Lecture 2

Rare and forbidden charm decays
Neutral D mixing and CP violation

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Rare & forbidden charm decays

What’s the rare?

FCNC processes are very rare in SM being suppressed by absence of tree level diagrams and by GIM mechanism;

FCNC in Charm are even more suppressed due to absence of high mass down-type quark;

Many new physics scenarios can therefore contribute enhancing these processes with new particles running in the loops or even at tree level

Some models predict enhancements in the up sector only

Lepton flavour, lepton number and baryon number violating decays are essentially forbidden in the Standard Model

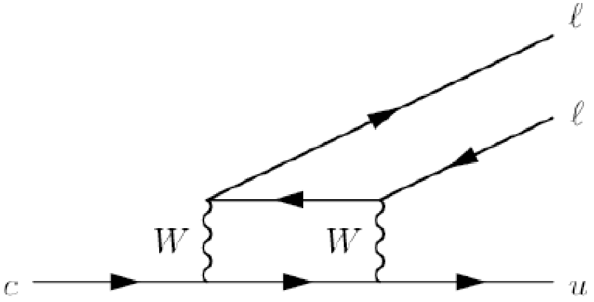
No theoretical uncertainties

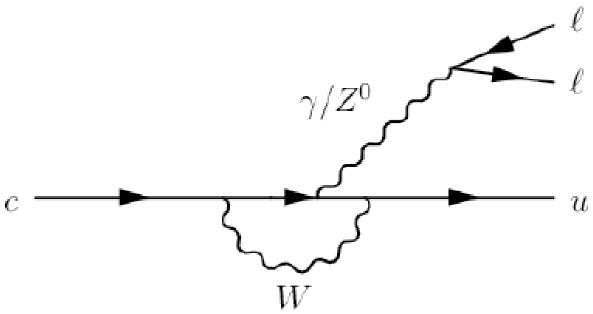
However in some new physics models they can be allowed at sizeable levels

If not seen can put strong constraints on NP parameters

FCNC in Charm

PRD66,(2002)014009





Standard Model:

- Short distance contributions heavily suppressed by GIM mechanism

$$\mathcal{B}_{D^+\to X_u^+ e^+ e^-} \simeq 2\cdot 10^{-8} \qquad \mathcal{B}_{D^0\to X_u^0 e^+ e^-} \simeq 8\cdot 10^{-9}$$

- SM rate dominated by long distance contribution due to $D\to XV\to X\ell^+\ell^-$ where $V=\phi,\rho,\omega$
- Long distance contribution are of non-perturbative nature giving large theoretical errors
- Branching fractions at 10^{-6}, but non-resonant part is at the level of 10^{-7}
- Outside of the resonances (both low and high q^2) there is still big room to discover new physics contributions

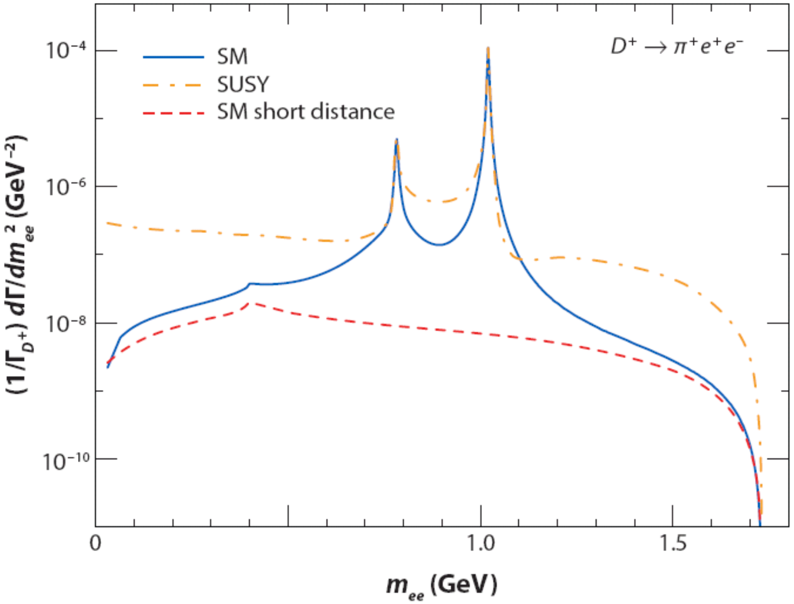
[Phys.Rev. D66 (2002) 014009]

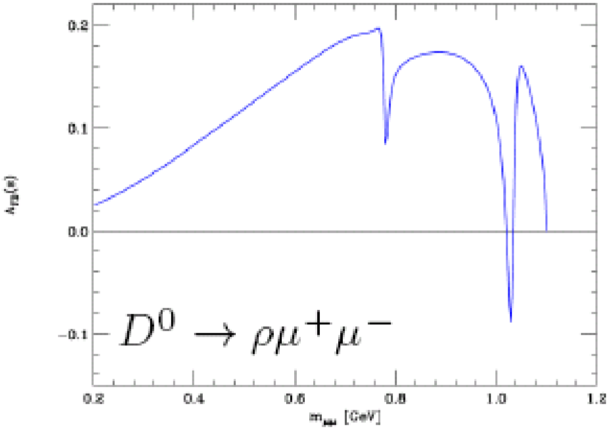
Flavour changing neutral currents: $c \to u\ell^+\ell^-$ new physics

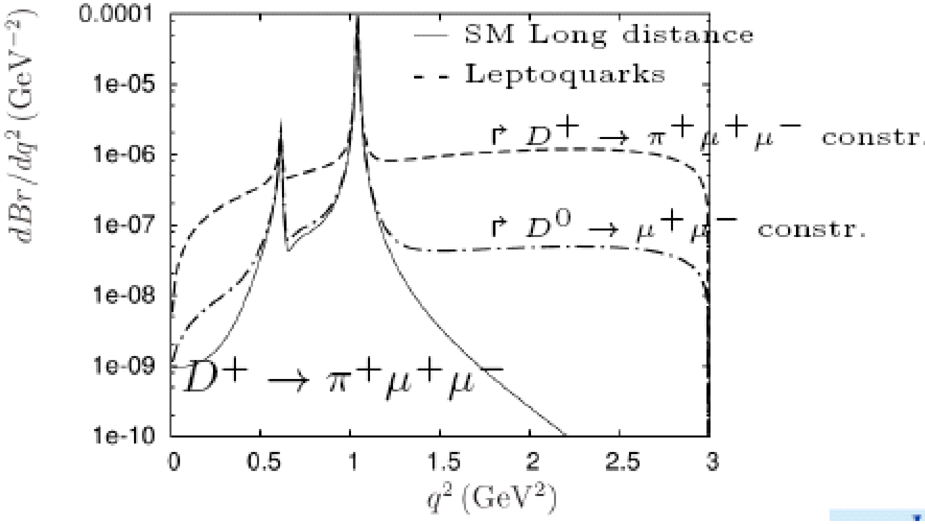
- Different new physics scenarios allow for enhancement of FCNC processes
- MSSM$\not{R}_p$ gives large contributions

  [Phys.Rev. D66 (2002) 014009]
- Leptoquarks can also contribute

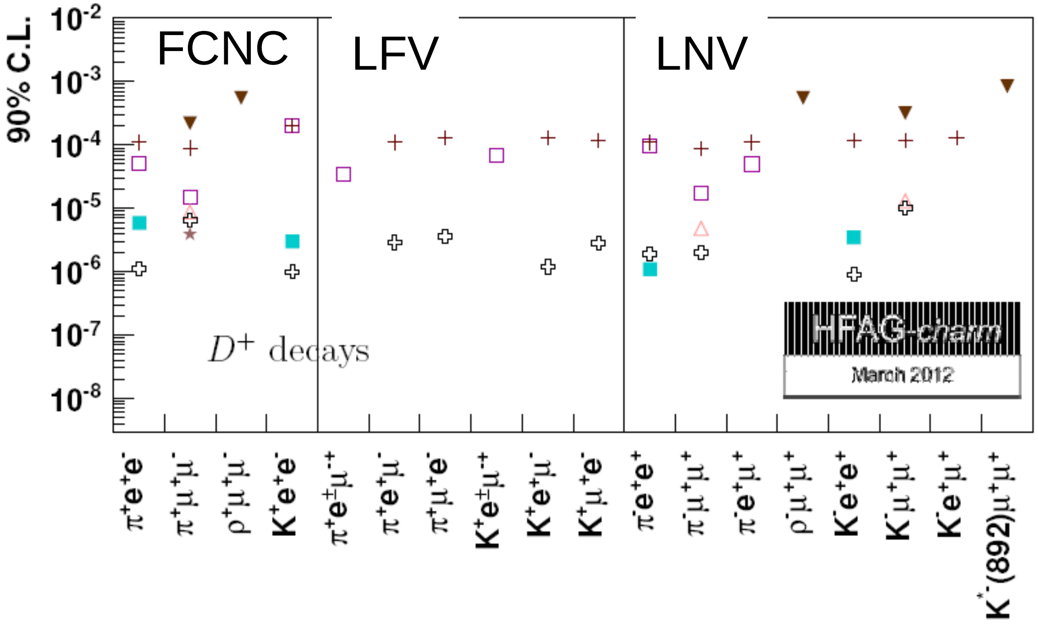
  [Phys.Rev. D79 (2009) 017502]
- For $D^0 \to \rho^0\mu^+\mu^-$ also forward backward asymmetry

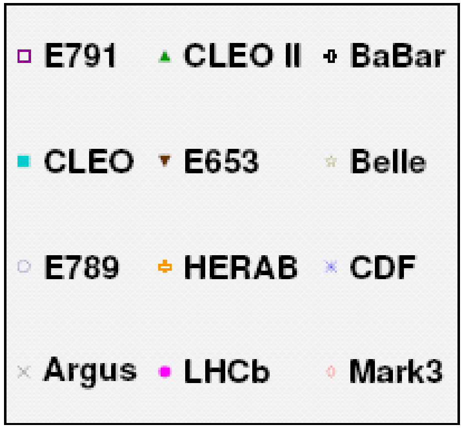


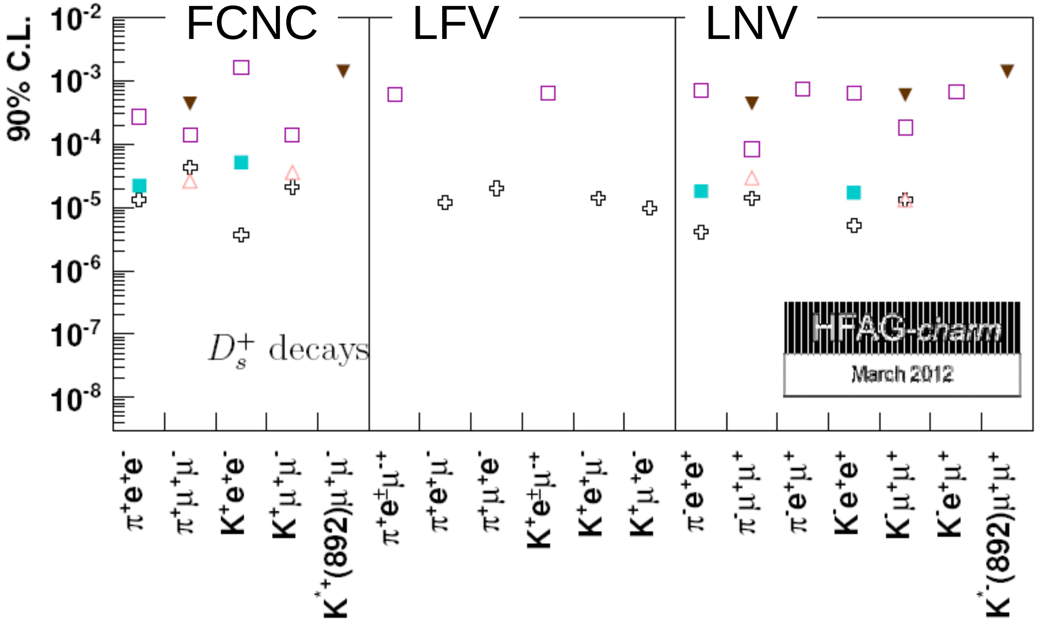


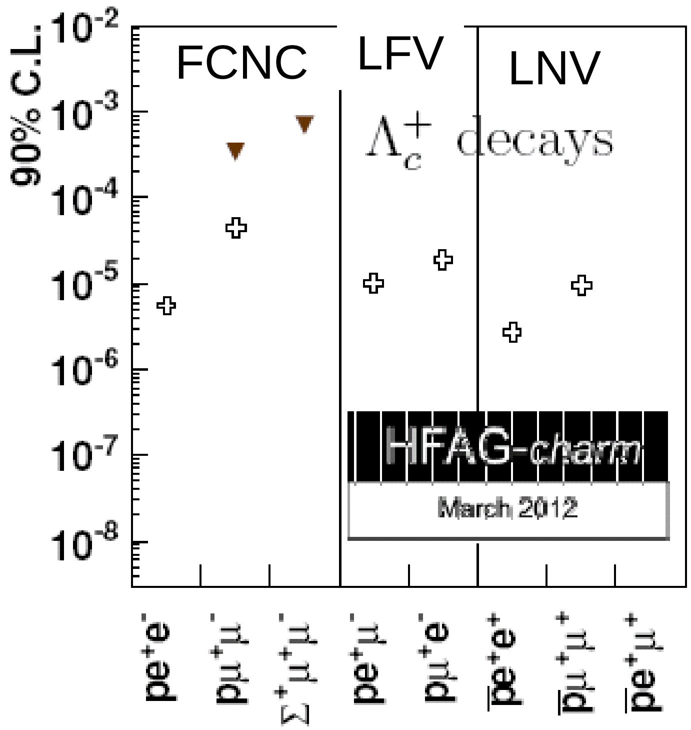


Overview of charm rare decays



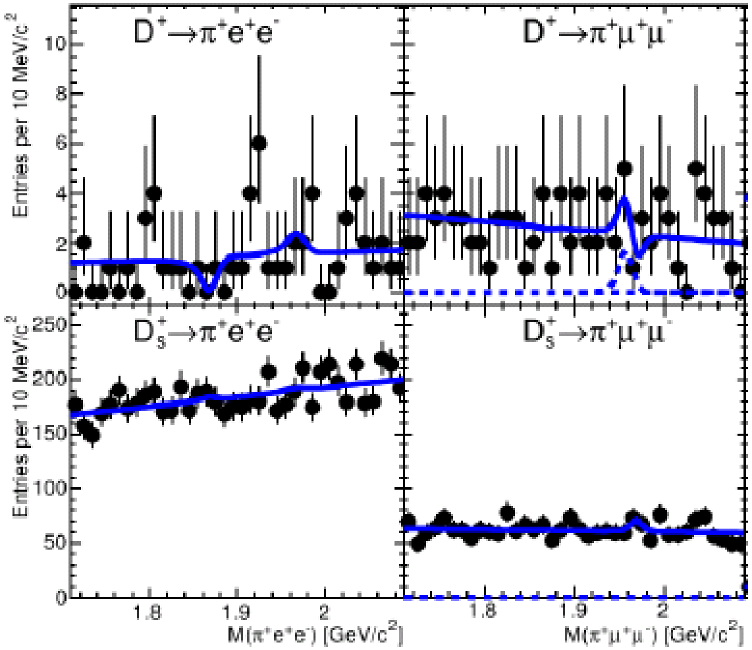


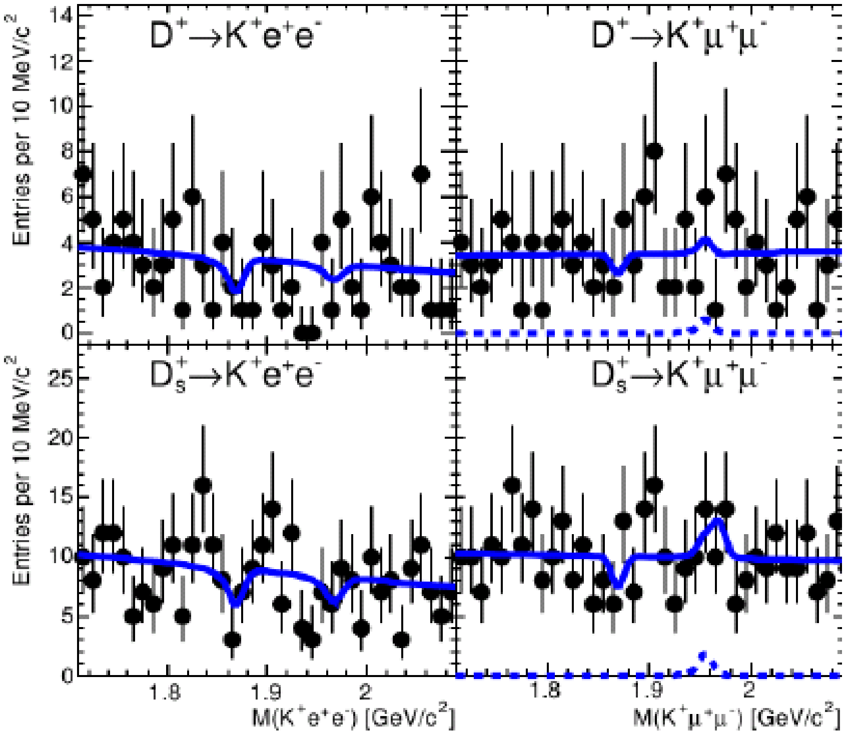


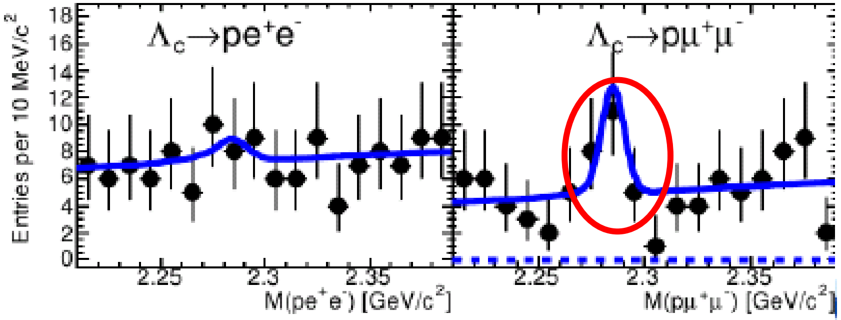


FCNC of charm from BABAR

[Phys.Rev. D84 (2011) 072006]







2.6 σ significance

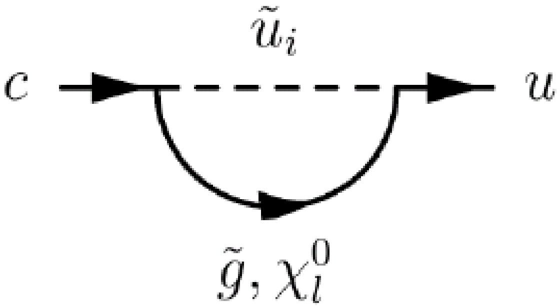
Decay	UL on $\mathcal{B}$ in 10^{-6} at 90% CL
$D^+\to\pi^+e^+e^-$	1.1
$D^+\to\pi^+\mu^+\mu^-$	6.5
$D_s^+\to\pi^+e^+e^-$	13
$D_s^+\to\pi^+\mu^+\mu^-$	43
$D^+\to K^+e^+e^-$	1.0
$D^+\to K^+\mu^+\mu^-$	4.3
$D_s^+\to K^+e^+e^-$	21
$D_s^+\to K^+\mu^+\mu^-$	14
$\Lambda_c^+\to pe^+e^-$	5.5
$\Lambda_c^+\to p\mu^+\mu^-$	44

