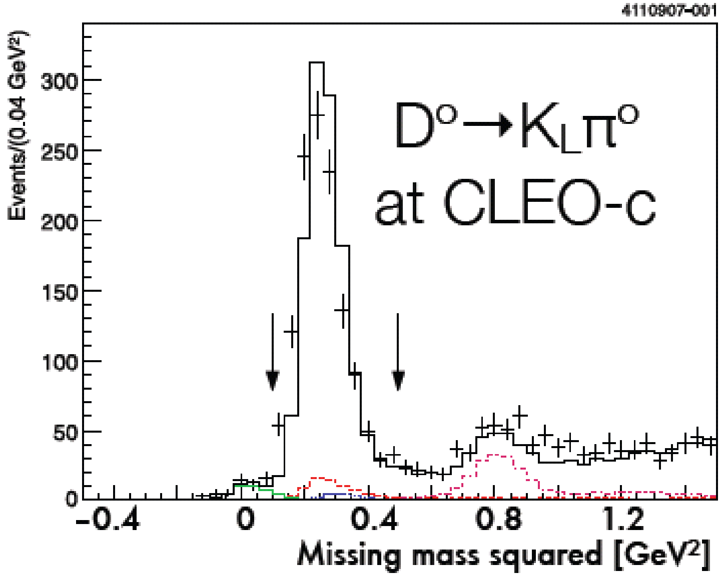
U-spin* prediction

$$\frac{\Gamma\left(D^0 \to K_S\pi^0\right) - \Gamma\left(D^0 \to K_L\pi^0\right)}{\Gamma\left(D^0 \to K_S\pi^0\right) + \Gamma\left(D^0 \to K_L\pi^0\right)} = -2\frac{A_{DCS}}{A_{CF}} = 2\tan^2\theta_C = 0.109$$

I. Bigi and H. Yamamoto, Physics Letters 349 (1995) 363-366

$D^o \rightarrow K_{L,S}\pi^0$, at CLEO-c

- Clean missing mass-squared peak at $m^2_{K^o} = 0.28 GeV^2$
- Lines: MC simulation. Crosses: Data.
- Result

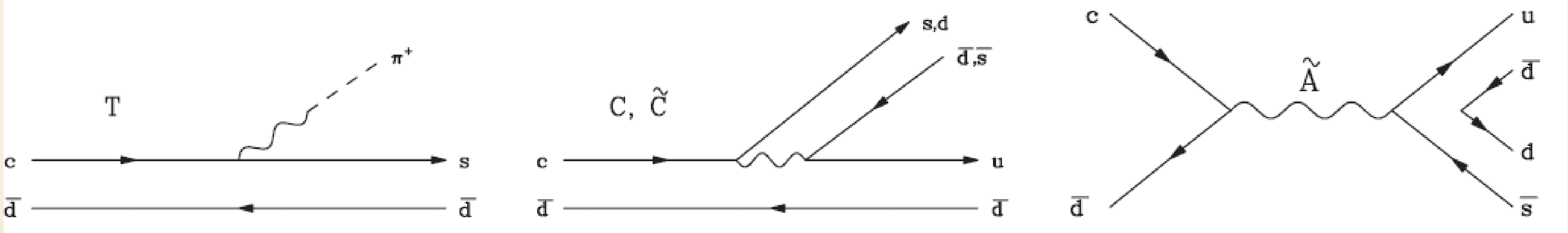


$$\frac{\Gamma\left(D^0 \rightarrow K_S\pi^0\right) - \Gamma\left(D^0 \rightarrow K_L\pi^0\right)}{\Gamma\left(D^0 \rightarrow K_S\pi^0\right) + \Gamma\left(D^0 \rightarrow K_L\pi^0\right)} = 0.108 \pm 0.025 \pm 0.024$$

In good agreement with U-spin prediction of $2\tan^2\theta=0.109$

281/pb at CLEO: PRL **100,** 091801 (2008)

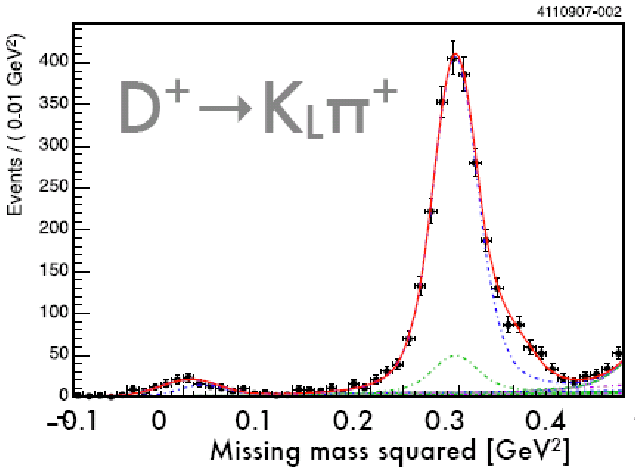
SU(3) breaking test in $D^+ \to K_{S,L}\pi^+$



- Similar logic as for D^0, but no U-spin symmetry.
- Still, possible to estimate effect, expect

$$\frac{\Gamma(D^+ \to K_S\pi^+) - \Gamma(D^+ \to K_L\pi^+)}{\Gamma(D^+ \to K_S\pi^+) + \Gamma(D^+ \to K_L\pi^+)} \approx 0.04$$

D.-N. Gao, Phys. Lett. B **645**, 59 (2007)



- Result:

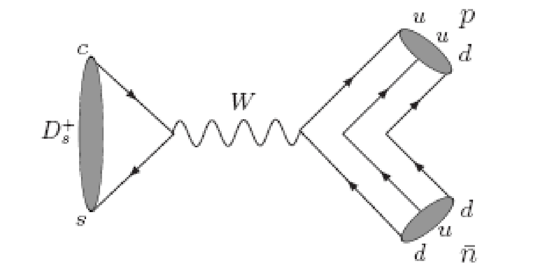
$$\frac{\Gamma(D^+ \to K_S\pi^+) - \Gamma(D^+ \to K_L\pi^+)}{\Gamma(D^+ \to K_S\pi^+) + \Gamma(D^+ \to K_L\pi^+)} = 0.022 \pm 0.016 \pm 0.018$$

281/pb at CLEO: PRL **100,** 091801 (2008)

Ds→pnbar only mode to baryon pairs

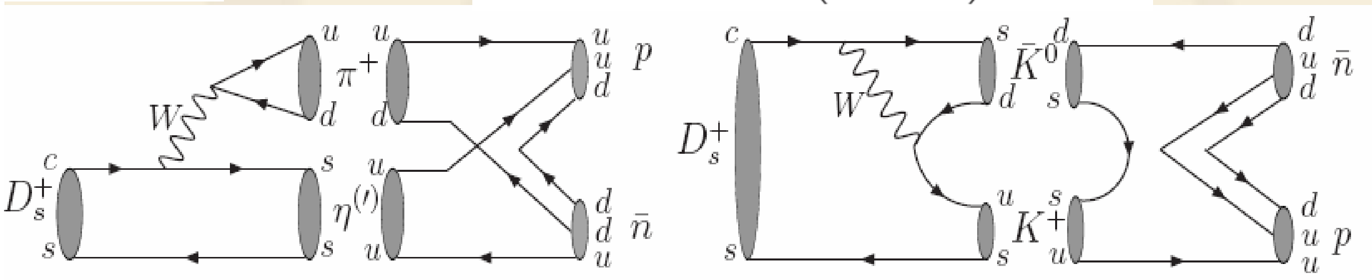
Short distance:

$\mathcal{B}(D_s^+ \to p\bar{n})_{\rm SD} = (0.4^{+1.1}_{-0.3}) \times 10^{-6}$

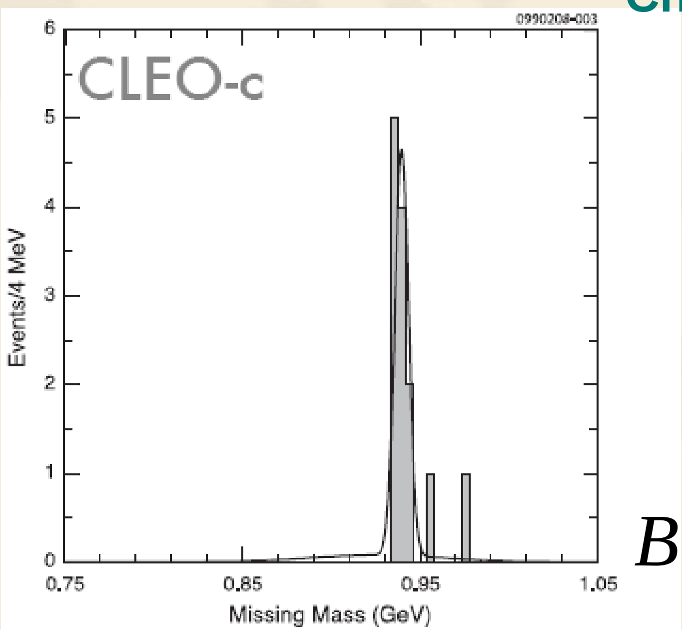


Long distance:

$\mathcal{B}(D_s^+ \to p\bar{n}) \approx \left(0.8^{+2.4}_{-0.6}\right) \times 10^{-3}$



Chen, Cheng, Hsiao: Phys.Lett.B663:326-329,2008

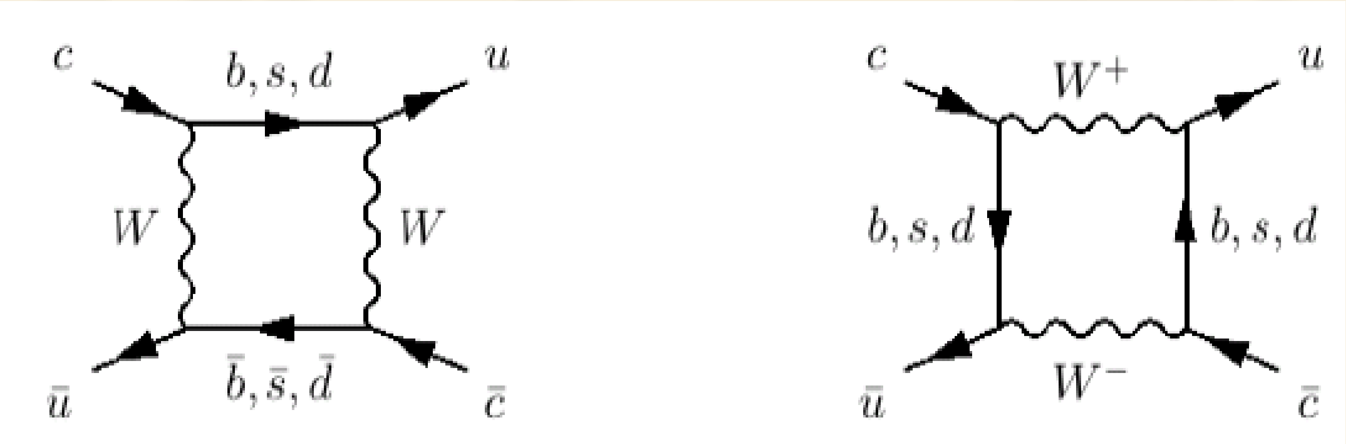


CLEO-c: Phys. Rev. Lett. 100, 181802 (2008)

m_{Ds} = 1.968 GeV , m_{D+} = 1.869 GeV
$m_p + m_{nbar}$ = 1.878 GeV

$$Br(D_S^+ \to p\bar{n}) = (1.30 \pm 0.36^{+0.12}_{-0.16}) \times 10^{-3}$$

Neutral D mixing



D^0 mixing notations

- Flavor mixing occurs when flavor eigenstates differ from mass eigenstates: well established phenomenon in neutral K, B_d, B_s systems.

