CLEO Challenges LQCD

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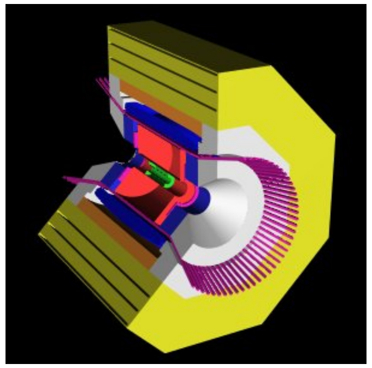
CLEO Collaboration

Outline

- Motivation
- Leptonic Charm Decays
- Semileptonic Charm Decays
- Conclusions



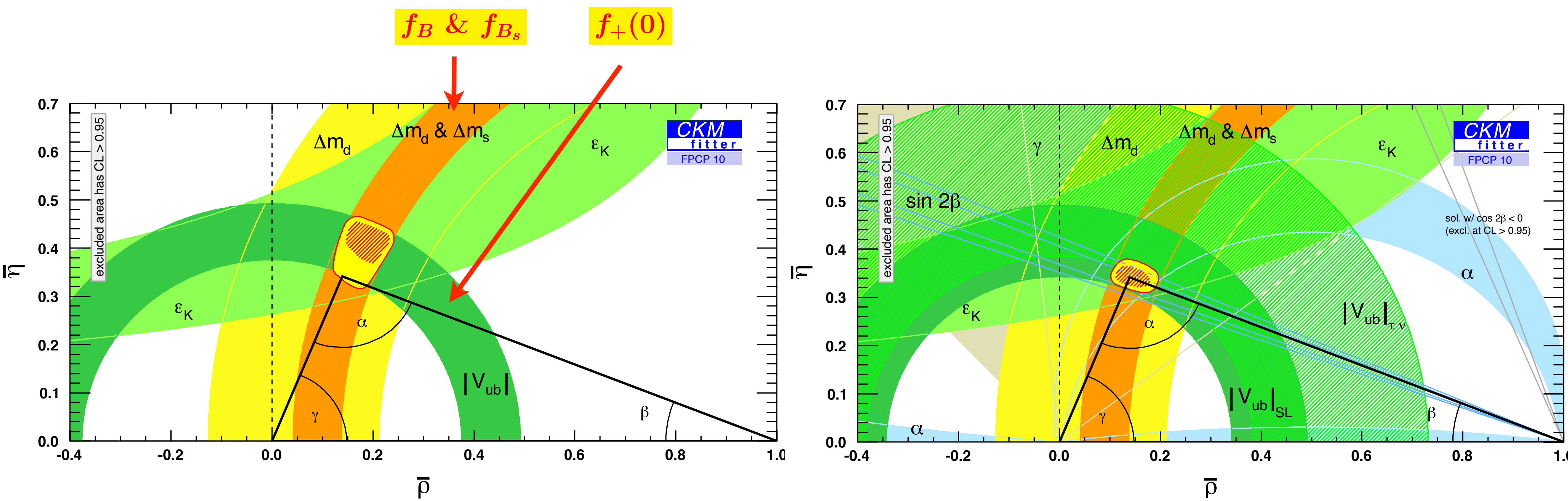
35th International Conference on High Energy Physics
Paris, July 22 – 28, 2010

Motivation

Overconstraining the CKM matrix is the principal goal of Heavy Flavor Physics.

- Inconsistencies would suggest New Physics in CP violation.
- Nonperturbative QCD parameters are required to extract $|V_{ub}|$, $|V_{td}|$, and $|V_{ts}|$ from measurements in the beauty sector.
  - Lattice QCD (LQCD) can provide these parameters.
    - Experimental validation of LQCD is essential to ensure reliability.
    - Precision charm sector measurements can challenge LQCD calculations.

Providing precise charm data to motivate and validate theoretical progress in nonperturbative heavy quark physics is a major focus of the CLEO-c program.



Example: Determining V_{td} from $B^0\bar{B}^0$ Mixing

The measured mass difference due to $B^0\bar{B}^0$ mixing is related to V_{td} by:

$$\Delta m_d = \frac{G_F^2}{6\pi^2}\,\eta_{QCD}\;M_B\;f_B^2 B_B\;m_t^2\;F(\frac{m_t^2}{m_W^2})\;V_{td}^2\;V_{tb}^2$$

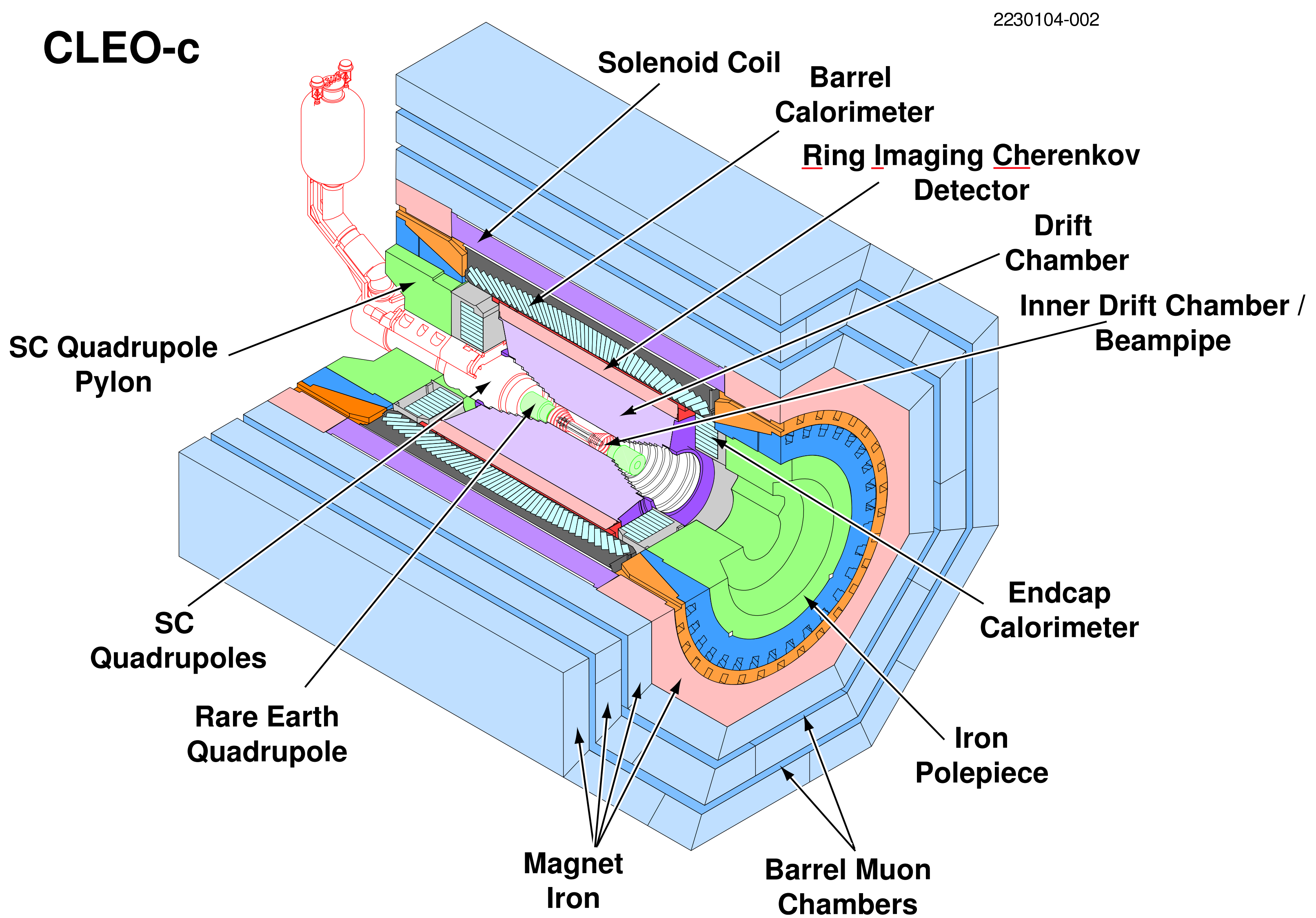
- Everything in this expression is quite well known, except the decay constant f_B and the bag constant B_B.
- Theoretical uncertainties in $f_B^2 B_B$ determine the width of the region in the ρ-η plane allowed by measurements of Δm_d.
- f_B could be measured in $B^- \to \ell^-\bar{\nu}$ decay, but – due to Cabibbo suppression – the branching fraction is very small for μ or τ and reconstructing $B^- \to \tau^-\bar{\nu}$ is very difficult.
- Analogous parameters f_D (f_{D_s}) can be measured much more easily in $D^+ \to \ell^+\nu$ ($D_s \to \ell^+\nu$) decay, which are less seriously (not) Cabibbo suppressed
  - Measurements of f_D (f_{D_s}) constrain or validate LQCD calculations of f_B.

Furthermore, measurements of form factors $f_+(0)$ for semileptonic D and D_s decay check or validate theoretical calculations of the form factor $f_+(0)$ required to determine V_{ub} from measurements of semileptonic B decay.

