Precision Charm Meson Decays

Leptonic, Semileptonic, Hadronic

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(+ CLEO & BESIII)

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? Why Charm ?

Previous "wisdom":
charm is a bit boring for flavor physics

Cabibbo-allowed decays dominate: hard to see rare processes

D Mixing is suppressed in SM & hard to estimate
CP violation suppressed

Light enough to make theory difficult (tough for HQET, etc.)
and lots of strong-interaction physics obscuring the weak

Better wisdom:
Charm is a gift!

B physics very productive… but limited by theory in many cases.
✦ Lattice QCD can help & charm can test it ✦

Today's Topics

Leptonic Decays $D_{(s)} \to \mu\nu$
to extract decay constants

$D \to Kl\nu$, $\pi l\nu$
to measure form factors

Testbeds for
modern Lattice QCD

$D^0 \to K\pi$ $D^+ \to K\pi\pi$ $D_s \to KK\pi$
normalization from golden-mode branching rations

NOTE:
Precision lifetimes (dominated by FOCUS) are also useful !

Current Leaders

CLEO-c: Tagging with D pairs very clean

Belle/BaBar: Continuum charm large statistics

Sometimes using "continuum tagging"

Key issue:

Agreement with latest unquenched Lattice QCD ?

Techniques

CLEO-c uses Tagging:

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

e^+e^- @4170 MeV: $D_s^+D_s^{*-}$ & c.c.

creates ONLY D pairs

Fully reconstruct one $D_{(s)}$

- Can then infer neutrinos (constrained kinematics)
- or get absolute hadronic BFs

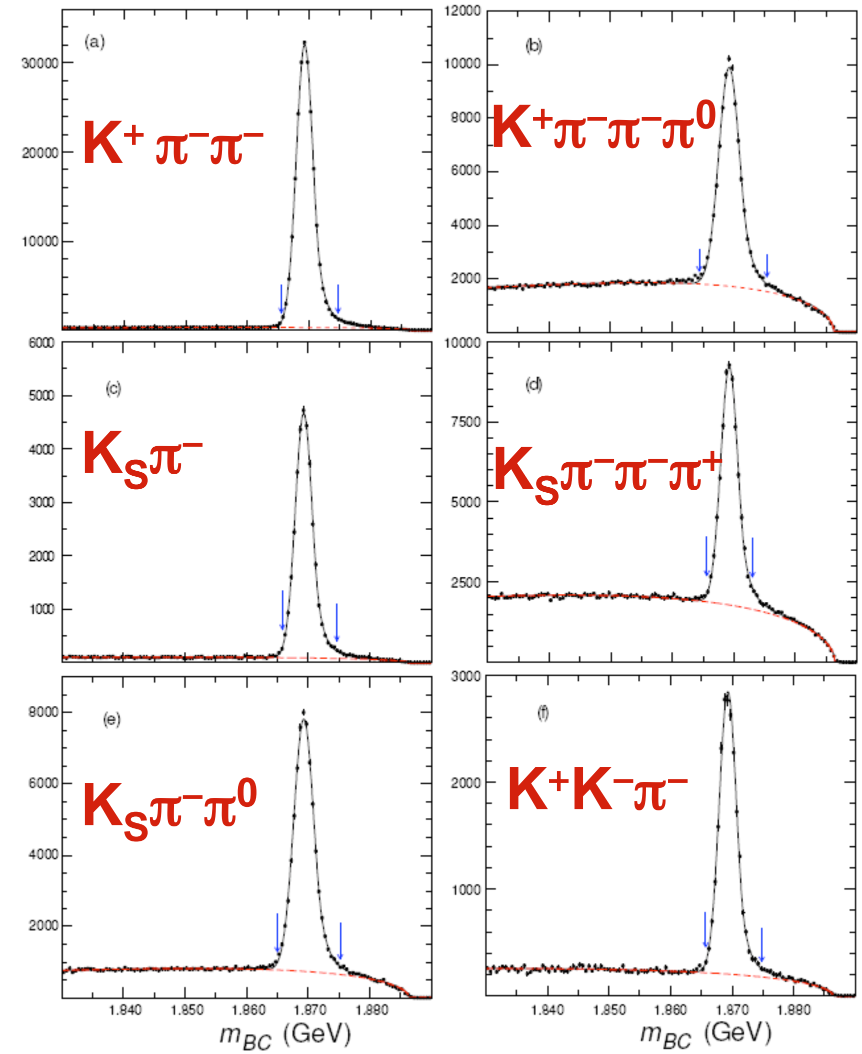
Typical tag rate per D:
15% / 10% / 5%
D^0 / D^+ / D_s

Belle:

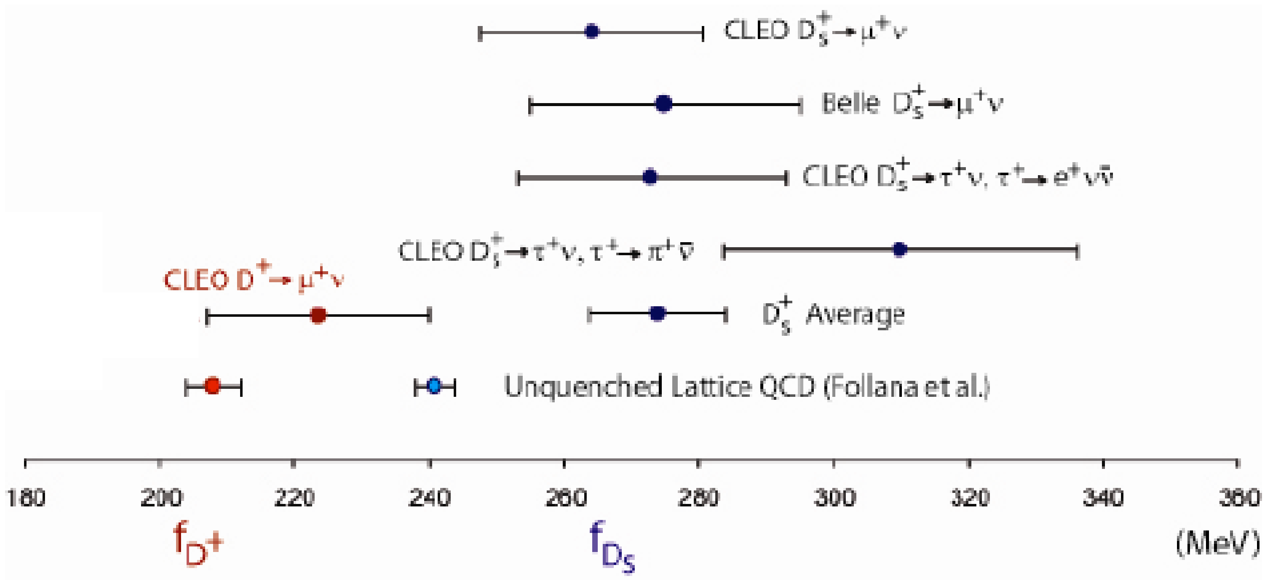
Has used a similar technique, with exclusive final states from continuum at 10 GeV

CLEO-c D^- Tags

= fully-recon. hadronic decay



Decay Constants: Pre-FPCP2008



D^+: Consistent with LQCD, but tests limited by experimental precision

D_s: Disagreement with latest Lattice result

D Decay Constant Status

Previous CLEO & Belle results average to give f_{Ds} = 274 ± 10 MeV

(see Rosner & Stone arXiv:0802.1043)

Best 2+1 unquenched lattice QCD obtains 241 ± 3 MeV

(Follana et.al, PRL 100, 062002 (2008))

- Dobrescu & Kronfeld argue that this could be the effect of NP, either charged Higgs (their own model) or leptoquarks

  (see arXiv:0803.0512)

  Kundu & Nandi suggest R-parity violating SUSY to explain large f_{Ds} and B_s mixing phase (see arXiv:0803.1898)

Modest update from CLEO-c at FPCP2008 recapped here, along with 2007 Belle result.

Next, recall the previous CLEO f_{D^+} result: f_D = 223 ± 17 MeV

Imprecise, compared to Follana et al., lattice: 207 ± 4 MeV

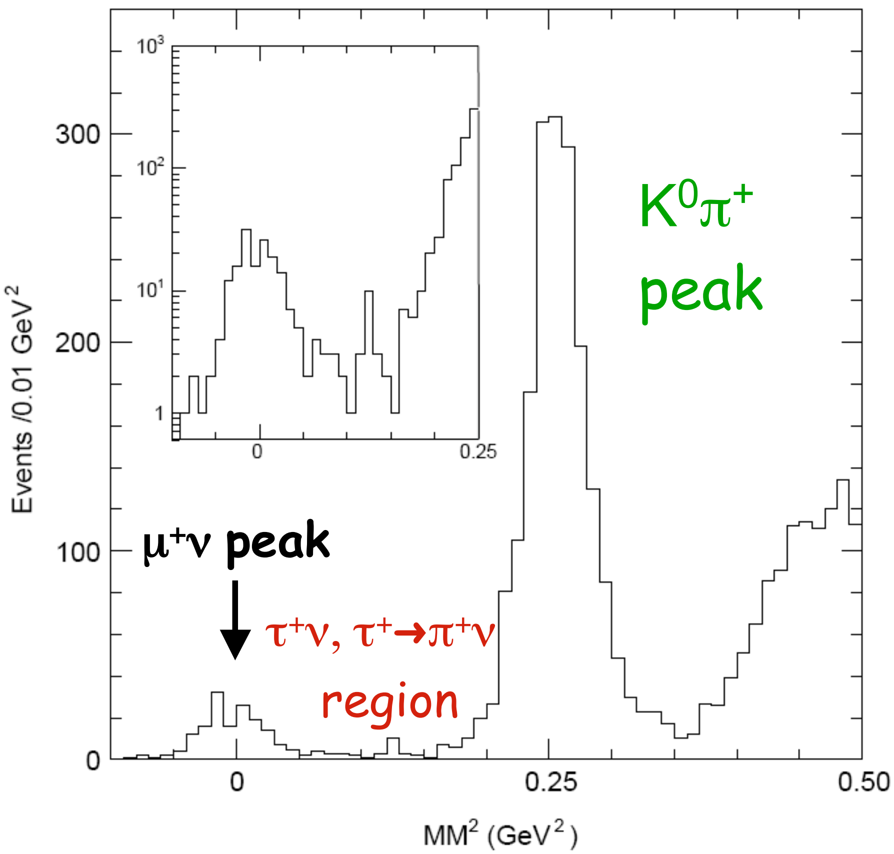
Significant update from CLEO-c at FPCP2008 recapped here.

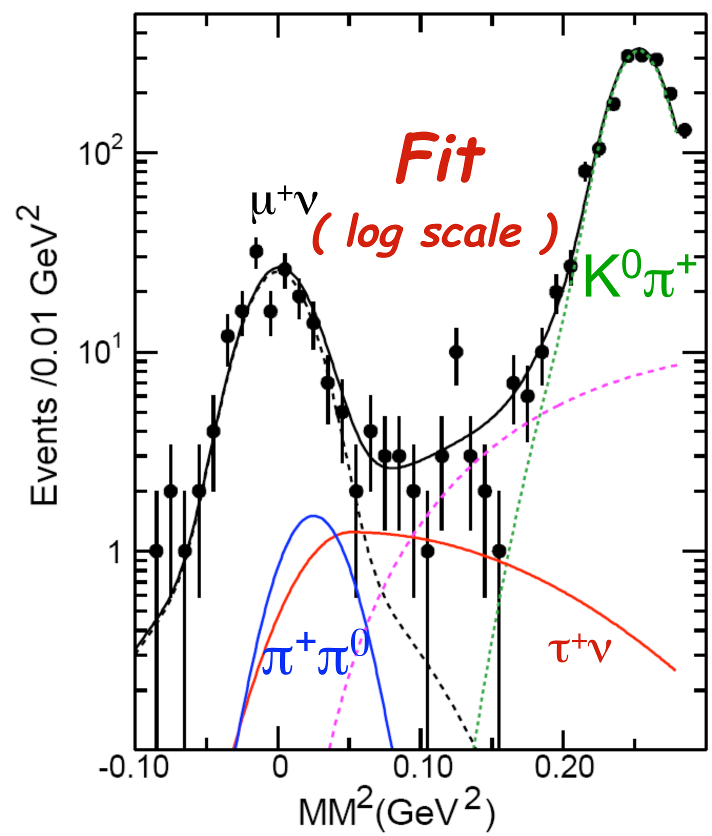
$D^+ \rightarrow \mu^+\nu$ Update

PRELIMINARY
FPCP2008
818 pb^{-1}

Neutrino from 4-momentum balance
can plot (missing mass)^2: MM^2

Clean, isolated signal peak: Power of D-tagging:
Recall that the signal is one track + neutrino !