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle \qquad |q|^2 + |p|^2 = 1$$

- Mixing parameters are expressed in terms of *x*, *y* functions of the mass and decay width differences:

$$x = \frac{m_1 - m_2}{\Gamma} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \qquad \text{where} \quad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

- Three types of CP violation:

$$\langle f|H|D^0\rangle = A_f \qquad \langle f|H|\overline{D}^0\rangle = \overline{A}_f$$

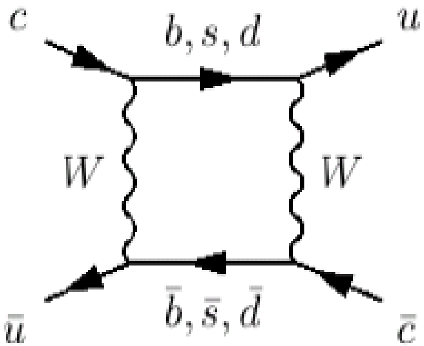
- in the decay (direct): $\left|\frac{\overline{A}_{\overline{f}}}{A_f}\right| \neq 1$
- in mixing (indirect): $r_m = \left|\frac{q}{p}\right| \neq 1$
- in the interference between mixing and decay: $\varphi_f \neq 0$

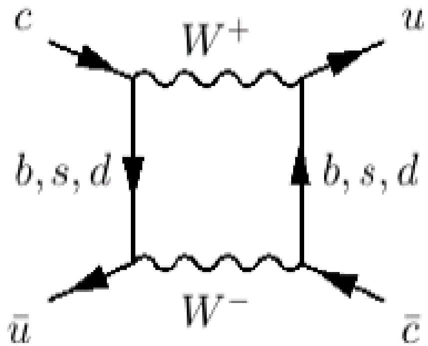
$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} = r_m \left|\frac{\overline{A}_f}{A_f}\right| e^{i(\delta_f + \varphi_f)}$$

$\varphi_f =$ weak phase
$\delta_f =$ strong phase

Standard Model predictions

SM mixing loops has down type quarks in the loops:



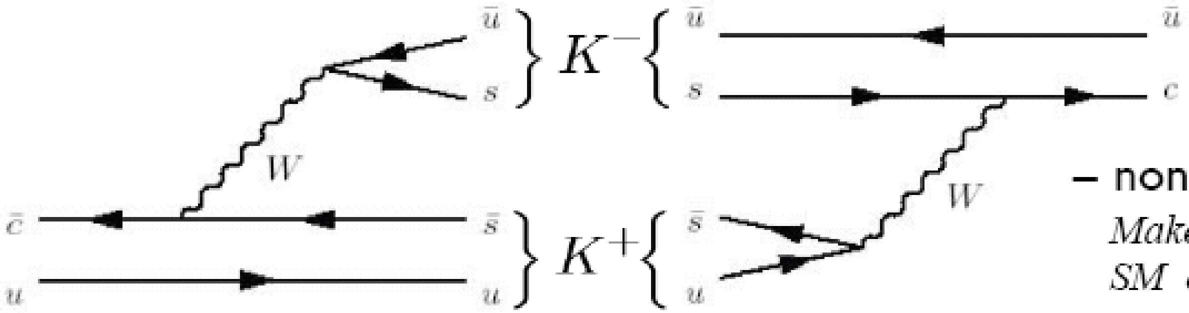


- b quark is CKM-suppressed
- s, d quark GIM suppressed

$$\Delta m \propto G_F^2 \frac{(m_s^2 - m_d^2)^2}{m_c^2}$$

→ $\Delta m_{\rm box} \sim 10^{-5} {\rm ps}^{-1}$ Tiny!

Expect hadronic intermediate states to dominate:



- non-perturbative contributions

  Makes it difficult to precisely predict SM expectations

In SM expected |x|<10-2, |y|<10-2 and CP violation below the per mil level. New Physics contributions could enhance mixing rate and/or generate CP violation up to percent level.

CP violation in Charm decays

- Standard Model: CP violation from KM phase in CKM quark mixing matrix:

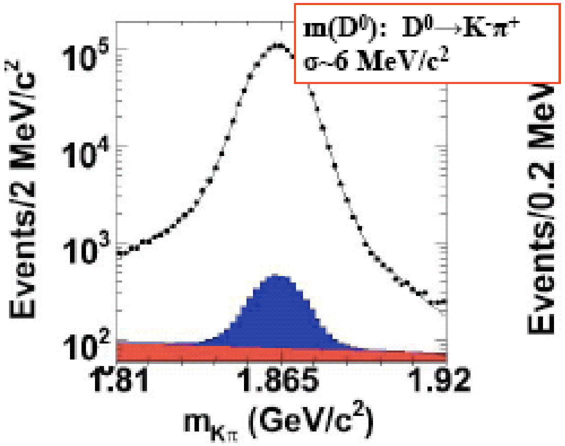
$$\begin{bmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta + \frac{i}{2}\eta\lambda^2) \\ -\lambda & 1-\frac{\lambda^2}{2} - \boxed{i\eta A^2\lambda^4} & A\lambda^2(1+i\eta\lambda^2) \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

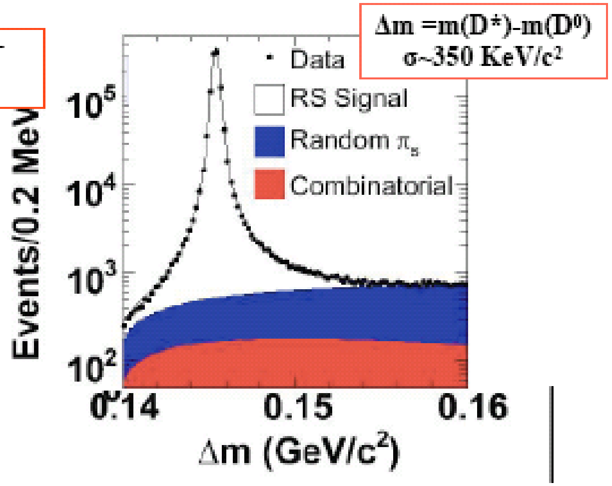
- Charmed Mesons:
  - CP violation is CKM suppressed $\mathcal{O}(10^{-3})$
  - Experimental Sensitivity $\mathcal{O}(10^{-2})$

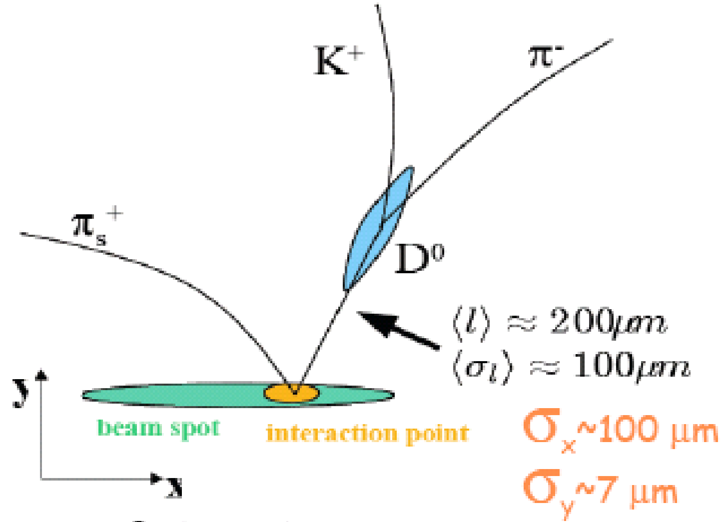
1% Signal = New Physics

Time-dependent results from B factories : BABAR and Belle as well as CDF & D0

Selection of D^0 mesons







3D flight path reconstruction

Select D^0 mesons via $D^{*+} \to D^0\pi^+$ decay:

- charge of slow pion identifies the flavor of D^0 at production;
- exploit $m(D^0)$, D^0 reco invariant mass and $\Delta m = m(D^*) - m(D)$, D^{*+}-D^0 mass difference for bkg rejection;

Cut on D^0 momentum in center of mass frame, $p^* > 2.5$-3.0 GeV/c rejects D^0 from B decays and combinatorial bkg.

proper time $$t = \frac{\vec{L}\cdot\vec{p}}{p}\frac{m_{D^0}}{p}$$

- D^0 vertex with beam spot (interaction region size) constraint applied. Determining decay time, t, and decay time error, σ_t, for each each event.

Typical resolution on proper-time: $\langle\sigma_t\rangle \simeq 0.5\tau_D = 0.2$ ps
thanks to the excellent performance of the Silicon Vertex Tracker.

Mixing analyses at the B factories

Decay		Note:
$D^0 \to K^+\pi^-$	★ BaBar, Belle, ★ CDF	*study of the time dependence* See backup slides.
$D^0 \to K^+K^-, \pi^+\pi^-$	★ BaBar, ★ Belle	*lifetime ratio wrt* $D^0 \to K^-\pi^+$
$D^0 \to \phi K^0_S$	Belle	*lifetime difference between CP-even and CP-odd eigenstates*
$D^0 \to K^+\pi^-\pi^0$	★ BaBar	*time-dependent Dalitz plot analysis*
$D^0 \to K^0_S\pi^+\pi^-$	New, BaBar, Belle	*time-dependent Dalitz plot analysis*
$D^0 \to K^0_S K^+K^-$	New, BaBar	*time-dependent Dalitz plot analysis*
$D^0 \to K^{(*)} l\nu$	BaBar, Belle	*time-integrated analysis* Not covered in this talk

Legend: ★ = mixing evidence > 3σ

New = new result

At B factories events are selected from $e^+e^- \to c\bar{c}$ annihilations:

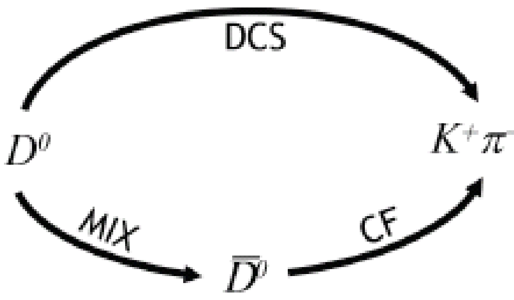
$\sigma\left(e^+e^- \to c\bar{c}\right) \simeq 1.3$ nb

Wrong sign $D^0 \to K^+\pi^-$ decays

- Wrong Sign (WS) final states from 2 sources: via double-Cabibbo-suppressed (DCS) decays or via mixing followed by Cabibbo-favored (CF) decays.

Time evolution $(|x| \ll 1, |y| \ll 1)$:

$$\frac{dN_{WS}}{dt} \propto e^{-\Gamma t}\left(\underbrace{R_D}_{\text{DCS}} + \underbrace{y'\sqrt{R_D}(\Gamma t)}_{\text{Interference}} + \underbrace{\frac{x'^2+y'^2}{4}(\Gamma t)^2}_{\text{Mixing}}\right)$$



$$R_D = \frac{B(D^0 \to K^+\pi^-)}{B(D^0 \to K^-\pi^+)} \simeq 3 \cdot 10^{-3}$$

phase between DCS and CF decays not directly measurable at B Factories

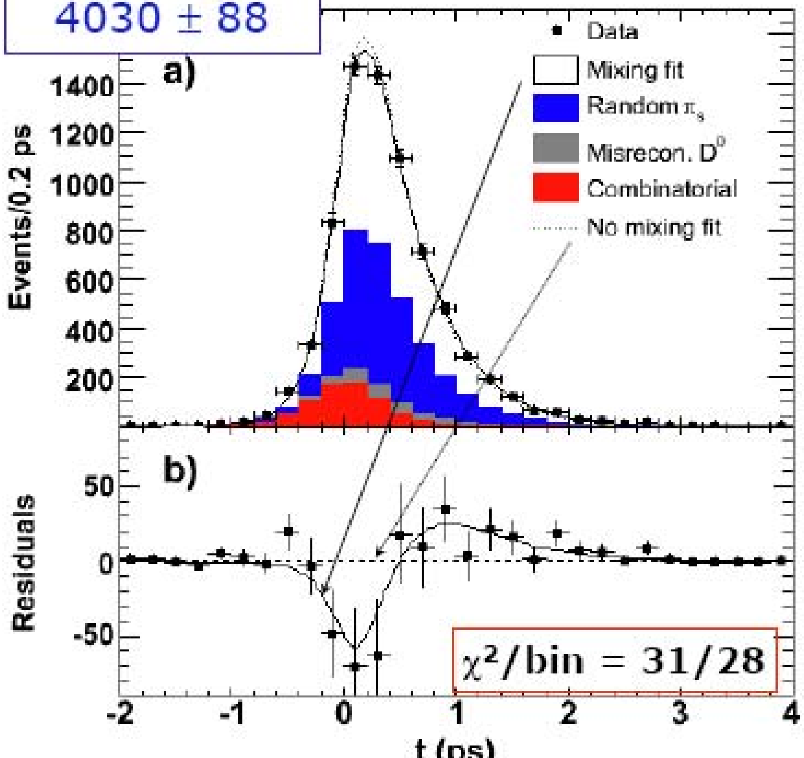
$$x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi} \qquad y' = -x\sin\delta_{K\pi} + y\cos\delta_{K\pi}$$

Analysis of the proper time distribution of WS events permits extraction of D^0 mixing parameters y', x'^2

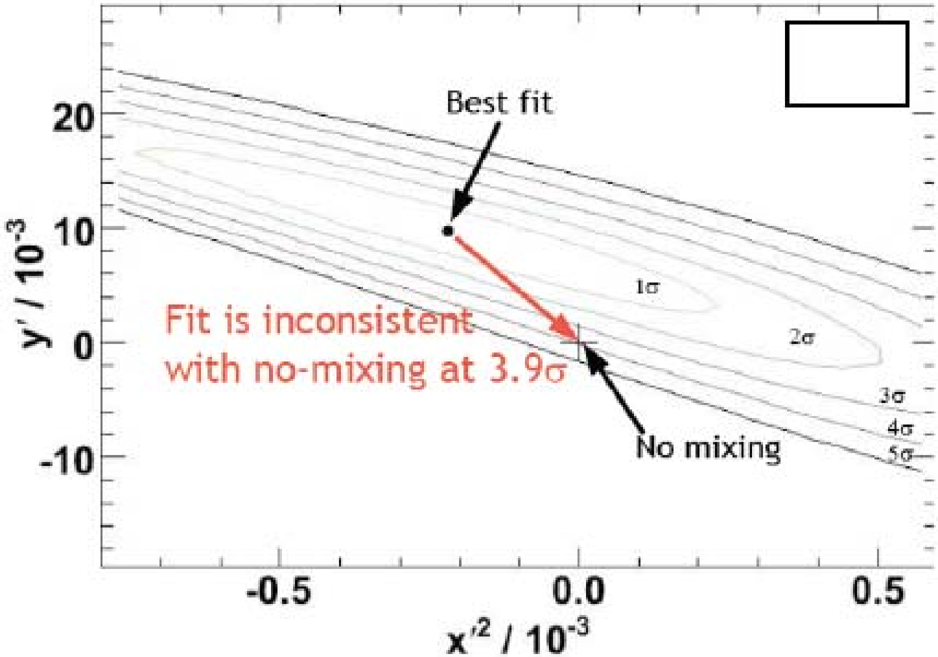
WS time fit: evidence of mixing at 3.9σ

PRL 98:211802,2007 (384 fb^{-1})

