Semileptonic decays of D mesons at CLEO

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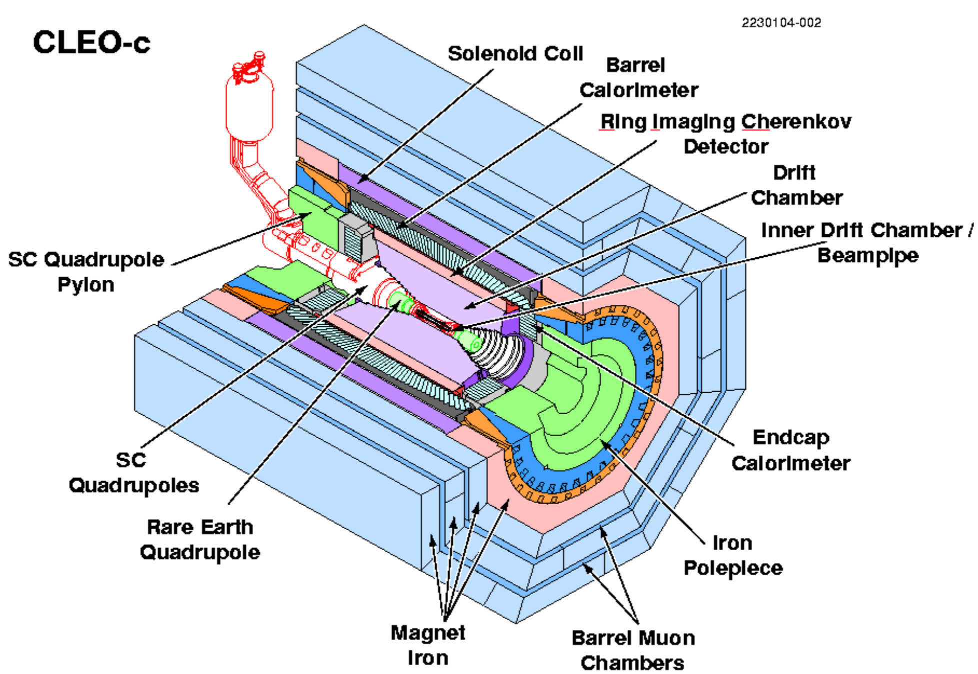
for the CLEO collaboration

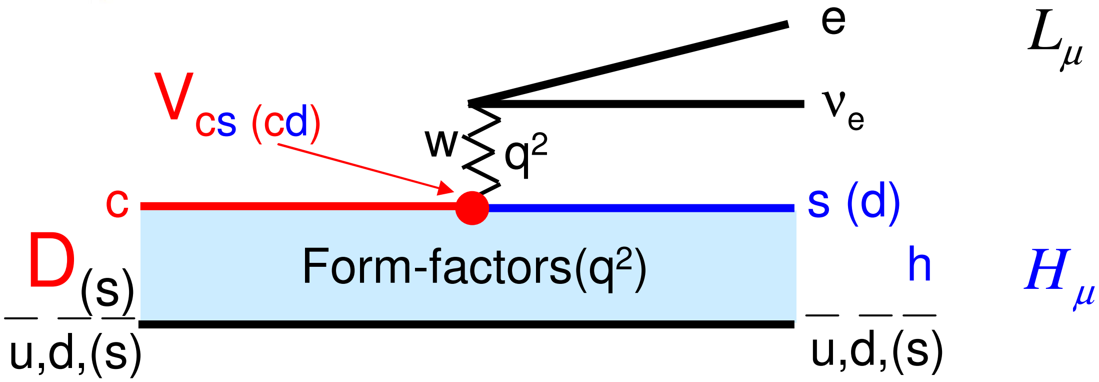
Content of the talk

- Report on two recent measurements with the CLEO-c detector:
  - Improved measurements of D meson semileptonic decays to π and K mesons [arXiv:0906.2983]
  - Study of semileptonic decay $D_s \rightarrow f_0(980)e^+\nu$ and implications for $B_s \rightarrow J/\psi f_0$ [*preliminary*].



- Data collected at charm threshold:
  - $e^+e^- \rightarrow \psi(3770) \rightarrow D\overline{D}$
  - $e^+e^- \rightarrow D_s^*\overline{D}_s$ at 4170 MeV
- CLEO-c detector:
  - Charged particle detection (1T): σ_p/p=0.6% at 1 GeV
  - Photon detection: σ_E/E=4.8% at 100 MeV, 2.2% at 1 GeV
  - Hadron ID: dE/dX+RICH (fake rates at a few % level)

Motivation for $D \to K/\pi\ e^+\nu$ Measurements



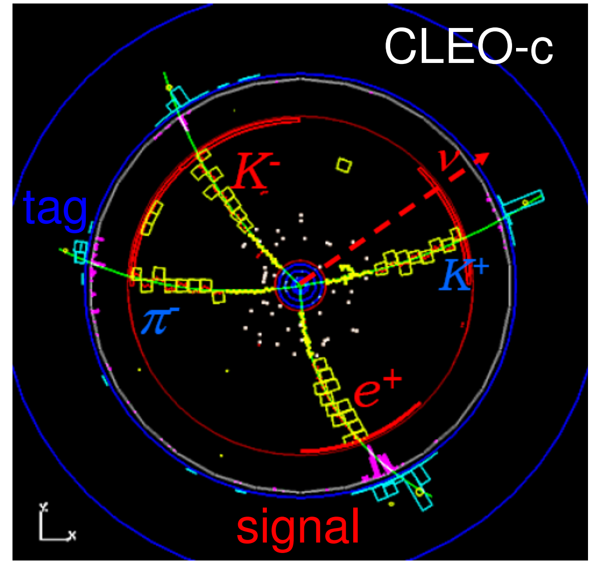
$$M(D \to h\, e\, \nu) = -i\frac{G_F}{\sqrt{2}} V_{cs\,(cd)} L_\mu H^\mu$$

Factorization!