$D^0 \to \gamma\gamma$

- SM short distance contribution at 3×10^{-11}
- Long distance contribution mainly due to Vector Meson Dominance, predicted to be [Phys.Rev. D66 (2002) 014009]

$$\mathcal{B}^{VMD}_{D^0\to\gamma\gamma} \simeq 3.5^{4.0}_{-2.6} \cdot 10^{-8}$$

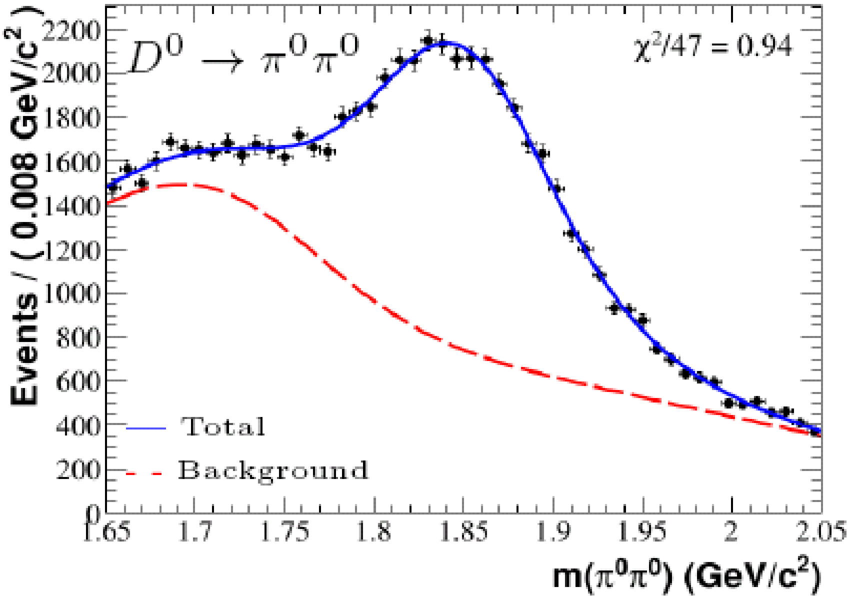
- However $c \to u\gamma$ process can be enhanced up to $6 \cdot 10^{-6}$ (200 times the SM) level in MSSM [Phys.Lett. B500 (2001) 304-312]

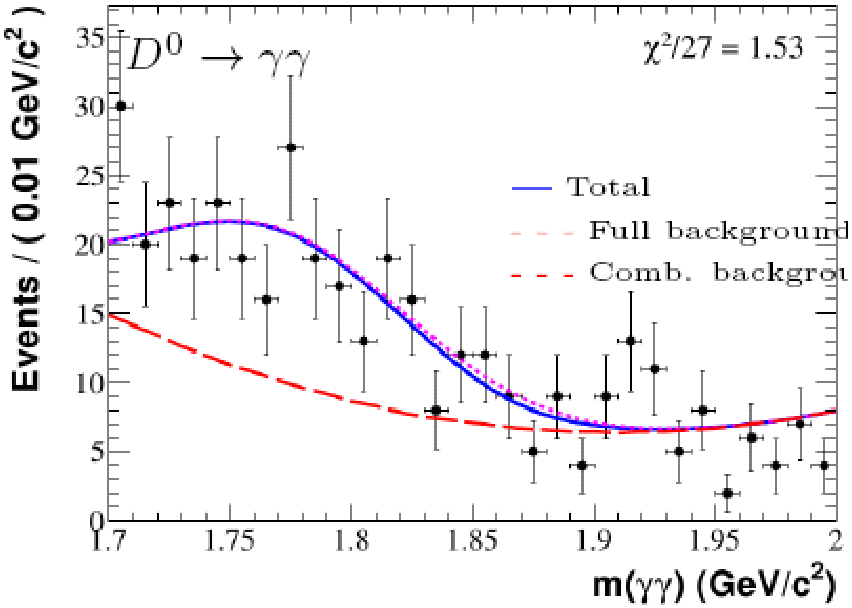


$D^0 \to \gamma\gamma$ at BaBar

Fit procedure:

- Unbinned maximum likelihood fit to invariant mass
- $D^0 \to \gamma\gamma$ signal: crystal ball and bifurcated gaussian
- Combinatorial background: 2^{nd} order Chebychev polynomial
- $D^0 \to \pi^0\pi^0$ background Crystal Ball function





Results:[BaBar submitted to Physical Revew D]
Measured a $D^0 \to \pi^0\pi^0$ branching fraction:

$$\mathcal{B}_{D^0 \to \pi^0\pi^0} = (8.4 \pm 0.1 \pm 0.3) \cdot 10^{-4}$$

For $D^0 \to \gamma\gamma$ found negative signal yield $N = -6 \pm 15$ events leading to an upper limit:

$$\mathcal{B}_{D^0 \to \gamma\gamma} < 2.2 \cdot 10^{-6} \quad \text{at90\%CL}$$

which is constraints NP to at most 70 times the SM.

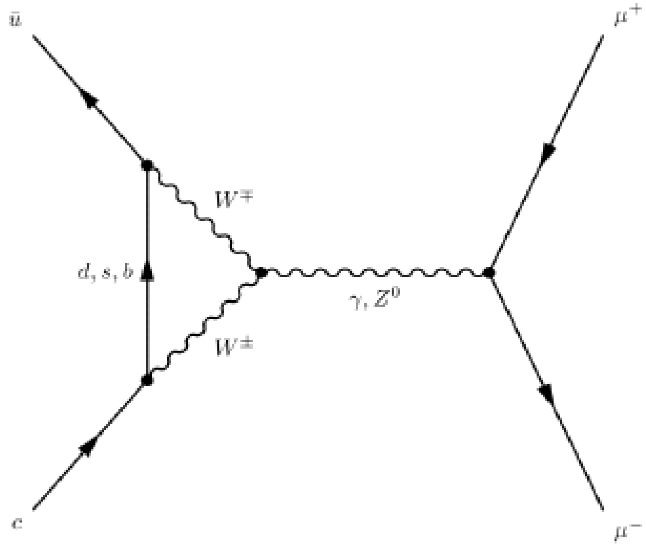
$D^0 \to \mu^+\mu^-$ decay: Standard Model

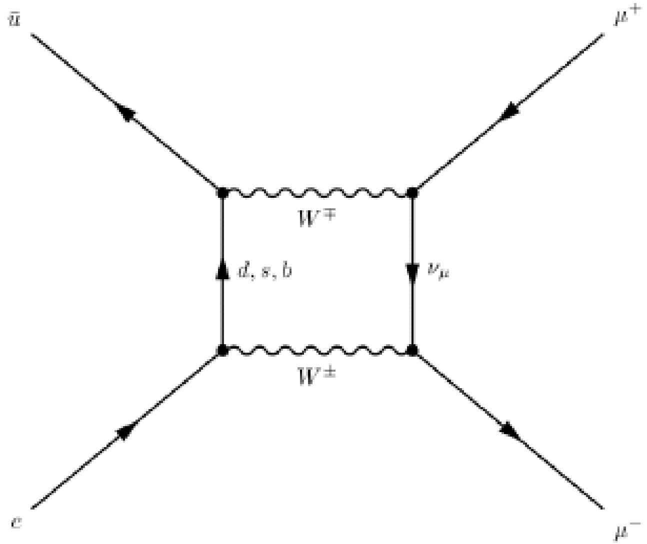
- Highly suppressed in the Standard Model. Short distance contribution $(D^0 \to \mu^+\mu^-) \simeq 10^{-18}$
- Dominated by long distance contribution in particular from $D^0 \to \gamma\gamma$: $\mathcal{B}(D^0 \to \mu^+\mu^-) \simeq 2.7 \times 10^{-5}\mathcal{B}(D^0 \to \gamma\gamma)$

  [Phys.Rev. D66 (2002) 014009]

  which gives an estimate: $\mathcal{B}(D^0 \to \mu^+\mu^-) \gtrsim 10^{-13}$
- Using BaBar upper limit: [BaBar 2011]: $\mathcal{B}(D^0 \to \gamma\gamma) < 2.2 \times 10^{-6}$ at 90% C.L. one could estimate an upper limit on this contribution of $\mathcal{B}(D^0 \to \mu^+\mu^-) \lesssim 6 \times 10^{-11}$

- $D^0 \to e^+e^-$ even more suppressed

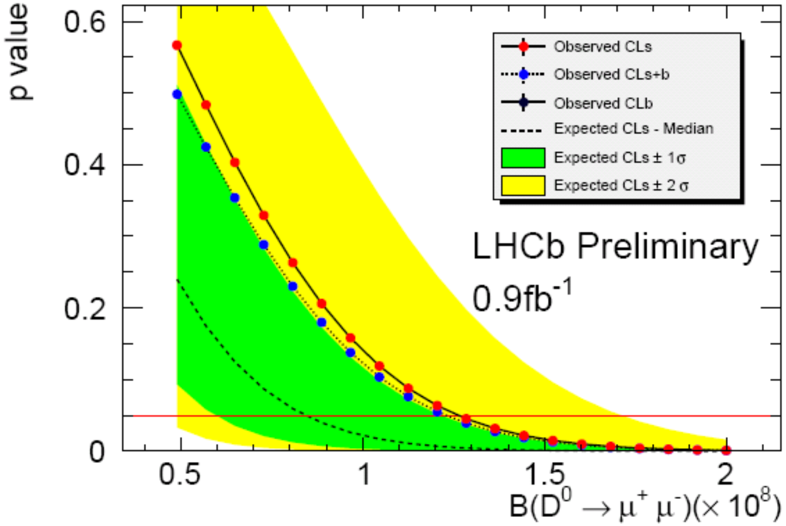


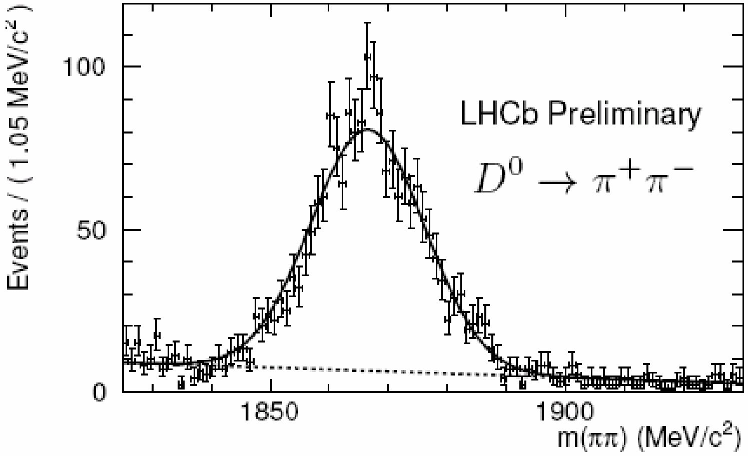


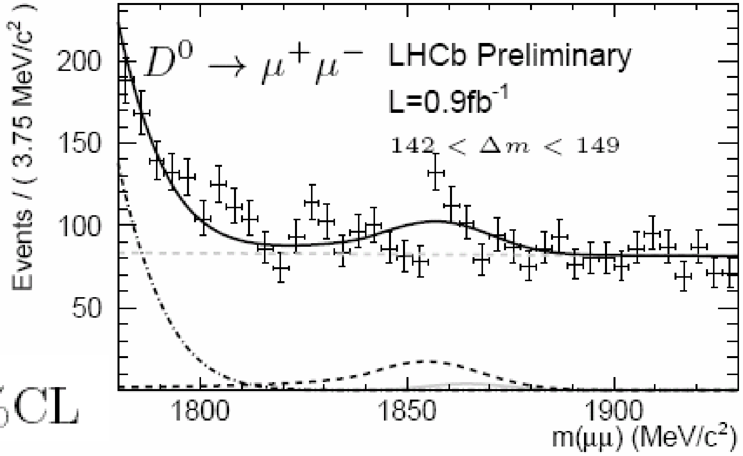
$D^0 \to \mu^+\mu^-$ at LHCb

- $0.9\ \text{fb}^{-1}$ of pp collisions at $\sqrt{s} = 7$ TeV were used
- An additional sample of $79\ \text{pb}^{-1}$ for background studies
- Monte Carlo generated samples with full detector simulation [LHCb-CONF-2012-005]

Normalization: $D^{*+} \to D^0(\to \pi^+\pi^-)\pi^+$ yield extracted with an unbinned extended two-dimensional fit in mass and Δm

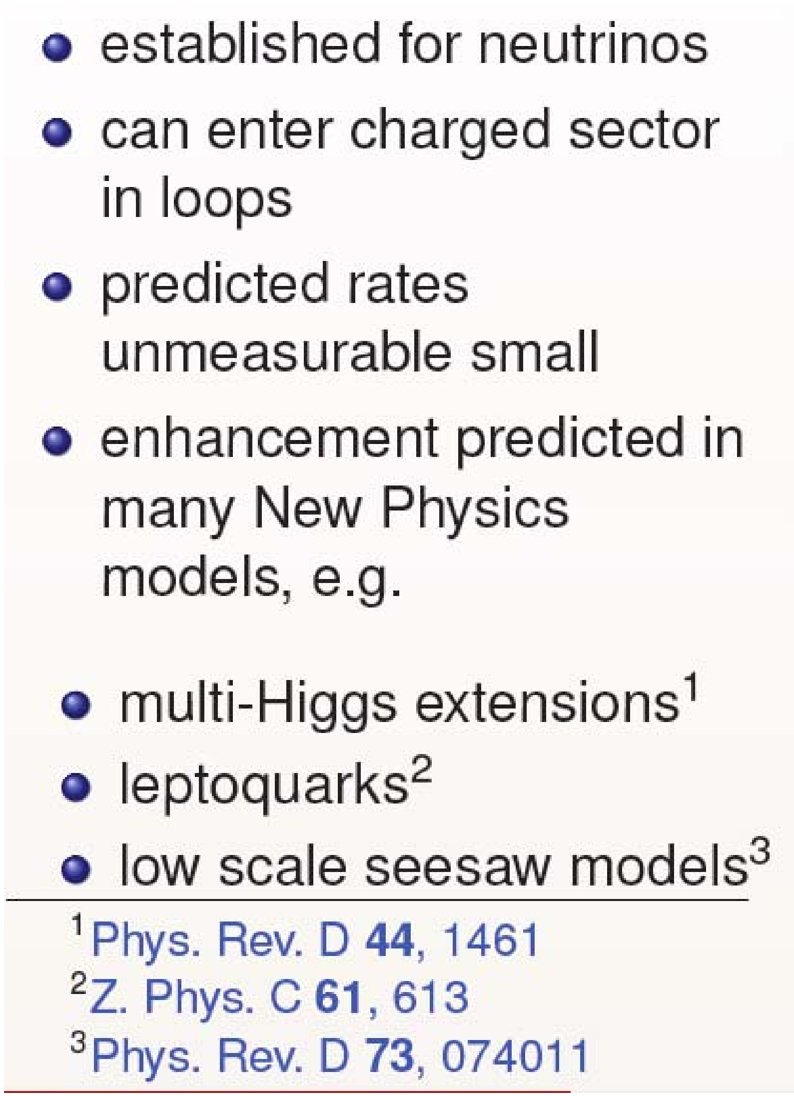






$$\mathcal{B}(D^0 \to \mu^+\mu^-) < 1.3\ (1.1) \cdot 10^{-8} \quad \text{at } 95\ (90)\%\text{CL}$$

LFV in charm decay



- established for neutrinos
- can enter charged sector in loops
- predicted rates unmeasurable small
- enhancement predicted in many New Physics models, e.g.
  - multi-Higgs extensions[1]
  - leptoquarks[2]
  - low scale seesaw models[3]

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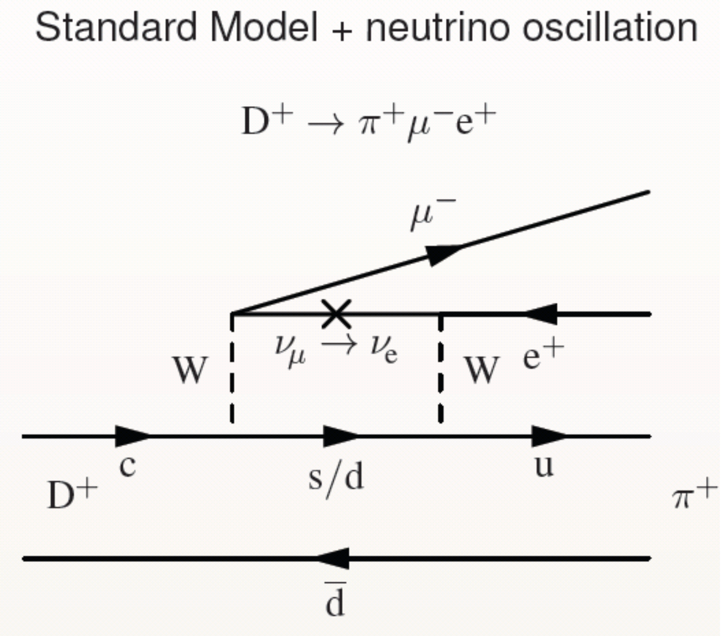
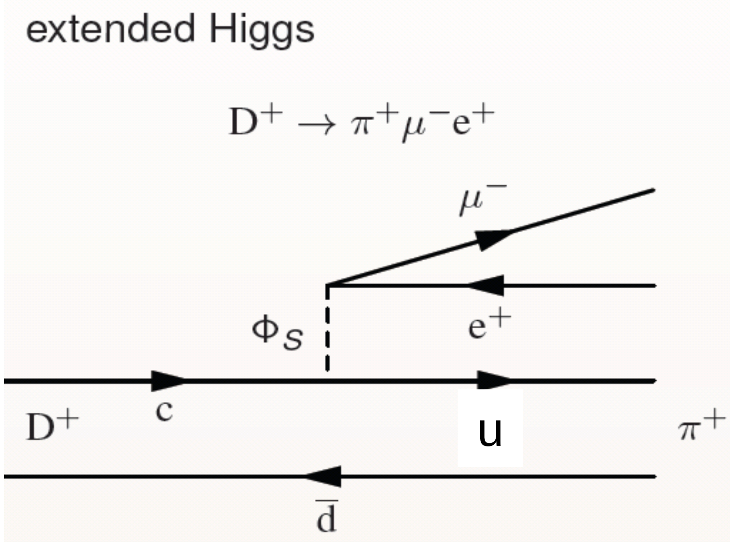
[1] Phys. Rev. D **44**, 1461

