Hadronic Charm Decays and Lifetimes from E791

(Fermilab E791 Collaboration*)

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*http://fnphyx-www.fnal.gov/experiments/e791

Outline

1. **The E791 Experiment**

2. **Measurement of the D_s Lifetime**

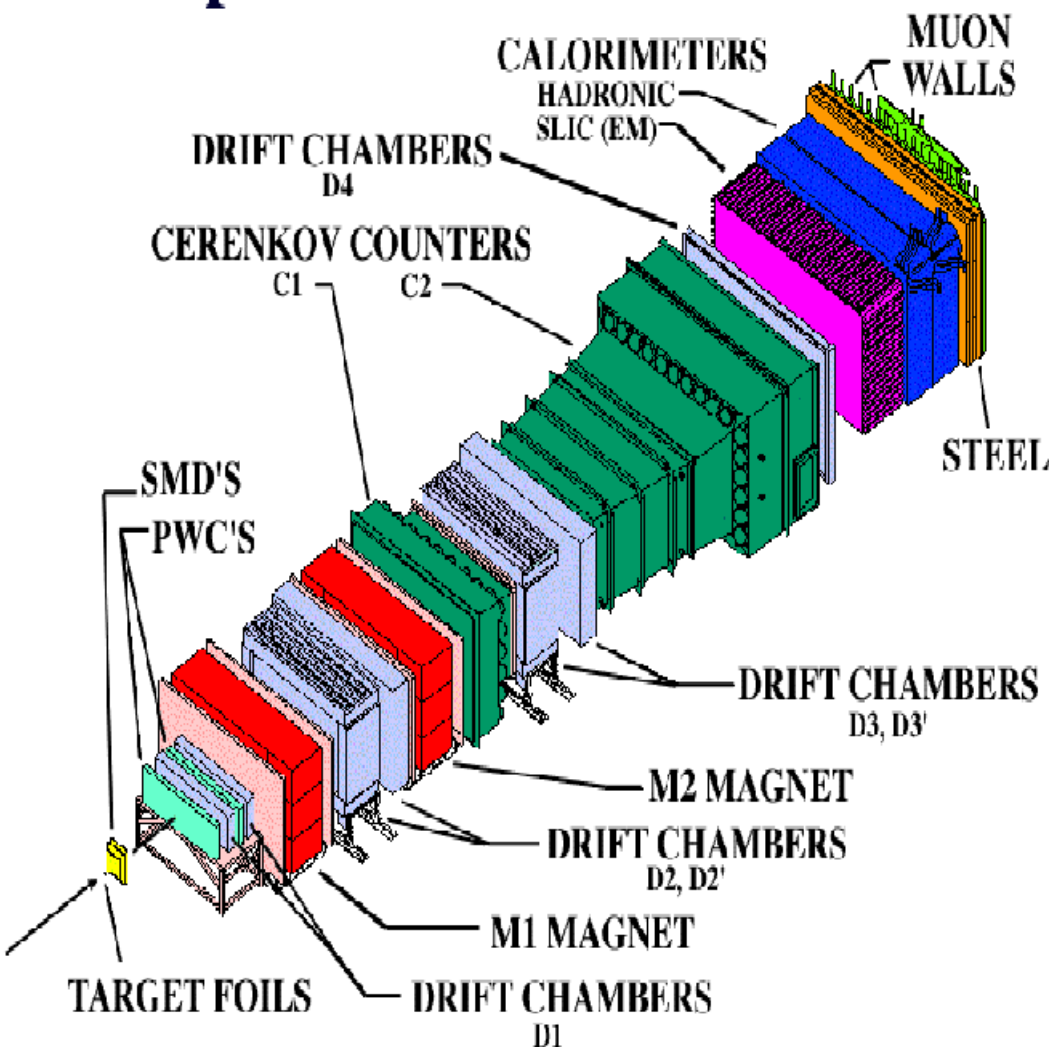
3. **D^0 Lifetime and Mixing Rate**

4. **Singly Cabibbo-suppressed Decay $D^0 \to K^-K^+\pi^-\pi^+$**

5. **Doubly Cabibbo-suppressed Decay $D^+ \to K^+\pi^+\pi^-$**

6. **Summary & Conclusions**

E-791 Spectrometer



The E791 Experiment

E791 is a high statistics charm production experiment which ran at Fermilab during the 1991–1992 fixed-target run. Over 20 billion events were collected with the Tagged Photon Spectrometer using a 500 GeV π^- beam. The spectrometer included:

- 5 thin target foils (1 platinum followed by 4 diamond).
- 23 planes of silicon microstrip detectors (6 upstream and 17 downstream).
- 10 planes of proportional wire chambers.
- 35 drift chamber planes.
- 2 multicell threshold Čerenkov counters.
- electromagnetic and hadronic calorimeters.
- muon detector.

Measurement of the D_s Lifetime

- Current D meson lifetimes:

$$\begin{aligned} \tau(D^+) &= 1.057 \pm 0.015 \text{ ps} \\ \tau(D^0) &= 0.415 \pm 0.004 \text{ ps} \\ \tau(D_s) &= 0.467 \pm 0.017 \text{ ps} \end{aligned}$$

- Ratio of D mesons lifetimes:

$$\tau(D^+) : \tau(D^0) : \tau(D_s) = 2.5 : 1 : 1.1$$

$$\Rightarrow \frac{\tau(D_s)}{\tau(D^0)} = 1.13 \pm 0.04 \quad (\ 3\sigma \text{ diff}\ )$$

- Possible sources of lifetime difference between D^+ and D^0: Large contribution from W-exchange and/or large destructive interference between D^+ amplitudes.

- Possible sources of lifetime difference between D_s and D^0: Phase space differences, W-exchange, W-annihilation, color factors, decay via τ lepton modes, and relativistic effects.

Fit Procedure

- Measure $D_s \to \phi\pi$ lifetime using a combined unbinned maximum liklehood fit of mass and RPLT distributions of D_s and $D^+ \to \phi\pi$.

- RPLT is defined as:

$$\text{RPLT} = (L - L_{min})/c\beta\gamma$$

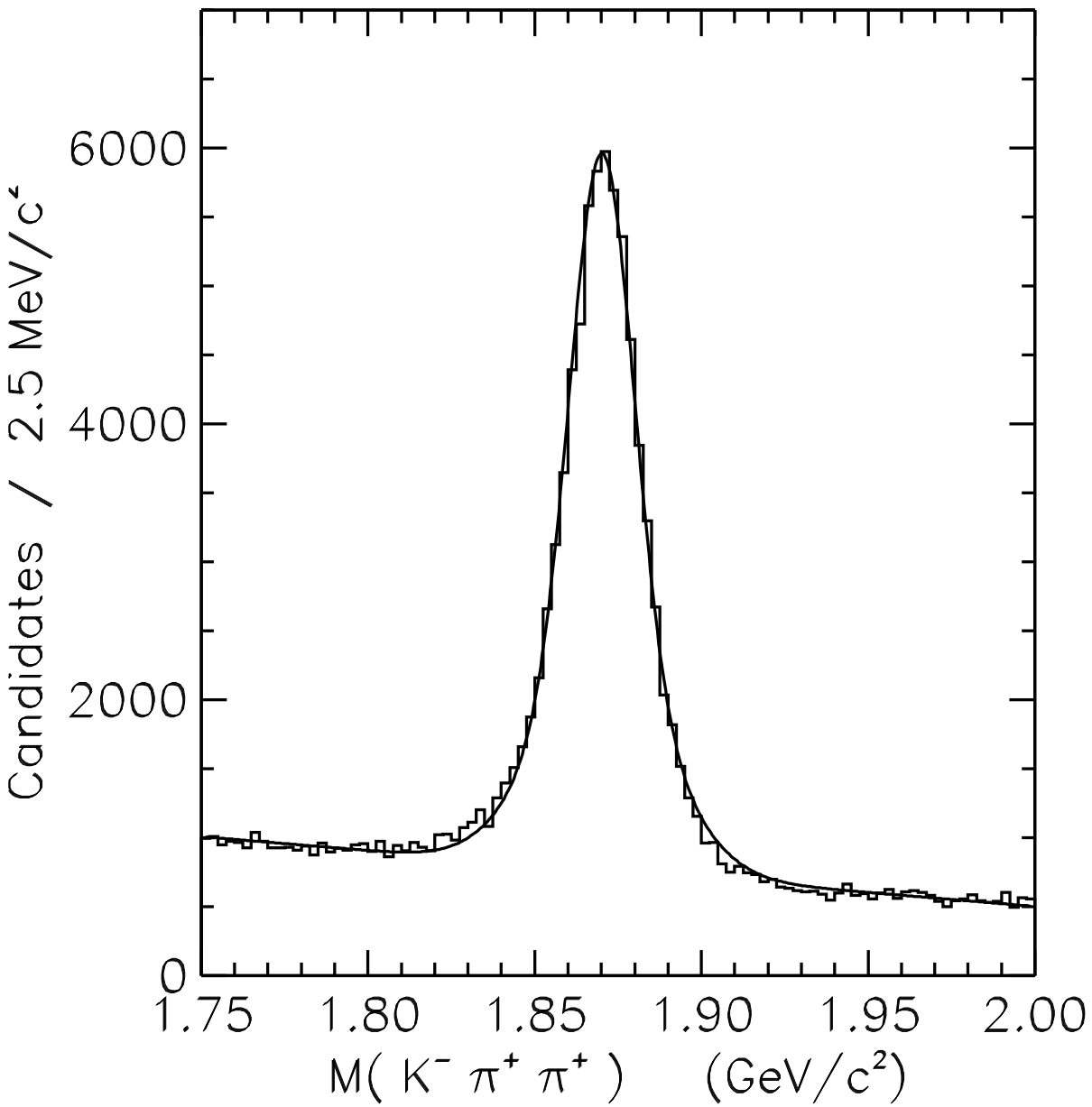
  where L_{min} is minimum L value allowed by our cuts on separation between secondary and primary vertices.

