Semileptonic & Rare Charm Decays

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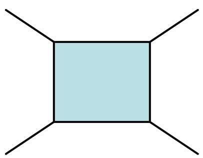
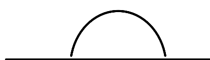
Rare Charm Decays

Potential FCNC Decays are Suppressed

Box and Penguin Diagrams are Smallish for Charm

No Top Quuark in the loop





Short Distance

10^{-19} ⟺ $BR(D^O \to \mu^+\mu^-)$

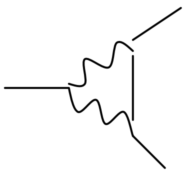
10^{-16} ⟺ $BR(D^O \to \gamma\gamma)$

10^{-8} ⟺ $BR(D^+ \to \pi^+\mu^+\mu^-)$

Rare Charm Decays

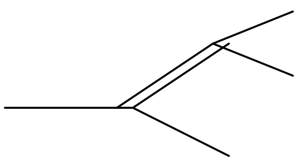
Enhancement from Long Distance Effects

Long Distance



10^{-13} ⟺ $BR(D^{O} \to \mu^{+}\mu^{-})$

10^{-8} ⟺ $BR(D^{O} \to \gamma\gamma)$



10^{-6} ⟺ $BR(D^{+} \to \pi^{+}\mu^{+}\mu^{-})$

Room for New Physics

Even More room for decays:

$$\to \mu^{+}\mu^{+}X$$

$$\to X\mu^{+}e^{-}$$

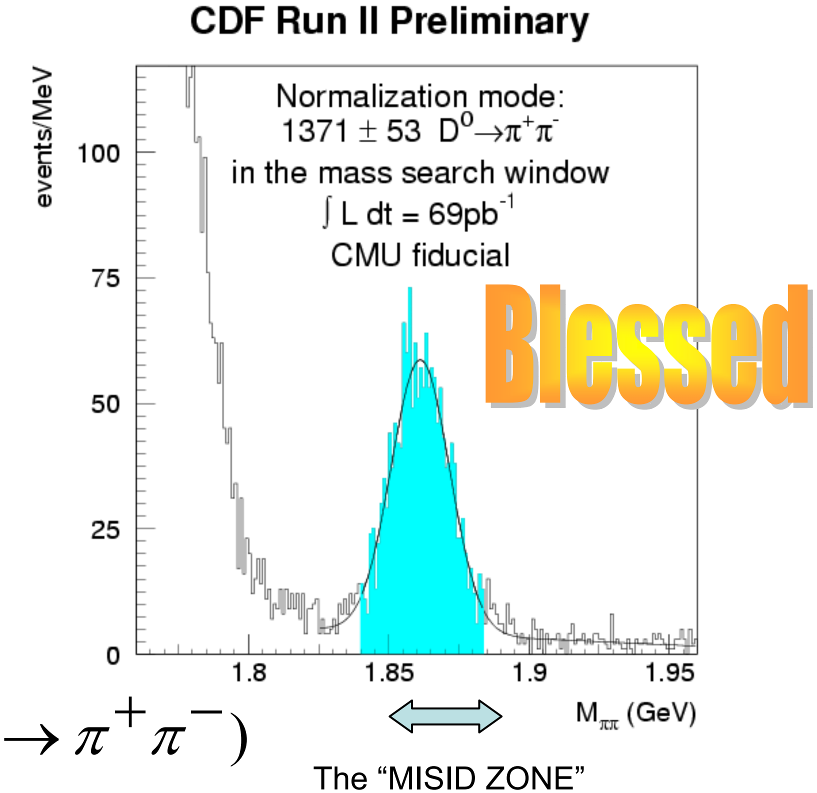
New Result from CDF $D^0 \rightarrow \mu^+\mu^-$

Use D* tagged D°'s $(\text{cut} \approx \pm 2.5\sigma_{\Delta M})$

Use Similar Normalization Mode

Very Similar Kinematics

Keep cuts "same"



Need Anyway:

- Background from Normalization

~(MISID)² = (0.013)² or (1/5 ev.)

$$BR(D^0 \rightarrow \mu^+\mu^-) \leq \frac{N_{RARE}}{N_{NORM}} \frac{eff_{NORM}}{eff_{RARE}} BR(D^0 \rightarrow \pi^+\pi^-)$$

"Blind" Search

Optimal: $S/(1.5+\sqrt{B})$

$\pi\pi$ $\qquad$ $\pi\pi_\mu + K_\mu\pi_\mu$

Sideband + (MISID)²

Back of the Envelope:

1.5E-3 (2.2/1371) = 2.4E-6

New Result from CDF $D^0 \to \mu^+\mu^-$

- Expected background
  - 1.7 ± 0.7 events
    - Fake: 0.22 ± 0.2
    - Combinatorial: 1.5 ± 0.7

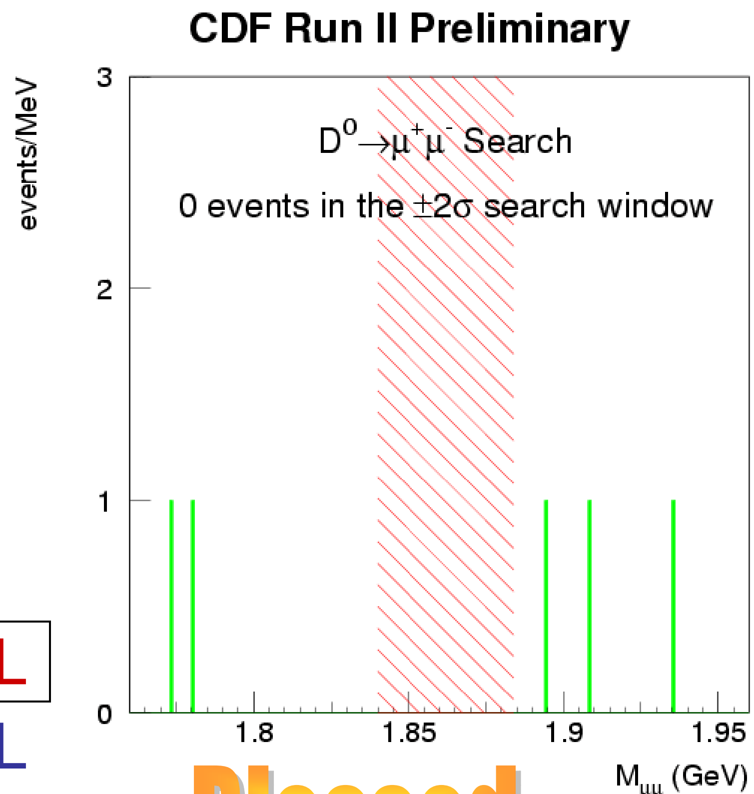
Open the Box

- 0 events in window
- New best limit

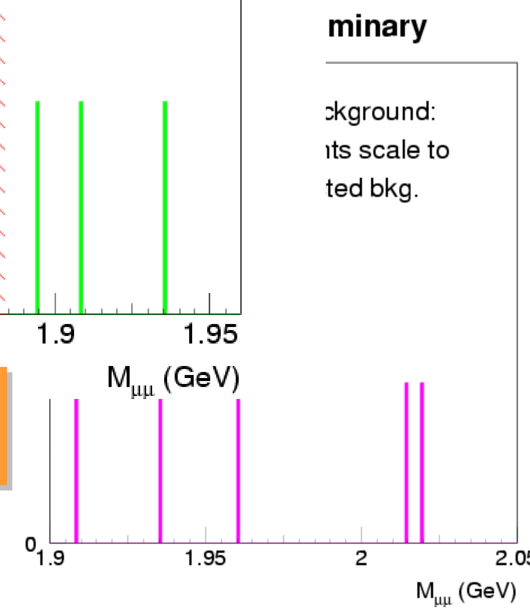
Br < 2.4 x 10^{-6} at 90% CL

Br < 3.1 x 10^{-6} at 95% CL

Previous Bests:
4.1 x 10^{-6} at 90% CL (BEATRICE)
4.2 x 10^{-6} at 90% CL (E771)



Blessed



Background Sideband
(Combinatorial Estimate)

New Result from CLEO $D^O \rightarrow \gamma\gamma$

Form D^0 mass from 2 photons
(Cuts optimized on $D^O \rightarrow \pi^O \pi^O$)
Mass must be within $2.5\sigma_M$ of M(D^0)

