Charm semileptonic decays from E791

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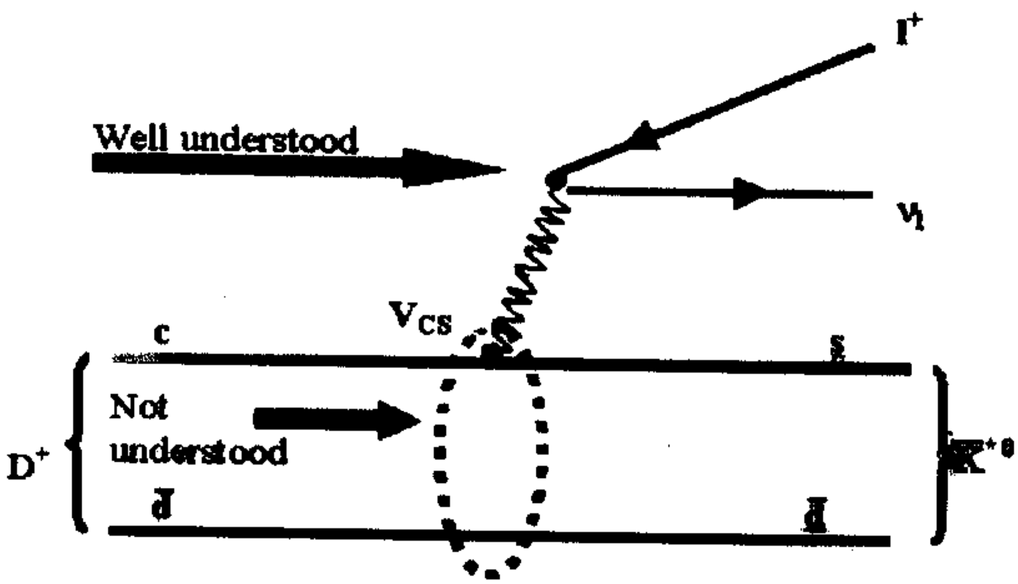
Outline

- Form factors for charm semileptonic decays.
- E791 measurements of form factor ratios for $D^+ \to \overline{K}^{*0} \ell^+ \nu_\ell$.
- E791 measurements of form factor ratios for $D_s^+ \to \Phi \ell^+ \nu_\ell$.
- E791 measurement of the branching fraction $\mathcal{B}(D^+ \to \rho^0 \ell^+ \nu_\ell)/\mathcal{B}(D^+ \to \overline{K}^{*0} \ell^+ \nu_\ell)$
- Summary.

Why measure form factors in charm decays ?

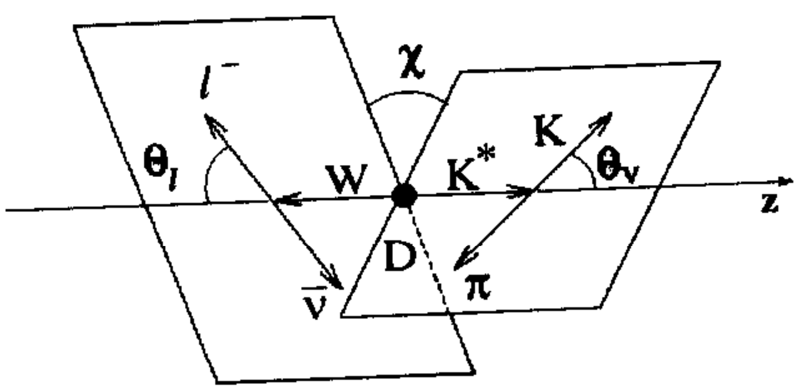


- To understand strong interaction effects associated with the hadronic vertex.
- To extract the CKM matrix element $\mid V_{ub} \mid$ from $B \to \rho \ell \overline{\nu}_\ell$.
  - Use well-measured charm decays as precision test bed for lattice QCD or phenomenological models to validate calculation of FF's for $B \to \rho \ell \overline{\nu}_\ell$.
  - Relate the FF's for c-decays to those for b-decays (heavy quark and SU(3) flavor symmetries).

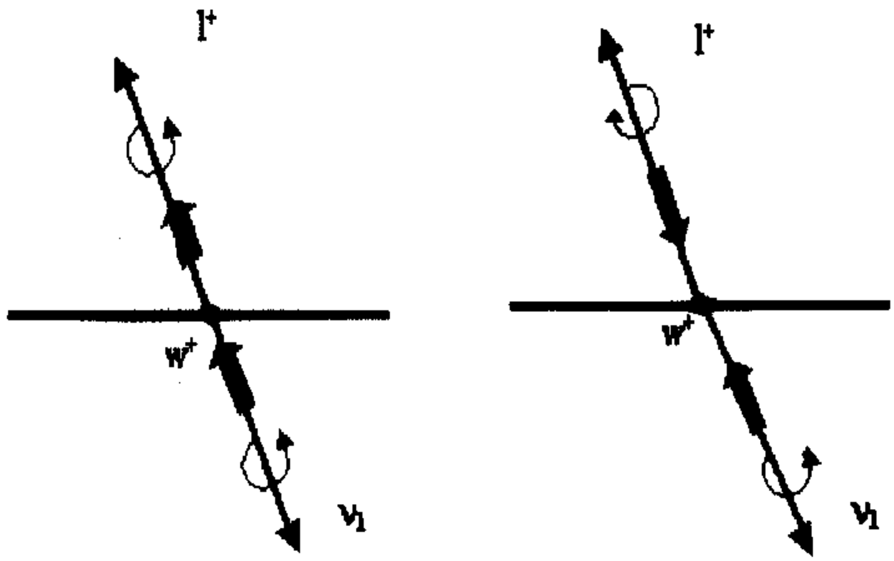
Extracting form factors from distribution of decay variables

- Decay channels: $D^+ \to \overline{K}^{*0}\ell^+\nu_\ell$, $\quad D_s^+ \to \Phi\ell^+\nu_\ell$
  where $\ell = e, \mu$.
- The hadronic current can be parametrized in terms of four Lorentz-invariant form factors: $A_1(q^2)$, $A_2(q^2)$, $A_3(q^2)$, $V(q^2)$,
  where q^2 is the square of W invariant mass.
- Non-vanishing lepton mass $\Rightarrow$ differential decay rate contains more terms, and the form factor $A_3(q^2)$ becomes relevant.
- From correlations between final-state particles, we can measure the ratios:
  $r_V = V(0)/A_1(0)$, $r_2 = A_2(0)/A_1(0)$ and $r_3 = A_3(0)/A_1(0)$.

Decay variables: q^2, $\cos\theta_\ell$, $\cos\theta_V$, χ



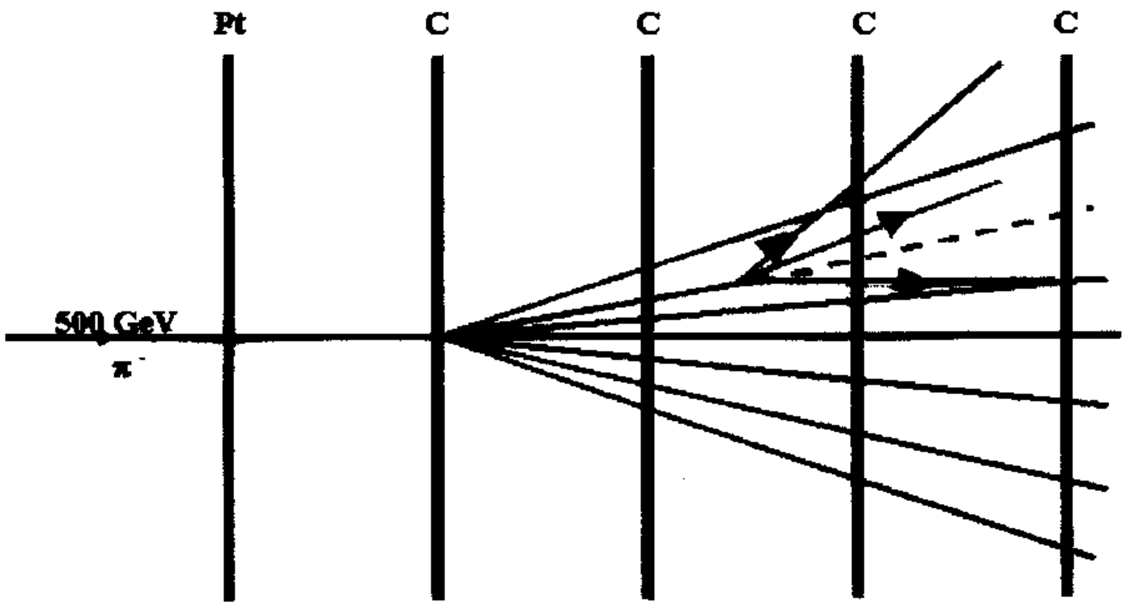
The Effects of the Lepton Mass



(a) "spin no-flip" **(b) "spin flip"**

- The effects of non-zero lepton mass:
  1. The overall factor: $(1 - m_\ell^2/q^2)^2$.
  2. New spin flip amplitudes (suppresed by a factor $m_\ell^2/2q^2$ in comparison with spin no-flip amplitudes).
  3. The fourth form factor $A_3(q^2)$ becomes relevant.

