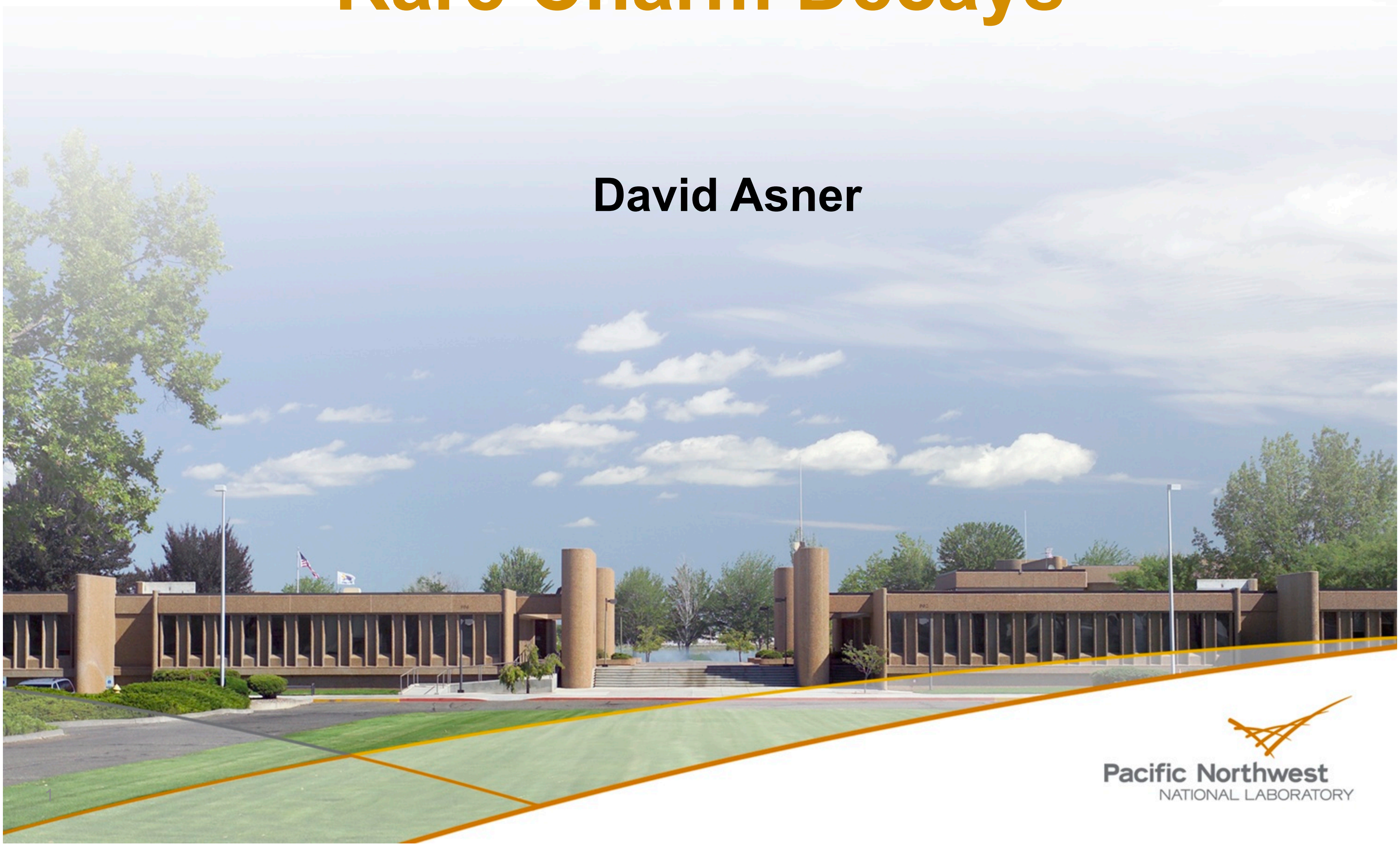
Rare Charm Decays



David Asner

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Rare Charm Processes

- Charm provides constraints on beyond Standard Model physics that is distinct from B & K sectors

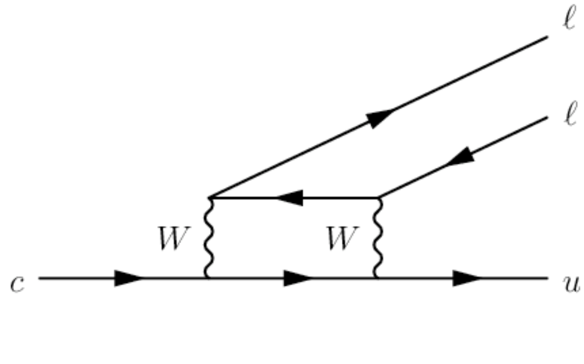
- Only now are experiments reaching “interesting” sensitivity
  - Rare Decays = Search for New Physics
  - Charm Mixing → Constraints on New Physics
  - CP Violation = Search for New Physics
    - In mixing
    - In decay

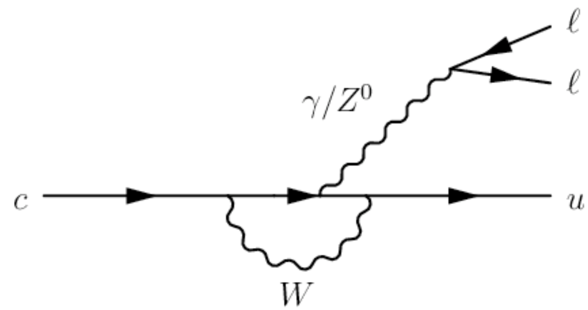
- This talk ONLY on Rare Charm Decays

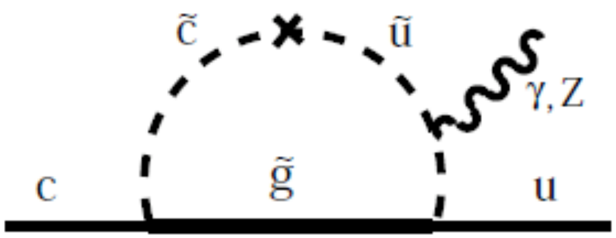
Outline

- Focus on neutral annihilation and radiative decays
  - Highlight sensitivity to new physics
  - Point out strengths & weaknesses of different channels
- Some comparison with beauty & strange systems
  - Better, worse, just different
- Contrast techniques used in different environments
- Motivate future studies
- Try to cover almost everything in last 5 years but will put most focus on $D \rightarrow hll$

Search for New Physics (NP) in Charm

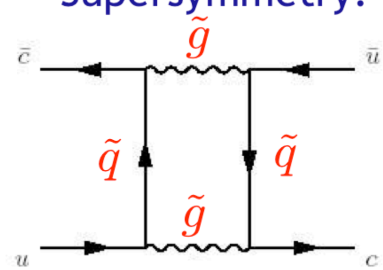




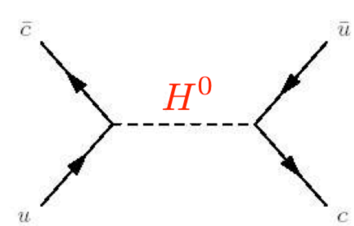


- Very low SM rates (BF($c \rightarrow ull$)~10^{-8}) for loop processes provide unique window to observe NP (TeV Scale) in rare charm processes
  - Rare Decays, D^0-D^0 oscillations & CP Violation
  - New Physics can introduce new particles into loop or new tree level neutral current phenomena
- New particles appearing on-shell at LHC must appear in virtual loops & affect amplitudes in K, B and Charm
  - Particles and couplings in rare charm processes are NOT the same as in rare B and K processes

Supersymmetry:



Extended Higgs:



New Physics Searches with Rare D

Example: $c \to u l^+ l^-$. Initially, exclusive modes look unpromising for NP searches, in contrast to B decays.

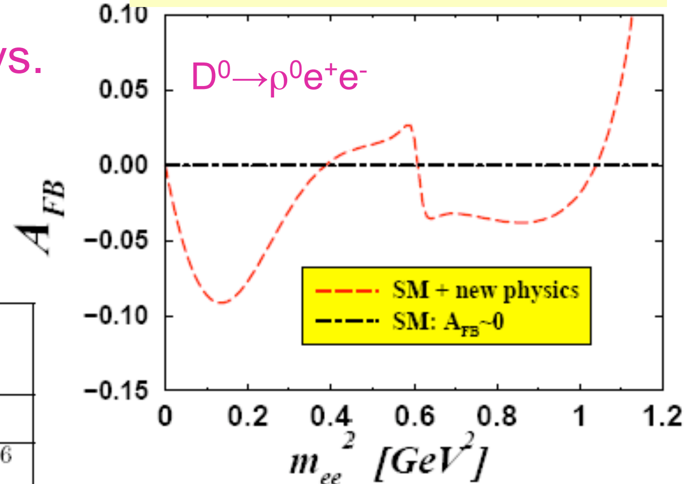
Why? Because short distance effects are swamped by long distance contributions.

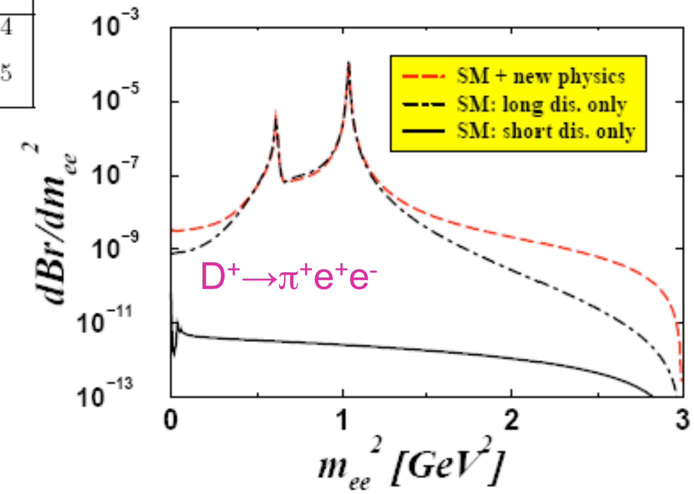
Br	short distance contribution only		total rate $\simeq$ long distance contr.	experiment
	SM	SM + NP		
$D^+ \to \pi^+ e^+ e^-$	6×10^{-12}	8×10^{-9}	1.9×10^{-6}	$< 7.4 \times 10^{-6}$
$D^+ \to \pi^+ \mu^+ \mu^-$	6×10^{-12}	8×10^{-9}	1.9×10^{-6}	$< 8.8 \times 10^{-6}$
$D^0 \to \rho^0 e^+ e^-$	negligible	5×10^{-10}	1.6×10^{-7}	$< 1.0 \times 10^{-4}$
$D^0 \to \rho^0 \mu^+ \mu^-$	negligible	5×10^{-10}	1.5×10^{-7}	$< 2.2 \times 10^{-5}$

However, differential distributions, and FB asymmetries, still have discriminating power.