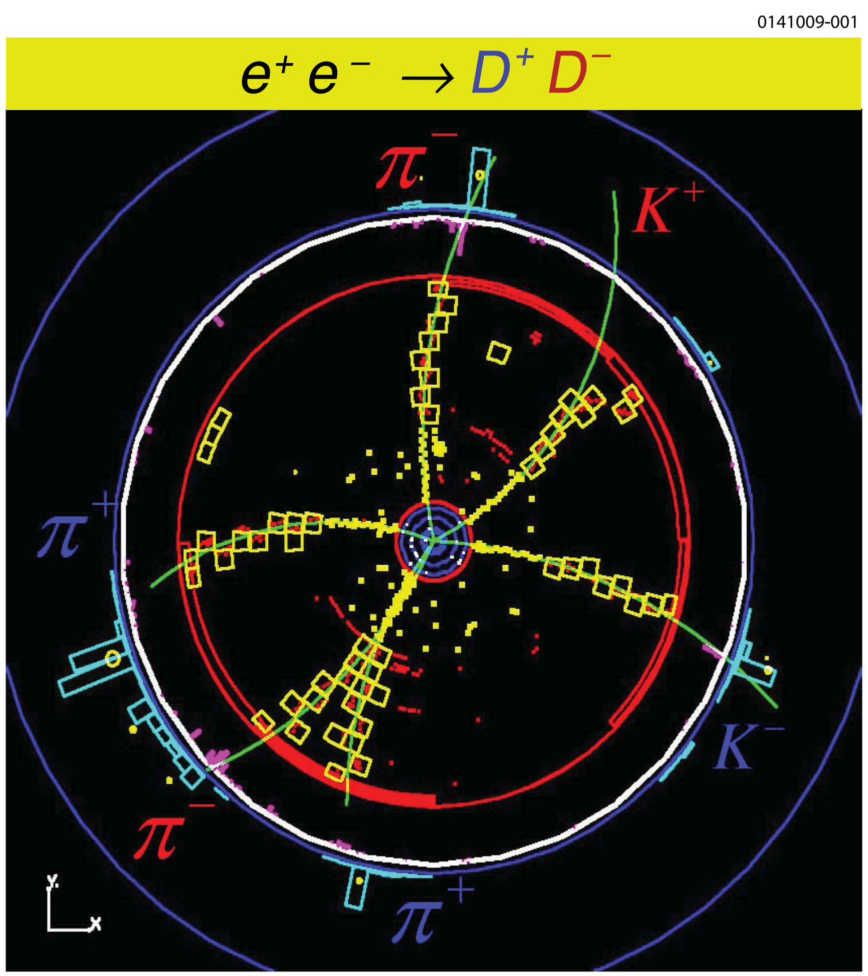
The CLEO-c Detector

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

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



Very Clean Events

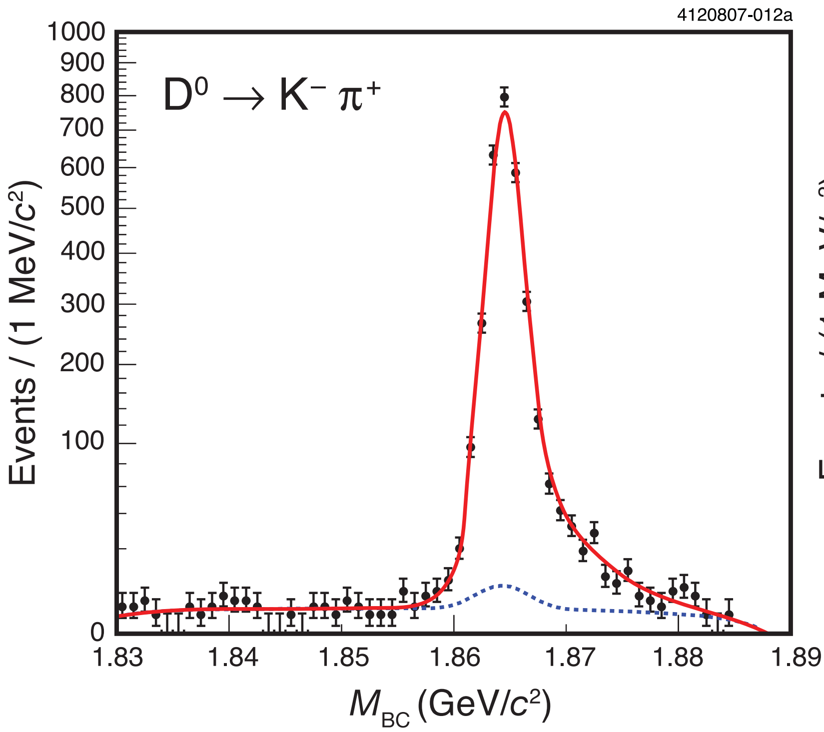


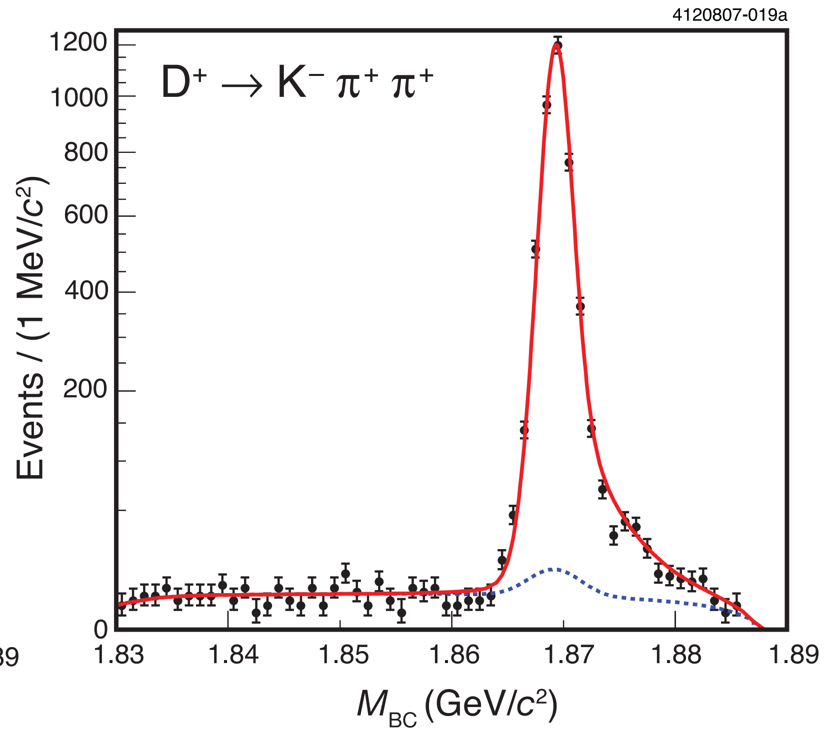
Double Tag Technique

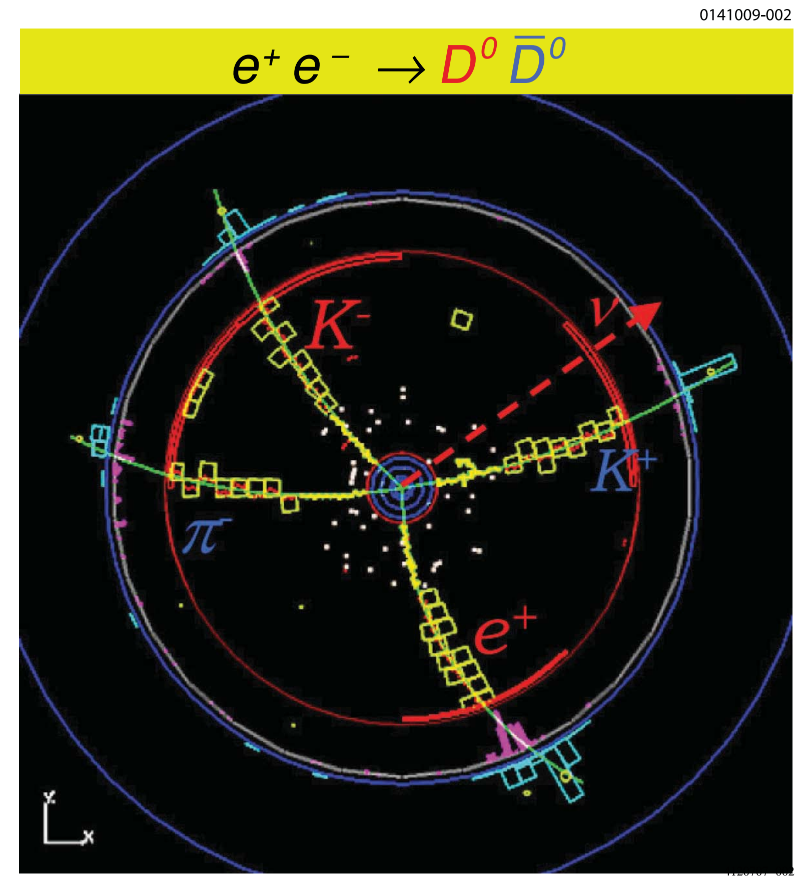
Many CLEO-c D & D_s measurements use Double Tags

