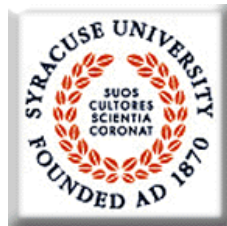
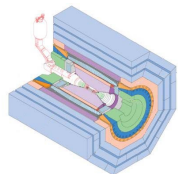


Semileptonic decays of D mesons at CLEO

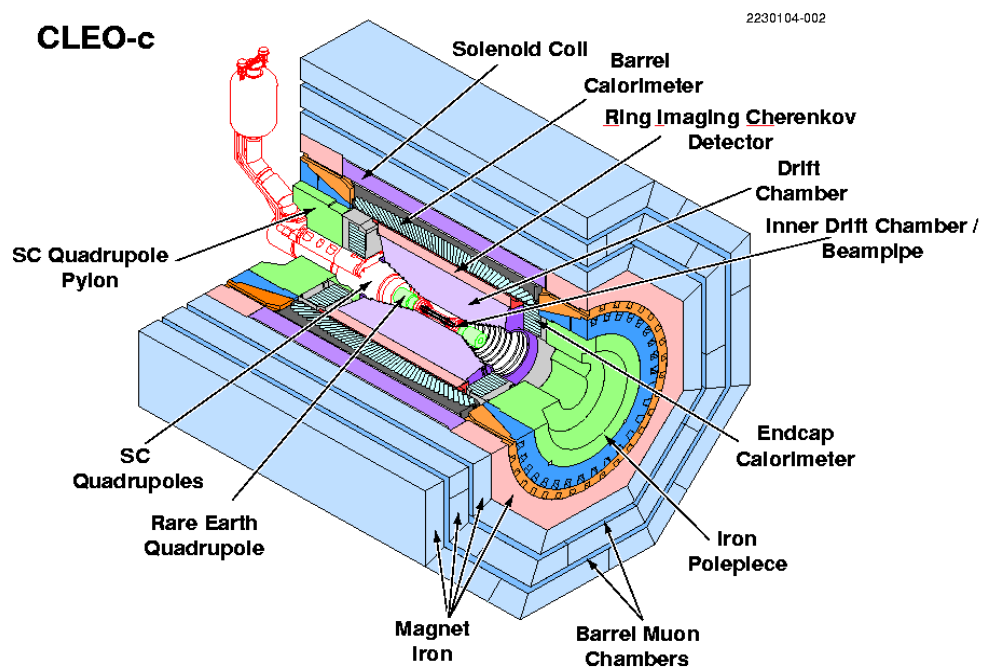
Tomasz Skwarnicki
for the CLEO collaboration



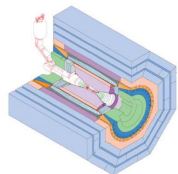


Content of the talk

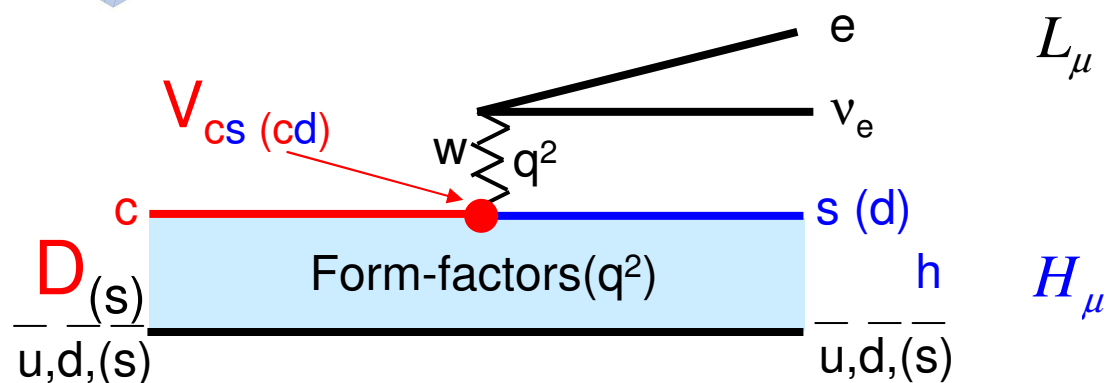
- Report on two recent measurements with the CLEO-c detector:
 - Improved measurements of D meson semileptonic decays to π and K mesons [arXiv:0906.2983]
 - Study of semileptonic decay $D_s \rightarrow f_0(980)e^+\nu$ and implications for $B_s \rightarrow J/\psi f_0$ [*preliminary*].



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



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

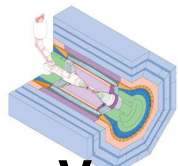


$$M(D \rightarrow h e \nu) =$$

$$-i \frac{G_F}{\sqrt{2}} V_{cs}(cd) L_\mu H^\mu$$

Factorization!

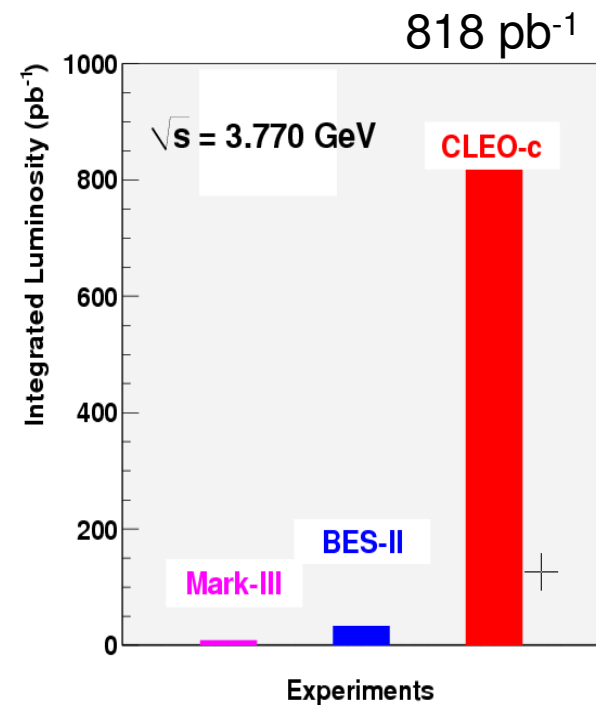
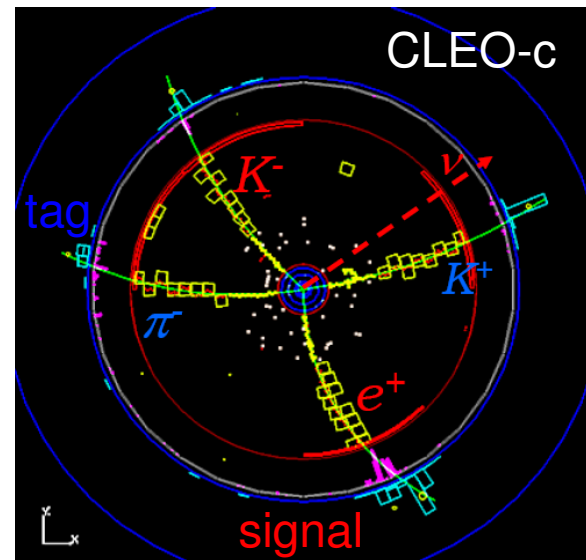
- Direct determination of $|V_{cs}(cd)|$.
- Theoretical (Lattice QCD) errors on the form-factor predictions dominate.
- Taking $|V_{cs}(cd)| = |V_{ud}(us)|$ can turn data into form-factor measurements (normalization and q^2 dependence) to test/develop LQCD.
- Potentially, leads to improved predictions 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.

