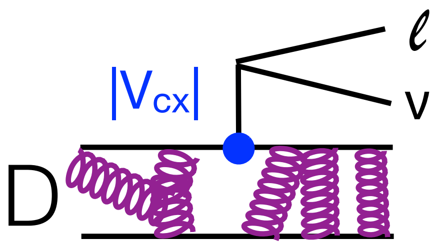
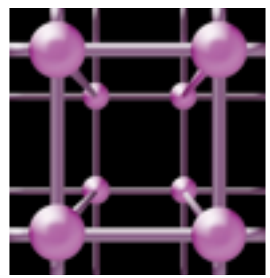
Semileptonic Charm Decays

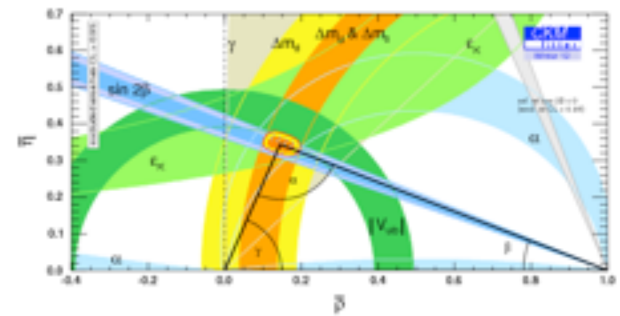
Jonas Rademacker on behalf of CLEO

Semileptonic Charm Decays



- Measure $|V_{cx}|$ × (QCD-form factor(s)). Take $|V_{cx}|$ from CKM unitarity to extract form factors, test LQCD. Or input LQCD and test CKM-unitarity.





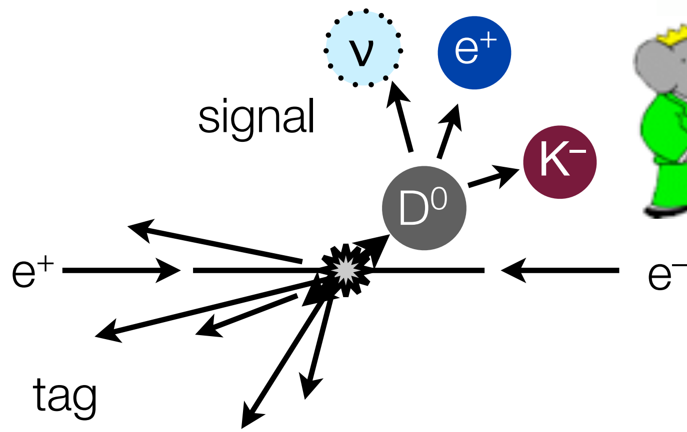
- Study S-wave in $D \to K\pi e\nu$, $D \to \pi\pi e\nu$, $D_s \to KKe\nu$
- Search for rare/forbidden modes like $D_s \to \omega e\nu$ to study the structure of the D_s and long-distance effects.
- Input to B physics
  - Validate LQCD form factor calculations, relied upon in extracting $|V_{ub}|$
  - Combine $D \to \rho e\nu$, $D \to K^* e\nu$, $B \to V \ell \ell$ to improve $|V_{ub}|$ (Phys.Rev. D70 (2004) 114005)
  - S-waves in $D \to \pi\pi e\nu$ helped motivate use of $B_s \to J/\psi\, f_0$ for ϕ_s.

Experimental Challenge: Find the ν in $D \rightarrow h\,\ell\,\nu$

- FOCUS: Get **direction of D** from vertex information, and 4-momenta of charged decay products $\Longrightarrow$ enough information to reconstruct ν.

- BaBar: Get **direction of the D** from momentum conservation.

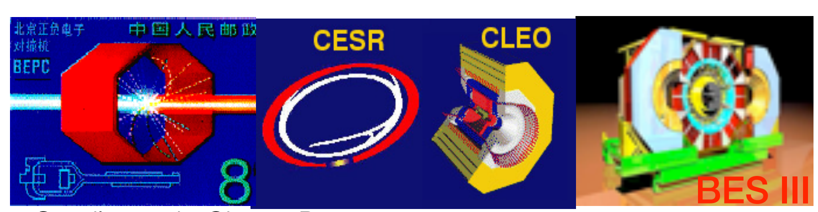
$$\vec{p}_D \propto - \sum_{\text{all except e,K from D}} \vec{p}_i$$



- BELLE: Fully reconstruct tag side as D* X. Better resolution than BaBar's method, but less statistics.

(see also Andrzej Bozek's talk on Tue)

- All much cleaner at threshold...



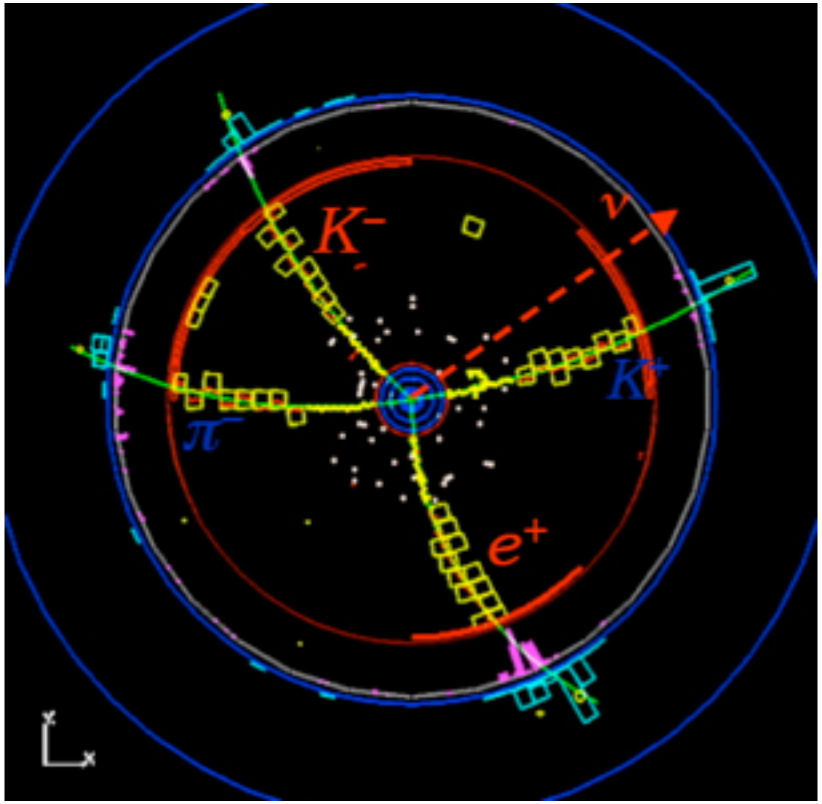
D→h ℓ ν @ charm threshold (CLEO-c/BES III)

$e^+ e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$

- 100% of beam energy converted to DD pair ⟹ very clean. Kinematic constraints allow reconstruction of ν.
- Always generate D-mesons in pairs. One D provides the normalisation for the other ⟹ absolute branching fractions.
- These features let CLEO-c, and now BES III, perform competitive leptonic & semileptonic measurements with each only ca 0.3%* of the D mesons produced the B-factories.

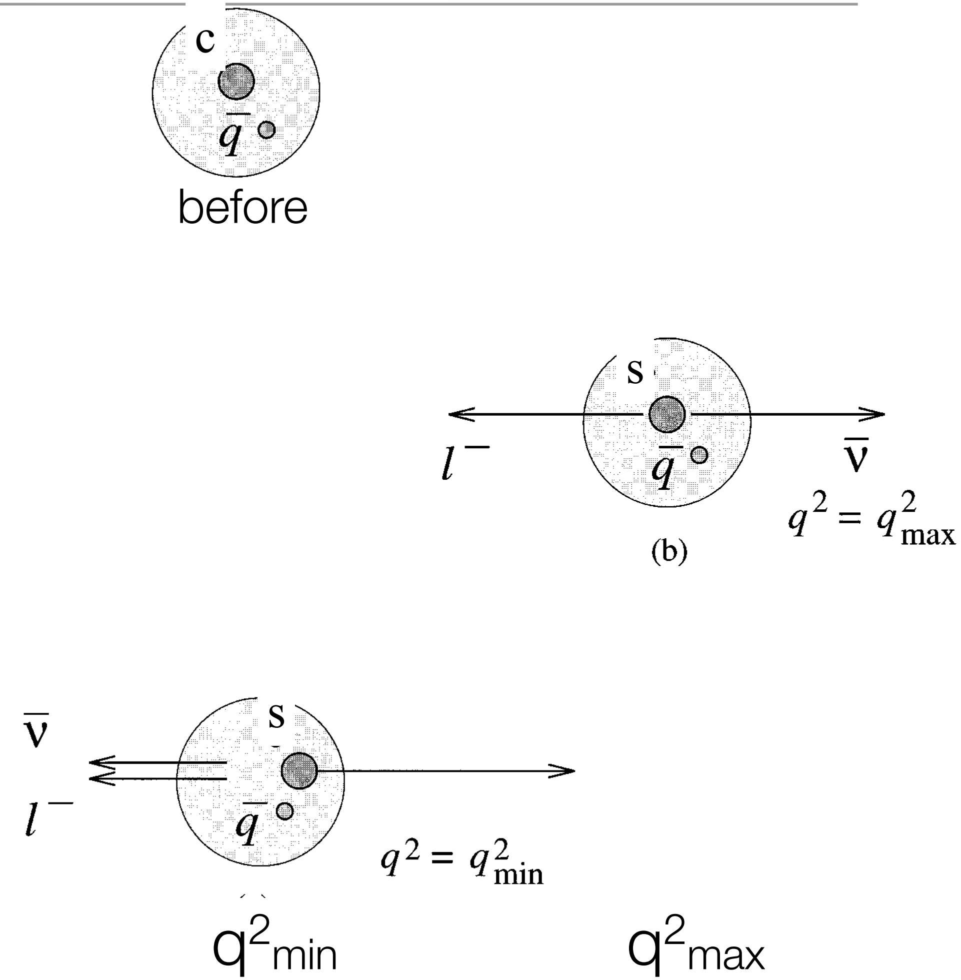
*) For BES III this corresponds roughly to what has been analysed; there is 3x as much data on tape.

CLEAN-c



$\psi(3770) \rightarrow \bar{D}^0(K^+\pi^-)D^0(K^-e^+\nu_e)$

Form factor in decays to pseudoscalars



- D→h ℓ ν, h = K, π, ...

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cx}| \, |\vec{p}_h|^3 \left| f_+^{D\to h}(q^2) \right|^2$$

(neglecting fermion masses)

- $q^2 = (p_\ell + p_\nu)^2$ = invariant mass-squared of lepton pair.

- $f_+(q^2)$ = form factor - the QCD bit.

- Measure $|V_{cx}| \cdot f_+(q^2)$. Get $|V_{cx}|$ from CKM-unitarity to measure $f_+(q^2)$ as a test of LQCD - or reverse the logic and test CKM-unitarity.

See review by Richman & Burchat, Rev.Mod.Phys. 67 (1995) 893-976

Form factor in decays to pseudoscalars

- $D \to h \ell \nu$, h = K, π, ...

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} \left|V_{cx}\right| \left|\vec{p}_h\right|^3 \left|f_+^{D\to h}(q^2)\right|^2$$

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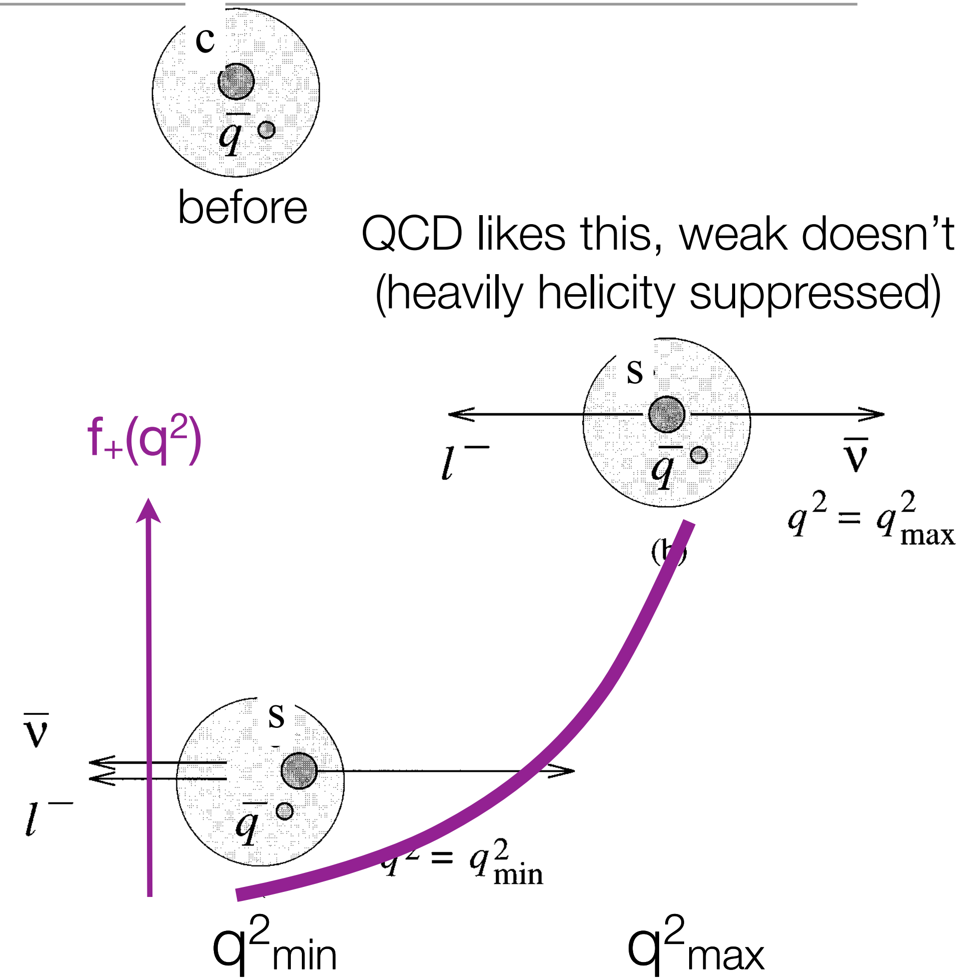
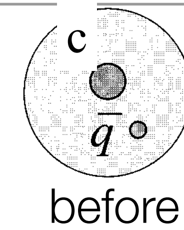


See review by Richman & Burchat, Rev.Mod.Phys. 67 (1995) 893-976

$D^0 \to \{K,\pi\}\, e^+ \nu$ Form factor parameterisations



- Simple pole model:

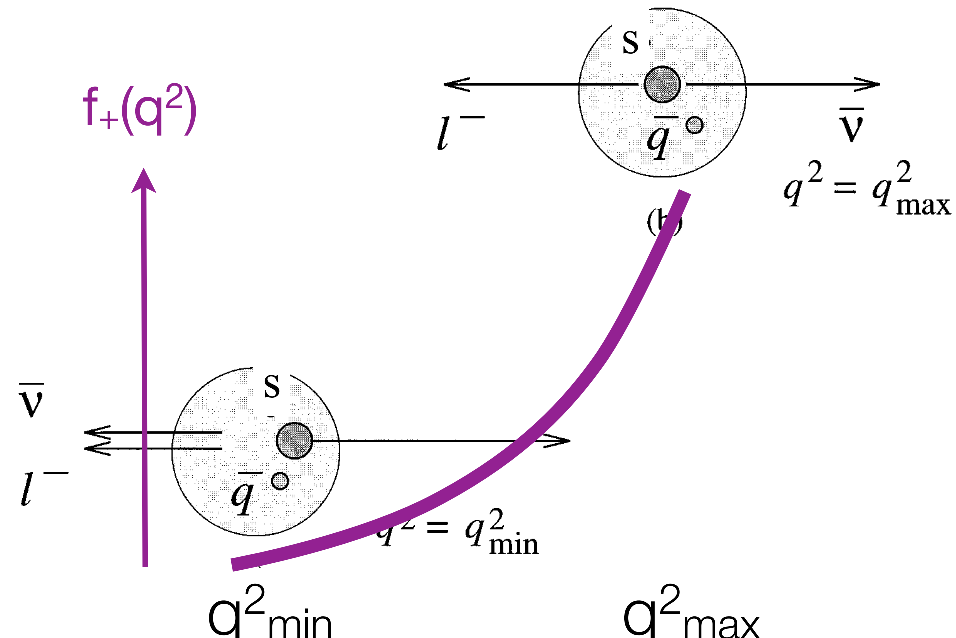
$$f_+(q^2) = \frac{f_+(0)}{1 - q^2/m^2_{pole}}$$

- Modified Pole Model (Becirevic and Kaidalov, PLB 478, 417)

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

- Series expansion (CLEO-c/BES III both explored 2nd and 3rd order):

$$f_+(q^2) \;=\; \frac{1}{P(q^2)\,\phi(q^2,t_0)} \sum_{k=0}^{\infty} a_k(t_0)\;\left[z(q^2,t_0)\right]^k$$



See review by Richman & Burchat, Rev.Mod.Phys. 67 (1995) 893-976

$D \to K e \nu$, $D \to \pi e \nu$

- Recent results
  - BaBar 2007 and 2010, D^o
  - CLEO-c 2009, 0.8/fb, D^o and $D^{\pm}$.
  - BES III May 2012: New result (so far, D^o only)
    2.9 /fb data taken
    0.9/fb analysed

BaBar: Phys.Rev. D76 (2007) 052005
CLEO: Phys.Rev. D80 (2009) 032005
BES III: New result, shown first at CHARM 2012 by Cunlei Liu

$D\to Ke\nu$, $D\to\pi e\nu$

BaBar: Phys.Rev. D76 (2007) 052005
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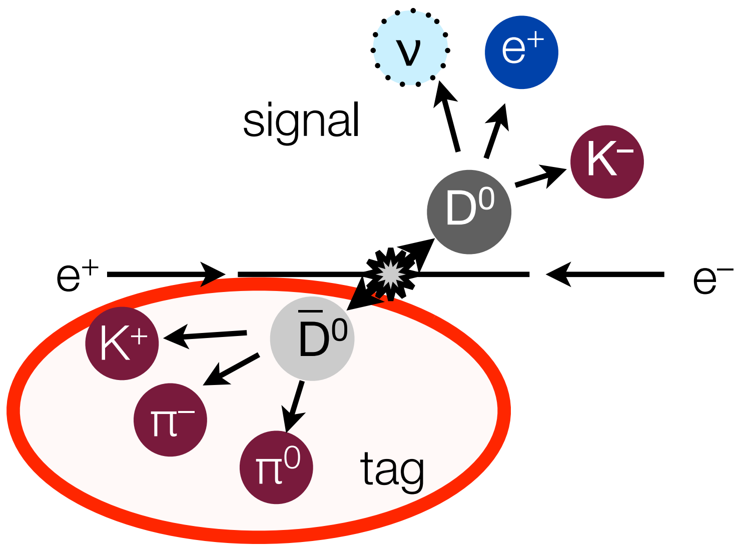
BES III: New result, shown first at CHARM 2012 by Cunlei Liu

