Experimental overview on $D_{(s)}^+$ purely leptonic decays

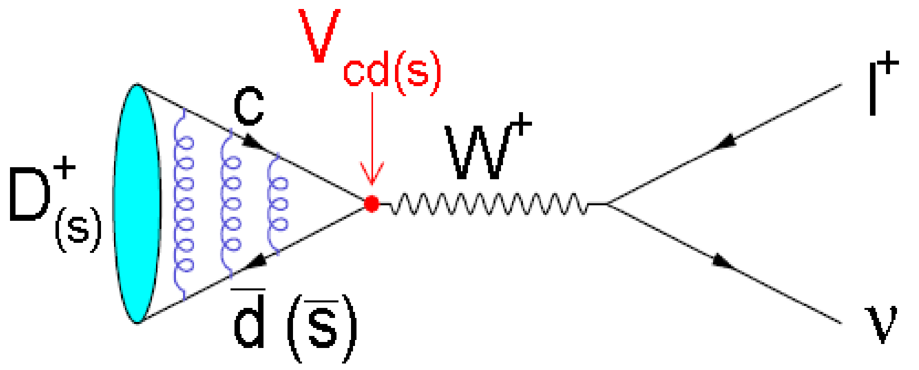
Hailong Ma (IHEP,CAS)

9th International Workshop on the CKM Unitarity Triangle,
Nov. 28-Dec. 2, 2016, TIFR, Mumbai, India

Contents

- Introduction
- $D_{(s)}^{+} \rightarrow l^{+}v$
  - Overview in the past 30 years
  - Measurement or prospect at BESIII
- Summary

Introduction



Leptonic D decays are ideal window to probe for weak and strong effects

In the SM:

$$\Gamma(D^+_{(s)} \to \ell^+ \nu_\ell) = \frac{G_F^2 f^2_{D^+_{(s)}}}{8\pi} |V_{cd(s)}|^2 m_\ell^2 m_{D^+_{(s)}} \left(1 - \frac{m_\ell^2}{m^2_{D^+_{(s)}}}\right)^2$$

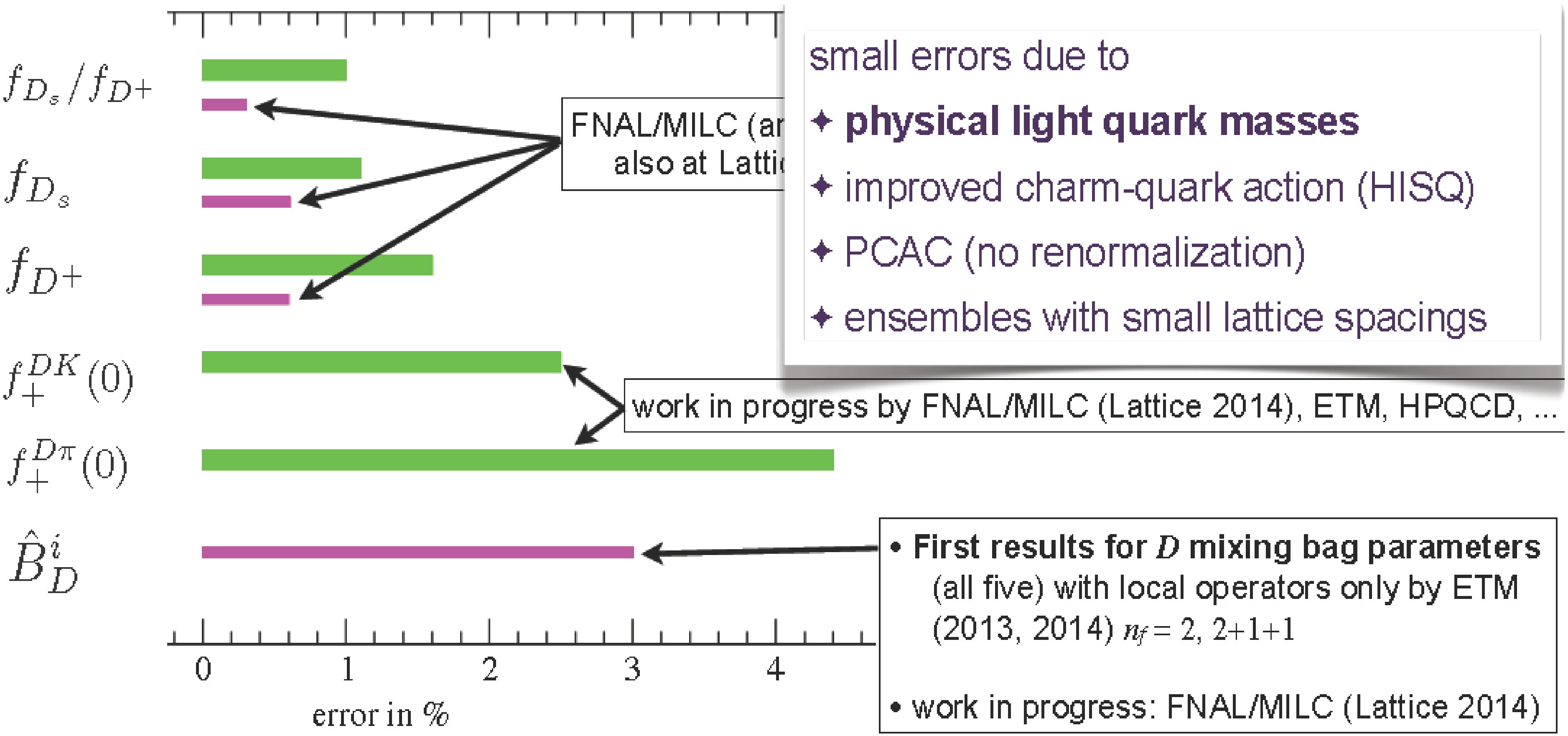
- **Precision measurements of decay constants f_{D+}, f_{Ds} of D mesons can calibrate LQCD calculations at higher accuracy. Once they pass experimental tests, the precise LQCD calculations on f_D/f_B, f_{Ds}/f_{Bs} will be helpful for measurements in B decays**

- **Recent LQCD calculations on $f_{D(s)+}$[0.5(0.5)%] provide good chance to precisely measure the CKM matrix element $|V_{cs(d)}|$, which are important for the unitarity test of the CKM matrix**

Progress in LQCD Calculation

Taking from Aida X. El-Khadra's talk at Beauty2014

errors (in %) comparison: **FLAG-2 averages** vs. **new results**

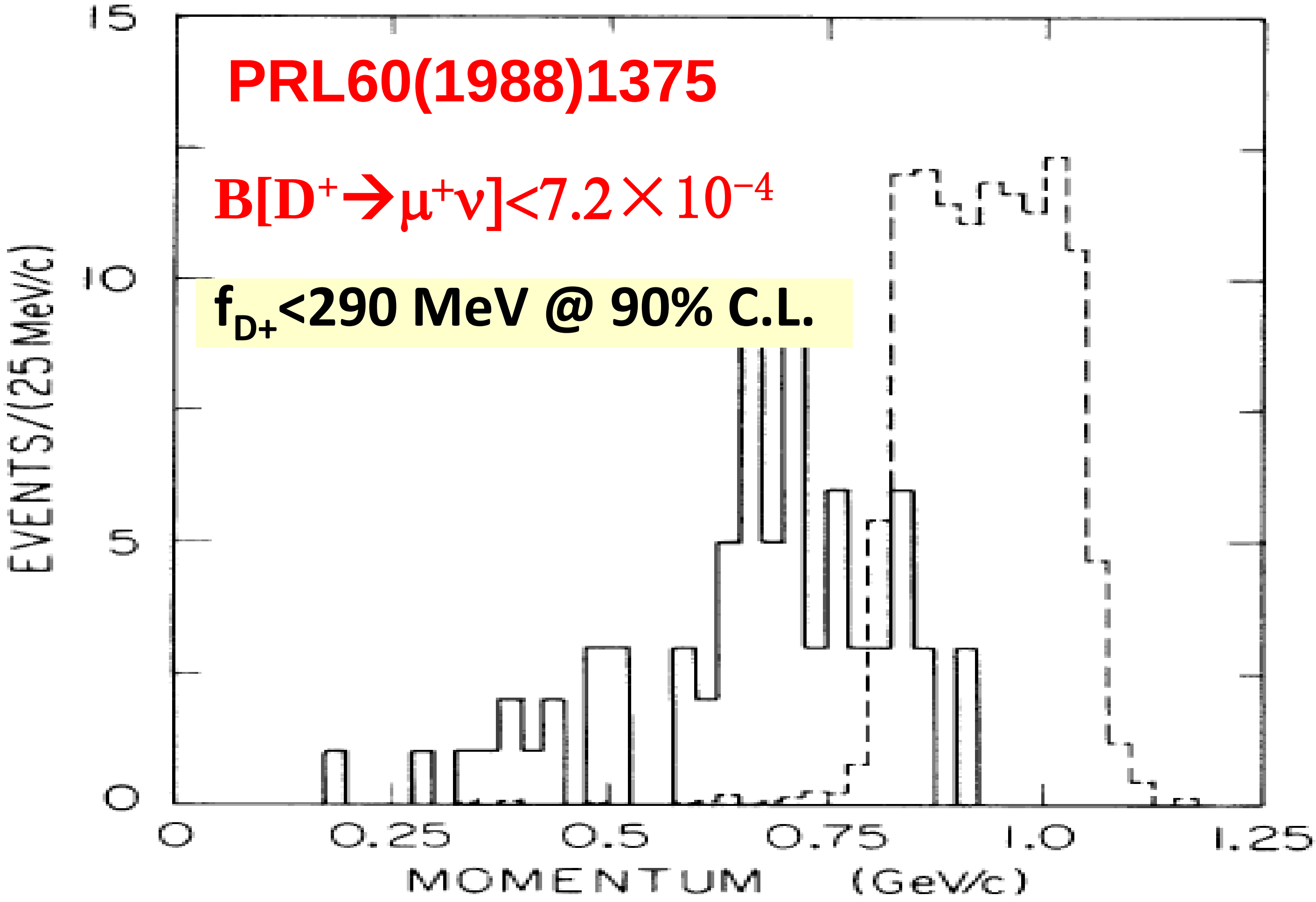


review by C. Bouchard @ Lattice 2014

Experimental review of $D^+ \rightarrow l^+ \nu$

No $D^+ \to \mu^+\nu$ signal found at Mark-III

9.6 pb^{-1} at $\psi(3770)$



PRL60(1988)1375

$B[D^+ \to \mu^+\nu] < 7.2 \times 10^{-4}$

f_{D+}<290 MeV @ 90% C.L.

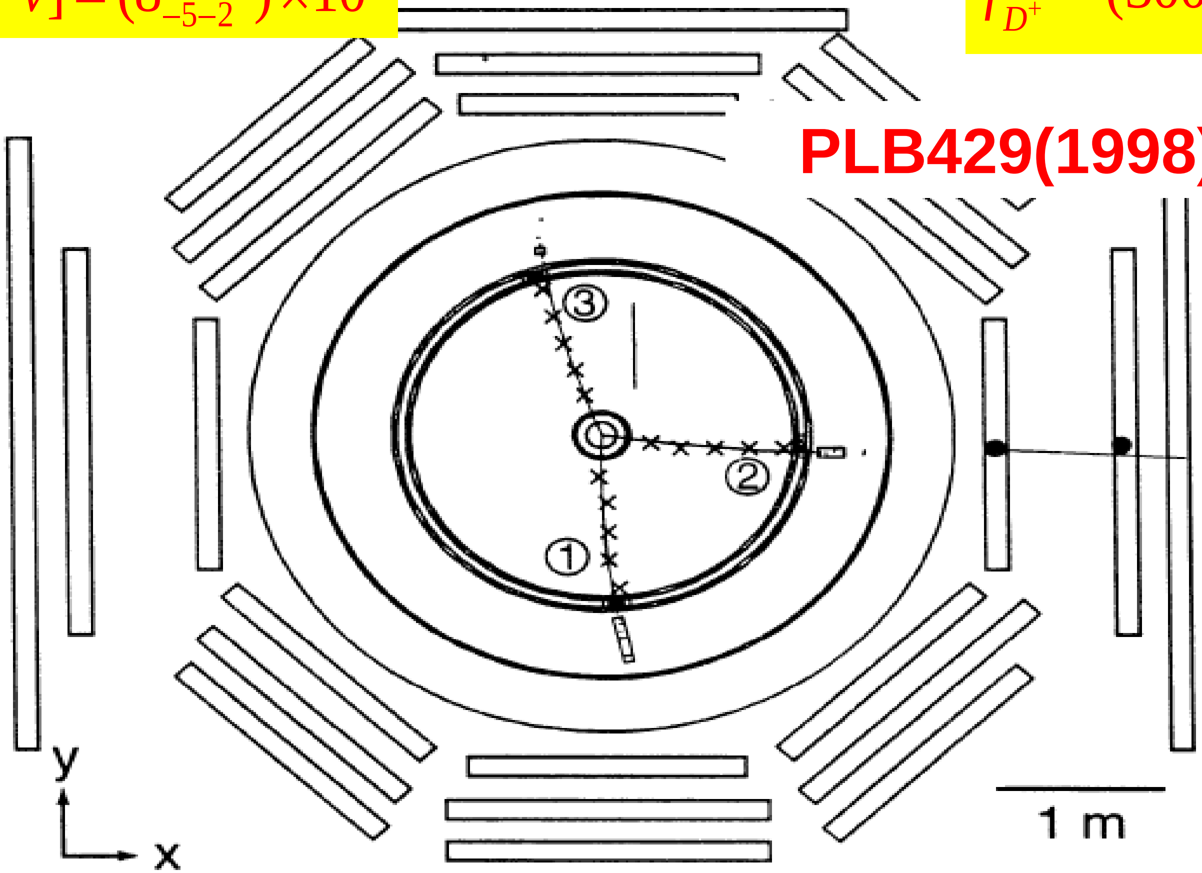
1 $D^+ \rightarrow \mu^+ \nu$ signal found at BES-I

