Rare D Decays (dirty and clean)

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CHARM 2007

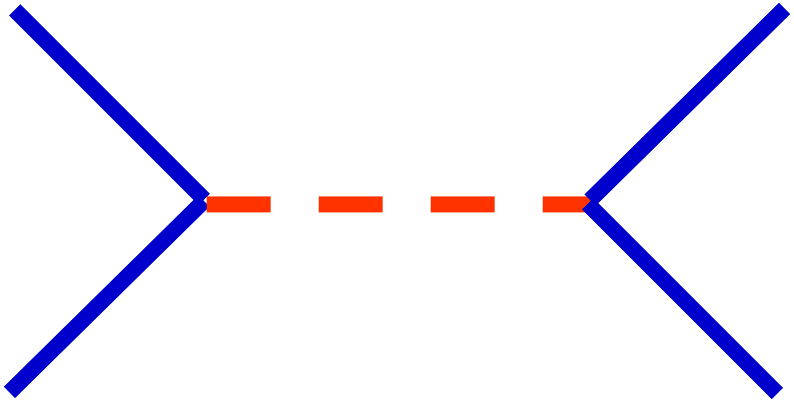
Outline

- Focus on annihilation and radiative decays
  - Highlight sensitivity to new physics
  - Point out strengths and weaknesses of different channels
- Compare to similar topologies in beauty and strange system
  - Better, worse, just different
- Contrast different techniques used in different environments
- Motivate future studies
- Try to cover almost everything in last 5 years but will put most focus on hl^+l^-

Charged Annihilation

Sensitive to tree level charged current phenomena

SM rate calculable and experimentally accessible



If you know the decay constant and CKM element you can limit new phenomena

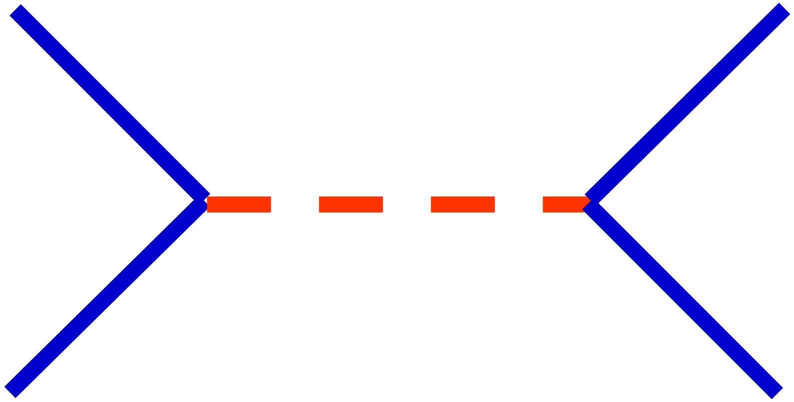
If you don't find any, you can make precise measurements of SM parameters

Charged Annihilation: B vrs D

Beauty:

3rd generation so very sensitive to high tanβ SUSY/ 2HDM…

Sensitivity limited by errors in V_{ub}, f_B + *stats*



Charm:

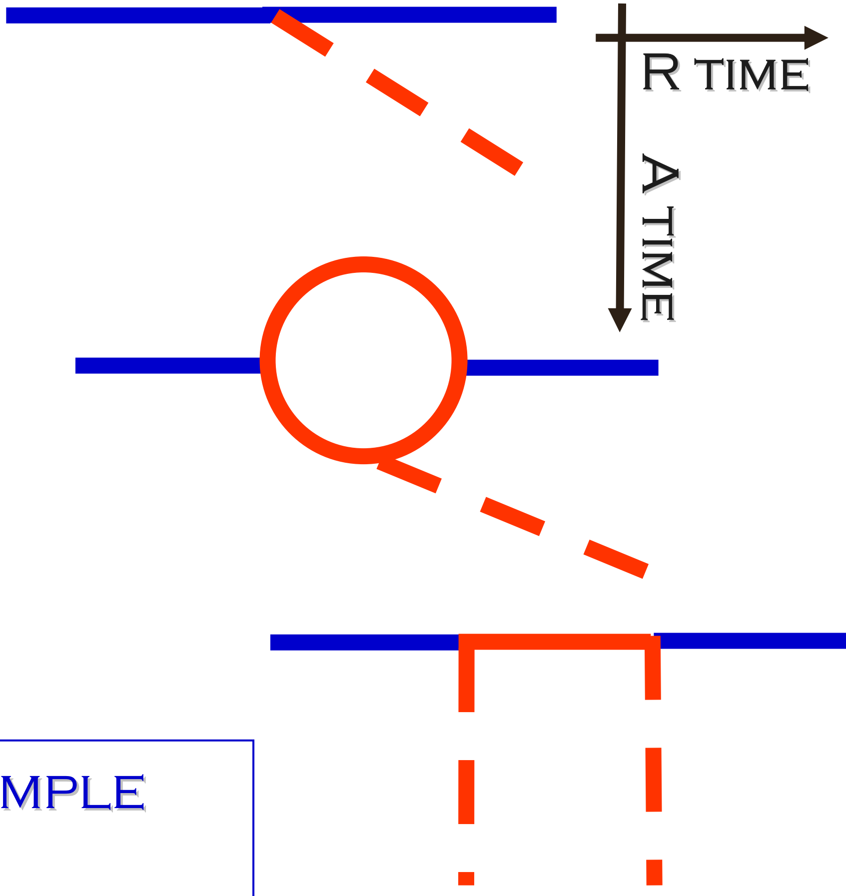
In some cases, not even a rare decay

Not as sensitive to 'favored' new phenomena models

$\tau\nu$ and $\mu\nu$ accessible

Ratios provide clean test of models that don't preserve lepton universality

Radiative (and neutral annihilation)



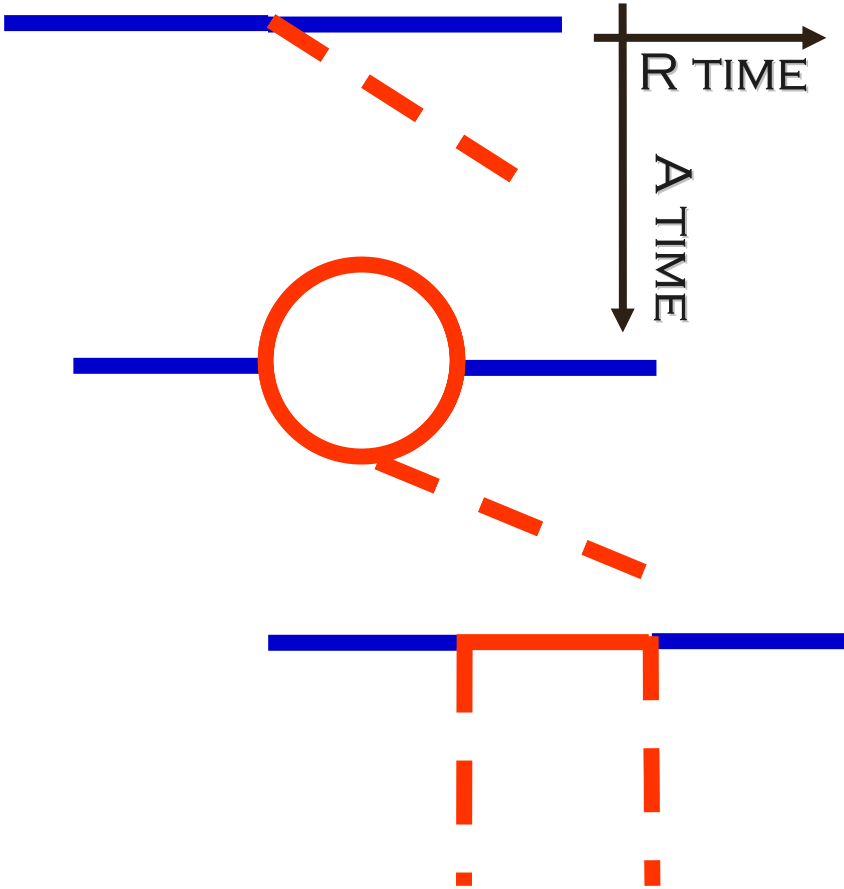
- Sensitive to tree level neutral current phenomena or anything that fits in a loop or box
- SM rate suppressed in all cases

- SM calculations range from simple to impossible.
- Completely different for different flavors

Rad and Neutral A: B, D, K

Radiative:

- Beauty
  - Precision: theory and exp.
- Strange
  - Precision theory, exp in reach
  - Lower SN rate = grater sensitivity
- Charm
  - Theory = long distance
  - Existing measurements beautiful but…

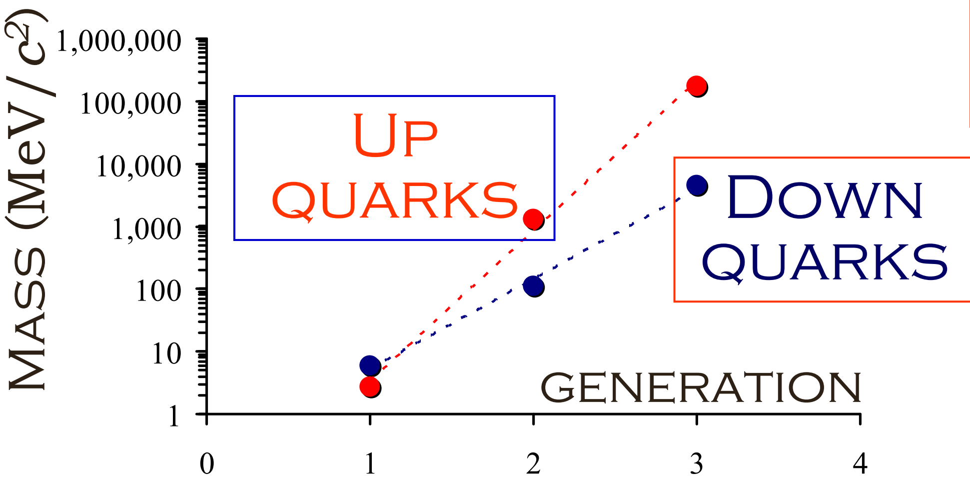


Neutral Annihilation:

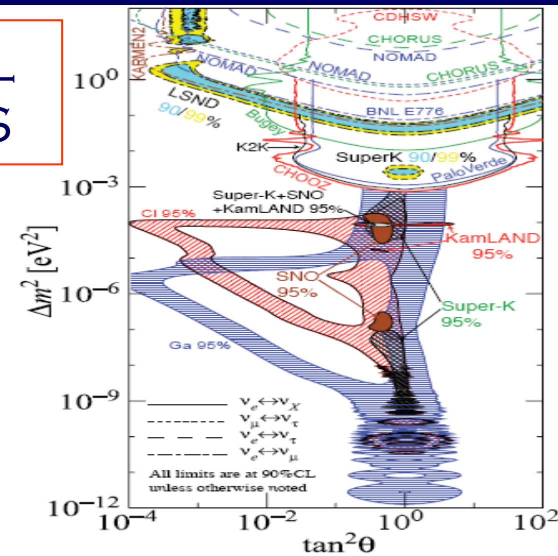
Almost all NP param space limited by exp measurements

Better limit = better physics (!)

What is the SM telling us?



Neutral leptons



SM cares about flavor and charge. How can BSM not?

