CLEO'S IMPACT ON CKM

Phil Rubin (George Mason University)
For the **CLEO** Collaboration

Recent Results

- $|V_{cd}|$, $|V_{cs}| \Rightarrow |V_{ub}|$ from $D \rightarrow (K/\pi)e\nu$
- $f_{D_s^+} \Rightarrow f_B$, f_{B_s} from $D_s^+ \rightarrow \ell^+\nu$
- γ/ϕ_3 with help from $D \rightarrow Kn\pi$

$|V_{cd}|$ and $|V_{cs}|$, etc.

- Cabibbo-Kobayashi-Maskawa Mixing Matrix

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

- $\mathbf{\Gamma_{ij} \propto |f|^2 |V_{ij}|^2}$
- LQCD comparisons and form factor shape constraints

$f_{D_s^+}$

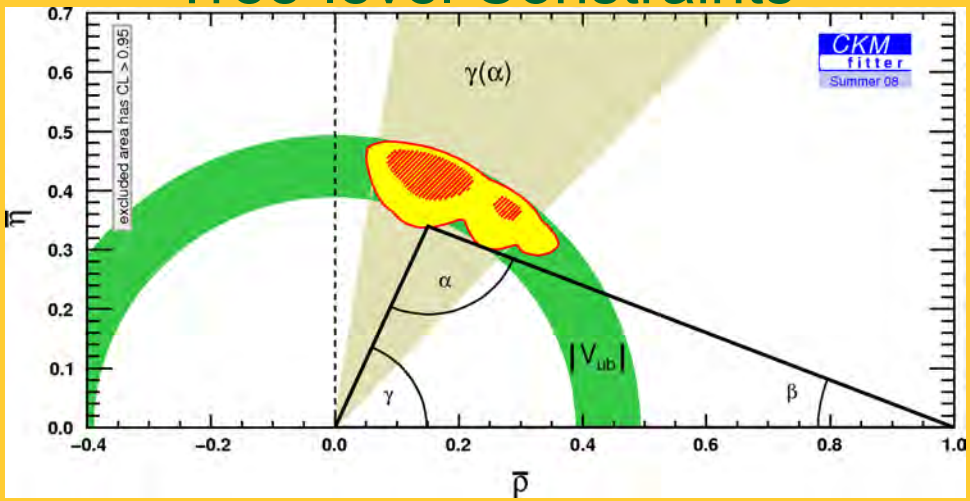
$$\Gamma(D_s^+ \to \ell^+\nu) = \frac{G_F^2 |V_{cs}|^2 f_{D_s^+}^2}{8\pi} m_{D_s^+} m_\ell^2 \left(1 - \frac{m_\ell^2}{m_{D_s^+}^2}\right)^2$$

- Compare $f_{D_s^+}$ to LQCD calculations
- LQCD also predicts, e.g., f_B, f_{B_s}/f_B
- Verification facilitates determination of
  - $|V_{ub}|$ from $B \to \ell\nu$
  - $|V_{td}|$ from $B^0 - \bar{B}^0$ mixing
  - $|V_{ts}|$ from $B_s - \bar{B}_s$ mixing

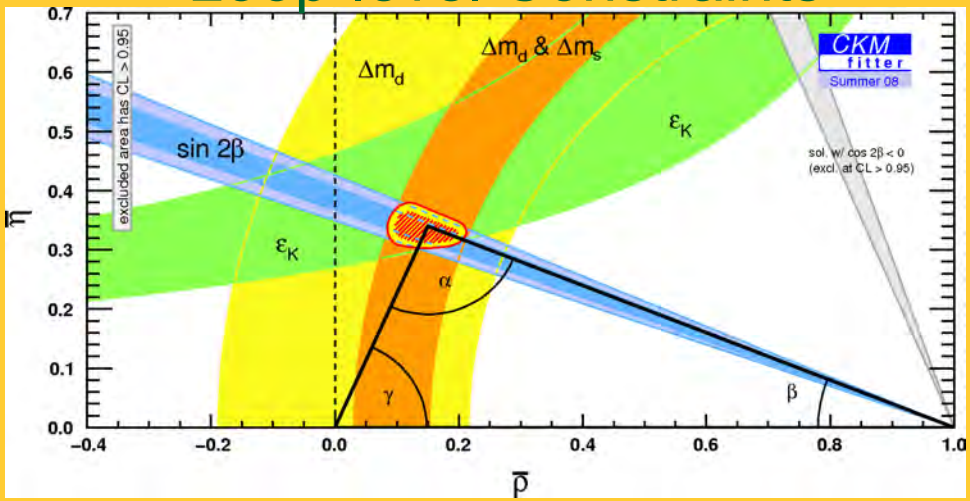
γ/ϕ_3

- Phase of V_{ub} relative to V_{cb}: $\gamma = \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right)$
- Sensitivity from interference between $b \to c$ and $b \to u$ transitions
- $\sigma_\gamma \geq 10°$

Tree-level Constraints

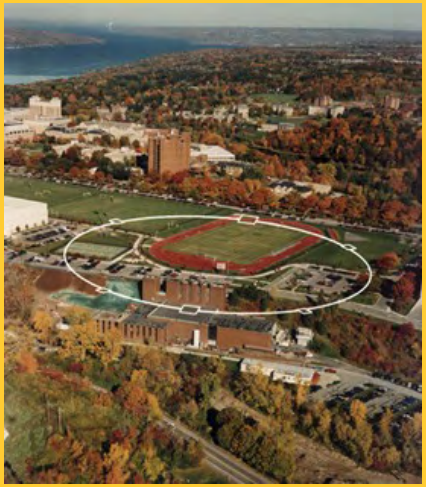


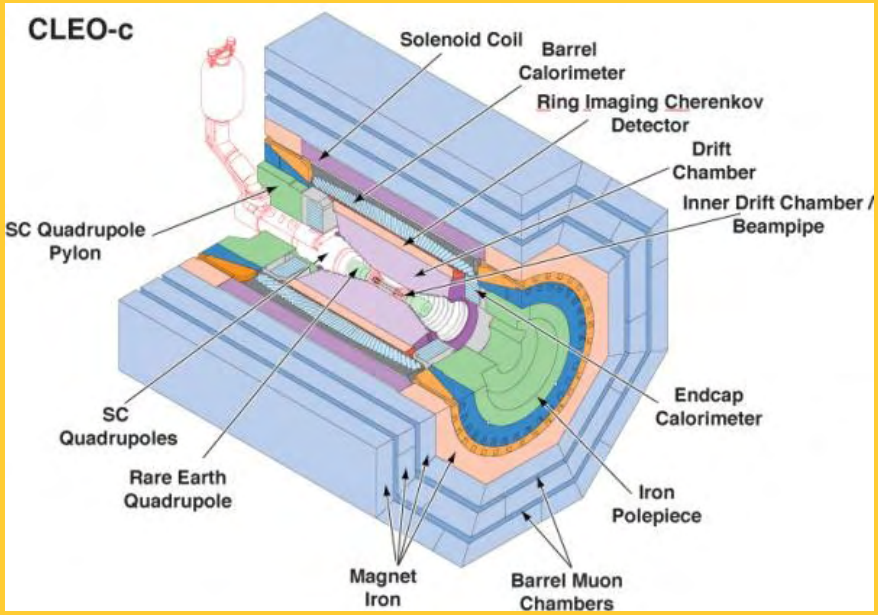
Loop-level Constraints



CLEO-c

Cornell Electron Storage Ring (CESR)





- Run just above $\mathbf{D\bar{D}}$ Threshold
- $\mathcal{L}_{int}$ = 818 pb^{-1}

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

  C = -1
- $\mathcal{L}_{int}$ ~ 600 pb^{-1}

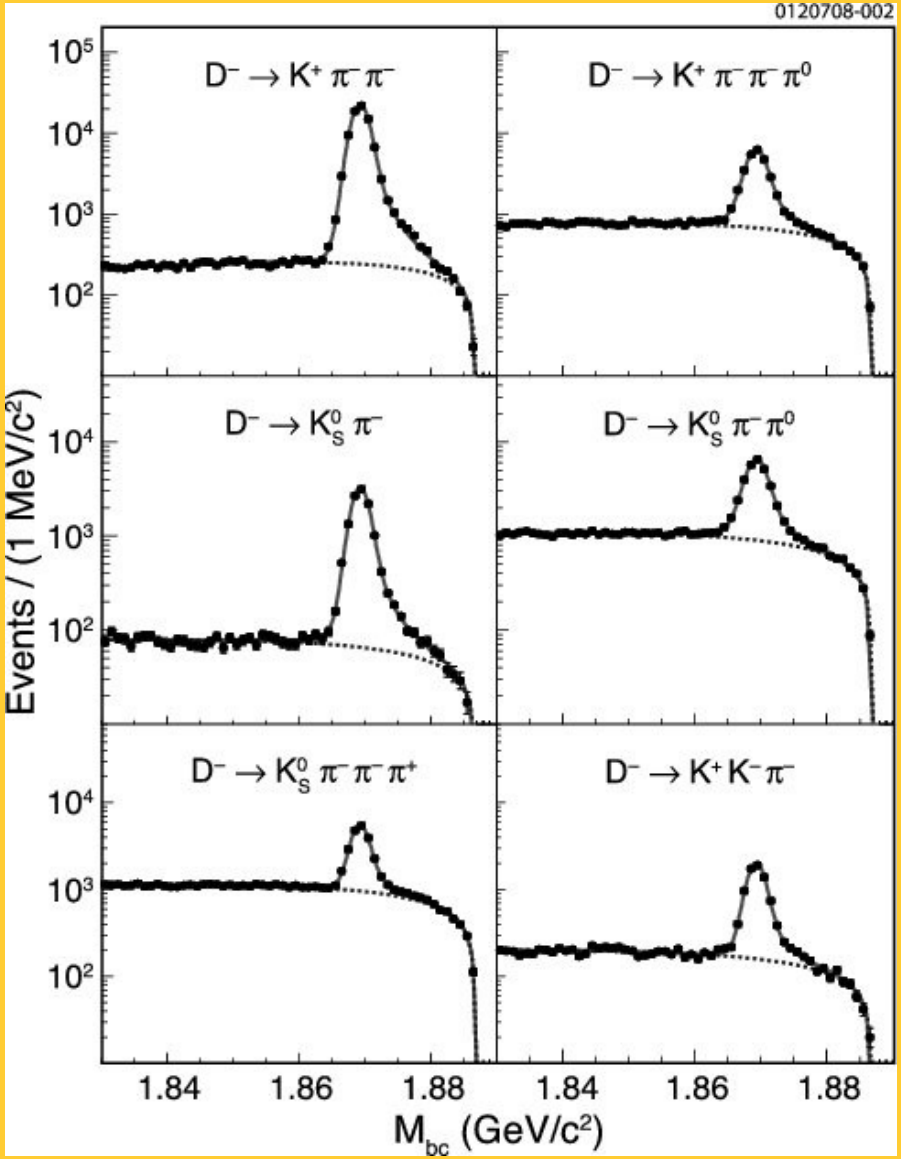
  E_{cm} = 4170 MeV

  $D_sD_s^*$ Threshold

Tagging

- Running near $D\bar{D}$ or $D_s\bar{D}_s^*$ threshold ⇒ two-particle production
- Detector hermeticity, and large cross-sections, branching fractions, and luminosities ⇒ efficient reconstruction of ≥ one particle: the **tag**
- Tagging ⇒ reduced background and kinematic ambiguity

