Leptonic D Decays

Roy A. Briere

Carnegie Mellon

(+ CLEO & BESIII)

FPCP09 Lake Placid
29 May 2009

Office of Science
U.S. DEPARTMENT OF ENERGY

NSF

Outline

Introduction

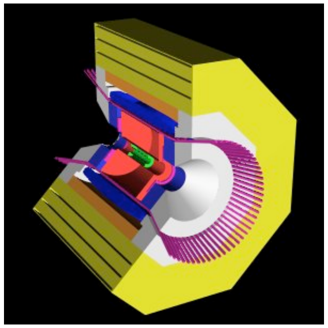
CLEO-c $D^+ \to \mu\nu$

Belle $D_s \to \mu\nu$

CLEO-c $D_s \to \mu\nu, \tau\nu$ [$\tau \to \pi\nu$]

CLEO-c $D_s \to \tau\nu$ [$\tau \to e\nu\nu$]

The Future…



@ charm
threshold

10 GeV
continuum
charm

BELLE

Theory-on-a-Page

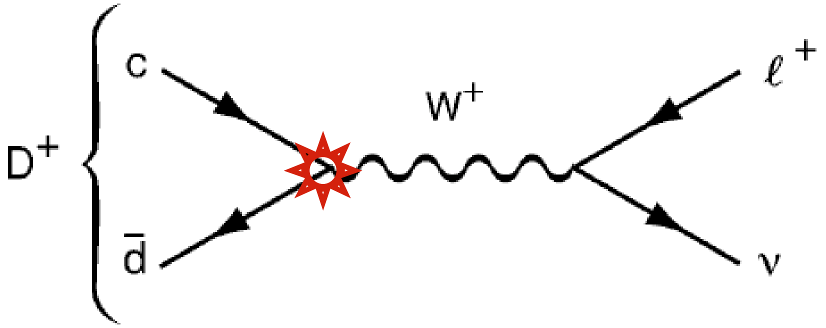
Decay Constant

Our Prey

Phase Space

inhibits tau,

esp. for D^+



$$\Gamma(D^+ \to \ell^+\nu) = \frac{G_F^2}{8\pi} f_{D^+}^2 m_\ell^2 M_{D^+}\left(1-\frac{m_\ell^2}{M_{D^+}^2}\right)^2 |V_{cd}|^2$$

Helicity Suppression

favors τ, μ over e

CKM

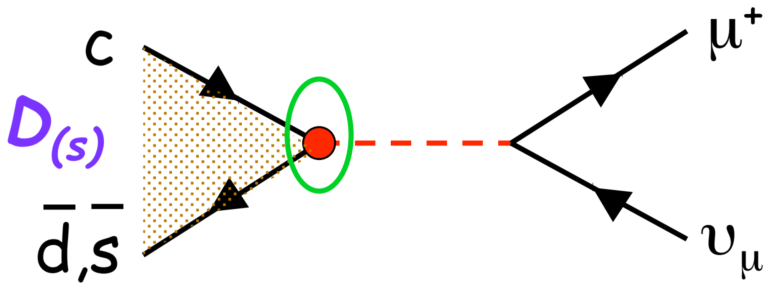
larger Γ & BR

for D_s

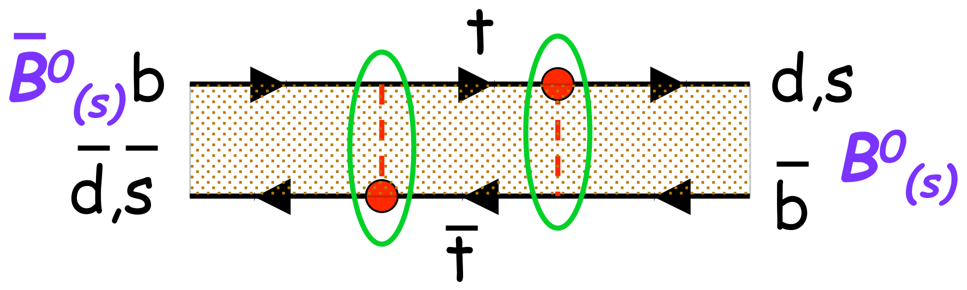
B Physics Connection

B mixing experimental results are not fully utilized due to f_B uncertainty

(accurate f_B directly from B leptonic is tough !!!)



f_D LQCD = experiment ?



use LQCD f_B here

Get V_{td}, V_{ts}

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

Key issue:

Precision tests of (unquenched) Lattice QCD

Helicity & Phase Space

$B(D^+ \Rightarrow \mu\nu) = 3.8 \times 10^{-4}$ × 2.1 "lifetime favored"

$$B(D_s^+ \Rightarrow \mu\nu) = \sim 5.6 \times 10^{-3} \quad \begin{cases} \times\ 19 & \text{Cabibbo favored} \\ \times\ 1.5 & \text{decay const} \\ \times\ 1.05 & \text{phase space} \end{cases}$$

D^+ SM ratios $e\upsilon : \mu\upsilon : \tau\upsilon \Leftrightarrow 2.3 \times 10^{-5} : 1 : 2.65$

D_s^+ SM ratios $e\upsilon : \mu\upsilon : \tau\upsilon \Leftrightarrow 2.3 \times 10^{-5} : 1 : 9.76$

Tau modes can be relevant with key one-prong tau decays:

18% $e\upsilon\upsilon$ 11% $\pi\upsilon$

for D^+: dominated by muons; small smeared-out tau rate
for D_s^+: can measure BOTH muon and tau channels
(more details later)

Electron channel: only limits, hard to approach Standard Model

CLEO f_D Technique

CLEO-c uses Tagging:

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

creates ONLY D pairs

Fully reconstruct one D

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

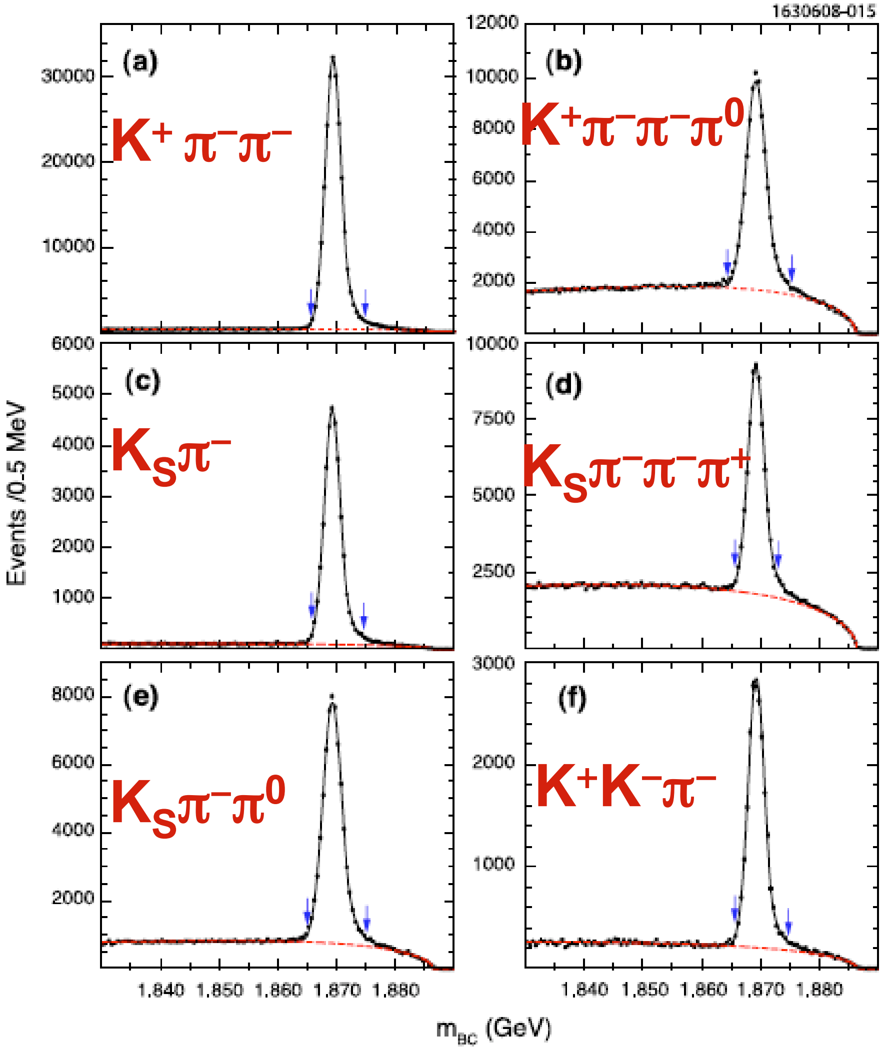
Typical tag rate per D:
15% / 10% / 5%
D^0 / D^+ / D_s

Belle (for D_s only):

