Leptonic Decays of Heavy Mesons

presented by

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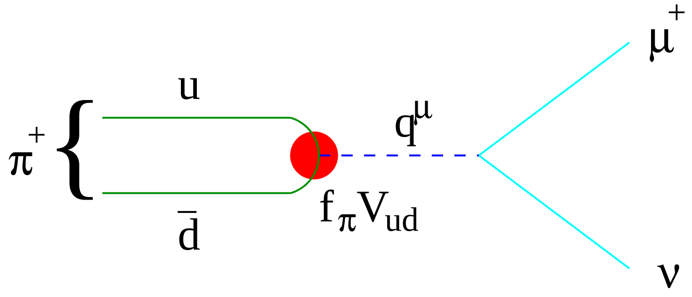
- Introduction and Motivation
- $D_s^+ \to \mu^+\nu$, $D_s^+ \to \tau^+\nu$, and $D^+ \to \mu^+\nu$
  WA75, E653, CHORUS, CLEO, L3, DELPHI, ALEPH, BES
- $B^+ \to \tau^+\nu$, $B^+ \to \mu^+\nu$, and $B^+ \to e^+\nu$
  ALEPH, L3, CLEO
- Summary and Conclusion

Syracuse, 14. Oct 1998

Strong Interaction:

- Confinement
  quarks $q \in [u, d, s, c, b]$ are bound
  in mesons $(q\bar{q})$ or baryons (qqq)
- u, d, s form Pseudoscalar meson octet
  $\pi^+ = (u\bar{d})$, π^0, π^-, η, K^+, K^-, K^0, and $\bar{\mathrm{K}}^0$
- if one of the quarks is heavy $q \in [c, b]$
  charmed mesons $(c\bar{q})$: D^+, D^o, D_s^+
  bottom mesons $(b\bar{q})$: B^+, B^o, B_s^+
  or their antiparticles
- Pion decay $\pi^+ \to \mu^+ \nu_\mu$



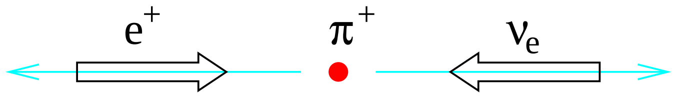
- Matrix element $M = \frac{G_F}{\sqrt{2}} f_\pi q^\mu V_{ud} \bar{u}(p)\gamma_\mu(1-\gamma^5)v(k)$
  where $f_\pi q^\mu =< 0|A^\mu|\pi >$ ($\pi \to$ red blob)
- f_π is called the pion decay constant
  $f_\pi = f_\pi(q^2)$ but $q^2 = m_\pi^2$
- Decay constant of meson $P_{Q\bar{q}} \Longleftrightarrow$ wave function overlap
  of $Q\bar{q}$ at zero separation ($f_P^2 \sim |\psi(0)|^2$)

Motivation

- Decay width

$$\Gamma(P^+_{Q\bar{q}} \to \ell^+\nu) = \frac{G_F^2}{8\pi}|V_{Q\bar{q}}|^2 f_P^2 M_P m_\ell^2 (1 - \frac{m_\ell^2}{M_P^2})^2$$

- Measure $f_\pi = 130.7 \pm 0.1 \pm 0.36$ MeV from lifetime τ_{π^+}
- Helicity suppression



$$\frac{\Gamma(\pi^+ \to \mathrm{e}^+\nu_e)}{\Gamma(\pi^+ \to \mu^+\nu_\mu)} = 1.230 \cdot 10^{-4}$$

- Rates are small due to helicity suppression and CKM matrix elements

Decay Constant f_P:

- Leptonic decay width $\Gamma(P^+ \to \ell^+\nu)$ for charged P^+
  $\longrightarrow$ $\boxed{\text{measurement of } f_P \text{ for heavy mesons}}$
- Pauli Interference effects in charged P^+
  $\longrightarrow$ changes lifetime ratios $\tau_{D^+}/\tau_{D^0} = 2.55 \pm 0.04$ and
  $\tau_{B^+}/\tau_{B^0_d} \simeq 1 + 0.05(f_B/200\mathrm{MeV})^2$
- Neutral meson wavefunction $(B_d = \bar{b}d)$
  $\longrightarrow$ affects $B^o\bar{B}^o$ mixing $< \bar{B}^o|j_\mu j^\mu|B^o >= \frac{4}{3}B_B f_B^2 m_b$
  and measurement of V_{td}

Calculations:

of Decay Constants f_P, no measurements for heavy quarks before 1993

- non-relativistic quark model formula
  $\longrightarrow f_P^2 = 12|\psi(0)|^2/M_P$
- Heavy quark effective theory (HQET)
  $\longrightarrow f_P \sim \frac{1}{\sqrt{M_P}}$ for large M_P
- Lattice QCD (Quantum ChromoDynamics)
  very active field, many results

$$\Longrightarrow \begin{array}{rcl} f_D & = & 170 \text{ to } 240 \text{ MeV} \\ f_{D_s} & = & 190 \text{ to } 270 \text{ MeV} \\ f_B & = & 170 \text{ to } 230 \text{ MeV} \\ \frac{f_D}{f_{D_s}} & = & 0.90 \pm 0.02 \end{array}$$

  Errors on f_D, f_{D_s} as small as 10 MeV, on f_B ~40 MeV
  f_B larger than earlier predictions from QCD sum rules
- Potential models
  Results vary a lot (75 to 356 MeV)
- QCD Sum Rules
  Earlier results low for f_B, when included in HQET better agreement with Lattice QCD

Expected Branching Ratios, Experiments

Estimated Branching Ratios:

- for $f_D = f_{D_s} = 250$ MeV and $f_B = 180$ MeV

	$\tau^+\nu_\tau$	$\mu^+\nu_\mu$	$e^+\nu_e$	
$\mathcal{B}(D^+ \to \ell^+\nu)$		$5 \cdot 10^{-4}$		$V_{cd} \sim \lambda$
$\mathcal{B}(D_s^+ \to \ell^+\nu)$	$5 \cdot 10^{-2}$	$5 \cdot 10^{-3}$	$1 \cdot 10^{-7}$	$V_{cs} \sim 1$
$\mathcal{B}(B^+ \to \ell^+\nu)$	$5 \cdot 10^{-5}$	$2 \cdot 10^{-7}$	$2 \cdot 10^{-11}$	$V_{ub} \sim \lambda^3$

- ratios well predicted, ie $\frac{\Gamma(D_s^+ \to \tau^+\nu)}{\Gamma(D_s^+ \to \mu^+\nu)} = 9.75$

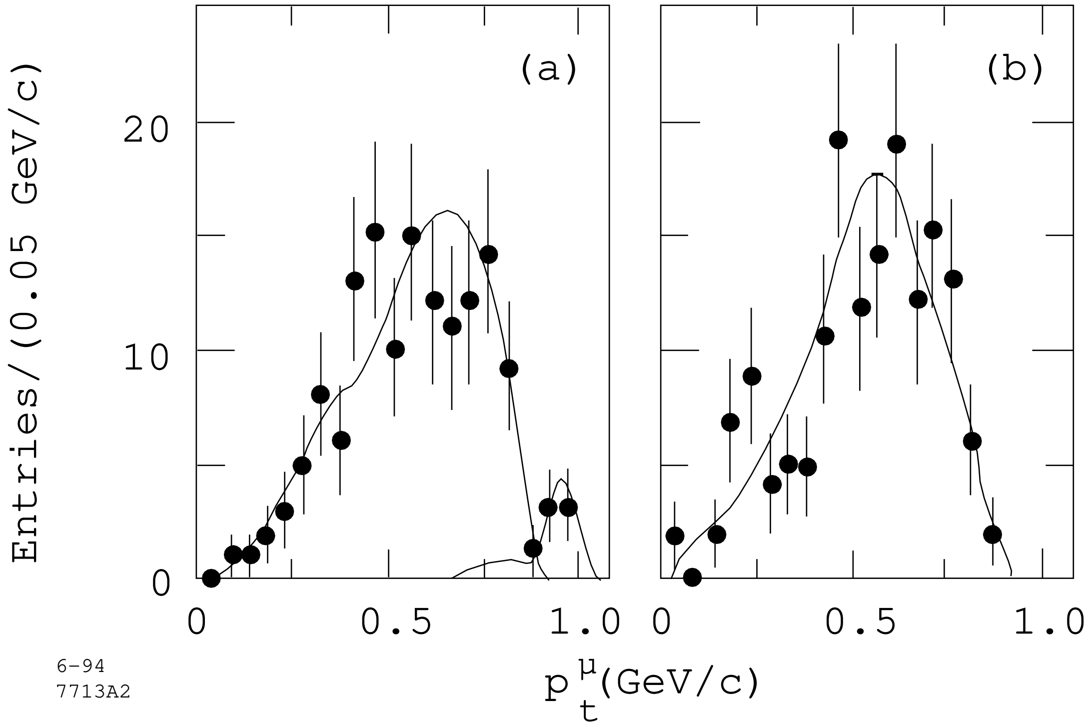
Experiments:

- Fixed target:
  WA 75 (350 GeV π^-), E653 (600 GeV π^-): D_s^+
- e^+e^- Colliders:

Experiment	CM Energy [GeV]	mode
BES	~ 4	D^+, D_s^+ at charm threshold
CLEO	~ 10.5	D_s^+, B^+ at b threshold
LEP	~ 91	D_s^+, B^+

First observation of $D_s^+ \to \mu^+\nu$

- 350 GeV π^- beam (CERN), emulsion target and μ trigger $\longrightarrow$ high spatial resolution, ie. kink search
- Signature for $D_s^+ \to \mu^+\nu$: 2-body decay in D_s rest frame momentum $p_\mu^{CM} = 0.98$ GeV $\longrightarrow$ in lab frame $p_{\perp\mu} \geq 0.9$ GeV, kinematic limit for $c \to X_s \ell\nu$ decays: $p_{\perp\mu} < 0.865$ GeV
- Signal sample 1-prong ($D^+ \to K^o\mu^+\nu$) — Control sample 2-prong ($D^o \to K^-\mu^+\nu$)



- Observe 6 events

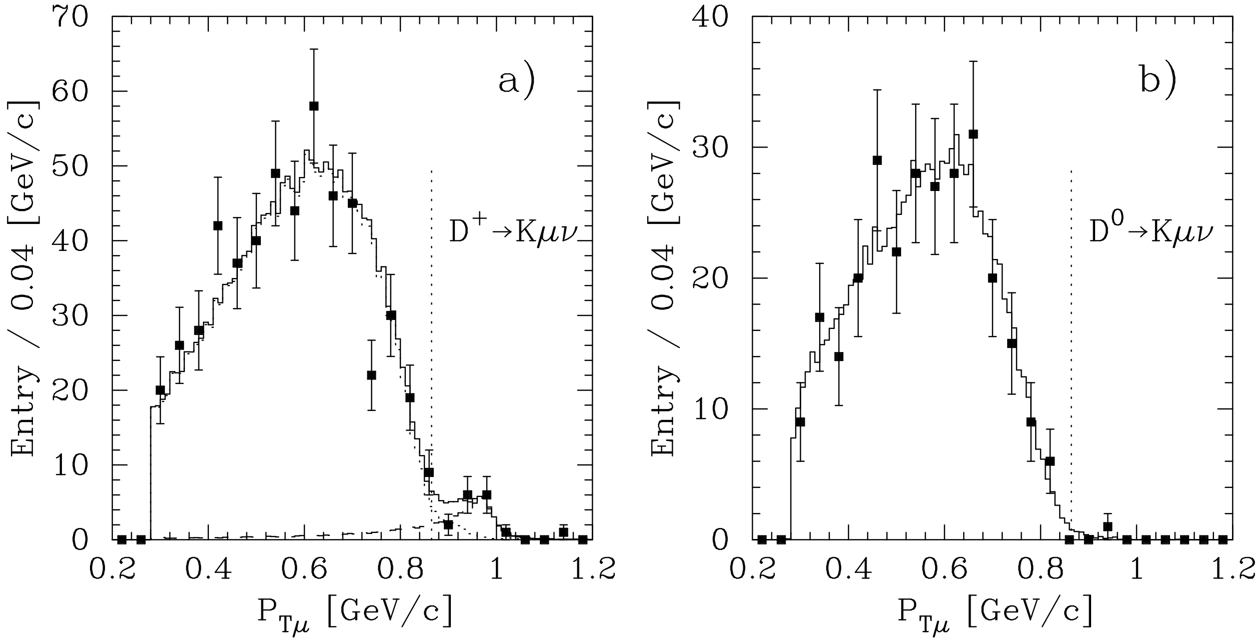
$\mathcal{B}(D_s^+ \to \mu^+\nu) = (4.0^{+1.8+0.8}_{-1.4-0.6} \pm 1.7) \cdot 10^{-3}$

$f_{D_s} = 232 \pm 45 \pm 20 \pm 48$ MeV

$D_s^+ \to \mu^+\nu$ from E653

Same technique as WA75

- 600 GeV π^- beam (Fermilab), emulsion target and μ trigger
- larger statistics
- Signal sample / charged 1-prong — Control sample / neutral 2-prong



- $N(D_s^+ \to \mu^+\nu) = 23.6 \pm 6.0\ ^{+1.0}_{-0.9}$

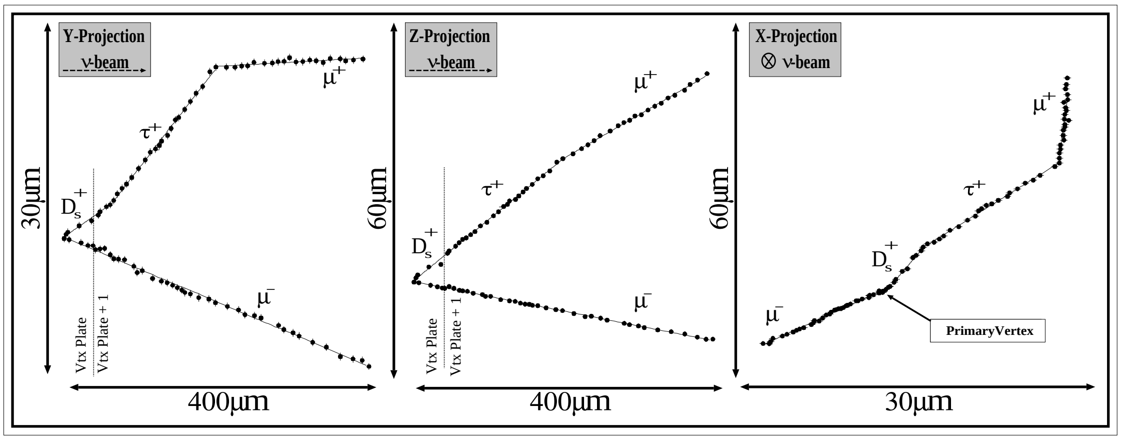
$$\frac{\Gamma(D_s^+ \to \mu^+\nu)}{\Gamma(D_s^+ \to \phi\pi^+)} = 0.16 \pm 0.06 \pm 0.03$$

$$f_{D_s} = 194 \pm 35 \pm 20 \pm 14 \text{ MeV}$$

$D_s^+ \to \tau^+\nu$ from CHORUS

Neutrino oscillation experiment

- uses ν_μ beam (CERN), emulsion target and μ trigger
- neutrino induced diffractive D_s^{*+} production
  $\nu_\mu N \to D_s^{(*)+} X$
- Search for double kink events
  $D_s^+ \to \tau^+\nu,\ \tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$
- Observe 1 candidate event



Experimental technique:

- $e^+e^- \to c\bar{c}X$ — $6 \cdot 10^6$ events
  $\to b\bar{b}, b \to c$ — not used

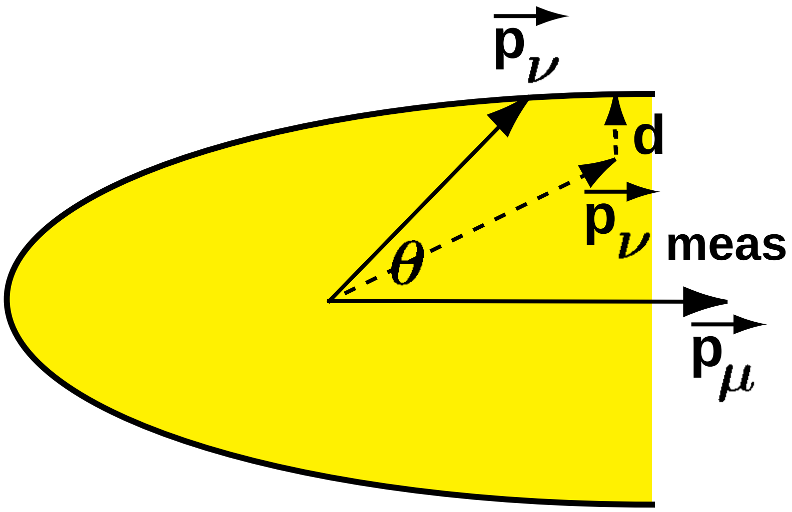
- Reconstruct $c \to D_s^{*+} \to \gamma D_s^+$
  $\hookrightarrow \mu^+\nu$

  Detect μ and γ,
  ν measured with missing momentum $\vec{p}_{miss}$ and energy E_{miss}

- Look at mass difference

$$\Delta M = M(\gamma\mu^+\nu) - M(\mu^+\nu)$$

- p_{miss} and E_{miss} calculated per hemisphere
- use D_s^+ mass as constraint:



Event Selection:

- Muon momentum:
  $p_\mu > 2.4$ GeV/c

  removes $b \to c\ell\nu$

- Missing Momentum:
  $p_{miss} > 0.8$ GeV/c
  $|{E_{miss}}^2 - {p_{miss}}^2| < 2$ GeV^2

  Missing mass

  $|\cos\theta_{p_{miss}}| < 0.9$

  Hermeticity

- Photon:
  energy $E_\gamma > 150$ MeV
  decay angle $\cos\theta(p_\gamma^{CM}, p_{D_s^*}) > -0.7$

- D_s^* candidate:
  $\cos\theta(p_{D_s^*}, p_{thrust}) > 0.975$

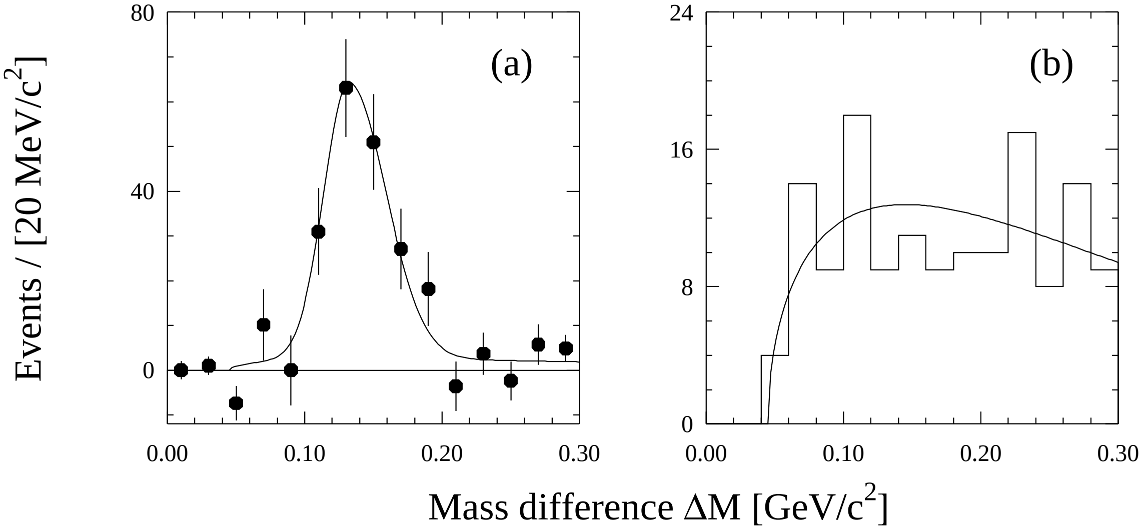
  removes $b \to u\ell\nu$

$D_s^+ \to \mu^+\nu$ from CLEO

Signal Shape: from data

$D^{*o} \to \gamma D^o$
$\hookrightarrow K^- \cancel{\pi}^+$

$D^{*+} \to \cancel{\pi}^+ D^o$
$\hookrightarrow K^- \cancel{\pi}^+$



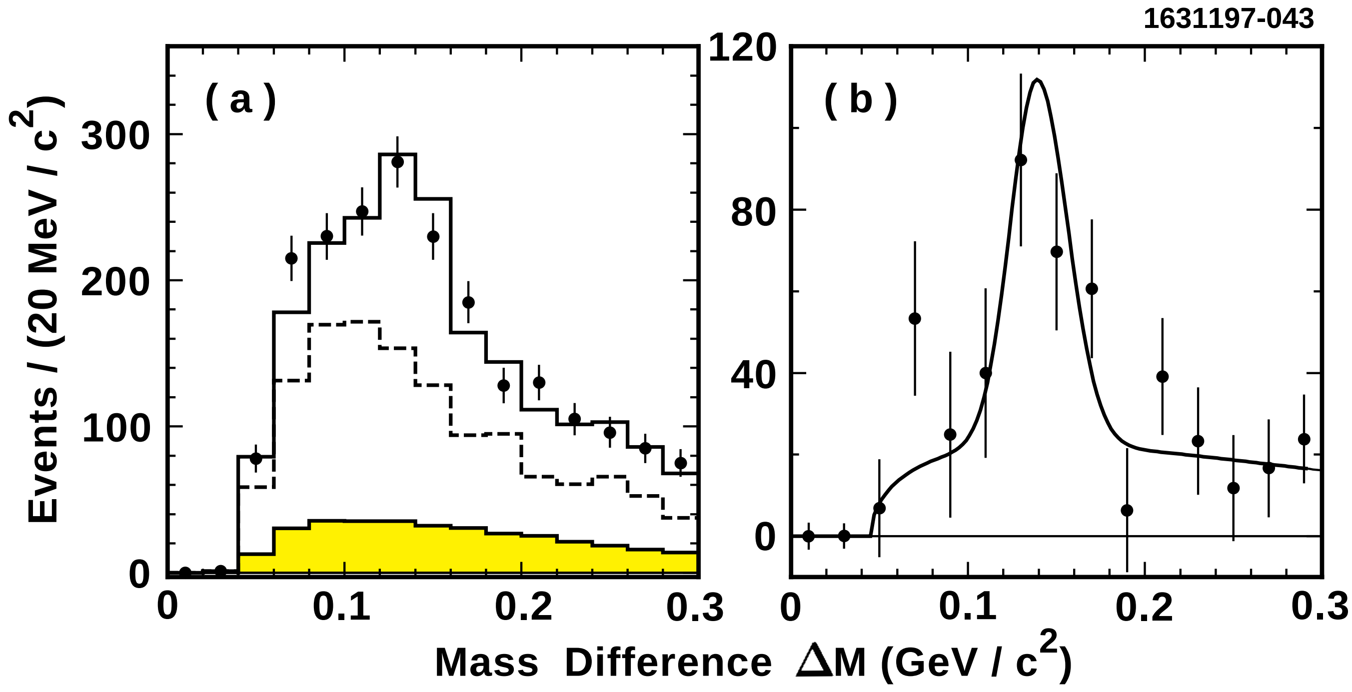
Signal

$D^+ \to \mu^+\nu$
or $D_s^+ \to \mu^+\nu$
with random γ

Physics background:

- $c \to X\ell\nu$ and $D_s^+ \to \tau^+\nu$
  estimated from electron data
- $\Gamma(D_s^+ \to e^+\nu) = 2 \cdot 10^{-5}\,\Gamma(D_s^+ \to \mu^+\nu)$
- scale factor $r(\mu/e) = 1.01 \pm 0.03$

Final mass difference distribution:



- 3 components:
  - electron data (dashed)
  - Excess of muon over electron fakes (shaded)
  - Signal contribution (1 free parameter)

    182 ± 22 $\quad D_s^{*+} \to \gamma D_s^+,\ D_s^+ \to \mu^+\nu.$

    250 ± 38 $\quad D_s^{*+}$ or $D^+ \to \mu^+\nu$ + random γ
- Result:

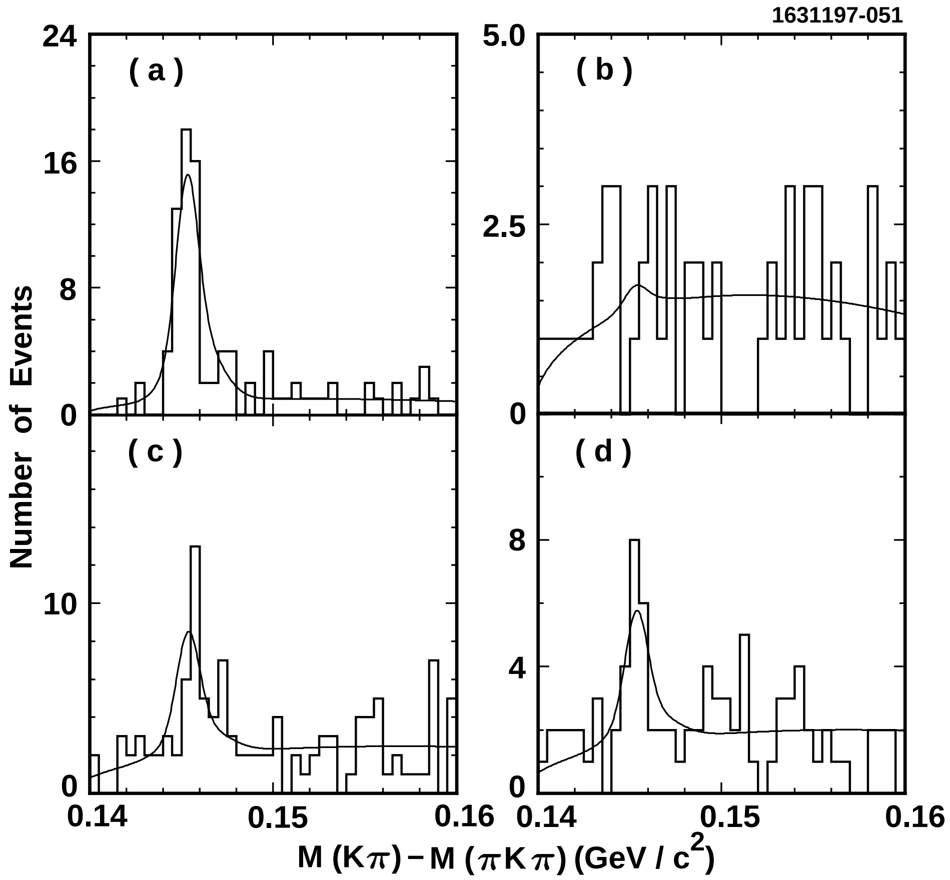
$$\frac{\Gamma(D_s^+ \to \mu^+\nu)}{\Gamma(D_s^+ \to \phi\pi^+)} = 0.173 \pm 0.023 \pm 0.035$$

$$f_{D_s} = 280 \pm 19 \pm 28 \pm 34 \text{ MeV}$$

Systematic errors:

Source of Error	Value	Size of error (%)
Muon fake rate	(0.69±0.05)%	9
Electron fake rate	(0.21±0.03)%	7
$\pi/K/p$ fractions (sources of fakes)	60%/27%/13%	7
μ/e normalization	1.01±0.03	9
Detection efficiency	(4.2±0.3)%	7
D_s^{*+}/D_s^+ production ratio	1.08±0.13	8
$\phi\pi^+$ normalization	24740±1200±810	3
Total systematic error		20

Muon and electron fakes: exclusive D^{*+} decays

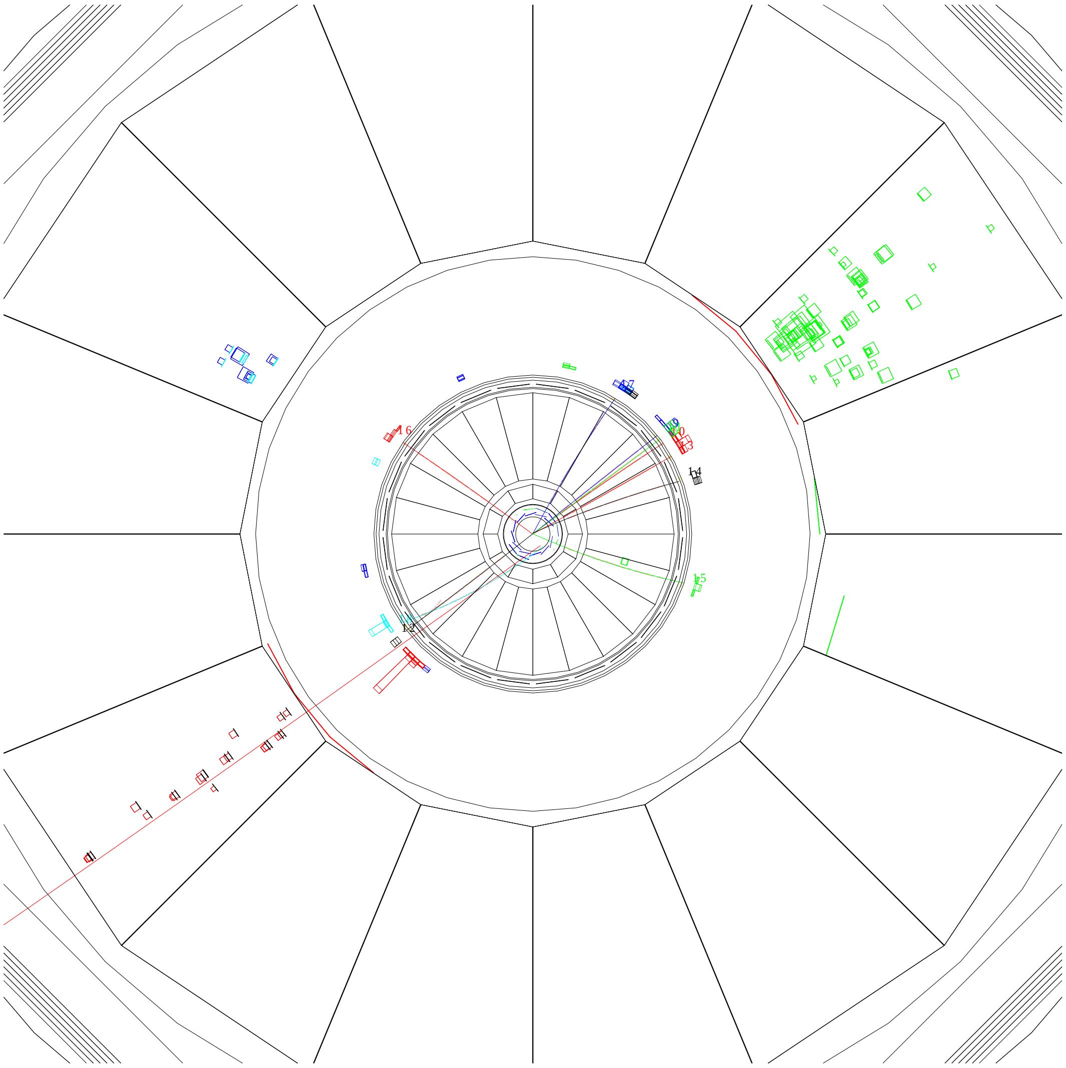


$D_s^+ \to \tau^+\nu$ from L3

Decay chain

$$
\begin{aligned}
c \to D_s^* \to \; & D_s\gamma \\
& D_s \to \; \tau\nu_\tau \\
& \qquad\quad \tau \to \mu(e)\nu_\tau\nu_{\mu(e)}
\end{aligned}
$$

Run # **537902** **Event #** **493** Total Energy : 59.07 GeV



$D_s^+ \to \tau^+\nu$ from L3

Event Selection:

- $e^+e^- \to Z \to c\bar{c}X$ $\quad < x_E > \sim 0.5$
  $\to Z \to b\bar{b}X, b \to c$ $\quad < x_E > \sim 0.3$, not used

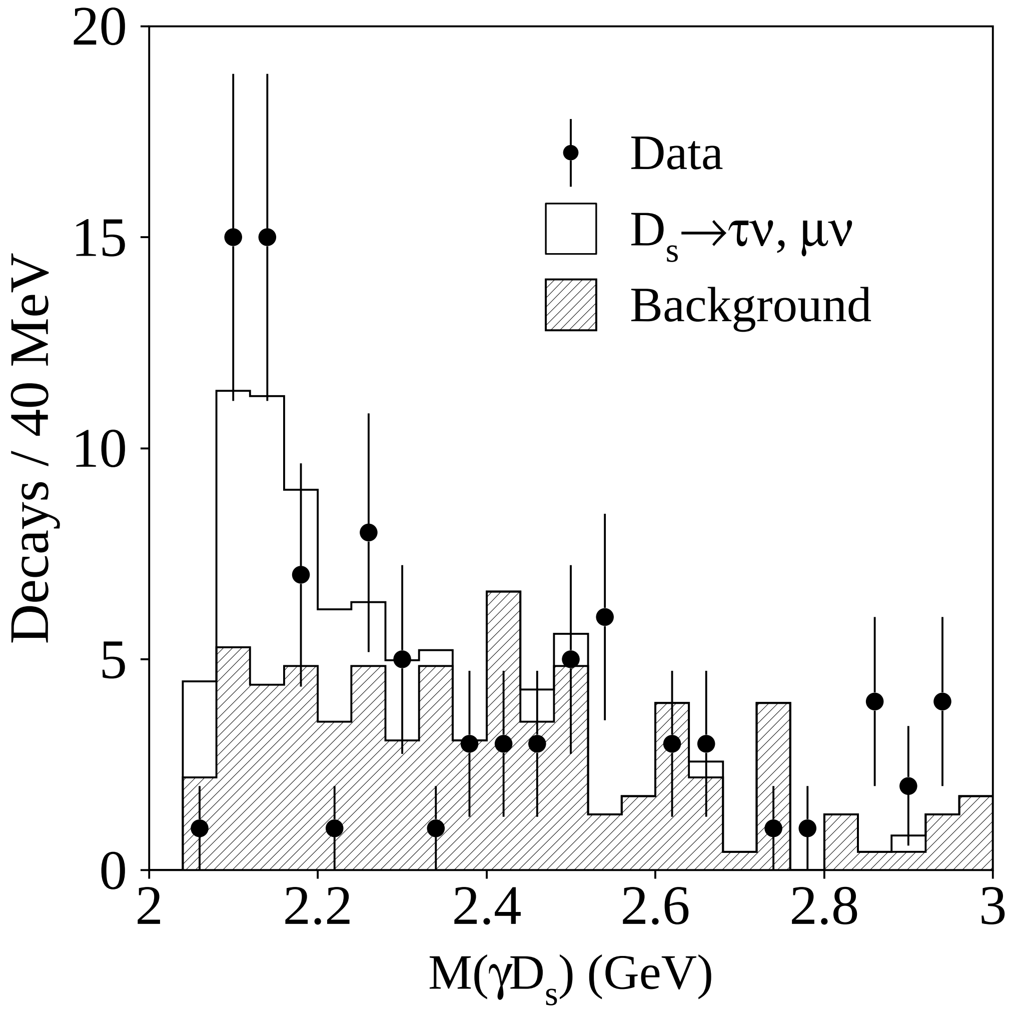
- Select lepton events (μ and e) with missing transverse energy
- Reconstruct D_s^+ using all particles but lepton:

$$E_{D_s} = M_Z - \sum_{i \neq \text{lepton}} E_i$$
$$\vec{P}_{D_s} = - \sum_{i \neq \text{lepton}} \vec{P}_i$$

