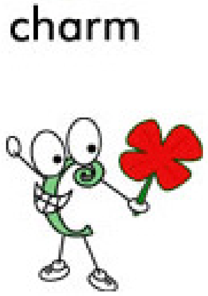
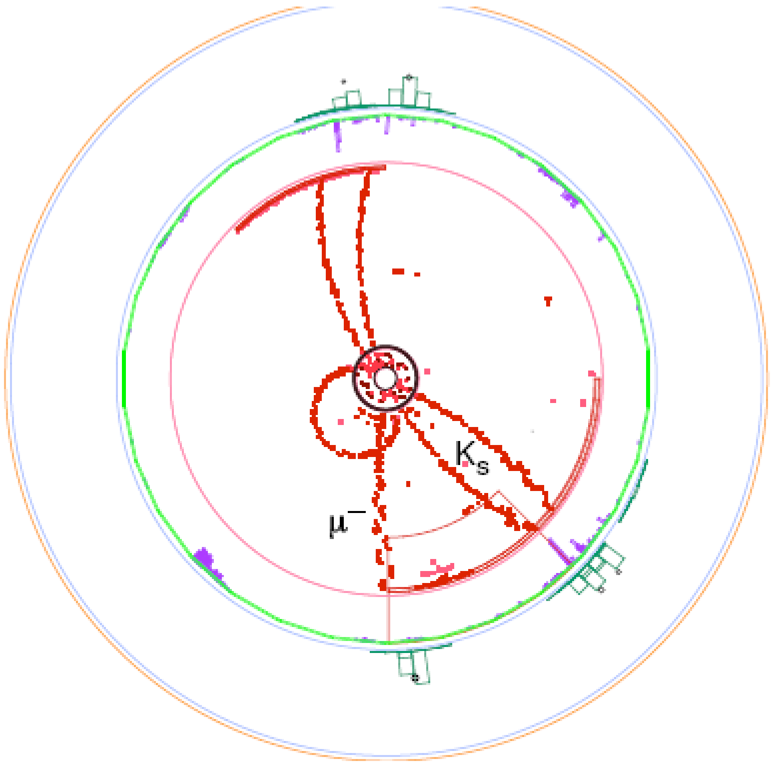
Leptonic Charm Decays

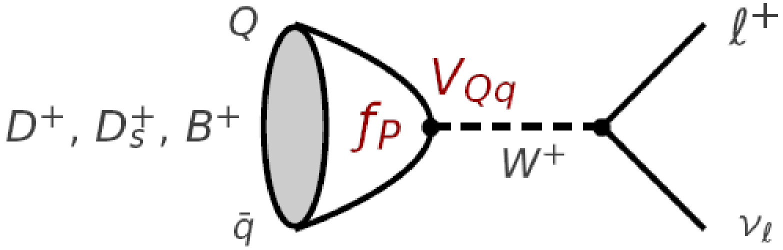




Bo Xin
Purdue University

CKM 2010 @ WARWICK
Sep 06 - 10, 2010

Leptonic Decays: A Clean Way to Access QCD



In the standard model:

$$\Gamma(P_{Q\bar{q}} \to \ell^+\nu_\ell) = \frac{G_F^2|V_{Qq}|^2 f_P{}^2}{8\pi} m_{Q\bar{q}} m_\ell^2 \left(1 - \frac{m_\ell^2}{m_{Q\bar{q}}^2}\right)^2$$

CKM matrix element

(well known from unitarity)

f_P is the decay constant, a measure of the overlap of the heavy and light quark wave functions.

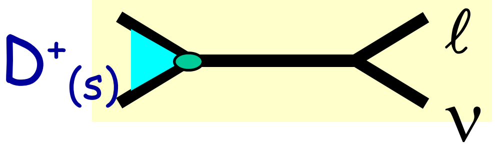
The rest:

Phase space factors

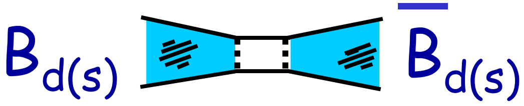
A single number contains all QCD effects

Leptonic Decays & B Mixing & New Physics

- B mixing proceeds through box diagrams
- QCD calculations enter the formulism in a similar way to leptonic decays.



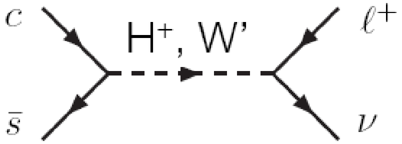
$$rate \propto f_{D_{(s)}}^{2} \; |V_{cd(s)}|^2$$



$$rate \propto f_{B_{(s)}}^{2} \; |V_{td(s)}|^2$$

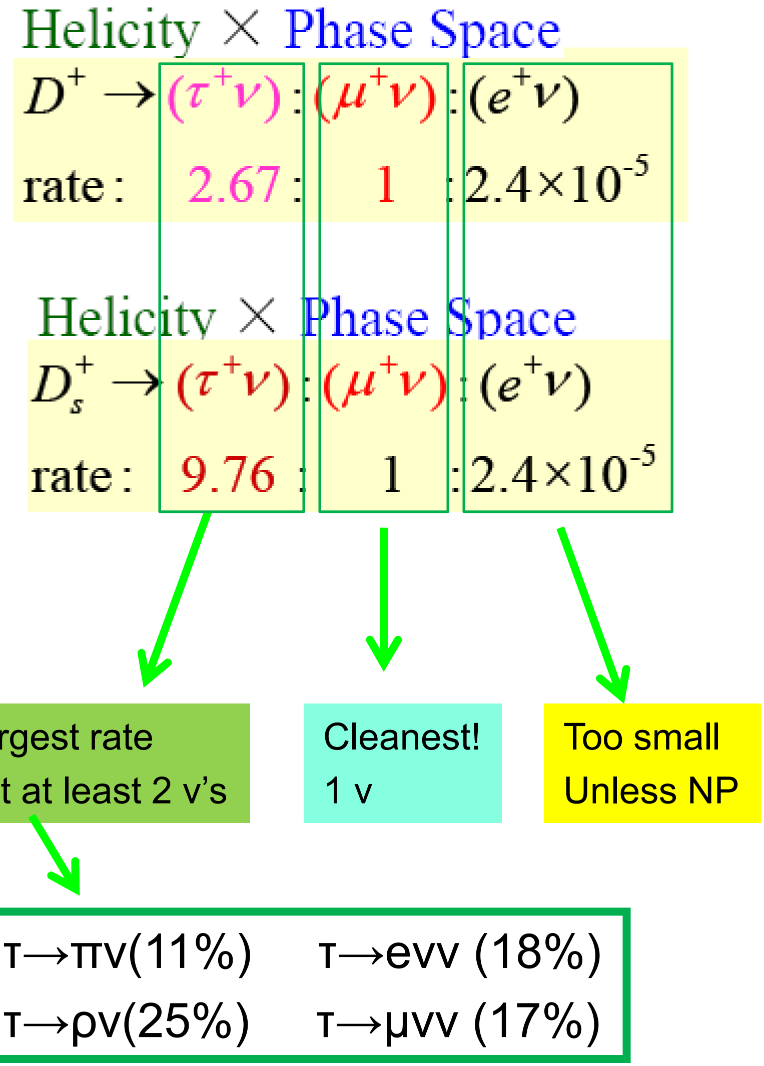
Reasons to study D and D_s leptonic decays:

- Check QCD calculations of decay constants (f_D and f_{D_s})
- More confidence in the calculations of f_B, which is crucial to test SM in B mixing
- Sensitive to new physics – various NP scenarios can affect the leptonic D branching ratios. e.g. charged Higgs can mediate.



The Experimental Measurements

The rates of the leptonic channels



Cabibbo suppressed

Helicity × Phase Space

$$D^+ \to (\tau^+\nu) : (\mu^+\nu) : (e^+\nu)$$

$$\text{rate} : 2.67 : 1 : 2.4\times10^{-5}$$

Cabibbo favored

Helicity × Phase Space

$$D_s^+ \to (\tau^+\nu) : (\mu^+\nu) : (e^+\nu)$$

$$\text{rate} : 9.76 : 1 : 2.4\times10^{-5}$$

Largest rate
But at least 2 ν's

Cleanest!
1 ν

Too small
Unless NP

τ→πν(11%) τ→eνν (18%)
τ→ρν(25%) τ→μνν (17%)

What have been measured:

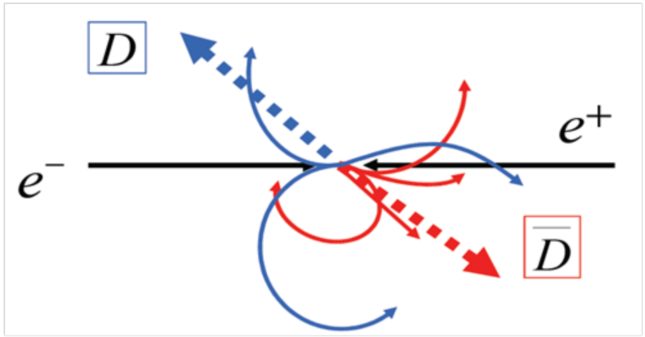
- ☐ $D^+ \to \mu^+ \nu$ CLEO
- ☐ $D_s^+ \to \mu^+ \nu$ CLEO BELLE 
- ☐ $D_s^+ \to \tau^+ \nu$, $\tau^+ \to \pi^+\nu$ CLEO
- ☐ $D_s^+ \to \tau^+ \nu$, $\tau^+ \to e^+\nu\nu$ CLEO 
- ☐ $D_s^+ \to \tau^+ \nu$, $\tau^+ \to \rho^+\nu$ CLEO
- ☐ $D_s^+ \to \tau^+ \nu$, ,$\tau^+ \to \mu^+\nu\nu$ 

CLEO-c and BABAR results are updated to full datasets.