[2] Z. Phys. C **61**, 613

[3] Phys. Rev. D **73**, 074011

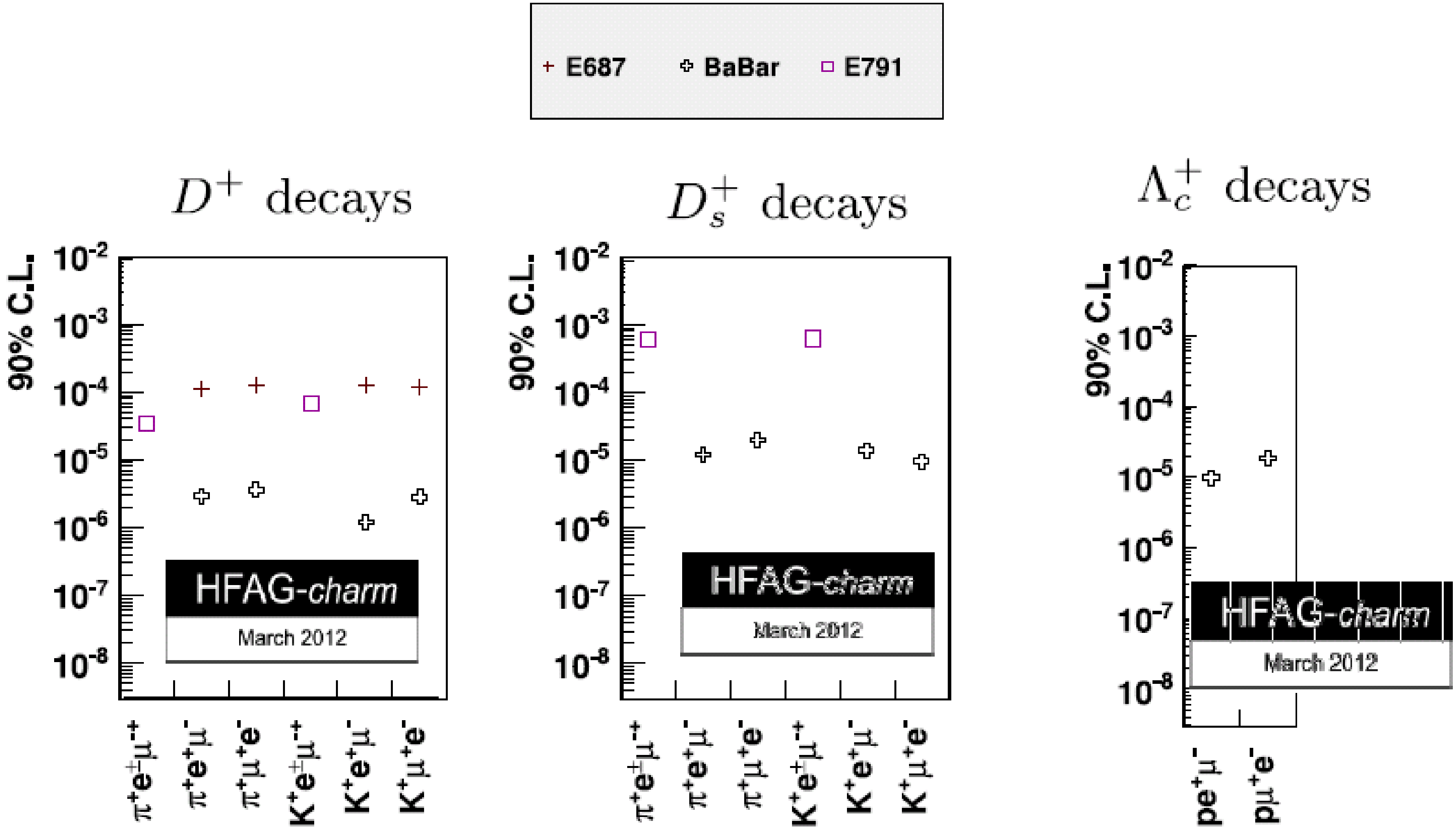


Standard Model + neutrino oscillation



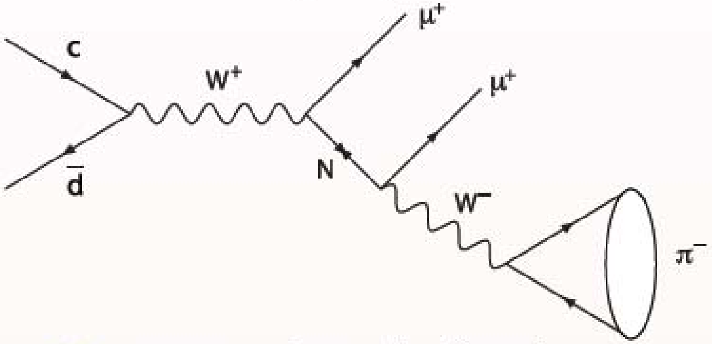
extended Higgs

Overview of LFV in charm

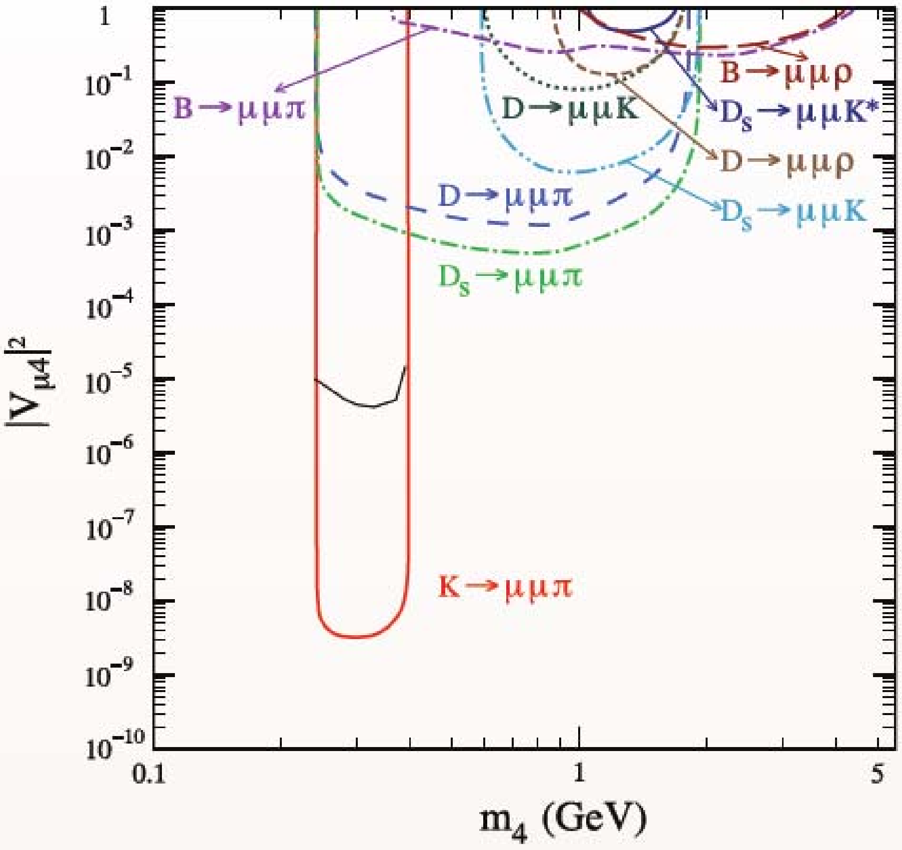


LNV in charm mesons

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



- resonant production in accessible mass range
- rates depend on Majorana neutrino–lepton coupling $|V_{\mu 4}|$ (e.g. arXiv:0901.3589)
- $m_4 = m_{\ell^-,\pi^+}$



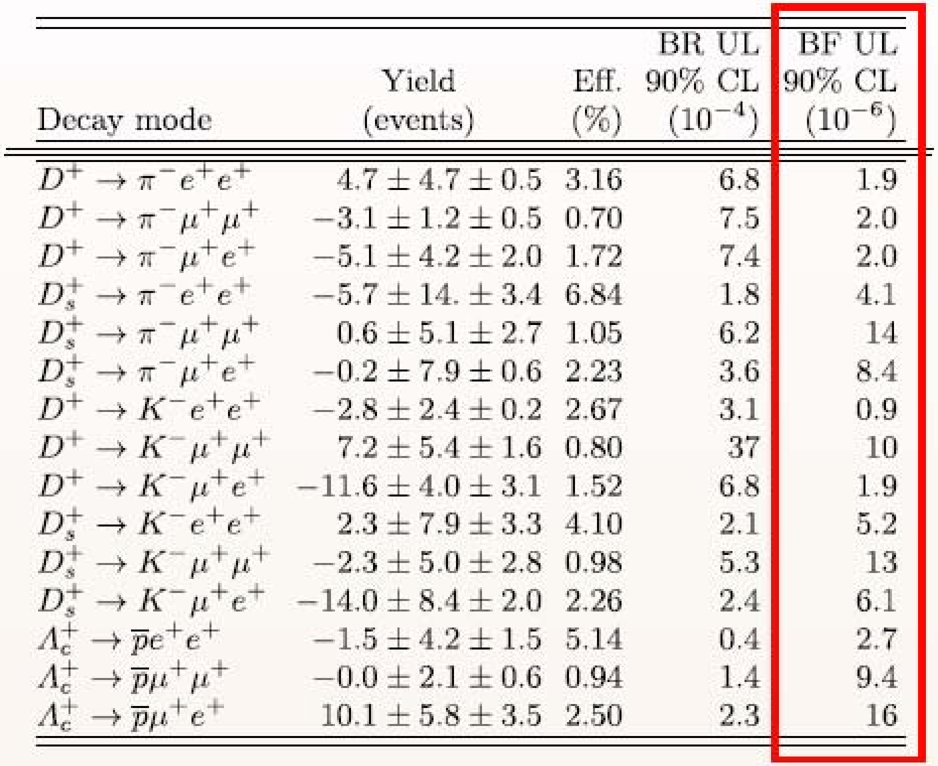
Status of 2009

arXiv:0901.3589

Limits on LNV in charm from BABAR

charm decays

- latest limits from BaBar
- includes Lepton Number and Flavour Violation
- comprehensive list of D^+, D_s^+, and Λ_c^+ decays



Decay mode	Yield (events)	Eff. (%)	BR UL 90% CL (10^{-4})	BF UL 90% CL (10^{-6})
$D^+ \to \pi^- e^+ e^+$	$4.7 \pm 4.7 \pm 0.5$	3.16	6.8	1.9
$D^+ \to \pi^- \mu^+ \mu^+$	$-3.1 \pm 1.2 \pm 0.5$	0.70	7.5	2.0
$D^+ \to \pi^- \mu^+ e^+$	$-5.1 \pm 4.2 \pm 2.0$	1.72	7.4	2.0
$D_s^+ \to \pi^- e^+ e^+$	$-5.7 \pm 14. \pm 3.4$	6.84	1.8	4.1
$D_s^+ \to \pi^- \mu^+ \mu^+$	$0.6 \pm 5.1 \pm 2.7$	1.05	6.2	14
$D_s^+ \to \pi^- \mu^+ e^+$	$-0.2 \pm 7.9 \pm 0.6$	2.23	3.6	8.4
$D^+ \to K^- e^+ e^+$	$-2.8 \pm 2.4 \pm 0.2$	2.67	3.1	0.9
$D^+ \to K^- \mu^+ \mu^+$	$7.2 \pm 5.4 \pm 1.6$	0.80	37	10
$D^+ \to K^- \mu^+ e^+$	$-11.6 \pm 4.0 \pm 3.1$	1.52	6.8	1.9
$D_s^+ \to K^- e^+ e^+$	$2.3 \pm 7.9 \pm 3.3$	4.10	2.1	5.2
$D_s^+ \to K^- \mu^+ \mu^+$	$-2.3 \pm 5.0 \pm 2.8$	0.98	5.3	13
$D_s^+ \to K^- \mu^+ e^+$	$-14.0 \pm 8.4 \pm 2.0$	2.26	2.4	6.1
$\Lambda_c^+ \to \overline{p} e^+ e^+$	$-1.5 \pm 4.2 \pm 1.5$	5.14	0.4	2.7
$\Lambda_c^+ \to \overline{p} \mu^+ \mu^+$	$-0.0 \pm 2.1 \pm 0.6$	0.94	1.4	9.4
$\Lambda_c^+ \to \overline{p} \mu^+ e^+$	$10.1 \pm 5.8 \pm 3.5$	2.50	2.3	16

Phys. Rev. D **84**, 072006 (2011)

Sensitivities for rare charm decay at BESIII and super-B

- **$D \to Xl^+l^-$ can be reached at 10^{-6} at BESIII**

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

BESIII may reach contribution from long distance

Sensitivities will be improved by order of two (10^{-8} -10^{-9}) at Super-B factories, and models can be tested.

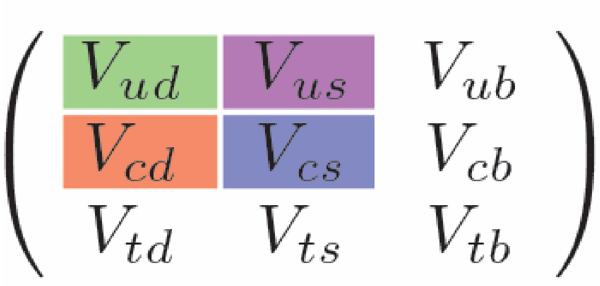
Questions

- **Can we measure $D^0 \to \nu\bar{\nu}$, or $\gamma\nu\bar{\nu}$?**
- **Can we measure $D \to K/\pi\nu\bar{\nu}$?**

Charm hadronic decays

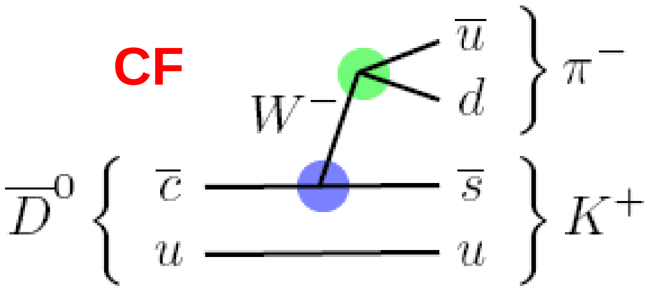
D hadronic decays

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

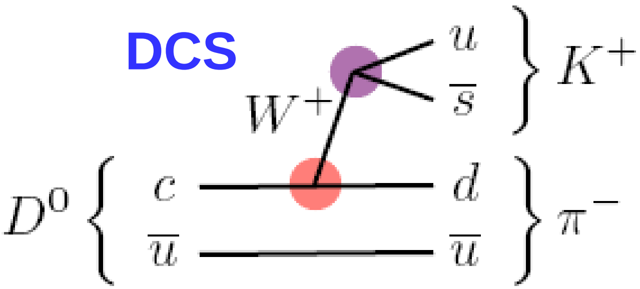


$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

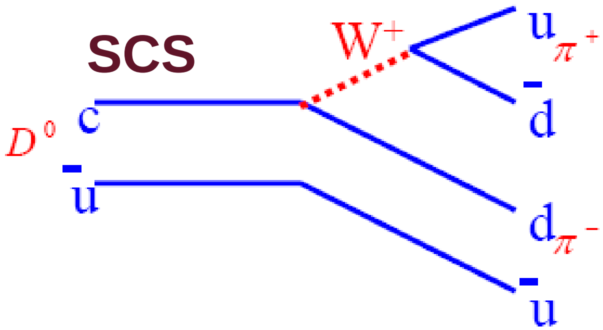
CF



DCS



SCS

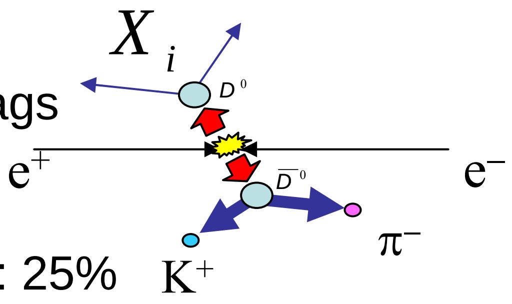


CF:SCS:DCS = 1: λ: λ^2

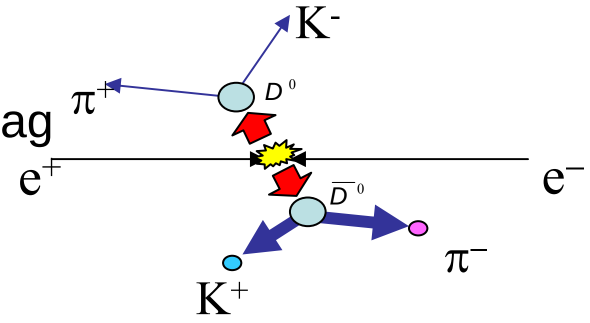
λ=tan(θc) = 0.2317
θc is Cabibbo angle

D tags

Single tags



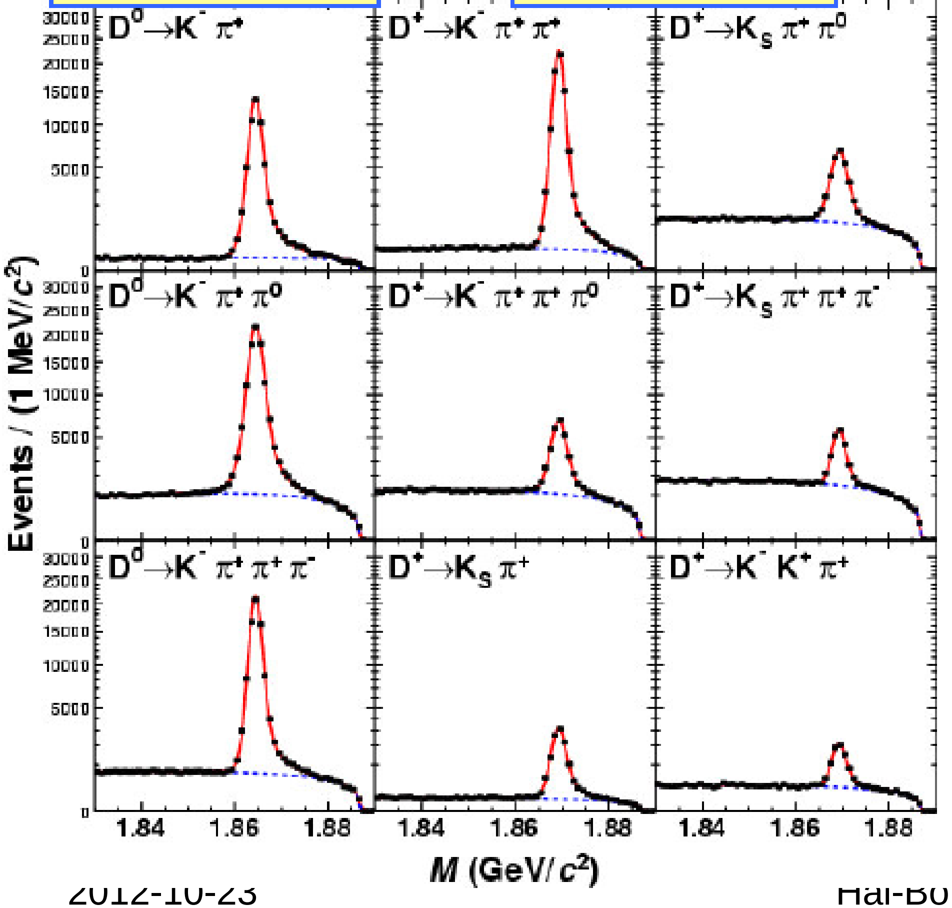
Double tag



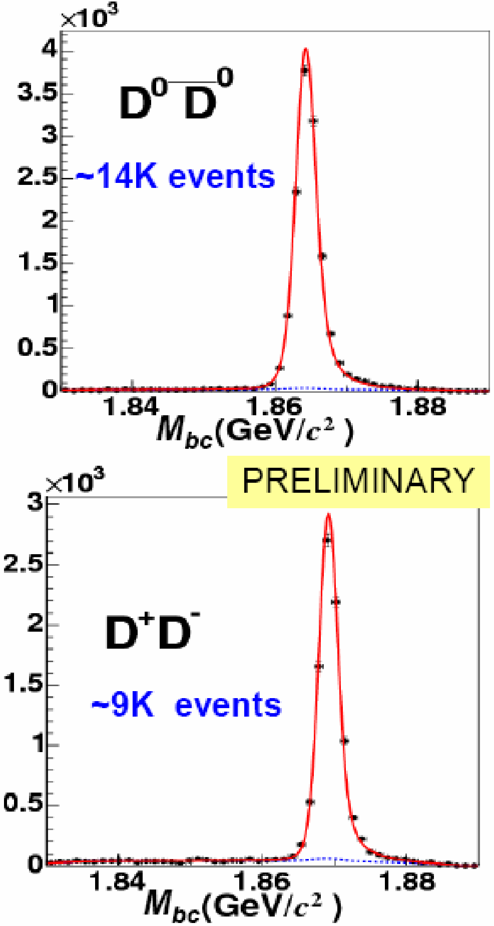
High net tag efficiency: 25%

D^0 / $\underline{D}^0$ ST: 230K

D^+/ D^- ST: 167K



Double tags in 281 pb^{-1}

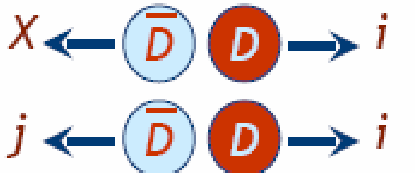


PRELIMINARY

Absolute branching fractions

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

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



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

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

Parameter	Fitted value	Fractional error Stat.(%)	 Syst.(%)	Δ_{FSR} (%)
$N_{D^0\bar{D}^0}$	$(1.031 \pm 0.008 \pm 0.013) \times 10^6$	0.8	1.3	+0.1
$\mathcal{B}(D^0 \to K^-\pi^+)$	$(3.891 \pm 0.035 \pm 0.059 \pm 0.035)\%$	0.9	1.8	−3.0
$\mathcal{B}(D^0 \to K^-\pi^+\pi^0)$	$(14.57 \pm 0.12 \pm 0.38 \pm 0.05)\%$	0.8	2.7	−1.1
$\mathcal{B}(D^0 \to K^-\pi^+\pi^+\pi^-)$	$(8.30 \pm 0.07 \pm 0.19 \pm 0.07)\%$	0.9	2.4	−2.4
$N_{D^+D^-}$	$(0.819 \pm 0.008 \pm 0.010) \times 10^6$	1.0	1.2	+0.1
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$	$(9.14 \pm 0.10 \pm 0.16 \pm 0.07)\%$	1.1	1.9	−2.3
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+\pi^0)$	$(5.98 \pm 0.08 \pm 0.16 \pm 0.02)\%$	1.3	2.8	−1.0
$\mathcal{B}(D^+ \to K^0_S\pi^+)$	$(1.526 \pm 0.022 \pm 0.037 \pm 0.009)\%$	1.4	2.5	−1.8
$\mathcal{B}(D^+ \to K^0_S\pi^+\pi^0)$	$(6.99 \pm 0.09 \pm 0.25 \pm 0.01)\%$	1.3	3.5	−0.4
$\mathcal{B}(D^+ \to K^0_S\pi^+\pi^+\pi^-)$	$(3.122 \pm 0.046 \pm 0.094 \pm 0.019)\%$	1.5	3.0	−1.9
$\mathcal{B}(D^+ \to K^+K^-\pi^+)$	$(0.935 \pm 0.017 \pm 0.024 \pm 0.003)\%$	1.8	2.6	−1.2