- Lifetime efficiency obtained from data and ratios of efficiencies from MC:

$$\epsilon_{RPLT}(D_s \to \phi\pi) = \epsilon^{Data}_{RPLT}(D^+ \to K\pi\pi) \times \frac{\epsilon^{MC}_{RPLT}(D_s \to \phi\pi)}{\epsilon^{MC}_{RPLT}(D^+ \to K\pi\pi)}$$

- The efficiencies were determined separately for D_s and D^+.

$$N(D^+ \to K^+\pi^-\pi^-) = 62651 \pm 337$$



Likelihood Function

The overall likelihood function is:

$$\mathcal{L} = \frac{e^{-(N_{pred}-N_{obs})^2/2N_{pred}}}{\sqrt{2\pi N_{pred}}} \prod_i \mathcal{L}_i$$

where $N_{pred} = N_{D^+} + N_{D_s} + N_{BG}$.

The likelihood for each candidate is:

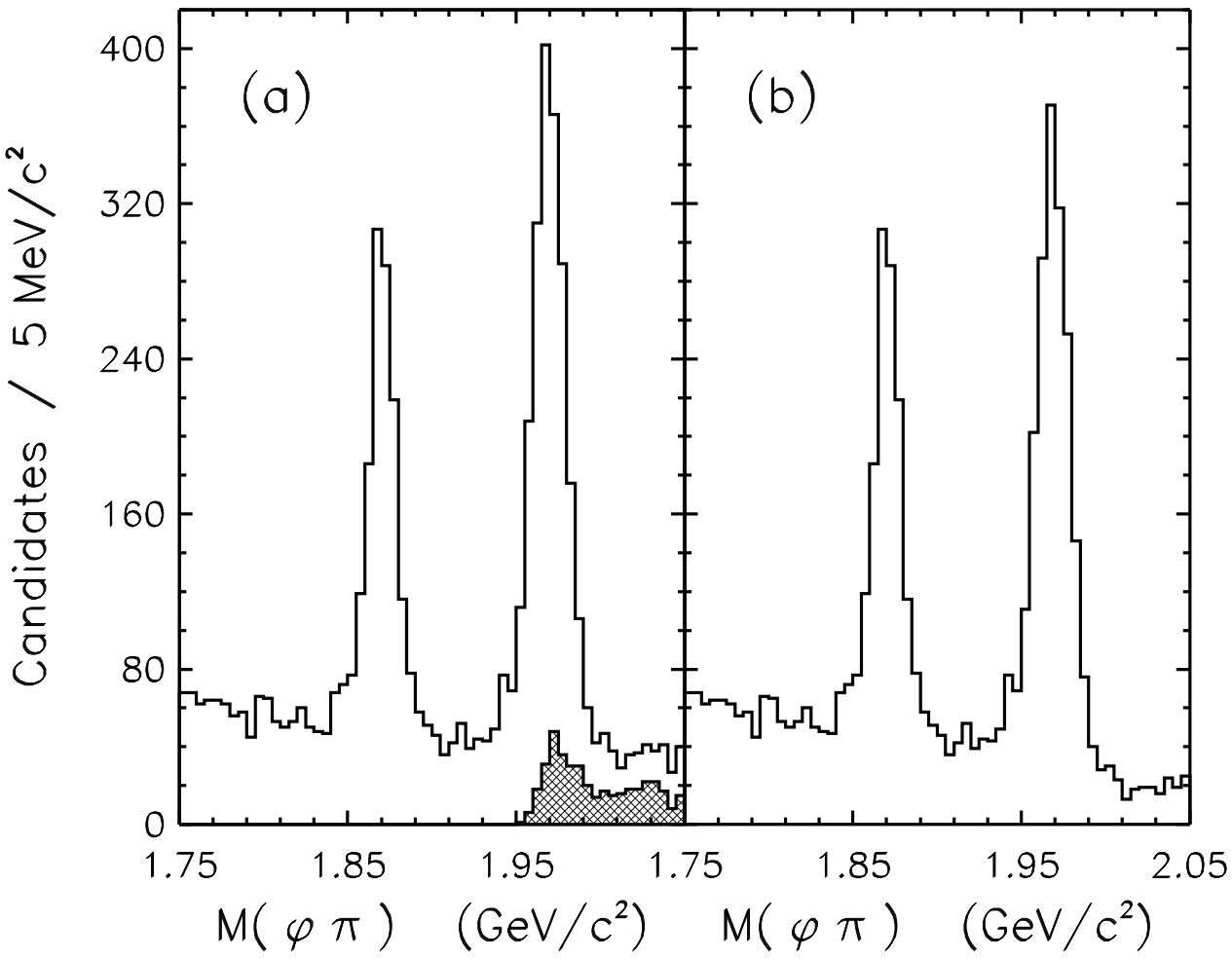
$$\mathcal{L}_i = S_{D^+}(m_i, t_i) + S_{D_s}(m_i, t_i) + B(m_i, t_i)$$

$$S_{D^+}(m_i, t_i) = F_{D^+} \times \frac{1}{\sqrt{2\pi}\sigma_{D^+}} e^{-(m_{D^+}-m_i)^2/2{\sigma_{D^+}}^2} \times \mathrm{Norm} \cdot \mathrm{Eff}_{D^+}(t_i) \cdot e^{-t_i/\tau_{D^+}}$$

$$S_{D_s}(m_i, t_i) = F_{D_s} \times \frac{1}{\sqrt{2\pi}\sigma_{D_s}} e^{-(m_{D_s}-m_i)^2/2{\sigma_{D_s}}^2} \times \mathrm{Norm} \cdot \mathrm{Eff}_{D_s}(t_i) \cdot e^{-t_i/\tau_{D_s}}$$

$$B(m_i, t_i) = F_{BG} \times \mathrm{Norm} \cdot (e^{-t_i/\tau_{BG_1}} + Ce^{-t_i/\tau_{BG_2}}) \times \begin{cases} A_1 + S_1 m_i & (\text{for } m_i < m_0) \\ A_2 + S_2 m_i & (\text{for } m_i \geq m_0) \end{cases}$$

where $F_{D^+} = N_{D^+}/N_{pred}$, $F_{D_s} = N_{D_s}/N_{pred}$, $F_{BG} = N_{BG}/N_{pred}$.