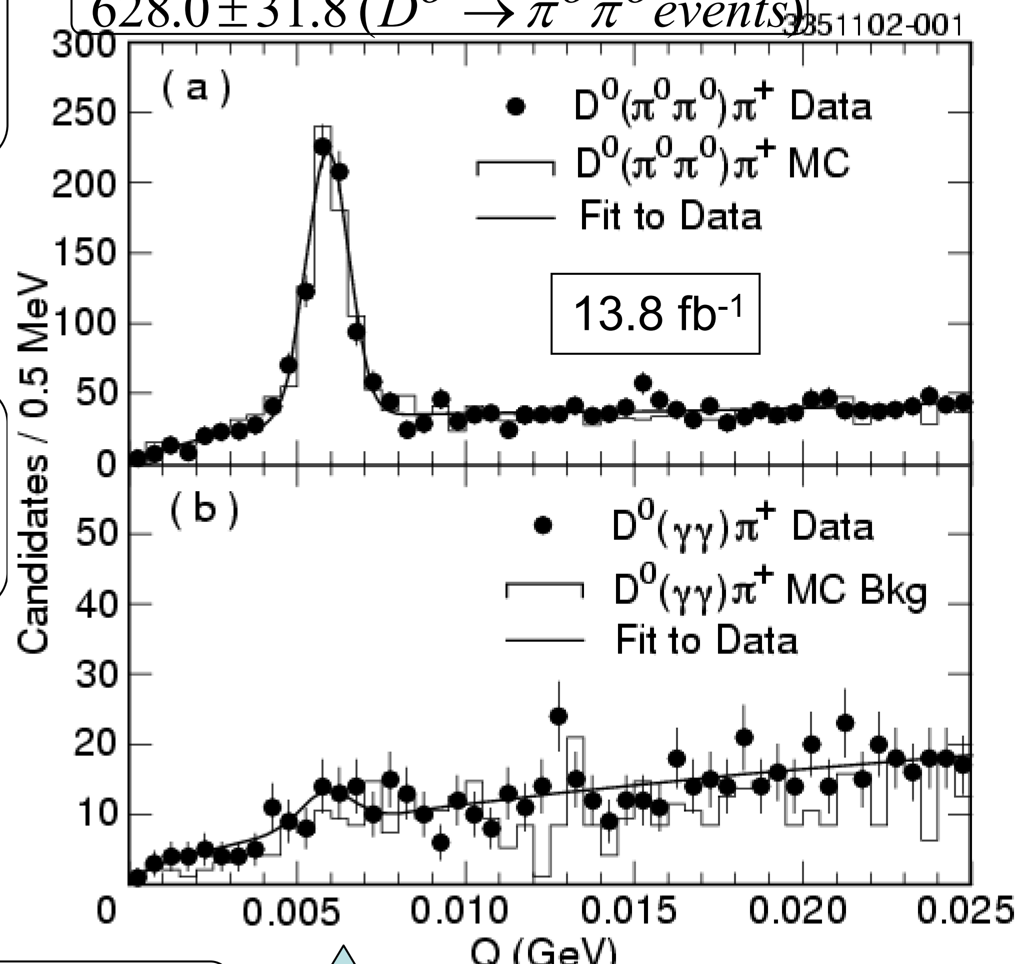
Veto candidate when extra photons form mass: $M(\pi^O) \pm 3\sigma_M$
(reduces $\pi^O \pi^O$ bkgnd from 4 to 1)

Find soft pion consistent with D momentum cuts and Particle ID
Form $Q = M(D^{*+}) - M(D^O)$

Fit data to Gaussian and threshold function

Gaussian width and center fixed from Monte Carlo

$628.0 \pm 31.8\ (D^O \rightarrow \pi^O \pi^O\ events)$



$19.2 \pm 9.3\ (D^O \rightarrow \gamma\gamma\ events)$

New Result from CLEO $D^O \to \gamma\gamma$

$$\frac{BR(D^0 \to \gamma\gamma)}{BR(D^0 \to \pi^O \pi^O)} = \frac{N_{RARE}}{N_{NORM}} \frac{eff_{NORM}}{eff_{RARE}} = 0.0194 \pm 0.0094 \quad \text{(stat)}$$

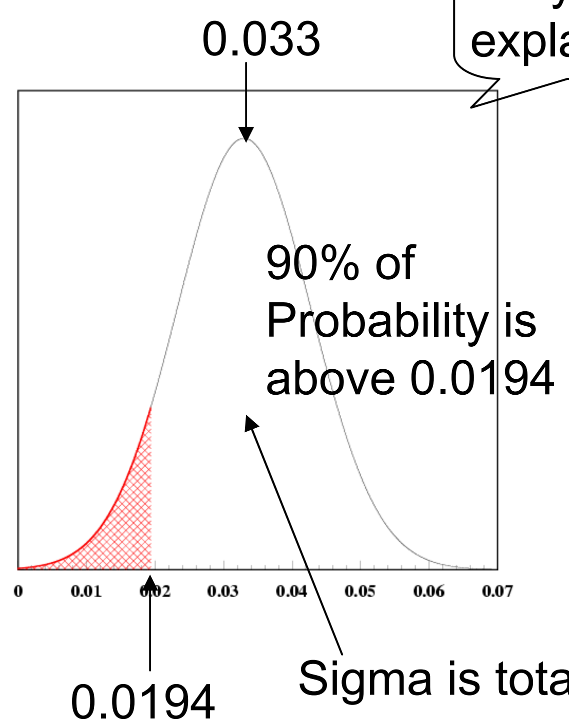
Systematic error 13.1% from finding efficiencies, fits, MC stats, D selection, Event selection (added in quadrature with stat error for upper limit estimate)

$$\frac{BR(D^0 \to \gamma\gamma)}{BR(D^0 \to \pi^O \pi^O)} < 0.033 @ 90\% \; C.L.$$

Using $BR(D^0 \to \pi^O \pi^O) = (8.4 \pm 2.2) \times 10^{-4}$

$$BR(D^0 \to \gamma\gamma) < 2.9 \times 10^{-5} @ 90\% \; C.L.$$

My toy explanation



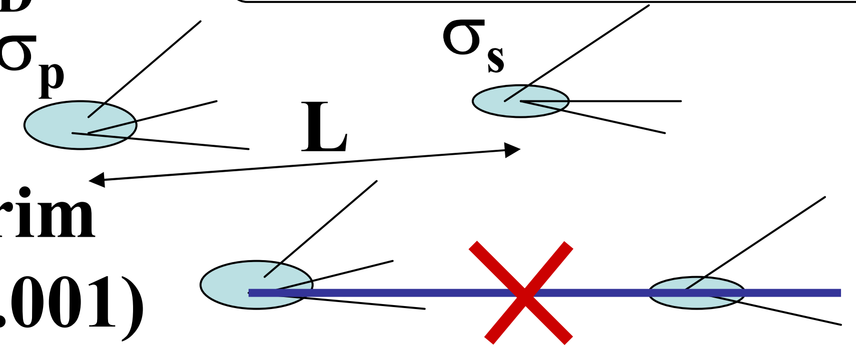
Phys. Rev. Lett. 90:101801, 2003
hep-ex/0212045

Final Results from FOCUS

$$D^{+}_{(S)} \rightarrow (\pi, K)^{\pm} \mu^{\mp} \mu^{+}$$

Look for 3 bodies with 2 muons

Cut Grid, based on vertexing, Particle ID



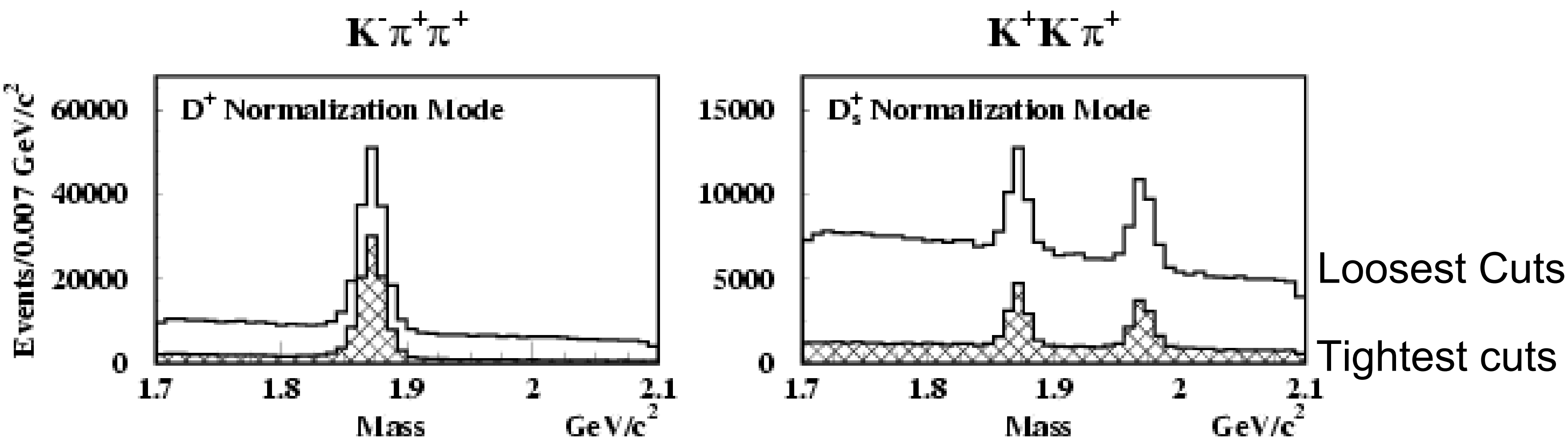
L/σ – vary from >5-21

ISO1 – CL DK's in prim (vary <0.1 –0.001)