22.3 pb^{-1} at 4.03 GeV

$B[D^+ \to \mu^+ \nu] = (8^{+16+5}_{-5-2}) \times 10^{-4}$

$f_{D^+} = (300^{+180+80}_{-150-40})$ MeV

PLB429(1998)188

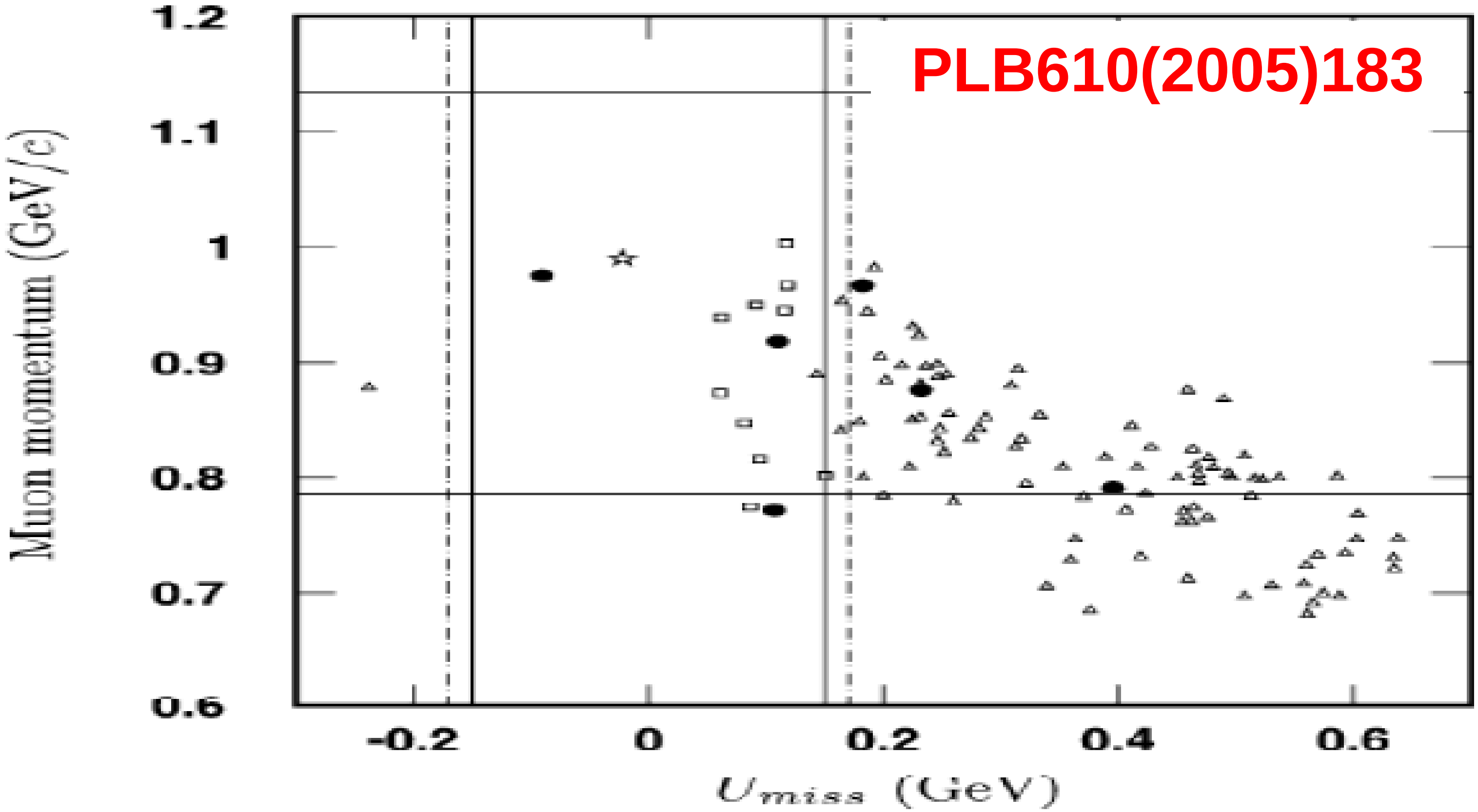


2.7 $D^+ \to \mu^+ \nu$ signals found at BES-II

33 pb^{-1} around $\psi(3770)$

$B[D^+ \to \mu^+ v] = (12.2^{+11.1}_{-5.3} \pm 1.0) \times 10^{-4}$

$f_{D^+} = (371^{+129}_{-119} \pm 25)$ MeV

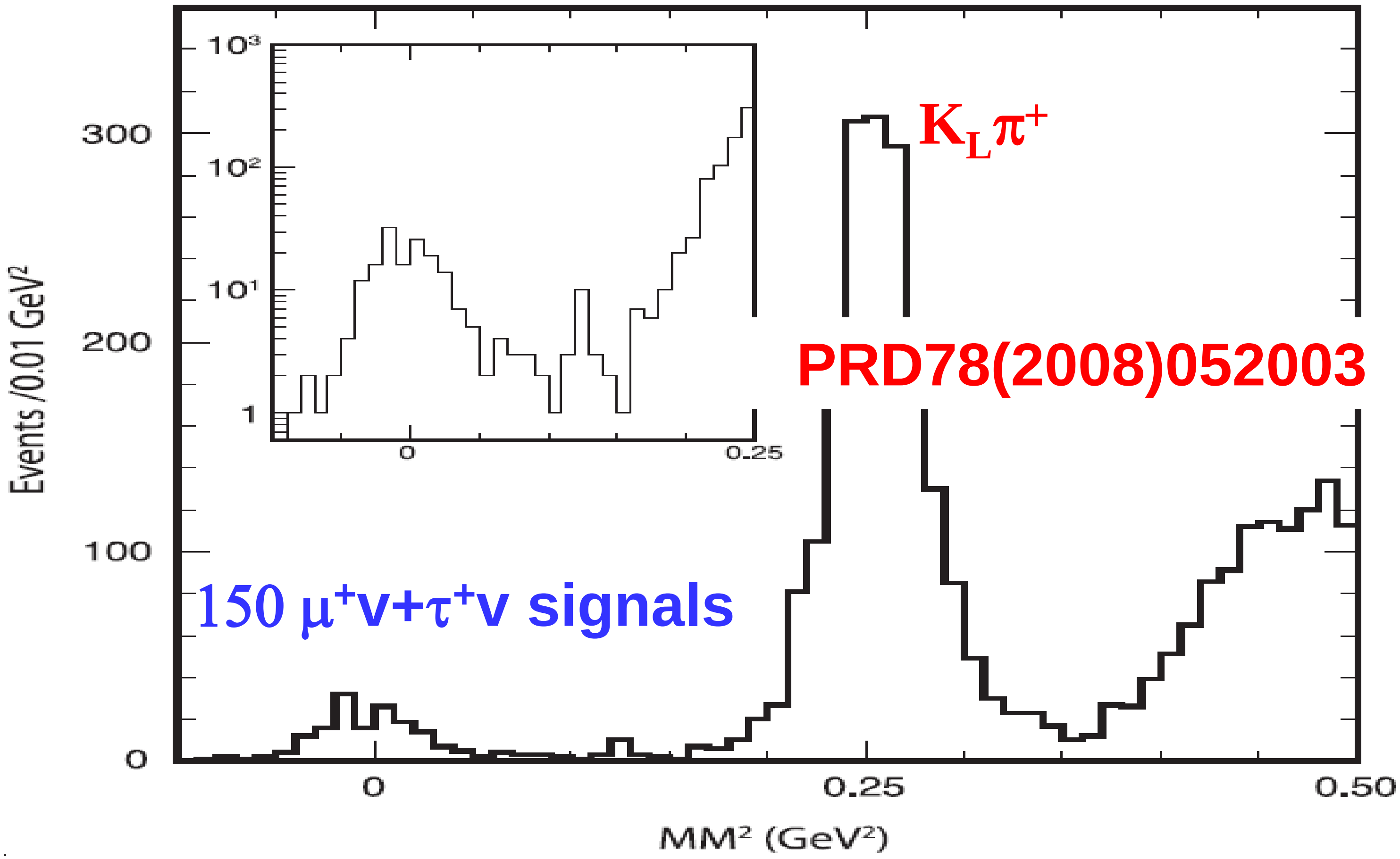


Measurements at CLEO-c

818 pb^{-1} around ψ(3770) (2004–2008)