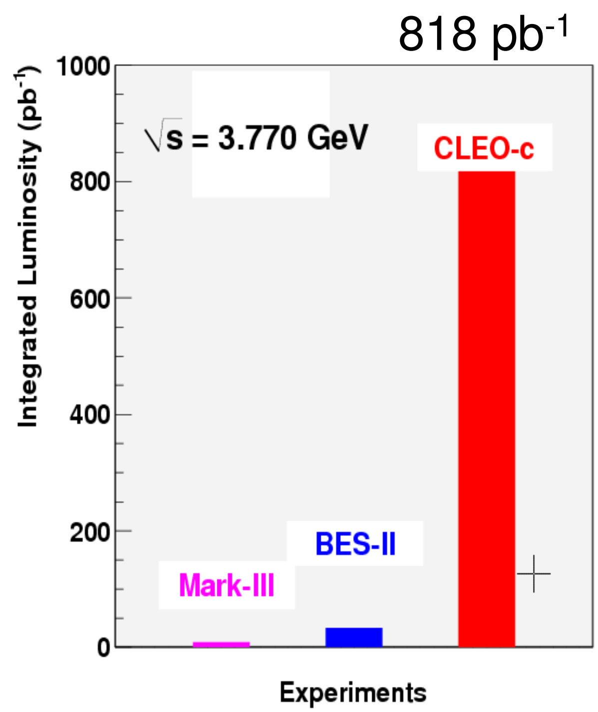
- Direct determination of $|V_{cs\,(cd)}|$.
- Theoretical (Lattice QCD) errors on the form-factor predictions dominate.
- Taking $|V_{cs\,(cd)}|=|V_{ud\,(us)}|$ can turn data into form-factor measurements (normalization and q^2 dependence) to test/develop LQCD.
- Potentially, leads to improved predictions for the form-factors in semileptonic b decays and improved determination of $|V_{ub}|$.
- Only one form-factor in decays to pseudoscalar mesons – easiest to deal with theoretically.

Tagging technique

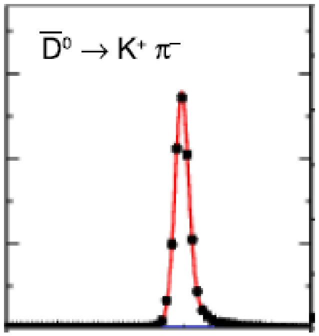
- **Very effective at threshold: $e^+e^- \to D\overline{D}$:**
  - No fragmentation particles produced
- **Reconstruct one D (tag) in several clean hadronic decay modes:**
  - Cut on $\Delta E = E_D - E_{beam}$
  - Fit $M_{bc} = \sqrt{E_{beam}^2 - \mathbf{p}_D^2}$ to determine N_{tag}
  - The tag determines momentum of the other D: $\mathbf{p}_{D\ signal} = -\mathbf{p}_{D\ tag}$



- **Find subsample in which the rest of reconstructed particles consists of an electron (e) and desired hadron (h) from semileptonic D-decay.**
  - Calculate missing (i.e. neutrino) energy ($E_{miss} = E_{beam} - E_e - E_h$) and momentum ($\mathbf{p}_{miss} = -\mathbf{p}_{D\ tag} - \mathbf{p}_e - \mathbf{p}_h$). Fit $U_{miss} = E_{miss} - |\mathbf{p}_{miss}|$ to extract N_{signal}.
  - $BR = (N_{signal}/\varepsilon_{signal}) / (N_{tag}/\varepsilon_{tag})$
  - Also determine differential rates in $q^2 = (E_{beam} - E_h)^2 - (-\mathbf{p}_{D\ tag} - \mathbf{p}_h)^2$

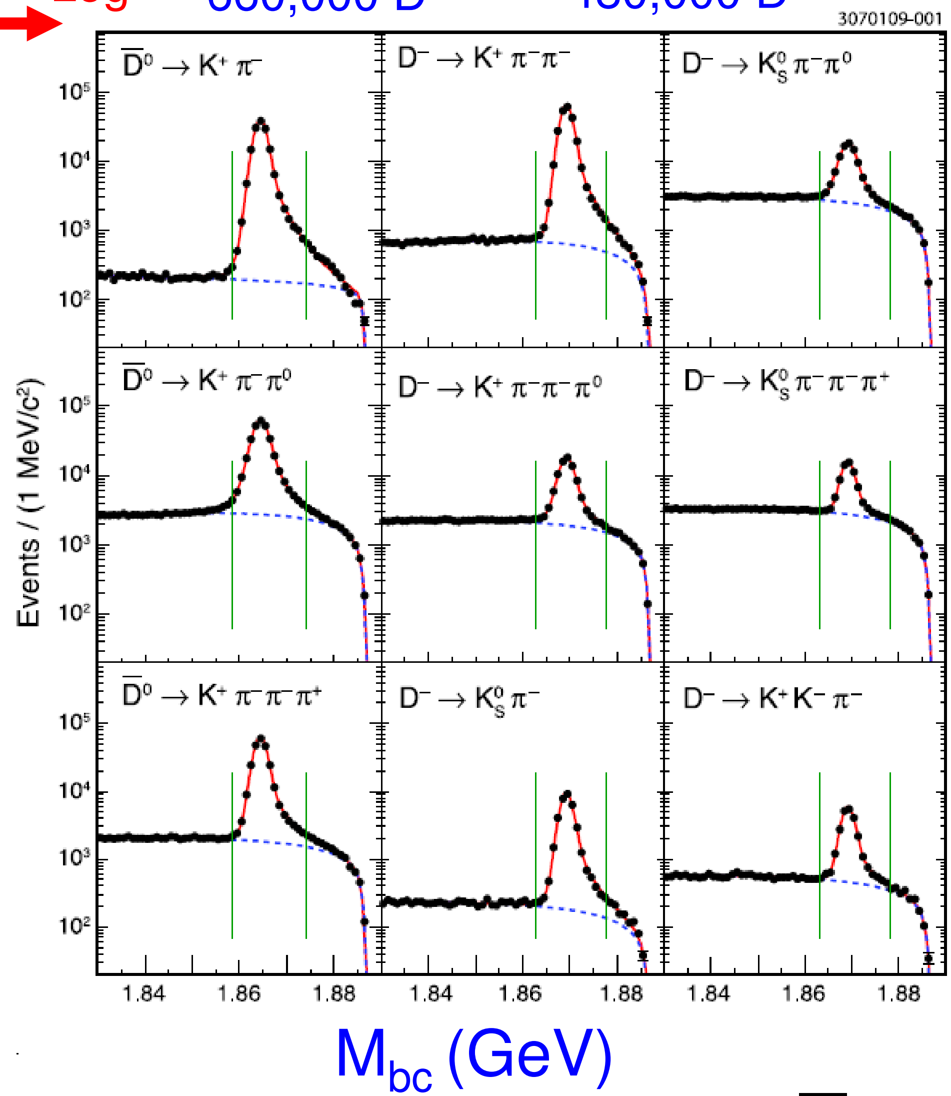


Tag



Linear ↔ Log

~660,000 D^0 ~480,000 $D^\pm$



- CLEO-c reconstructs a tag in about ~20% of all $D\bar{D}$ events
- Compared to ~0.1% tagging efficiency for $\Upsilon(4S) \to B\bar{B}$