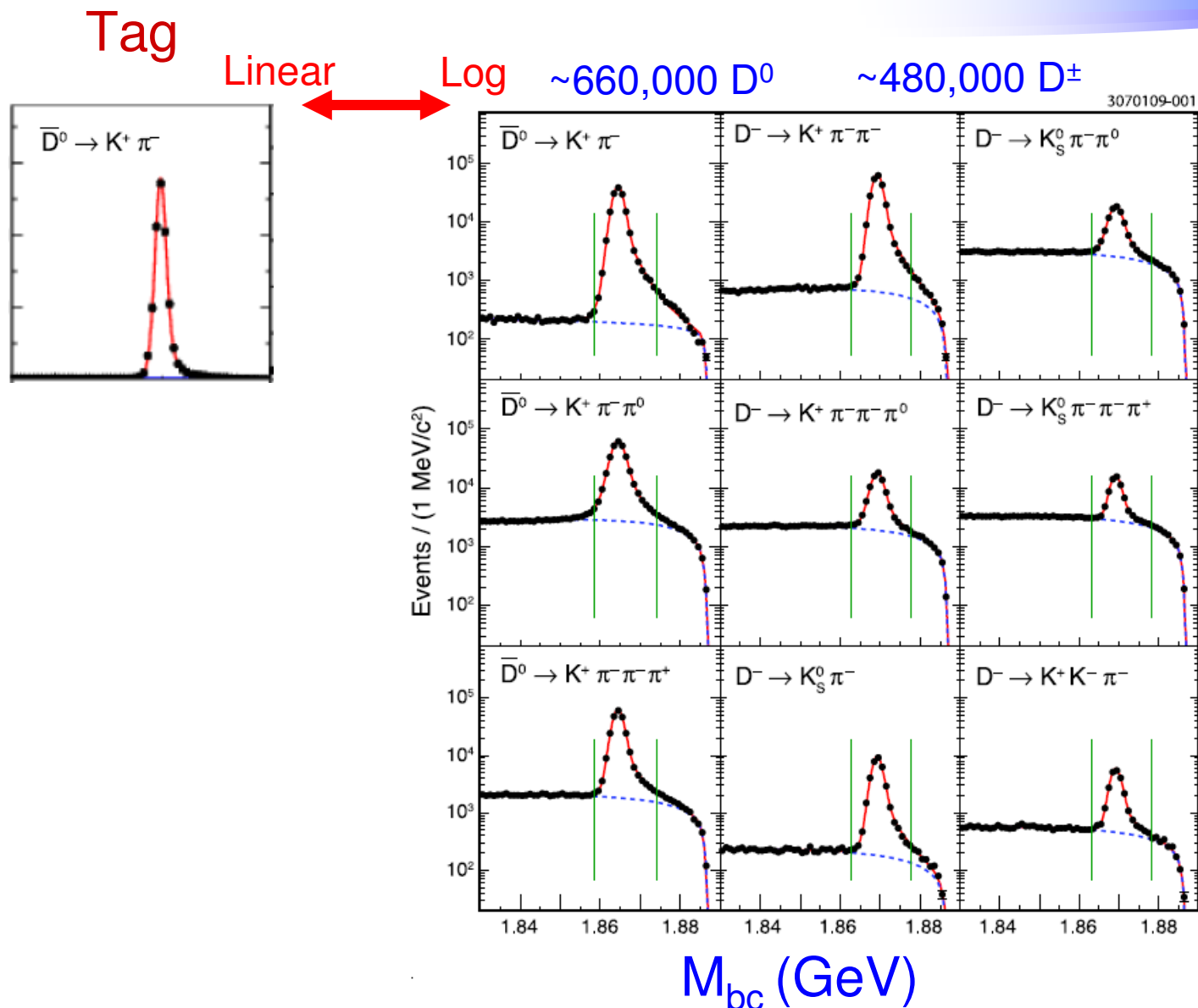
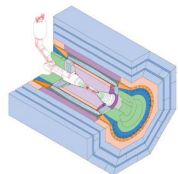


Tagging technique

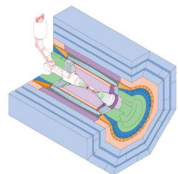
- **Very effective at threshold: $e^+e^- \rightarrow D\bar{D}$:**
 - No fragmentation particles produced
- **Reconstruct one D (tag) in several clean hadronic decay modes:**
 - Cut on $\Delta E = E_D - E_{\text{beam}}$
 - Fit $M_{bc} = \sqrt{E_{\text{beam}}^2 - \mathbf{p}_D^2}$ to determine N_{tag}
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

$$\mathbf{p}_{D \text{ signal}} = -\mathbf{p}_{D \text{ tag}}$$
- **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 ($E_{\text{miss}} = E_{\text{beam}} - E_e - E_h$) and momentum ($\mathbf{p}_{\text{miss}} = -\mathbf{p}_{D \text{ tag}} - \mathbf{p}_e - \mathbf{p}_h$). Fit $U_{\text{miss}} = E_{\text{miss}} - |\mathbf{p}_{\text{miss}}|$ to extract N_{signal} .
 - $\text{BR} = (N_{\text{signal}}/\epsilon_{\text{signal}}) / (N_{\text{tag}}/\epsilon_{\text{tag}})$
 - Also determine differential rates in $q^2 = (E_{\text{beam}} - E_h)^2 - (-\mathbf{p}_{D \text{ tag}} - \mathbf{p}_h)^2$