DCL – CL of DK vertex (>1 -- 4%)

MuCL – CL for Muon ID (>1 – 10%)

Cuts on P(μ) for μ's, Cerenkov for π's and K's



Final Results from FOCUS

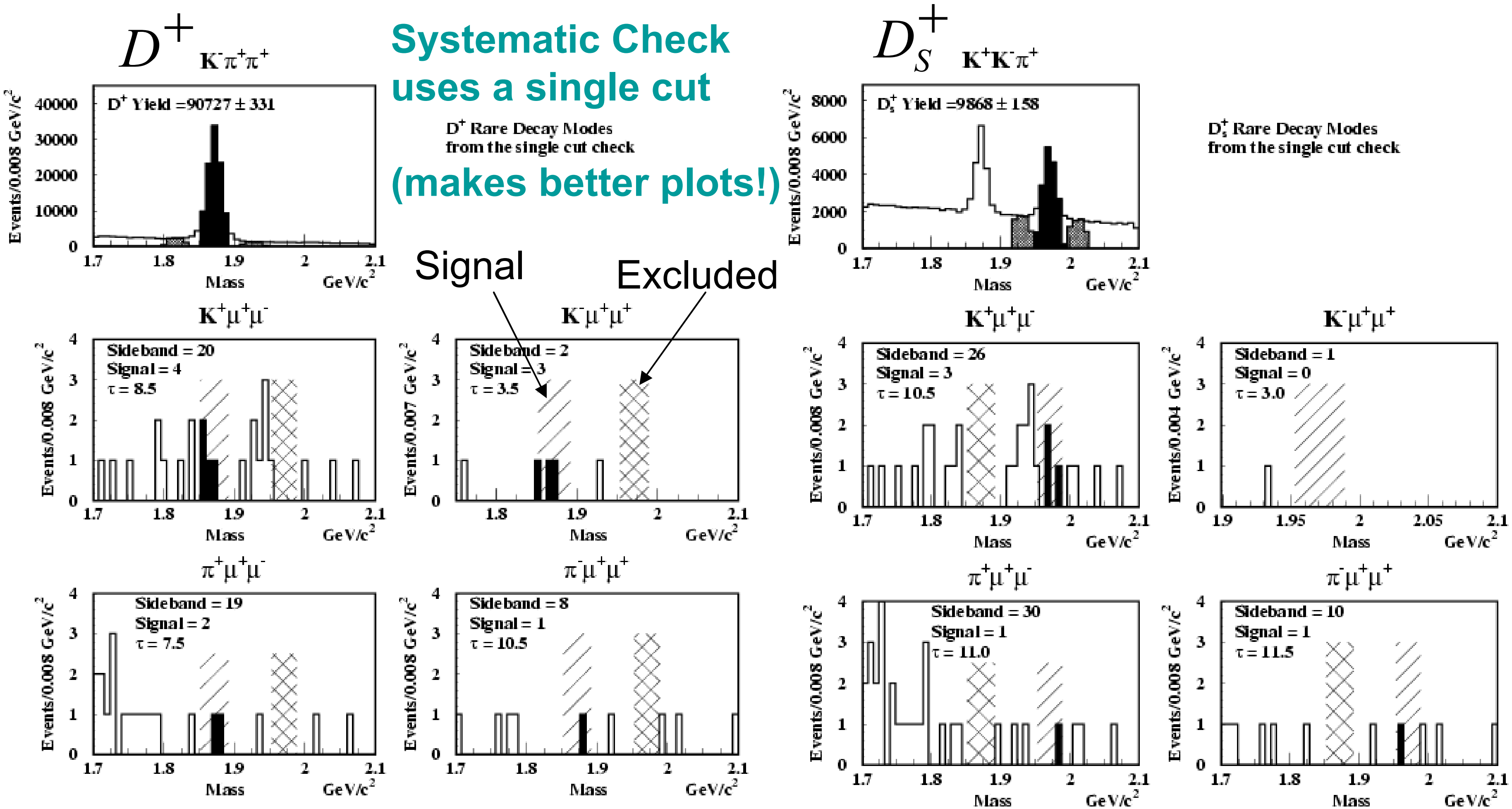
Use Dual Bootstrap

$$D^+_{(S)} \rightarrow (\pi, K)^{\pm} \mu^{\mp} \mu^+$$

- First Bootstrap sets cuts for optimal Sensitivity (Blind)
  - Second Bootstrap calculates quoted Sensitivity and Branching Ratio

Systematic Check uses a single cut

(makes better plots!)



Final Results from FOCUS

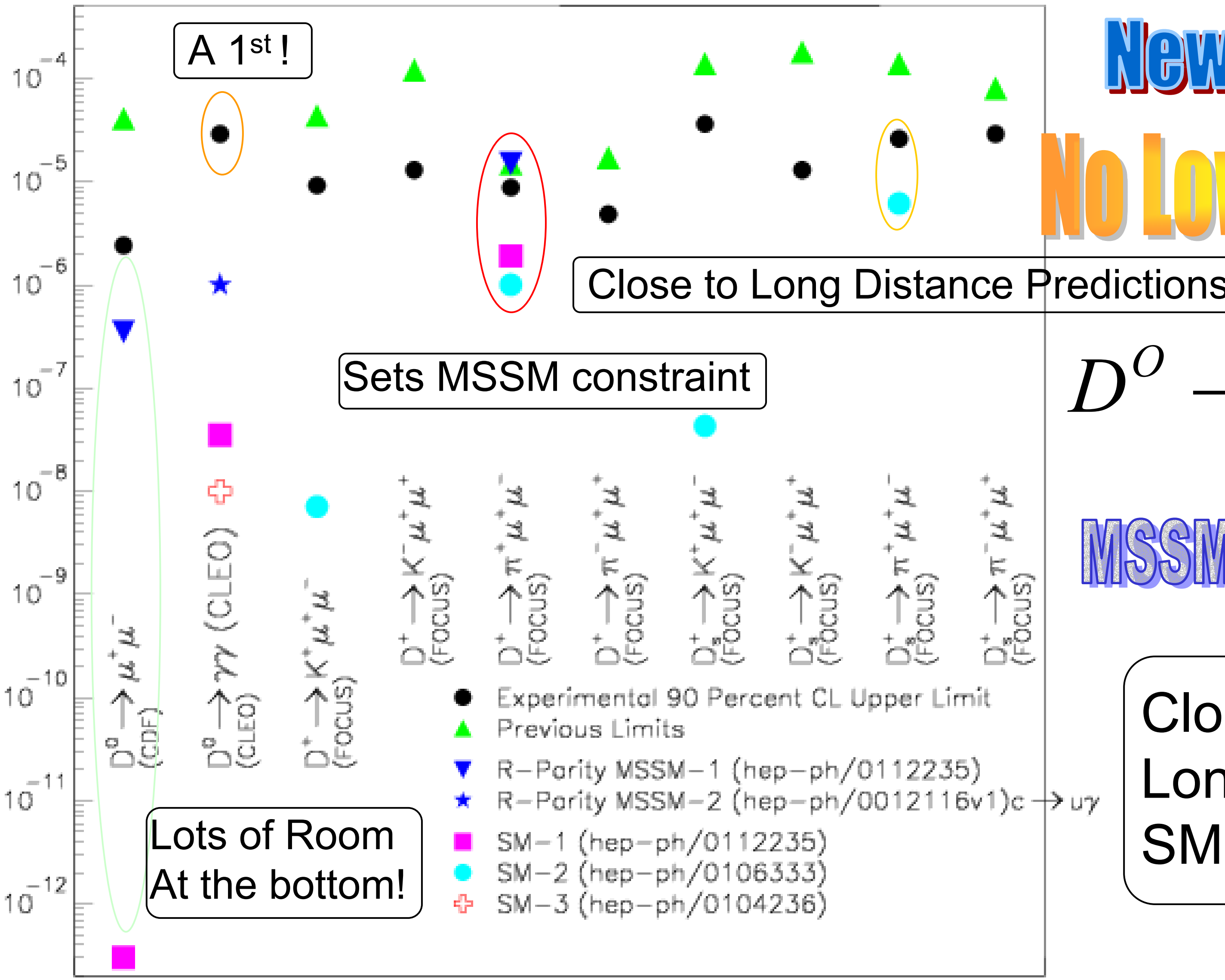
$$D^{+}_{(S)} \rightarrow (\pi, K)^{\pm} \mu^{\mp} \mu^{+}$$