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

CLEO-c D^- Tags

= fully-recon. hadronic decay



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

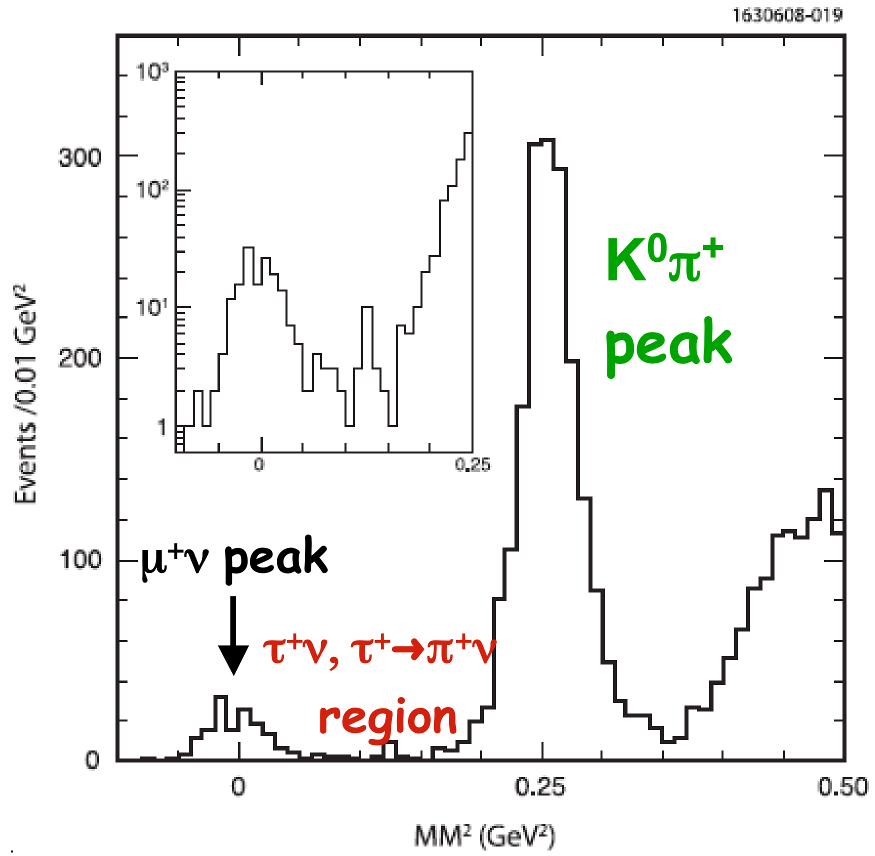
PRD 78, 052003
2008 818 pb^{-1}

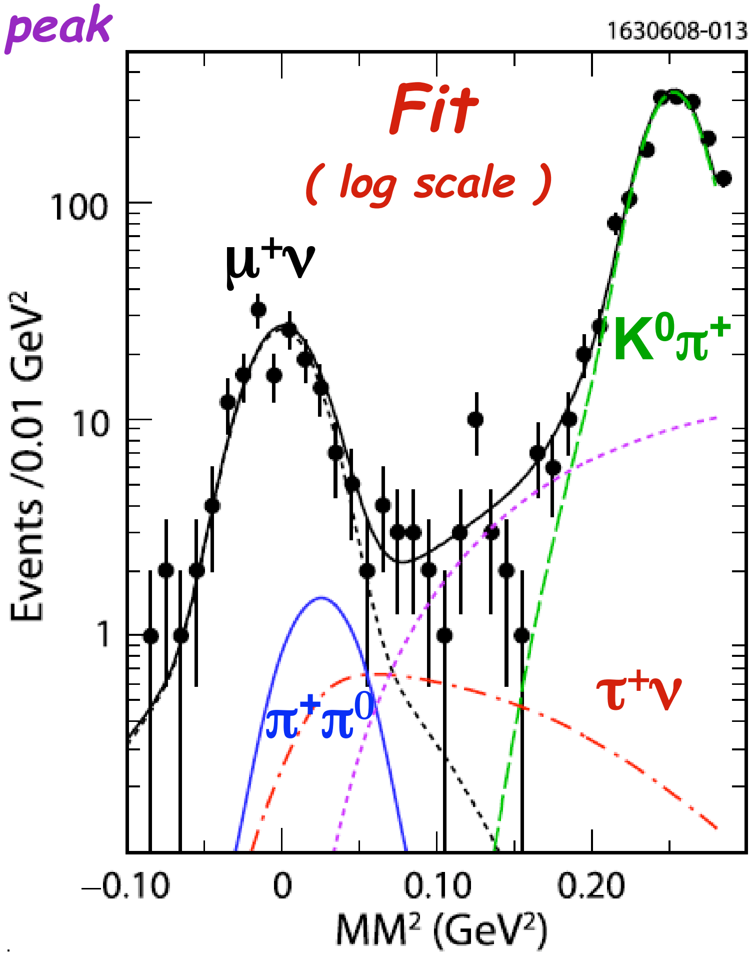
Neutrino from 4-momentum balance
can plot (missing mass)^2: MM^2

Signal side is one track + unobserved neutrino

Veto on extra unmatched showers > 250 MeV

>>> D-tagging gives a clean, isolated signal peak





Systematics: Backgrounds

PRD 78, 052003
2008 818 pb^{-1}

Previous page, signal plot:

"muon": <300 MeV in CsI calorimeter

This page, background check:

"muon": >300 MeV in CsI calorimeter

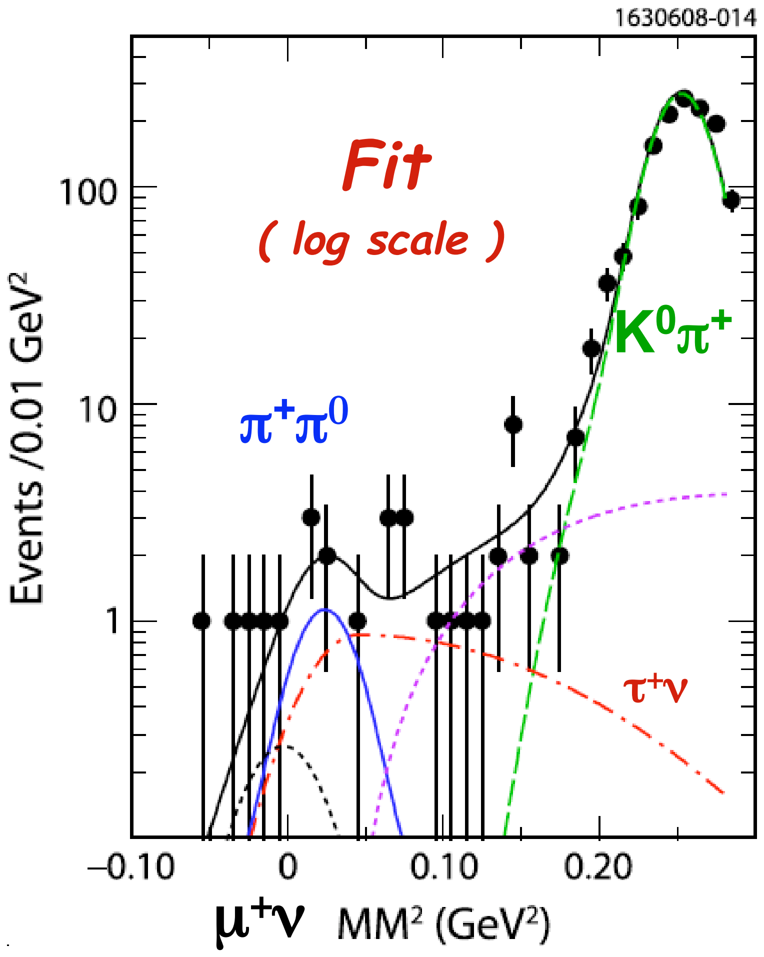
$\tau^+\nu$, $\tau^+ \rightarrow \pi^+\nu$ **shows up in both**

$\pi^+\pi^0$ **background** would be problematic,
but is small and well-simulated

$\tau^+\nu$ has known kinematics,
rate related to signal in SM

Tails of the $K^0\pi^+$ peak will be
shown to be well-understood next…

Other backgrounds are small,
and peak away from signal region



Systematics: Resolution

PRD 78, 052003
2008 818 pb^{-1}

Missing-mass is intrinsically powerful,

But one needs to understand resolution, including mis-reconstruction.

In data, tag one D:

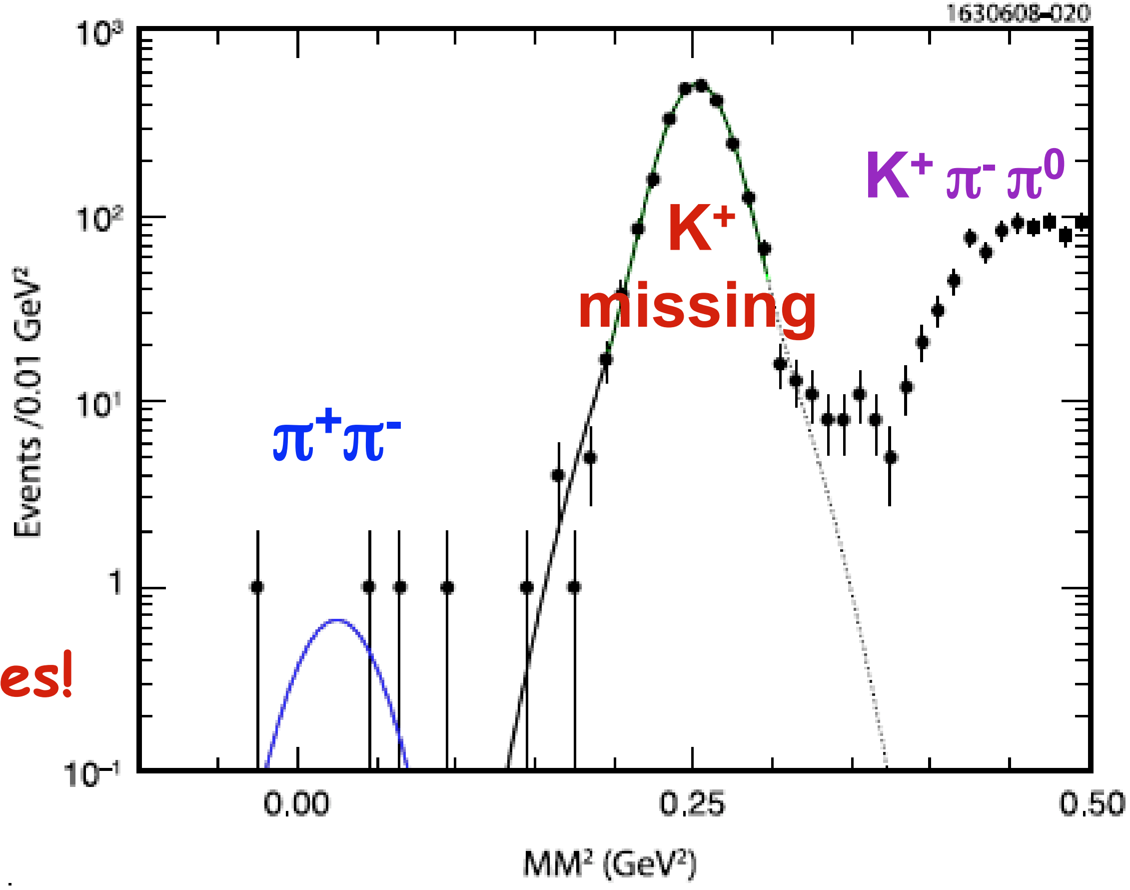
$D^0 \rightarrow K^-\pi^+$

Study other D:

$D^{0bar} \rightarrow K^+\pi^-$

ignore a well-ID'd Kaon

Nice double-Gaussian resolution over 3 decades!