And total rate can still be sizably enhanced in some cases: $D^0 \to \mu\mu \sim 10^{-13}$ in SM, can go up to 10^{-7} in R-parity violating SUSY

NP models with extra up-type quark. From arXiv:0801.1833

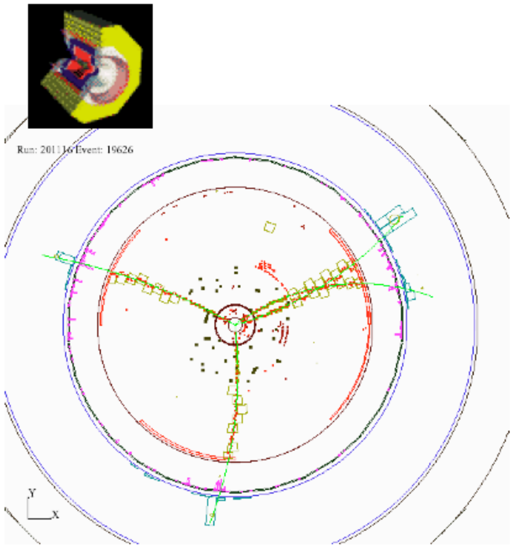


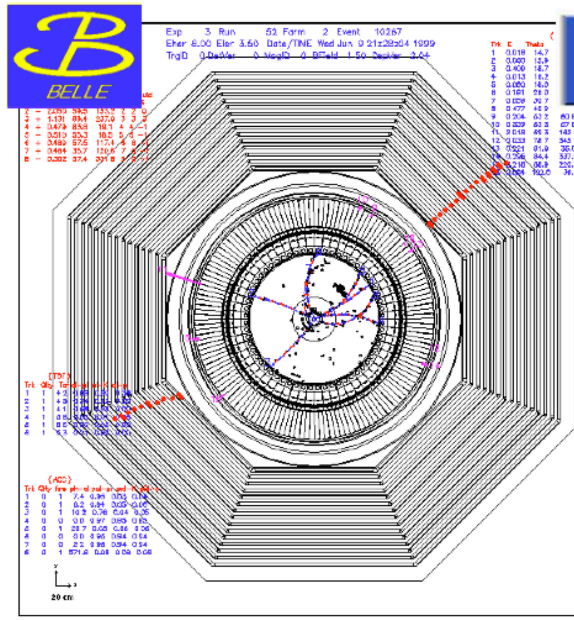


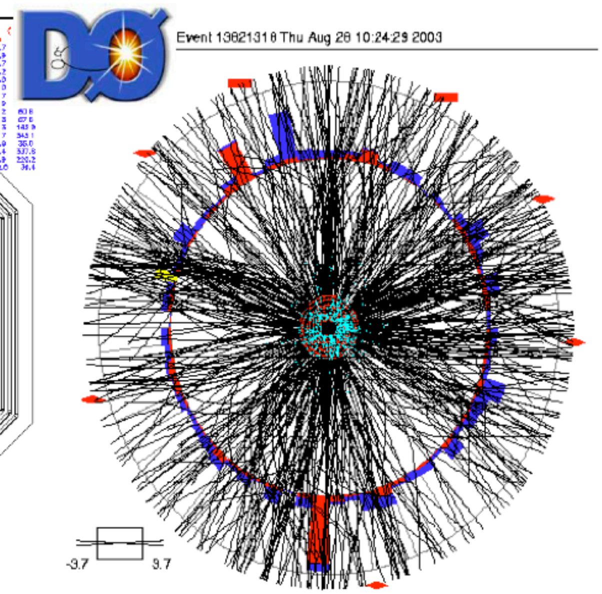
Radiative Decay & Neutral Annihilation – B, D, K

- Standard Model calculations range from simple to impossible
- Radiative Decay
  - Beauty
    - Precision: theory and experiment
  - Strange
    - Precision theory, experiment within reach
    - Lower SM rate = greater sensitivity
  - Charm
    - Theory = long distance
    - Existing measurements beautiful but…
- Neutral Annihilation
  - Almost all New Physics parameter space limited by experimental measurements
  - Better limit = better physics (!)

Different Experimental Environments







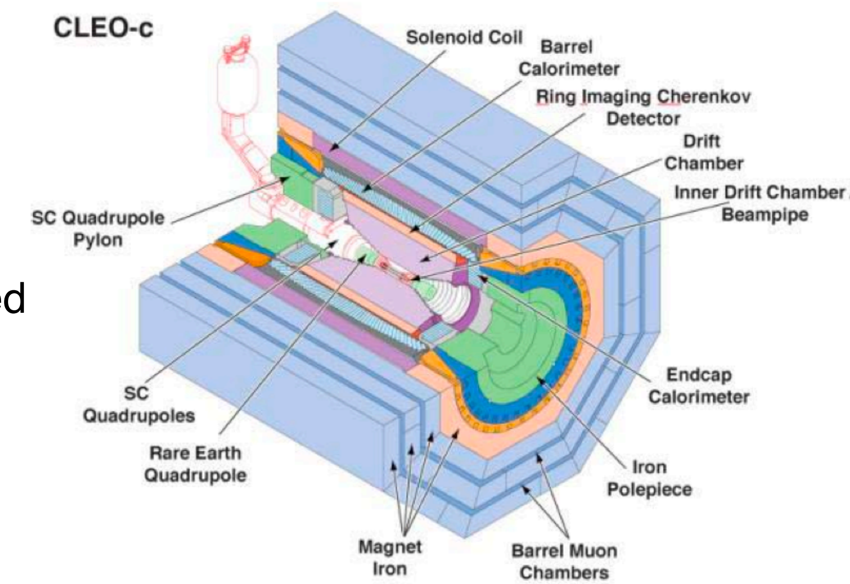
e+e- at Charm Threshold
~5 tracks/event

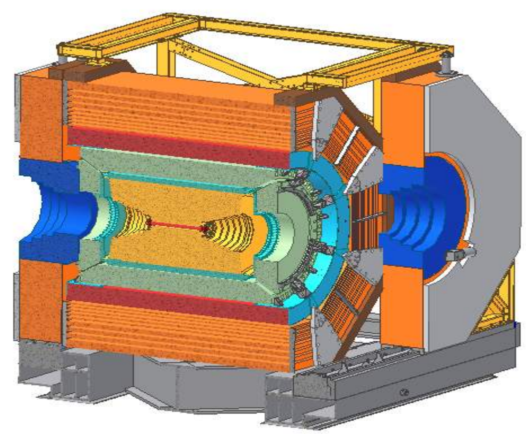
e+e- at ~10 GeV
~10 tracks/event

Tevatron
50 tracks/interaction
Up to 10 interactions/event

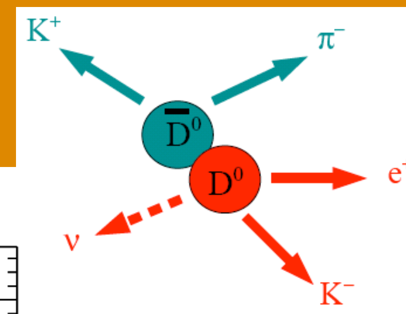
Charm Threshold: CLEO-c and BESIII

- Events are extremely clean
  - Charged & neutral multiplicities in ψ(3770) events are only 5.0 & 2.4 ~ 1/2 that of continuum charm at √s = 10.58 GeV
- Events at Threshold are pure DD
  - No additional fragmentation particles produced
  - Allows use of kinematic constraints, missing mass methods
- Double Tag studies are pristine
  - Backgrounds heavily suppressed
  - Minimizes statistical errors and systematic uncertainties
- Signal to Background optimal
  - σ(ψ(3770)→DD) ~ 1/2 σ(e^+e^-→hadrons) bkgd
- Neutrino/K_L Reconstruction
  - Undetected energy & momentum interpreted as neutrino/K_L 4-vector
- Large enough data samples for competitive rare decay studies

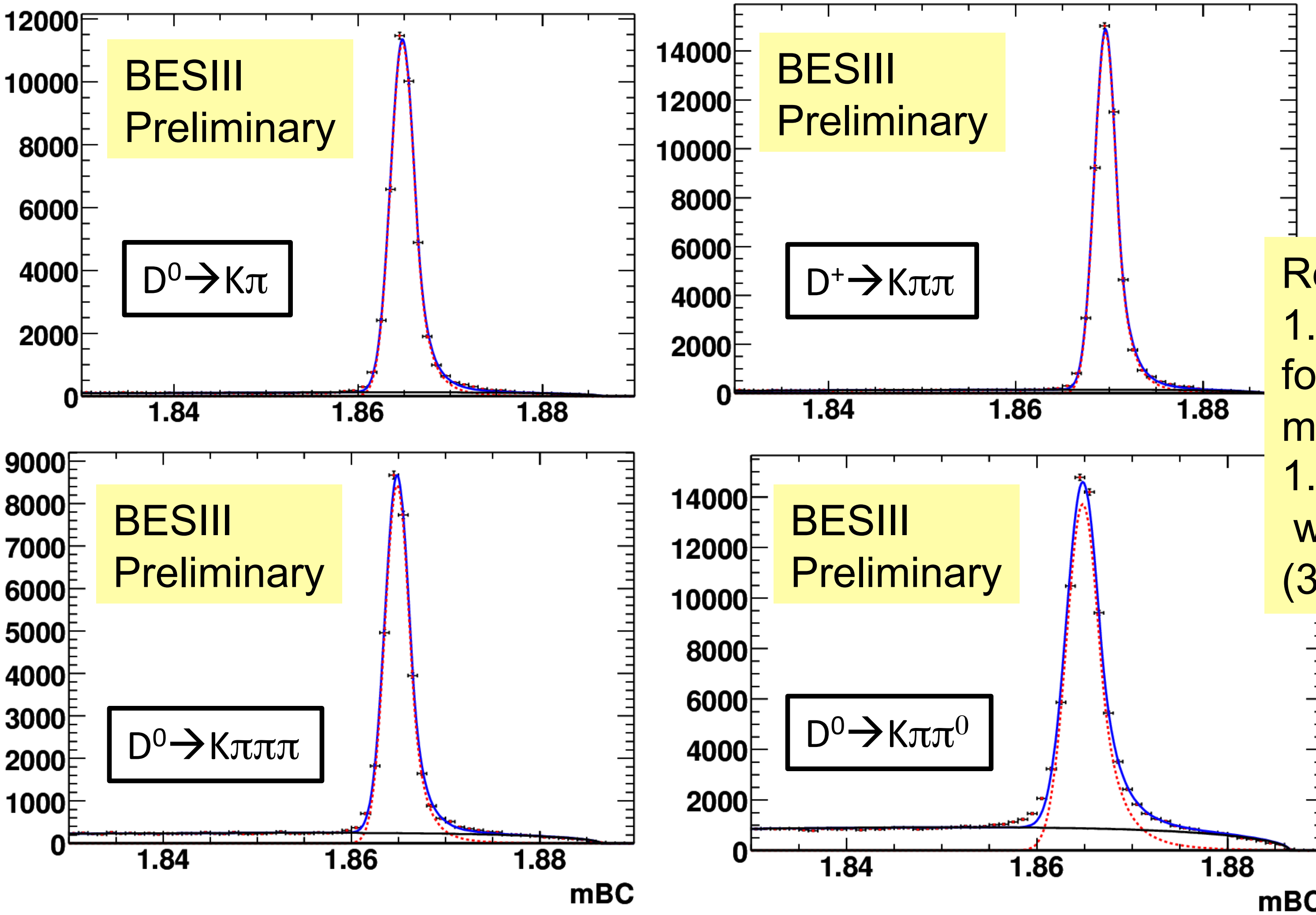




Clean single tag at BESIII



@$\psi(3770)$ with $420 pb^{-1}$ first clean single tagging sample:



Resolution:
1.3 MeV
for pure charged modes;
1.9 MeV for modes with one π^0.
(3 σ cut on ΔE)

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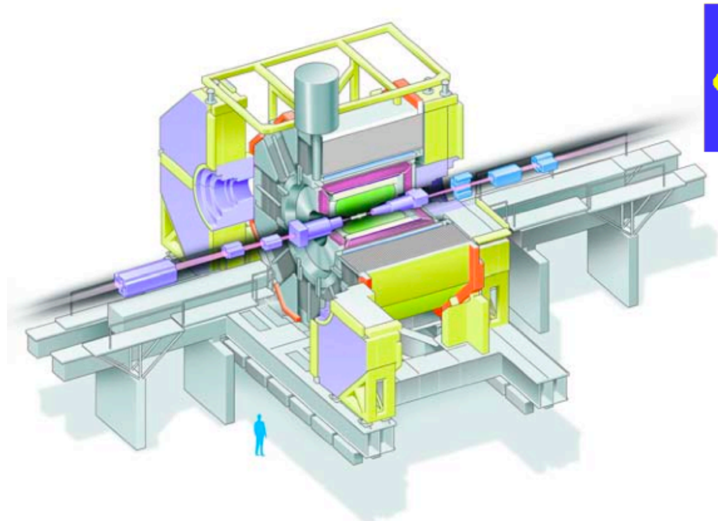
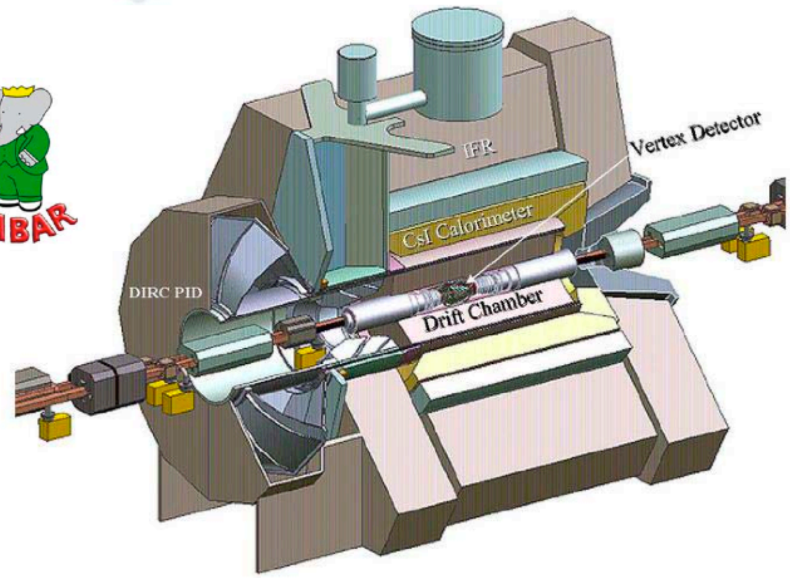
ϒ(4S): Belle and BaBar