$D^+ \to \mu^+\nu$ Results

PRELIMINARY
FPCP2008
818 pb^{-1}

Fix $\tau\nu/\mu\nu$ at SM ratio of 2.65 :

$\mathcal{B}(D^+ \to \mu^+\nu) = (3.86 \pm 0.32 \pm 0.09) \times 10^{-4}$

$f_{D^+} = (206.7 \pm 8.5 \pm 2.5)$ MeV

Best number in context of SM

Float $\tau\nu/\mu\nu$:

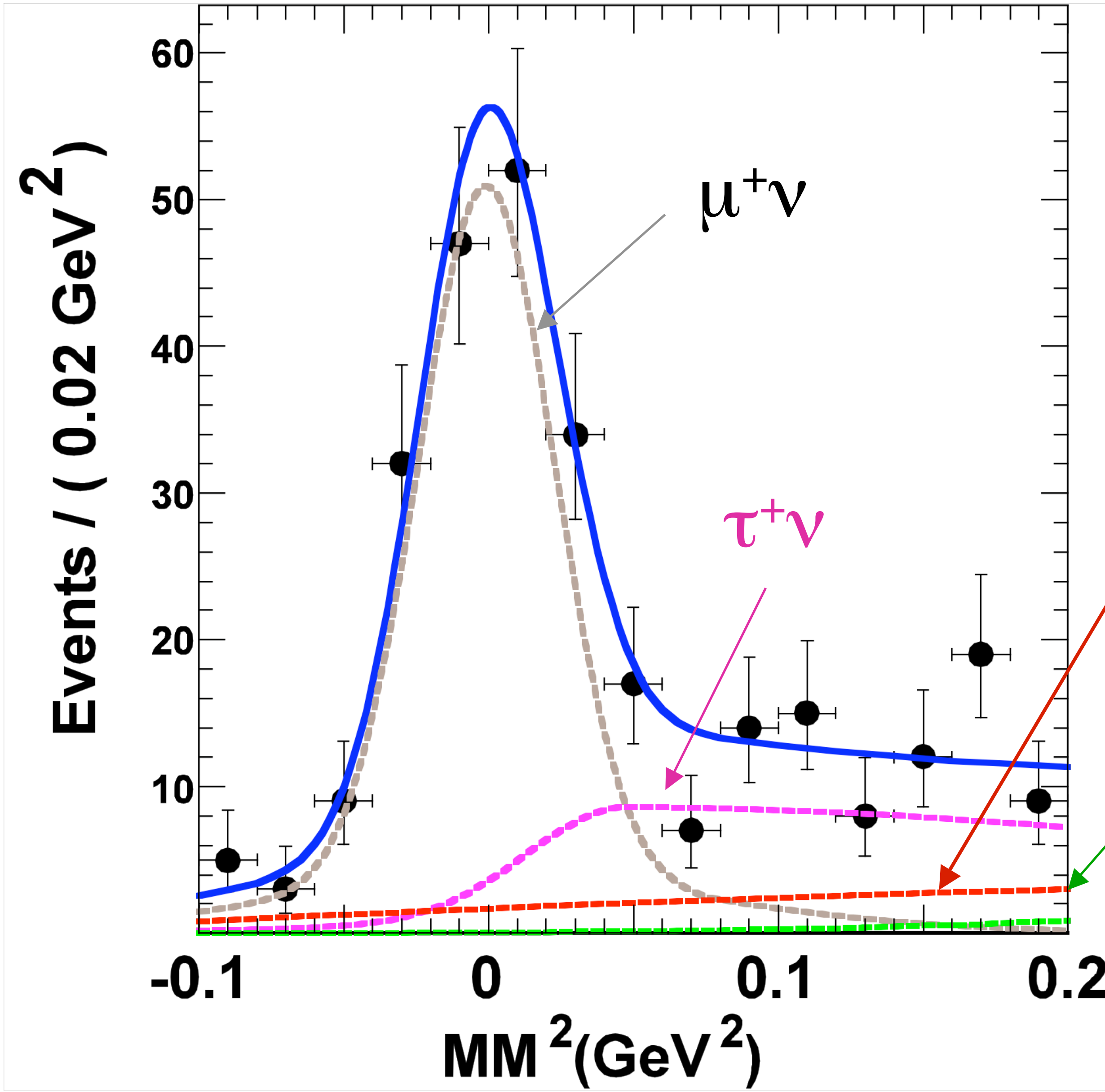
$\mathcal{B}(D^+ \to \mu^+\nu) = (3.96 \pm 0.35 \pm 0.10) \times 10^{-4}$

$f_{D^+} = (208.5 \pm 9.3 \pm 2.5)$ MeV consistent

Best number for use with Non-SM models

$D_s \rightarrow \mu^+\upsilon$ & $\tau^+\upsilon$
(w/ $\tau^+ \rightarrow \pi\,\upsilon$)

PRELIMINARY
FPCP2008
~400 pb^{-1}
(& 200 more soon)



Background
D_s sidebands

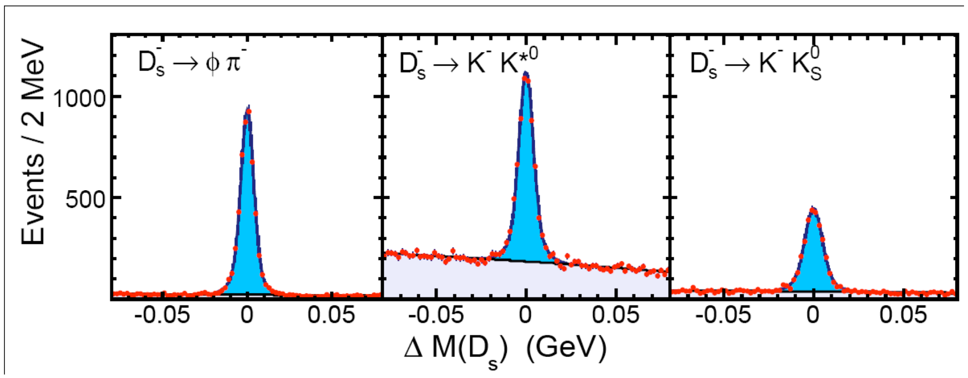
Extra g
background

Have published:
PRL99, 071802
PRD76, 072002
(2007) 314 pb^{-1}

$D_s \to \tau^+\nu \;\; (\tau^+ \to e^+\nu\nu)$

PRL100, 161801
(2007) 298 pb^{-1}

Use only cleanest tags (for now)

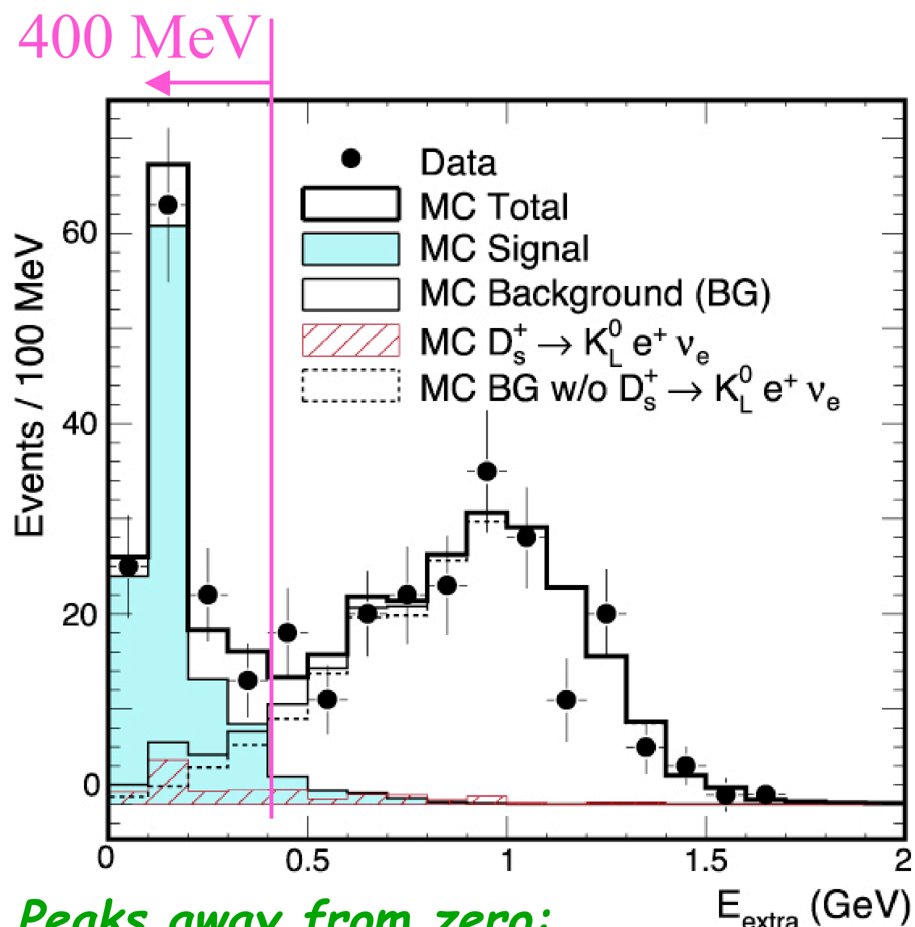


Always have >1 neutrino!

Abandon use of MM^2

Semileptonic events tend to have hadronic Energy in CsI (but careful re: K_L !)

Plot E_{extra} in Calorimeter (Extra: not tag or e)



Peaks away from zero:

E_{extra} can include γ from D_s^* decay

CLEO-c D_s Summary

PRELIMINARY
FPCP2008

Mode	$\mathcal{B}$ (%)	f_{D_s} (MeV)
(1) $\mu\nu+\tau\nu$ (fix SM ratio)	$\mathcal{B}^{eff}(D_s \to \mu\nu) = (0.613 \pm 0.044 \pm 0.020)$	$268.2 \pm 9.6 \pm 4.4$
(2) $\mu\nu$ only	$\mathcal{B}(D_s \to \mu\nu) = (0.600 \pm 0.054 \pm 0.020)$	$265.4 \pm 11.9 \pm 4.4$
(3) $\tau\nu$, $\tau\to\pi\nu$	$\mathcal{B}(D_s \to \tau\nu) = (6.1 \pm 0.9 \pm 0.2)$	$271 \pm 20 \pm 4$
(4) $\tau\nu$, $\tau\to e\nu\nu$	$\mathcal{B}(D_s \to \tau\nu) = (6.17 \pm 0.71 \pm 0.36)$	$273 \pm 16 \pm 8$
CLEO Average of (1) & (4)		$269.4 \pm 8.2 \pm 3.9$

- ***CLEO-c updated both D and D_s at FPCP2008:***
- Due to time, I can't do justice to the many nice cross-checks…
- please see S. Stone's FPCP talk for more details.

Belle: $D_s \to \mu^+ \upsilon$

arXiv:0709.1340
(2007) 548 fb^{-1}

Use "Continuum tagging":

$e^+e^- \to D^{\pm,0} K^{\pm,0} X D_s^*$,

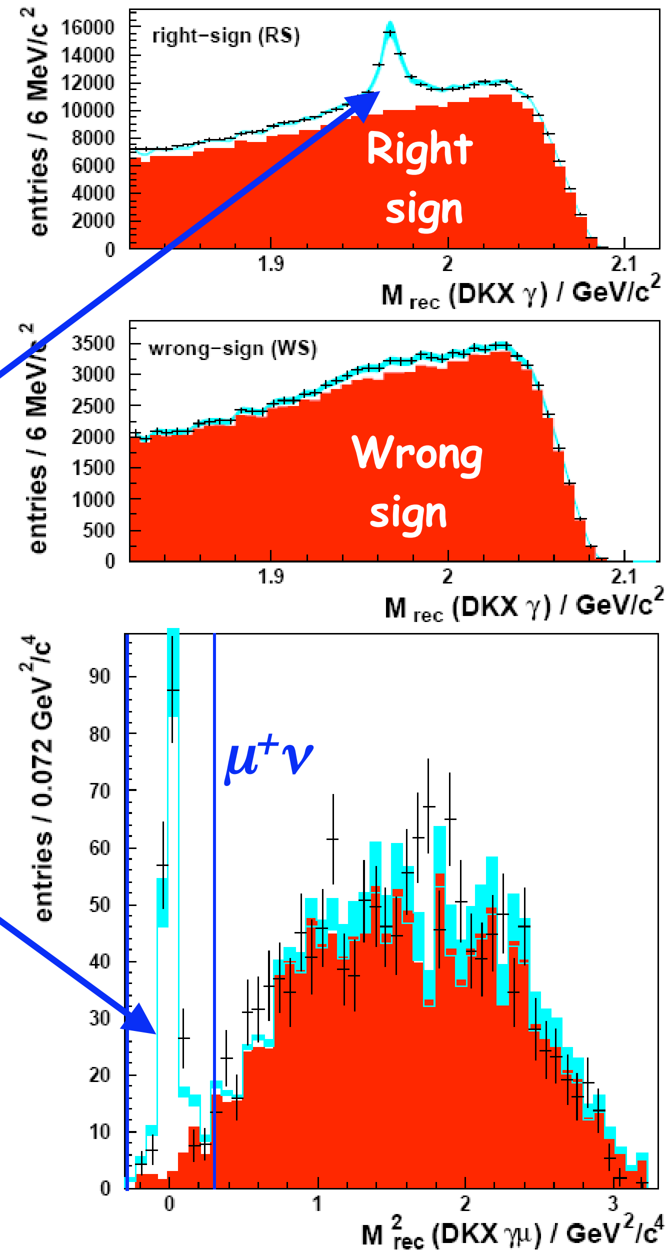
$X = n\pi$ -or- $n\pi\,\gamma$ (fragmentation)

about 25% of D BF used

Use recoil mass:

against DKXγ counts total D_s

against DKX$\gamma\mu$ counts $D_s \to \mu^+\upsilon$



$\mathcal{B}(D_S^+ \to \mu^+\nu) =$

$(0.644 \pm 0.076 \pm 0.057)\%$

$f_{Ds} = 275 \pm 16 \pm 12$ MeV

Decay Constant Summary

Weighted Ave. CLEO+Belle: f_{Ds} = 270.4 ± 7.3 ± 3.7 MeV

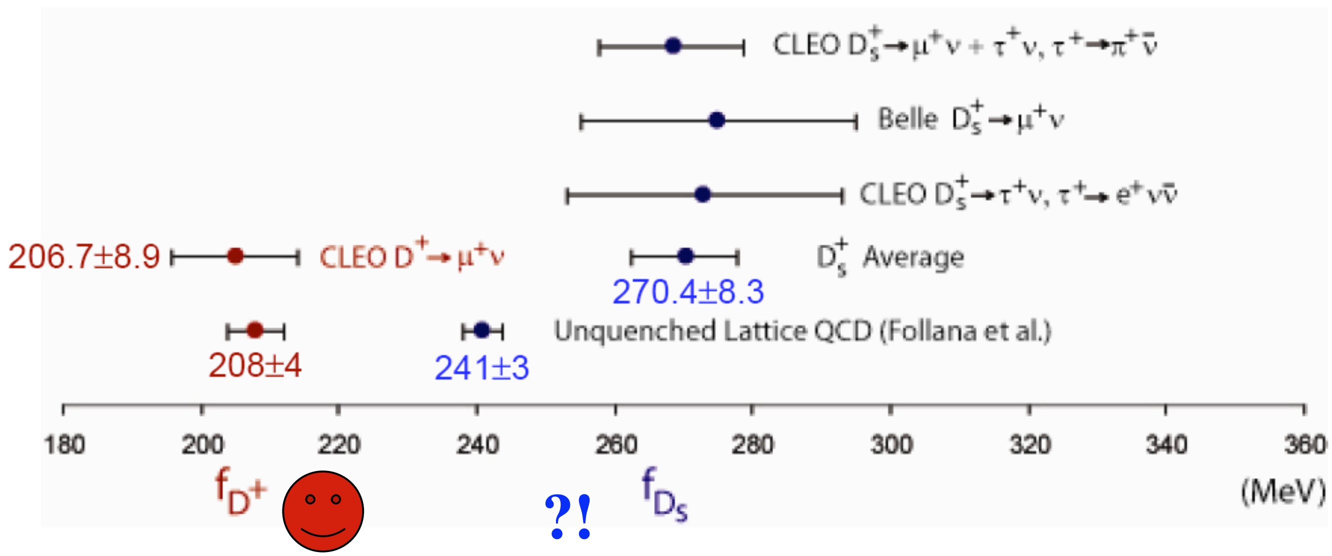
(systematic errors are uncorrelated)

Using f_{D^+} = (206.7 ± 8.5 ± 2.5) MeV

f_{Ds}/f_{D^+} = 1.31 ± 0.06 ± 0.02 larger than predicted

$\Gamma(D_S^+ \to \tau^+\nu) / \Gamma(D_S^+ \to \mu^+\nu)$ = 10.3 ± 1.1, SM = 9.72

Consistent with lepton universality



Note: BaBar f_{Ds} PRL 98, 141801 (2007) & others depending on "B($D_s \to \varphi\pi$)" are omitted here...