Decay Mode	Dual Bootstrap	Sensitivity	Sys. Error	Result W/sys	Single Cut(w/sys)	Previous (E791)
$D^+ \Rightarrow K^+\mu^+\mu^-$	9.1×10^{-6}	7.5×10^{-6}	7.5%	9.2×10^{-6}	12×10^{-6}	44×10^{-6}
$D^+ \Rightarrow K^-\mu^+\mu^+$	13×10^{-6}	4.8×10^{-6}	7.5%	13×10^{-6}	12×10^{-6}	120×10^{-6}
$D^+ \Rightarrow \pi^+\mu^+\mu^-$	8.8×10^{-6}	7.6×10^{-6}	7.5%	8.8×10^{-6}	7.4×10^{-6}	15×10^{-6}
$D^+ \Rightarrow \pi^-\mu^+\mu^+$	4.9×10^{-6}	5.6×10^{-6}	7.5%	4.8×10^{-6}	5.2×10^{-6}	17×10^{-6}
$D_s^+ \Rightarrow K^+\mu^+\mu^-$	3.3×10^{-5}	3.3×10^{-5}	27.5%	3.6×10^{-5}	3.8×10^{-5}	1.4×10^{-4}
$D_s^+ \Rightarrow K^-\mu^+\mu^+$	1.3×10^{-5}	2.1×10^{-5}	27.5%	1.3×10^{-5}	2.0×10^{-5}	1.8×10^{-4}
$D_s^+ \Rightarrow \pi^+\mu^+\mu^-$	2.4×10^{-5}	3.1×10^{-5}	27.5%	2.6×10^{-5}	1.8×10^{-5}	1.4×10^{-4}
$D_s^+ \Rightarrow \pi^-\mu^+\mu^+$	2.6×10^{-5}	2.3×10^{-5}	27.5%	2.9×10^{-5}	2.2×10^{-5}	0.8×10^{-4}

(E687)

Dominated by PDG rate to normalizing mode

Rare Decay Round-Up



Still Room for New Physics

No Lower Limits

$$D^0 \to \gamma\gamma$$

A 1st!

MSSM Constraint

Closing in on
Long range
SM predictions

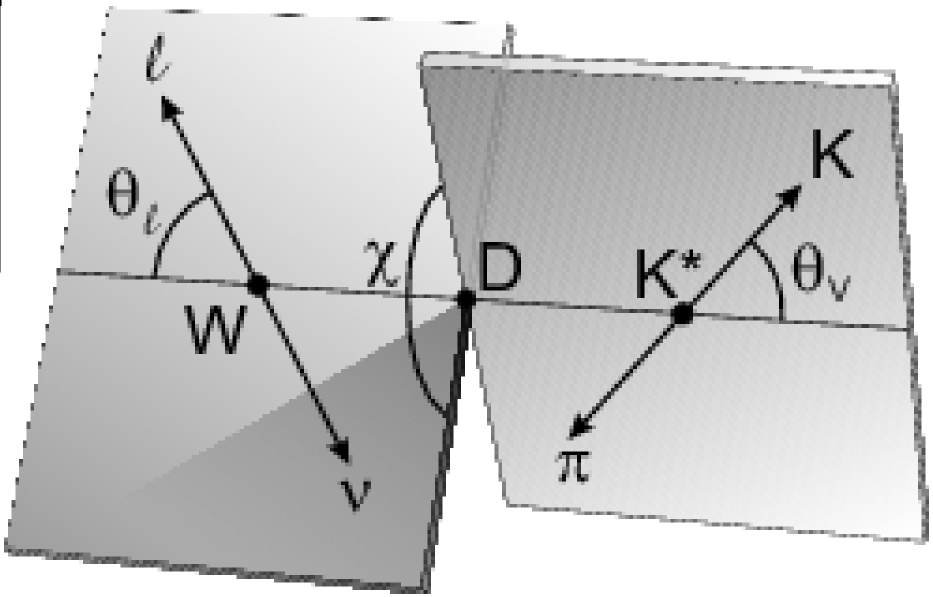
Semileptonic Charm Decays

More than just CKM measurement tools…

$D^+ \to (K^-\pi^+)\mu^+\nu$ (Interference)

$\frac{\Gamma(D^+ \to \overline{K}^{*0}\mu^+\nu)}{\Gamma(D^+ \to K^-\pi^+\pi^+)}, \frac{\Gamma(D_S^+ \to \phi\mu^+\nu)}{\Gamma(D_S^+ \to \phi\pi^+)}$

$D^+ \to \overline{K}^{*0}\mu^+\nu$ (Form Factors)



$\Lambda_C^+ \to \Lambda^0 e^+\nu$ (Form Factors, M_{Pole})

$\Lambda_C^+ \to \Lambda^0 e^+\nu$ (CP Asymmetry)

Simple Equation: (D decay, No form factors, V decays to spin 0 particles)

$$\frac{d^2\Gamma}{d\cos\theta_V d\cos\theta_\ell} \propto \{(1+\cos\theta_\ell)^2\Gamma_+ + (1-\cos\theta_\ell)^2\Gamma\_\}\sin^2\theta_V + 4\sin^2\theta_\ell\cos^2\theta_V\Gamma_0$$

Neutrino is left handed

V products spinless

Prefers W spin along muon,e

Prefer L_Z=0

Gets Complicated…

Scalar Resonance?

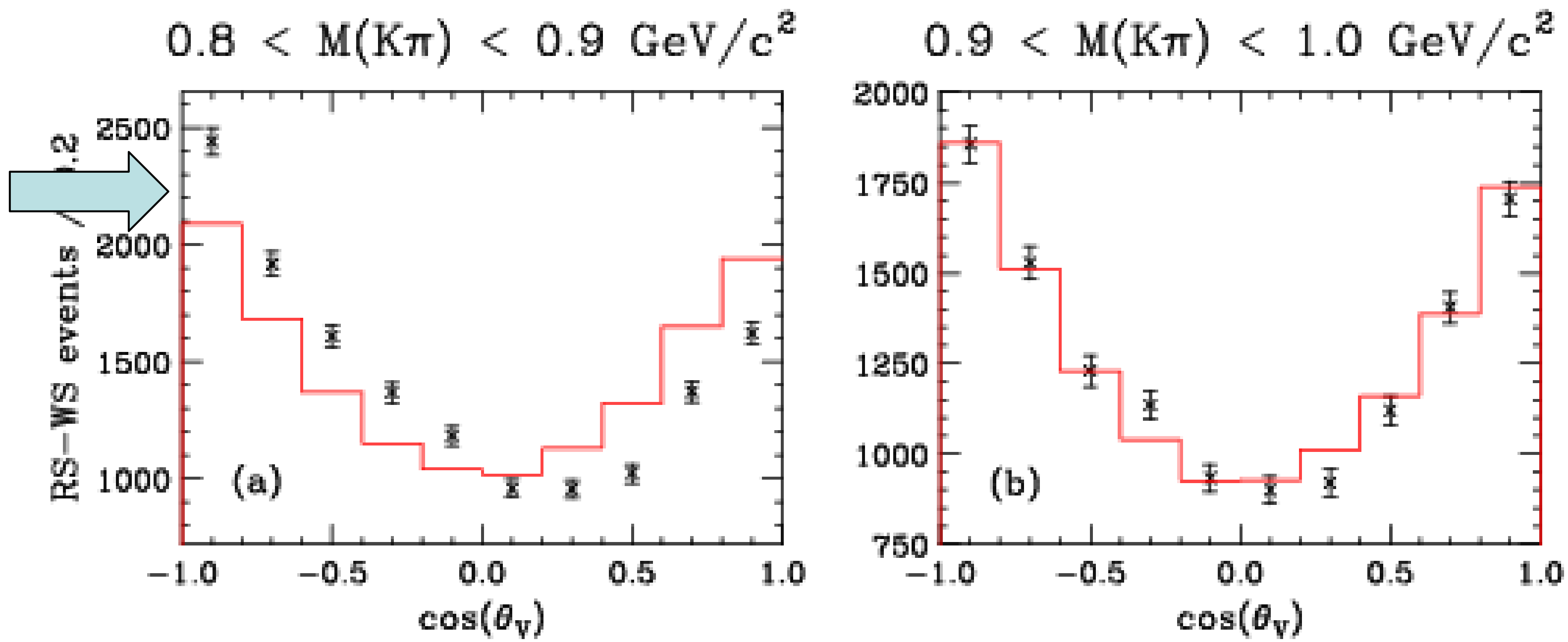
Baryons (spin ½)

Form Factors

CP?