Fitted signal
4030 ± 88



WS *mixing* fit projection in signal region
1.843 GeV/c^2<m_D<1.883 GeV/c^2
0.1445 GeV/c^2<Δm< 0.1465 GeV/c^2



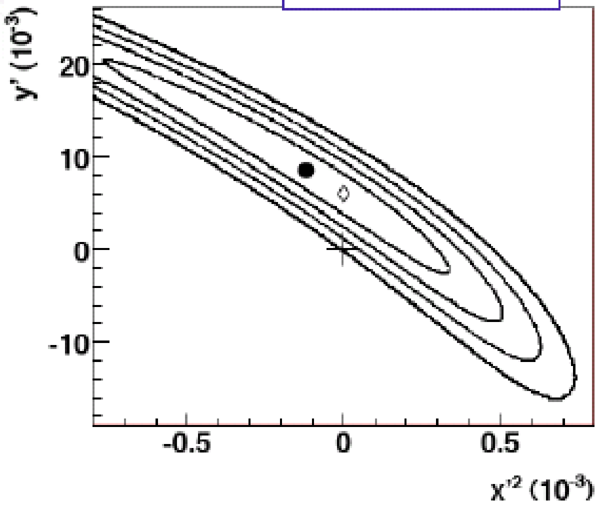
R_D: $(3.03 \pm 0.16 \pm 0.10) \times 10^{-3}$
x'^2: $(-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$
y': $(9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$

No evidence for CP violation fitting separately D^0 and $\overline{D}^0$

Belle & CDF measurements

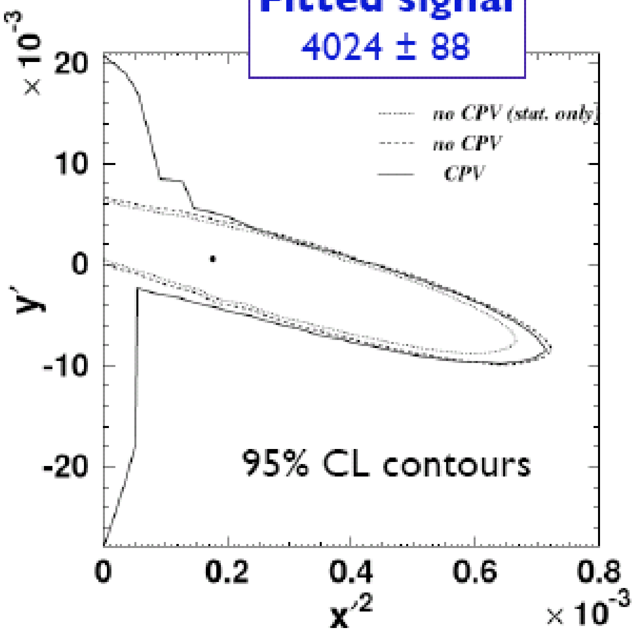
CDF: PRL 100:121802,2008 ($1.5 fb^{-1}$)

Fitted signal (12.7 ± 0.3)K



Belle: PRL 96:151801,2006 ($400 fb^{-1}$)

Fitted signal 4024 ± 88



Experiment	$R_D(10^{-3})$	$y'\,(10^{-3})$	$x'^2\,(10^{-3})$	Mixing Signif.
CDF	3.04 ± 0.55	8.5 ± 7.6	-0.12 ± 0.35	3.8
BABAR [8]	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37	3.9
Belle [9]	3.64 ± 0.17	$0.6\ ^{+4.0}_{-3.9}$	$0.18\ ^{+0.21}_{-0.23}$	2.0

$$x'^2 = (0.18^{+0.21}_{-0.23}) \times 10^{-3}$$

$$y' = (0.6^{+4.0}_{-3.9}) \times 10^{-3}$$

Evidence of mixing at 3.8σ

No mixing point at 2σ

36

Study of event distribution as a function of Dalitz plot position and time

The time dependent decay amplitudes at t=0 for charm meson tagged as D^0 or D^0bar:

$$\mathcal{M}(s_+, s_-, t) = \mathcal{A}(s_+, s_-)g_+(t) + \frac{q}{p}\mathcal{A}(s_-, s_+)g_-(t),$$
$$\overline{\mathcal{M}}(s_+, s_-, t) = \frac{q}{p}\overline{\mathcal{A}}(s_+, s_-)g_+(t) + \overline{\mathcal{A}}(s_-, s_+)g_-(t),$$

$$\frac{dN_f(s_{12}, s_{13}, t)}{ds_{12}ds_{13}dt} \propto e^{-\Gamma t}\left\{|A_f|^2 + \left[y\,\mathrm{Re}(A_f^*\bar{A}_f) - x\,\mathrm{Im}(A_f^*\bar{A}_f)\right](\Gamma t) + \frac{x^2+y^2}{4}(\Gamma t)^2|\bar{A}_f|^2\right\}$$

larger sensitivity in regions populated by Doubly Cabibbo Suppressed and CP eigenstates.

$$A_f = A(s_{12}, s_{13}) \quad \bar{A}_f = \bar{A}(s_{12}, s_{13}) \text{ and } (s_{12}, s_{13}) = \text{Dalitz plot location}$$

- if f and $\bar{f}$ belong to the same Dalitz plot (e.g. $K_S^0\pi^+\pi^-$) by assuming CP conservation in decay $(\bar{A}_f = A_{\bar{f}})$ is possible to extract directly x, y mixing parameters, without $D^0 - \overline{D}^0$ relative strong phase uncertainty.

Method pioneered by CLEO Collaboration: D.Asner *et. al. Phys.Rev.D72:012001,2005*.

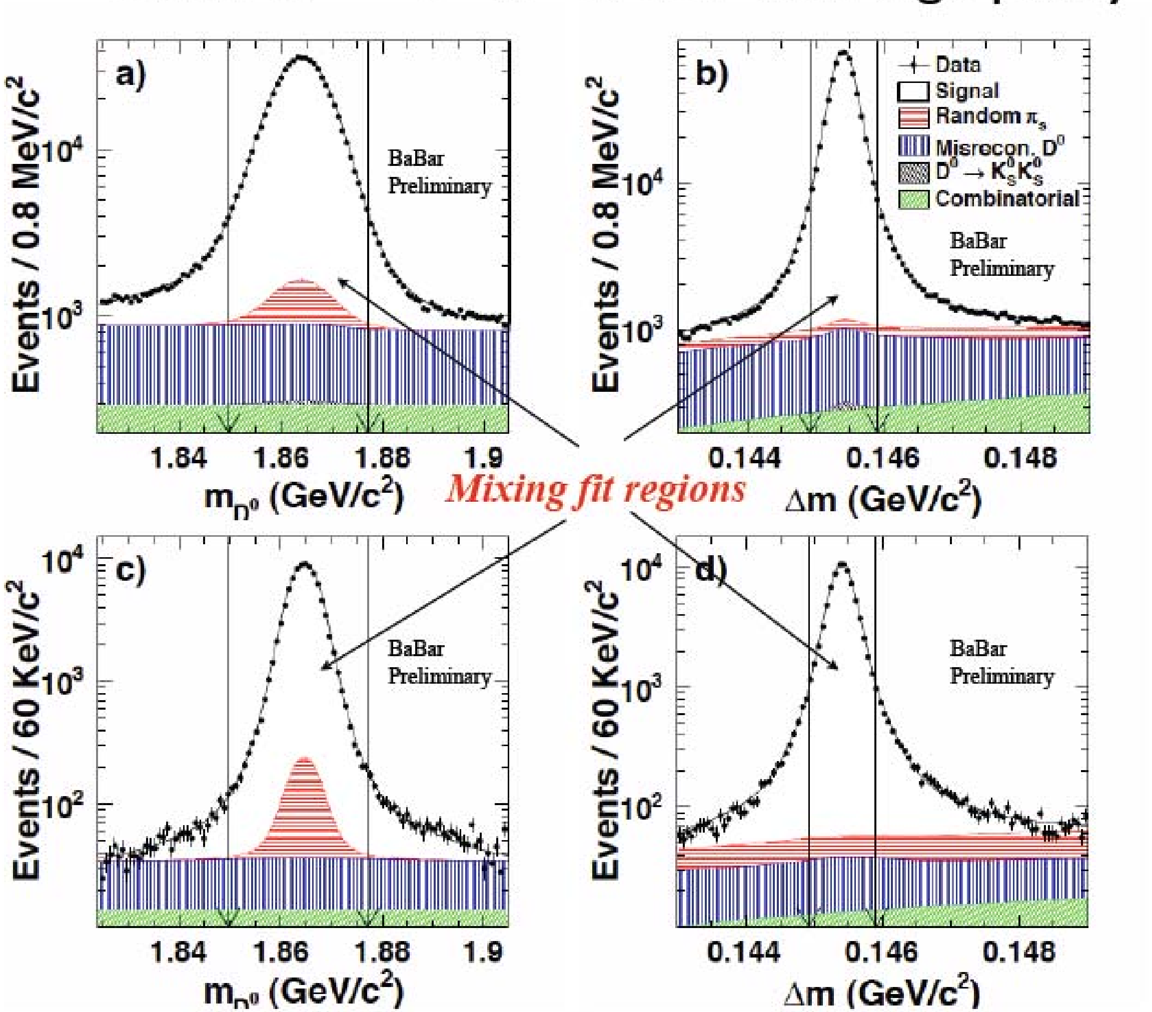
$D^0(t) \to K_S\pi^+\pi^- + K_S K^+K^-$ analysis