Systematic Error Summary

PRD 78, 052003
2008 818 pb^{-1}

Error on f_D is 1/2 of this

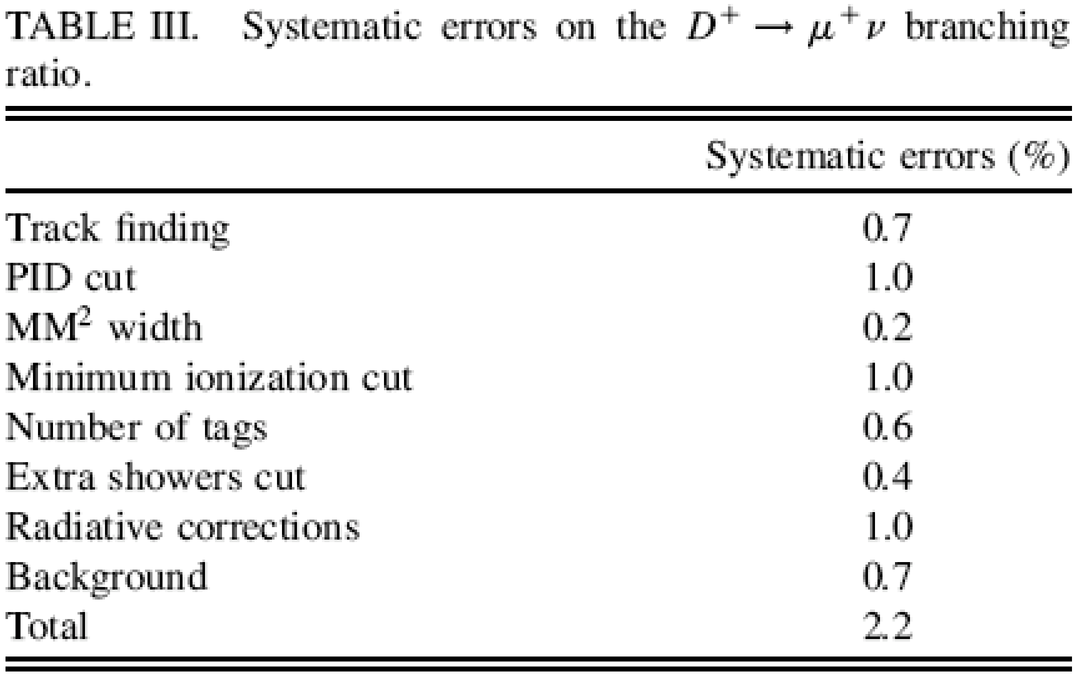


TABLE III. Systematic errors on the $D^+ \to \mu^+ \nu$ branching ratio.

	Systematic errors (%)
Track finding	0.7
PID cut	1.0
MM^2 width	0.2
Minimum ionization cut	1.0
Number of tags	0.6
Extra showers cut	0.4
Radiative corrections	1.0
Background	0.7
Total	2.2

Already only
1.1% on f_D !

No one dominant
Source of error.

May be hard
to improve ???

But… most of systematics are based on data.

$D^+ \rightarrow \mu^+\upsilon$ Results

PRD 78, 052003
2008 818 pb^{-1}

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

$\mathcal{B}(D^+ \rightarrow \mu^+\upsilon) = (3.82 \pm 0.32 \pm 0.09) \times 10^{-4}$

$f_{D^+} = (205.8 \pm 8.5 \pm 2.5)$ MeV [± 4.1% ± 1.2%]

Best number in context of SM

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

$\mathcal{B}(D^+ \rightarrow \mu^+\upsilon) = (3.93 \pm 0.35 \pm 0.10) \times 10^{-4}$

$f_{D^+} = (207.6 \pm 9.3 \pm 2.5)$ MeV consistent

Best number for use with Non-SM models

(Only small loss of precision)

Note: numbers are radiatively corrected; -1% on BR

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

PRL 100, 241801
(2008) 548 fb^{-1}

Use "Continuum tagging":

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

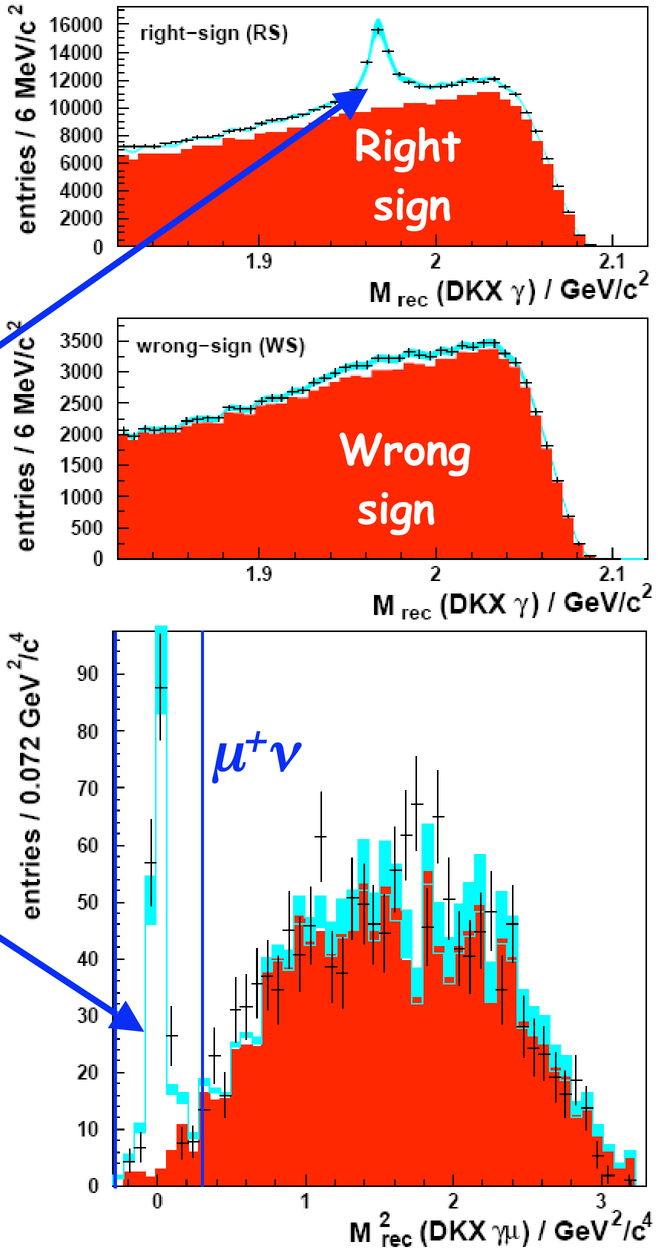
"X" = $n\pi$ -or- $n\pi\,\gamma$ (fragmentation)

about 25% of D BF used

Use recoil mass:

against DKXγ counts total D_s

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



$\mathcal{B}(D_s^+ \to \mu^+\nu) = (0.644 \pm 0.076 \pm 0.057)\%$

$f_{D_s} = 274 \pm 16 \pm 12$ MeV *

[± 5.8% ± 4.4%]

* including radiative correction of -1% in BR

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

PRL 100, 241801
(2008) 548 fb^{-1}

Systematic error totals 4.4% on f_D

3.2% MC statistics

2.2% background

1.5% Tag simulation

1.4% Muon ID

Many checks with careful attention paid to tags:

simulation accuracy, stability of result, …

Super B Factory: 3.2 ab^{-1} = final CLEO-c stat error

Need to control systematics 3x better to match CLEO-c

That may not be crazy, but may be hard to push far beyond ?

Still would be a nice independent cross-check

$D_s \to \mu^+\upsilon$ & $\tau^+\upsilon$
($\tau^+ \to \pi\,\upsilon$)