FOCUS saw discrepancies in the data

Yikes!



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

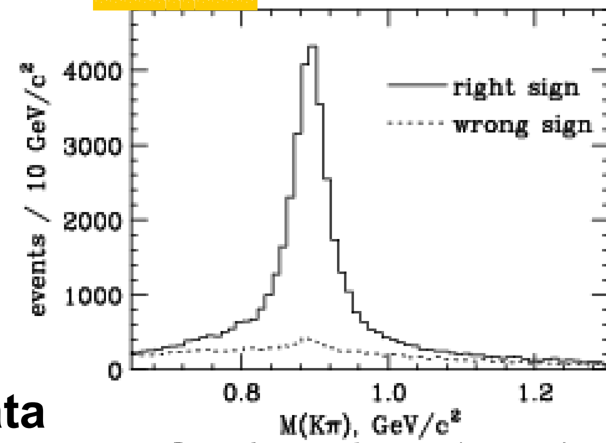
(Did NOT obey)

$$\frac{d^5\Gamma}{dm_{k\pi}\,dq^2\,d\cos\theta_V\,d\cos\theta_\ell\,d\chi} \propto \left\{ \left| \begin{array}{c} \sin\theta_V (1+\cos\theta_\ell) e^{i\chi} B_{K^{*0}} H_+(q^2) \\ -\sin\theta_V (1-\cos\theta_\ell) e^{-i\chi} B_{K^{*0}} H_-(q^2) \\ -2\cos\theta_V \sin\theta_\ell B_{K^{*0}} H_0(q^2) \end{array} \right|^2 \right\}$$

Phys.Lett.B535:43-51, 2002
hep-ex/0203031

FOCUS added a term, things got better

With a Clean $K\pi\mu\nu$ signal

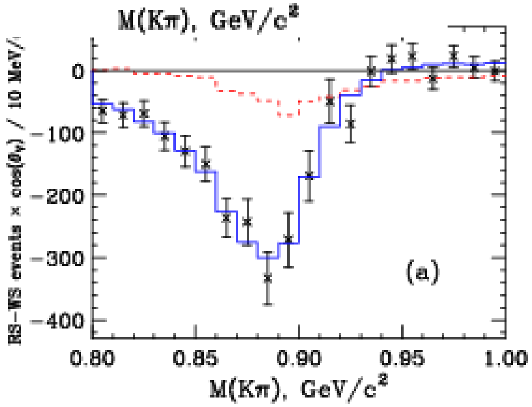


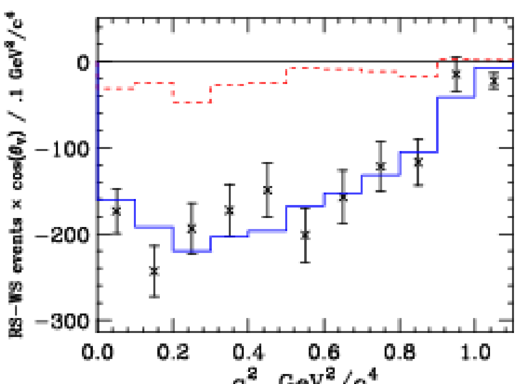
$$\frac{d^5\Gamma}{dm_{k\pi}\,dq^2\,d\cos\theta_V\,d\cos\theta_\ell\,d\chi} \propto$$

$$\left\{ \left| \begin{array}{c} (1+\cos\theta_\ell)\sin\theta_V e^{i\chi} B_{K^{*0}} H_+(q^2) \\ -(1-\cos\theta_\ell)\sin\theta_V e^{-i\chi} B_{K^{*0}} H_-(q^2) \\ -2\sin\theta_\ell(\cos\theta_V B_{K^{*0}} + A e^{i\delta}) H_0(q^2) \end{array} \right|^2 \right\}$$

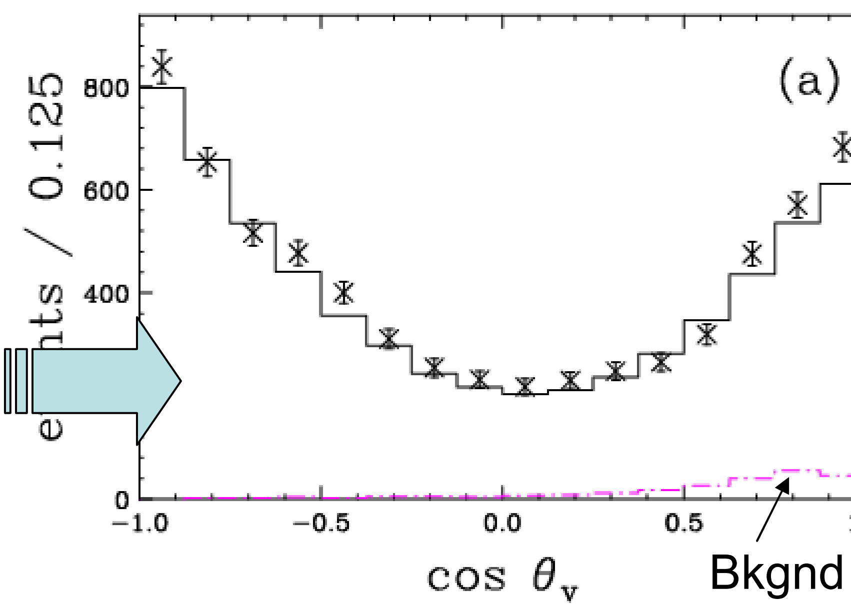
L=0 ansatz

The data (error bars) preferred the L=0 ansatz (solid) over no extra term (dashed)





And the distributions were ready for fitting



FOCUS BR Measurements $\frac{\Gamma(D^+ \to \overline{K}^{*0}\mu^+\nu)}{\Gamma(D^+ \to K^-\pi^+\pi^+)}, \frac{\Gamma(D_S^+ \to \phi\mu^+\nu)}{\Gamma(D_S^+ \to \phi\pi^+)}$

Cuts similar to rare search:

ISO1 ⇨ ISO2 – No unused tracks consistent with charm vertex (CL < 0.1%)

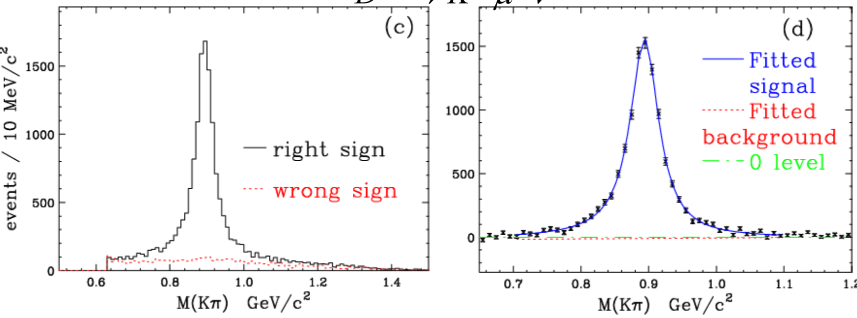
OoM – Charm vertex outside of target and silicon by $3\sigma_{Vertex}$

$$M(K^-\pi^+\mu^+\{\nu\}) - M(K^-\mu^+\{\nu\}) > 0.18\, GeV/c^2 \text{ (cuts } D^{*+} \to D^0\pi^+)$$

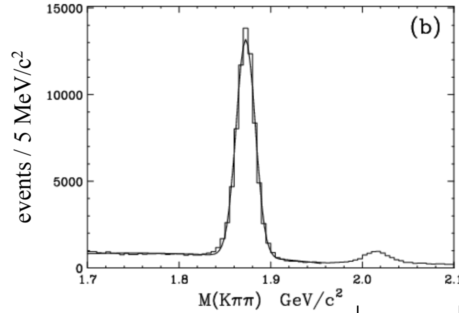
$D^+ \to \overline{K}^{*0}\mu^+\nu$ Includes S-wave interference