- Recent results
  - BaBar 2007 and 2010, D^0
  - CLEO-c 2009, 0.8/fb, D^0 and $D^\pm$.
  - BES III May 2012: New result (so far, D^0 only)
    2.9 /fb data taken
    0.9/fb analysed

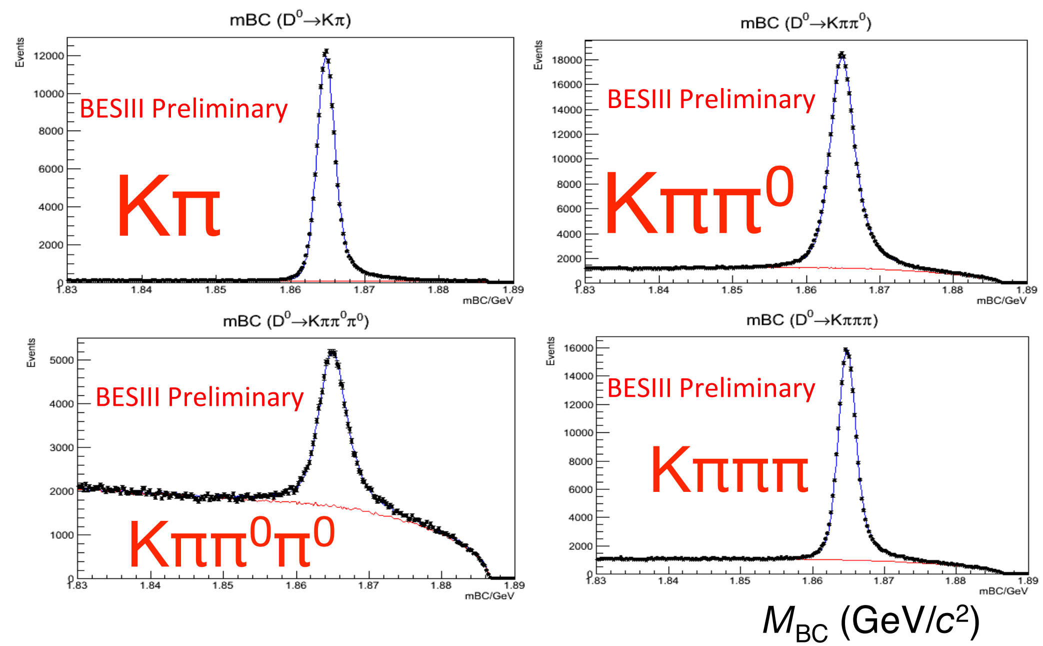
$D^0 \rightarrow \{K,\pi\}\, e^+ \nu$ new BES III result

BES III 2012 (prelim)



- Step 1: Reconstruct ~3/4 M tag D (provides normalisation)

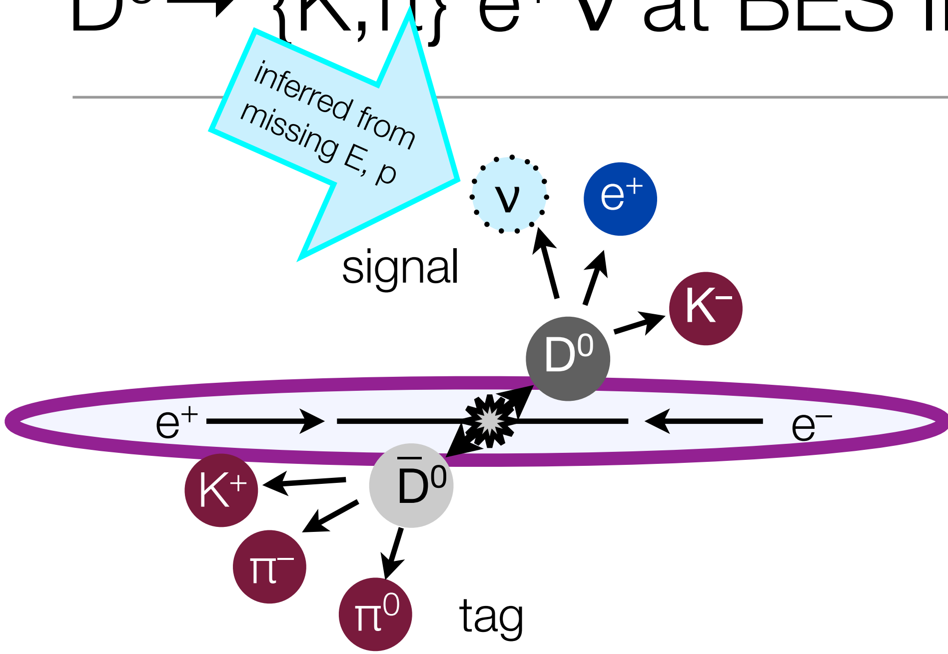
beam-constrained mass of tag D



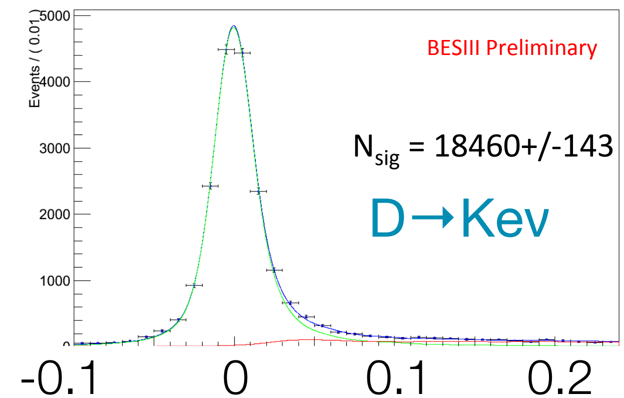
BES III: CHARM 2012 by Chunlei Liu

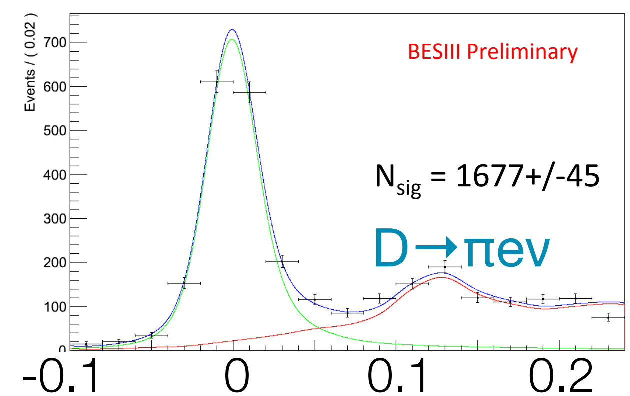
$D^0 \to \{K,\pi\}\, e^+ \nu$ at BES III

BES III 2012 (prelim)



$$U \equiv E_{\rm miss} - |\vec{p}_{\rm miss}| \text{ (GeV)}$$





- Step 1: Reconstruct Tag D
- Step 2: Find U (~ missing mass) from beam constraint and e and η, η', φ.

BES III: CHARM 2012 by Chunlei Liu

$D^0 \to \{K,\pi\}\, e^+ \nu$ Branching Fractions

BES III 2012 (prelim)

BES III prelim (0.9/fb)

BESIII Preliminary

Mode	measured branching fraction(%)	PDG	CLEOc
$\bar{D}^0 \to K^+ e^- \bar{\nu}$	3.542 ±0.030±0.067	3.55 ±0.04	3.50 ±0.03 ±0.04
$\bar{D}^0 \to \pi^+ e^- \bar{\nu}$	0.288 ±0.008±0.005	0.289 ±0.008	0.288 ±0.008±0.003

BES III: CHARM 2012 by Chunlei Liu

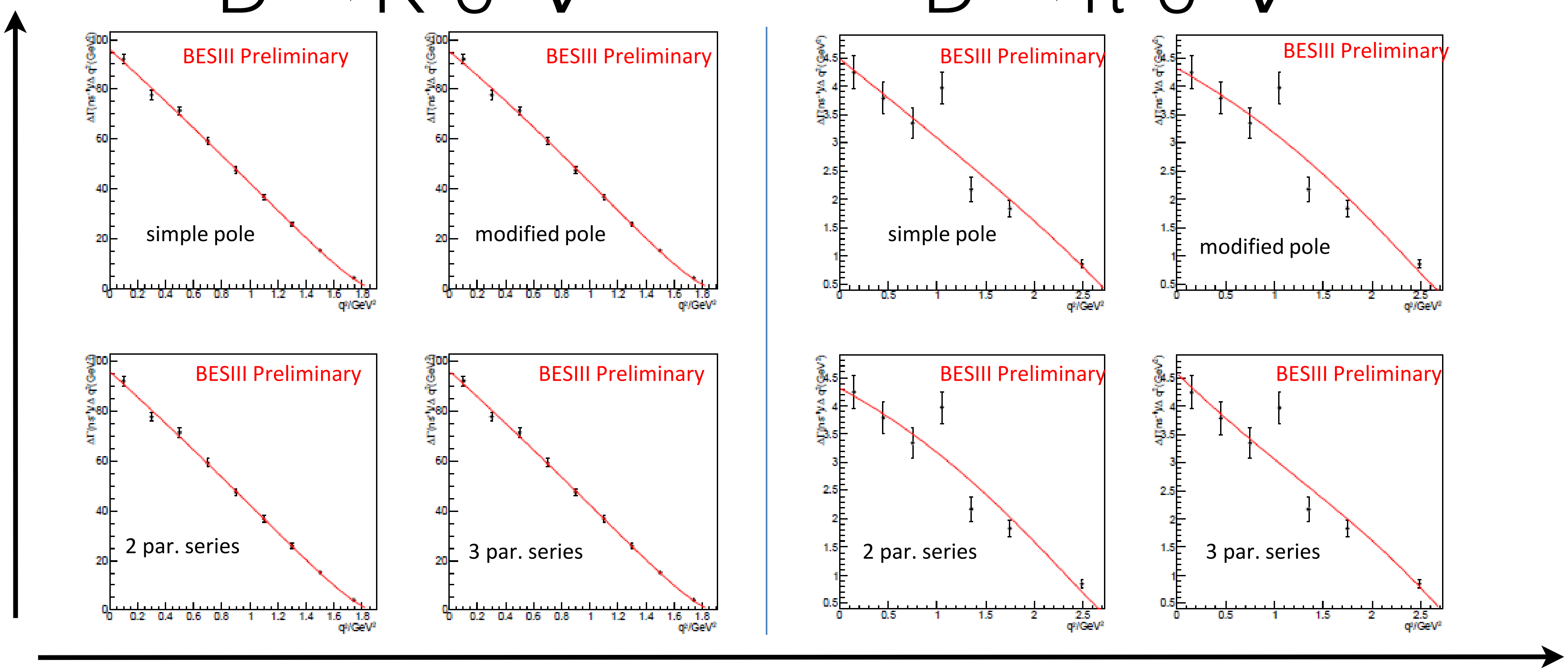
$D^0 \to \{K,\pi\}\, e^+ \nu$ fits to decay rates

BES III 2012 (prelim)

$d\Gamma/dq^2$: BES III data with fits using different form factor models

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

$d\Gamma/dq^2$



q^2/GeV^2

BES III: CHARM 2012 by Chunlei Liu

BES III form factor fit results

BES III 2012 (prelim)

BESIII Preliminary

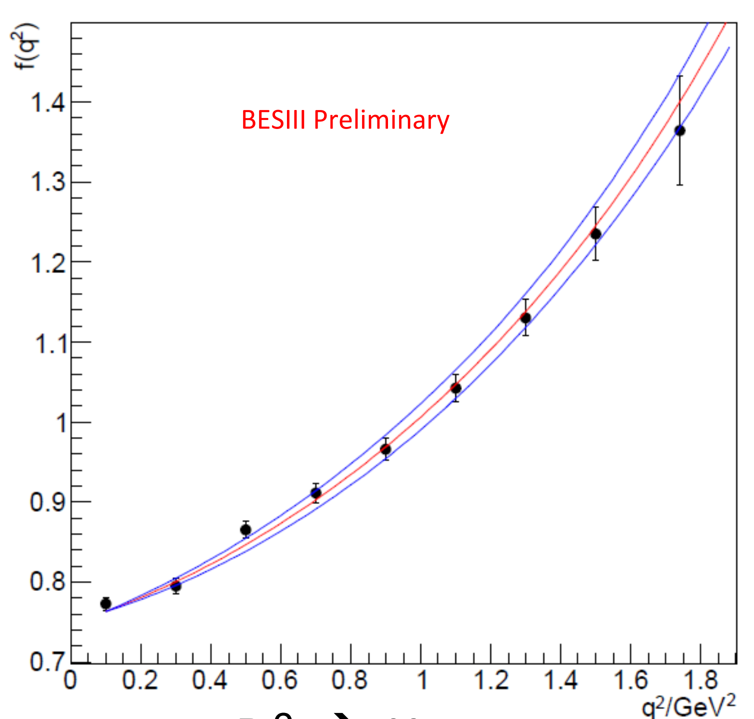
Simple Pole	$f_+(0)\|V_{cd(s)}\|$	m_{pole}	
$D^0 \to Ke\nu$	$0.729\pm0.005\pm0.007$	$1.943\pm0.025\pm0.003$	
$D^0 \to \pi e\nu$	$0.142\pm0.003\pm0.001$	$1.876\pm0.023\pm0.004$	
Modified Pole	$f_+(0)\|V_{cd(s)}\|$	α	
$D^0 \to Ke\nu$	$0.725\pm0.006\pm0.007$	$0.265\pm0.045\pm0.006$	
$D^0 \to \pi e\nu$	$0.140\pm0.003\pm0.002$	$0.315\pm0.071\pm0.012$	
2 par. series	$f_+(0)\|V_{cd(s)}\|$	r_1	
$D^0 \to Ke\nu$	$0.726\pm0.006\pm0.007$	$-2.034\pm0.196\pm0.022$	
$D^0 \to \pi e\nu$	$0.140\pm0.004\pm0.002$	$-2.117\pm0.163\pm0.027$	
3 par. series	$f_+(0)\|V_{cd(s)}\|$	r_1	r_2
$D^0 \to Ke\nu$	$0.729\pm0.008\pm0.007$	$-2.179\pm0.355\pm0.053$	$4.539\pm8.927\pm1.103$
$D^0 \to \pi e\nu$	$0.144\pm0.005\pm0.002$	$-2.728\pm0.482\pm0.076$	$4.194\pm3.122\pm0.448$

BES III: CHARM 2012 by Chunlei Liu

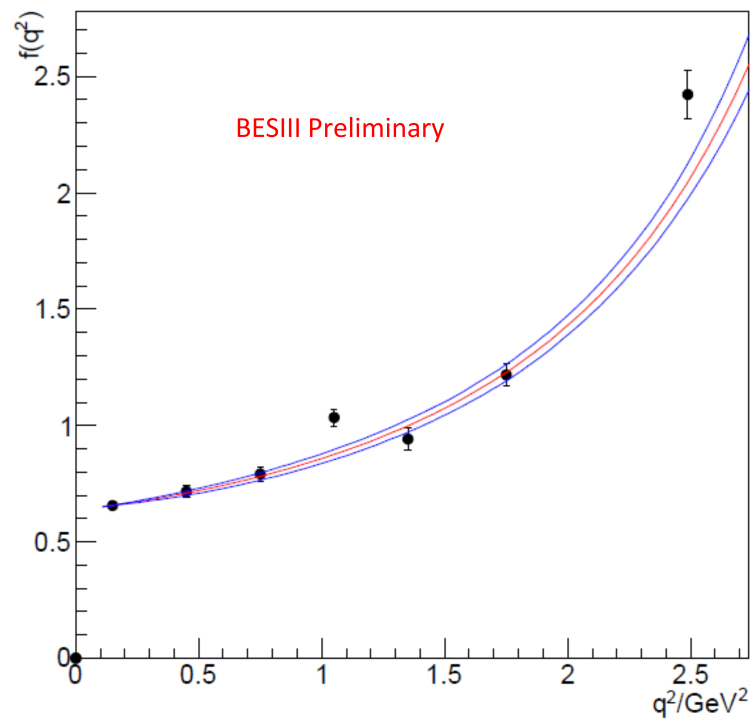
Form factor shapes: BES III / LQCD

BES III 2012 (prelim)
Fermilab/The Lattice/MILC 2011

note: these compare shape-only, no absolute scale.