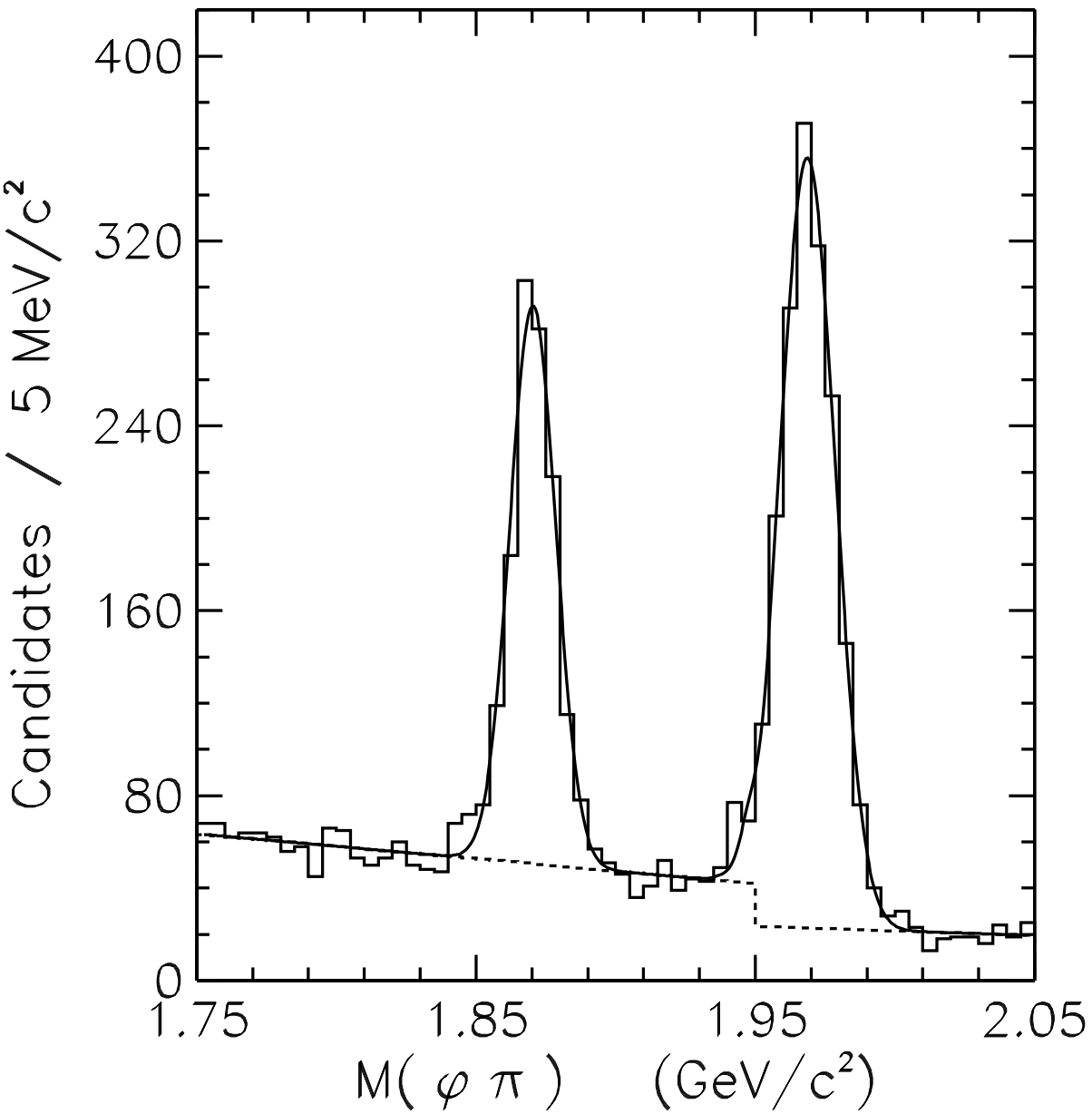


Hatched $\Rightarrow$ Reflections from $D^+ \to K^-\pi^+\pi^+$

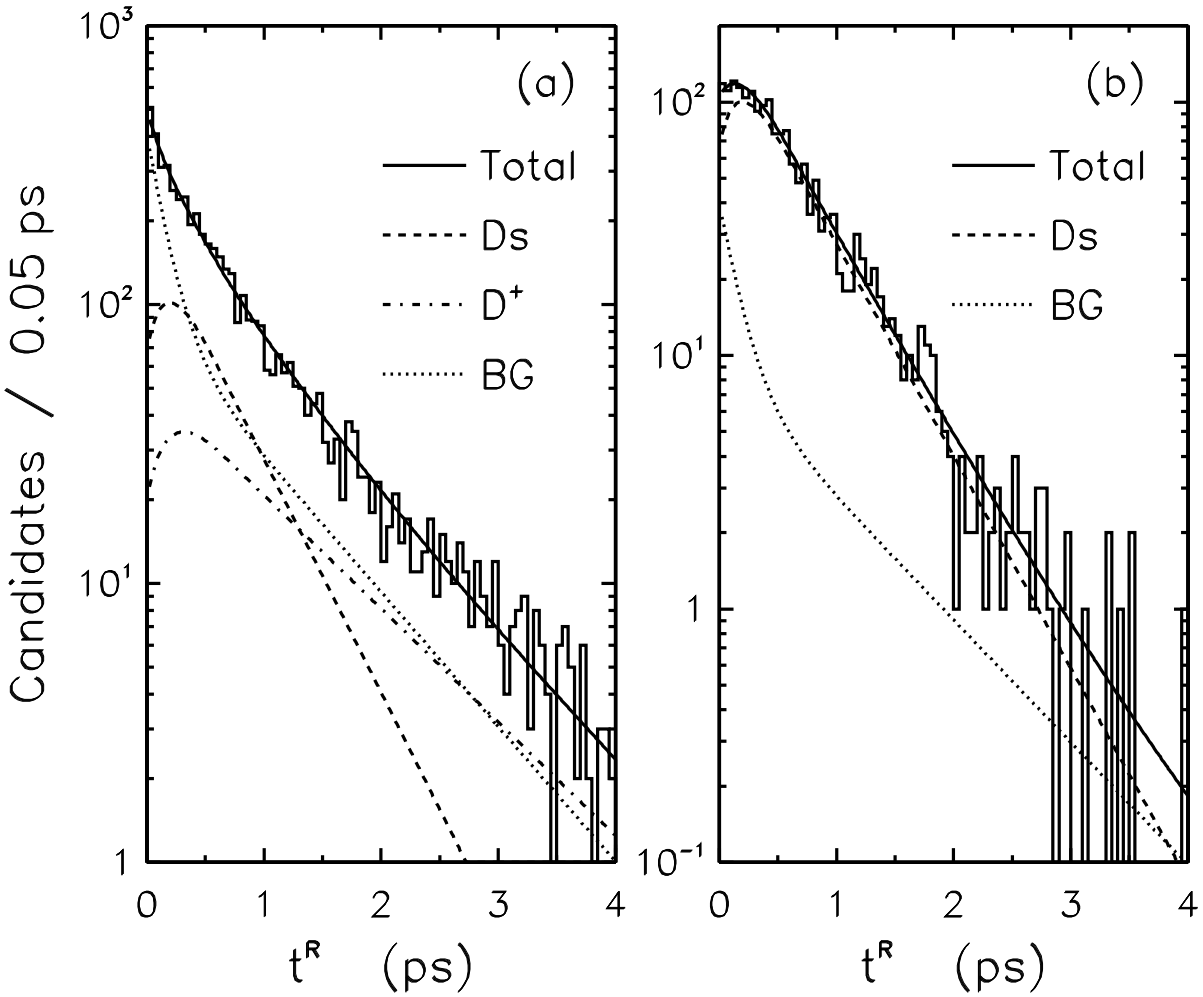
(a) $\Rightarrow$ Before excluding reflections

(b) $\Rightarrow$ After excluding reflections

$$\begin{cases} N(D_s \to \phi\pi) &= 1662 \pm 56 \\ \\ N(D^+ \to \phi\pi) &= 997 \pm 39 \end{cases}$$



$$\begin{cases} \tau(D_s \to \phi\pi) \;=\; 0.518 \pm 0.014 \pm 0.007 \textbf{ ps} \\ \\ \tau(D^+ \to \phi\pi) \;=\; 1.065 \pm 0.048 \textbf{ ps} \quad \textbf{(stat error)} \end{cases}$$



(a) $\Rightarrow$ All events that pass our cuts

(b) $\Rightarrow$ Events within ± 25 MeV of M(D_s)

Current D_s Lifetimes Measurements

Experiment	$\tau(D_s)$ ps
Data Book	0.467 ± 0.017
E687	$0.475 \pm 0.020 \pm 0.007$
E791	$0.518 \pm 0.014 \pm 0.007$

$$\text{E791 Measurement} \Rightarrow \frac{\tau(D_s)}{\tau(D^0)} = 1.25 \pm 0.04$$

$$\Rightarrow 6\sigma \text{ difference !!!}$$

D^0 Lifetime and Mixing Rate

Preliminary

$D^0 \to K^- K^+$ (CP-even eigenstate)
$D^0 \to K^- \pi^+$ (CP-even and CP-odd mixture)

$$\begin{aligned}
\frac{1}{\tau_{K^-K^+}} - \frac{1}{\tau_{K^-\pi^+}} &= \Gamma(K^-K^+) - \Gamma(K^-\pi^+) \\
&\approx \Gamma_2 - (\Gamma_1 + \Gamma_2)/2 \\
&= (\Gamma_2 - \Gamma_1)/2 \\
&= \Delta\Gamma/2
\end{aligned}$$

Mixing rate may be due to both mass and width differences:

$$r_{mix} = \frac{\Gamma(D^0 \to \overline{D}^0 \to \overline{f})}{\Gamma(D^0 \to f)} = \frac{1}{2}(x^2 + y^2)$$

where: $\begin{cases} x = \Delta M/\Gamma \\ y = \Delta\Gamma/2\Gamma \end{cases}$

$\Delta\Gamma$ can be determined experimentally using two methods:

- Measure $\tau_{K^-K^+}$ and $\tau_{K^-\pi^+}$ separately and then take the difference of their inverse.
- Fit the log of the ratio of number of $D^0 \to K^-K^+$ to $D^0 \to K^-\pi^+$ as a function of reduced proper time:

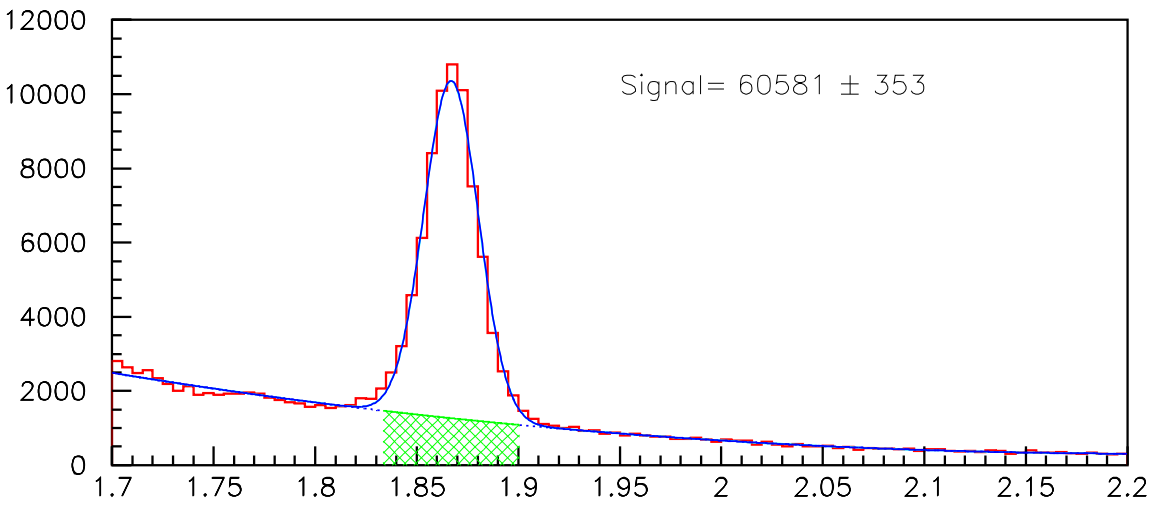
$$\begin{aligned} N(D^0 \to K^-K^+) &= A_{KK}\ e^{-\Gamma_2 t} \\ N(D^0 \to K^-\pi^+) &= A_{K\pi}\ e^{-\frac{1}{2}(\Gamma_1+\Gamma_2)t} \end{aligned}$$

$$\Rightarrow ln\left[\frac{N(D^0 \to K^-K^+)}{N(D^0 \to K^-\pi^+)}\right] = ln\left(\frac{A_{KK}}{A_{K\pi}}\right) - \frac{\Delta\Gamma}{2}t$$

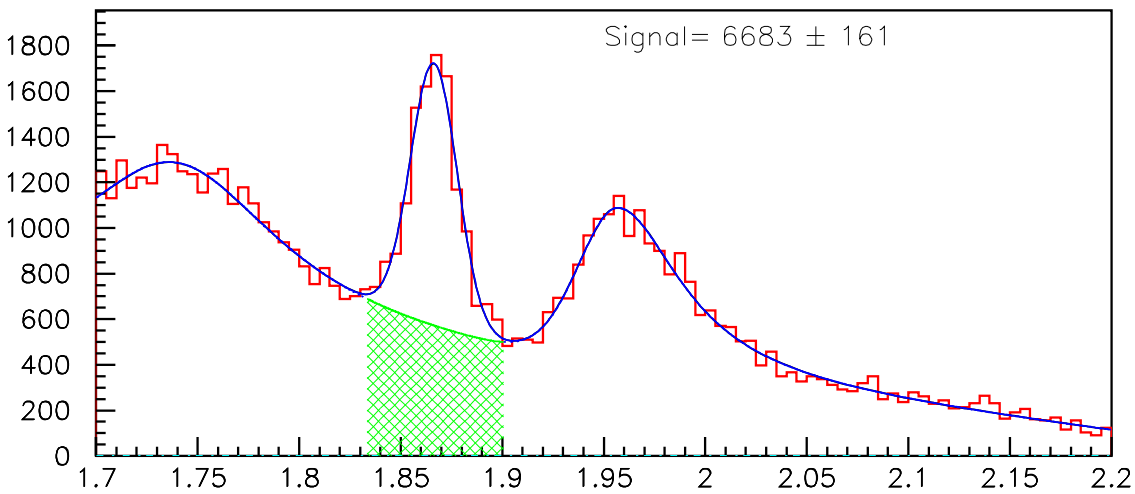
$\Rightarrow$ The slope yields $-\Delta\Gamma/2$.

The second method is prefered since common systematic errors cancel in the ratio.

$$\begin{cases} N(D^0 \to K^-\pi^+) &= 60581 \pm 353 \qquad (172\sigma) \\ N(D^0 \to K^-K^+) &= 6683 \pm 161 \qquad (42\sigma) \end{cases}$$