Phys.Lett.B540:25-32, 2002
hep-ex/0206013

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



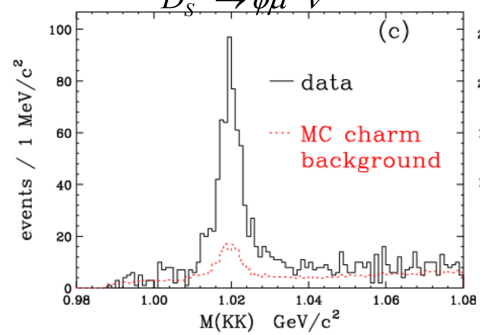
$D^+ \to K^-\pi^+\pi^+$



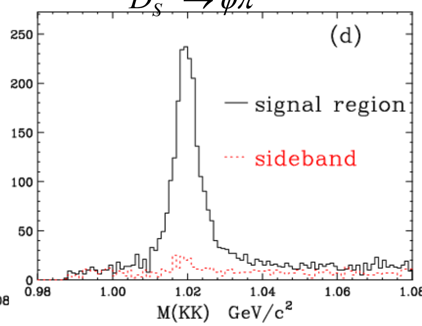
$$\frac{\Gamma(D^+ \to \overline{K}^{*0}\mu^+\nu)}{\Gamma(D^+ \to K^-\pi^+\pi^+)} =$$

$$0.602 \pm 0.010(stat) \pm 0.021(sys)$$

$D_S^+ \to \phi\mu^+\nu$



$D_S^+ \to \phi\pi^+$



Systematic errors :

expressed as a fraction of σ_{stat}

for D^+ (D_S^+) :

(add in if > 1)

Vary Cuts ⇒ 0.71, (1.06)

Splitting Samples ⇒ 1.57, (1.12)

Vary fit (Bk, ff) ⇒ 1.57, (0.94)

Total (quadrature) ⇒ 2.2, (1.5)

$$\frac{\Gamma(D_S^+ \to \phi\mu^+\nu)}{\Gamma(D_S^+ \to \phi\pi^+)} =$$

$$0.54 \pm 0.033(stat) \pm 0.048(sys)$$

FOCUS Form Factors $D^+ \to \overline{K}^{*0} \mu^+ \nu$

$$H_\pm(q^2) = (M_D + m_{K\pi}) A_1(q^2) \mp 2 \frac{M_D K}{M_D + m_{K\pi}} V(q^2)$$

$H_t(q^2)$ has m_μ^2 factor, set $= 0$

Tried in fit, no sensitivity (E791?)

$$H_0(q^2) = \frac{1}{2m_{K\pi}\sqrt{q^2}} \left[(M_D^2 - m_{K\pi}^2 - q^2)(M_D + m_{K\pi}) A_1(q^2) - 4 \frac{M_D^2 K^2}{M_D + m_{K\pi}} A_2(q^2) \right]$$

$$A_i(q^2) = \frac{A_i(0)}{1 - q^2/M_A^2}, (M_A = 2.5\, GeV/c^2) \qquad V(q^2) = \frac{V(0)}{1 - q^2/M_V^2}, (M_V = 2.1\, GeV/c^2)$$

Fit to $r_v = \frac{V(0)}{A_1(0)} \quad r_2 = \frac{A_2(0)}{A_1(0)}$ and S-wave parameters, A and δ

Technique: (common – vary generated parameters in Montecarlo by using agreement with reconstructed distributions and data)

Pioneered by D.M. Schmidt for E691 K*ev analysis: NIM A 328 (1993)

1st find S-wave with PDG r's,

3 bins in $\cos\theta_V$, 3 in $\cos\theta_\ell$, 3 in χ and 4 in $m_{K\pi}$

then fit for r's

S-wave term Breaks symmetry

5 bins in $\cos\theta_V$, 5 in $\cos\theta_\ell$, 3 in $|\chi|$ and 3 in q^2/q^2_{max}

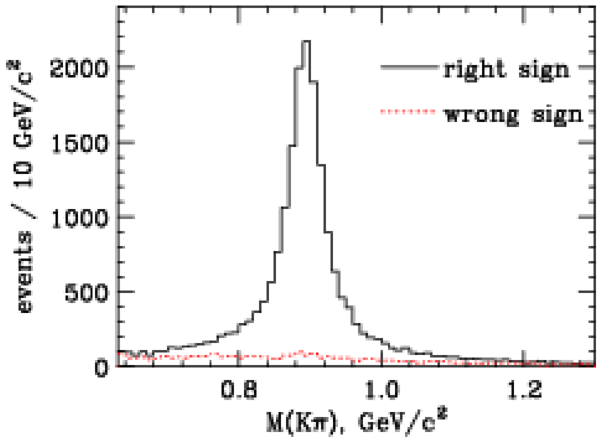
S-wave term and r's essentially decouple

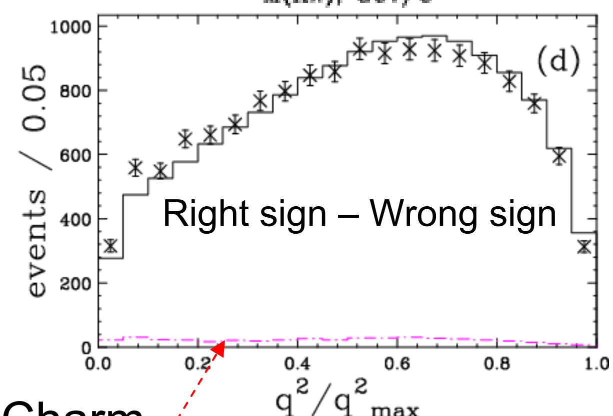
FOCUS Form Factors $D^+ \to \overline{K}^{*0} \mu^+ \nu$

Cuts similar to previous, some change to get uniform acceptance, one extra

OoM – Charm vertex outside of target and silicon by $1\sigma_{Vertex}$

Cut on $q^2 < 0.2\ GeV^2/c^2$ ⇐ r's are flat, feeling m_μ? Goodness of fit issue





Charm Background

Systematic Checks

S-wave – varied cuts
35 fits – Sample Variance

Form Factor (3 sources)

1) Varied Cuts
2) Split sample

$P_D,\ D\overline{D},\ m_{K\pi}\ (0.9\ GeV/c^2)$

3) Vary MC input
 Charm Backgrounds

$$-2 < \frac{A_3(0)}{A_1(0)} < 2$$

Results:

$$A = 0.330 \pm 0.022 \pm 0.015$$
$$\delta = 0.68 \pm 0.07 \pm 0.05$$

$\pm(stat) \pm (sys)$

$$r_V = 1.504 \pm 0.057 \pm 0.039$$
$$r2 = 0.875 \pm 0.049 \pm 0.064$$

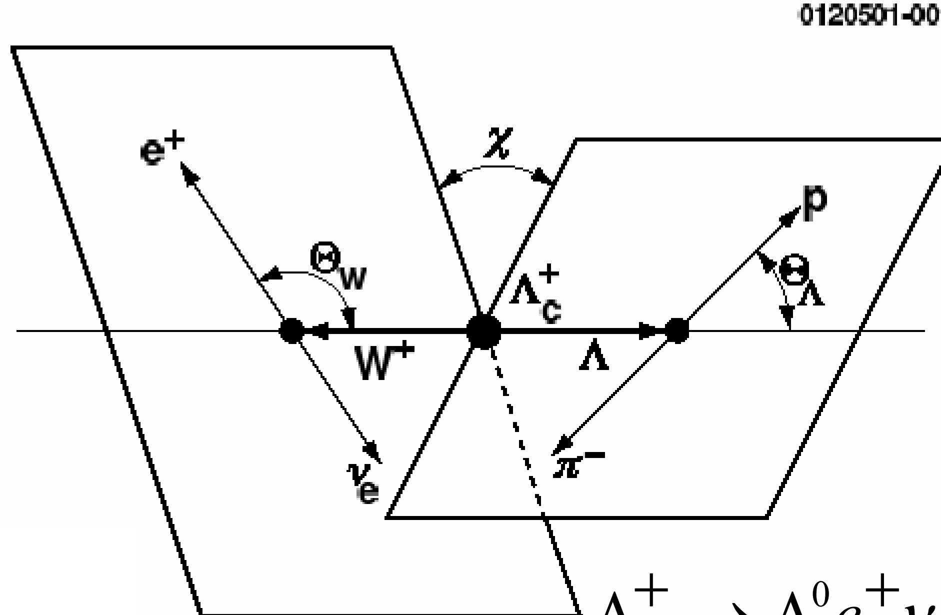
Phys.Lett.B544:89-96, 2002
hep-ex/0207049

