Searching for New Physics in Beauty and Charm

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SMU HEP Seminar
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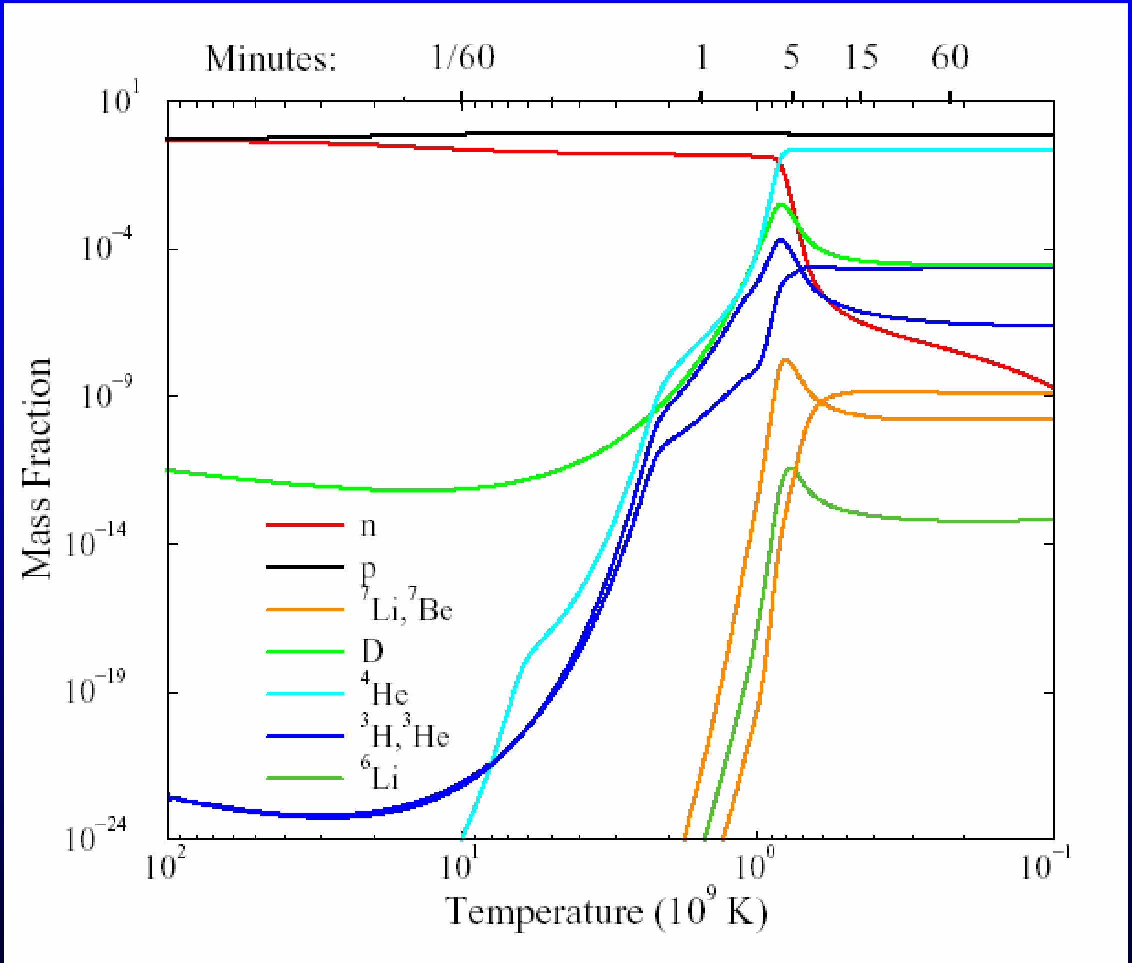
What is new physics?

- Current theories explain the entire dynamics of our universe from about 1 second after birth.
- What was happening before the 1st second?
  - New physics is what ever it takes to answer this question.

Matter at t ≥ 1 second: BBN

General Relativity + Astronomy + Particle Physics + Nuclear Physics

Evolution of light elements in first hour of the universe



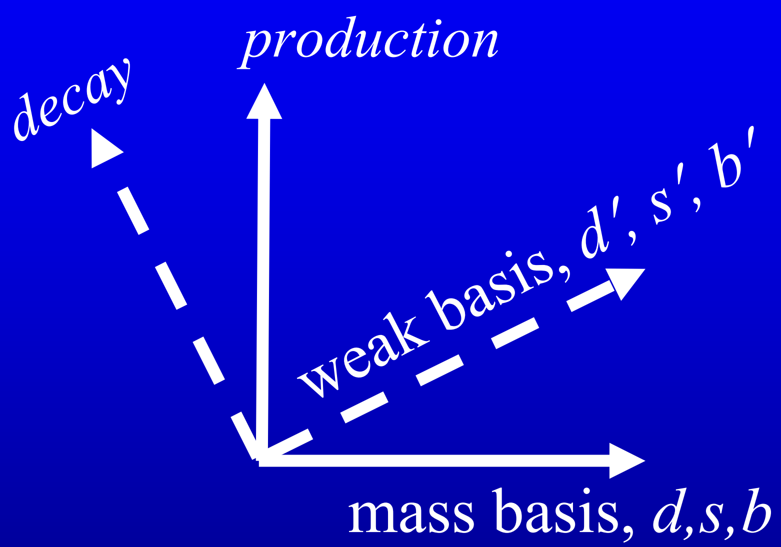
But:

Small excess of baryons is an initial condition of BBN, not a prediction.

No explanation of the evolution of anti-elements

Burles, Nollett, Turner astro-ph/99003300

CPV: Standard Model to the rescue?



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

quarks: $d'_i = V_{ij}\, d_j$

antiquarks: $\overline{d'_i} = V_{ij}^{*}\,\overline{d_j}$

$$\mathbf{V_{ub} \neq V_{ub}^{*},\ V_{td} \neq V_{td}^{*} \Rightarrow \text{CPV}}$$

Provides a mechanism to generate a net baryon number through decay of heavy to light particles

Standard Model CPV

Three properties govern size of CPV in SM:

$$Mag(\text{CPV}) \approx f(m^2_j - m^2_i) \times f(\theta_{ij}) \times \sin\phi_{CP}$$

- quarks:
  - Large mass splitting ↑
  - Small mixing angles ↓
  - Large ϕ_{CP} ↑

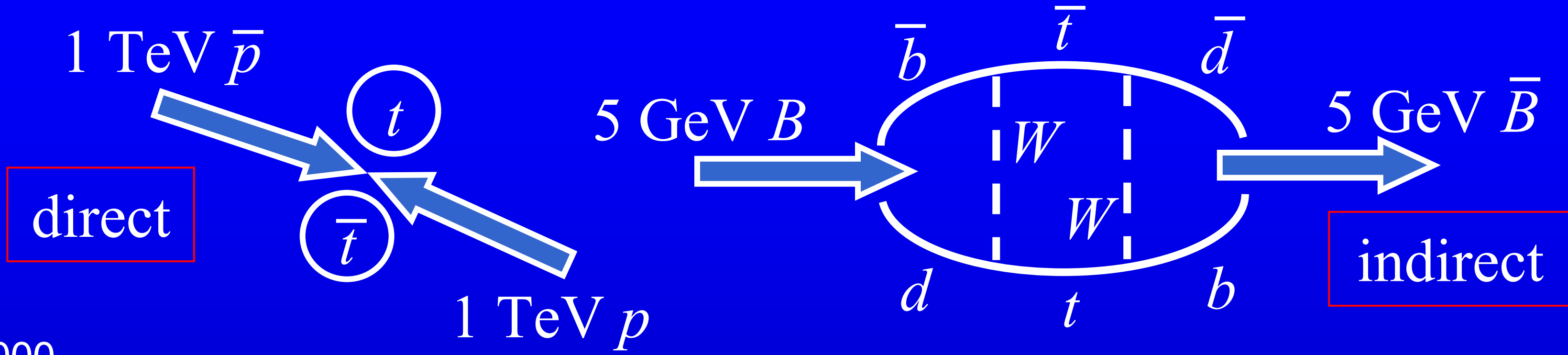
~15 orders of magnitude too small
Huet, Sather PRD51 379 (1995)

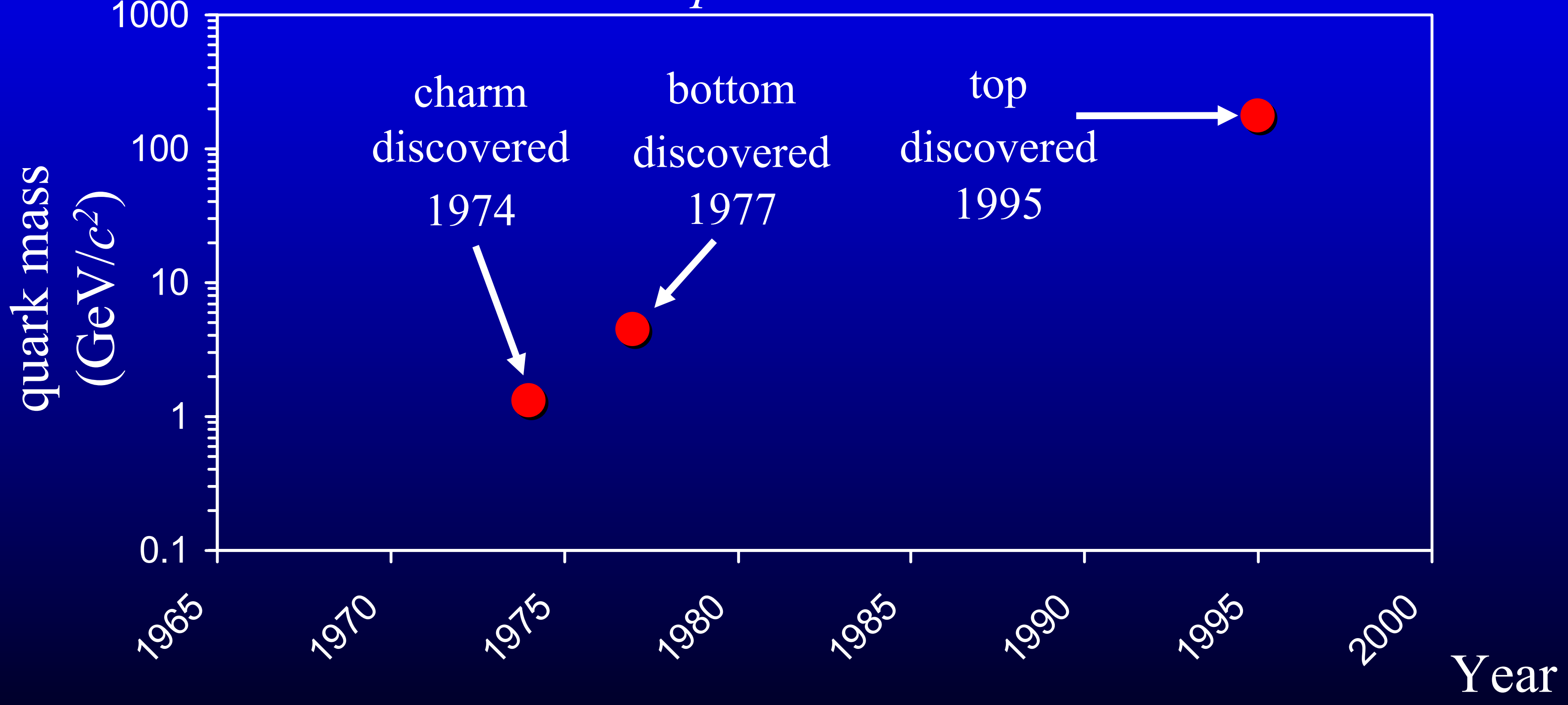
- neutrinos:
  - small mass splitting ↓
  - large mixing angles ↑
  - ϕ_{CP} ?