*e-Print: **arXiv:1004.5053** [hep-ex]*

New

468.5 fb^{-1} data

- Select $D^{*+} \to D^0\pi^+$ events with high purity



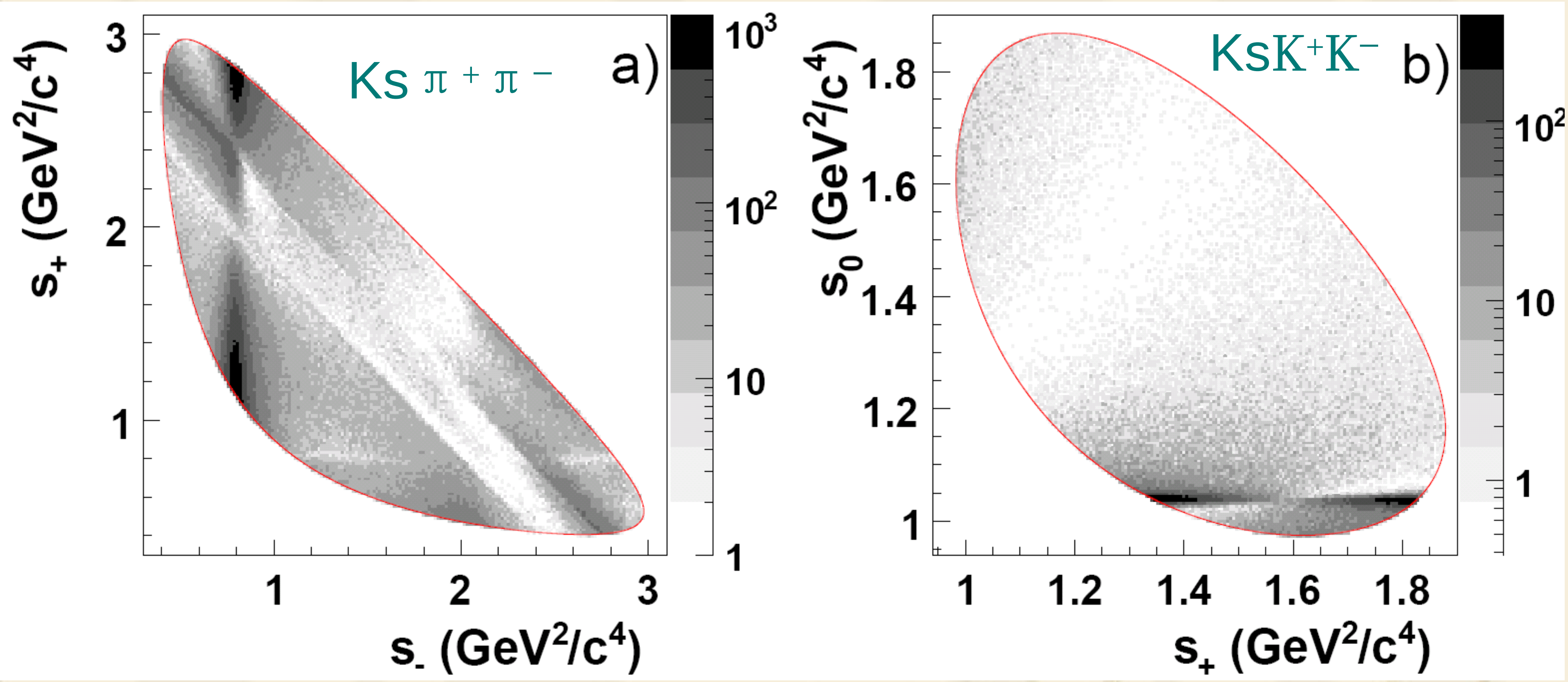
$K_S\pi^+\pi^-$

N_{sig}= (540.8±0.8)x10^3
Purity= 98.5%

$K_S K^+K^-$

N_{sig}= (79.9±0.3)x10^3
Purity= 99.2%

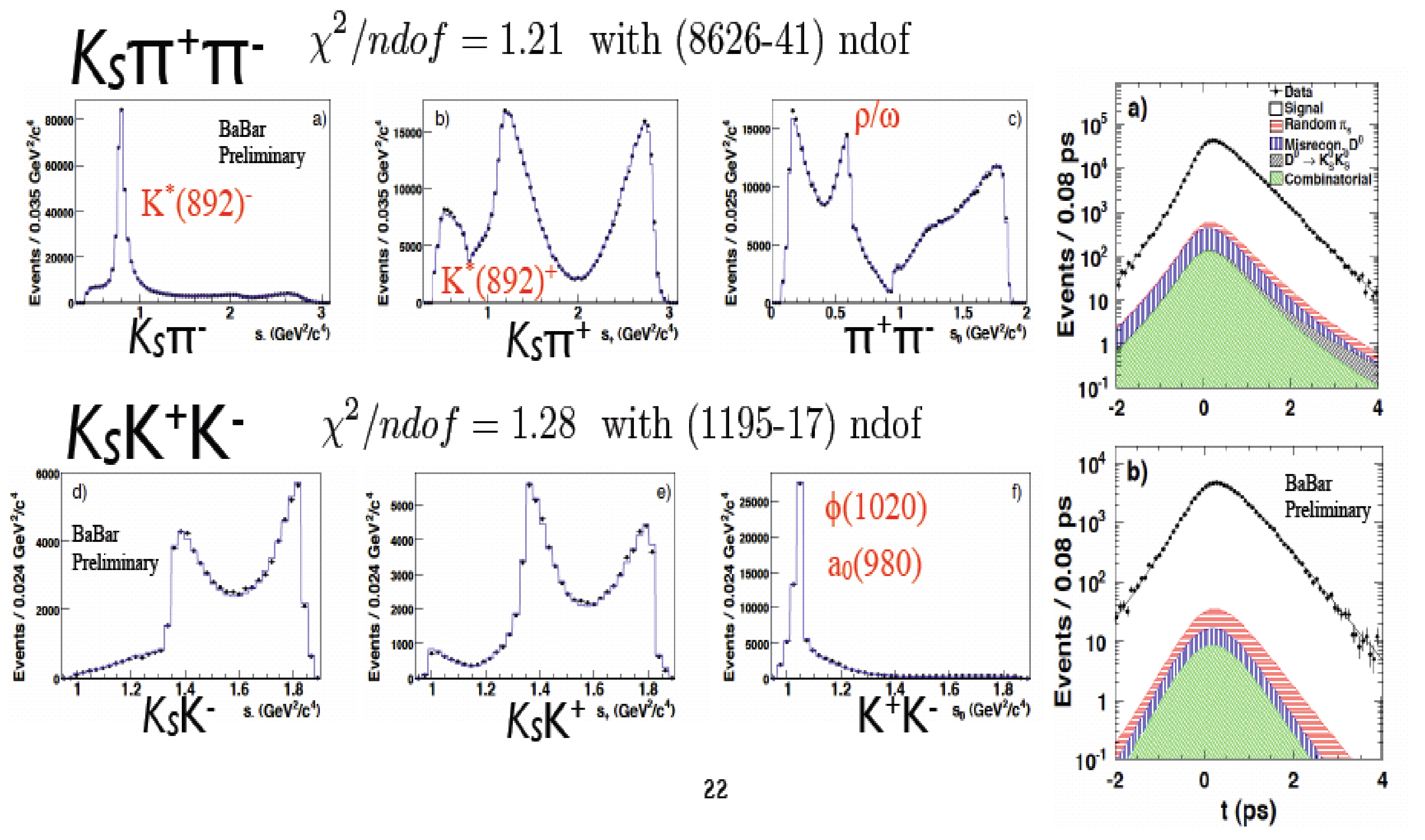
Parameterization of DP



DCS decays: $K^*(892)^+$, $K^*0(1430)^+$, $K^*2(1430)^+$
CP=–1 eigenstate : $K_S\rho_0$

CP=+1: $Ks\phi$
CP=–1:$Ksa_0(980)$

Mixing fit on the Dalitz plot

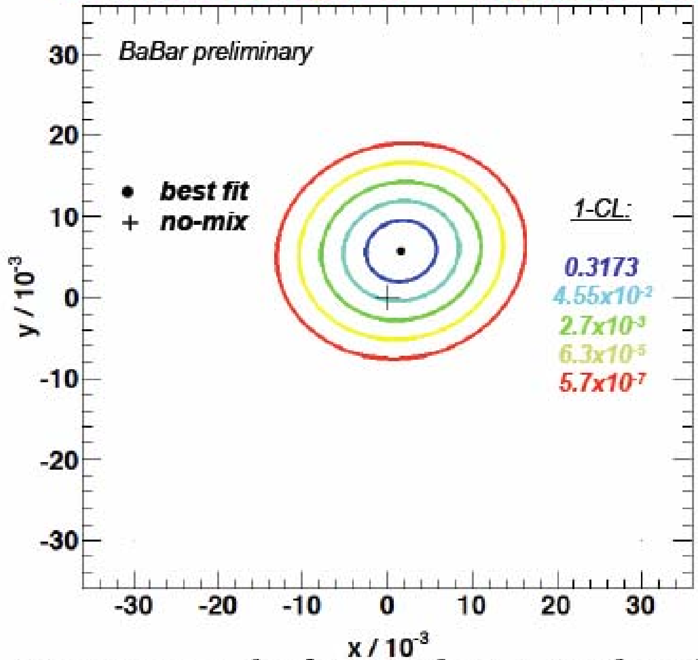


Mixing fit results

New

e-Print: ***arXiv:1004.5053*** *[hep-ex]*

Combined $K_S\pi^+\pi^- + K_SK^+K^-$ fit



No mixing disfavored at 1.9σ level

Experimental systematics

Source	$x[\%]$	$y[\%]$
SVT misalignment	0.0279	0.0826
Fit bias	0.0745	0.0662
Charge-flavor correlation (mistagging)	0.0487	0.0398
Event selection	0.0395	0.0508
Efficiency map	0.0367	0.0175
Background Dalitz-plot distribution	0.0331	0.0142
D^0 mass window	0.0250	0.0250
Proper lifetime PDF	0.0134	0.0128
Signal and background yields	0.0109	0.0069
Mixing in background	0.0103	0.0082
Dalitz-plot normalization	0.0106	0.0053
Proper lifetime error PDF	0.0058	0.0087
Experimental systematics	0.1177	0.1302

D^0 decay amplitude model systematics

Dominated by uncertainty on K*(892), K-matrix, Kπ Lass parameters	0.0678	0.0532
Total	0.0830	0.0685

Combined $K_S\pi^+\pi^- + K_SK^+K^-$ fit results assuming CP conservation:

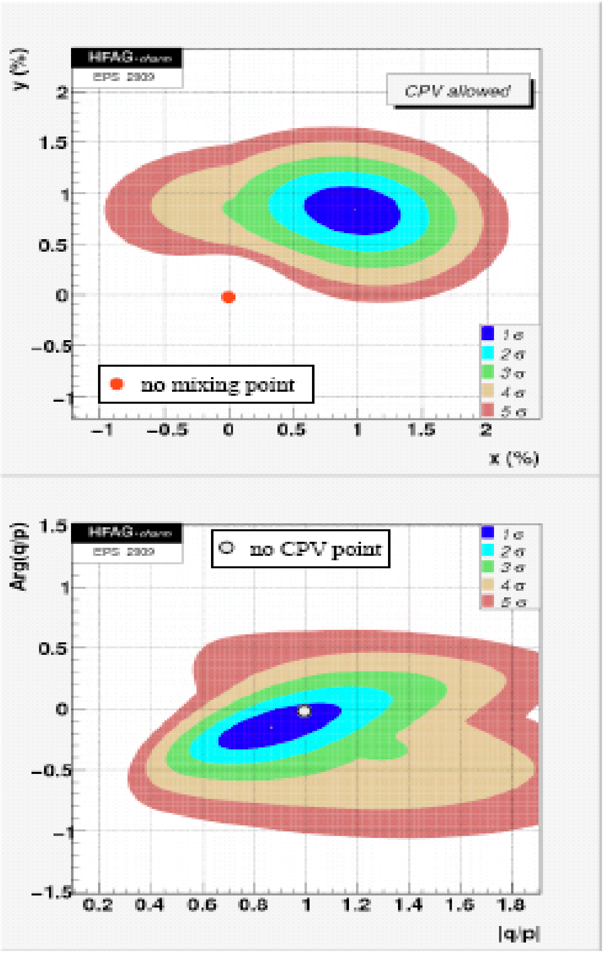
$$x = [0.16 \pm 0.23(\text{stat.}) \pm 0.12(\text{syst.}) \pm 0.08(\text{model})]\,\%$$

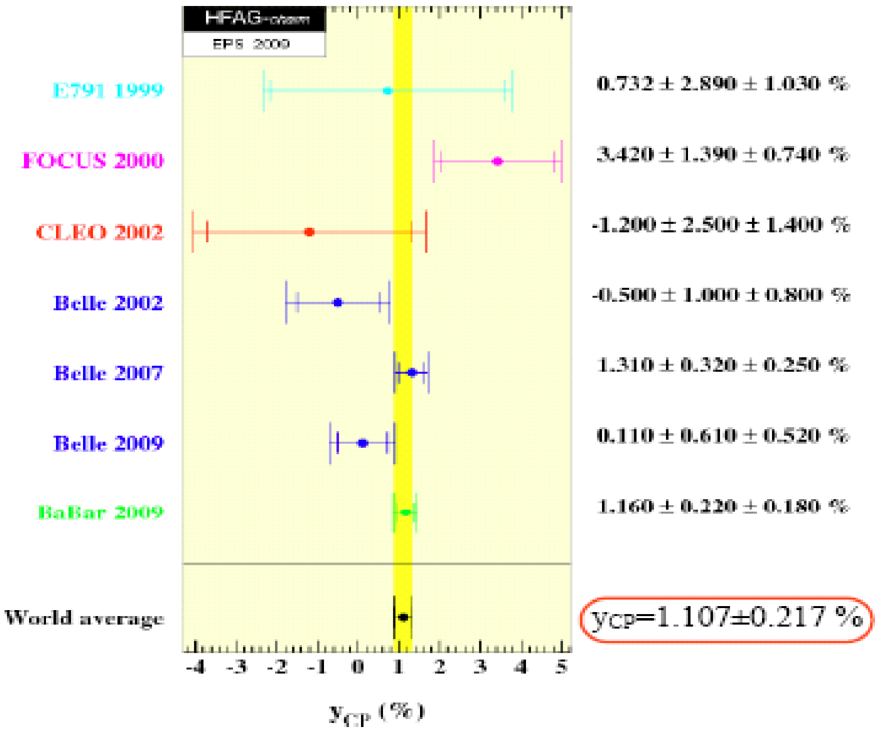
$$y = [0.57 \pm 0.20(\text{stat.}) \pm 0.13(\text{syst.}) \pm 0.07(\text{model})]\,\%$$

Best measurement of x parameter so far.