- Still pretty clean
- Excellent PID
- All charmed hadron species accessible
- Enormous data sets now
- Anticipate 50x more at Belle II and SuperB





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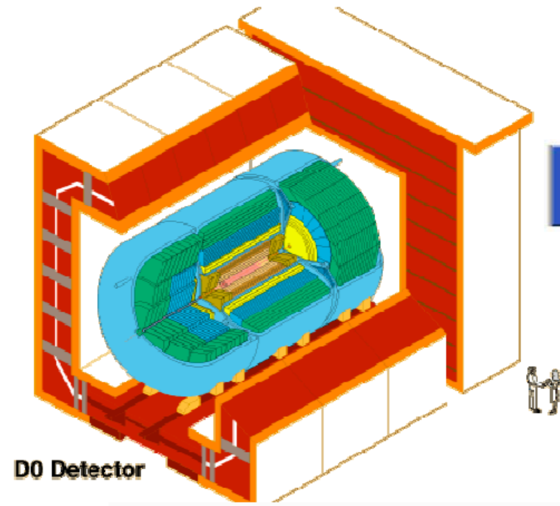
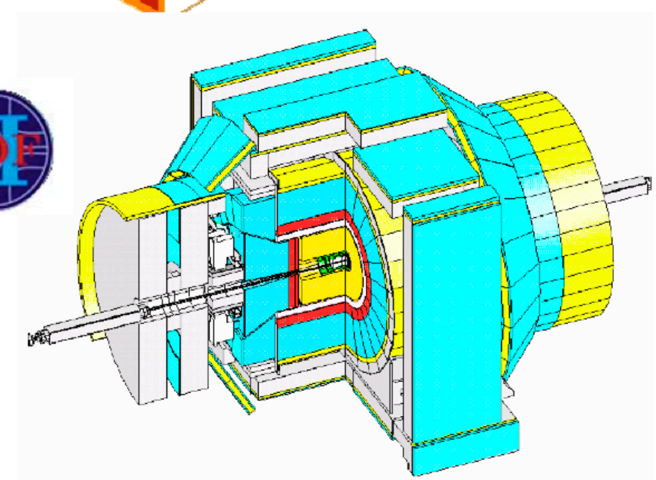
Tevatron: D0 & CDF (also LHCb ATLAS & CMS)

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

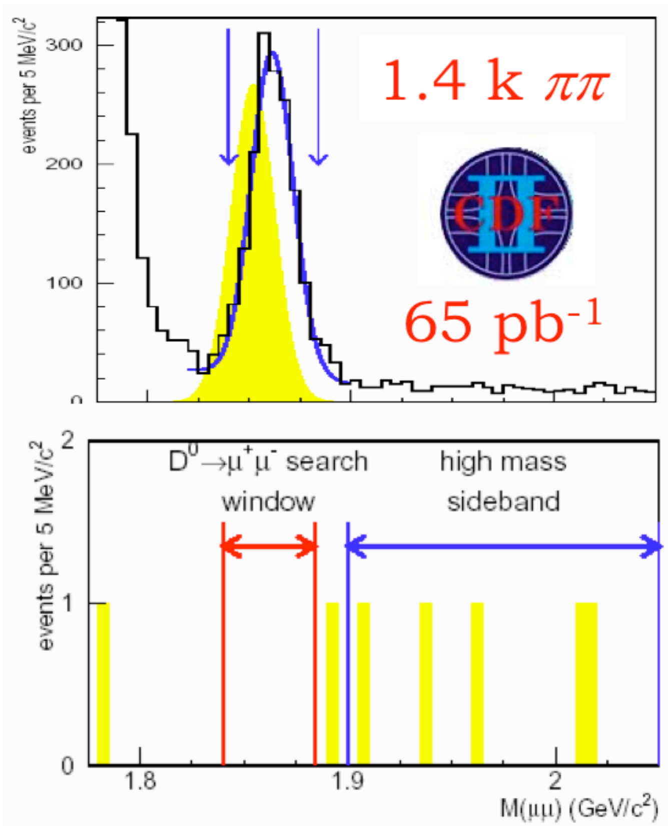




Neutral Leptonic Decays: D→μμ

Earlier CDF Measurement

Only 65 pb^{-1} but better figures!



General Analysis Strategy

- Normalize to, then veto D* tagged ππ.
- Fakes measured with D* tagged Kπ

CDF 65 pb^{-1} $D \rightarrow \mu\mu < 2.5 \times 10^{-6}$

PRD 68, 091101 2003

Neutral Leptonic Decays: D→μμ

CDF Public Note 9226 (2008)

Expectation: D→μμ SM<10^{-13}

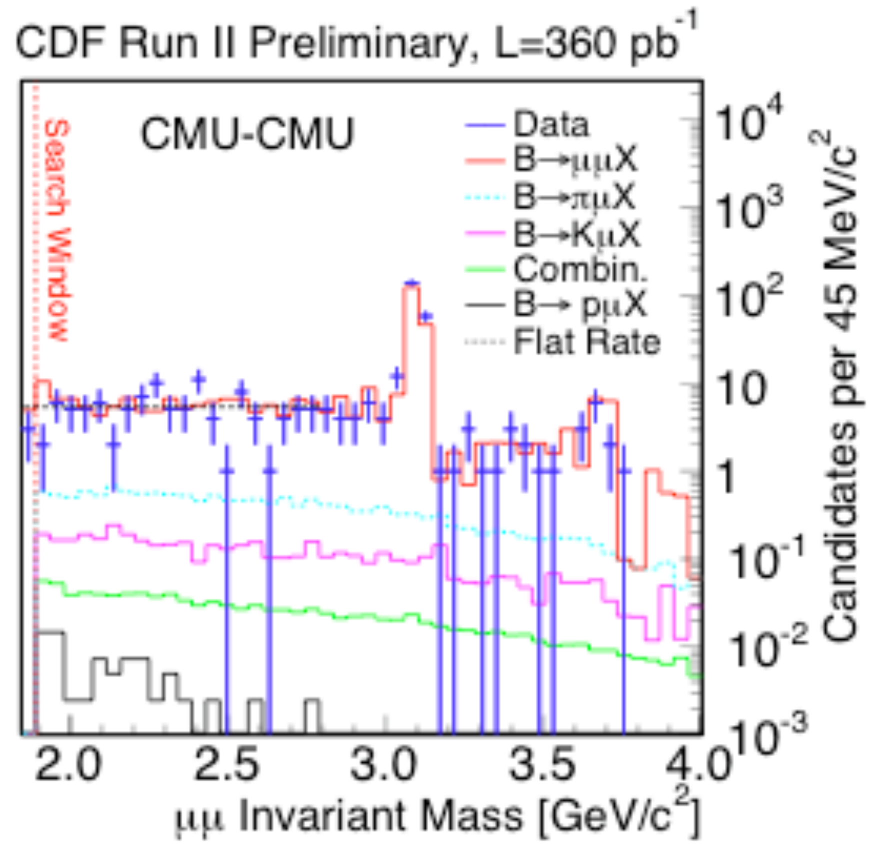
RPV SUSY~10^{-7}

CDF 65 pb^{-1} D →μμ < 2.5×10^{-6}

CDF 360 pb^{-1} D →μμ < 4.3×10^{-7}

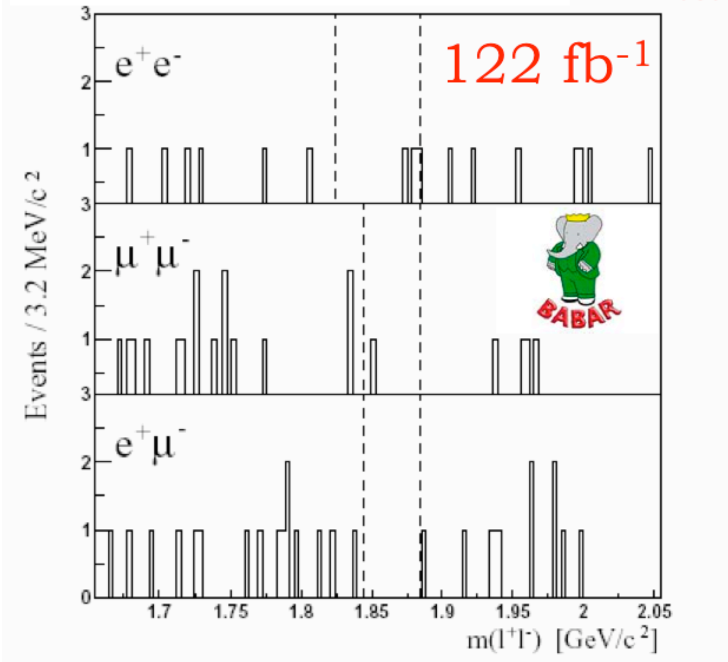
5.5x more luminosity → 5.8x better limit

R-parity coupling violating constraint
$\lambda_{21k}\lambda_{22k} = 1.5\sqrt{B(D^0\to\mu^+\mu^-)} < 9.8\times10^{-4}$

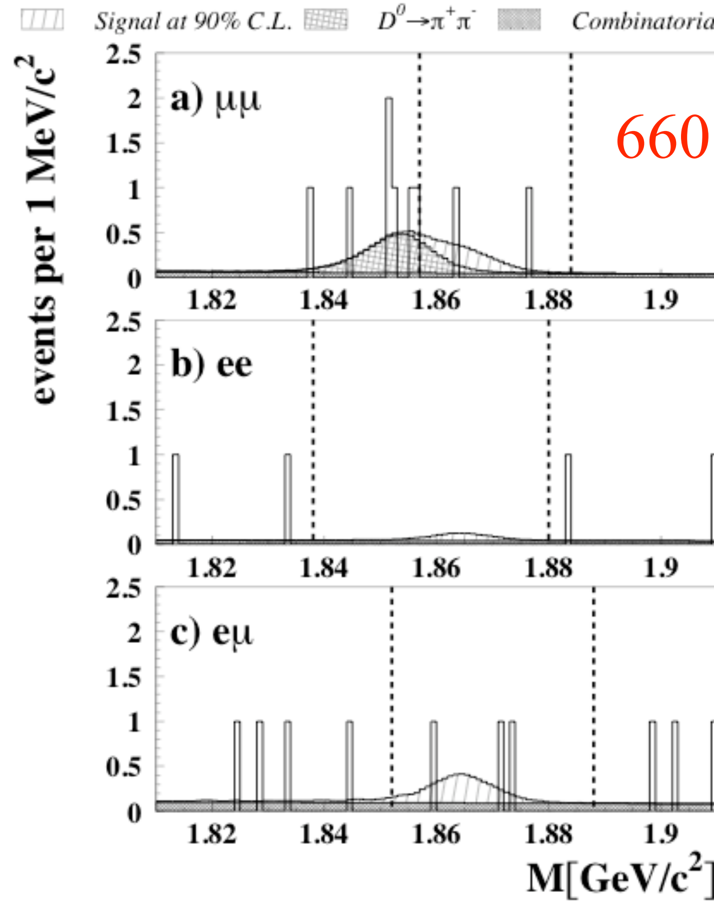


Neutral Leptonic Decays: D→μμ

Phys.Rev.Lett.93:191801,2004 $7\ k\ \pi\pi$



$$B(D^0 \to \mu^+\mu^-) < 1.3\times 10^{-6}$$
$$B(D^0 \to e^+e^-) < 1.2\times 10^{-6}$$