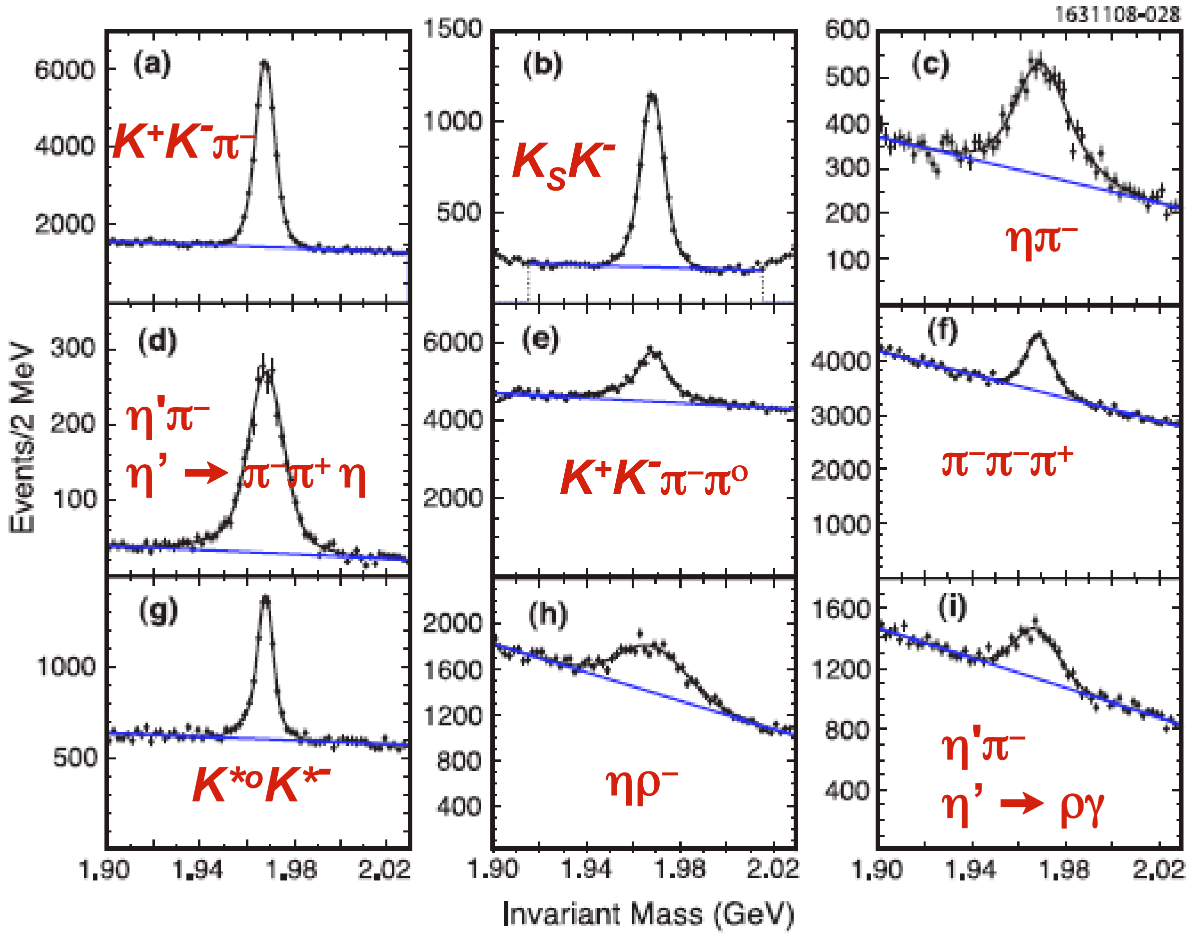
PRD 79, 052001
(2009) 600 pb^{-1}

D_s: Larger leptonic BF, but tougher for tagging

Use data from 4170 MeV: $D_s^{*+} D_s^- +$ c.c events

On top of uds +*plus* other charm contiuunum

Invariant mass of 9 tag modes



$D_s \rightarrow \mu^+\nu$ & $\tau^+\nu$
($\tau^+ \rightarrow \pi\,\nu$)

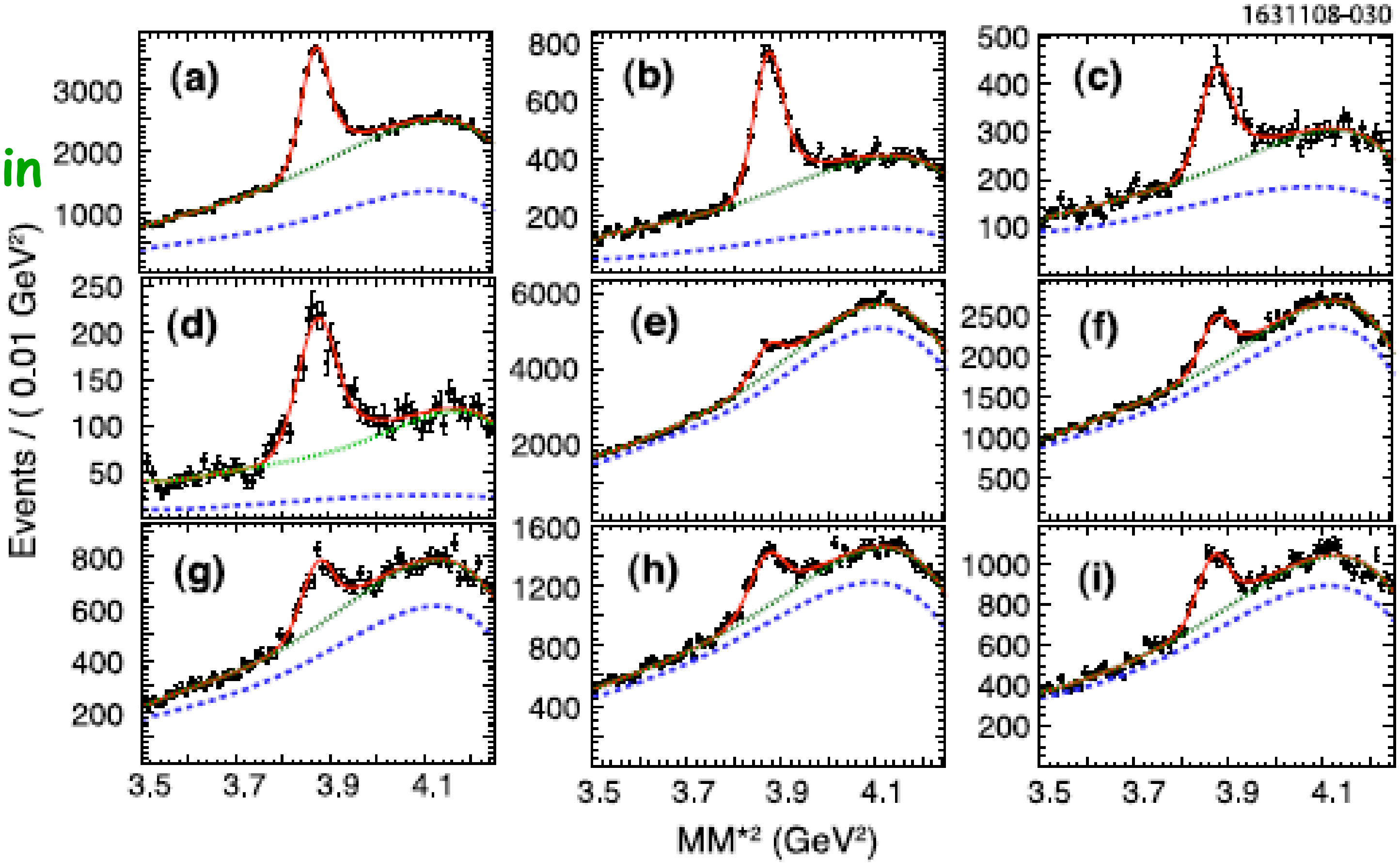
PRD 79, 052001
(2009) 600 pb^{-1}

Look at missing mass after adding photon

(from $D_s^* \rightarrow D_s\gamma$)

Plot missing-mass^2 against $D_s\,\gamma$ system

Need photon
to fully constrain
the other D_s...



More on the Method…

PRD 79, 052001 (2009) 600 pb^{-1}

As with D+ analysis, separate two cases:

Case (i): signal track deposits <300 MeV in CsI calorimeter

dominantly $\mu^+\upsilon$ (but ~ 1/2 of $\tau^+\nu$, $\tau^+\to\pi^+\nu$ is also here)

Case (ii): signal track deposits >300 MeV in CsI calorimeter

dominantly $\tau^+\upsilon$ (~ 1/2 of $\tau^+\nu$, $\tau^+\to\pi^+\nu$; very little $\mu^+\upsilon$)

Similar to D^+ case: Veto on extra unmatched showers > 300 MeV

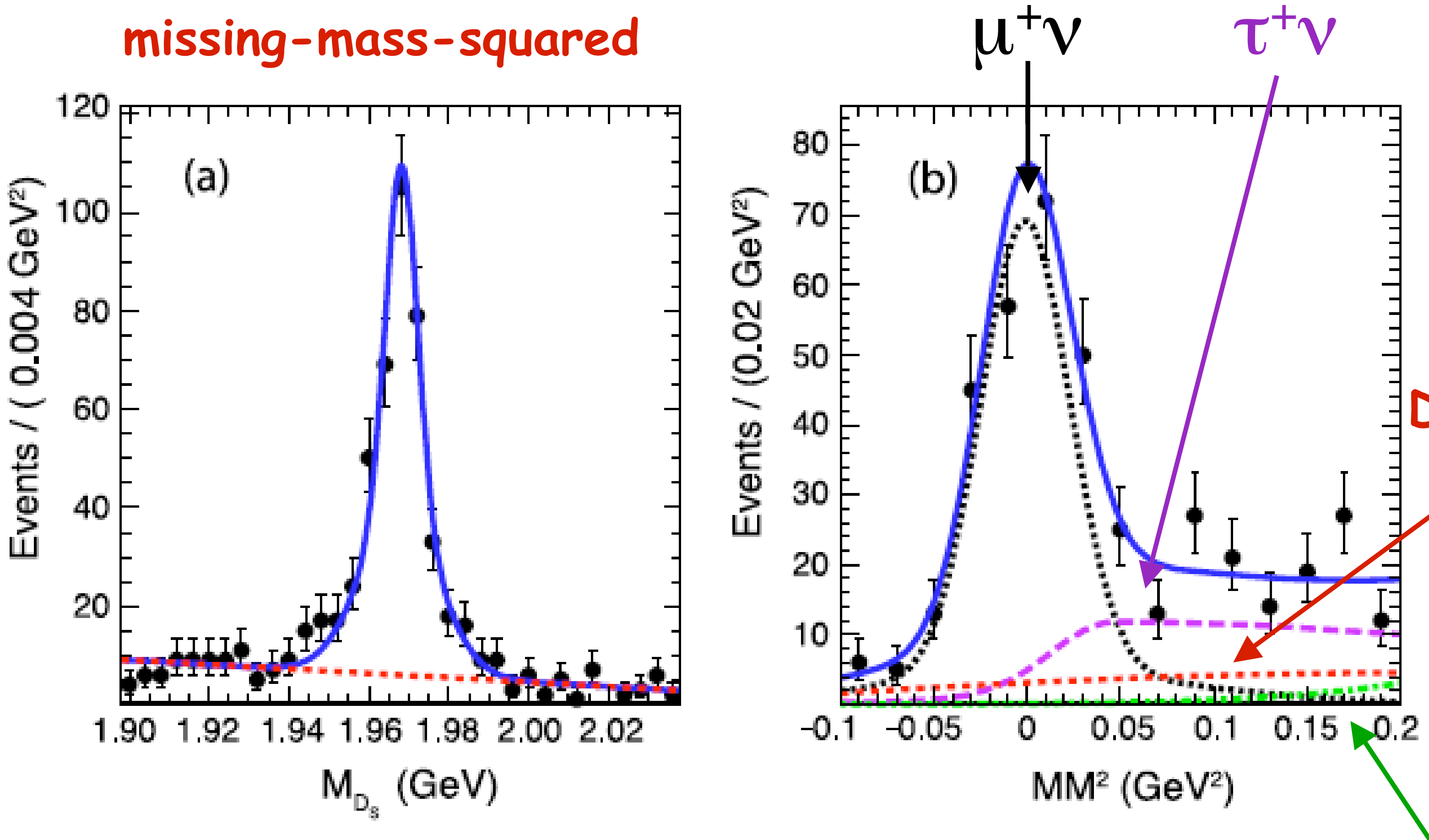
First, I will show combined data, then separated…