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

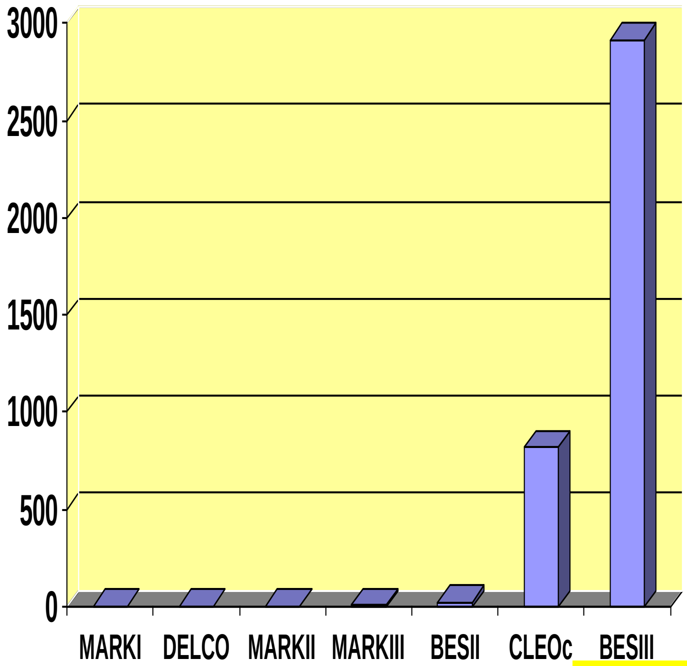
$f_{D+} = 205.8 \pm 7.5 \pm 2.5$ MeV



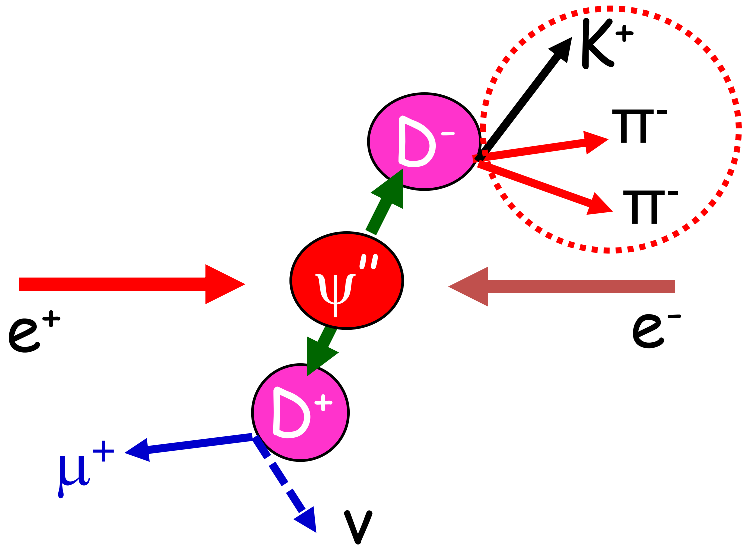
D^+ sample at BESIII

2.93 fb^{-1} data were taken at $\psi(3770)$

2010.1-2011.5



3.6×CLEOc

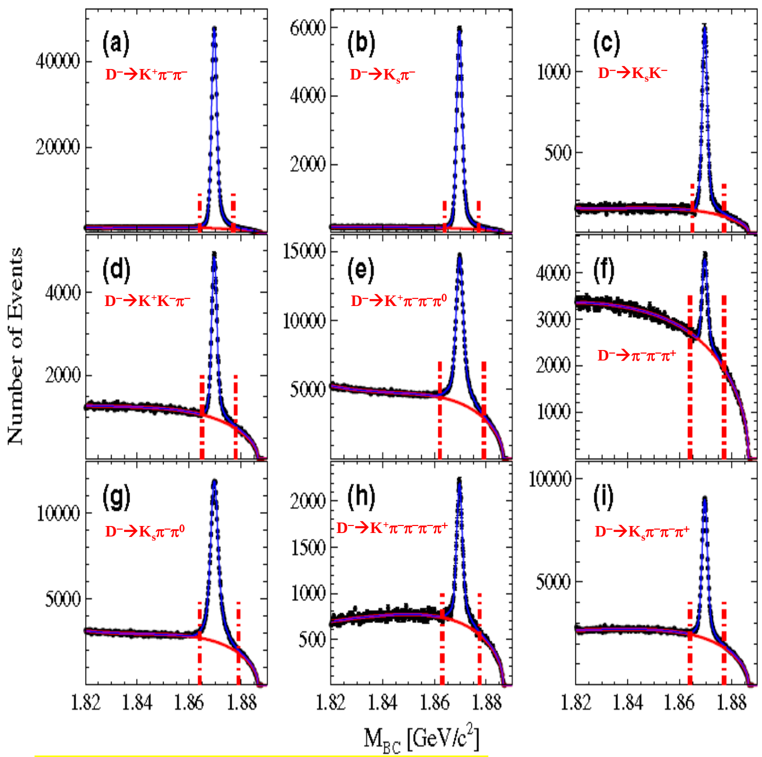


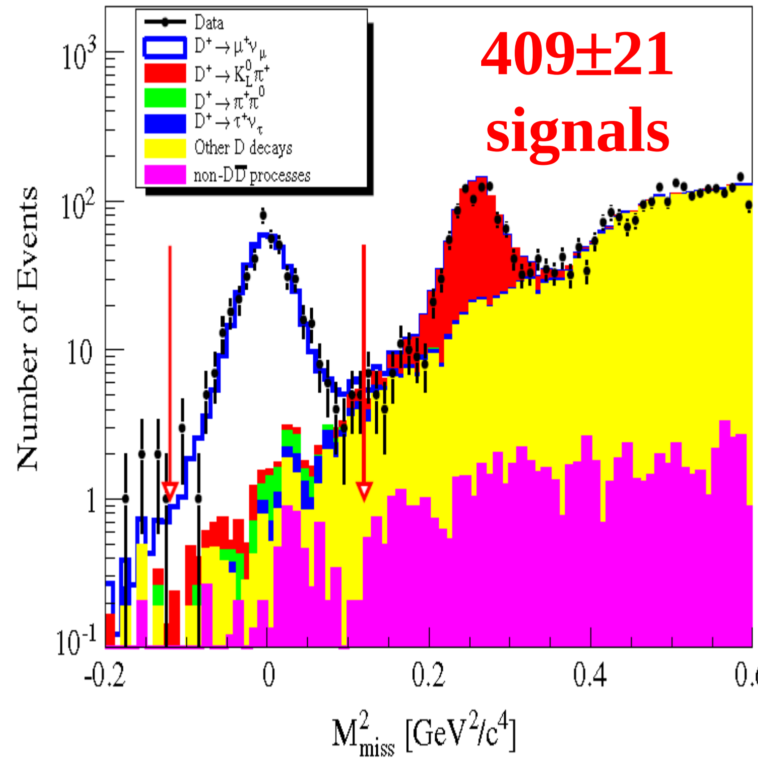
At the recoil side of singly tagged D^- mesons, Leptonic decays can be studied

Improved $B[D^+ \to \mu^+ \nu]$, f_{D+} and $|V_{cd}|$ at BESIII

$\psi(3770) \to D^+D^-$

PRD89(2014)051104R





$N_{D^-_{tag}} = (170.31 \pm 0.34) \times 10^4$

$B[D^+ \to \mu^+ \nu] = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$

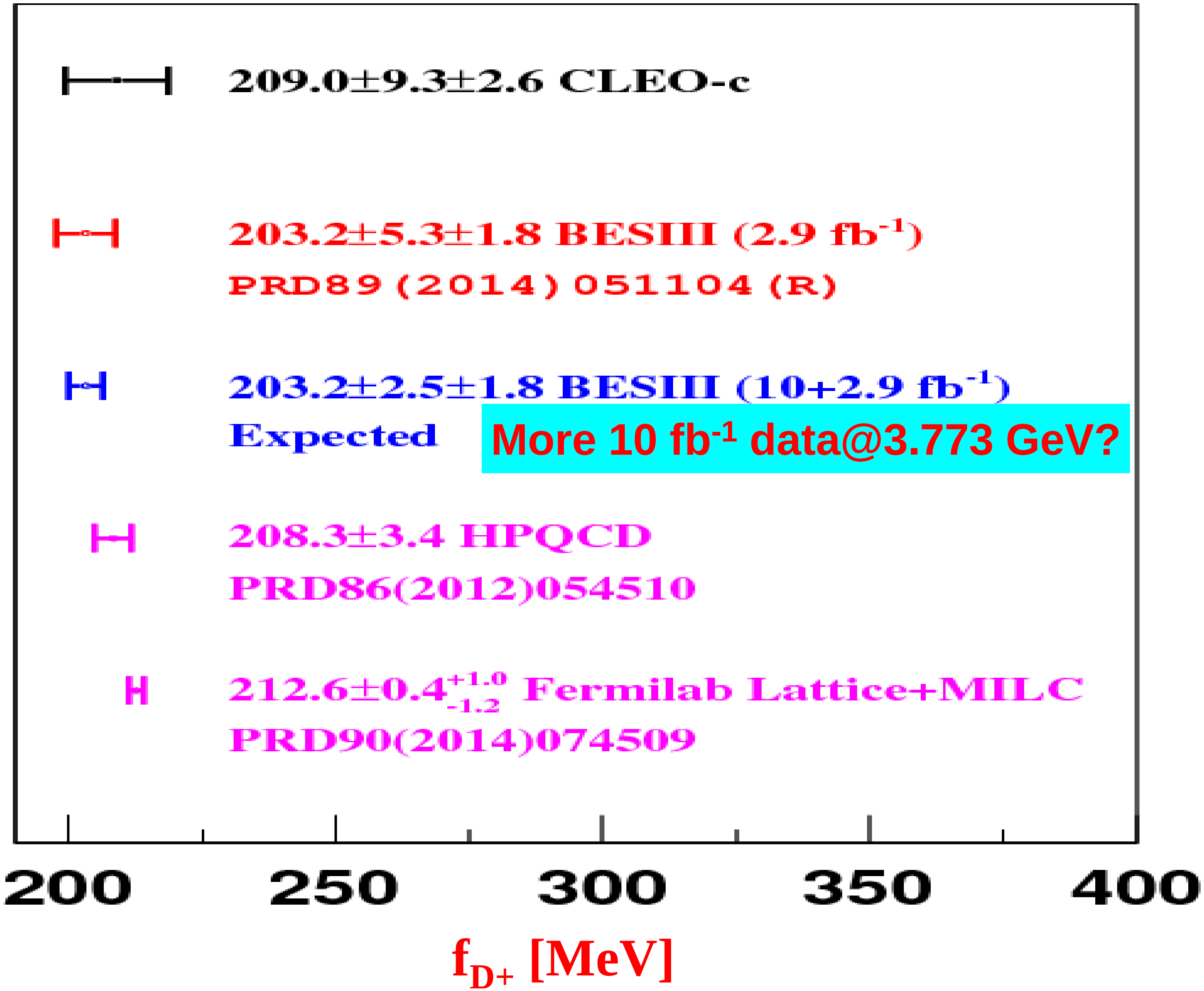
Input τ_{D+}, m_{D+}, $m_{\mu+}$ on PDG and $|V_{cd}|$ of CKM-Fitter

$f_{D+} = (203.2 \pm 5.3 \pm 1.8)$ MeV

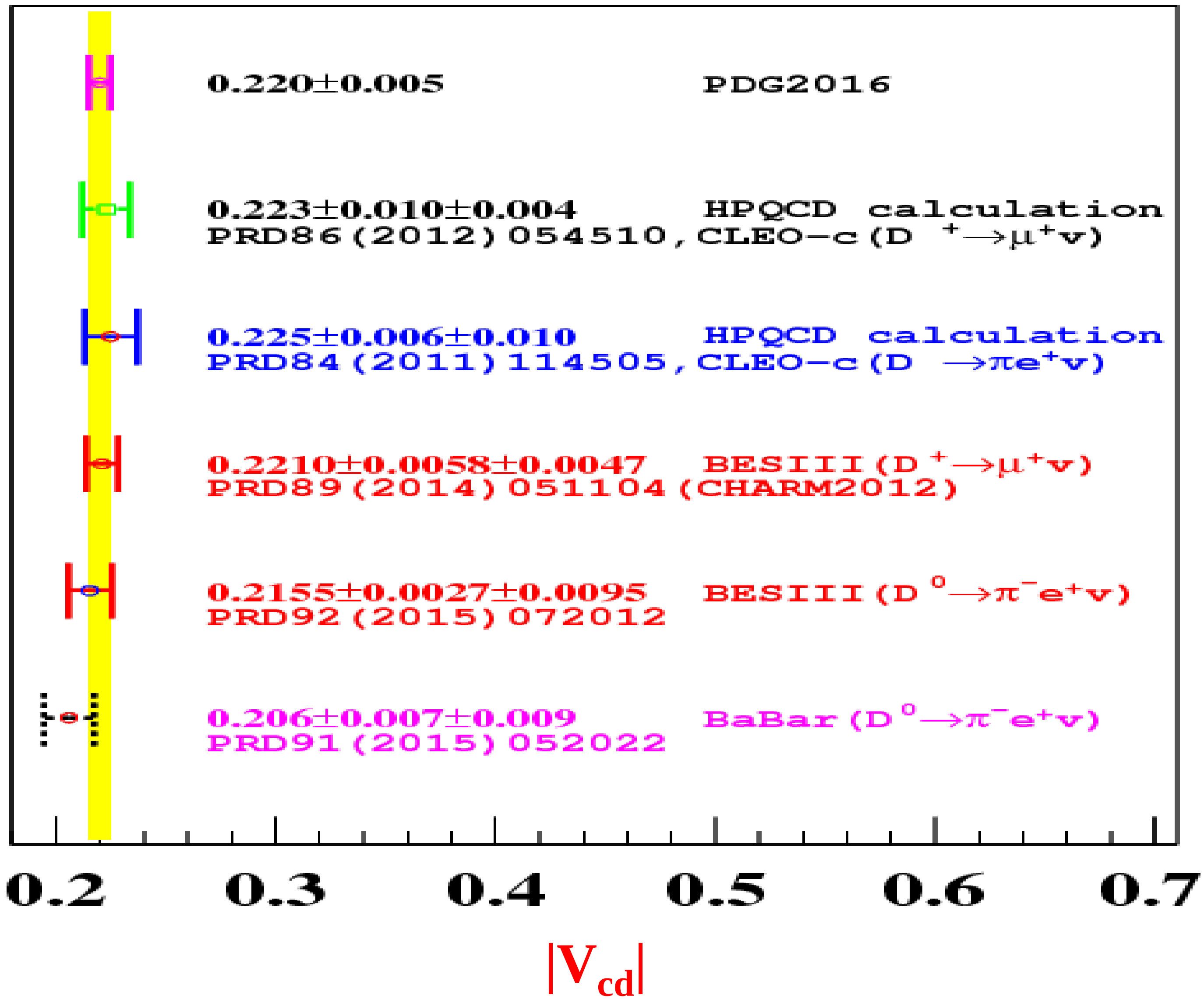
Input τ_{D+}, m_{D+}, $m_{\mu+}$ on PDG and LQCD calculated $f_{D+}=207\pm4$ MeV[PRL100(2008)062002]