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



Signal – π, K (tagged)

~1,400 events

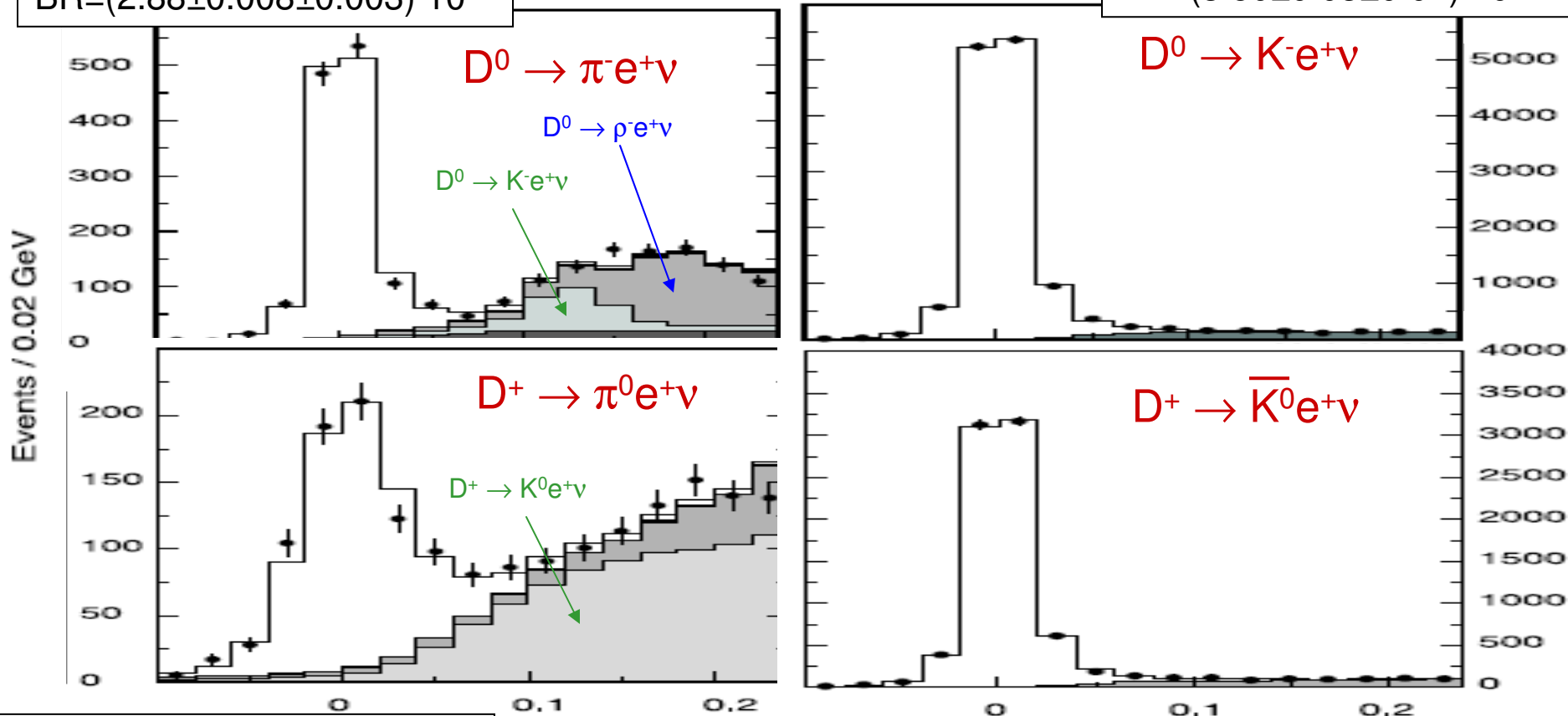
$$\text{BR} = (2.88 \pm 0.008 \pm 0.003) \cdot 10^{-3}$$

Cabibbo suppressed

Cabibbo favored

~14,000 events

$$\text{BR} = (3.50 \pm 0.03 \pm 0.04) \cdot 10^{-2}$$



~800 events

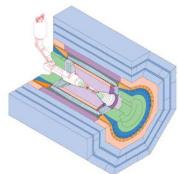
$$\text{BR} = (4.05 \pm 0.016 \pm 0.009) \cdot 10^{-3}$$

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

~8,500 events

$$\text{BR} = (8.83 \pm 0.01 \pm 0.02) \cdot 10^{-3}$$

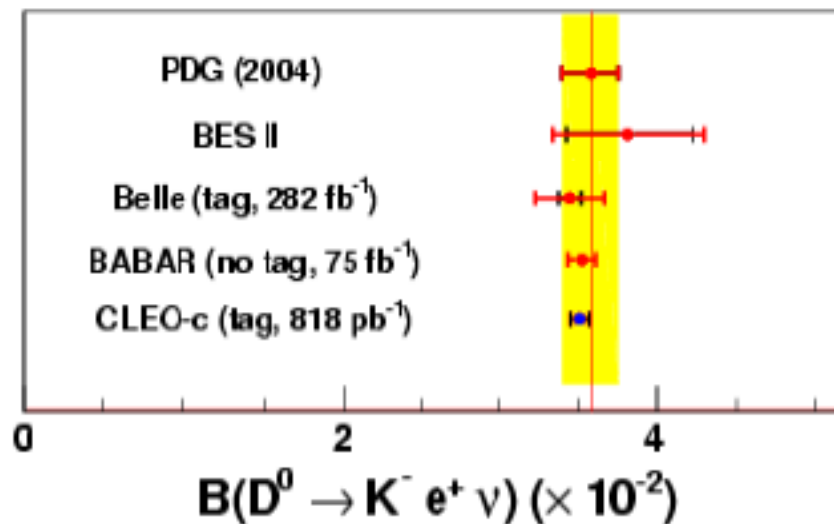
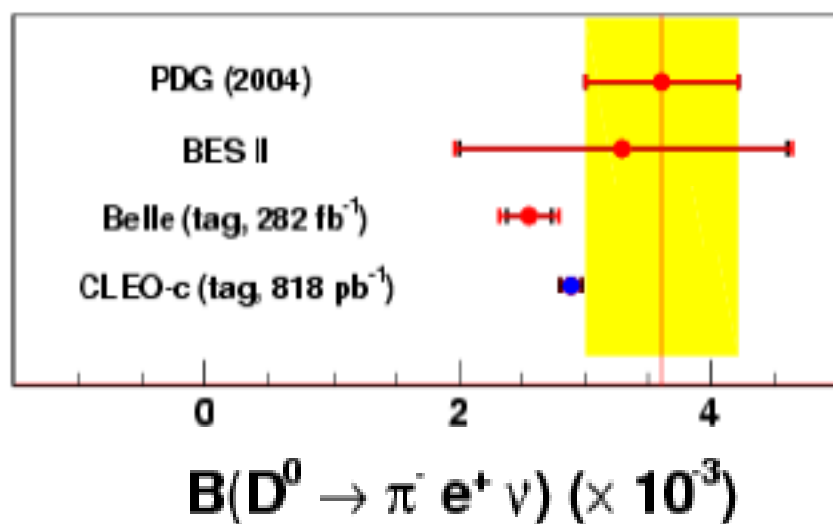
- Excellent background suppression. Small feed-across due to threshold kinematics.