Analysis Technique to Measure f_D at 3770 MeV

818 pb^{-1} @3770

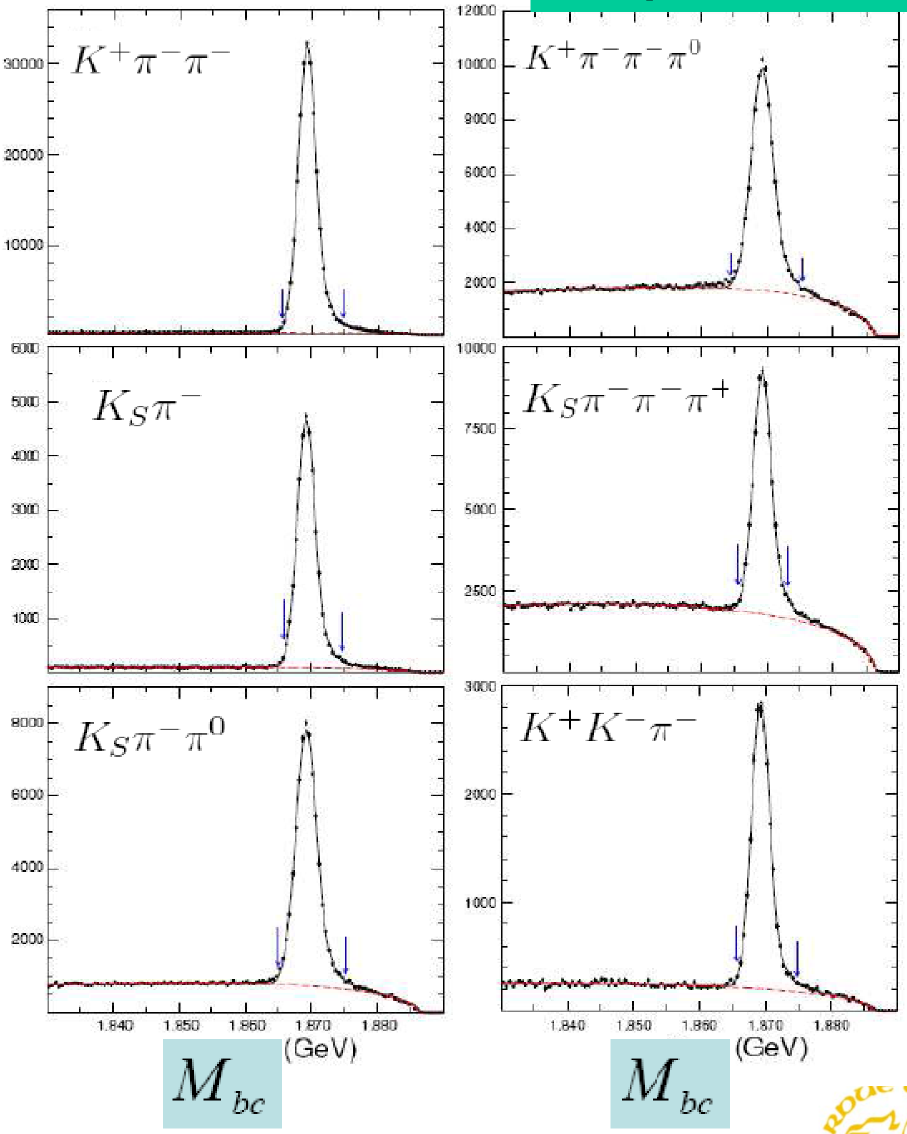
- Candidate events are selected by reconstructing a D, called a tag, in several hadronic modes
- Then we reconstruct the leptonic decay in the system recoiling from the tag



$$M_{bc} = \sqrt{E_{beam}^2/c^4 - \left|\vec{p}_D\right|^2/c^2}$$

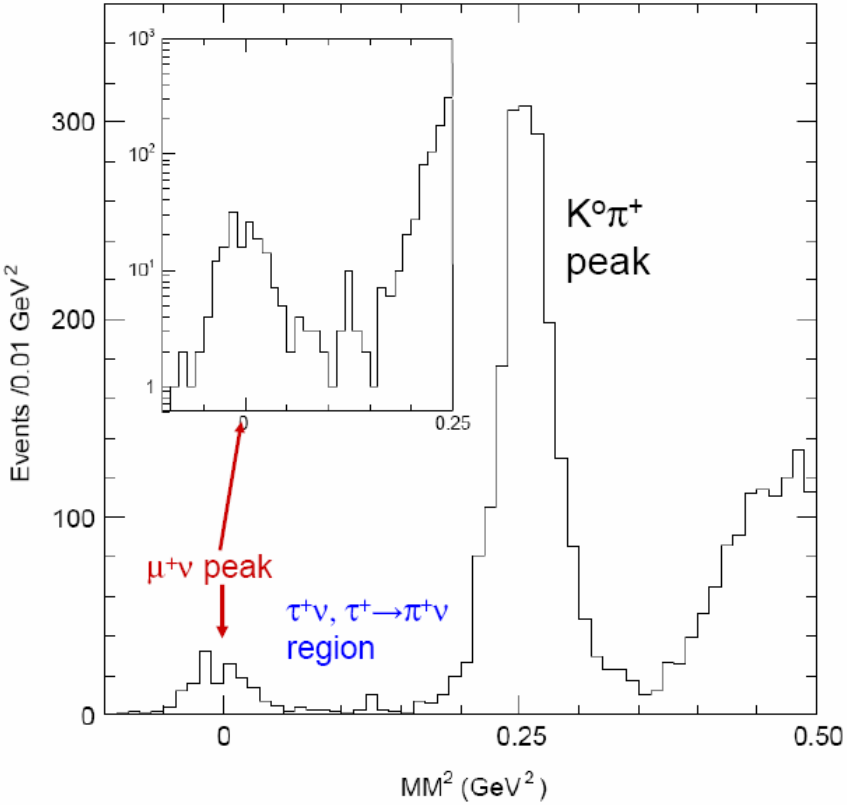
Total of 460,000 tags

Background 89,400



The MM^2 Distribution for $D^+ \to \mu^+ \nu$

- After finding a D tag, seek events with
  - only one additional oppositely charged track within $|\cos\theta| < 0.9$ and
  - no additional photons > 250 MeV (to veto $D^+ \to \pi^+\pi^0$)
- Charged track must deposit only minimum energy in calorimeter < 300 MeV
  - True for 98.8% of muons
  - Rejects 45% of π's
- Compute missing mass squared (MM^2). If close to zero then almost certainly we have a $\mu^+\nu$ decay.



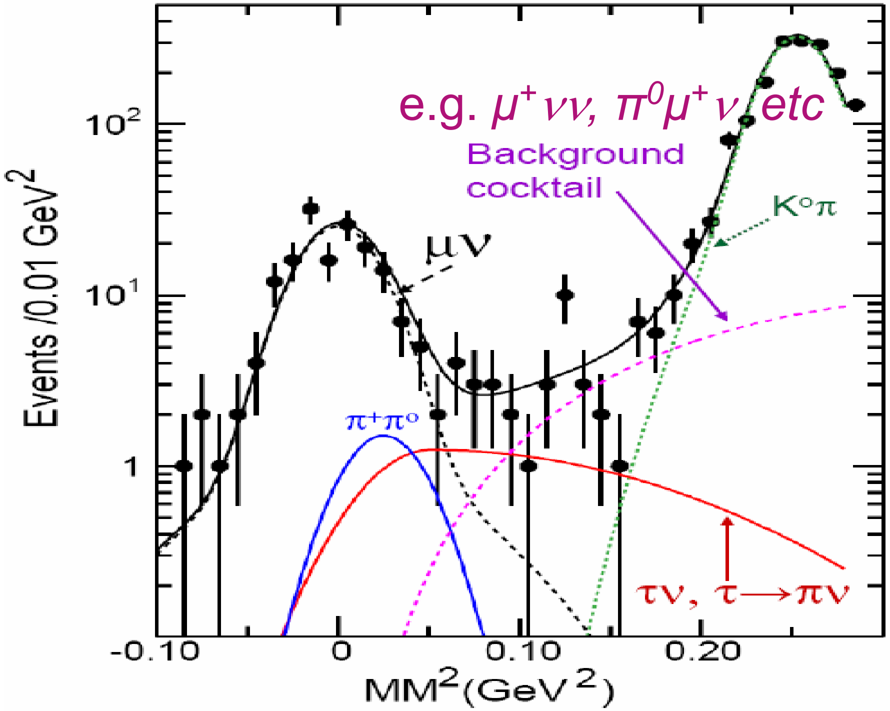
PRD 78, 052003 (2008)

$$MM^2 = (E_{beam} - E_\mu)^2 - (-\overrightarrow{P}_{D\,tag} - \overrightarrow{P}_\mu)^2$$

Fit MM^2 to sum of signal & background

Fitting shapes:

- $\mu^+ \nu$, $\tau^+ \nu$ (signal) : from MC
  - Checked using $D^+ \to K_S{}^0 \pi^+$ (ignoring the $K_S{}^0$ and look at MM^2)
- $\overline{K^0} \pi^+$: from data
  - Using double tag $D\overline{D}$ events where both D decays to charged $K\pi$ (ignore a Kaon and look at MM^2)


e.g. $\mu^+ \nu\nu$, $\pi^0 \mu^+ \nu$, etc

- When $\tau^+ \nu / \mu^+ \nu$ is fixed to SM ratio
  - $(149.7 \pm 12.0\ \mu^+ \nu) + (25.8)\ \tau^+ \nu$
  - $\mathcal{B}(D^+ \to \mu^+ \nu) = (3.82 \pm 0.32 \pm 0.09) \times 10^{-4}$
  - $f_{D^+} = (205.8 \pm 8.5 \pm 2.5)$ MeV ►best number in context of SM
- When $\tau^+ \nu / \mu^+ \nu$ is allowed to float
  - $(153.9 \pm 13.5\ \mu^+ \nu) + (13.5 \pm 15.3)\ \tau^+ \nu$
  - $\mathcal{B}(D^+ \to \mu^+ \nu) = (3.93 \pm 0.35 \pm 0.10) \times 10^{-4}$
  - $f_{D^+} = (207.6 \pm 9.3 \pm 2.5)$ MeV ►Best number for use with Non-SM models
- Upper limits: $B(D^+ \to e^+ \nu) < 8.8 \times 10^{-6}$ (90% C.L.)
  $B(D^+ \to \tau^+ \nu) < 8.8 \times 10^{-6}$ (90% C.L.)