- use mass constraint $M_{D_s}^2 = E_{D_s}^2 - \vec{P}_{D_s}^2$ to improve E_{D_s} (kinematic fit)
- Photon energy 3 GeV $< E_\gamma <$ 5 GeV
- D_s energy $E_{D_s} >$ 30 GeV
- Energy of most energetic hadron with charge opposite to lepton $E_{h^-} <$ 3 GeV

Final Data Sample:

$$N(D_s^+ \to \tau^+\nu) = 15.6 \pm 6.0$$



$$\mathcal{B}(D_s^+ \to \tau^+\nu) = 0.074 \pm 0.028 \pm 0.016 \pm 0.018$$

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

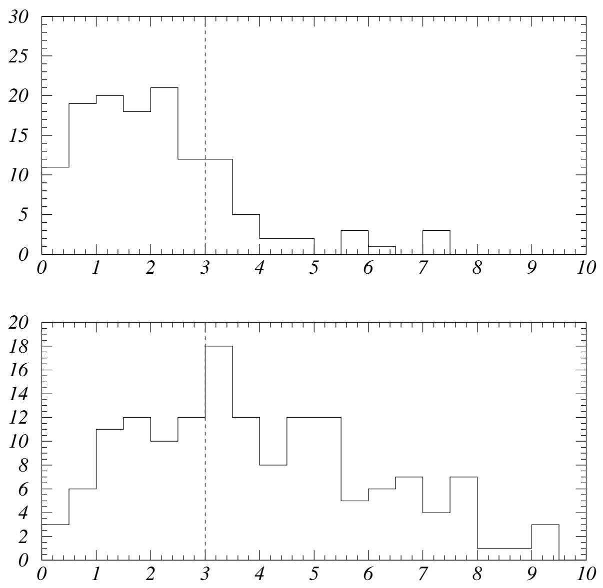
$D_s^+ \to \tau^+\nu$ from L3

Systematic checks:

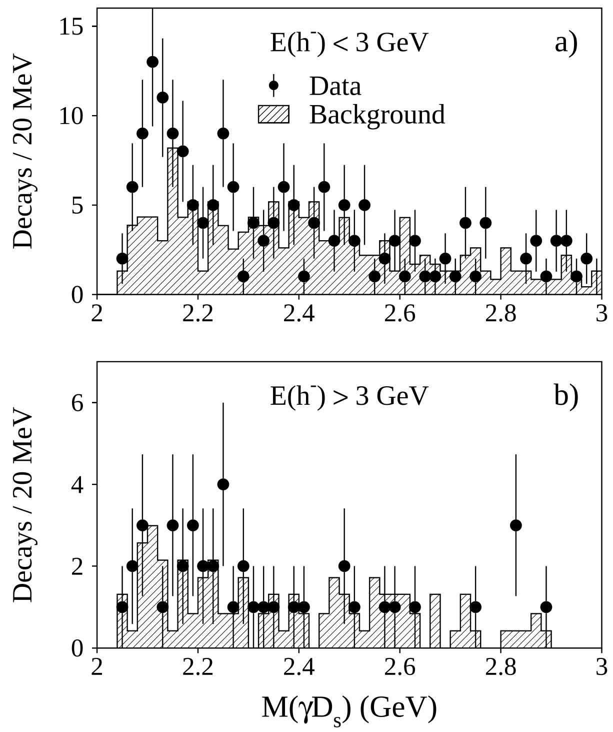
$E_{h^-} < 3$ GeV - D_s enriched sample (A)

$E_{h^-} > 3$ GeV - D_s depleted sample (B)

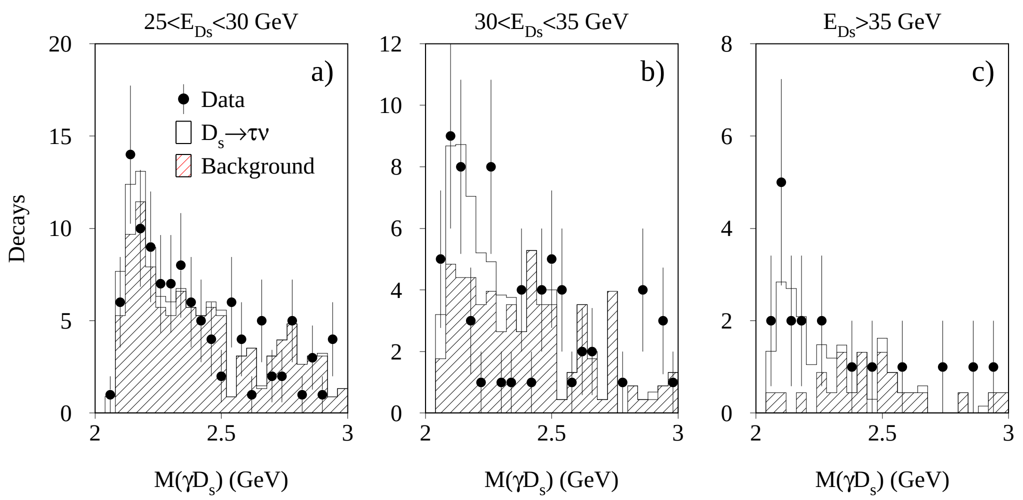
$D_s^+ \to \tau^+\nu$ Monte Carlo



E_{h^-} (GeV)