CLEO Form Factors and CP $\Lambda_C^+ \to \Lambda^0 e^+ \nu$

Spin ½ Λ baryon adds a new wrinkle…

$$\left|\tfrac{1}{2}1\right\rangle, \left|\tfrac{1}{2}-1\right\rangle, \left|\tfrac{1}{2}0\right\rangle, \left|-\tfrac{1}{2}1\right\rangle, \left|-\tfrac{1}{2}-1\right\rangle, \left|-\tfrac{1}{2}0\right\rangle$$

Körner and Krämer use supplementary definitions for X and the lepton angle



$\Lambda_C^+ \to \Lambda^0 e^+ \nu$

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_\Lambda d\cos\theta_W d\chi} \propto$$

$$\{|H_{\left|\frac{1}{2}1\right\rangle}|^2 \left(\tfrac{3}{8}(1\pm\cos\theta_W)^2(1+\alpha_\Lambda\cos\theta_\Lambda\right)+$$

$$|H_{\left|-\frac{1}{2}-1\right\rangle}|^2 \left(\tfrac{3}{8}(1\mp\cos\theta_W)^2(1-\alpha_\Lambda\cos\theta_\Lambda\right)+$$

$$|H_{\left|\frac{1}{2}0\right\rangle}|^2 \tfrac{3}{4}\sin^2\theta_W(1+\alpha_\Lambda\cos\theta_\Lambda)+$$

$$|H_{\left|-\frac{1}{2}0\right\rangle}|^2 \tfrac{3}{4}\sin^2\theta_W(1-\alpha_\Lambda\cos\theta_\Lambda)+$$

$$\mathrm{Re}(H_{\left|-\frac{1}{2}0\right\rangle}H^*_{\left|\frac{1}{2}1\right\rangle})\alpha_\Lambda\cos\chi\sin\theta_W\sin\theta_\Lambda\tfrac{3}{2\sqrt{2}}(1\pm\cos\theta_W)+$$

$$\mathrm{Re}(H_{\left|\frac{1}{2}0\right\rangle}H^*_{\left|-\frac{1}{2}-1\right\rangle})\alpha_\Lambda\cos\chi\sin\theta_W\sin\theta_\Lambda\tfrac{3}{2\sqrt{2}}(1\mp\cos\theta_W)\}$$

One pole mass describes the decay

$$f(q^2) = \frac{f(q^2_{Max})}{1-q^2/M^2_{Pole}}(1-q^2_{Max}/M^2_{Pole})^2$$

Helicty H's made from 2 form factors:

expect $|f_1(q^2)| > |f_2(q^2)|$

spin is *sticky* $(\Lambda_B \to \Lambda_C, f_2 \approx 0)$

Integrate over variables and look at asymmetries:

(other choices possible)

$$\frac{d^2\Gamma}{dq^2 d\cos\theta_\Lambda} \propto (1+\alpha_{\Lambda_C}\alpha_\Lambda\cos\theta_\Lambda)$$

(no sign change for particle and anti-particle)

CLEO Form Factors and CP $\Lambda_C^+ \to \Lambda^0 e^+ \nu$

13.4 fb^{-1} from CLEO II and II.5

Look for Λe^+ pairs where $\Lambda \to p\,\pi^-$

$P(\nu) = ?\ \ Find\ \ P(\Lambda_C)\ direction$

- Event thrust axis for direction
- Try to close kinematics:

$$\vec{P}^{\,2}_{\Lambda_C} = (\vec{P}_\Lambda + \vec{P}_e + \vec{P}_\upsilon)^2$$

(use fragmentation to break ambg)

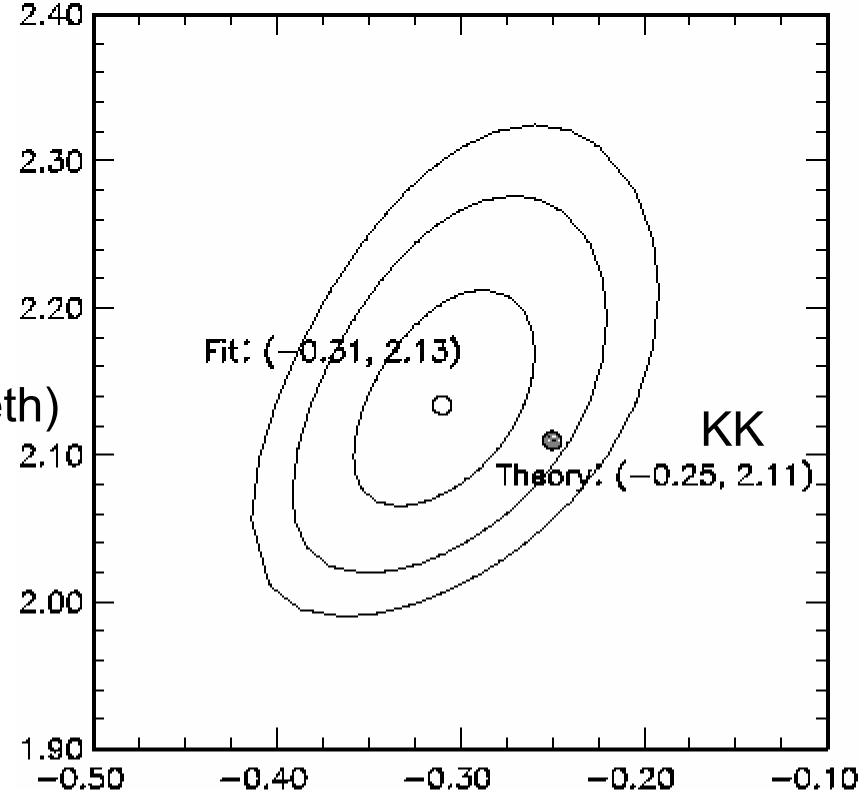
Technique: (again the Schmidt meth)

4-D r and pole mass

2-D asymmetry

Systematics:
-Background Normalizations
-Kinematic Closing
-Fitting simulation
-Efficiencies

Results: (To be sent to PRL)



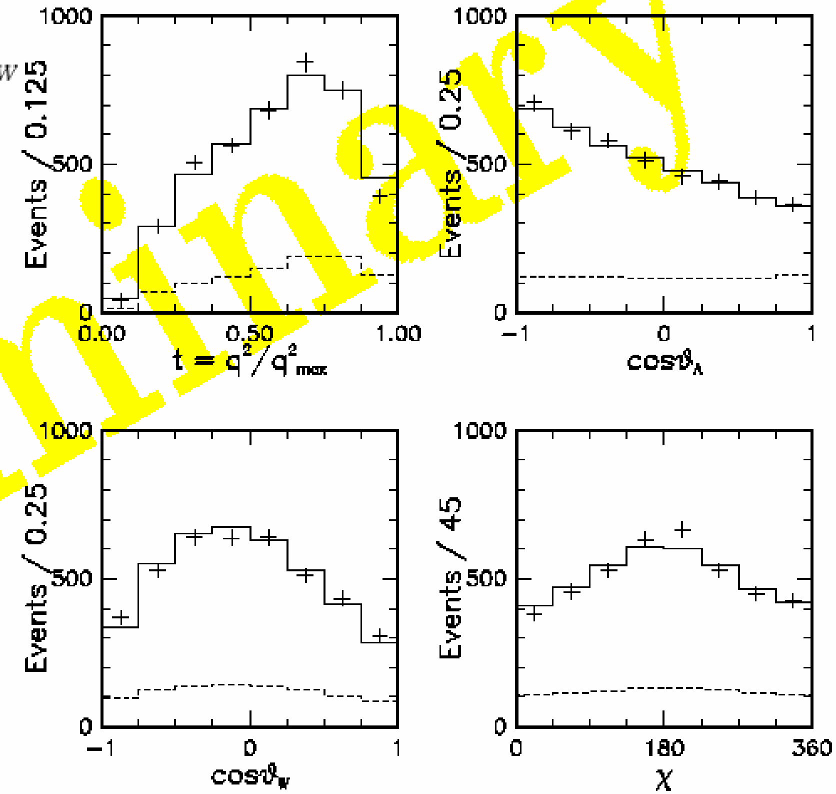
$$R = f_2 / f_1 = -0.31 \pm 0.05(stat) \pm 0.04(sys)$$

$$M_{pole} = 2.13 \pm 0.07(stat) \pm 0.10(sys)\ GeV/c^2$$

CLEO Form Factors and CP $\Lambda_C^+ \to \Lambda^0 e^+ \nu$

FF & Search for CPV in $\Lambda_c^+ \to \Lambda e^+ \nu_e$ (cont.)