PRD 78, 052003 (2008)

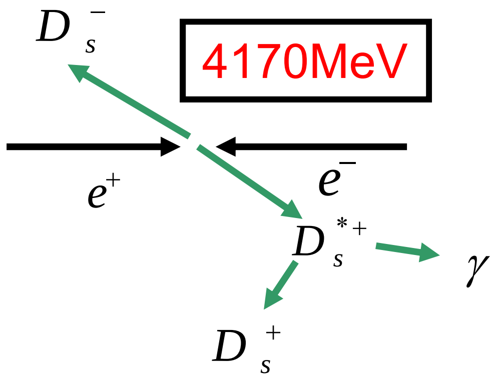
Analysis Technique to Measure f_{D_s} at 4170 MeV

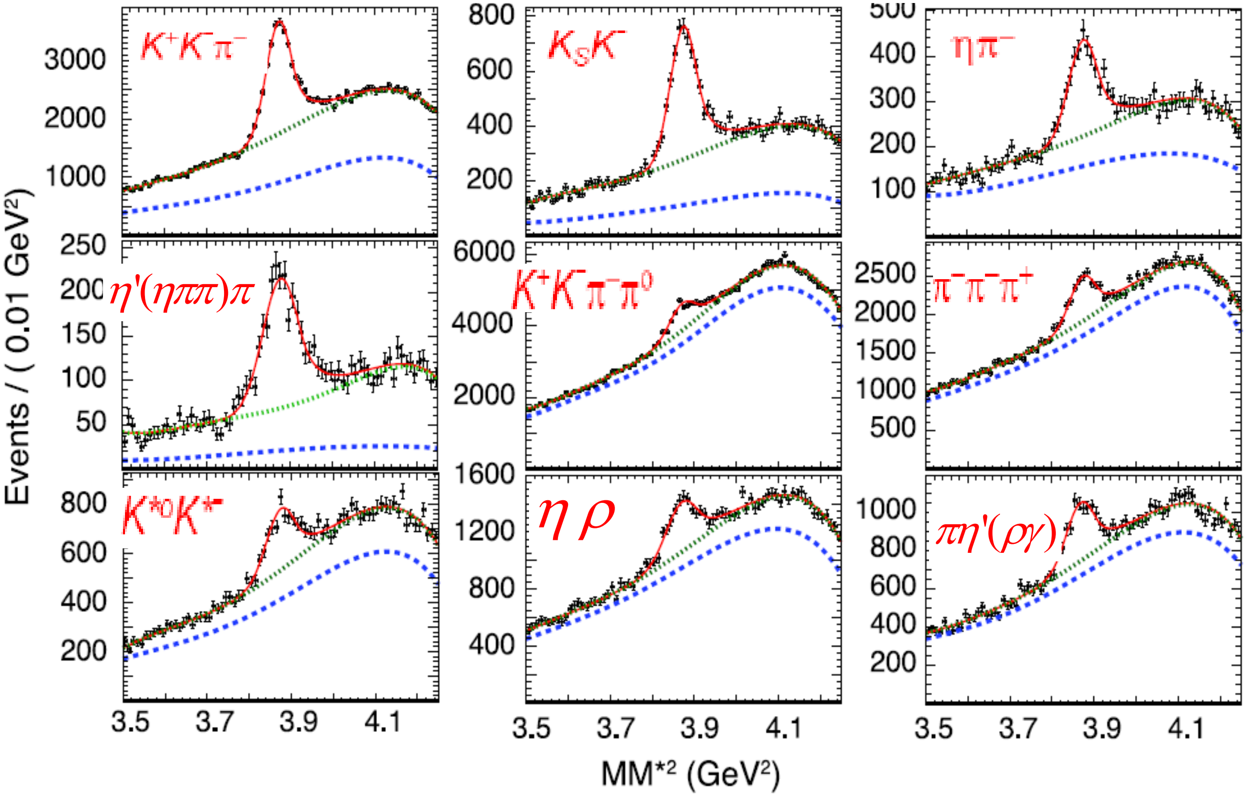
- ❑ Candidate events are selected by reconstructing a D_s in several hadronic modes

- ❑ The tag is then combined with a well reconstructed γ, The missing mass squared against the γ-tag pair

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

$e^+e^- \to D^*_s D_s$





9 D_s tag modes:
N(tag)=70514±963
N(tag+γ)=43859±936
reconstructed from
~5.5 x 10^5 D_s^* D_s events

600 pb^{-1} @4170
(CLEO-c full dataset)

MM² Distributions for $D_s^+ \to \mu^+ \nu$ and $\tau^+\nu$

- ❑Find MM²

$$MM^2 \equiv (\mathbf{p}_{\text{beam}} - \mathbf{p}_{D_s^-} - \mathbf{p}_\gamma - \mathbf{p}_\mu)^2$$

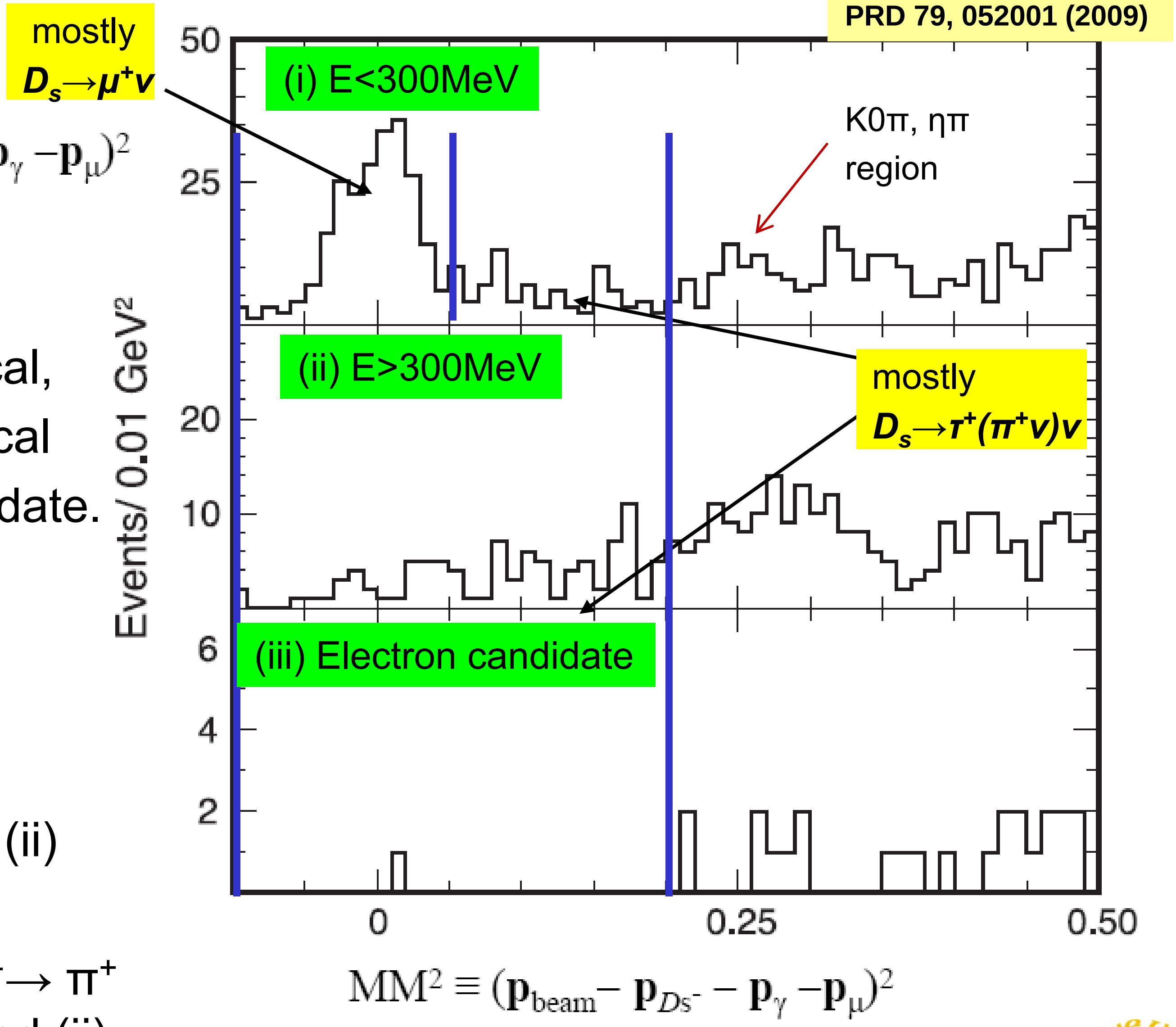
from

candidate muon for

(i) E<300MeV in Ecal,

(ii) E>300MeV in Ecal

or from (iii) e^- candidate.


mostly $D_s \to \mu^+ \nu$

PRD 79, 052001 (2009)