Signal – π, K (tagged)

Cabibbo suppressed

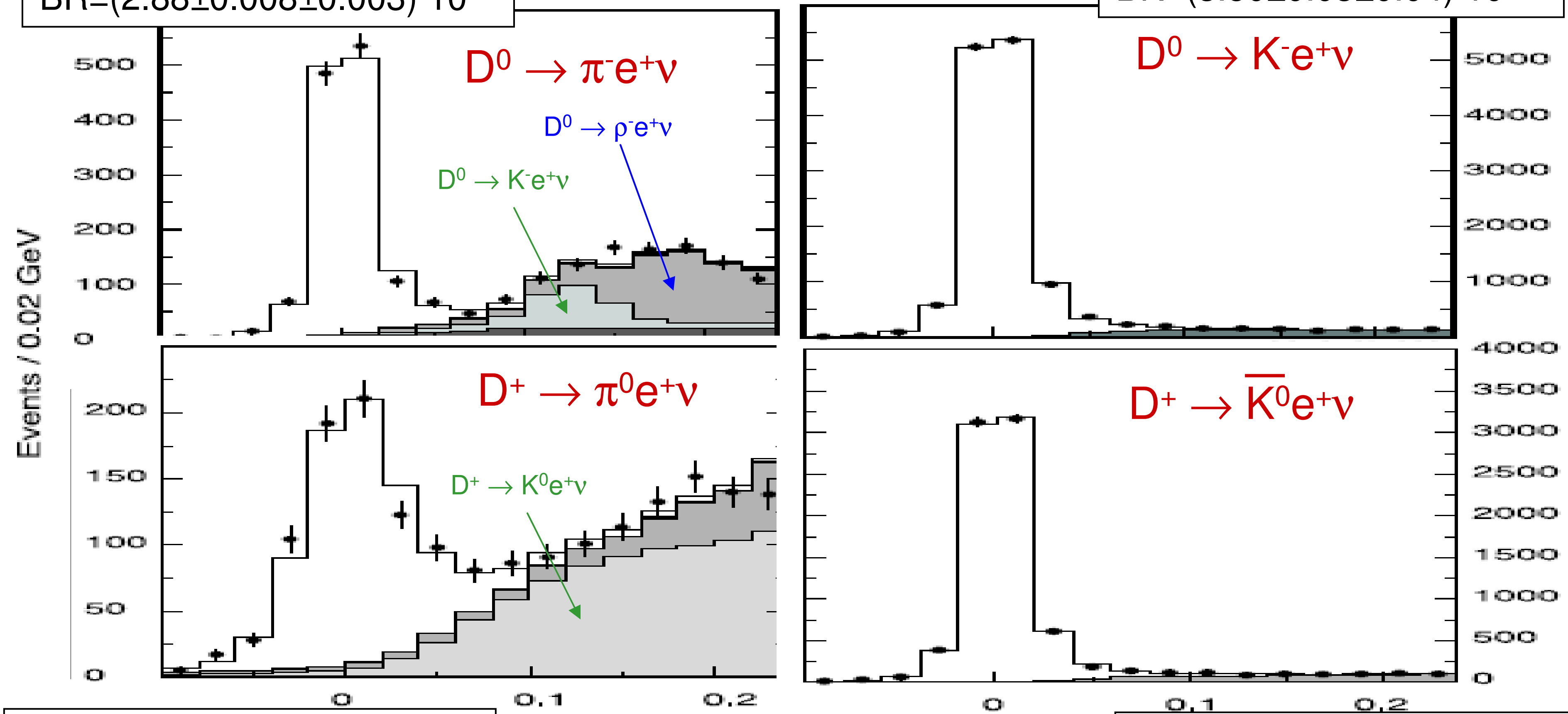
~1,400 events

BR=(2.88±0.008±0.003) 10^{-3}

Cabibbo favored

~14,000 events

BR=(3.50±0.03±0.04) 10^{-2}



~800 events

BR=(4.05±0.016±0.009) 10^{-3}

$U_{miss} = E_{mis} - |\mathbf{p}_{mis}|$ (GeV)