Semileptonic Decays

Concentrate on Form Factors

- o Pseudoscalar modes for Lattice QCD tests

  Key: $D \rightarrow \pi l \nu$ as test of $B \rightarrow \pi l \nu$ (needed for V_{ub})

- o $D_s \rightarrow KKe\nu$: newest precision result

Omitting:

- o Many other branching ratios

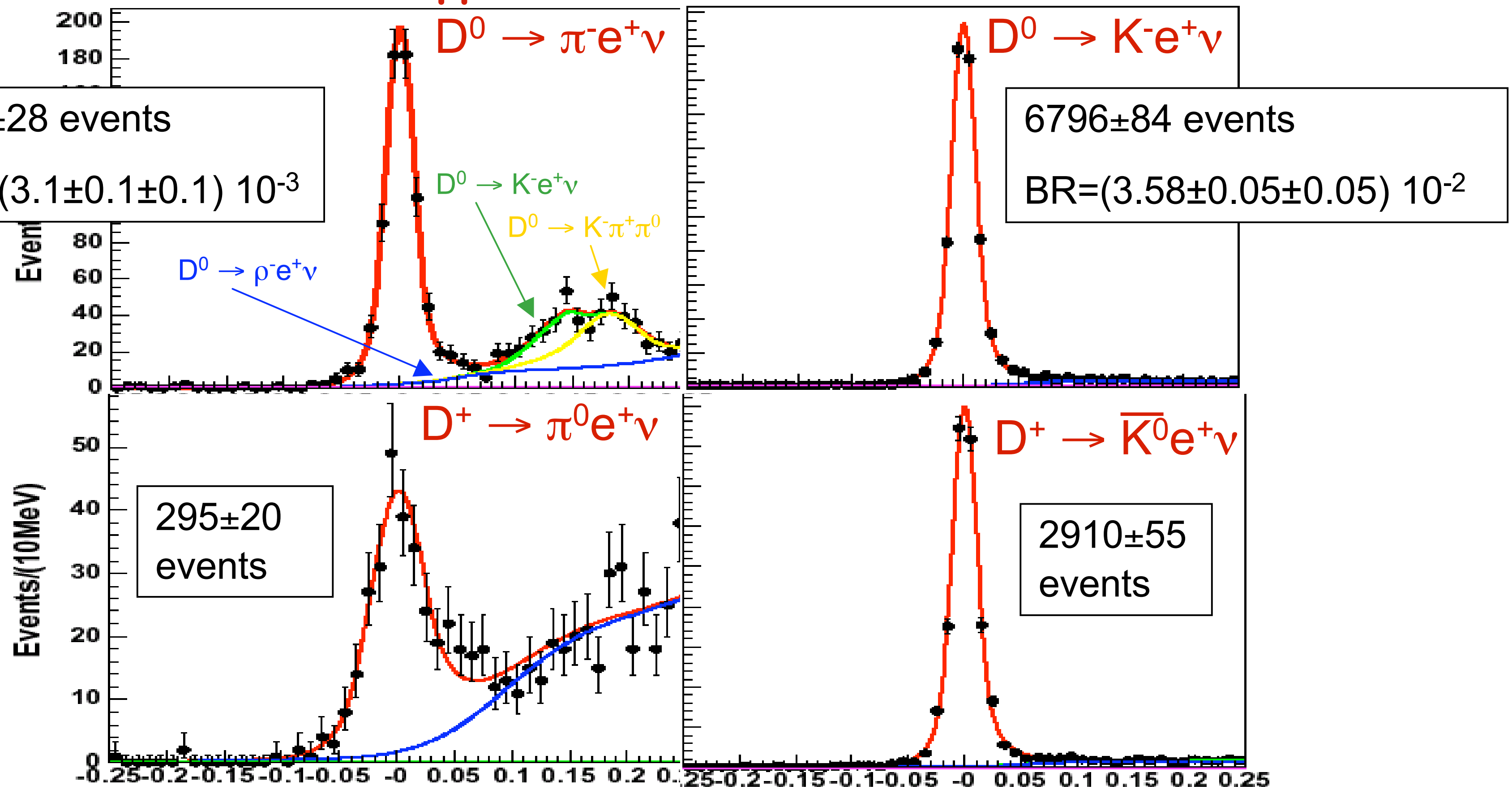
  esp. $D \rightarrow \rho/\omega/\eta/K_1\ e\ \nu$ (CLEO)

- o Non-Parametric FF analysis (CLEO)
- o Untagged $D \rightarrow Kl\nu$ (BaBar)

$D^{0+} \rightarrow \pi e \nu$, $K e \nu$ (tagged)

Preliminary
281 pb^{-1}

Cabibbo suppressed — Cabibbo favored



$U_{miss} = E_{mis} - |p_{mis}|$ (GeV)

Excellent background suppression

Small K-π feed-across due to threshold kinematics

Past results: K-π signals overlapped completely!

$D^0 \to \pi l\nu,\ Kl\nu$

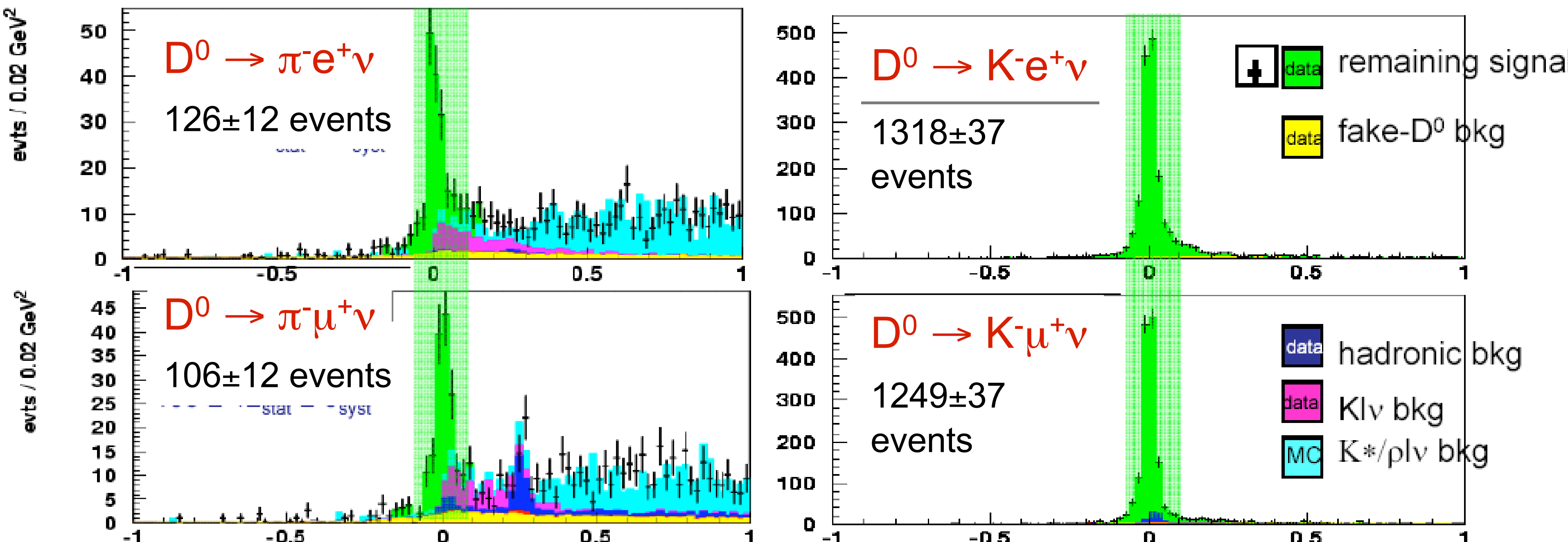
PRL 97, 061804 (2006) 282 fb^{-1}

Use "Continuum tagging" again: $e^+e^- \to D^{(*)}_{tag}\ D^*_{signal}\ X$.

Reconstruct all particles (except for neutrino)

Tagging provides absolute normalization ~56,000 tagged D^0

Cabibbo suppressed | Cabibbo favored



$m_{miss}^2 = E_{miss}^2 - p_{miss}^2$ (GeV) $\quad$ $m_{miss}^2 = E_{miss}^2 - p_{miss}^2$ (GeV)

Impressive results in difficult production environment

Both e and m measured, but only D^0

vs. CLEO-c: 1000x lumi, but ~3x less signal events & ~10x worse signal/noise

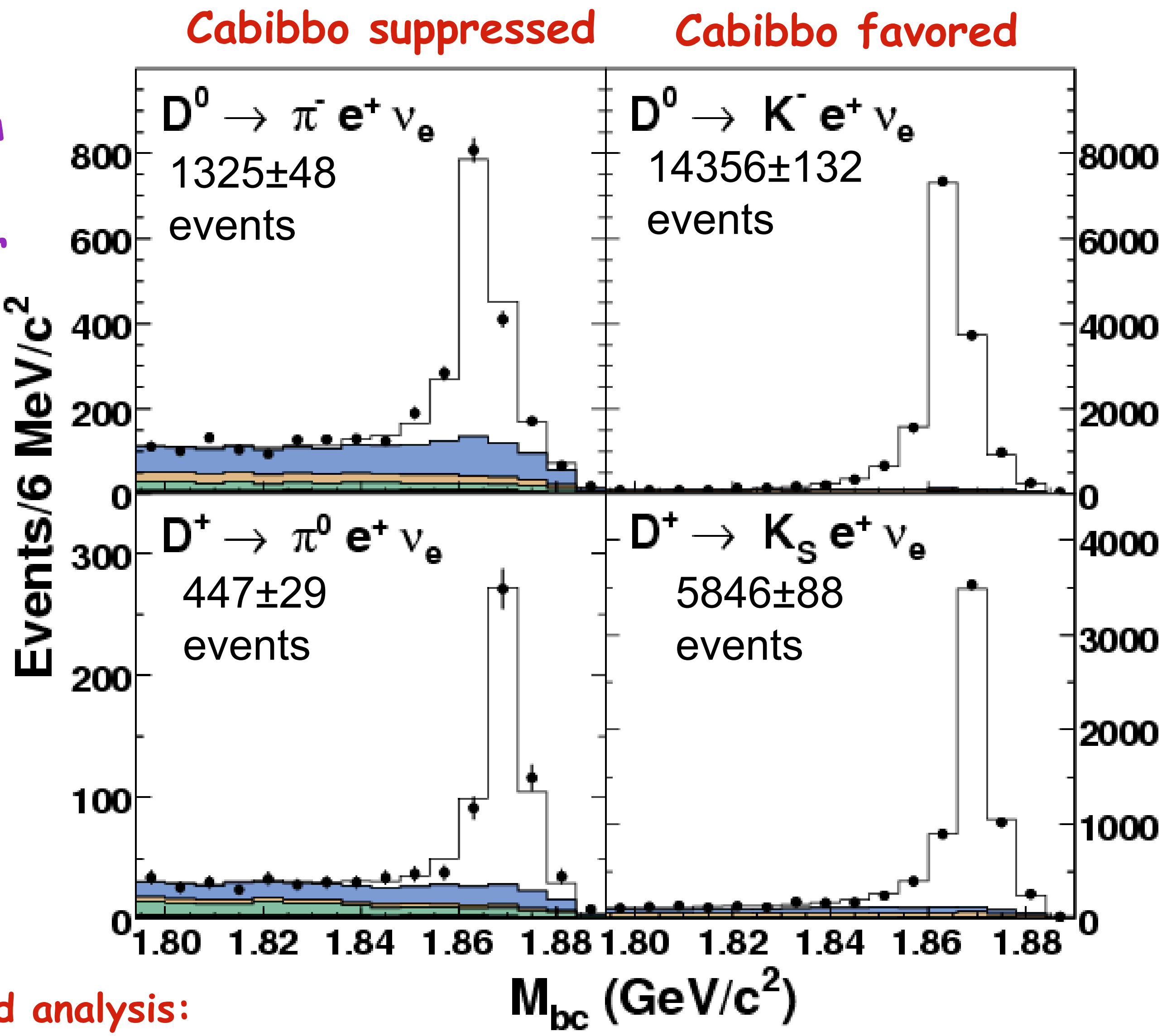
$D^{0+} \to \pi e \nu,\ K e \nu$ (untagged)

arXiv:0712.1012
arXiv:0712.0998
(to appear PRL/D)
281 pb^{-1}

Use global 4-momentum balance

Infer neutrino 4-vector w/o explicit tag

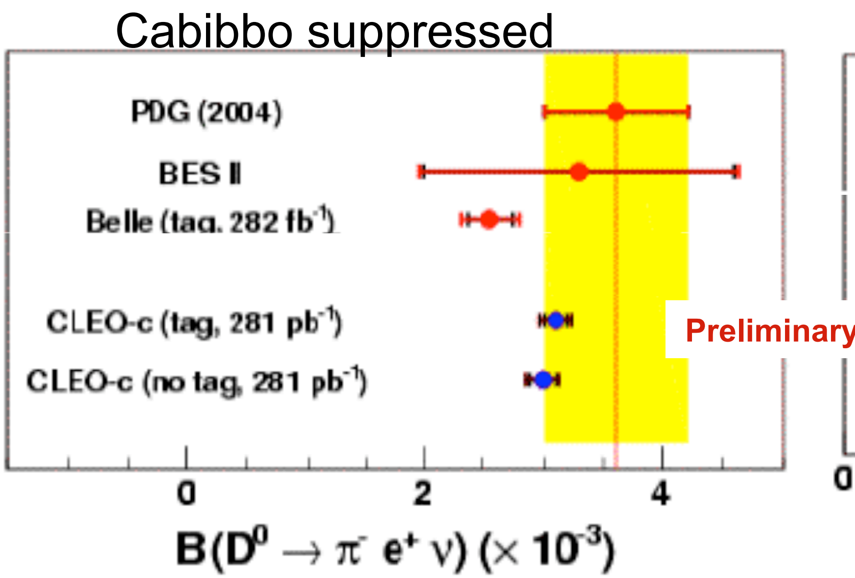
Can then use familiar beam-contsrained mass

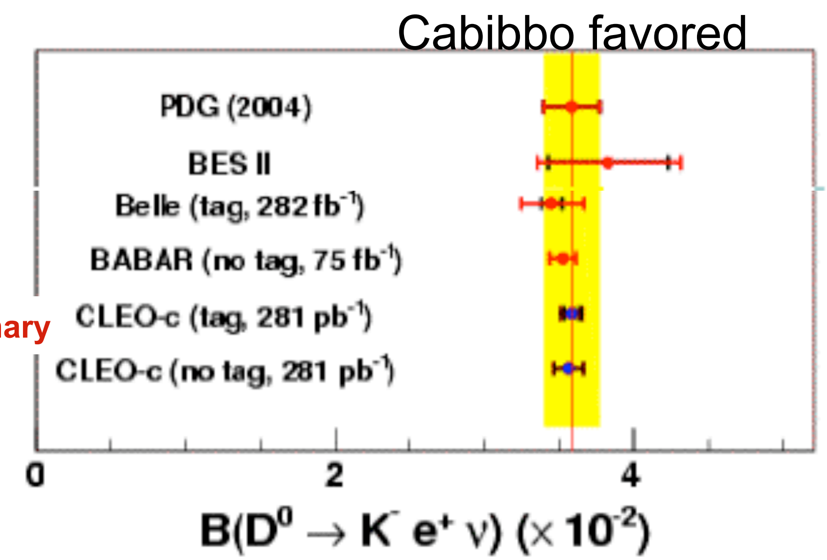


Compared to the tagged analysis:

- Factor ~2 increase in the signal statistics.