Jury still out

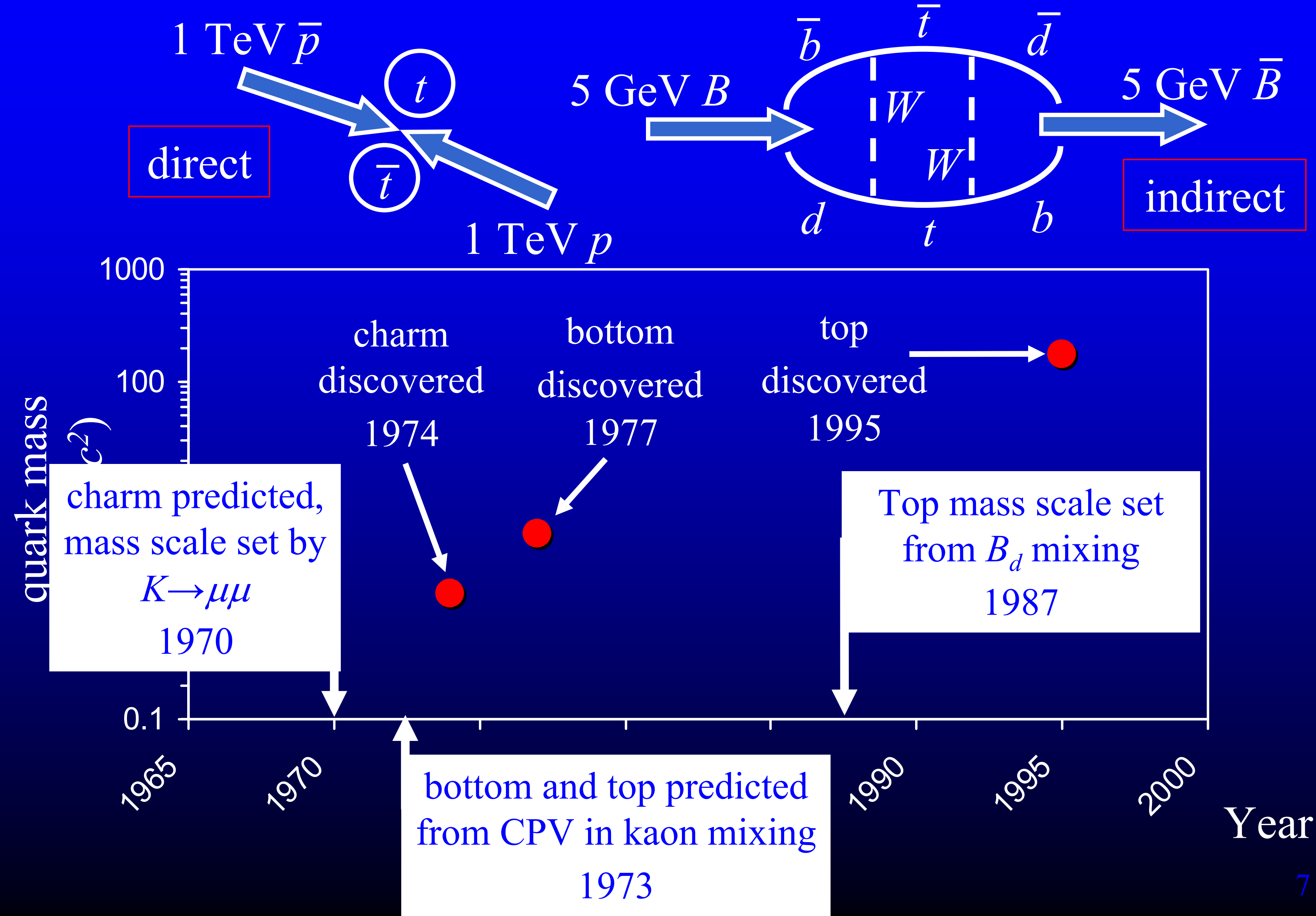
Need new sources of CPV!
More generations, more interactions….new particles

Direct versus Indirect

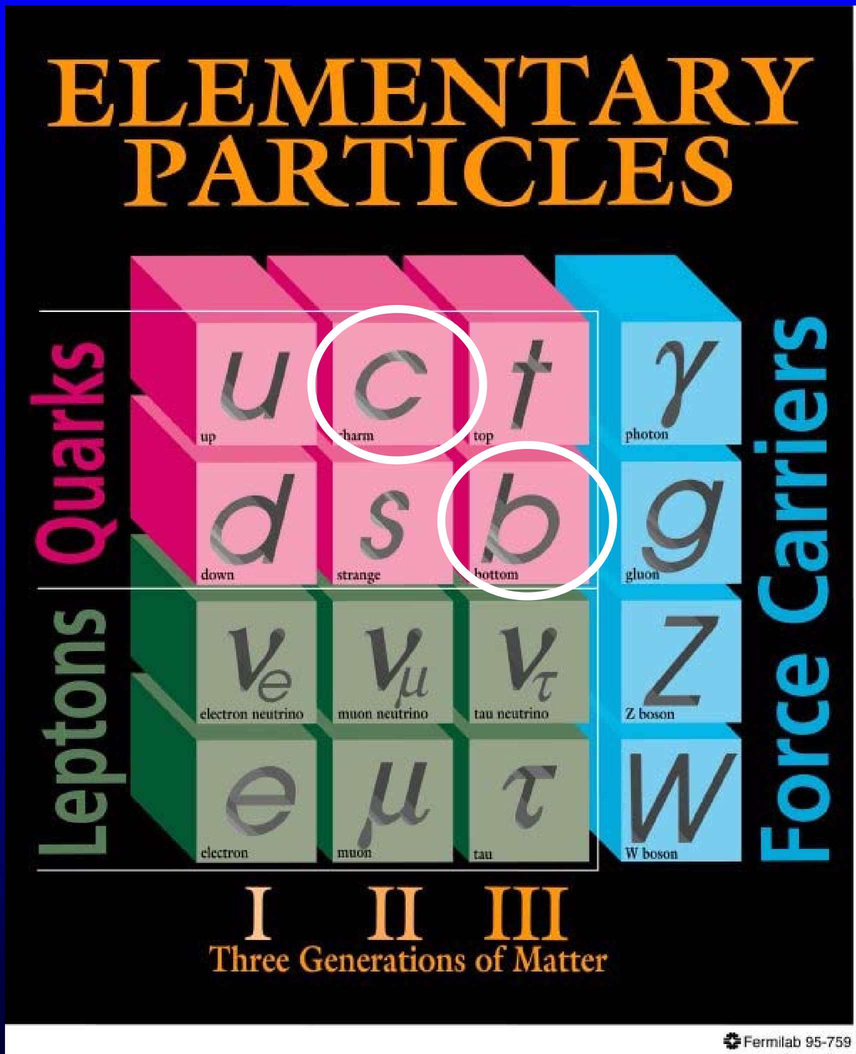




Direct versus Indirect



Cast of Characters



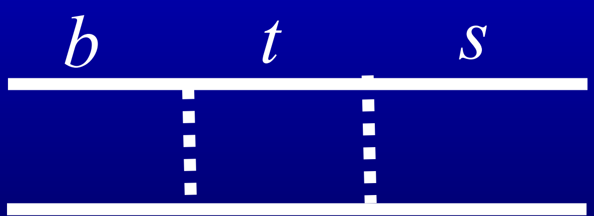
Mesons

B^0: ($\bar{b}\ d$), B_s: ($\bar{b}\ s$),

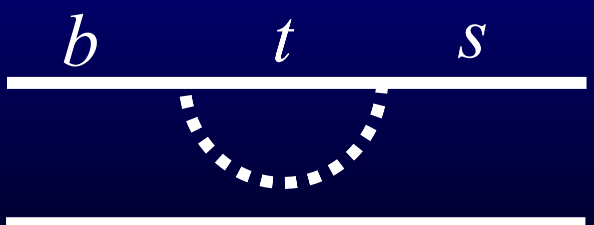
D^+: ($c\ \bar{d}$), D_s: ($c\ \bar{s}$)

Neutral Flavor Changing Interactions

Box:



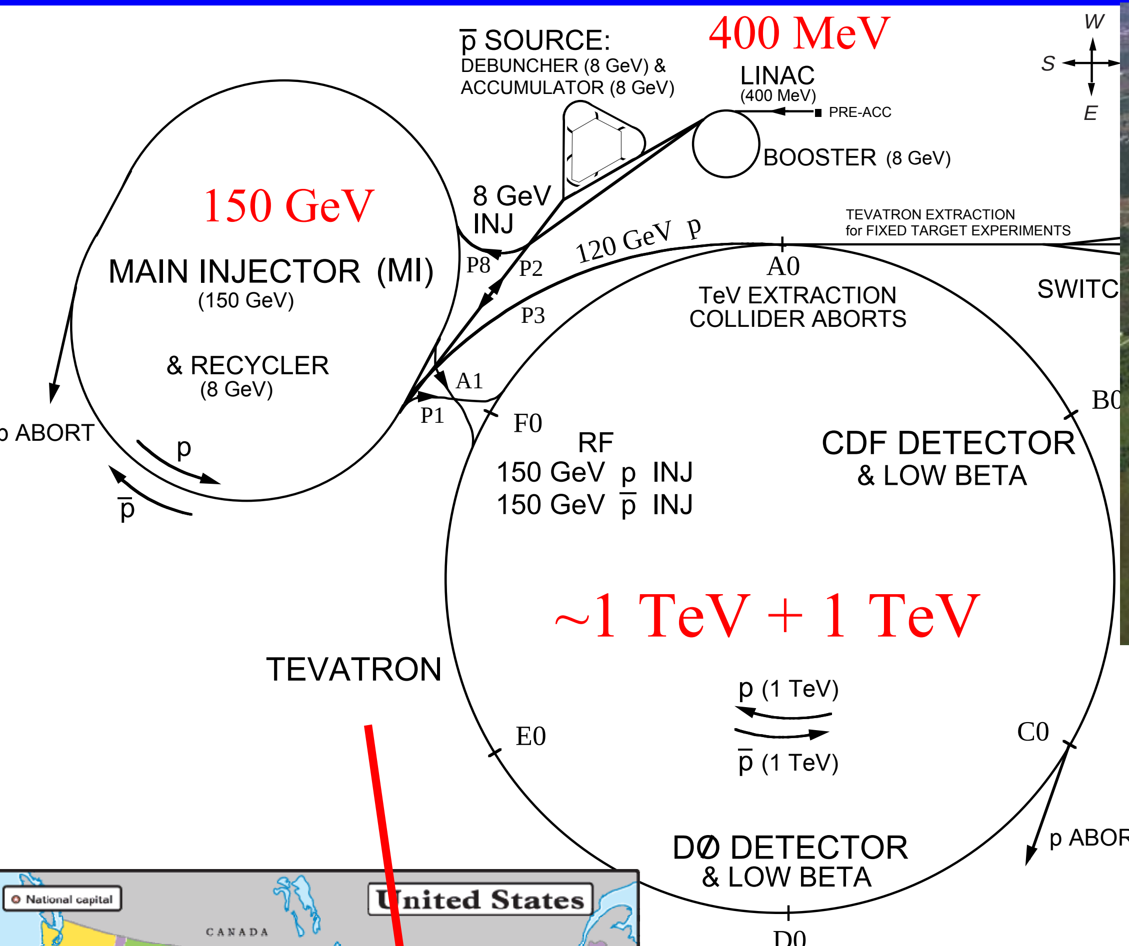
Penguin:

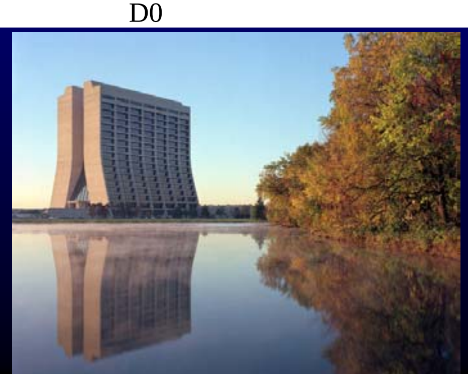


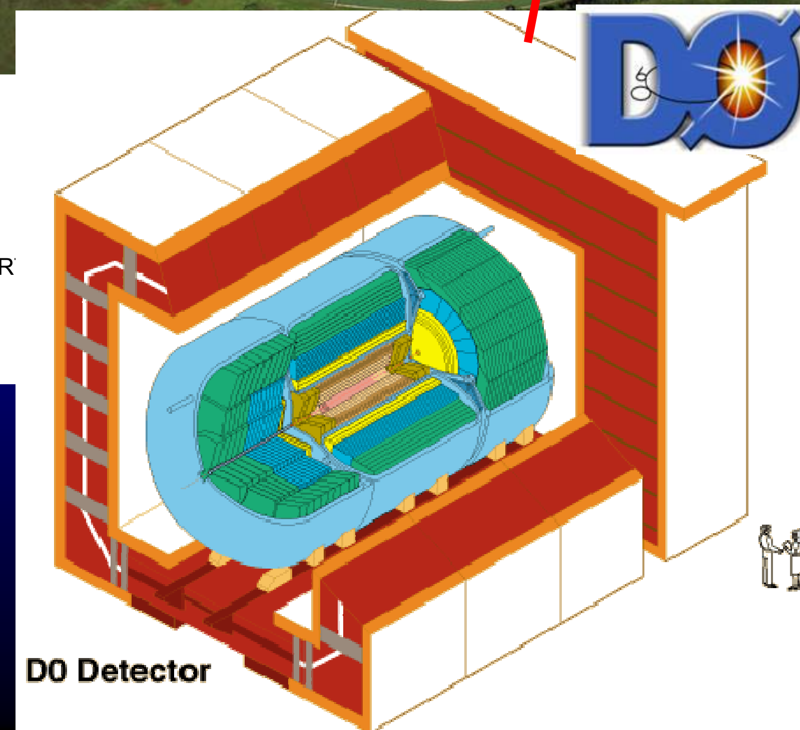
$Rate \approx (m_t / m_W)^2$

Apparatus

The Tevatron and DØ Detector







~700 Scientists

83 institutions

20 countries

4 continents

(big parties, good food, exotic meeting locations…)

~70 Member B group with ~20 people working on mixing and CPV
~2 working on charm

Comparison: ~100-300 member groups working on mixing and CPV in the Belle, BaBar, CDF, and LHCb collaborations.

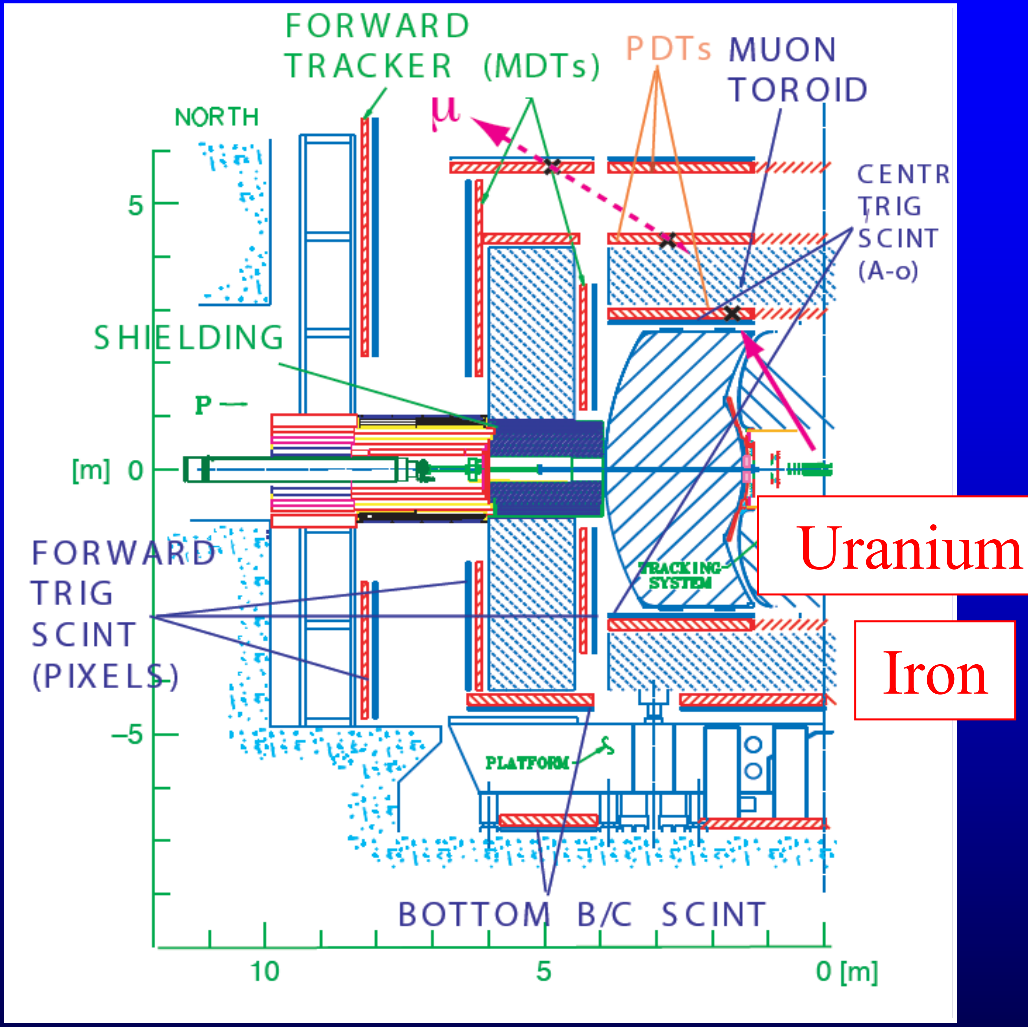
Why the Tevatron?

Don't they do *B* physics at *B* factories now?

	B factory on $\Upsilon(4S)$ @ $L = 10^{34}\ cm^{-2}s^{-1}$	Tevatron @ $L = 10^{32}\ cm^{-2}s^{-1}$
B production rate	~10 Hz	~1 kHz
B_s production rate	0	~100 Hz
Longitudinal boost	~0.5	~1-2
Transverse boost	~0	~1-2

Tevatron is the only B_s factory

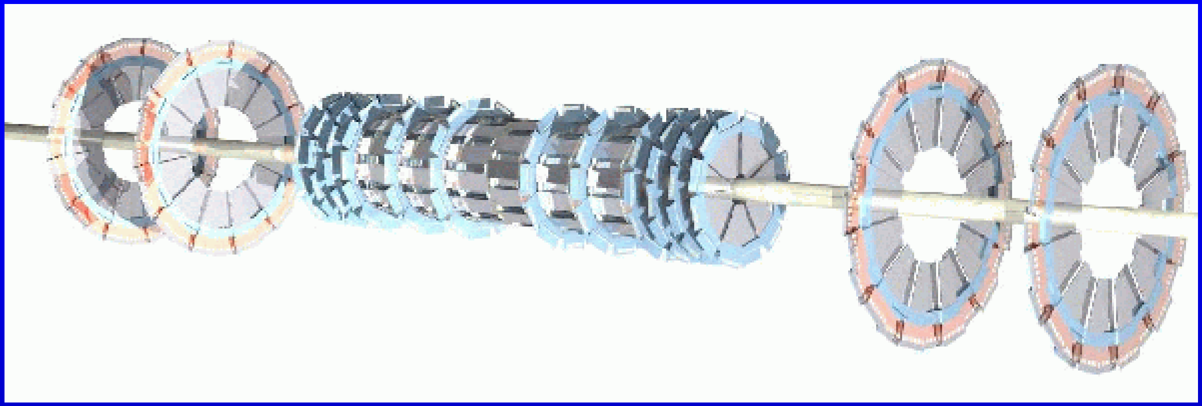
Why DØ?