$D_s \to \mu^+\upsilon$ & $\tau^+\upsilon$
($\tau^+ \to \pi\,\upsilon$)

PRD 79, 052001
(2009) 600 pb^{-1}

2-dimensional fit
to D_s Tag mass and
missing-mass-squared

Two signal modes

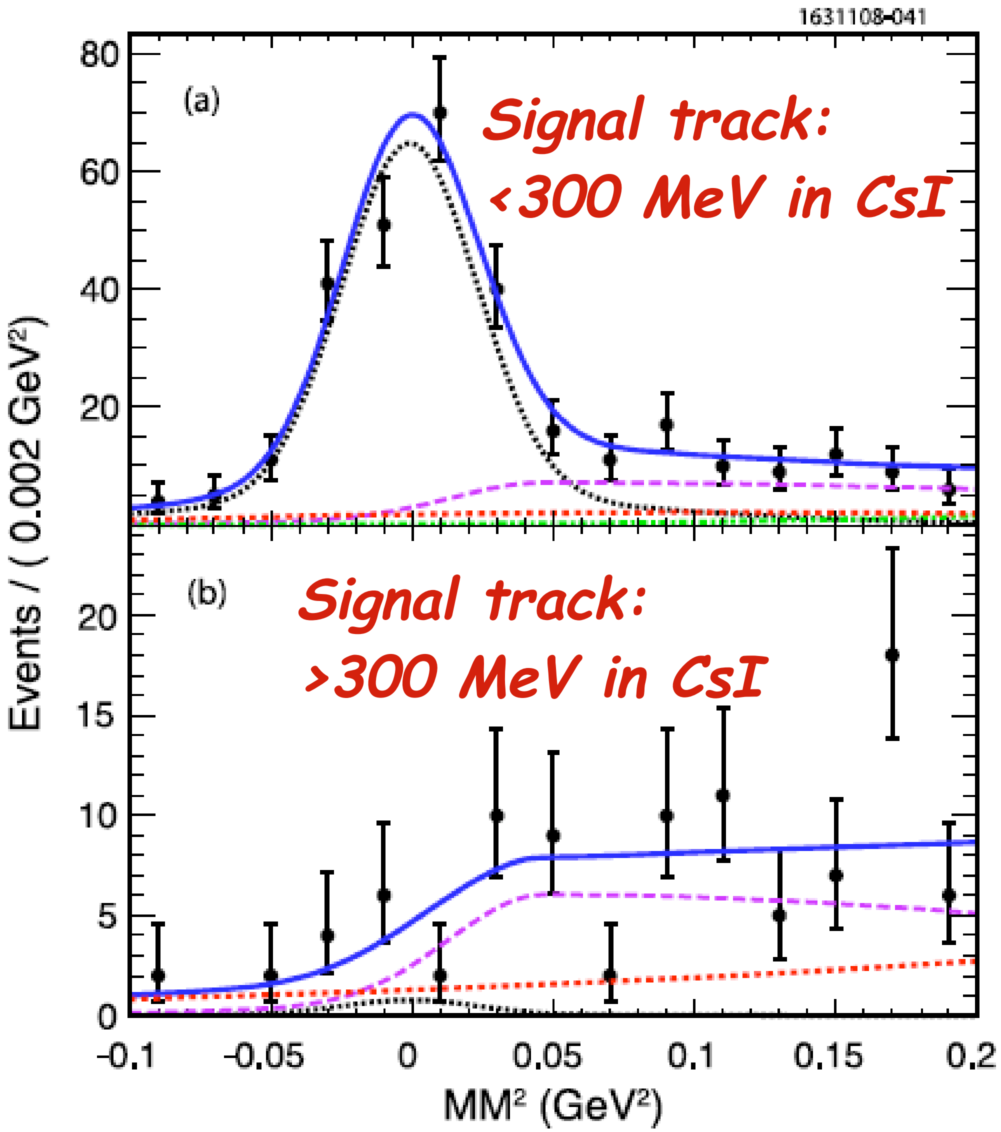


Background
D_s sidebands

Real D_s
background

Separated Data

PRD 79, 052001
(2009) 600 pb^{-1}



Signal track:
<300 MeV in CsI

Signal track:
>300 MeV in CsI

Color-code:

$\mu^+\nu$

$\tau^+\nu$

Background
D_S sidebands

Real D_s
background

Backgrounds

PRD 79, 052001
(2009) 600 pb^{-1}

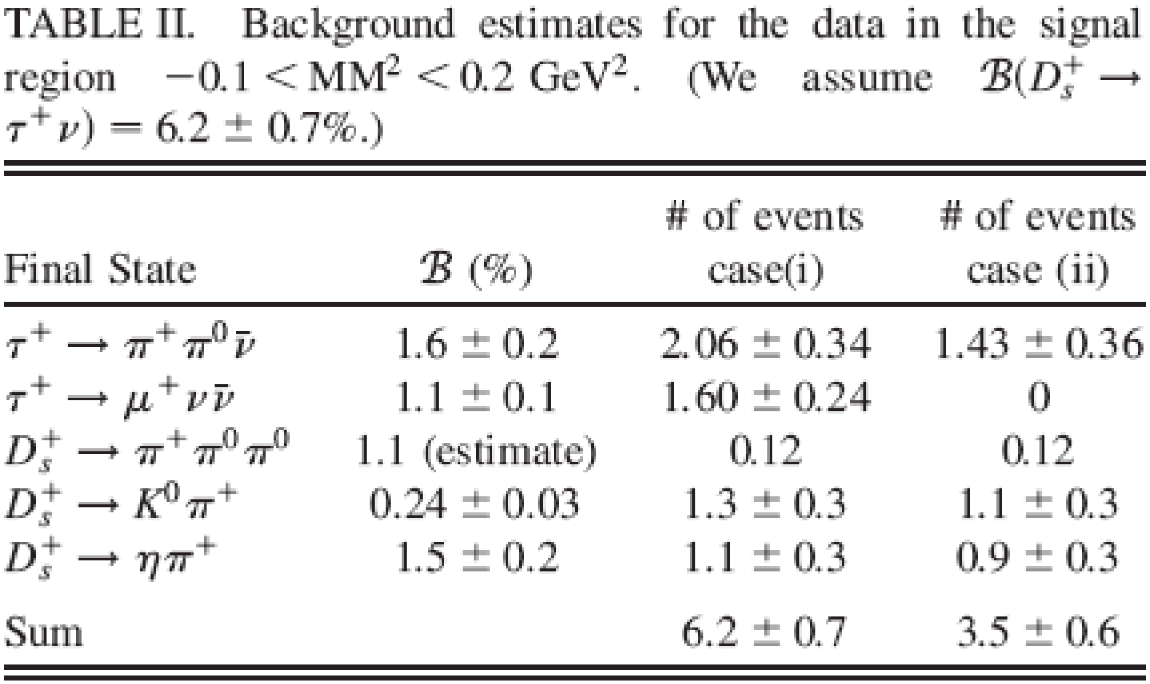


TABLE II. Background estimates for the data in the signal region $-0.1 < \text{MM}^2 < 0.2\ \text{GeV}^2$. (We assume $\mathcal{B}(D_s^+ \to \tau^+\nu) = 6.2 \pm 0.7\%$.)