$V_{\rm CKM}$ = Down quarks

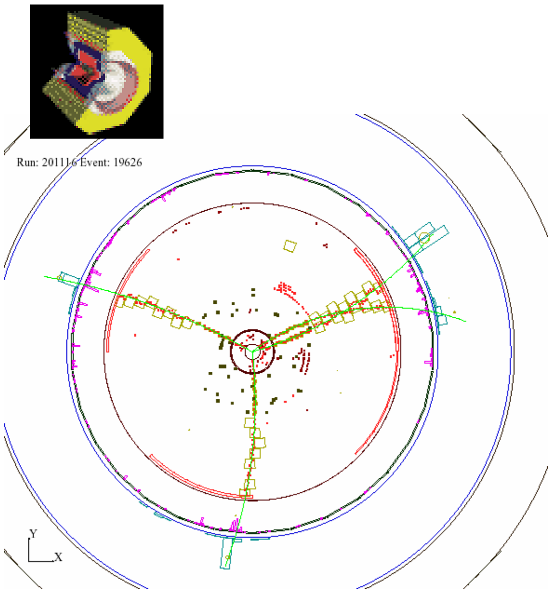
$$\begin{pmatrix} 0.97383^{+0.00024}_{-0.00023} & 0.2272^{+0.0010}_{-0.0010} & (3.96^{+0.09}_{-0.09}) \times 10^{-3} \\ 0.2271^{+0.0010}_{-0.0010} & 0.97296^{+0.00024}_{-0.00024} & (42.21^{+0.10}_{-0.80}) \times 10^{-3} \\ (8.14^{+0.32}_{-0.64}) \times 10^{-3} & (41.61^{+0.12}_{-0.78}) \times 10^{-3} & 0.999100^{+0.000034}_{-0.000004} \end{pmatrix}$$

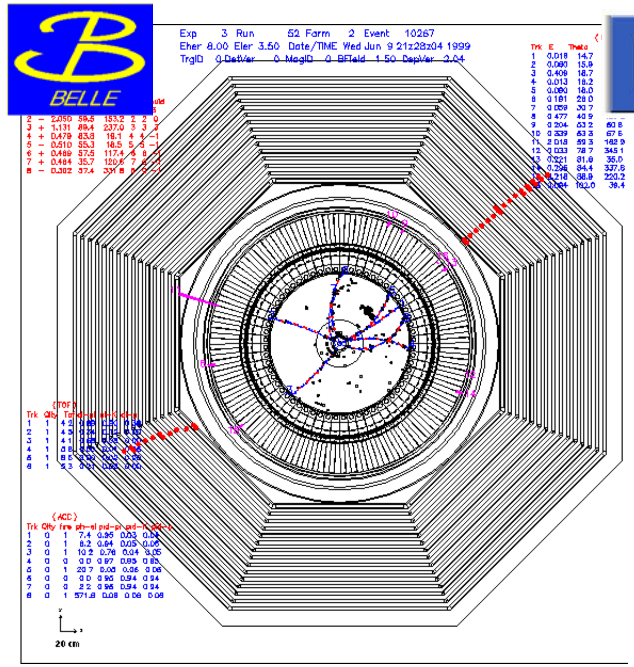
Up quarks

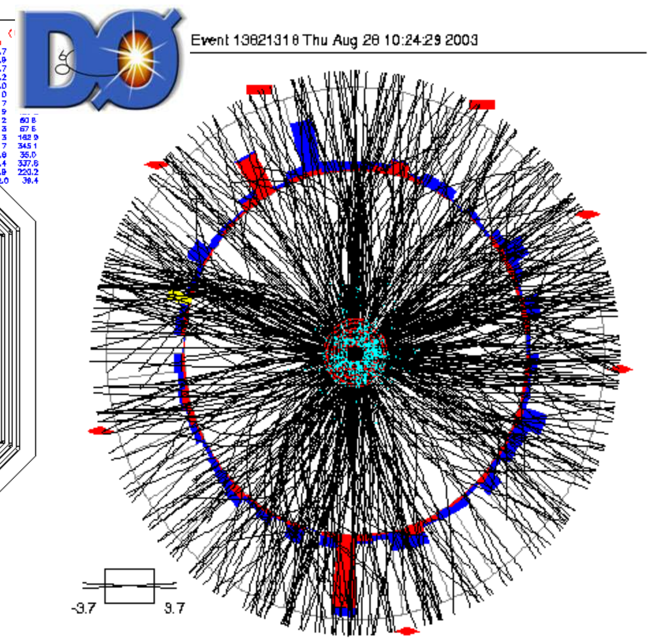
$$V_{???} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Charged leptons

Different Environments







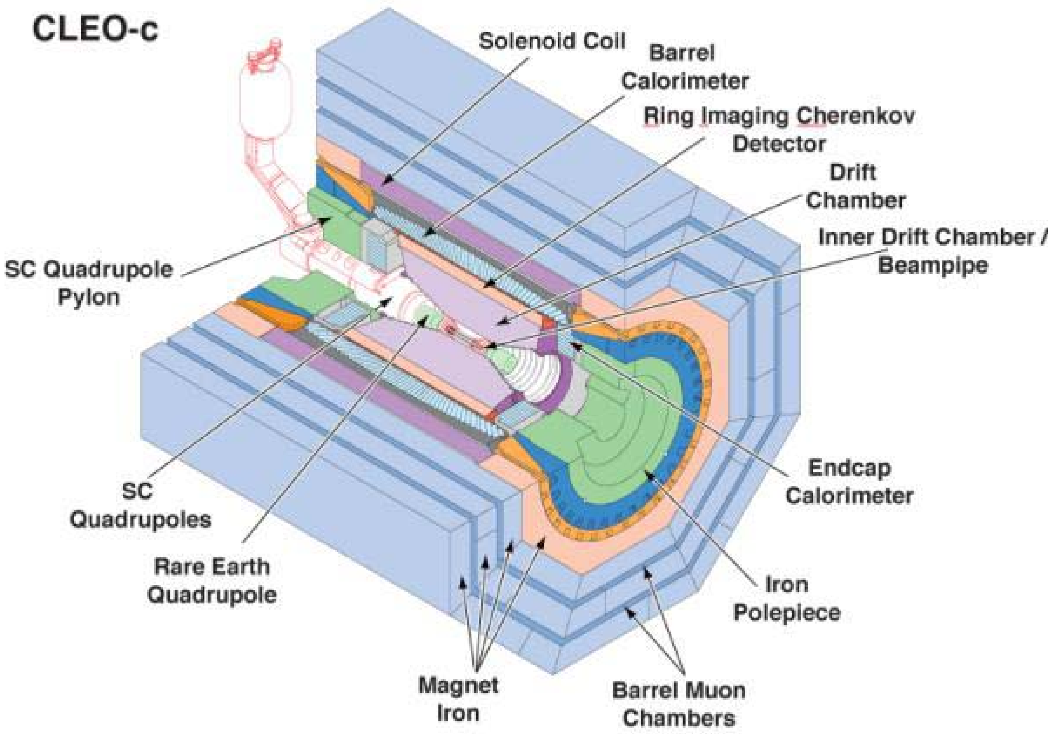
e^+e^- at threshold
Average
~5 tracks / evt

e^+e^- above threshold
Average
~10 tracks / evt

Tevatron
Average
~50 tracks / int.
Up to 10 int/evt

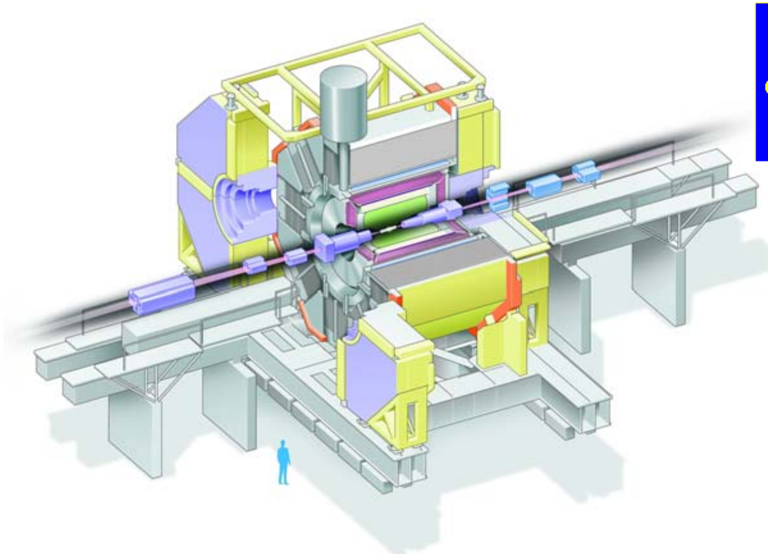
Threshold: CLEO-c

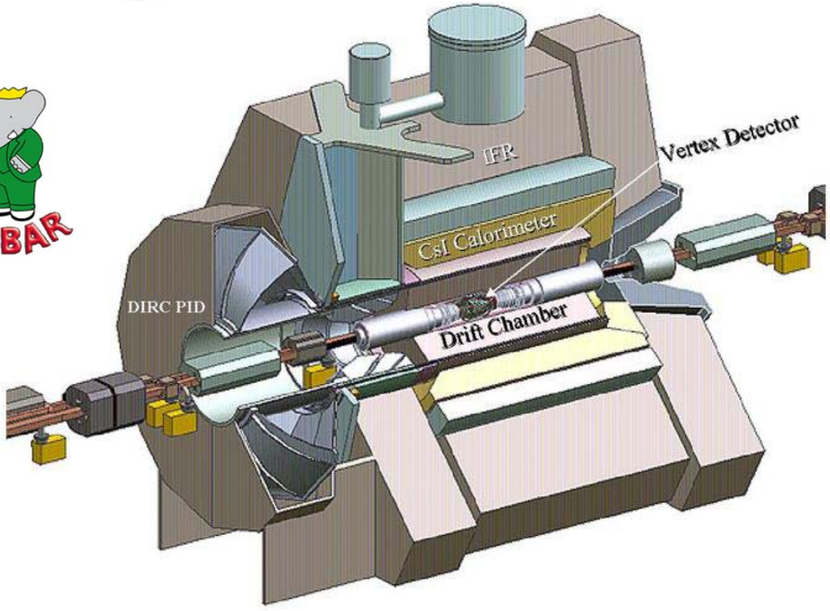
- Very clean
- Beam constraints
- Double tags
- Now enough data for competitive rare decay studies



4S: Belle & BaBar

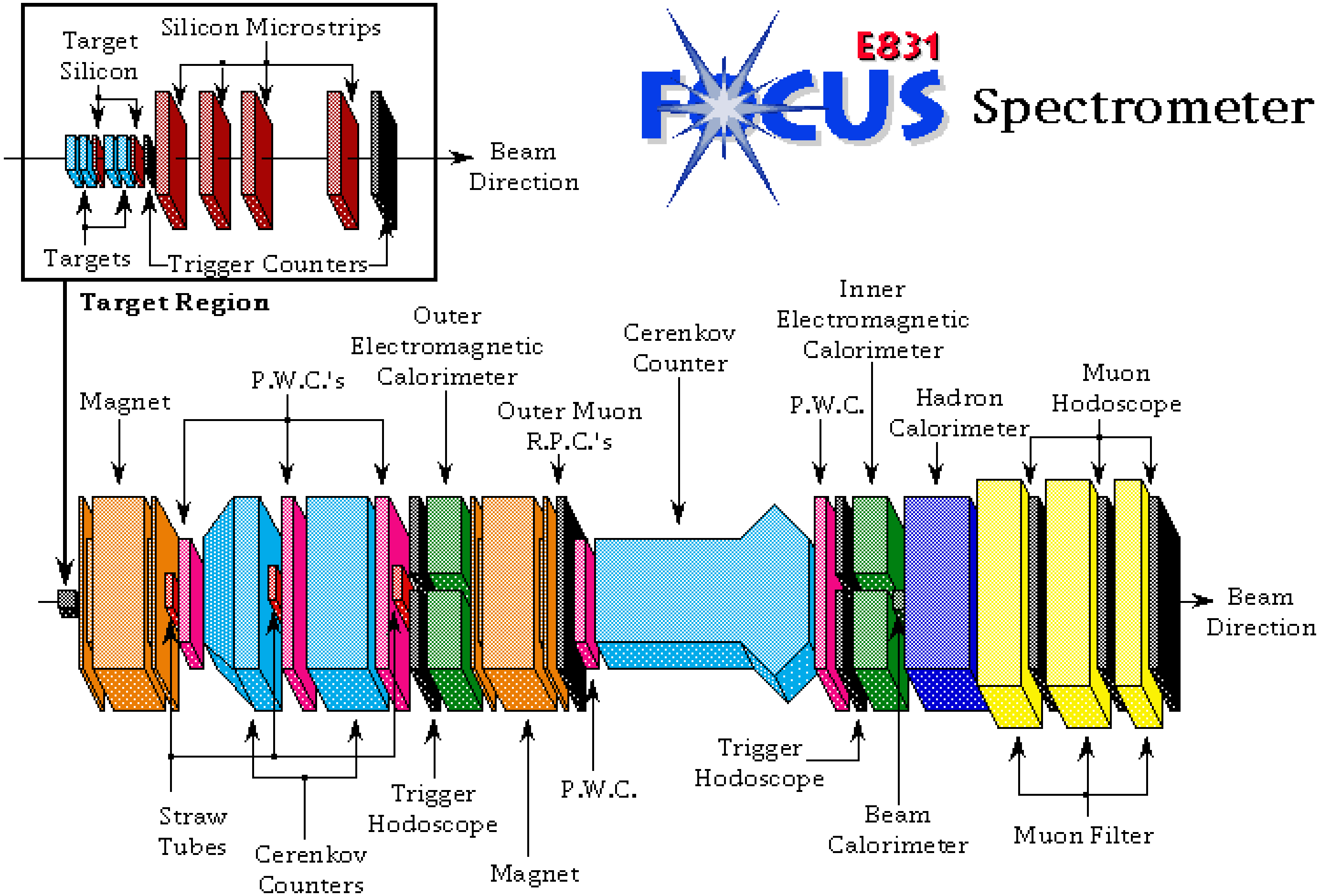
- Still pretty clean
- Excellent PID
- All charmed hadron species accessible
- Enormous data sets and still growing