Branching Ratios





Significant improvement in precision by recent BaBar/Belle/CLEO-c measurements

(CLEO-c best, especilly for $\pi e \upsilon$)

Pseudoscalar Form Factors

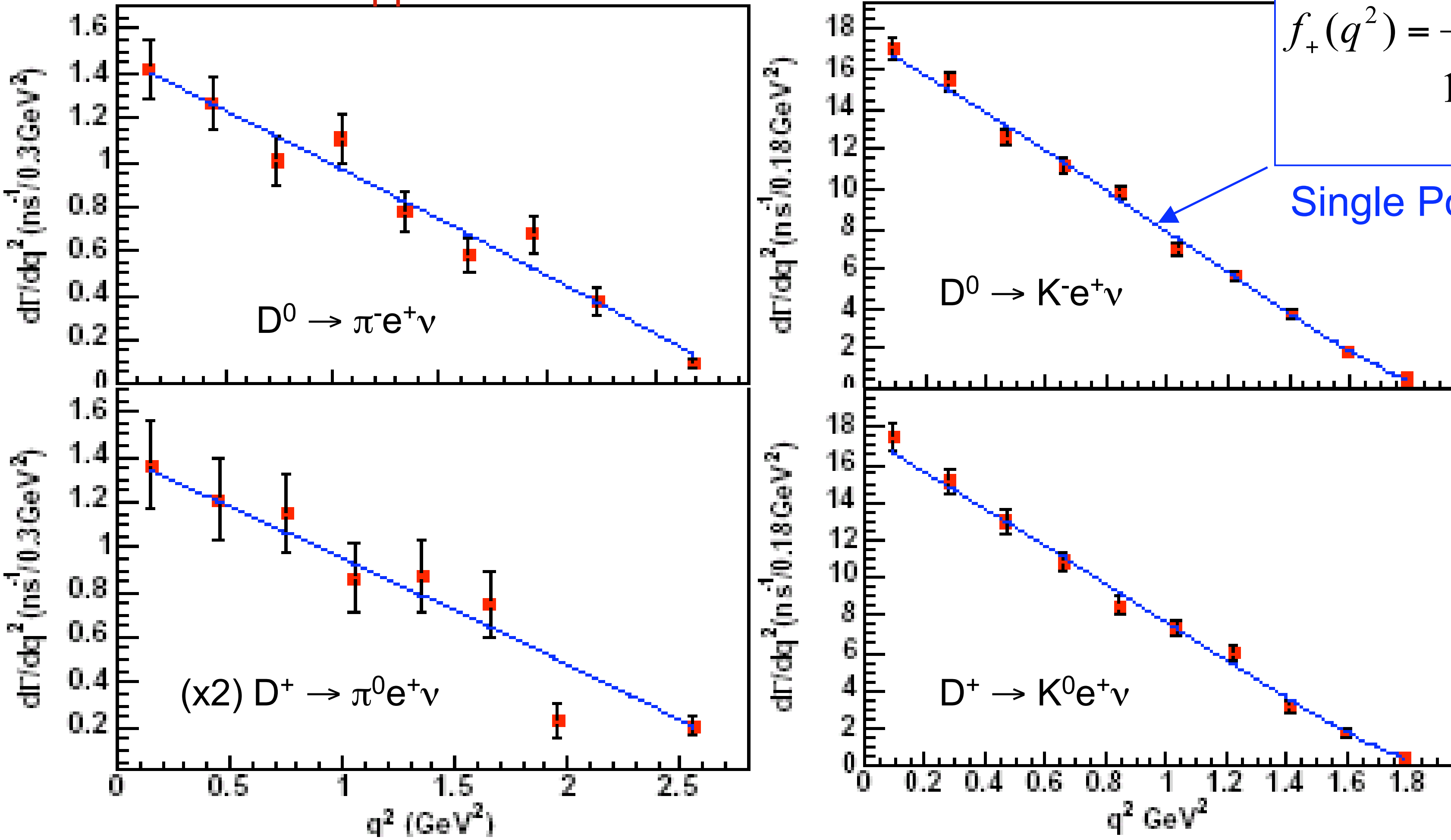
Preliminary
Tagged
281 pb^{-1}

Cabibbo suppressed

Cabibbo favored

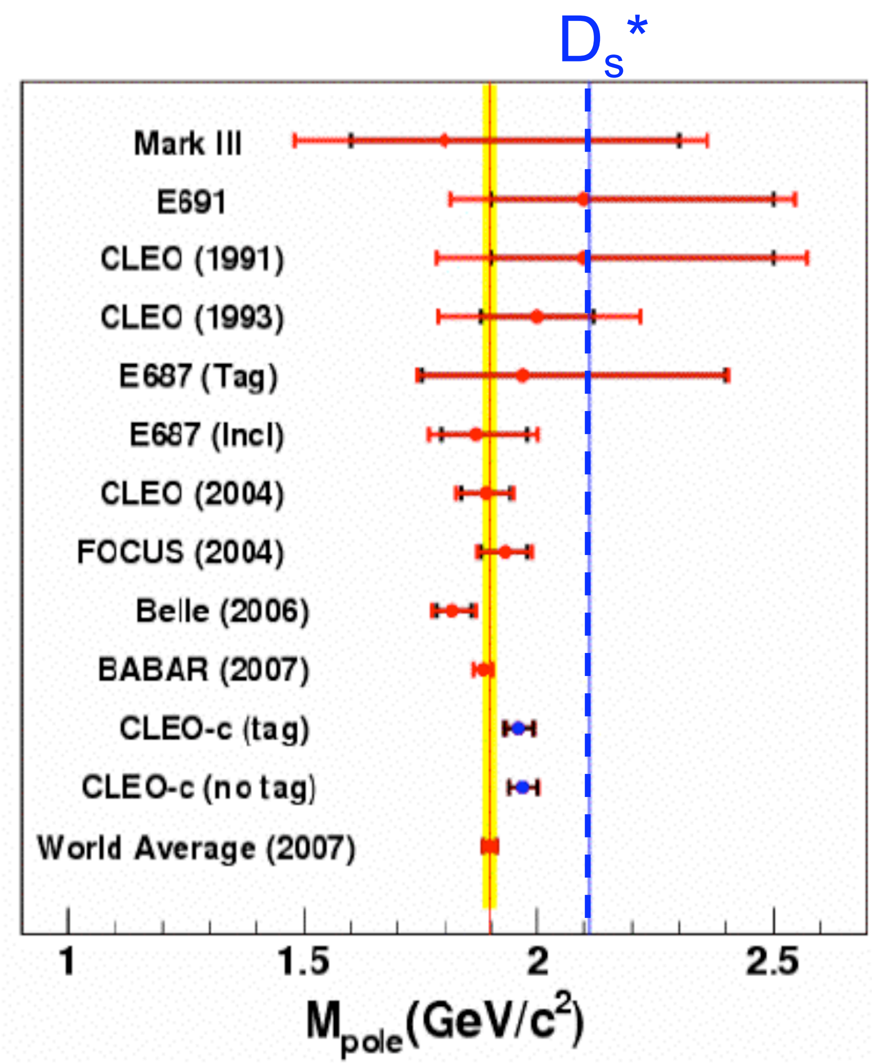
$$f_+(q^2) = \frac{f_+(0)}{1 - \dfrac{q^2}{M_{pole}^{\;2}}}$$

Single Pole Model



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

$D \to K e \nu$ Form Factor Pole Mass

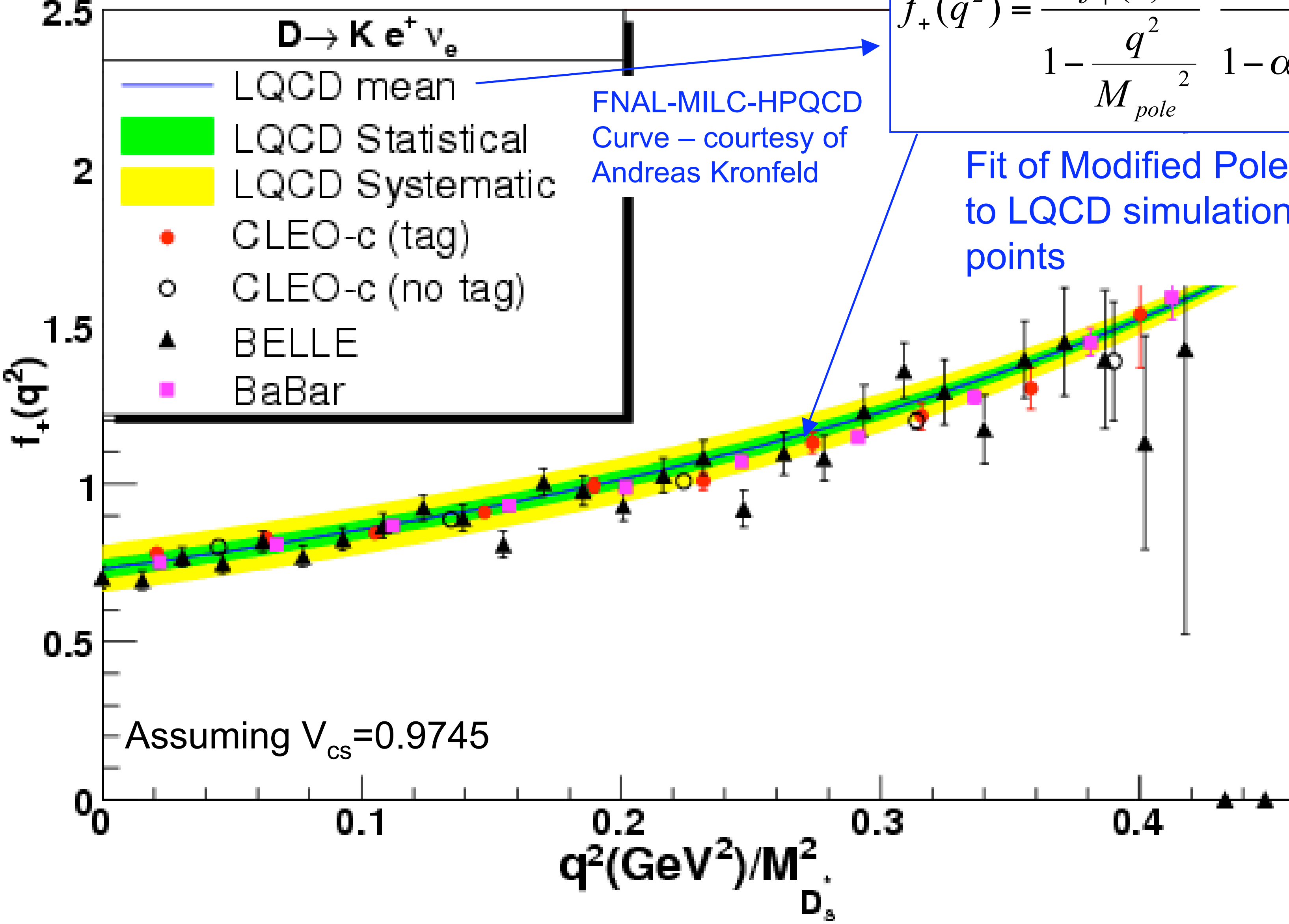


Single Pole Model describes data reasonably well,

but not with spectroscopic D_s^* mass

(from Ian Shipsey's talk at LQCD workshop, FNAL, Dec 2007 – see for more extensive discussion of form factor results)

D → Kev Form Factor vs. LQCD

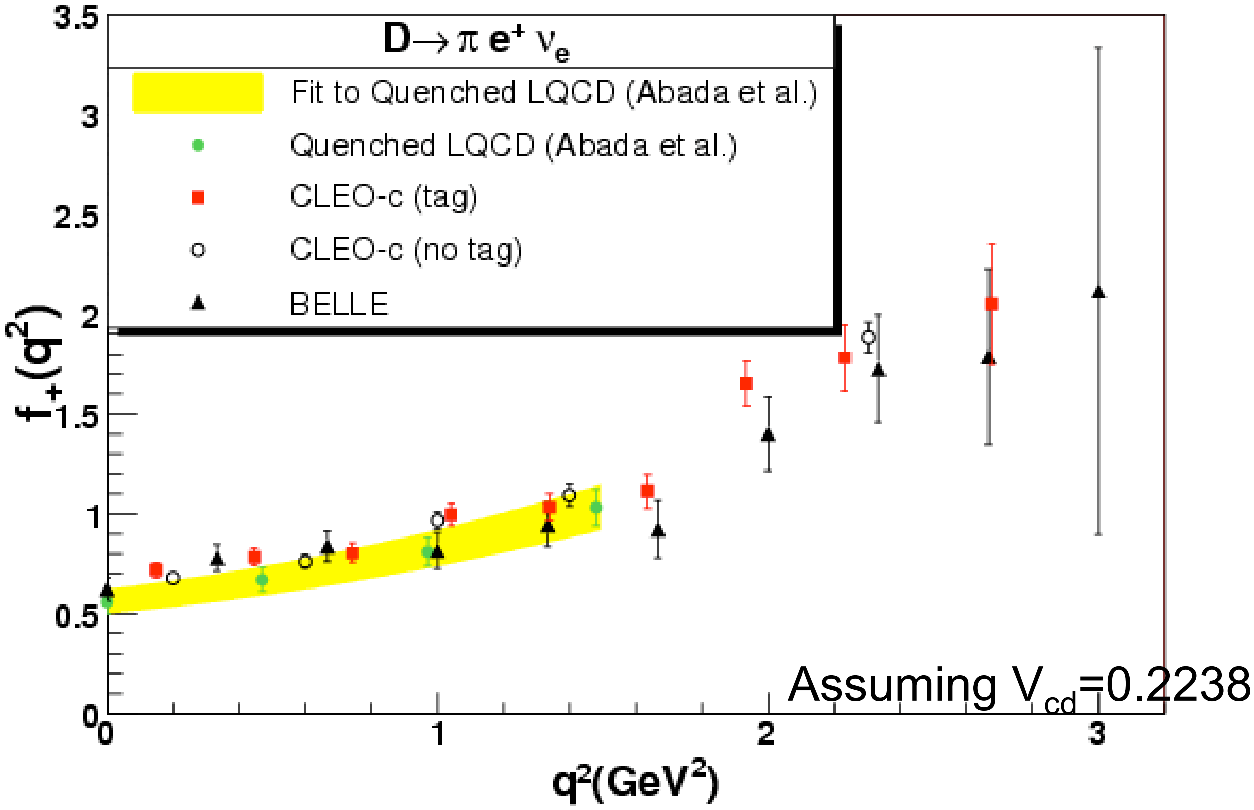


$$f_+(q^2) = \frac{f_+(0)}{1 - \frac{q^2}{M_{pole}^2}} \frac{1}{1 - \alpha \frac{q^2}{M_{pole}^2}}$$

FNAL-MILC-HPQCD Curve – courtesy of Andreas Kronfeld

Fit of Modified Pole Model to LQCD simulation points

$D \to \pi e \nu$ Form Factor vs. LQCD



Careful re: comparisons on next page:

If paremetrization wrong, comparisons can be misleading!