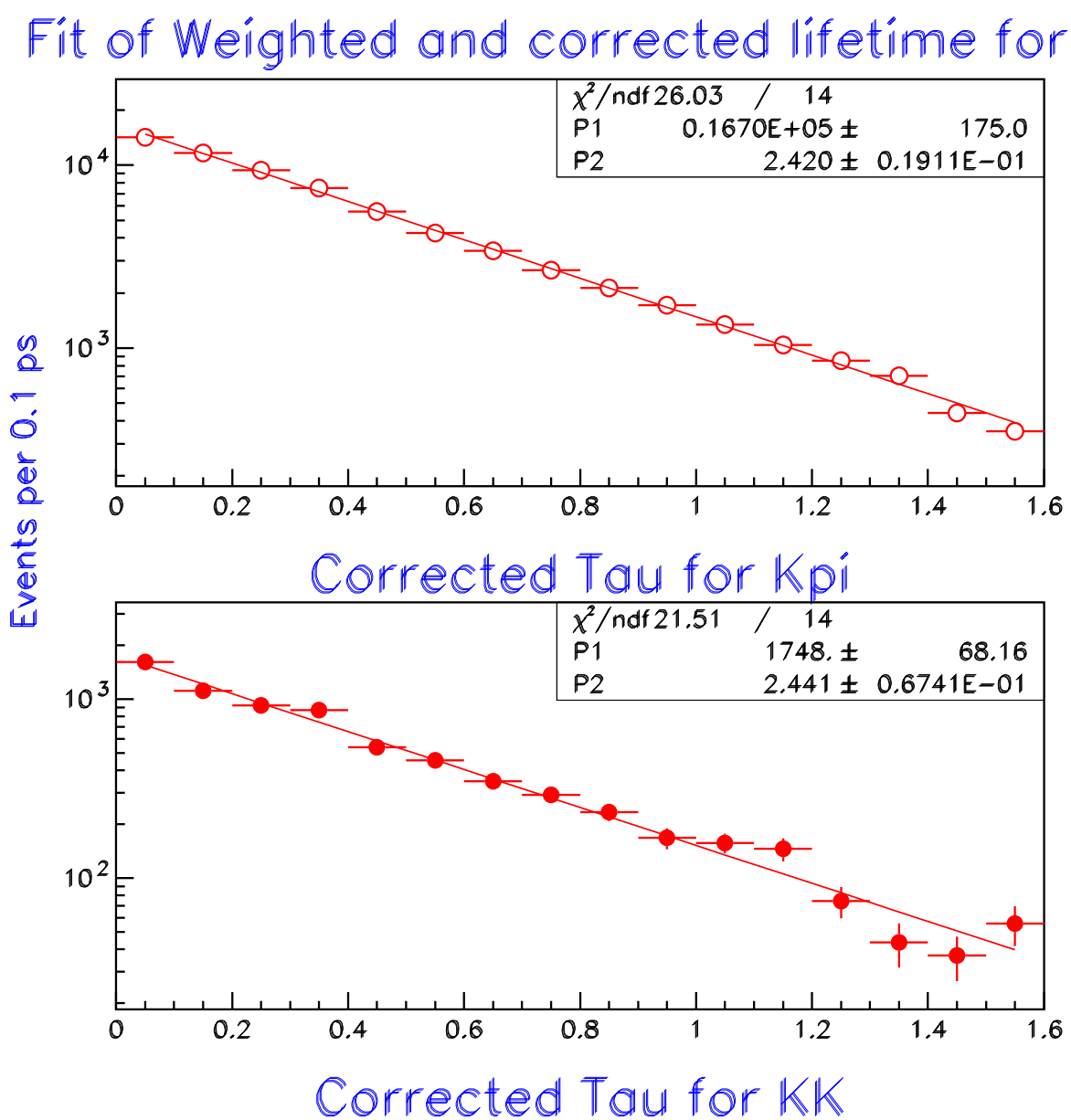


Kpi mass plot used in lifetime analysis

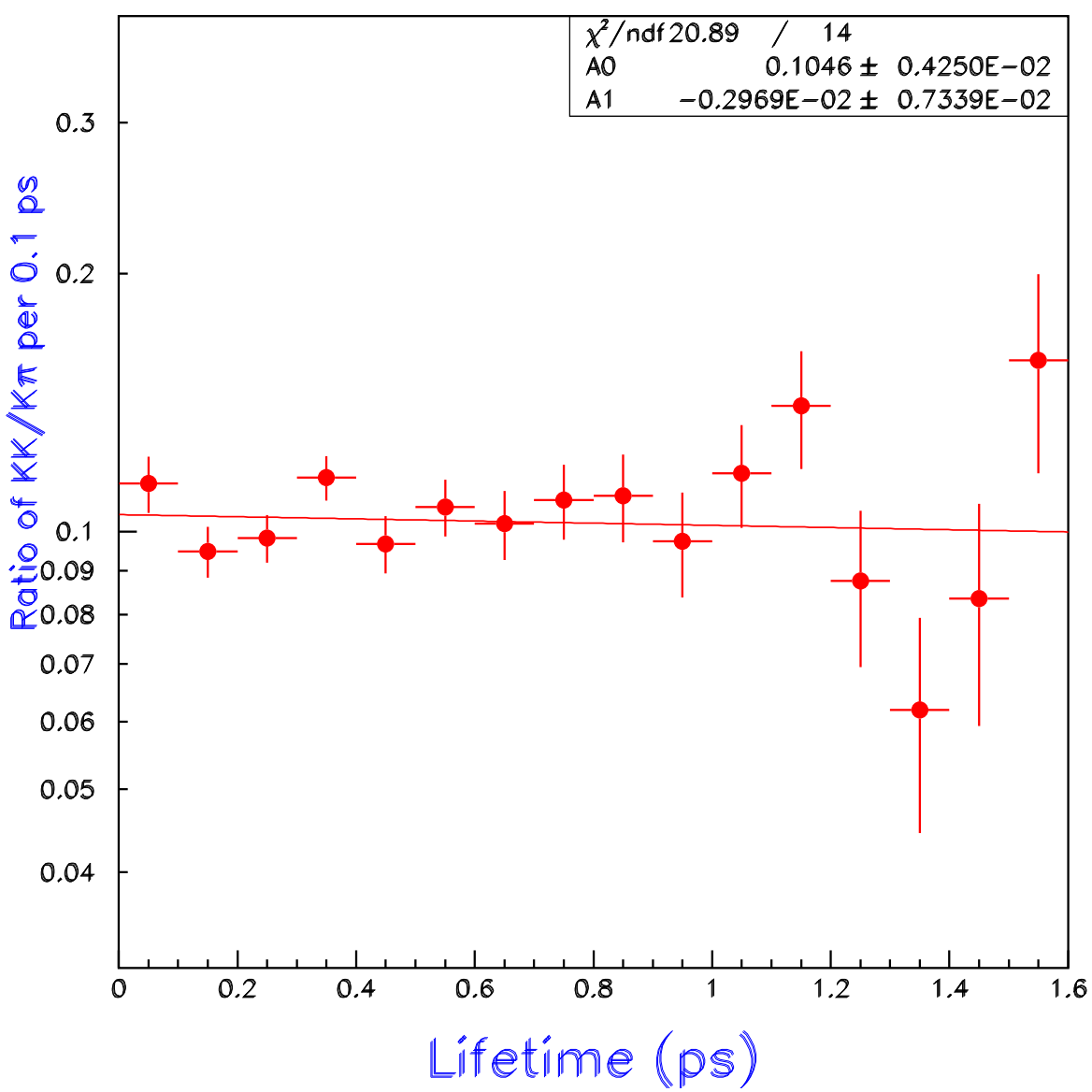


KK used in lifetime analysis

$$\begin{cases} \tau(D^0 \to K^-\pi^+) &= 0.413 \pm 0.003 \ \textbf{ps} \\ \\ \tau(D^0 \to K^-K^+) &= 0.410 \pm 0.011 \ \textbf{ps} \end{cases}$$



$$\Delta\Gamma \;=\; 0.056 \pm 0.142 \;\; \mathbf{ps}^{-1}$$



Preliminary Results

E791 preliminary results (statistical errors only):

- $D^0 \to K^-\pi^+$:

$$N = 60581 \pm 353 \quad (172\sigma)$$
$$\tau = 0.413 \pm 0.003 \text{ ps}$$

- $D^0 \to K^-K^+$:

$$N = 6683 \pm 161 \quad (42\sigma)$$
$$\tau = 0.410 \pm 0.011 \text{ ps}$$

- Fit for $\Delta\Gamma$ directly:

$$\Delta\Gamma = 0.056 \pm 0.142 \text{ ps}^{-1}$$
$$\Rightarrow \; y = \Delta\Gamma/2\Gamma = 0.012 \pm 0.030$$

We compare this to current measurements:

$r_{mix} = \frac{1}{2}(x^2 + y^2) < 0.5\% \quad$ (90% CL)
$\Rightarrow \; y < 0.1$

Singly Cabibbo-suppressed Decay $\mathbf{D^0 \to K^- K^+ \pi^- \pi^+}$

Phys. Lett. B 423 185-193 (1998)

Decays Modes Studied:

- Four-body non-resonant:

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

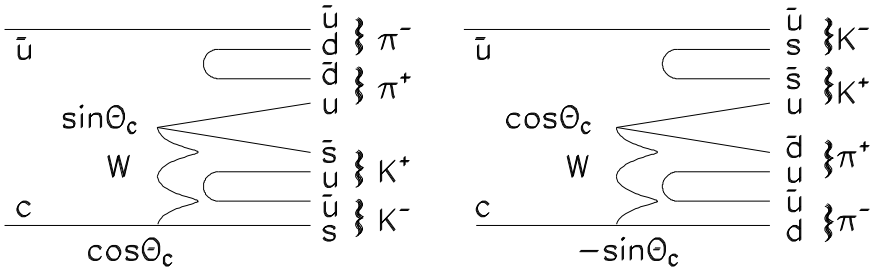
- Two-body:

$$\begin{aligned} D^0 &\to \overline{K}^{*0} K^{*0} \\ D^0 &\to \phi \rho^0 \end{aligned}$$

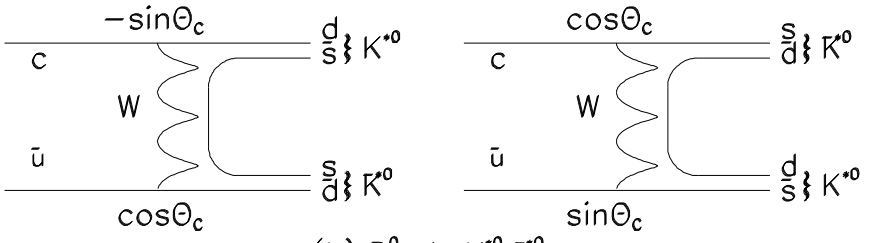
- Three–body:

$$\begin{aligned} D^0 &\to \overline{K}^{*0} K^+ \pi^- \\ D^0 &\to K^{*0} K^- \pi^+ \\ D^0 &\to \phi \pi^+ \pi^- \end{aligned}$$

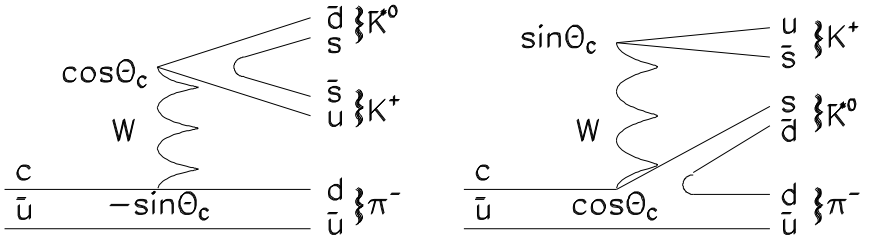
Feynamn Diagrams for $D^0 \to K^-K^+\pi^-\pi^+$



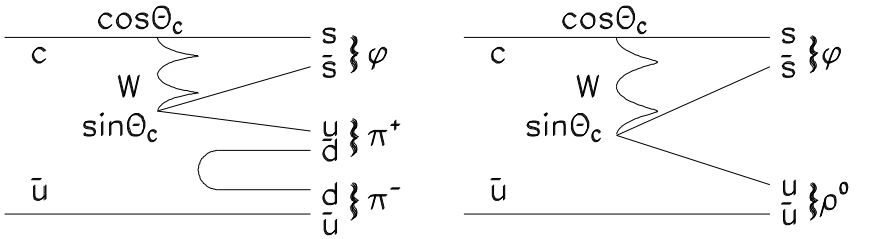
(a) $D^0 \to K^- K^+ \pi^- \pi^+$ (nonresonant)