660 fb^{-1}

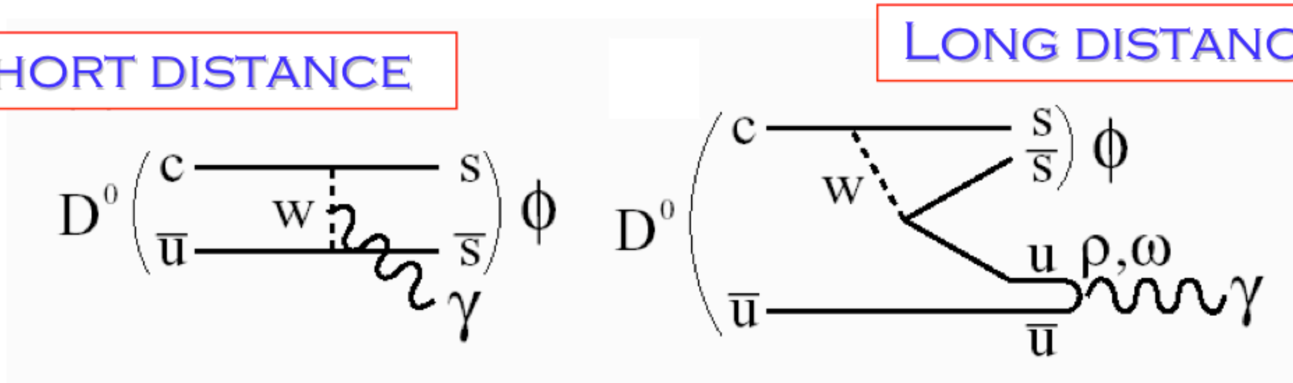
Best limits on neutral leptonic decays Belle
Phys.Rev.D81:091102,2010 →

$$\mathcal{B}\left(D^0 \to \mu^+\mu^-\right) < 1.4\times 10^{-7}$$
$$\mathcal{B}\left(D^0 \to e^+e^-\right) < 7.9\times 10^{-8}$$
$$\mathcal{B}\left(D^0 \to e^\pm\mu^\mp\right) < 2.6\times 10^{-7}$$

Two Body Radiative Decays

Short distance

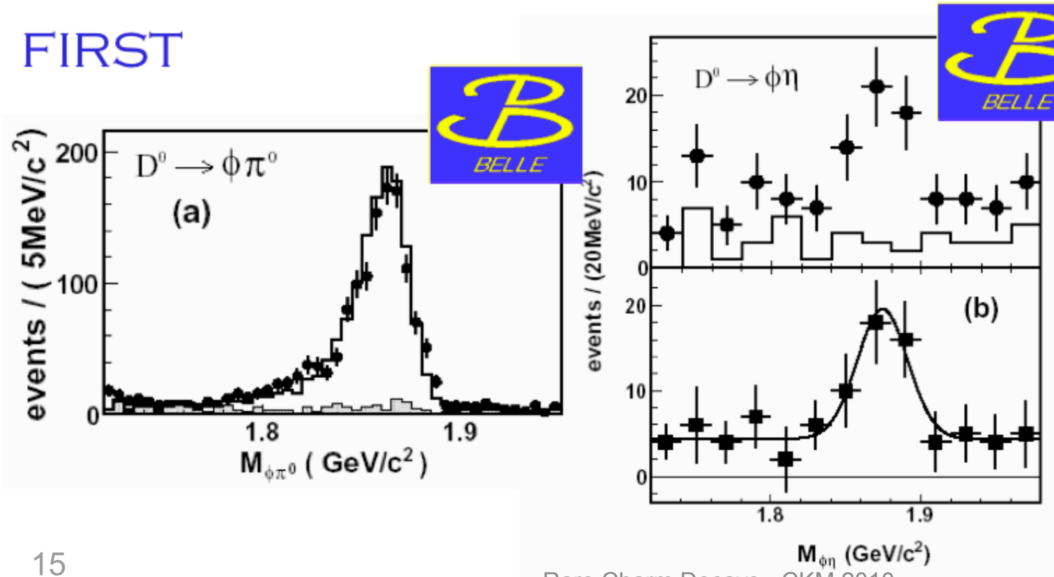
Long distance

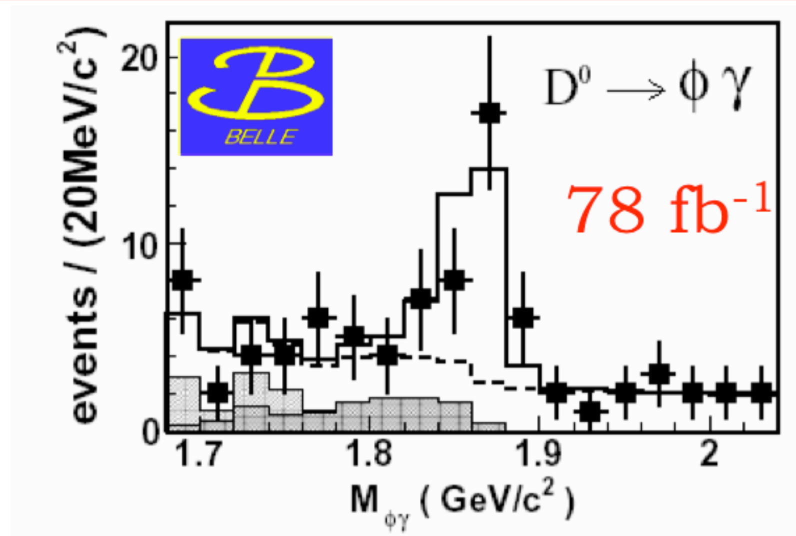


Phys.Rev.Lett.92:101803,2004

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

Peaking backgrounds not measured so measure them first

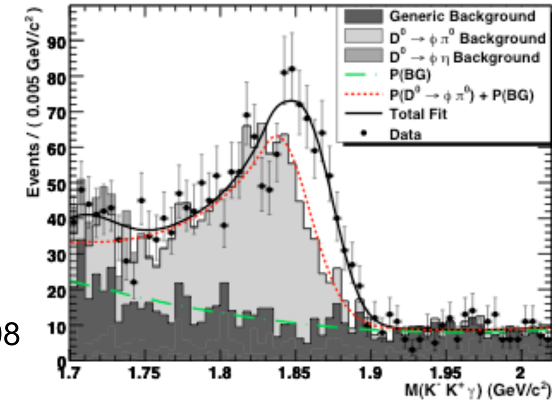




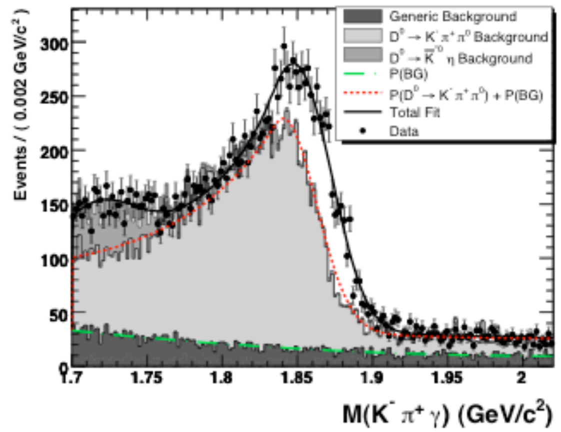
First radiative charm decay

Two-body Radiative Decays

PRD78:071101,2008

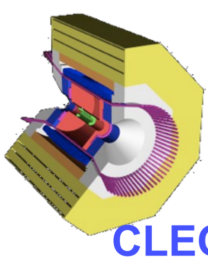


M(KKγ)

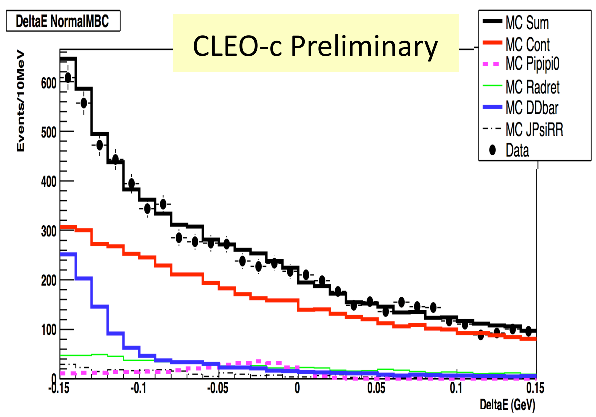


M(Kπγ)

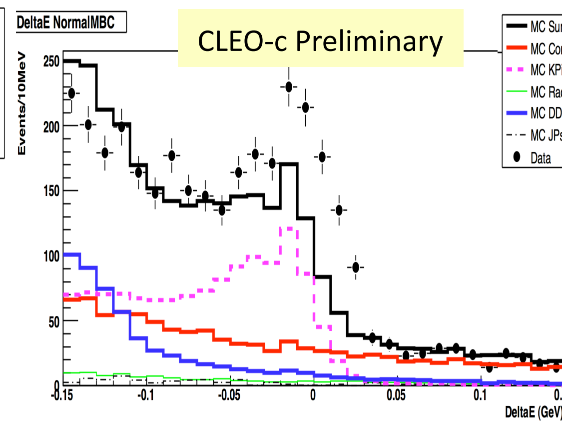
First observation of
$D \to K^* \gamma$
$(3.22\pm0.20\pm0.27)\times10^{-4}$
Long Distance
Interactions not NP



Ph.D. Thesis (2008)
PRD in preparation



ΔE(ργ)



ΔE(K*γ)

Confirmation of
$D \to K^* \gamma$
$(4.37\pm0.37\pm0.52)\times10^{-4}$

Improved limits
Note: SM prediction
$B(D\to\rho\gamma) \approx B(D\to\omega\gamma)$
Deviation indicates NP

Note: “other” D NOT reconstructed
Could ~eliminated all but **“π^0” background**
- price tag 1/8 statistics

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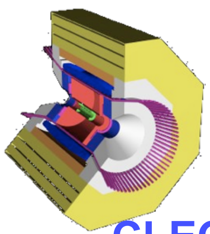
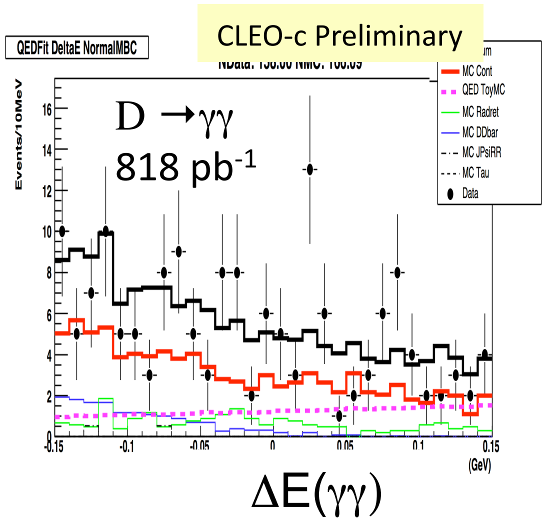
Two Body Radiative Decays



CLEO



Expectation: $D \rightarrow \gamma\gamma$ SM~10^{-8}

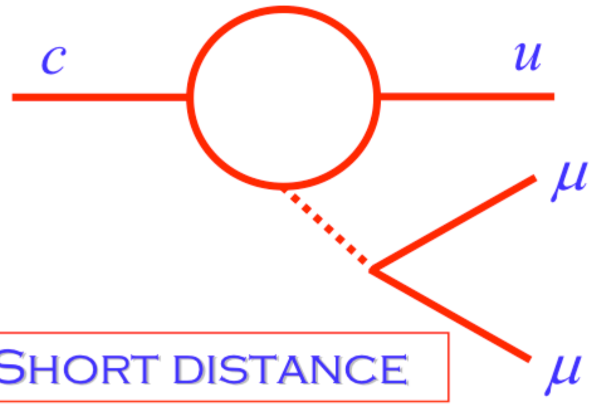
Could be enhanced by New Physics

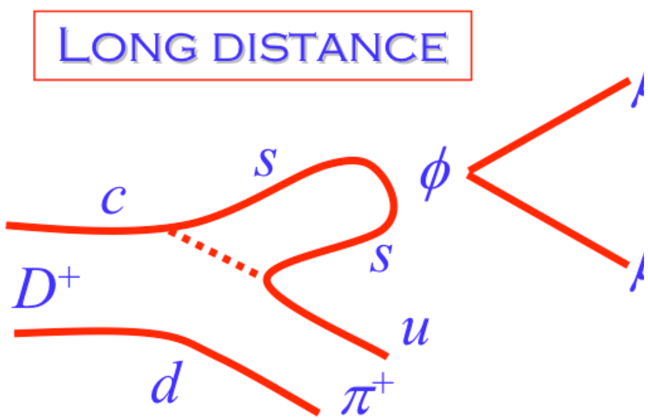
CLEO $D \rightarrow \gamma\gamma < 8.6\mathrm{x}10^{-6}$