$|V_{cd}| = 0.2210 \pm 0.0058 \pm 0.0047$

Comparison of f_{D+}



Comparison of $|V_{cd}|$



Search for $D^+ \rightarrow \tau^+ \nu$ at BESIII

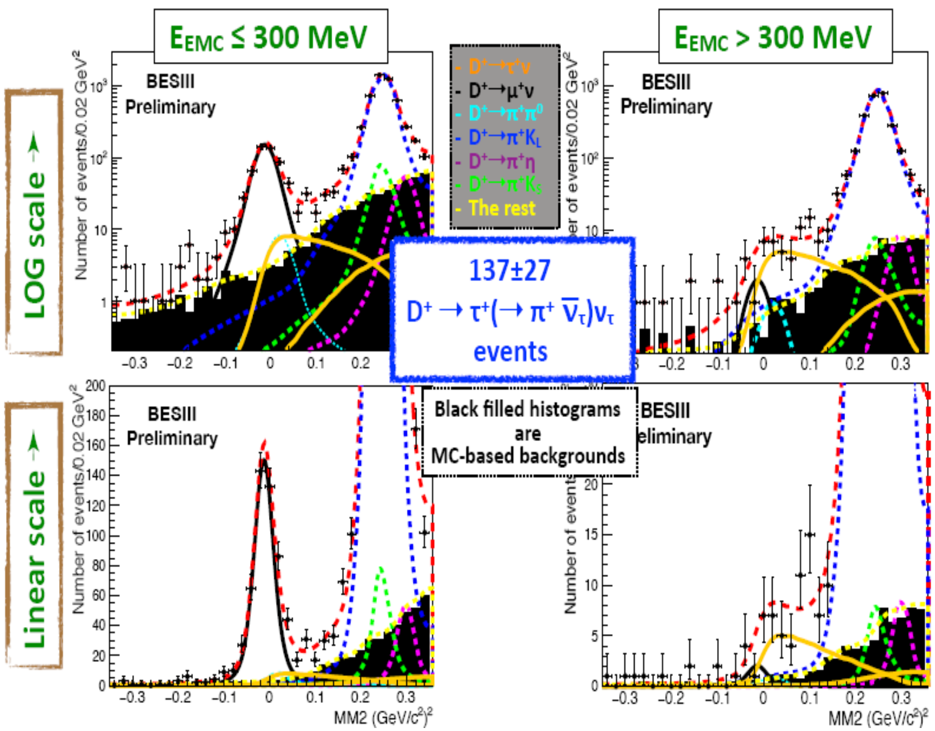
$$R \equiv \frac{\Gamma(D^+ \to \tau^+\nu)}{\Gamma(D^+ \to \mu^+\nu)} = \frac{m_{\tau^+}^2 \left(1 - \frac{m_{\tau^+}^2}{M_{D^+}^2}\right)^2}{m_{\mu^+}^2 \left(1 - \frac{m_{\mu^+}^2}{M_{D^+}^2}\right)^2}$$

- With the known masses, R = 2.67±0.01 (very small uncertainty!).
- Based on the previously measured $BF(D^+ \to \mu^+\nu_\mu) = (3.74\pm0.17)\times10^{-4}$,
  expect $BF(D^+ \to \tau^+\nu_\tau) = (9.99\pm0.45)\times10^{-4}$.
  CLEO was very close ($< 1.2\times10^{-3}$ @ 90% C.L.) w/ 0.818 fb^{-1} data.
- Requirements are very similar to PRD 89, 051104 (R) (2014).
  Notable differences are listed below.
- Tag side:
  - 6 tag modes: $D^+ \to K^-\pi^+\pi^-, K^-\pi^+\pi^-\pi^0, K_S\pi^+, K_S\pi^+\pi^0, K_S\pi^+\pi^-\pi^+, K^-K^+\pi^+$,
    where $K_S \to \pi^+\pi^-$ and $\pi^0 \to \gamma\gamma$.
- Signal side:
  - No PID on the signal charged track.
  - The missing momentum (representing the neutrino(s) for a signal event) not in beam direction.
  - The most energetic neutral EMC shower (i.e., not matched to the charged track) not aligned with the missing momentum.

==> With the all requirements, signal efficiency ~ 72%.
The last two requirements suppress backgrounds from
$D^+ \to K_L \pi^+$ and $D^+ \to \pi^0 \pi^+$ in the signal region of MM2.

Search for $D^+ \rightarrow \tau^+ \nu$ at BESIII

Fitting to DATA

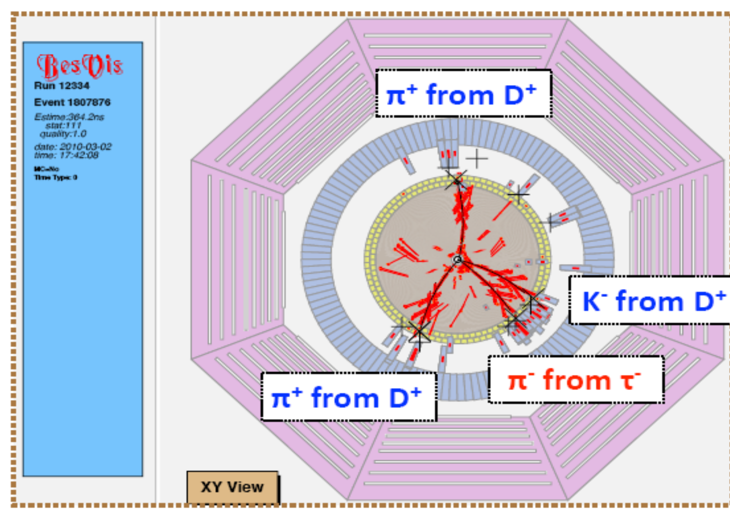


(un-binned maximum likelihood fit)

- Fix the $D^+ \to \mu\nu$ component based on the world average. Float it in our systematic check.
- Float $D^+ \to \tau^+(\to \text{generic decays})\nu_\tau$ component. (our signal efficiency is still for $D^+ \to \tau^+(\to \pi^+ \bar{\nu}_\tau)\nu_\tau$ events)
- Peaking backgrounds:
  - $D^+ \to K_L\pi^+$: Large: Float its normalization.
  - $D^+ \to K_S\pi^+$: Small: Fix its size based on the PDG.
  - $D^+ \to \pi^0\pi^+$: Small: Fix its size based on the PDG.
  - $D^+ \to \eta\pi^+$: Small: Fix its size based on the PDG.
- The rest of the background (relatively smooth): Fix its shape based on MC (in the nominal fit only) and float its normalization.
- All shapes are MC-based (KeysPDF), convoluted with a common single Gaussian (the mean and the width of this Gaussian are floated).

Preliminary Result

- 137±27 $D^+ \to \tau^+(\to \pi^+ \bar{\nu}_\tau)\nu_\tau$ events.
- > 4σ statistical significance. First evidence!
- $BF(D^+ \to \tau^+\nu_\tau) = [1.20 \pm 0.24(\text{stat.})] \times 10^{-3}$.
- R = 3.21±0.64
  consistent with the SM prediction, R = 2.66±0.01,
  within ~0.9σ.



Experimental studies of $D_s^+ \rightarrow l^+ v$

Measurement at WA75

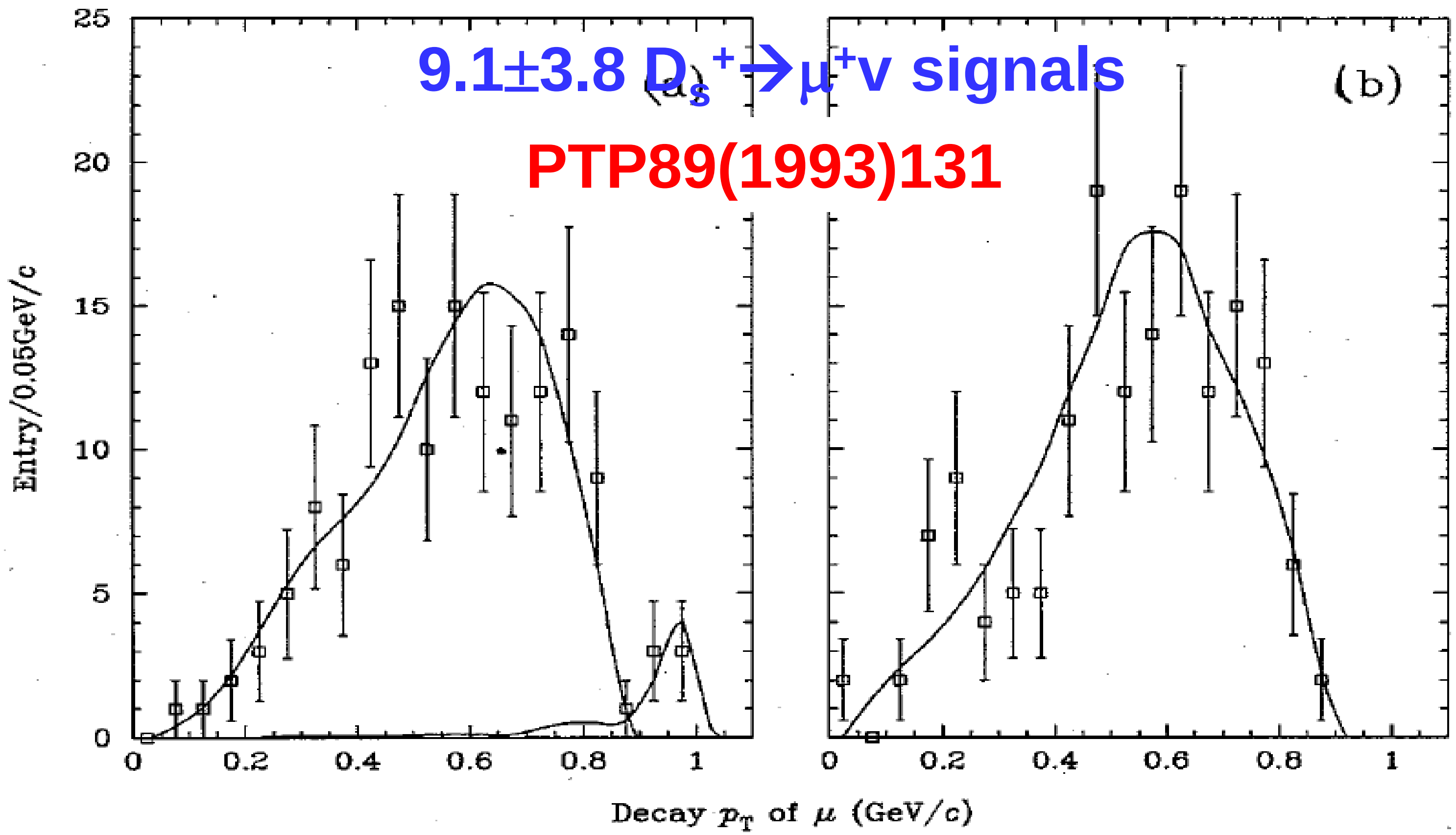
Fixed target experiment

$B[D_s^+ \to \mu^+ v] = (4.0^{+1.8+0.8}_{-1.4-0.6} \pm 1.7) \times 10^{-3}$

f_{Ds+}=232±45±20±48 MeV

9.1±3.8 $D_s^+ \to \mu^+ v$ signals

PTP89(1993)131



Measurement at CLEOII

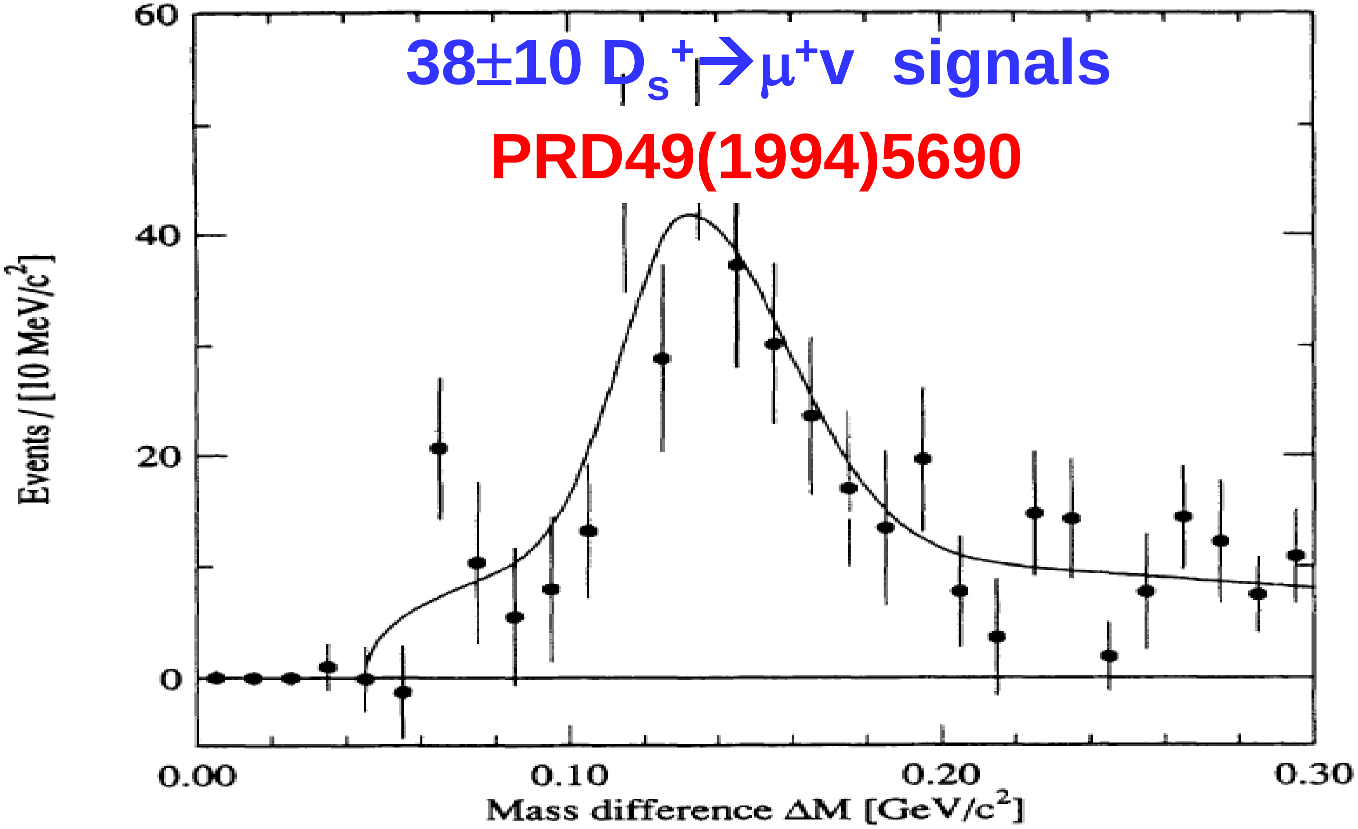
2.13 fb^{-1} at 10.6 GeV

$$\frac{\Gamma(D_s^+ \to \mu^+ \nu)}{\Gamma(D_s^+ \to \phi \pi^+)} = 0.245 \pm 0.052 \pm 0.074$$