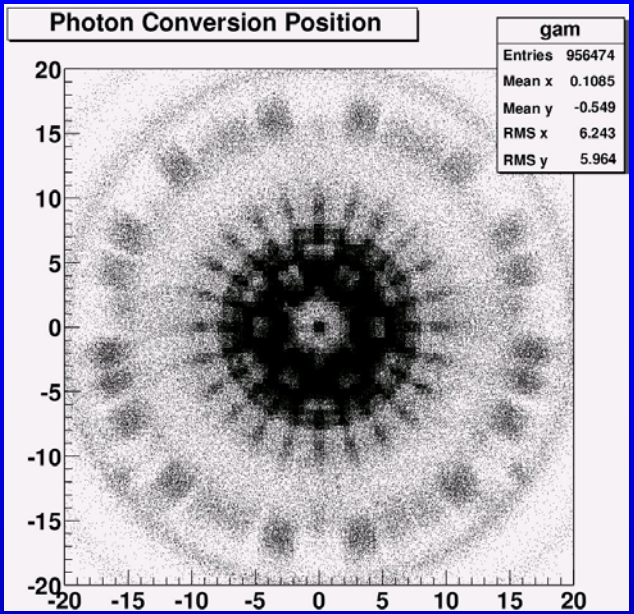


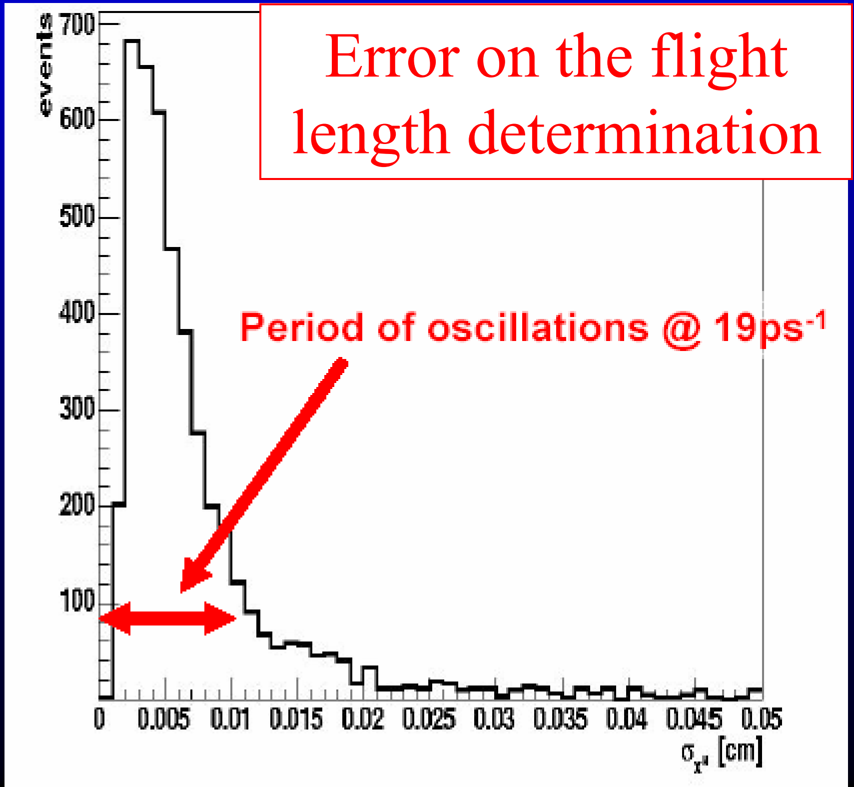
Excellent muon identification

Large semileptonic *B* samples ideal for mixing and CPV studies

Why DØ?



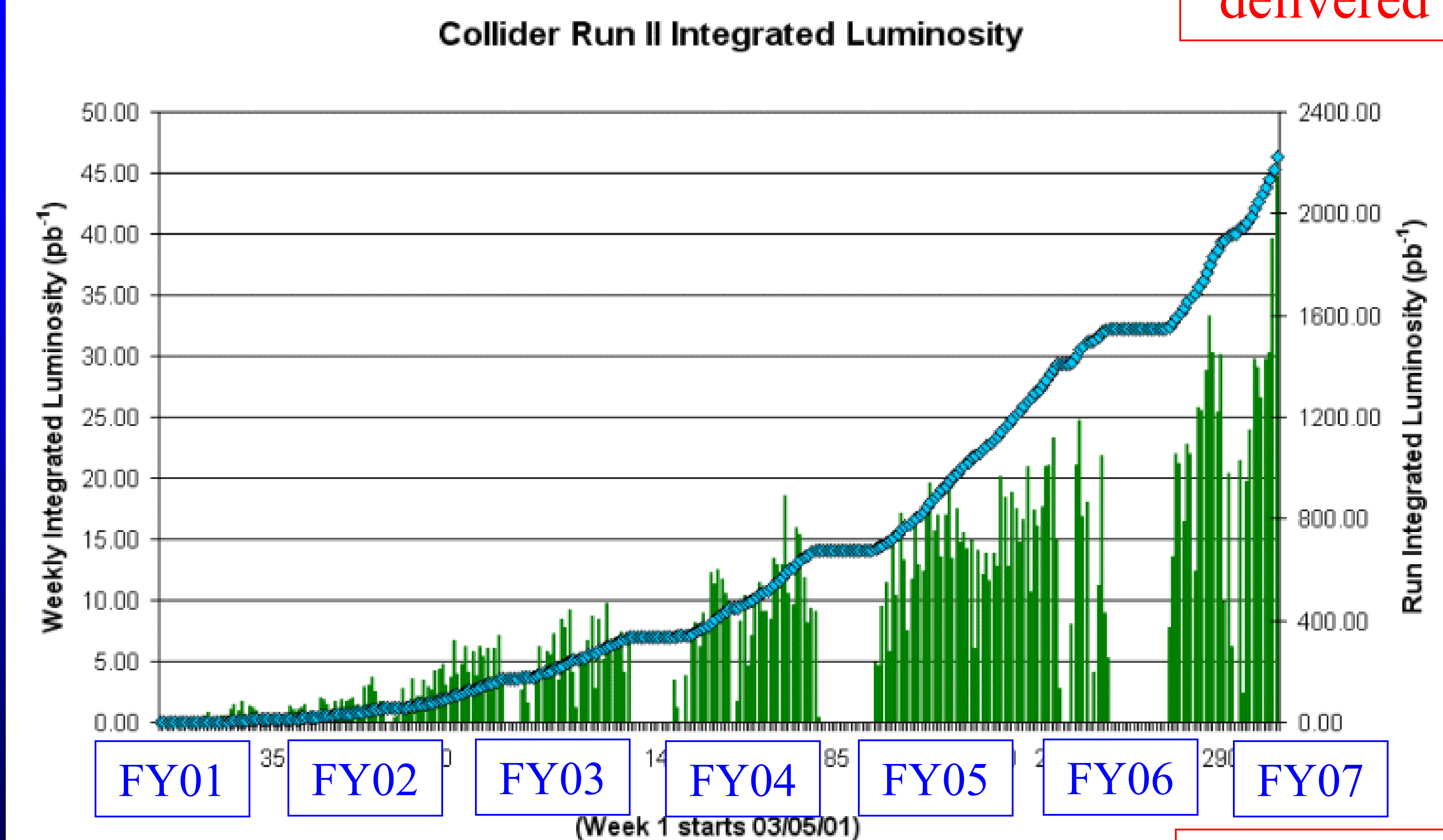




Excellent vertexing capabilities for flight length determination

Just enough resolution to probe SM expected value of the B_s mixing frequency

Tevatron Data Set



>2.2 fb^{-1} delivered

Run IIa: 1.3 fb^{-1} on tape

Run IIb: 700 pb-1 analyzed

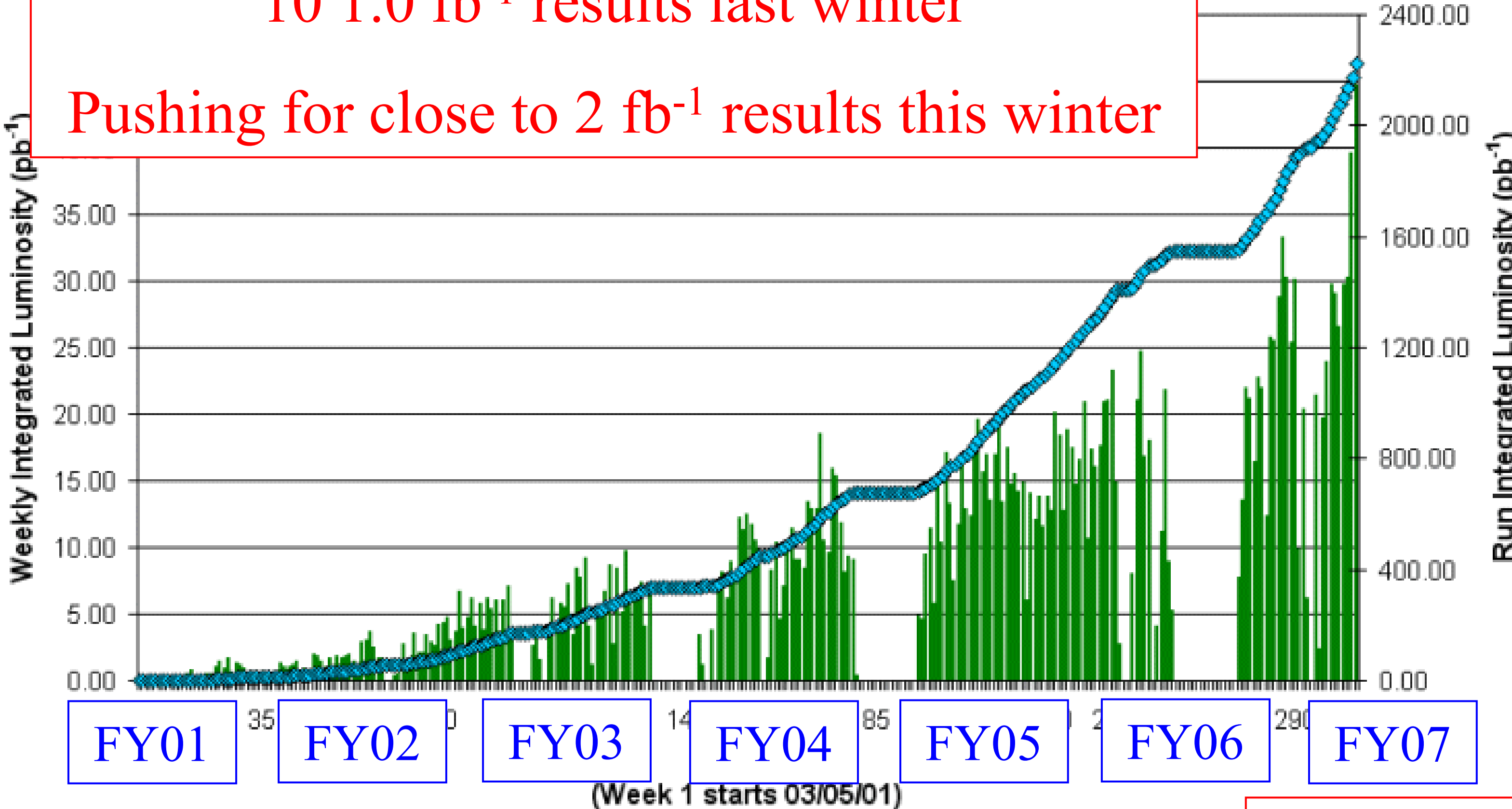
Tevatron Data Set

$>2.2\ fb^{-1}$ delivered

Fast turn around in the heavy flavor group

10 1.0 fb^{-1} results last winter

Pushing for close to 2 fb^{-1} results this winter



Run IIa: 1.3 fb^{-1} on tape

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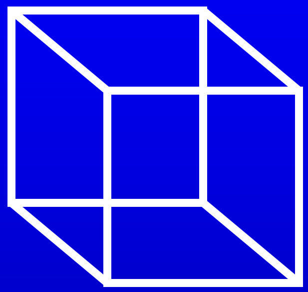
B_s Mixing

Neutral Meson Mixing



Is the cube going into the page or coming out of the page?

$$|cube,1\rangle = \frac{1}{\sqrt{2}}\left(|in\rangle + |out\rangle\right)$$

$$|cube,2\rangle = \frac{1}{\sqrt{2}}\left(|in\rangle - |out\rangle\right)$$

Time Evolution of a two state neutral meson system:

$$|M(t)\rangle_1 = \left(g^+(t)|M\rangle + g^-(t)|\overline{M}\rangle\right)$$

$$|M(t)\rangle_2 = \left(g^-(t)|M\rangle + g^+(t)|\overline{M}\rangle\right)$$

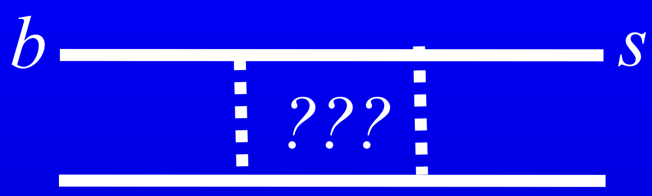
$$|g^\pm(t)|^2 = \frac{e^{-\Gamma t}}{2}\left[\cosh\left(\frac{\Delta\Gamma}{2}t\right) \pm \cos(\Delta m t)\right]$$

Matter and antimatter constantly talk to each other!