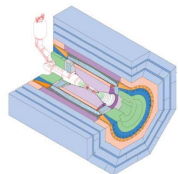
Branching Ratio Results - Comparison

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.

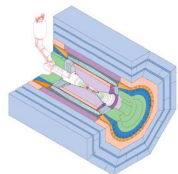
h – pseudoscalar:

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

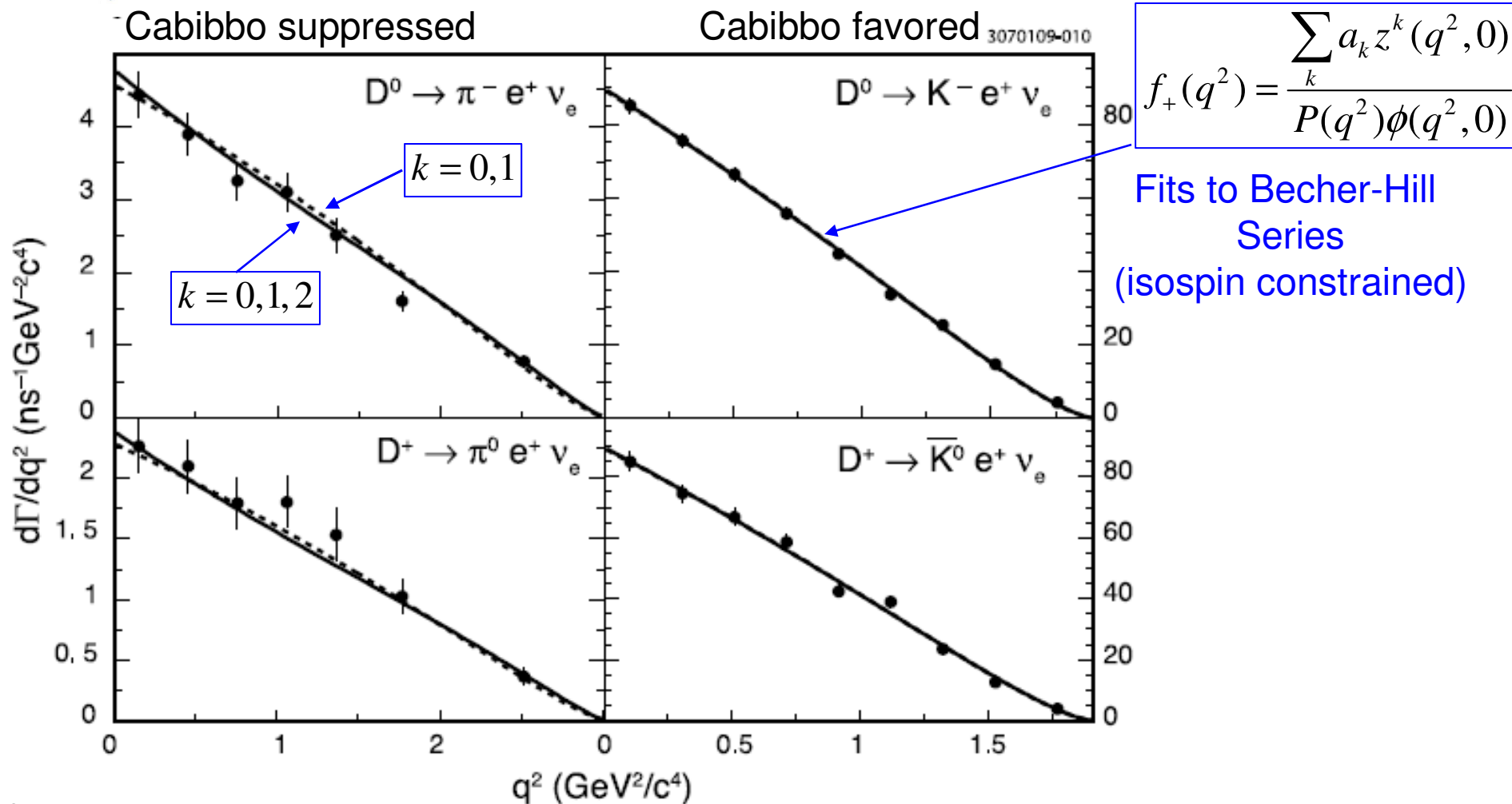
h – vector:

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

Simplicity favors pseudoscalar decay modes.