Agreement Data - Monte Carlo for E_{D_s}

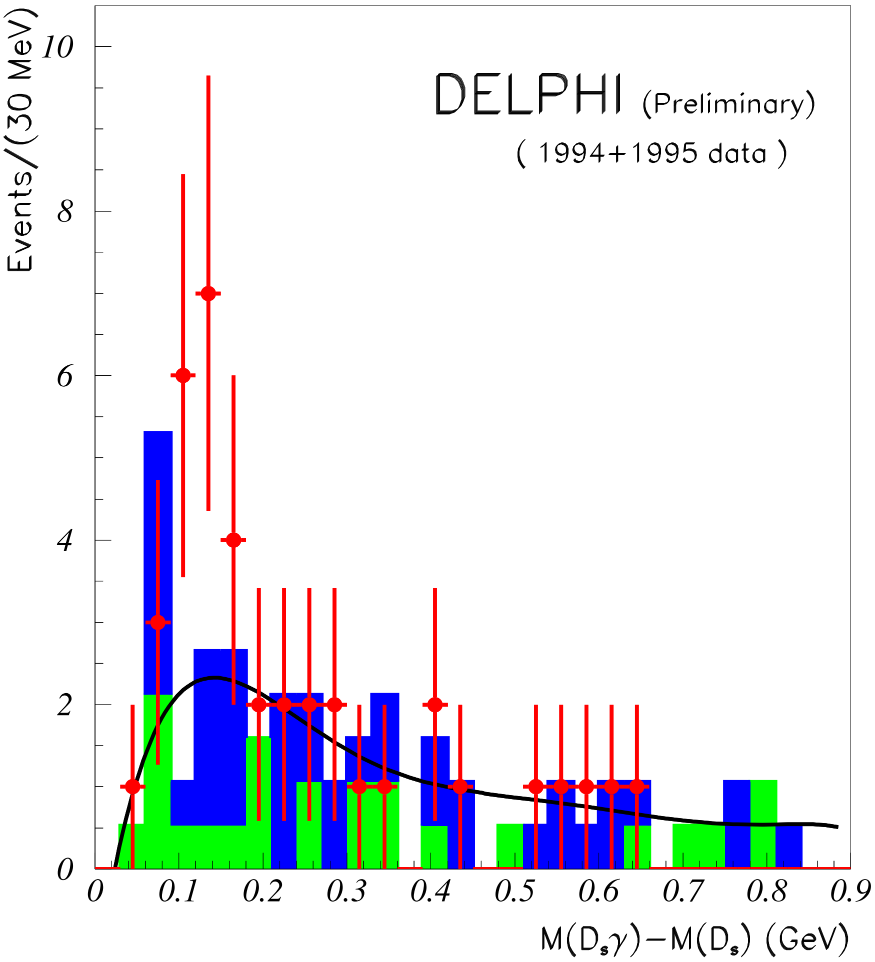


$D_s^+ \to \tau^+\nu$ from DELPHI

Analysis similar to L3

- Preliminary result

$$N(D_s^+ \to \tau^+\nu) = 10.8 \pm 5.4$$



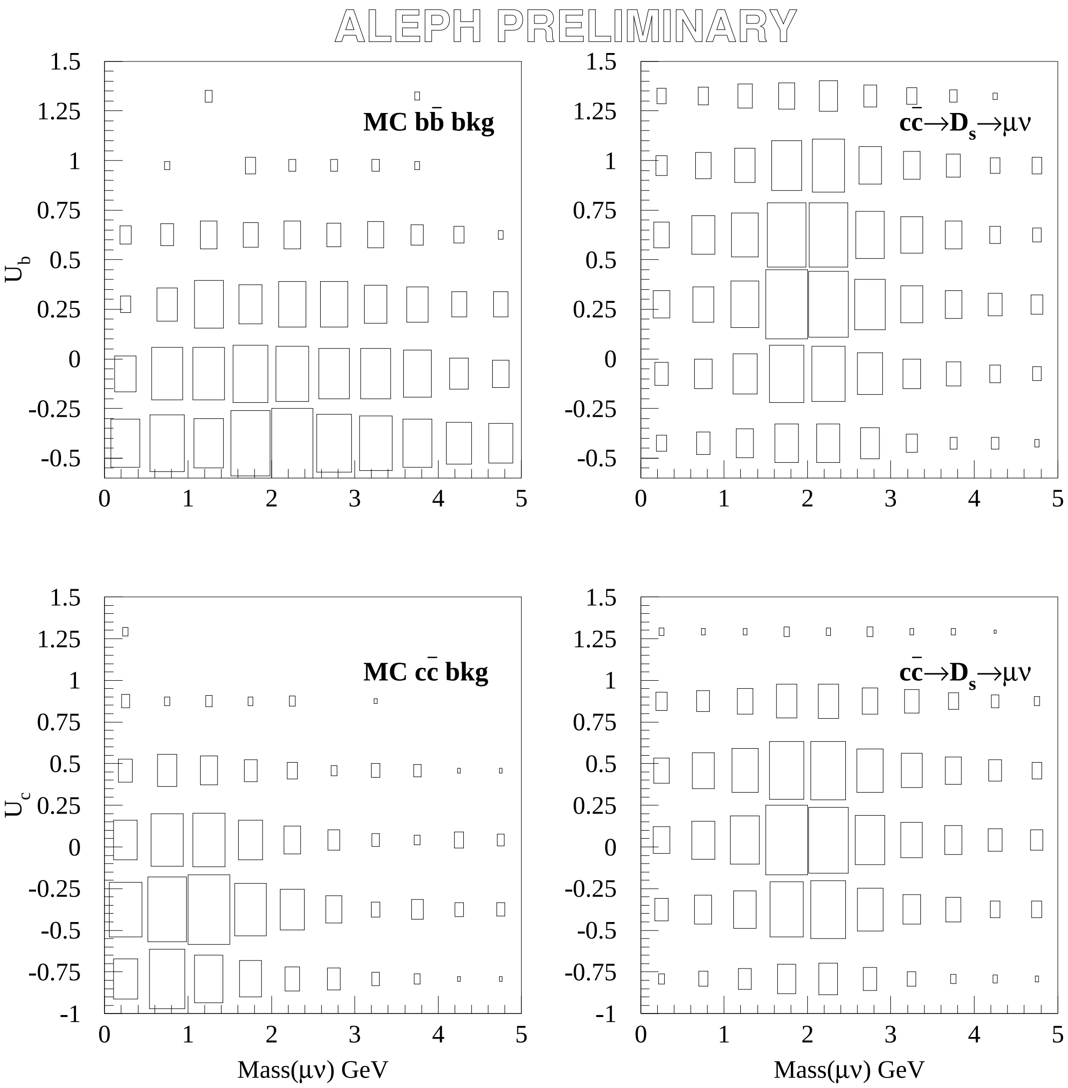
$$\mathcal{B}(D_s^+ \to \tau^+\nu) = 0.085 \pm 0.042 \pm 0.026$$

$$f_{D_s} = 330 \pm 95 \text{ MeV}$$

$D_s^+ \to \mu^+\nu$ from ALEPH

Event Selection:

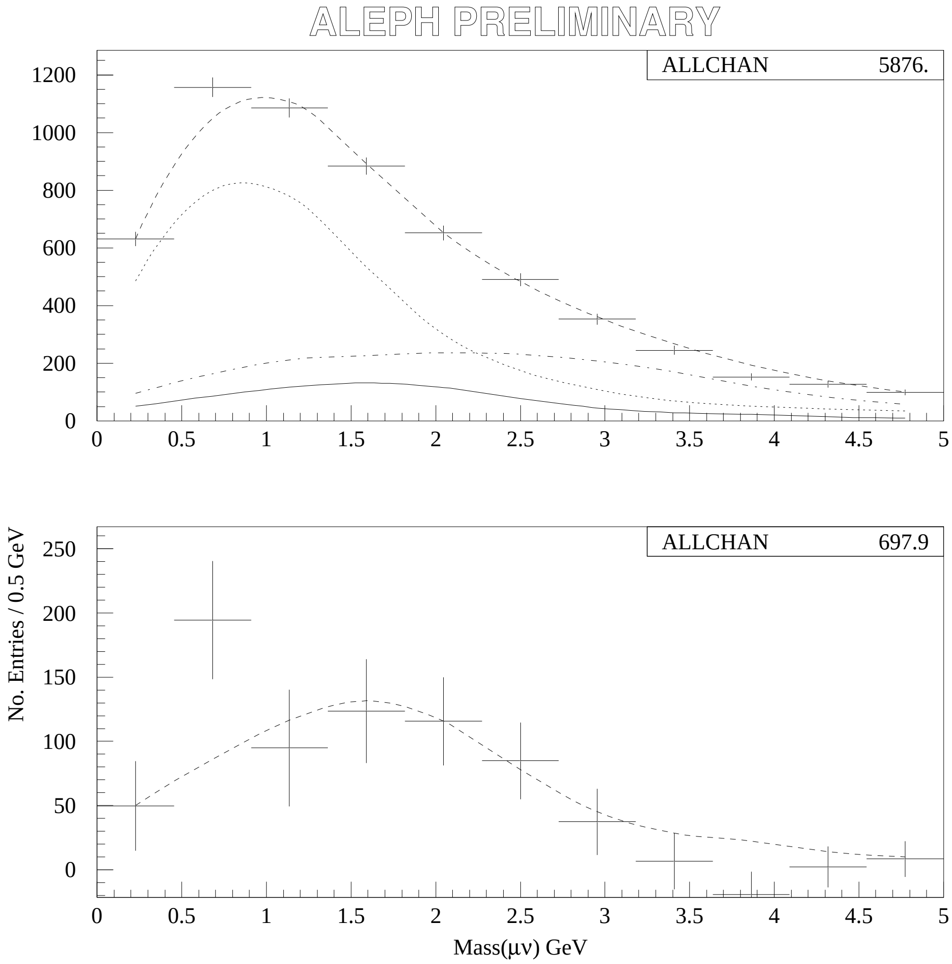
- Optimized for $D_s^+ \to \mu^+\nu$ in $e^+e^- \to Z \to c\bar{c}$ events
- Use kinematic fit (missing momentum), lifetime tag, rapidity
- Construct $b\bar{b}$- and $c\bar{c}$-background discriminants U_b and U_c



$D_s^+ \to \mu^+\nu$ from ALEPH

Simultaneous Fit to mass $M(\mu\nu)$ in 6×6 bins in the U_b and U_c plane

- Preliminary result



- $N(D_s^+ \to \mu^+\nu + D_s^+ \to \tau^+\nu) = 747 \pm 93$

$$\mathcal{B}(D_s^+ \to \mu^+\nu) = (0.64 \pm 0.21 \pm 0.15)\%$$

$$f_{D_s} = 284 \pm 18 \pm 49 \pm 34 \text{ MeV}$$

$e^+e^- \to D_s^+ D_s^-$ at $E_{CM} = 4.03$ GeV

- Fully reconstruct $D_s^+ \to \phi\pi^+, \bar{K}^{*0}K^+, \bar{K}^0 K^+$
  $\longrightarrow N(D_s^+) = 94.3 \pm 12.3$
- look for $D_s^+ \to \tau^+\nu$ and $D_s^+ \to \mu^+\nu$
  on other side of event
  $\longrightarrow$ 3 candidates with 0.35 background events

$$
\begin{aligned}
D_s &\to \tau\nu,\ \tau \to e\nu\bar{\nu} \\
D_s &\to \tau\nu,\ \tau \to \mu\nu\bar{\nu} \\
D_s &\to \mu\nu
\end{aligned}
$$

