Leptonic D & D_s Decays from CLEO-c and Prospects for BESIII

Roy A. Briere
Carnegie Mellon

(+ CLEO-c & BESIII)

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U.S. DEPARTMENT OF ENERGY

NSF

Outline

Introduction

CLEO-c Results:

all published; so I'll try to add some insights…

$D^+ \to \mu\nu$

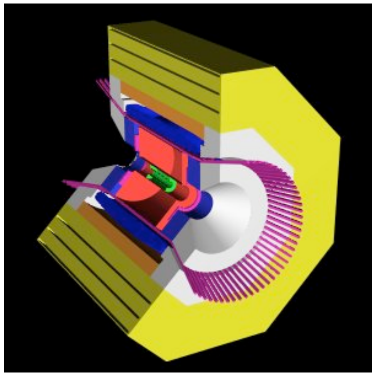
$D_s \to \mu\nu, \tau\nu$ [$\tau \to \pi\nu$]

$D_s \to \tau\nu$ [$\tau \to e\nu\nu$]

$D_s \to \tau\nu$ [$\tau \to \rho\nu$]

The Future at BESIII

CLEO-c

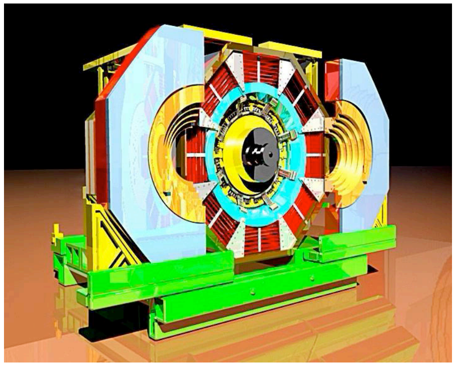


Take-home message:

charm threshold gives

BOTH f_D and f_{Ds}

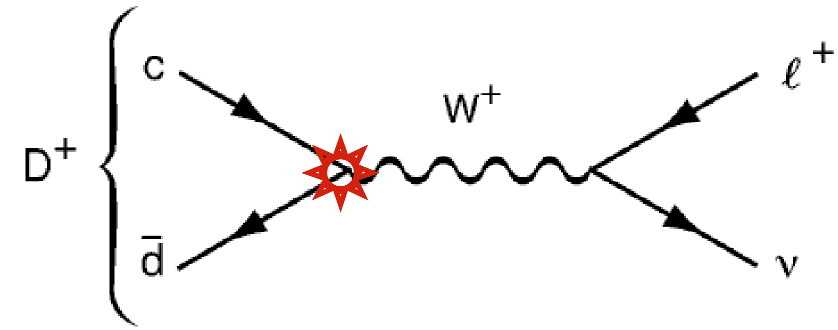
BESIII



Theory-on-a-Page

Phase Space
inhibits τ ,
esp. for D^+

Decay Constant
Our Prey



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

Helicity Suppression
favors τ, μ over e

CKM
larger Γ & BR for D_s

Comparing $D_{(s)}$ and $B_{(s)}$

B^0, B^0_s mixing experimental results are not fully utilized: theory limited due to $f_{B(s)}$ uncertainty

Charm: has <u>both</u> D^+, D_s^+ leptonic decays

- *Can measure SU(3) breaking*

Beauty: have only B^+ leptonic (= B^0 via isospin)

- *Hard to measure directly*
- *AND, we need f_{Bs} in addition to f_B*

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

Can do precision tests of modern lattice QCD, including SU(3) breaking, in the charm sector

Helicity & Phase Space

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

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

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 certain large one-prong tau decays:

18% $e\upsilon\upsilon$ 11% $\pi\upsilon$ 25.5% $\rho\upsilon$

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:

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

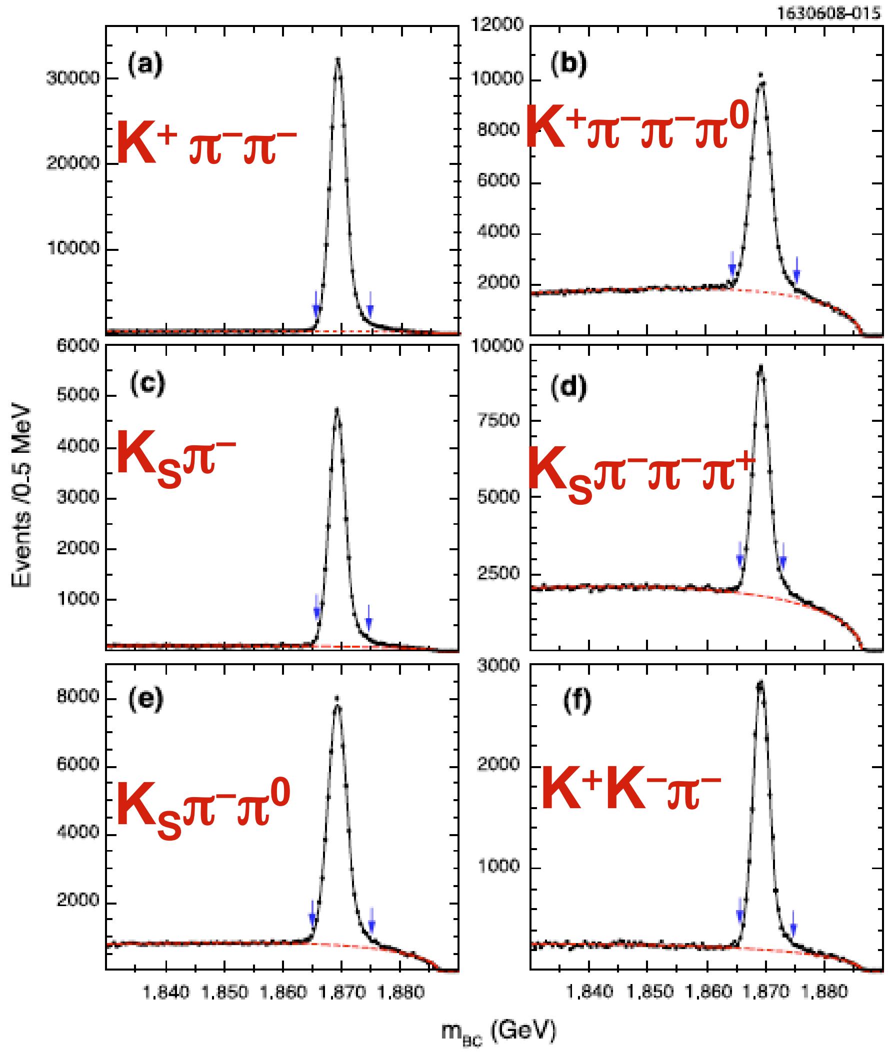
creates ONLY D pairs

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

CLEO-c D^- Tags
= fully-recon. hadronic decay



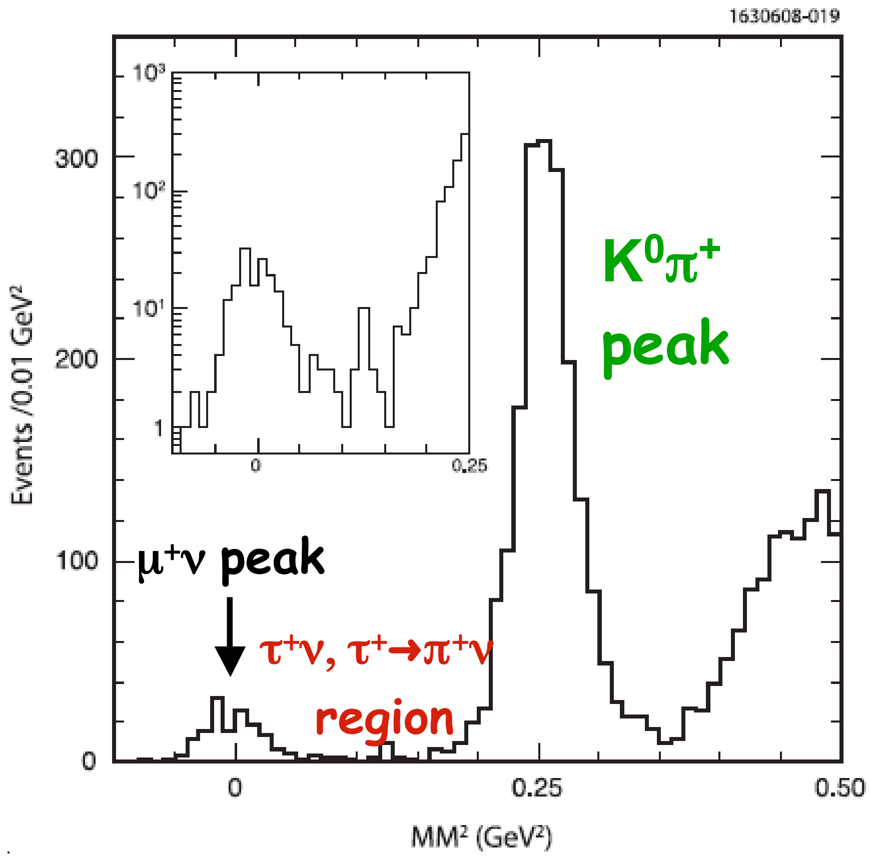
$D^+ \to \mu^+\upsilon$

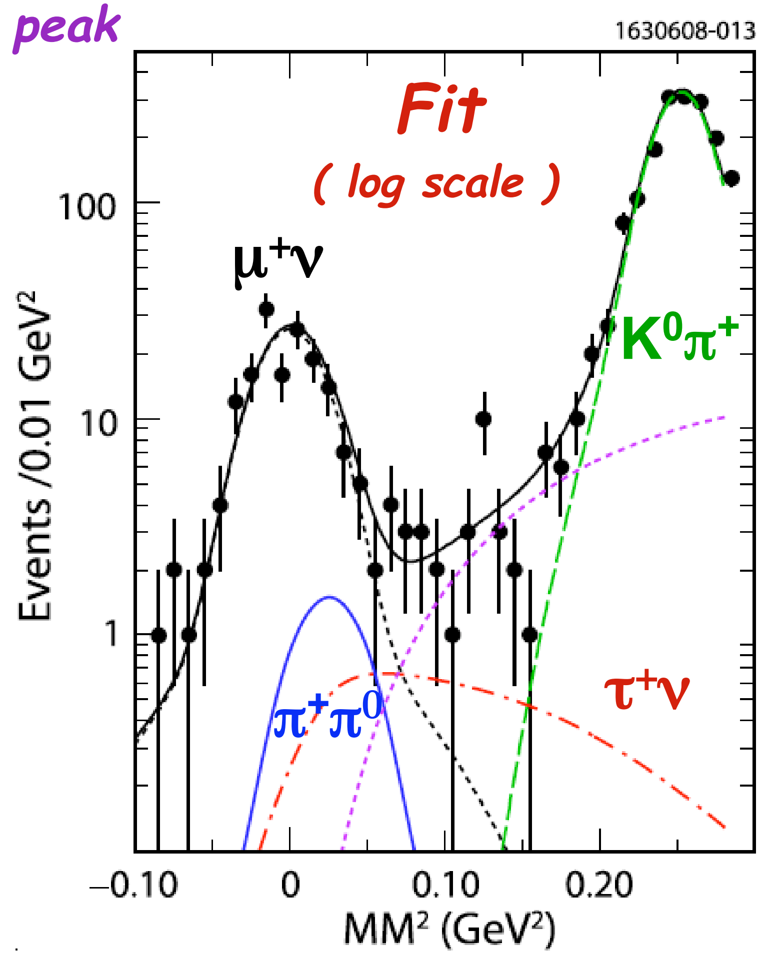
PRD 78, 052003
2008 818 pb^{-1}

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

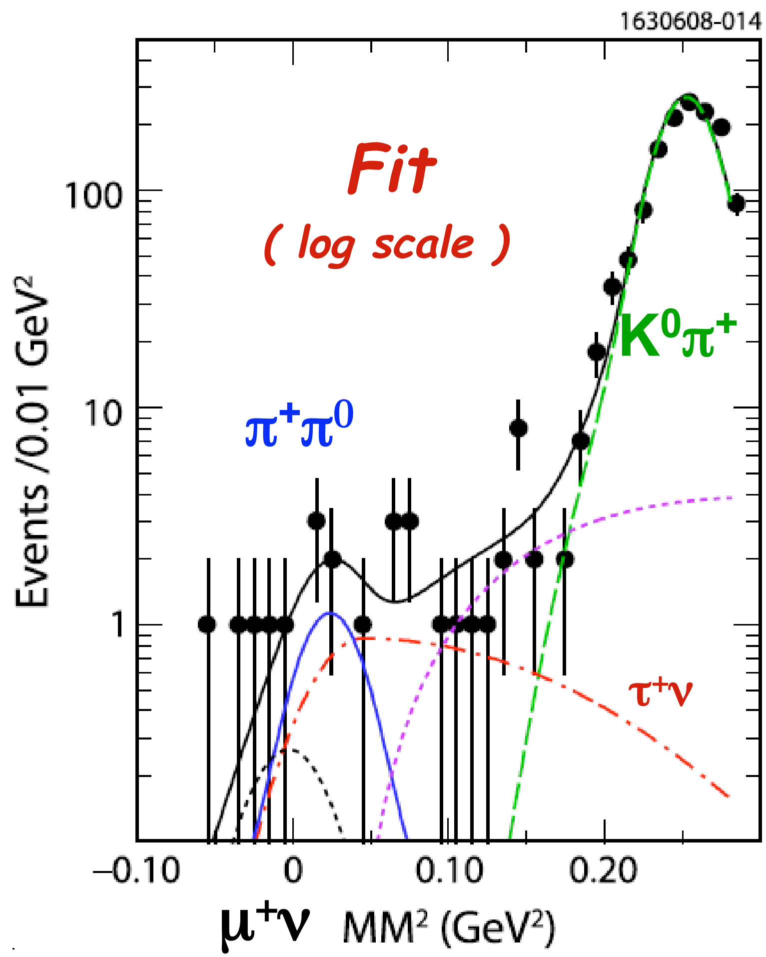
$\tau^+\nu$, $\tau^+ \to \pi^+\nu$ **shows up in both**

$\pi^+\pi^0$ **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:

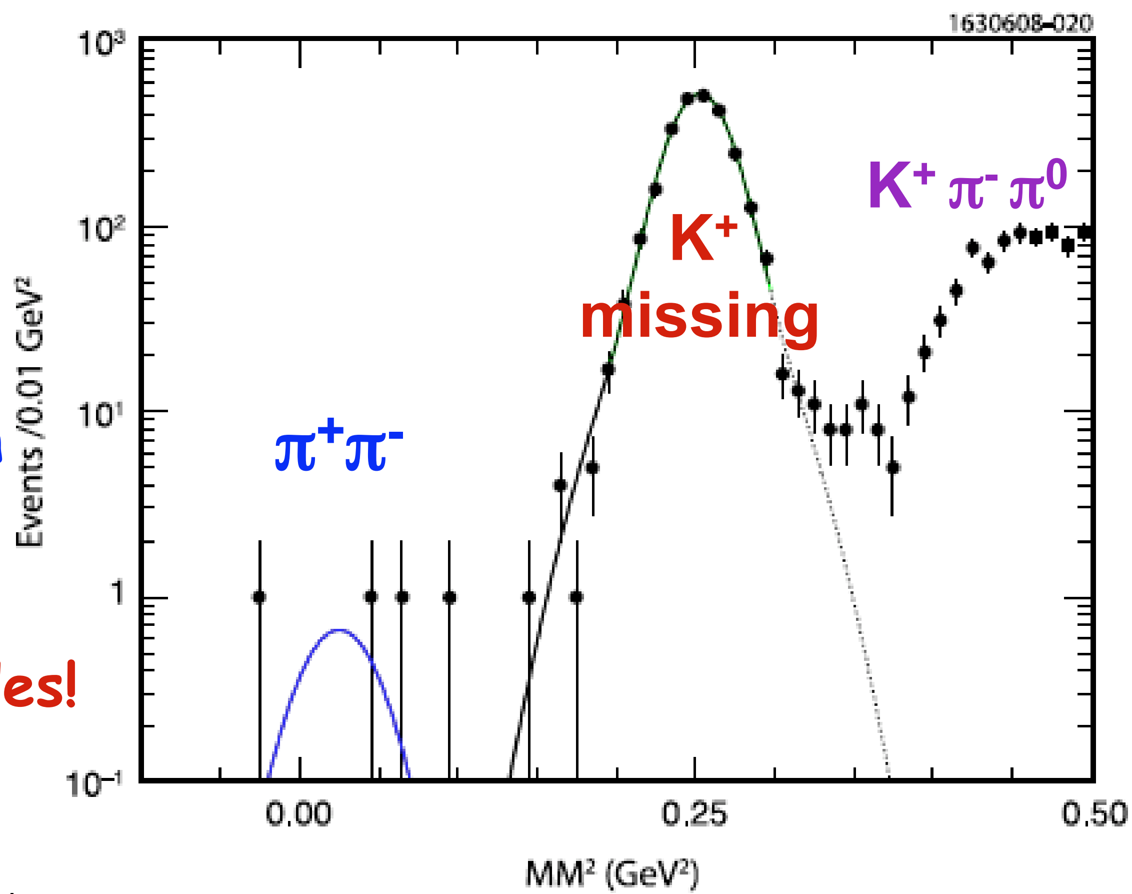
$D^0 \rightarrow K^-\pi^+$

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}

Already only
1.1% on f_D !

No one dominant
source of error.

May be hard
to improve ???

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

But… most of systematics are based on data.

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

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

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

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

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

Float $\tau\nu/\mu\upsilon$: (for non-SM scenarios, only small loss of precision)

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

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

Selected Lattice QCD:

2+1 unquenched lattice QCD*	213	$\pm$	4	MeV
2+1 unquenched lattice QCD**	217	$\pm$	10	MeV

* Follana et al. (HPQCD/UKQCD), PRL 100, 062002 (2008)
central value updated indirectly from 207 to 213,
in Davies et al. (HPQCD), arXiv:1008.4018