$f_{Ds+} = 344 \pm 37 \pm 52 \pm 42$ MeV

38±10 $D_s^+ \to \mu^+ \nu$ signals

PRD49(1994)5690

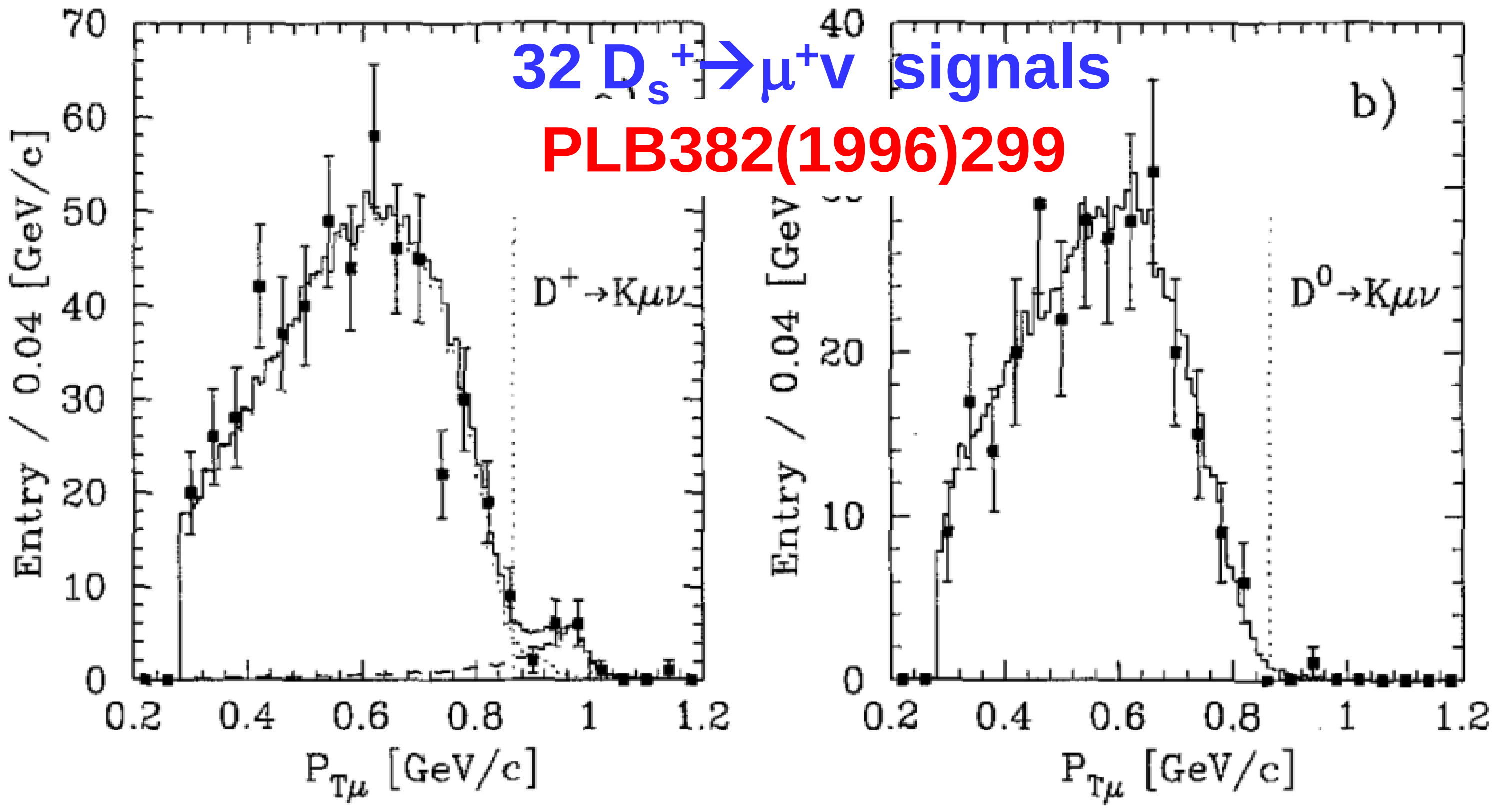


Measurement at E653

Fermilab fixed target experiment

$B[D_s^+ \rightarrow \mu^+\nu] = (3.0 \pm 1.2 \pm 0.6 \pm 0.5) \times 10^{-3}$

$f_{Ds+} = 194 \pm 35 \pm 20 \pm 14$ MeV



32 $D_s^+ \rightarrow \mu^+\nu$ signals

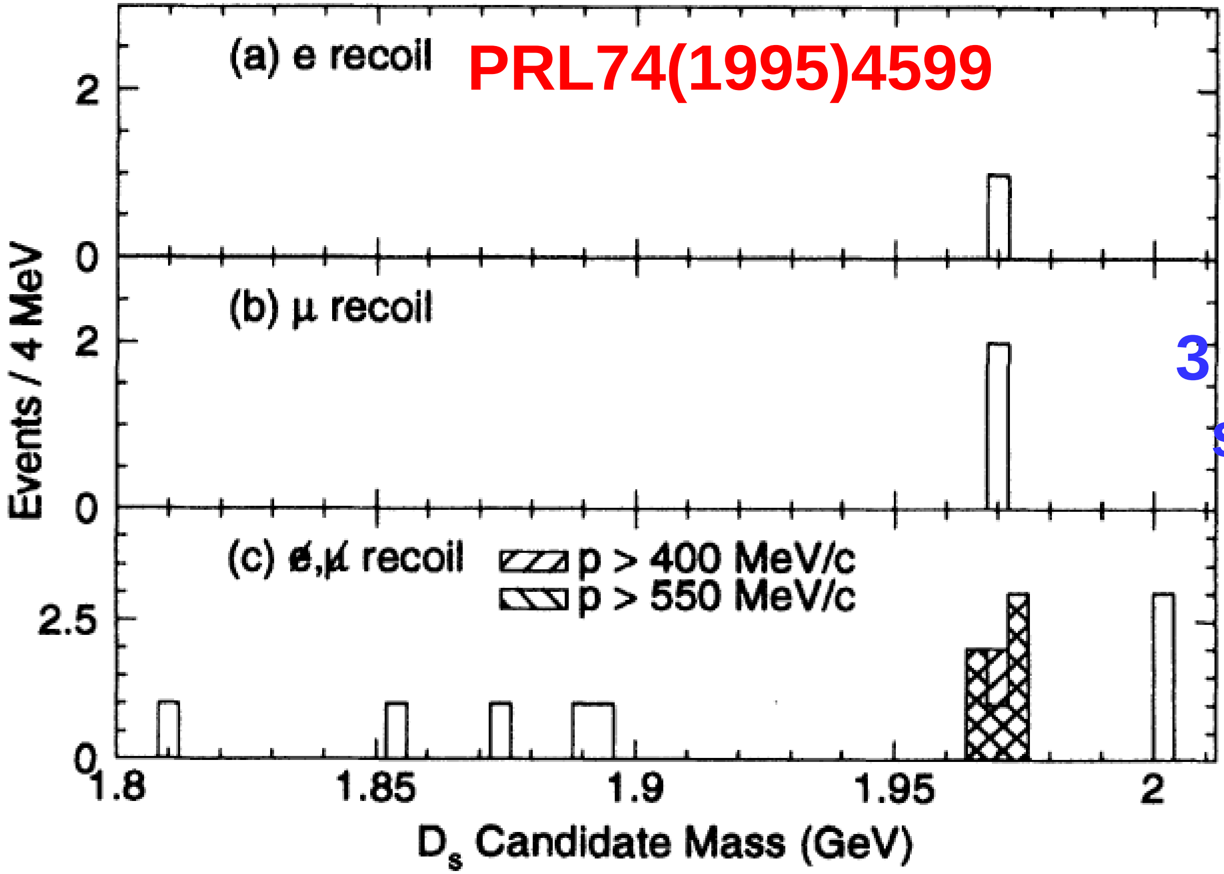
PLB382(1996)299

First absolute measurement from BES-I

22.3 pb^{-1} at 4.03 GeV

$$B[D_s^+ \to \mu^+ \nu] = (1.5^{+1.3+0.3}_{-0.6-0.2})\ \%$$

$$f_{D_s^+} = (430^{+150+40}_{-130-40})\ \text{MeV}$$



PRL74(1995)4599

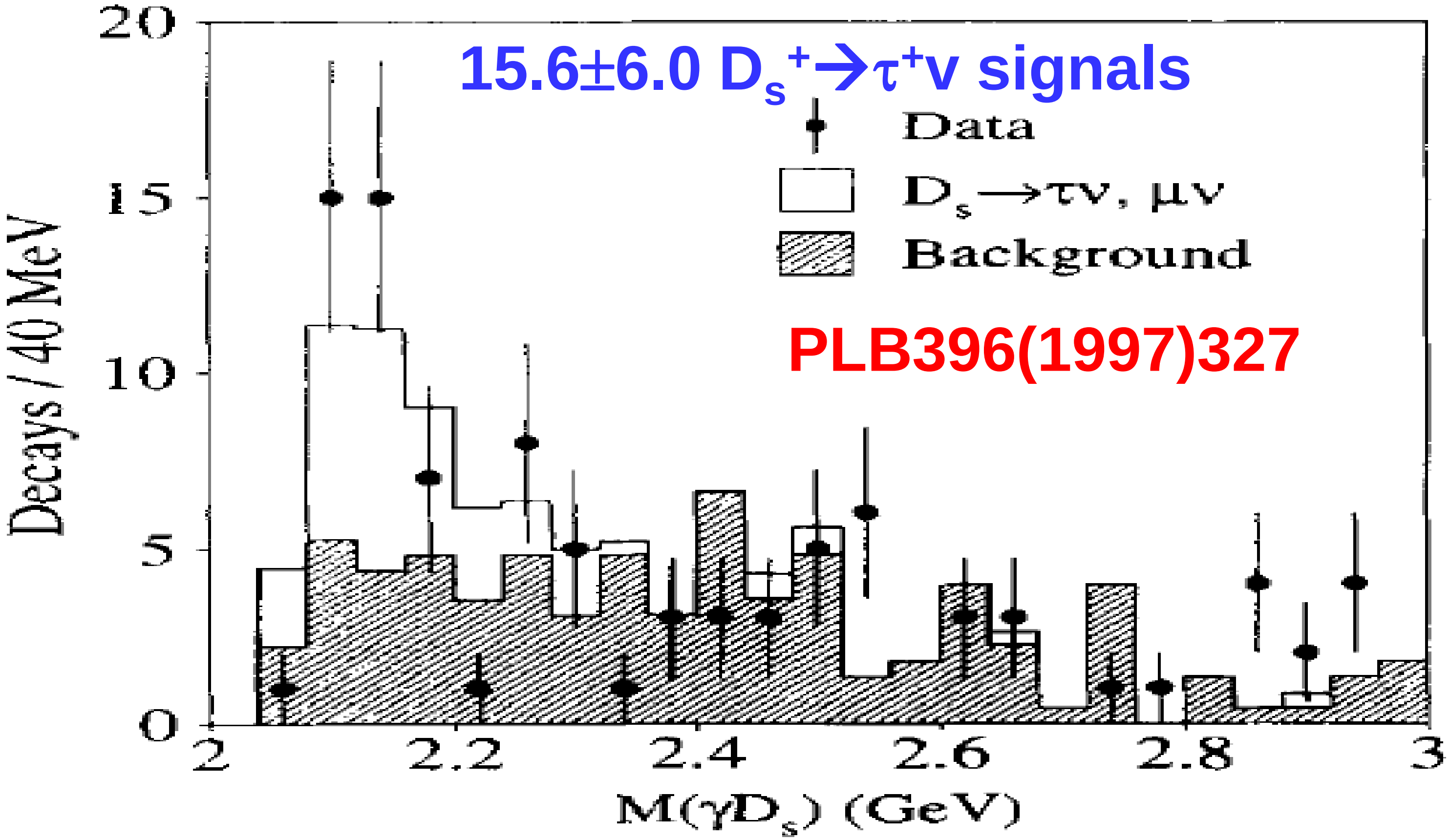
3 $D_s^+ \to \mu^+ \nu$ signals

Measurement at L3

$Z \rightarrow q\bar{q}$, 49.6 pb^{-1} at 91.2 GeV

$B[D_s^+ \rightarrow \tau^+ \nu] = (7.4 \pm 2.8 \pm 1.6 \pm 1.8)\%$

$f_{D_s^+} = 309 \pm 58 \pm 33 \pm 38$ MeV

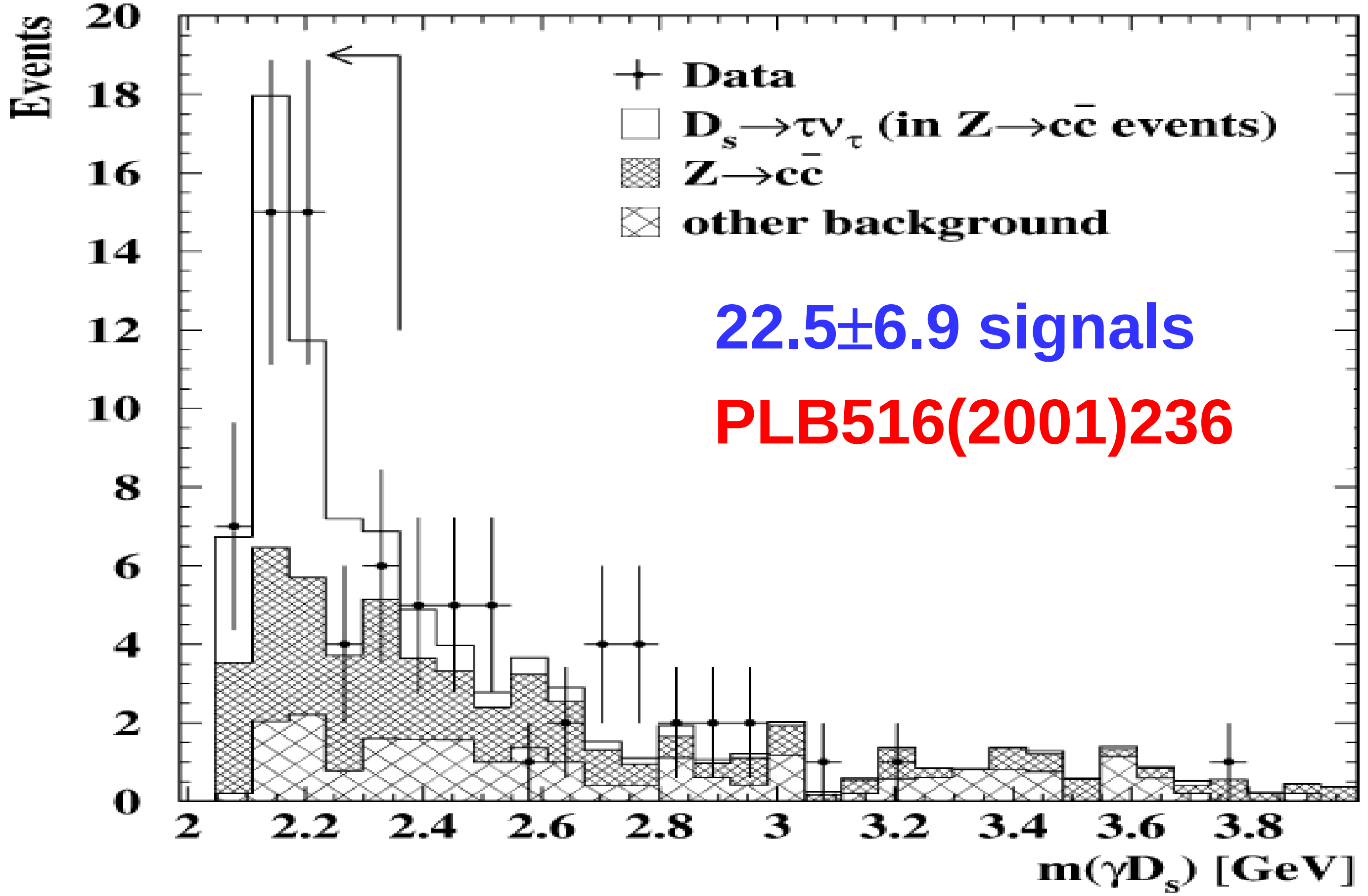


Measurement at OPAL

3.9×10^6 $Z\rightarrow q\bar{q}$