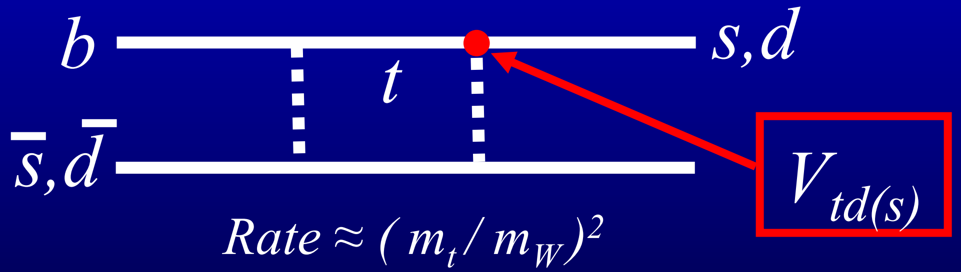
$\Delta\Gamma$: width(lifetime) difference, Δm: mass difference between states

Why Mixing?

- General rule of neutral flavor changing processes:
  - New physics:
    - Second order loop or box
    - New particles can enter the loop
    - SM contribution is suppressed



  - Precision SM tests:
    - no new physics? Measure fundamental Standard Model parameters
    - clean in *B* mesons
      - b quark is heavy,
      - top loop dominates.

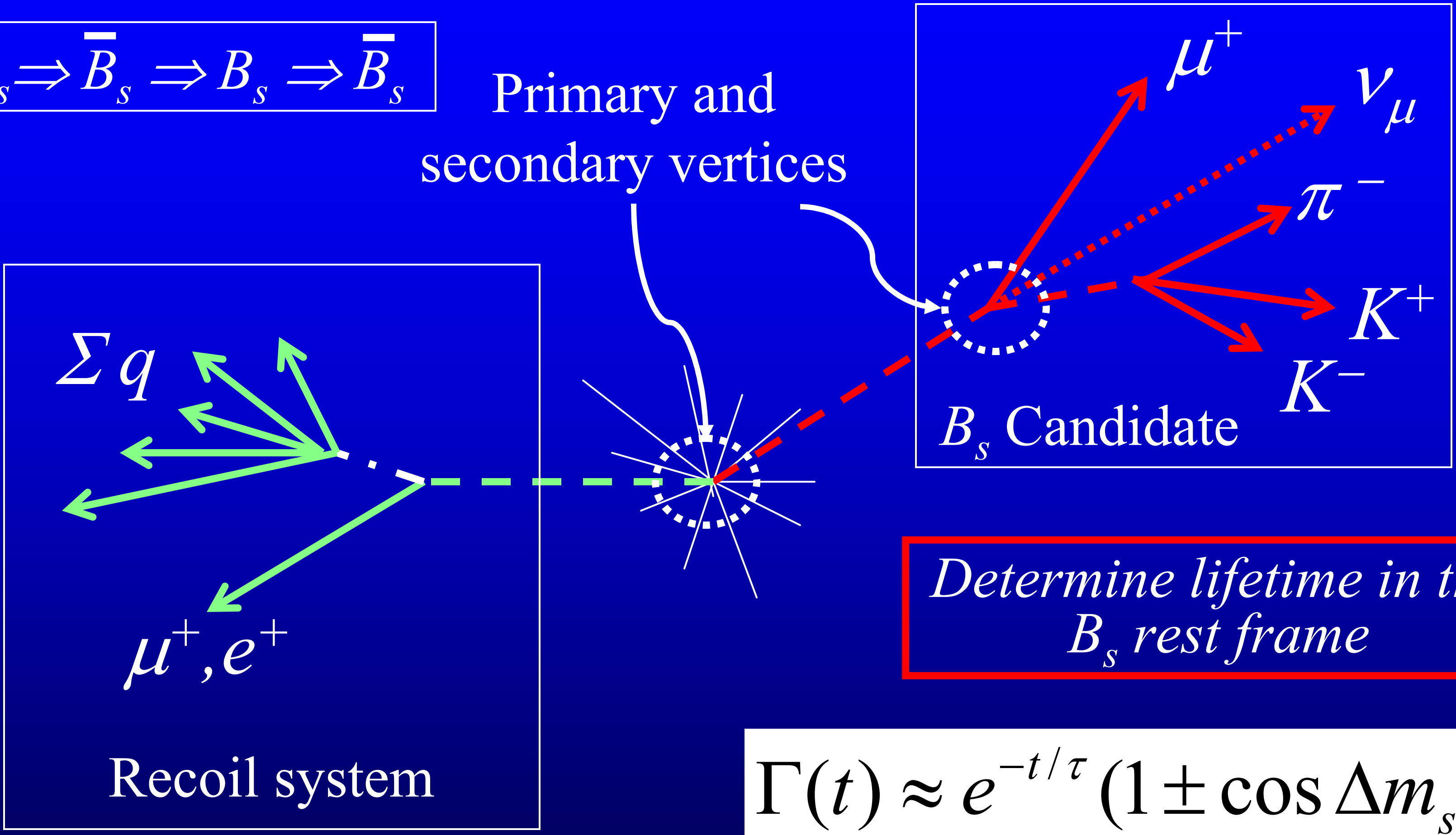


- Every measurement of mixing has lead to a major discovery:
    - *K*: CPV, 3rd generation, B_d: top mass, ν: neutrino mass

Analysis Overview

Reconstruct the B_s in a flavor specific final state

$$B_s \Rightarrow \bar{B}_s \Rightarrow B_s \Rightarrow \bar{B}_s$$



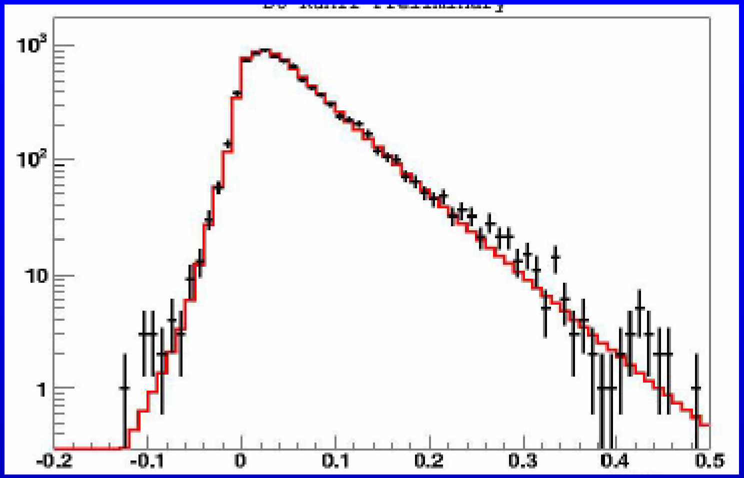
Determine lifetime in the B_s rest frame

$$\Gamma(t) \approx e^{-t/\tau}(1 \pm \cos \Delta m_s t)$$

Determine initial flavor by studying recoil system

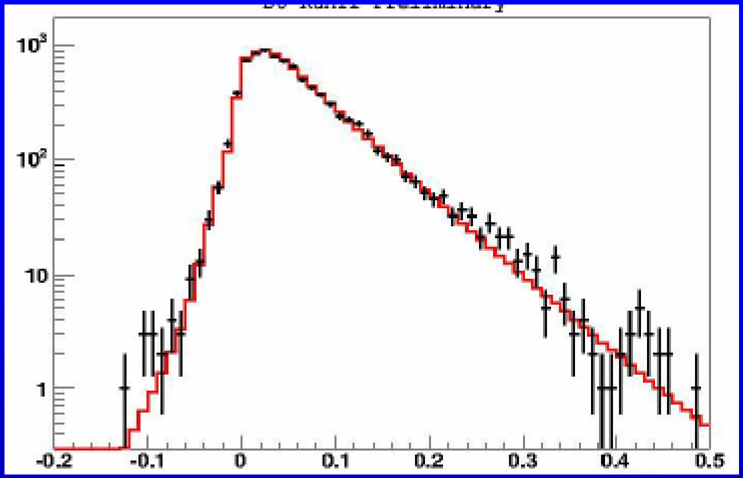
Extract the mixing frequency from the time dependence of mixed and unmixed samples

Mixing Frequency Extraction

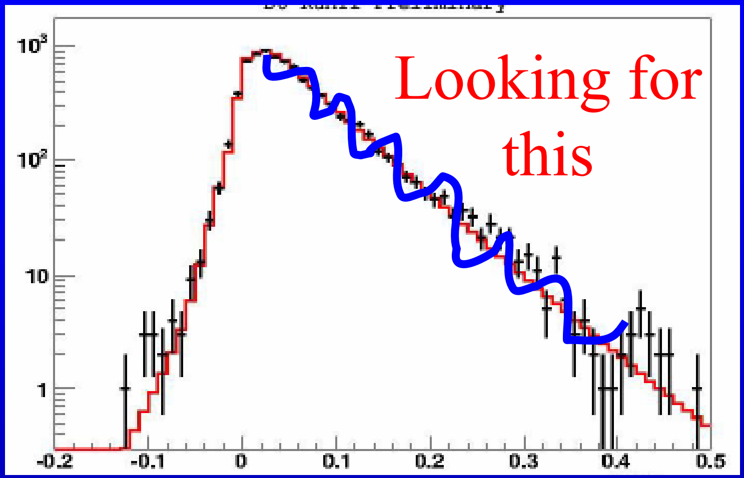


Reconstructed decay length (cm)