$D^0 \rightarrow K e \nu$



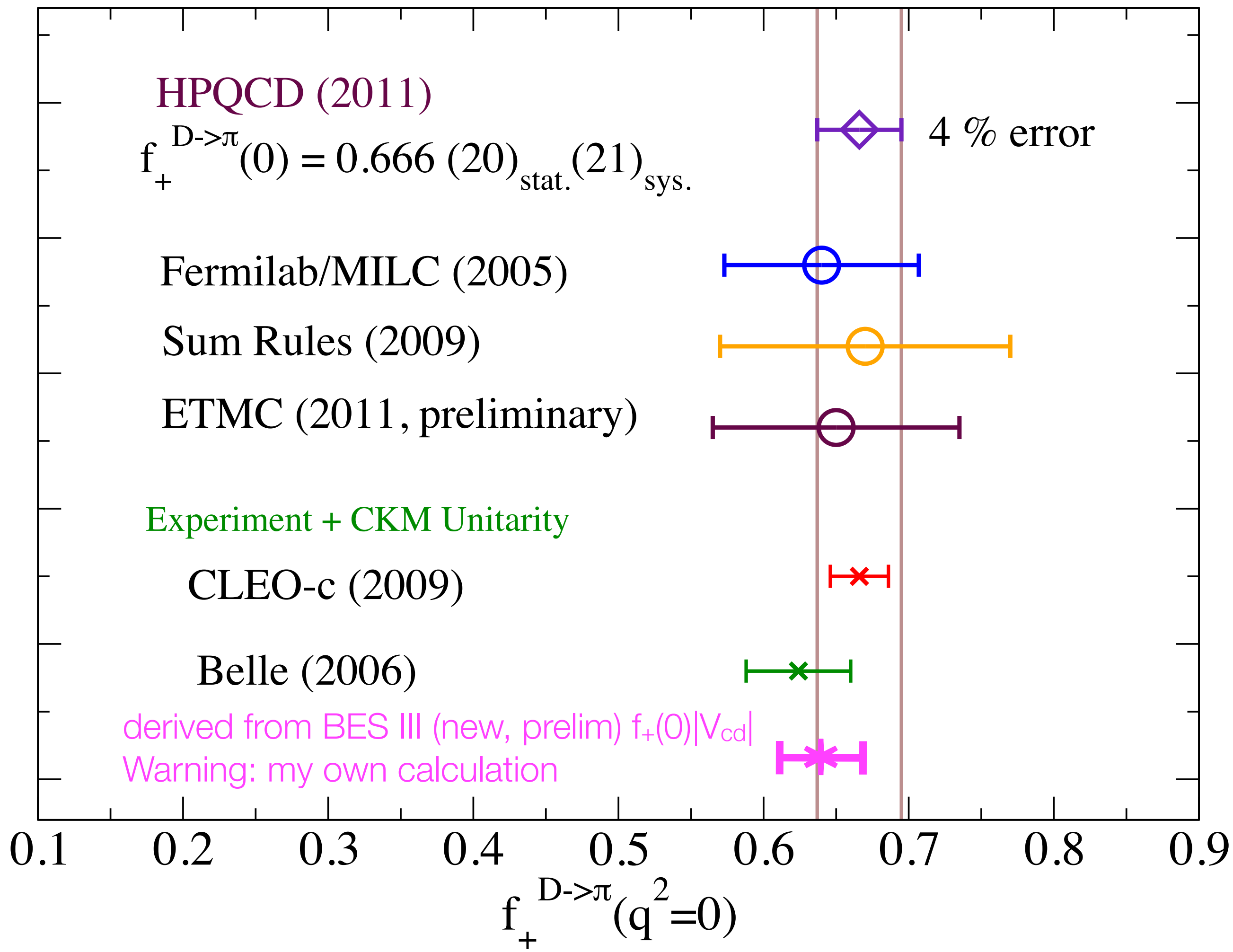
$D^0 \rightarrow \pi e \nu$

Points: BES III preliminary with stat errors
Curves: Fermilab/The Lattice/MILC with 1σ stat error band, arXiv:1111.5471 (Nov 2011)

BES III: CHARM 2012 by Chunlei Liu

$f_+^{D\to\pi}(0)$ from experiment and theory

Taken from Na, Davies, Follana, Koponen, Lepage and Shigemitsu, Phys.Rev. D84 (2011) 114505 and modified (added BES III)

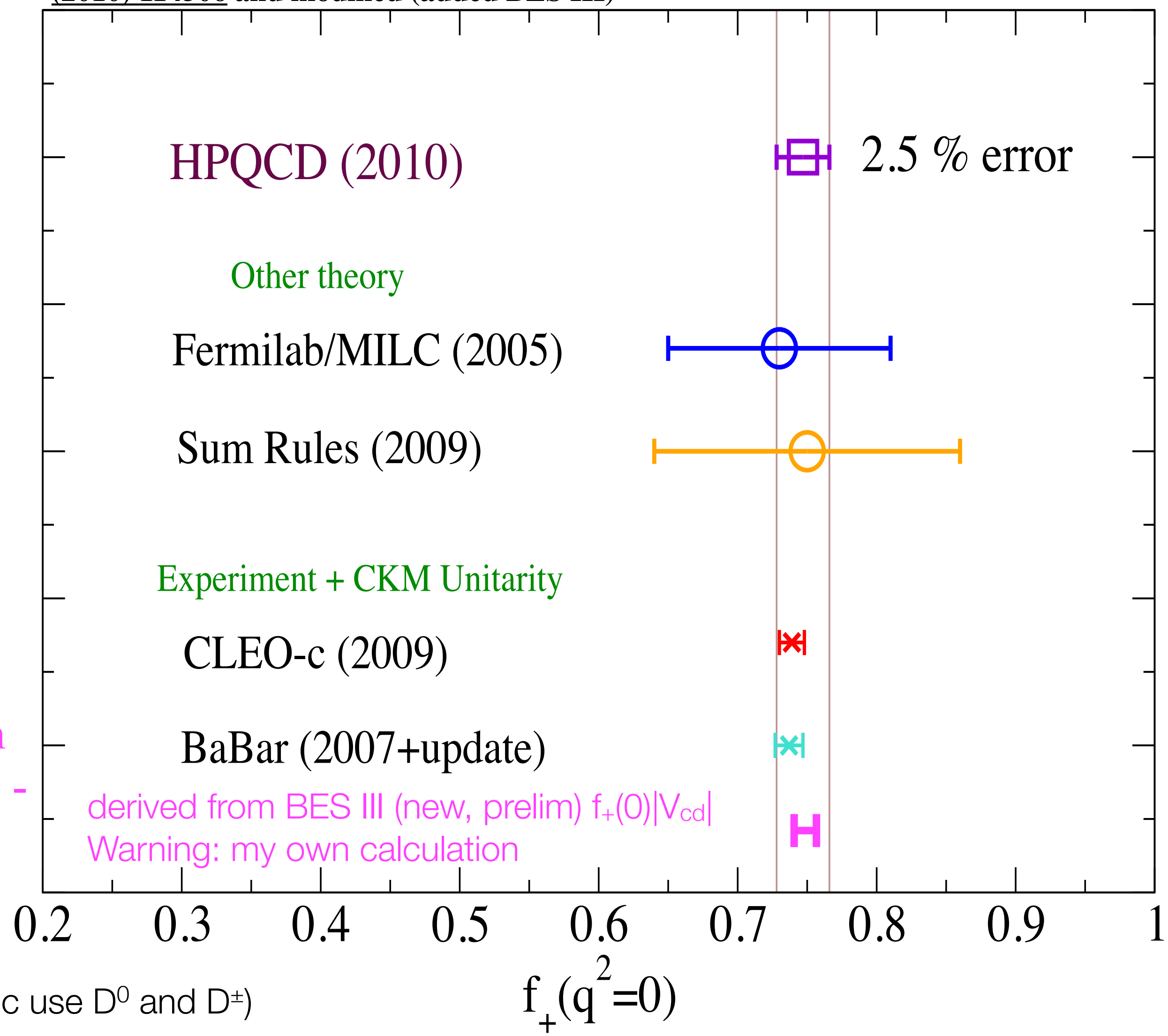


With $|V_{cd}| = 0.2252 \pm 0.0007$, I get from BES III new result (3 par series - as used by CLEO-c):

(note: BES III result from D^0 only, CLEO-c use D^0 and $D^{\pm}$)

$f_+^{D\to K}(0)$ from experiment and theory

Taken from Na, Davies, Follana, Koponen, Lepage and Shigemitsu, Phys.Rev. D82 (2010) 114506 and modified (added BES III)

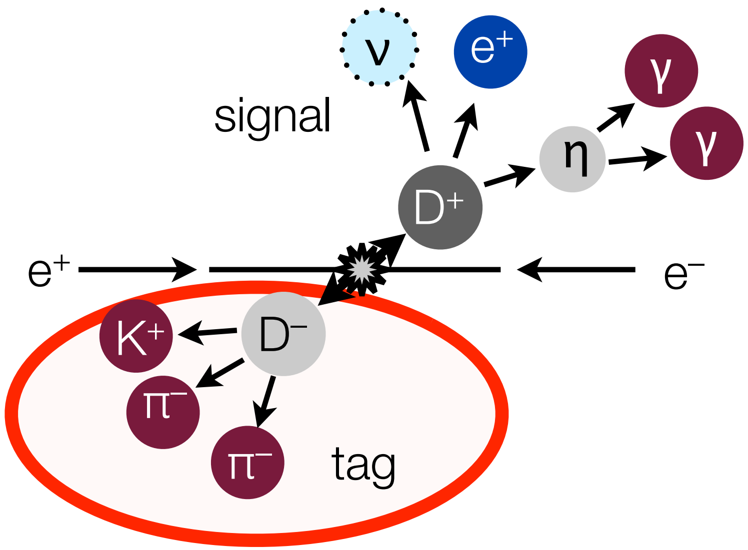


With $|V_{cs}| = 0.97345$, I get from BES III new result (3 par series - as used by CLEO-c):

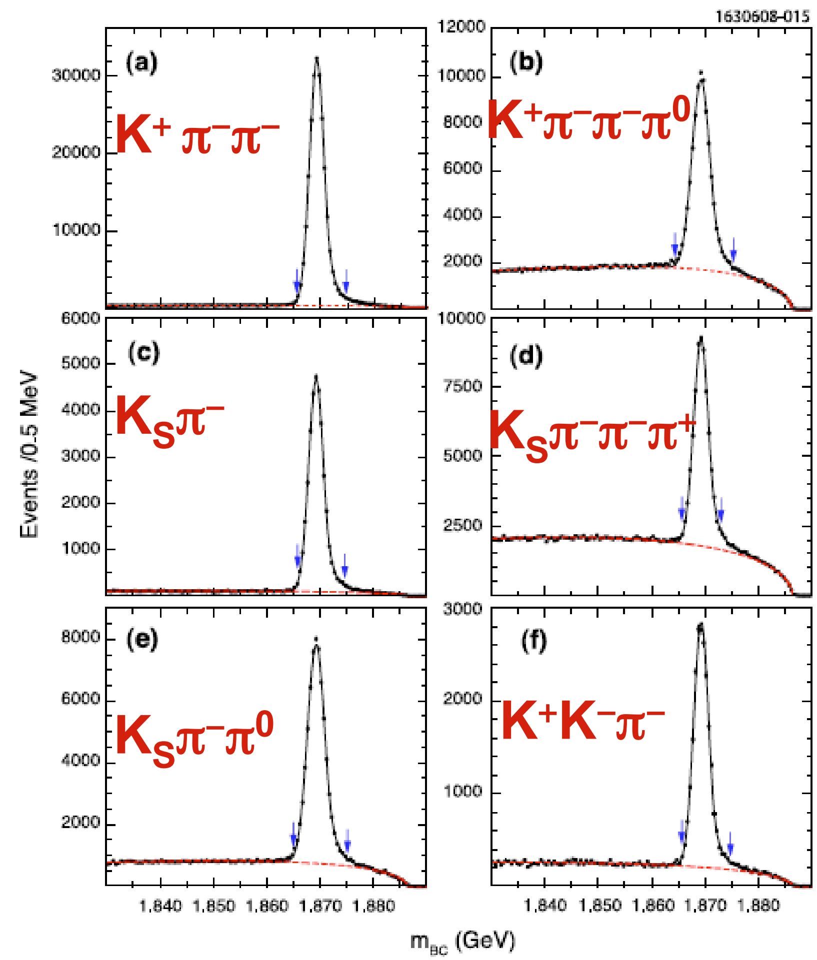
(note: BES III result from D^0 only, CLEO-c use D^0 and $D^\pm$)

CLEO-c 2011

CLEO-c: $D^+ \to \{\eta, \eta' \text{ or } \varphi\}\, e^+ \nu$ (tagged)



beam-constrained mass of tag D



plots from different CLEO-c paper (using same technique): PRD 78, 052003 (2008)

M_{BC} (GeV/c^2)

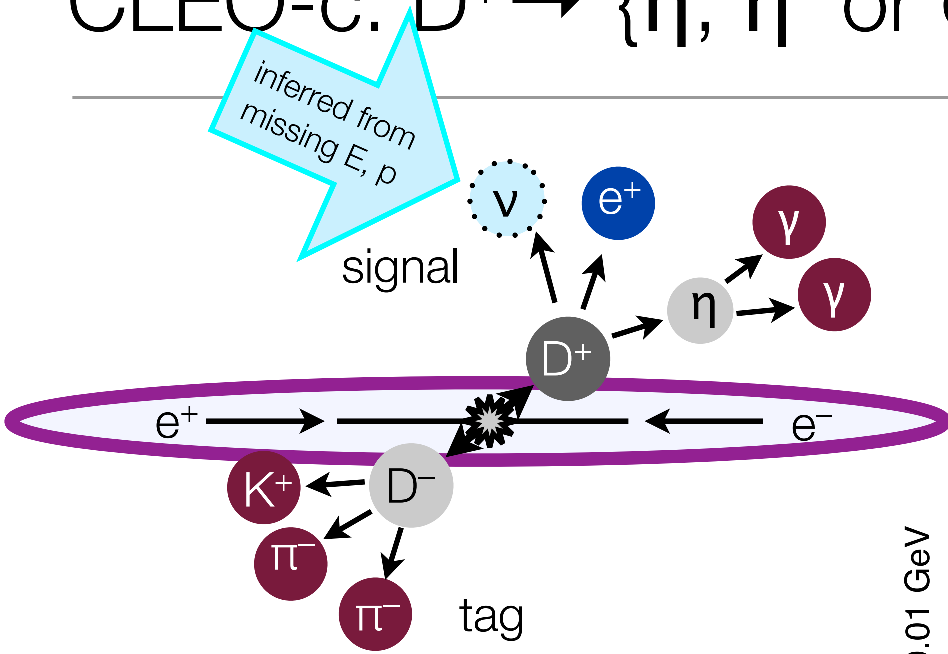
- Step 1: Reconstruct Tag D (provides normalisation)

481k tags

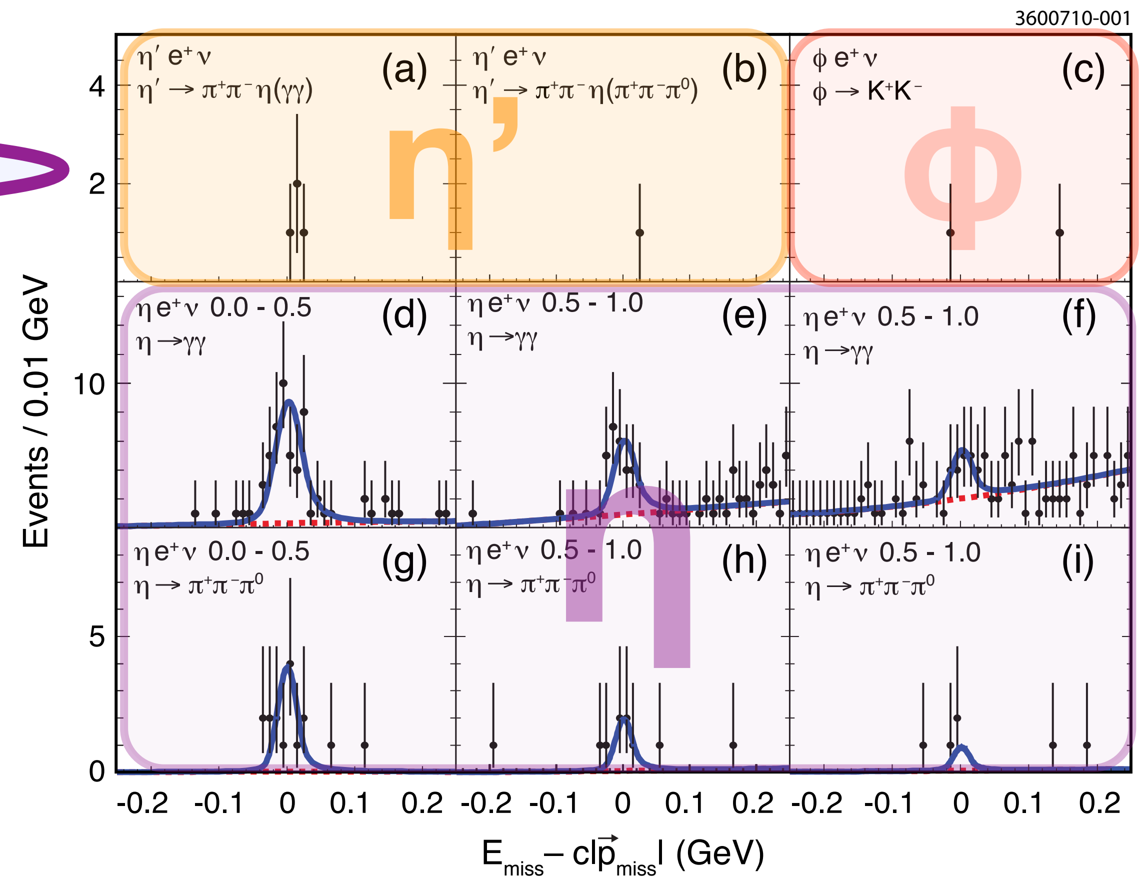
<u>CLEO: Phys.Rev. D84 (2011) 032001</u>

CLEO-c: $D^+ \to \{\eta, \eta' \text{ or } \varphi\}\, e^+ \nu$ (tagged)

CLEO-c 2011



$$U \equiv E_{\text{miss}} - |\vec{p}_{\text{miss}}|$$



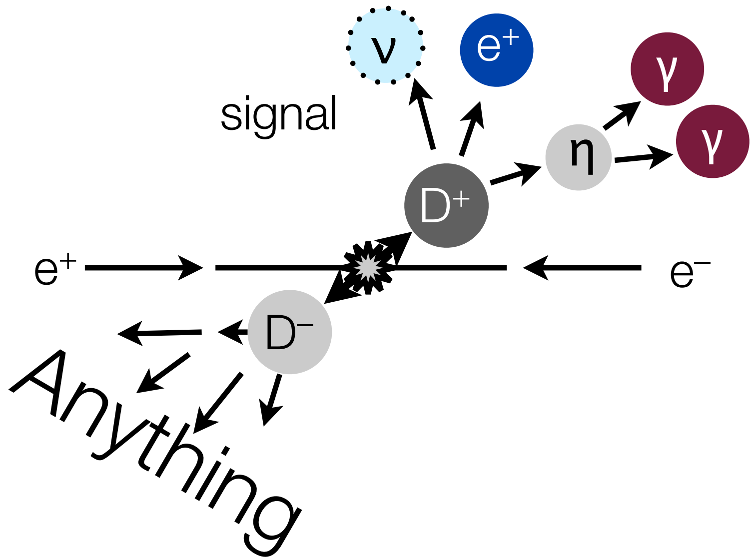
- Step 1: Reconstruct Tag D
- Step 2: Find U (~ missing mass) from beam constraint and e and η, η’, ϕ.