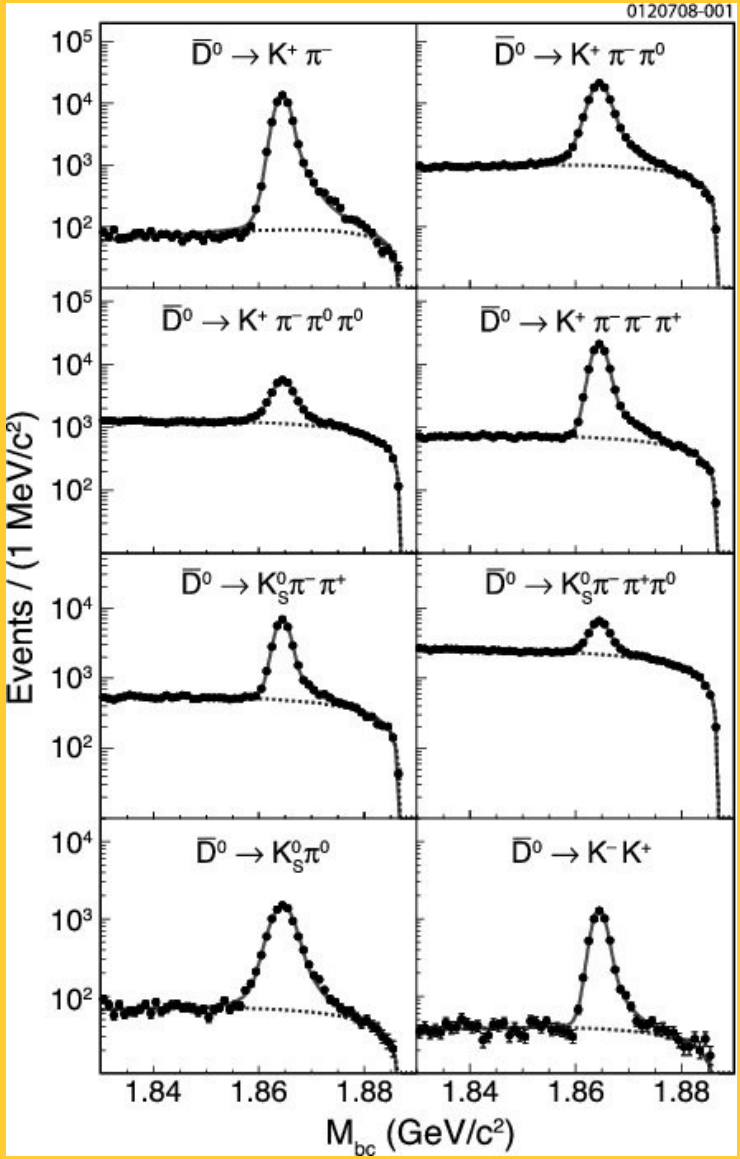
D^- Tag Modes for SL Analysis



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

- $\mathbf{M_{bc} \equiv \sqrt{E^2_{beam} - |\vec{p}_D|^2}}$
- $\mathbf{\Delta E = E_{candidate} - E_{beam}}$
- Dashed line: background

$\bar{D}^0$ Tag Modes for SL Analysis

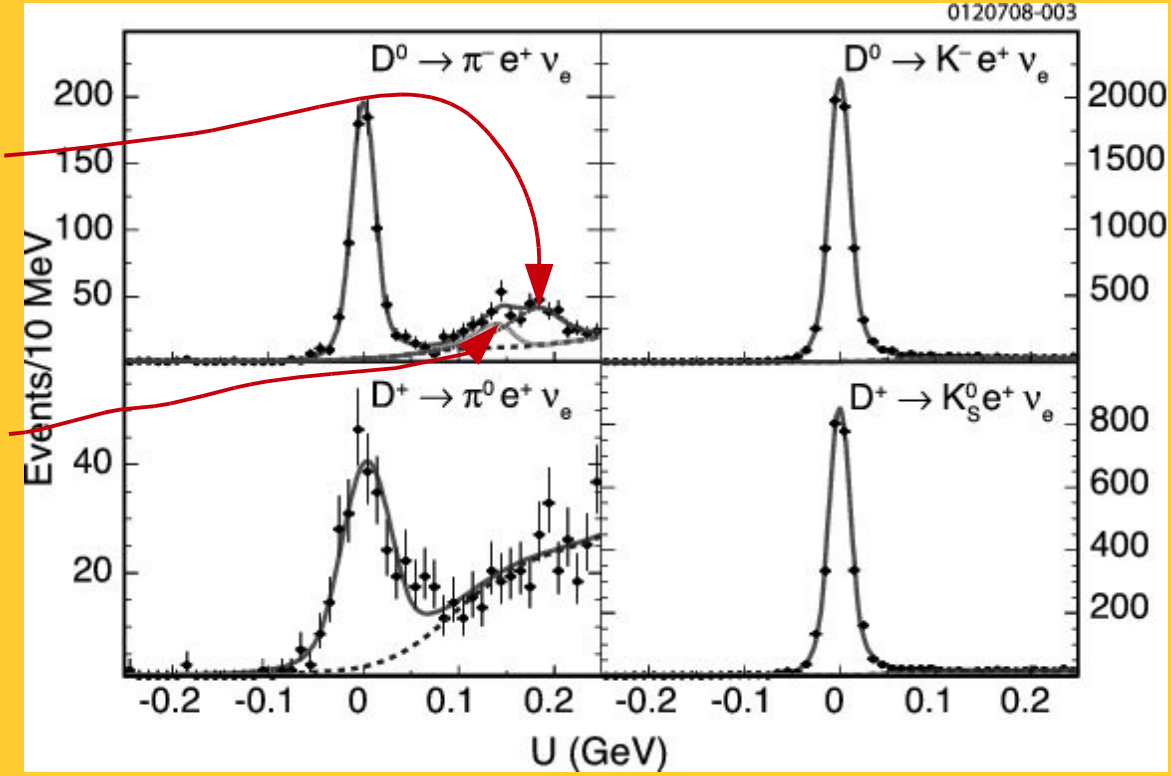


$$\bar{D}^0 \to K^+\pi^-$$
$$\bar{D}^0 \to K^+\pi^-\pi^0$$
$$\bar{D}^0 \to K^+\pi^-\pi^0\pi^0$$
$$\bar{D}^0 \to K^+\pi^-\pi^-\pi^+$$
$$\bar{D}^0 \to K_S\pi^-\pi^+$$
$$\bar{D}^0 \to K_S\pi^-\pi^+\pi^0$$
$$\bar{D}^0 \to K_S\pi^0$$
$$\bar{D}^0 \to K^-K^+$$

Neutrino (U=0) "Reconstruction"