** Bazavov et al. (FNAL/MILC), arXiv:0912.5221

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

Also, with updated V_{cs} : "SM result" is $f_D+ = (206.7 \pm 8.5 \pm 2.5)$ MeV

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

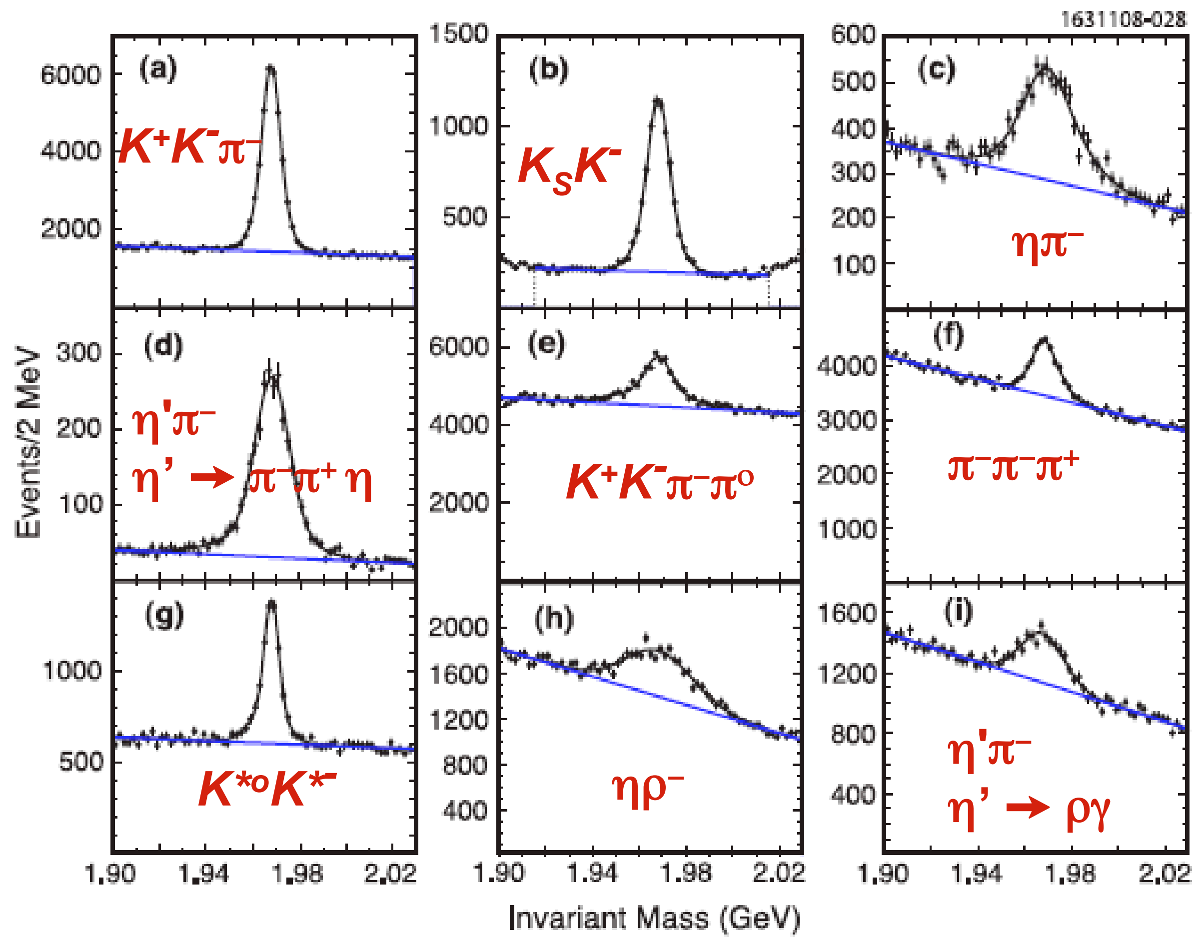
PRD 79, 052001 (2009) 600 pb^{-1}

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 contiunuum

Invariant mass of 9 tag modes



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

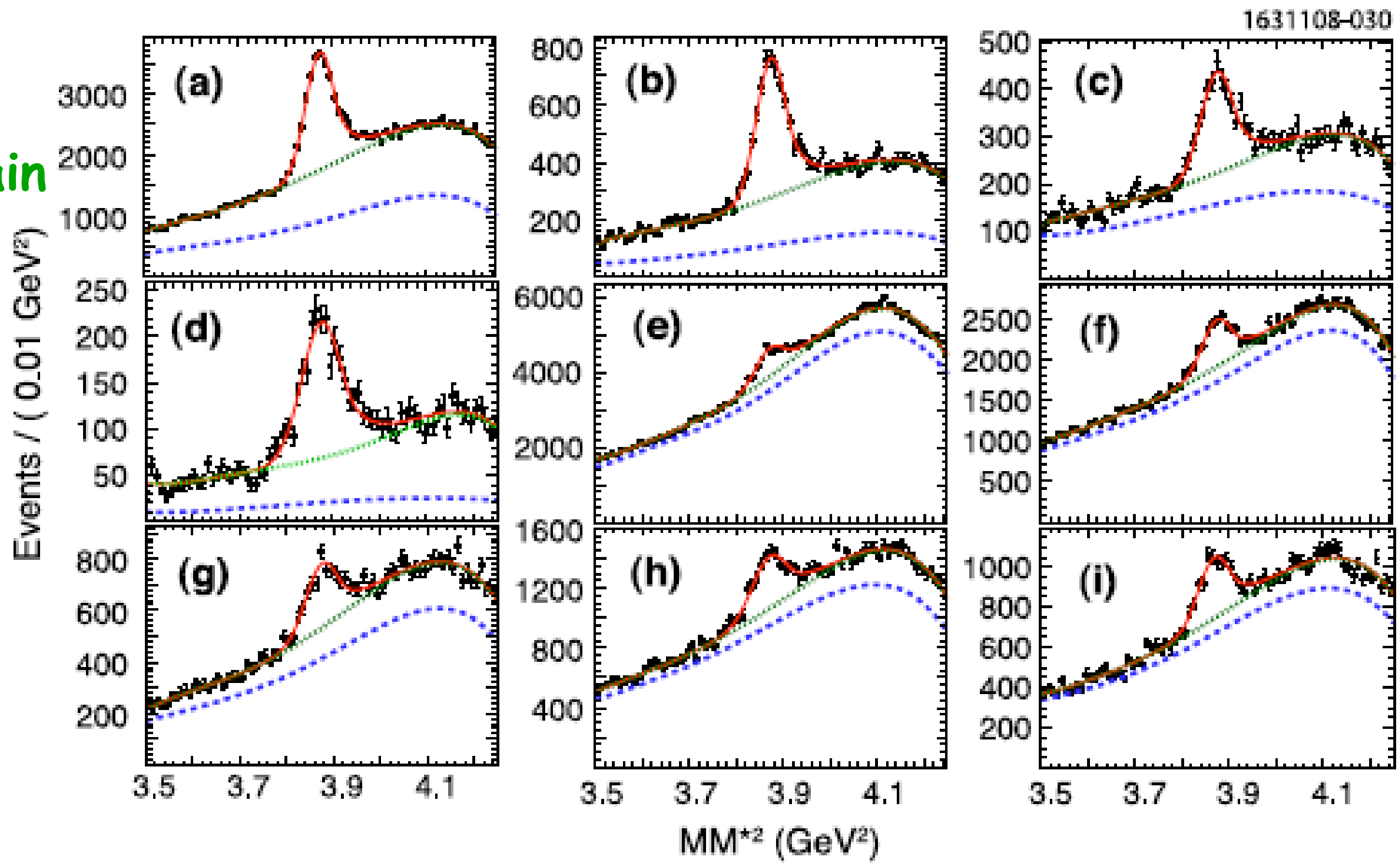
PRD 79, 052001 (2009) 600 pb^{-1}

Look at missing mass after adding photon

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

Plot missing-mass² 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 $\tau^+\nu$, $\tau^+\rightarrow\pi^+\nu$ is also here)

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

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

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

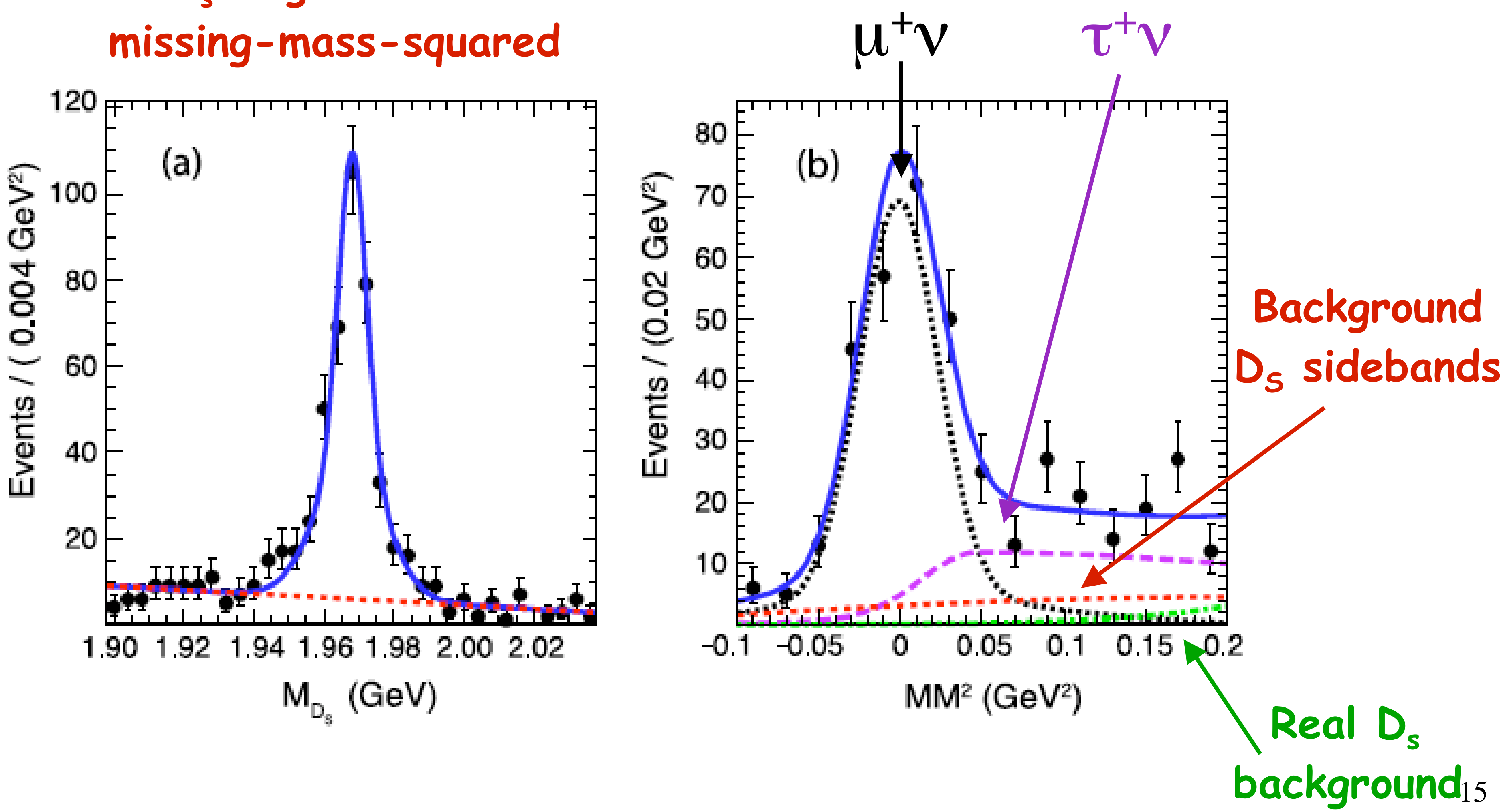
First, I will show combined data, then separated…