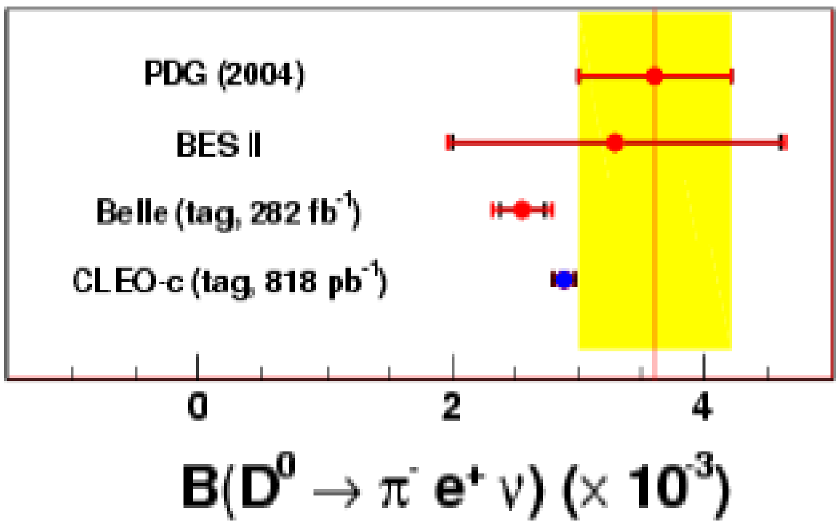
~8,500 events

BR=(8.83±0.01±0.02) 10^{-3}

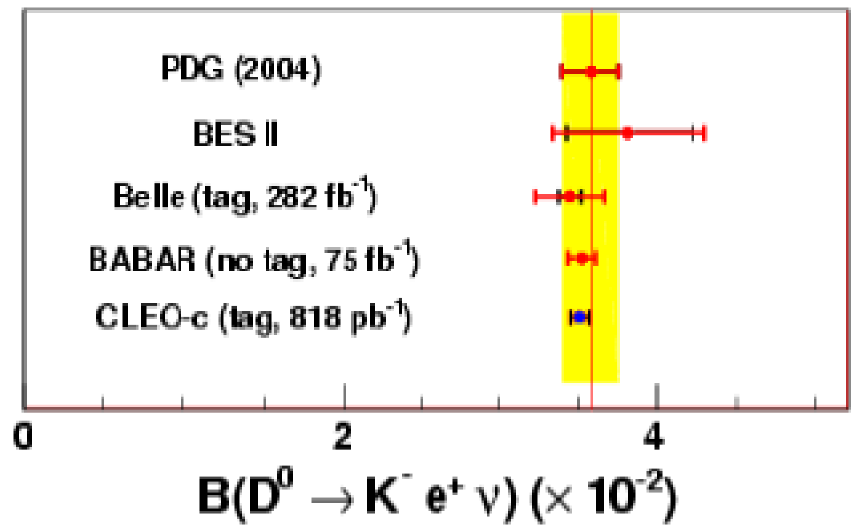
- Excellent background suppression. Small feed-across due to threshold kinematics.

Branching Ratio Results - Comparison

Cabibbo suppressed



Cabibbo favored



- Significant improvement in precision by recent BaBar/Belle/CLEO-c measurements (CLEO-c most precise).

Form factors

- Form factors are related to probability of forming final state hadron at given q^2.
- Theoretical predictions for form factors needed to turn the measured rates into $V_{cs\ (cd)}$ determinations.
- Theory often calculates this probability at fixed q^2 and uses parameterizations to extrapolate to full q^2 range.
- Theoretical approaches include phenomenological models, QCD sum rules, LQCD.
- Only the latter is systematically improvable.

h – pseudoscalar:

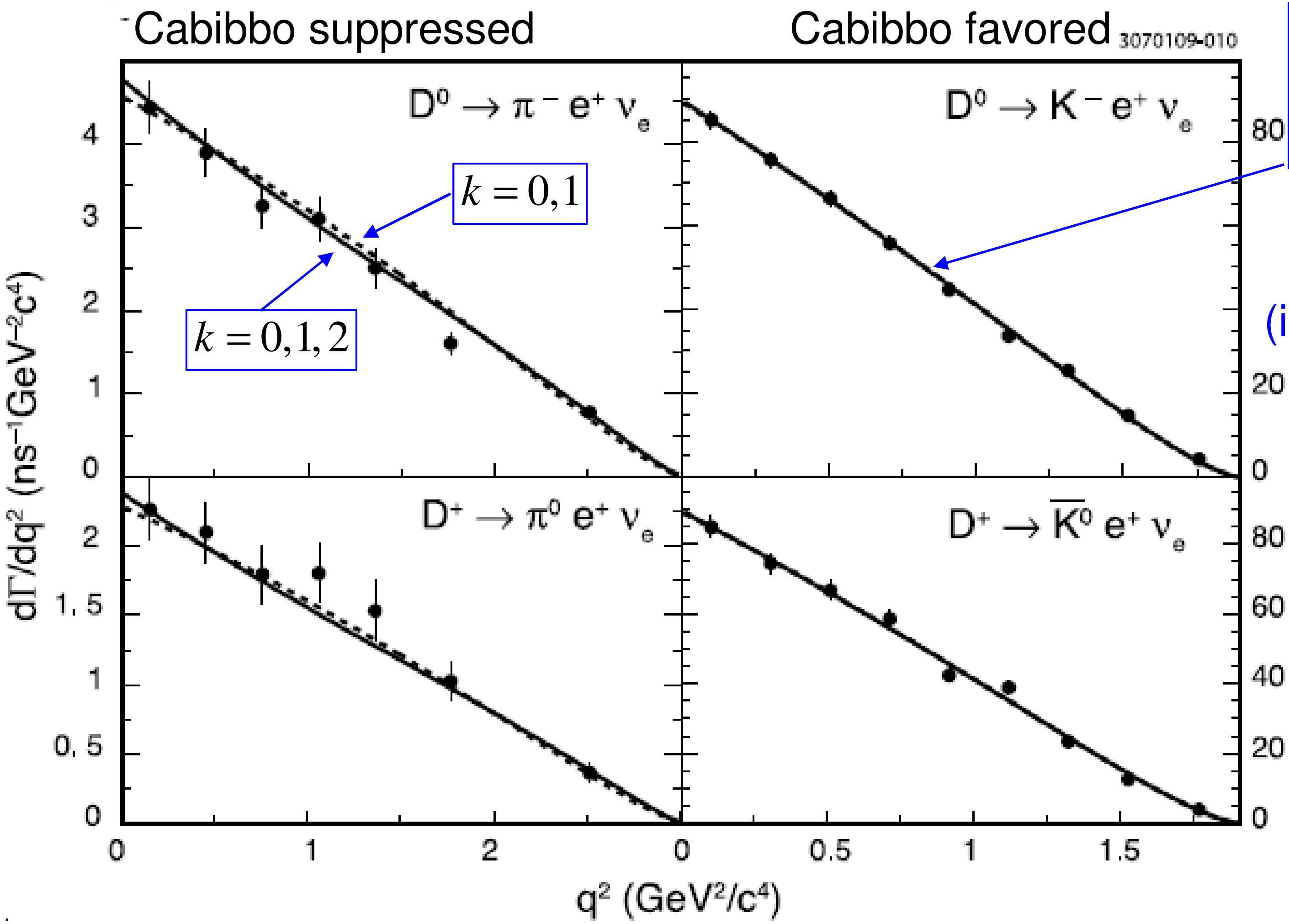
$$H^\mu = f_+(q^2)(P_D + P_h)^\mu \qquad \text{(for } m_l = 0\text{)}$$

h – vector:

$$H^\mu = \frac{2i\varepsilon^{\mu\nu\alpha\beta}}{m_D + m_h} e_\nu^* P_{h\alpha} P_{D\beta} V(q^2) - (m_D + m_h) e^{\mu*} A_1(q^2) + \frac{e^{*\alpha} q_\alpha}{m_D + m_h} (P_D + P_h)^\mu A_2(q^2)$$

Simplicity favors pseudoscalar decay modes.