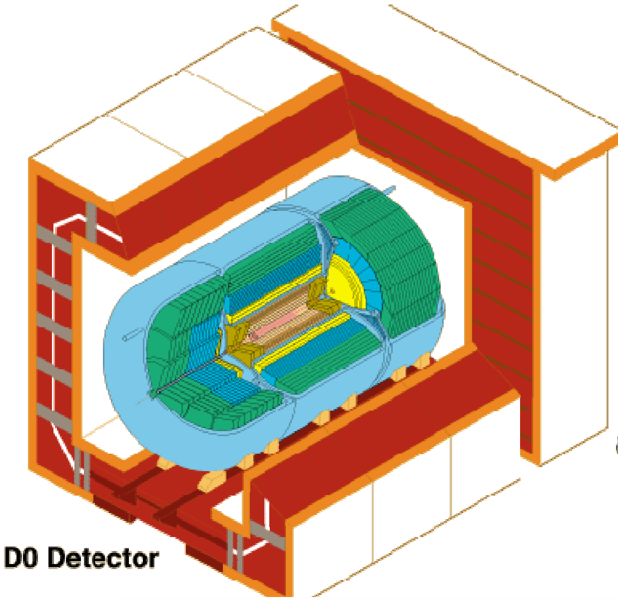
Fixed Target: FOCUS

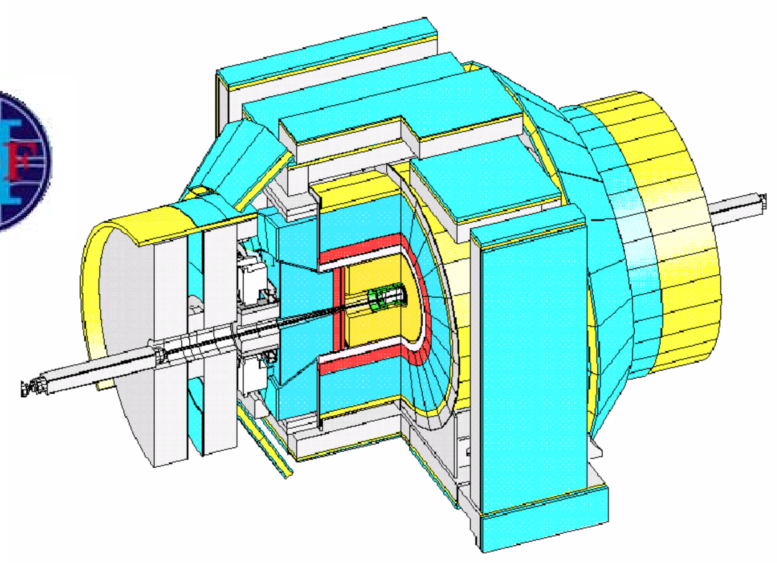
- Large boost, all species available. Dedicated experiment



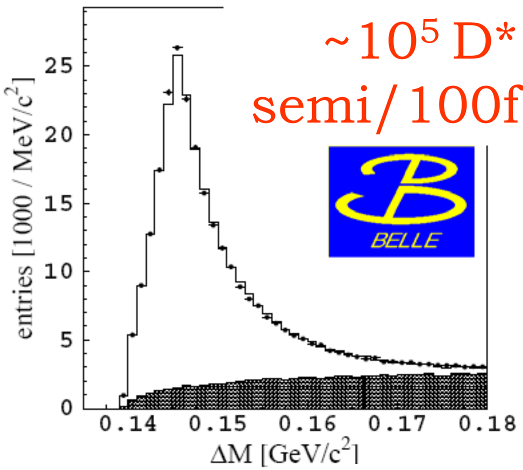
Energy Frontier: DØ & CDF

- Enormous cross-sections
- Large boost
- All species available
- Good dimuon triggers
- Lots of data and collecting much more

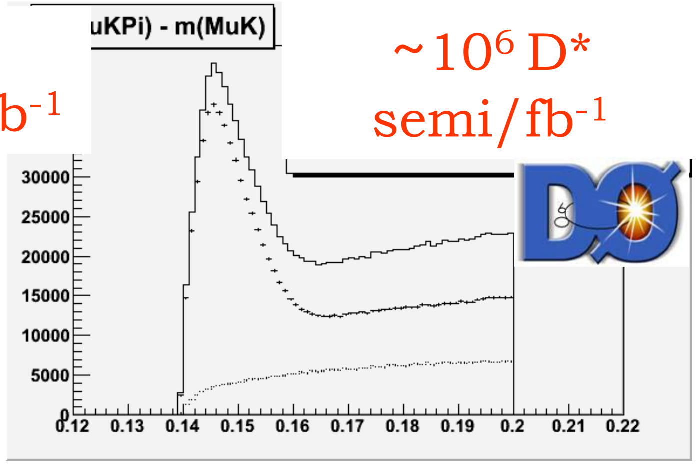




Some comparisons



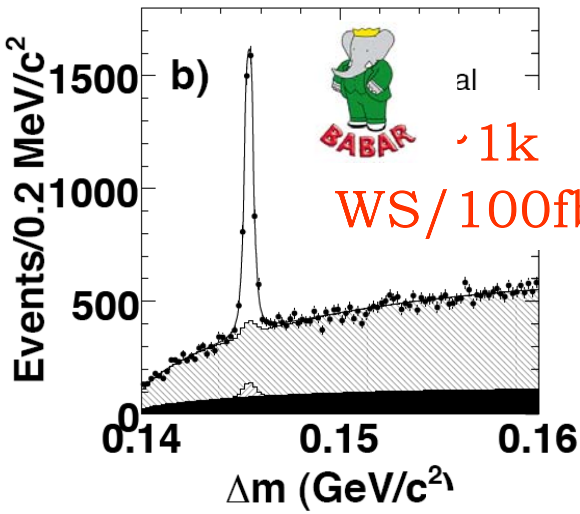
~10^5 D* semi/100fb^{-1}



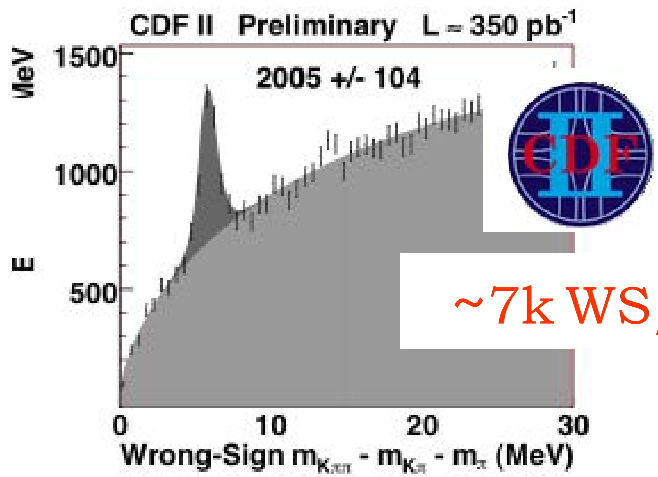
~10^6 D* semi/fb^{-1}

A ton of data at the Tevatron waiting for you!

m(Kπμ) – m(Kπ)



~1k WS/100fb^{-1}



~7k WS/fb^{-1}

m(Kππ) – m(Kπ)

Charged Leptonic Decays

- New this summer: Belle $D_s \to \mu\nu$
  - Covered in detail tomorrow by Laurenz Widhalm

$$B(D_s \to \mu\nu) = (6.44 \pm 0.76 \pm 0.52) \times 10^{-3}$$

Belle preliminary

- My combination PDG'06, Belle, BaBar 07, Cleo-c 07:

$$B(D_s \to \mu\nu) = (6.25 \pm 0.49) \times 10^{-3}$$

- Now measured to ~8%
  - ~37% error in $B \to \tau\nu$

NP Limits?

Ratio: $$\frac{\Gamma(D_s \to \tau\nu)}{\Gamma(D_s \to \mu\nu)} = \frac{m_\tau^2}{m_\mu^2} \times \frac{\left(m_{D_s}^2 - m_\tau^2\right)^2}{\left(m_{D_s}^2 - m_\mu^2\right)^2}$$

My comb: $$B(D_s \to \tau\nu) = (7.28 \pm 1.00)\%$$

Exp/theory $\tau\nu/\mu\nu$: $$R\left({}^{\tau\nu}\!/\!{}_{\mu\nu}\right) = 0.73 \pm 0.12$$

Exp/theory $B \to \tau\nu$: $$R\left(B \to \tau\nu\right) = 0.9 \pm 0.4$$

Carena++ hep-ph/0704.1143 + UTFIT

Exp/theory $B \to D^*\tau\nu$: $$Order(30\%)$$

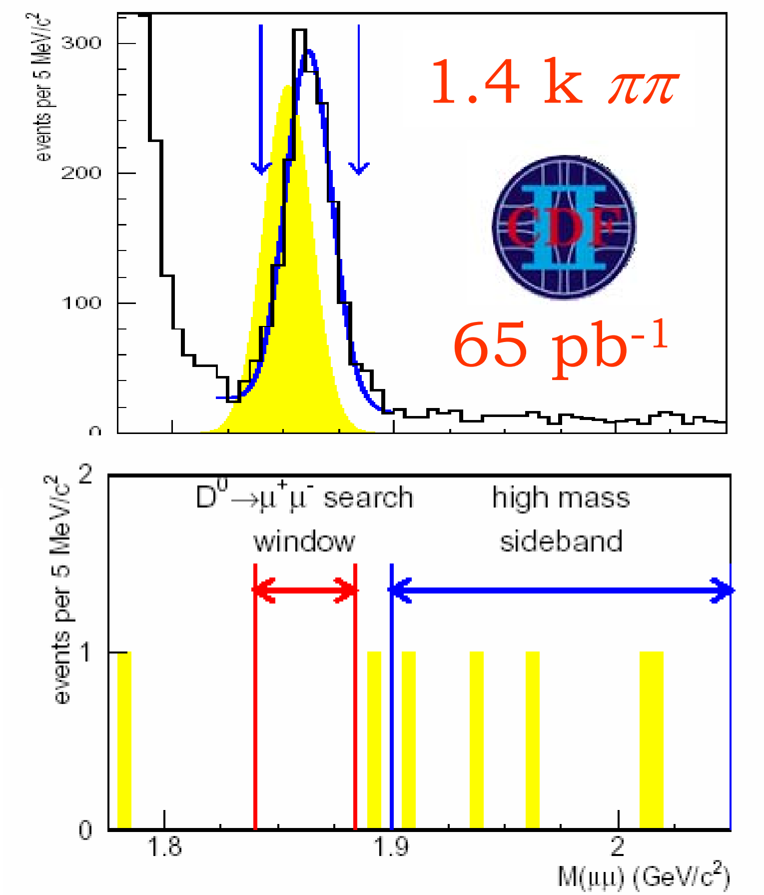
Precision looking for a theory

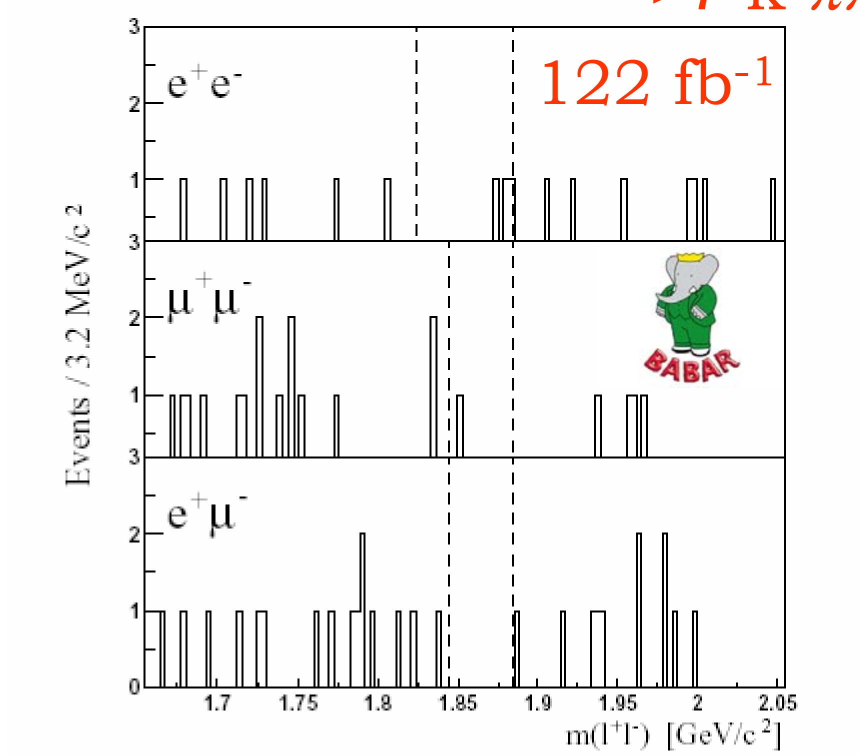
Neutral Leptonic Decays

Normalize to, then veto D* tagged $\pi\pi$.