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

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

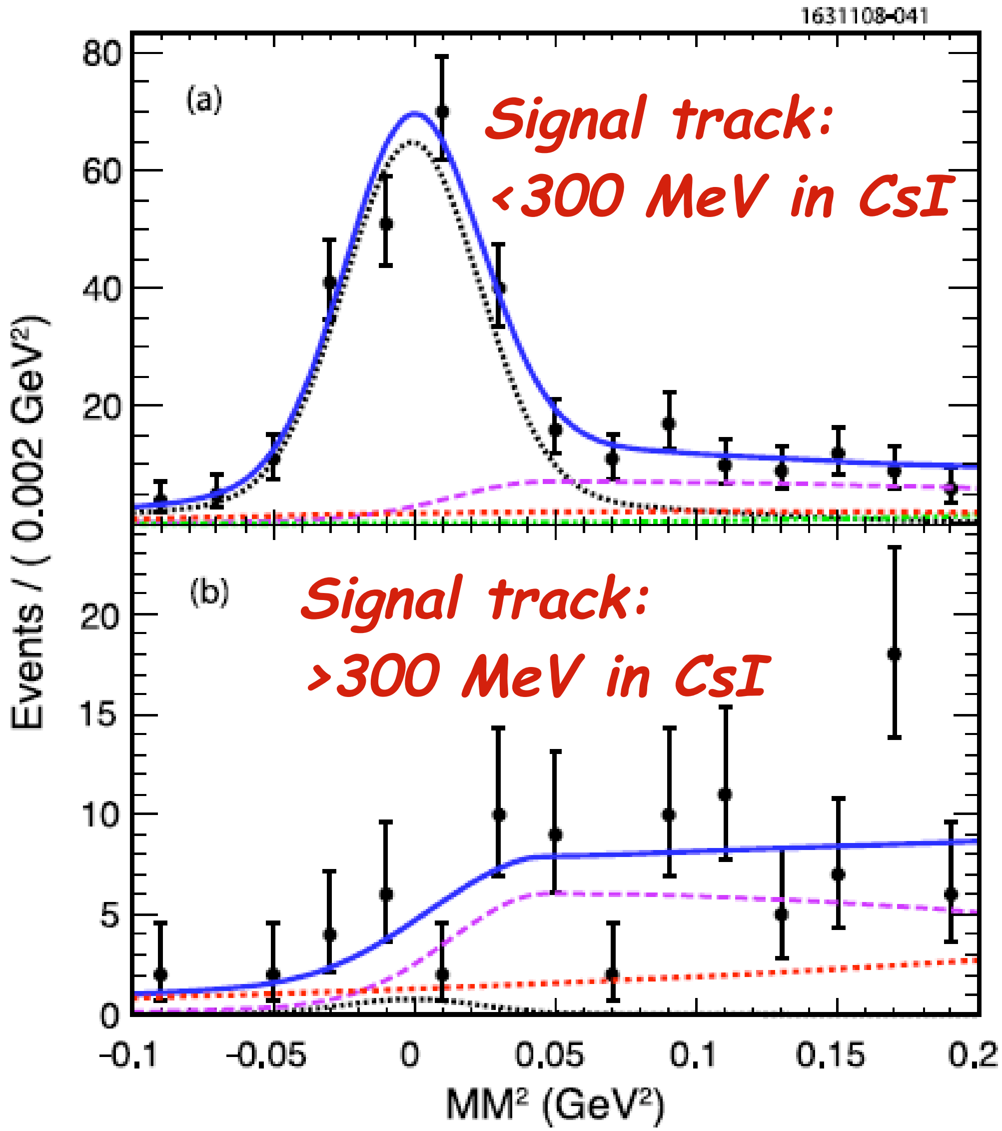
2-dimensional fit to D_s Tag mass and missing-mass-squared

Two signal modes



Separated Data

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



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 $-0.1 < \mathrm{MM}^2 < 0.2$ 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_{Ds} 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_{Ds} = (263.3 ± 8.2 ± 3.9) MeV [± 3.1% ± 1.5%]

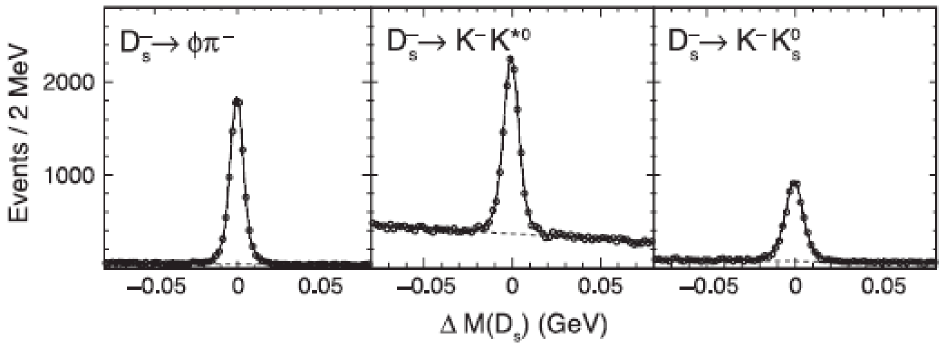
$\Gamma(D^+ \to \tau^+\nu) / \Gamma(D^+ \to \mu^+\nu)$ = 11.74 ± 1.7 ± 0.2 [SM = 9.76]