Pseudoscalar Form Factors



$$f_+(q^2) = \frac{\sum_k a_k z^k(q^2,0)}{P(q^2)\phi(q^2,0)}$$

Fits to Becher-Hill Series (isospin constrained)

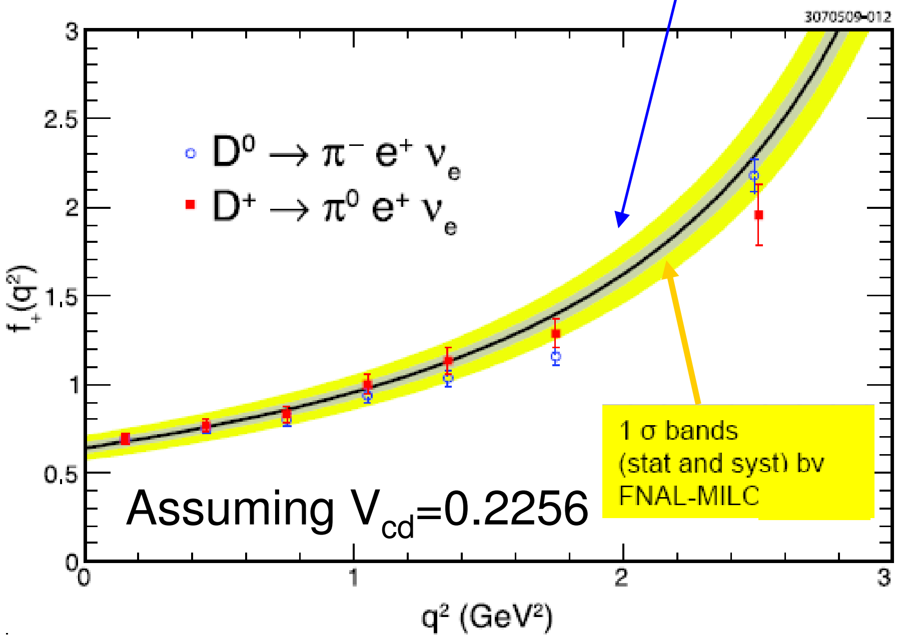
$$\frac{d\Gamma}{dq^2} = \frac{G_F}{24\pi^3} P^3_{K(\pi)} \left|V_{cs(cd)}\right|^2 \left|f_+(q^2)\right|^2$$

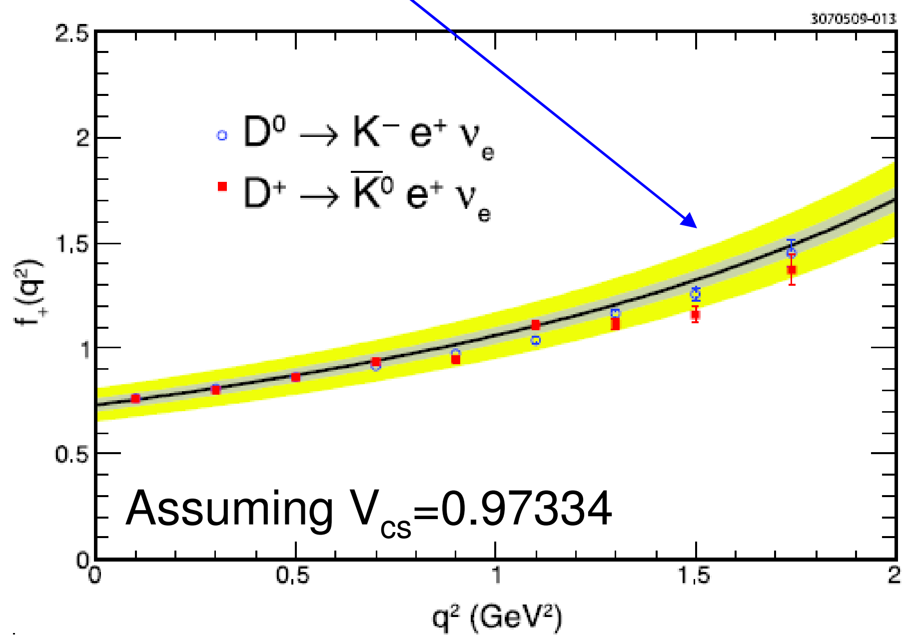
- Much of the visible variation is due to the phase-space factor (P^3).