(b) $D^0 \to K^{*0} \bar{K}^{*0}$



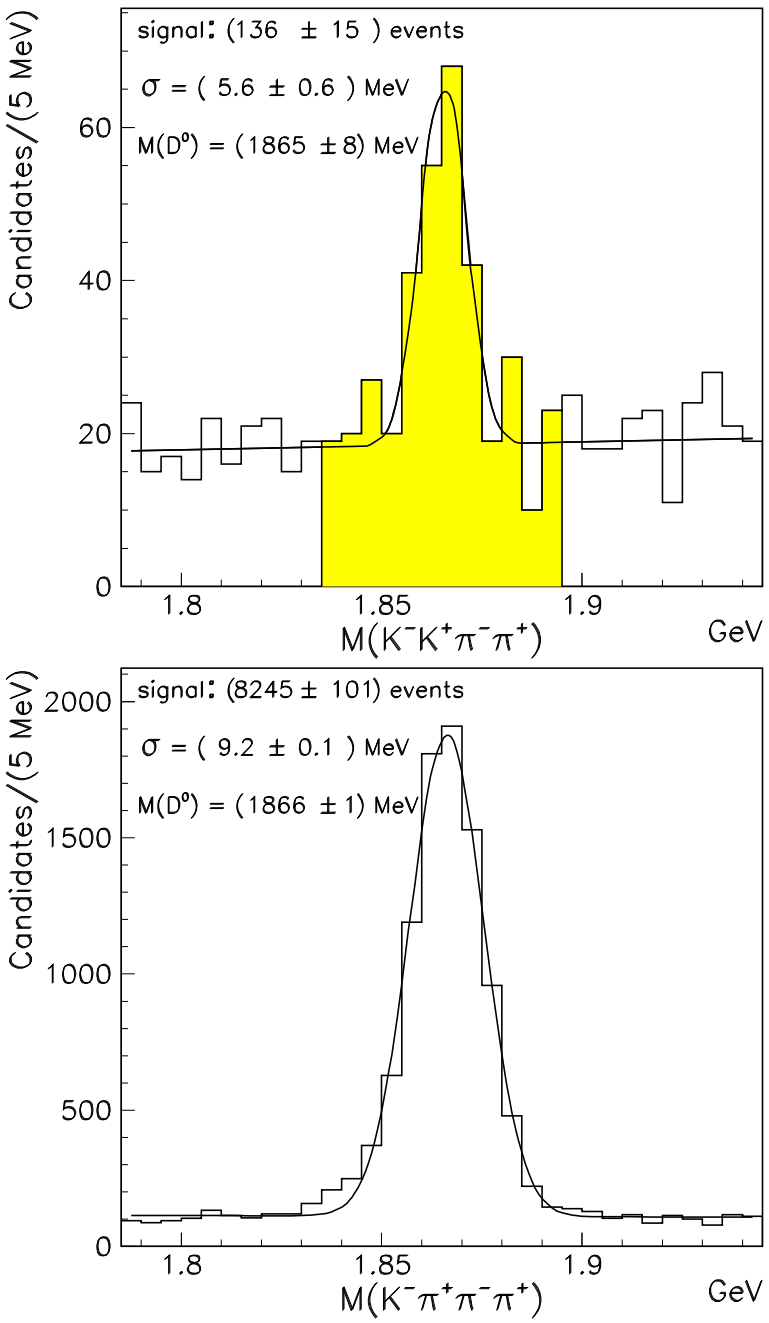
(c) $D^0 \to \bar{K}^{*0} K^+ \pi^-$



(d) $D^0 \to \varphi\pi^-\pi^+$ (e) $D^0 \to \varphi\rho^0$

$$\begin{cases} N(D^0 \to K^-K^+\pi^-\pi^+) &= 136 \pm 15 \\ N(D^0 \to K^-\pi^+\pi^-\pi^+) &= 8245 \pm 101 \end{cases}$$

Events in shaded area were used in the resonant substructure analysis



Branching Fractions

- Measured yields:

$$N(D^0 \to K^-K^+\pi^-\pi^+) = 136 \pm 15$$
$$N(D^0 \to K^-\pi^+\pi^-\pi^+) = 8245 \pm 101$$

- Ratio of branching fractions:

$$\frac{B(D^0 \to K^-K^+\pi^-\pi^+)}{B(D^0 \to K^-\pi^+\pi^-\pi^+)} = (3.13 \pm 0.37 \pm 0.36)\%$$

  This result is lower than the naive expectation:

$$\frac{B(D^0 \to K^-K^+\pi^-\pi^+)}{B(D^0 \to K^-\pi^+\pi^-\pi^+)} \approx \tan^2\theta_C \approx 5\%$$

  This may be evidence of the tree-level GIM suppression expected for most of the amplitudes.

- Using PDG value for CF branching fraction, we find:

$$B(D^0 \to K^-K^+\pi^-\pi^+) = (0.254 \pm 0.030 \pm 0.033)\%$$

Resonant Substructure

- A coherent amplitude analysis of the resonant substructure of $D^0 \to K^-K^+\pi^-\pi^+$ is used to extract decay fractions.

- This is the first reported analysis to allow interference among amplitudes in this decay.

- Significant phase angles among different modes indicate very strong interference.

- Measured branching fractions relative to $D^0 \to K^-\pi^+\pi^-\pi^+$:

Mode	Branching Fraction
$\phi\rho^0$	$(2.0 \pm 0.9 \pm 0.8)\%$
$\phi\pi^+\pi^-$	$(0.9 \pm 0.4 \pm 0.5)\%$
$\overline{K}^{*0}K^{*0}$	$< 2.0\%$ (90% CL)
$\overline{K}^{*0}K^+\pi^- + K^{*0}K^-\pi^+$	$< 1.0\%$ (90% CL)

Doubly Cabibbo-suppressed Decay $\mathbf{D^+ \to K^+\pi^+\pi^-}$

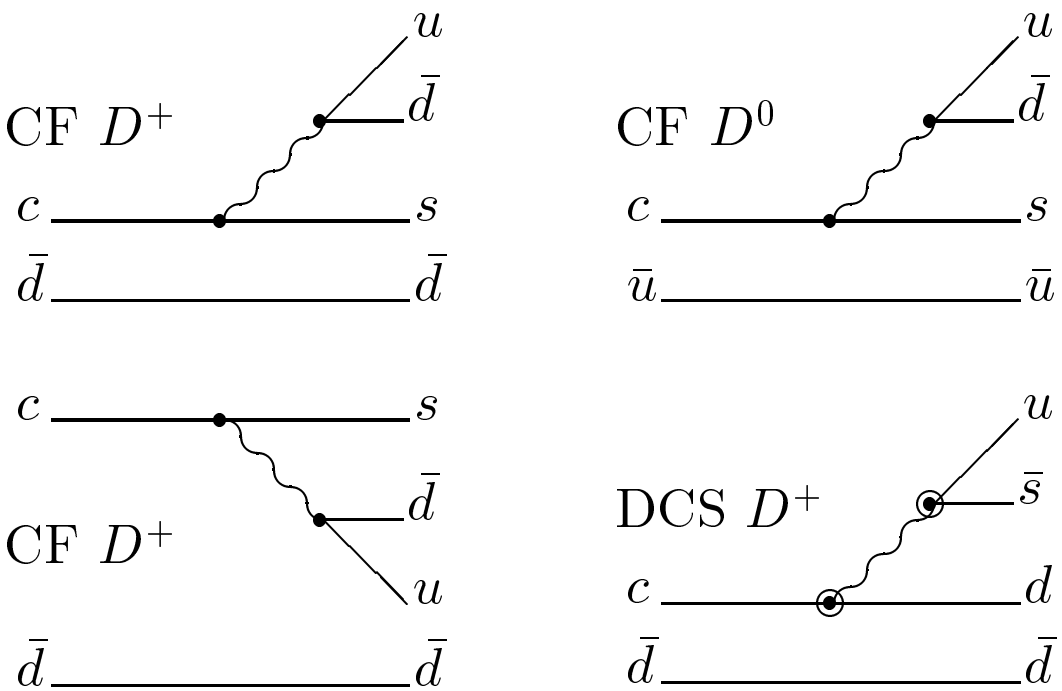
Phys. Lett. B 404 187-193 (1997)