Quantity	Value
$\sigma(e^+e^- \to D^0\bar{D}^0)$	$(3.66 \pm 0.03 \pm 0.06)$ nb
$\sigma(e^+e^- \to D^+D^-)$	$(2.91 \pm 0.03 \pm 0.05)$ nb
$\sigma(e^+e^- \to D\bar{D})$	$(6.57 \pm 0.04 \pm 0.10)$ nb
$\sigma(e^+e^- \to D^+D^-)/\sigma(e^+e^- \to D^0\bar{D}^0)$	$0.79 \pm 0.01 \pm 0.01$

CLEO: PRD76(2007)112001

Typical branching fractions

From PDG2012

$$\mathrm{CF: BR(D^0} \to K^-\pi^+) = (3.89 \pm 0.05)\%$$

$$\mathrm{SCS: BR(D^0} \to \pi^+\pi^-) = (1.397 \pm 0.026) \times 10^{-3}$$

$$\mathrm{DCS: BR(D^0} \to K^+\pi^-) = (1.48 \pm 0.07) \times 10^{-4}$$

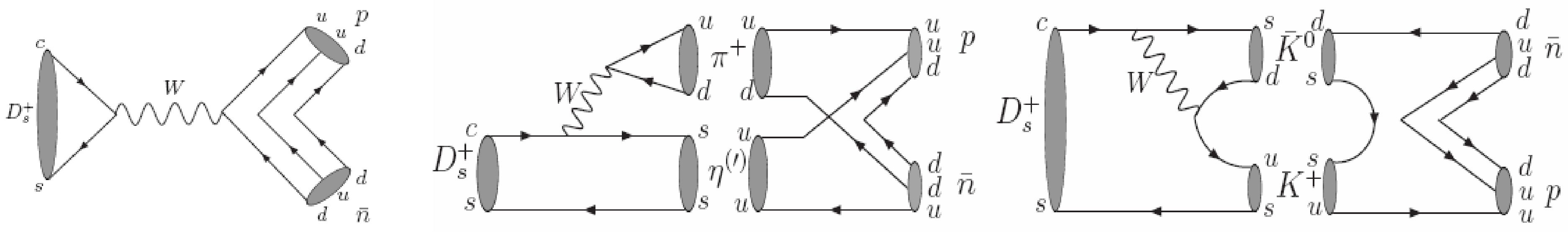
$$\frac{\mathrm{BR(D^0} \to \pi^+\pi^-)}{\mathrm{BR(D^0} \to K^-\pi^+)} = (3.59 \pm 0.07)\% \sim \lambda^2 = 5.3\%$$

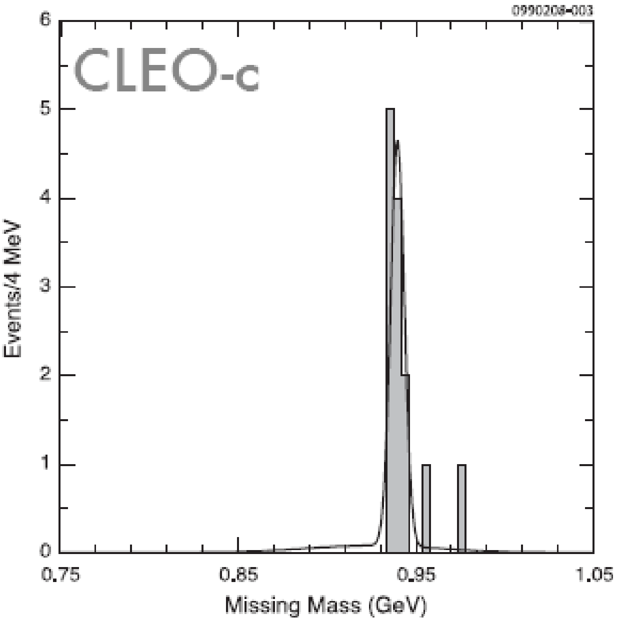
$$\frac{\mathrm{BR(D^0} \to K^+\pi^-)}{\mathrm{BR(D^0} \to K^-\pi^+)} \cong \frac{\mathrm{BR(D^0} \to K^+\pi^-)}{\mathrm{BR(\overline{D}^0} \to K^+\pi^-)} = (3.8 \pm 0.15) \times 10^{-3} \sim \lambda^4 = 2.8 \times 10^{-3}$$

It is interesting to access the relative phase (strong phase difference) between CF and DCS decays: $\mathrm{A}_{\mathrm{K}^+\pi^-} = A(\mathrm{D}^0 \to K^+\pi^-)$, $\overline{\mathrm{A}}_{\mathrm{K}^+\pi^-} = A(\overline{\mathrm{D}}^0 \to K^+\pi^-)$:

$$\frac{\mathrm{A}_{\mathrm{K}^+\pi^-}}{\overline{A}_{K^+\pi^-}} = -\sqrt{R_D}\,\mathrm{e}^{-\mathrm{i}\delta_{\mathrm{K}\pi}}, \quad \left|\frac{\mathrm{A}_{\mathrm{K}^+\pi^-}}{\overline{\mathrm{A}}_{\mathrm{K}^+\pi^-}}\right| \sim O(\tan^2\theta_c) = O(\lambda^2)$$

Ds→pnbar only mode to baryon pairs





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

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

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

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

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

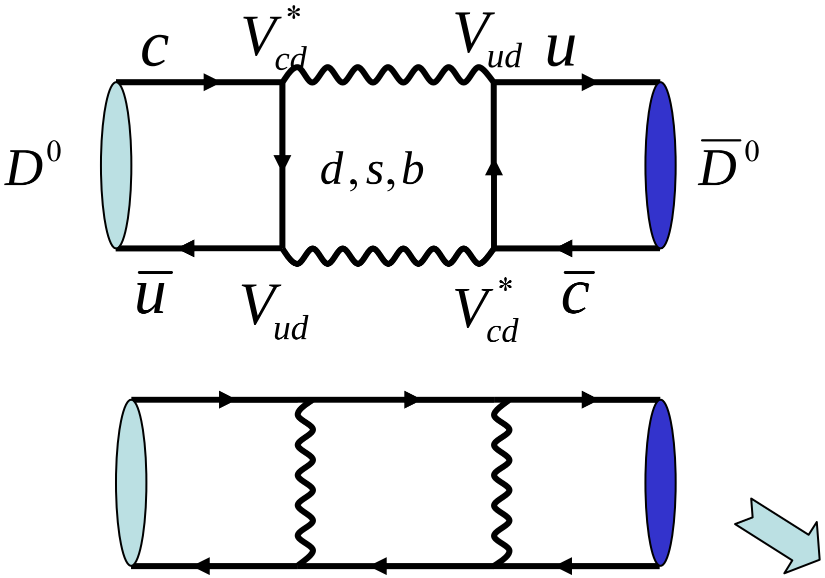
1) Introduction and general definitions

2) Time-dependent measurements of D^0—$\overline{D}^0$ mixing

3) Measurements of D^0 mixing at charm threshold

I Introduction

D^0 and $\overline{D}^0$ can transform into each under weak interaction



$$D^0 \rightleftarrows \overline{D}^0$$

D^0 and $\overline{D}^0$ can not be separated absolutely

- The D^0-$\overline{D}^0$ mixing occurs via loop diagrams involving intermediate down-type quarks, it provides unique information about weak interaction
- In the standard model, the mixing amplitude is quite small

It is severely suppressed by the GIM mechanisms

$$A \propto \sum_{i,j=d,s,b} f(m_i, m_j)(V_{ui}V_{ci}^*)(V_{uj}V_{cj}^*)$$

Loop-integration function

The b-quark contribution is highly suppressed by the CKM factor

λ=0.22

$$\begin{array}{c} \\ u \\ c \\ t \end{array} \quad V_{CKM} = \begin{array}{c} \begin{array}{ccc} d & \qquad\qquad s & \qquad\qquad b \end{array} \\ \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} \end{array} + O(\lambda^4)$$

The CKM suppression factor

$$|V_{ub}V_{cb}^{*}|/|V_{us}V_{cs}^{*}| = O(3\times 10^{-4})$$

The b-quark contribution in the loop diagram can be neglected

- Thus, the mixing in D^0 system involves only the first two generations. CP violation is absent in both the mixing and decay amplitudes, and therefore can be neglected.
- The mixing amplitude vanishes in the limit of SU(3) flavor symmetry , $m_s=m_d$, due to the GIM suppression.
- Mixing is only the effect of SU(3) breaking

$$T_{mixing} \sim \sin^2\theta_C \times [SU(3)\ \text{breaking}]$$

II The basic formulas

In general the neutral D meson exists as a mixture state of D^0 and $\overline{D}^0$

$$\left|D\right\rangle = a\left|D^0\right\rangle + b\left|\overline{D}^0\right\rangle$$

Assume there is a neutral D state at t=0:

$$\left|\psi(0)\right\rangle = a(0)\left|D^0\right\rangle + b(0)\left|\overline{D}^0\right\rangle$$

Then at any time t, the state evolves into

$$\left|\psi(t)\right\rangle = \underbrace{a(t)\left|D^0\right\rangle + b(t)\left|\overline{D}^0\right\rangle}_{\text{Oscillation within neutral D state}} + \underbrace{c_1(t)\left|f_1\right\rangle + c_2(t)\left|f_2\right\rangle + \cdots}_{\text{States D decays into}}$$

If we only consider the oscillation within the neutral D state, then we can consider the evolution of the following state

$$\left|D(t)\right\rangle = a(t)\left|D^0\right\rangle + b(t)\left|\overline{D}^0\right\rangle$$

which can be written in the form of matrix product

$$D(t) = \begin{pmatrix} D^0 & \overline{D}^0 \end{pmatrix} \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

then we can use $\begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$ to stand for the wave

function of the neutral D meson state

The Shrödinger equation for the evolution of the wave function is

$$i\frac{\partial}{\partial t}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = H\begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

2×2

H needs not be Hermite because D meson can decay in the evolution

$$H \equiv M - \frac{i}{2}\Gamma$$

$M^{+} = M$

$\Gamma^{+} = \Gamma$

$$H = \frac{H + H^{+}}{2} + \frac{H - H^{+}}{2}$$

M

$-\frac{i}{2}\Gamma$

The matrix H expressed explicitly in term of the matrix elements

$$H = \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{21} - \frac{i}{2}\Gamma_{21} & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}$$

The matrix elements are determined by the Hamiltonians of strong, electromagnetic and weak interactions

$$H_{total} = H_{st} + H_{em} + H_{w}$$

The magnitude of weak interaction is greatly smaller than the strong and electromagnetic interaction

$$H_{w} << H_{st} + H_{em}$$

The eigen-equation

$$\begin{pmatrix} M_{11}-\frac{i}{2}\Gamma_{11} & M_{12}-\frac{i}{2}\Gamma_{12} \\ M_{21}-\frac{i}{2}\Gamma_{21} & M_{22}-\frac{i}{2}\Gamma_{22} \end{pmatrix}\begin{pmatrix} a \\ b \end{pmatrix}=\mu\begin{pmatrix} a \\ b \end{pmatrix}$$

Solve the equation, one can get the eigenvalues and eigenfunctions

$$\mu_{1,2}=\frac{1}{2}[M_{11}+M_{22}-\frac{i}{2}(\Gamma_{11}+\Gamma_{22})$$

$$\mp\sqrt{(\delta m-\frac{i}{2}\delta\Gamma)^2+4(M_{12}-\frac{i}{2}\Gamma_{12})(M_{21}-\frac{i}{2}\Gamma_{21})}]$$

$\delta m \equiv M_{11}-M_{22}$

$\delta\Gamma \equiv \Gamma_{11}-\Gamma_{22}$

Theorems:

① If CPT is conserved, then M_{11}=M_{22}, and $\mathit{\Gamma}_{11}$= $\mathit{\Gamma}_{22}$.

② If T is conserved, then $\frac{\mathit{\Gamma}_{12}^{*}}{\mathit{\Gamma}_{12}}=\frac{M_{12}^{*}}{M_{12}}$

The real parts of $\mu_{1,2}$ are masses m_1 and m_2 of the two eigenstates

The imaginary parts are decay widths of the two eigenstates: Γ_1, and Γ_2

That is

$$\mu_{1,2} \equiv m_{1,2} - \frac{i}{2}\Gamma_{1,2}$$

If CPT is conserved:

Then

$$|D_1\rangle = p|D^0\rangle + q|\overline{D}^0\rangle$$

$$\mu_1 = m_1 - \frac{i}{2}\Gamma_1$$

$$|D_2\rangle = p|D^0\rangle - q|\overline{D}^0\rangle$$

$$\mu_2 = m_2 - \frac{i}{2}\Gamma_2$$

$$\frac{q}{p} = \sqrt{\frac{M_{21} - \frac{i}{2}\Gamma_{21}}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

p and q satisfy the normalization condition

$$p^2 + q^2 = 1$$

III The mixing parameters

Two physical parameters that characterize the mixing are

$$x \equiv \frac{\Delta m}{\Gamma} = \frac{m_2 - m_1}{\Gamma}$$

$$y \equiv \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$

Where Γ is the average decay widths of the two eigenstates D_1 and D_2

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

Short distance contributions to the D^0 mixing

Numerically, the box diagram contribution to the mixing rate:

$$\Delta m_D^{\text{box}} \approx 2.5 \times 10^{-17}\ \text{GeV}$$

which leads to

$$x^{\text{box}} \approx 1.6 \times 10^{-5}$$

The bare quark loop contribution to $\Delta\Gamma$ is even further suppressed by additional powers of m_s / m_c

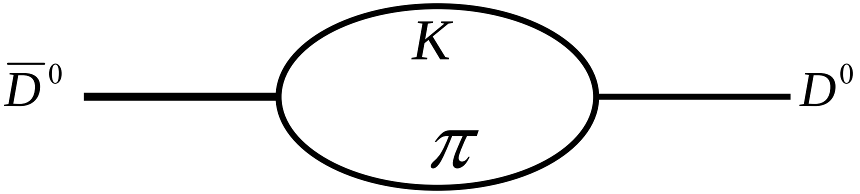
Numerically, one finds

$$y^{\text{box}} \sim \text{few} \times 10^{-7}$$

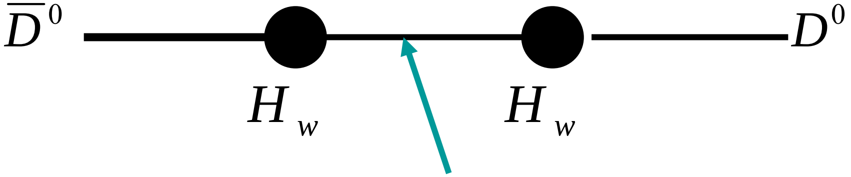
Long distance contributions to the D^0 mixing

The small result of box diagram can be enhanced by various long-distance effects, or by contributions of higher-dimension operator in the OPE

Long-distance effects



$$\pi\pi,\ KK,\ K\pi\pi,\ K\pi\pi\pi,\ K\pi\pi\pi\pi,\ etc.$$



$$K(1460),\ \eta(1760),\ \pi(1800),\ K(1830),\cdots$$

Long-distance contributions can severely enhance the mixing parameters, although it is difficult to calculate them accurately.

It is estimated that long-distance dynamics can enhance the mixing parameters to be

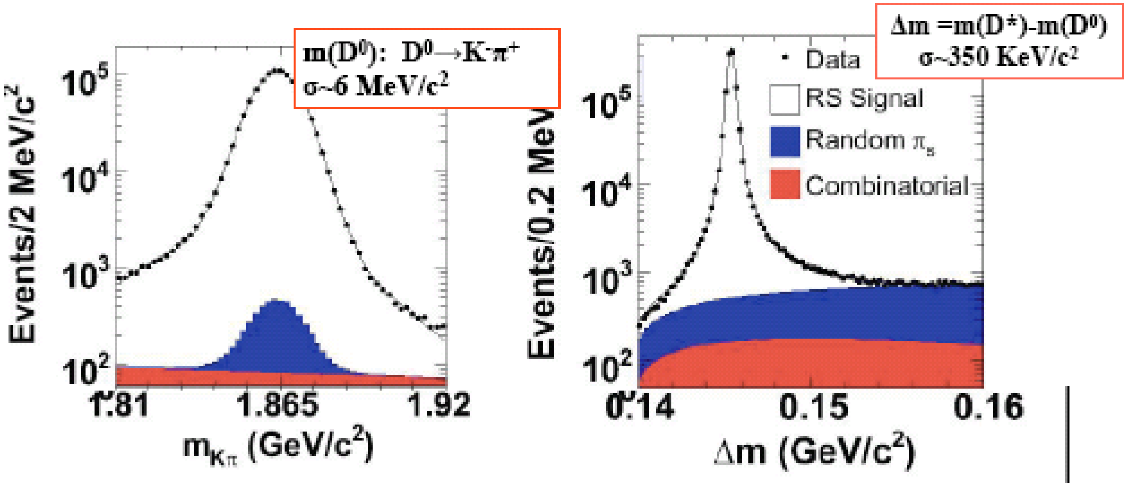
$$x,\ \ y \sim 10^{-4} - 10^{-3}$$

J.F. Donoghue et.al, Phys. Rev. D33, 179 (1986)

E. Golowich, A.A. Petrov, Phys. Lett. B427, 172 (1998)

Time-dependent results from B factories : BABAR, Belle CDF and D0

Selection of D^0 mesons



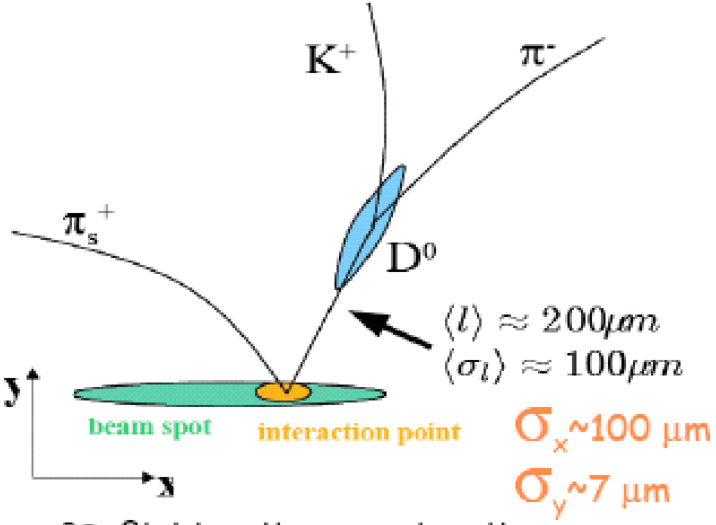
$m(D^0)$: $D^0 \to K^-\pi^+$
σ~6 MeV/c^2

$\Delta m = m(D^*) - m(D^0)$
σ~350 KeV/c^2

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.