Comparison to LQCD

Modified Pole Model
fit to FNAL-MILC
lattice calculations

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

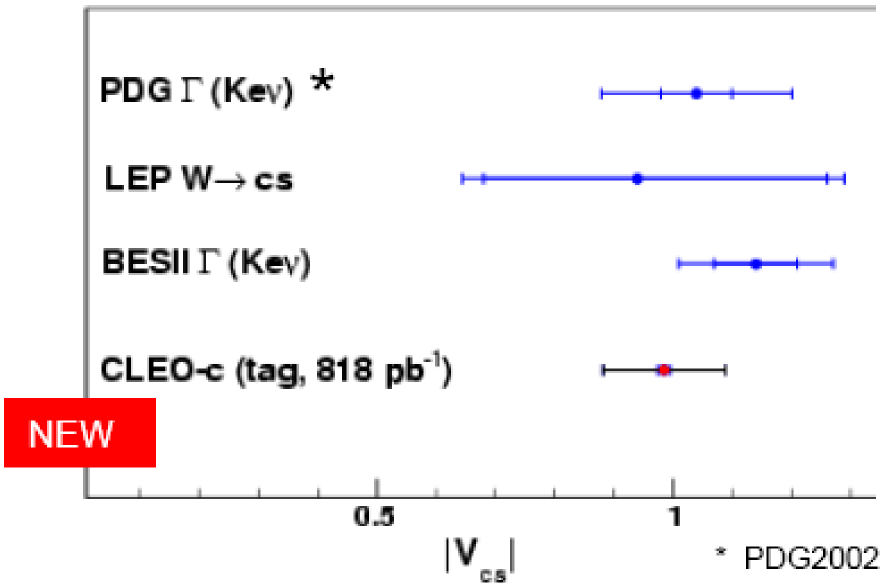


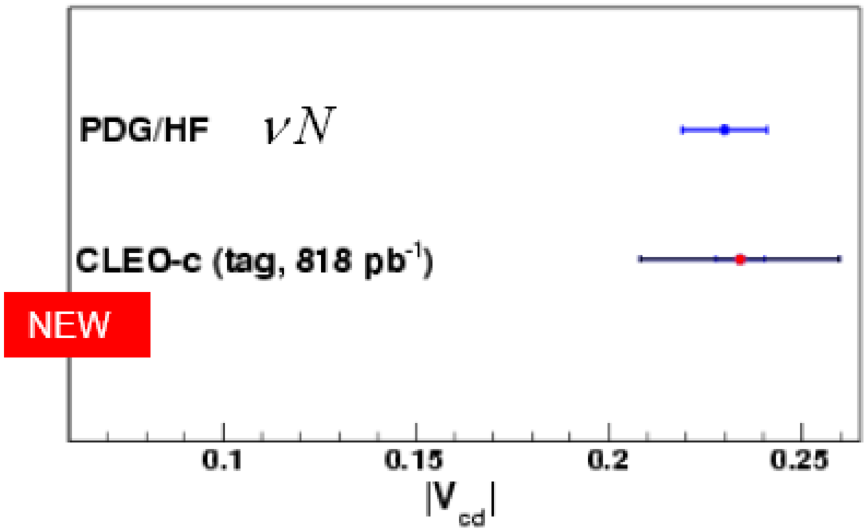


- Good agreement between the data and LQCD on $f_+(0)$
- Shape of q^2 dependence also consistent, though data prefer lower α.
- Lattice calculation errors (10%) much bigger than the experimental errors (2.9%,1.2%)

CKM results

Combine measured $|V_{cx}|f_+(0)$ values (*fit of Hill&Becher f.f. parameterization)* with FNAL-MILC calculations for $f_+(0)$





$|V_{cs}|$

0.985±0.009±0.006±0.103
stat syst LQCD

$|V_{cd}|$

0.234±0.007±0.002±0.025
stat syst LQCD

- Improvements in LQCD calculations are needed

Motivation for $D_s \to f_0\, e^+\nu$ Measurement

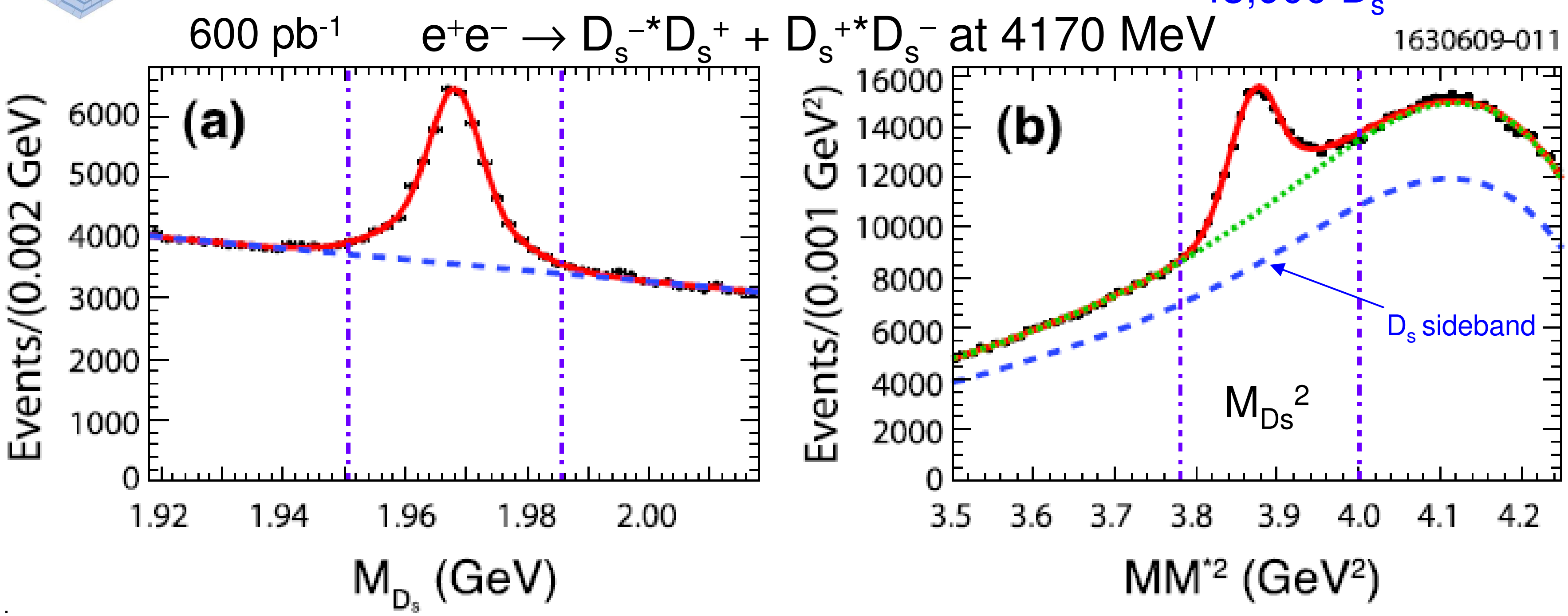
- CP violating phase of B_s-$\overline{B_s}$ oscillations (ϕ_s) is very small in SM. Sensitive to NP contributions.
- Present approach (CDF+D0) is to use $B_s \to J/\psi\ \phi$:
  - Simultaneous fit of CP asymmetry to time and angular distributions (to disentangle CP-odd and -even amplitudes)
  - CDF+D0 results ~2.2σ away from the SM prediction!
- Stone&Zhang [PRD79,074024] suggested $B_s \to J/\psi\ f_0$ as useful alternative:
  - CP-eigenstate. No angular analysis is needed.
  - BR not know at present. Can be predicted from $D_s \to f_0\, e^+\nu$ rate at q^2=0.

$$\frac{\Gamma(B_s \to J/\psi\ f_0(980), f_0 \to \pi^+\pi^-)}{\Gamma(B_s \to J/\psi\ \phi, \phi \to K^+K^-)} \approx \left.\frac{\Gamma(D_s \to e^+\nu\, f_0(980), f_0 \to \pi^+\pi^-)}{\Gamma(D_s \to e^+\nu\ \phi, \phi \to K^+K^-)}\right|_{q^2=0}$$

- Can study properties of f_0 (poorly known!) in clean environment.