Note: “other” D NOT reconstructed
Reduce “all” backgrounds - price tag 1/8 statistics

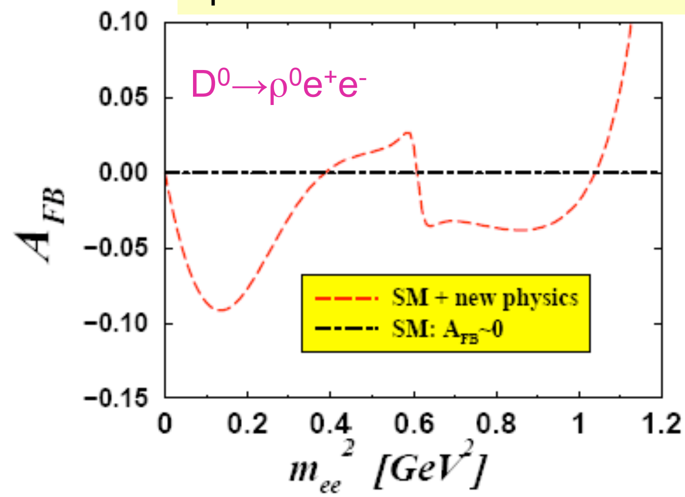
- BESIII sensitivity in 10 fb^{-1} (12x CLEO-c) ~10^{-7}
- Expect SuperB factory to have Standard Model reach

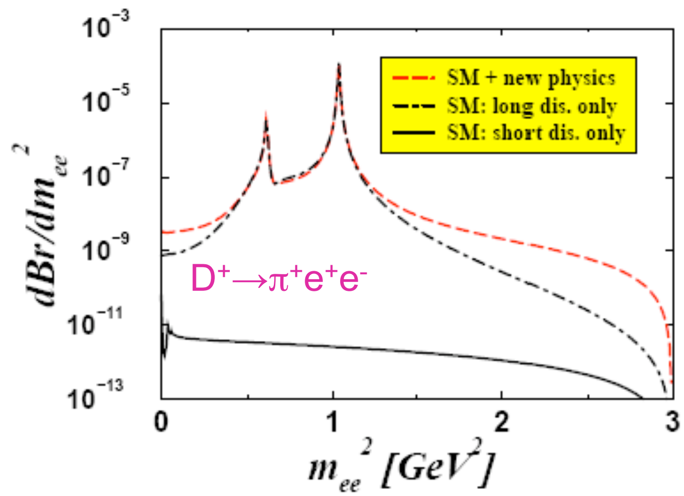
Two-body vs Three-body "Radiative" Decays





NP models with extra up-type quark. From arXiv:0801.1833





Two processes: long distance (strong scale) and short distance (weak scale)

short distance effects are swamped by long distance contributions

Differential distributions, and Forward-backward asymmetries, still have discriminating power.

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CLEO-c

Update previous result
PRL95, 221802 (2005) 281 pb^{-1}@Ψ(3770)
to full data sample 818 pb^{-1} @ Ψ(3770)
and 602 pb^{-1} @ 4.17 GeV (DsDs*)

4.76×10^6 D+
1.10×10^6 Ds+

Do NOT reconstruct tag D+ or Ds+

Search for D(s) → hee, h=π or K

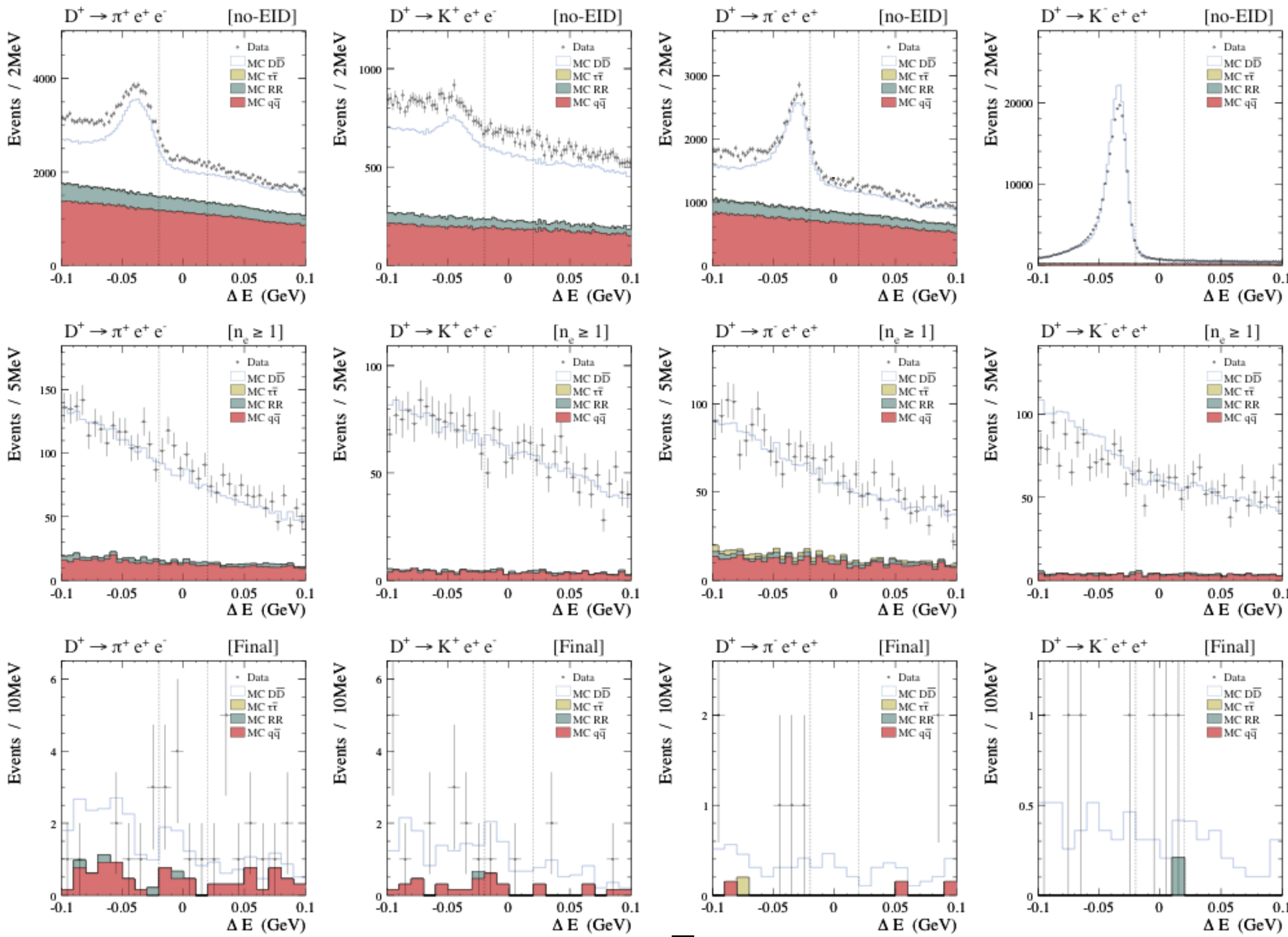
Remove double semileptonic decays missing energy veto

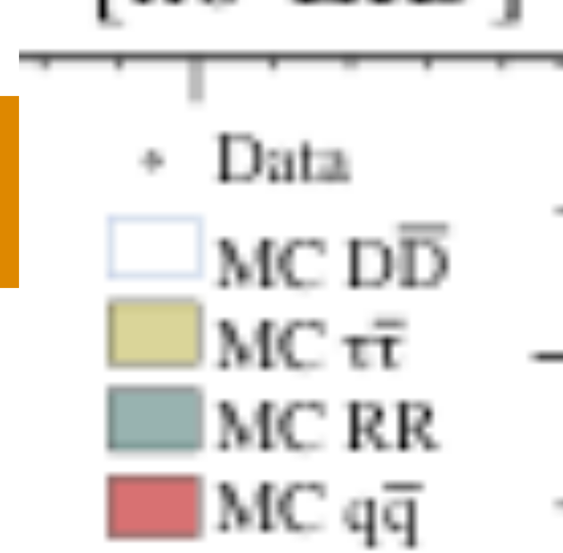
Event Selection & Kinematic Variables

- "Usual" π, K, e ID
- At Ψ(3770)
  - $\Delta E = E_D - E_{beam}$ & $M_{bc} = (E_{beam}^2 - p_D^2)^{1/2}$
  - Signal Box
    - $(\Delta E, M_{bc}) = (\pm 20\ \text{MeV}, \pm 5\ \text{MeV})$
- At 4170 MeV
  - M(Ds) and M_{recoil}(Ds)
  - Signal Box
    - $(\Delta M, \Delta M_{recoil}) = (\pm 20\ \text{MeV}, \pm 55\ \text{MeV})$
- BREM photons are recovered around each electron candidate (100 mrad)
- π, K p > 50 MeV, cosθ < 0.93
- electrons p > 200 MeV, cosθ < 0.90