CLEO: Phys.Rev. D84 (2011) 032001

Generic Reconstruction of $D^+ \to \{\eta, \eta' \text{ or } \varphi\}\, e^+\nu$

CLEO-c 2011

- We have 2.4M D^+D^- events, but only 0.5M tags - the generic reconstruction is an attempt to make use of the other 1.9M.
- Instead of fully reconstructing a tag D in specific decay modes, the generic reconstruction adds up all momenta & energies in the event to identify the neutrino.
- Several cuts (eg exactly one electron in the decay), plus the specific reconstruction of η, π^0 and K_S help clean up the sample.
- Signal yield normalised to $D \to K\pi\pi$ - normalisation mode reconstructed in the same manner as signal.



CLEO: Phys.Rev. D84 (2011) 032001

Combined CLEO-c $D^+ \to \{\eta, \eta' \text{ or } \varphi\}\ e^+\nu$ results

CLEO-c 2011

$D^+ \to \{\eta, \eta', \varphi\}\ e^+\nu$ Branching Fractions & Limits

- First observation of $D^+ \to \eta' e^+\nu$ (5.8σ)

$$\mathcal{B}(D^+ \to \eta' e^+ \nu_e) = (2.16 \pm 0.53 \pm 0.07) \times 10^{-4}$$

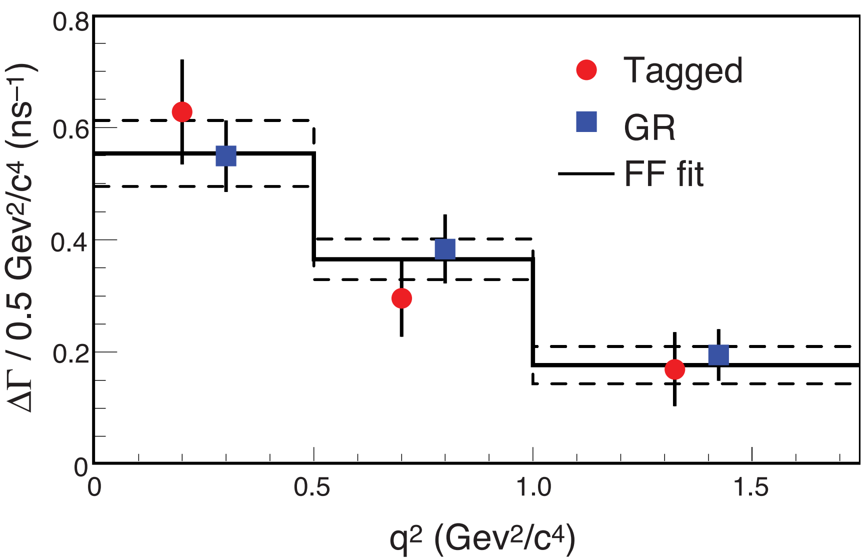
- Improved $D^+ \to \eta\ e^+\nu$ BR:

$$\mathcal{B}(D^+ \to \eta e^+ \nu_e) = (11.4 \pm 0.9 \pm 0.4) \times 10^{-4}$$

- Limit on $D^+ \to \phi\ e^+\nu$ ~twice as stringent as previous CLEO-c limit:

$$\mathcal{B}(D^+ \to \phi e^+ \nu_e) < 0.9 \times 10^{-4} \quad (90\% \text{ C.L.}).$$

First $D^+ \to \eta\ e^+\nu$ form factor measurement



Precision dominated by Generic Reconstruction sample

$$f_+(0)\,|V_{cd}| = 0.086\,(6)_{(\text{stat})}(1)_{(\text{sys})}$$

(results identical for simple pole or modified pole parameterisation)

Results consistent with both ISGW2 [1] and Fajfer-Kamenic [2] models.

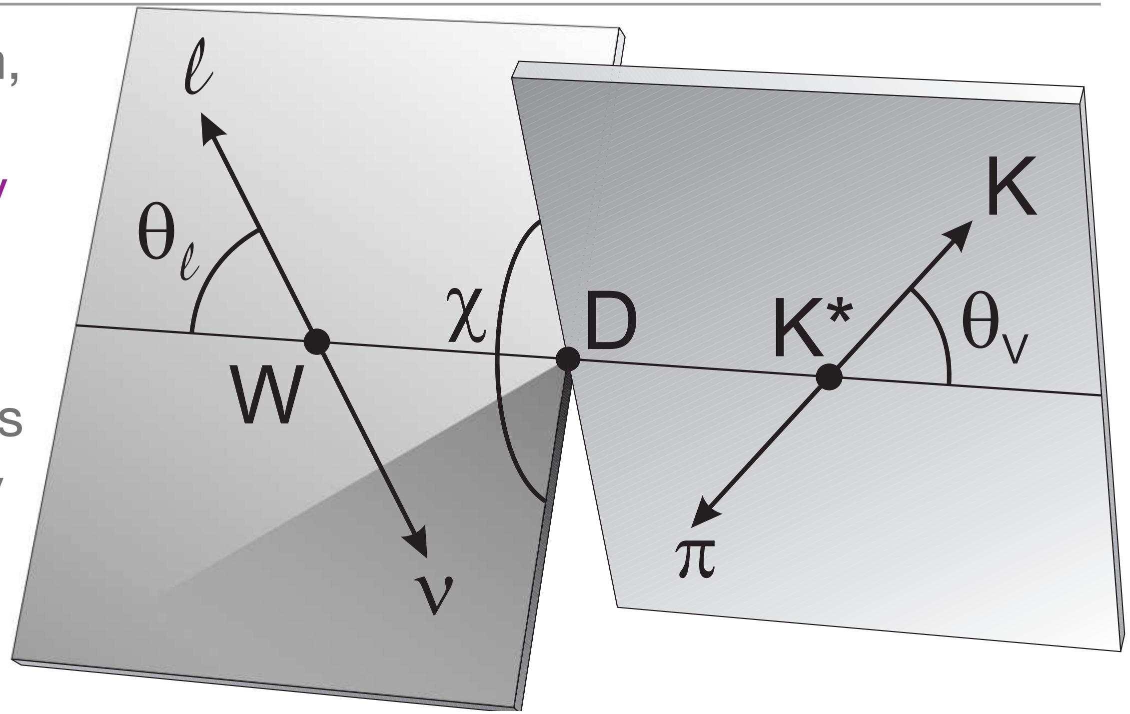
[1] D. Scora and N. Isgur, Phys. Rev. D 52, 2783 (1995)

[2] S. Fajfer and J. Kamenik, Phys. Rev. D 71, 014020 (2005).

CLEO: Phys.Rev. D84 (2011) 032001

D → V ℓ ν

- Need 5 variables, m^2 of V system, q^2 of eν system, plus 3 angular variables to disentangle 3 helicity states.
- Need 3 form factors (for massless ℓ) 2 axial and one vector. Usually parameterised with simple pole.
- Frequently experiments measure the ratios r_V, r_A.
- Combine D→ρeν D→K*eν and B→V $\ell\,\ell$ to improve $|V_{ub}|$ (see Phys.Rev. D70 (2004) 114005)



$$V(q^2) = \frac{V(0)}{1 - q^2/m_V^2}; \quad A_{1,2}(q^2) = \frac{A_{1,2}(0)}{1 - q^2/m_A^2}$$

$$r_V \equiv \frac{V(0)}{A_1(0)} \qquad r_A \equiv \frac{A_2(0)}{A_1(0)}$$

D→K* e ν, D→Kπ e ν

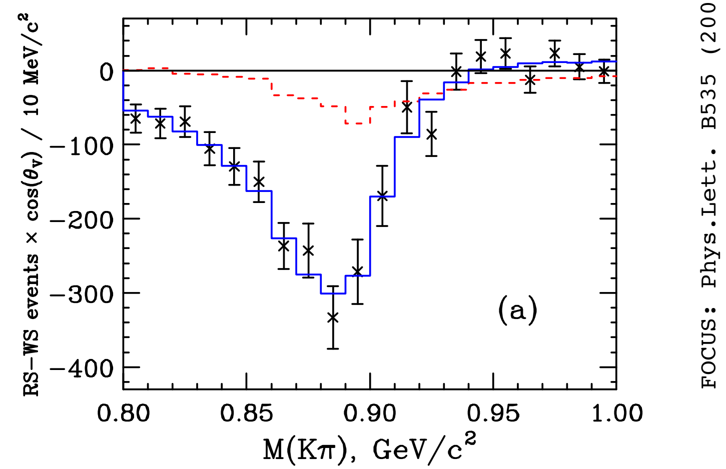
- BaBar (2011) measure the D→K* e ν form-factors, using 1/4 M D→Kπeν signal events. Amongst the result:

$$m_A = (2.63 \pm 0.10 \pm 0.13)\ \text{GeV}$$
$$r_V = (1.463 \pm 0.017 \pm 0.032)\ \text{GeV}$$
$$r_2 = (0.801 \pm 0.020 \pm 0.020)\ \text{GeV}$$

- The decay also has a significant D→{Kπ-S-wave} e ν, component, first observed by FOCUS in 2002. BaBar (2011) find and S-wave fraction in D→Kπeν:
  (5.78 ± 0.16 ± 0.15)%

S-wave in this channel was first seen by FOCUS (2002).

The plot shows the cos(θ$_V$) - weighted distribution in M(Kπ). S – P wave interference results in an asymmetry in cos(θ$_V$).



blue: fit with S-wave
red: without

BaBar: Phys.Rev. D83 (2011) 072001

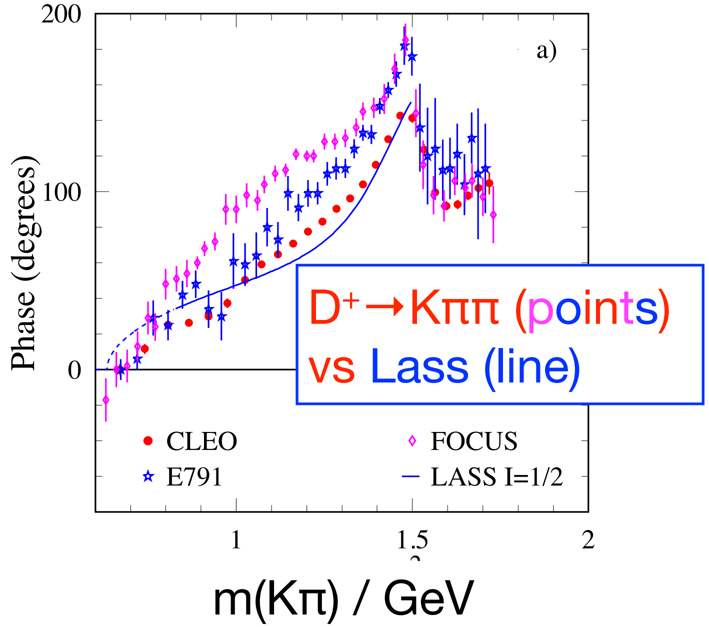
FOCUS: Phys.Lett. B535 (2002) 43-51

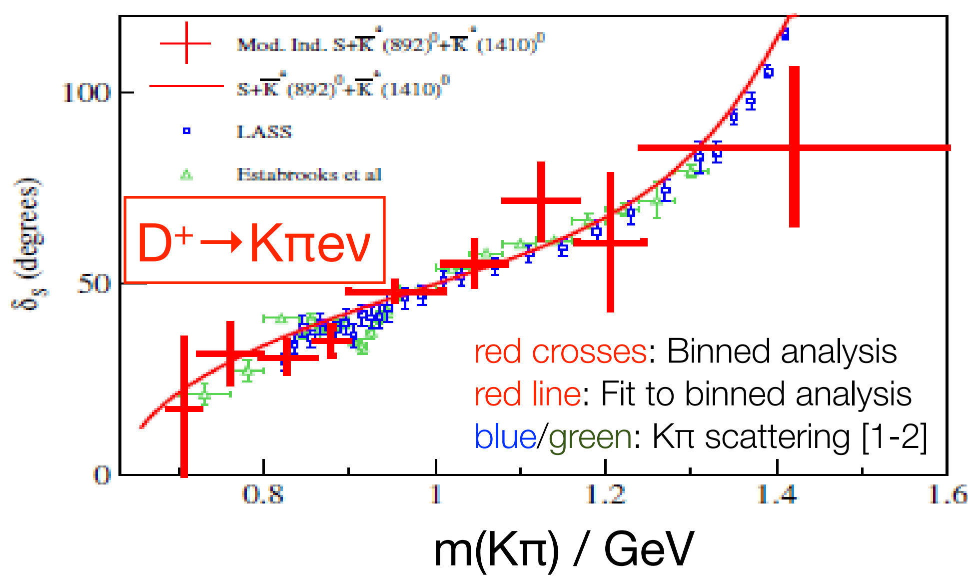
Using D→K* e ν as interferometer to measure D→Kπ e ν S-wave

BaBar 2011

- BaBar (2011) performed a detailed analysis of the Kπ S-wave using its interference with K* to extract both magnitude and phase.

- Model-independent measurement of the phase is in much better agreement with scattering data (LASS [1], Estabrooks et al [2]) than S-wave contributions measured in $D^+ \to K^-\pi^+\pi^-$ [3-6].





[1] D. Aston et al., Nucl. Phys. B 296, 493 (1988). (LASS)
[2] P. Estabrooks et al., Nucl. Phys. B 133, 490 (1978).
[3] E.M. Aitala et al. (Fermilab E791 Collaboration), Phys. Rev. D 73, 032004 (2006). [4] J.M. Link et al. (FOCUS Collaboration), Phys. Lett. B 653, 1 (2007).
[5] J.M. Link et al. (FOCUS Collaboration), Phys. Lett. B 681, 14 (2009). [6] A. Bonvicini et al. (CLEO Collaboration), Phys. Rev. D 78, 052001 (2008).

Non-parametric $D \to K\pi\ e/\mu\ \nu$ form factors

CLEO-c 2010

- CLEO-c (2010) use a projective reweighting technique pioneered by FOCUS (2006).

- Basic idea: rates (after integrating over χ) can be expressed as

$$\frac{d^4\,\Gamma(\theta_\ell, \theta_V, m^2_{K\pi}, q^2)}{d\theta_\ell, d\theta_V, dm^2_{K\pi}, dq^2} = F_0(\theta_\ell, \theta_V)\left|\mathrm{BW}(m^2_{K\pi})\right|^2 q^2 \left|H_0(q^2)\right|^2$$
$$+F_+(\theta_\ell, \theta_V)\left|\mathrm{BW}(m^2_{K\pi})\right|^2 q^2 \left|H_+(q^2)\right|^2$$
$$+F_-(\theta_\ell, \theta_V)\left|\mathrm{BW}(m^2_{K\pi})\right|^2 q^2 \left|H_-(q^2)\right|^2$$
$$+\ldots$$

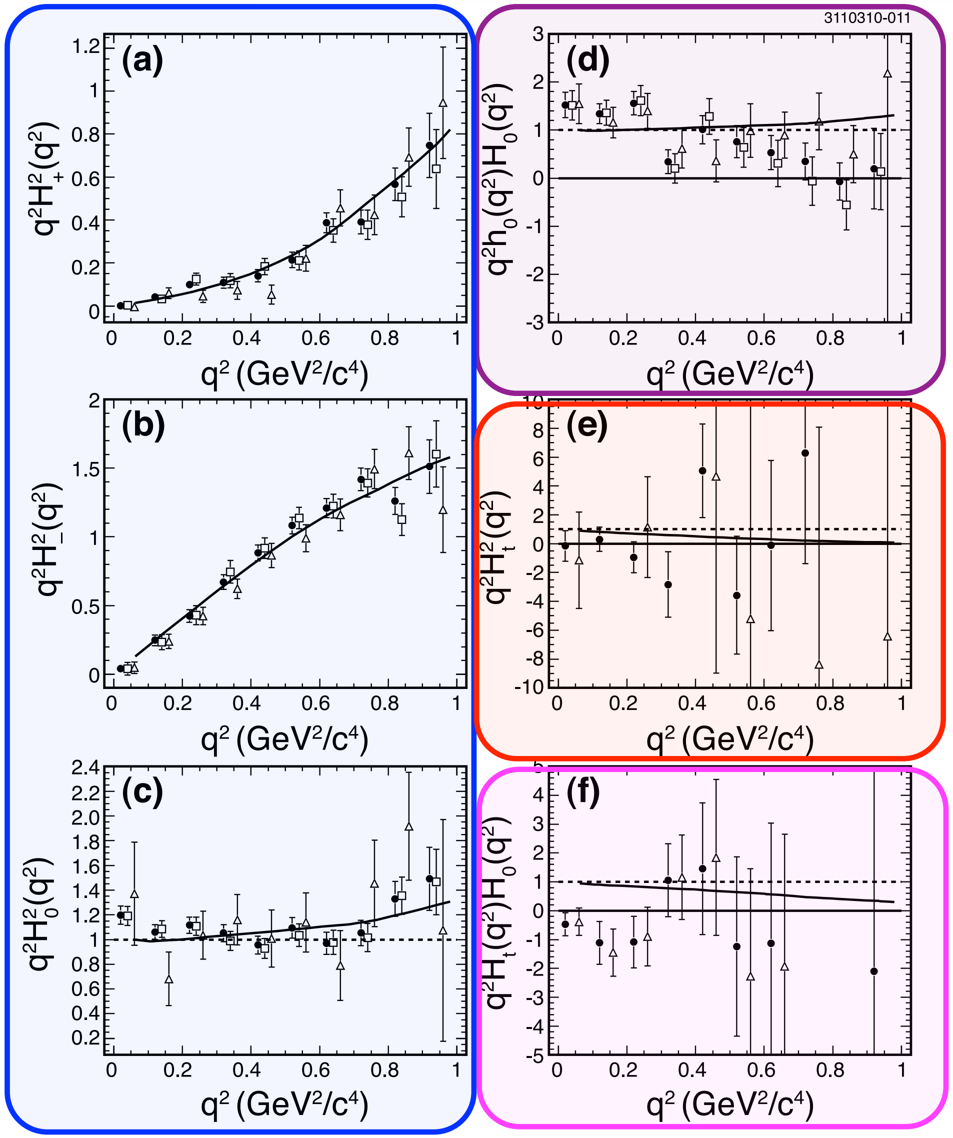
- .... histogram in q^2 = integrate over θ_l, θ_V. Find functions $F^{\perp}_i(\theta_l, \theta_V)$ orthogonal to the $F_i(\theta_l, \theta_V)$. Weighting events by $F^{\perp}_i(\theta_l, \theta_V)$ removes the corresponding terms from the q^2 projection.