Fakes measured with D* tagged $K\pi$

>7 k $\pi\pi$





$$B(D \rightarrow \mu^+\mu^-) < 2.5\times10^{-6}$$

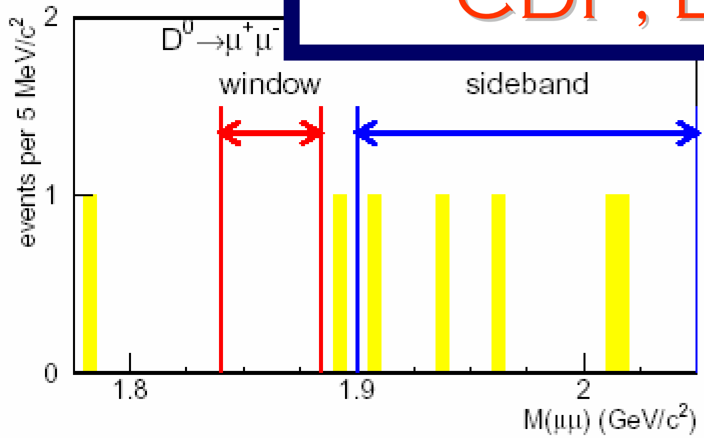
$$B(D^0 \rightarrow \mu^+\mu^-) < 1.3\times10^{-6}$$

$$B(D^0 \rightarrow e^+e^-) < 1.2\times10^{-6}$$

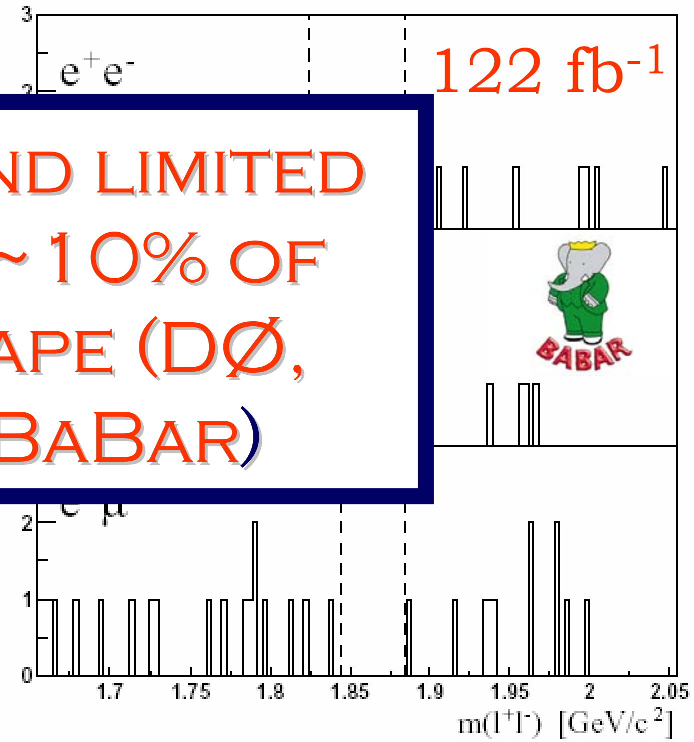
Neutral Leptonic Decays

Normalize to, then veto D* tagged $\pi\pi$.

Fakes measured with D* tagged $K\pi$



>7 k $\pi\pi$



Not background limited and based on ~10% of the data on tape (DØ, CDF, Belle, BaBar)

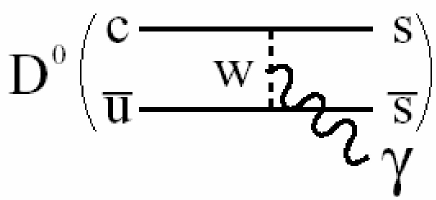
$$B(D \to \mu^+\mu^-) < 2.5\times10^{-6}$$

$$B(D^0 \to \mu^+\mu^-) < 1.3\times10^{-6}$$

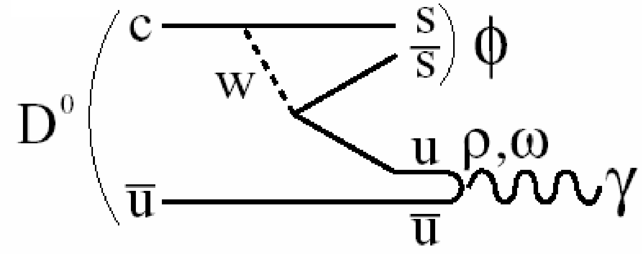
$$B(D^0 \to e^+e^-) < 1.2\times10^{-6}$$

2-Body Radiative

Short distance

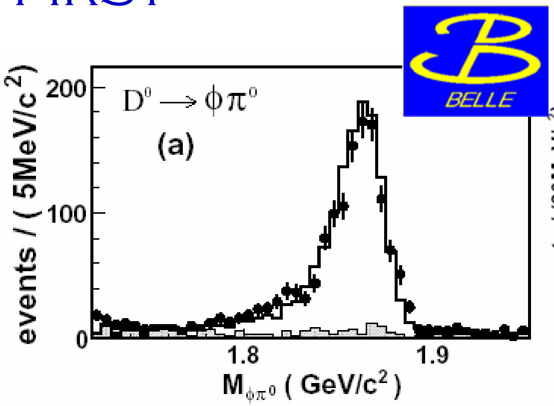


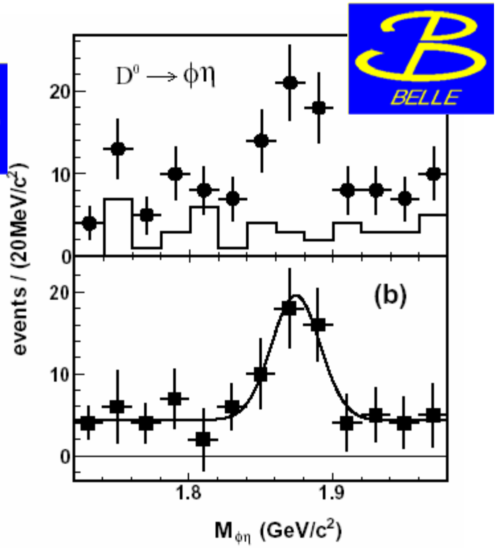
Long distance

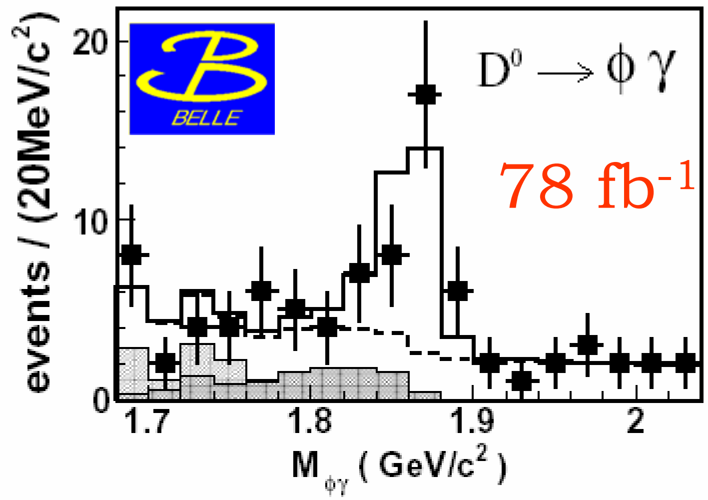


$$B(D^0 \to \phi\gamma) = (2.60^{+0.70+0.15}_{-0.61-0.17}) \times 10^{-5}$$

Peaking backgrounds not measured so measure them first



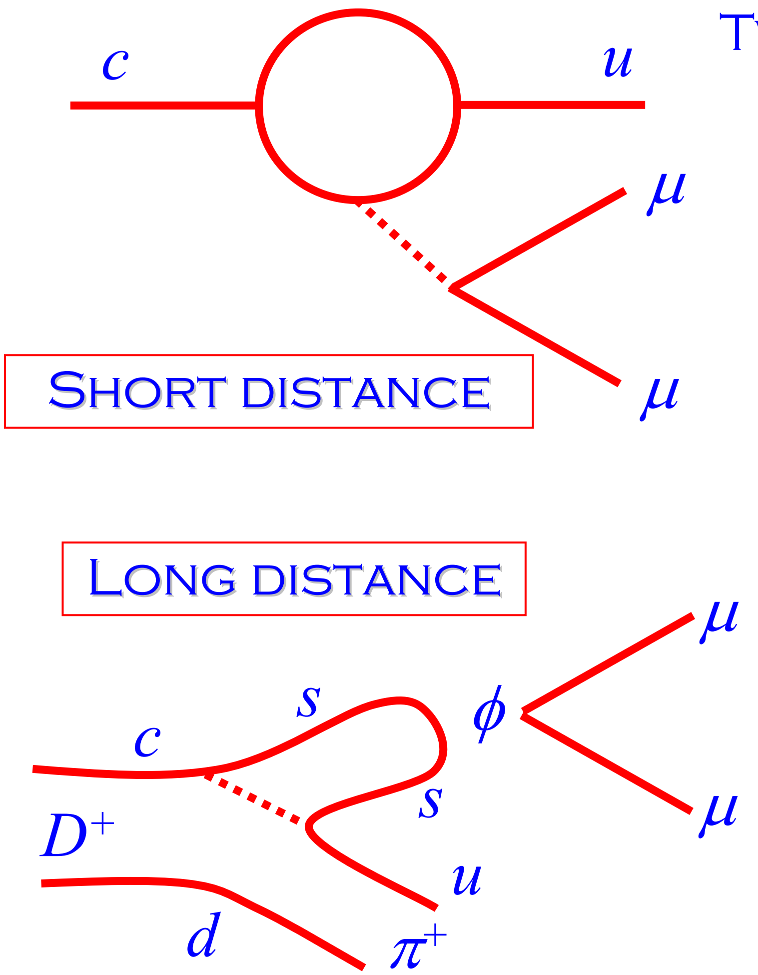


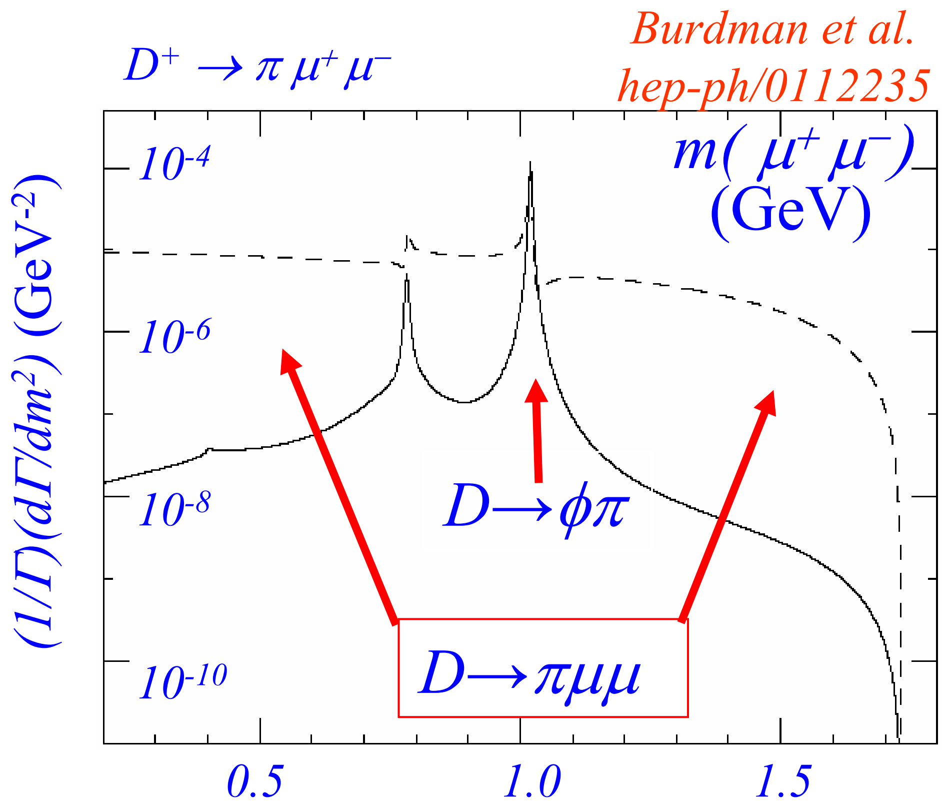


First radiative charm decay

2 vrs 3 body radiative

Two processes: Long distance (strong scale), short distance (weak scale)