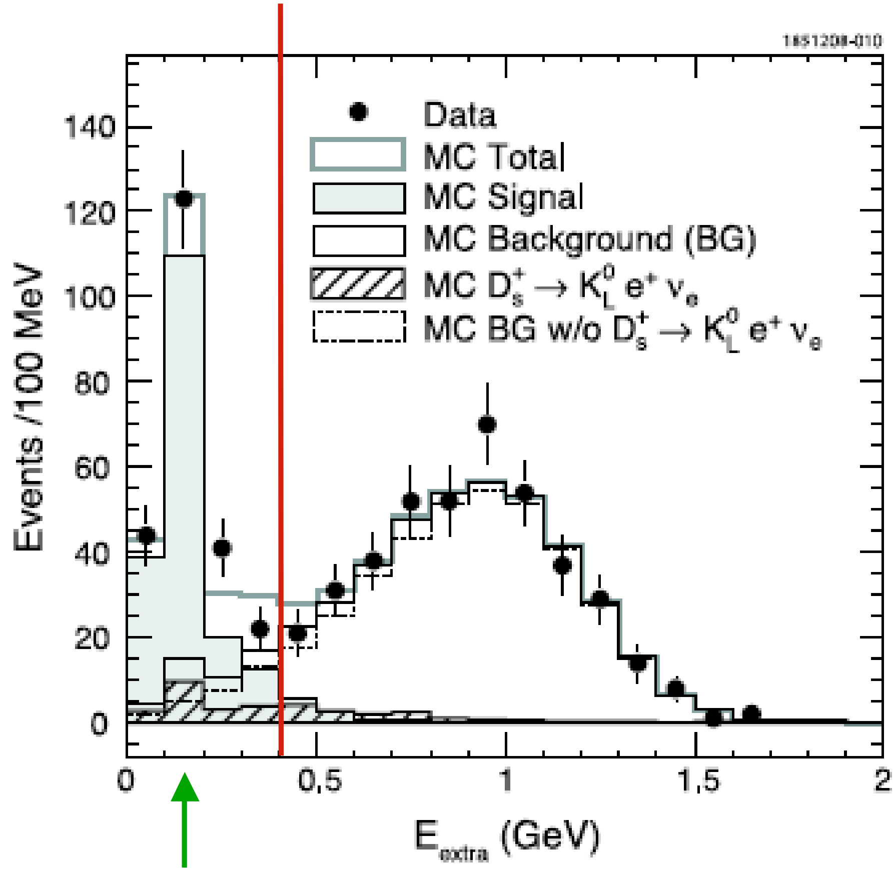
$D_s \to \tau^+\upsilon \quad (\tau^+ \to e^+\upsilon\upsilon)$

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

Signal region: <400 MeV

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)

Peaks away from zero:
E_{extra} may 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
$D_s^+ \to K_L^0 e^+ \nu_e$ (peaking)	3.2
Extra shower	1.1
Extra track	1.1
$Q_{\rm net} = 0$	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

#tag effect smaller than before:
no γ from D_s^* required…

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

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

PRD 80, 112004 (2009) 600 pb^{-1}

Signal (large frac. of total)

$\eta\rho^+$

Fake D_s

$K\pi\pi^0$

Sum of 6 minor exclusive

other

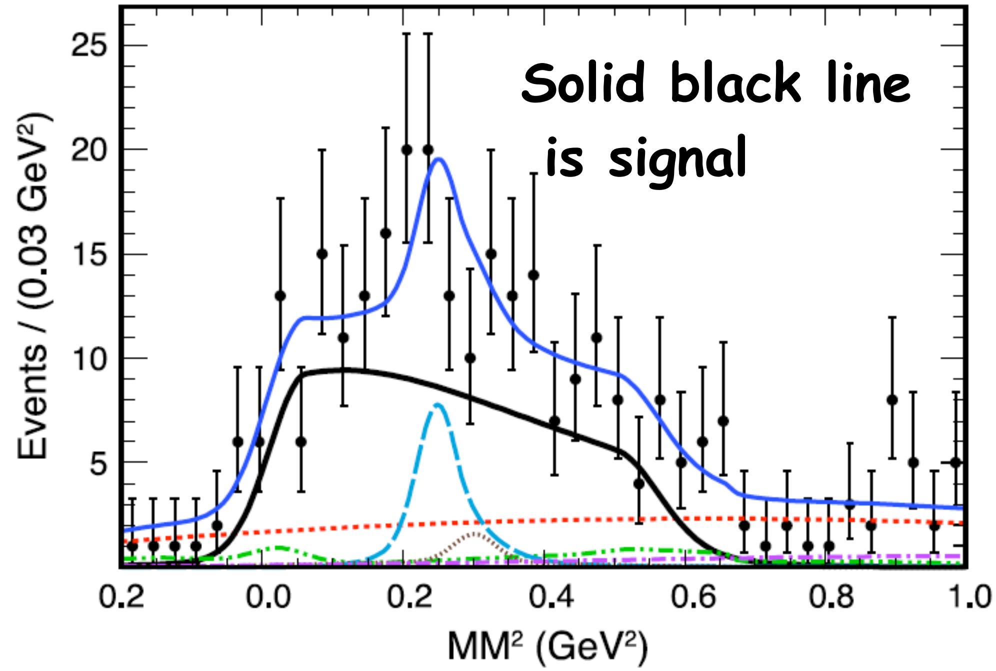


TABLE II. Systematic errors on determination of the branching fraction.

Error source	Size (%)
Finding the π^+ track from the ρ^+ decay	0.3
Hadron identification	1.0
Finding the π^0 from the ρ^+ decay	1.3
$E_{\text{extra}} < 0.2$ GeV and π^0 efficiencies on background	1.1
$E_{\text{extra}} < 0.2$ GeV signal efficiency	2.0
Background modeling	1.1
Number of tags	2.0
Tag bias	1.0
Total	3.8

No time for details: comprehensive analysis !

CLEO f_{Ds} Summary

PRD 80, 112004 (2009) 600 pb^{-1}

TABLE IV. Recent absolute measurements of f_{D_s} from CLEO-c.

Experiment	Mode	$\mathcal{B}$ (%)	f_{D_s} (MeV)
This result	$\tau^+\nu\ (\rho^+\bar{\nu})$	$(5.52 \pm 0.57 \pm 0.21)$	$257.8 \pm 13.3 \pm 5.2$
CLEO-c [9]	$\tau^+\nu\ (\pi^+\bar{\nu})$	$(6.42 \pm 0.81 \pm 0.18)$	$278.0 \pm 17.5 \pm 4.4$
CLEO-c [13]	$\tau^+\nu\ (e^+\nu\bar{\nu})$	$(5.30 \pm 0.47 \pm 0.22)$	$252.6 \pm 11.2 \pm 5.6$
Average	$\tau^+\nu$	$(5.58 \pm 0.33 \pm 0.13)$	$259.7 \pm 7.8 \pm 3.4$
CLEO-c [9]	$\mu^+\nu$	$(0.565 \pm 0.045 \pm 0.017)$	$257.6 \pm 10.3 \pm 4.3$
Average	$\tau^+\nu + \mu^+\nu$		$\boxed{259.0 \pm 6.2 \pm 3.0}$

CLEO-c: ±2.4% ±1.2%

New HFAG World Ave 257.3 ± 5.3 MeV (see backup slides)

Selected Lattice QCD:

2+1 unquenched lattice QCD*	248	±	2.5	MeV
2+1 unquenched lattice QCD**	260	±	10	MeV

* Davies et al. (HPQCD), arXiv:1008.4018

** Bazavov et al. (FNAL/MILC), arXiv:0912.5221

Statistical Power for D_s

$mean^2/\sigma_{stat}^2$, normalized to $D_s \to \mu^+\upsilon$

(like an "additional luminosity" factor…)

$D_s \to \mu^+\upsilon$:	1.00	Done as joint analysis
$D_s \to \tau^+\upsilon;\ \tau^+ \to \pi^+\upsilon$	0.40	
$D_s \to \tau^+\upsilon;\ \tau^+ \to e^+\upsilon\upsilon$	0.81	Doubles stat. power !
$D_s \to \tau^+\upsilon;\ \tau^+ \to \rho^+\upsilon$	0.59	

External Systematics

Effects on decay constants are listed;
this is 1/2 of the effect on BF

› not currently dominant ‹

$D_{(s)}$ Lifetimes:

0.34% for D 0.7% for D_s (from FOCUS)

radiative corrections on $D_{(s)} \to \mu^+\upsilon$:

0.5% (conservative? improvable?)