- Assume lepton universality

$$\mathcal{B}(D_s^+ \to \mu^+\nu) = (1.5\,^{+1.3}_{-0.6}\,^{+0.3}_{-0.2}) \cdot 10^{-2}$$

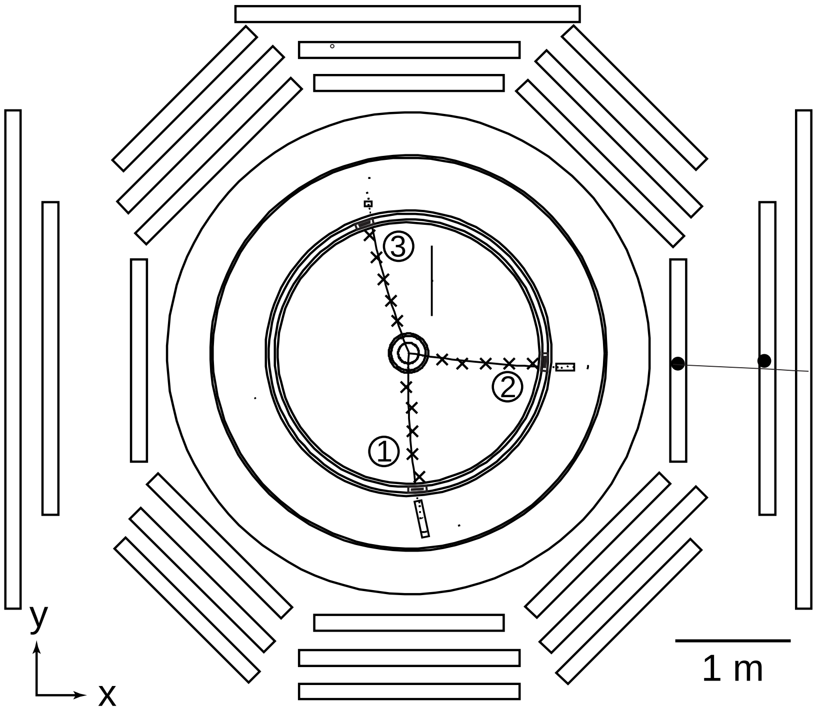
$$f_{D_s} = 430\,^{+150}_{-130} \pm 40 \text{ MeV}$$

$e^+e^- \to D^{*+}D^-$ at $E_{CM} = 4.03$ GeV

- Fully reconstruct decay chain $D^{*+}D^-$

$$\begin{aligned} D^{*+} &\to \pi^+ D^0, \pi^0 D^+ \\ D^+ &\to \mu^+ \nu_\mu \end{aligned}$$

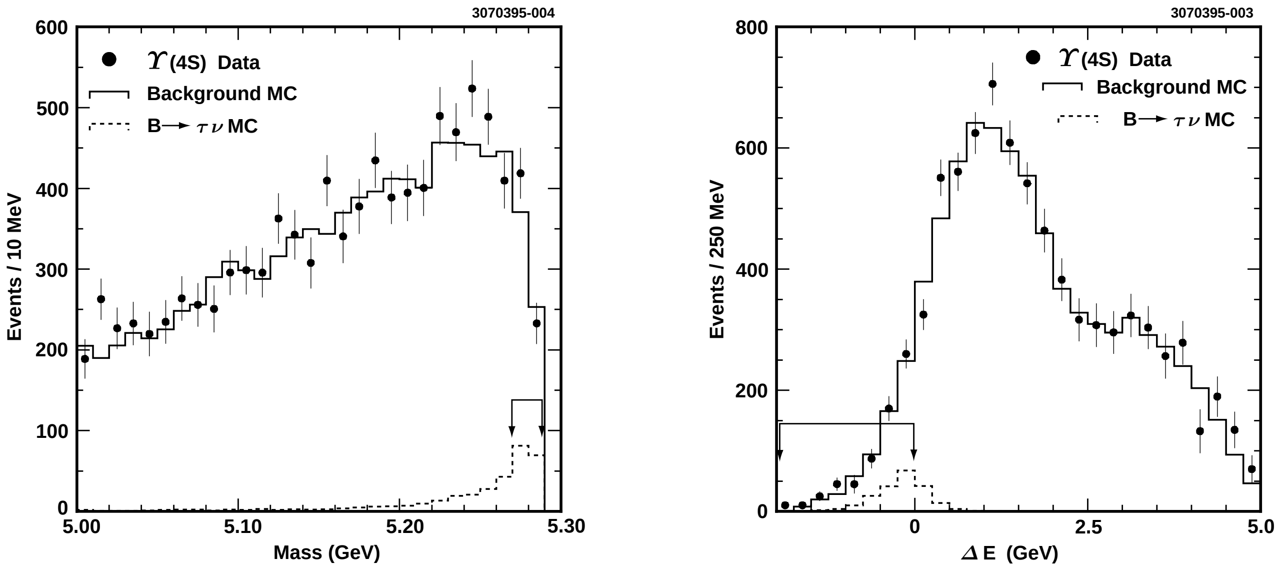
- 1 candidate event found (0.2 background expected)



$$\mathcal{B}(D^+ \to \mu^+\nu) = (0.08\,^{+0.16}_{-0.05}\,^{+0.05}_{-0.02}) \cdot 10^{-2}$$
$$f_D = 300\,^{+180}_{-150}\,^{+80}_{-40}\ \text{MeV}$$

$$e^+e^- \to \Upsilon(4S) \to B^+B^-$$
$$\hookrightarrow \tau^+\nu$$
$$\hookrightarrow \mu^+(e^+)\nu\bar{\nu}$$

- Reconstruct E, $\vec{p}$ recoiling against lepton
  $\longrightarrow$ must be consistent with a B
- $M^2 = E_{\mathrm{beam}}^2 - p^2$ $\quad\quad$ $\Delta E = E - E_{\mathrm{beam}}$



$c\bar{c}$ contribution subtracted with data taken below $\Upsilon(4S)$ resonance

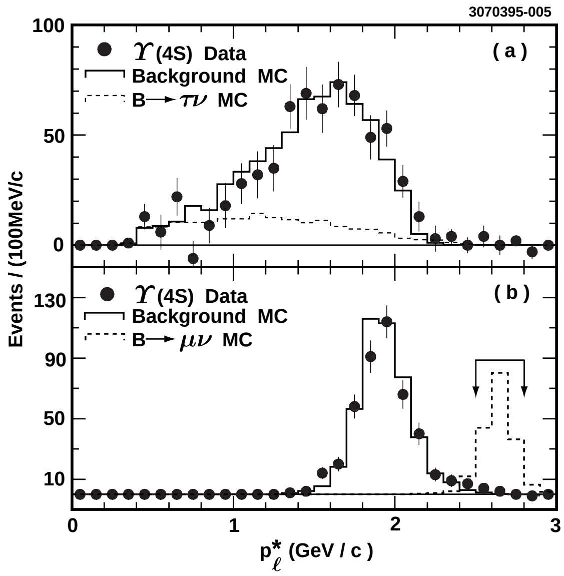
- Fit to 2-dimensional distribution
  $\longrightarrow N(B^+ \to \tau^+\nu) = -9 \pm 36$

$$\mathcal{B}(B^+ \to \tau^+\nu) < 2.2 \cdot 10^{-3} \text{ at } 90\% \text{ CL}$$

$B^+ \to \mu^+\nu$ and $B^+ \to e^+\nu$ from CLEO

$$e^+e^- \to \Upsilon(4S) \to B^+B^-$$
$$\hookrightarrow \quad \mu^+\nu, e^+\nu$$

- 2-body decay $\longrightarrow p_l^*$ well defined
  in B rest frame ($p_B = 320$ MeV)



a) $B^+ \to \tau^+\nu$

b) $B^+ \to \mu^+\nu$

looser B selection
harder continuum suppression

- Observe: $\quad$ 3 μ and 2 e events
  Expected background: $\quad 4.4 \pm 1.4$ events

$$\mathcal{B}(B^+ \to \mu^+\nu) < 2.1 \cdot 10^{-5} \text{ at } 90\% \text{ CL}$$
$$\mathcal{B}(B^+ \to e^+\nu) < 1.5 \cdot 10^{-5} \text{ at } 90\% \text{ CL}$$