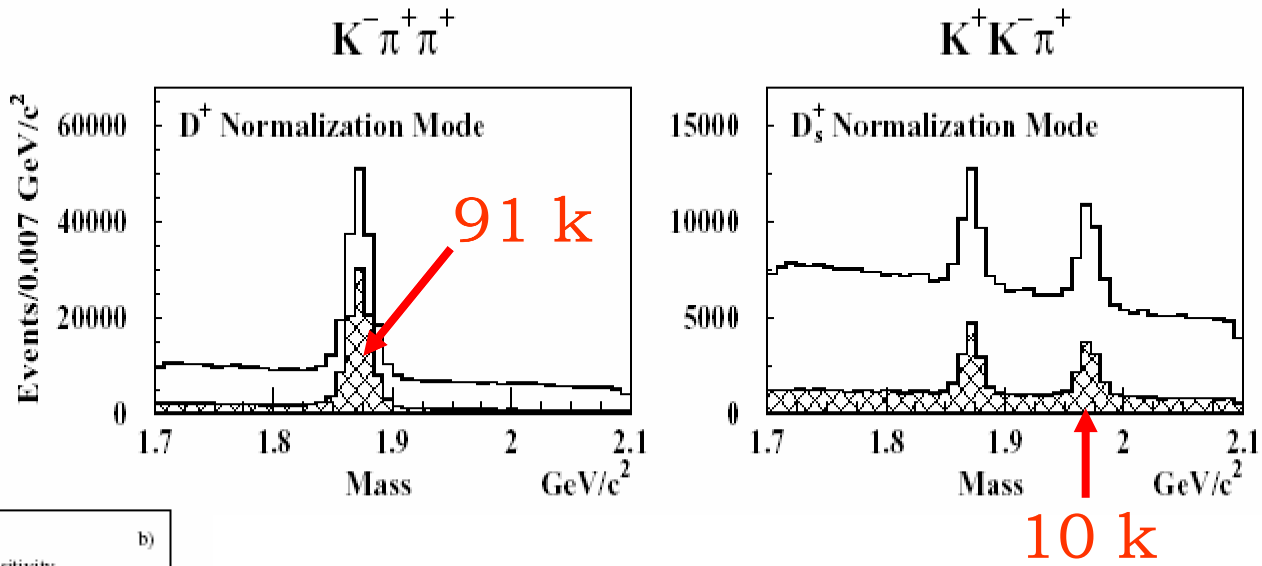


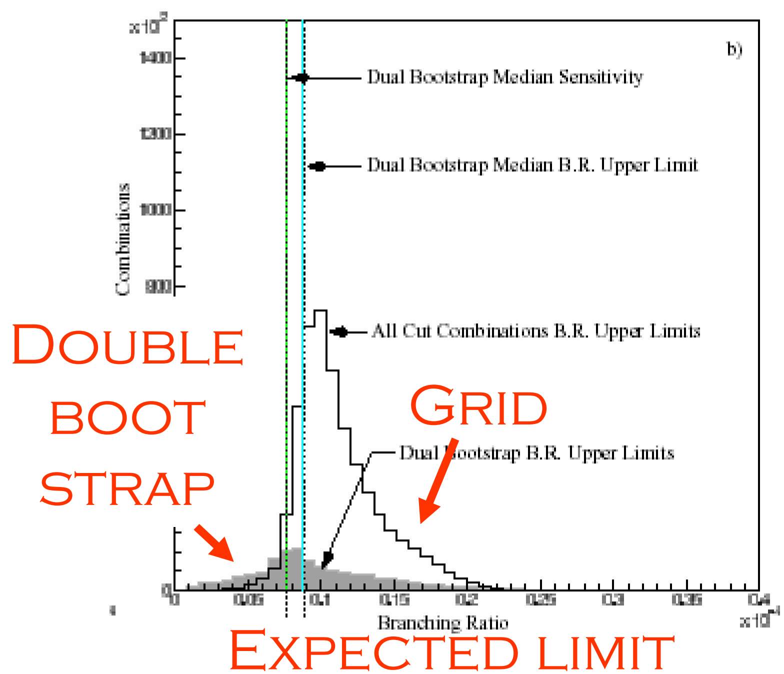


Clear separation of long distance and short distance components

Focus

1996-1997 fixed target run data



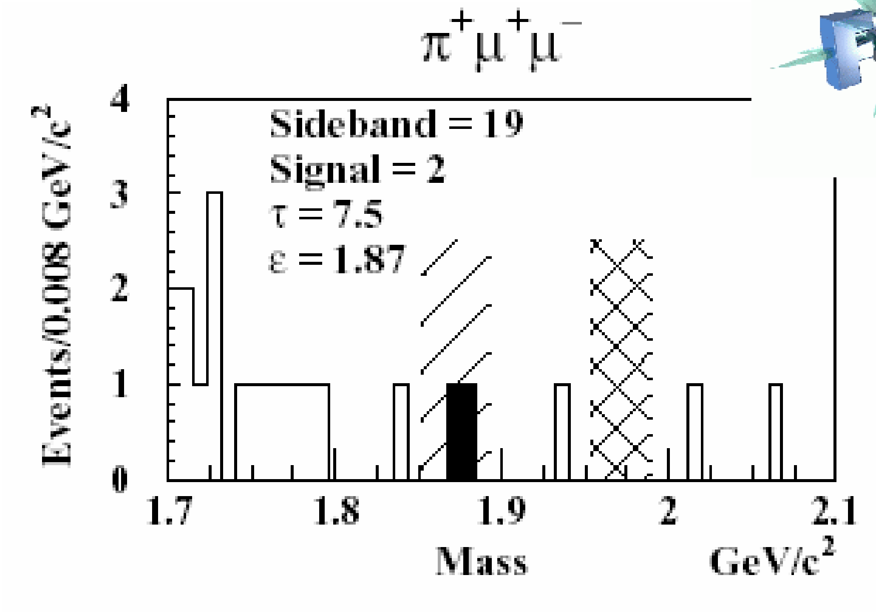


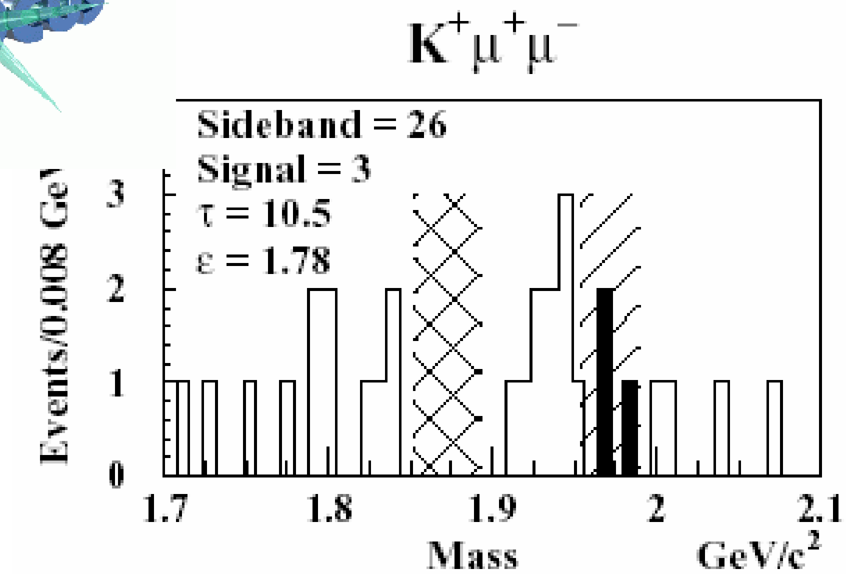
Background reduction takes advantage of very large boost

Good PID system to separate modes

Lots of effort into getting very best limit out

Focus results





$$B(D^+ \rightarrow \pi^+\mu^+\mu^-) < 8.8\times10^{-6}$$

$$B(D_s^+ \rightarrow K^+\mu^+\mu^-) < 36\times10^{-6}$$

Also several forbidden decay channel results in backup

Number to beat for B factories and Tevatron

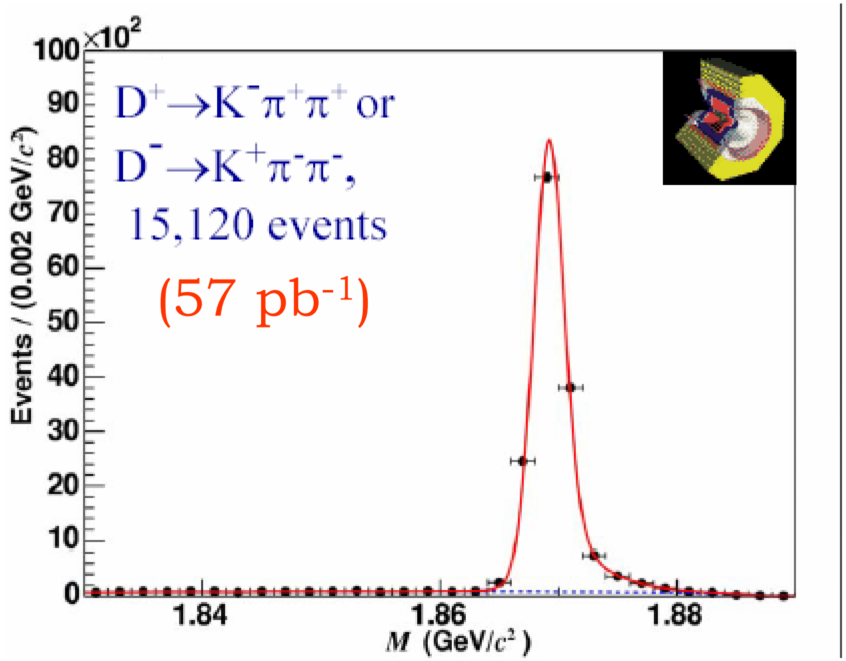
Cleo-c

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

1.6 million $D^{\pm}$

Use beam kinematics

Double semileptonics removed with missing energy type vetos

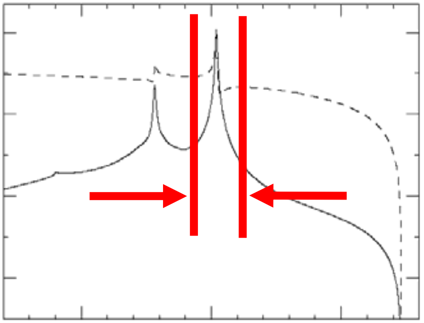


Focus on the di-electron mode

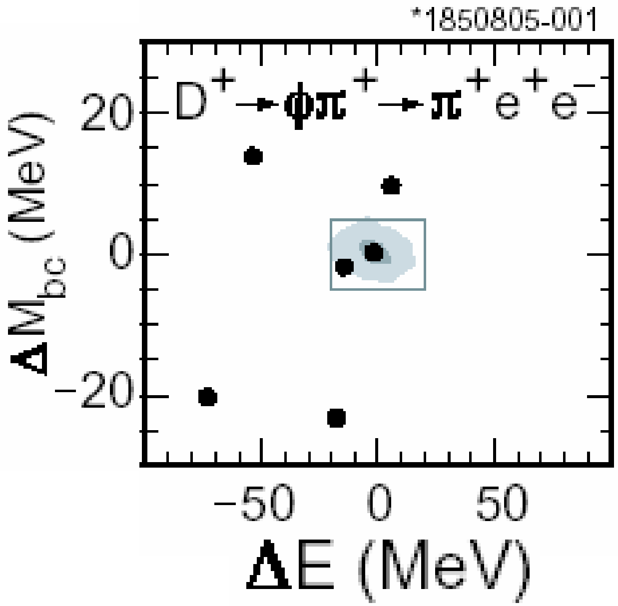
~0.1% fakes from peaking backgrounds

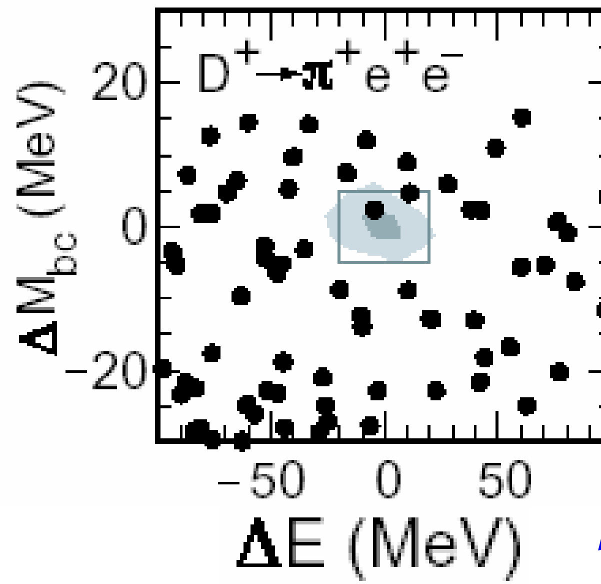
Absolute BF measurement

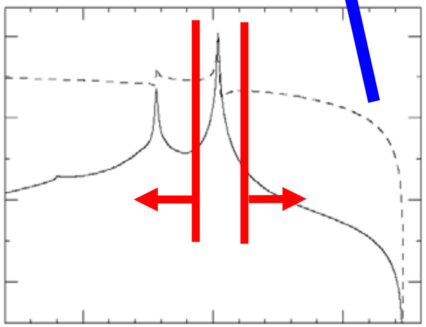
Cleo-c results



$m(e^+e^-)$







$m(e^+e^-)$

$$B(D^+ \to \pi^+\phi \to \pi^+e^+e^-) = (2.7^{+3.6}_{-1.8} \pm 0.2)\times 10^{-6}$$