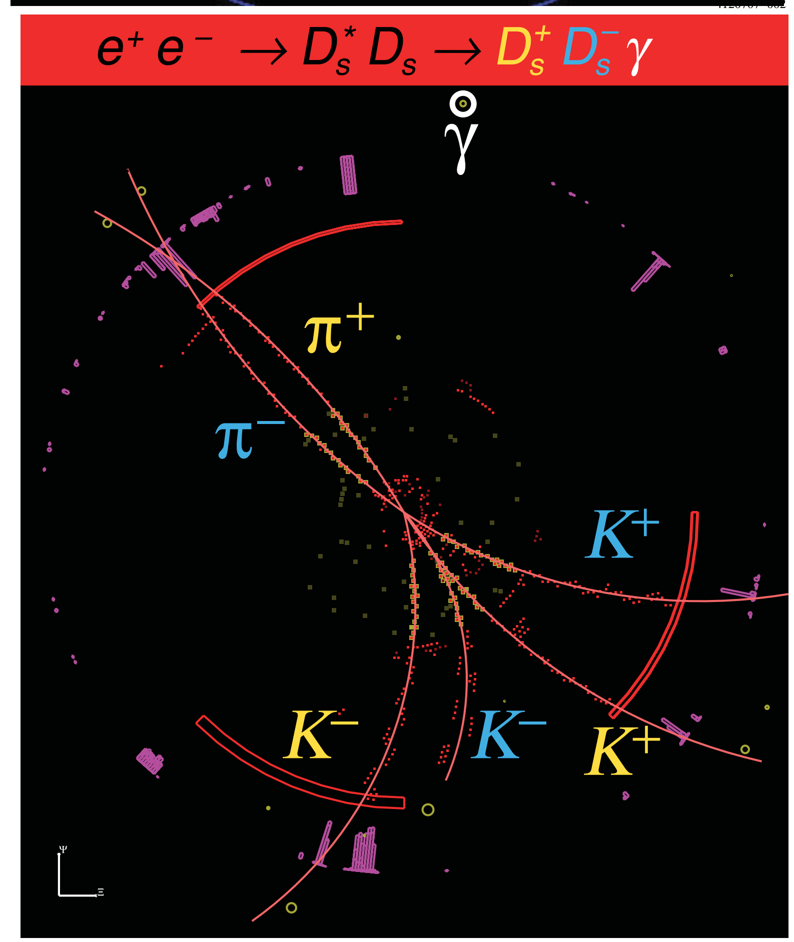
- Simple $D\bar{D}$ states
  - $e^+e^- \to \psi(3770) \to D^0\bar{D}^0$ or D^+D^-
  - $e^+e^- \to \psi(4170) \to D_s\bar{D}_s^* \to D_s^+D_s^-\gamma$
- Reconstruct one $\bar{D}_{(s)}$ to get a clean tagged sample of $D_{(s)}$ signal decays
- Reconstruct the $D_{(s)}$ in a signal mode *e.g.*, leptonic or semileptonic
- Enables accurate measurements of absolute branching fractions (pioneered by MARK III)
- Very clean events and tags

(Square root plots make backgrounds visible)

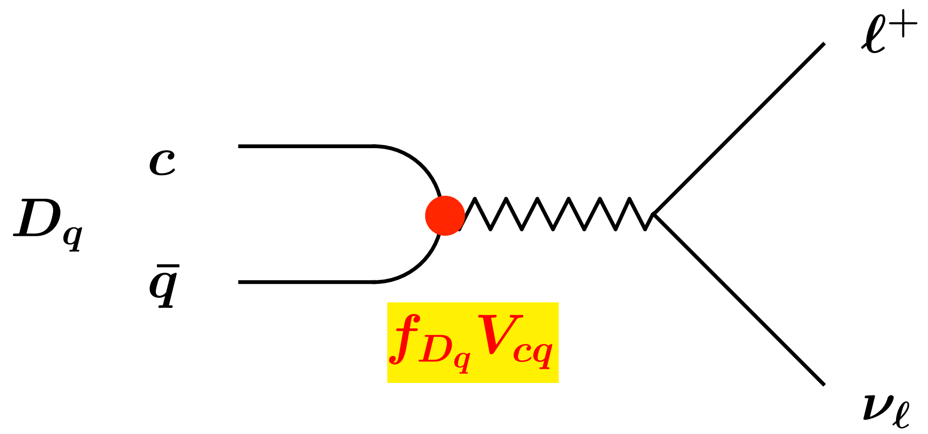








Leptonic Charm Decays



The factor $f_{D_q}V_{cq}$ occurs in the decay amplitude for the $c\bar{q}W$ vertex

- The decay widths for leptonic D^+ and D_s^+ decays are:

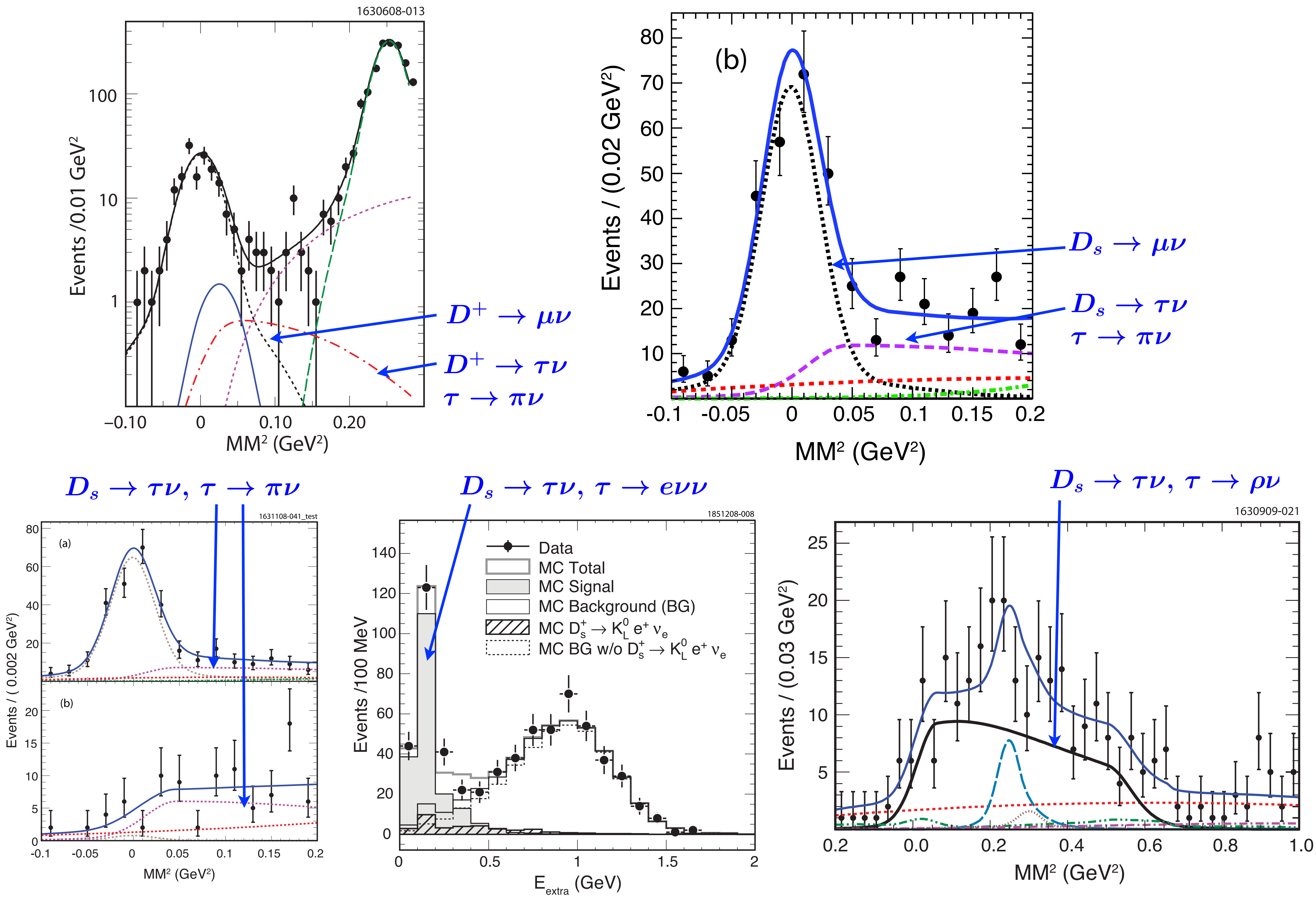
$$\Gamma(D_q^+ \to \ell^+\nu_\ell) = \frac{1}{8\pi} G_F^2 M_{D_q}\, m_\ell^2 \left(1 - \frac{m_\ell^2}{M_{D_q}^2}\right) |f_{D_q}V_{cq}|^2$$

- Measurements of $\mathcal{B}(D^+ \to \ell^+\nu_\ell)$ and $\mathcal{B}(D_s^+ \to \ell^+\nu_\ell)$
  Determine $f_{D^+}V_{cd}$ and $f_{D_s}V_{cs}$
- We measure $f_{D_q}V_{cq}$ and use PDG values of V_{cq} to get f_{D_q}
  - Eventually get V_{cd} and V_{cs} from semileptonic D decays and QCD form factors
- f_{D^+} and f_{D_s} measurements constrain or validate LQCD calculations of f_B and f_{B_s}