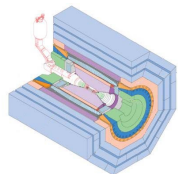


Pseudoscalar Form Factors



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

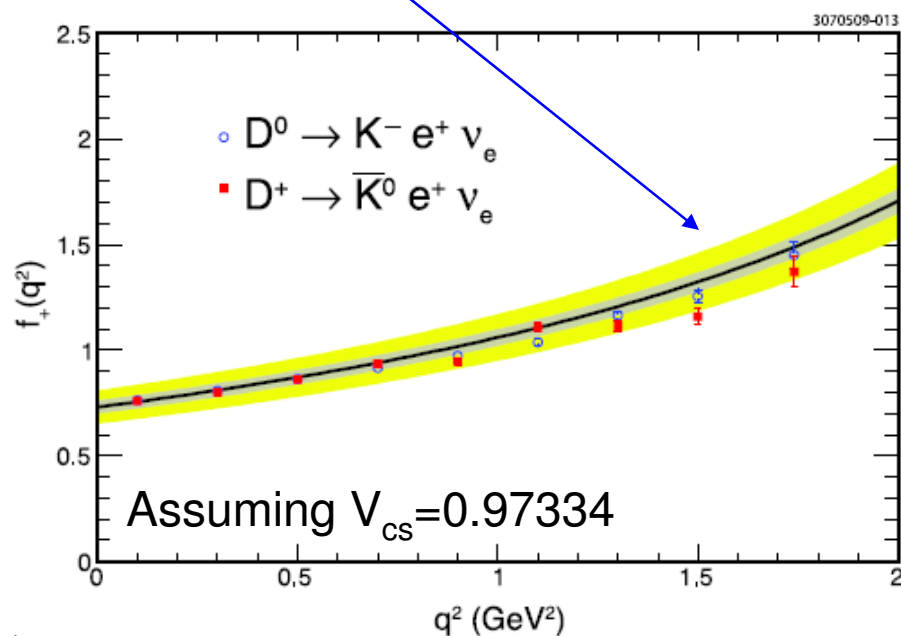
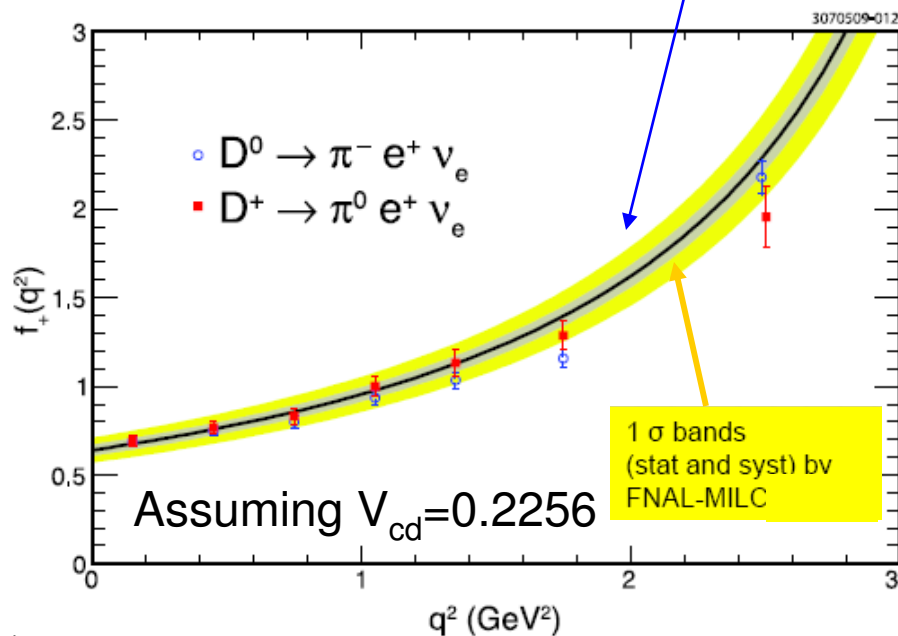
- Much of the visible variation is due to the phase-space factor (P^3).



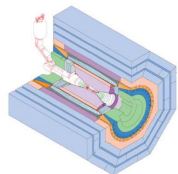
Comparison to LQCD

Modified Pole Model
fit to FNAL-MILC
lattice calculations

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

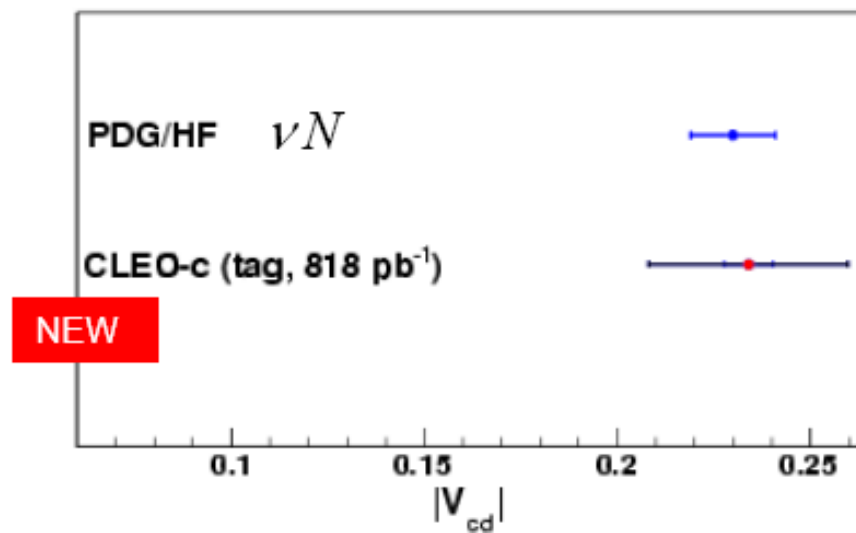
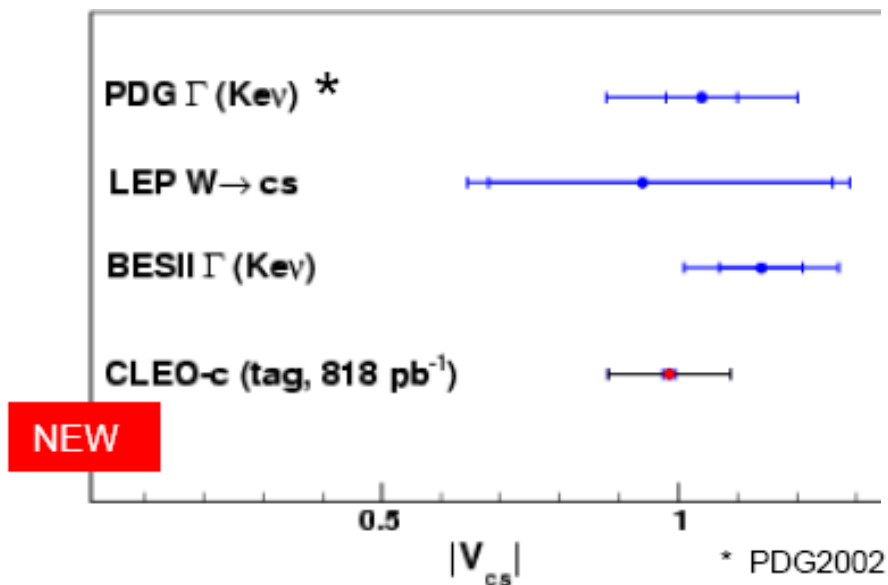