Some features of E791 Experiment

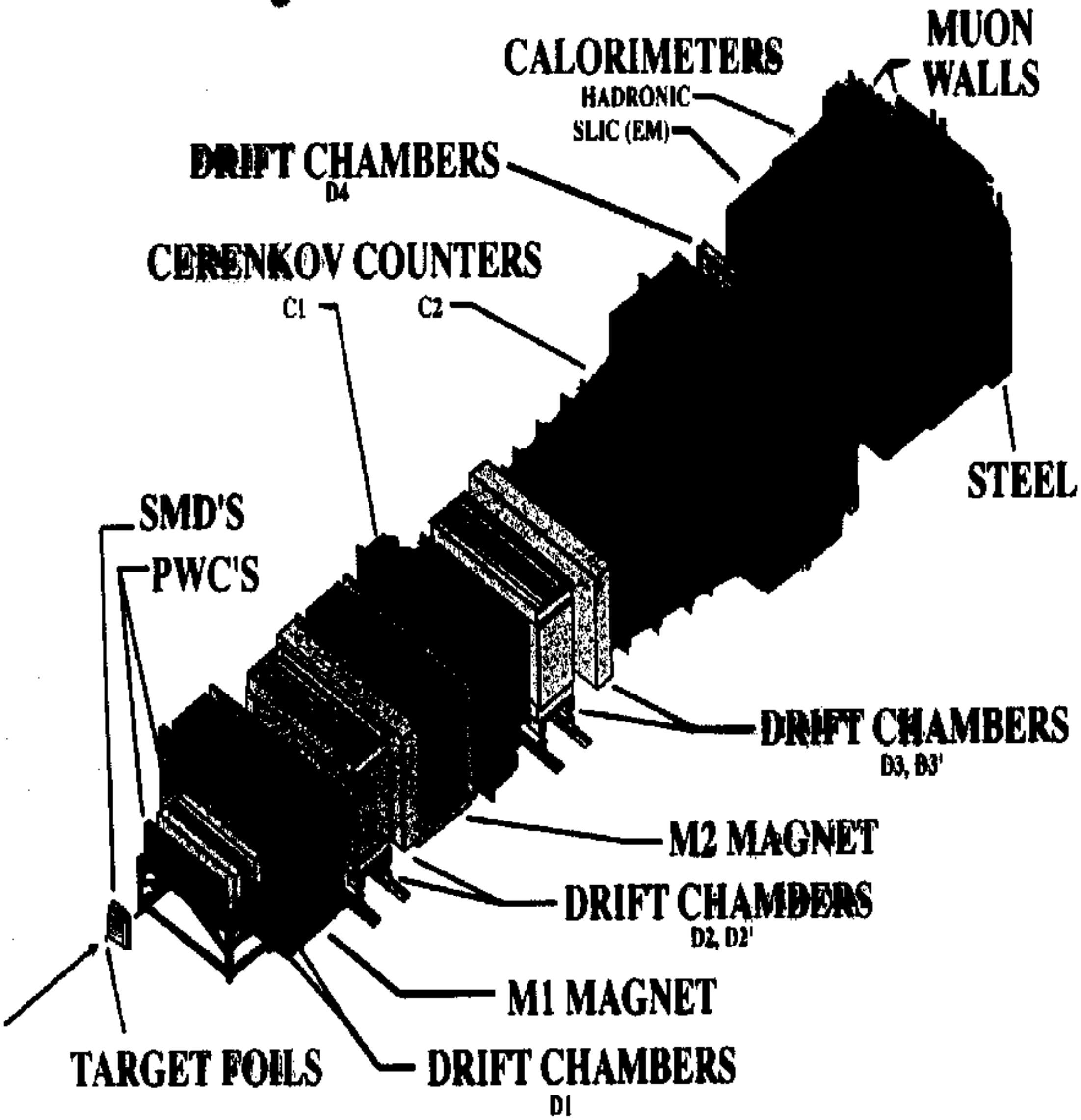


- Tracking system: 23 planes of silicon microstrip detectors, 45 planes of drift and proportional wire chambers and 2 large-aperture dipole magnets.

- Hadron identification: 2 threshold Čerenkov counters. Pions are misidentified as kaons with a probability less than 5 %.

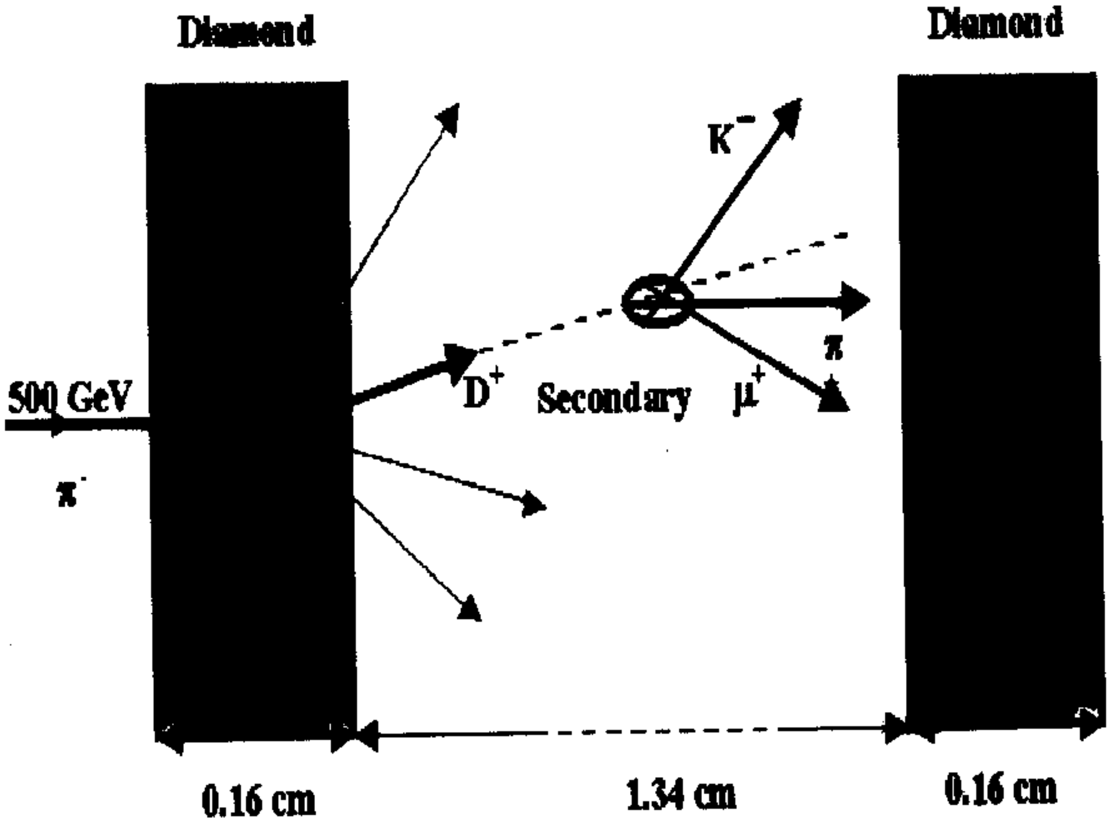
- Muon identification: 1 wall of scintillation counters. The probability to misidentify a hadron as a muon is ≈ 3 % ($p_\mu > 8$ GeV/c).