Mixing Frequency Extraction

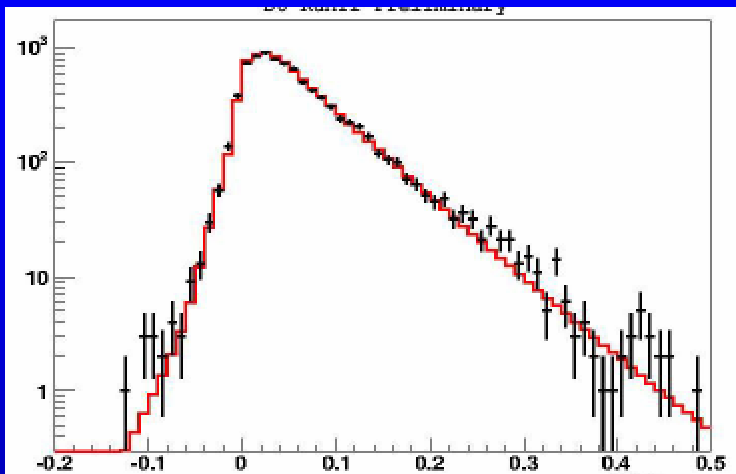


Reconstructed decay length (cm)



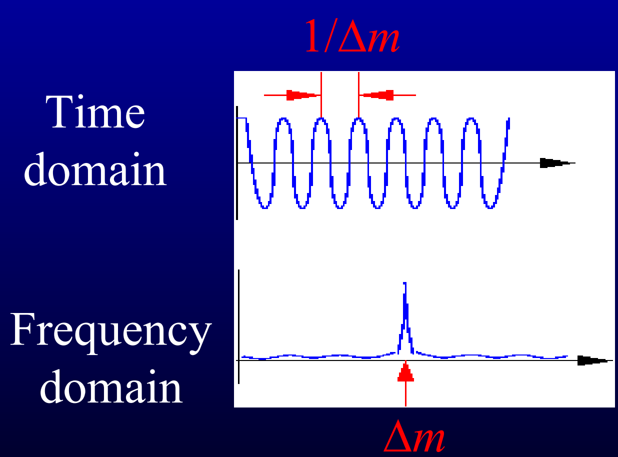
Reconstructed decay length (cm)

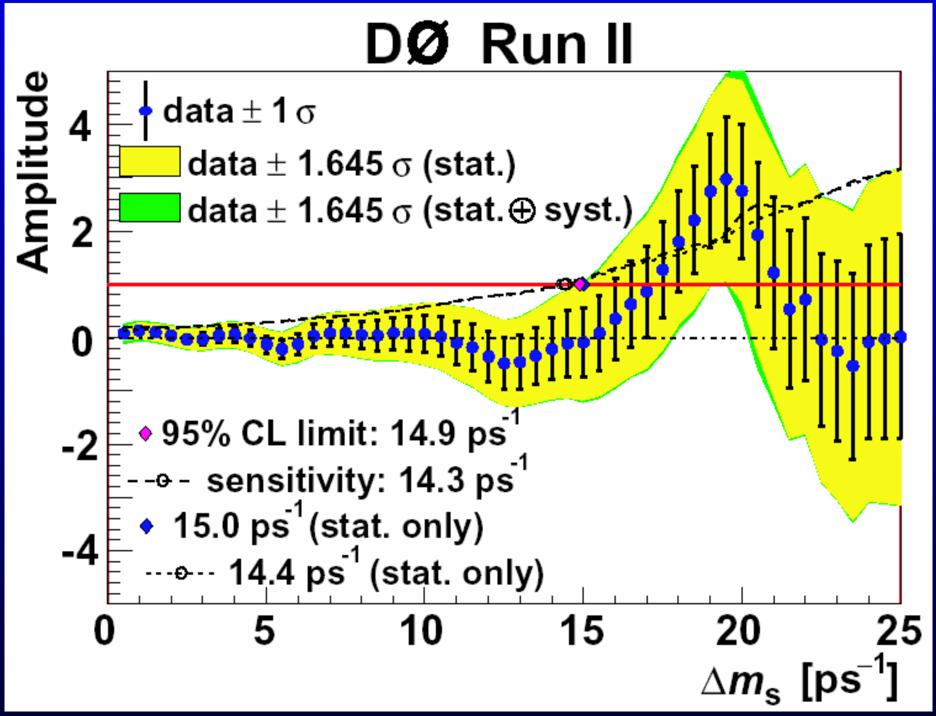
Mixing Frequency Extraction



Reconstructed decay length (cm)

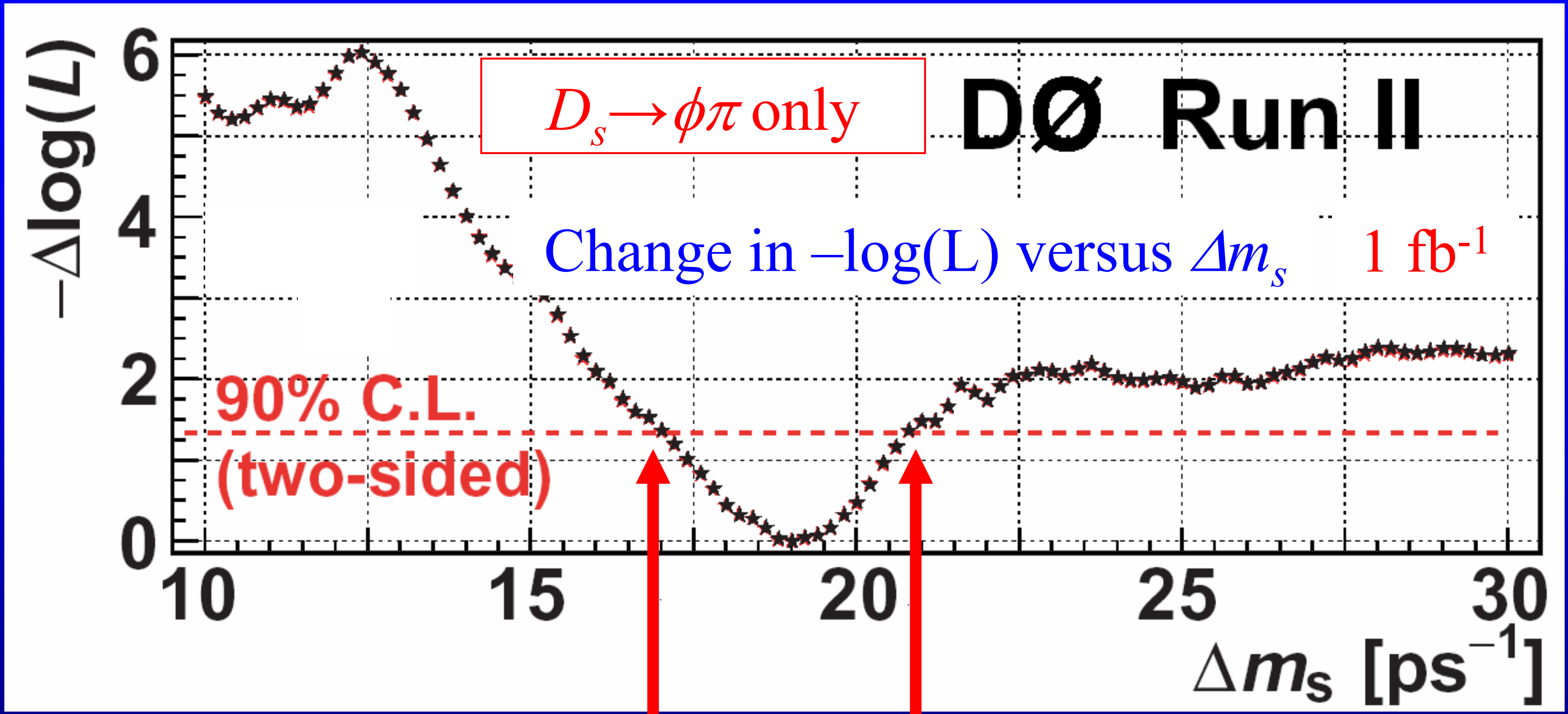
Perform a Fourier analysis of the decay length distribution to extract the mixing frequency





Power Spectrum for winter data set

Winter 06 Mixing Frequency Results



17 < Δm_s < **21 ps^{-1} @ 90% CL**

Maximum likelihood at Δm_s = 19 ps^{-1}

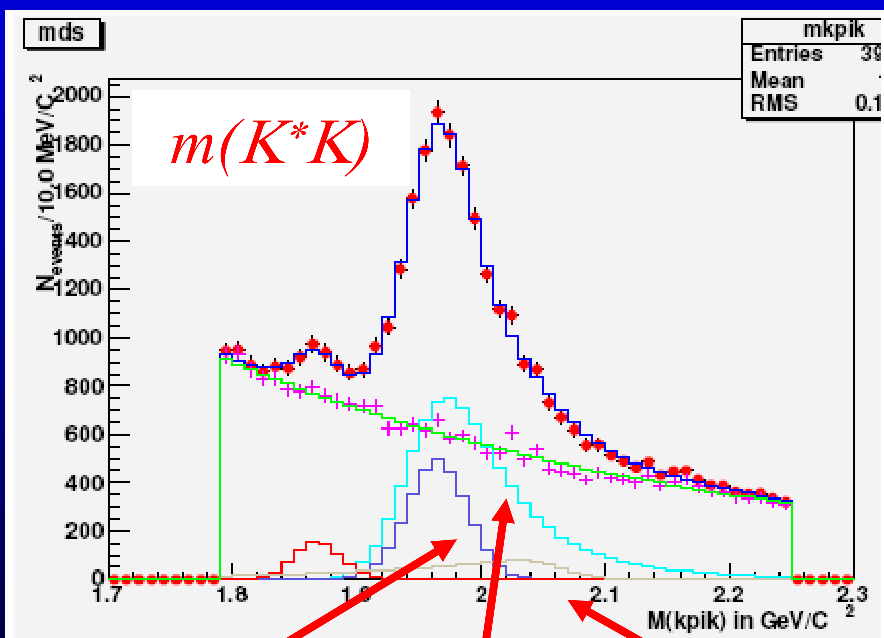
First time Δm_s bounded on both sides!!!!!