σ_x~100 μm
σ_y~7 μm

3D flight path reconstruction

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

		Note:
$D^0 \to K^+\pi^-$	★ BELLE ★ CDF II	*study of the time dependence* See backup slides.
$D^0 \to K^+K^-, \pi^+\pi^-$	★ ★ 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*
$D^0 \to K^+\pi^-\pi^0$	★	*time-dependent Dalitz plot analysis*
$D^0 \to K^0_S\pi^+\pi^-$	New BELLE	*time-dependent Dalitz plot analysis*
$D^0 \to K^0_S K^+K^-$	New	*time-dependent Dalitz plot analysis*
$D^0 \to K^{(*)}l\nu$	BELLE	*time-integrated analysis* Not covered in this talk

Legend: ★ = mixing evidence $> 3\sigma$

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 $D^0 \rightarrow K^+\pi^-$ decays

Remind: right sign-> Cabibbo-favord 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 $(|x| \ll 1, |y| \ll 1)$:

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

$$\begin{tikzcd}
D^0 \arrow[rr, bend left, "DCS"] \arrow[dr, "MIX"'] & & K^+\pi^- \\
& \overline{D}^0 \arrow[ur, "CF"'] &
\end{tikzcd}$$

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

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

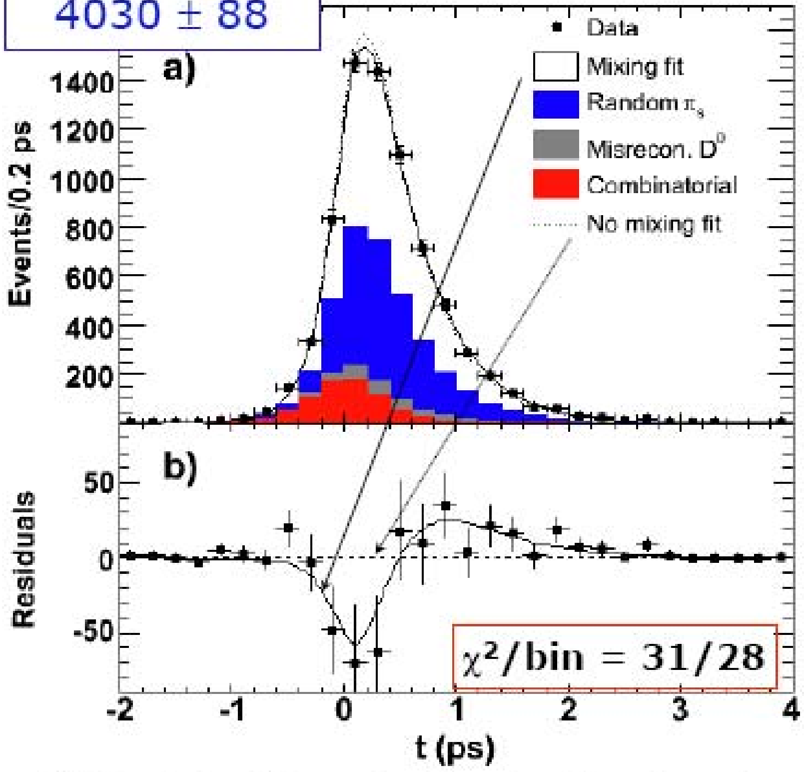
$$x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi} \qquad y' = -x\sin\delta_{K\pi} + y\cos\delta_{K\pi}$$

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

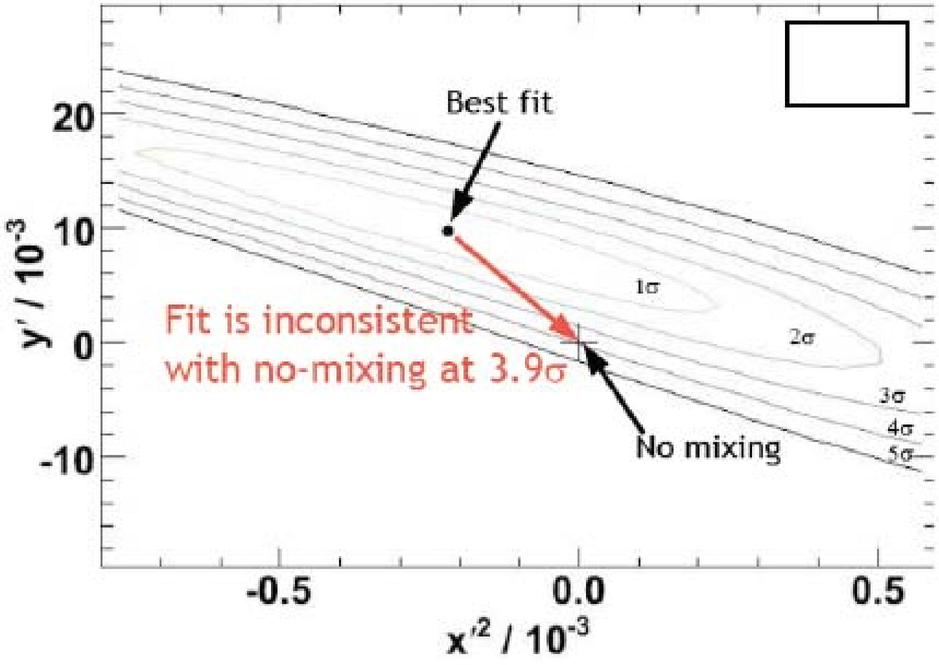
WS time fit: evidence of mixing at 3.9σ

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

Fitted signal
4030 ± 88



WS *mixing* fit projection in signal region
$1.843\ \mathrm{GeV}/c^2 < m_D < 1.883\ \mathrm{GeV}/c^2$
$0.1445\ \mathrm{GeV}/c^2 < \Delta m < 0.1465\ \mathrm{GeV}/c^2$



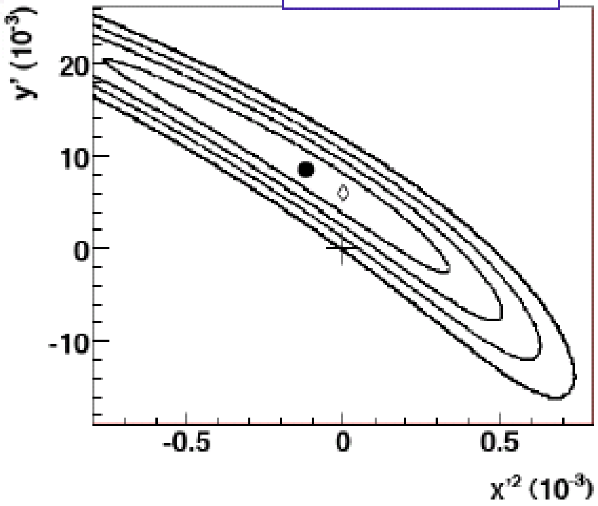
R_D: $(3.03 \pm 0.16 \pm 0.10) \times 10^{-3}$
x'^2: $(-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$
y': $(9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$

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

Belle & CDF measurements

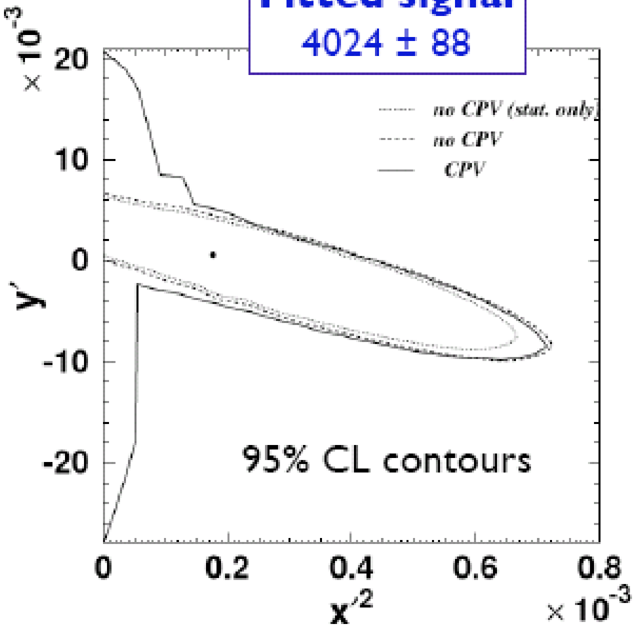
CDF: PRL 100:121802,2008 (1.5fb^{-1})

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

Evidence of mixing at 3.8σ

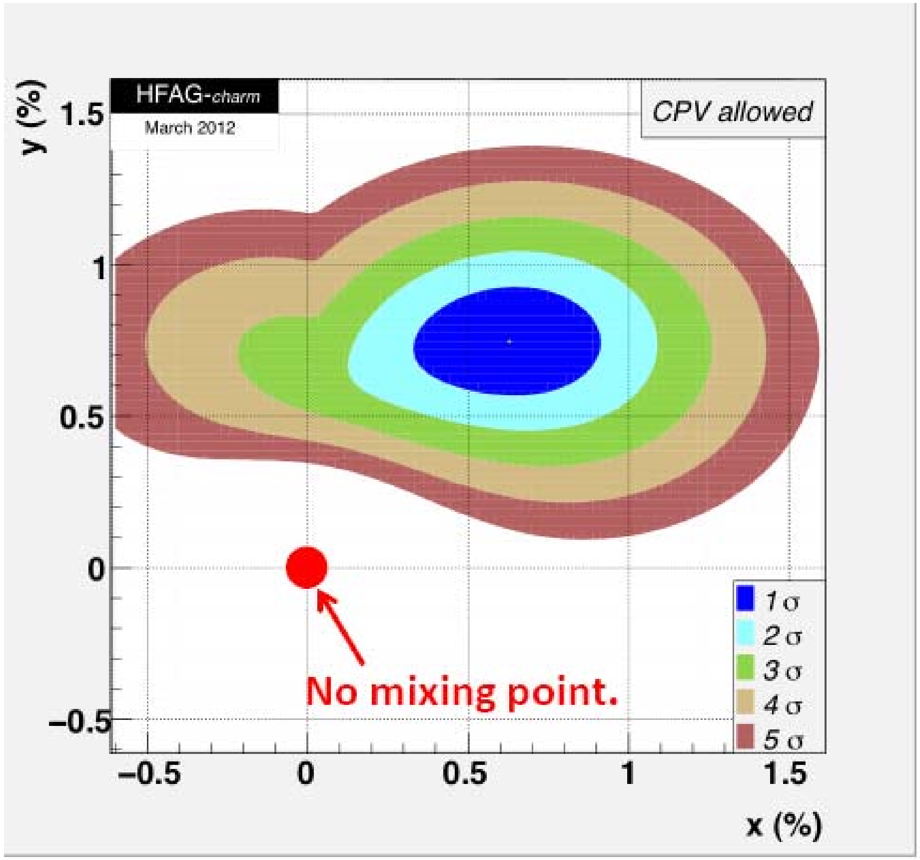
36

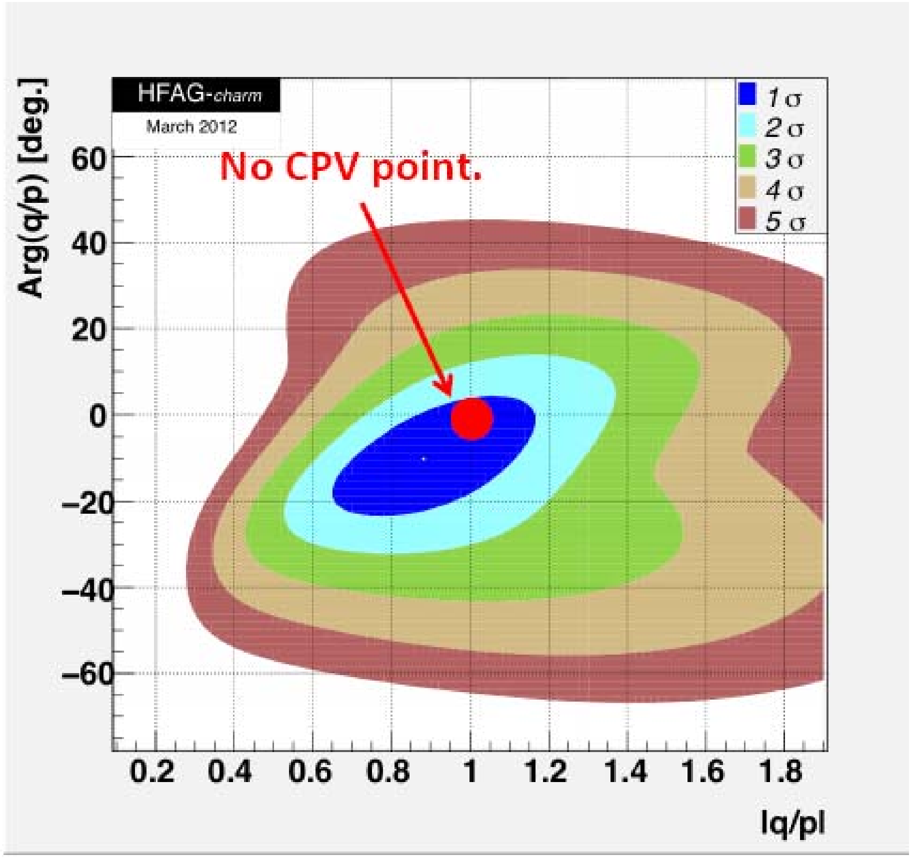
$$x'^2 = (0.18^{+0.21}_{-0.23}) \times 10^{-3}$$

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

No mixing point at 2σ

HFAG 2012 averaged results





World average (mixing):

$x = (0.63 \pm 0.19)\%$

$y = (0.75 \pm 0.12)\%$

World average (CPV): **CPV in mixing**

$|q/p| = (0.88 \pm 0.17)$

$\phi = (-10.3 \pm 9.2)^\circ$

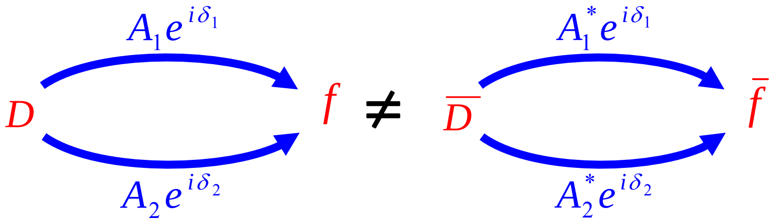
➔ **No-mixing excluded at > 10 σ; no CPV consistent within 1 σ.**

CP violation in charm

Three types of CP violation in meson

$$\langle f|H|D^0\rangle = A_f \quad \langle f|H|\overline{D}^0\rangle = \overline{A}_f$$
$$f = K\pi, KK, \pi\pi, \text{etc.}$$

1. in the decay (direct):



$$\left|\frac{\overline{A}_{\bar{f}}}{A_f}\right| \neq 1 \quad \Longrightarrow \text{CPV}$$

2. in mixing (indirect):

$$D^0 \Rightarrow \overline{D}^0 \neq \overline{D}^0 \Rightarrow D^0$$

$$r_m = \left|\frac{q}{p}\right| \neq 1 \quad \Longrightarrow \text{CPV}$$

3. in the interference between mixing and decay (indirect):

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

strong phase

weak phase

$$\varphi_f \neq 0 \quad \Longrightarrow \text{CPV}$$

$\varphi_f \equiv \varphi$ if no weak phase in the decay amplitude

2 weak amplitudes with phase difference

Direct CP violation

In SM Direct CPV only for Singly Cabibbo suppressed decays.

$$Acp \approx \frac{\mathrm{Im}\left[V_{cd}V_{ud}^{*}V_{cs}V_{us}^{*}\right]}{\lambda^{2}}\sin\delta_{PT}\frac{P}{T} \equiv A^{2}\eta\lambda^{4}\sin\delta_{PT}\frac{P}{T} \leq 10^{-3}$$

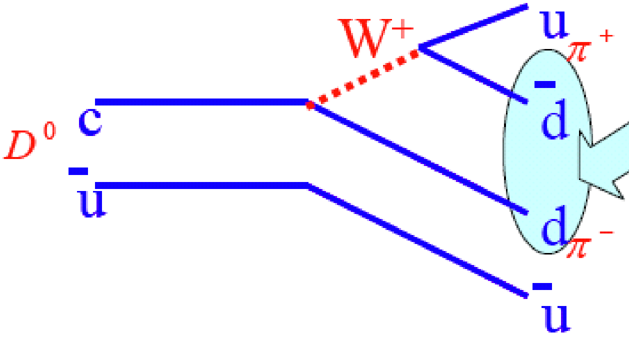
Standard Model Contribution $A_{CP} \sim 10^{-3}$

New Physics up to ~1%

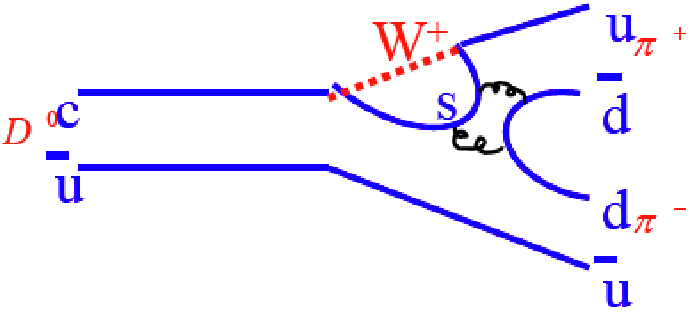
If CP~1% observed:is it NP or hadronic enhancement of SM? Strategy: analyze many channels to elucidate source of CPV.

1) Consider $D^0 \rightarrow \pi^+\pi^-$

(same for K^+K^-, $K^+K^-\pi^+$, $\phi\pi^+$, K^*K $K^+K^-\pi^0$, $\pi^+\pi^-\pi^+$, $\pi^+\pi^-\pi^0$, etc...)



Since this decay is Singly Cabibbo Suppressed…



…we can modify it's topology in a simple way to get a penguin.