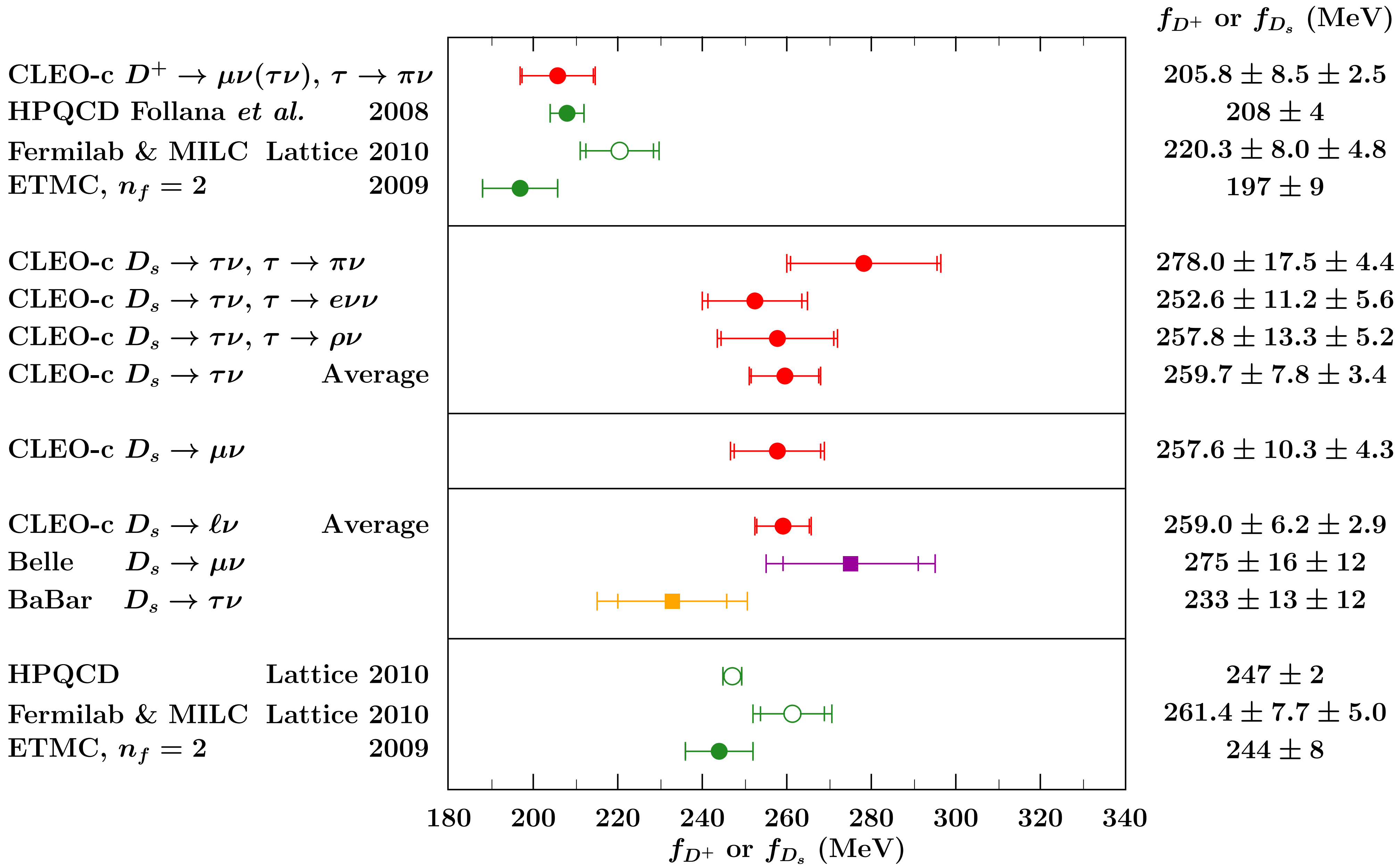
Start with a hadronic D^+ or D_s^+ tag

- The γ from $D_s\bar{D}_s^* \to D_s^+D_s^-\gamma$ is a nuisance
  - Find the γ and include it in reconstruction or
  - ignore it and include it in the extra calorimetry energy

D^+ and D_s Leptonic Decay Signals

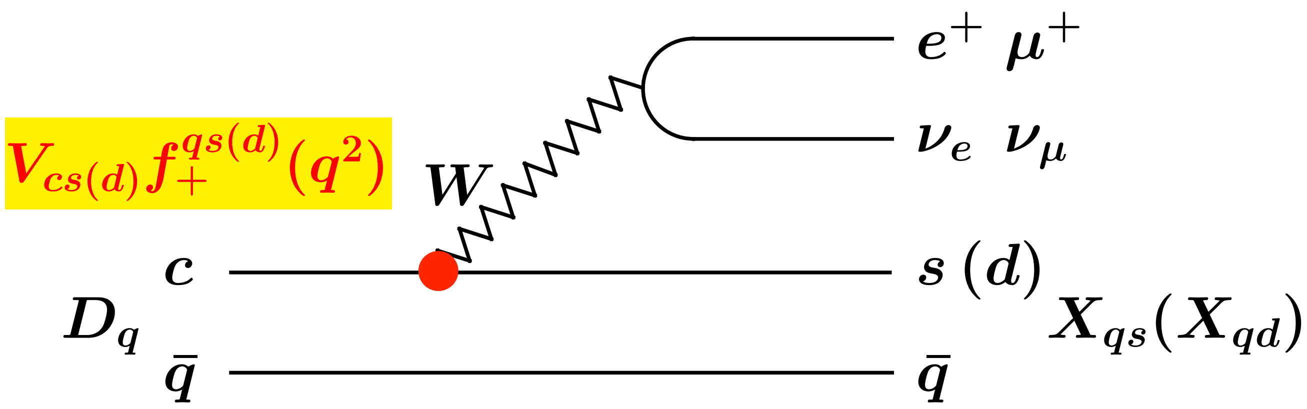


f_{D^+} & f_{D_s} Results and LQCD



- Agreement of the f_{D^+} result with LQCD is excellent
- Agreement of f_{D_s} results with LQCD is less certain
- CLEO-c results dominated by statistical errors
  - Excellent opportunity for BESIII to contribute with larger data samples
    - Would challenge LQCD at a new level of precision

Exclusive Semileptonic D Decays



Final States X

$\bar{q}$	D_q	X_{qs} V_{cs}	X_{qd} V_{cd}
$\bar{u}$	D^0	$K^-, K^{*-}, \ldots$	π^- , $\rho^-, \ldots$
$\bar{d}$	D^+	$\bar{K}^0$, $\bar{K}^{*0}, \ldots$	π^0 , $\rho^0, \ldots$
$\bar{s}$	D_s	η , $\phi^0, \ldots$	$K^0, K^{*0}, \ldots$

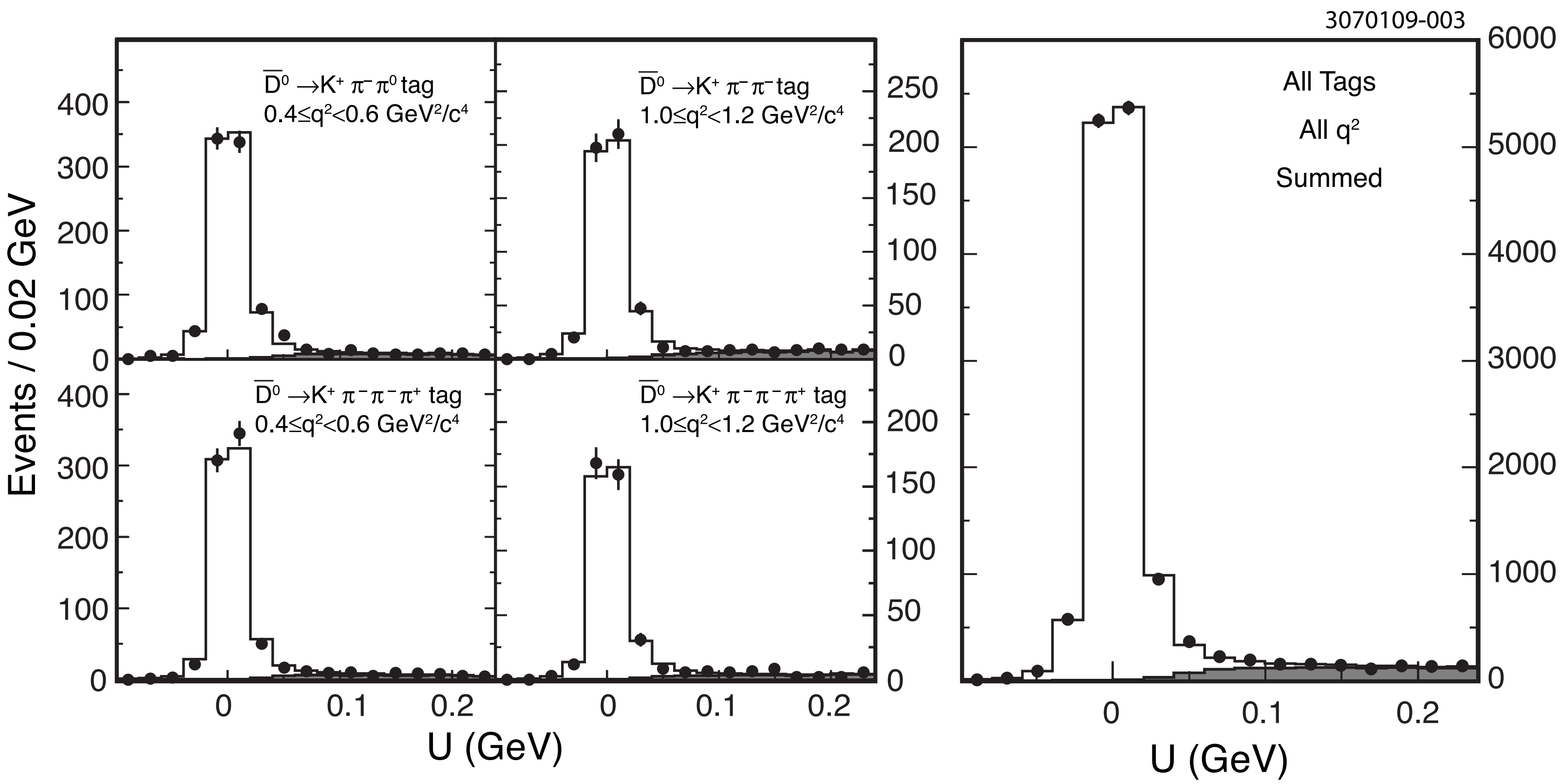
- Exclusive semileptonic decays depend on the mass-squared (q^2) of the virtual W through form factors $f(q^2)$
- Decay to a pseudoscalar meson P_{qs} involves only one form factor

$$\frac{\Gamma(D_q \to P_{qs}\,\ell^+\nu_\ell)}{dq^2} = \frac{G_F^2 p^3}{24\pi^3} \, |V_{cs}\ f_+^{qs}(q^2)|^2 \qquad \text{(also } s \to d\text{)}$$