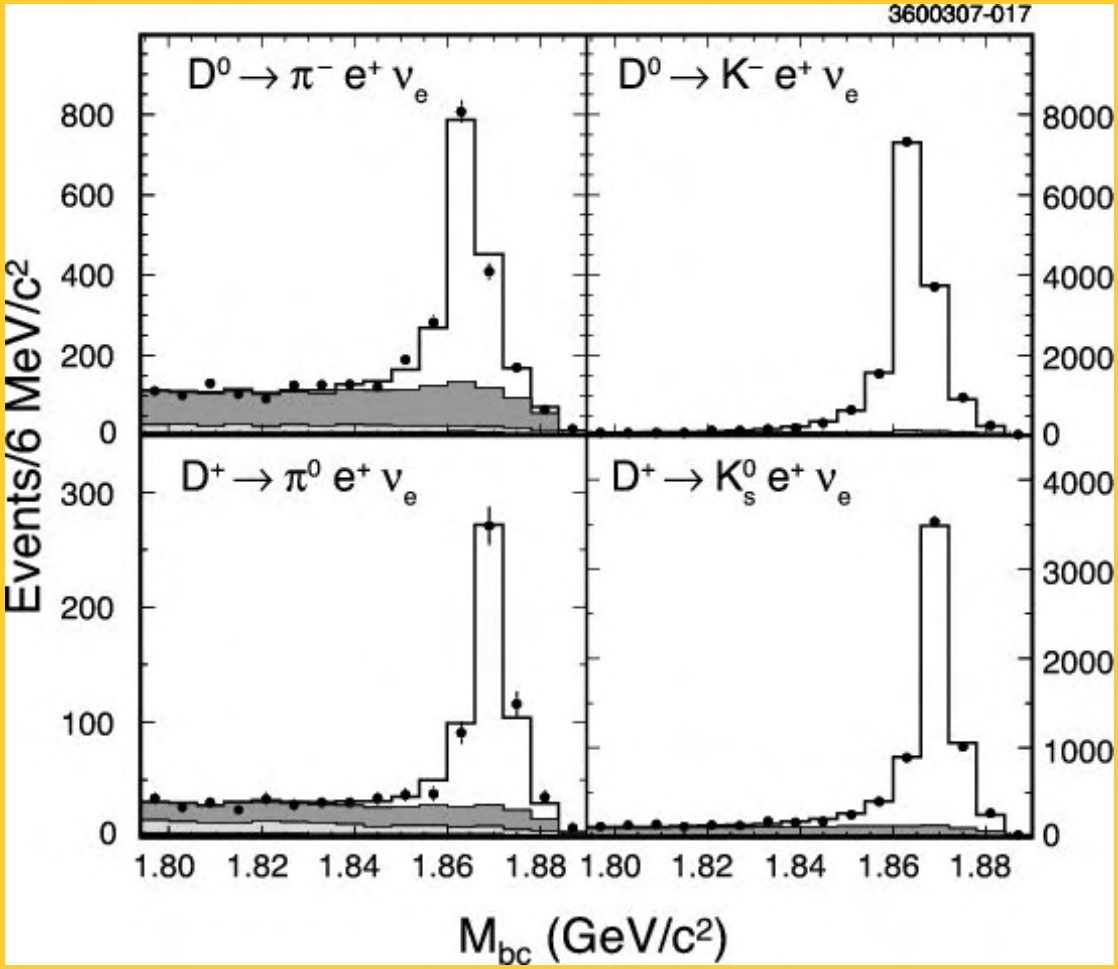
$D^0 \to K^- \pi^+ \pi^0$

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



- $U \equiv E_{miss} - |\vec{p}_{miss}|$
- Corrected for ~3 mrad crossing angle
- $\sigma_U \approx 12$ MeV (≈ 24 MeV with π^0)

Untagged $D \to (K/\pi)e\nu$



- Reconstruct ν 4-momentum
- Use with (K/π) and e and require energy consistency
- Better efficiency, more background, larger systematics

$D \to (K/\pi)e\nu$ Branching Fractions

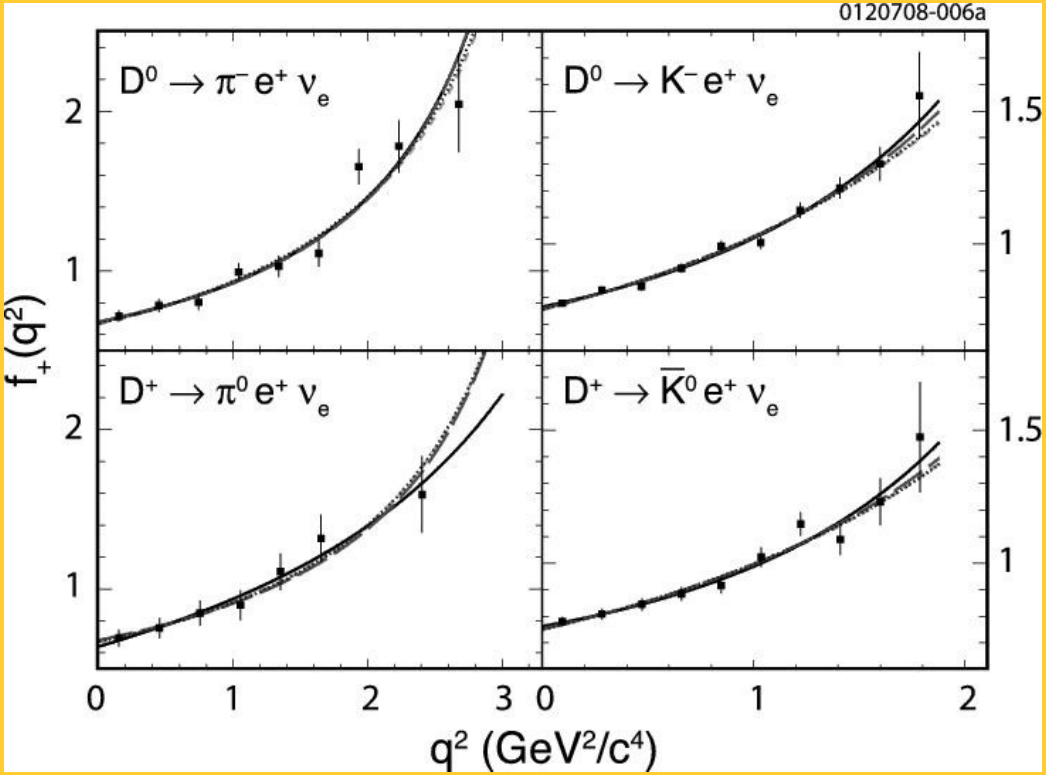
- 281 pb^{-1}; full data-set result coming soon
- Resolutions comparable
- Averages include correlations

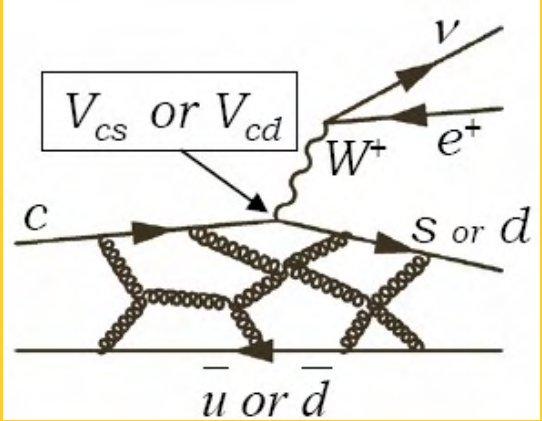
Branching Fractions [%]

	Tagged	Untagged	Average
$\pi^- e^+ \nu_e$	0.308 (13) (4)	0.299 (11) (9)	0.304 (11) (5)
$\pi^0 e^+ \nu_e$	0.379 (27) (23)	0.373 (22) (13)	0.378 (20) (12)
$K^- e^+ \nu_e$	3.60 (5) (5)	3.56 (3) (9)	3.60 (3) (6)
$K^0 e^+ \nu_e$	8.87 (17) (21)	8.53 (13) (23)	8.69 (12) (19)

Form Factors from $D \to (K/\pi)e\nu$ [1]

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





Form Factors from $D \to (K/\pi) e \nu$ [2]

Simple pole:

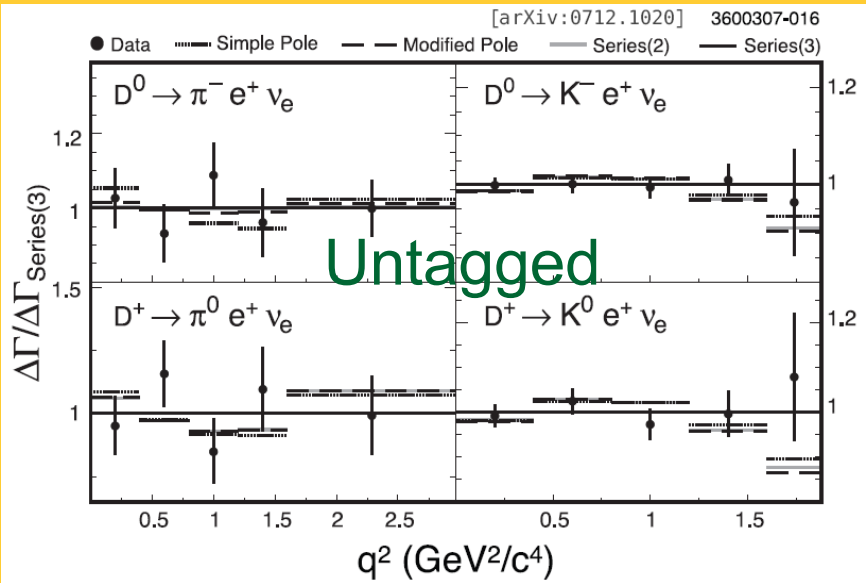
$$f_+(q^2) = \frac{f_+(0)}{\left(1 - \frac{q^2}{M^2_{pole}}\right)}$$

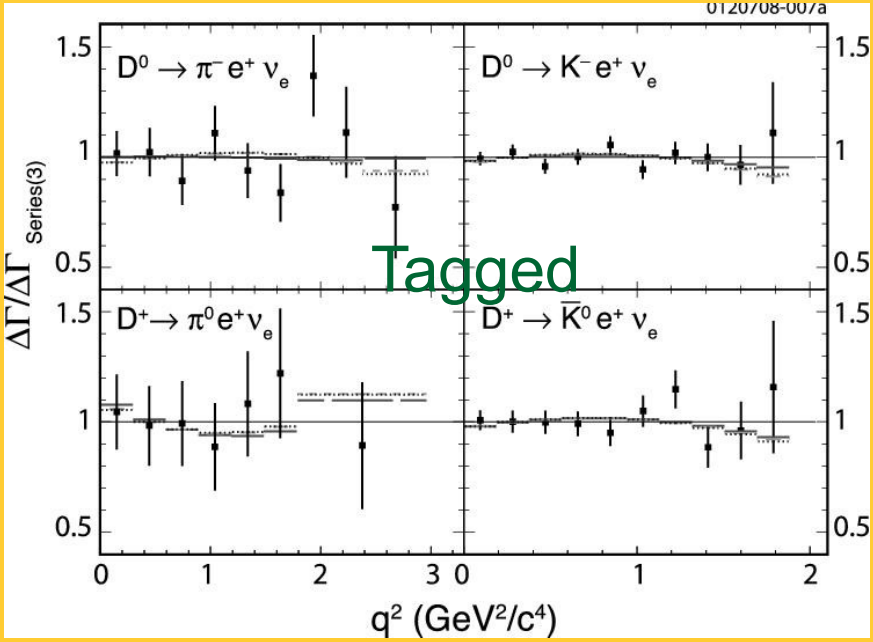
Modified pole:

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

Series expansion (Becher & Hill, PLB 633,61):

$$f_+(q^2) = \frac{a_0}{P(q^2)\phi(q^2,\ t_0)}\left(1 + \sum_k a_k(t_0) z(q^2,\ t_0)^k\right)$$