$B[D_s^+ \rightarrow \tau^+\nu] = (7.1\pm2.1\pm2.0)\%$

$f_{D_s^+} = 286\pm44\pm41$ MeV



Measurement at ALPHA

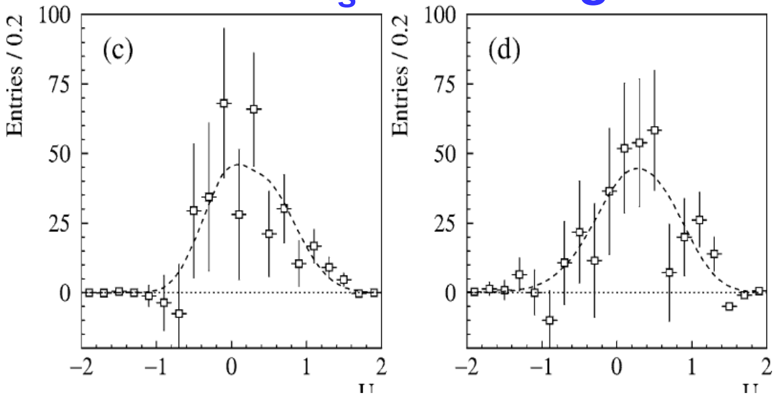
3.96×10^{6} Z hadronic decays

f_{D_s+}=285±19±40 MeV

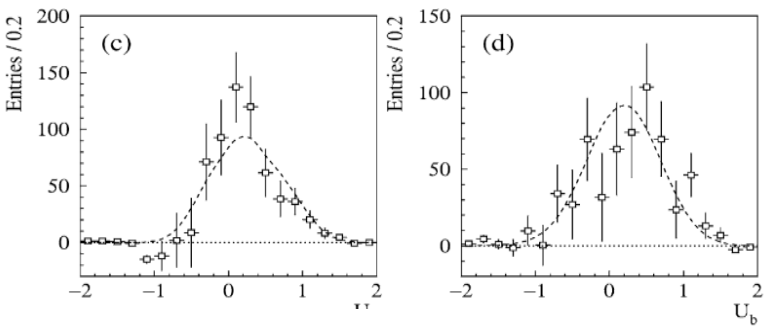
$B[D_s^+ \rightarrow \mu^+\nu] = (0.47\pm0.25)\times10^{-3}$

$B[D_s^+ \rightarrow \tau^+\nu] = (5.79\pm0.77\pm1.84)\%$

306±62 $D_s^+ \rightarrow \tau^+ v$ signals



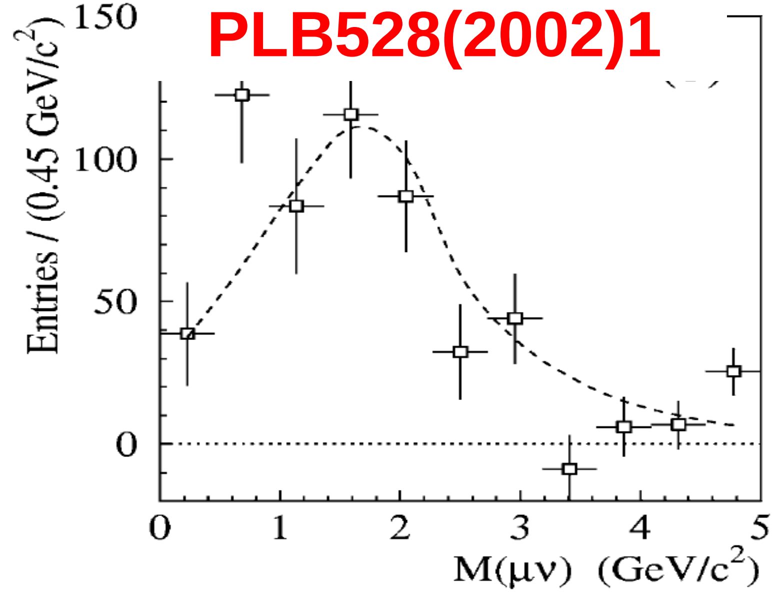
Electron channel



Muon channel

575±84 $D_s^+ \rightarrow \mu^+ v$ signals

PLB528(2002)1



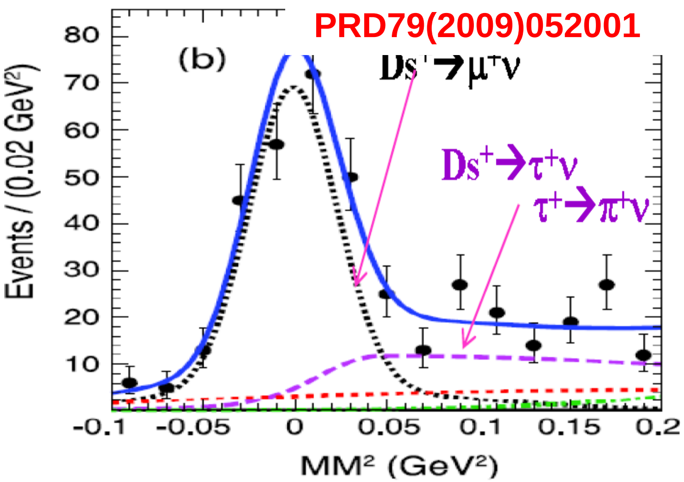
Absolute measurements at CLEO-c

$D_s^{*+}D_s^-$, 600 pb^{-1} @ 4.17 GeV

Absolute measurement gives significantly improved statistical and systematic errors [697 signal]

235±14 $D_s^+ \to \mu^+ \nu + \tau^+ \nu$ signals

126±16 $D_s^+ \to \tau^+ \nu$ signals



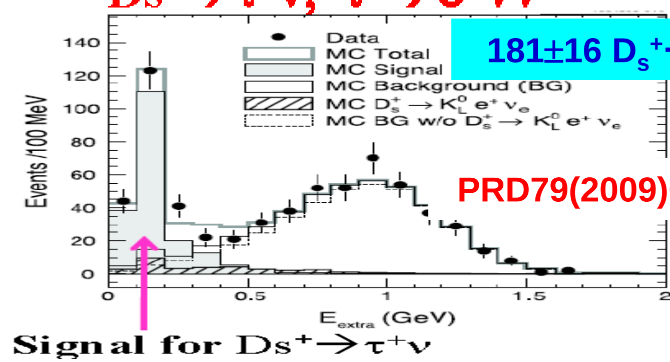
$B[D_s^+ \to \mu^+ \nu] = (5.65 \pm 0.45 \pm 0.17) \times 10^{-3}$