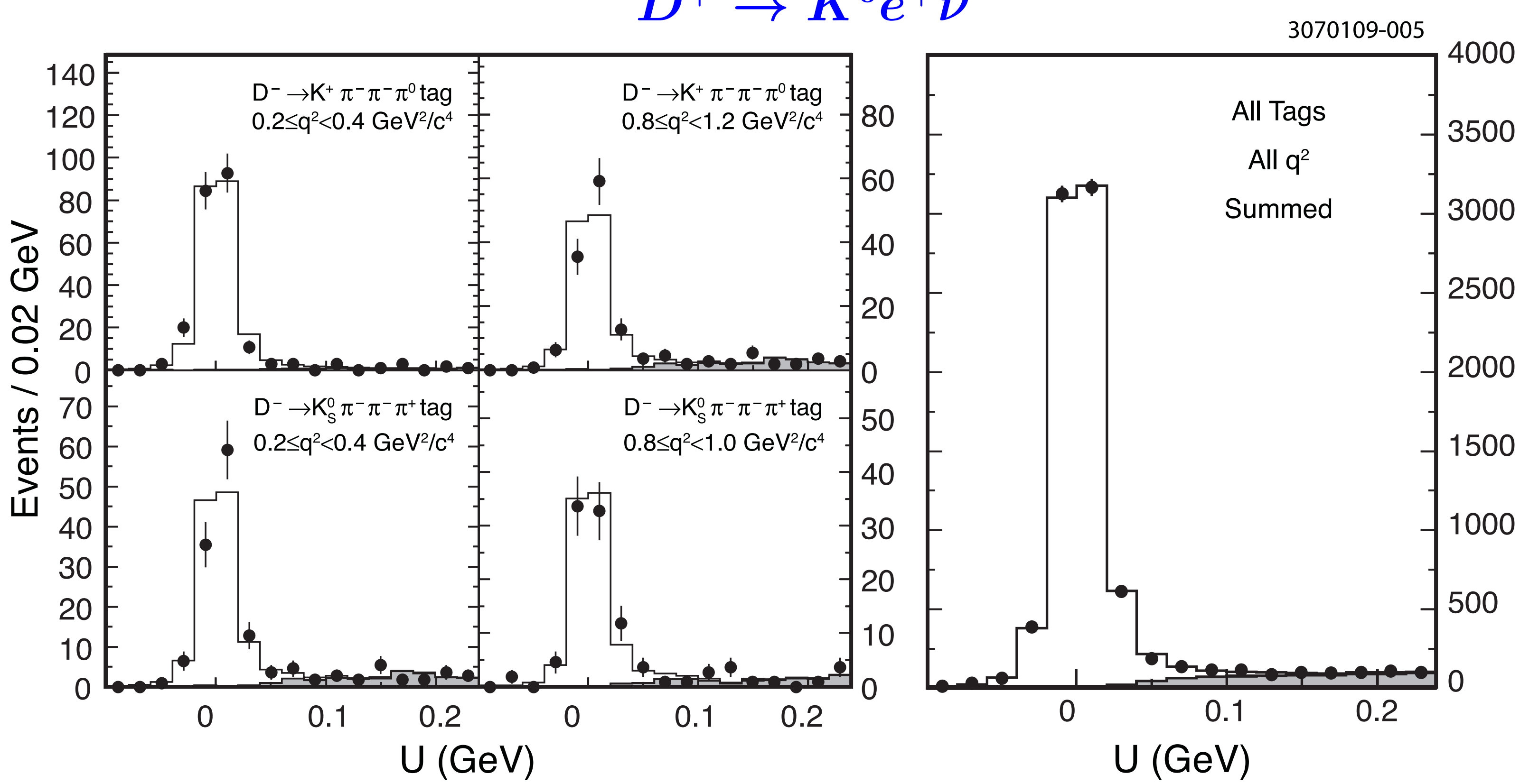
- CLEO-c measures $|V_{cs} f_+^{qs}(q^2)|$ and $|V_{cd} f_+^{qd}(q^2)|$ to test QCD theories of $f(q^2)$
  - Goal is to validate theories of $f_+(q^2)$ for application in the B meson sector
  - Most important for V_{ub} from $b \to u$ transitions where HQET does not apply
- Decay to a vector meson (V) involves 3 form factors and a more complicated expression involving 3 decay angles (or 3 other variables) in addition to q^2