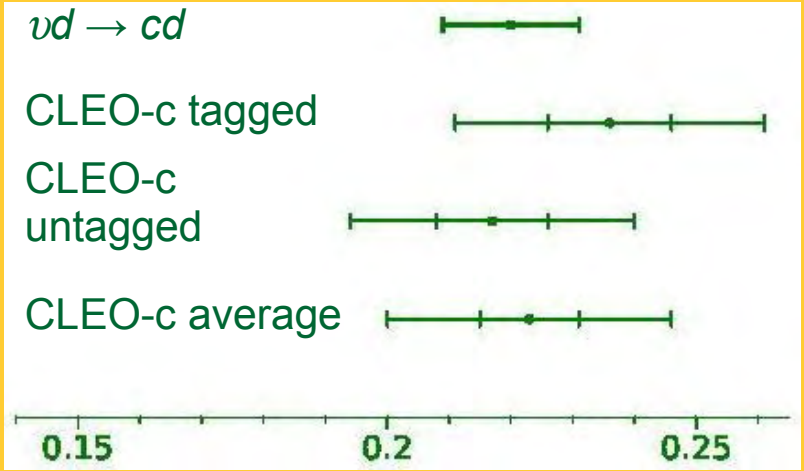
$|V_{cd}|$ and $|V_{cs}|$ from $D \to (K/\pi)e\nu$

- $|V_{cd}| = 0.233 \pm 0.008 \pm 0.003 \pm 0.023$

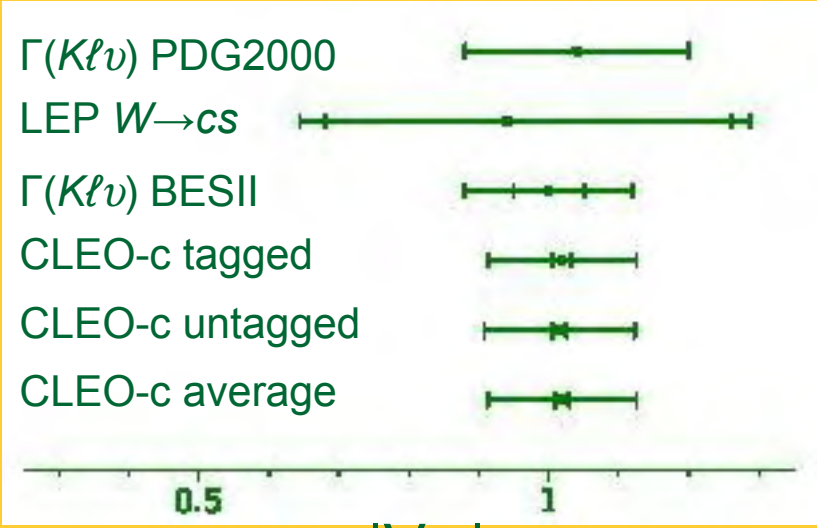
Most precise *D* meson SL decay determination