E-791 Spectrometer



Data Selection

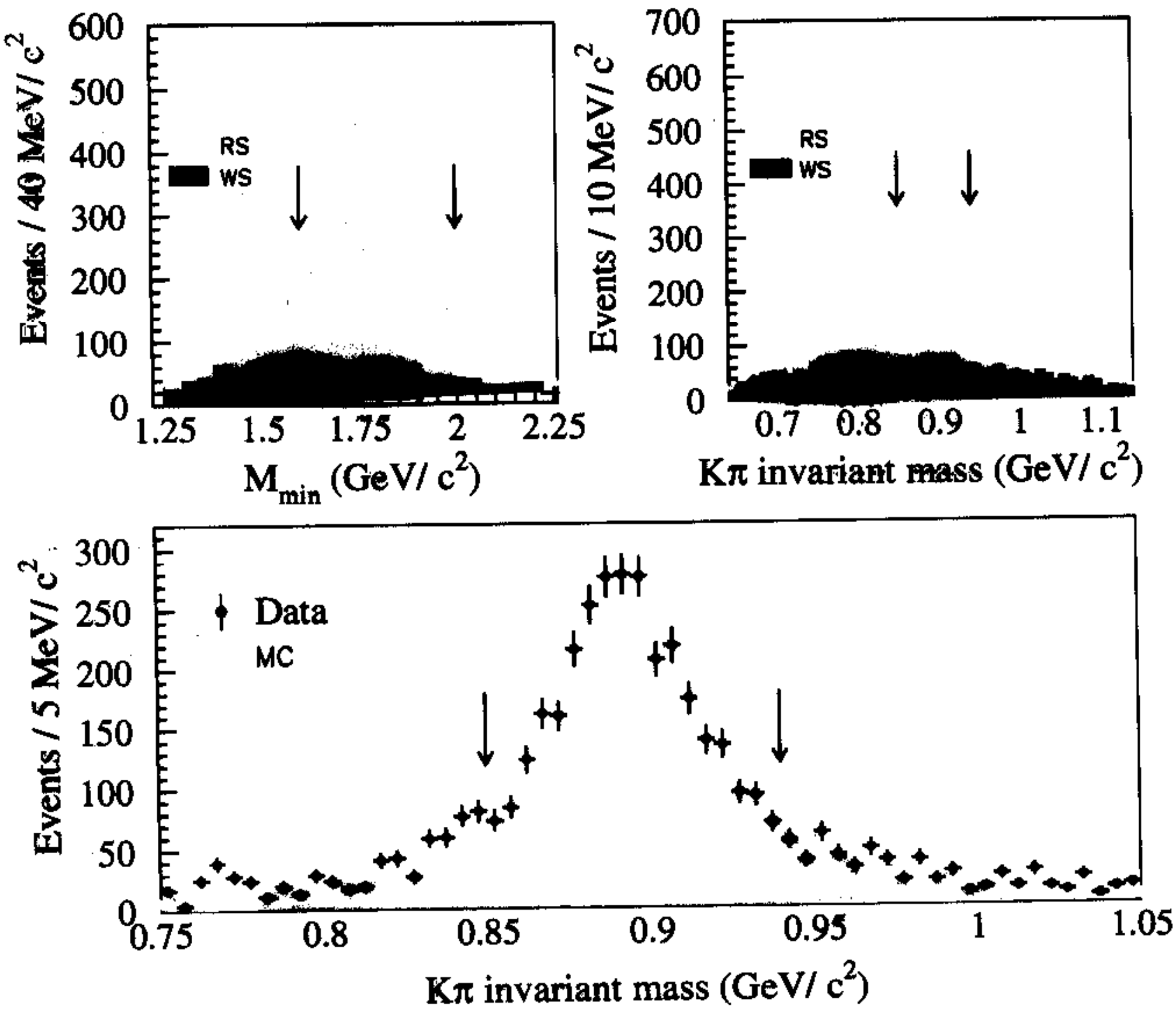
$$D^+ \to \overline{K}^{*0}\mu^+\nu_\mu$$



- The "right-sign" sample is made of $K^-\pi^+\mu^+\nu_\mu$ vertices. It contains both signal and background events.
- Background is modeled by the "wrong-sign" events $(K^+\pi^-\mu^+\nu_\mu)$.
- The cuts used to optimize the significance of the signal are the same as in electronic channel, except those related to lepton identification.
- Typical values of vertex longitudinal resolution and separation between primary and secondary are $\sigma_z = 0.3$ mm and $l = 10$ mm.

E791 $D^+ \to \overline{K}^{*0} \mu^+ \nu_\mu$ Signal

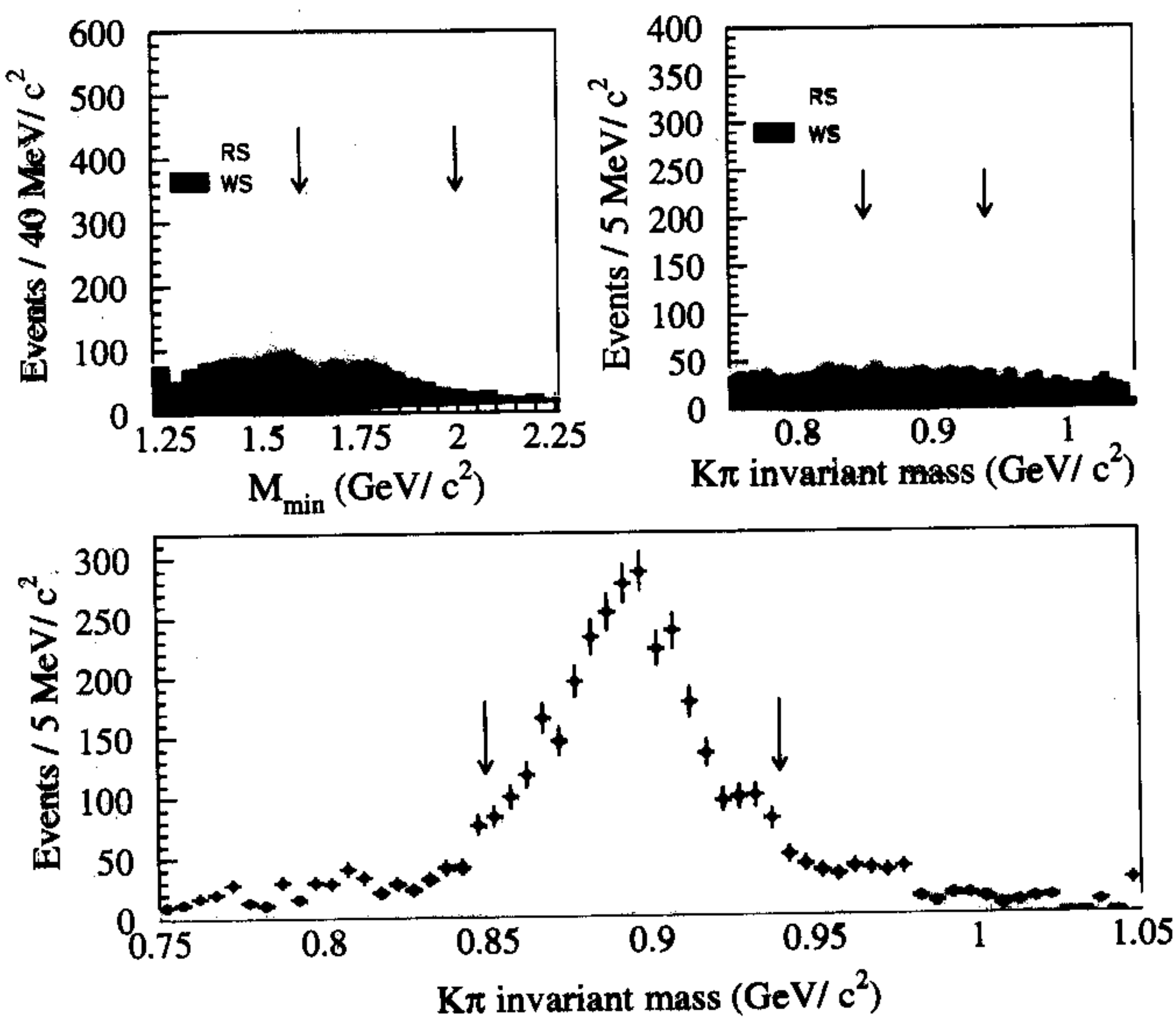
- For the signal region $1.6 < M_{min} < 2.0$ GeV and $0.85 < M_{K\pi} < 0.94$ GeV.
- Final data sample: 3629 right-sign and 595 wrong-sign events.