Much recent effort on systematic series expansions… but no time today

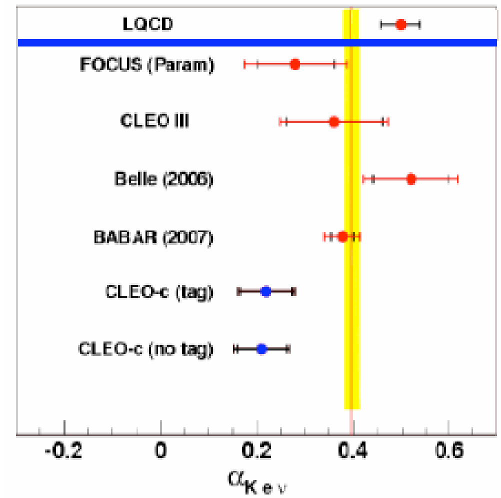
A recent paper: T. Becher & R. Hill PLB 633, 61 (2006)

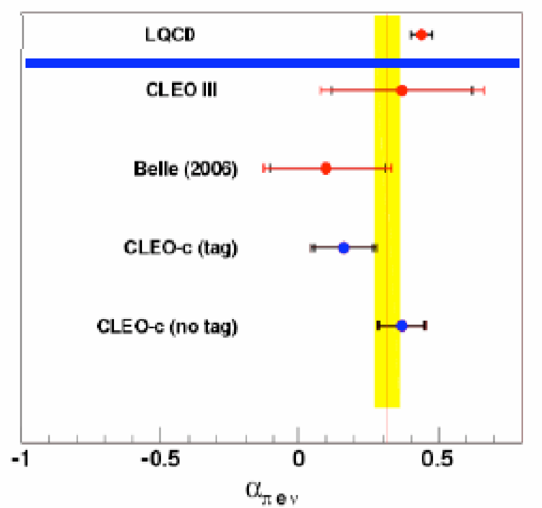
(previous work: Boyd, Grinstein, Lebed, Savage, Arnesen, Rothstein, Stewart…)

CLEO untaqgged paper uses these expansions along with older pole forms

More Tests of LQCD

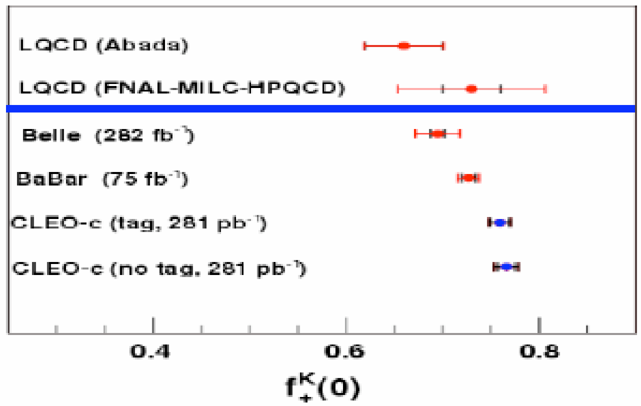
Slope

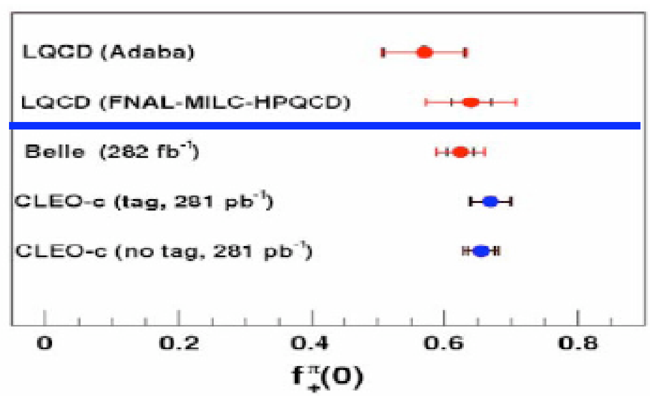




Normalization

(assuming $|V_{cs\ (cd)}| = |V_{ud\ (us)}|$)





$D \rightarrow K e \nu$

Normalization errors

Channel	Experi-ments	theory
$D \rightarrow K e \nu$	2%	10%
$D \rightarrow \pi e \nu$	4%	10%

$D \rightarrow \pi e \nu$

Theoretical errors larger than experimental

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

Preliminary
FPCP2008
214 fb^{-1}

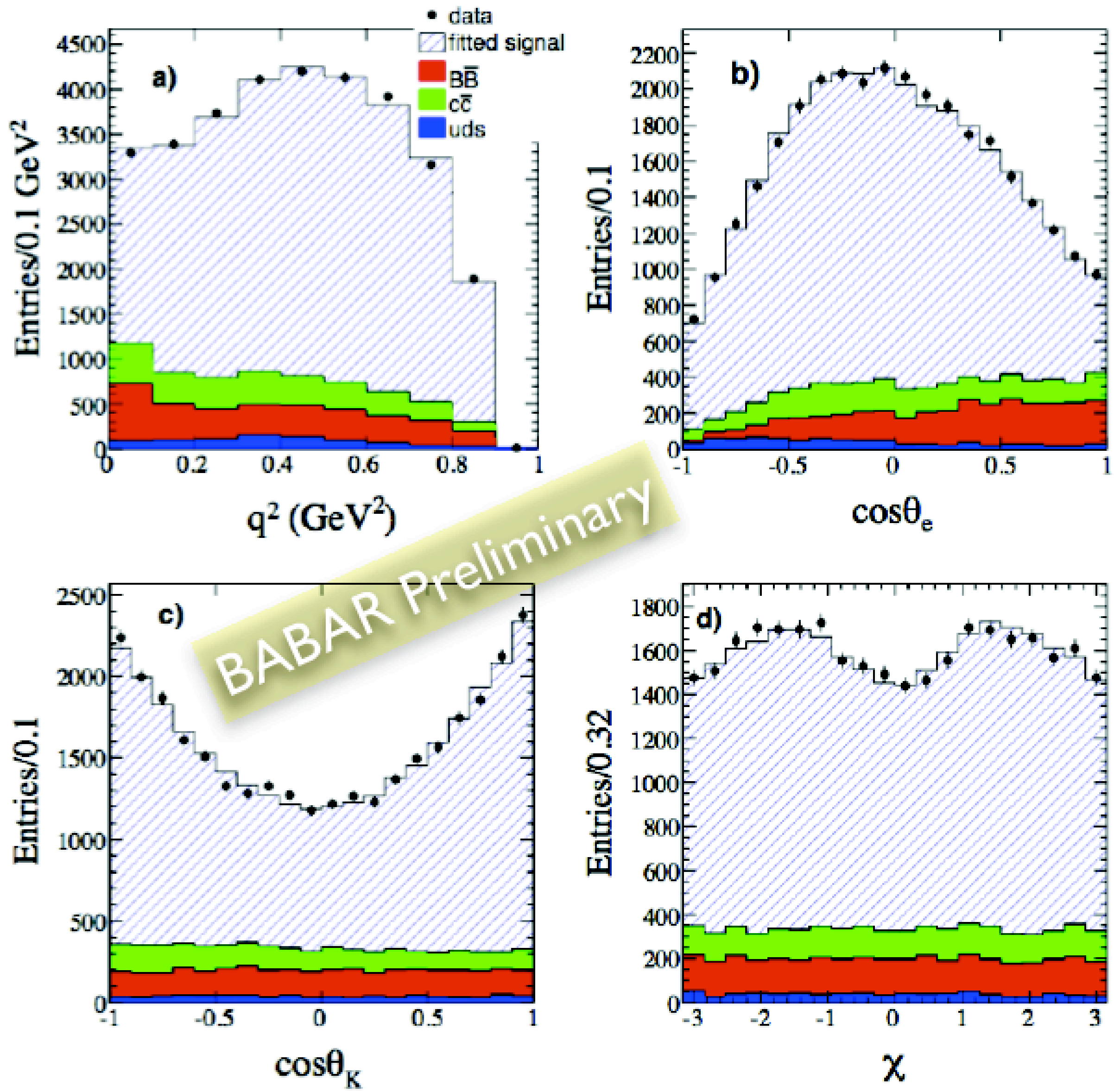
Untagged Analysis

Detailed form factor analysis 25K events
(more complicated w/ a vector meson)

$D_s \to \phi e\nu$

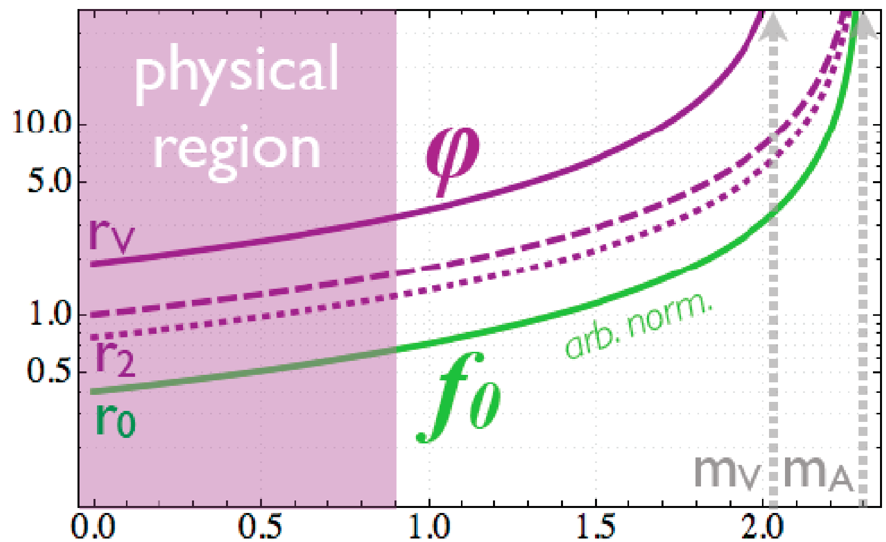
$D_s \to f_0 e\nu$
(first evidence)

Excellent angular fits:



Preliminary
FPCP2008
214 fb^{-1}

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



3 form-factors for ϕ

(fix r_1 = 1.0)

1 form-factor for f_0

FIT:

Float ratios to r_1 at q^2=0

M_V fixed; M_A floats

$N_{sig} = 25{,}152 \pm 177 \pm 367$

$r_V = 1.868 \pm 0.061 \pm 0.079$

$r_2 = 0.763 \pm 0.072 \pm 0.062$

$r_0 = 15.3 \pm 2.6 \pm 1.0$

$m_A = 2.30\,^{+0.24}_{-0.18} \pm 0.21$ GeV

Agreement with Lattice, except r_V

(need better model?)

$r_V = 1.35 \pm 0.08$

$r_2 = 0.98 \pm 0.09$

Lattice: UKQCD
Hep-lat/0109035

+ $BF(D_S \to KK\pi)$, $BF(\varphi \to KK)$, D_S lifetime, V_{cs}:

$A_1(q^2 = 0) = 0.605 \pm 0.012 \pm 0.018 \pm 0.018$

$A_1(q^2{=}0) = 0.63 \pm 0.02$

Precision Hadronic Branching Fractions

Systematics:

tracking, PID efficiency
always present
BUT… some nice techniques to measure w/ tagging

Background issues:
better with threshold tagging…

Similar considerations for semileptonic, leptonic
but statistics still dominate there
(interested in Cabibbo-suppressed semileptonic,
or rare fully leptonic modes…)

Topics:

Hadronic modes and Golden-Mode BFs: D^0, D^+ & D_s
Quantum correlations & $K\pi$ Phase

Omitted

- In Backup slides: Interference $D \to K_{L/S}\,\pi$
- MANY other decay modes (Cabibbo-suppressed, …)