- $|V_{cs}| = 1.019 \pm 0.010 \pm 0.007 \pm 0.106$

Most precise determination

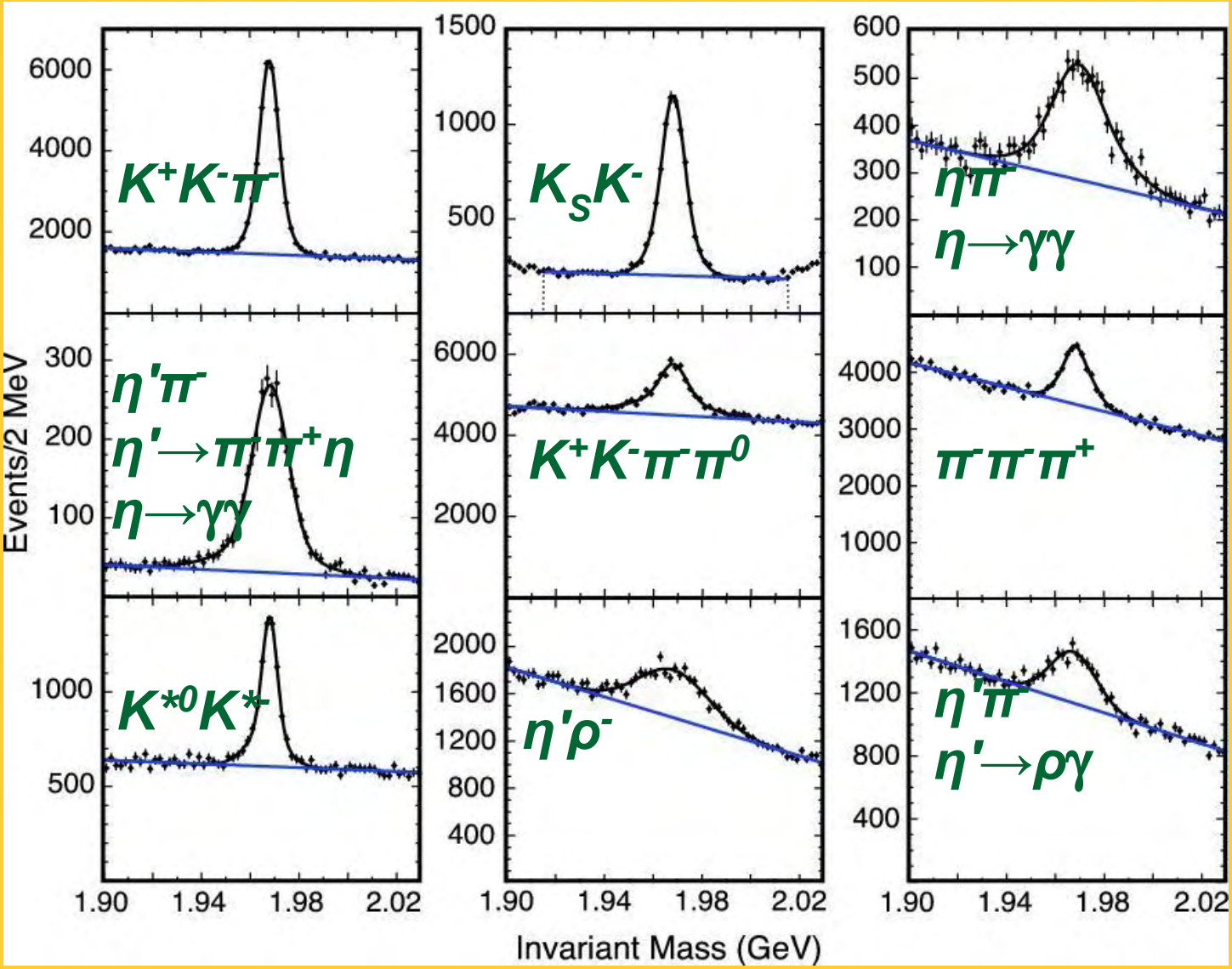


$|V_{cd}|$



$|V_{cs}|$

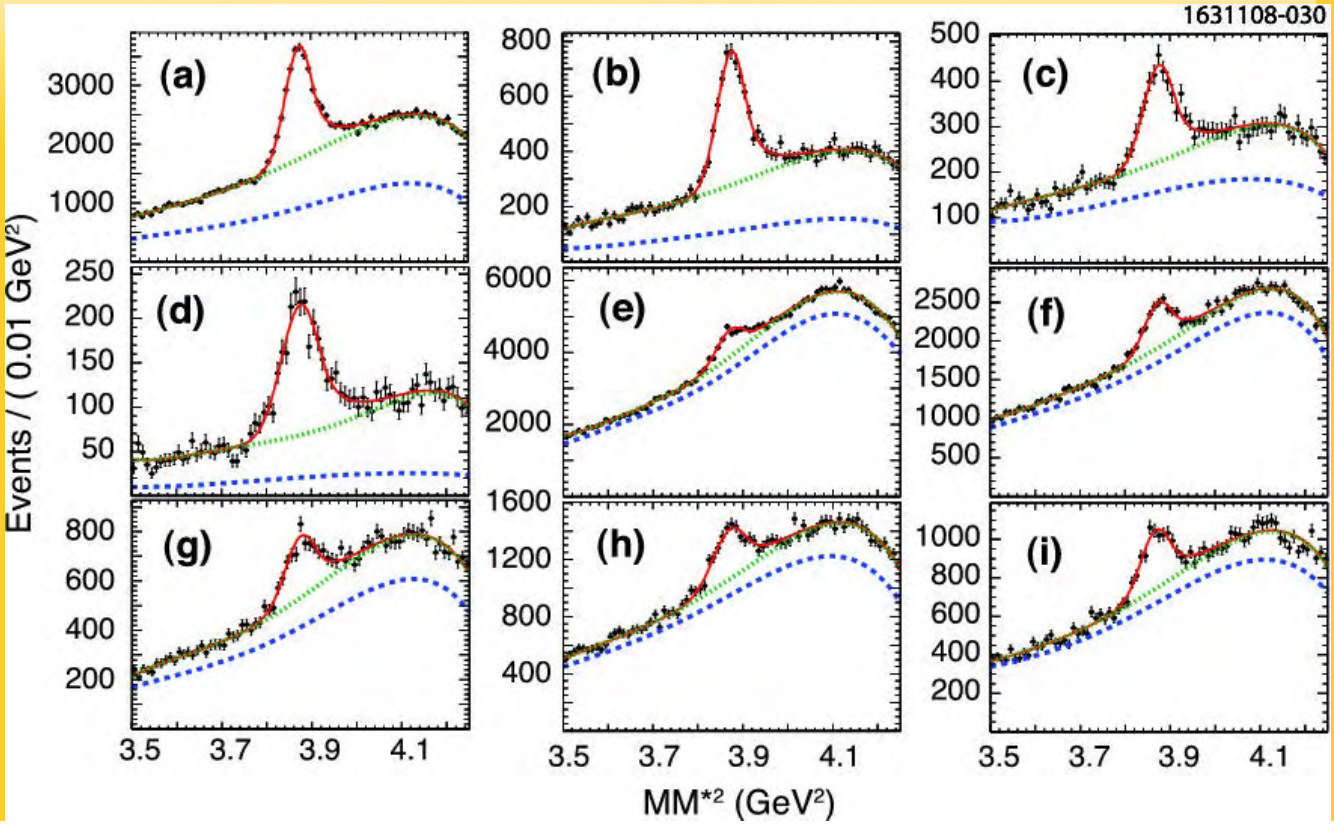
D_s^- Tag Modes for $f_{D_s^+}$



Identify D_s^+ for $f_{D_s^+}$

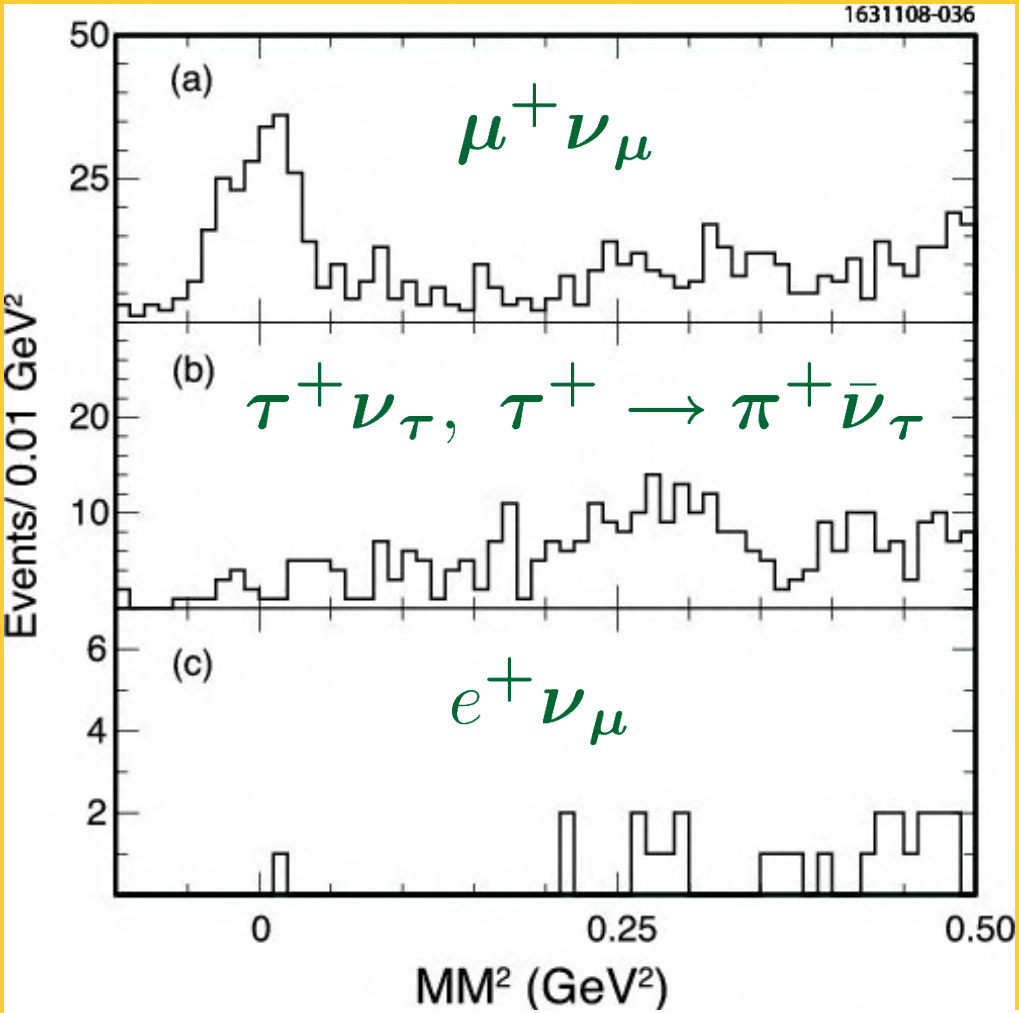
- Combine γ with tag

(a) $K^+K^-\pi^-$
(b) K_sK^-
(c) $\eta\pi^-$
(d) $\eta'\pi^-$, $\eta'\to\pi^-\pi^+\eta$
(e) $K^+K^-\pi^-\pi^0$
(f) $\pi^-\pi^-\pi^+$
(g) $K^{*0}K^{*-}$
(h) $\eta'\rho^-$
(i) $\eta'\pi^-$, $\eta'\to\rho\gamma$



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

$D_s^+ \to \ell^+ \nu_\ell$ for $f_{D_s^+}$



- D_s^- tag, γ, one + track, no cluster > 300 MeV

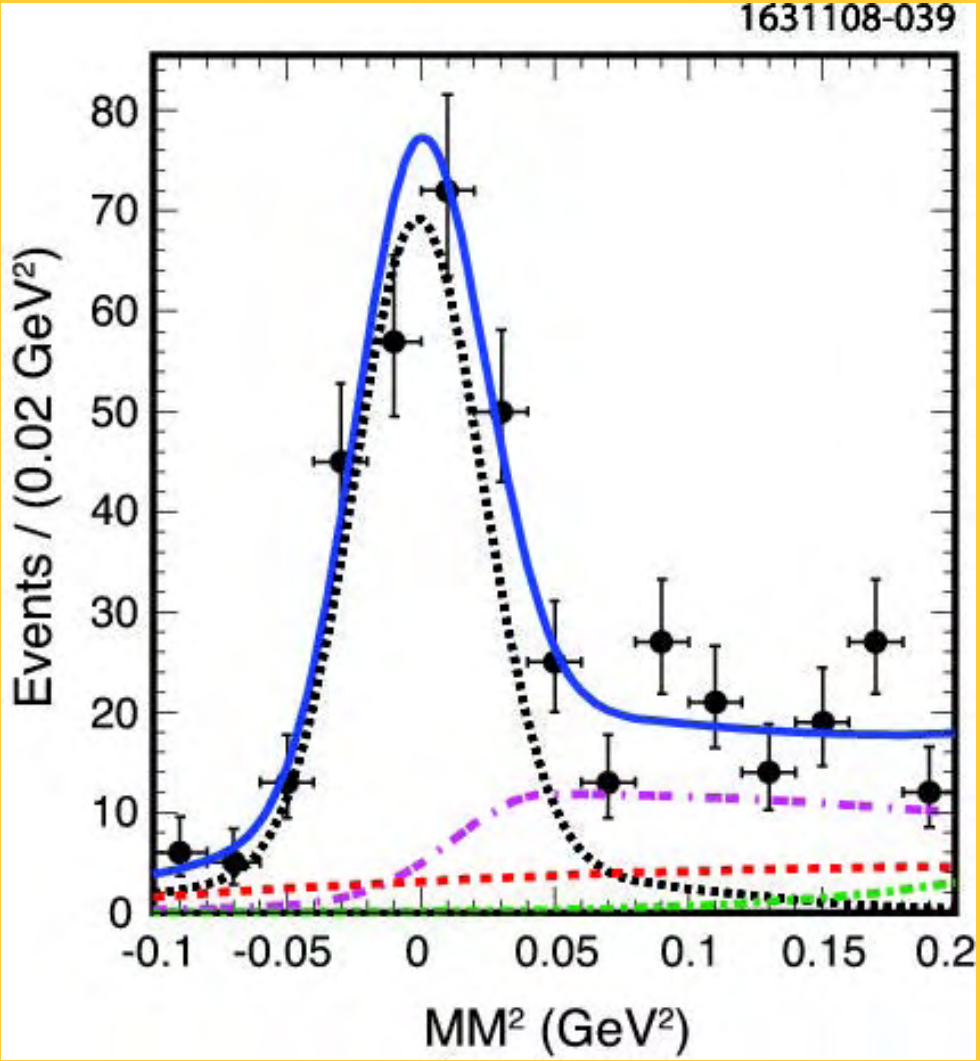
(a) < 300 MeV in calorimeter (track)

(b) > 300 MeV in calorimeter (track)

(c) Track = electron

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

$D_s^+ \to \ell^+ \nu_\ell$



Cases (a) & (b)

Sum

$\mu^+ \nu_\mu$

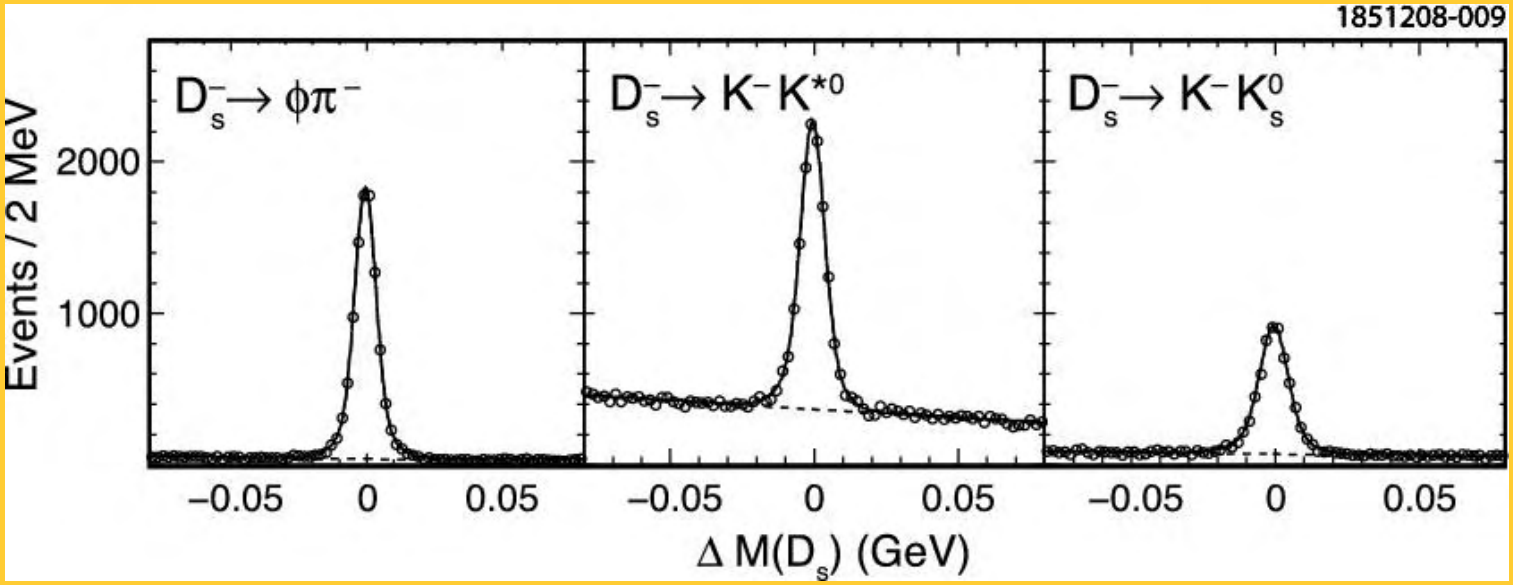
$\tau^+ \nu_\tau, \ \tau^+ \to \pi^+ \bar{\nu}_\tau$