- $M_{min} = p_t + \sqrt{p_t^2 + m_{vis}^2}$

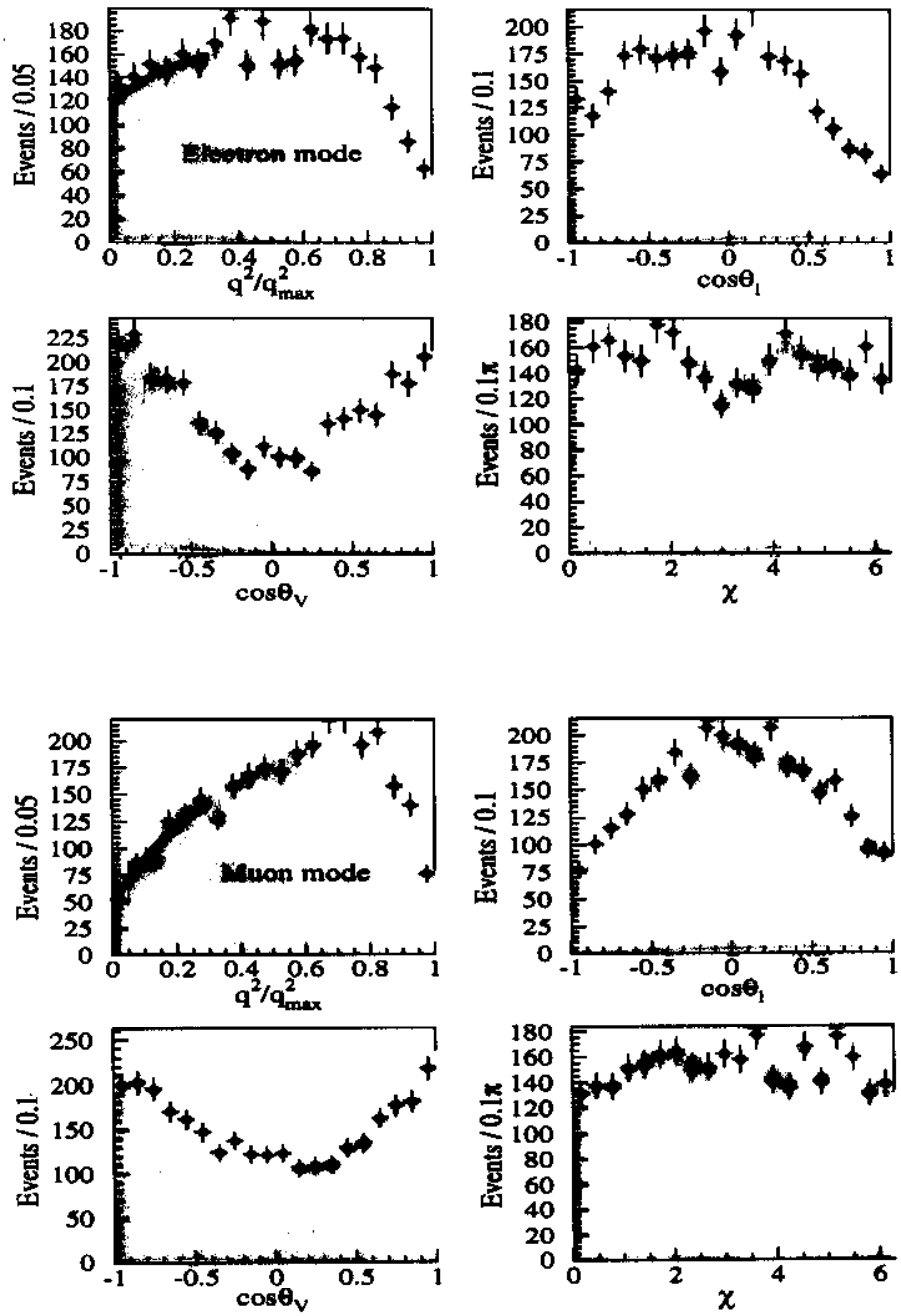
E791 $D^+ \to \overline{K}^{*0} e^+ \nu_e$ Signal

- For the signal region $1.6 < M_{min} < 2.0$ GeV and $0.85 < M_{K\pi} < 0.94$ GeV.
- Final data sample: 3595 right-sign and 602 wrong-sign events.



- $M_{min} = p_t + \sqrt{p_t^2 + m_{vis}^2}$

Decay variable distributions for E791 $D^+ \to K^{*0}\ell^+\nu_\ell$



Crosses: data   Histograms: Monte Carlo

Final results for $D^+ \to \overline{K}^{*0}\ell^+\nu_\ell$

- Electron mode: $RS = 3595$ $\quad$ $WS = 602$

  $r_V = 1.90 \pm 0.11 \pm 0.08$ $\quad$ $r_2 = 0.75 \pm 0.08 \pm 0.09$

- Muon mode: $RS = 3629$ $\quad$ $WS = 595$

  $r_V = 1.84 \pm 0.11 \pm 0.08$ $\quad$ $r_2 = 0.71 \pm 0.08 \pm 0.09$

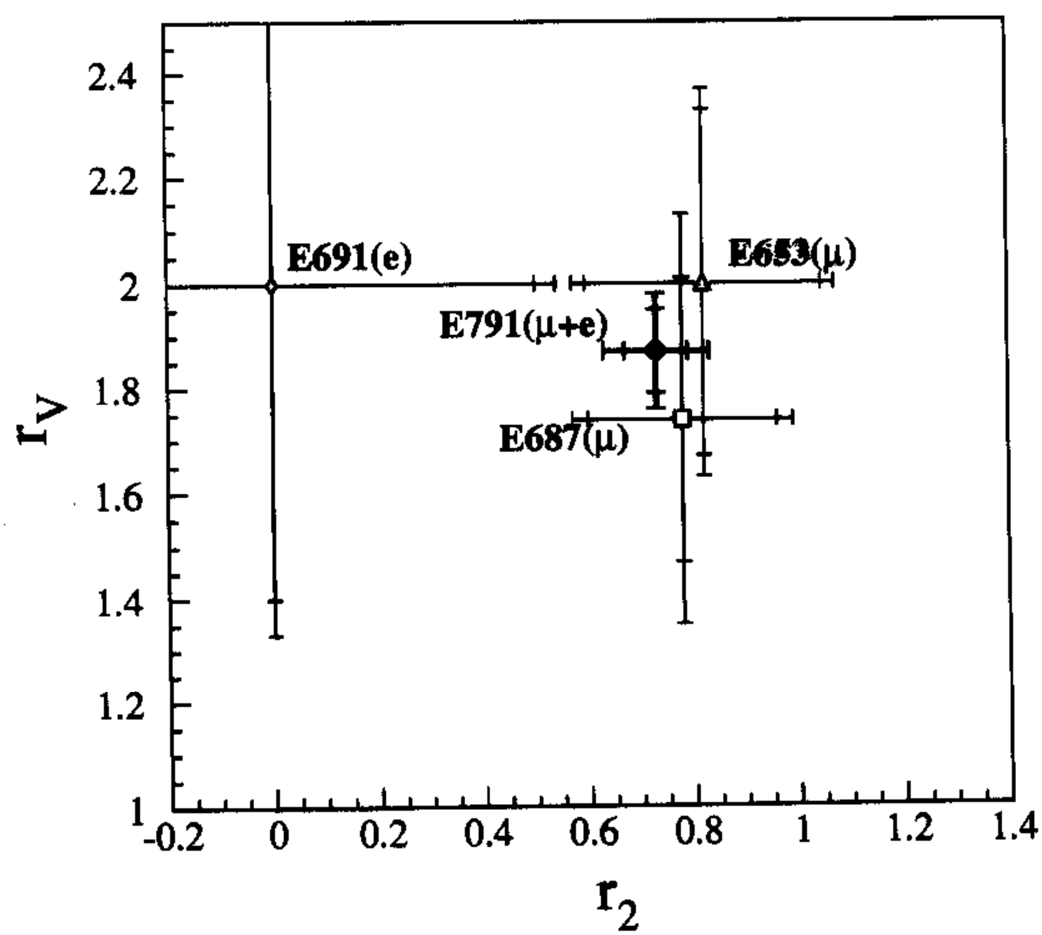
  $r_3 = 0.04 \pm 0.33 \pm 0.29$ (first measured)

- Combined results ($e + \mu$ modes):

  $\boldsymbol{r_V = 1.87 \pm 0.08 \pm 0.07}$ $\quad$ $\boldsymbol{r_2 = 0.73 \pm 0.06 \pm 0.08}$

Comparison of form factor measurements for $D^+ \to \overline{K}^{*0} \ell^+ \nu_\ell$

Group	Events	$r_V = V(0)/A_1(0)$	$r_2 = A_2(0)/A_1(0)$
E791 (e & μ)	6000	$1.87 \pm 0.08 \pm 0.07$	$0.73 \pm 0.06 \pm 0.08$
E791 (μ)	3000	$1.84 \pm 0.11 \pm 0.09$	$0.75 \pm 0.08 \pm 0.09$
E791 (e)	3000	$1.90 \pm 0.11 \pm 0.09$	$0.71 \pm 0.08 \pm 0.09$
E687 (μ)	900	$1.74 \pm 0.27 \pm 0.28$	$0.78 \pm 0.18 \pm 0.10$
E653 (μ)	300	$2.00 \pm 0.33 \pm 0.16$	$0.82 \pm 0.23 \pm 0.11$
E691 (e)	200	$2.0 \pm 0.6 \pm 0.3$	$0.0 \pm 0.5 \pm 0.2$