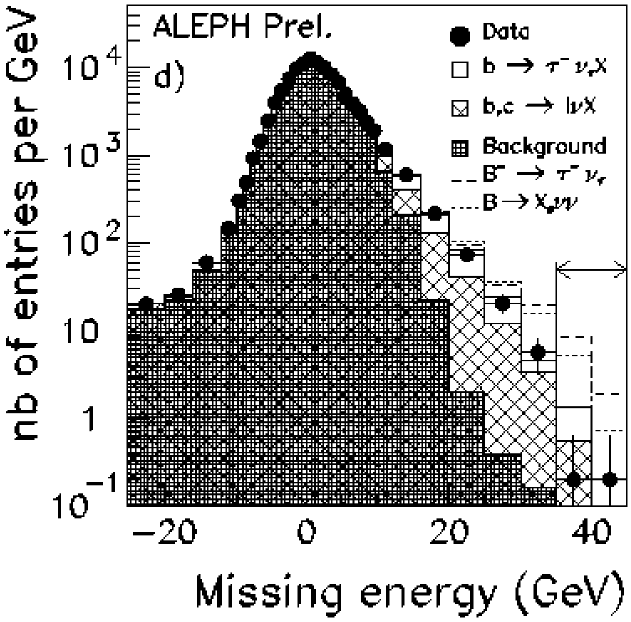
$B^+ \to \tau^+ \nu$ from ALEPH

Strategy

- Look for events with very large E_{miss}
- Use hadronic τ decay modes

$$b \to B^+ \to \tau^+ \nu_\tau$$
$$\tau^+ \to \text{hadrons } \bar{\nu}_\tau$$

$\longrightarrow$ veto leptons, from $b \to c\ell\nu$
$\longrightarrow$ lifetime b-tag



$E_{miss} > 35$ GeV

2 candidate events

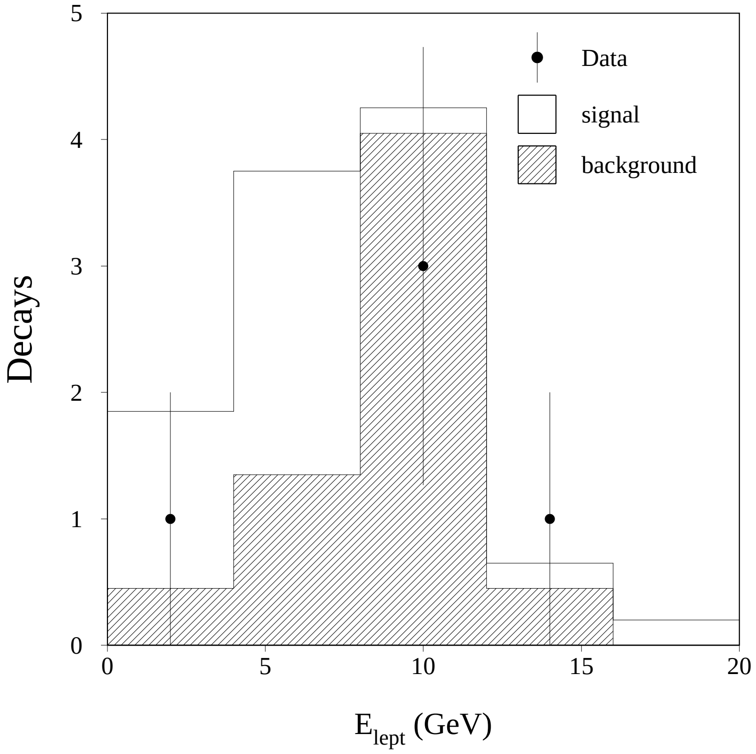
$$\mathcal{B}(B^+ \to \tau^+\nu) < 1.6 \cdot 10^{-2} \;\text{ at }\; 90\% \text{ CL}$$

Similar strategy as $D_s^+ \to \tau^+\nu$

- Reconstruct B meson
  $\longrightarrow B$ meson energy $E_B > 30$ GeV
- Leptonic and hadronic τ decays used
- Lepton sample

$$
\begin{aligned}
b \to B^+ \to \ & \tau^+\nu_\tau \\
& \tau^+ \to \ \ell^+\nu_\ell\bar{\nu}_\tau
\end{aligned}
$$

- Selection criteria
  lepton not coming from primary vertex
  Neutral energy in 30^o cone around $B < 0.5$ GeV

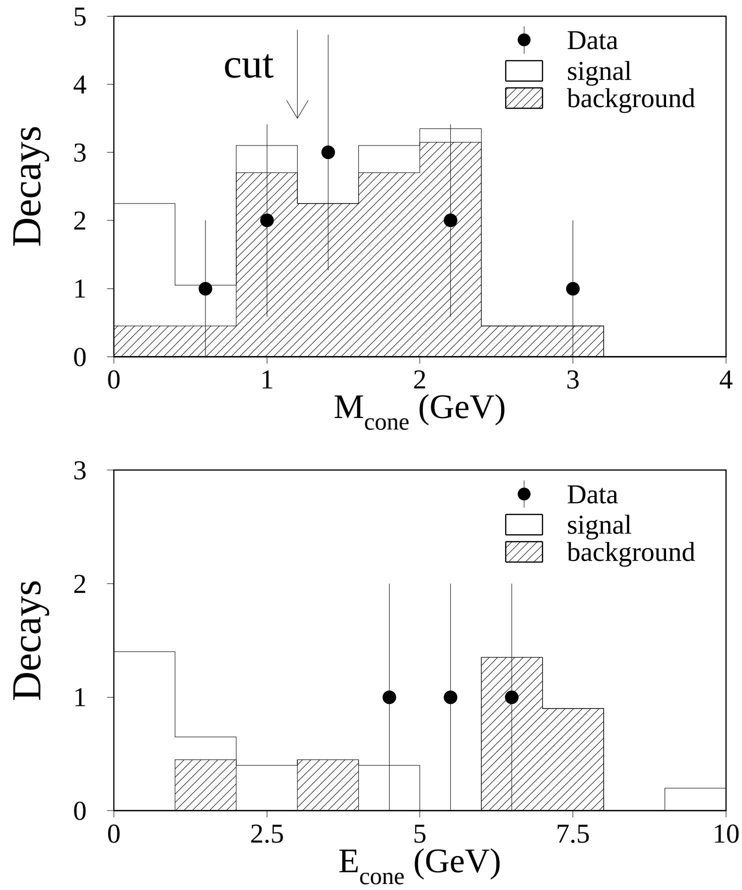


5 candidate events

- Hadron sample

$$b \to B^+ \to \tau^+\nu_\tau$$
$$\tau^+ \to \text{hadrons } \bar{\nu}_\tau$$

- Selection criteria
  as lepton sample, in addition mass of all particles but τ in 30^o cone $M_{cone} < 1.2$ GeV



- 3 candidate events below M_{cone} cut

- Combined fit to lepton and hadron samples $\Longrightarrow$
  $N < 3.8$ at 90% CL

$$\mathcal{B}(B^+ \to \tau^+\nu) < 5.7 \cdot 10^{-4} \text{ at } 90\% \text{ CL}$$

Summary of f_{D_s} and f_D Measurements

Experiment	Events	f_{D_s} (MeV)
WA75 (1993)	6	$232 \pm 45 \pm 20 \pm 42$
E653 (1996)	$23.6 \pm 6.0\ ^{+1.0}_{-0.9}$	$194 \pm 35 \pm 20 \pm 14$
CLEO (1994/98)	182 ± 22	$280 \pm 19 \pm 28 \pm 34$
BES (1994/96)	3	$430^{+150}_{-130} \pm 40$
L3 (1996)	15.6 ± 6.0	$309 \pm 58 \pm 33 \pm 38$
DELPHI (1997)	10.8 ± 5.4	330 ± 95
ALEPH (1998)	747 ± 93	$284 \pm 18 \pm 49 \pm 34$

- Average

$$f_{D_s} = 260 \pm 19(exp.) \pm 32(norm.)\ \mathrm{MeV}$$

- 1 candidate event for $D^+ \to \mu^+\nu$ (BES)

$$f_D = 300\ ^{+180}_{-150}\ ^{+80}_{-40}\ \mathrm{MeV}$$

- In agreement with recent theoretical predictions from Lattice QCD
- Some older potential models excluded
- In agreement with results from $\bar{B} \to D^* D_s^-$ using factorization

Conclusions

- Many measurements of $D_s^+ \to \mu^+\nu$ and $D_s^+ \to \tau^+\nu$
  $\Longrightarrow f_{D_s} = 260 \pm 38$ MeV
- Lattice QCD calculations
  $\Longrightarrow f_{D_s} = 190$ to 270 MeV
- Experiments start to test Lattice QCD, good for calculations of f_B.
- Upper limits are obtained for

$$\begin{aligned} \mathcal{B}(B^+ \to \tau^+\nu) &< 5.7 \cdot 10^{-4} \\ \mathcal{B}(B^+ \to \mu^+\nu) &< 2.1 \cdot 10^{-5} \text{ at } 90\% \text{ CL} \\ \mathcal{B}(B^+ \to e^+\nu) &< 1.5 \cdot 10^{-5} \end{aligned}$$

- need more effort for measuring f_B
  Prediction: $\mathcal{B}(B^+ \to \tau^+\nu) \approx 5 \cdot 10^{-5}$