(i) E<300MeV

K0π, ηπ region

(ii) E>300MeV

mostly $D_s \to \tau^+(\pi^+ \nu)\nu$

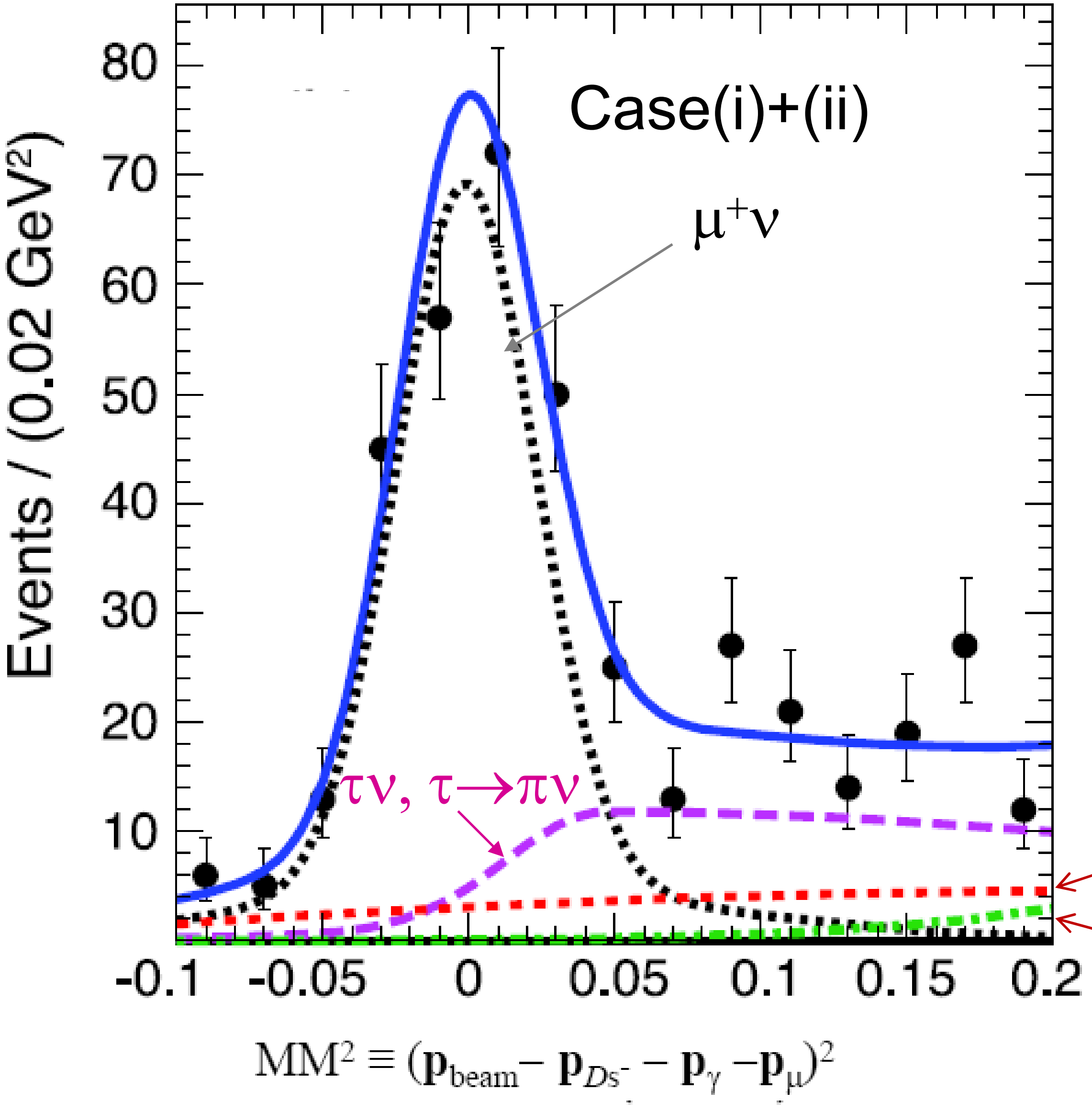
(iii) Electron candidate

- ❑98.8:1.2 split of $\mu^+\nu$ events in case(i) and (ii)

- ❑55:45 split of $\tau^+\nu$, $\tau^+ \to \pi^+ \nu$ events in case (i) and (ii)

Fit MM^2 to Sum of Signal & Background

PRD 79, 052001 (2009)



$MM^2 \equiv (p_{beam} - p_{D_s^-} - p_\gamma - p_\mu)^2$

Fake D_S tags

Background from real D_s decays

fix $\tau^+ \nu / \mu^+ \nu$ to SM

- 235.5 ± 13.8 $\mu^+ \nu$ events
- $f_{Ds}=(263.3\pm8.2\pm3.9)$ MeV

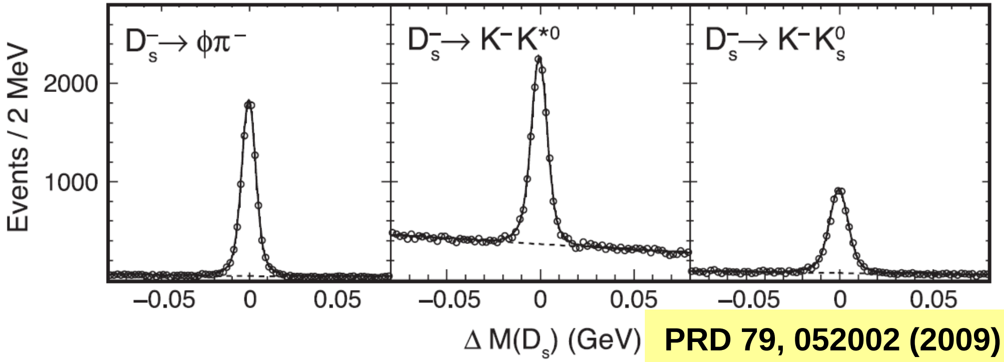
float $\tau^+ \nu / \mu^+ \nu$

- $B(D_s^+ \to \mu^+ \nu)= (0.565\pm0.045\pm0.017)\%$
- $B(D_s^+ \to \tau^+ \nu)= (6.42\pm0.81\pm0.18)\%$

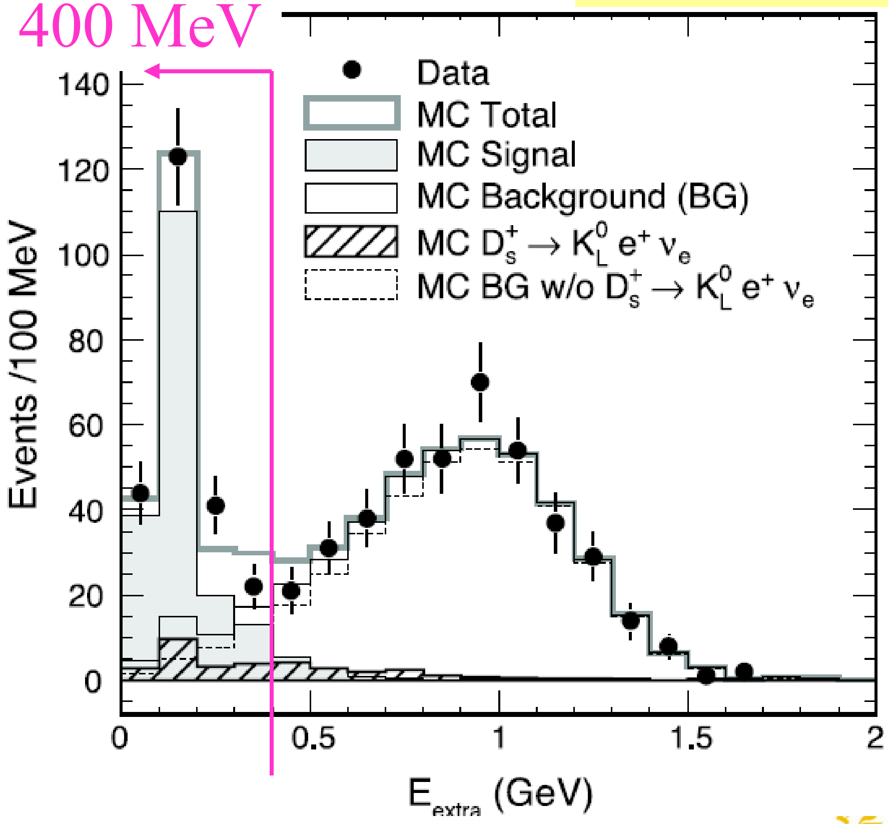
- $f_{Ds}/f_D=1.26\pm0.06\pm0.02$

$D_s^- \rightarrow \tau^+ \nu,\ \tau^+ \rightarrow e^+ \nu\nu$

- $B(D_S^+ \rightarrow \tau^+\nu) \bullet B(\tau^+ \rightarrow e^+\nu\nu) \sim 1.3\%$
- Searching for events opposite a tag with one electron and not much other energy
- Opt to use only a subset of the cleanest tags



PRD 79, 052002 (2009)



- Find events with an e^+ opposite D_S^- tags & no other tracks, with

  E_{extra}<400 MeV
  ($E_{extra} = \Sigma$ extra energy in calorimeter)

- No need to find g from D_S^*

- $B(D_S^+ \rightarrow \tau^+\nu) = (5.30 \pm 0.47 \pm 0.22)\%$
- $f_{Ds} = (252.6 \pm 11.1 \pm 5.2)$ MeV

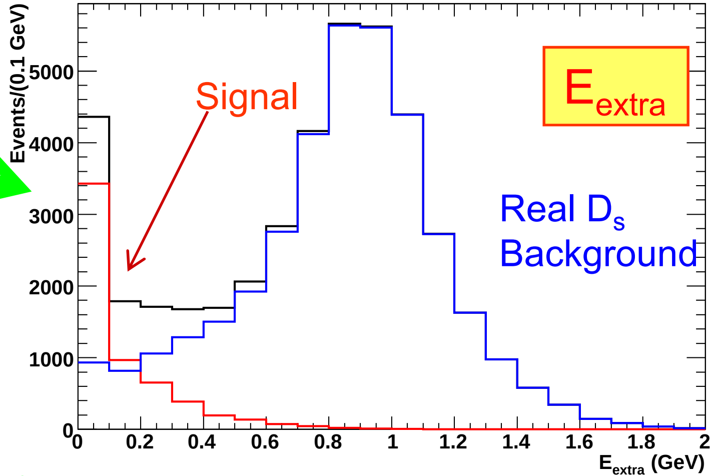
$D_s^- \to \tau^+ \nu$, $\tau^+ \to \rho^+ \nu$