- Good agreement between the data and LQCD on $f_+(0)$
- Shape of q^2 dependence also consistent, though data prefer lower α .
- Lattice calculation errors (10%) much bigger than the experimental errors (2.9%, 1.2%)



CKM results

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



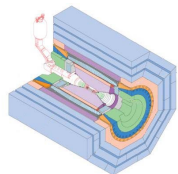
$$|V_{cs}| = 0.985 \pm 0.009 \pm 0.006 \pm 0.103$$

stat syst LQCD

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

stat syst LQCD

- Improvements in LQCD calculations are needed

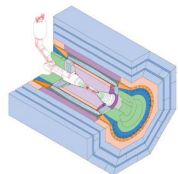


Motivation for $D_s \rightarrow f_0 e^+ \nu$ Measurement

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

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

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

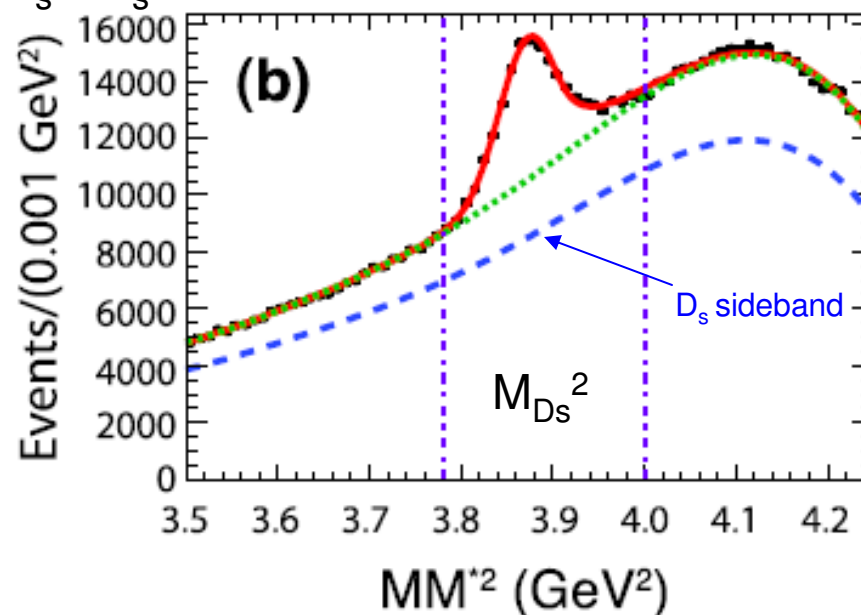
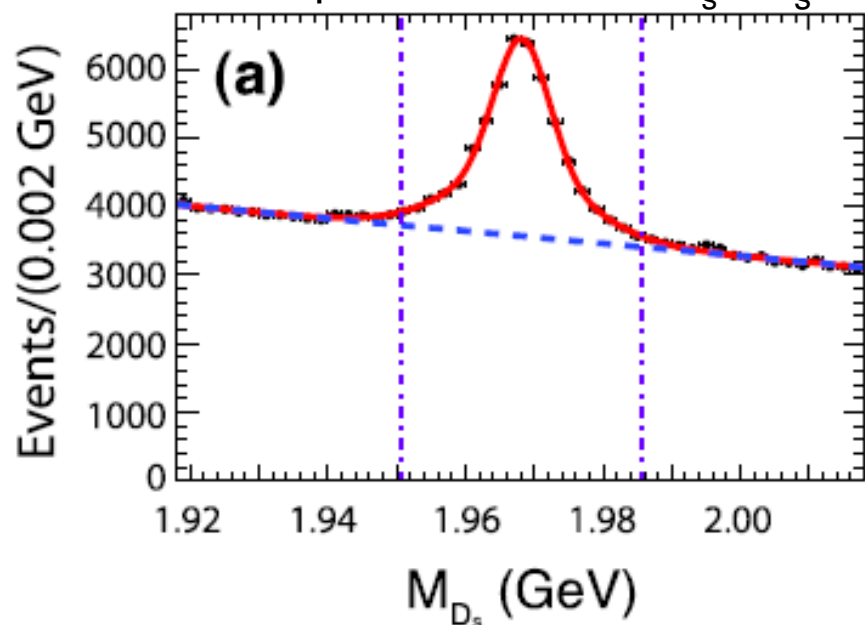