HFAG EPS 2009 results

http://www.slac.stanford.edu/xorg/hfag/charm/index.html





$x = (0.976 \pm 0.249)\%$ $|q/p| = 0.866 \pm 0.160$

$y = (0.833 \pm 0.160)\%$ $\varphi = -0.148 \pm 0.126$ rad

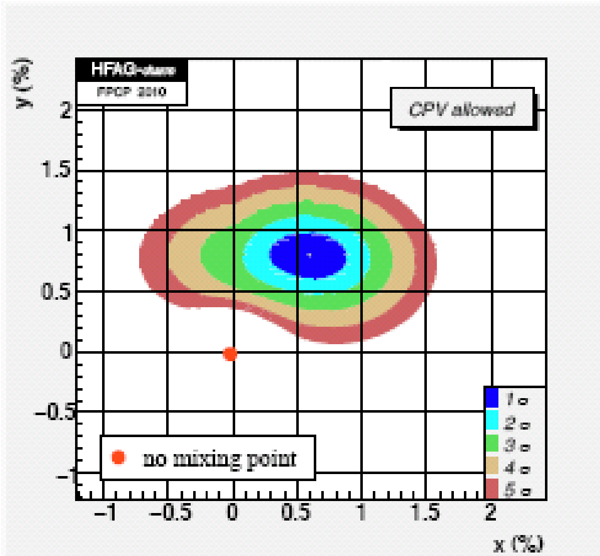
Mixing significance exceeds 10.2σ

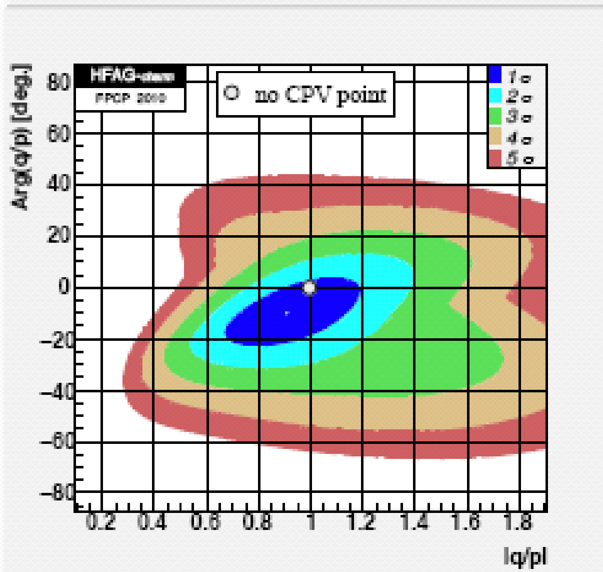
No CPV point is within 1σ contour

New

HFAG preliminary FPCP2010 results

courtesy of Alan Schwartz on behalf of HFAG





note different vertical axis scale

HFAG averages including new BaBar $K_S\pi^+\pi^-$ + $K_SK^+K^-$ results:

- *sizable improvement in mixing contours*
- *noticeable effect on x parameter value*

EPS 2009	FPCP 2010
$x = (0.976 \pm 0.249)\%$	$x = (0.59 \pm 0.20)\%$
$y = (0.833 \pm 0.160)\%$	$y = (0.80 \pm 0.13)\%$
$\lvert q/p\rvert = 0.866 \pm 0.160$	$\lvert q/p\rvert = 0.91^{+0.19}_{-0.16}$
$\varphi = -0.148 \pm 0.126$ rad	$\varphi = -10^{+9.3}_{-8.7}$ deg
	$(\varphi = -0.175^{+0.162}_{-0.152}$ rad)

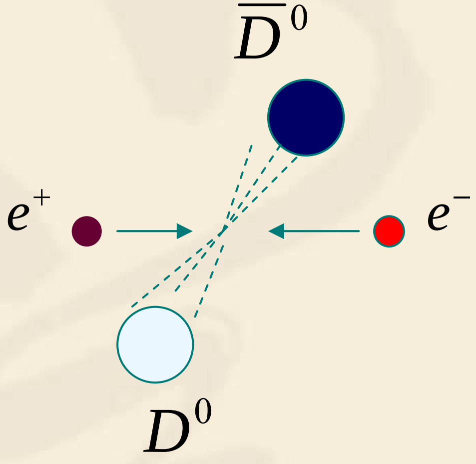
Mixing significance still exceeding 10.2σ

No CPV point is within 1σ contour

Mixing and CP at BESIII

Measure D^0 mixing and quantum correlation

$$e^+e^- \to \psi(3770) \to D^0\overline{D}^0 \to (K^\pm\pi^\mp)(K^\pm\pi^\mp)$$



$(K^\pm\pi^\mp)(K^\pm\pi^\mp)$ is in P wave and C odd since $\psi(3770)$ is 1^{--} state;
Bose-Einstein statistics does not allow both D^0s decay into identical final states.
However if mixing happened:
(D_H is not identical to D_L)

$$e^+e^- \to \psi(3770) \to D_H^0 D_L^0 \to (K^\pm\pi^\mp)_H (K^\pm\pi^\mp)_L$$

At BESIII, one can look at D mixing by using the correlation in the threshold.

Quantum Correlation

At BES-III:

$D\overline{D}$ pair with L =1 must be in anti-asymmetric state

$$|D^0\overline{D}^0\rangle^{C=-1} = \frac{1}{\sqrt{2}}\left[|D^0\rangle|\overline{D}^0\rangle - |\overline{D}^0\rangle|D^0\rangle\right]$$

the interference comes for free:

$$M_{ij}^2 = \left|\langle i|D^0\rangle\langle j|\overline{D^0}\rangle - \langle j|D^0\rangle\langle i|\overline{D^0}\rangle\right|^2$$

PRD 73, 034024 (2006)
Asner and Sun
I.I.Bigi SLAC report-33, 1989 page 169

(C=–1) $e^+e^- \to \psi(3770) \to$	D	$\overline{D}$
Forbidden if no mixing	$K^-\pi^+$	$K^-\pi^+$
Forbidden if no mixing	$K^-l^+\nu$	$K^-l^+\nu$
Forbidden by CP conservation	CP+	CP+
Forbidden by CP Conservation	CP–	CP–
Interference of CF with DCS	$K^-\pi^+$	CP±

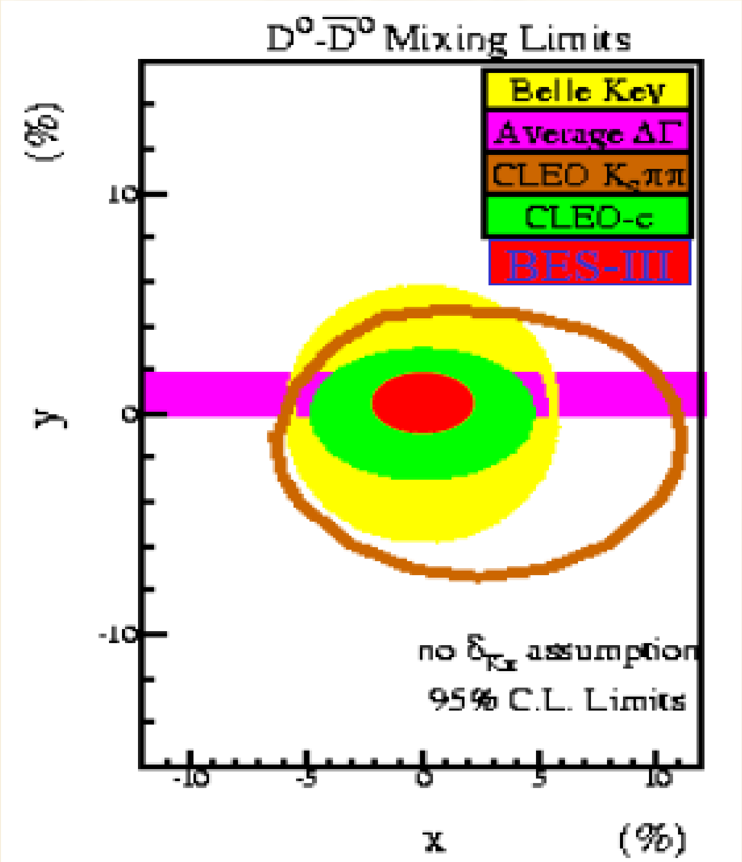
The mixing rate R_M can be measured at the first order
Strong phase $\delta_{K\pi}$ is from CP tagged $D\to K\pi$
CP violation is measured in a production rate.

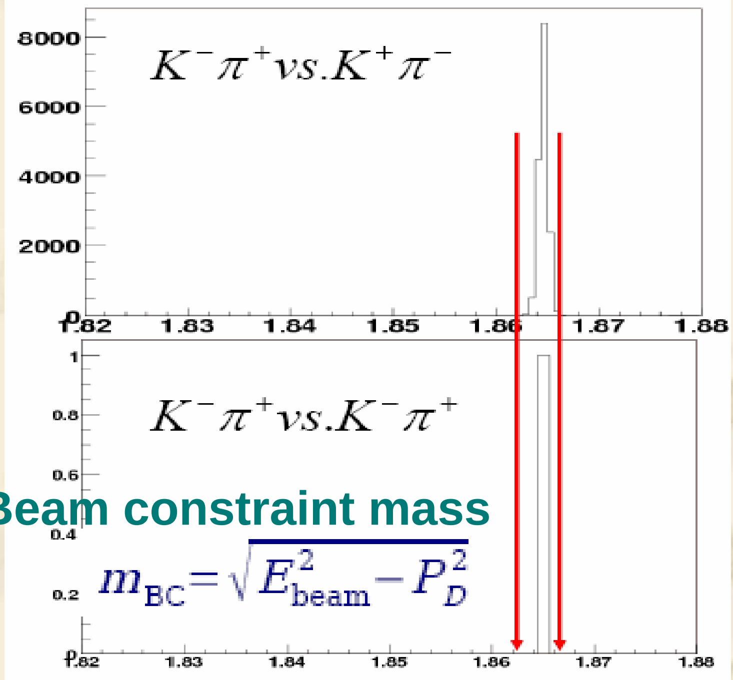
Mixing rate R_M from $\psi(3770) \to D^0\bar{D}^0 \to (K^-\pi^+)(K^-\pi^+)$

$$R_M = \frac{x^2+y^2}{2} = \frac{N[(K^\pm\pi^\mp)(K^\pm\pi^\mp)]}{N[(K^\pm\pi^\mp)(K^\mp\pi^\pm)]}$$

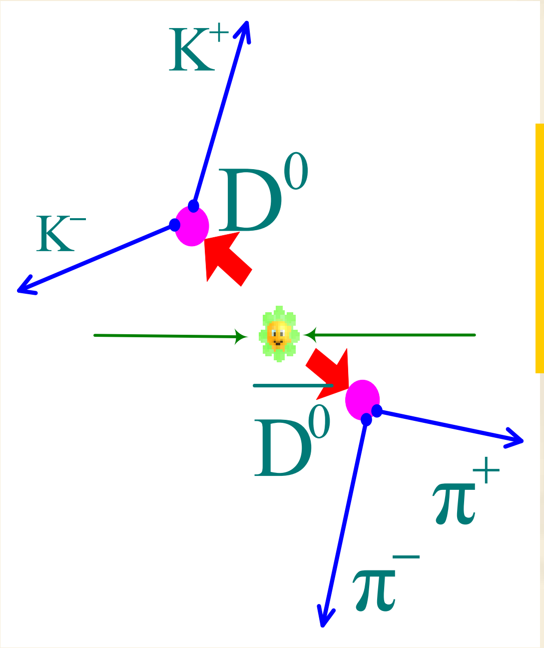
Sensitivity in 20 fb^{-1} data at BES-III: $R_M < 1.5 \times 10^{-4}$

2 events in the signal region due to mis-ID. (the mis-ID rate for pi as a Kaon is 1%).





CP Violation at $\psi(3770)$ at BESIII



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

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

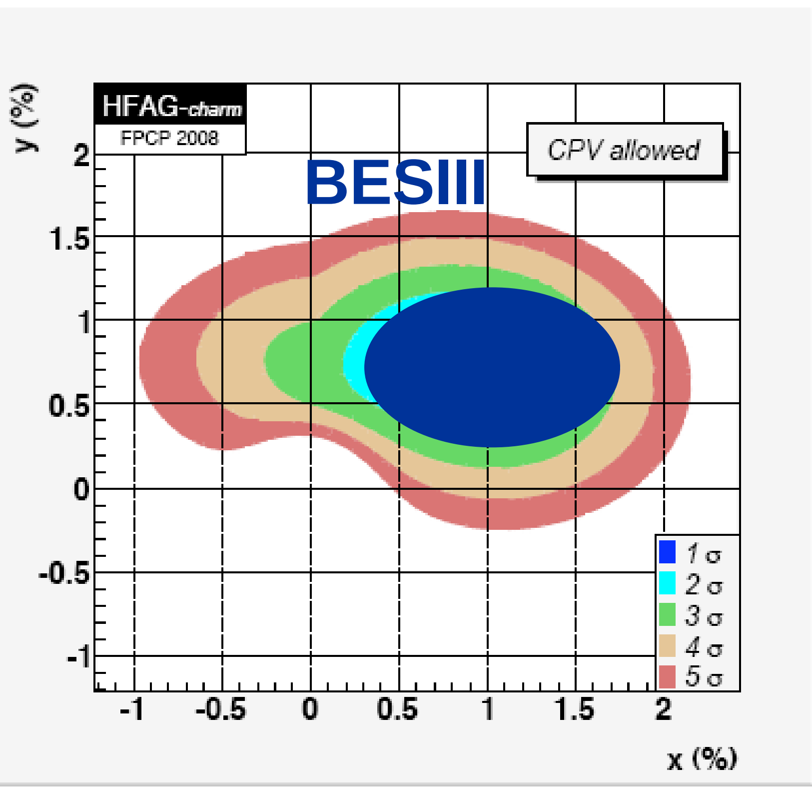
for the decay of $\psi'' \to f_1 f_2$

$$CP(f_1 f_2) = CP(f_1)\cdot CP(f_2)\cdot(-1)^L = -CP(\psi'') = +$$

A_{CP} sensitivity : $\Delta A \sim 10^{-3}$

Sensitivities (20 fb^{-1} at $\psi(3770)$ peak)