CLEO: Phys.Rev. D81 (2010) 112001; FOCUS: Phys. Lett. B 633, 183 (2006)

Non-parametric D→Kπ e/μ ν form factors

CLEO-c 2010

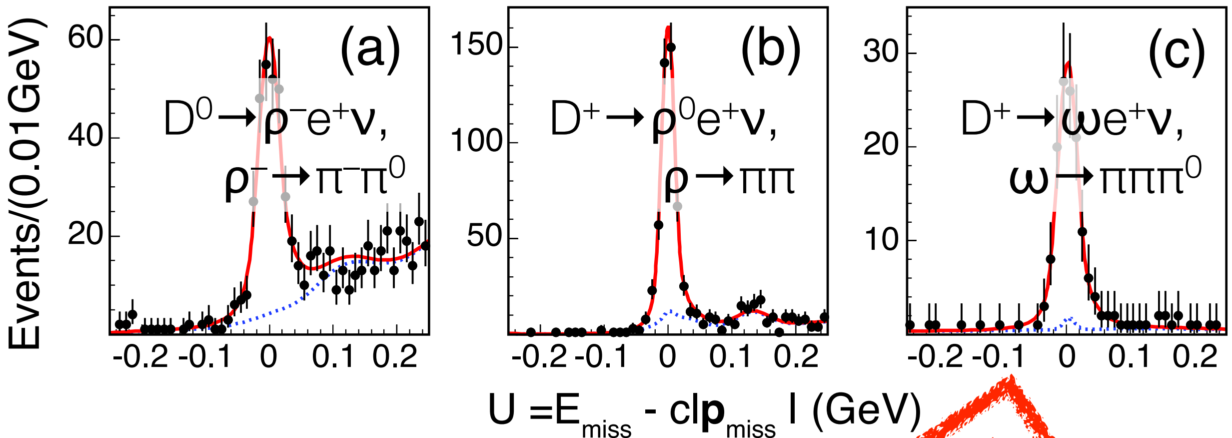
- Plots on left compare model-independent measurements with simple pole model - generally good agreement.
- Confirms evidence for S-wave.
- Cleo-c's analysis consideres highly-suppressed amplitudes with right-handed e/μ (adds a helicity, H_T, and a form factor, A_3)
- $H_T H_0$ interference less than LQCD prediction.

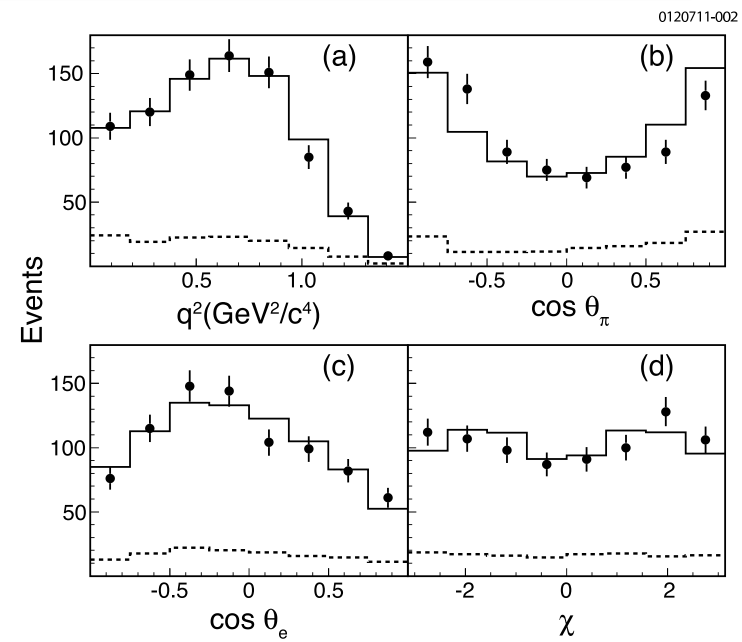


CLEO: **Phys.Rev. D81 (2010) 112001**

Form factors for $D^0 \to \rho^- e^+ \nu$, $D^+ \to \rho^0 e^+ \nu$

CLEO-c 2011





$$A_1(0) = 0.56 \pm 0.01^{+0.02}_{-0.03}$$

$$A_2(0) = 0.47 \pm 0.06 \pm 0.04$$

$$V(0) = 0.84 \pm 0.09^{+0.05}_{-0.06}$$

First measurement.

Decay Mode	ϵ (%)	$N_{\text{tag, SL}}$	$\mathcal{B}_{\text{SL}}$	$\mathcal{B}_{\text{SL}}$(prev)	$\mathcal{B}_{\text{SL}}$(ISGW2)	$\mathcal{B}_{\text{SL}}$(FK)
$D^0 \to \rho^- e^+ \nu_e$	26.03 ± 0.02	304.6 ± 20.9	$1.77 \pm 0.12 \pm 0.10$	$1.94 \pm 0.39 \pm 0.13$	1.0	2.0
$D^+ \to \rho^0 e^+ \nu_e$	42.84 ± 0.03	447.4 ± 24.5	$2.17 \pm 0.12^{+0.12}_{-0.22}$	$2.1 \pm 0.4 \pm 0.1$	1.3	2.5
$D^+ \to \omega e^+ \nu_e$	14.67 ± 0.03	128.5 ± 12.6	$1.82 \pm 0.18 \pm 0.07$	$1.6^{+0.7}_{-0.6} \pm 0.1$	1.3	2.5

$$\frac{\Gamma(D^0 \to \rho^- e^+ \nu_e)}{2\Gamma(D^+ \to \rho^0 e^+ \nu_e)} = 1.03 \pm 0.09^{+0.08}_{-0.02}$$

CLEO: arXiv:1112.2884 [hep-ex] (Dec 2011)

$D_S \to \varphi\mu\nu$ form factors: Experiment & Lattice

- Due to higher mass of spectator quark, expect more reliable lattice QCD form factor calculations than for D^+.
- Recent results for $D_S \to \phi\, e\, \nu$ show good agreement:

	HPQCD 2011	BaBar 2008 [3]	UKQCD 2001 [2]
$A_1(0)$	0.594(22)	0.607(11)(19)(18)	0.63(2)
Local $A_1(0)$	0.603(20)	–	–
$V(0)$	0.903(67)	$1.122(85)^*$	0.85(4)
$A_0(0)$	0.686(17)	–	0.63(2)
$A_2(0)$	0.401(80)	$0.463(61)^*$	0.62(5)
r_V	1.52(12)	1.849(60)(95)	$1.35(7)^*$
r_2	0.62(12)	0.763(71)(65)	$0.98(8)^*$

Table and HPQCD results from: Donald, Davies, Koponen: arXiv:1111.0254 [hep-lat], Nov 2011
BaBar: Phys.Rev. D78 (2008) 051101

$D_s \to KK\, e\, \nu$ and the f_0 at BaBar

BaBar 2008

- $D_s \to KK\, e\, \nu$ at BaBar:
  KK system **dominated by φ**, but there is a significant **S-wave** component (first observed by BaBar), evident in as an **asymmetry in cos(θ_V)**.

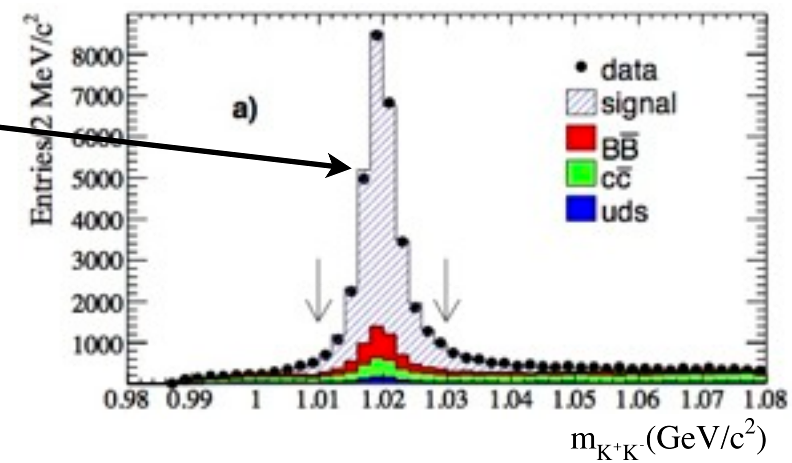
- BaBar measure an f_0 BR:

$$\frac{BR(D_s \to f_0 e^+ \nu)}{BR(D_s \to \varphi\, e^+ \nu)} = (4.5^{+2.5}_{-1.6} \pm 0.6)\%$$

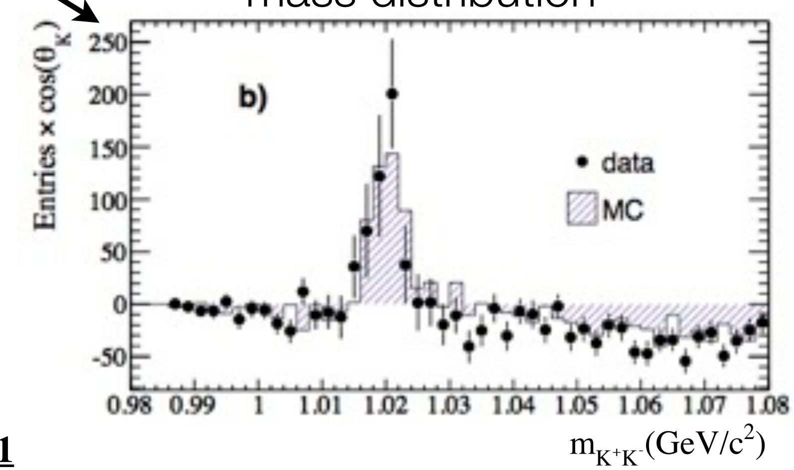
- Which is similar to the D^+ system:

$$\frac{BR(D^+ \to K^- \pi^+ e^+ \nu)_S}{BR(D^+ \to K^- \pi^+ e^+ \nu)_{total}} = (5.79 \pm 0.16 \pm 0.15)\%$$

KK mass distribution



cos(θ_V)-weighted KK mass distribution

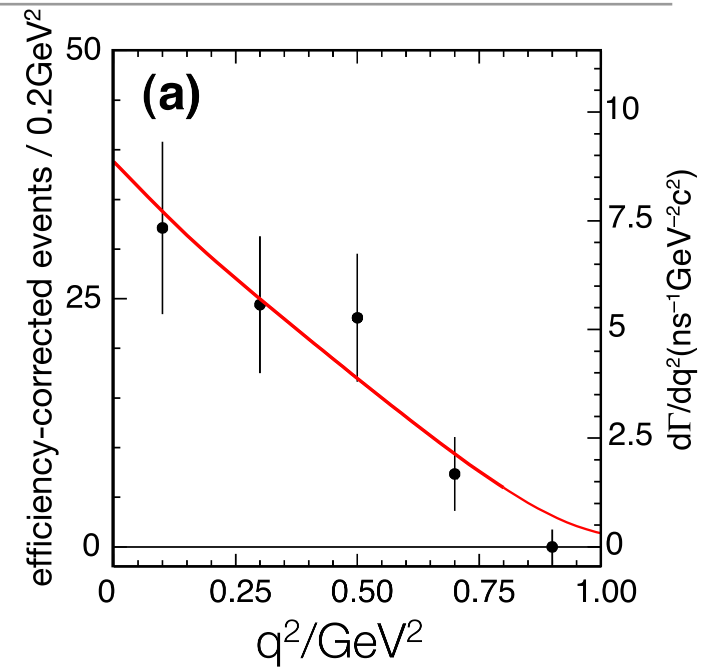


BaBar: Phys.Rev. D78 (2008) 051101

$D_s^+ \to f_0 \mu^+ \nu$ at CLEO-c

CLEO-c 2009
+ LHCb 2012

- $D_s \to f_0\, e\, \nu$ was subsequently analysed by CLEO-c (2009) with $f_0 \to \pi\pi$.
- CLEO-c performed a full form-factor analysis.
- The result was used to evaluate the form-factor ratio at $q^2 = 0$.



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

CLEO: Phys.Rev. D80 (2009) 052009

- This provided further evidence that $\mathcal{B}(B_s \to J/\psi\, f_0)/\mathcal{B}(B_s \to J/\psi\, \phi)$ could be large enough to make a significant contribution to measuring $\sin(\phi_s)$. Recently, LHCb found:

$$\frac{\mathcal{B}\left(\overline{B}_s^0 \to J/\psi \pi^+\pi^-\right)}{\mathcal{B}\left(\overline{B}_s^0 \to J/\psi \phi\right)} = (21.28 \pm 0.51 \pm 0.56)\%$$

(see also Yuehong Xie and Liming Zhang's talks, yesterday)

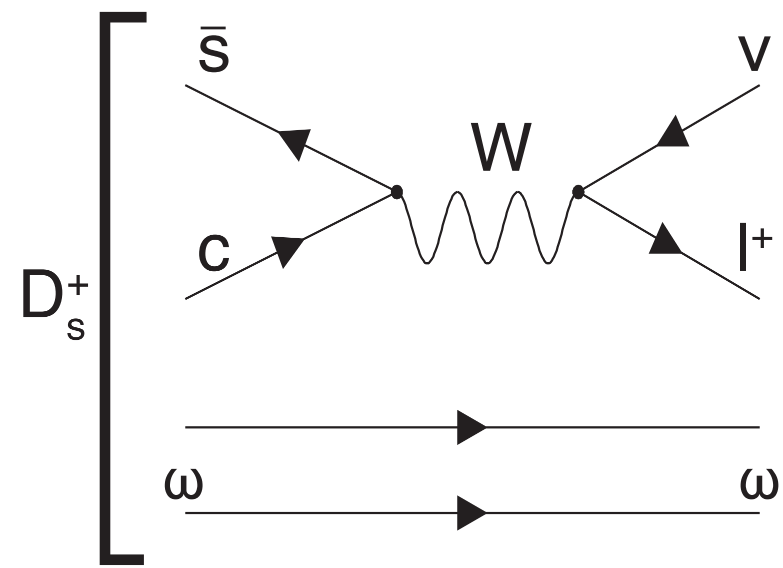
LHCb: arXiv:1204.5643 [hep-ex] (2012)

CLEO-c search for $D_s \to \omega e \nu$

CLEO-c 2011

- Highly suppressed. Potential processes (Gronau & Rosner Phys.Rev. D79 (2009) 074006):
  - Via ω-ϕ mixing (ω has $s\bar{s}$ component)? BR < $2 \cdot 10^{-4}$
  - Via weak annihilation (radiate an ω in a non-perturbative process before annihilating)? BR ~ (0.13 ± 0.05)%
- Anything larger might hint at a **four-quark content** of the D_s (4-quark systems have been suggested to explain several exotic charmonium states).

$D_s \to \omega e \nu$ as a probe for a 4-quark contribution to the D_s



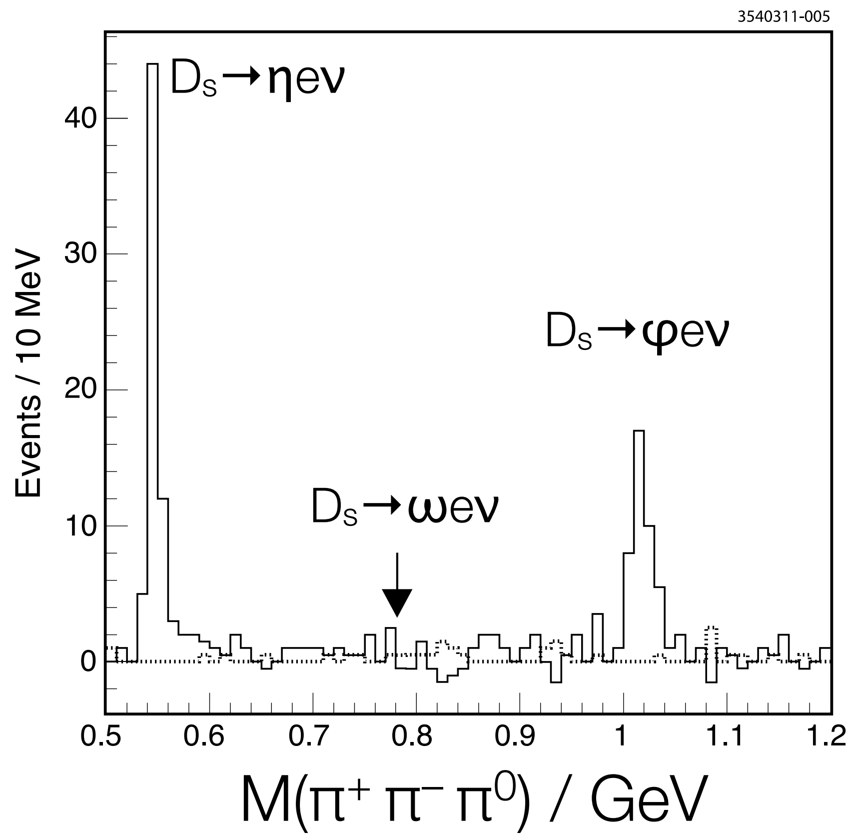
CLEO-c search for $D_s \to \omega e \nu$

CLEO-c 2011

- Analysis makes careful use of control channels $D_s \to \eta e\nu$ and $D_s \to \phi e\nu$.
- No evidence for $D_s \to \omega e\nu$.
- At 90% CL:

$$\mathcal{B}(D_s^+ \to \omega e^+ \nu) < 0.20\%$$

(compatible with Gronau & Rosner's estimate of (0.13 ± 0.05)%, no evidence of 4-quark content of D_s.)



(background subtracted)

Phys.Rev. D84 (2011) 012005

CLEO: Phys.Rev. D84 (2011) 012005

Calculate $\Lambda_c \to \Lambda \ell \nu$

- Λ_c branching fractions are normalised to $\Lambda_c \to pK\pi$, which has a 26% uncertainty.