$$B(D^+ \to \pi^+e^+e^-) < 7.4\times 10^{-6}$$

BaBar

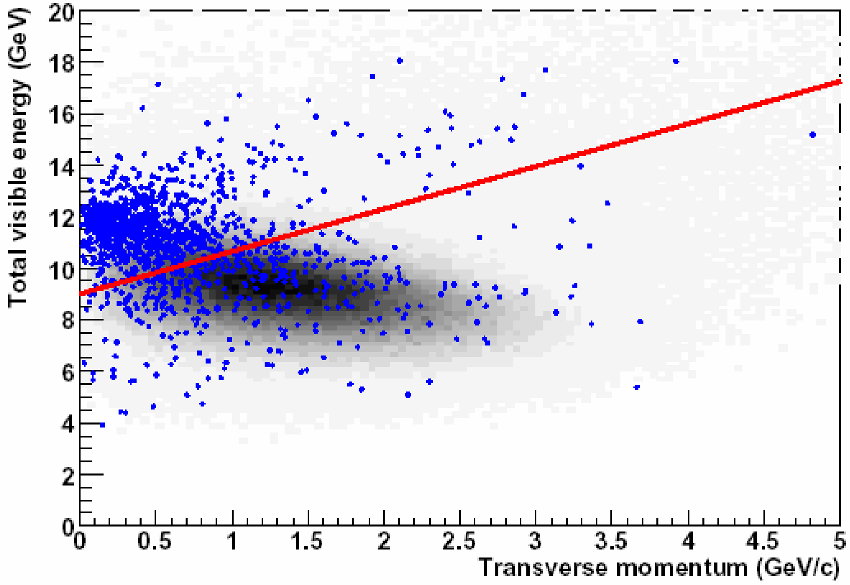
288 fb^{-1}

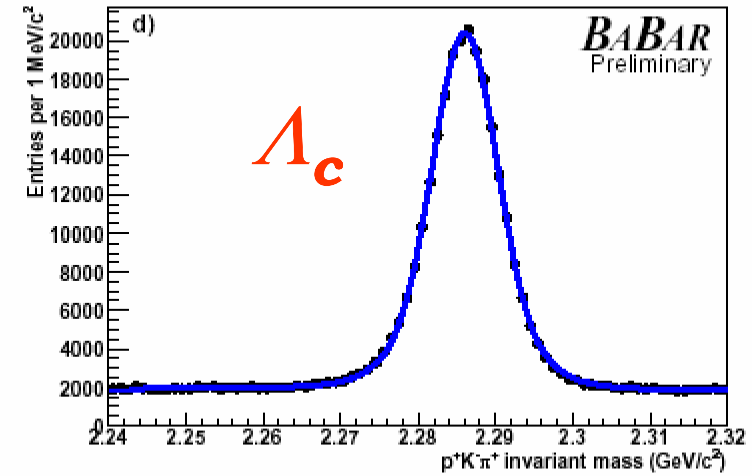
Very similar to CLEO approach

Select continuum D's to be able to make missing energy vetos

Expanded to include all hadron species and both di-electrons and di-muons

2-D Missing energy veto





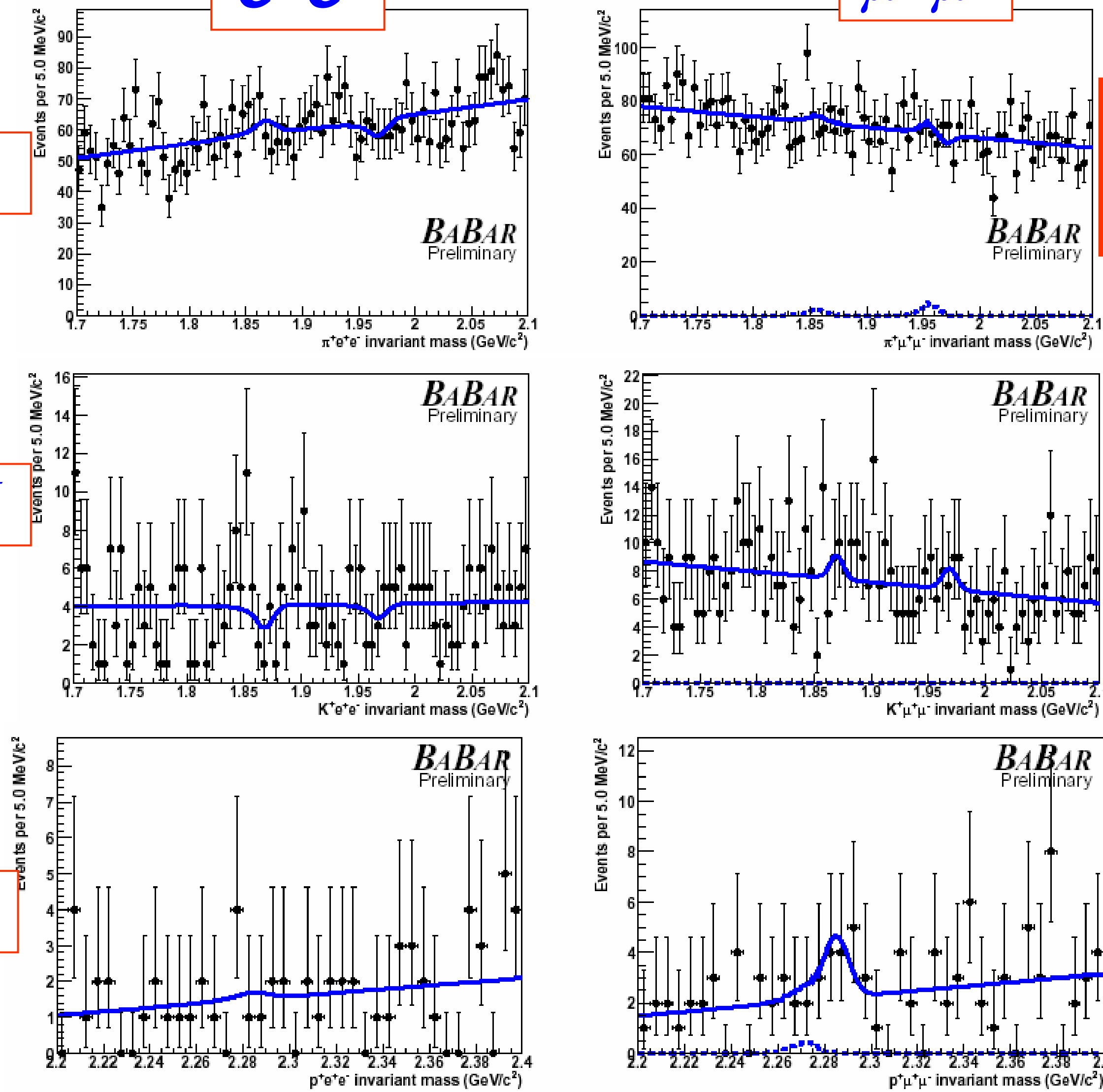
BaBar results

e^+e^- | $\mu^+\mu^-$

π

K

p

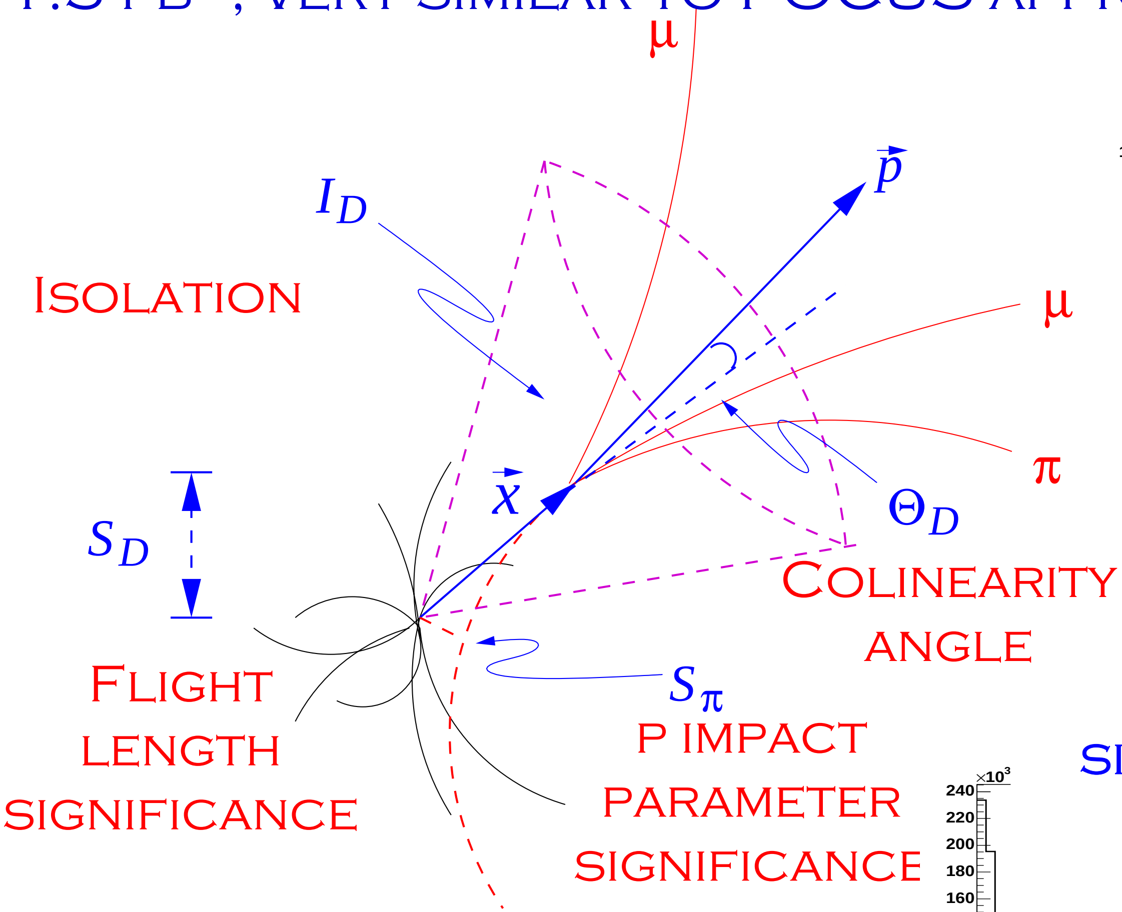


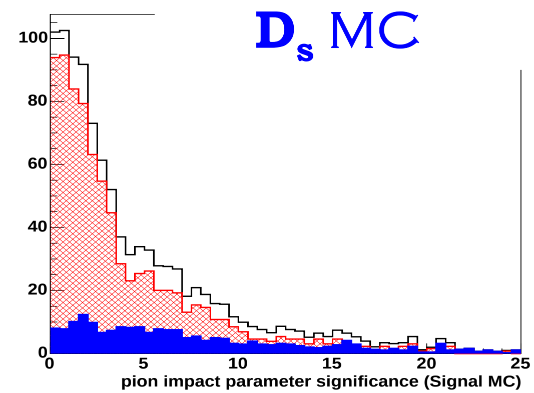
$$B(D^+ \to \pi^+ e^+ e^-) < 11.2\times10^{-6}$$
$$B(D^+ \to \pi^+ \mu^+ \mu^-) < 24.4\times10^{-6}$$

$$B(D_s^+ \to K^+ e^+ e^-) < 11.2\times10^{-6}$$
$$B(D_s^+ \to K^+ \mu^+ \mu^-) < 6.6\times10^{-6}$$

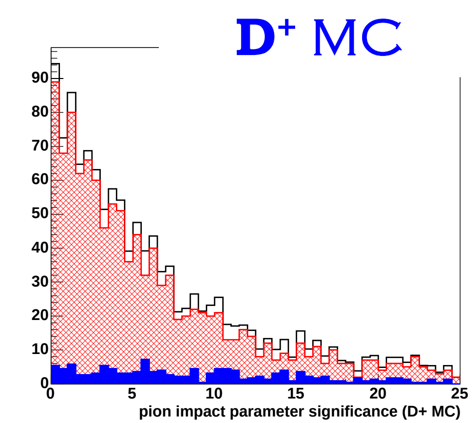
$$B(\Lambda_c \to p e^+ e^-) < 3.6\times10^{-6}$$
$$B(\Lambda_c \to p \mu^+ \mu^-) < 40.4\times10^{-6}$$