- ❑ Same tagging technique as $D_s^+ \to \mu^+ \nu$
- ❑ E_{extra} (Σ extra energy in calorimeter)
  - ✓ used as an important discriminant
- ❑ The MM2 distribution:
  - ✓ The signal does not peak, because there are two neutrinos.
  - ✓ the important backgrounds do peak.
- ❑ The peaking backgrounds in MM^2 ($K^0\pi\pi^0$, $\eta\rho^+$, and $\pi\pi^0\pi^0$)
  - ❑ Branching fractions measured using a double tag technique
  - ❑ the same set of Ds tags

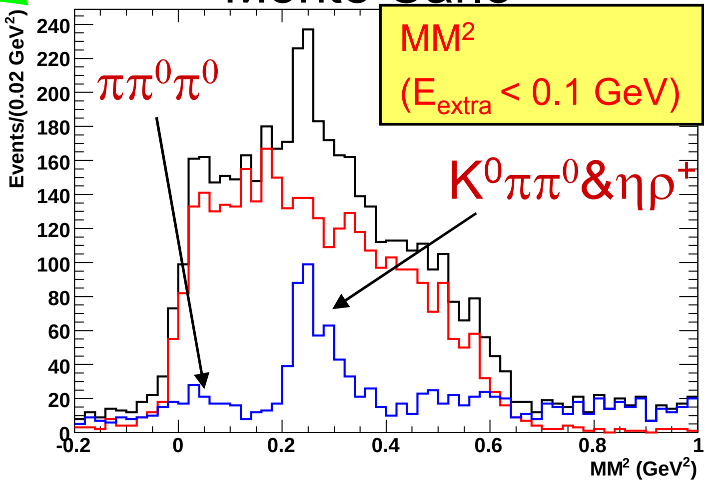
$$\begin{aligned}
\mathcal{B}(D_s^+ \to K^0\pi^+\pi^0) &= (1.00 \pm 0.18 \pm 0.04)\%, \\
\mathcal{B}(D_s^+ \to \pi^+\pi^0\pi^0) &= (0.65 \pm 0.13 \pm 0.03)\%, \\
\mathcal{B}(D_s^+ \to \eta\rho^+) &= (8.9 \pm 0.6 \pm 0.5)\%.
\end{aligned}$$

PRD 80, 112004 (2009)

Monte Carlo



Monte Carlo



$$MM^2 \equiv (p_{beam} - p_{D_s^-} - p_\gamma - p_\mu)^2$$

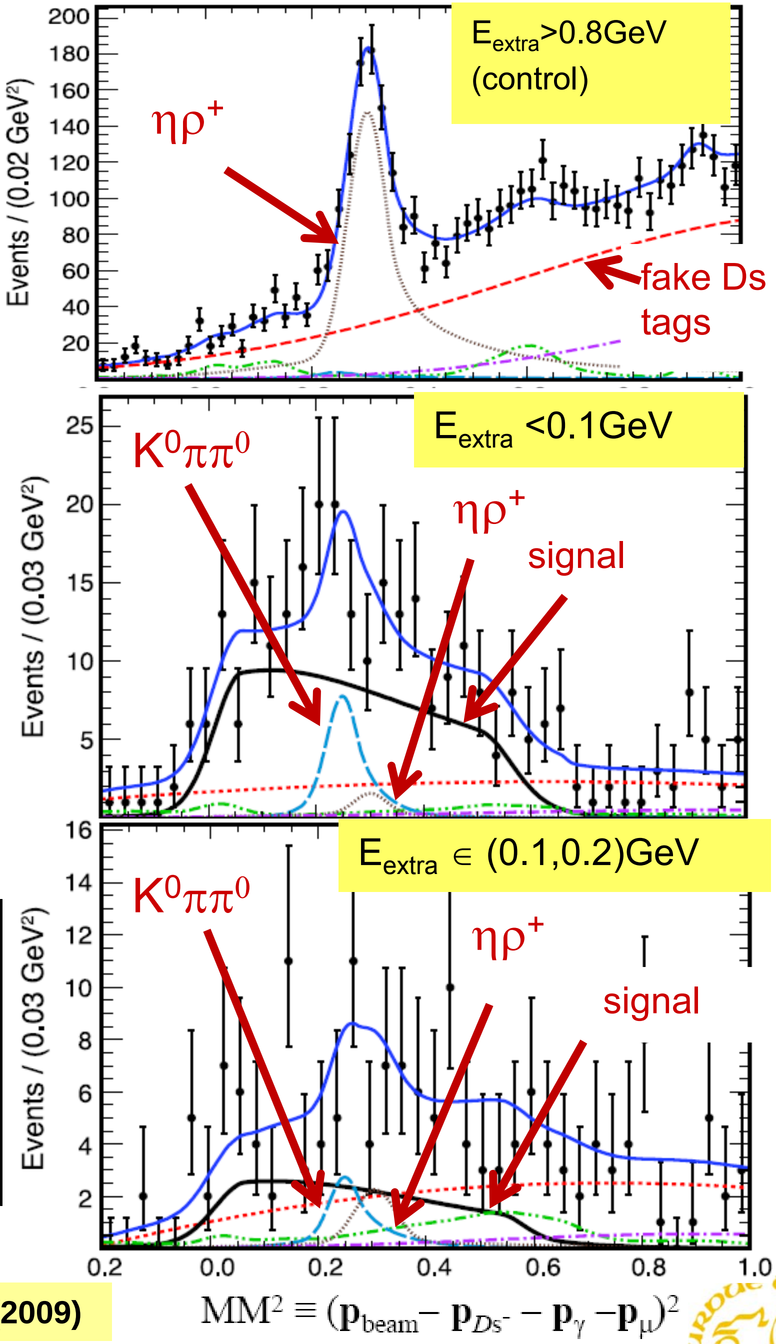
$D_s^- \to \tau^+ \nu$, $\tau^+ \to \rho^+ \nu$

- ❑Simultaneous fit to the Ds tag invariant mass & the MM^2 distributions, separately in three E_{extra} intervals,
  - E_{extra} >0.8 GeV signal is absent.
    (to check understanding of background)
  - E_{extra} <0.1 GeV : signal dominates,
  - $E_{extra} \in (0.1, 0.2)$ GeV S & B are about equal

- ❑External Gaussian constraints on the expected background yields are included in the likelihood fit, allowing them to vary within the measured branching fraction error

E_{extra}	Signal yields	Efficiency	$\mathcal{B}(D_s^+ \to \tau^+ \nu)$
[0,0.1] GeV	155.2 ± 16.5	25.3%	**(5.48 ± 0.59)%**
[0.1,0.2] GeV	43.7 ± 11.3	6.9%	**(5.65 ± 1.47)%**
[0,0.2] GeV	198.8 ± 20.0	32.2%	**(5.52 ± 0.57 ± 0.21)%**

✓ f_{D_s} = (257.8±13.3±5.2) MeV

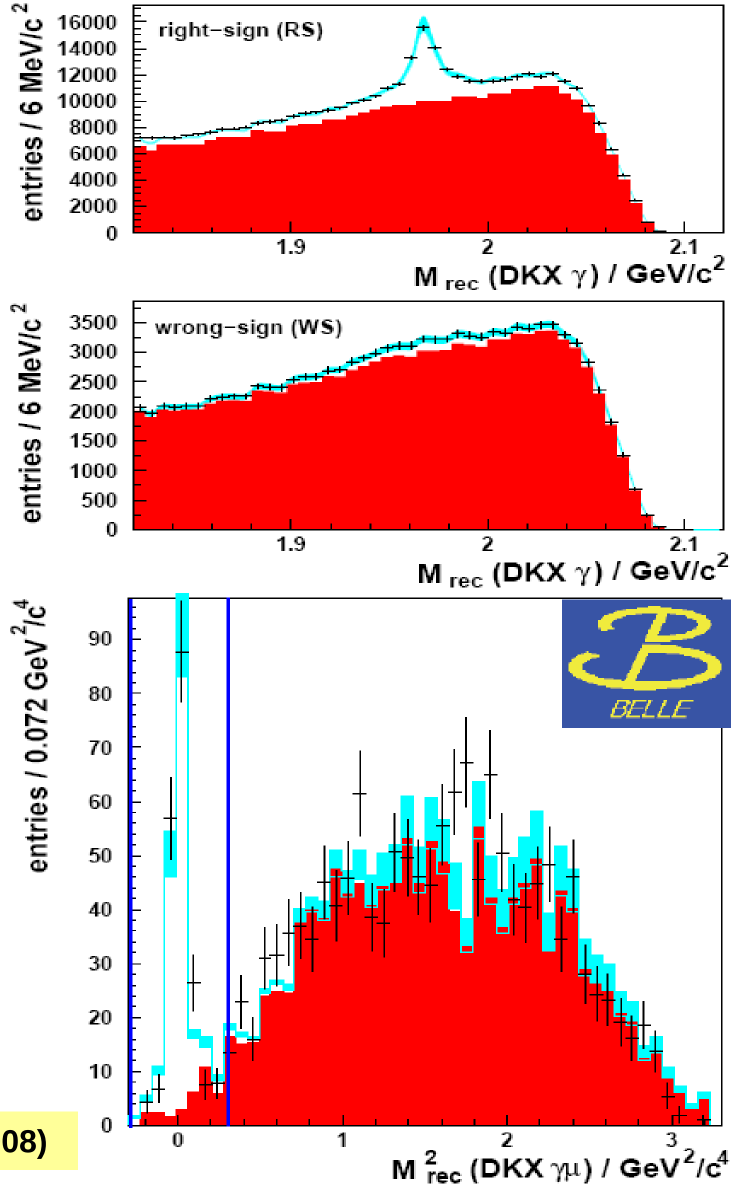


PRD 80, 112004 (2009)