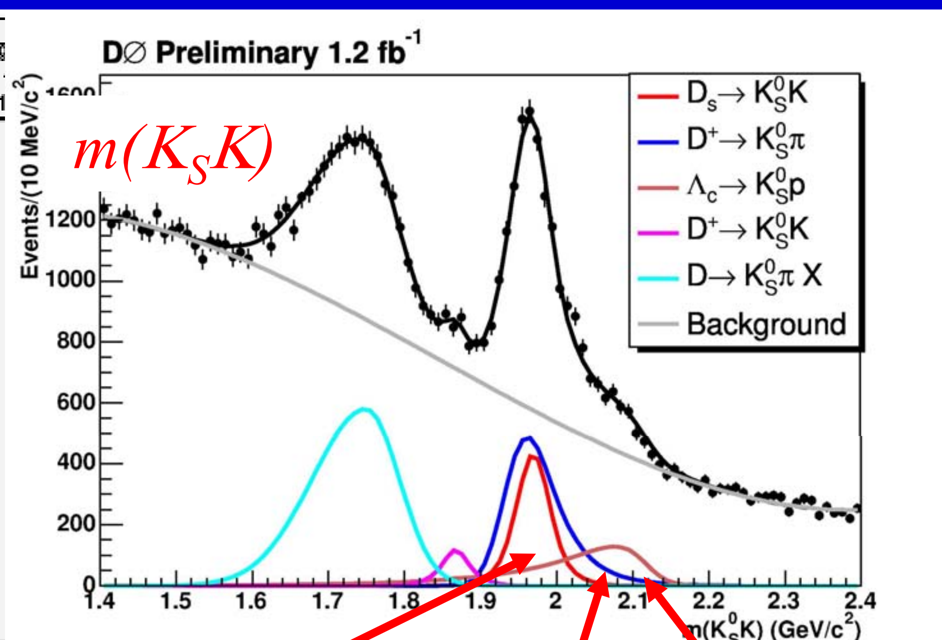
Reflections

Original results based on $D_s \to \phi\pi$

Needed to add more channels: K^*K and K_SK

Difficult to include these modes without particle identification

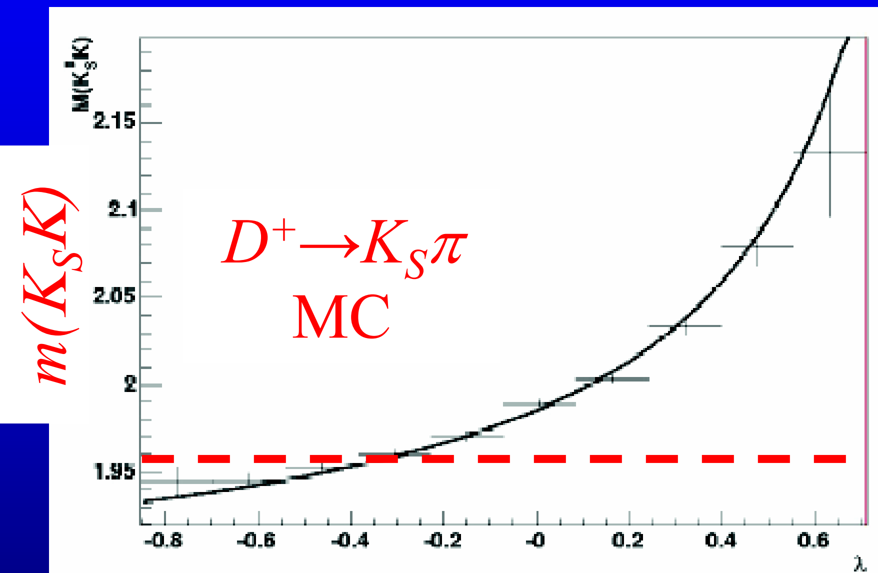




$D_s \to K^*K$ $D^+ \to K\pi\pi$ $\Lambda_c \to pK\pi$ $D_s \to K_SK$ $D^+ \to K_S\pi$ $\Lambda_c \to K_Sp$

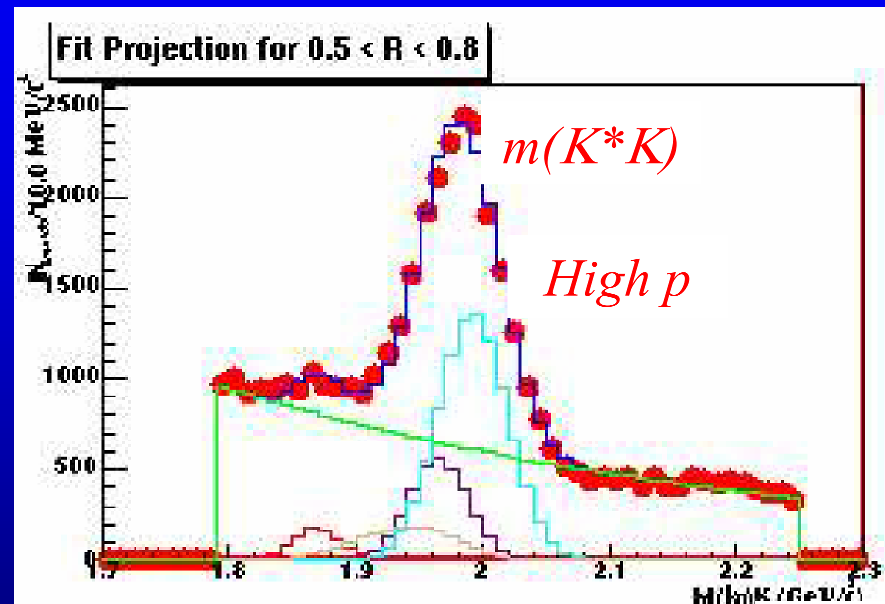
Taming Reflections

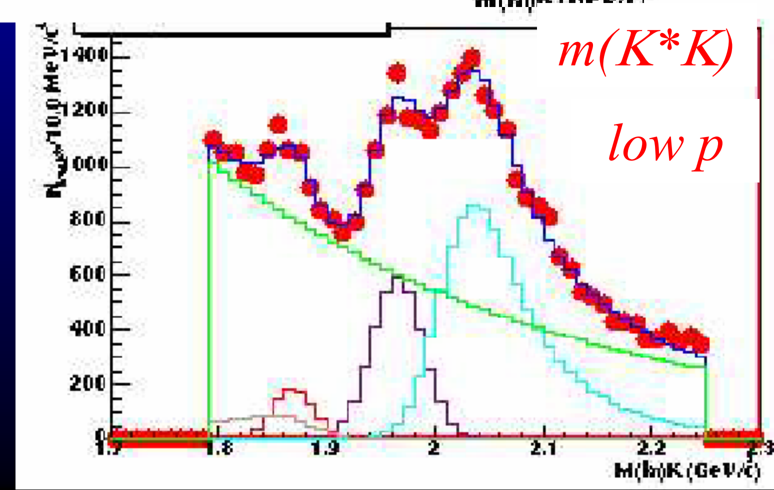
Take advantage of the fact that the mass shift is a function of the track momentum



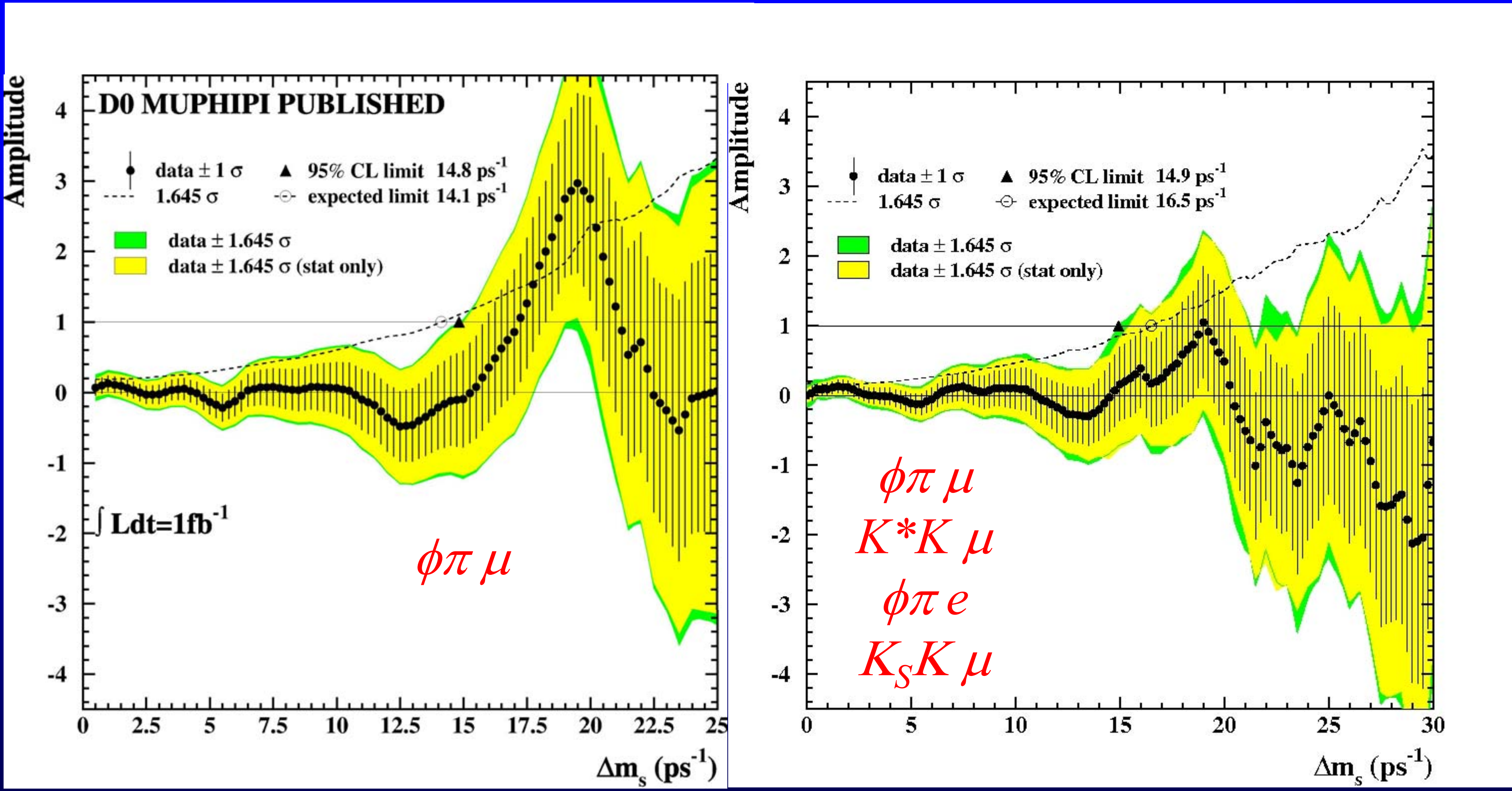
Momentum asymmetry between K_S and K candidate

$$M^2(\lambda) = M_{D^+}^2 + \left(\frac{2}{1-\lambda}\right)\left(M_K^2 - M_\pi^2\right)$$