BABAR

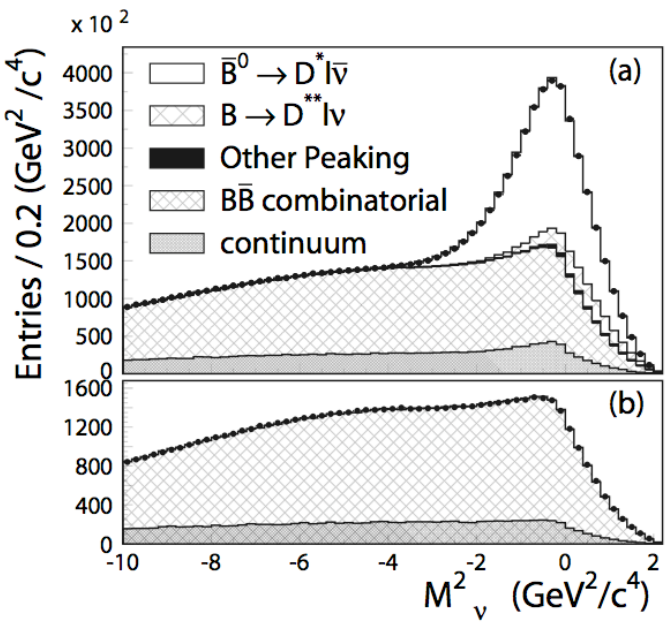
$D^0 \to K^- \pi^+$

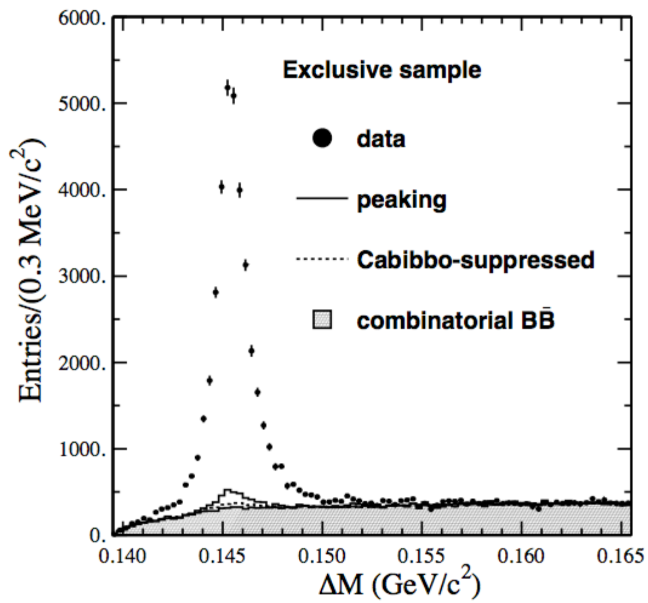
PRL 100, 051802 (2008) 232 fb^{-1}

Partial reconstruction of $B^0 \to D^{*+} (X)\, l^- \upsilon_l$

Slow pion used to estimate D* momentum

Full recon of $D^0 \Rightarrow K^- \pi^+$ within inclusive sample



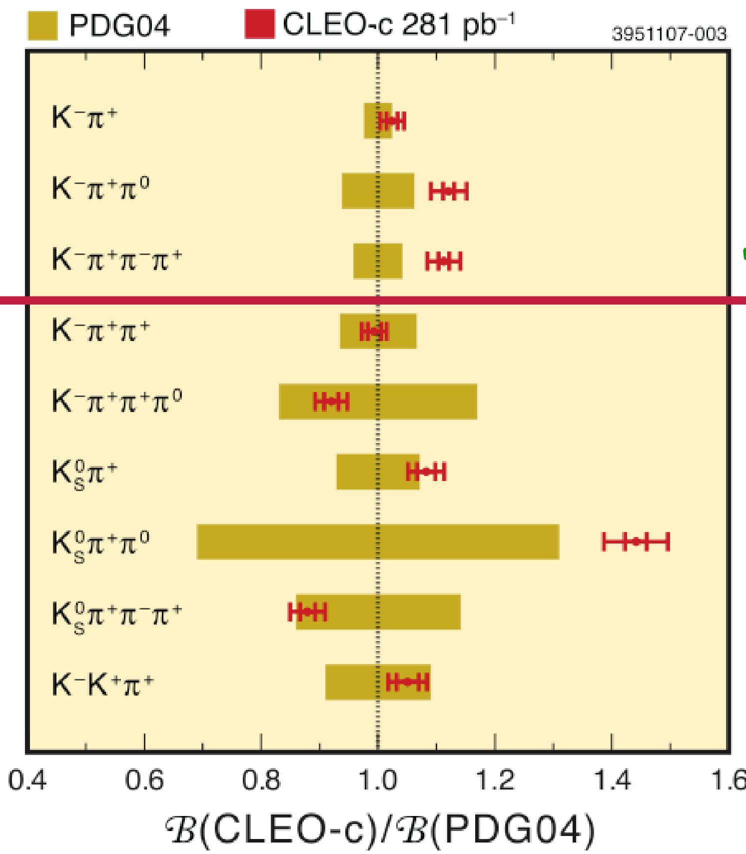


BF = (4.007 ± 0.037 ± 0.072)%

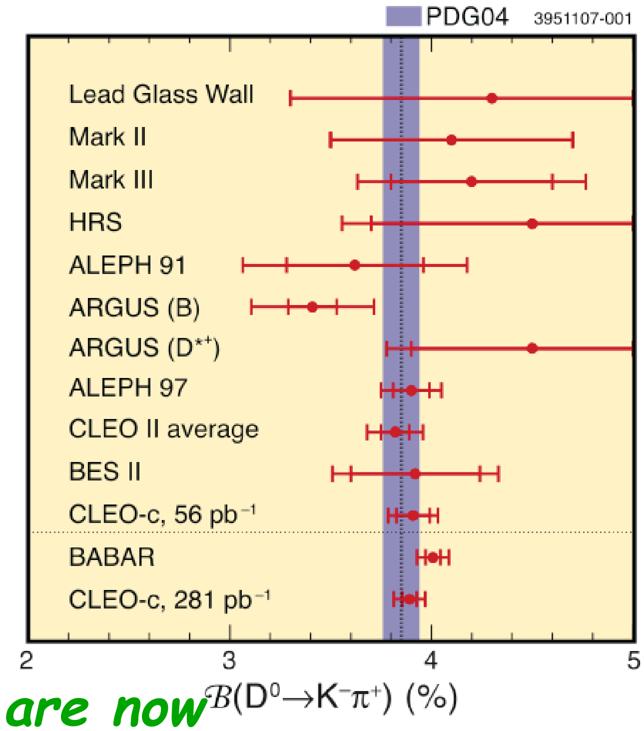
Systematics: 1.8% = 1.5% exlcusive effic. $\oplus$ 1.0% inclusive

D^0 & D^+ Comparisons

NOTE: method cancels
#DD pairs algebraically;
& tag eff. almost cancels

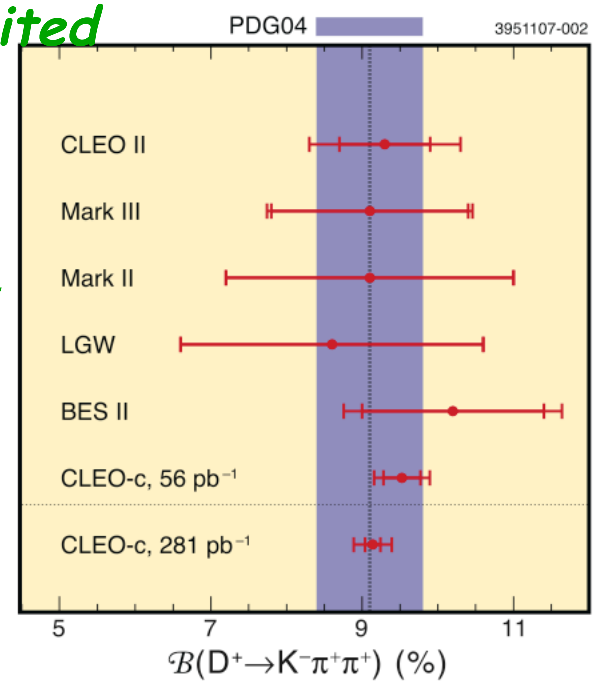


D^0 → $K^-\pi^+$



"Golden Modes" are now systematics limited

D^+ → $K^-\pi^+\pi^+$



Use PDG04 since PDG06 included 56 pb⁻¹ CLEO-c

PRD 76, 112001 (2007) 281 pb⁻¹

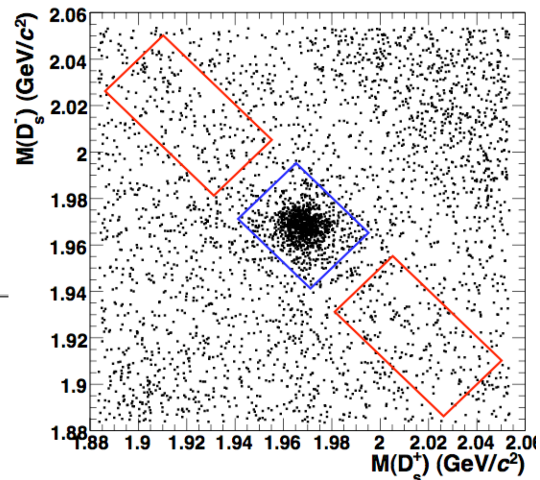
D_s Branching Ratios

PRL 100, 161804 (2008) 298 pb^{-1}

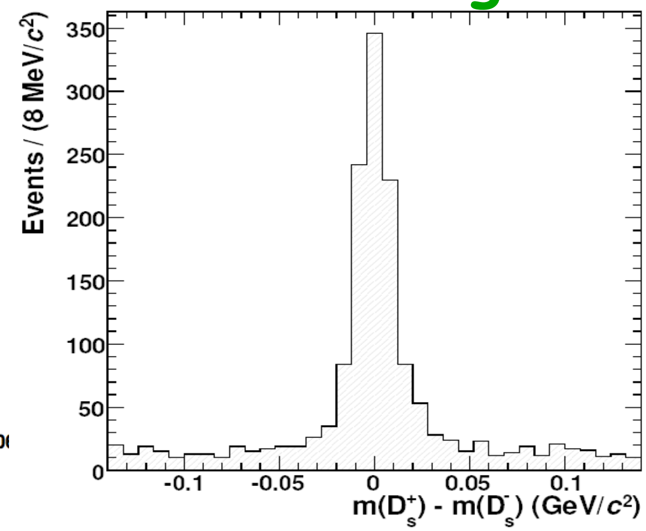
Data @ E_{cm} = 4170 MeV

~1 nb of $D_s^*D_s$

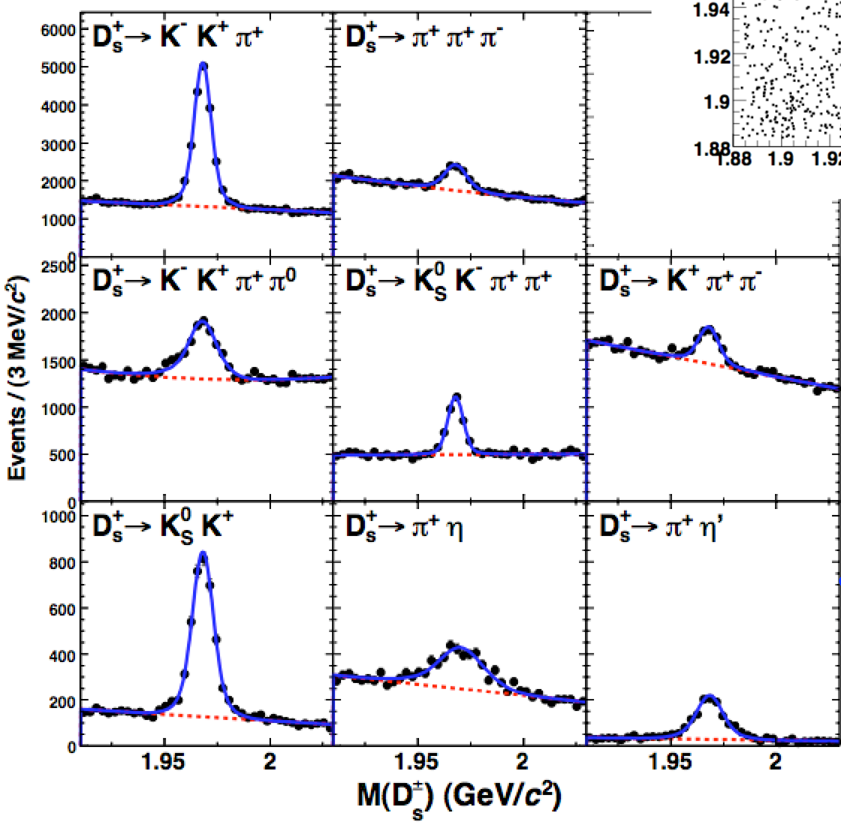
Double tags



Double tags



Projected $M(D_s^+) - M(D_s^-)$



Single tags

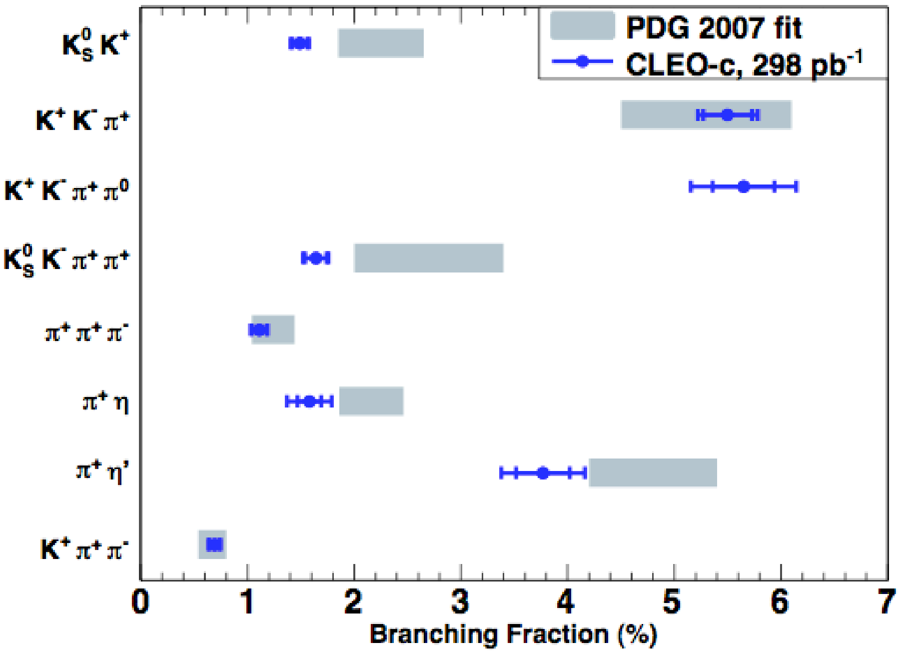
~1000 double tags

Sets scale of stat. error: ~3.5%

(~1/2 of total dataset)

D_s Branching Ratios

PRL 100, 161804 (2008) 298 pb^{-1}



NEW key normalizing mode:

$B (D_s \rightarrow K^+ K^- \pi^+)$

$= (5.50 \pm 0.23 \pm 0.16)$ %

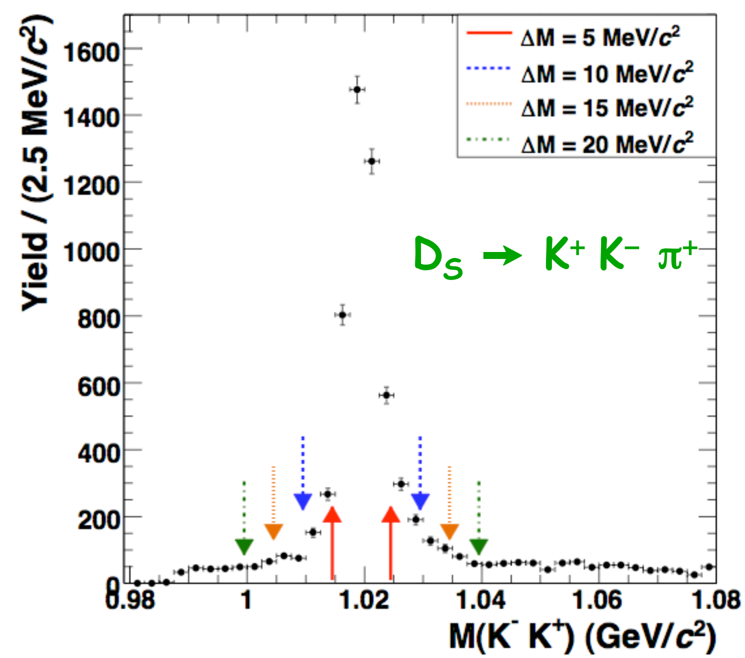
$\phi\ \pi^+$ "Branching fraction" ill-defined