If we ignore non-spectator amplitudes, the hadronic decay rates:

$$\Gamma_{CF}(D^0)/\Gamma_{CF}(D^+) \approx 3.2$$

$$\Gamma_{DCS}(D^+)/\Gamma_{CF}(D^0) \approx \tan^4\theta_C$$

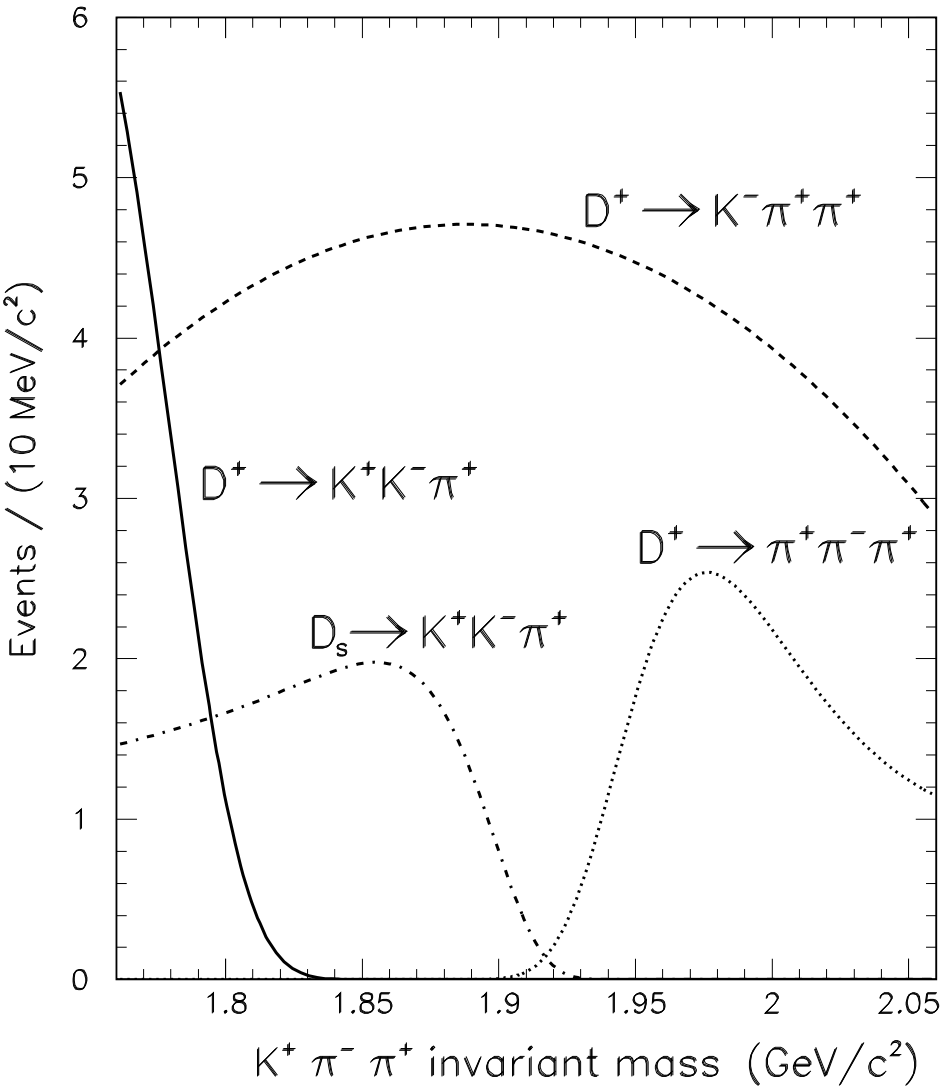
$$\Rightarrow \Gamma_{DCS}(D^+)/\Gamma_{CF}(D^+) \approx 3.2 \times \tan^4\theta_C$$



Background in $K^+\pi^+\pi^-$ Sample

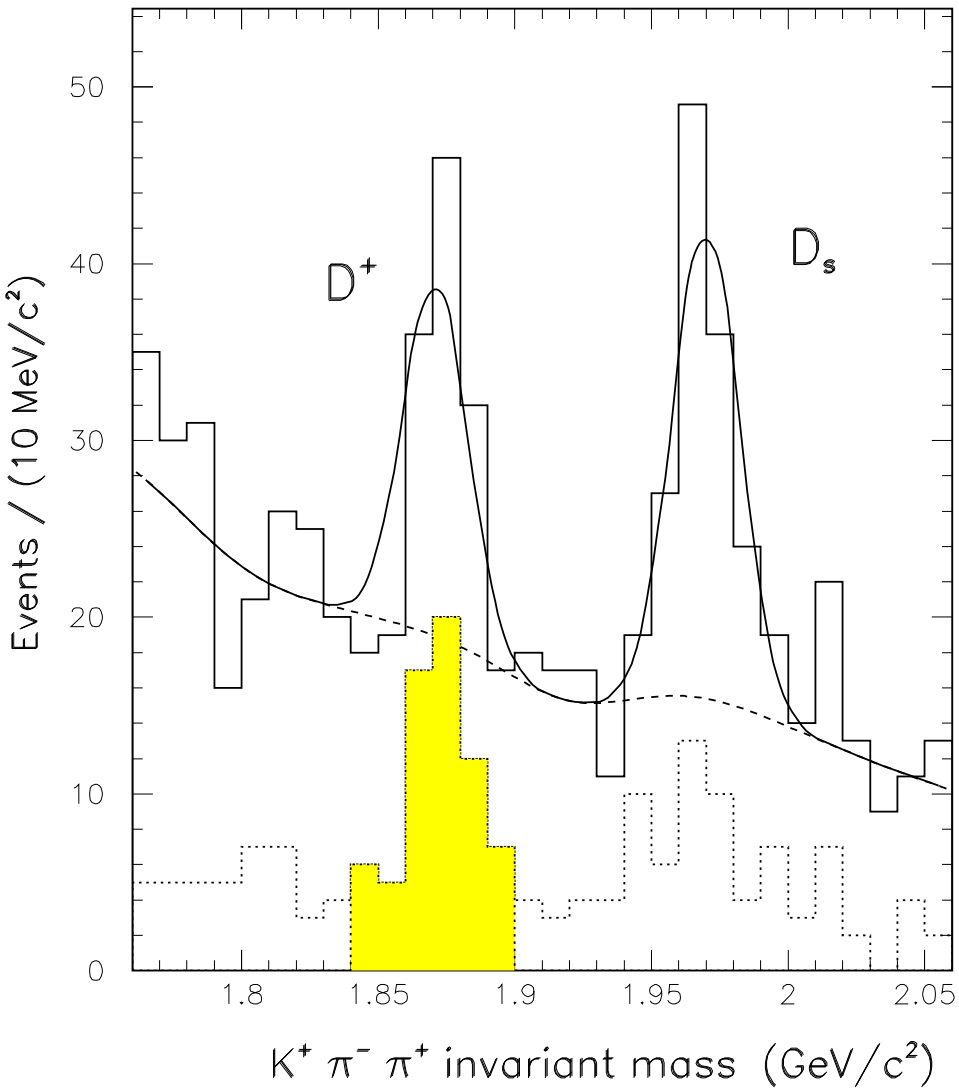
- Combanitoral background: spread smoothly across M($K^+\pi^+\pi^-$).
- D^+ and D_s with missing neutrals, such as $D^+ \to \overline{K}^{*0} l^+\nu$, $K^-\pi^+\pi^+\pi^0$ and $D_s \to \phi l^+\nu$: spread smoothly across M($K^+\pi^+\pi^-$).
- D^0 2-prong decays with a spurious added track, such as $D^0 \to K^-\pi^+$: concentrate above fitted M($K^+\pi^+\pi^-$) region.
- D^0 4-prong decays with a missing track, such as $D^0 \to K^-\pi^+\pi^+\pi^-$: concentrate below fitted M($K^+\pi^+\pi^-$) region.
- D^+ and D_s 3-body hadronic decays, such as $D^+ \to K^-\pi^+\pi^+$, $K^-K^+\pi^+$, $\pi^-\pi^+\pi^+$ and $D_s \to K^-K^+\pi^+$: modeled using real data and MC simulations.