CLEO-c Results: D→hee

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





No electron identification

1 electron identification

2 electron identification

ΔE

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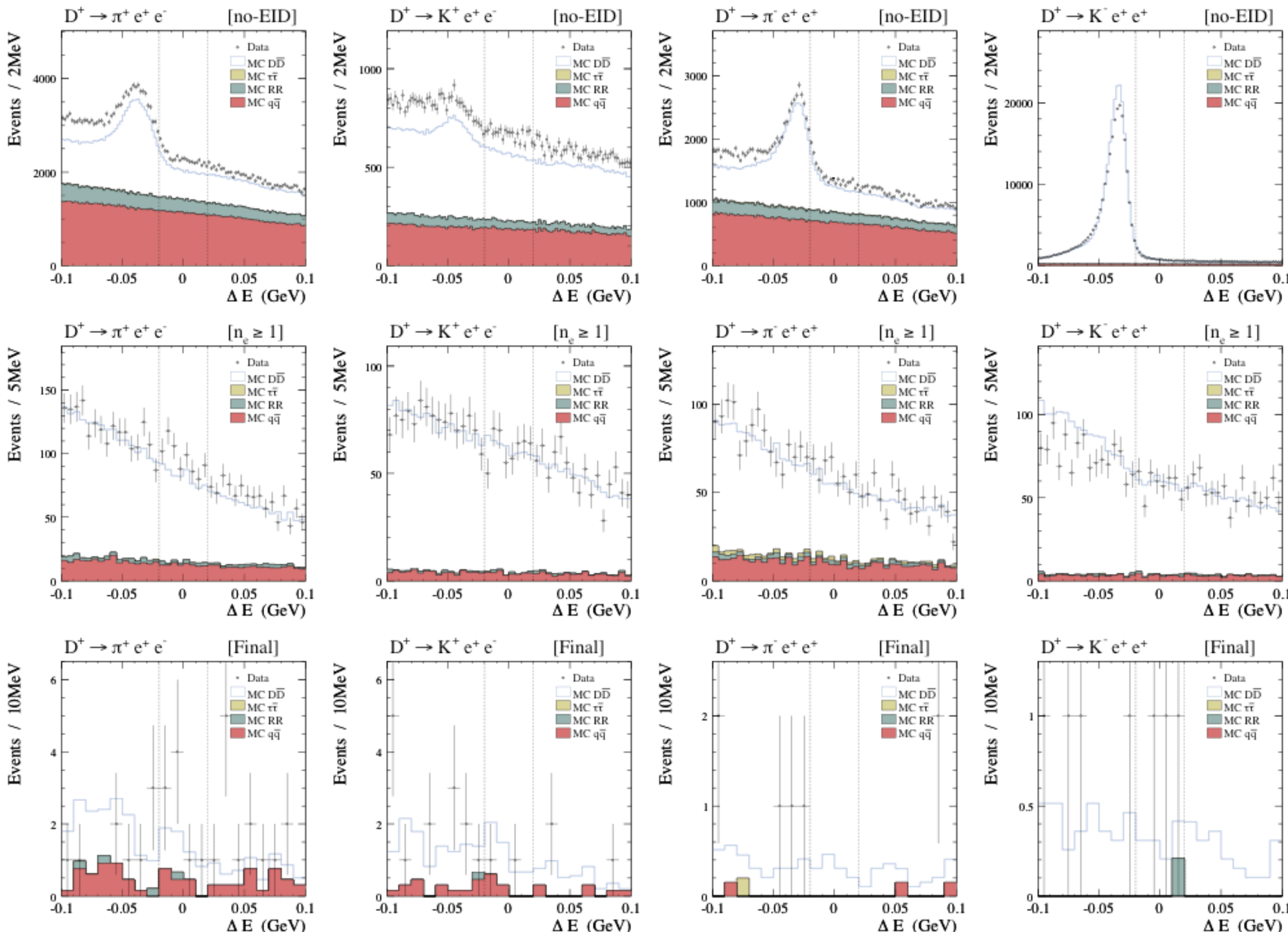
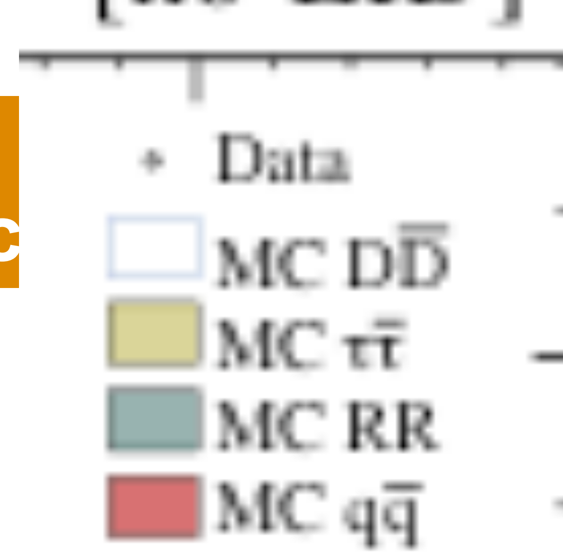
CLEO-c Results: $D_s \rightarrow hee$ (with tight c

$D_s^+ \rightarrow \pi^+ e^+ e^-$ | $D_s^+ \rightarrow K^+ e^+ e^-$ | $D_s^+ \rightarrow \pi^- e^+ e^+$ | $D_s^+ \rightarrow K^- e^+ e^+$





No electron identification

1 electron identification

2 electron identification

ΔE

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CLEO-c: Final Results

Channel	$\mathcal{B}$
$D^+ \to \pi^+ e^+ e^-$	$< 5.9 \times 10^{-6}$
$D^+ \to \pi^- e^+ e^+$	$< 1.1 \times 10^{-6}$
$D^+ \to K^+ e^+ e^-$	$< 3.0 \times 10^{-6}$
$D^+ \to K^- e^+ e^+$	$< 3.5 \times 10^{-6}$
$D^+ \to \pi^+ \phi(e^+ e^-)$	$(1.7^{+1.4}_{-0.9} \pm 0.1) \times 10^{-6}$
	$< 3.7 \times 10^{-6}$

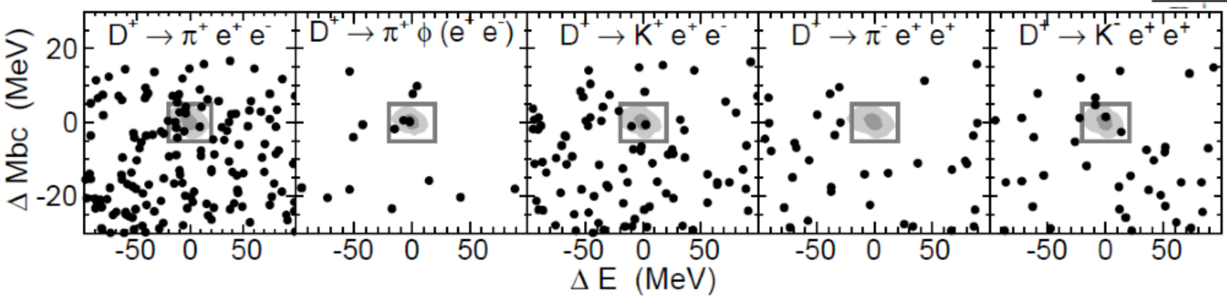


FIG. 1. Scatter plots of $\Delta M_{\rm bc}$ vs ΔE. The two contours for each mode enclose regions determined with signal MC simulation to contain 50% and 85% of signal events, respectively. The signal region, defined by $(\Delta E, \Delta M_{\rm bc}) = (\pm 20\,{\rm MeV}, \pm 5\,{\rm MeV})$, is shown as a box.

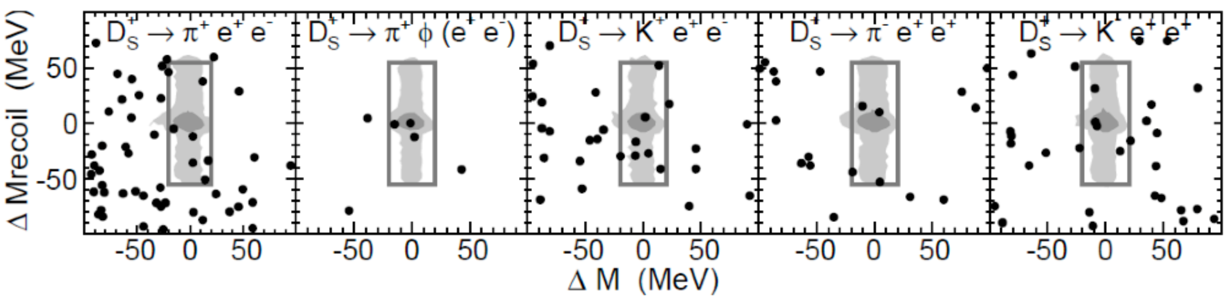


FIG. 2. Scatter plots of $\Delta M_{\rm recoil}$ vs ΔM. The two contours for each mode enclose regions determined with signal MC s to contain 40% and 85% of signal events, respectively. The signal region, defined by $(\Delta M, \Delta M_{\rm recoil}) = (\pm 20\,{\rm MeV}, \pm$ is shown as a box.

$D_s^+ \to \pi^+ e^+ e^-$	$< 2.2 \times 10^{-5}$
$D_s^+ \to \pi^- e^+ e^+$	$< 1.8 \times 10^{-5}$
$D_s^+ \to K^+ e^+ e^-$	$< 5.2 \times 10^{-5}$
$D_s^+ \to K^- e^+ e^+$	$< 1.7 \times 10^{-5}$
$D_s^+ \to \pi^+ \phi(e^+ e^-)$	$(0.6^{+0.8}_{-0.4} \pm 0.1) \times 10^{-5}$
	$< 1.8 \times 10^{-5}$

BABAR

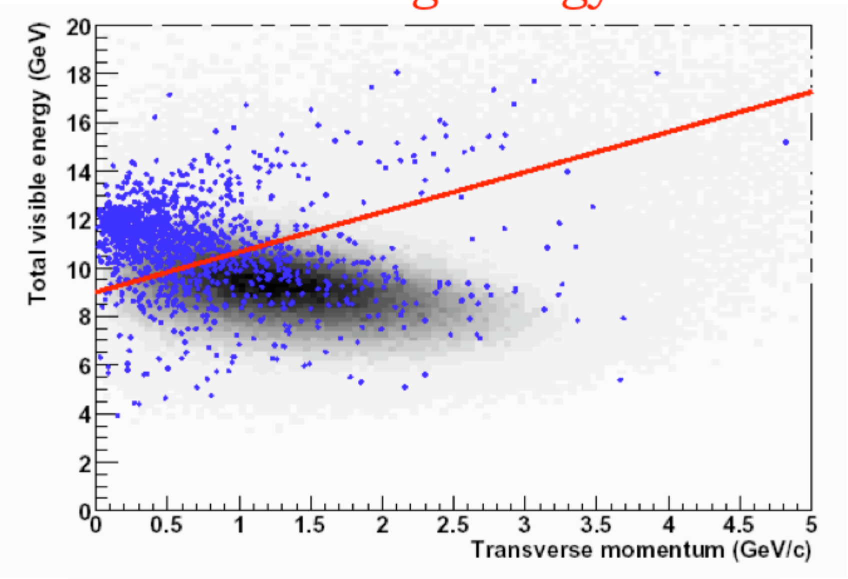
288 fb^{-1}

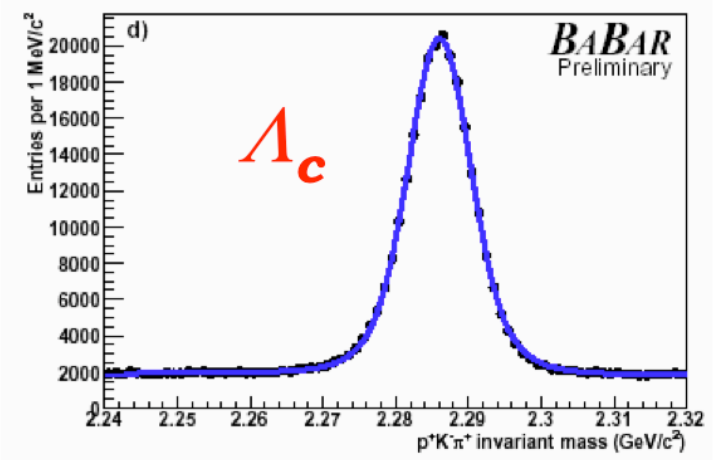
Very similar to CLEO approach

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

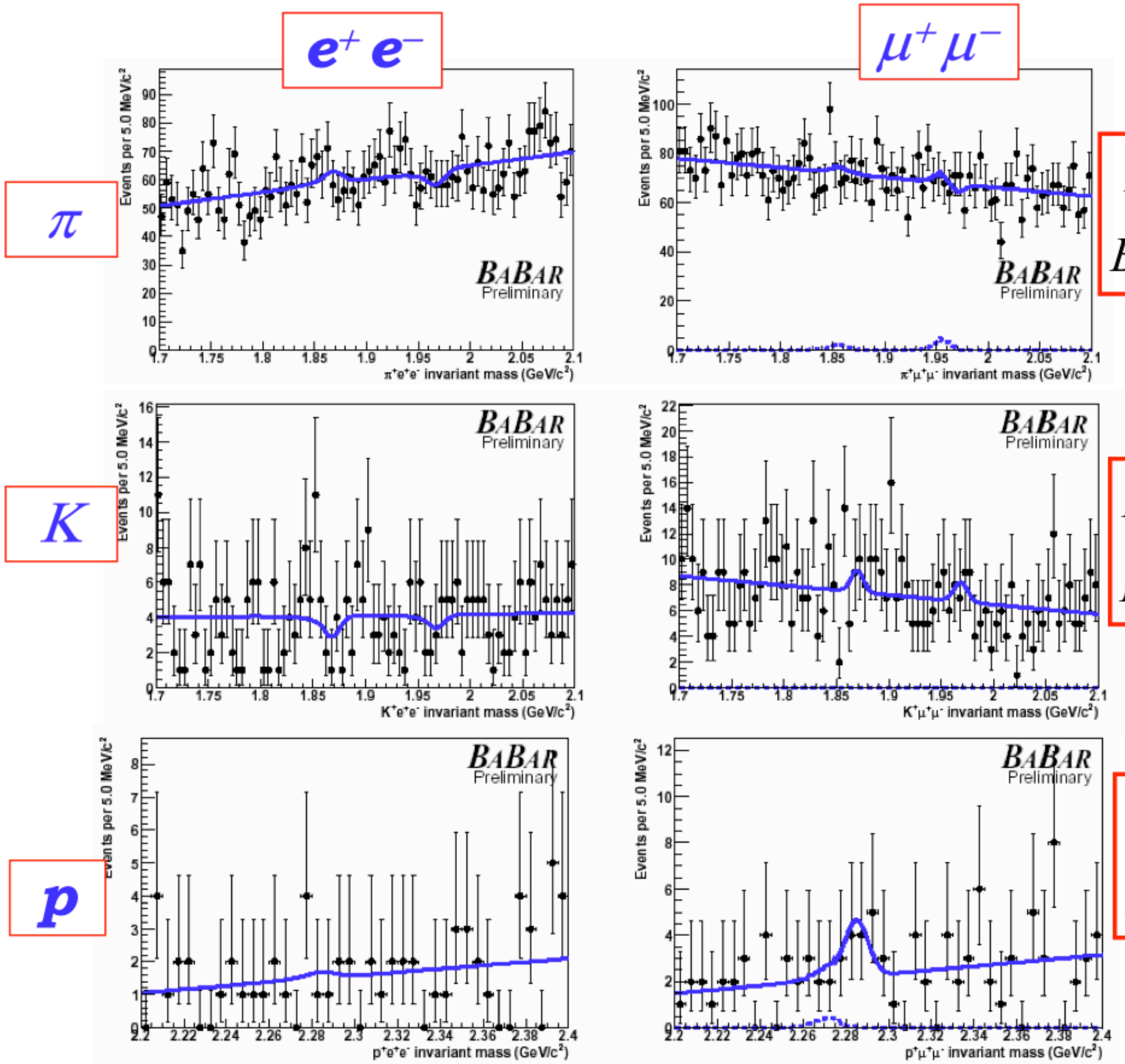
Expanded to include all hadron species and both di-electrons and di-muons