D_s^+ sidebands

Other D_s^+

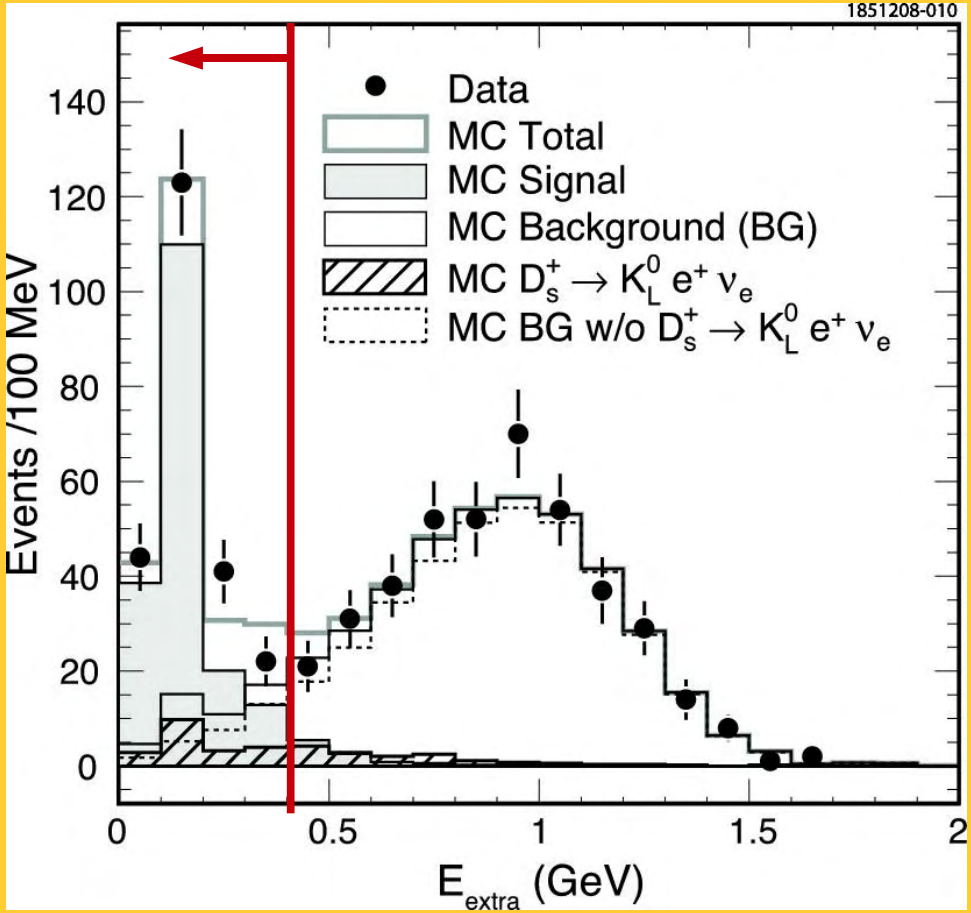
D_s^- Tag for $D_s^+ \to \tau^+\nu_\tau$

- A second analysis, $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$
  - Tag only $\varphi\pi^-$, K^-K^{*0}, and $K^-K_S^0$
  - Find only e^+ opposite D_s^- tag
  - $\Delta M(D_s)$ sideband subtraction



$D_s^+ \rightarrow \tau^+ \nu_\tau$ Signal

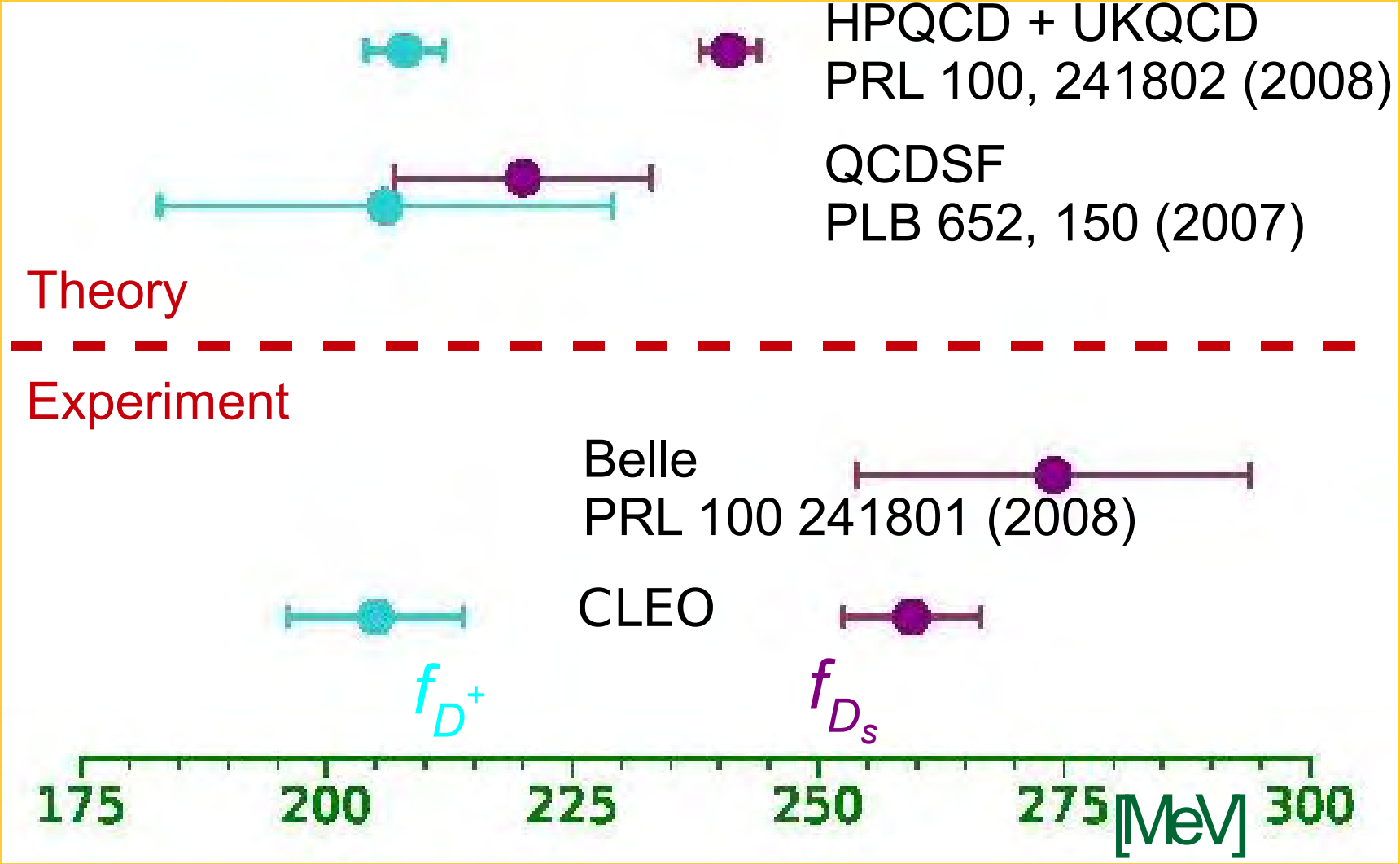
- Expect extra energy: 100 MeV to 200 *M*eV from $D_s^* \rightarrow \gamma(\pi^0) D_s$
- Signal E_{extra} < 400 MeV



$f_{D_s^+}$ from $D_s^+ \to \ell^+ \nu_\ell$

Mode	BF (%)	f_{D_s} (MeV)
(1) $\mu\nu$	0.565 ± 0.045 ± 0.017	257.3 ± 10.3 ± 3.9
(2) $\tau\nu$ (with $\tau \to \pi\nu$)	6.42 ± 0.81 ± 0.18	278.7 ± 17.1 ± 3.8
(3) $\mu\nu$(eff) ($\tau\nu/\mu\nu$ fixed to SM ratio)	0.591 ± 0.037 ± 0.018	263.3 ± 8.2 ± 5.2
(4) $\tau\nu$ (with $\tau \to e\nu\nu$)	5.30 ± 0.47 ± 0.22	252.5 ± 11.1 ± 5.2
CLEO average from (3) & (4)		259.5 ± 6.6 ± 3.1

$f_{D_s^+}$ and f_{D^+}

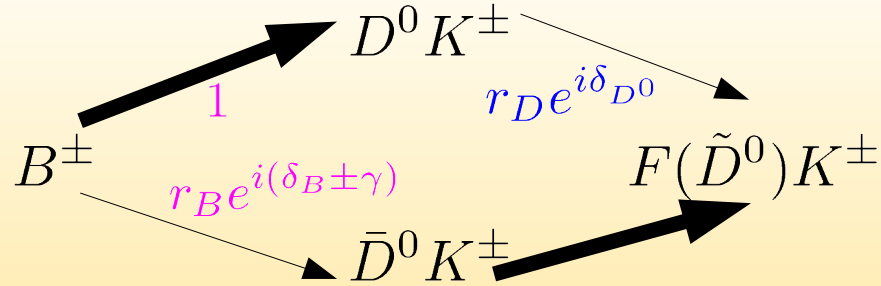

HPQCD + UKQCD
PRL 100, 241802 (2008)
QCDSF
PLB 652, 150 (2007)
Theory
Experiment
Belle
PRL 100 241801 (2008)
CLEO
f_{D^+}
f_{D_s}
175
200
225
250
275
300
[MeV]