Tag

~43,900 D_s

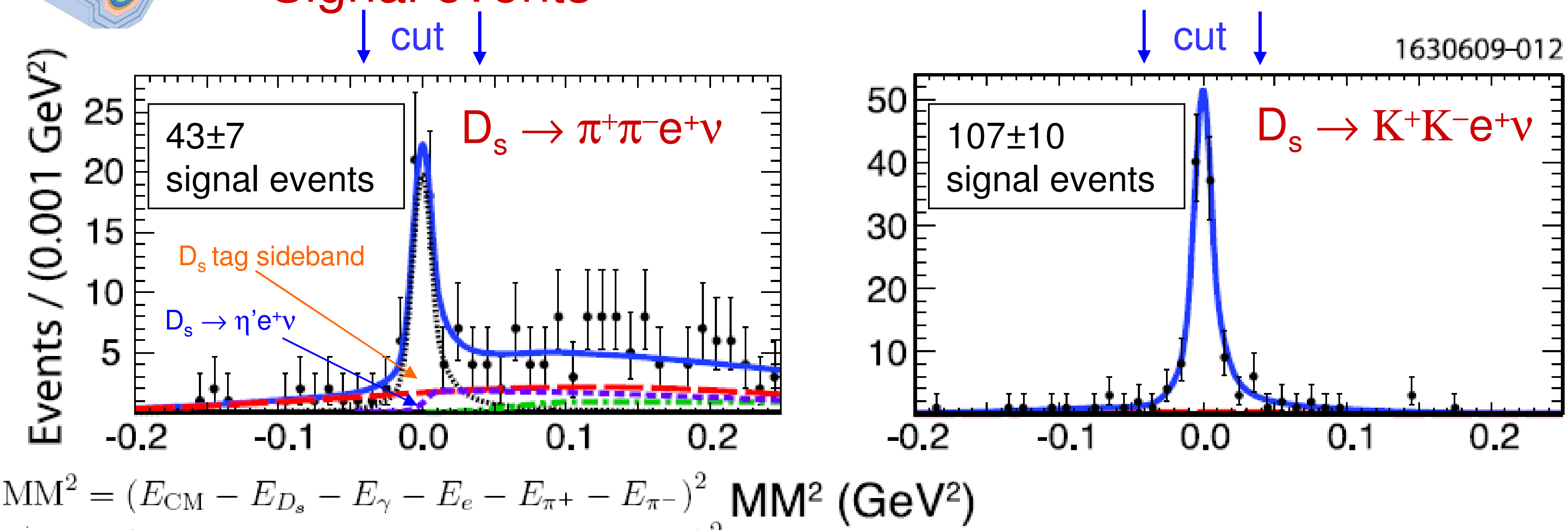


Mode	Signal	Bkg.
$K^+K^-\pi^-$	$16,087\pm373$	39,563
K_sK^-	$4,215\pm228$	6,297
$\eta\pi^-, \eta\to\gamma\gamma$	$2,005\pm145$	5,016
$\eta'\pi^-, \eta'\to\pi^+\pi^-\eta, \eta\to\gamma\gamma$	$1,647\pm131$	1,565
$K^+K^-\pi^-\pi^0$	$6,441\pm471$	89,284
$\pi^+\pi^-\pi^-$	$5,014\pm402$	43,286
$K^{*-}K^{*0}, K^{*-}\to K_s\pi^-, K^{*0}\to K^+\pi^-$	$2,352\pm176$	12,088
$\eta\rho^-, \eta\to\gamma\gamma, \rho^-\to\pi^-\pi^0$	$3,295\pm425$	24,114
$\eta'\pi^-, \eta'\to\rho^0\gamma$	$2,802\pm227$	17,006
ALL	$43,859\pm926$	238,218

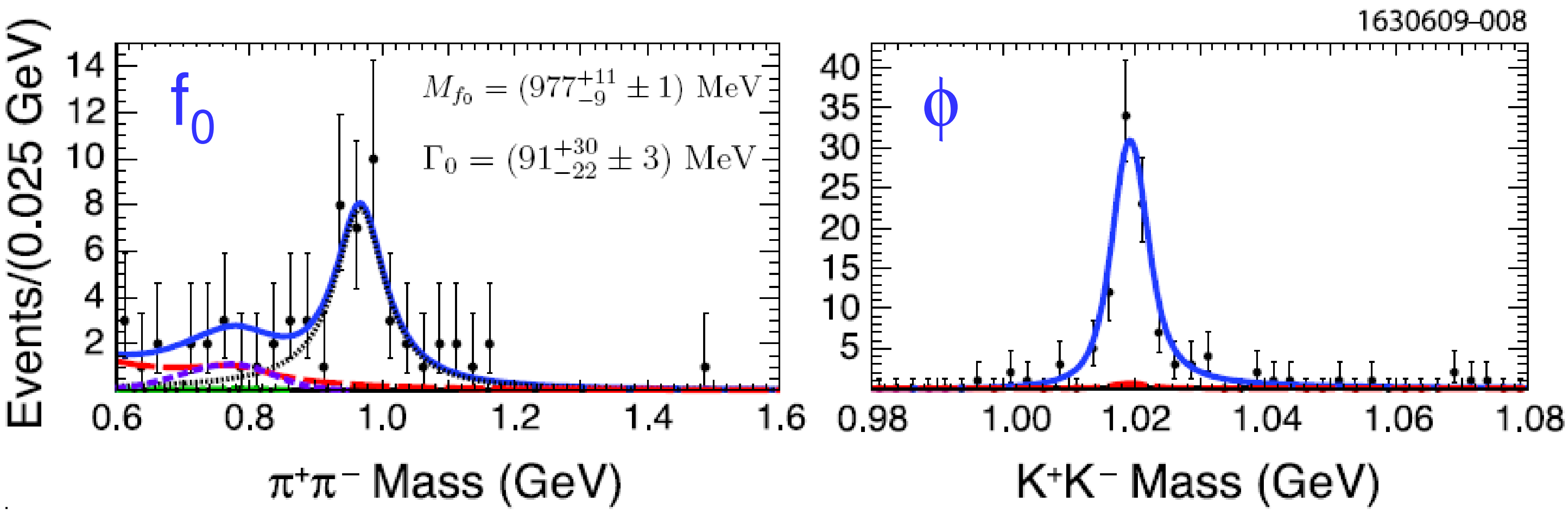
- Additional step needed due to presence of photon from $D_s^* \to \gamma D_s$