Tag

~43,900 D_s

600 pb⁻¹ $e^+e^- \rightarrow D_s^{*-}D_s^+ + D_s^{*+}D_s^-$ at 4170 MeV

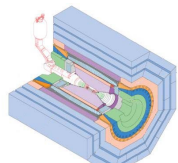
1630609-011



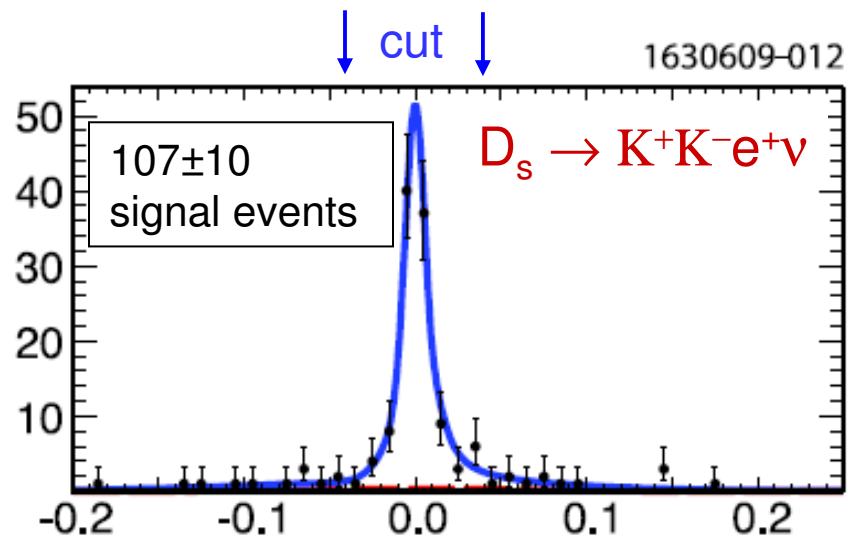
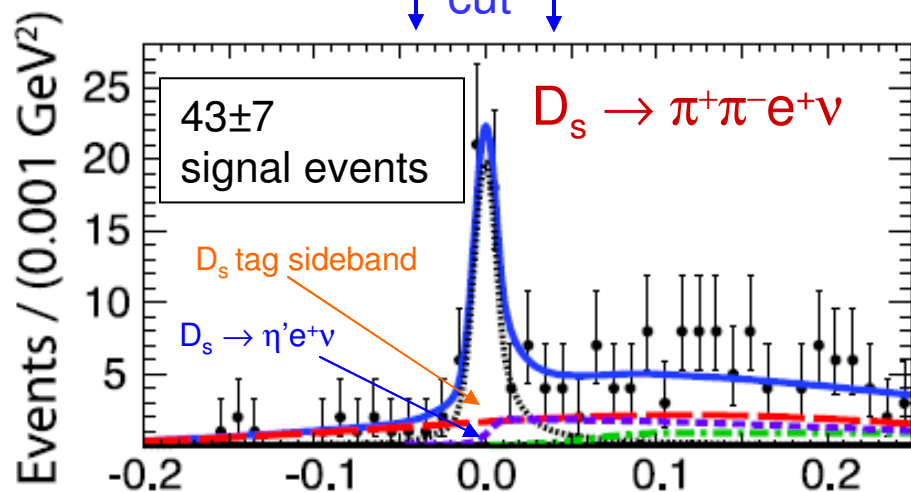
- Additional step needed due to presence of photon from $D_s^{*} \rightarrow \gamma D_s$

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

Mode	Signal	Bkg.
$K^+ K^- \pi^-$	$16,087 \pm 373$	39,563
$K_s^- K^-$	$4,215 \pm 228$	6,297
$\eta \pi^-, \eta \rightarrow \gamma \gamma$	$2,005 \pm 145$	5,016
$\eta' \pi^-, \eta' \rightarrow \pi^+ \pi^- \eta, \eta \rightarrow \gamma \gamma$	$1,647 \pm 131$	1,565
$K^+ K^- \pi^- \pi^0$	$6,441 \pm 471$	89,284
$\pi^+ \pi^- \pi^-$	$5,014 \pm 402$	43,286
$K^{*-} K^{*0}, K^{*-} \rightarrow K_s^- \pi^-, K^{*0} \rightarrow K^+ \pi^-$	$2,352 \pm 176$	12,088
$\eta \rho^-, \eta \rightarrow \gamma \gamma, \rho^- \rightarrow \pi^- \pi^0$	$3,295 \pm 425$	24,114
$\eta' \pi^-, \eta' \rightarrow \rho^0 \gamma$	$2,802 \pm 227$	17,006
ALL	$43,859 \pm 926$	238,218

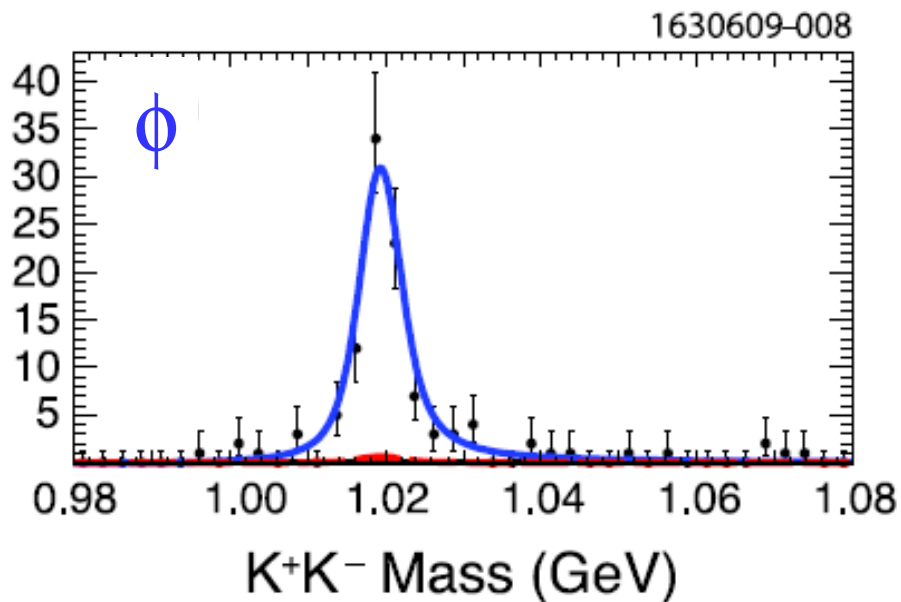
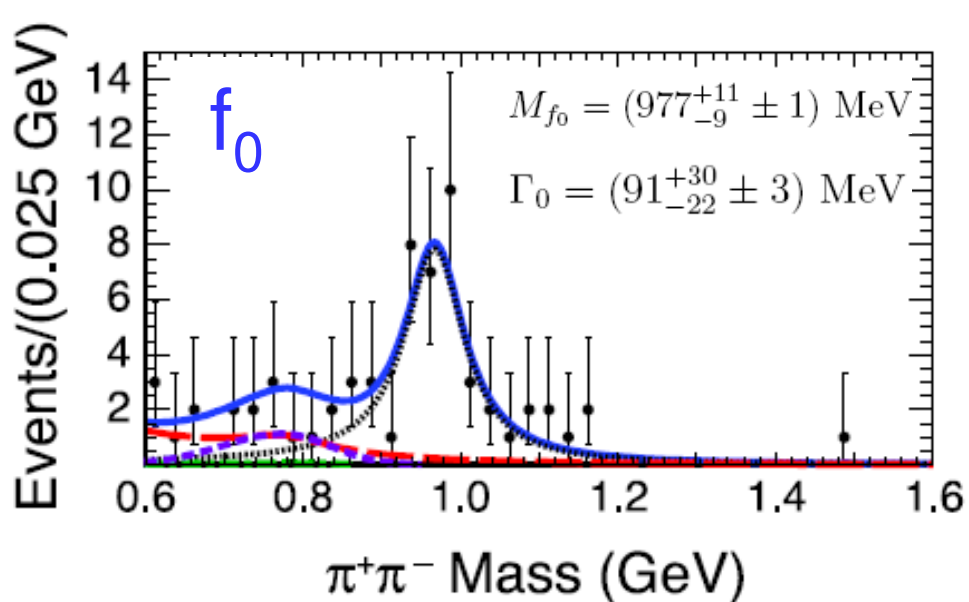