Final State	$\mathcal{B}$ (%)	# of events case(i)	# of events case (ii)
$\tau^+ \to \pi^+\pi^0\bar{\nu}$	1.6 ± 0.2	2.06 ± 0.34	1.43 ± 0.36
$\tau^+ \to \mu^+\nu\bar{\nu}$	1.1 ± 0.1	1.60 ± 0.24	0
$D_s^+ \to \pi^+\pi^0\pi^0$	1.1 (estimate)	0.12	0.12
$D_s^+ \to K^0\pi^+$	0.24 ± 0.03	1.3 ± 0.3	1.1 ± 0.3
$D_s^+ \to \eta\pi^+$	1.5 ± 0.2	1.1 ± 0.3	0.9 ± 0.3
Sum		6.2 ± 0.7	3.5 ± 0.6

Rates are for full range of signal plots I've shown…

For reference, $\mu^+\upsilon$ signal is 235.5 ± 13.8 events

Systematic Errors

PRD 79, 052001
(2009) 600 pb^{-1}

Error on f_{D_s} is 1/2 on this

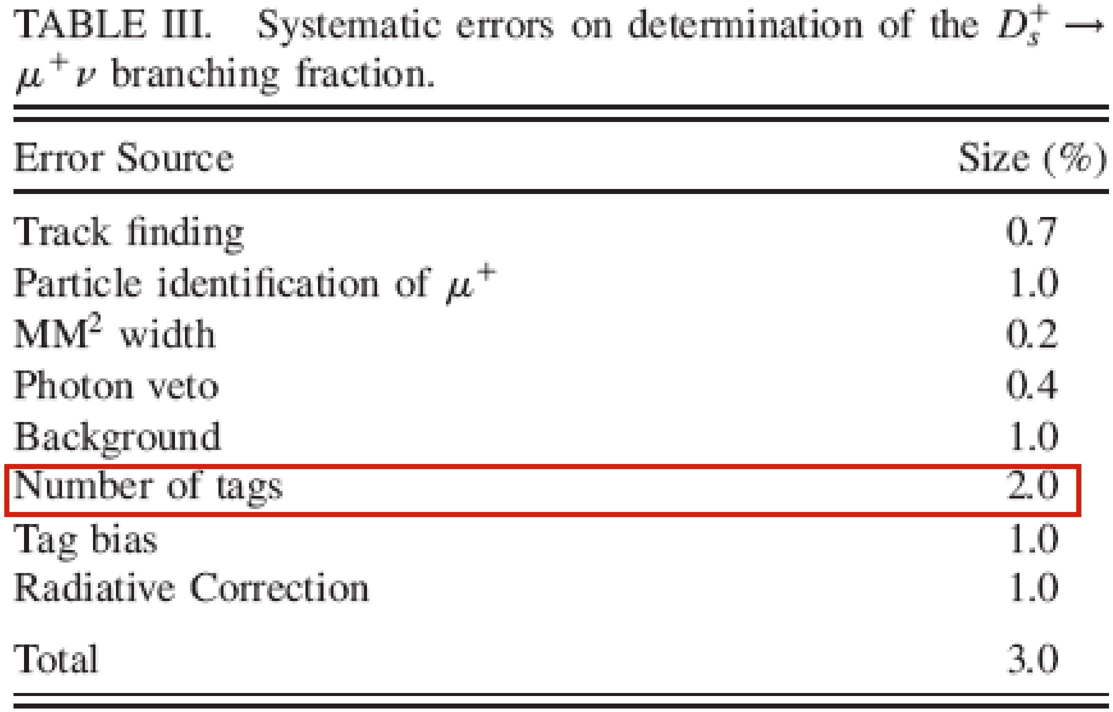


TABLE III. Systematic errors on determination of the $D_s^+ \to \mu^+\nu$ branching fraction.

Error Source	Size (%)
Track finding	0.7
Particle identification of μ^+	1.0
MM^2 width	0.2
Photon veto	0.4
Background	1.0
Number of tags	2.0
Tag bias	1.0
Radiative Correction	1.0
Total	3.0

Largest single error
is # tags:
might be better at
4030 MeV, with no D_s^*
(but only 30%
of cross-section!)

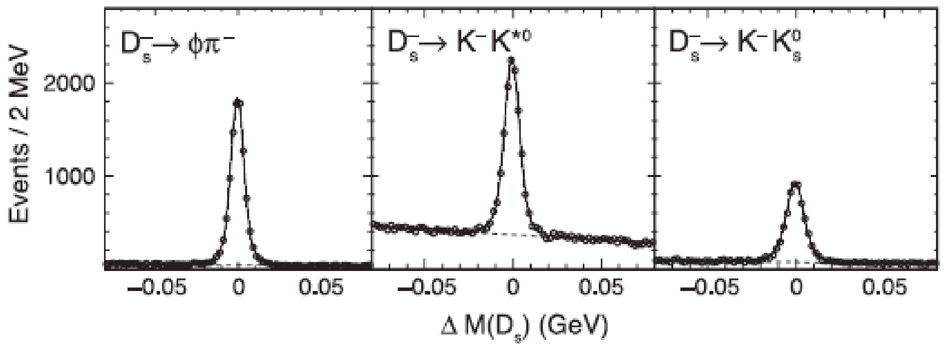
f_{D_s} = (263.3 ± 8.2 ± 3.9) MeV [± 3.1% ± 1.5%]

$\Gamma(D^+ \to \tau^+\nu) / \Gamma(D^+ \to \mu^+\nu)$ = 11.74 ± 1.7 ± 0.2 [SM = 9.76]

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

PRD 79, 052002
(2009) 602 pb^{-1}

Uses only cleanest tags:

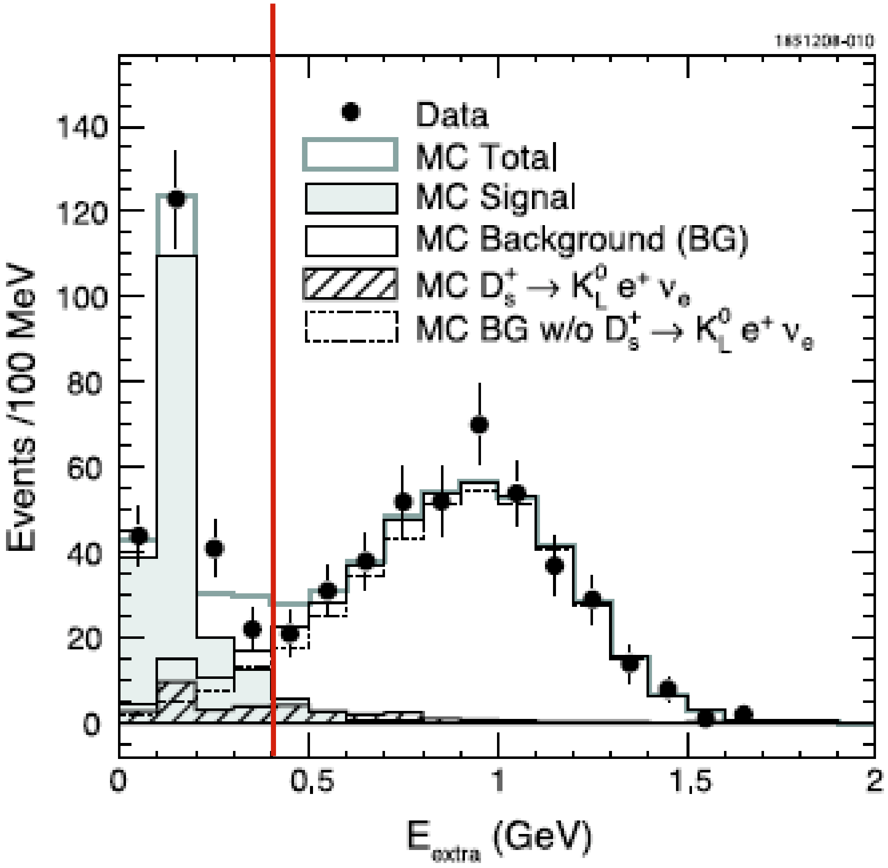


Always have >1 neutrino!
Abandon use of MM^2

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

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

Signal region:
<400 MeV

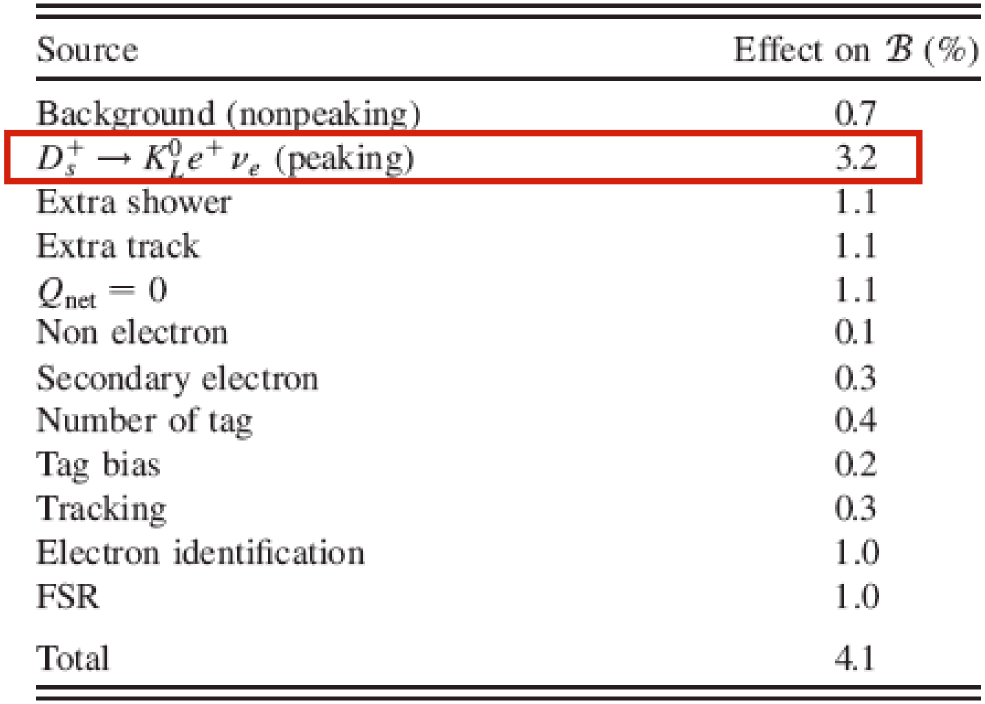


Peaks away from zero:
E_{extra} can include γ from D_s^* decay

Systematic Errors

PRD 79, 052002
(2009) 602 pb^{-1}

Error on f_{Ds} is 1/2 of this



Source	Effect on $\mathcal{B}$ (%)
Background (nonpeaking)	0.7
$D_s^+ \rightarrow K_L^0 e^+ \nu_e$ (peaking)	3.2
Extra shower	1.1
Extra track	1.1
$Q_{\mathrm{net}} = 0$	1.1
Non electron	0.1
Secondary electron	0.3
Number of tag	0.4
Tag bias	0.2
Tracking	0.3
Electron identification	1.0
FSR	1.0
Total	4.1

Errors on f_{Ds}:

1.6% from $K_L e \upsilon$
(BR + energy deposit)

1.3% all others
combined

f_{Ds} = (252.5 ± 11.1 ± 5.2) MeV [± 4.4% ± 2.1%]