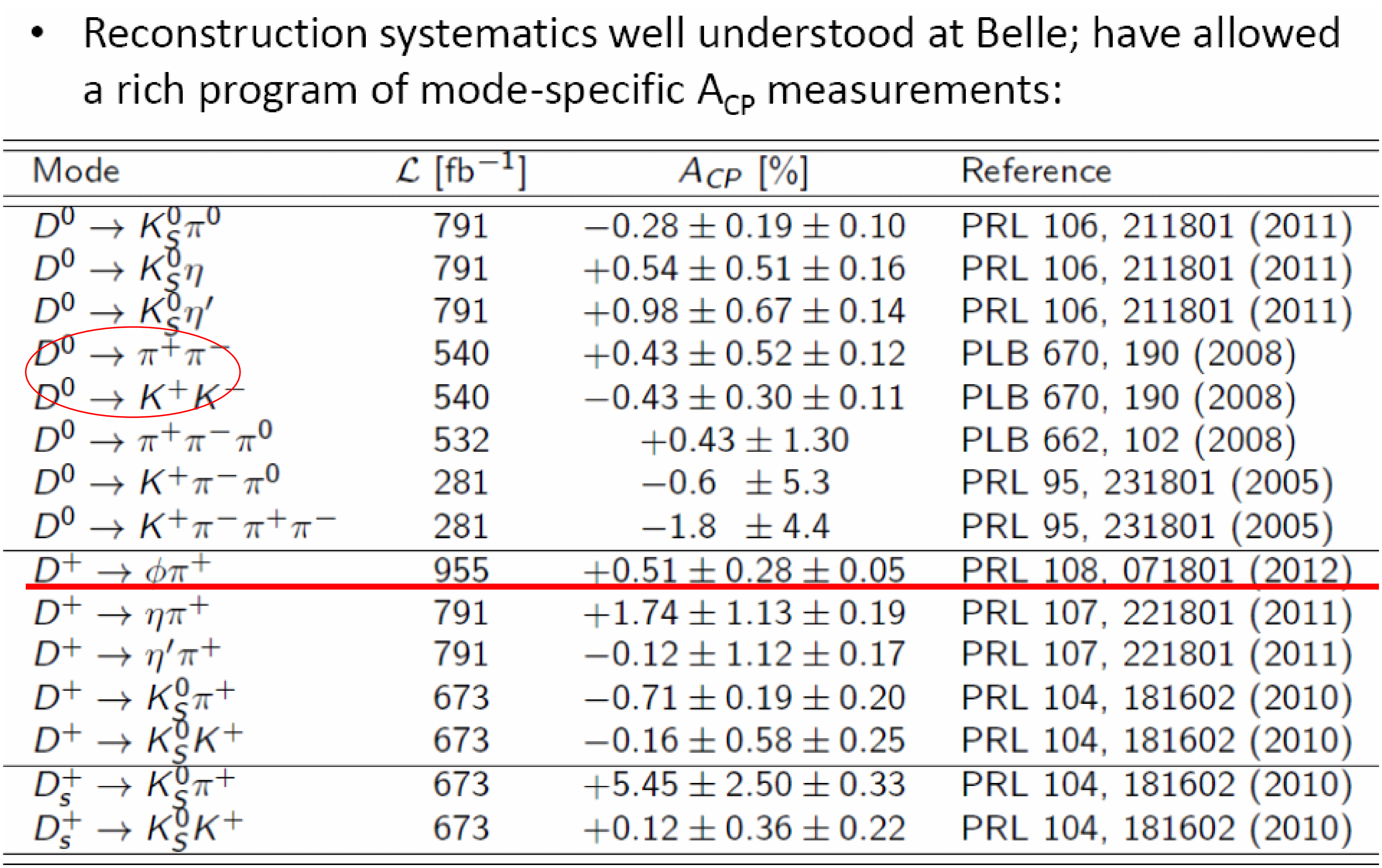
CP asymmetry:

$$A_{CP}^{f} = \frac{\Gamma(D\rightarrow f)-\Gamma(\overline{D}\rightarrow\overline{f})}{\Gamma(D\rightarrow f)+\Gamma(\overline{D}\rightarrow\overline{f})} \approx a_d^f + a_m^f + a_i^f$$

Experimentally observed as

$$A_{CP}^{f} = \frac{N(D\rightarrow f)-N(\overline{D}\rightarrow\overline{f})}{N(D\rightarrow f)+N(\overline{D}\rightarrow\overline{f})}$$

Direct CP violation: example results from Belle

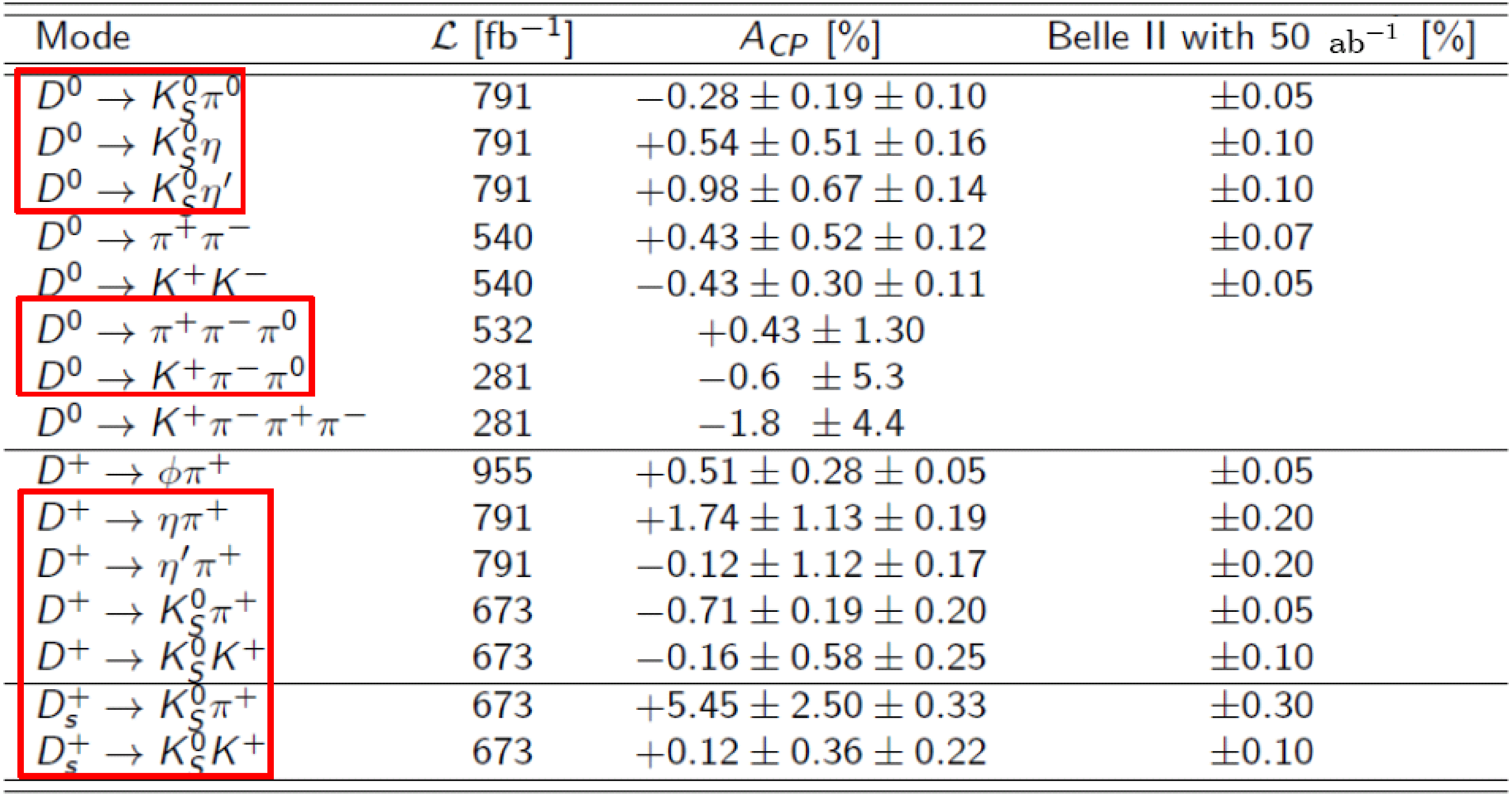


- Reconstruction systematics well understood at Belle; have allowed a rich program of mode-specific A_{CP} measurements:

Mode	$\mathcal{L}$ [fb^{-1}]	A_{CP} [%]	Reference
$D^0 \to K_S^0 \pi^0$	791	$-0.28 \pm 0.19 \pm 0.10$	PRL 106, 211801 (2011)
$D^0 \to K_S^0 \eta$	791	$+0.54 \pm 0.51 \pm 0.16$	PRL 106, 211801 (2011)
$D^0 \to K_S^0 \eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	PRL 106, 211801 (2011)
$D^0 \to \pi^+ \pi^-$	540	$+0.43 \pm 0.52 \pm 0.12$	PLB 670, 190 (2008)
$D^0 \to K^+ K^-$	540	$-0.43 \pm 0.30 \pm 0.11$	PLB 670, 190 (2008)
$D^0 \to \pi^+ \pi^- \pi^0$	532	$+0.43 \pm 1.30$	PLB 662, 102 (2008)
$D^0 \to K^+ \pi^- \pi^0$	281	-0.6 ± 5.3	PRL 95, 231801 (2005)
$D^0 \to K^+ \pi^- \pi^+ \pi^-$	281	-1.8 ± 4.4	PRL 95, 231801 (2005)
$D^+ \to \phi \pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	PRL 108, 071801 (2012)
$D^+ \to \eta \pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	PRL 107, 221801 (2011)
$D^+ \to \eta' \pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	PRL 107, 221801 (2011)
$D^+ \to K_S^0 \pi^+$	673	$-0.71 \pm 0.19 \pm 0.20$	PRL 104, 181602 (2010)
$D^+ \to K_S^0 K^+$	673	$-0.16 \pm 0.58 \pm 0.25$	PRL 104, 181602 (2010)
$D_s^+ \to K_S^0 \pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	PRL 104, 181602 (2010)
$D_s^+ \to K_S^0 K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	PRL 104, 181602 (2010)

Direct CP violation: prospect at Belle-II

- Belle II can reach < 0.1% uncertainty on A_{CP} for a variety of modes…



Mode	$\mathcal{L}$ [fb^{-1}]	A_{CP} [%]	Belle II with 50 ab^{-1} [%]
$D^0 \to K_S^0 \pi^0$	791	$-0.28 \pm 0.19 \pm 0.10$	± 0.05
$D^0 \to K_S^0 \eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.10
$D^0 \to K_S^0 \eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	± 0.10
$D^0 \to \pi^+ \pi^-$	540	$+0.43 \pm 0.52 \pm 0.12$	± 0.07
$D^0 \to K^+ K^-$	540	$-0.43 \pm 0.30 \pm 0.11$	± 0.05
$D^0 \to \pi^+ \pi^- \pi^0$	532	$+0.43 \pm 1.30$	
$D^0 \to K^+ \pi^- \pi^0$	281	-0.6 ± 5.3	
$D^0 \to K^+ \pi^- \pi^+ \pi^-$	281	-1.8 ± 4.4	
$D^+ \to \phi \pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	± 0.05
$D^+ \to \eta \pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	± 0.20
$D^+ \to \eta' \pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	± 0.20
$D^+ \to K_S^0 \pi^+$	673	$-0.71 \pm 0.19 \pm 0.20$	± 0.05
$D^+ \to K_S^0 K^+$	673	$-0.16 \pm 0.58 \pm 0.25$	± 0.10
$D_s^+ \to K_S^0 \pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.30
$D_s^+ \to K_S^0 K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.10

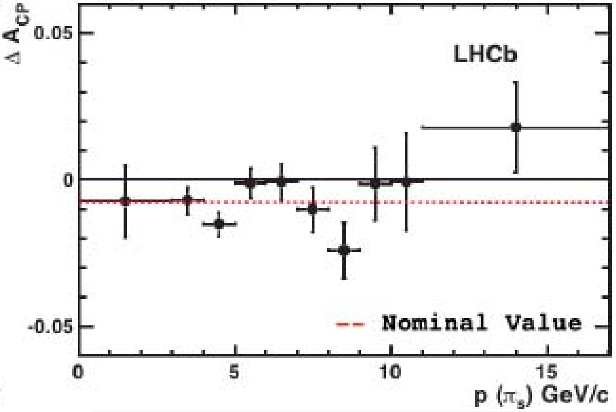
Modes well suited to measurement at Super B factories.

*Systematics related to control sample statistics are assumed to scale with luminosity.

Direct CP violation in $D^0 \to \pi^+\pi^-$, K^+K^-

$\Delta A_{cp} = A_{cp}(D^0 \to K^+K^-) - A_{cp}(D^0 \to \pi^+\pi^-)$ [%]

LHCb	$-0.82 \pm 0.21 \pm 0.11$	PRL2012
CDF	$-0.62 \pm 0.21 \pm 0.10$	charm2012
BaBar	(see below)	PRD2011
Belle	$-0.87 \pm 0.41 \pm 0.06$	ICHEP2012
WA	-0.678 ± 0.147 ($>4\sigma$)	HFAG2012



L=0.6 fb^{-1} LHCb

Phys.Rev.Lett. 108 (2012) 111602

Is this a sign of New Physics?

Individual A_{CP} are not significant

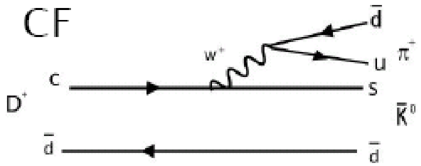
	$A_{cp}(D^0 \to K^+K^-)$ [%]	$A_{cp}(D^0 \to \pi^+\pi^-)$ [%]
CDF	$-0.24 \pm 0.22 \pm 0.09$	$+0.22 \pm 0.24 \pm 0.11$
BaBar	$0.00 \pm 0.34 \pm 0.13$	$-0.24 \pm 0.52 \pm 0.22$
Belle	$-0.32 \pm 0.21 \pm 0.09$	$+0.55 \pm 0.36 \pm 0.09$

Need to search for A_{CP} in other modes

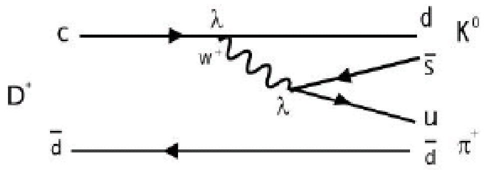
Direct CP on $D^+ \to K_s\pi^+$

- Two sources of CPV in $D^+ \to K_s\pi^+$ arxiv.1203.6409
  - Interference btw CF($D^+ \to \overline{K}^0\pi^+$) and DCS($D^+ \to K^0\pi^+$) modes: $A_{CP}^{\Delta C}$

CF



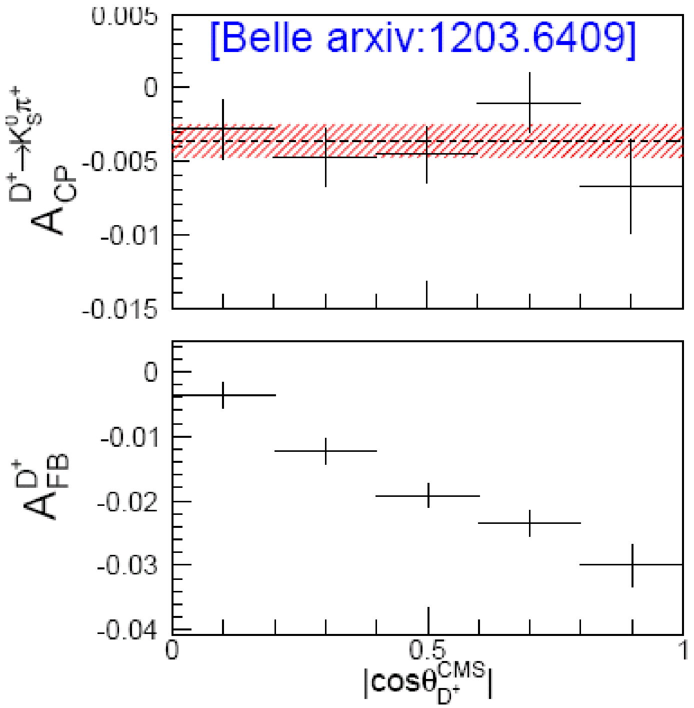
DCS



  - CP violation in K⁰ system: $A_{CP}^{K^0} = (-0.332 \pm 0.006)\%$

$$A_{CP}^{D^+ \to K_s^0\pi^+} = \frac{\Gamma(D^+ \to K_s^0\pi^+) - \Gamma(D^- \to K_s^0\pi^-)}{\Gamma(D^+ \to K_s^0\pi^+) - \Gamma(D^- \to K_s^0\pi^-)} = A_{CP}^{\Delta C} + A_{CP}^{K^0}$$

Belle	**(−0.363 ± 0.094 ± 0.067)%**
BaBar	(−0.44 ± 0.13 ± 0.10)%
CLEO	(−1.3 ± 0.7 ± 0.3)%
FOCUS	(−1.6 ± 1.5 ± 0.9)%
WA	(−0.41 ± 0.09)%



>4σ non-zero CPV, but fully consistent with K_S^0 asymmetry,

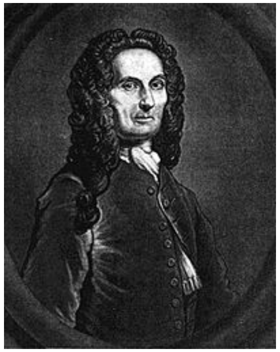
and intrinsic charm asymmetry is consistent with zero

Mixing and CP violation at threshold

The Lure of Phases

Interference is fascinating, but not new: classical waves interfere…
We may be surprised that it happens for "particles",
that's the core of the surprise of wave-particle duality.

"Wave mechanics" is made simpler with complex notation:



DeMoivre: $(\cos x + i \sin x)^n = \cos nx + i \sin nx$

Euler: $e^{ix} = \cos x + i \sin x \longrightarrow \boxed{e^{i\pi} + 1 = 0}$

Interference is always the key to accessing phases !
For us, the key quantum effects are:
EPR-like correlations of D meson pairs
Multiple amplitudes (diagrams) for a given final state.

Phases everywhere

Phases in time evolution: e^{iHt} (e^{imt} in rest frame)

These are relevant to D^0 oscillations, due to mass difference

Relative phases of components of multi-body decays (Dalitz plots),

phases in BW as energy varies: (unstable: m → m - i Γ /2)

Lifetime (complex mass) in time dep. --> transformed to E-dependence

Dramatic interference patterns when resonance bands cross

“Discrete phases”: +,– eigenvalues of C, P and CP:

Lead to dramatic effects at the ψ(3770)

CKM (weak) phases:

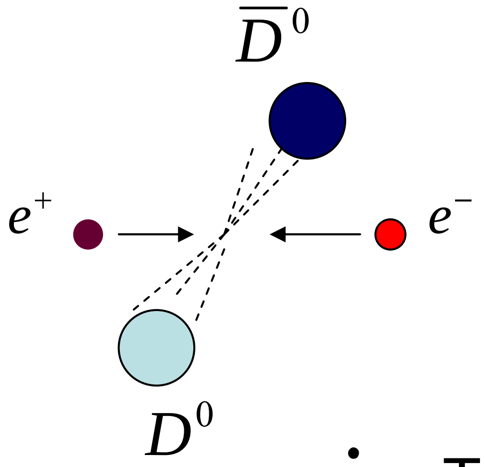
One clear source of CP violation in SM

Strong Final-state Interaction (FSI) Phases:

Interact with weak phases to give direct CP violation

The decay rate of a correlated state

For a physical process producing $D^0 \bar{D}^0$ such as



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

The $D^0 \bar{D}^0$ pair will be a quantum-correlated state

The quantum number of ψ'' is $J^{PC} = 1^{--}$

∴ The C number of $D^0 \bar{D}^0$ pair in this process is $C = -$

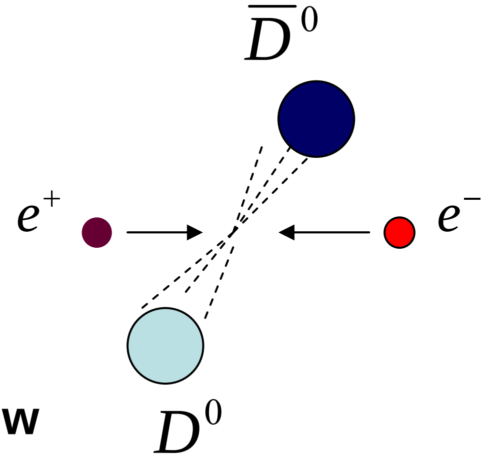
For a correlated state with $C = -$

$$\hat{C}\left|D^0\right\rangle = \left|\overline{D}^0\right\rangle$$

$$\hat{C}\left|\overline{D}^0\right\rangle = \left|D^0\right\rangle$$

$$\psi_- = \frac{1}{\sqrt{2}}(\left|D^0\right\rangle\left|\overline{D}^0\right\rangle - \left|\overline{D}^0\right\rangle\left|D^0\right\rangle)$$

Measure D^0 mixing and quantum correlation



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

$(K^\pm\pi^\mp)(K^\pm\pi^\mp)$

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

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

One can look at D mixing by using the correlation in the threshold.

D^0 Mixing @ $\psi(3770)$

There's a very nice well-known D^0 mixing signature at 3770

>> No DCSD: cancels with these correlated D pairs

>> Like-sign $(K^-\pi^+)(K^-\pi^+)$ (+ c.c.) are pure mixing !