Hardonic 3-body Charm Decay Background

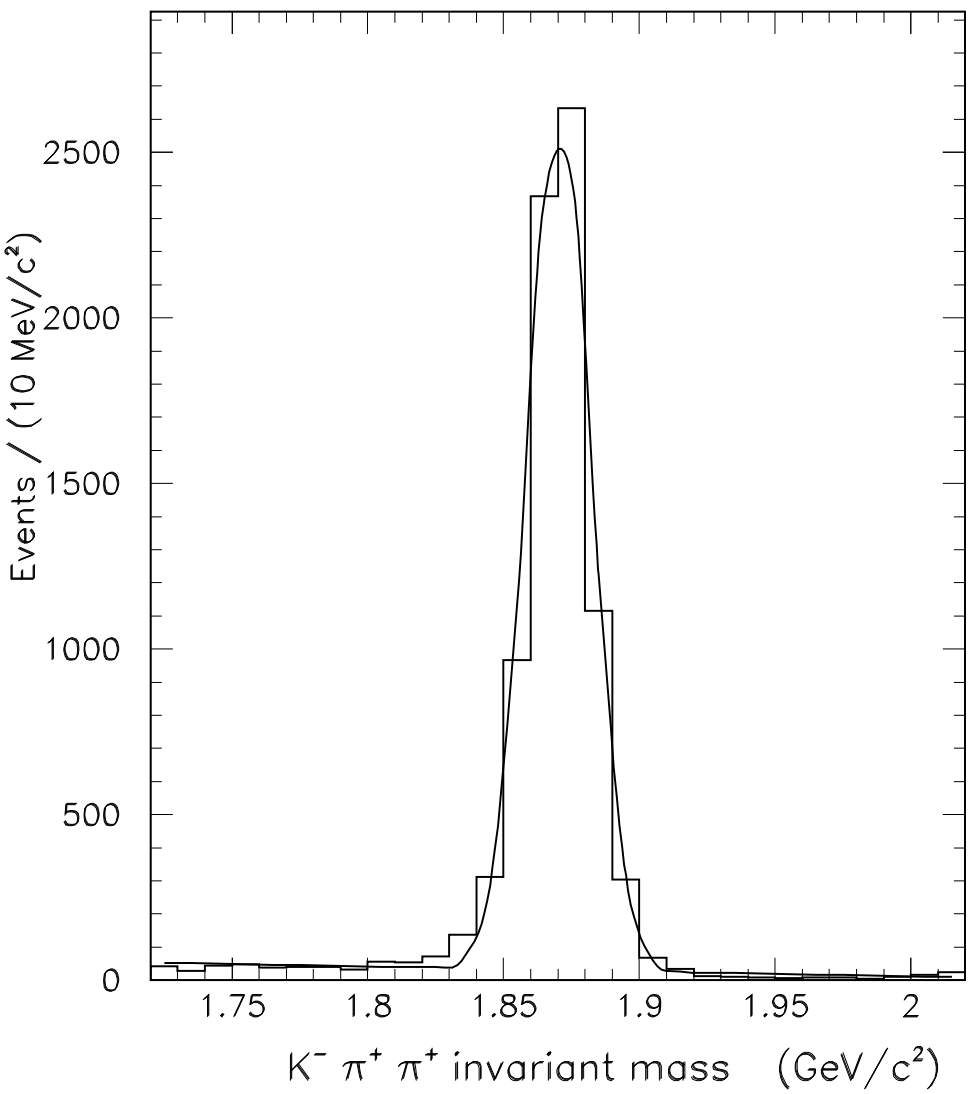


$$N(D^+ \to K^+\pi^+\pi^-) = 59 \pm 13$$

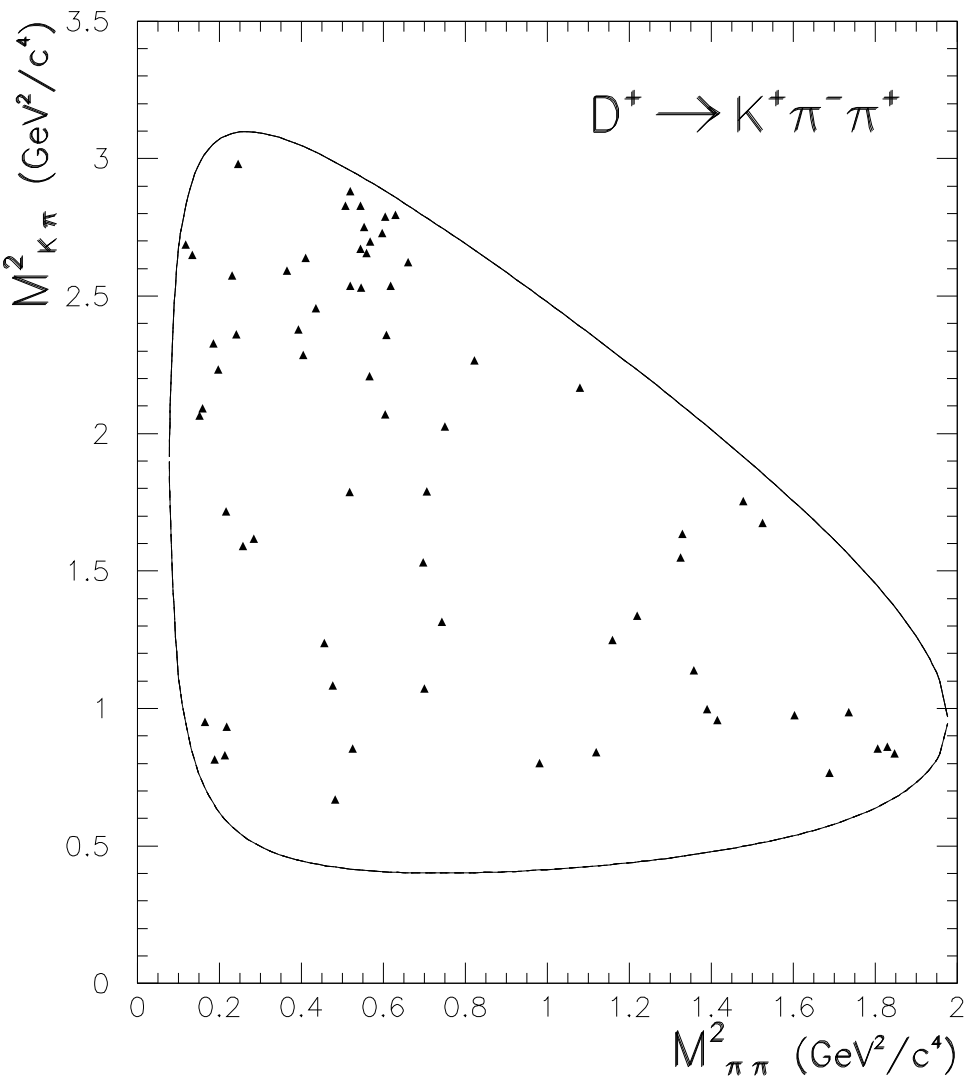
Events in shaded area were used for Daltiz plot analysis (42 ± 9)



$$N(D^+ \to K^-\pi^+\pi^+) = 7688 \pm 90$$



Dalitz Plot for DCS $D^+ \to K^-\pi^+\pi^+$



Branching Fractions

- Measured yields:

$$N(D^+ \to K^+\pi^+\pi^-) = 59 \pm 13$$
$$N(D^+ \to K^-\pi^+\pi^+) = 7688 \pm 90$$

- Ratio of branching fractions:

$$\frac{B(D^+ \to K^+\pi^+\pi^-)}{B(D^+ \to K^-\pi^+\pi^+)} = (7.7 \pm 1.7 \pm 0.8) \times 10^{-3}$$
$$= (3.0 \pm 0.8) \times \tan^4\theta_C$$

- Using PDG value for CF branching fraction, we find the branching fraction:

$$\Rightarrow B(D^+ \to K^+\pi^+\pi^-) = (7.0 \pm 1.5 \pm 0.9) \times 10^{-4}$$

- Results of Dalitz plot fit:

Mode	Branching Fraction
non-resonant	$(2.5 \pm 1.3) \times 10^{-4}$
$\overline{K}^{*0}(890)\pi^+$	$(2.5 \pm 1.2) \times 10^{-4}$
$K^+\rho^0(770)$	$(2.6 \pm 1.3) \times 10^{-4}$

Summary & Conclusions

- New precise measurement of the D_s lifetime, $\tau(D_s) = 0.518 \pm 0.014 \pm 0.007$ ps. We find the ratio $\tau(D_s)/\tau(D^0) = 1.25 \pm 0.04$ showing significantly different lifetimes for the D_s and D^0.

- Preliminary measurements of lifetimes of $D^0 \to K^-\pi^+$ and K^-K^+, and first directly measured limit on the decay width difference for the D^0-$\overline{D}^0$ system, $\Delta\Gamma = 0.056 \pm 0.142$ ps^{-1}.

- Measure $B(D^0 \to K^-K^+\pi^-\pi^+)/B(D^0 \to K^-\pi^+\pi^-\pi^+) = (3.13 \pm 0.37 \pm 0.36)\%$, lower than naive expectations, and may be evidence of tree-level GIM suppression. Coherent amplitude analysis is used to study resonant substructure of SCS decay $D^0 \to K^-K^+\pi^-\pi^+$.

- Measure $B(D^+ \to K^+\pi^+\pi^-)/B(D^+ \to K^-\pi^+\pi^+) = (7.7 \pm 1.7 \pm 0.8) \times 10^{-3}$. Dalitz plot analysis performed to search for resonant substructure of DCS decay $D^+ \to K^+\pi^+\pi^-$

- These E791 results are either new or have more precision than previous results. In the near future, E791 expects to present results on:
  - Λ_c decay, resonant substructure, and polarization.
  - High statistics study of the CF D^+ decay and Dalitz plot analysis.
  - D^+ and $D_s \to \pi^-\pi^+\pi^+$ Dalitz plot analysis.
  - $D^0 \to K^-K^-K^+\pi^+$ Dalitz plot analysis.
  - ...