Also quote B $\mathcal{B} (D_s \rightarrow K^+ K^- \pi^+)$

with various $M(K^+ K^-)$ windows:

$\mathcal{B}_{\Delta M}$ for mass within $\pm\ \Delta M$ of ϕ

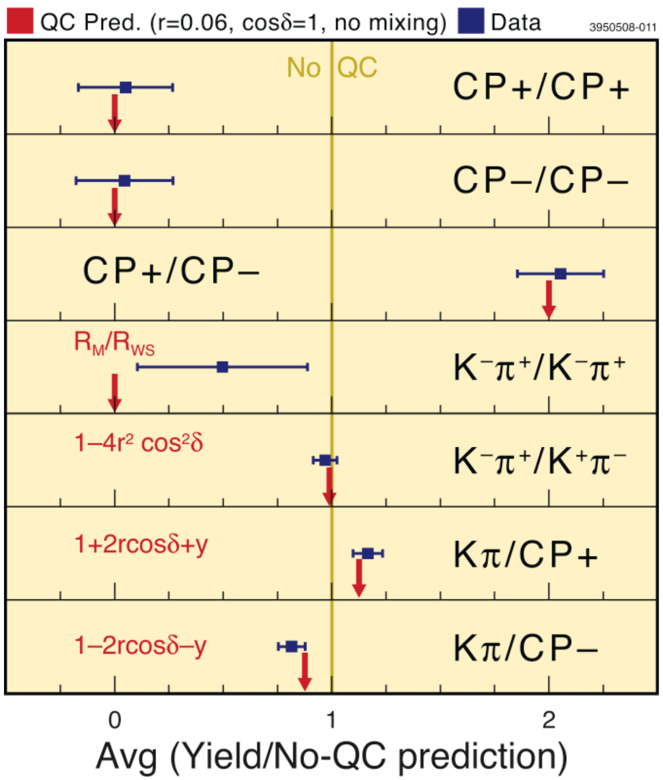
Value	This result $\mathcal{B}$ (%)
$\mathcal{B}_5$	$1.69 \pm 0.08 \pm 0.06$
$\mathcal{B}_{10}$	$1.99 \pm 0.10 \pm 0.05$
$\mathcal{B}_{15}$	$2.14 \pm 0.10 \pm 0.05$
$\mathcal{B}_{20}$	$2.24 \pm 0.11 \pm 0.06$



Quantum Coherence & Kπ phase

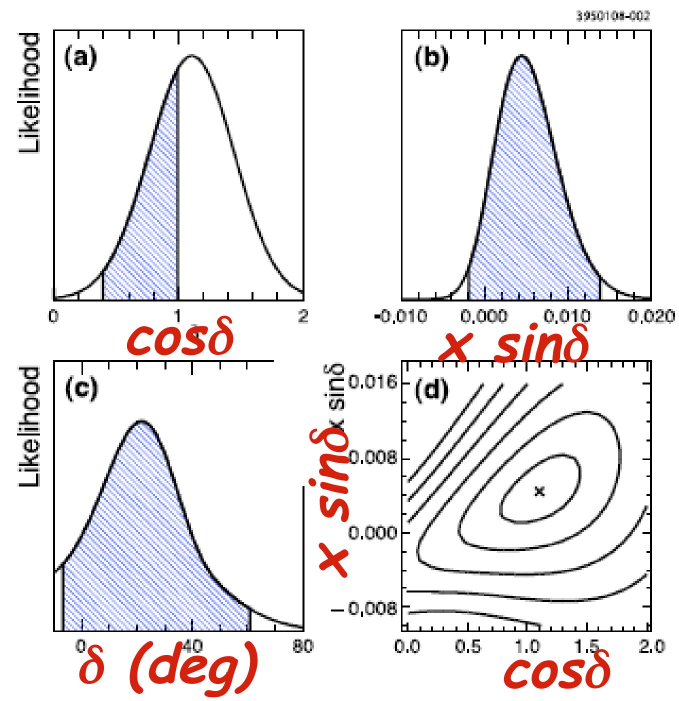
arXiv:0802.2264
arXiv:0802.2268
PRL/D to appear
281 pb^{-1}

Correlated D pairs are produced at the ψ(3770):



Allows a measurement of strong Kπ FSI phase, of great interest for D mixing results !

Simultaneous fit to:
hadronic & semilep modes
+ external mixing inputs:
(x, y, x'², y', r²)



$\cos\delta = 1.10 \pm 0.35 \pm 0.07$

$\delta = (22\,^{+11}_{-12}\;\;^{+9}_{-11})^{\circ}$

Not Covered…

Mixing, Dalitz, Spectroscopy:
well-covered in other talks

Much other work:

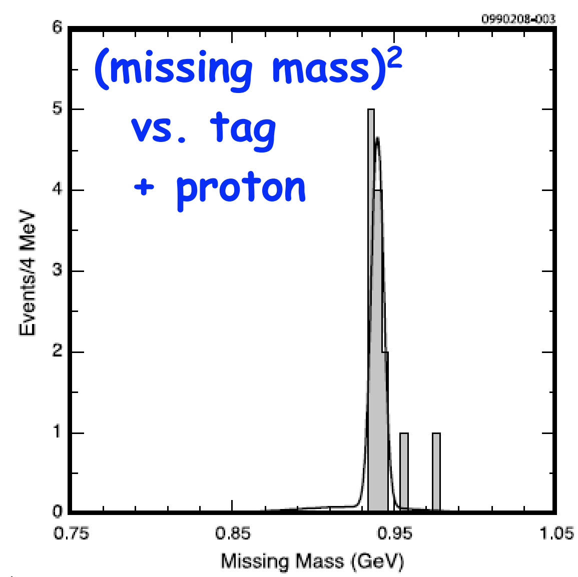
- o CLEO: other hadronic & semileptonic modes
  (Cabibbo-suppressed, etc.)
- o BaBar: $D \to Kl\upsilon$ (2007, untagged)
- o Various: CPV searches, Rare decays
- o etc.

One "fun" new result:

$B(\, D_s \to p\,\bar{n}\,) =$

$(1.30 \pm 0.36 + 0.12 - 0.16) \times 10^{-3}$

CLEO PRL 100, 181802 (2008)



Conclusions

Tests of Lattice QCD becoming precise

Intriguing disagreement for f_{Ds} ?

Charm threshold best for experimental precision

Outlook

Lattice QCD marches onwards with CPU, techniques, …
Much existing data left to mine at BaBar, Belle, CLEO
Very soon we will have data at BESIII & LHC-b, …
Super-B, … ???

Charm is alive & well

Acknowledgments

Thanks to CLEO collaborators I've borrowed from:
P. Onyisi, M. Shepherd, T. Skwarnicki, S. Stone, W. Sun, …

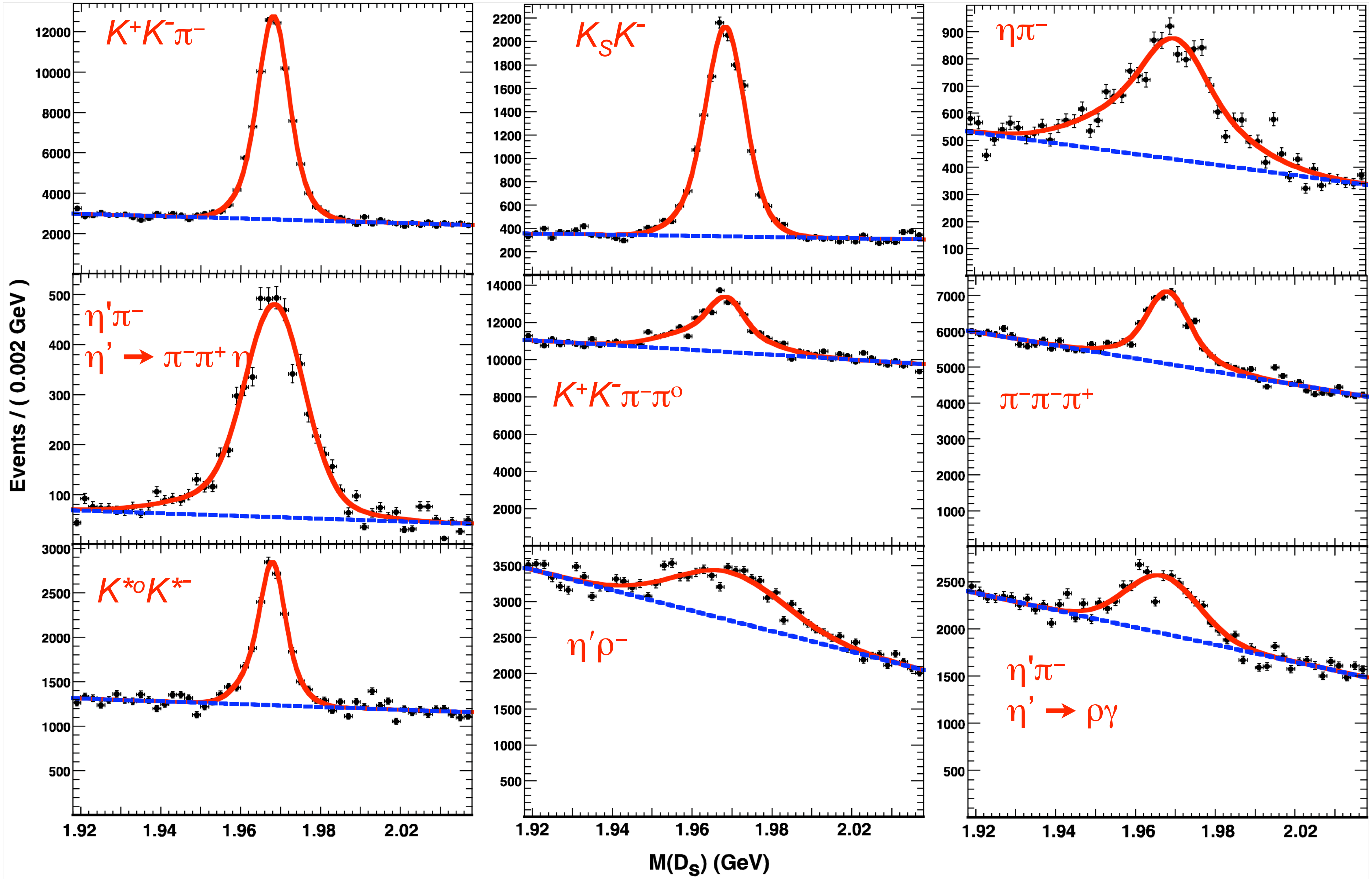
& to my Charming BaBar & Belle colleagues:
(S. Prell, Y. Sakai, P. Chang)
Thanks for convenient web pages with results!

& to my new BESIII collaborators:
Thanks for providing me a future of continuing charm physics…

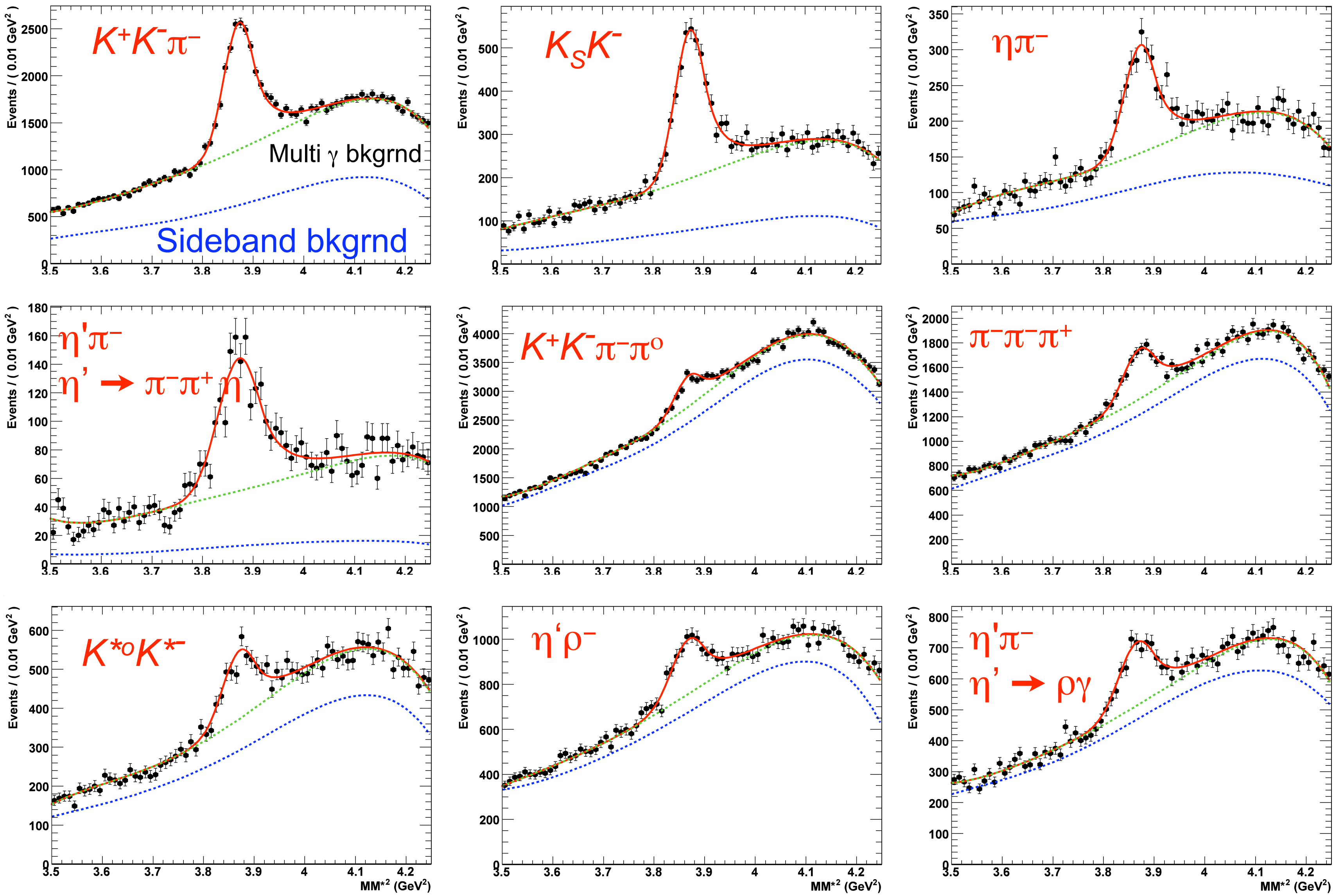
& finally to the HQL08 organizers:
Thanks for the opportunity to speak, and the great conference