- This in turn dominates many uncertainties - Λ_c BF, $\Lambda_b \to \Lambda_c X$ BF, Λ_b production fractions

$$\frac{\Lambda_b}{f_u + f_d} = [0.404 \pm 0.017(\mathrm{stat}) \pm 0.027(\mathrm{syst}) \pm 0.105(\mathrm{Br})]$$
$$\times [1 - (0.031 \pm 0.004(\mathrm{stat}) \pm 0.003(\mathrm{syst}))p_T(\mathrm{GeV})] \ .$$

- Rosner suggests to use a *calculated* $\Lambda_c \to \Lambda e \nu$ BF for normalisation instead. Currently measured as $\mathcal{B}(\Lambda_c \to \Lambda e \nu) = (2.1 \pm 0.6)\%$.

- Requires a challenging calculation of 4 form factors on lattice. But a precision of better than 25% would already help!

Jonathan Rosner: arXiv:1205.4964 [hep-ph] (23 May 2012)

Summary

- Many new and improved form factor measurements. Where LQCD exist, they are generally in good agreement with data. Time to tackle baryons?

- Beyond the form factor: innovative ways of using semileptonic charm decays include rare decays to learn about the structure of D_s; $D \to V \ell \nu$ as interferometer to measure S-wave phases.

Summary

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Summary

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- Most results are from experiments that have stopped data taking, and most are statistics limited, but there is a future:

  BES III have shown first results, from 1/3 of their data - there is much more to come.

Backup

Quark content of f_0

CLEO-c

- If $|f_0\rangle = \cos\theta\,|\bar{s}s\rangle + \sin\theta\,\frac{1}{\sqrt{2}}\,|\left(\bar{u}u + \bar{d}d\right)\rangle$ (Aliev & Savci)
- From BES' $\frac{\mathcal{B}(f_0 \to K^+K^-)}{\mathcal{B}(f_0 \to \pi^+\pi^-)} = (25^{+17}_{-11})\%$. Assuming KK, ππ dominate: $\mathcal{B}(f_0 \to \pi^+\pi^-) = (50^{+7}_{-9})\%$

  and thus from CLEO-c: $\mathcal{B}(D_s^+ \to f_0 e^+\nu) = (0.40 \pm 0.06 \pm 0.06)\%$
- Using $\mathcal{B}(D_s^+ \to f_0 e^+\nu) = \cos^2\theta \times (0.41)\%$(Aliev & Savci)
  CLEO-c get: $\cos^2\theta = 0.98^{+0.02}_{-0.21}$
- Intriguing: If f_0 is predominantly s-sbar, why does it predominantly decay to ππ? 4-quark content?

[17] T. M. Aliev and M. Savci, "Semileptonic decays of pseudoscalar mesons to scalar f_0 meson," arXiv:hep-ph/0701108. A previous work, I. Bediaga, F. S. Navarra and M. Nielsen, Phys. Lett. B **579**, 59 (2006), predicts a smaller width with a 50% error, which leads to a smaller value of $\cos^2\theta$ with a large error.

[18] M. Ablikim et al. (BES), Phys. Rev. D 70, 092002 (2004); M. Ablikim et al. (BES), Phys. Rev. D 72, 092002 (2005)

[2] A. H. Fariborz, R. Jora, and J. Schechter, "Global Aspects of the Scalar Meson Puzzle," arXiv:0902.2825v1 [hep-ph]; A. V. Anisovich *et al.*, "The Riddle of the $f_0(980)$ and $a_0(980)$: Are They the Quark-Antiquark States?" arXiv:hep-ph/0508260 and references contained therein; T. Branz, T. Gutsche, V. E. Lyubovitskij, Phys. Rev. D **79**, 014035 (2009) arXiv:0812.094 [hep-ph]; V. Baru, J. Haidenbauer, C. Hanhart, Yu. Kalashnikova, A. Kudryavtsev, Phys. Lett. B **586**, 53 (2004) arXiv:hep-ph/0308129.

CLEO: Phys.Rev. D80 (2009) 052009

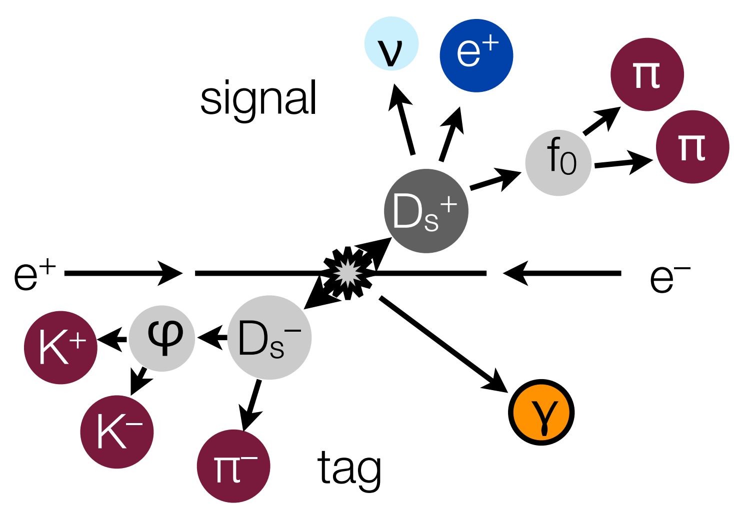
$D_s^+ \to f_0 \mu^+ \nu$ and $D_s^+ \to \varphi \mu^+ \nu$ at CLEO-c

CLEO-c

- CLEO produces $D_s^* D_s \to D_s\, D_s\, \gamma$ (giving an additional photon).

$$\left.\begin{array}{c} e^+e^- \to D_s^{*+}\, D_s^- \\ \text{or} \\ e^+e^- \to D_s^+\, D_s^{*-} \end{array}\right\} \to D_s^+\, D_s^-\, \gamma$$

- Step 1: Fully reconstruct "tag D_s"
- Step 2: Identify photon and use beam constraint to reconstruct signal Ds mass: $(p_{beam} - p_{tag} - p_\gamma)^2$ = consistent with Ds mass for signal.
- Step 3: Find missing mass from beam constraints and reconstructed signal.



$D_s^+ \to f_0 \mu^+ \nu$ and $D_s^+ \to \varphi \mu^+ \nu$ at CLEO-c

CLEO-c

- Motivation: Relationship to B->J/psi f0. originally related to Ds->f0 pi:

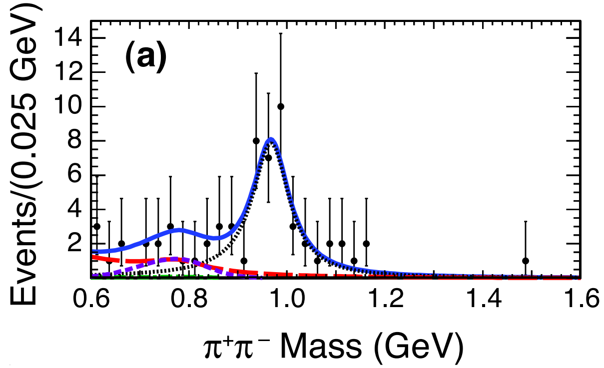
$$R_{f/\phi} \equiv \frac{\Gamma\left(B_s^0 \to J/\psi f_0,\ f_0 \to \pi^+\pi^-\right)}{\Gamma\left(B_s^0 \to J/\psi \phi,\ \phi \to K^+K^-\right)} = \frac{\Gamma\left(D_s^+ \to f_0\pi^+,\ f_0 \to \pi^+\pi^-\right)}{\Gamma\left(D_s^+ \to \phi\pi^+,\ \phi \to K^+K^-\right)} \approx (20\text{--}30)\%$$

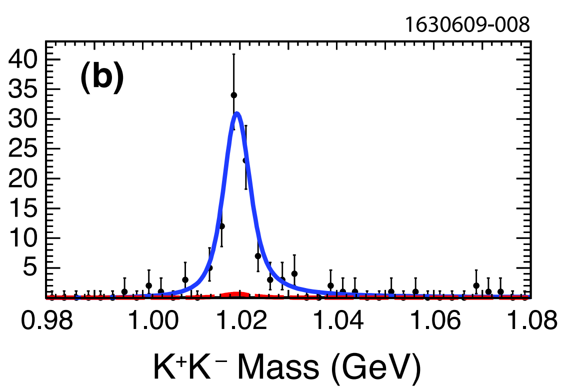
- But: J/psi is spin 1, while pi+ is spin 0. Hence, it might be better to use the ratio of rates at q^2 = 0 (maximising the phase space, thus making it more similar to the B decay):

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

CLEO-c

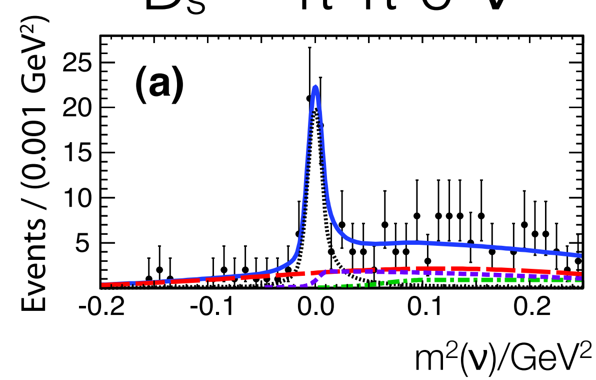
$D_s^+ \to f_0 \mu^+ \nu$ and $D_s^+ \to \phi \mu^+ \nu$ at CLEO-c



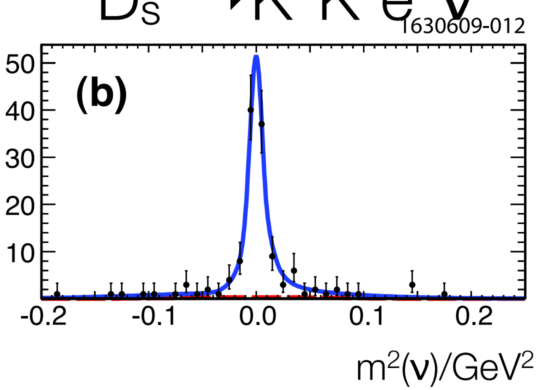


reconstructed ν mass-squared $(p_{beam} - \Sigma p_{reco})^2$

$D_s^+ \to \pi^+\pi^- e^+ \nu$



$D_s^+ \to K^+K^- e^+ \nu$



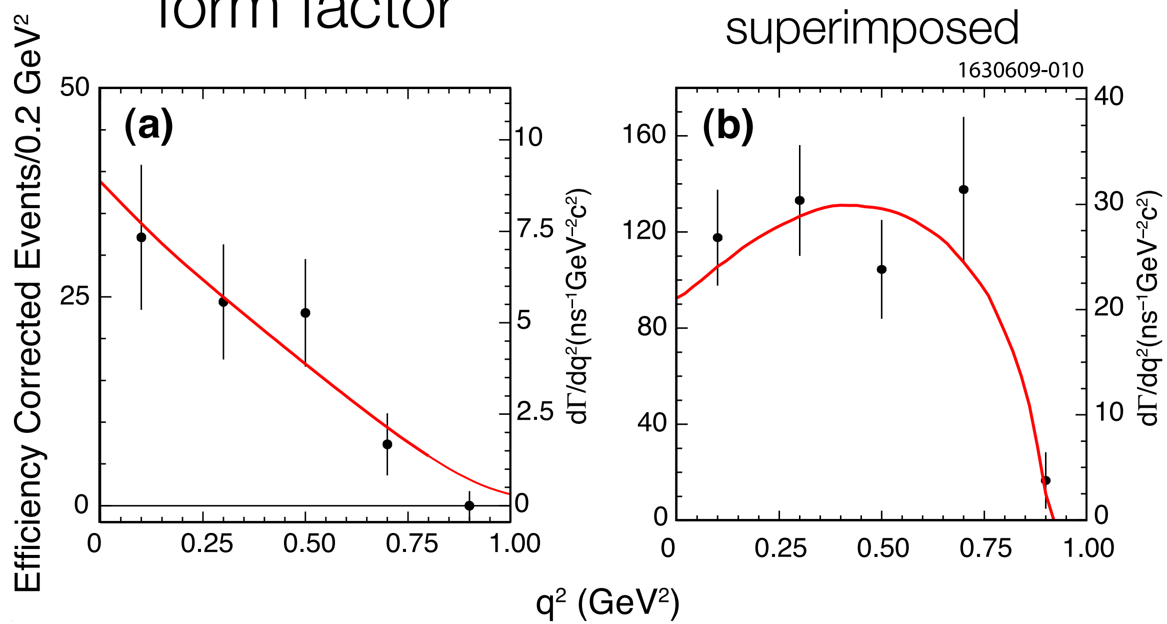
$D_s^+ \to f_0 \mu^+ \nu$ and $D_s^+ \to \varphi \mu^+ \nu$ at CLEO-c

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

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

CLEO-c fit for f_0 form factor

CLEO-c data for φ form factor with BaBar result superimposed



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

LHCb found: R for the $f_0(980)$, $0.149 \pm 0.006^{+0.028}_{-0.003}$,

$D_s^+ \to f_0 \mu^+ \nu$ and $D_s^+ \to \varphi \mu^+ \nu$ at CLEO-c

CLEO-c

Mode	Invariant Mass		MM^{*2}	
	Signal	Background	Signal	Background
$K^+K^-\pi^-$	26534±274	25122	16087±373	39563
K_SK^-	6383±121	3501	4215±228	6297
$\eta\pi^-$; $\eta \to \gamma\gamma$	2993 ± 156	5050	2005±145	5016
$\eta'\pi^-$; $\eta' \to \pi^+\pi^-\eta$, $\eta \to \gamma\gamma$	2293±82	531	1647±131	1565
$K^+K^-\pi^-\pi^0$	11649±754	78588	6441±471	89284
$\pi^+\pi^-\pi^-$	7374±303	60321	5014±402	43286
$K^{*-}K^{*0}$; $K^{*-} \to K_S^0\pi^-$, $K^{*0} \to K^+\pi^-$	4037±160	10568	2352±176	12088
$\eta\rho^-$; $\eta \to \gamma\gamma$, $\rho^- \to \pi^-\pi^0$	5700±281	24444	3295±425	24114
$\eta'\pi^-$; $\eta' \to \rho^0\gamma$,	3551±202	19841	2802±227	17006
Sum	70514 ± 963	227966	43859±936	238218

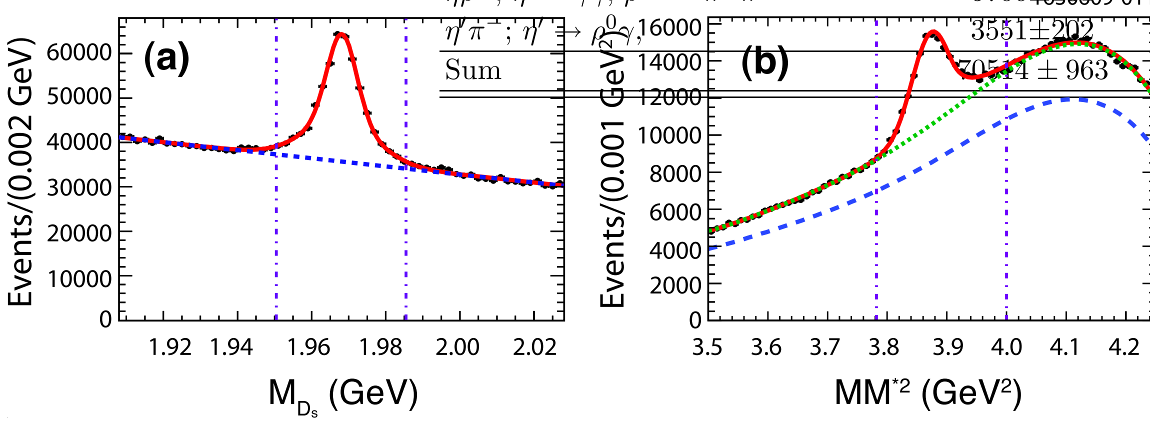
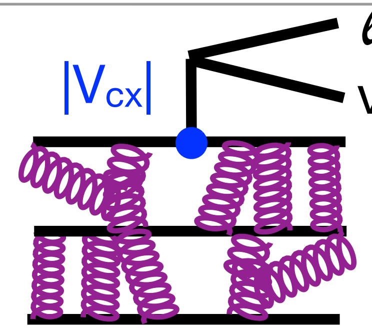
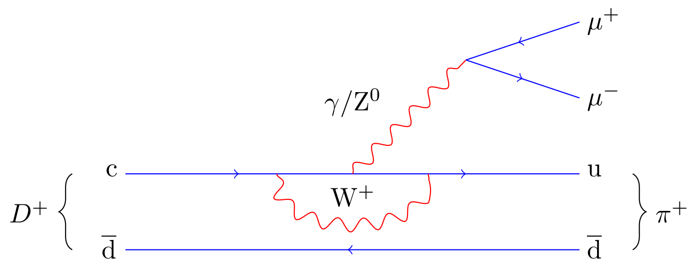
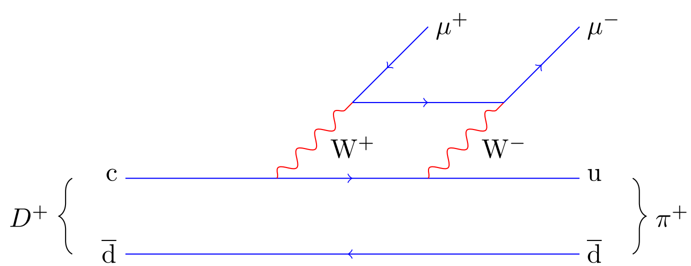


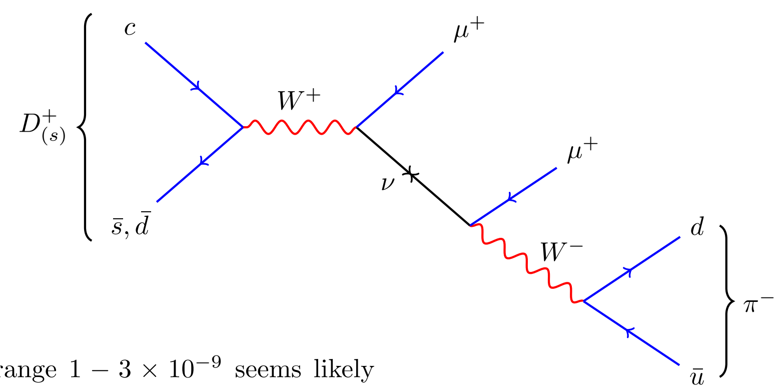
FIG. 2: (a) Invariant mass of D_s^- candidates summed over all decay modes and fit to a two-Gaussian signal shape plus a straight line for the background. The vertical dot-dashed lines indicate the ±17.5 MeV definition of the signal region. (b) The MM^{*2} distribution summed over all modes. The curves are fits to the number of signal events using the Crystal Ball function and two 5th order Chebychev background functions; the dashed curve shows the background from fake D_s^- tags, while the dotted curve in (b) shows the sum of the backgrounds from multiple photon combinations and fake D_s^- tags. The vertical dashed lines show the region of events selected for further analysis.