- Mixing parameters
  - $R_M=(x^2+y^2)/2 < 10^{-4}$ in $K\pi$ and $Ke\nu$ channels
  - Probe y: $\Delta y_{CP} < 0.7\%$,
  - $\Delta\cos\delta_{K\pi} < 0.06$
- CP Violation
  - $\Delta A_{CP} \sim 10^{-3}$ in D^+ decays (direct CPV),
- Improvement to ϕ_3/γ measurement in $B \rightarrow D^{(*)}K < 2^o$ (CLEO-c: $\sim 5^o$)



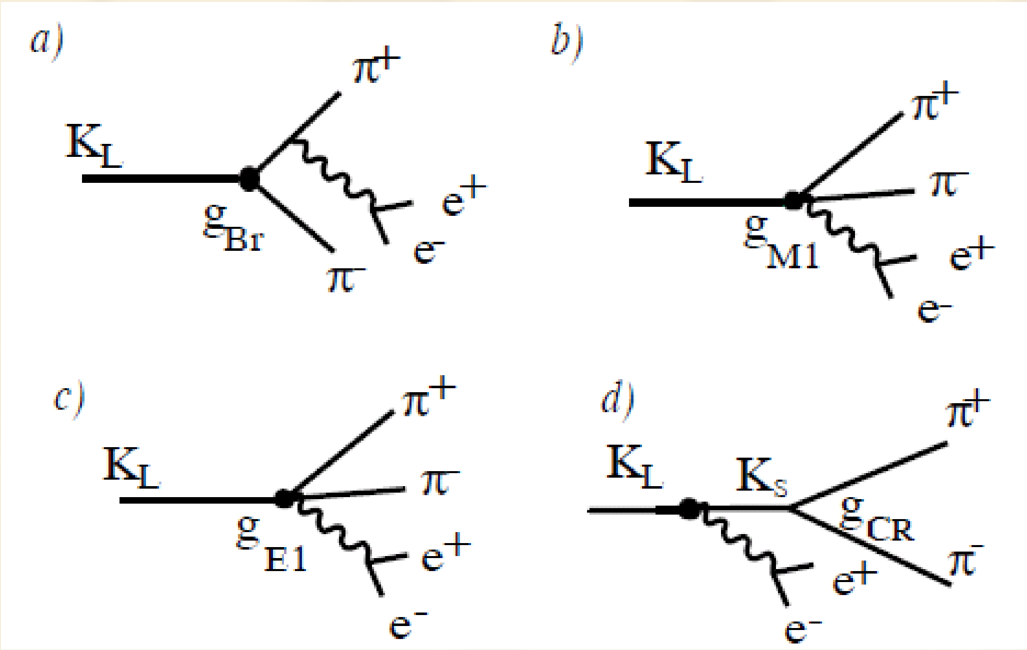
Outline for CP measurement for D-VV

- Motivation
- T violation in T odd triple-products in D decays
- CP violation in coherent process at BESIII
- Probes of New Physics at BESIII
- Summary

X.W.Kang and Hai-Bo Li, Phys. Lett.B684, 137(2010)

J. Charles, S. Descotes-Genon, X.W.Kang, Hai-Bo Li and G.R.Lu
Phys. Rev.D 81, 054032(2010)[arXiv:0912.0899 (hep-ph)]

Large CP violation in $K_L\to\pi^+\pi^-e^+e^-$



a) Bremsstrahlung
b) CP-conserving M1 γ emission
c) CP-violating E1 γ emission
d) Charge radius process

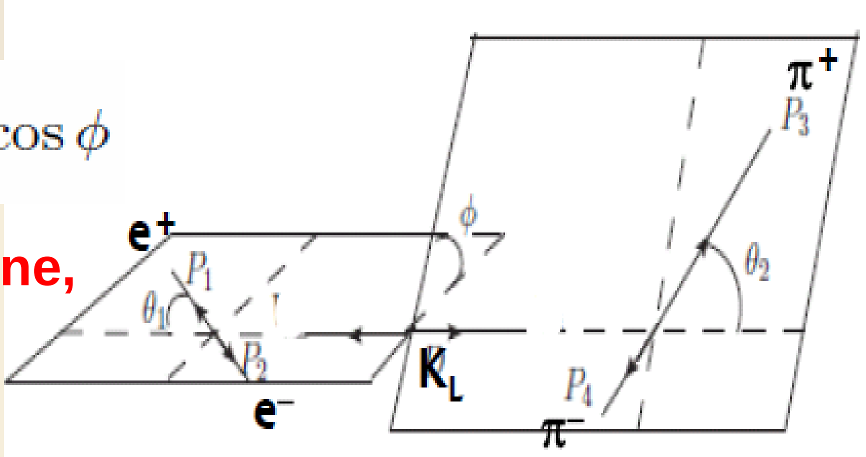
$$\mathcal{M}(K_L\to\pi^+\pi^-e^+e^-)=e|f_S|\left[\frac{g_P}{m_K^2}[k^2\mathcal{P}_\mu-(\mathcal{P}\cdot k)k_\mu]\frac{1}{k^2-2\mathcal{P}\cdot k}+\frac{g_{E1}}{m_K^4}[(\mathcal{P}\cdot k)p_{+\mu}-(p_+\cdot k)\mathcal{P}_\mu]\right.$$
$$\left.+\frac{g_{M1}}{m_K^4}\epsilon_{\mu\nu\rho\sigma}k^\nu p_+^\rho p_-^\sigma+g_{BR}\left(\frac{p_{+\mu}}{p_+\cdot k}-\frac{p_{-\mu}}{p_-\cdot k}\right)\right]\frac{e}{k^2}\bar{u}(k_-)\gamma^\mu v(k_+)$$

L.M.Sehgal and M.Wanninger PRD46, 1035(1992)

CP observable in $K_L \to \pi^+\pi^- e^+ e^-$

T odd observable in $K_L \to \pi^+\pi^- e^+ e^-$:

$$\frac{d\Gamma}{d\phi} = \Gamma_1 \cos^2\phi + \Gamma_2 \sin^2\phi + \Gamma_3 \sin\phi\cos\phi$$



ϕ is the angle between $\pi^+\pi^-$ and e^+e^- plane, and T-odd term $\Gamma_3\sin\phi\cos\phi$ contains the interference between M1 and bremsstrahlung amplitudes.

CP observable in $K_L \to \pi^+\pi^- e^+ e^-$:

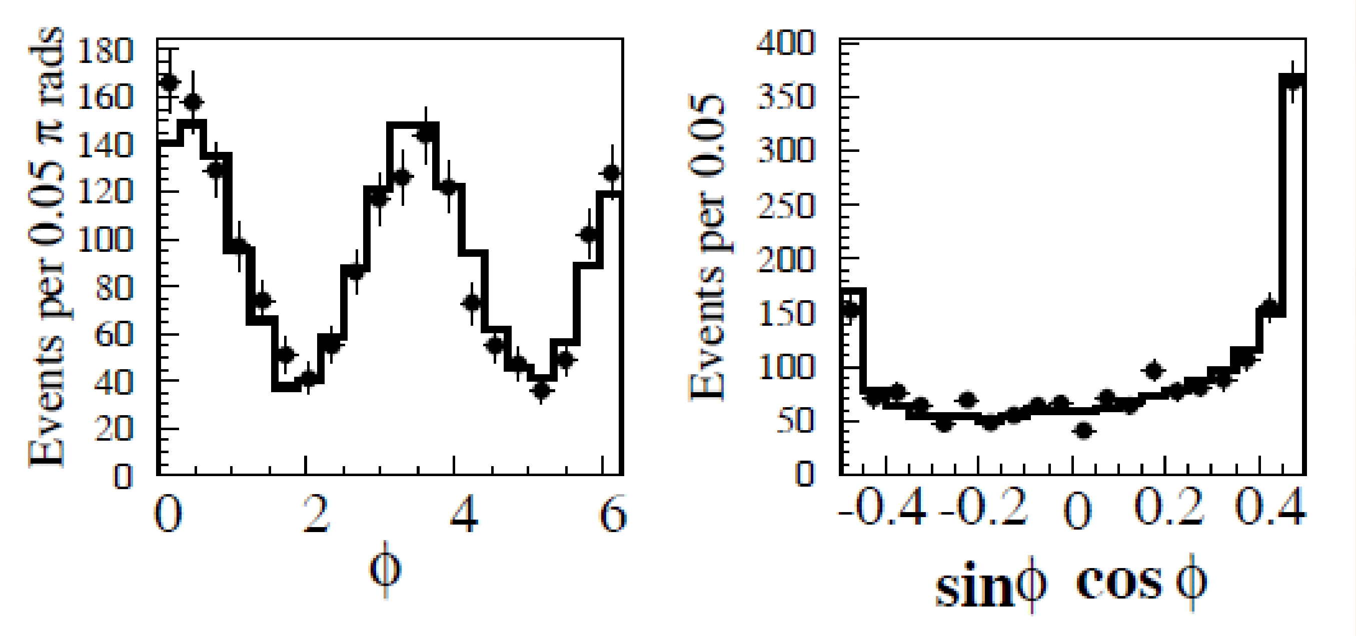
$$A = \frac{N_{\sin\phi\cos\phi\ >\ 0.0} - N_{\sin\phi\cos\phi\ <\ 0.0}}{N_{\sin\phi\cos\phi\ >\ 0.0} + N_{\sin\phi\cos\phi\ <\ 0.0}}$$

Theoretical predication:
A = (14.3±1.3)% **[L.M.Sehgal and M.Wanninger PRD46, 1035(1992)]**

with BR($K_L \to \pi^+\pi^- e^+ e^-$) = $(3.32 \pm 0.14 \pm 0.28) \times 10^{-7}$.

Measurement of CP in $K_L \to \pi^+\pi^- e^+ e^-$

$$A = \frac{N_{\sin\phi\cos\phi\ >\ 0.0} - N_{\sin\phi\cos\phi\ <\ 0.0}}{N_{\sin\phi\cos\phi\ >\ 0.0} + N_{\sin\phi\cos\phi\ <\ 0.0}}$$



A = (13.6±1.4±1.5)% [KTeV: arXiv:hep-ex/050801]

which agrees well with theoretical prediction:

A = (14.3±1.3)%

[L.M.Sehgal and M.Wanninger PRD46, 1035(1992)]

CP violation in D $\rightarrow$VV

How about in D case?

Bigi suggested that one can look at the T-odd moment in $D \to K^+K^-\pi^+\pi^-$: [hep-ph/070127]

$$\frac{d\Gamma}{d\phi}(D \to K\bar{K}\pi^+\pi^-) = \Gamma_1\cos^2\phi + \Gamma_2\sin^2\phi + \Gamma_3\cos\phi\sin\phi$$

$$\frac{d\Gamma}{d\phi}(\bar{D} \to K\bar{K}\pi^+\pi^-) = \bar{\Gamma}_1\cos^2\phi + \bar{\Gamma}_2\sin^2\phi + \bar{\Gamma}_3\cos\phi\sin\phi$$

$$\Gamma_3 \neq \bar{\Gamma}_3 \implies \text{CP violation!}$$

Advantage: large branching fraction for D into 4-body final states (10%).

We expect to see difference in Γ_3 vs. $\bar{\Gamma}_3$.

T violating asymmetry measured by FOCUS experiment [PLB622, 239(2005)]:

Decay mode	$\mathcal{A}$ (%)
$D^0 \to K^+K^-\pi^+\pi^-$	$1.0 \pm 5.7 \pm 3.7$
$D^+ \to K_S K^+\pi^+\pi^-$	$2.3 \pm 6.2 \pm 2.2$
$D_S^+ \to K_S K^+\pi^+\pi^-$	$-3.6 \pm 6.7 \pm 2.3$

Large decay branching fractions in D system

D^0 decay

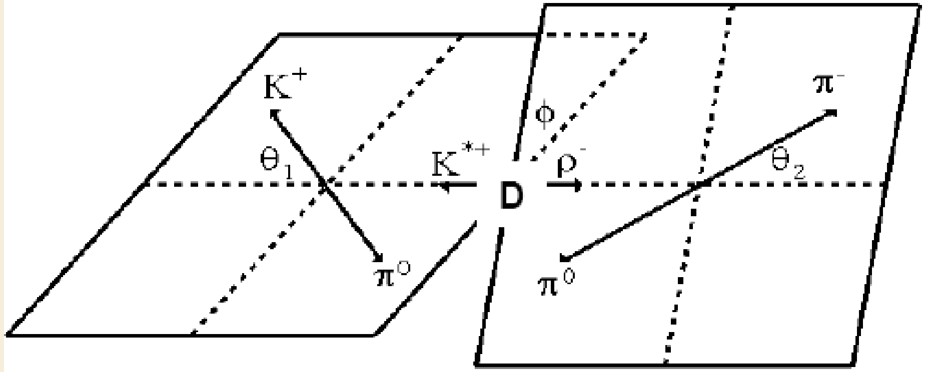
Poor data in PDG !