$D_S^+\to\mu^+\nu$ at Belle

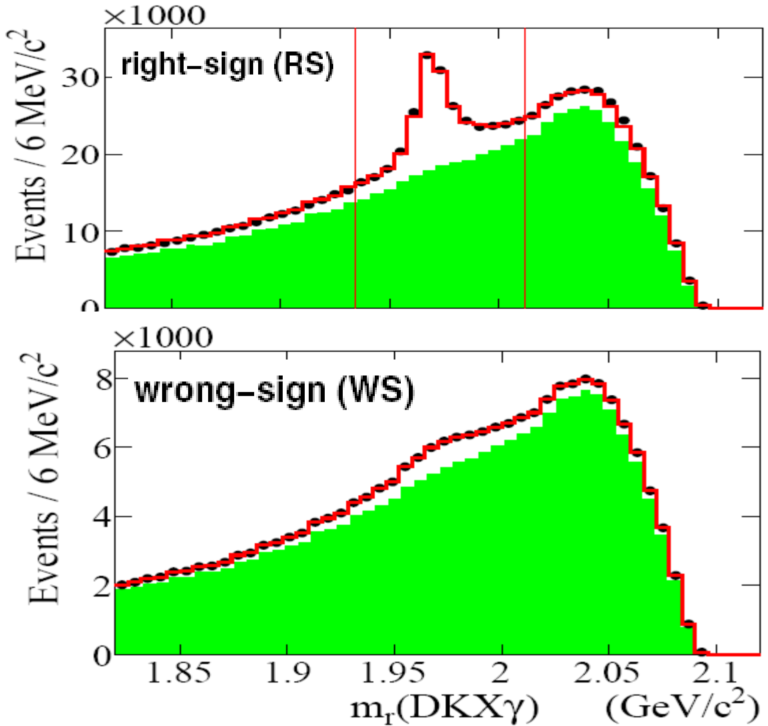
- Full event reconstruction using 548 fb^{-1} data
- Look for $e^+e^-\to D^{\pm,0}K^{\pm,0}X(D_s^*)$, $D_s^*\to D_s + \gamma$ where X=nπ or (nπ+ γ)
- Signal D_s is identified by recoil mass $M_{rec}(DKX\gamma)$, using the known beam momentum and 4-momentum conservation
- Then require a candidate μ^+ and compute $M_{rec}(DKX\gamma\mu)$
- No additional charged tracks
- $B(D_S^+ \to \mu^+\nu) = (0.644\pm0.076\pm0.057)\%$
- $f_{Ds}= (275\pm16\pm12)$ MeV

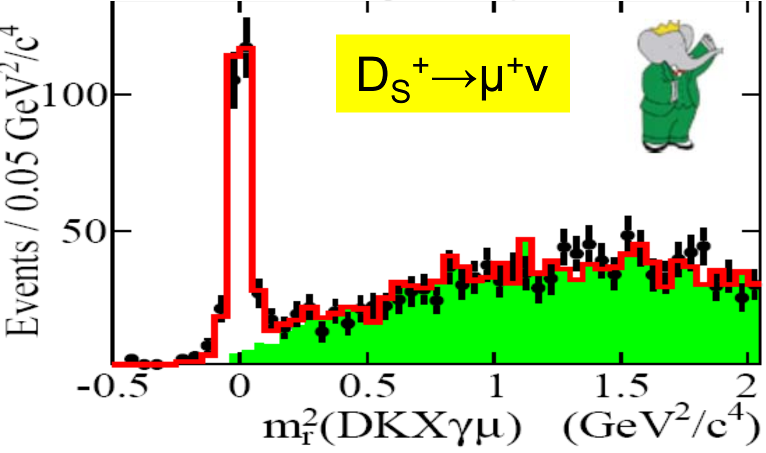
PRL 100, 241801 (2008)



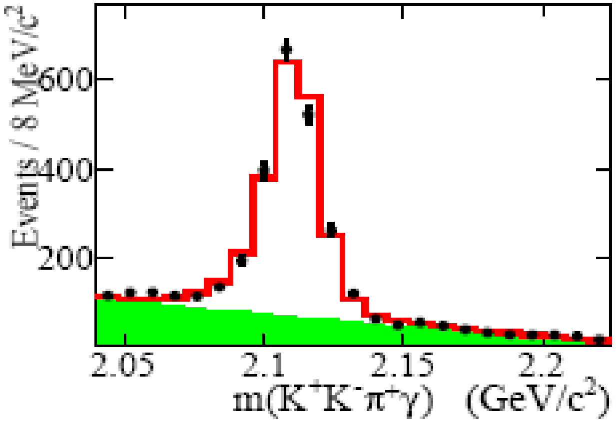
$D_S^+ \to l^+\nu$ at BaBar

arXiv: 1008.4080

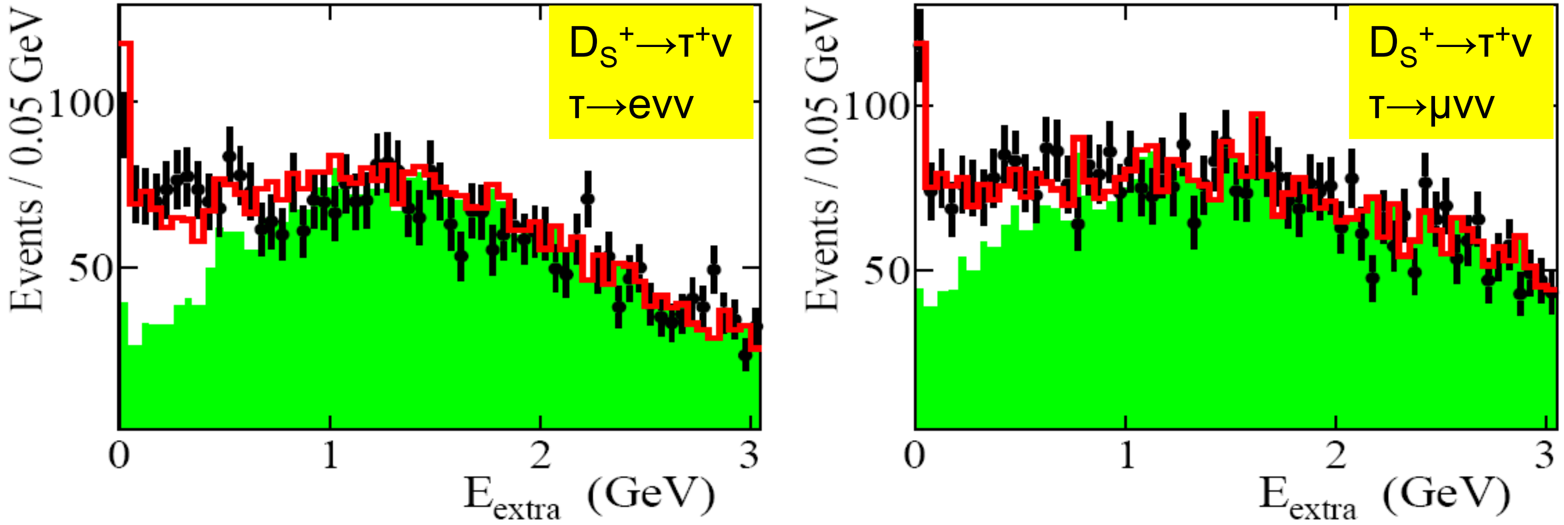




- Similar to the Belle technique:
  Look for $e^+e^- \to D^{\pm,0}K^{\pm,0}X(D_s^*)$, $D_s^* \to D_s + \gamma$
  where D= $D^{\pm,0}$, or Λ_c^+, K= $K^{\pm,0}(\overline{p})$, X=nπ,
  No additional charged tracks
- Signal D_s is identified by recoil mass $m_r(DKX\gamma)$,
- $\mu^+\nu$ signal is reconstructed by computing $m_r(DKX\gamma\mu)$
- Cross-check analysis method by measuring $B(D_S^+ \to KK\pi)$ using the same inclusive D_s sample, result consistent with CLEO-c.



$D_S^+ \to l^+\nu$ at BaBar



- $\tau^+\nu$, $\tau \to e\nu\nu$ or $\tau \to \mu\nu\nu$ signals are reconstructed using E_{extra} in calorimeter
- $\tau^+\nu$, $\tau \to \mu\nu\nu$ is separated from $\mu^+\nu$ by requiring $m_r(DKX\gamma\mu) > 0.5 GeV^2/c^4$
- The signal yields are obtained by fitting the extra energy distributions using PDFs determined from Monte Carlo.