τ BFs for $D_s \to \tau^+\upsilon$ ($\tau^+ \to e^+\upsilon\upsilon$, $\pi^+\upsilon$, $\rho^+\upsilon$):

0.14%, 0.32%, 0.18%

V_{cd} : 0.5% V_{cs} , masses: negligible

The Future @ Threshold

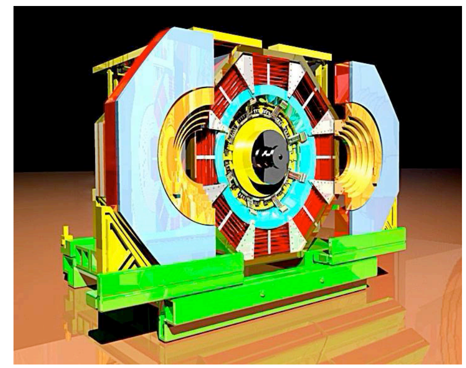
BESIII :

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

> 12x (4x) CLEO data for D (D_s) would lower statistical errors
to equal the CLEO-c systematics (assuming equal efficiencies !)

BESIII data in-hand :

Jan-Jul 2010: ~910 pb^{-1} @ $\psi(3770)$
(and a peak scan, in addition)
Expect improved luminosity next 3770 run



Tasks :

Achieve CLEO-c efficiency and systematic understanding

> Different PID: TOF vs. RICH

> Similar drift chamber, calorimetry
(BESIII CsI has small barrel/endcap gap)

> More luminosity, but also higher currents and more noise …

Further Observations…

Note that one can take ratios of leptonic decay constants and semileptonic form-factors to cancel CKM matrix elements

$D^+ \rightarrow \mu^+\nu$ & $D^0 \rightarrow \pi^- e^+\nu$ both Cabibbo-suppressed

$D_s^+ \rightarrow \mu^+\nu$ & $D^0 \rightarrow K^- e^+\nu$ larger modes

We can also compare the relative ease of the two leptonic modes

CLEO-c stat errors, normalized to 1 fb^{-1} each:

f_D 3.7 % f_{Ds} 1.9 % --> D_s easier w.r.t. statistics

Energy for Ds running: 4015 vs. 4170 MeV

- CESR-c was better at higher E_{cm} , BEPC-II better closer to 3770
- Cross section*: 0.27 nb D_sD_s @ 4015 vs. 0.92 nb D_sD_s* @ 4170
- Better efficiency without D_s* transition photon

* CLEO-c, PRD 80, 072001

Conclusions

Charm decay constants can verify lattice QCD
Verified lattice QCD helps extract V_{td}, V_{ts} from $B_{(s)}$ mixing
Charm threshold gives BOTH f_D and f_{Ds}

CLEO-c, at charm threshold, has best results
- ONLY significant f_D result
- Slightly better than B factories for f_{Ds},
  - but noticeably better on systematics

Current agreement with LQCD is good,

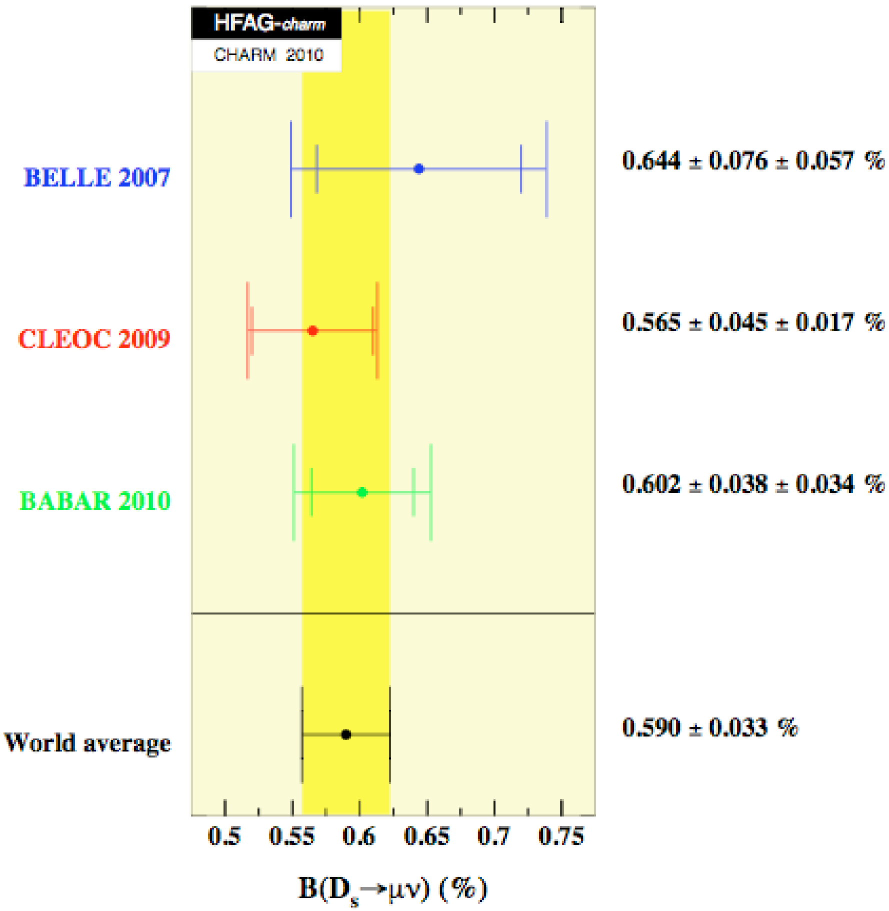
BESIII has taken data at 4x CLEO-c luminosity
- CLEO-size dataset in hand for D
- No Ds running, yet …

If BESII analyses do as well as CLEO-c, the larger datasets will clearly continue to improve experimental precision …