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

Signal events

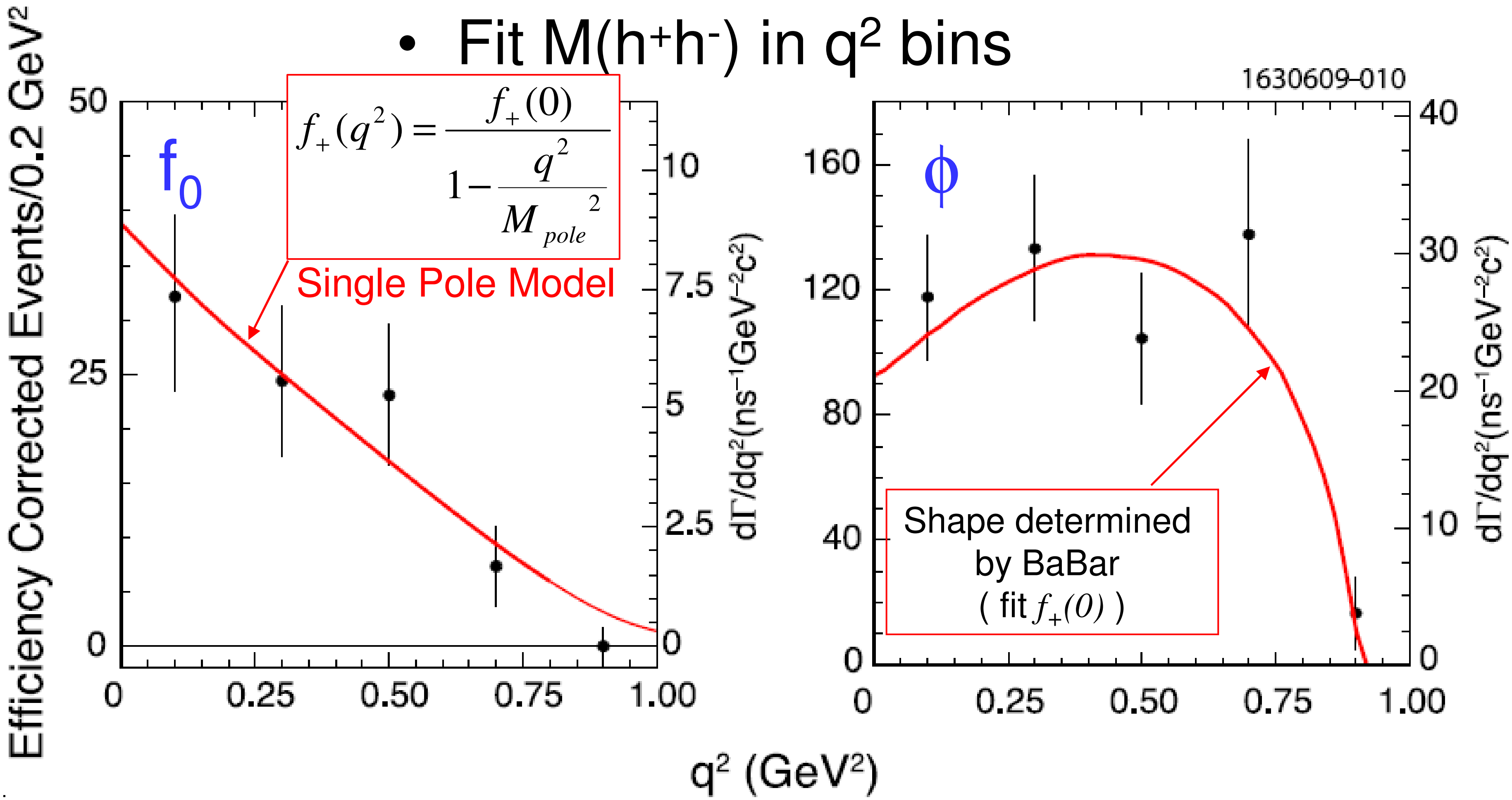


$$\mathrm{MM}^2 = (E_{\mathrm{CM}} - E_{D_s} - E_\gamma - E_e - E_{\pi^+} - E_{\pi^-})^2 - (\mathbf{p}_{\mathrm{CM}} - \mathbf{p}_{D_s} - \mathbf{p}_\gamma - \mathbf{p}_e - \mathbf{p}_{\pi^+} - \mathbf{p}_{\pi^-})^2$$



Form factors and BR

- Fit $M(h^+h^-)$ in q^2 bins



From the sum of efficiency corrected yield in all q^2 bins:

$$BR(D_s \to f_0(980)e^+\nu, f_0 \to \pi^+\pi^-) = (0.20 \pm 0.03 \pm 0.01)\%$$

$$BR(D_s \to \phi e^+\nu) = (2.36 \pm 0.23 \pm 0.13)\%$$

From fits of $f_+(0)$

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

Preliminary

- Assuming

$$R_{f/\phi} = \frac{\Gamma(B_s \to J/\psi\, f_0(980), f_0 \to \pi^+\pi^-)}{\Gamma(B_s \to J/\psi\,\phi, \phi \to K^+K^-)}$$

- Since no angular analysis needed expect $B_s \to J/\psi\ f_0$ to provide a complementary way to $B_s \to J/\psi\ \phi$ of measuring CP-violating phase ϕ_s
- Need explicit measurement of BR for $B_s \to J/\psi\ f_0$ to confirm

Summary

- Our knowledge of semileptonic D-decays and related parameters has been significantly improved thanks to high luminosities at B-factories (BaBar, Belle) and data taken at the charm threshold (CLEO-c). CLEO-c most precise.
  - BR($D \to K e \nu$) 6% error $\to$ 1.4%
  - combined with LQCD calculations (10% errors) leads to best direct determination of V_{cs}
  - BR($D \to \pi e \nu$) 45% error $\to$ 3%
  - Potential for best direct determination of V_{cd} if LQCD errors are improved
- From preliminary result

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

predict $B_s \to J/\psi\, f_0$ can provide a complementary way to $B_s \to J/\psi\, \phi$ of measuring CP-violating phase ϕ_s