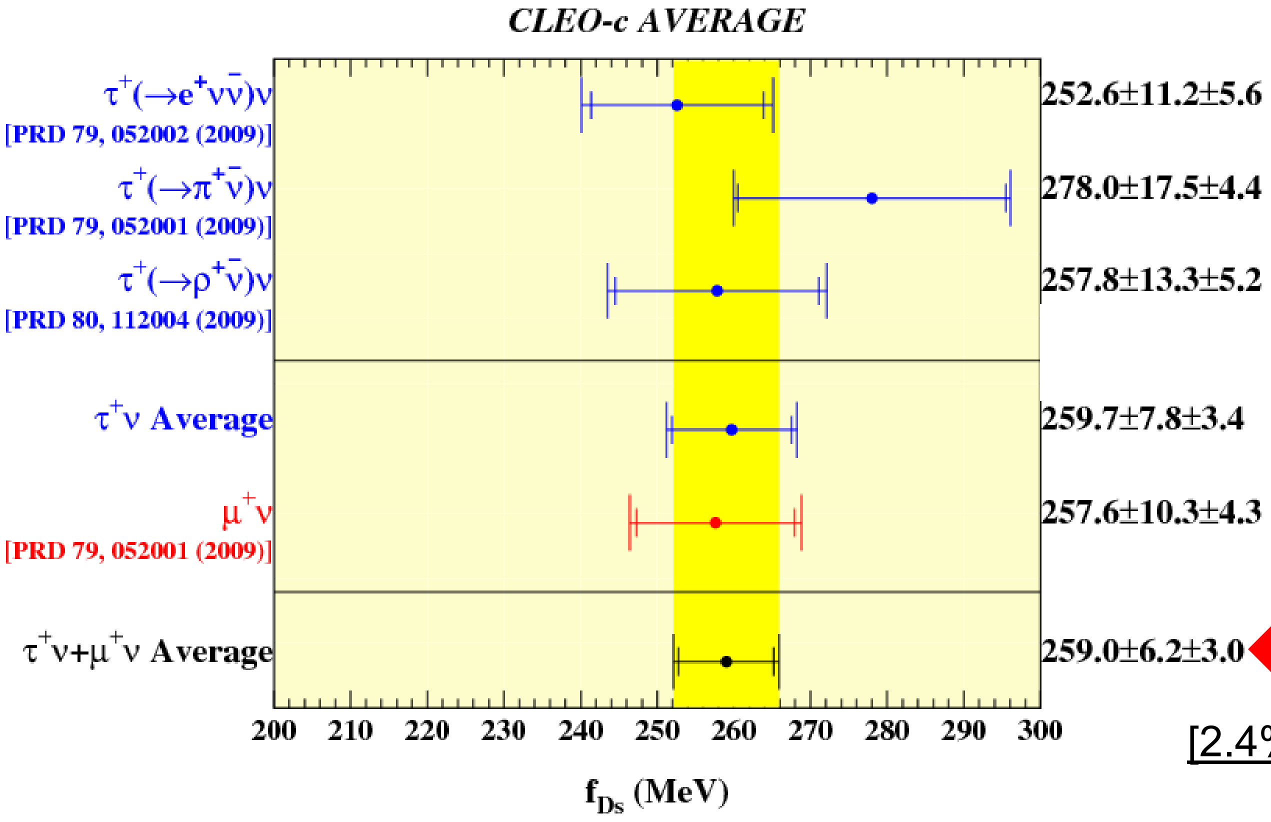
arXiv: 1008.4080

Supersedes previous BABAR results

Decay	Signal Yield	$\mathcal{B}(D_s^- \to \ell^- \overline{\nu}_\ell)$	f_{D_s} (MeV)
$D_s^- \to e^- \overline{\nu}_e$	$6.1 \pm 2.2 \pm 5.2$	$< 2.3 \times 10^{-4}$ at 90% C.L.	
$D_s^- \to \mu^- \overline{\nu}_\mu$	275 ± 17	$(6.02 \pm 0.38 \pm 0.34) \times 10^{-3}$	$265.7 \pm 8.4 \pm 7.7$
$D_s^- \to \tau^- \overline{\nu}_\tau$ $(\tau^- \to e^- \overline{\nu}_e \nu_\tau)$	408 ± 42	$(5.07 \pm 0.52 \pm 0.68) \times 10^{-2}$	$247 \pm 13 \pm 17$
$D_s^- \to \tau^- \overline{\nu}_\tau$ $(\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau)$	340 ± 32	$(4.91 \pm 0.47 \pm 0.54) \times 10^{-2}$	$243 \pm 12 \pm 14$

BABAR averaged $f_{Ds} = (258.6 \pm 6.4 \pm 7.5)$ MeV

CLEO-c f_{Ds} Average



All systematic errors include ±1.8 MeV

due to uncertainties on τ_{Ds}(dominant), *Vcs & Masses*

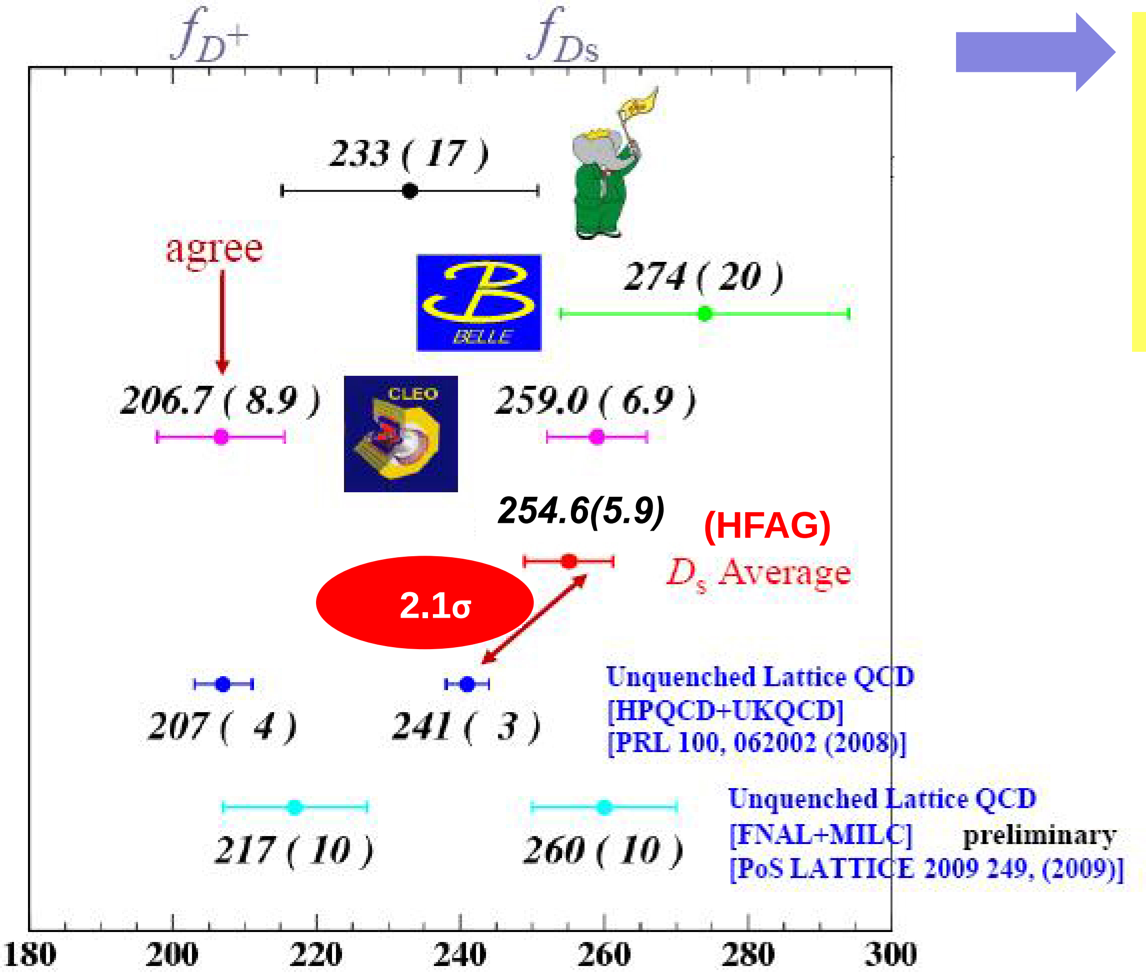
CLEO-c f_{Ds} Average

[2.4% stat + 1.1% syst]

Measurements from $\tau^+\nu$ and $\to\mu\nu$ are consistent

$$\frac{f_{D_s}(D_s^+ \to \tau^+\nu)}{f_{D_s}(D_s^+ \to \mu^+\nu)} = 1.01 \pm 0.05$$

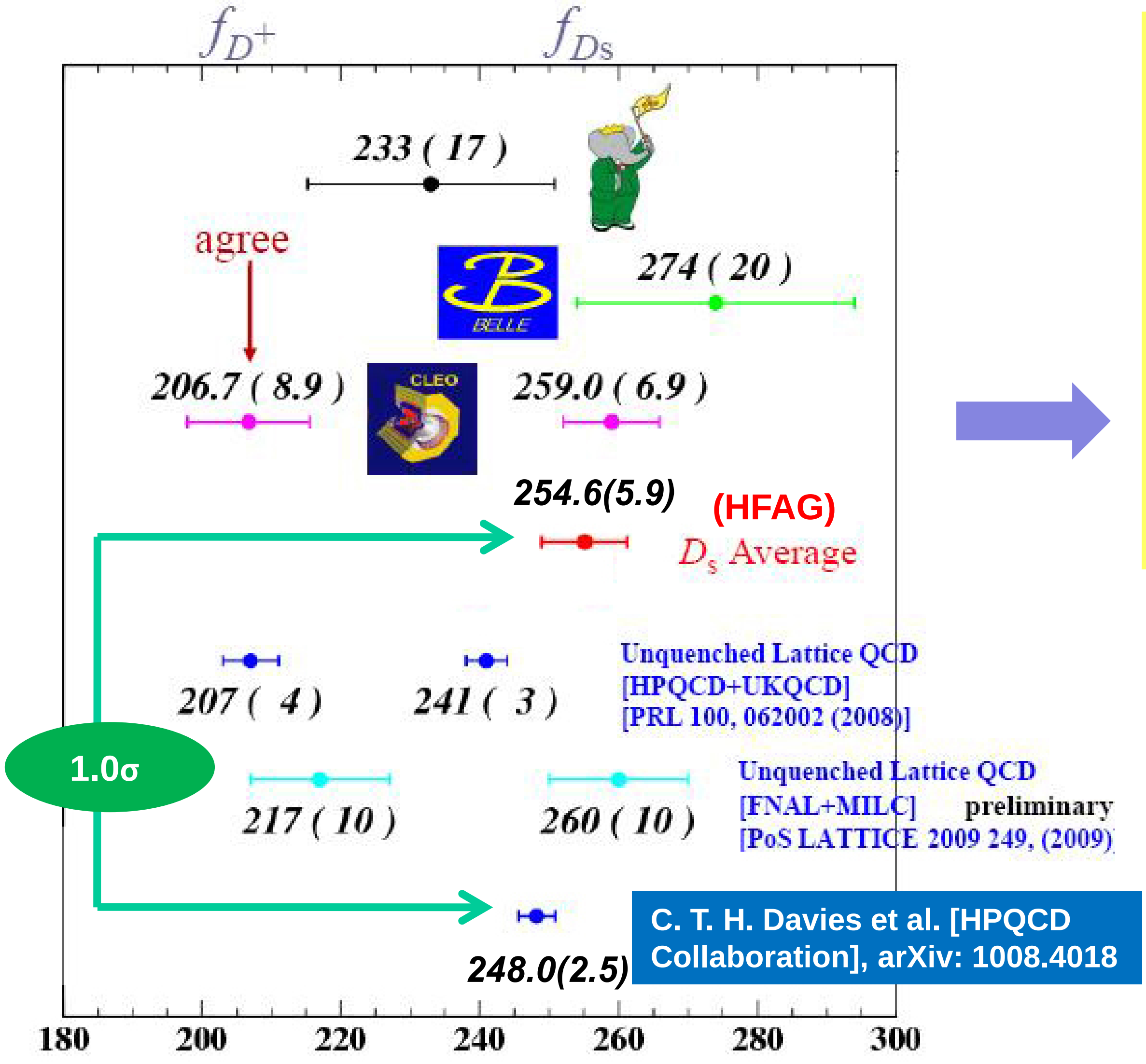
Conclusions (1)



- Before Aug 24, 2010

In the past two years, there has been a tension between theory and experiment, which also led to much speculation about the existence of New Physics.