Rare Semileptonic D decays









Predictions of the rate of these processes are sparse though something in the range $1 - 3 \times 10^{-9}$ seems likely for the FCNC decay [3, 4, 5] though it is noted that great care should be taken when avoiding pollution from the long-distance resonance contributions. The LFV mode is forbidden in the SM.

[3] S. Fajfer, S. Prelovsek, and P. Singer, *Rare charm meson decays $D \to P\, l^+ l^-$ and $c \to u\, l^+ l^-$ in SM and MSSM*, Phys. Rev. **D64** (2001) 114009, `arXiv:hep-ph/0106333`.

[4] S. Fajfer, N. Kosnik, and S. Prelovsek, *Updated constraints on new physics in rare charm decays*, Phys. Rev. **D76** (2007) 074010, `arXiv:0706.1133`.

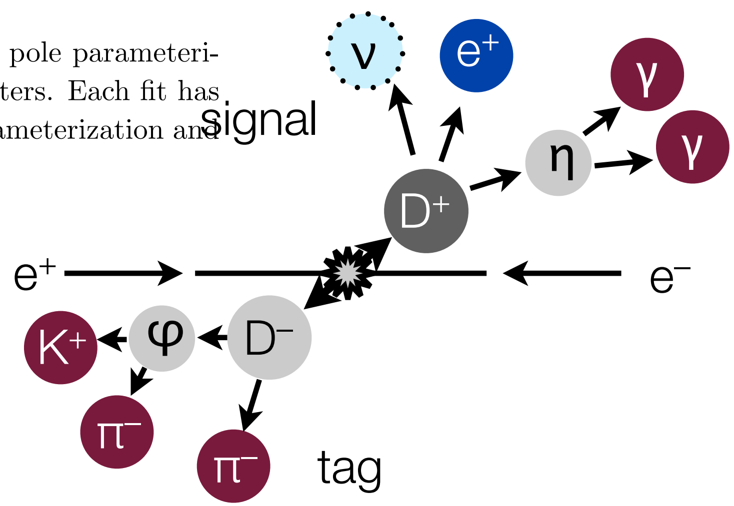
[5] A. Paul, I. I. Bigi, and S. Recksiegel, *On $D \to X_u\, l^+ l^-$ within the Standard Model and Frameworks like the Littlest Higgs Model with T Parity*, Phys. Rev. **D83** (2011) 114006, `arXiv:1101.6053`.

Combine

Analysis	$f_+(0)\lvert V_{cd}\rvert$	r_1	ρ	χ^2/d.o.f.
Tagged	0.094(9)(3)	2.17(4.50)(1.12)	0.83	0.7/(3 − 2)
GR	0.085(6)(1)	−2.89(2.24)(32)	0.81	0.0/(3 − 2)
Combined	0.086(6)(1)	−1.83(2.23)(28)	0.81	2.5/(6 − 2)

TABLE VI. $D^+ \to \eta e^+ \nu_e$ form factor fit results using the simple and modified pole parameterizations. The quantity ρ is the correlation coefficient between the two fit parameters. Each fit has $(6-2)$ degrees of freedom. The shape parameter is $m_{\rm pole}$ for the simple pole parameterization and α for the modified pole parameterization.

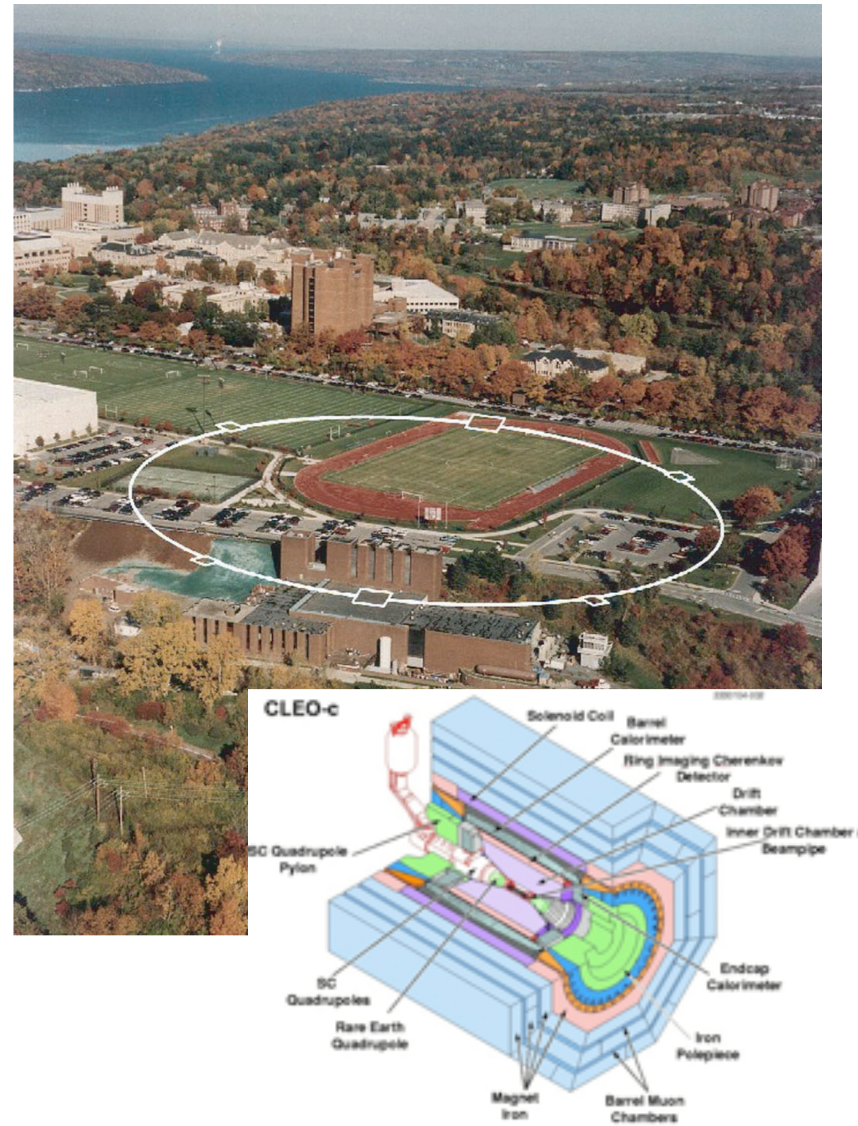
	Simple Pole	Modified Pole
$f^+(0)\lvert V_{cd}\rvert$	$0.086 \pm 0.005 \pm 0.001$	$0.086 \pm 0.005 \pm 0.001$
shape parameter	$1.87 \pm 0.24 \pm 0.00$	$0.21 \pm 0.44 \pm 0.05$
ρ	0.75	−0.80
χ^2	2.5	2.5



These measurements are consistent with our previous results [6], which they supersede, and with the particle data group's upper limits [10]. They are also consistent with predictions from both the ISGW2 [2] and Fajfer-Kamenic [21] models. The upper limit for $D^+ \to \phi e^+ \nu_e$ is about twice as restrictive as our previous limit [6].

CLEO-c at CESR

- CLEO-c at the CESR e+ e- collider on the Cornell campus.
- CLEO-c run now complete, with
  - 818 pb^{-1} at $\psi(3770)$, corresponding to 3.0M D^oD^o and 2.4M D^+D^- events
  - 600 pb^{-1} at 4170 MeV, corresponding to 600k $D_sD_s^*$ events



BES results

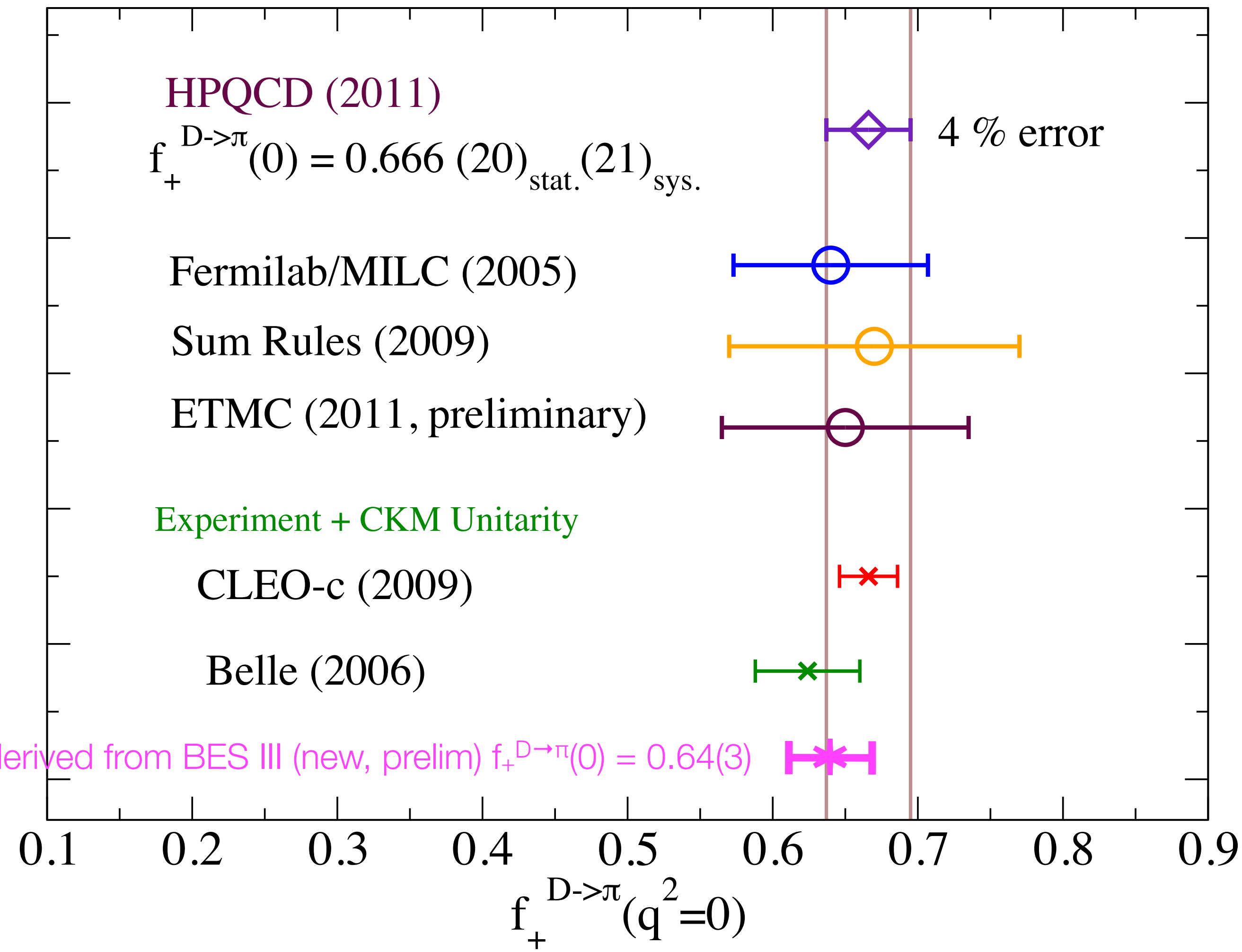
BESIII Preliminary

Mode	Data Yield	Fraction of All Tags (%)	Tag Efficiency(%)
$D^0 \to K^-\pi^+$	159,929 ± 413	20.7	62.08±0.07
$D^0 \to K^-\pi^+\pi^0$	323,348 ± 667	41.8	33.56±0.03
$D^0 \to K^-\pi^+\pi^0\pi^0$	78,467 ± 480	10.1	14.93±0.04
$D^0 \to K^-\pi^+\pi^-\pi^+$	211,910 ± 550	27.4	36.80±0.04

$f_+^{D\to\pi}(0)$ from experiment and theory

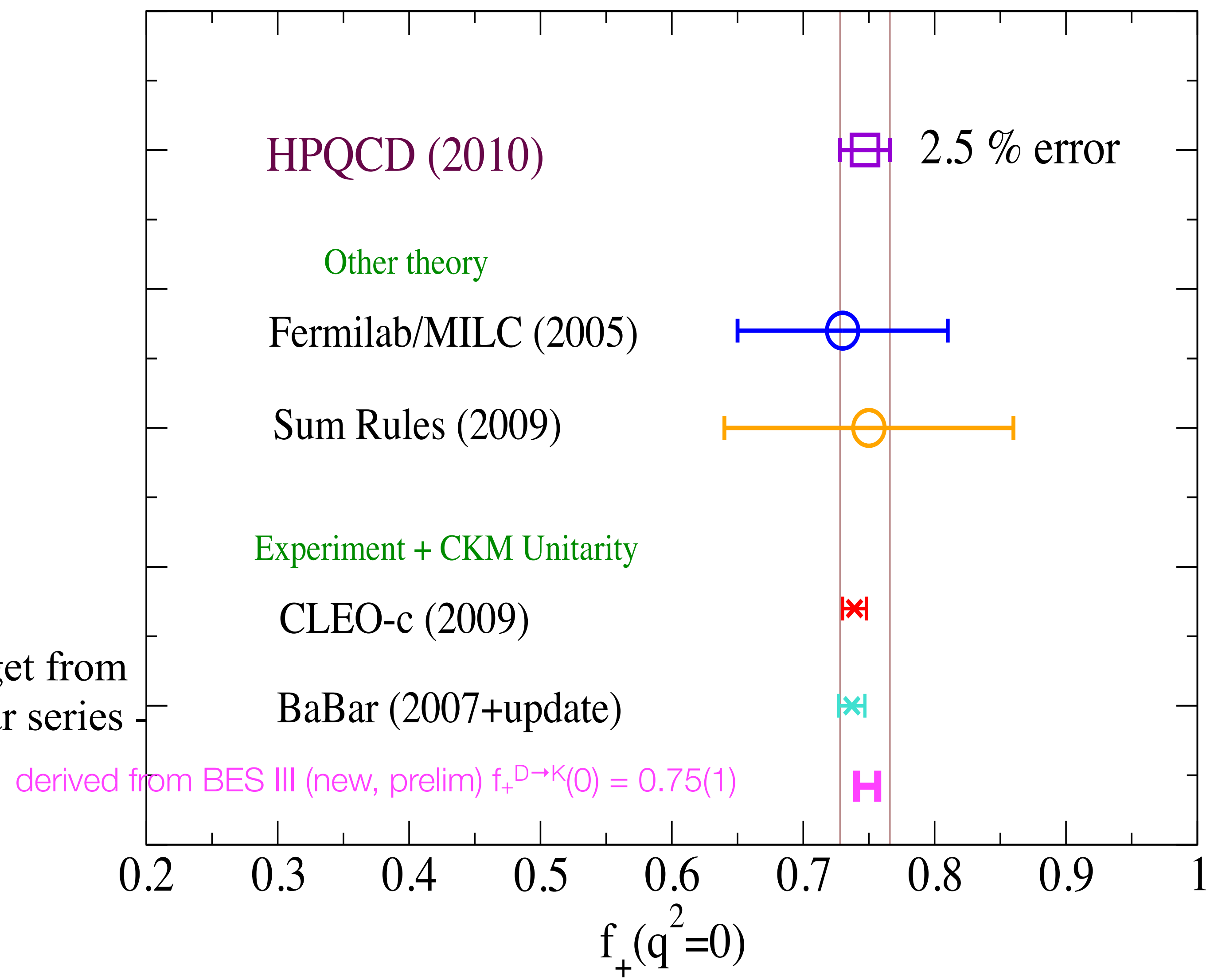
Note: CLEO-c result from combination of D+ and D0 decays, which explains the better stat error - for individual channels, uncertainties are virtually identical

Taken from Phys.Rev. D84 (2011) 114505 and modified (added BES III)



With $|V_{cd}| = 0.2252 \pm 0.0007$, I get from BES III new result (3 par series - as used by CLEO-c): derived from BES III (new, prelim) $f_+^{D\to\pi}(0) = 0.64(3)$

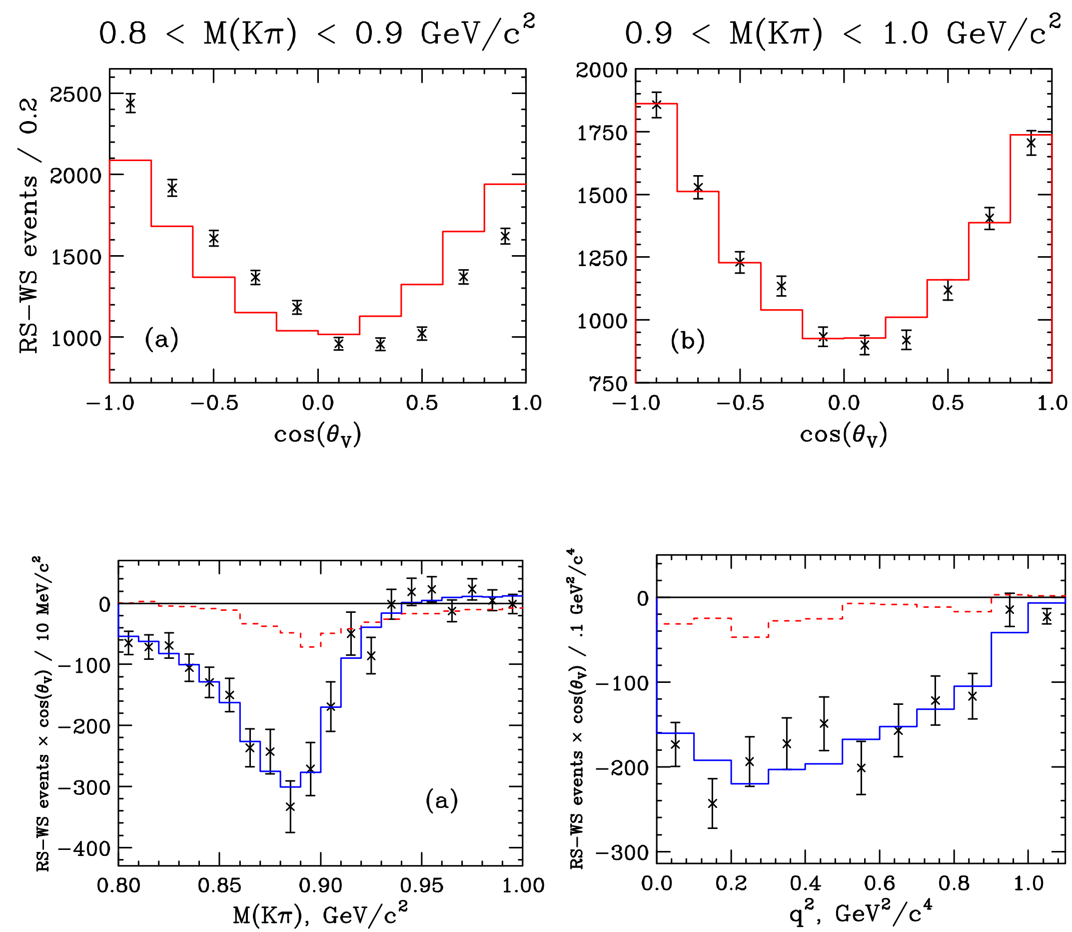
Taken from Phys.Rev. D82 (2010) 114506 and modified (added BES III)