$B[D_s^+ \to \tau^+ \nu] = (6.42 \pm 0.81 \pm 0.18)\%$

$f_{Ds+} = 263.3 \pm 8.2 \pm 1.9$ MeV

$Ds^+ \to \tau^+ \nu,\ \tau^+ \to e^+ \nu \nu$

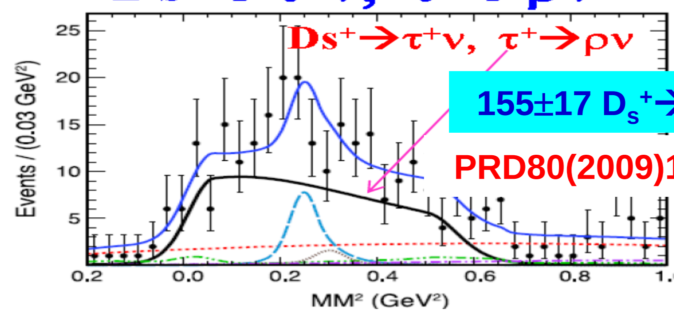
181±16 $D_s^+ \to \tau^+ \nu$ signals



$B[D_s^+ \to \tau^+ \nu] = (5.30 \pm 0.47 \pm 0.21)\%$

$f_{Ds+} = 252.2 \pm 11.1 \pm 5.2$ MeV

$Ds^+ \to \tau^+ \nu,\ \tau^+ \to \rho \nu$



$B[D_s^+ \to \tau^+ \nu] = (5.52 \pm 0.57 \pm 0.22)\%$

$f_{Ds+} = 257.8 \pm 13.3 \pm 5.2$ MeV

Absolute measurements at BaBar

523 fb^{-1} @ 10.58 GeV

Better statistical [1023] but larger systematics

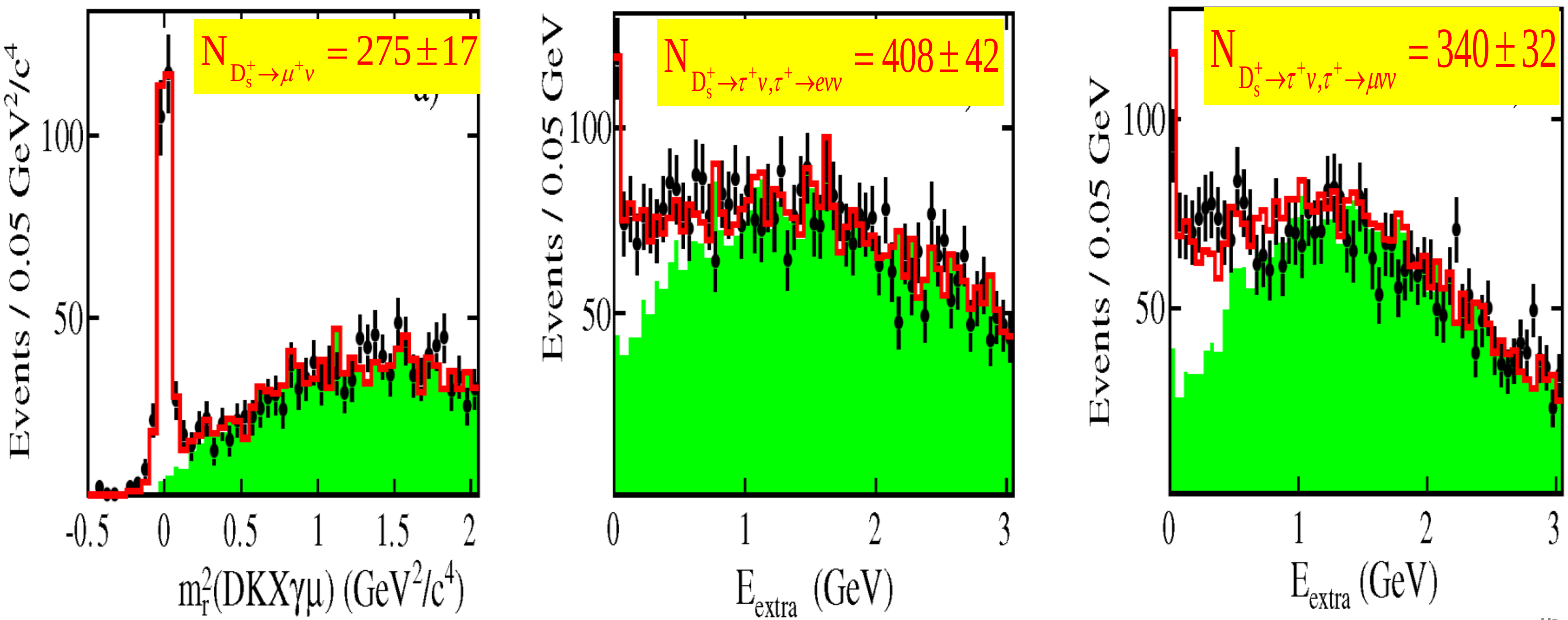
$$e^+e^- \to c\bar{c} \to D_{\rm tag}K_{\rm frag}X_{\rm frag}D_s^{*-}$$

$B[D_s^+ \to \mu^+\nu]=(6.02\pm0.38\pm0.34)\times10^{-3}$

$B[D_s^+ \to \tau^+\nu]=(5.00\pm0.35\pm0.49)\%$

PRD82(2010)091103

f_{Ds+}=258.6±6.4±7.5 MeV



Absolute measurements at Belle

913 fb^{-1} @ 10.58 GeV

Better statistical [2698] but larger systematics

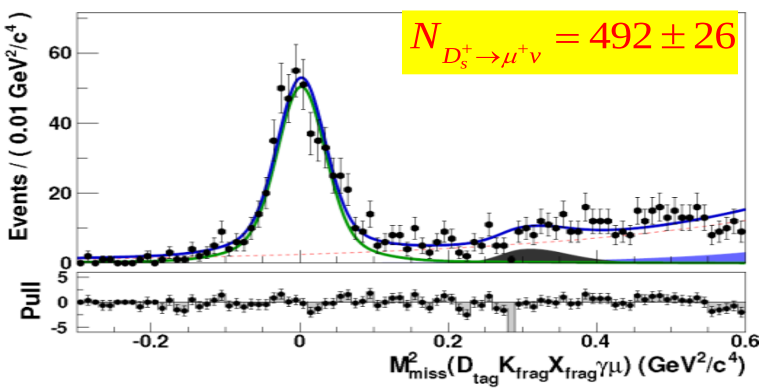
$$e^+e^- \to c\bar{c} \to D_{\rm tag} K_{\rm frag} X_{\rm frag} D_s^{*-}$$

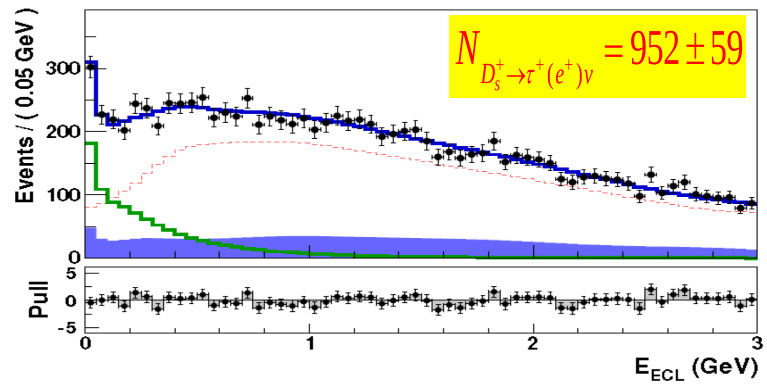
JHEP1309(2013)129

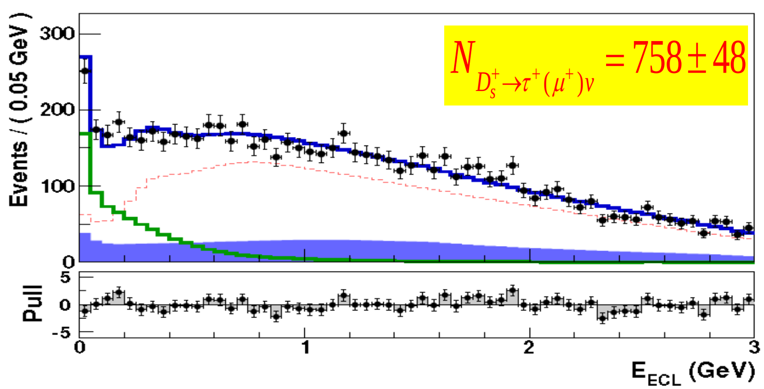
$B[D_s^+ \to \mu^+\nu] = (5.31 \pm 0.28 \pm 0.20) \times 10^{-3}$

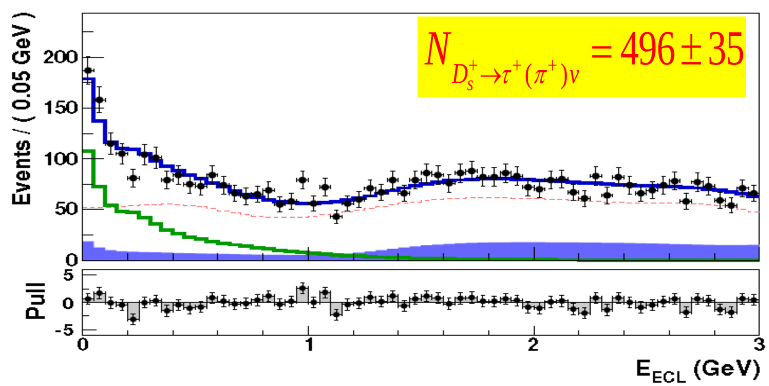
$B[D_s^+ \to \tau^+\nu] = (5.70 \pm 0.21 \pm 0.31)\%$