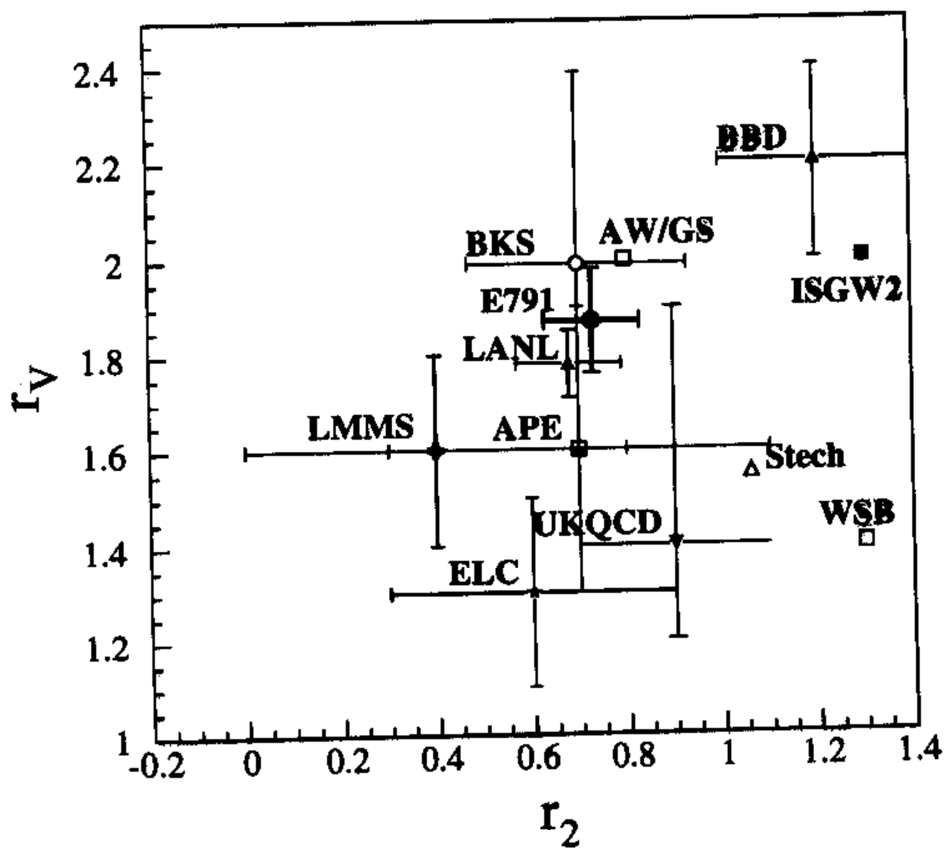


Comparison of E791 form factor measurements for $D^+ \to \overline{K}^{*0}\ell^+\nu_\ell$ with theory

Group	Type	$r_V = V(0)/A_1(0)$	$r_2 = A_2(0)/A_1(0)$
E791 (e & μ)	Exp.	$1.87 \pm 0.08 \pm 0.07$	$0.73 \pm 0.06 \pm 0.08$
ISGW2 (1995)	HQET	2.0	1.3
WSB (1985)	Quark model	1.4	1.3
KS (1989)	Quark model	1.0	1.0
AW/GS (1988,90)	Quark model	2.0	0.8
Stech (1997)	Quark model	1.55	1.06
BKS (1991,93)	LQCD	$1.99 \pm 0.22 \pm 0.33$	$0.70 \pm 0.16 \pm 0.17$
LMMS (1992)	LQCD	1.6 ± 0.2	0.4 ± 0.4
ELC (1994)	LQCD	1.3 ± 0.2	0.6 ± 0.3
APE (1995)	LQCD	1.6 ± 0.3	0.7 ± 0.4
UKQCD (1995)	LQCD	$1.4 + 0.5 - 0.2$	0.9 ± 0.2
LANL (1996)	LQCD	1.78 ± 0.07	0.68 ± 0.11
BBD (1991)	Sum rules	2.2 ± 0.2	1.2 ± 0.2

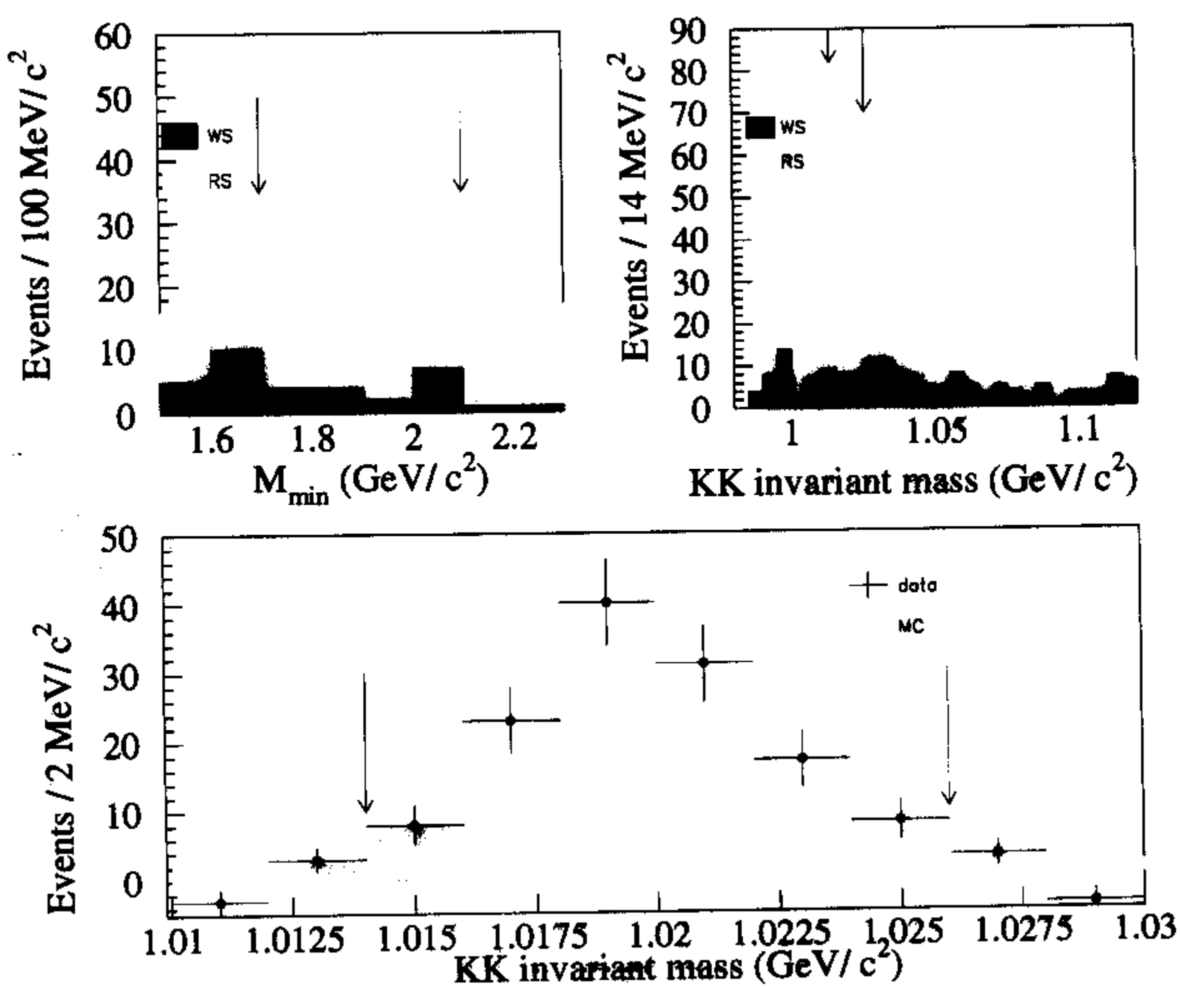
Comments:

1. LQCD does OK.
2. Expt. (E791 data) really challenges theory.



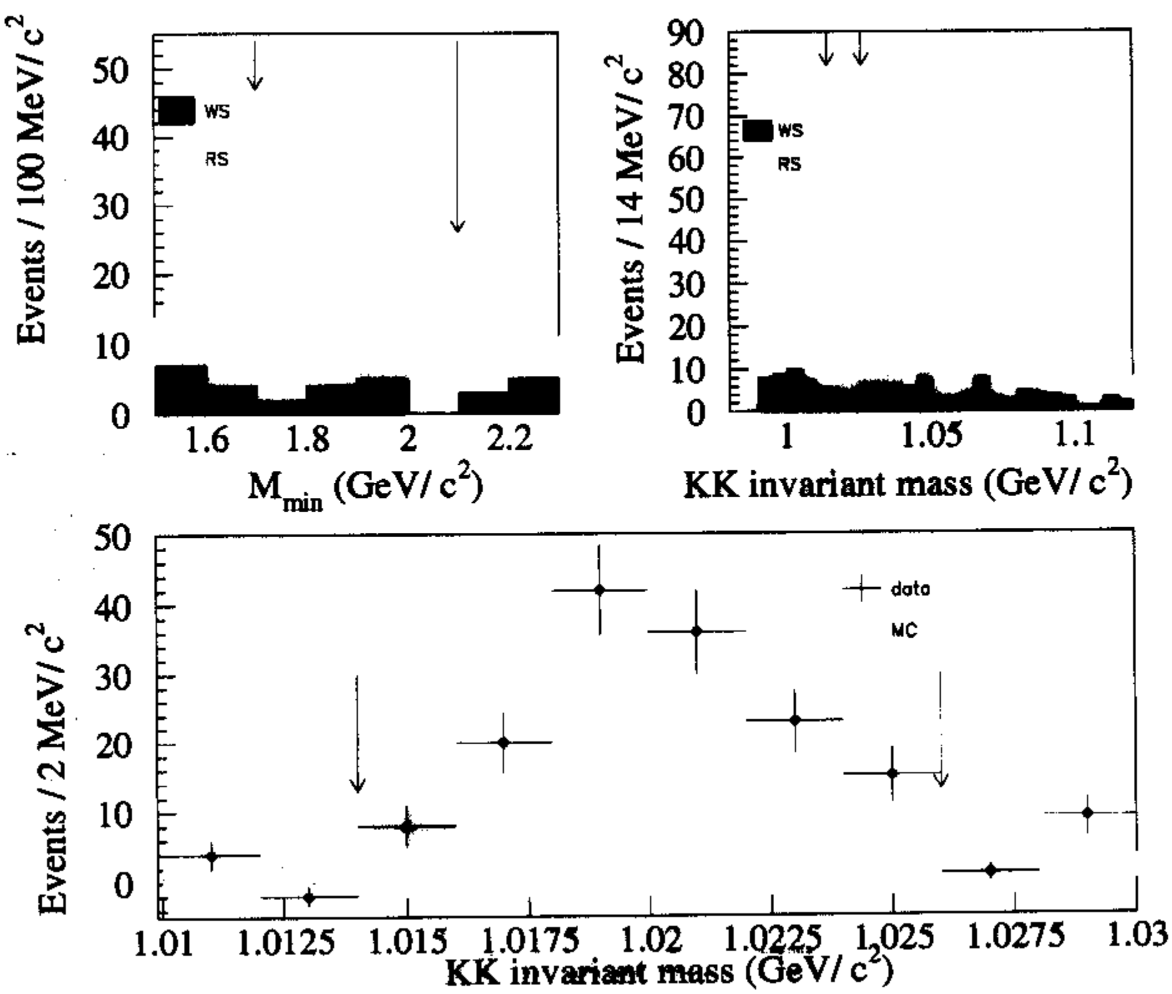
E791 $D_s^+ \to \Phi\mu^+\nu_\mu$ Signal

- For the signal region $1.7 < M_{min} < 2.1$ GeV and $1.014 < M_{KK} < 1.026$ GeV.
- Final data sample: 161 right-sign and 17 wrong-sign events.
- Combinatorics $\Rightarrow$ Background $\approx$ twice WS.

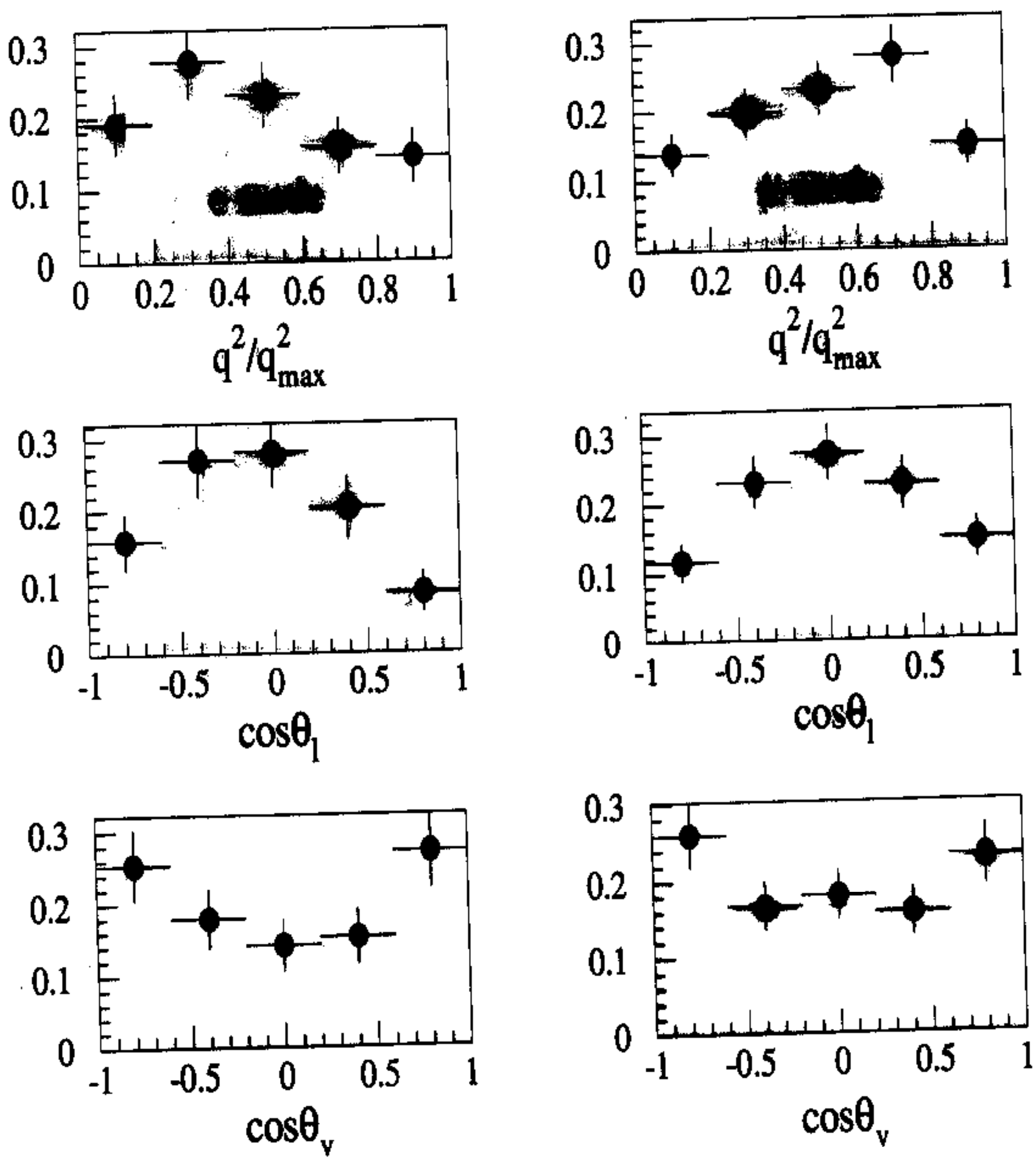


E791 $D_s^+ \to \Phi e^+ \nu_e$ Signal

- For the signal region $1.7 < M_{min} < 2.1$ GeV and $1.014 < M_{KK} < 1.026$ GeV.
- Final data sample: 166 right-sign and 11 wrong-sign events.
- Combinatorics ⇒ Background ≈ twice WS.



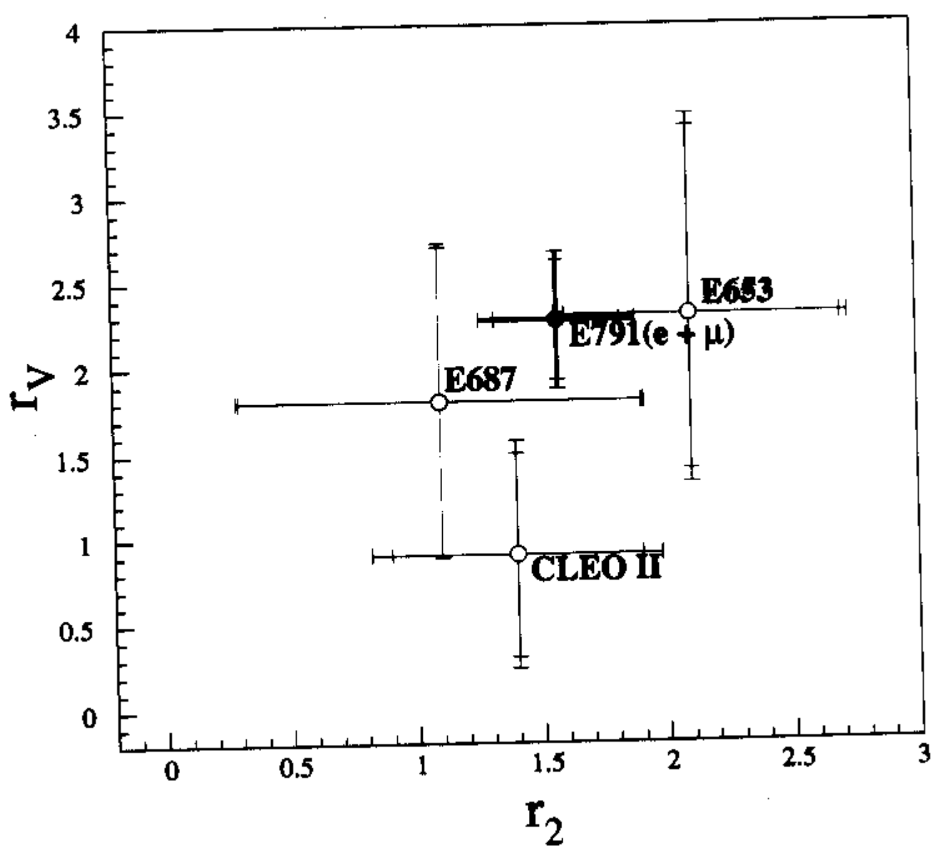
Decay variable distributions for E791 $D_s^+ \to \Phi \ell^+ \nu_\ell$