- Distributions of four kinematic variables and (unbinned) fit projections ⇒



- Integrating the dif. rate over χ and $\cos\theta_W$

$$\frac{d\Gamma}{dq^2 d\cos\theta_\Lambda} \propto (1 + \alpha_{\Lambda_c^+}\alpha_\Lambda \cos\theta_\Lambda)$$

- Extract from the fit

  the decay asymmetry parameter:

  $\alpha_{\Lambda_c^+} = -0.85 \pm 0.03_{stat} \pm 0.02_{syst}$

  @ $< q^2 >= 0.67$ $(Gev/c)^2$

  for world average $\alpha_\Lambda = 0.642 \pm 0.013$

Search for CPV

- Split statistics for two charge conjugate states:

  $\alpha_{\Lambda_c^+}\alpha_\Lambda = -0.561 \pm 0.026_{stat}$

  $\alpha_{\bar{\Lambda}_c^+}\alpha_{\bar{\Lambda}} = -0.535 \pm 0.024_{stat}$

- CP asymmetry:

$$A_{\Lambda_c^+} = \frac{\alpha_{\Lambda_c^+} + \alpha_{\bar{\Lambda}_c^+}}{\alpha_{\Lambda_c^+} - \alpha_{\bar{\Lambda}_c^+}} = 0.01 \pm 0.03_{stat} \pm 0.01_{syst} \pm 0.02_{A_\Lambda}$$

Semileptonic Round-up

Very Interesting!

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

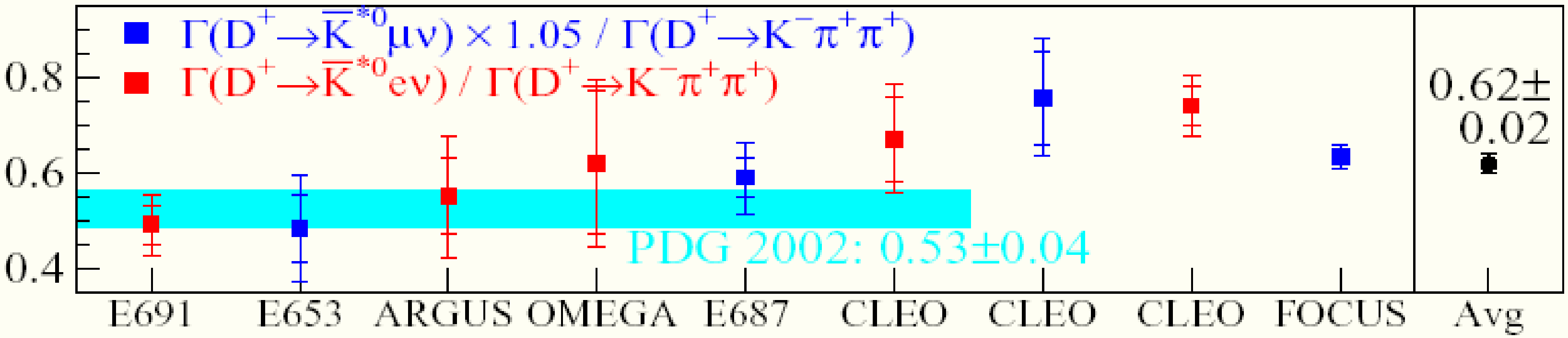
Interference effects

Need other experiments to look

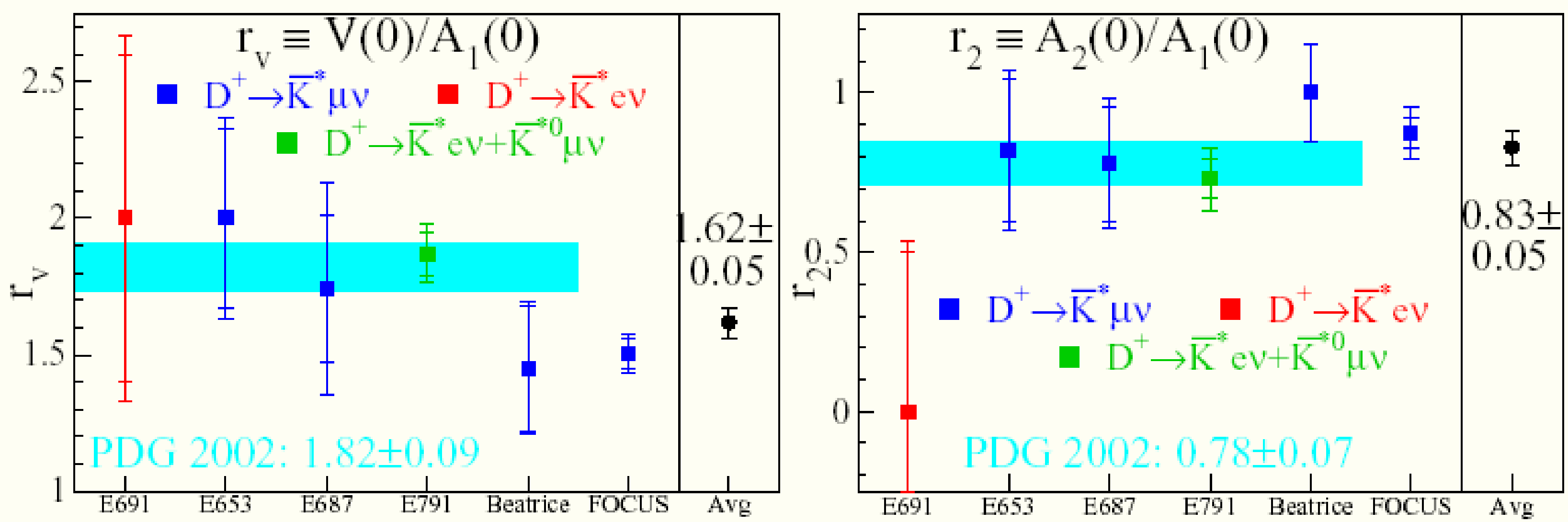
Probably more in there…

Branching ratio: (FOCUS includes effect of scalar interference)

Lowers by 5.5%



Form factors: (FOCUS includes effect of scalar interference)

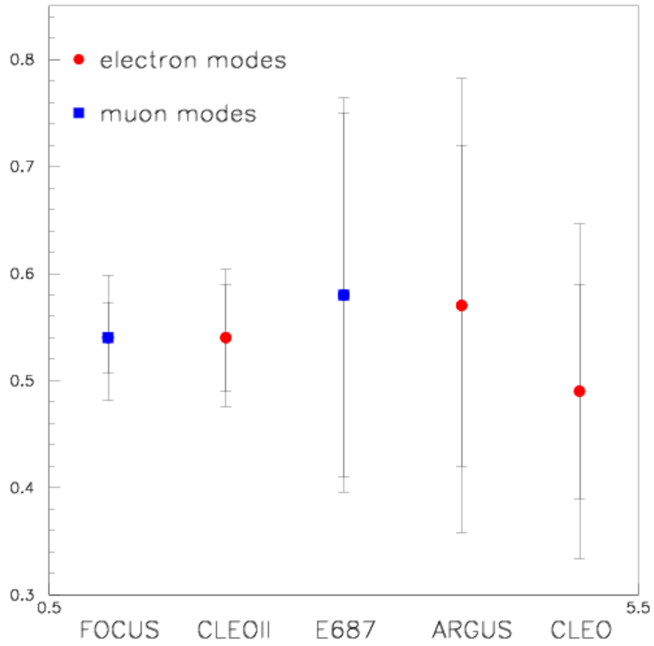


(From K. Stenson's APS review)

Semileptonic Round-up

$$\frac{\Gamma(D_S^+ \to \phi\mu^+\nu)}{\Gamma(D_S^+ \to \phi\pi^+)}$$

We all seem to agree!



$$\Lambda_C^+ \to \Lambda^0 e^+ \nu$$

No Surprises!

No CP violation

f_2 / f_1 close to expected

α_{Λ_C} Expect ~-1 from HQET

Good agreement
in the Distributions

I didn't miss 'em!

$\Omega_C^0 \to \Omega^- \ell^+ \upsilon_\ell$ BELLE (Ruslan Chistov will cover in Spectroscopy)

$D^0 \to K^{*+} e^- \nu$ CLEO (Too prelininary)

$\Omega_C^0 \to \Omega^- e^+ \upsilon_e$ CLEO (Too preliminary)

$D_S^+ \to \eta \ell \nu$ CLEO (Too prelininary)

Would be nice to measure:

$D^0 \to \pi^+ e^- \upsilon_e \, , D^0 \to K^+ e^- \upsilon_e$

$D^+ \to \overline{K}^{*0} \mu^+ \nu$ Interference effects confirmed

$D \to P \ell \upsilon / D \to V \ell \upsilon$

Rare Decays from CDF, BELLE and BARBAR