D^0 and D^+ Semileptonic Decays

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



$D^+ \to \bar{K}^0 e^+ \nu$

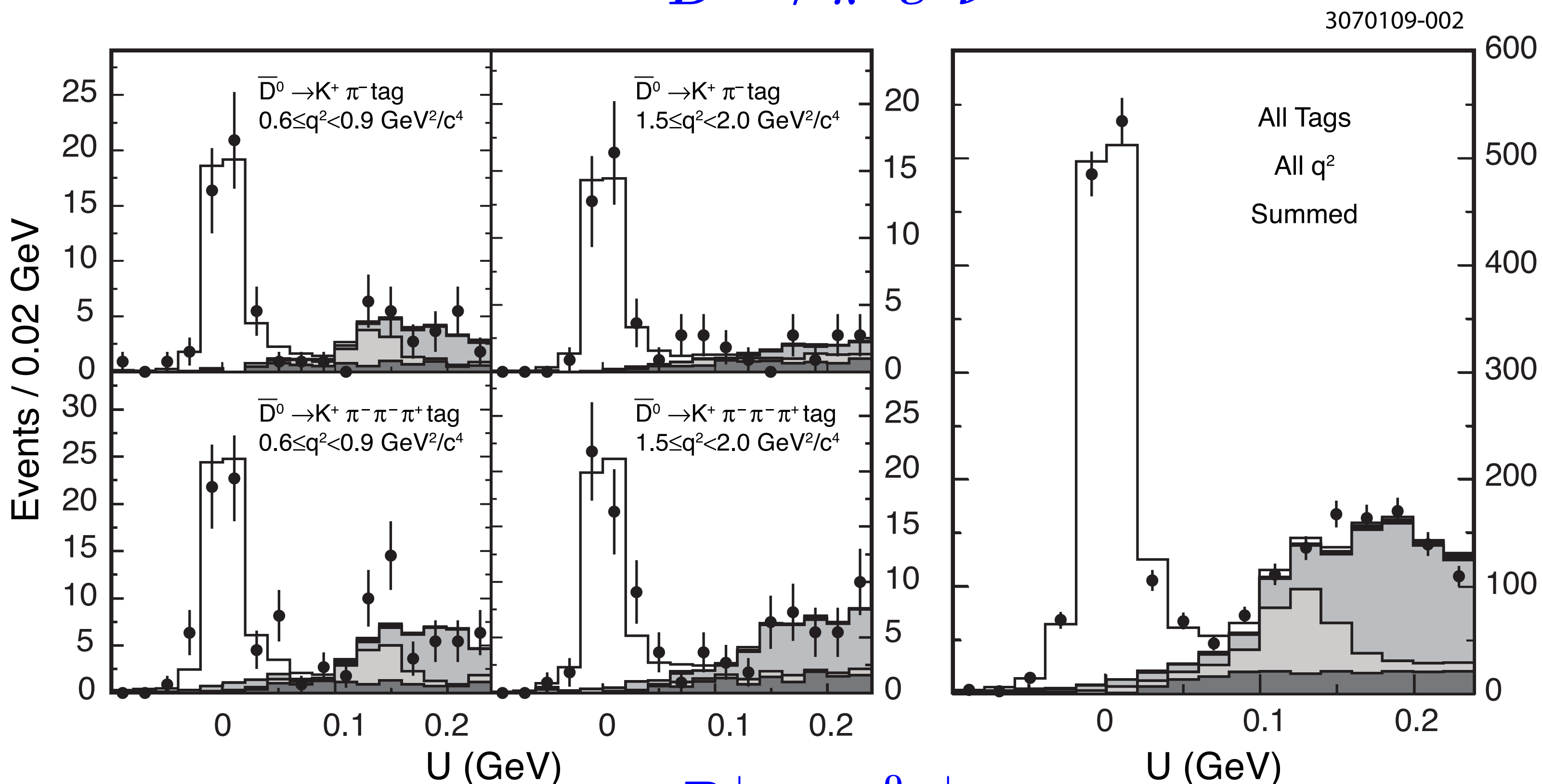


Technique

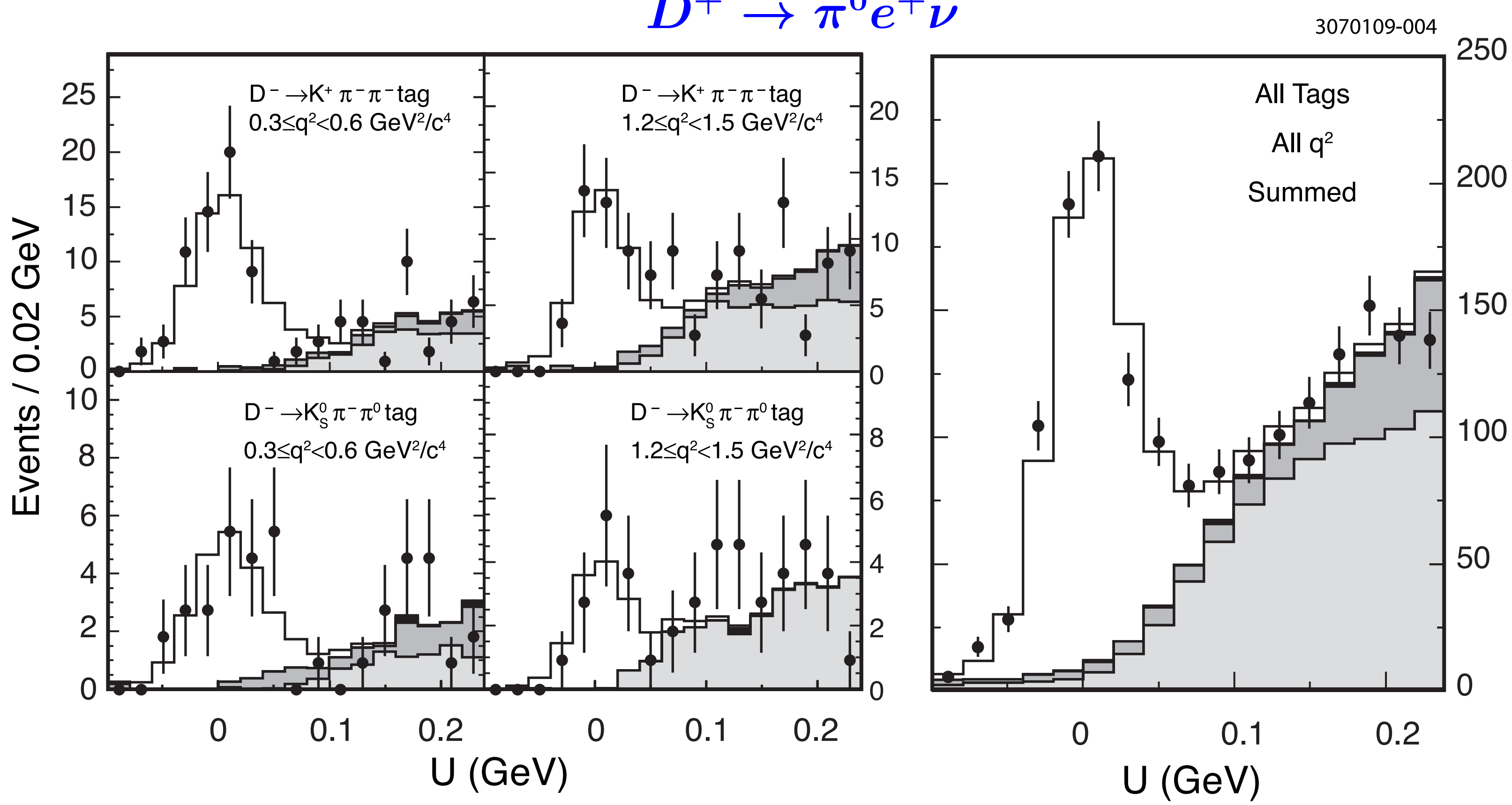
- Find a fully reconstructed hadronic decay tag
- Find a semileptonic candidate in the event
- Determine $E_{\rm miss}$ & $P_{\rm miss}$ from detector hermiticity
- Fit the $U \equiv E_{\rm miss} - cP_{\rm miss}$ distribution for the signal
- Extremely clean signals in Cabibbo-favored $D \to K e \nu$ modes

D^0 and D^+ Semileptonic Decays

$D^0 \to \pi^- e^+ \nu$



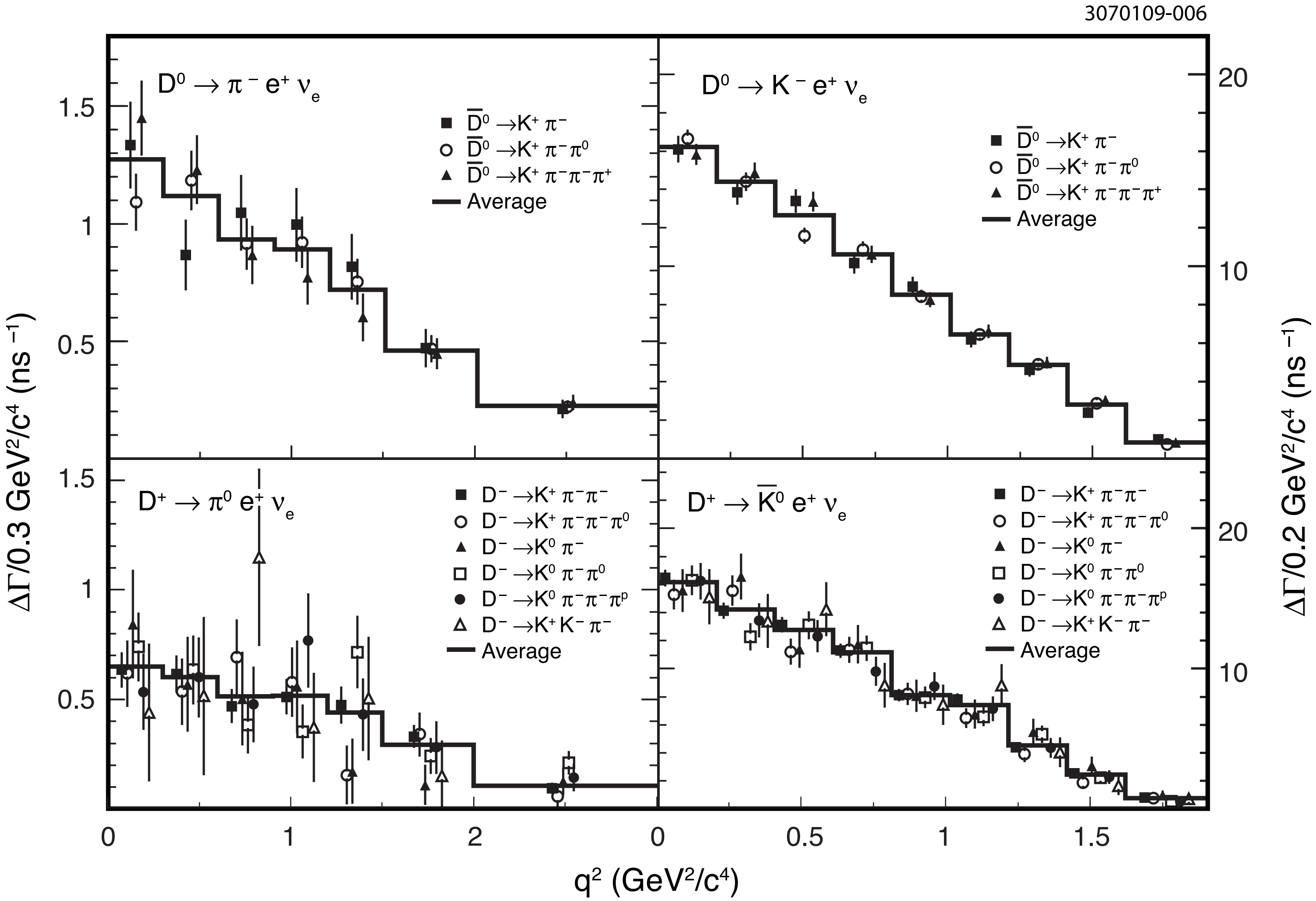
$D^+ \to \pi^0 e^+ \nu$



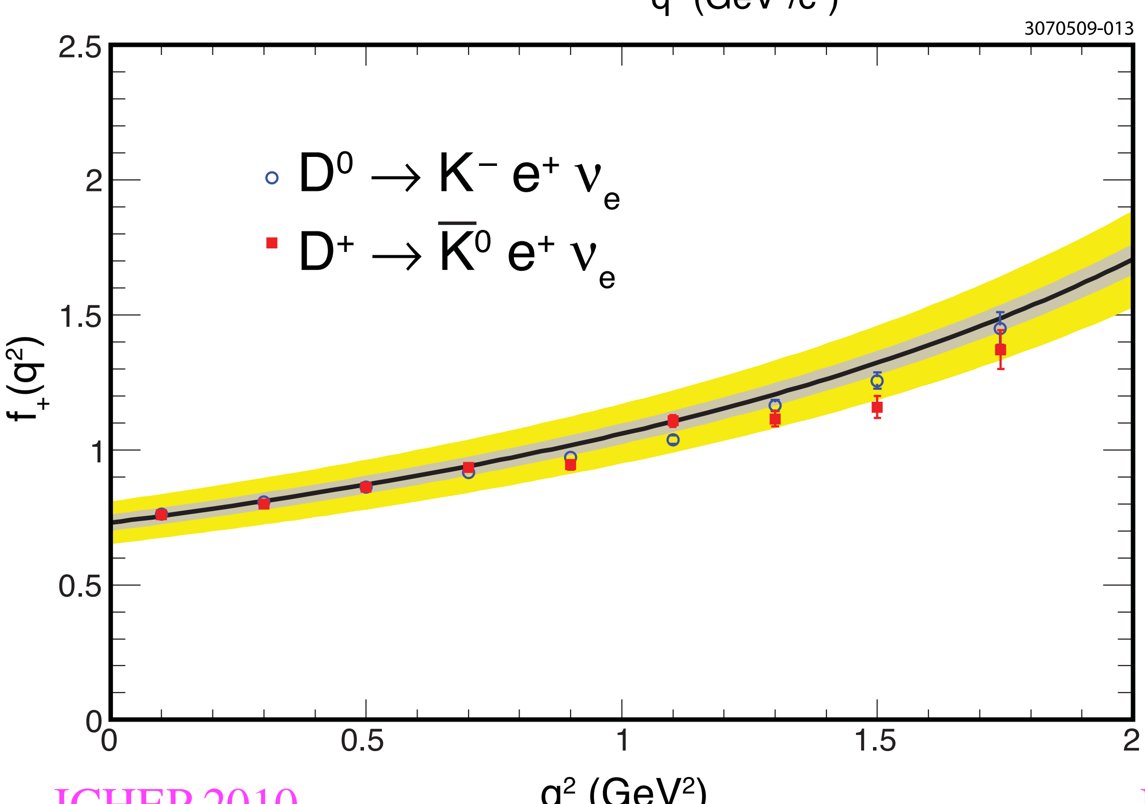
- Clean and robust signals in Cabibbo-suppressed $D \to \pi e \nu$ modes
- Excellent isospin agreement for branching fractions and form factors