Coherence

- $C_{\psi(3770)} = -1 \Rightarrow \mathbf{D^0} - \bar{\mathbf{D}}^{\mathbf{0}}$ QM Correlated
- CP-tags along with flavor- and channel-tags
- Model-independent access to decay amplitude size and phase (Dalitz plot)
- $\Rightarrow$ Reduced systematic uncertainty in, e.g., γ/ϕ_3 measurement

γ/ϕ_3 Via $D \to K_{S,L}\pi\pi$ [1]

- $\mathcal{A}(\mathrm{B}^{\pm} \to \tilde{\mathrm{D}}^{0}\mathrm{K}^{\pm}) \propto \mathcal{A}_{\mathrm{D}^0}(\mathrm{x},\ \mathrm{y}) + \mathrm{r_B}\mathrm{e}^{\mathrm{i}(\delta_{\mathrm{B}} \pm \gamma)}\mathcal{A}_{\bar{\mathrm{D}}^0}(\mathrm{x},\ \mathrm{y})$
- $\tilde{\mathrm{D}}^{0} \to \mathrm{K}_{(\mathrm{S})}(\mathrm{K}/\pi)\mathrm{n}\pi$



- Without mixing or CP-violation,

$$\mathcal{A}_{\bar{\mathrm{D}}^0}(\mathrm{x},\ \mathrm{y}) = \mathcal{A}_{\mathrm{D}^0}(\mathrm{y},\ \mathrm{x})$$

- Rates then depend on strong phase difference

$$\Delta\delta_{\mathrm{D}^0} \equiv \delta_{\mathrm{D}^0}(\mathrm{x},\ \mathrm{y}) - \delta_{\mathrm{D}^0}(\mathrm{y},\ \mathrm{x})$$

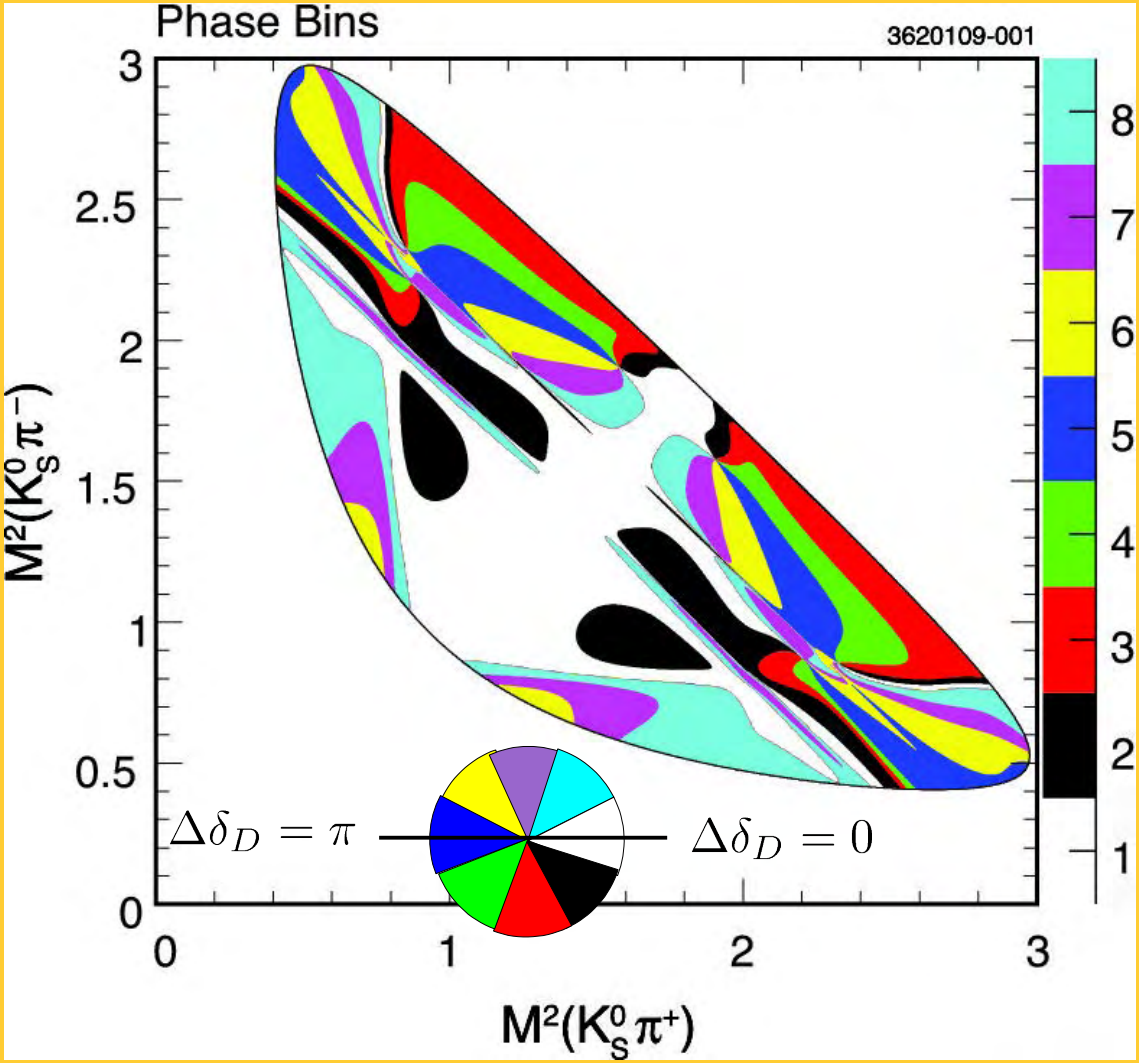
- Interference amplitudes parameterized by

$$\cos\left[\Delta\delta_{\mathrm{D}^0}(\mathrm{x},\ \mathrm{y})\right] \text{ and } \sin\left[\Delta\delta_{\mathrm{D}^0}(\mathrm{x},\ \mathrm{y})\right]$$

γ/ϕ_3 Via $D \to K_{S,L}\pi\pi$ [2]

- $\tilde{D}^0 \to K_S \pi^+ \pi^-$ Cabibbo favored
- Divide Dalitz plot in 2N bins, indexed *-i to i*, about $x=y \Rightarrow \quad x \leftrightarrow y \Leftrightarrow i \leftrightarrow -i$
  - *Giri, et al.* [PRD 68, 054018 (2003)]
- Bin to minimize $\Delta\delta_{D^0}$ variation within a bin
  - Bondar, *et al*. [EPJC 47, 347 (2006)]
- Equalize phase difference bins using BaBar isobar model
  - [PRL 95, 121802 (2005)]

γ/ϕ_3 Via $D \to K_{S,L}\pi\pi$ [3]



- CP tags sensitive to $\cos[\Delta\delta_{D^0}(x, y)]$
- $\tilde{D}^0 \to K_S\pi^+\pi^-$ tags sensitive to both

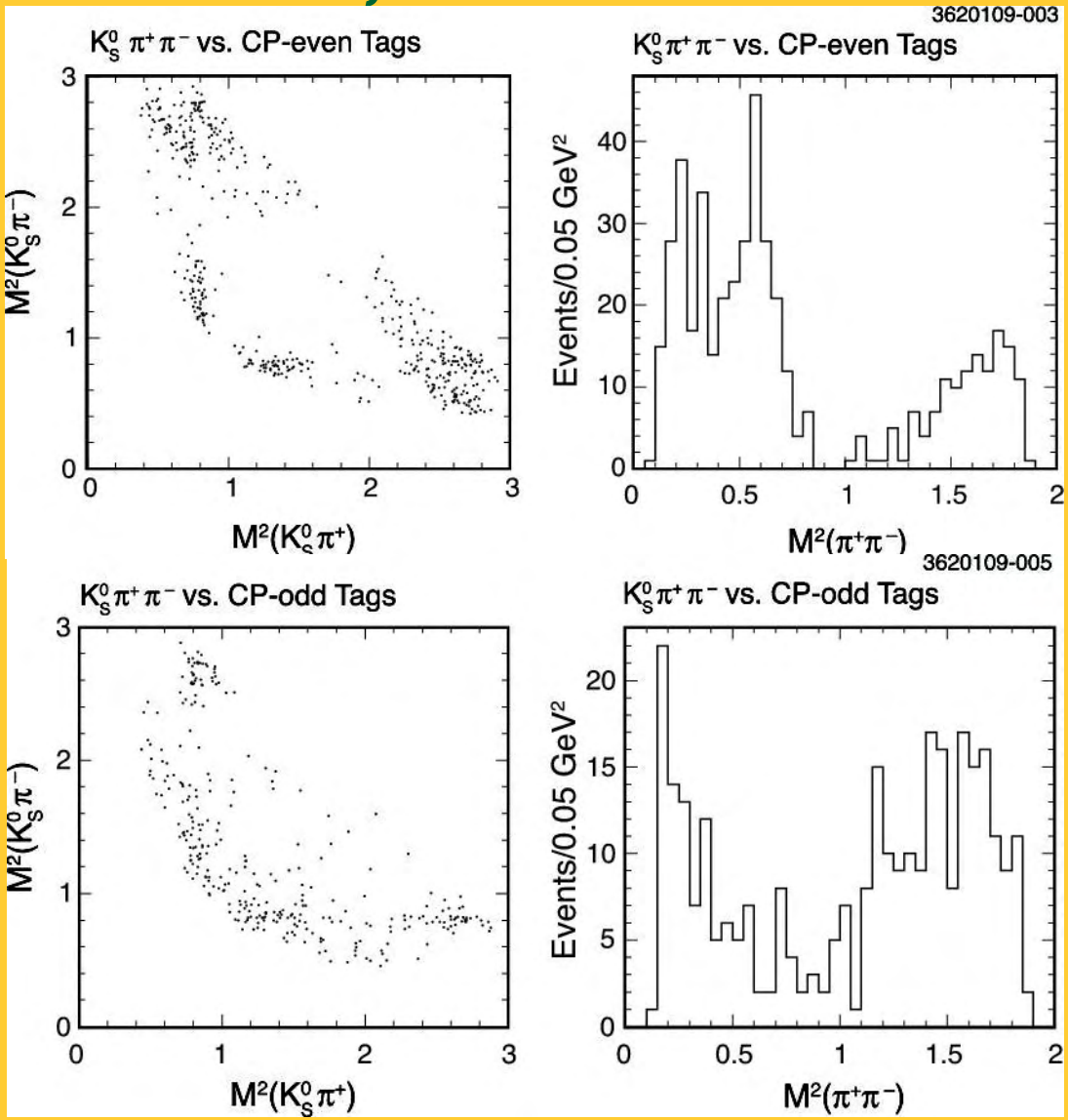
  $\cos[\Delta\delta_{D^0}(x, y)]$

  and

  $\sin[\Delta\delta_{D^0}(x, y)]$

γ/ϕ_3 Via $D \to K_{S,L}\pi\pi$ [4]