2-D Missing energy veto





BABAR Results



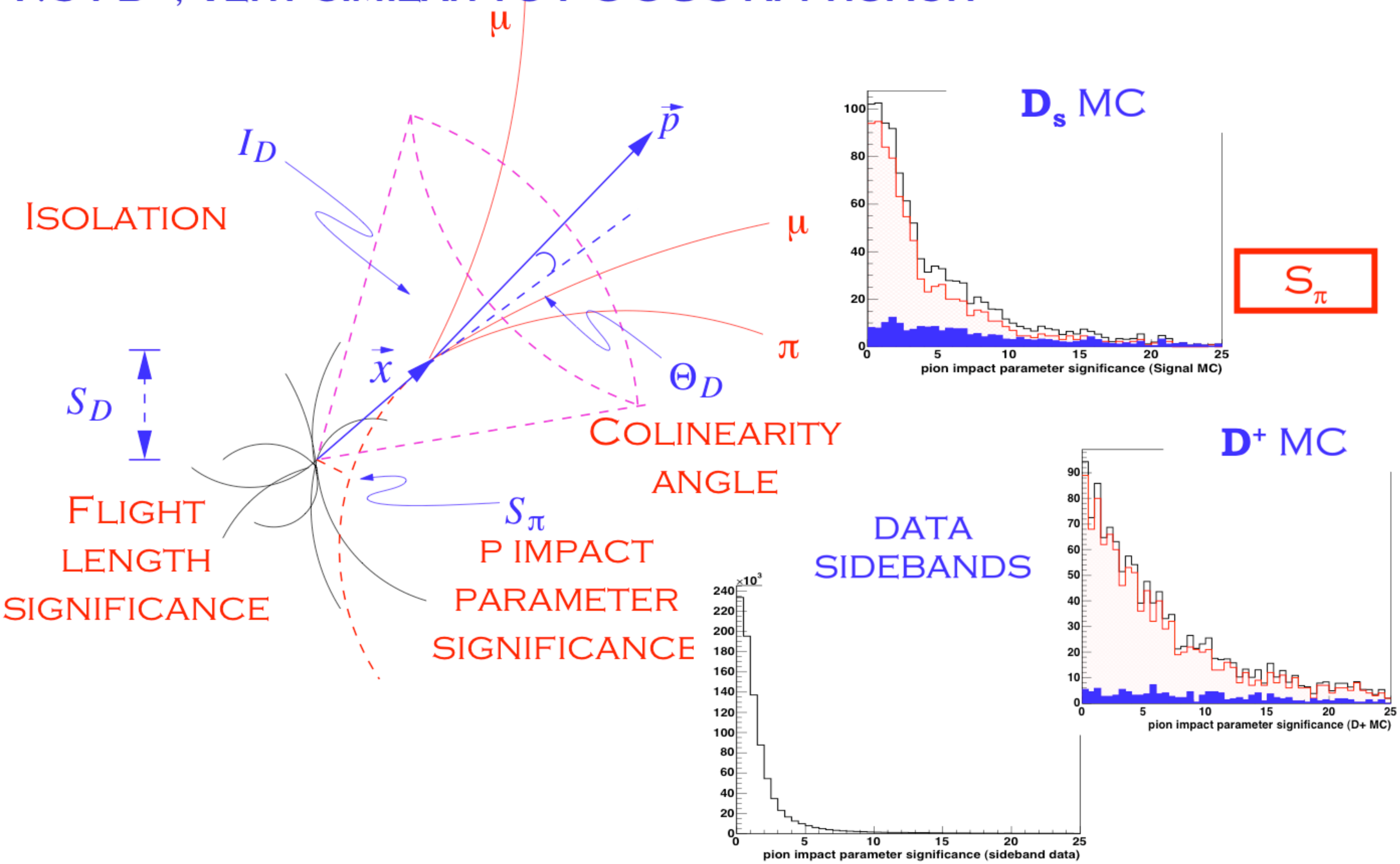
$$B(D^+ \to \pi^+ e^+ e^-) < 11.2\times 10^{-6}$$
$$B(D^+ \to \pi^+ \mu^+ \mu^-) < 24.4\times 10^{-6}$$

$$B(D_s^+ \to K^+ e^+ e^-) < 11.2\times 10^{-6}$$
$$B(D_s^+ \to K^+ \mu^+ \mu^-) < 6.6\times 10^{-6}$$

$$B(\Lambda_c \to p e^+ e^-) < 3.6\times 10^{-6}$$
$$B(\Lambda_c \to p \mu^+ \mu^-) < 40.4\times 10^{-6}$$

D0 Experiment

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



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D0 Experiment

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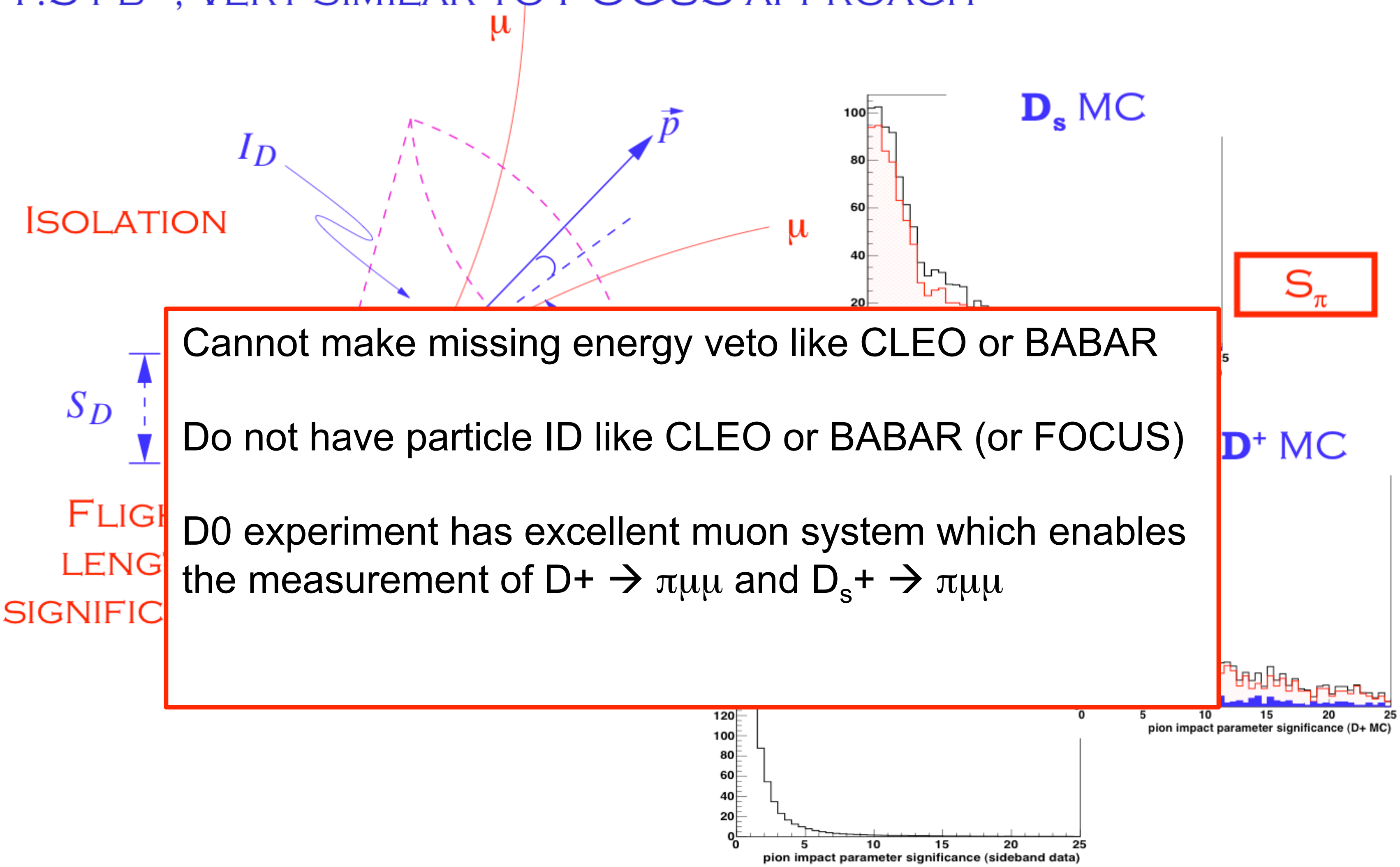
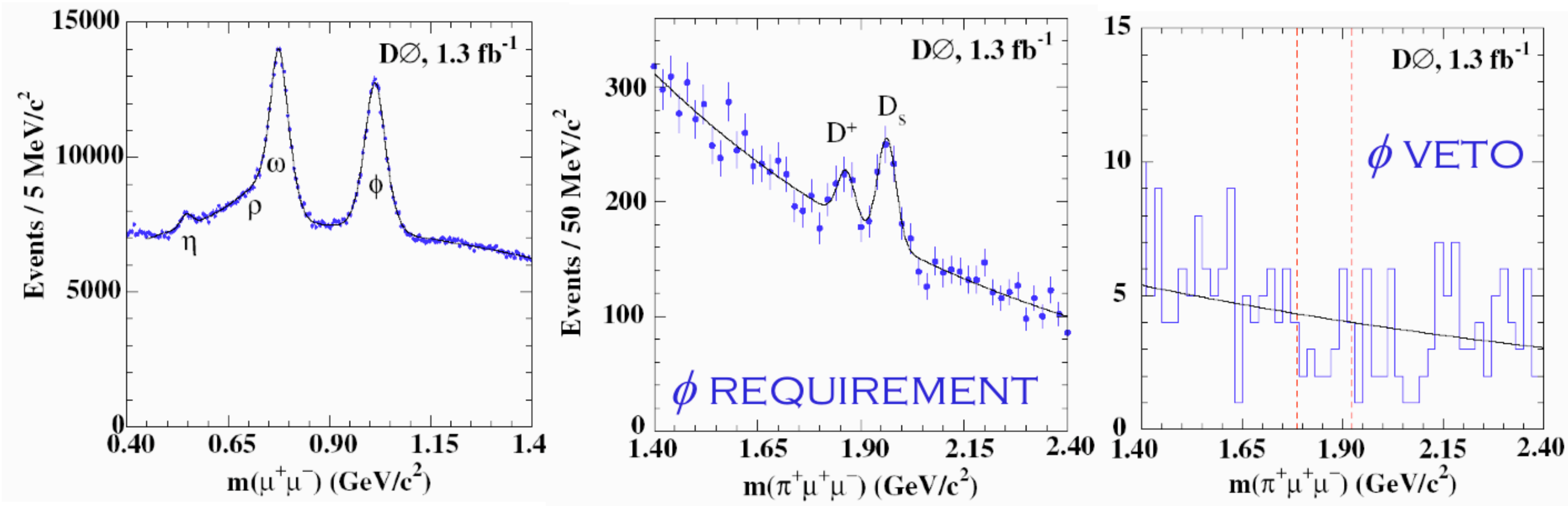