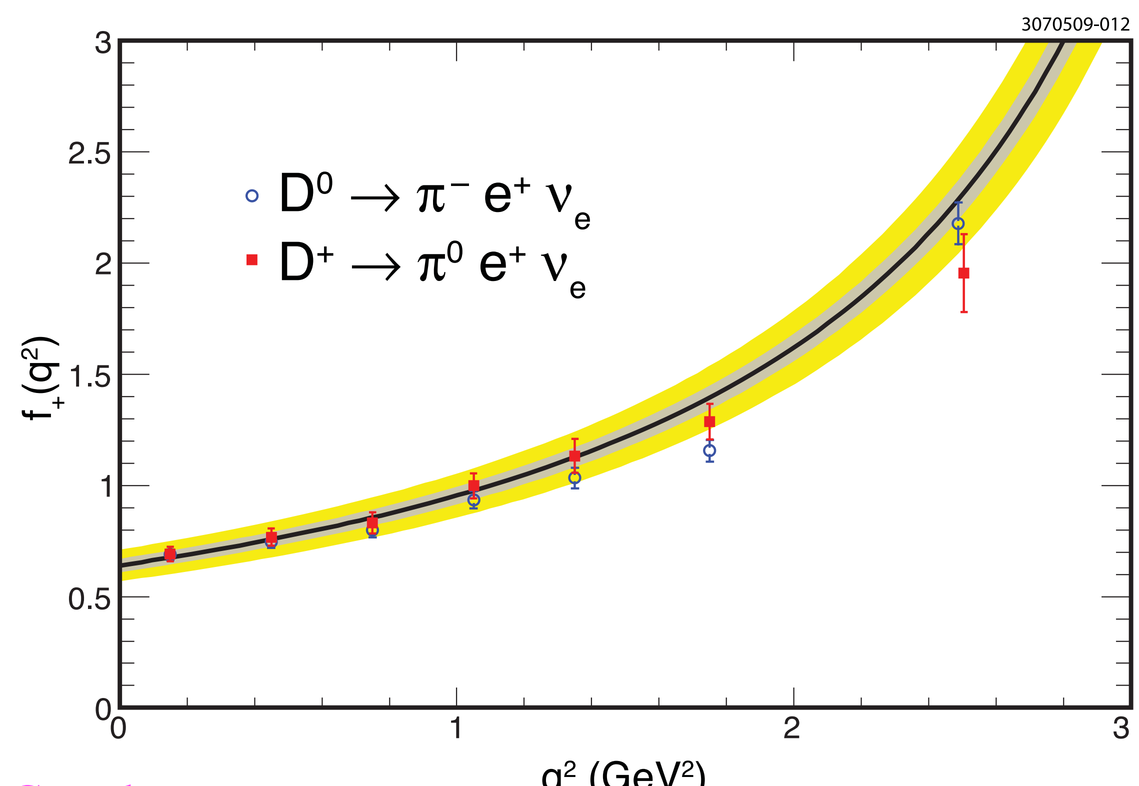
- Determine $f_+(0)$ from fits of $d\Gamma/dq^2$ distributions to the parametrization of T. Becher and R. J. Hill
- Determine branching fractions from integration of the fits over q^2

D^0 and D^+ Semileptonic Form Factors



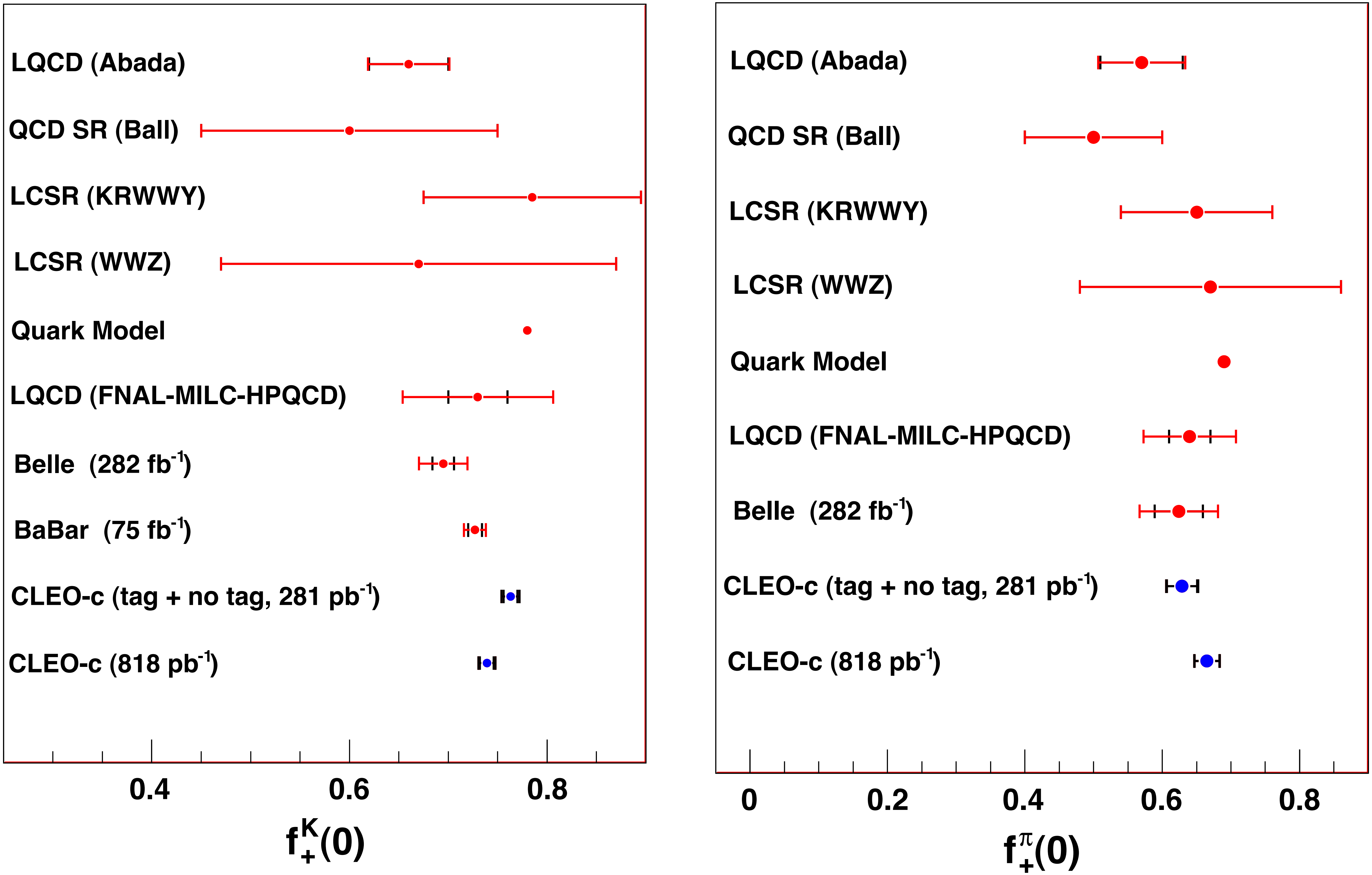
- **Excellent agreement for $d\Gamma/dq^2$ distributions among tag modes**
- **Agreement with LQCD good at low q^2**
- **Agreement with LQCD less good at high q^2**





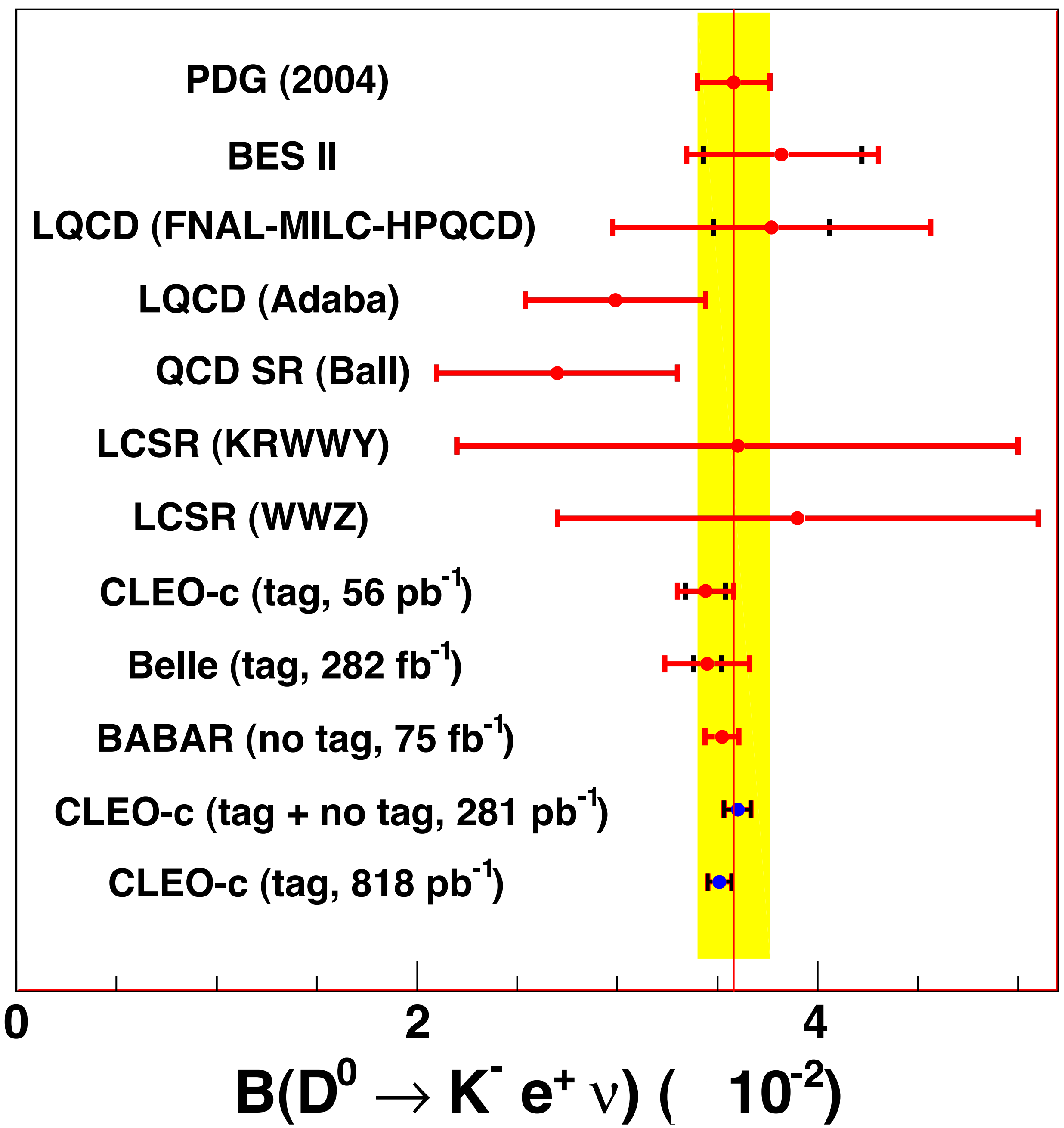
$f_+(0)$ for D^0 and D^+ Semileptonic Decays