Mode	Single Tag Yield	$K_S^0\pi^+\pi^-$ Yield	$K_L^0\pi^+\pi^-$ Yield
Flavor Tags			
$K^-\pi^+$	144563 ± 403	1447	2858
$K^-\pi^+\pi^0$	258938 ± 581	2776	5130
$K^-\pi^+\pi^+\pi^-$	220831 ± 541	2250	4110
$K^-e^+\nu$	123412 ± 4591	1356	-
CP-Even Tags			
K^+K^-	12867 ± 126	124	345
$\pi^+\pi^-$	5950 ± 112	62	172
$K_S^0\pi^0\pi^0$	6562 ± 131	56	-
$K_L^0\pi^0$	27955 ± 2013	259	-
CP-OddTags			
$K_S^0\pi^0$	19059 ± 150	189	281
$K_S^0\eta$	2793 ± 69	39	41
$K_S^0\omega$	8512 ± 107	83	-
$K_S^0\pi^+\pi^-$	-	575	867



γ/ϕ_3 Via $D \to K_{S,L}\pi\pi$ [5]

i	$(\cos\Delta\delta_{D^0})_i$	$(\sin\Delta\delta_{D^0})_i$
1	$0.743 \pm 0.037 \pm 0.022 \pm 0.013$	$0.014 \pm 0.160 \pm 0.077 \pm 0.045$
2	$0.611 \pm 0.071 \pm 0.037 \pm 0.009$	$0.014 \pm 0.215 \pm 0.055 \pm 0.017$
3	$0.059 \pm 0.063 \pm 0.031 \pm 0.057$	$0.609 \pm 0.190 \pm 0.076 \pm 0.037$
4	$-0.495 \pm 0.101 \pm 0.052 \pm 0.045$	$0.151 \pm 0.217 \pm 0.069 \pm 0.048$
5	$-0.911 \pm 0.049 \pm 0.032 \pm 0.021$	$-0.050 \pm 0.183 \pm 0.045 \pm 0.036$
6	$-0.736 \pm 0.066 \pm 0.030 \pm 0.018$	$-0.340 \pm 0.187 \pm 0.052 \pm 0.047$
7	$0.157 \pm 0.074 \pm 0.042 \pm 0.051$	$-0.827 \pm 0.185 \pm 0.060 \pm 0.036$
8	$0.403 \pm 0.046 \pm 0.021 \pm 0.002$	$-0.409 \pm 0.158 \pm 0.050 \pm 0.002$

- Uncertainty from $\Delta\delta_{D^0}$ presently contributes 7º to 9º to γ/ϕ_3 width
- CLEO's model-independent determination should reduce this effect to 2º or less

γ/ϕ_3 Via $D \to K\pi(n\pi)$ [1]

- Atwood-Dunietz-Soni (ADS) Method
  - $\tilde{D}^0 \to K^+\pi^-$

$$\Gamma(B^- \to (K^+\pi^-)_D K^-) \propto r_B^2 + (r_D^{K\pi})^2 + 2 r_B r_D^{K\pi} \cos(\delta_B + \delta_D^{K\pi} - \gamma)$$

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

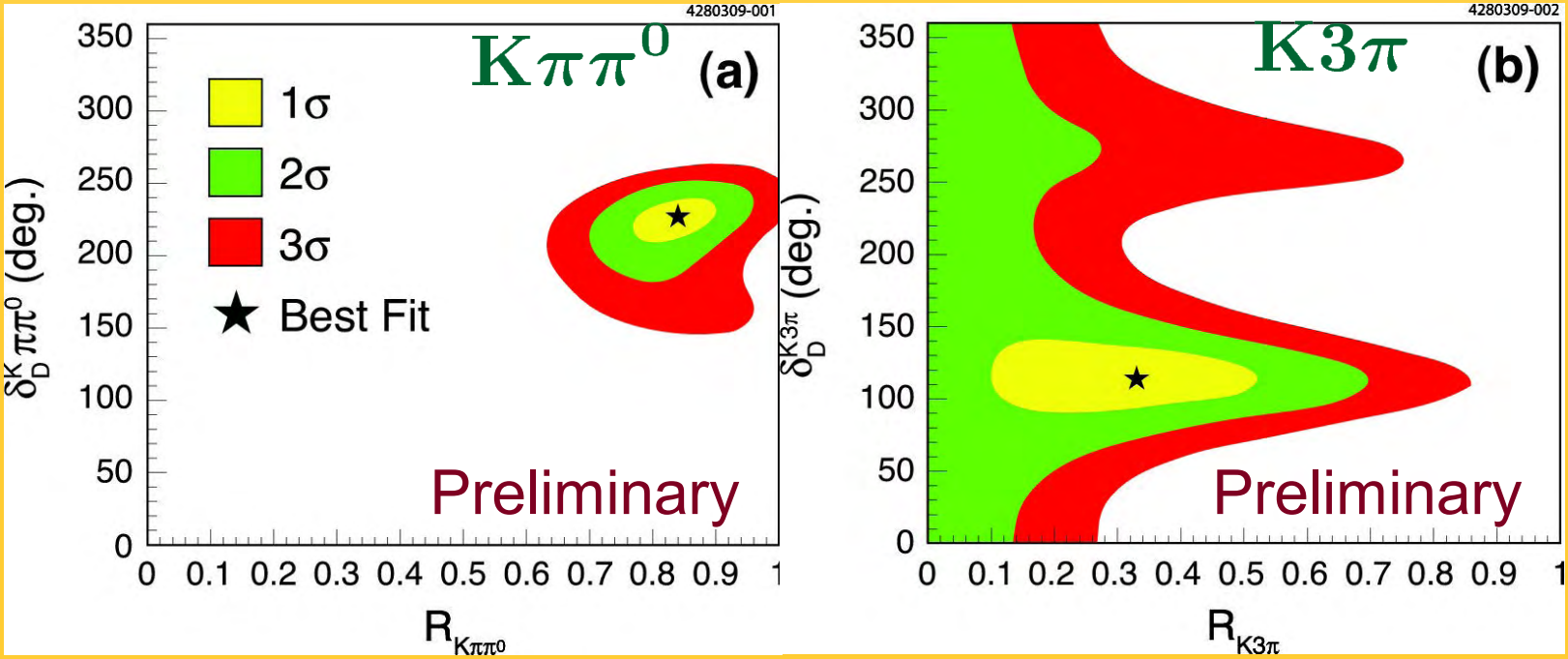
coherence factor

$$\Gamma(B^- \to (K^+3\pi)_D K^-) \propto r_B^2 + (r_D^{K3\pi})^2 + 2 R_D^{K3\pi} r_B r_D^{K3\pi} \cos(\delta_B + \delta_D^{K3\pi} - \gamma)$$

  - Coherent double-tag rates sensitive to combinations of R and δ
    - $K^\pm\pi^\pm\pi^-\pi^+ \; vs. \; K^\pm\pi^\pm\pi^-\pi^+ \Rightarrow \left(R_D^{K3\pi}\right)^2$
    - $K^\pm\pi^\pm\pi^-\pi^+ \; vs. \; DP \Rightarrow R_D^{K3\pi}\cos(\delta_D^{K3\pi})$
    - $K^\pm\pi^\pm\pi^-\pi^+ \; vs. \; K^\pm\pi^\mp \Rightarrow R_D^{K3\pi}\cos(\delta_D^{K\pi} - \delta_D^{K3\pi})$

γ/ϕ_3 Via $D \to K\pi(n\pi)$ [2]

- $\delta_D^{K\pi} = \left(22^{+11+9}_{-12-11}\right)^\circ \Rightarrow \delta_D^{K\pi} = \left(22.5^{+10.5}_{-12.0}\right)^\circ$ (ICHEP08 HFAG)
- Preliminary:
  - $R_D^{K3\pi} = 0.33^{+0.20}_{-0.23}$ $\quad \delta_D^{K3\pi} = \left(114^{+20}_{-23}\right)^\circ$
  - $R_D^{K\pi\pi^0} = 0.84 \pm 0.07$ $\quad \delta_D^{K\pi\pi^0} = \left(227^{+14}_{-17}\right)^\circ$



CLEO'S IMPACT ON CKM

- $|V_{cd}|$, $|V_{cs}| \Rightarrow |V_{ub}|$ *from* $D \rightarrow (K/\pi)e\nu$

  PRL 100, 251802 (2008), PRD 77, 112005 (2008)

  arXiv: 0810.38 (accepted by PRD)

- $f_{D_s^+} \Rightarrow f_B$, f_{B_s} from $D_s^+ \rightarrow \ell^+\nu$

  arXiv:0901.1147 (accepted by PRD)

  arXiv:0901.1216 (accepted by PRD)

- γ/ϕ_3 *with help from* $D \rightarrow Kn\pi$

  ADS $K\pi$: PRL 100, 221801 (2008), PRD 78, 012001 (2008)

  Dalitz K_S and ADS $Kn\pi$ results to be submitted to PRL, PRD