f_{Ds+}=255.5±4.2±5.1 MeV





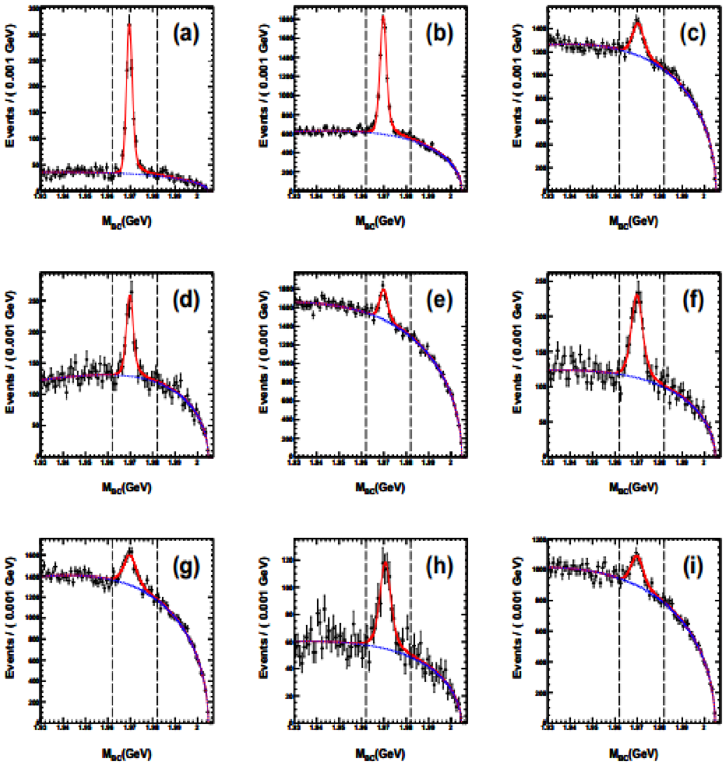




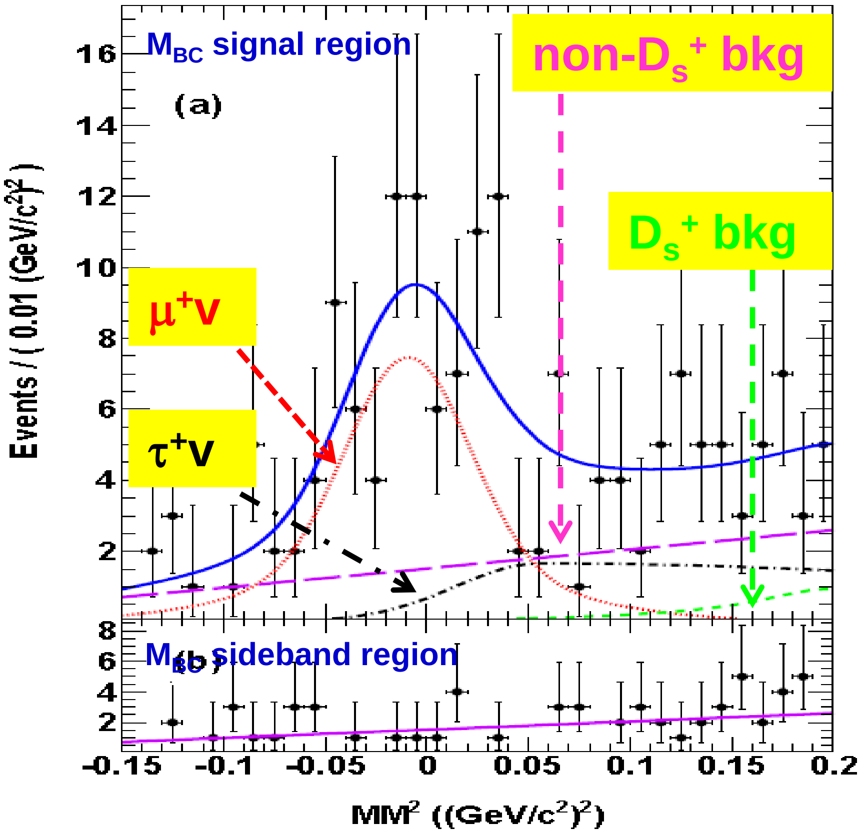
Absolute measurements@4.009 at BESIII

482 pb^{-1} @ 4.009 GeV

PRD94(2016)072004



$N_{D_s^- tag} = 15127 \pm 312$

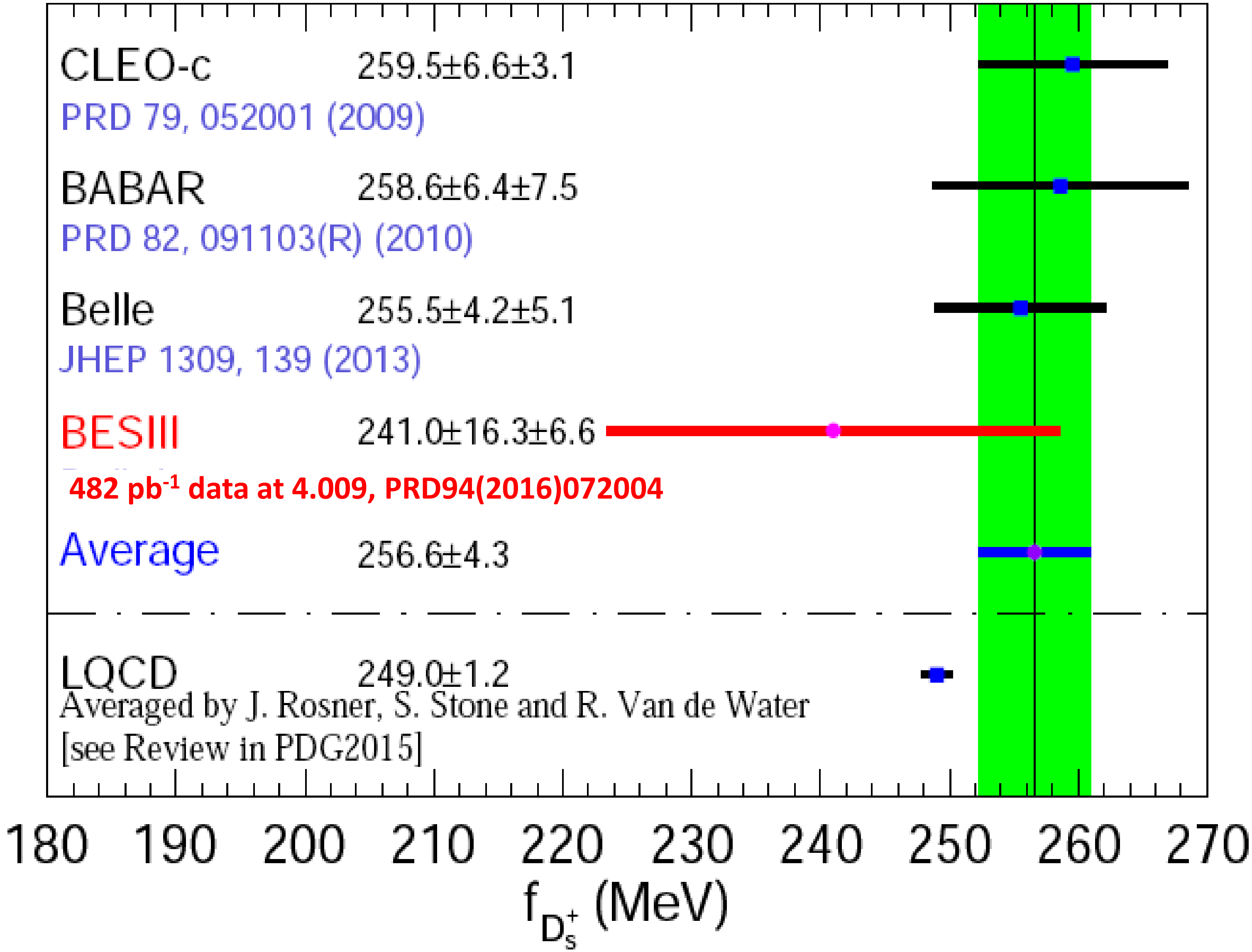


$B[D_s^+ \to \mu^+\nu] = (0.495 \pm 0.067 \pm 0.026)\%$

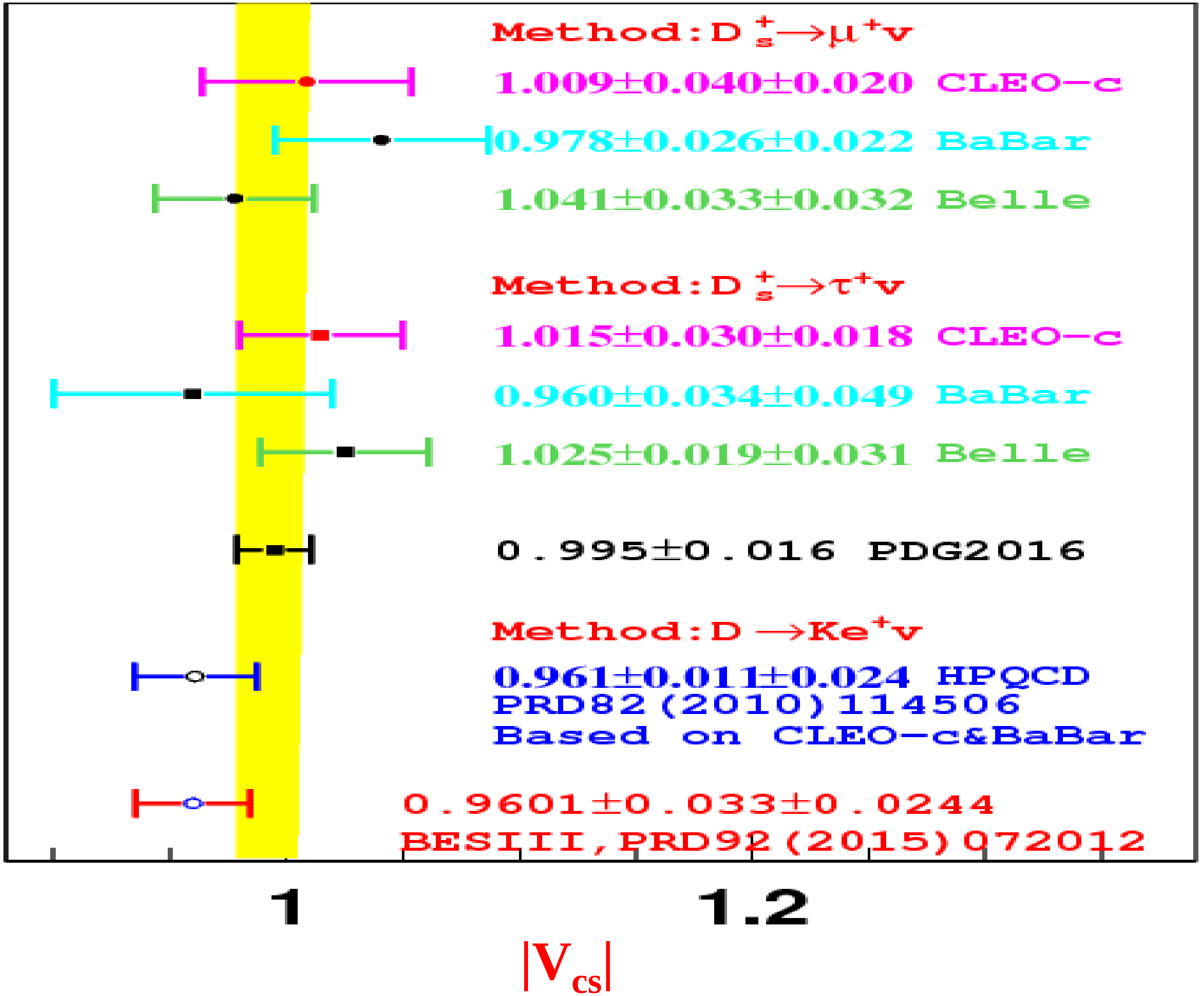
$B[D_s^+ \to \tau^+\nu] = (4.83 \pm 0.65 \pm 0.26)\%$

$f_{D_s^+} = (241.0 \pm 16.3 \pm 6.6)$ MeV

Comparision of f_{D+}



Comparison of $|V_{cs}|$



Comparisons of Existing f_{D+}, f_{Ds+} and $f_{D+}:f_{Ds+}$

	Experiments	Femilab Lattice+MILC (2014)		HPQCD (2012)	
	Averaged	Expected	Δ	Expected	Δ
f_{D+}(MeV)	203.9±4.7	$212.6\pm0.4^{+1.0}_{-1.2}$	1.8σ	208.3±3.4	0.8σ
f_{Ds+}(MeV)	256.9±4.4	$249.0\pm0.3^{+1.1}_{-1.5}$	1.7σ	246.0±3.6	1.4σ
$f_{D+}:f_{Ds+}$	1.260±0.036	$1.1712\pm0.0010^{+0.0029}_{-0.0032}$	2.5σ	1.187±0.013	1.9σ

- Precisions of the LQCD calculations of f_{D+}, f_{Ds+}, $f_{D+}:f_{Ds}$ are 0.5%, 0.5% and 0.3%

- The experimentally measured and the theoretical expected f_{D+}, f_{Ds+}, $f_{D+}:f_{Ds+}$ differ by ~2σ

- Further improved measurement with larger data sample is necessary!

Prospect on $D_s^+ \to l^+ \nu$ at BESIII

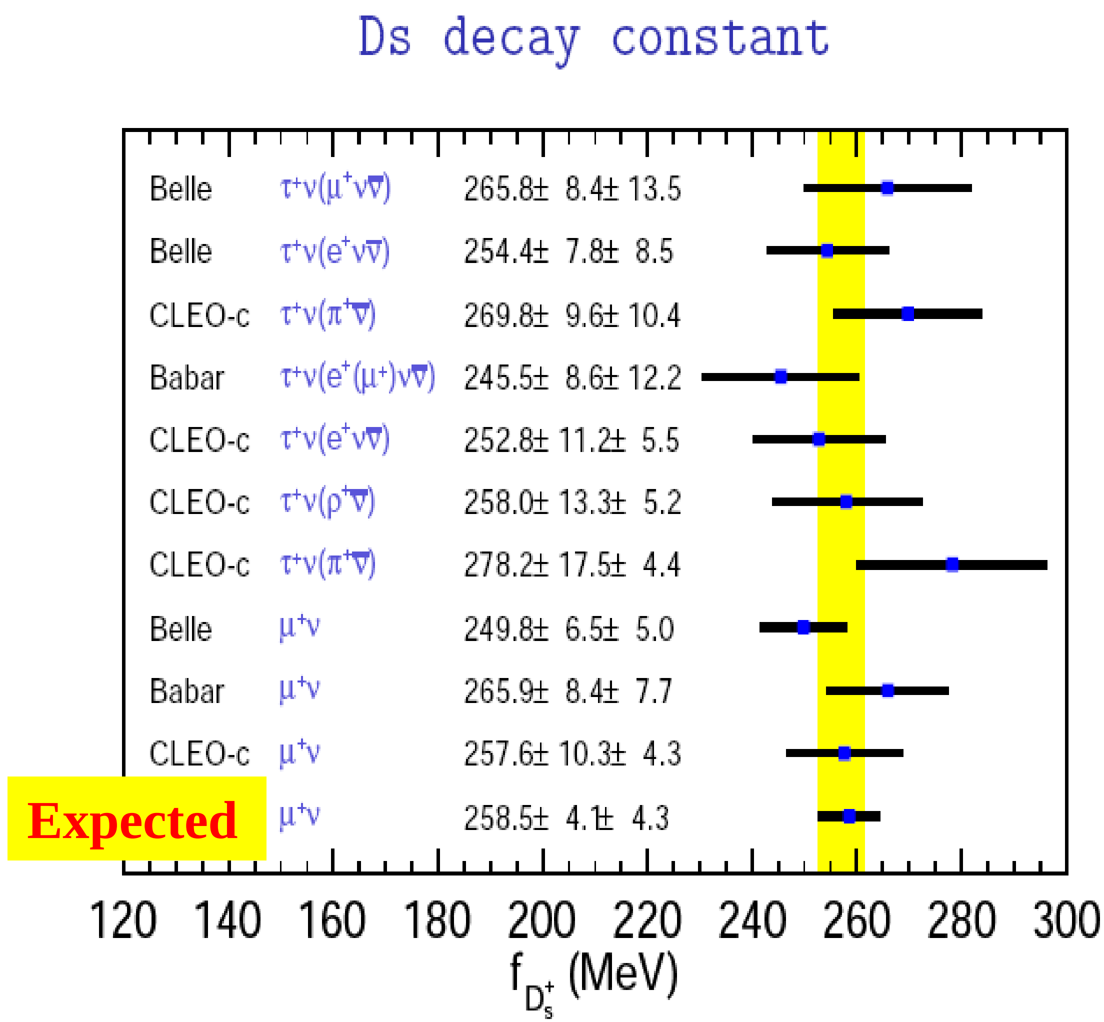
~3 fb^{-1} data@ 4.18 GeV is in hand

μ counter of BESIII may help to suppress background in $D_s^+ \to \mu^+ \nu$

Statistics roughly estimated with CLEO-c results

If systematic is the same as CLEO-c measurement

$D_s^+ \to \tau^+ \nu$ should further improve measurements



Summary

- In recent 10 years, significantly improved measurements of $f_{D(s)+}$ and $|V_{cs(d)}|$ using $D_{(s)}^+$ leptonic decays have been obtained. These are key for LQCD calibration and CKM UT.

- BESIII measure f_{D+} and $|V_{cd}|$ using $D^+ \rightarrow \mu^+ v$ with 3 fb^{-1} data at $\psi(3770)$. More data, more chance.

- BESIII preliminary result shows evidence for $D^+ \rightarrow \tau^+ v$

- BESIII report f_{Ds+} with 482 pb^{-1} data at 4.009 GeV. Improved measurement of f_{Ds+} and $|V_{cs}|$ by $D_s^+ \rightarrow l^+ v$ with 3 fb^{-1} data at 4.18 GeV is expected in the near future

Thank you!