Note: rad. corr. is small, since tau has only 9 MeV kin. E

Combining CLEO-c

$D_s \to \tau^+\upsilon$ ($\tau^+ \to e^+\upsilon\upsilon$)

f_{Ds} = (252.5 ± 11.1 ± 5.2) MeV [± 4.4% ± 2.1%]

$D_s \to \mu^+\upsilon$, $\tau^+\upsilon$ ($\tau^+ \to \pi^+\upsilon$)

f_{Ds} = (263.3 ± 8.2 ± 3.9) MeV [± 3.1% ± 1.5%]

Combine two CLEO-c D_s results; recall D result

f_{Ds} = (259.5 ± 6.6 ± 3.1) MeV [± 2.5% ± 1.2%]

f_D = (205.8 ± 8.5 ± 2.5) MeV [± 4.1% ± 1.2%]

D_s / D Ratio:

f_{Ds} / f_D = 1.26 ± 0.06 ± 0.02

Khodjamirian obtains bounds: f_D < 230 MeV f_{Ds} < 270 MeV

(from 2-pt. Correlation functions; arXiv:0812:3747v1)

Experiment vs. Theory

Final CLEO f_{D^+} result:	f_D = 205.8 ± 8.9 MeV
2+1 unquenched lattice QCD*	208 ± 4 MeV
2+1 unquenched lattice QCD**	207 ± 11 MeV

Excellent Agreement, to ~5% (7%) accuracy

Final CLEO $f_{D_s^+}$ result:	f_{Ds} = 259.5 ± 7.3 MeV
2+1 unquenched lattice QCD obtains*	241 ± 3 MeV
2+1 unquenched lattice QCD obtains**	249 ± 11 MeV

*2.3 σ high ? **Or need more accuracy?

CLEO-c ratio of $f_{D_s^+}/f_{D^+}$	f_{Ds}/f_D = 1.26 ± 0.06
2+1 unquenched lattice QCD obtains*	1.162 ± 0.009
2+1 unquenched lattice QCD obtains**	1.20 ± 0.024

*1.6 σ high ? **Or need more accuracy?

* Follana et al. (HPQCD/UKQCD), PRL 100, 062002 (2008)

** Bernard et al. (FNAL/MILC), arXiv:0904.1895

Other predictions are in backup slides.

If D_s Discrepancy is Real…

Models need to raise f_{Ds} without much effect on f_D

Dobrescu & Kronfeld argue that possible New Physics could be either a charged Higgs (their own model) or leptoquarks

[PRL 100, 241802 (2008)]

Kundu & Nandi suggest R-parity violating SUSY to explain large f_{Ds} and B_s mixing phase [PRD 78, 015009 (2008)]

Hewett, and Akeroyd & Chen, also discussed 2 Higgs doublet model

[H: arXiv:hep-ph/9505246
A: PrThPh 111, 295 (2004); A&C: PRD 75 075004 (2007)]

Note that mass-dependent Higgs couplings exactly mimic the V-A helicity suppression, preserving the $e:\mu:\tau$ ratio

Electron Mode Limits

CLEO-c

$B(D^+ \to e^+\nu) < 8.8 \times 10^{-6}$ [960 x SM expectation]

No events in signal area

$B(D_s^+ \to e^+\nu) < 1.2 \times 10^{-4}$ [890 x SM expectation]

One event in signal area

CP-Asymmetries

CLEO-c

$[\Gamma(D^+ \to \mu^+\nu) - \Gamma(D^- \to \mu^-\nu)] / (SUM) = (8 \pm 8)\ \%$

$[\Gamma(D_s^+ \to \mu^+\nu) - \Gamma(D_s^- \to \mu^-\nu)] / (SUM) = (4.8 \pm 6.1)\ \%$

The Future

CLEO-c @ Charm Threshold: Largely Done

-- Both f_D, f_{Ds} together (and two D_s methods)

-- Also best semileptonic results:

can ratio out CKM $|V_{cq}|$ for pure LQCD test, etc.

BESIII @ Charm Threshold:

-- Now at 3 x 10^{32} $cm^{-2}s^{-1}$ [~ 4x CLEO-c; goal is 10 x 10^{32}]

-- 12x (4x) CLEO data for D (D_s) would lower statistical errors

to equal the CLEO-c systematics

Super B Factories

-- Updated f_{Ds} ? (f_D not feasible)

-- Need to maintain detector understanding at very high rates

-- Likely syst. limitations, BUT the only cross-check on the horizon

Conclusions

Experiment:

-- The future is luminosity *plus* systematic error control

Lattice QCD

-- More methods reaching high-precision

-- Continuing CPU, technical advances

Phenomenology:

-- Models that can accommodate possible deviations

BACKUP SLIDES

f_{Ds} Results Summary

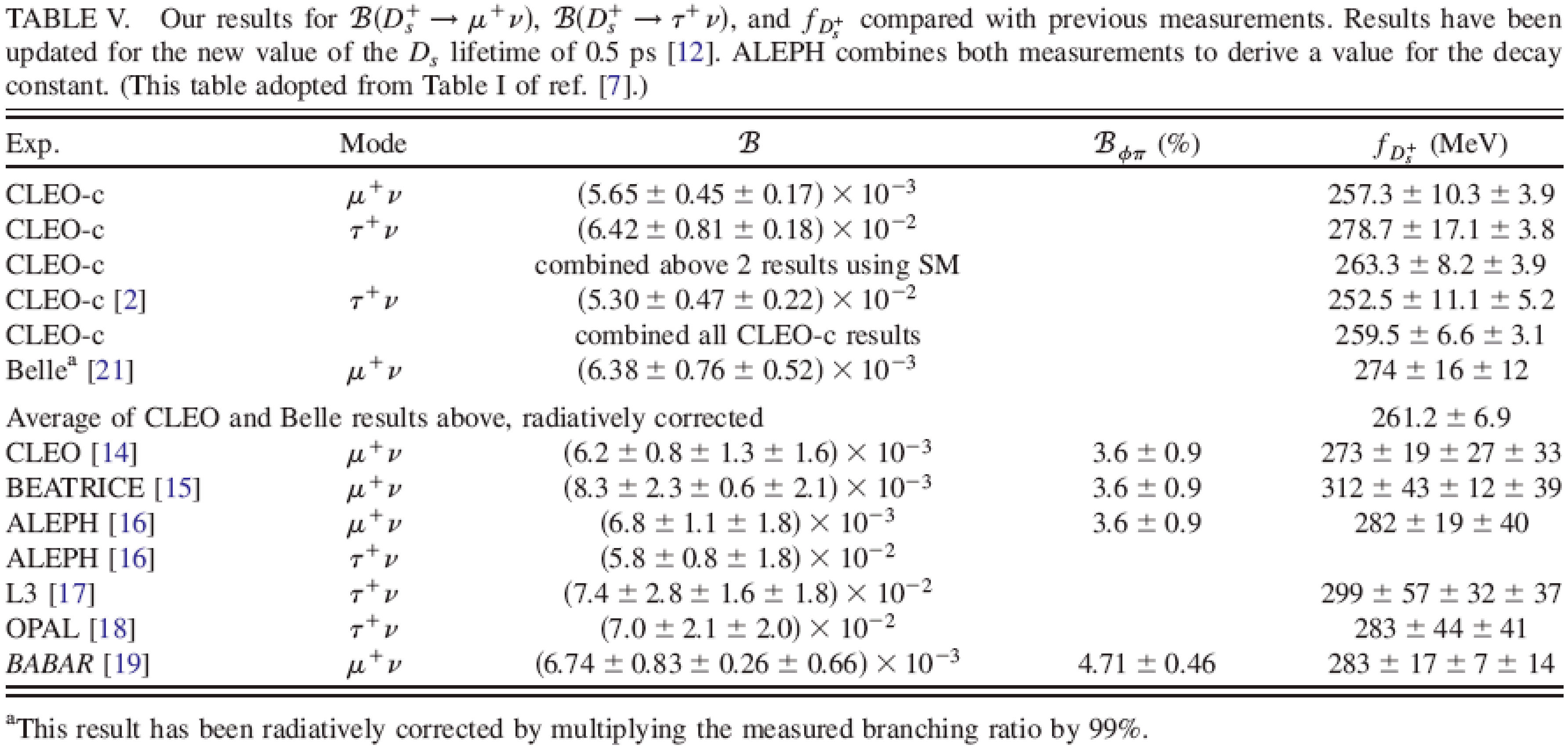


TABLE V. Our results for $\mathcal{B}(D_s^+ \to \mu^+ \nu)$, $\mathcal{B}(D_s^+ \to \tau^+ \nu)$, and $f_{D_s^+}$ compared with previous measurements. Results have been updated for the new value of the D_s lifetime of 0.5 ps [12]. ALEPH combines both measurements to derive a value for the decay constant. (This table adopted from Table I of ref. [7].)