BACKUP SLIDES

f_{D_s}: D_s Mass Peaks



f_{D_s}: D_s γ (Missing Mass) ^{2}



Systematics on BF

$D^+ \to \mu^+\nu$

Source of Error	%
Finding the μ^+ track	0.7
Min. ionization of μ^+ in EM cal	1.0
Particle identification of μ^+	1.0
MM^2 width	0.2
Extra showers in event > 250 MeV	0.4
Background	0.7
Number of single tag D^+	0.6
Total	**2.2**

$D_s \to \mu^+\nu$ & $\tau^+\nu$ (w/ $\tau^+ \to \pi\,\nu$)

Source of Error	%
Finding the μ^+ track	0.7
Particle identification of μ^+	1.0
MM^2 width	0.2
Extra showers with > 300 MeV	0.4
Background	0.5
Number of single tag D_S^-	3.0
Total	**3.3**

D^0, D^+ Branching Fractions

Single Tags: $N_j = N_{DD} \mathcal{B}_j \varepsilon_j$

Double Tags: $N_{ij} = N_{DD} \mathcal{B}_i \mathcal{B}_j \varepsilon_{ij}$

$$\mathcal{B}_i = N_{ij} \varepsilon_j / N_j \varepsilon_{ij}$$

$$N_{DD} = N_i N_j \varepsilon_{ij} / N_{ij} \varepsilon_i \varepsilon_j$$

Key points:

$\mathcal{B}$ independent of N_{DD} (usual Achilles' heel)

$\varepsilon_j / \varepsilon_{ij} \sim \varepsilon_i$: ~ independent of tag j

Systematics:

-- *Study efficiencies with tag data*

CLEO-c semileptonic tagging analysis technique: big impact

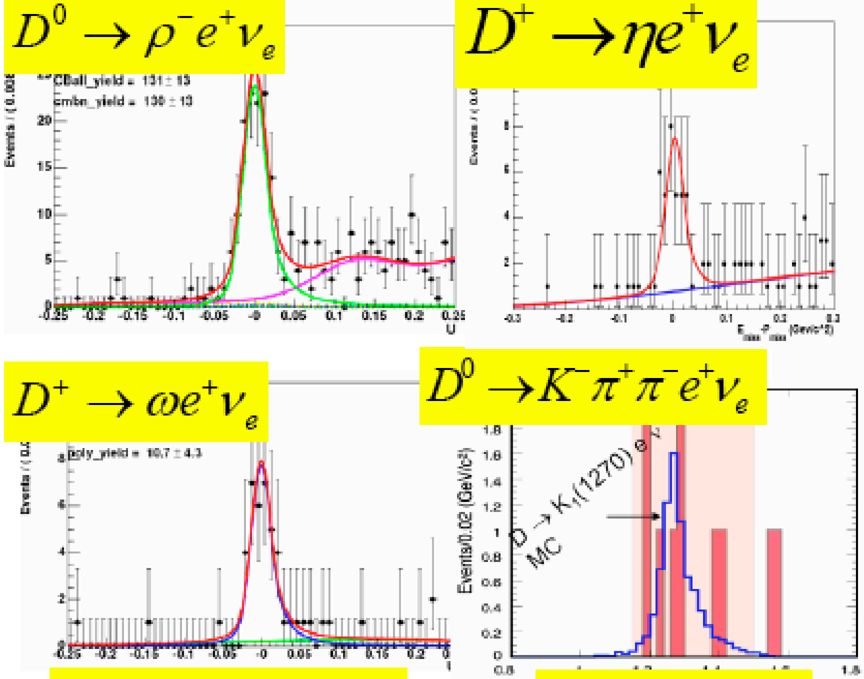
1st Observations:

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

$D^+ \to \eta e^+ \nu_e$

$D^+ \to \omega e^+ \nu_e$

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



$D^+ / D^0 \to X e^+ \nu_e$

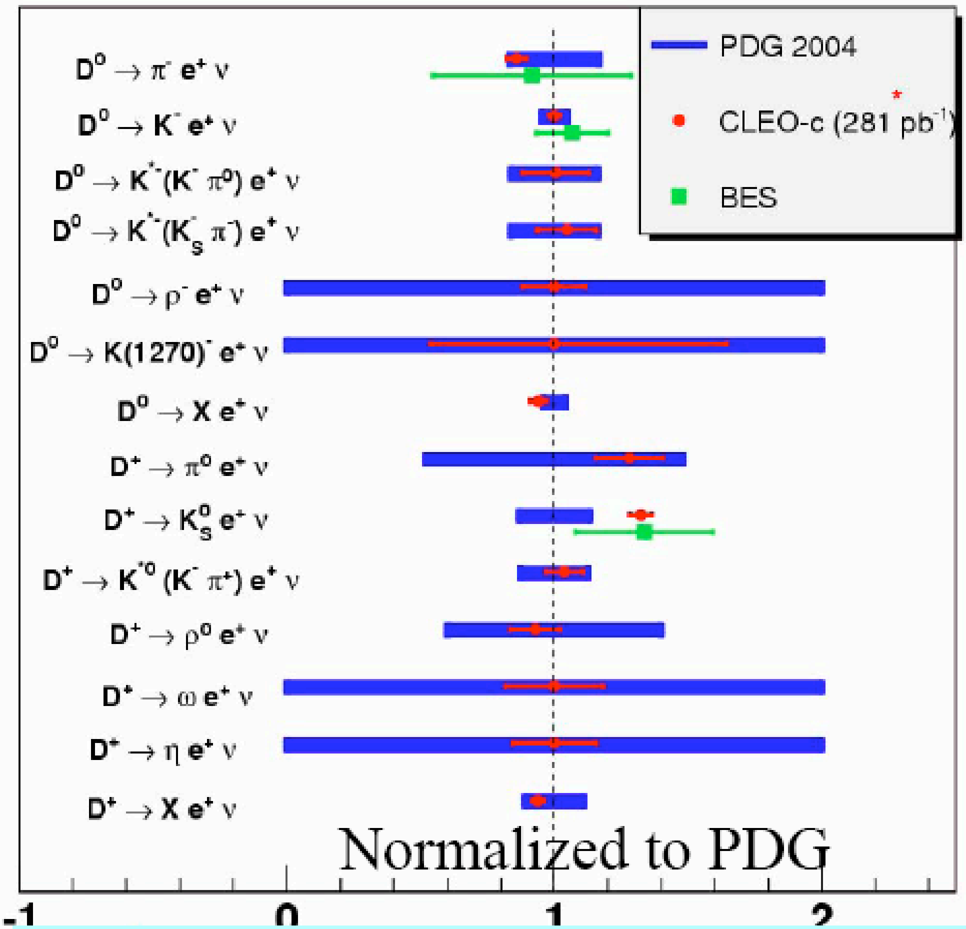
$D \to K^* e^+ \nu_e$ form factors

$D \to K / \pi e^+ \nu_e$

BFs 56/pb

References:
PRL 95, 181801 (2005);
PRL 95, 181802 (2005)
PRL. 99, 191801 (2007)

Precision Measurements:



$D \to K / \pi e^+ \nu$ branching fractions are for 56/pb

CLEO's measurements most precise for ALL modes; *4 modes* observed for the first time

$D \rightarrow Kl\nu$

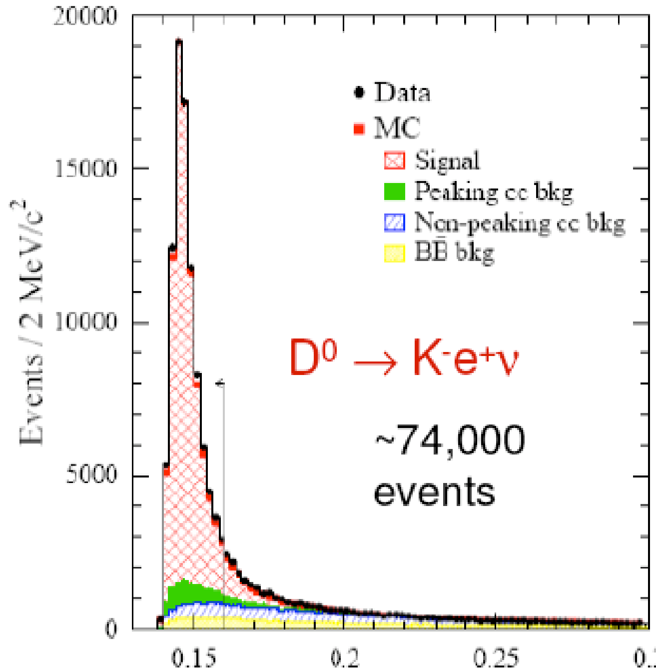
PRD 76, 052005 (2007) 75 fb^{-1}

Neutrino "reconstruction" technique

Tagged with $D^{*-} \rightarrow D^0 p\pi^-$

Very large signal statistics.

Cabibbo favored



M(D^{*-}) - M(D^0) (GeV)

Compared to CLEO-c results:

- Factor ~300 more luminosity
- Factor ~5 more signal events
- Normalization to BR($D^0 \rightarrow K^-\pi^+$) [determined by CLEO-c]
- Poor q^2 resolution (unfolding needed for form factor measurements)
- Much worse signal/noise (method not suitable for Cabibbo suppressed decays)

Interference in $K_L\,\pi$, $K_S\,\pi$

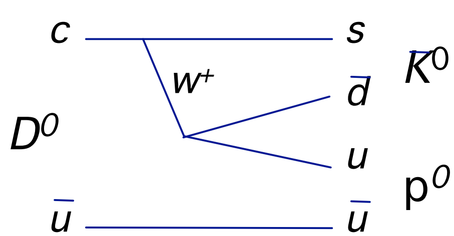
D Decay diagrams source both K^0 and K^0bar
$\Rightarrow$ These interfere in physical K_L, K_S final states: K_S, K_L asymmetry

$R(D) = [\, B(D \Rightarrow K_S\pi) - B(D \Rightarrow K_L\pi) \,] \,/\, [\, B(D \Rightarrow K_S\pi) + B(D \Rightarrow K_L\pi) \,]$

Bigi & Yamamoto   [PLB 349, 363 (1995)]

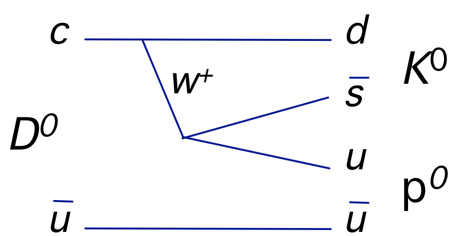
D^0 : expect BF asymmetry of: $R(D^0) = 2\tan^2\theta_C \sim 10\%$

D^+ : more diagrams to consider... $R(D+)$ see next page...



Cabibbo-favored

$$\bar{K}^0 = \frac{1}{\sqrt{2}}\left(K_S^0 - K_L^0\right)$$

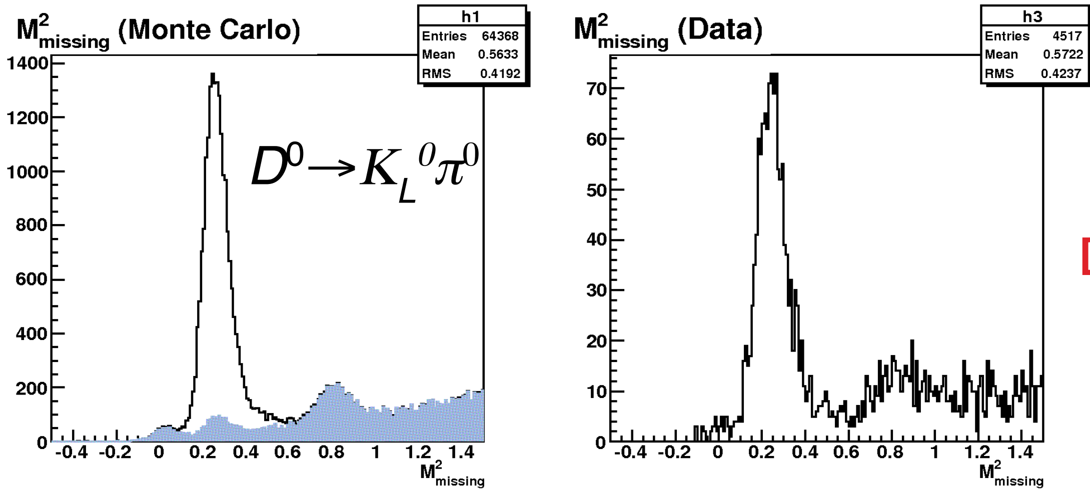


Cabibbo-suppressed

$$K^0 = \frac{1}{\sqrt{2}}\left(K_S^0 + K_L^0\right)$$

Interference in $K_L\,\pi$, $K_S\,\pi$

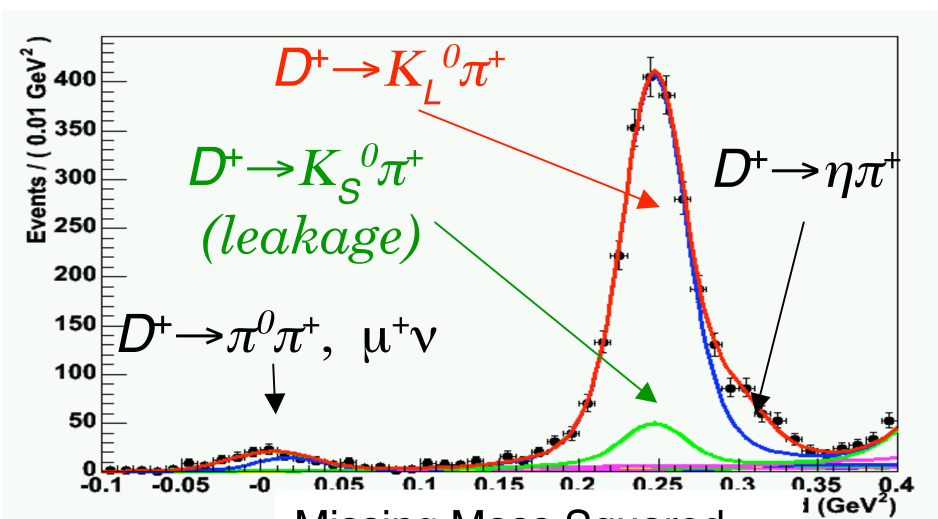
PRL 100, 091801 (2008) 281 pb^{-1}



Missing Mass Squared

D^0: $R_D = 0.108 \pm 0.025 \pm 0.024$

(consistent with 2 $\tan^2\theta_C$)



Missing Mass Squared

D^+: $R_D = 0.022 \pm 0.016 \pm 0.018$

Dao-Neng Gao predicts:
$R(D^+) = 0.035$ to 0.044
(arXiv:hep-ph/0610389v2)

J. Rosner, CHARM2007:
$R(D^+) = 0.067 \pm 0.007$