With $|V_{cs}| = 0.97345$, I get from BES III new result (3 par series - as used by CLEO-c):

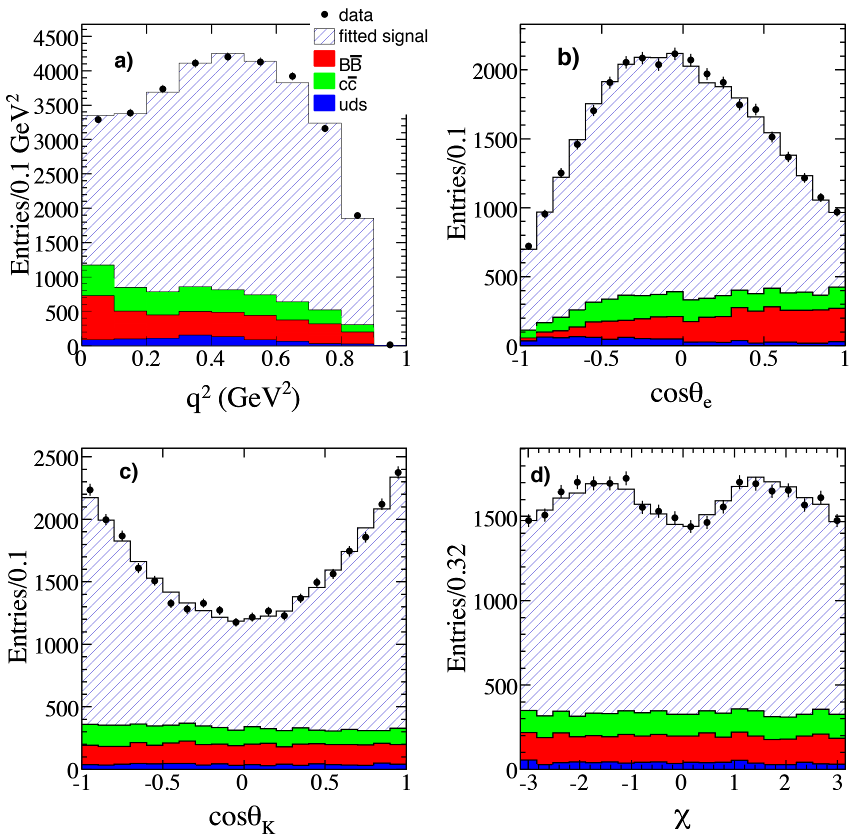
FOCUS - evidence for Kπ S-wave in D→Kπ μν

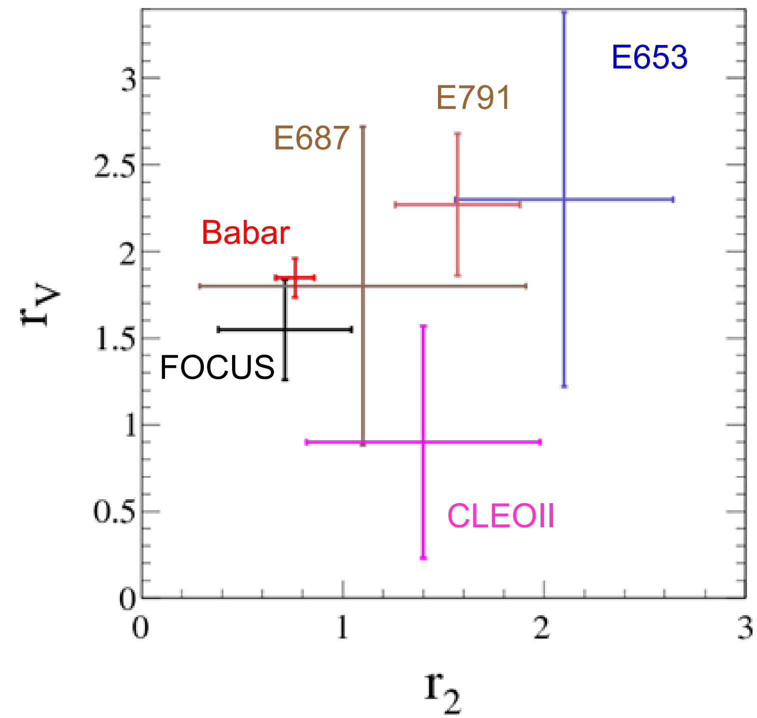
- FOCUS find discrepancies between data (black) and D→K* μν MC (red) in in cos(θ$_V$) distribution below pole.
- S wave – P wave interference results in asymmetry in cos(θ$_V$).
- Plots below show cos(θ$_V$) - weighted distributions in M(Kπ) and q^2.
- Discrepancies get resolved by adding a constant S-wave term $Ae^{i\delta} = 0.36 \cdot e^{(i\pi/4)} \text{GeV}^{-1}$ (blue).



FOCUS: Phys.Lett. B535 (2002) 43-51

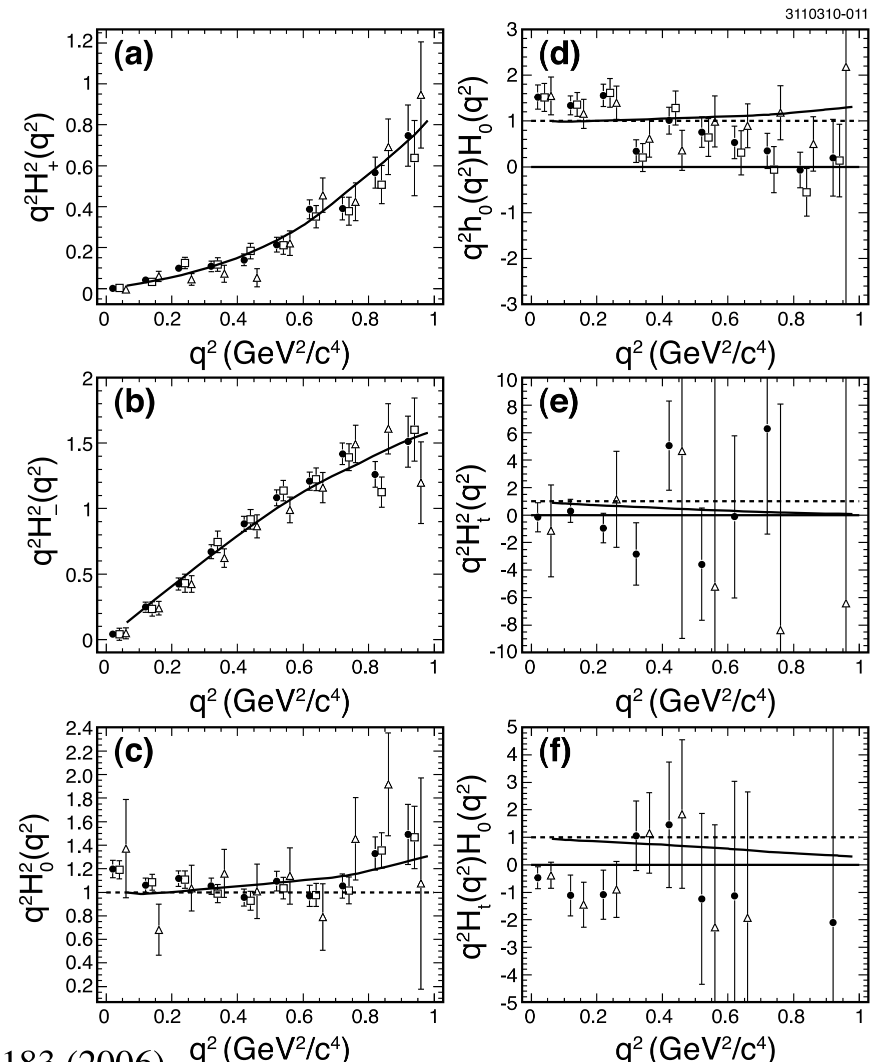
Ds→KK e ν at BaBar (2008)





Non-parametric form factors

- CLEO-c (2010) use a projective reweighting technique pioneered by FOCUS (2006).
- Includes parameterisation for highly-suppresssed right-handed lepton (adds a helichity H_T, and form factor, A_3)
- Projection = integration over all but one variable. Weights are choses such that this integral is zero for all terms, except for the terms of interest.

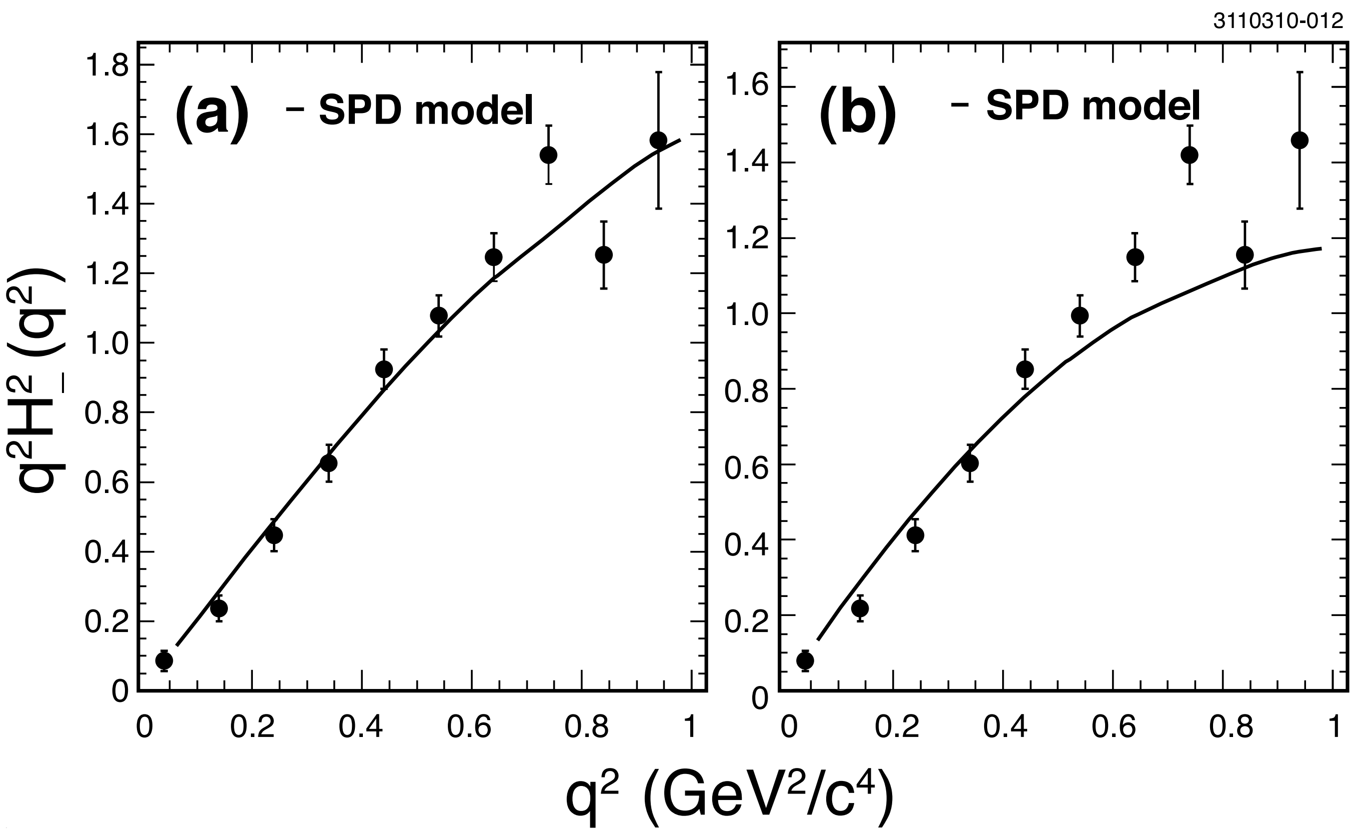


CLEO: Phys.Rev. D81 (2010) 112001; FOCUS: Phys. Lett. B 633, 183 (2006)

Non-parametric vs simple pole

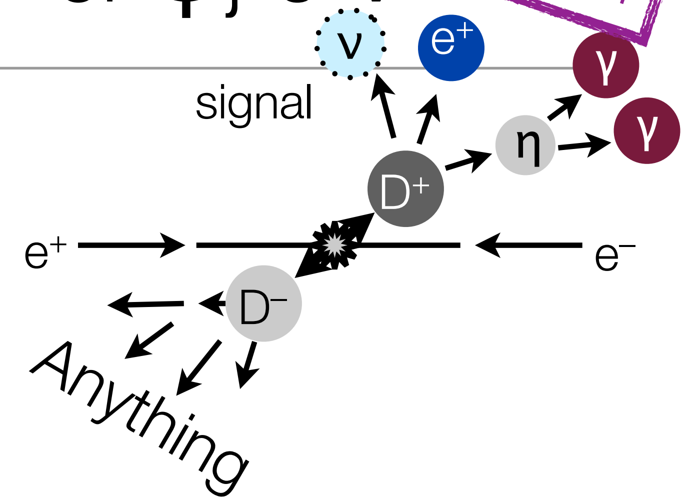
finite pole mass

infinite pole mass

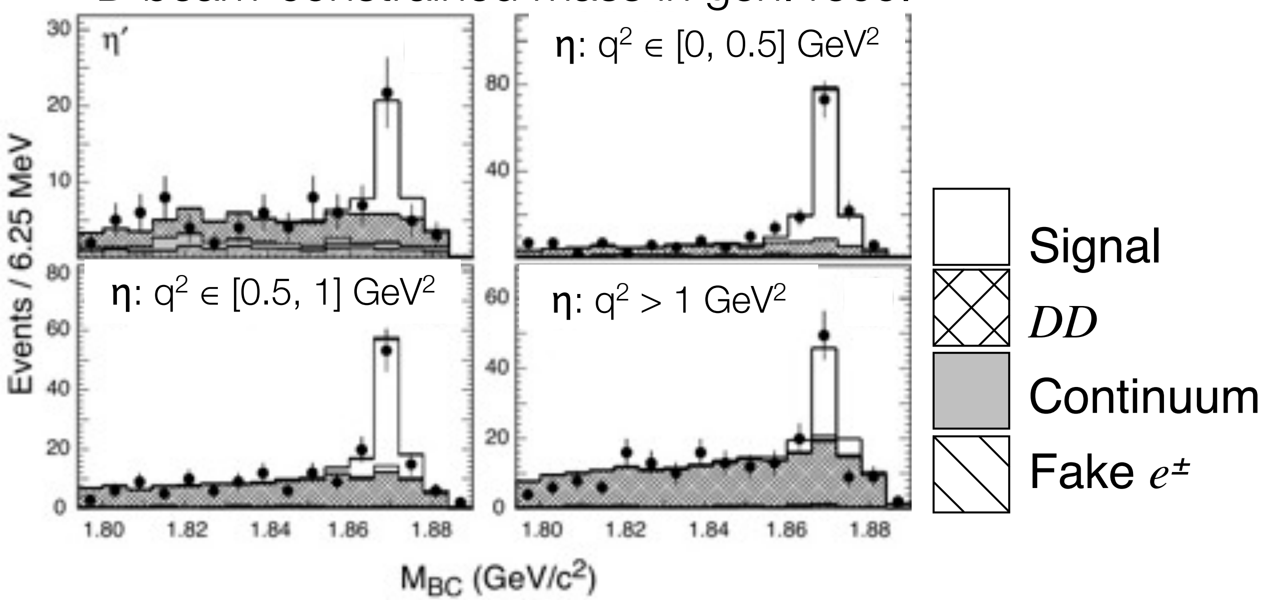


Generic Reconstruction of $D^+ \to \{\eta, \eta' \text{ or } \phi\}\, e^+\nu$

CLEO-c 2011



D beam-constrained mass in gen. reco.



- Leads to first observation of $D^+ \to \eta' e^+ \nu$, CL: 5.8σ

- GR dominates precision on $D^+ \to \eta\, e^+ \nu$ form factor.

CLEO: Phys.Rev. D84 (2011) 032001

Mode	$\mathcal{B}_{\text{tag}}$ $[10^{-4}]$	R_{GR} [%]	$\mathcal{B}_{\text{GR}}$ $[10^{-4}]$
$\eta' e^+ \nu_e$	$2.5^{+1.6}_{-1.0}(0.1)$	0.237(58)(5)	2.16(53)(7)
$\phi\, e^+ \nu_e$	< 0.9 @ 90% confidence level (C.L.)		
$\eta e^+ \nu_e$	11.1(1.3)(0.4)	1.28(11)(4)	11.7(1.0)(0.4)
$\eta e^+ \nu_{e,\text{0-0.5}}$	6.53(94)(26)	0.625(69)(18)	5.71(63)(20)
$\eta e^+ \nu_{e,\text{0.5-1.0}}$	3.08(71)(13)	0.437(68)(13)	3.99(62)(15)
$\eta e^+ \nu_{e,\geq 1.0}$	1.77(67)(16)	0.223(52)(10)	2.03(47)(10)