But it's HARD in practice :

$$\#\text{events} = N_{DD}\, B_{K\pi}{}^2\, \varepsilon_{K\pi}{}^2\, (x^2 + y^2)$$

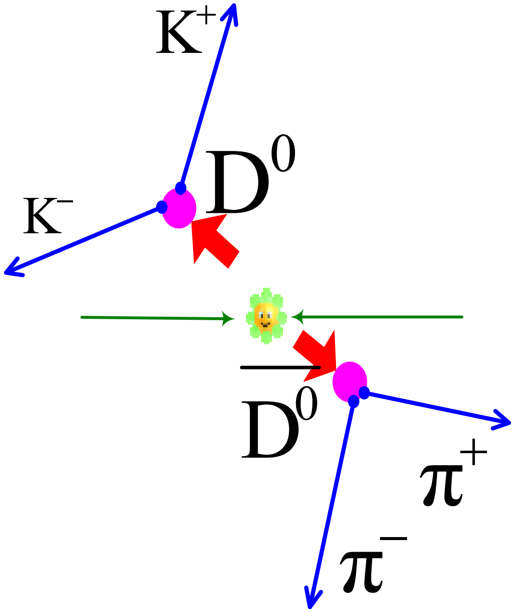
$$N_{DD} = 3.7 \times 10^6\ /\text{fb}^{-1} \qquad B_{K\pi}{}^2 = 1.5 \times 10^{-3}$$

$$\varepsilon_{K\pi}{}^2 = 0.4 \qquad (x^2 + y^2) = 1 \times 10^{-4}$$

Result: #events = 0.2 / fb^{-1}

The only number we have control over is the efficiency, $\varepsilon_{K\pi}$
But PID needs to be tight, to avoid background from $K\pi$ swaps …

CP Violation at $\psi(3770)$



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 $\psi'' \to f_1 f_2$

$$\mathrm{CP}(f_1 f_2) = \mathrm{CP}(f_1)\cdot\mathrm{CP}(f_2)\cdot(-1)^{L} = -$$

$$\mathrm{CP}(\psi'') = +$$

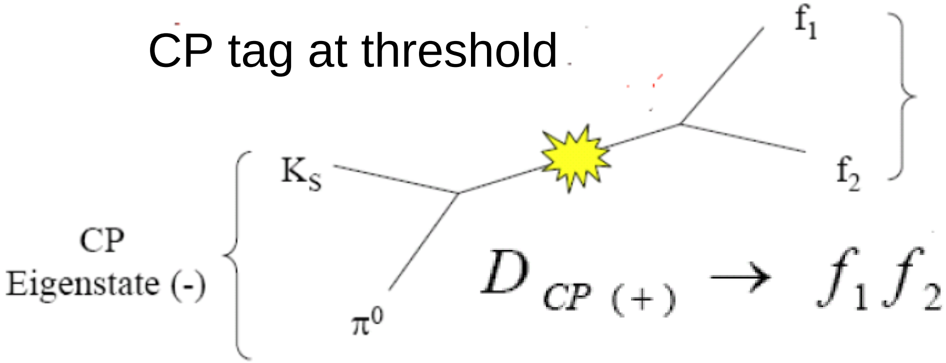
At BESIII, A_{CP} sensitivity : $\Delta A \sim 10^{-3}$

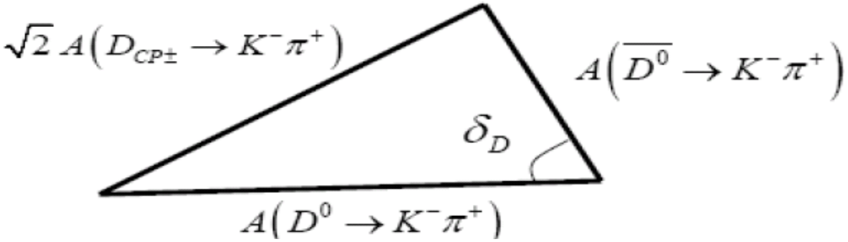
Access strong phase at threshold

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

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

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





$$\frac{\langle K^-\pi^+|\overline{D}^0\rangle^{DCS}}{\langle K^-\pi^+|D^0\rangle^{CF}} \equiv -r_{K\pi}e^{-i\delta_{K\pi}}$$

ψ(3770)L=1 C=-1

CP anti-correlated

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

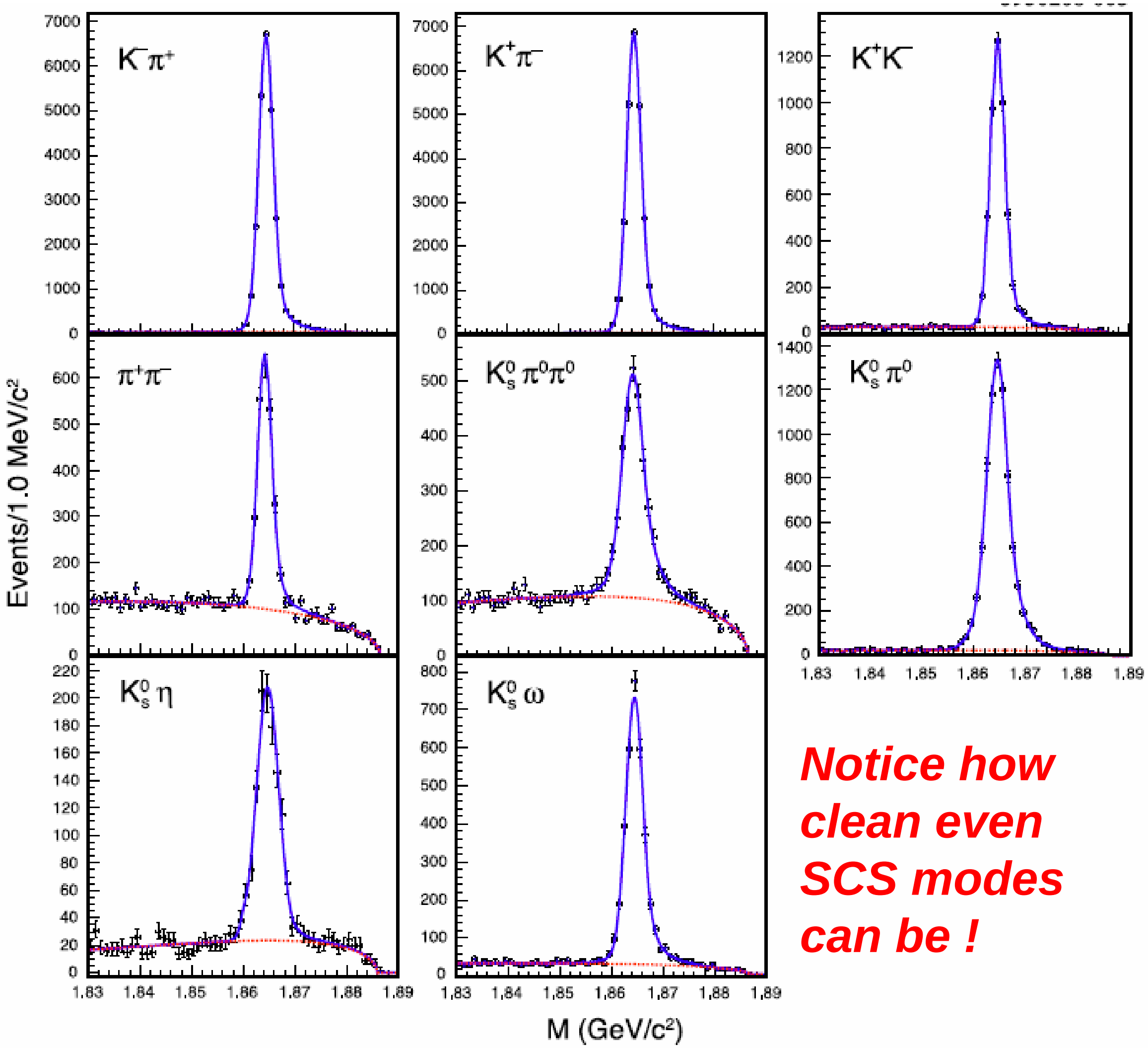
Quantum Correlation Analysis

PRD 78, 012001
PRL100, 221801
281 pb^{-1} (2008)

Familiar hadronic tags:
[shown at right]
- Approximate flavor tags
- CP tags (both signs)

Hadronic tags with K_L:
- Can also do, given the kinematic constraints
- Adds more CP tags

Semileptonic tags:
- Exact flavor tag
- Good for certain parameters

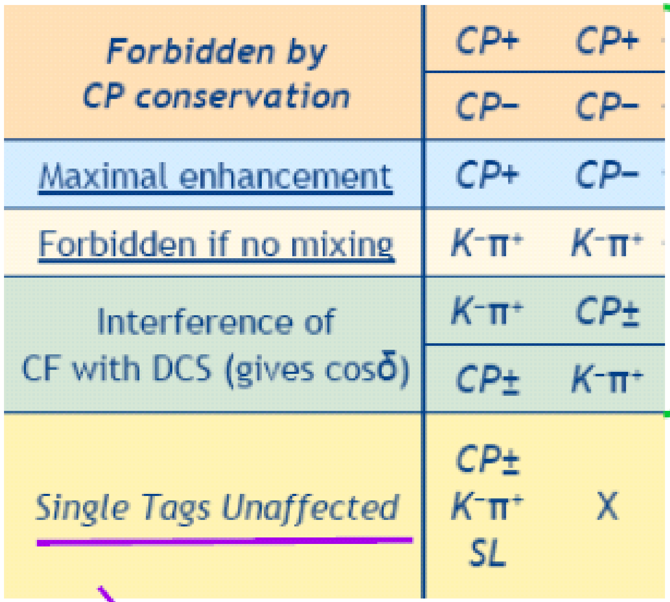


Notice how clean even SCS modes can be !

Quantum Correlation Analysis

Correlated D pairs are produced at the ψ(3770):
Produces a C = -1 initial state.

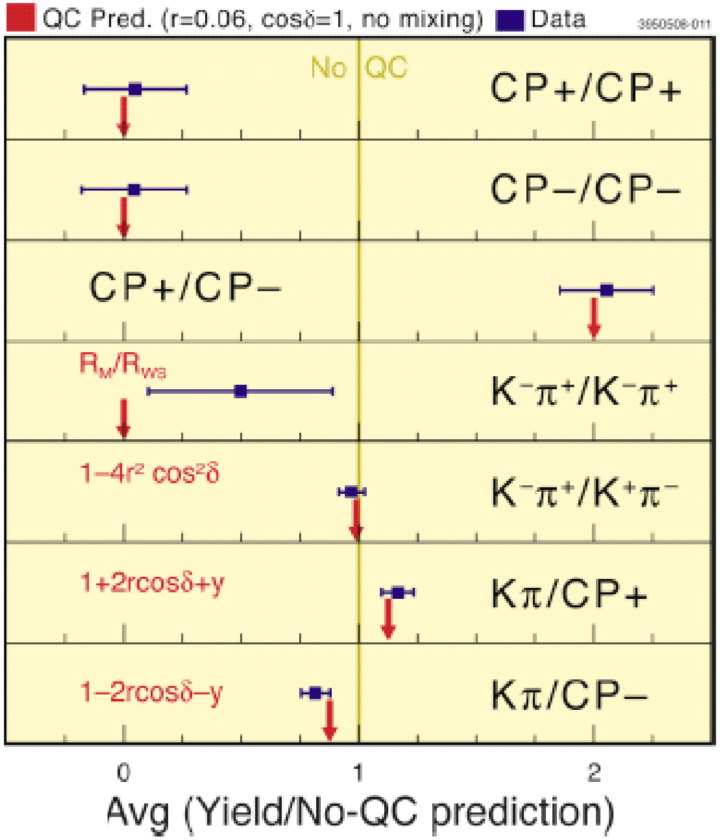
CLEO-c Results
vs. theory



Forbidden by CP conservation	*CP+*	*CP+*
	CP−	*CP−*
Maximal enhancement	*CP+*	*CP−*
Forbidden if no mixing	$K^-\pi^+$	$K^-\pi^+$
Interference of CF with DCS (gives cosδ)	$K^-\pi^+$	*CP±*
	CP±	$K^-\pi^+$
Single Tags Unaffected	*CP±* $K^-\pi^+$ *SL*	X

Nicely Confirmed!

Useful reference



Key variables:

x,y : familiar D0 mixing variables

$r_{K\pi}$: Wrong-to-right sign amplitude ratio $|A(D^0 \to K^+\pi^-) / A(\overline{D}^0 \to K^+\pi^-)|$

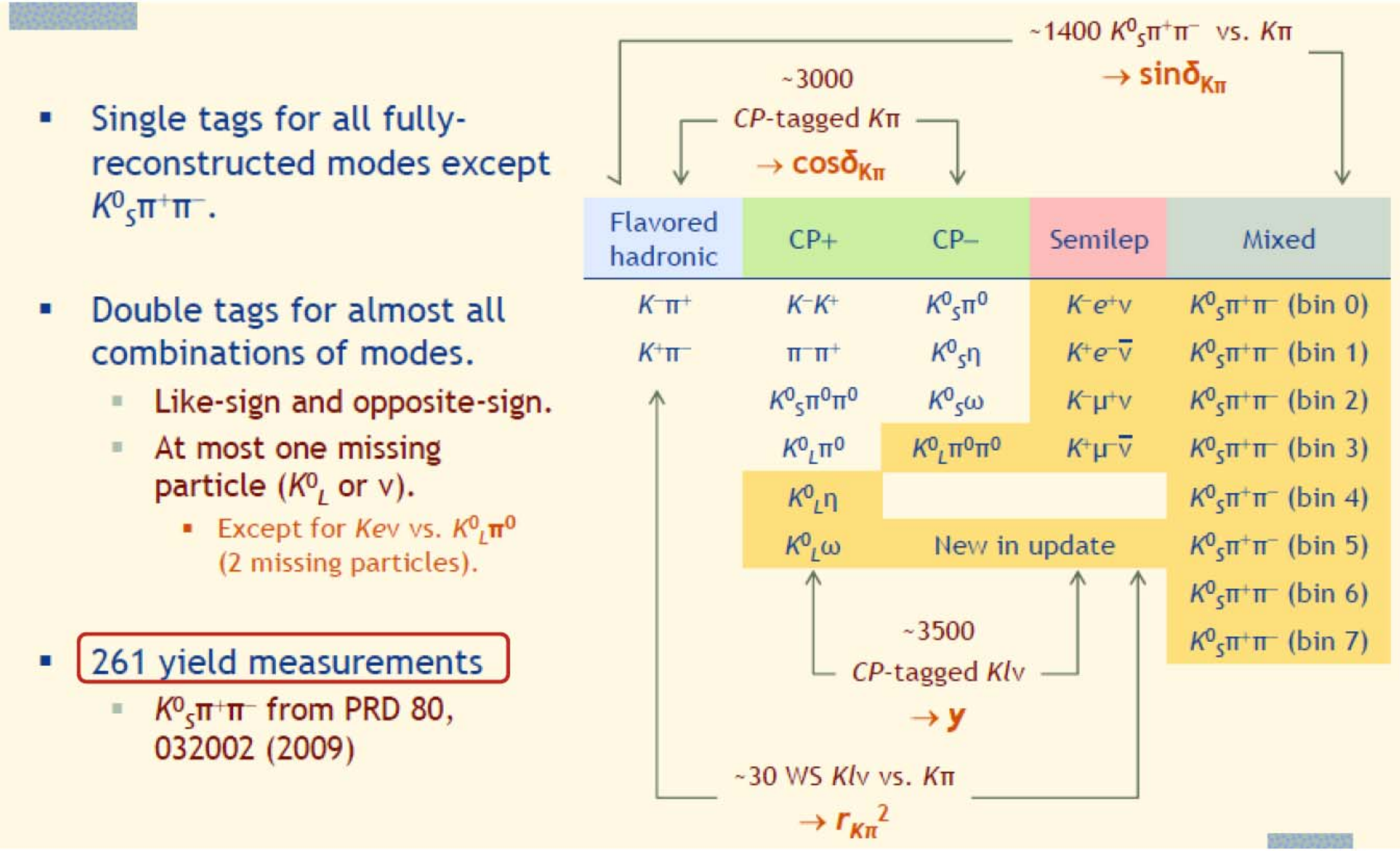
$\delta_{K\pi}$: strong Kπ FSI phase (which rotates x,y to x',y')

This is the -phase of the previous amplitude ration

:

$$\frac{\left\langle K^-\pi^+ \middle| \overline{D}^0 \right\rangle^{DCS}}{\left\langle K^-\pi^+ \middle| D^0 \right\rangle^{CF}} \equiv -r_{K\pi} e^{-i\delta_{K\pi}}$$

CLEO-c QCA: Modes Used



- Single tags for all fully-reconstructed modes except $K^0_S\pi^+\pi^-$.
- Double tags for almost all combinations of modes.
  - Like-sign and opposite-sign.
  - At most one missing particle (K^0_L or ν).
    - Except for $Ke\nu$ vs. $K^0_L\pi^0$ (2 missing particles).
- 261 yield measurements
  - $K^0_S\pi^+\pi^-$ from PRD 80, 032002 (2009)

~1400 $K^0_S\pi^+\pi^-$ vs. $K\pi$ → $\sin\delta_{K\pi}$

~3000 CP-tagged $K\pi$ → $\cos\delta_{K\pi}$

Flavored hadronic	CP+	CP–	Semilep	Mixed
$K^-\pi^+$	K^-K^+	$K^0_S\pi^0$	$K^-e^+\nu$	$K^0_S\pi^+\pi^-$ (bin 0)
$K^+\pi^-$	$\pi^-\pi^+$	$K^0_S\eta$	$K^+e^-\bar{\nu}$	$K^0_S\pi^+\pi^-$ (bin 1)
	$K^0_S\pi^0\pi^0$	$K^0_S\omega$	$K^-\mu^+\nu$	$K^0_S\pi^+\pi^-$ (bin 2)
	$K^0_L\pi^0$	$K^0_L\pi^0\pi^0$	$K^+\mu^-\bar{\nu}$	$K^0_S\pi^+\pi^-$ (bin 3)
	$K^0_L\eta$			$K^0_S\pi^+\pi^-$ (bin 4)
	$K^0_L\omega$	New in update		$K^0_S\pi^+\pi^-$ (bin 5)
				$K^0_S\pi^+\pi^-$ (bin 6)
				$K^0_S\pi^+\pi^-$ (bin 7)

~3500 CP-tagged $Kl\nu$ → y

~30 WS $Kl\nu$ vs. $K\pi$ → $r_{K\pi}^2$

CLEO-c QCA: Results

Fit has 51 parameters :

N_{DD} + 21 BFs

24 amplitudes & phases for $K_S\pi^+\pi^-$

5 $K\pi$ and mixing parameters

(see table below)

Two distinct fits:

without external input

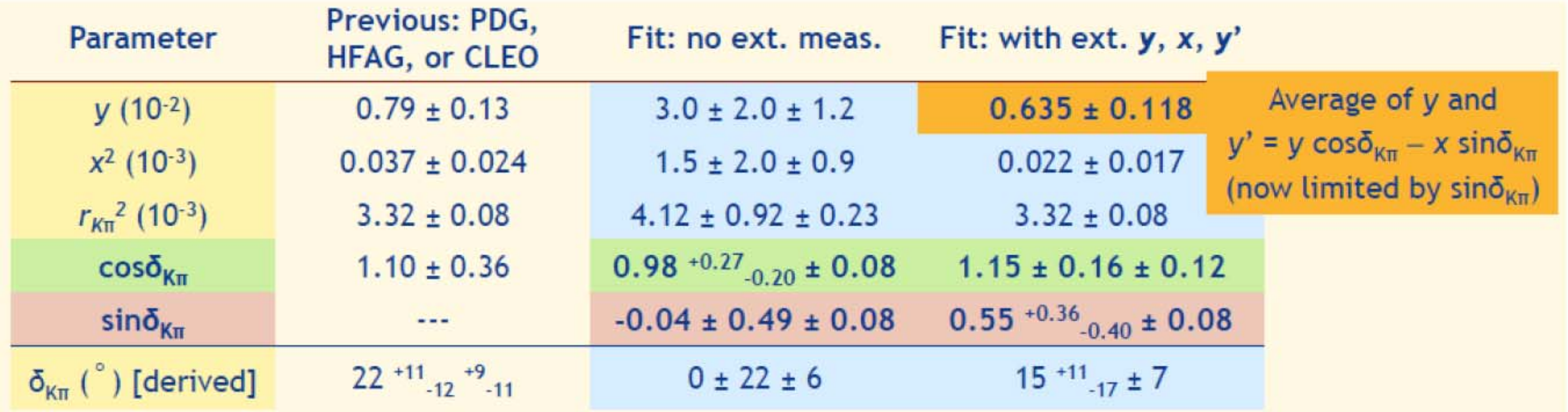
with external y, x, y' [2010 HFAG ave.]