1.3 fb^{-1}, very similar to FOCUS approach

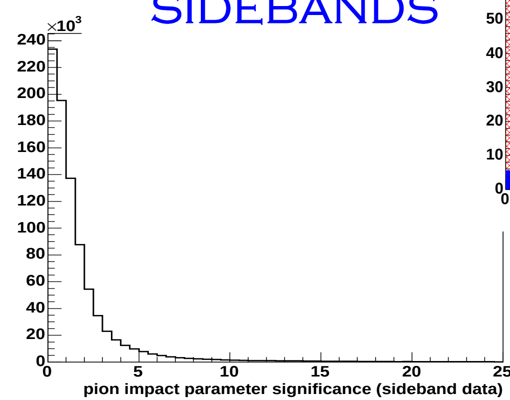




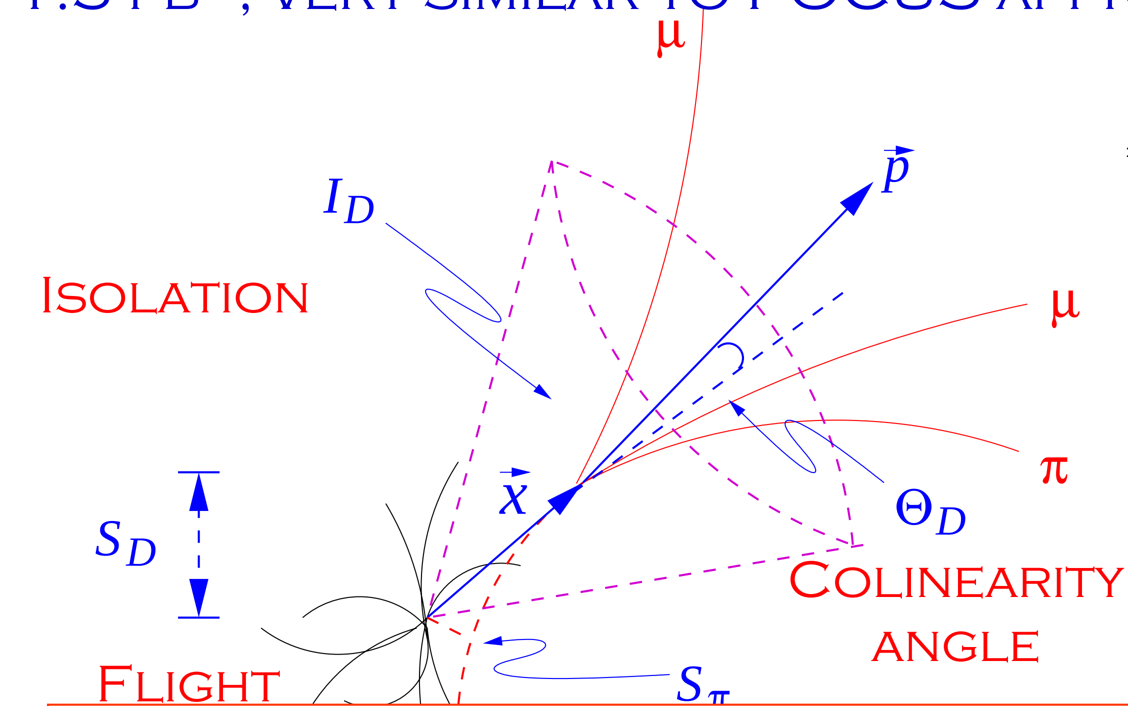
S_π

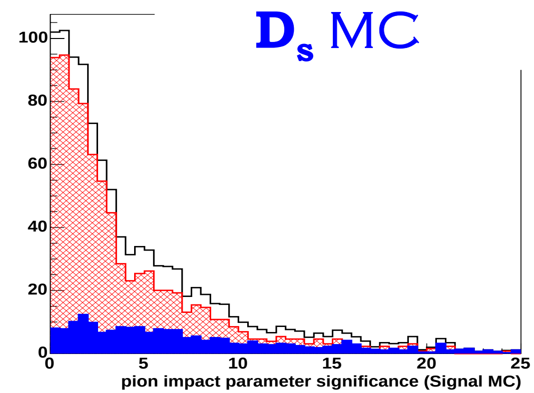


data
sidebands

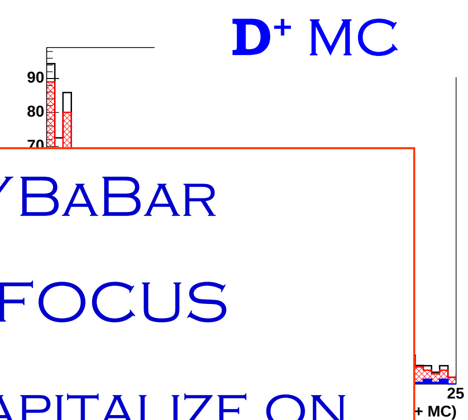


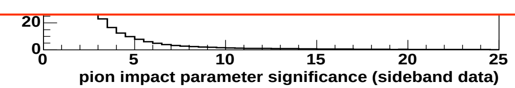
1.3 fb^{-1}, very similar to FOCUS approach





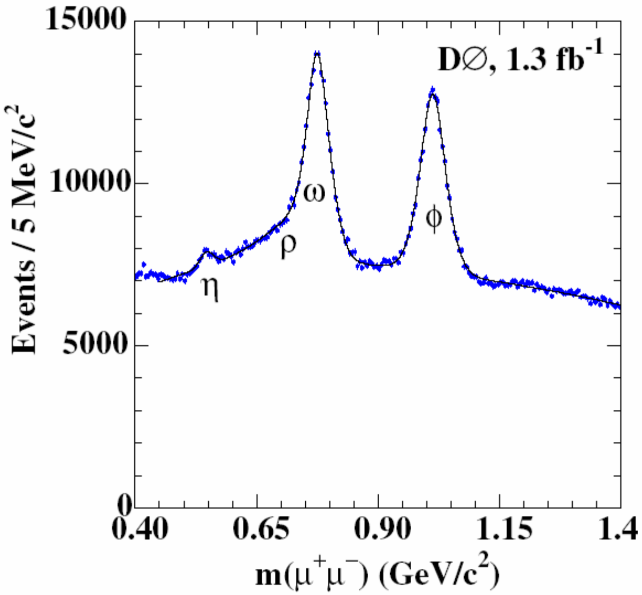
S_π

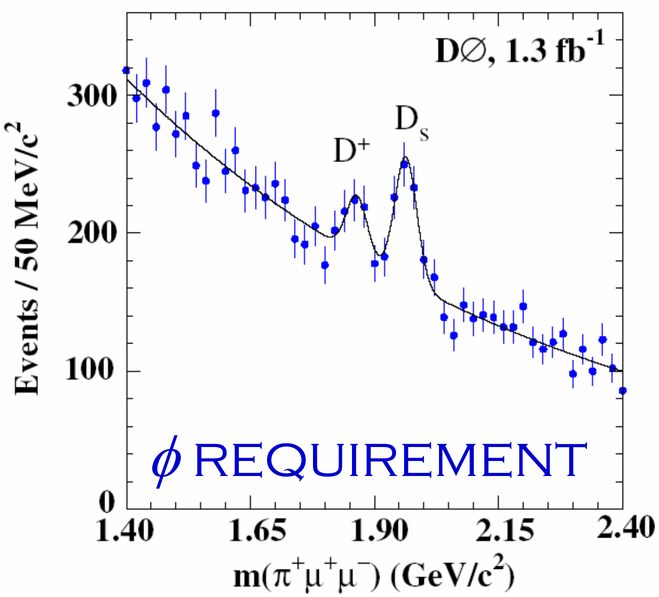


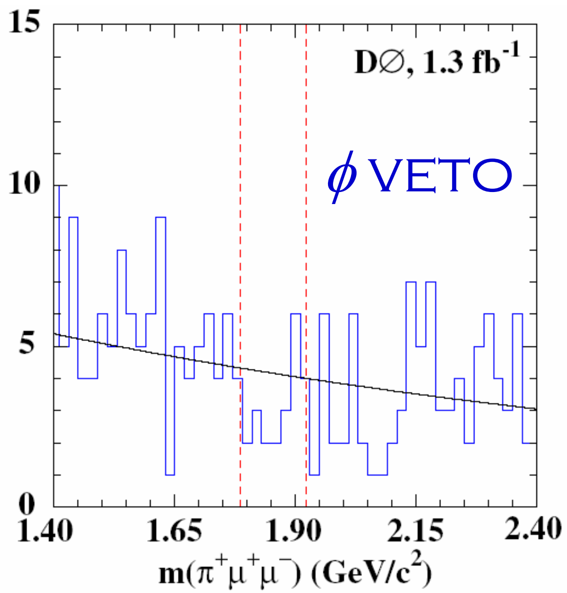


- Cant make missing energy veto like CLEO/BaBar
- Don't have particle ID like CLEO/BaBar/FOCUS
- Outstanding muon system allows us to capitalize on enormous cross section with no punch through

DØ Results





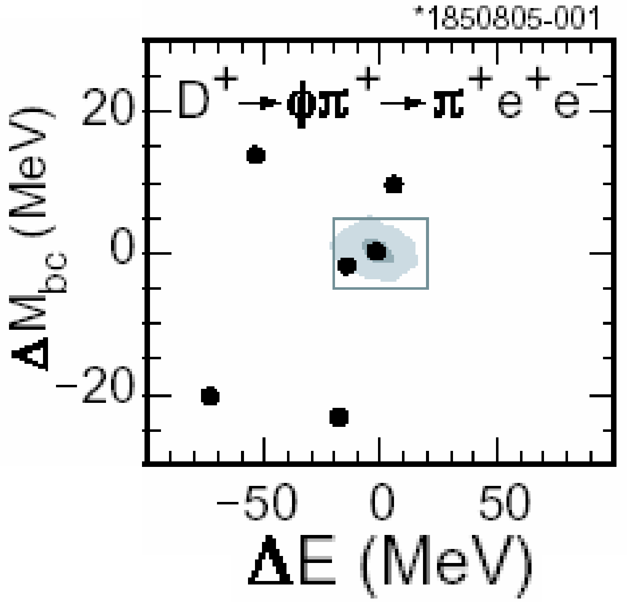


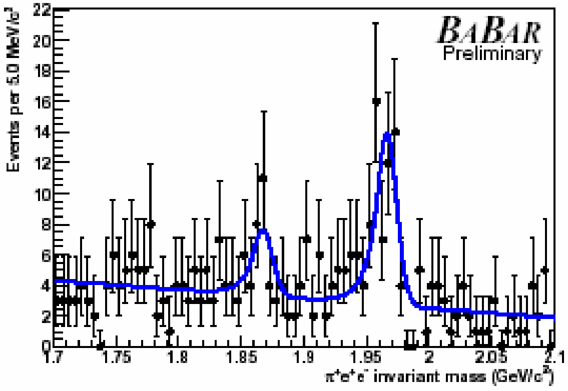
$$B(D^+ \to \pi^+\phi \to \pi^+\mu^+\mu^-) = (1.8 \pm 0.5 \pm 0.6) \times 10^{-6}$$

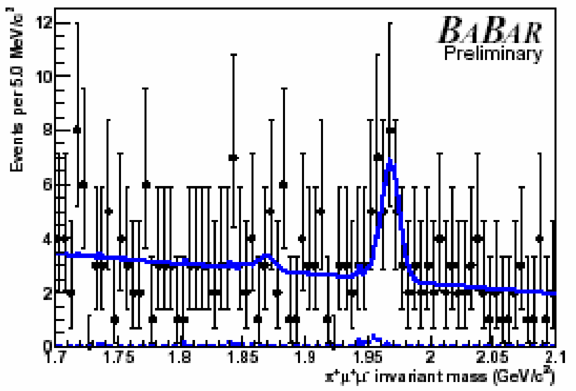
$$B(D^+ \to \pi^+\mu^+\mu^-) < 3.9 \times 10^{-6}$$

1.3 fb^{-1} #s updated for this conference

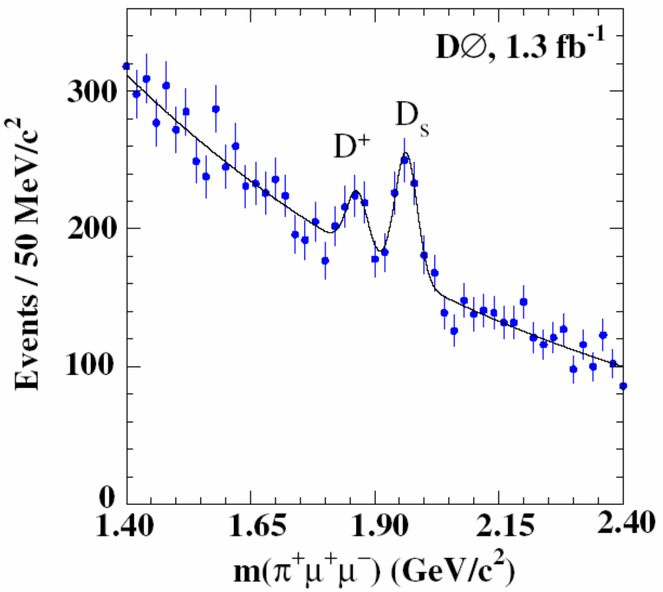
Some comparisons: $\phi\pi$





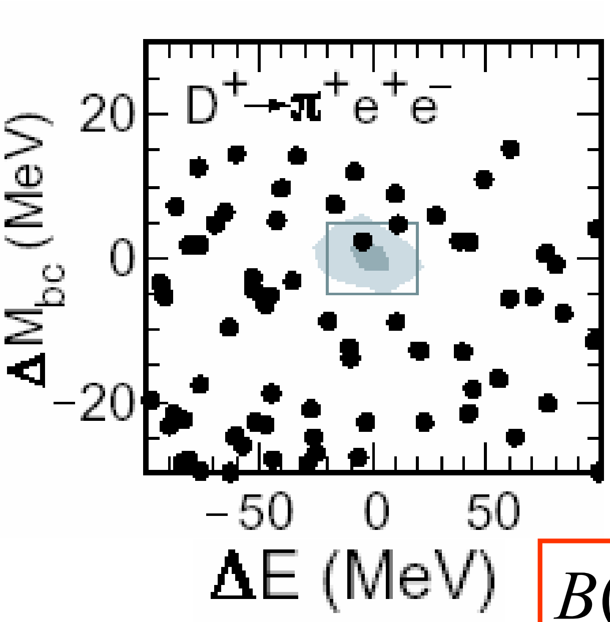


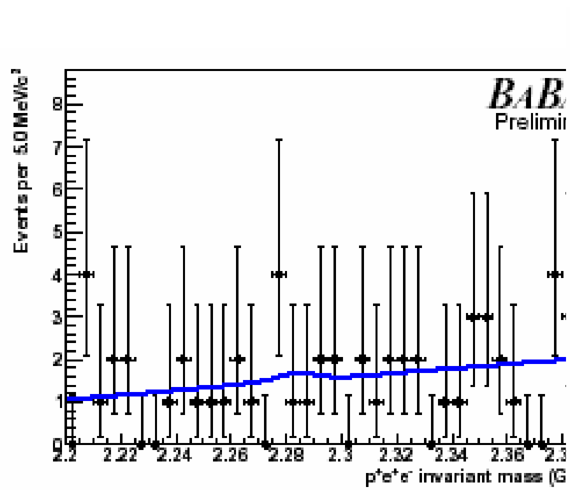
Milestone I: All three have reached sensitivity to see $\phi\pi$ in the $ll\pi$ channel