$\overline{K}^*(892)^0 \rho^0$		(1.50 ± 0.33) %	
$\overline{K}^*(892)^0 \rho^0$ transverse		(1.6 ± 0.5) %	
$\overline{K}^*(892)^0 \rho^0$ S-wave		(2.9 ± 0.6) %	
$\overline{K}^*(892)^0 \rho^0$ S-wave long.		$< 3 \times 10^{-3}$	CL=90%
$\overline{K}^*(892)^0 \rho^0$ P-wave		$< 3 \times 10^{-3}$	CL=90%
$\overline{K}^*(892)^0 \rho^0$ D-wave		(2.0 ± 0.6) %	
$K^*(892)^- \rho^+$		(6.4 ± 2.5) %	
$K^*(892)^- \rho^+$ longitudinal		(3.1 ± 1.2) %	
$K^*(892)^- \rho^+$ transverse		(3.4 ± 2.0) %	
$K^*(892)^- \rho^+$ P-wave		< 1.5 %	CL=90%

D^+ decay

$\overline{K}^*(892)^0 \rho^+$ total	[ss]	(1.8 ± 1.4) %	
$\overline{K}^*(892)^0 \rho^+$ S-wave	[ss]	(1.4 ± 1.5) %	
$\overline{K}^*(892)^0 \rho^+$ P-wave		$< 1 \times 10^{-3}$	CL=90%
$\overline{K}^*(892)^0 \rho^+$ D-wave		$(8 \pm 7) \times 10^{-3}$	
$\overline{K}^*(892)^0 \rho^+$ D-wave longitudinal		$< 7 \times 10^{-3}$	CL=90%
$K^*(892)^+ \overline{K}^*(892)^0$		(2.6 ± 1.1) %	

Partial waves in D → VV decays



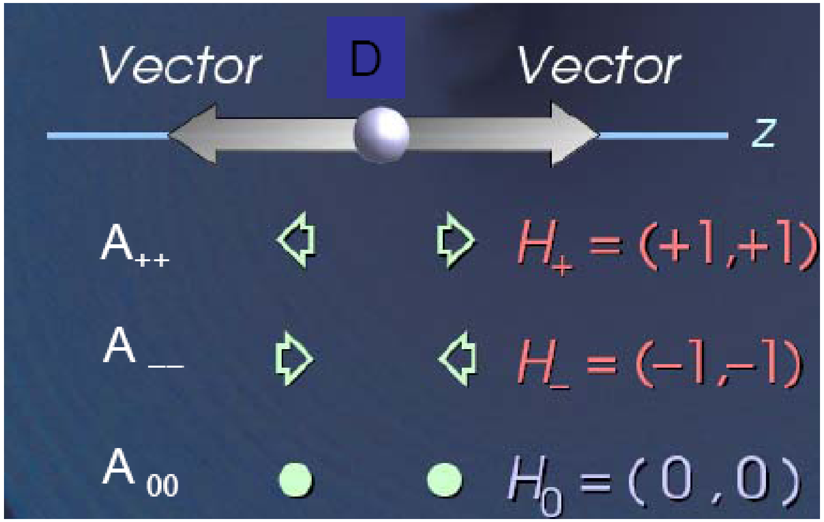
$$CP\text{-even longitudinal} \quad : A_0 \quad = \quad -\tfrac{1}{\sqrt{3}}S \quad +\sqrt{\tfrac{2}{3}}D$$

$$CP\text{-even transverse} \quad : A_{\parallel} \quad = \quad \sqrt{\tfrac{2}{3}}S \quad +\tfrac{1}{\sqrt{3}}D$$

$$CP\text{-odd transverse} \quad : A_{\perp} \quad = \quad P$$

Conservation of angular momentum: D meson: J=M=0.

The constraint $|\lambda_1 - \lambda_2| \leq M$ implies that $\lambda_1=\lambda_2=\lambda$:



$$A = \langle f|\mathcal{H}|i\rangle = A_{00} + A_{++} + A_{--}$$

Transverse Polarization

$$A_{\parallel} = \frac{(H_+ + H_-)}{\sqrt{(2)}} \qquad A_{\perp} = \frac{(H_+ - H_-)}{\sqrt{(2)}}$$

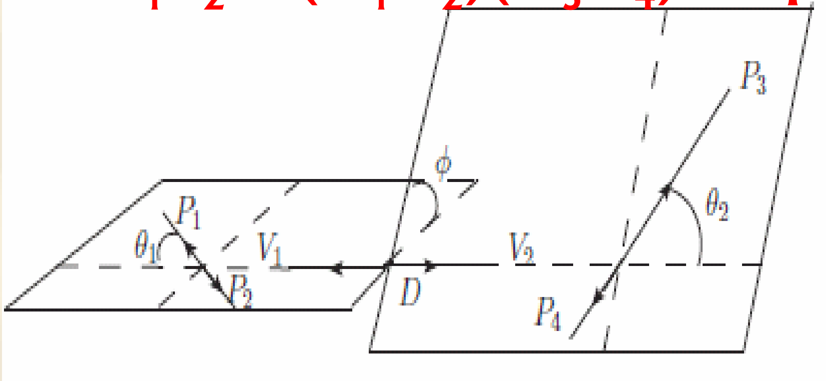
(Parallel) (Perpendicular)

Longitudinal Polarization

$$A_0 = H_0$$

Angular dependence partial waves in D→VV

Rich final state interaction may induce relatively large CP violation in D → V_1V_2 →(M_1M_2)(M_3M_4) ---- provide T-odd observables:



$$
\begin{aligned}
A_0 &= A_0; \\
A_{||} &= \frac{1}{\sqrt{2}}(A_{11} + A_{-1-1}); \\
A_\perp &= \frac{1}{\sqrt{2}}(A_{11} - A_{-1-1})
\end{aligned}
$$

$$
\frac{d\Gamma}{d\cos\theta_1 d\cos\theta_2 d\phi} \propto \frac{1}{2}\sin^2\theta_1\sin^2\theta_2\cos^2\phi|A_{||}|^2 + \frac{1}{2}\sin^2\theta_1\sin^2\theta_2\sin^2\phi|A_\perp|^2 + \cos^2\theta_1\cos^2\theta_2|A_0|^2
$$

$$
-\frac{1}{2}\sin^2\theta_1\sin^2\theta_2\sin 2\phi Im(A_\perp A_{||}^*) - \frac{\sqrt{2}}{4}\sin 2\theta_1\sin 2\theta_2\cos\phi Re(A_{||}A_0^*) + \frac{\sqrt{2}}{4}\sin 2\theta_1\sin 2\theta_2\sin\phi Im(A_\perp A_0^*)
$$

$$
\mathcal{A}_T^{||} \equiv \frac{\mathrm{Im}(A_\perp A_{||}^*)}{|A_0|^2 + |A_\perp|^2 + |A_{||}|^2},
\qquad
\mathcal{A}_T^{0} \equiv \frac{\mathrm{Im}(A_\perp A_0^*)}{|A_0|^2 + |A_\perp|^2 + |A_{||}|^2},
$$

The triple-product is connected with angular dependence. Note that non-zero T-odd correlation doesn't necessarily imply CP violation since the strong phase may fake it.

Source of CP in D→ VV

Let us first consider the process $D(p) \to V_1(k, \epsilon_1)V_2(q, \epsilon_2)$, where the two vectors V_1, V_2 are characterized as their four-momenta and polarizations (k, ϵ_1) and (q, ϵ_2), respectively. We can write the most general invariant amplitude as a sum of three terms that we will call s, d, p [14–17],

$$\mathcal{M} \equiv as + bd + icp = a\epsilon_1^* \cdot \epsilon_2^* + \frac{b}{m_1 m_2}(p \cdot \epsilon_1^*)(p \cdot \epsilon_2^*) + i\frac{c}{m_1 m_2}\epsilon^{\alpha\beta\gamma\delta}\epsilon_{1\alpha}^*\epsilon_{2\beta}^* k_\gamma p_\delta,$$

T-odd

$$\overline{\mathcal{M}} = \bar{a}\epsilon_1^* \cdot \epsilon_2^* + \frac{\bar{b}}{m_1 m_2}(p \cdot \epsilon_1^*)(p \cdot \epsilon_2^*) - i\frac{\bar{c}}{m_1 m_2}\epsilon^{\alpha\beta\gamma\delta}\epsilon_{1\alpha}^*\epsilon_{2\beta}^* k_\gamma p_\delta,$$

where m_1 (m_2) is the mass of V_1 (V_2), and the scalar coefficients a, b and c are generally complex and can receive contributions from several amplitudes with different phases. Thus, one can parameterize the coefficients as [14]

$$a = \sum_j a_j e^{i\delta_{sj}} e^{i\phi_{sj}},$$

$$b = \sum_j b_j e^{i\delta_{dj}} e^{i\phi_{dj}},$$

$$c = \sum_j c_j e^{i\delta_{pj}} e^{i\phi_{pj}},$$

Amplitudes D/$\bar{\text{D}}$→VV

$$|\mathcal{M}|^2 = |a|^2|\epsilon_1^* \cdot \epsilon_2^*|^2 + \frac{|b|^2}{m_1^2m_2^2}|(k \cdot \epsilon_2^*)(q \cdot \epsilon_1^*)|^2$$
$$+ \frac{|c|^2}{m_1^2m_2^2}|\epsilon^{\alpha\beta\gamma\delta}\epsilon_{1\alpha}^*\epsilon_{2\beta}^*k_\gamma p_\delta|^2$$
$$+ 2\frac{\mathrm{Re}(ab^*)}{m_1m_2}(\epsilon_1^* \cdot \epsilon_2^*)(k \cdot \epsilon_2^*)(q \cdot \epsilon_1^*)$$
$$+ 2\frac{\mathrm{Im}(ac^*)}{m_1m_2}(\epsilon_1^* \cdot \epsilon_2^*)\epsilon^{\alpha\beta\gamma\delta}\epsilon_{1\alpha}^*\epsilon_{2\beta}^*k_\gamma p_\delta$$
$$+ 2\frac{\mathrm{Im}(bc^*)}{m_1^2m_2^2}(k \cdot \epsilon_2^*)(q \cdot \epsilon_1^*)\epsilon^{\alpha\beta\gamma\delta}\epsilon_{1\alpha}^*\epsilon_{2\beta}^*k_\gamma p_\delta.$$

T-odd observable, but not : CP observable:

$$\mathcal{A}_\mathcal{T} \propto \mathrm{Im}(ac^*) = \sum_{i,j} a_i c_j \sin[(\phi_{si} - \phi_{pj}) + (\delta_{si} - \delta_{pj})].$$

$$|\overline{\mathcal{M}}|^2 = |\bar{a}|^2|\epsilon_1^* \cdot \epsilon_2^*|^2 + \frac{|\bar{b}|^2}{m_1^2m_2^2}|(k \cdot \epsilon_2^*)(q \cdot \epsilon_1^*)|^2$$
$$+ \frac{|\bar{c}|^2}{m_1^2m_2^2}|\epsilon^{\alpha\beta\gamma\delta}\epsilon_{1\alpha}^*\epsilon_{2\beta}^*k_\gamma p_\delta|^2$$
$$+ 2\frac{\mathrm{Re}(\bar{a}\bar{b}^*)}{m_1m_2}(\epsilon_1^* \cdot \epsilon_2^*)(k \cdot \epsilon_2^*)(q \cdot \epsilon_1^*)$$
$$- 2\frac{\mathrm{Im}(\bar{a}\bar{c}^*)}{m_1m_2}(\epsilon_1^* \cdot \epsilon_2^*)\epsilon^{\alpha\beta\gamma\delta}\epsilon_{1\alpha}^*\epsilon_{2\beta}^*k_\gamma p_\delta$$
$$- 2\frac{\mathrm{Im}(\bar{b}\bar{c}^*)}{m_1^2m_2^2}(k \cdot \epsilon_2^*)(q \cdot \epsilon_1^*)\epsilon^{\alpha\beta\gamma\delta}\epsilon_{1\alpha}^*\epsilon_{2\beta}^*k_\gamma p_\delta.$$

T violating triple-product

Comparing a triple correlation for CP conjugate transitions allows to distinguish CP violation from final state interaction effects,

$$\frac{1}{2}(\mathcal{A}_T + \bar{\mathcal{A}}_T) \propto \frac{1}{2}[\mathrm{Im}(ac^*) - \mathrm{Im}(\bar{a}\bar{c}^*)] = \sum_{i,j} a_i c_j \sin(\phi_{si} - \phi_{pj}) \cos(\delta_{si} - \delta_{pj}),$$

For longitudinal component:

$$\mathcal{A} = \frac{1}{2}(\mathcal{A}_T^0 + \bar{\mathcal{A}}_T^0) = \frac{1}{2}\left(\frac{\mathrm{Im}(A_\perp A_0^*)}{|A_0|^2 + |A_\perp|^2 + |A_\parallel|^2} + \frac{\mathrm{Im}(\bar{A}_\perp \bar{A}_0^*)}{|\bar{A}_0|^2 + |\bar{A}_\perp|^2 + |\bar{A}_\parallel|^2}\right)$$

For parallel component:

$$\mathcal{A}' = \frac{1}{2}(\mathcal{A}_T^\parallel + \bar{\mathcal{A}}_T^\parallel) = \frac{1}{2}\left(\frac{\mathrm{Im}(A_\perp A_\parallel^*)}{|A_0|^2 + |A_\perp|^2 + |A_\parallel|^2} + \frac{\mathrm{Im}(\bar{A}_\perp \bar{A}_\parallel^*)}{|\bar{A}_0|^2 + |\bar{A}_\perp|^2 + |\bar{A}_\parallel|^2}\right)$$

Sensitivity of T violating triple product at BESIII

The expected errors on T-odd asymmetry at BESIII with 20 fb^{-1} luminosity on $\psi(3770)$ peak (72×10^6 DDbar pairs).