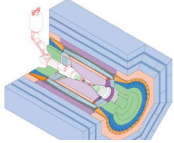
Signal events



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

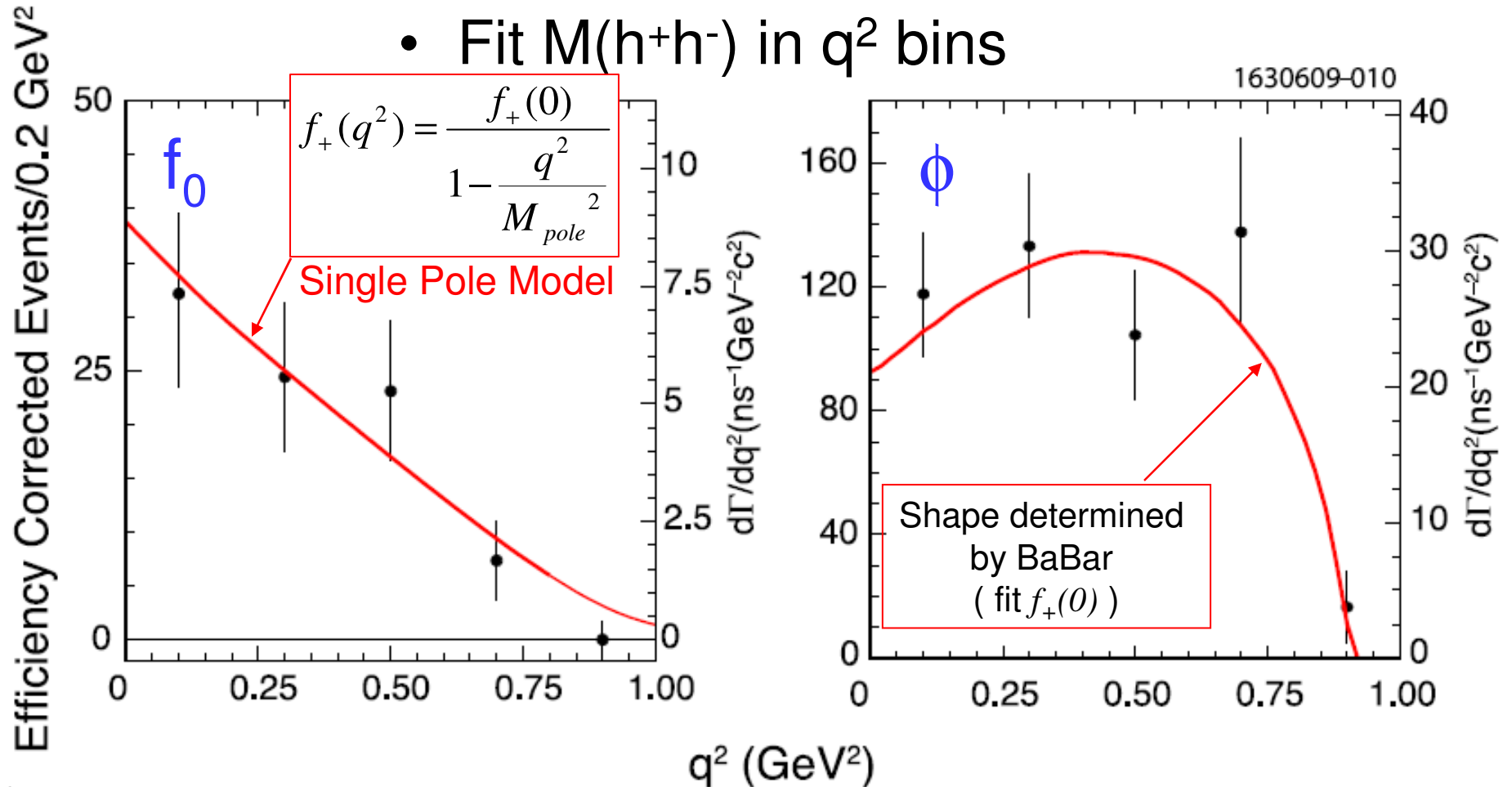
MM² (GeV²)





Form factors and BR

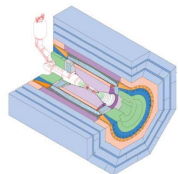
- Fit $M(h^+h^-)$ in q^2 bins



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

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

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



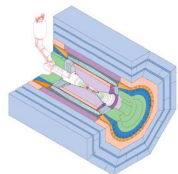
From fits of $f_+(0)$

$$R_{f/\phi} \equiv \frac{\Gamma(D_s \rightarrow e^+ \nu f_0(980), f_0 \rightarrow \pi^+ \pi^-)}{\Gamma(D_s \rightarrow e^+ \nu \phi, \phi \rightarrow K^+ K^-)} \Bigg|_{q^2=0} = (42 \pm 11)\% \quad \text{Preliminary}$$

- Assuming

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

- Since no angular analysis needed expect $B_s \rightarrow J/\psi f_0$ to provide a complementary way to $B_s \rightarrow J/\psi \phi$ of measuring CP-violating phase ϕ_s
- Need explicit measurement of BR for $B_s \rightarrow J/\psi f_0$ 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.
 - $\text{BR}(D \rightarrow K e \nu)$ 6% error \rightarrow 1.4%
 - combined with LQCD calculations (10% errors) leads to best direct determination of V_{cs}
 - $\text{BR}(D \rightarrow \pi e \nu)$ 45% error \rightarrow 3%
 - Potential for best direct determination of V_{cd} if LQCD errors are improved
- From preliminary result

$$R_{f_1 \phi} = \frac{\Gamma(D_s \rightarrow e^+ \nu f_0(980), f_0 \rightarrow \pi^+ \pi^-)}{\Gamma(D_s \rightarrow e^+ \nu \phi, \phi \rightarrow K^+ K^-)} \Big|_{q^2=0} = (42 \pm 11)\%$$

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