Conclusions (2)



C. T. H. Davies et al. [HPQCD Collaboration], arXiv: 1008.4018

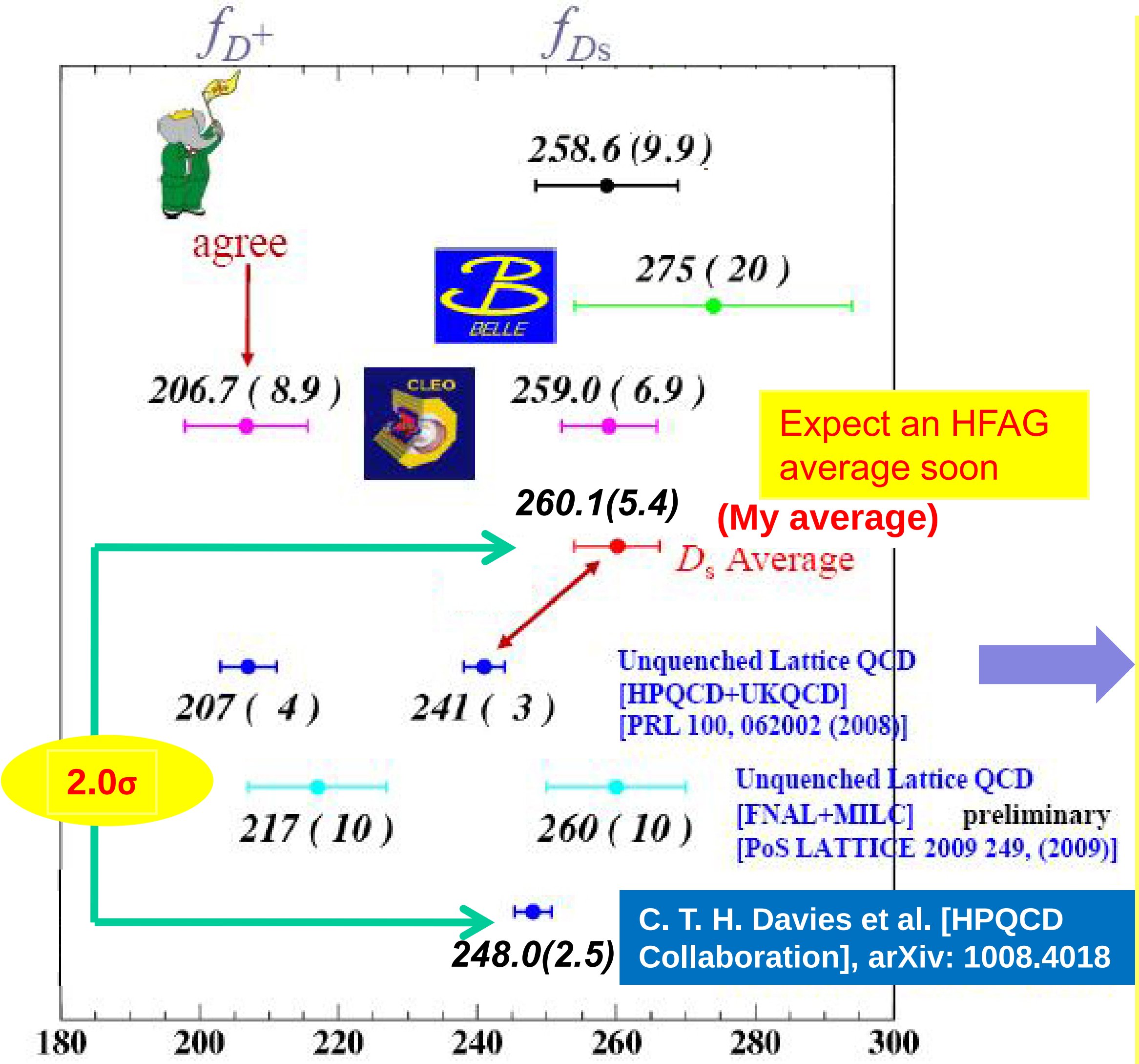
❑Before Aug 24, 2010

In the past two years, there has been a tension between theory and experiment, which also led to much speculation about the existence of New Physics.

❑On Aug 24, 2010

HPQCD submitted their new results, which is 1σ from the HFAG average.

Conclusions (3)



Expect an HFAG average soon

C. T. H. Davies et al. [HPQCD Collaboration], arXiv: 1008.4018

❑Before Aug 24, 2010

In the past two years, there has been a tension between theory and experiment, which also led to much speculation about the existence of New Physics.

❑On Aug 24, 2010

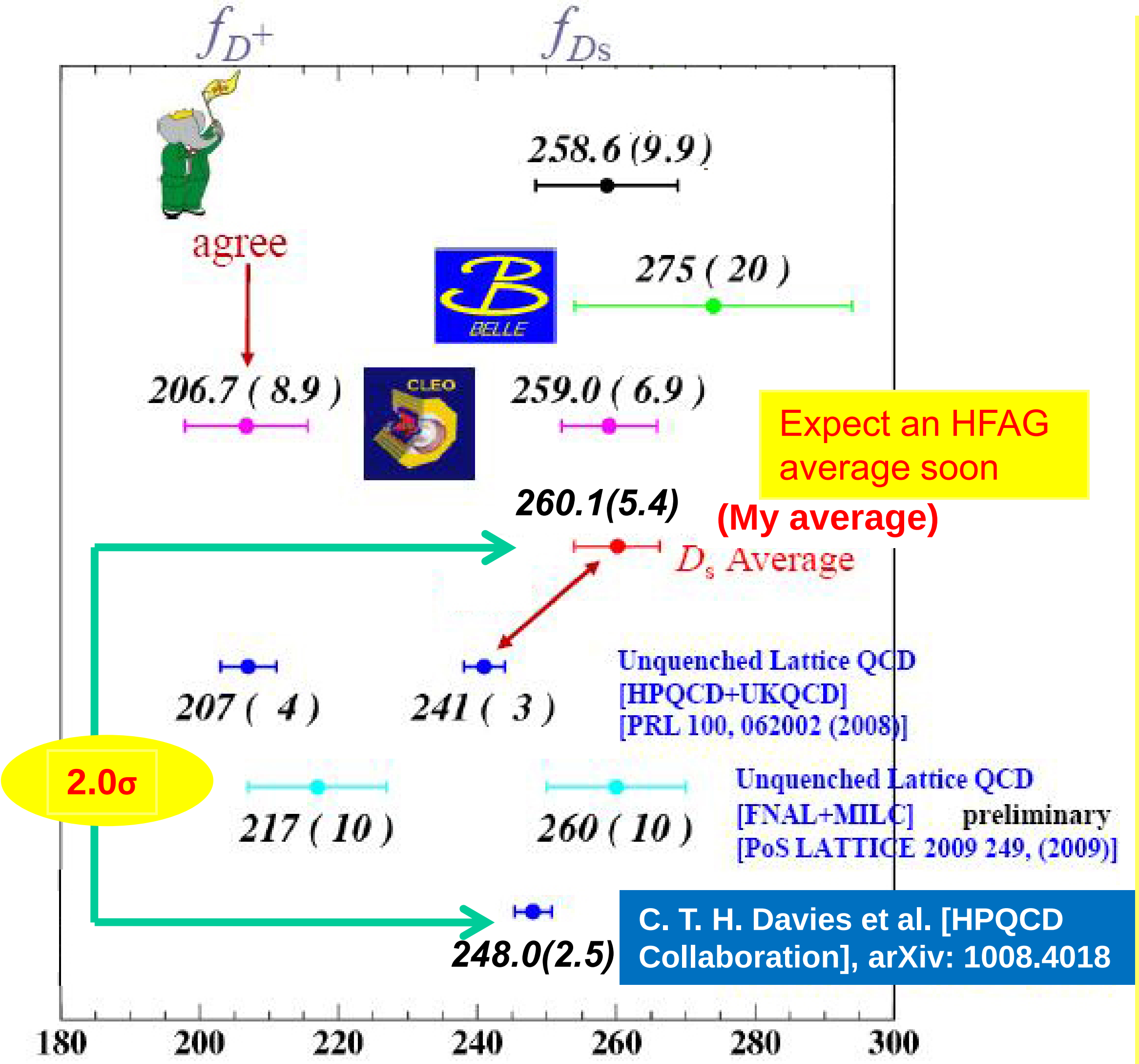
HPQCD submitted their new results, which is 1σ from the HFAG average.

❑Also on Aug 24, 2010

BABAR submitted new fDs results using their full data set. And these supersedes their 2007 results which was an relative measurement

❑Experiments have achieved 4.3% precision on fD and 2.1% on fDs

Conclusions (4)



Expect an HFAG average soon

(My average)

2.0σ

C. T. H. Davies et al. [HPQCD Collaboration], arXiv: 1008.4018

- Before Aug 24, 2010

In the past two years, there has been a tension between theory and experiment, which also led to much speculation about the existence of New Physics.

- On Aug 24, 2010

HPQCD submitted their new results, which is 1σ from the HFAG average.

- Also on Aug 24, 2010

BABAR submitted new fDs results using their full data set. And these supersedes their 2007 results which was an relative measurement

- Experiments have achieved 4.3% precision on fD and 2.1% on fDs

BESIII plans to take 20fb^{-1} each at 3770 and 4170 MeV 1-2 % uncertainties on f_D and f_{Ds} expected!