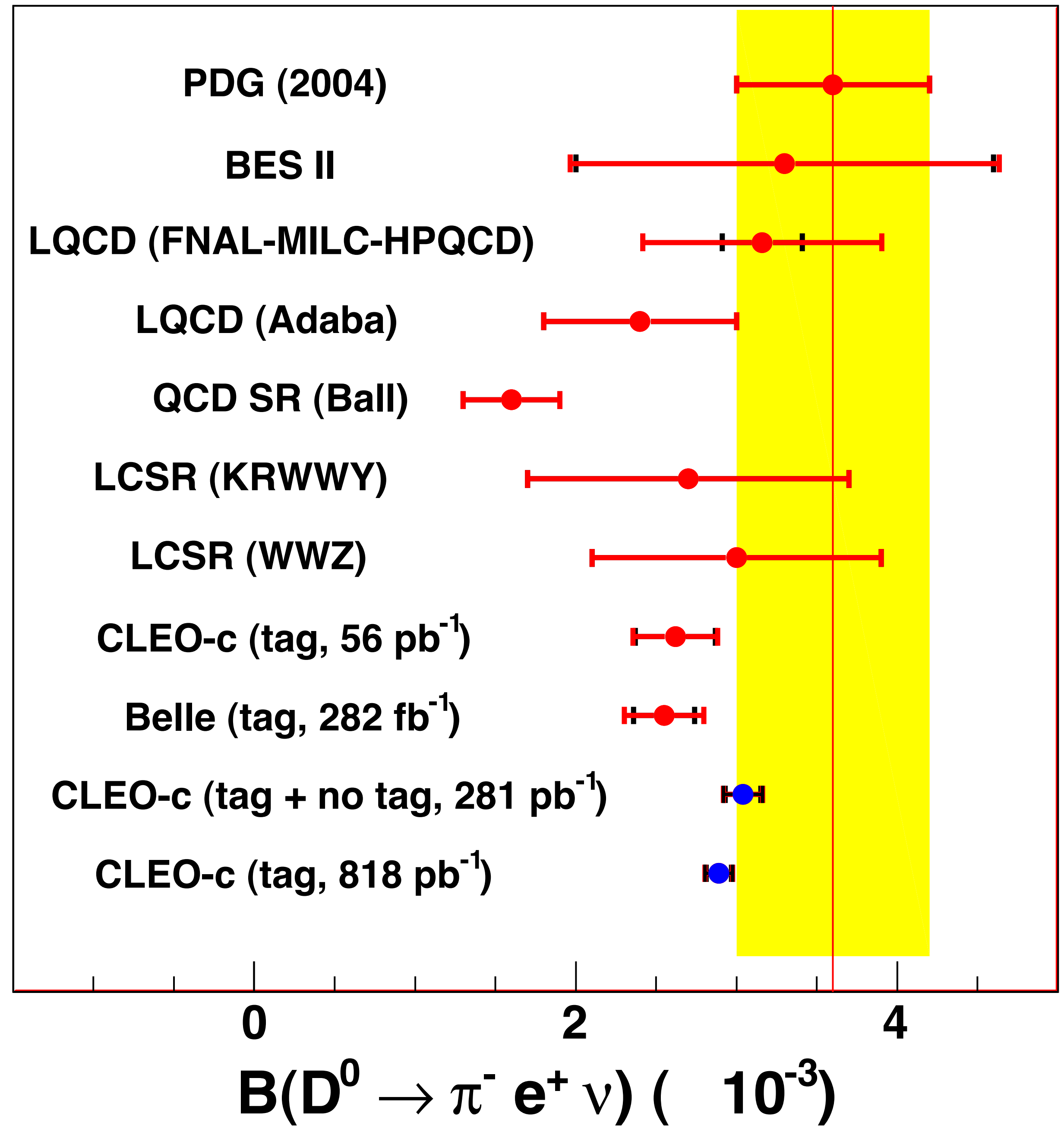
Results averaged over isospins



D^0 and D^+ Semileptonic Branching Fractions

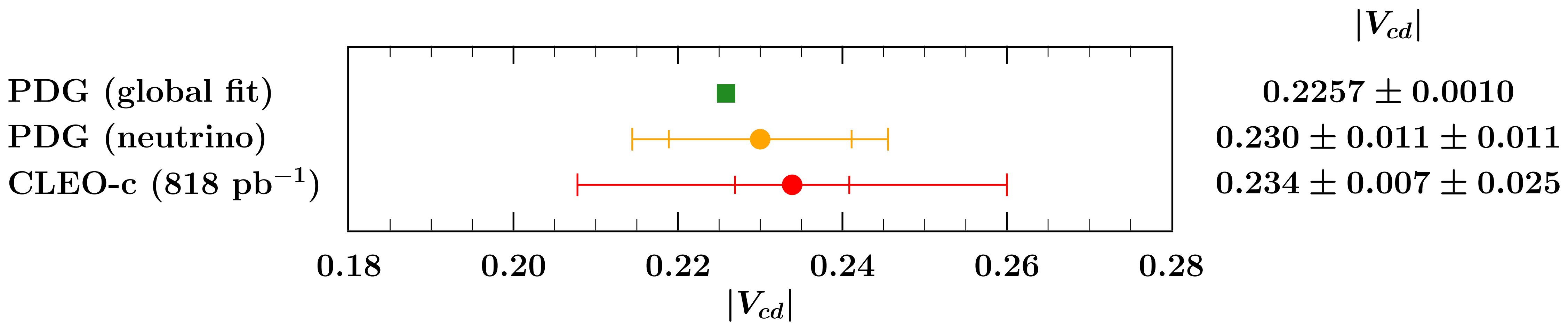
Results averaged over isospins

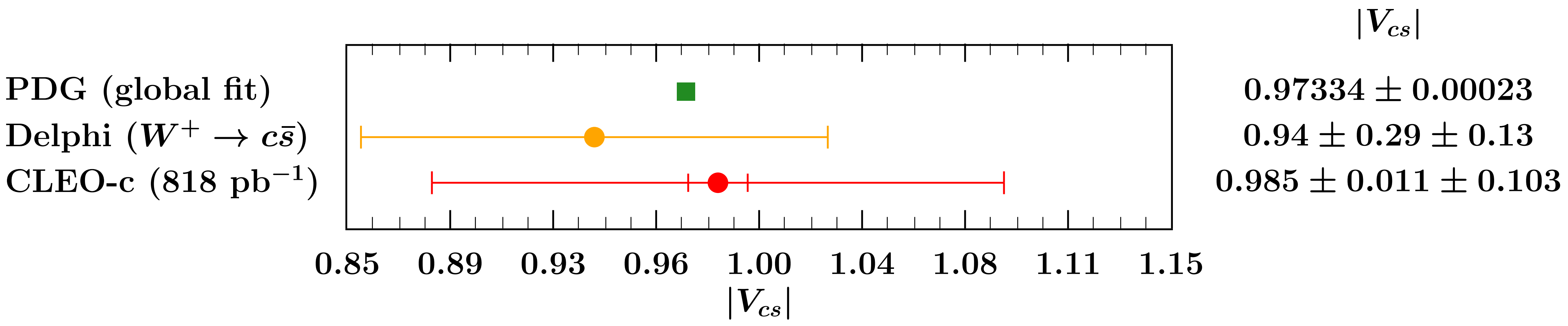




Measurements of $|V_{cd}|$ and $|V_{cs}|$

- Require values of $f_+(0)$ from LQCD
- Inner error bars are combined experimental statistical and systematic uncertainties
- Outer error bars include $f_+(0)$ uncertainties from LQCD
- LQCD uncertainties dominate
  - Serious challenge for LQCD





Conclusions

Reported leptonic and semileptonic results from the the full $\psi(3770)$ and $\psi(4170)$ data samples

- f_{D^+} and f_{D_s} results are statistics limited
  - Agreement of the f_{D^+} result with LQCD is excellent
  - Agreement of f_{D_s} results with LQCD is less certain
  - CLEO-c results dominated by statistical errors
    - Excellent opportunity for BESIII to contribute with larger data samples
    - Would challenge LQCD at a new level of precision
- Precision measurements of $D \to Ke\nu$ and $D \to \pi e\nu$ branching fractions and form factors
  - Branching fraction results agree with earlier measurements
  - Form factor agreement with LQCD good at low q^2
  - Form factor agreement with LQCD less good at high q^2
  - LQCD uncertainties dominate measurements of $|V_{cd}|$ and $|V_{cs}|$
    - Significant challenge for LQCD