Cannot make missing energy veto like CLEO or BABAR

Do not have particle ID like CLEO or BABAR (or FOCUS)

D0 experiment has excellent muon system which enables the measurement of D+ → πμμ and D_s+ → πμμ

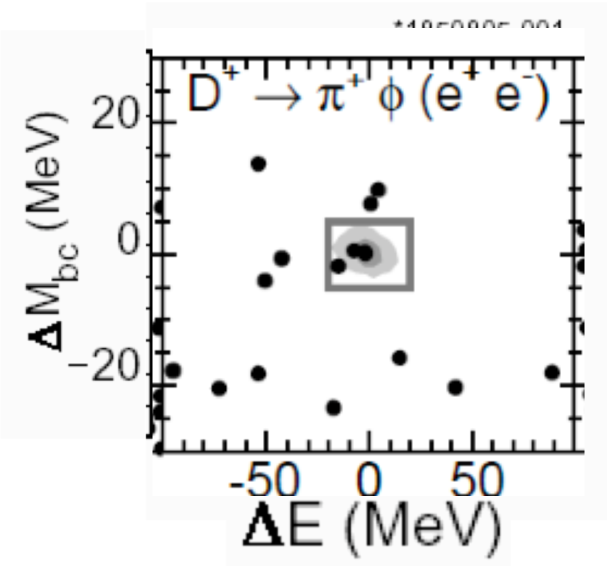
D0 Results

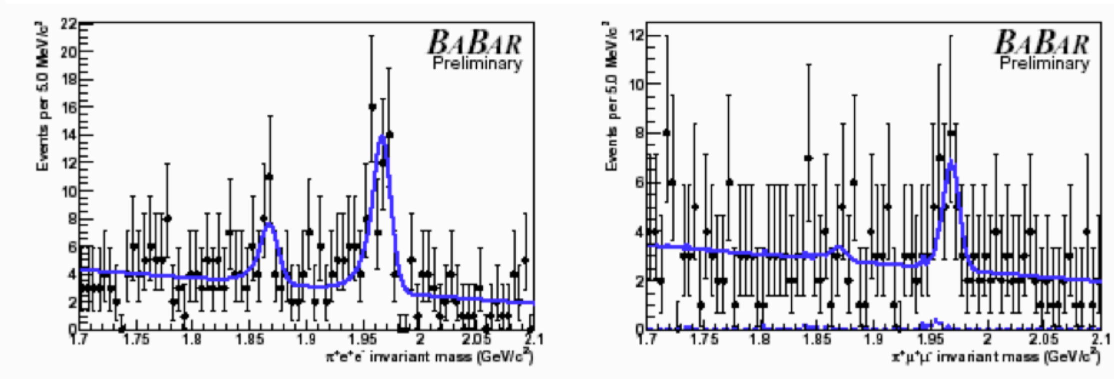


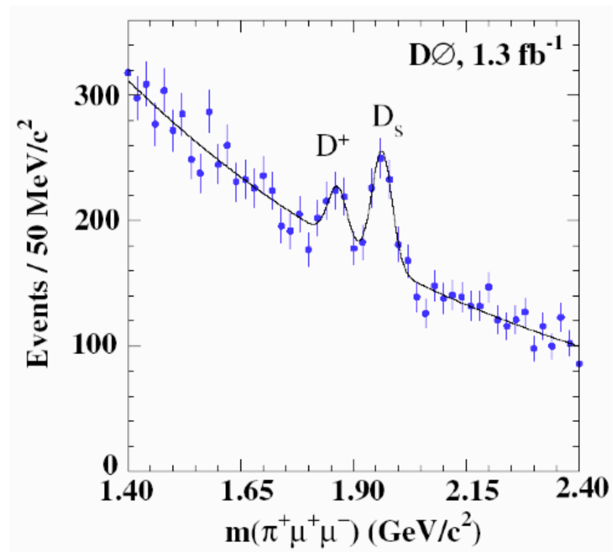
$$B(D^+ \to \pi^+\phi \to \pi^+\mu^+\mu^-) = (1.8 \pm 0.5 \pm 0.6) \times 10^{-6}$$

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

Some Comparisons: D → φπ+



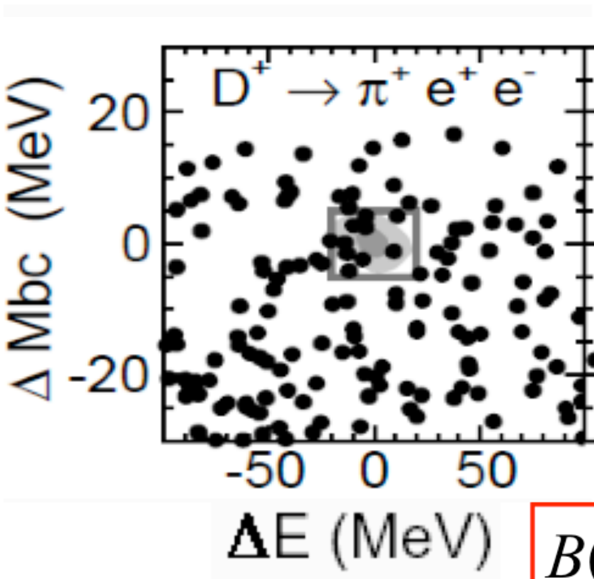


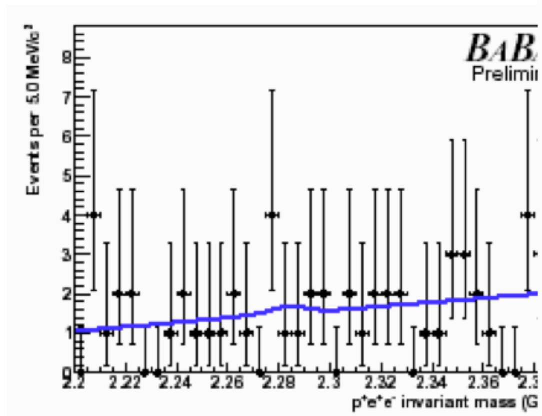


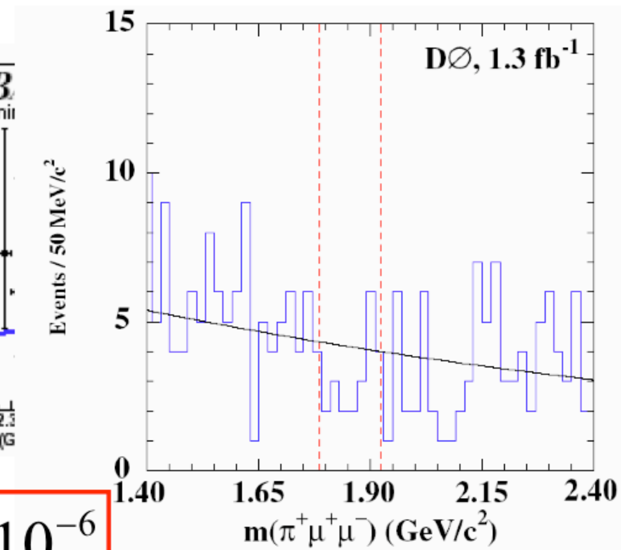
Milestone I: All three have reached sensitivity to see $\phi\pi$ in the $ll\pi$ channel

Some Comparisons: c → ull

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







$$B(\Lambda_c \rightarrow p e^+ e^-) < 3.6 \times 10^{-6}$$

$$B(D^+ \rightarrow \pi^+ e^+ e^-) < 5.9 \times 10^{-6}$$

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

Some Comparisons: c → ull

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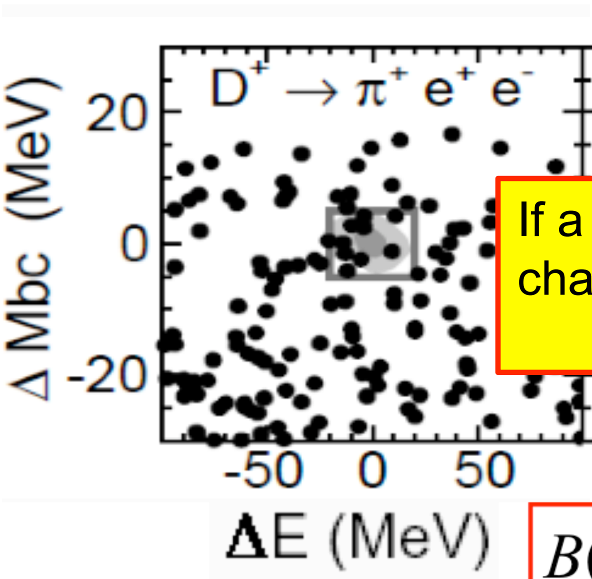

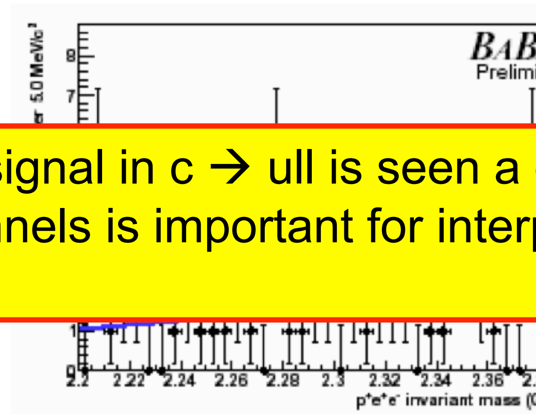

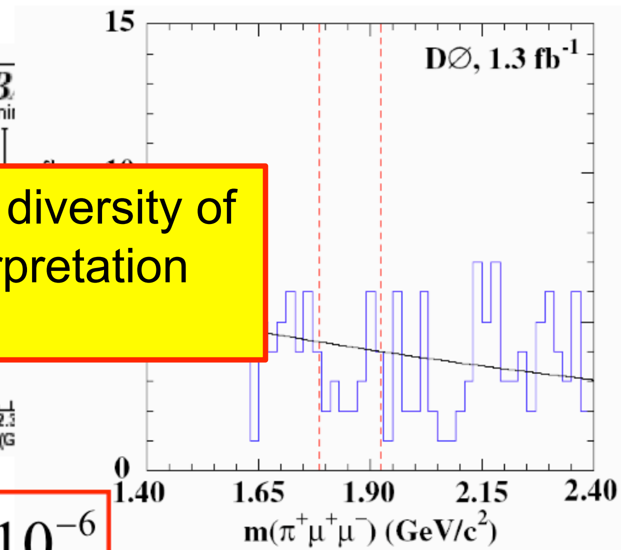

If a signal in c → ull is seen a diversity of channels is important for interpretation

$$B(\Lambda_c \to p e^+ e^-) < 3.6 \times 10^{-6}$$

$$B(D^+ \to \pi^+ e^+ e^-) < 5.9 \times 10^{-6}$$

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

Expectations & Conclusions

- Rare Charm Decays are a unique probe for New Physics
- Very diverse set of results from 5 experiments at 3 energies
  - Other than CLEO-c - only fraction of data analyzed
- Leptonic Decays - ~10^{-7} limits from Belle (660 fb^{-1})
  - Comparable results expected from CDF with current data sample
  - Comparable results expected from BESIII with 10 fb^{-1}
  - LHCb expects to set limit of 4×10^{-8} in 100 pb^{-1}
- Radiative Decays – $\rho\gamma, \omega\gamma, \gamma\gamma$ limits from CLEO-c ~10^{-5}
  - 12x data (eventually from BESIII) – 10^{-7} limit expected
  - Note in SM long distance effects $D \rightarrow \gamma\gamma \approx D \rightarrow \mu\mu$ so $D \rightarrow \gamma\gamma$ determines size of New Physics window in $D \rightarrow \mu\mu$
- c → ull – variety of limits from CLEO, Babar, D0 ~10^{-6}
  - Expect LHCb will do better than 10^{-7} before BESIII results ~10^{-7}
    - LHCb sensitivity studies not yet performed