Crosses: data   Histograms: Monte Carlo

Comparison of form factor measurements for $D_s^+ \to \Phi \ell^+ \nu_\ell$

Group	Events	$r_V = V(0)/A_1(0)$	$r_2 = A_2(0)/A_1(0)$
E791 (e & μ)	327(54)	$2.28 \pm 0.35 \pm 0.20$	$1.57 \pm 0.25 \pm 0.18$
E791 (μ)	161(32)	$2.31 \pm 0.54 \pm 0.26$	$1.49 \pm 0.36 \pm 0.20$
E791 (e)	166(22)	$2.24 \pm 0.47 \pm 0.21$	$1.64 \pm 0.34 \pm 0.20$
CLEO II (e)	474(166)	$0.9 \pm 0.6 \pm 0.3$	$1.4 \pm 0.5 \pm 0.3$
E653 (μ)	24(5)	$2.3^{+1.1}_{-0.9} \pm 0.4$	$2.1^{+0.6}_{-0.5} \pm 0.2$
E687 (μ)	90	$1.8 \pm 0.9 \pm 0.2$	$1.1 \pm 0.8 \pm 0.1$

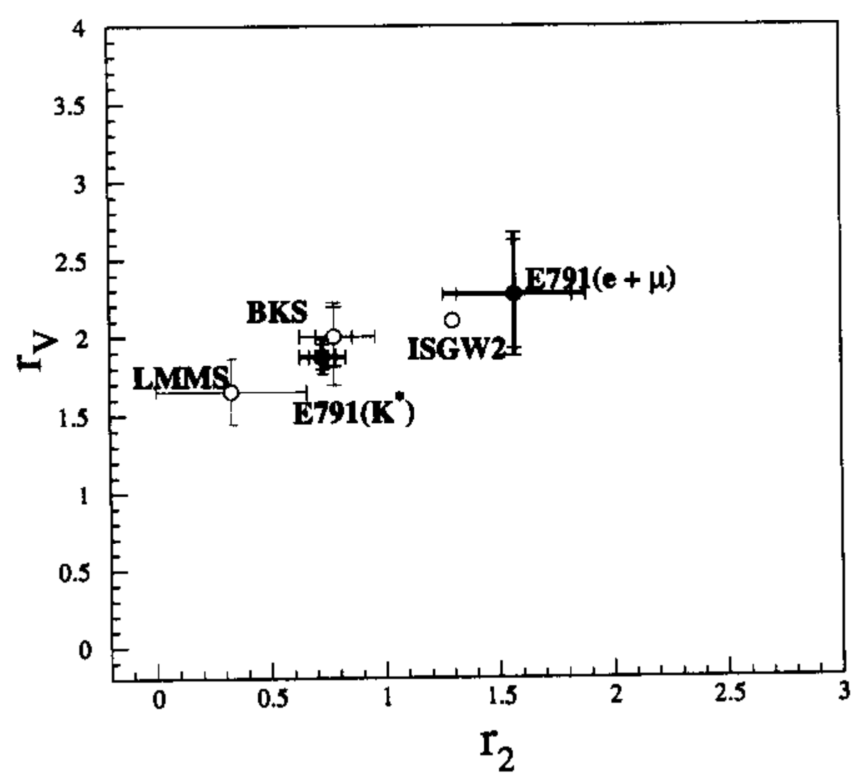


Comparison of E791 form factor measurements for $D_s^+ \to \Phi \ell^+ \nu_\ell$ with theory

Group	$r_V = V(0)/A_1(0)$	$r_2 = A_2(0)/A_1(0)$
E791 ($D_s^+ \to \phi \ell^+ \nu_\ell$)	2.28 ± 0.41	1.57 ± 0.31
E791 ($D^+ \to \overline{K}^{*0} \ell^+ \nu_\ell$)	1.87 ± 0.11	0.73 ± 0.10
BKS	$2.00 \pm 0.19^{+0.20}_{-0.25}$	$0.78 \pm 0.08^{+0.17}_{-0.13}$
LMMS	1.65 ± 0.21	0.33 ± 0.33
ISGW2	2.1	1.3

Comments:

1. r_V is similar to that for $K^\star \ell \nu$.
2. r_2 appears to be larger ($\approx 2\sigma$).



Summary

- **Final results:**

Form factor ratios for $D^+ \to \overline{K}^{*0} \ell^+ \nu_\ell$:

$$\boldsymbol{r_V = 1.87 \pm 0.08 \pm 0.07 \quad r_2 = 0.73 \pm 0.06 \pm 0.08}$$

$\boldsymbol{r_3 = 0.04 \pm 0.33 \pm 0.29}$ (for muons only)

Branching fraction $\frac{\mathcal{B}(D^+ \to \rho^0 \ell^+ \nu_\ell)}{\mathcal{B}(D^+ \to \overline{K}^{*0} \ell^+ \nu_\ell)}$

$$\boldsymbol{\frac{\mathcal{B}(D^+ \to \rho^0 \ell^+ \nu_\ell)}{\mathcal{B}(D^+ \to \overline{K}^{*0} \ell^+ \nu_\ell)} = 0.047 \pm 0.013}$$

- **Preliminary results:**

Form factor ratios for $D_s^+ \to \Phi \ell^+ \nu_\ell$:

$$\boldsymbol{r_V = 2.28 \pm 0.35 \pm 0.20 \quad r_2 = 1.57 \pm 0.25 \pm 0.18}$$

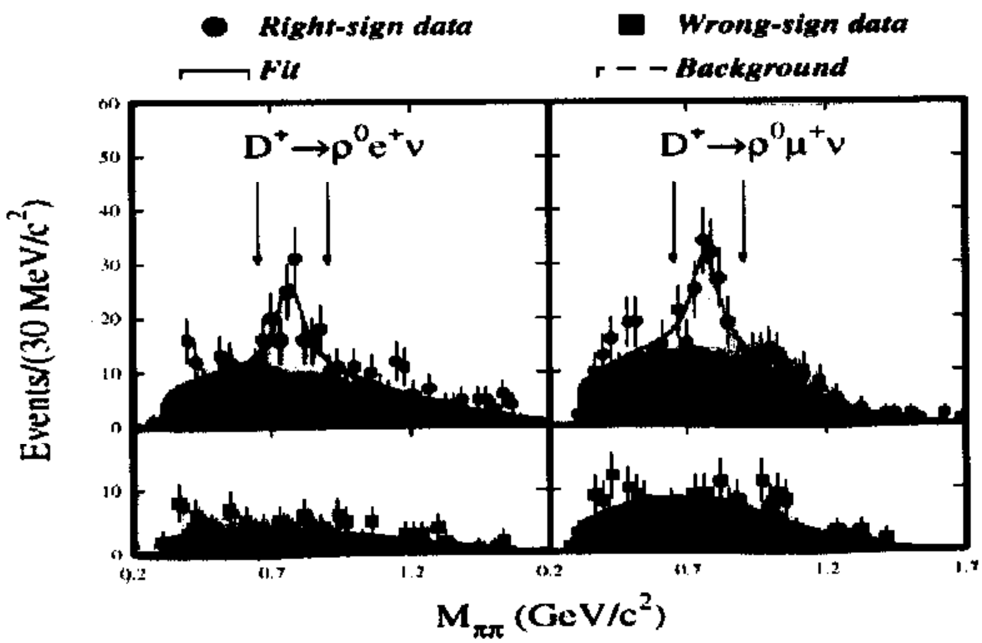
Final results for $\mathcal{B}(D^+ \to \rho^0 \ell^+ \nu_\ell)/\mathcal{B}(D^+ \to \overline{K}^{*0} \ell^+ \nu_\ell)$