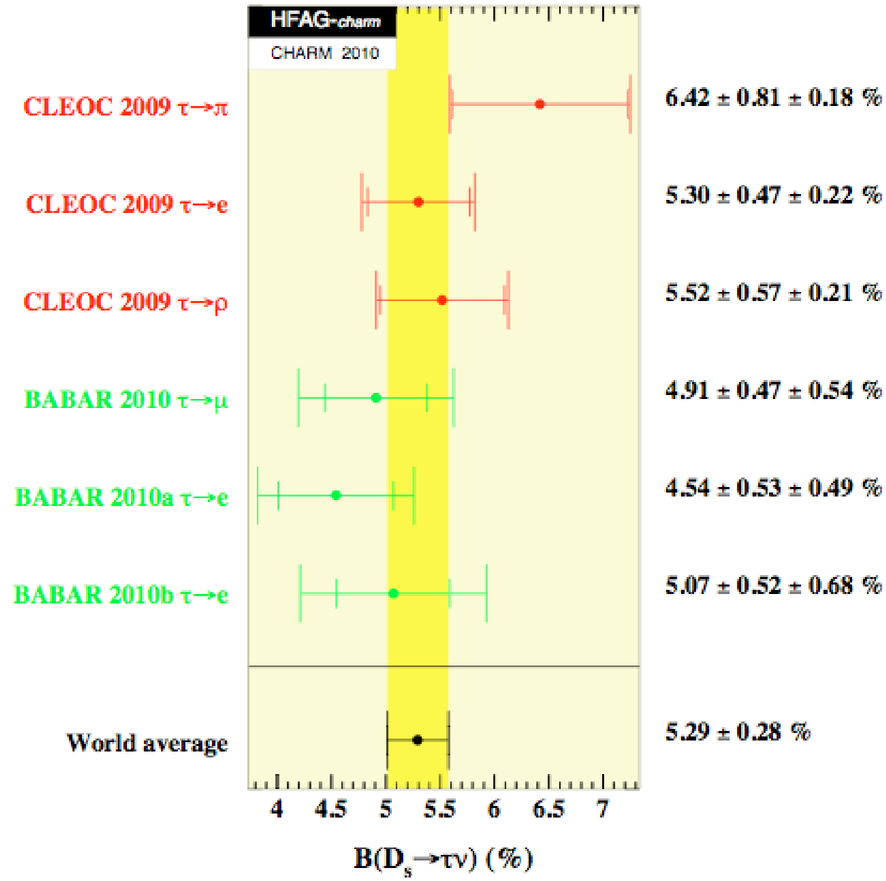
BACKUP SLIDES

New HFAG D_s Branching Fractions

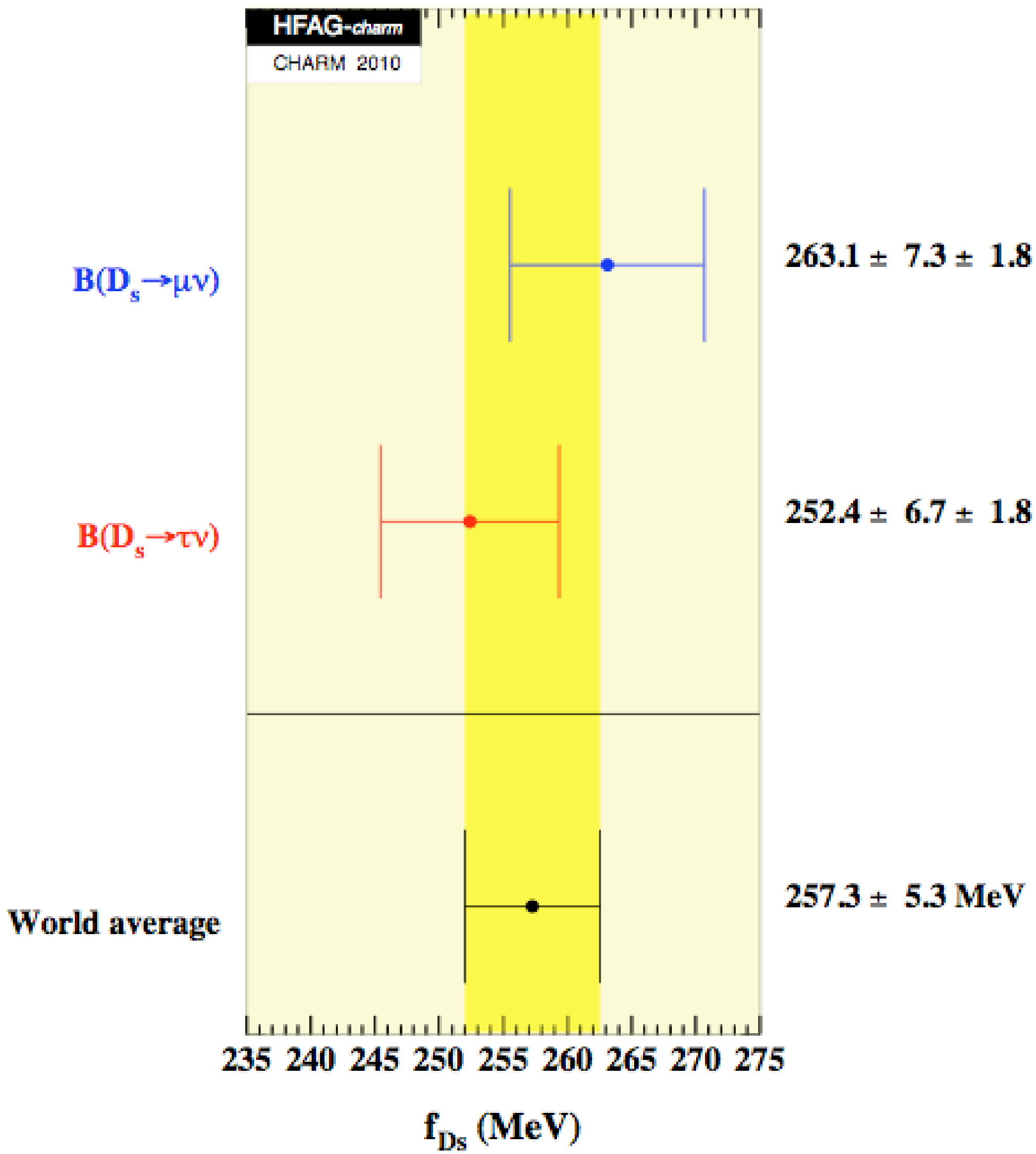
$B\ (D_s \to \mu\nu)$



$B\ (D_s \to \tau\nu)$



New HFAG f_{Ds}



Note that f_D is all CLEO-c (no B-factories)

Electron Mode Limits

CLEO-c

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

No events in signal area

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

One event in signal area

CP Asymmetries

CLEO-c

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

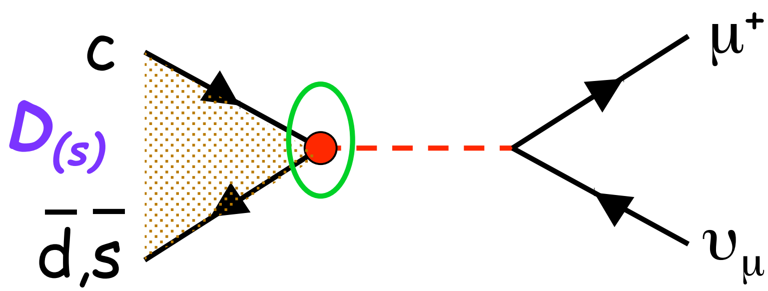
$[\Gamma(D_s^+ \rightarrow \mu^+\nu) - \Gamma(D_s^- \rightarrow \mu^-\nu)] / (SUM) = (4.8 \pm 6.1)\ \%$

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

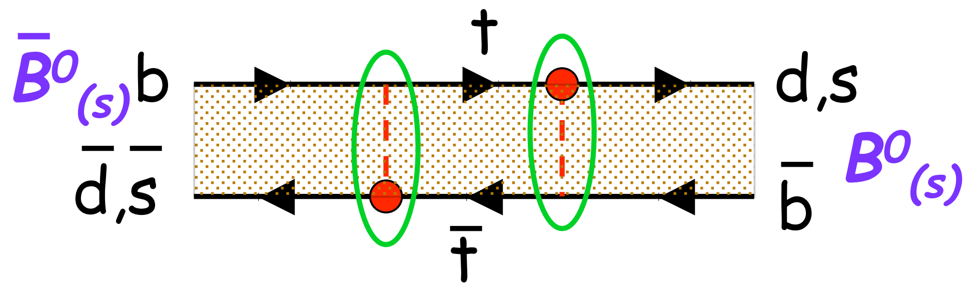
PRD 79, 052001
(2009) 600 pb^{-1}

B Physics Connection

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



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

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