Stat.errors on y & $r_{K\pi}$ $\cos\delta_{K\pi}$:

3x better than 2008 analysis !

First direct measurements of $r_{K\pi}^2$, $\sin\delta_{K\pi}$

Systematics: still preliminary

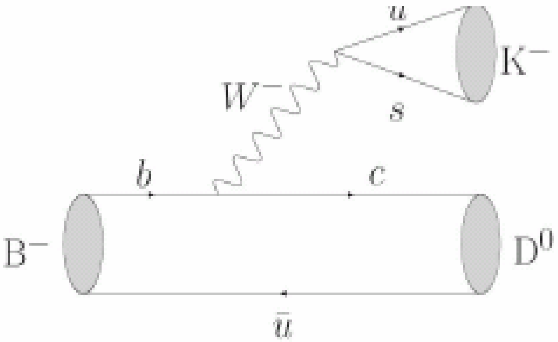


Parameter	Previous: PDG, HFAG, or CLEO	Fit: no ext. meas.	Fit: with ext. *y, x, y'*
y (10^{-2})	0.79 ± 0.13	$3.0 \pm 2.0 \pm 1.2$	0.635 ± 0.118
x^2 (10^{-3})	0.037 ± 0.024	$1.5 \pm 2.0 \pm 0.9$	0.022 ± 0.017
$r_{K\pi}^2$ (10^{-3})	3.32 ± 0.08	$4.12 \pm 0.92 \pm 0.23$	3.32 ± 0.08
$\cos\delta_{K\pi}$	1.10 ± 0.36	$0.98\ ^{+0.27}_{-0.20} \pm 0.08$	$1.15 \pm 0.16 \pm 0.12$
$\sin\delta_{K\pi}$	---	$-0.04 \pm 0.49 \pm 0.08$	$0.55\ ^{+0.36}_{-0.40} \pm 0.08$
$\delta_{K\pi}$ ($^\circ$) [derived]	$22\ ^{+11}_{-12}\ ^{+9}_{-11}$	$0 \pm 22 \pm 6$	$15\ ^{+11}_{-17} \pm 7$

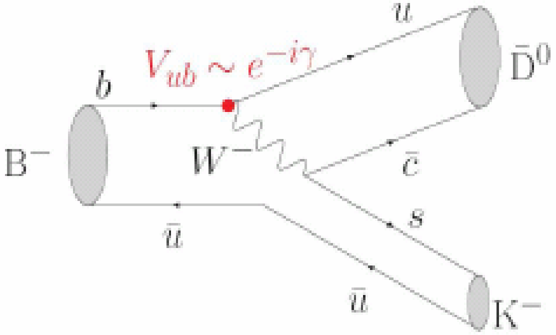
Average of y and $y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$ (now limited by $\sin\delta_{K\pi}$)

ϕ_3/γ extraction

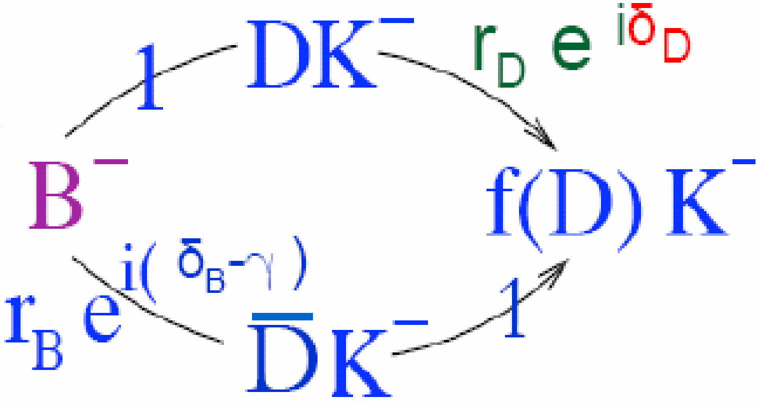
$B^- \longrightarrow D^0 K^-$



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



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



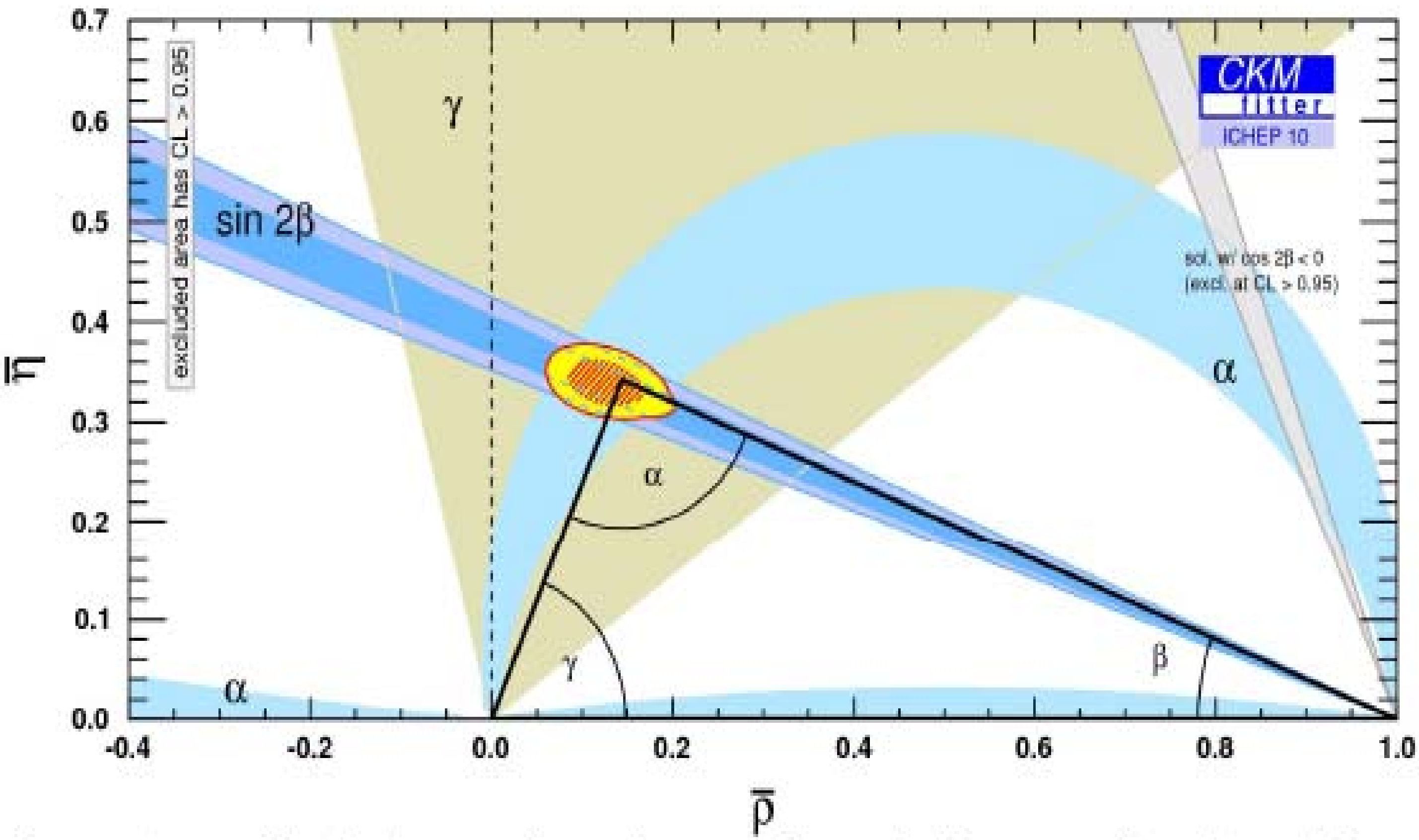
- Sensitivity through interference between b→u and b→c transitions
- Require D^0 and $\overline{D}^0$ decay to a common final state, f(D):

  $K^0_S hh$; $K\pi$; $K\pi\pi\pi$; $K\pi\pi^0$

- Comparison of B^- and B^+ rates allow γ to be extracted
- But other parameters to be considered
  - in particular δ_D – **accessed in quantum-correlated D-decays**

r_D & δ_D analogous to B-decay quantities.
For multibody decays, these
vary over Dalitz space

Status of direct determination of γ/ϕ_3



- γ is the least well determined angle of the unitarity triangle with an uncertainty of ~20° from direct measurements
  - $\sigma_\beta = 1°$

CP-tagged D-decays: the essential idea

Dalitz plots of CP-tagged decays at the Ψ(3770) provide additional info to flavour tagged events

Sensitivity to the cosine of strong phase difference between the D^0 & $\bar{D}^0$ **(cosδ)**

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

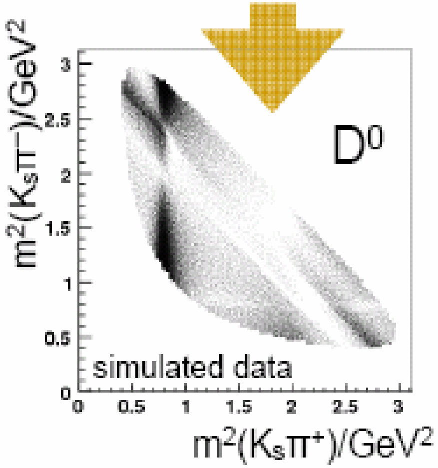
$D^0 \rightarrow K_S\pi^+\pi^-$

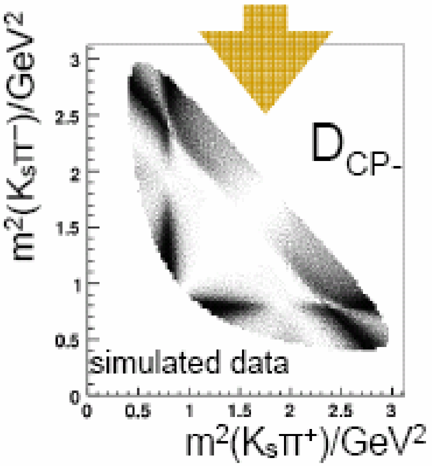
$\psi'' \rightarrow D_a D_b$

$D_a \rightarrow K^+K^-$ eg. CP+

$D_b \rightarrow K_S\pi^+\pi^-$

Flavour tagged distribution $\propto$ $|D^0|^2$ **or** $|\bar{D}^0|^2$





CP-tagged $\propto$

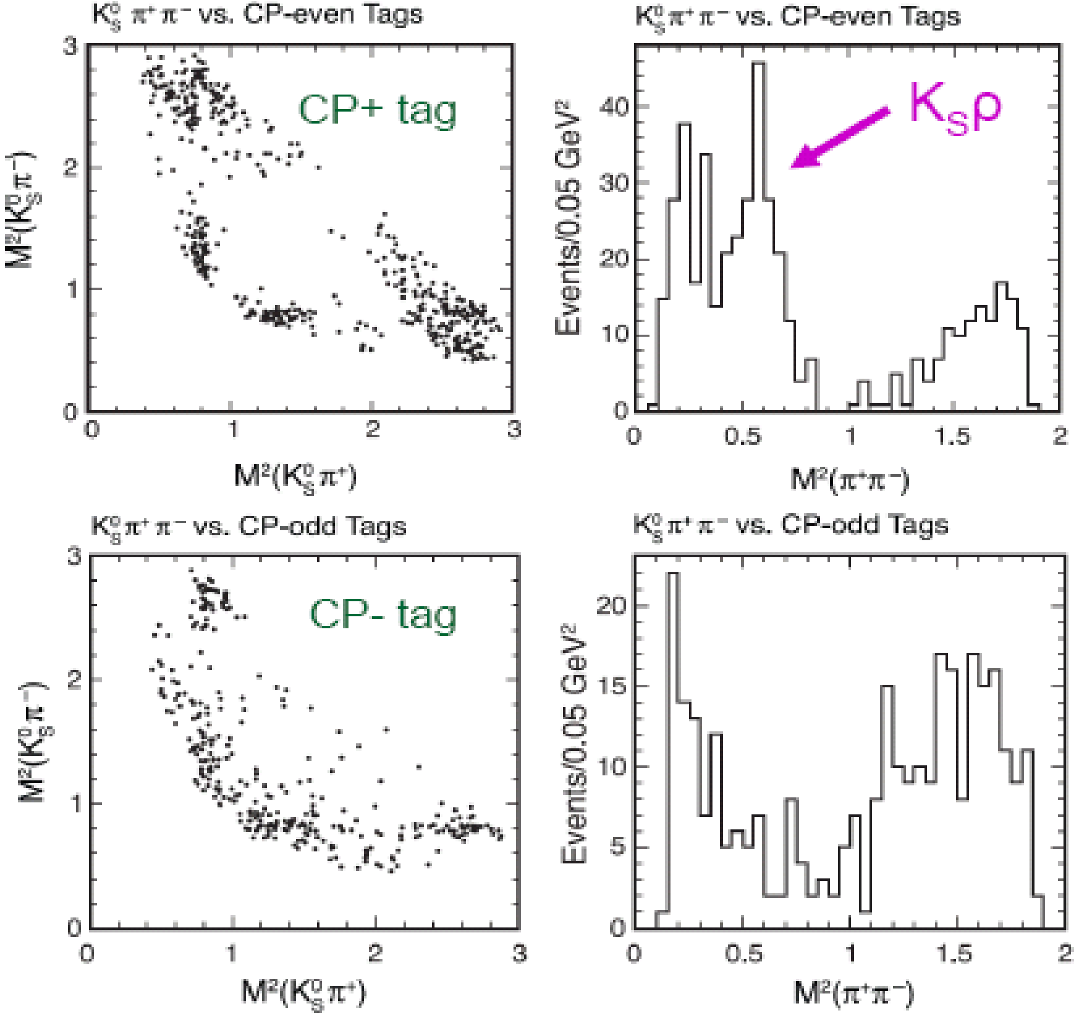
$|D^0|^2 + |\bar{D}^0|^2 \pm 2\,|D^0||\bar{D}^0|\,\cos\delta$

In a Dalitz-plot bin combinations of flavour & CP-tagged data give access to cosδ

In addition, quantum-correlations allow *other* hadronic decays to be used

CP-tagged $D^0 \to K_s \pi^+ \pi^-$ Dalitz plots

Clear differences seen between CP-odd and CP-even:

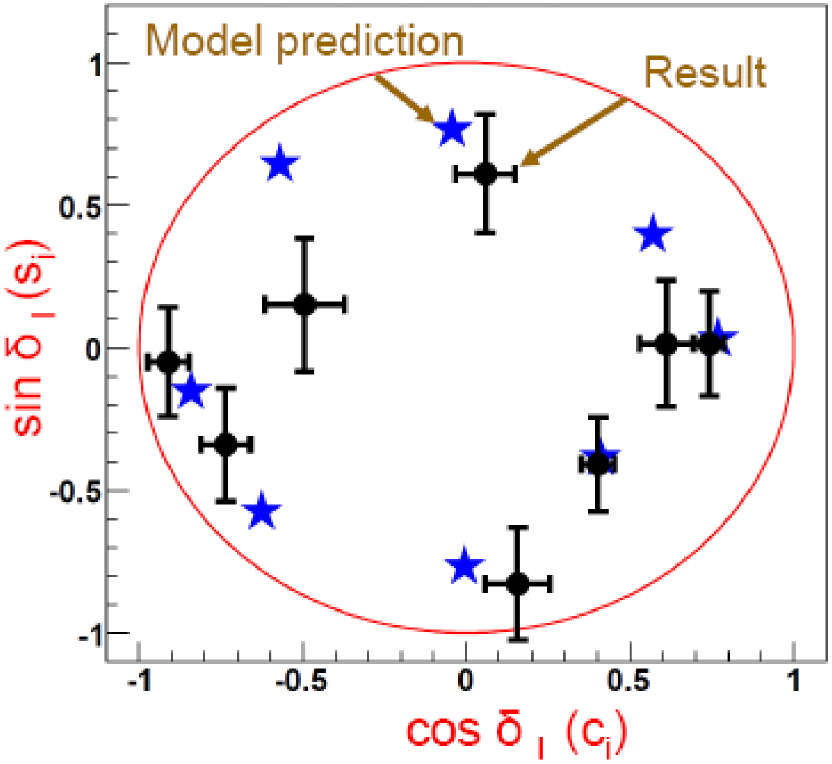


CLEO-c, PRD 80 (2009) 032002

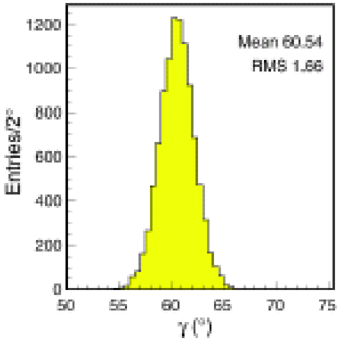
First CLEO-c results and γ/ϕ_3 impact

R. Briere *et al.*, PRD 80 (2009) 032002

(model = BABAR PRL 95 (2005) 121802)



Projected uncertainty on γ arising from uncertainty on c_i & s_i is 1.7°:



- Smaller than model error
- Plus experimental in origin - dominated by finite CLEO-c statistics

Downside - binning leads to ~20% loss in σ_{stat} relative to unbinned approach

Selected Theory References

Quantum Correlations

Goldhaber & Rosner, Phys. Rev. D15, 1254 (1977)
Gronau, Grossman & Rosner, Phys.Lett. B508, 37 (2001)
Asner & Sun, Phys. Rev. D73, 034024 (2006); E: ibid, D77, 019901 (2008)

Attn. PDG: K_S != 1/2 of K^0 or K^{0bar}

Bigi & Yamamoto Phys. Lett. B349, 363 (1995)

Coherence Factors

Atwood & Soni, Phys. Rev. D68, 033003 (2003)

B physics: CKM gamma with "DK" modes

Gronau & London, Phys. Lett. B253, 483 (1991) "GLW": SCS CP-eigenstates
Gronau & Wyler, Phys. Lett. B265, 172 (1991)

Atwood, Dunetz & Soni, Phys. Rev. Lett. 78, 3257 (1997) "ADS": CF + DCSD
Atwood, Dunetz & Soni, Phys. Rev. D63, 036005 (2001)

Giri, Grossman, Soffer & Zupan, Phys. Rev. D68, 054018 (2003)
Bondar & Poluektov, Eur. Phys. J. C 47, 347 (2006) CF multi-body: larger strong phases?
Bondar & Poluektov, Eur. Phys. J. C 55, 51 (2008)

D^0 Mixing with $K_SK\pi$

Malde & Wilkinson, Phys. Lett. B701, 353 (2011)

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 Super-B-Roma

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

Marcello A. Giorgi @ICHEP2010

KEKB to SuperKEKB How to upgrade

Belle II

New IR

New superconducting /permanent final focusing quads near the IP

New beam pipe & bellows

Replace short dipoles with longer ones (LER)

Add / modify RF systems for higher beam current

Low emittance positrons to inject

Positron source

Damping ring

New positron target / capture section

Redesign the lattices of HER & LER to squeeze the emittance

Low emittance gun

TiN-coated beam pipe with antechambers

Low emittance electrons to inject

To get x40 higher luminosity

Summary

Theoretical uncertainties are large due to long-distance contribution to rare charm FCNC and neutral D mixing ;

New Physics searches in rare and forbidden charm decays have become considerably more sensitive;

CPV at percent level may indicate New Physics;

We expect to get more from experimental side:

- **measurements of as many CP asymmetries as possible;**
- **LHC will soon play leading role in charm mixing and CPV measurements;**
- **measurements at the charm threshold as pioneered by CLEO-c are needed to determine strong phases and coherence factors;**
- **Super-B factory will settle down the charm mixing and see observable CPV effects in many decay modes.**

Global fit to those observables will improve development of theoretical tools in charm .