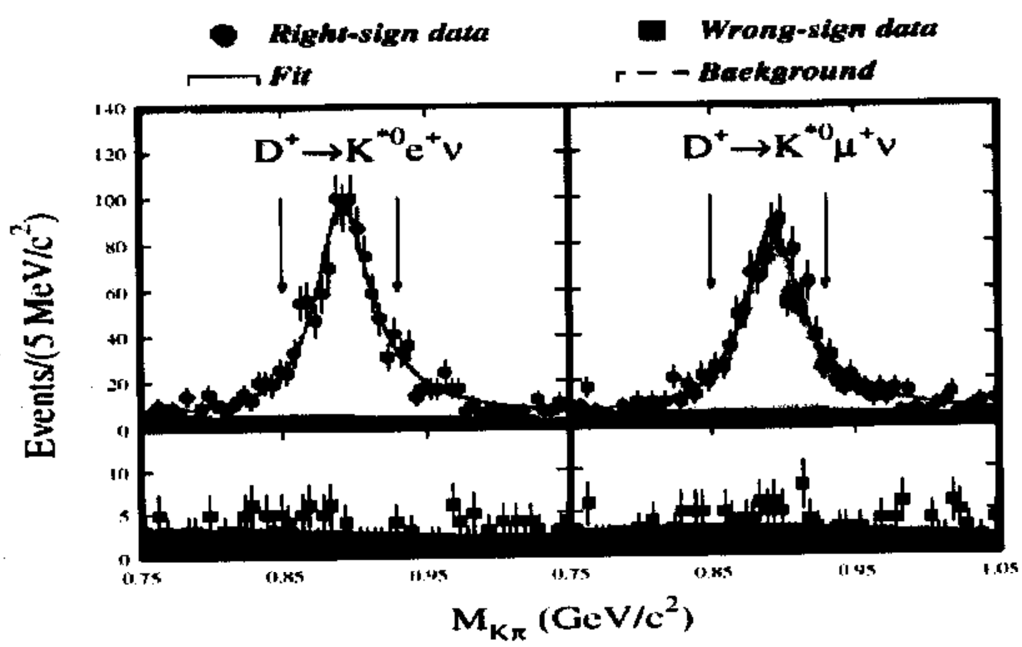
- Electron mode: $\frac{\mathcal{B}(D^+ \to \rho^0 e^+ \nu_e)}{\mathcal{B}(D^+ \to \overline{K}^{*0} e^+ \nu_e)} = \mathbf{0.045 \pm 0.014 \pm 0.009}$
- Muon mode: $\frac{\mathcal{B}(D^+ \to \rho^0 \mu^+ \nu_\mu)}{\mathcal{B}(D^+ \to \overline{K}^{*0} \mu^+ \nu_\mu)} = \mathbf{0.051 \pm 0.015 \pm 0.009}$
- Combined results: $\frac{\mathcal{B}(D^+ \to \rho^0 \ell^+ \nu_\ell)}{\mathcal{B}(D^+ \to \overline{K}^{*0} \ell^+ \nu_\ell)} = \mathbf{0.047 \pm 0.013}$

Other results

Group	Method	ℓ	$\frac{\mathcal{B}(D^+ \to \rho^0 \ell^+ \nu_\ell)}{\mathcal{B}(D^+ \to \overline{K}^{*0} \ell^+ \nu_\ell)}$
E653	Exp.	μ	$0.044^{+0.031}_{-0.025} \pm 0.014$
ISGW2	Quark model	ℓ	0.022
Jaus	Quark Model	ℓ	0.030
			$\frac{1}{2}\frac{\mathcal{B}(D^0 \to \rho^- \ell^+ \nu_\ell)}{\mathcal{B}(D^0 \to \overline{K}^{*-} \ell^+ \nu_\ell)}$
BSW	Quark Model	ℓ	0.037
ELC	LQCD	ℓ	0.047 ± 0.032
APE	LQCD	ℓ	0.043 ± 0.018
UKQCD	LQCD	ℓ	$0.036^{+0.010}_{-0.013}$
LMMS	LQCD	ℓ	0.040 ± 0.011
Casalbuoni	HQET	ℓ	0.06

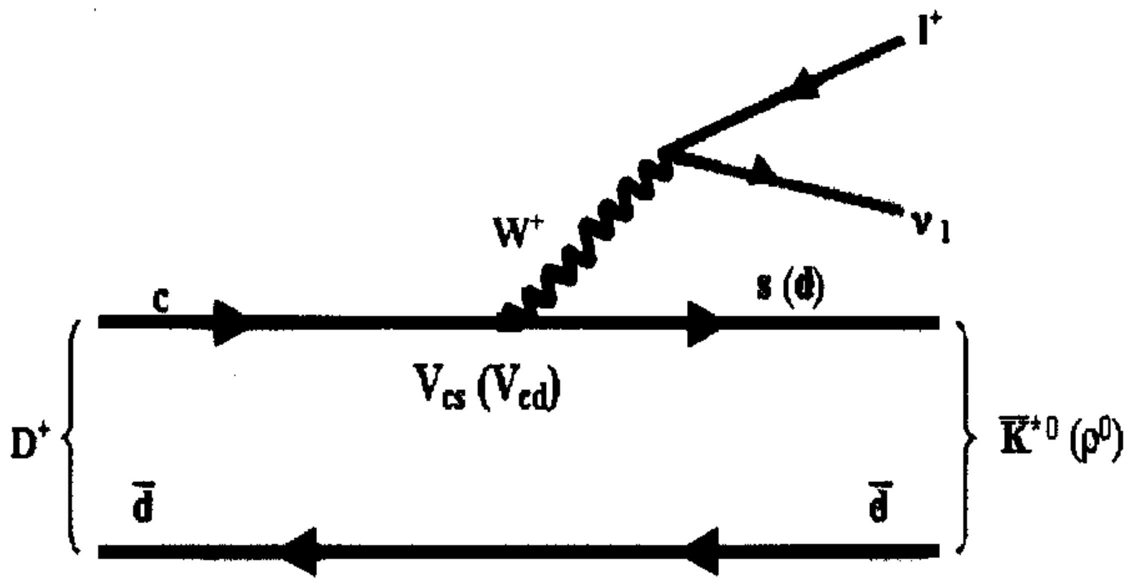
E791 measurement of the branching fraction $\mathcal{B}(D^+ \to \rho^0 \ell^+ \nu_\ell)/\mathcal{B}(D^+ \to \overline{K}^{*0} \ell^+ \nu_\ell)$





- $D^+ \to \rho^0 e^+ \nu_e \Rightarrow 49 \pm 17$ $\quad D^+ \to \overline{K}^{*0} e^+ \nu_e \Rightarrow 892 \pm 52.$
- $D^+ \to \rho^0 \mu^+ \nu_\mu \Rightarrow 58 \pm 18$ $\quad D^+ \to \overline{K}^{*0} \mu^+ \nu_\mu \Rightarrow 769 \pm 54.$

Why measure $\mathcal{B}(D^+ \to \rho^0 \ell^+ \nu_\ell)/\mathcal{B}(D^+ \to \overline{K}^{*0} \ell^+ \nu_\ell)$?



- To validate theoretical calculations.

- To check the SU(3) symmetry of the form factors.

$$\mathcal{B}(D^+ \to \rho^0 \ell^+ \nu_\ell)/\mathcal{B}(D^+ \to \overline{K}^{*0} \ell^+ \nu_\ell) = \frac{|V_{cd}|^2}{|V_{cs}|^2} \cdot \frac{f(FF^{(D\to\rho)})}{f(FF^{(D\to K^*)})}$$

Assuming SU(3) symmetry of the form factors:

- $FF^{(D\to\rho)}(q^2_{max}) = FF^{(D\to K^*)}(q^2_{max})$
- $\mathcal{B}(D^+ \to \rho^0 \ell^+ \nu_\ell)/\mathcal{B}(D^+ \to \overline{K}^{*0} \ell^+ \nu_\ell) = 0.044$

(e.g. Ligeti, Stewart and Wise, Phys. Lett. B420 (1998) 359.)

Preliminary results for $D_s^+ \to \Phi \ell^+ \nu_\ell$

- Electron mode: $RS = 166$ $WS = 11$

  $r_V = 2.24 \pm 0.47 \pm 0.21$ $r_2 = 1.64 \pm 0.34 \pm 0.20$

- Muon mode: $RS = 161$ $WS = 16$

  $r_V = 2.31 \pm 0.54 \pm 0.26$ $r_2 = 1.49 \pm 0.36 \pm 0.20$

- Combined results ($e + \mu$ modes):

$$\mathbf{r_V = 2.28 \pm 0.35 \pm 0.20 \qquad r_2 = 1.57 \pm 0.25 \pm 0.18}$$