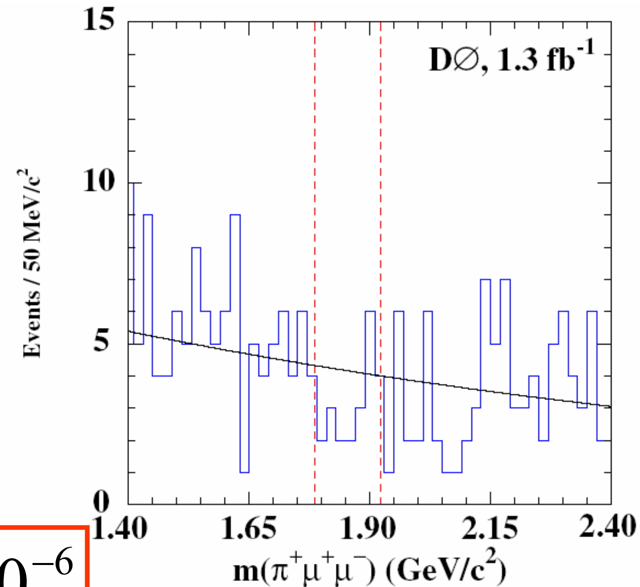


Some comparisons: ul^+l^-

Milestone II: All three have set limits near 10^{-6} level using modes best suited for their experiment/environment







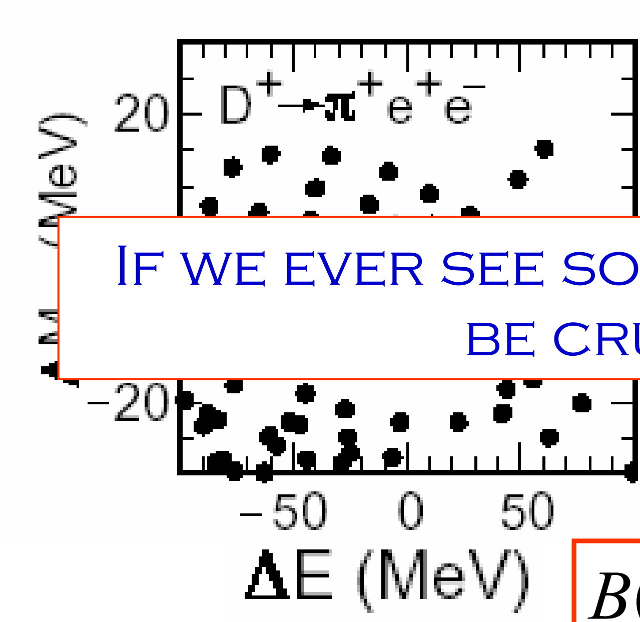
$$B(\Lambda_c \to p e^+ e^-) < 3.6\times10^{-6}$$

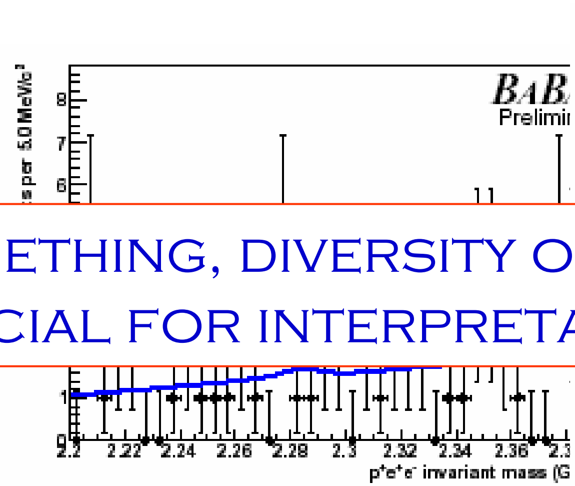
$$B(D^+ \to \pi^+ e^+ e^-) < 7.4\times10^{-6}$$

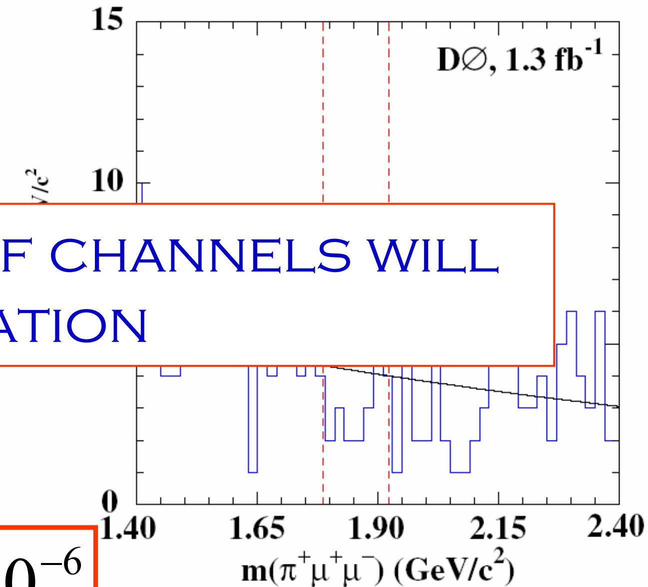
$$B(D^+ \to \pi^+ \mu^+ \mu^-) < 3.9\times10^{-6}$$

SOME COMPARISONS: ul^+l^-

MILESTONE II: ALL THREE HAVE SET LIMITS NEAR 10^{-6} LEVEL USING MODES BEST SUITED FOR THEIR EXPERIMENT/ENVIRONMENT







IF WE EVER SEE SOMETHING, DIVERSITY OF CHANNELS WILL BE CRUCIAL FOR INTERPRETATION

$$B(\Lambda_c \to pe^+e^-) < 3.6\times10^{-6}$$

$$B(D^+ \to \pi^+e^+e^-) < 7.4\times10^{-6}$$

$$B(D^+ \to \pi^+\mu^+\mu^-) < 3.9\times10^{-6}$$

$10^{-6} \rightarrow 10^{-7}$ w/ $hl^{+}l^{-}$

- BaBar: fraction of data set, background limited
- Belle: whole data set
- DØ: Fraction of data set but background limited
- CDF: Whole data set
- Enough data on tape to make significant progress and much more coming
- Knowing how to do things like combine Λ_c and D would be helpful
- Getting smarter about background suppression real key

Conclusions

- Not so rare
  - Annihilation now at precision level
- Rare charm from 10^{-5} to 10^{-6}
  - Very diverse set of results from 6 experiments at 4 energies
    - None specifically designed for rare charm
    - All basically done by one or two people
- Rare charm at 10^{-7}
  - Data sets will exist
    - Large fraction already on tape

FOCUS Full Results

Decay Mode	Sensitivity	F-C	R-L	**R-L incl.** σ_r	Single Cut incl. σ_r
$D^+ \to K^+\mu^+\mu^-$	7.5	11	9.1	9.2	12
$D^+ \to K^-\mu^+\mu^+$	4.8	13	13	13	12
$D^+ \to \pi^+\mu^+\mu^-$	7.6	9.3	8.7	8.8	7.4
$D^+ \to \pi^-\mu^+\mu^+$	5.5	4.6	4.8	4.8	5.1
$D_s^+ \to K^+\mu^+\mu^-$	33	31	33	36	38
$D_s^+ \to K^-\mu^+\mu^+$	21	11	13	13	20
$D_s^+ \to \pi^+\mu^+\mu^-$	31	20	24	26	18
$D_s^+ \to \pi^-\mu^+\mu^+$	23	29	26	29	22

BaBar full results

	$D^0 \to e^+e^-$	$D^0 \to \mu^+\mu^-$	$D^0 \to e^\pm\mu^\mp$
$N_{\rm bg}^{hh}$	0.02	3.34 ± 0.31	0.21
$N_{\rm bg}^{\rm comb}$	2.21 ± 0.38	1.28 ± 0.32	1.93 ± 0.36
$N_{\rm bg}$	2.23 ± 0.38	4.63 ± 0.45	2.14 ± 0.36
S $[10^{-7}]$	2.25 ± 0.12	4.53 ± 0.30	3.27 ± 0.20
$N_{\rm obs}$	3	1	0
UL obtained	1.2×10^{-6}	1.3×10^{-6}	8.1×10^{-7}

Decay mode	Yield (events)	Efficiency	BR (10^{-4}) (90% CL)	BF (10^{-6}) (90% CL)
$D^+ \to \pi^+e^+e^-$	$24.0^{+25.0+3.4}_{-24.1-5.1}$	3.93%	< 17.7	< 11.2
$D^+ \to \pi^+\mu^+\mu^-$	$1.5^{+20.1+3.4}_{-19.3-2.6}$	1.09%	< 38.7	< 24.4
$D^+ \to \pi^+e^+\mu^-$	$4.1^{+17.8+3.1}_{-16.3-2.1}$	2.27%	< 17.1	< 10.8
$D^+ \to \pi^+\mu^+e^-$	$-12.1^{+15.5+3.2}_{-14.8-0.0}$	2.29%	< 9.3	< 5.9
$D_s^+ \to \pi^+e^+e^-$	$-1.7^{+5.3+0.2}_{-4.6-2.0}$	1.14%	< 2.1	< 7.6
$D_s^+ \to \pi^+\mu^+\mu^-$	$-9.4^{+5.0+0.2}_{-4.4-1.4}$	0.31%	< 5.1	< 18.5
$D_s^+ \to \pi^+e^+\mu^-$	$4.8^{+4.7+0.8}_{-3.9-0.3}$	0.66%	< 6.2	< 22.3
$D_s^+ \to \pi^+\mu^+e^-$	$0.5^{+4.0+1.0}_{-3.3-0.1}$	0.65%	< 3.8	< 13.9
$D^+ \to K^+e^+e^-$	$5.9^{+8.9+3.8}_{-7.8-0.3}$	3.21%	< 8.2	< 5.2
$D^+ \to K^+\mu^+\mu^-$	$2.9^{+8.0+0.2}_{-7.0-3.7}$	0.75%	< 22.2	< 14.0
$D^+ \to K^+e^+\mu^-$	$-3.4^{+6.5+1.0}_{-5.6-0.1}$	1.64%	< 5.7	< 3.6
$D^+ \to K^+\mu^+e^-$	$-4.4^{+7.1+1.4}_{-6.1-3.0}$	1.64%	< 5.9	< 3.7
$D_s^+ \to K^+e^+e^-$	$-3.8^{+6.2+1.5}_{-5.3-1.3}$	2.81%	< 1.8	< 6.6
$D_s^+ \to K^+\mu^+\mu^-$	$5.0^{+6.5+0.1}_{-6.1-0.3}$	0.68%	< 7.1	< 25.4
$D_s^+ \to K^+e^+\mu^-$	$-3.7^{+5.1+1.4}_{-4.4-1.4}$	1.40%	< 1.5	< 5.6
$D_s^+ \to K^+\mu^+e^-$	$-6.5^{+4.9+0.2}_{-4.3-1.1}$	1.40%	< 1.0	< 3.6
$\Lambda_c^+ \to pe^+e^-$	$0.9^{+4.1+0.4}_{-3.4-0.1}$	4.11%	< 0.7	< 3.6
$\Lambda_c^+ \to p\mu^+\mu^-$	$6.9^{+4.7+0.3}_{-3.7-0.6}$	0.67%	< 8.1	< 40.4
$\Lambda_c^+ \to pe^+\mu^-$	$0.2^{+2.9+0.5}_{-2.0-0.5}$	1.19%	< 1.8	< 8.9
$\Lambda_c^+ \to p\mu^+e^-$	$-0.2^{+2.5+0.5}_{-1.7-0.9}$	1.18%	< 1.5	< 7.5

CLEO full results

Mode	ϵ (%)	N	n	$\sigma_{\rm syst}$ (%)	$\mathcal{B}$ (10^{-6})
$\pi^+e^+e^-$	36.41	1.99	2	8.7	< 7.4
$\pi^-e^+e^+$	43.85	0.48	0	7.1	< 3.6
$K^+e^+e^-$	26.18	1.47	0	10.0	< 6.2
$K^-e^+e^+$	35.44	0.50	0	7.2	< 4.5
$\pi^+\phi(e^+e^-)$	46.22	0.04	2	7.4	$2.7^{+3.6}_{-1.8} \pm 0.2$