VV	Br (%)	Eff. (ϵ)	Expected errors
$\rho^0\rho^0 \to (\pi^+\pi^-)(\pi^+\pi^-)$	0.18	0.74	0.004
$\bar{K}^{*0}\rho^0 \to (K^-\pi^+)(\pi^+\pi^-)$	1.08	0.68	0.002
$\rho^0\phi \to (\pi^+\pi^-)(K^+K^-)$	0.14	0.26	0.006
$\rho^+\rho^- \to (\pi^+\pi^0)(\pi^-\pi^0)$	0.6*	0.55	0.002
$K^{*+}K^{*-} \to (K^+\pi^0)(K^-\pi^0)$	0.08*	0.55	0.006
$K^{*0}\bar{K}^{*0} \to (K^+\pi^-)(K^-\pi^+)$	0.048	0.62	0.002
$\bar{K}^{*0}\rho^+ \to (K^-\pi^+)(\pi^+\pi^0)$	1.33	0.59	0.001

X.W.Kang and Hai-Bo Li, Phys. Lett.B684, 137(2010)

Extracting CP violation and strong phase in D decays by using quantum correlations in $\psi(3770) \to D^0 \bar{D}^0 \to (V_1 V_2)(V_3 V_4)$ and $\psi(3770) \to D^0 \bar{D}^0 \to (V_1 V_2)(K\pi)$

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CP in $\psi(3770) \to D^0\overline{D}^0 \to (V_1V_2)(V_3V_4)$

CP violation in D decays

- **challenging in Standard Model but clear New physics signal**
- **BEPCII will provide intricate DDbar pairs in definite quantum state (L=1):**

$$|(D\bar{D})_{L=1}\rangle = \frac{-|D_1\rangle|D_2\rangle + |D_2\rangle|D_1\rangle}{\sqrt{2}}$$

Neglecting CP violation in mixing, the CP eigenstates can be defined as

$$|D_1\rangle = \frac{|D^0\rangle + |\bar{D}^0\rangle}{\sqrt{2}}, \qquad |D_2\rangle = \frac{|D^0\rangle - |\bar{D}^0\rangle}{\sqrt{2}}$$

D→VV high branching ratio (a few % for ρK*)

$\psi(3770) \to D^0\overline{D}^0 \to (V_1V_2)(V_3V_4)$ **well reconstructed at BESIII**

Quantum correlation

For the following process, $D^0\overline{D}^0$ **in antisymmetric state (L=1):**

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

with f_a and f_b CP eigenstates of same CP-parity, we have **CP violation:**

$$CP|\psi\rangle = |\psi\rangle, \qquad CP|f_a f_b\rangle = \eta_a \eta_b (-1)^\ell |f_a f_b\rangle = -|f_a f_b\rangle$$

For $\psi(3770) \to D^0\overline{D}^0 \to (V_1V_2)(V_3V_4)$ **observables for CP violation can be reconstructed (polarization fractions, interference between partial waves) if angular analysis is available.**

Large branching fraction and reconstruction efficiency

$$\psi \to D_1 D_2, \quad D_1 \to V_1 V_2, \quad D_2 \to V_3 V_4,$$
$$V_1 \to M_1 M_1', V_2 \to M_2 M_2', V_3 \to M_3 M_3', V_4 \to M_4 M_4'.$$

The transversity amplitudes A for $D_{1,2} \to VV'$ have simple transformation laws under CP:

$$A_0^{D\to VV'} \to +\eta_{CP}(V)\eta_{CP}(V')\eta_{CP}(D)A_0^{D\to\bar{V}\bar{V}'},$$ **Longitudinal CP+**

$$A_{||}^{D\to VV'} \to +\eta_{CP}(V)\eta_{CP}(V')\eta_{CP}(D)A_{||}^{D\to\bar{V}\bar{V}'},$$ **Parallel CP+**

$$A_{\perp}^{D\to VV'} \to -\eta_{CP}(V)\eta_{CP}(V')\eta_{CP}(D)A_{\perp}^{D\to\bar{V}\bar{V}'}.$$ **Perpendicular CP–**

VV	$\eta_{CP}(V)\eta_{CP}(V)$	Br (%)	Eff. (ϵ)
$\rho^0\rho^0$	1	0.18	0.24
$\bar{K}^{*0}\rho^0 \to (K_S\pi^0)(\pi^+\pi^-)$	1	0.27	0.12
$\rho^0\phi \to (\pi^+\pi^-)(K^+K^-)$	1	0.14	0.07
$\bar{K}^{*0}\omega \to (K_S\pi^0)(\pi^+\pi^-\pi^0)$	1	0.33	0.09
$\rho^+\rho^-$	1	[0.6]	0.18
$\rho^0\omega \to (\pi^+\pi^-)(\pi^+\pi^-\pi^0)$	1	[$\simeq$ 0]	0.18
$K^{*+}K^{*-} \to (K_S\pi^+)(K_S\pi^-)$	1	[0.08]	0.07
$K^{*0}\bar{K}^{*0} \to (K_S\pi^0)(K_S\pi^0)$	1	0.003	0.09

Efficiencies At BESIII

CP observables in the correlation

One obtains, neglecting CP-violation in DD mixing, the following result for the combined branching ratio, which can be recovered from [16]

$$\mathcal{BR}((D^0\bar{D}^0)_{C=-1} \to f_a f_b) = 2\mathcal{BR}(D^0 \to f_a)\mathcal{BR}(D^0 \to f_b)(|\rho_a - \rho_b|^2 + r_D|1 - \rho_a\rho_b|^2), \quad (17)$$

with the ratio of CP-conjugate amplitudes and the combination of D-mixing parameters

$$\rho_f = \eta_f(1+\delta_f)e^{i\alpha_f}$$

$$\rho_f = \frac{A(\bar{D}^0 \to f)}{A(D^0 \to f)}, \qquad r_D = (x^2 + y^2)/2 < 10^{-4}. \quad (18)$$

where $x = \Delta m/\Gamma$ and $y = \Delta\Gamma/(2\Gamma)$ are the difference of masses and widths of the mass eigenstates in the $D\bar{D}$ system, normalised by their average width [6].

If CP is conserved in D decays: $\rho_f = \eta_f$, is the CP eigenvalue (+1 or –1), for both D decay into eigenstates with same CP-parity, we have:

$$\mathcal{BR}((D^0\bar{D}^0)_{C=-1} \to f_a f_b) = 0$$

Thus,

$$\mathcal{BR}((D^0\bar{D}^0)_{C=-1} \to f_a f_b) \neq 0$$

will indicate CP violation in the correlated process. For D→VV, we can construct observables for CP violation by considering different partial waves with the same CP parities.

CP observables in combined rates

$$\psi(3770) \to D^0\overline{D}^0 \to (V_1V_2)(V_3V_4)$$

$$V_i \to M_i M_i^{'} \quad (\mathrm{i}=1,2,3,4)$$

We have the CP violating amplitudes:

$$(A_0^{D_1\to V_1V_2})(A_0^{D_2\to V_3V_4}), \quad (A_0^{D_1\to V_1V_2})(A_{II}^{D_2\to V_3V_4})$$

$$(A_{II}^{D_1\to V_1V_2})(A_0^{D_2\to V_3V_4}), \quad (A_{\perp}^{D_1\to V_1V_2})(A_{\perp}^{D_2\to V_3V_4}),$$

$$(A_{II}^{D_1\to V_1V_2})(A_{II}^{D_2\to V_3V_4}),$$

For example, both D→ VV in the longitudinal polarizations, we construct the angular dependence CP observable:

$$\int d\Gamma_{4V}\frac{1}{128}(5\cos^2\theta_{V_1}-1)(5\cos^2\theta_{V_2}-1)(5\cos^2\theta_{V_3}-1)(5\cos^2\theta_{V_4}-1)$$
$$=|A^{\psi V_1V_2V_3V_4}|^2|A_0^{D^0\to V_1V_2}|^2|A_0^{D^0\to V_3V_4}|^2\times|\rho^0_{V_1,V_2}-\rho^0_{V_3,V_4}|^2.$$

Sensitivity at BESIII with 20fb^{-1} luminosity

Reaction	Efficiency	Upper limits at BES-III($\times 10^{-7}$)
$D^0\bar{D}^0 \to (\rho^+\rho^-)(\bar{K}^{*0}\omega)$	0.13	2.46
$D^0\bar{D}^0 \to (\rho^0\rho^0)(\bar{K}^{*0}\rho^0)$	0.17	1.88
$D^0\bar{D}^0 \to (\bar{K}^{*0}\rho^0)(K^{*0}\omega)$	0.10	3.19
$D^0\bar{D}^0 \to (\bar{K}^{*0}\rho^0)(\rho^0\phi)$	0.09	3.55
$D^0\bar{D}^0 \to (\bar{K}^{*0}\omega)(\rho^0\phi)$	0.08	3.99
$D^0\bar{D}^0 \to (\rho^0\rho^0)(\bar{K}^{*0}\omega)$	0.15	2.13
$D^0\bar{D}^0 \to (\rho^0\rho^0)(\rho^0\phi)$	0.13	2.46
$D^0\bar{D}^0 \to (\rho^+\rho^-)(\rho^0\phi)$	0.11	2.90
$D^0\bar{D}^0 \to (\rho^+\rho^-)(K^{*+}K^{*-})$	0.11	2.90

Table 5: The projected 90%-C.L. upper limits on CP violating branching fraction of some most interesting (VV)(VV) modes from correlated $D^0\bar{D}^0$ pairs with 20 fb^{-1} data taken at $\psi(3770)$ peak at BES-III.

CP violating rate and phase difference

From the following combined CP violating decay rate

$$\mathcal{BR}((D^0\bar{D}^0)_{C=-1} \to f_a f_b) = 2\mathcal{BR}(D^0 \to f_a)\mathcal{BR}(D^0 \to f_b)(|\rho_a - \rho_b|^2 + r_D|1 - \rho_a\rho_b|^2),$$

with the parameterization:

$$\rho_f = \eta_f(1+\delta_f)e^{i\alpha_f}$$

η_f : value of CP parity

δ_f : term of CP violation in decay

α_f : phase difference between D and $\bar{\mathrm{D}}$

As an example for $D^0\overline{D}^0 \to (\rho^0\rho^0)(\overline{K}^{*0}\rho^0)$, the above formula can be written as:

$$\mathcal{BR}((D^0\bar{D}^0)_{C=-1} \to \rho^0\rho^0, \bar{K}^{*0}\rho^0)\Big|_{(0,||)}^{CPV} \simeq 8 \times \mathcal{BR}^0(D^0 \to \rho^0\rho^0) \cdot \mathcal{BR}^{||}(D^0 \to \bar{K}^{*0}\rho^0)\sin^2\frac{\alpha_a - \alpha_b}{2}$$

Combining the CP violating rate and polarization fractions, one can extract the phase difference (α_a-α_b).

Extracting phase difference

From the following formula, if the CP violating rate on the left and polarization fractions on the right side are measured, the strong phase difference can be determined:

$$\mathcal{BR}((D^0\bar{D}^0)_{C=-1} \to \rho^0\rho^0, \bar{K}^{*0}\rho^0)\Big|_{(0,||)}^{CPV} \simeq 8 \times \mathcal{BR}^0(D^0 \to \rho^0\rho^0) \cdot \mathcal{BR}^{||}(D^0 \to \bar{K}^{*0}\rho^0)\sin^2\frac{\alpha_a - \alpha_b}{2}$$

For example, the current values for the polarized fractions in $\rho\rho$ and ρK^* yields the upper limit $|\alpha_a - \alpha_b| < 4.4^\circ$ at 90% confidence level from the channel $(D^0\bar{D}^0)_{C=-1} \to \rho^0\rho^0, \bar{K}^{*0}\rho^0\Big|_{(0,||)}$. At a future Super τ-charm factory, with a data set of 2 ab^{-1}, the constraint would be more severe, $|\alpha_a - \alpha_b| < 0.5^\circ$ at 90% confidence level.