Exp.	Mode	$\mathcal{B}$	$\mathcal{B}_{\phi\pi}$ (%)	$f_{D_s^+}$ (MeV)
CLEO-c	$\mu^+\nu$	$(5.65 \pm 0.45 \pm 0.17) \times 10^{-3}$		$257.3 \pm 10.3 \pm 3.9$
CLEO-c	$\tau^+\nu$	$(6.42 \pm 0.81 \pm 0.18) \times 10^{-2}$		$278.7 \pm 17.1 \pm 3.8$
CLEO-c		combined above 2 results using SM		$263.3 \pm 8.2 \pm 3.9$
CLEO-c [2]	$\tau^+\nu$	$(5.30 \pm 0.47 \pm 0.22) \times 10^{-2}$		$252.5 \pm 11.1 \pm 5.2$
CLEO-c		combined all CLEO-c results		$259.5 \pm 6.6 \pm 3.1$
Belle[a] [21]	$\mu^+\nu$	$(6.38 \pm 0.76 \pm 0.52) \times 10^{-3}$		$274 \pm 16 \pm 12$
Average of CLEO and Belle results above, radiatively corrected				261.2 ± 6.9
CLEO [14]	$\mu^+\nu$	$(6.2 \pm 0.8 \pm 1.3 \pm 1.6) \times 10^{-3}$	3.6 ± 0.9	$273 \pm 19 \pm 27 \pm 33$
BEATRICE [15]	$\mu^+\nu$	$(8.3 \pm 2.3 \pm 0.6 \pm 2.1) \times 10^{-3}$	3.6 ± 0.9	$312 \pm 43 \pm 12 \pm 39$
ALEPH [16]	$\mu^+\nu$	$(6.8 \pm 1.1 \pm 1.8) \times 10^{-3}$	3.6 ± 0.9	$282 \pm 19 \pm 40$
ALEPH [16]	$\tau^+\nu$	$(5.8 \pm 0.8 \pm 1.8) \times 10^{-2}$		
L3 [17]	$\tau^+\nu$	$(7.4 \pm 2.8 \pm 1.6 \pm 1.8) \times 10^{-2}$		$299 \pm 57 \pm 32 \pm 37$
OPAL [18]	$\tau^+\nu$	$(7.0 \pm 2.1 \pm 2.0) \times 10^{-2}$		$283 \pm 44 \pm 41$
BABAR [19]	$\mu^+\nu$	$(6.74 \pm 0.83 \pm 0.26 \pm 0.66) \times 10^{-3}$	4.71 ± 0.46	$283 \pm 17 \pm 7 \pm 14$

[a] This result has been radiatively corrected by multiplying the measured branching ratio by 99%.

Table from CLEO-c f_{Ds} paper

f_D, f_{D_s} Prediction Summary

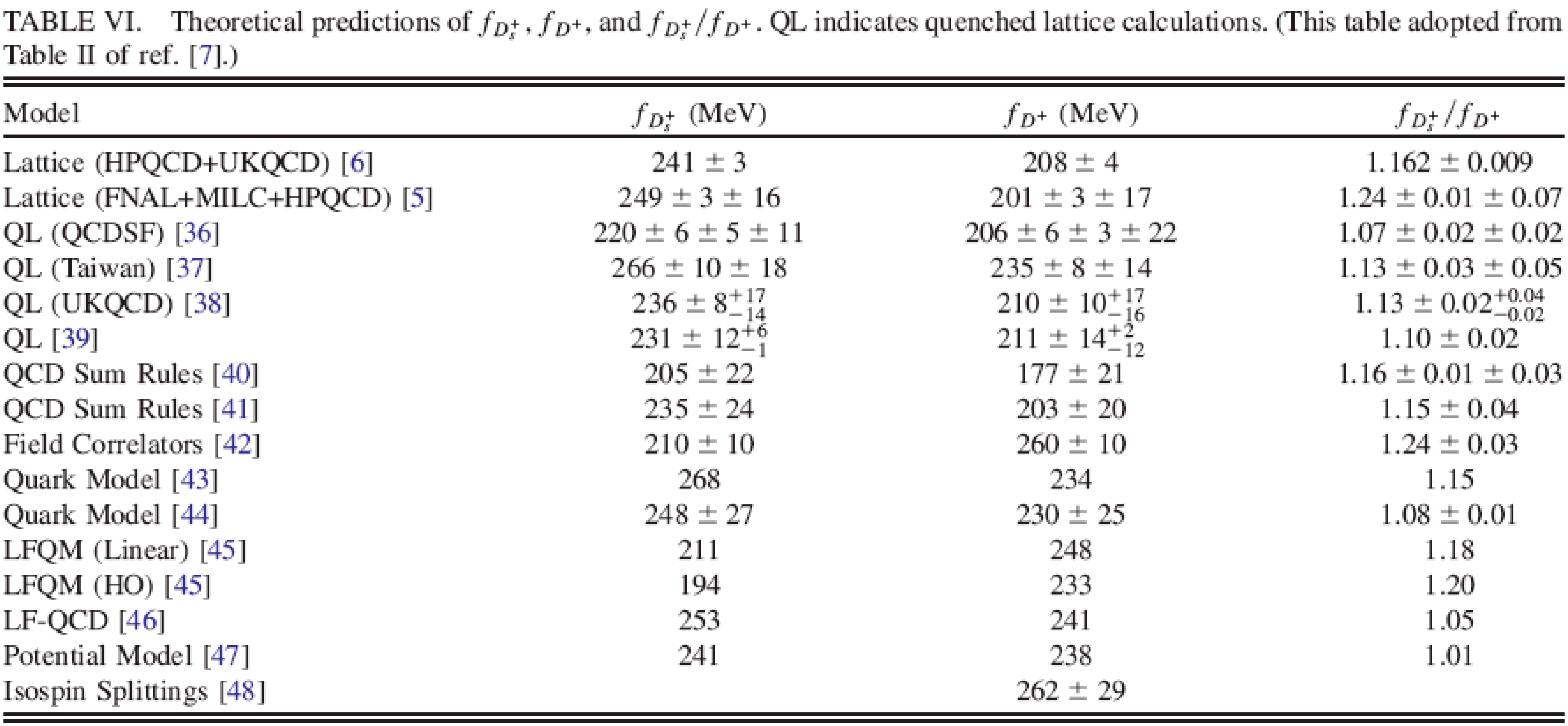


TABLE VI. Theoretical predictions of $f_{D_s^+}$, f_{D^+}, and $f_{D_s^+}/f_{D^+}$. QL indicates quenched lattice calculations. (This table adopted from Table II of ref. [7].)

Model	$f_{D_s^+}$ (MeV)	f_{D^+} (MeV)	$f_{D_s^+}/f_{D^+}$
Lattice (HPQCD+UKQCD) [6]	241 ± 3	208 ± 4	1.162 ± 0.009
Lattice (FNAL+MILC+HPQCD) [5]	$249 \pm 3 \pm 16$	$201 \pm 3 \pm 17$	$1.24 \pm 0.01 \pm 0.07$
QL (QCDSF) [36]	$220 \pm 6 \pm 5 \pm 11$	$206 \pm 6 \pm 3 \pm 22$	$1.07 \pm 0.02 \pm 0.02$
QL (Taiwan) [37]	$266 \pm 10 \pm 18$	$235 \pm 8 \pm 14$	$1.13 \pm 0.03 \pm 0.05$
QL (UKQCD) [38]	$236 \pm 8^{+17}_{-14}$	$210 \pm 10^{+17}_{-16}$	$1.13 \pm 0.02^{+0.04}_{-0.02}$
QL [39]	$231 \pm 12^{+6}_{-1}$	$211 \pm 14^{+2}_{-12}$	1.10 ± 0.02
QCD Sum Rules [40]	205 ± 22	177 ± 21	$1.16 \pm 0.01 \pm 0.03$
QCD Sum Rules [41]	235 ± 24	203 ± 20	1.15 ± 0.04
Field Correlators [42]	210 ± 10	260 ± 10	1.24 ± 0.03
Quark Model [43]	268	234	1.15
Quark Model [44]	248 ± 27	230 ± 25	1.08 ± 0.01
LFQM (Linear) [45]	211	248	1.18
LFQM (HO) [45]	194	233	1.20
LF-QCD [46]	253	241	1.05
Potential Model [47]	241	238	1.01
Isospin Splittings [48]		262 ± 29	

Table from CLEO-c f_{Ds} paper

(FNAL/MILC arXiv:0904.1895 appeared later)

BaBar f_{Ds} Result

BaBar (2007) 230 fb^{-1}
PRL 98, 141801

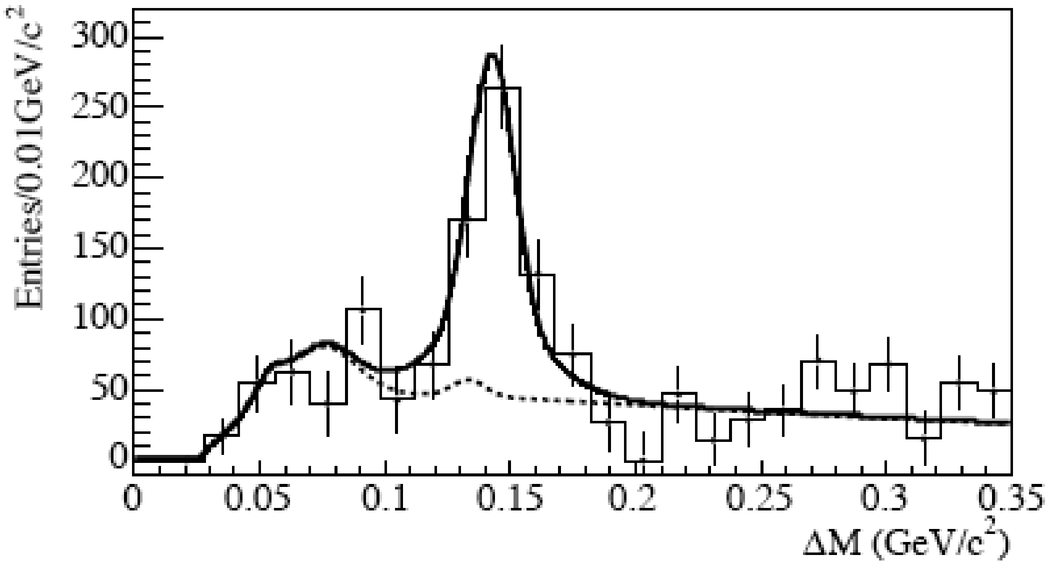


FIG. 3: ΔM distribution after the tag sidebands and the electron sample are subtracted. The solid line is the fitted signal and background distribution ($N_{\rm Sig} f_{\rm Sig} + N_{\rm Bkgd} f_{\rm Bkgd}$), the dashed line is the background distribution ($N_{\rm Bkgd} f_{\rm Bkgd}$) alone.

f_D = 283 ± 17 ± 7 ± 14 MeV

[last error from B($\phi\pi$)]