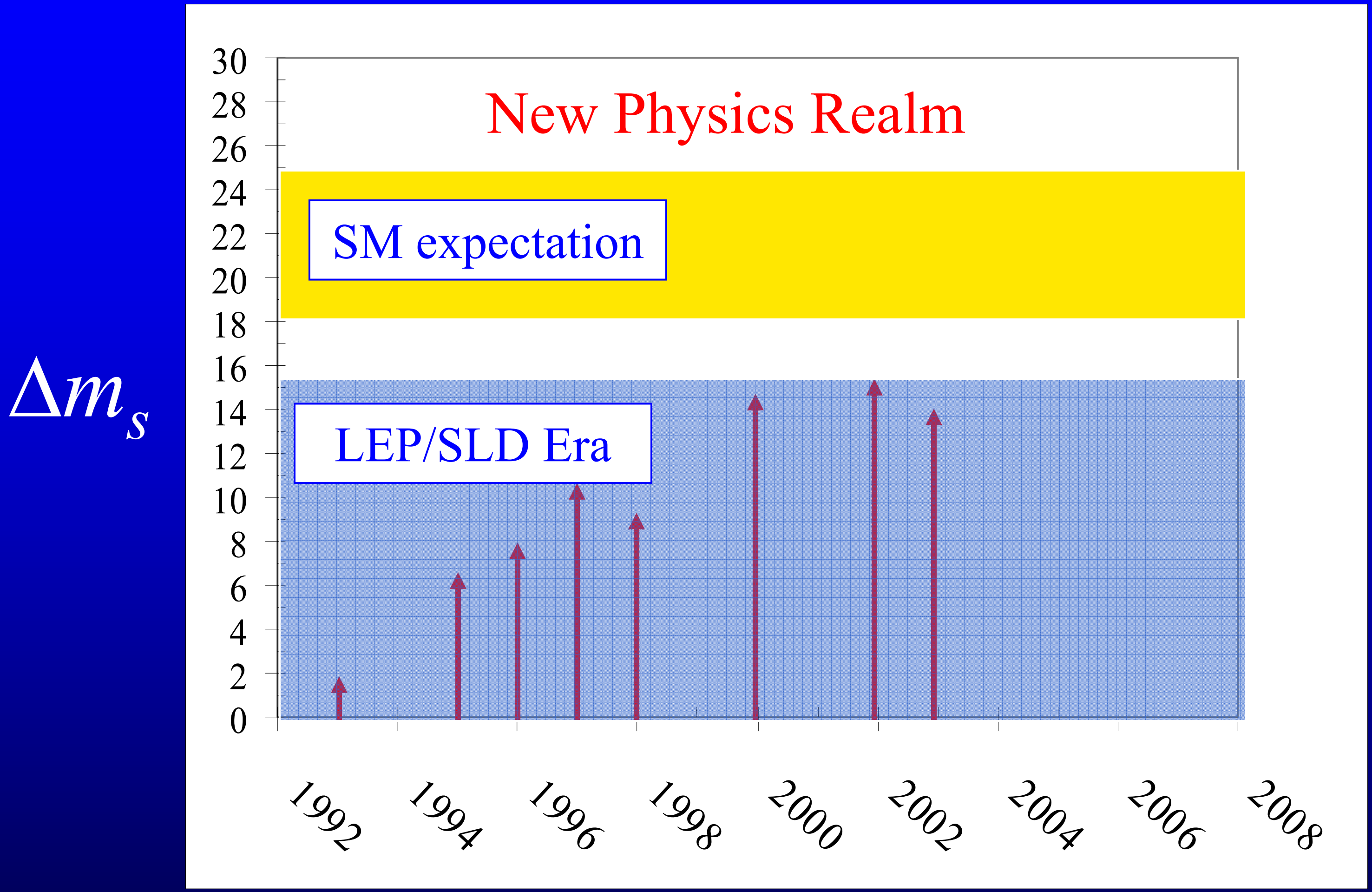


Fall 06 Results



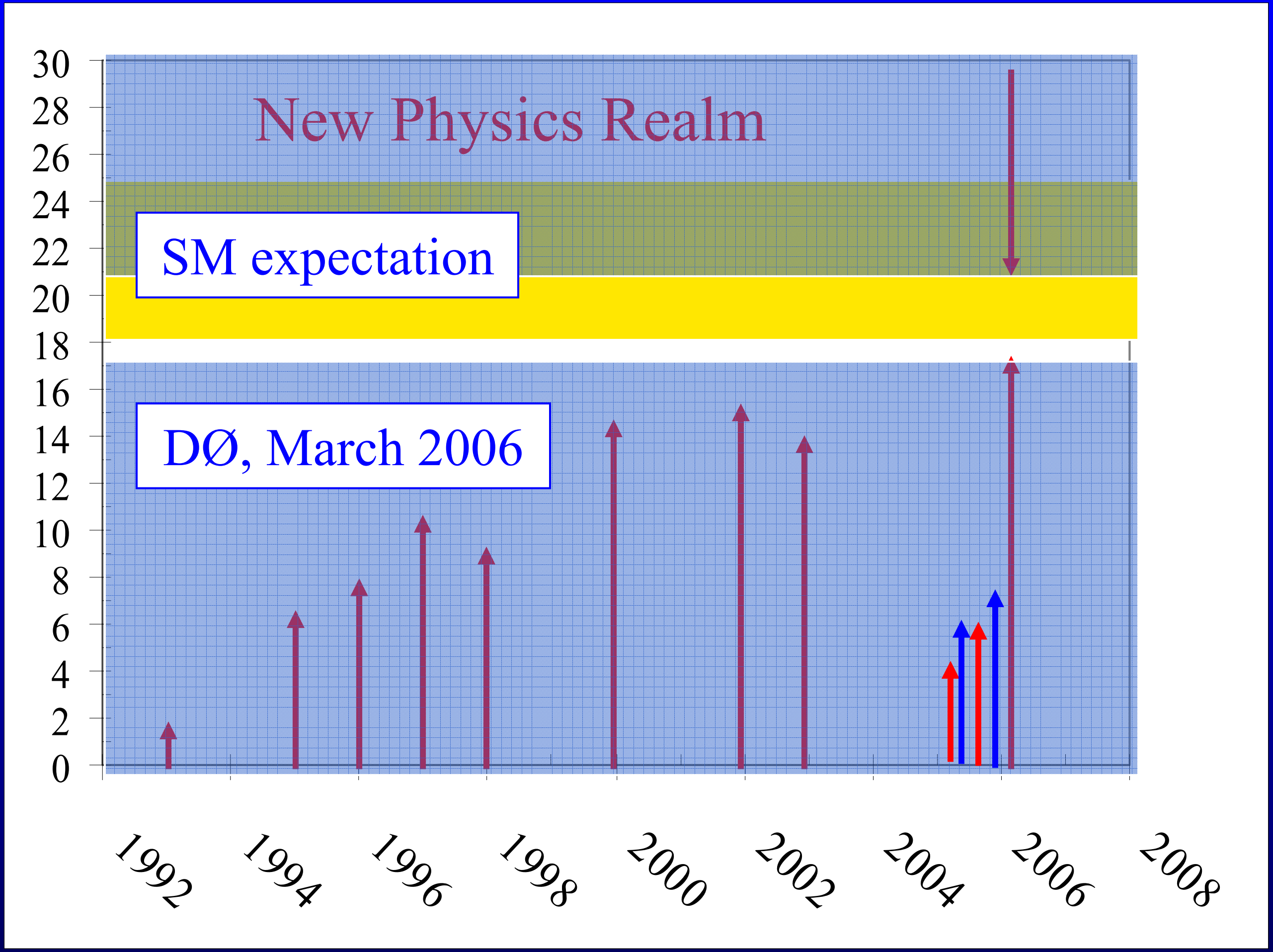
Extra data ‘cured’ fluctuation

Time Evolution of Results



LEP/SLD/CDF I were able to exclude values below about 15 ps^{-1}

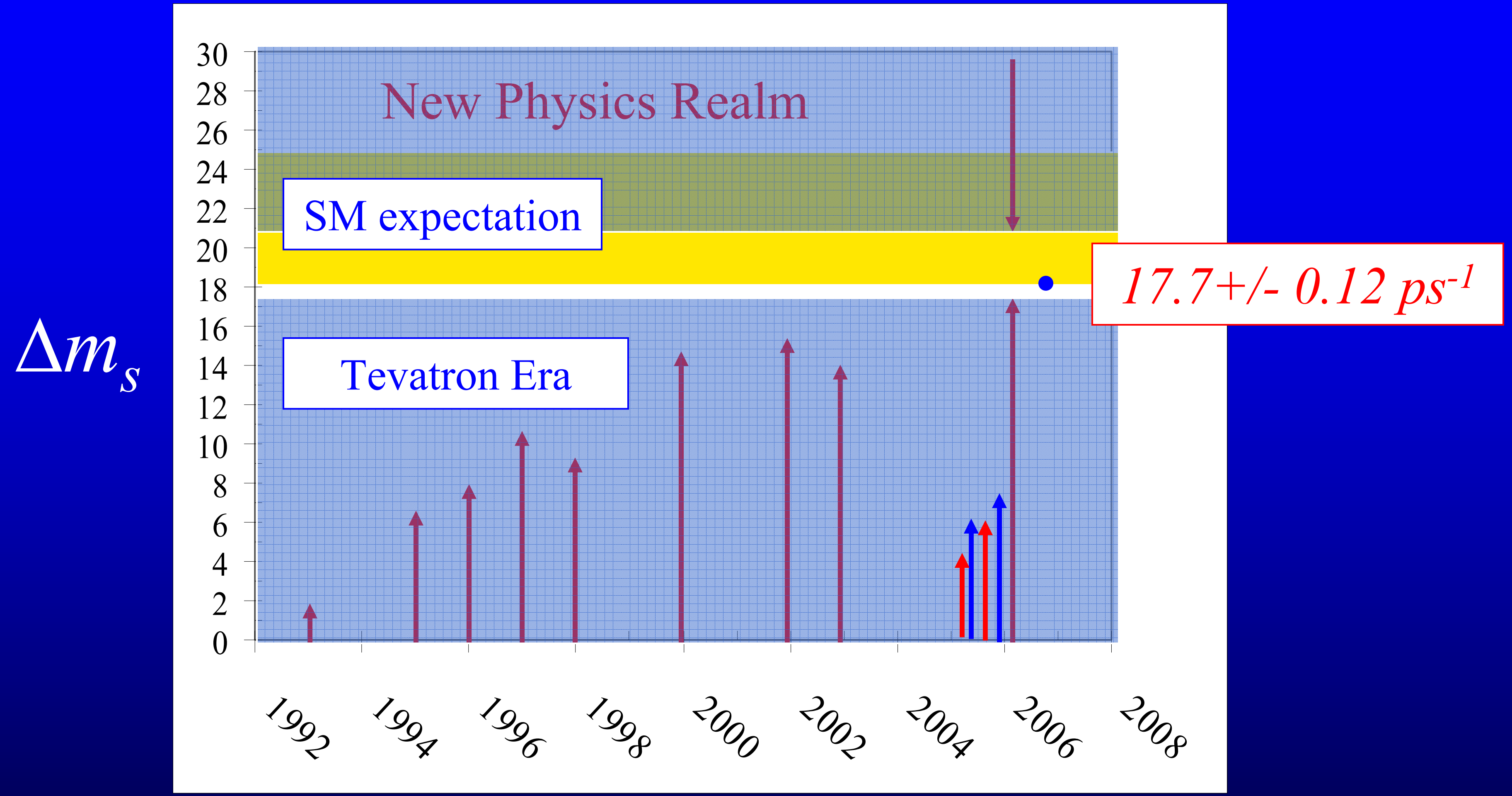
Time Evolution of Results



Δm_s

March 06: DØ provides first upper bound on the B_s oscillation frequency. Rules out large new physics effects at high confidence level. Still 5% chance of background fluctuation.

Time Evolution of Results



Confirmed by CDF in April 2006. >5σ measurement Fall 2006.

Closes the chapter on the magnitude of the Bs oscillation frequency.

Indirect Searches so far

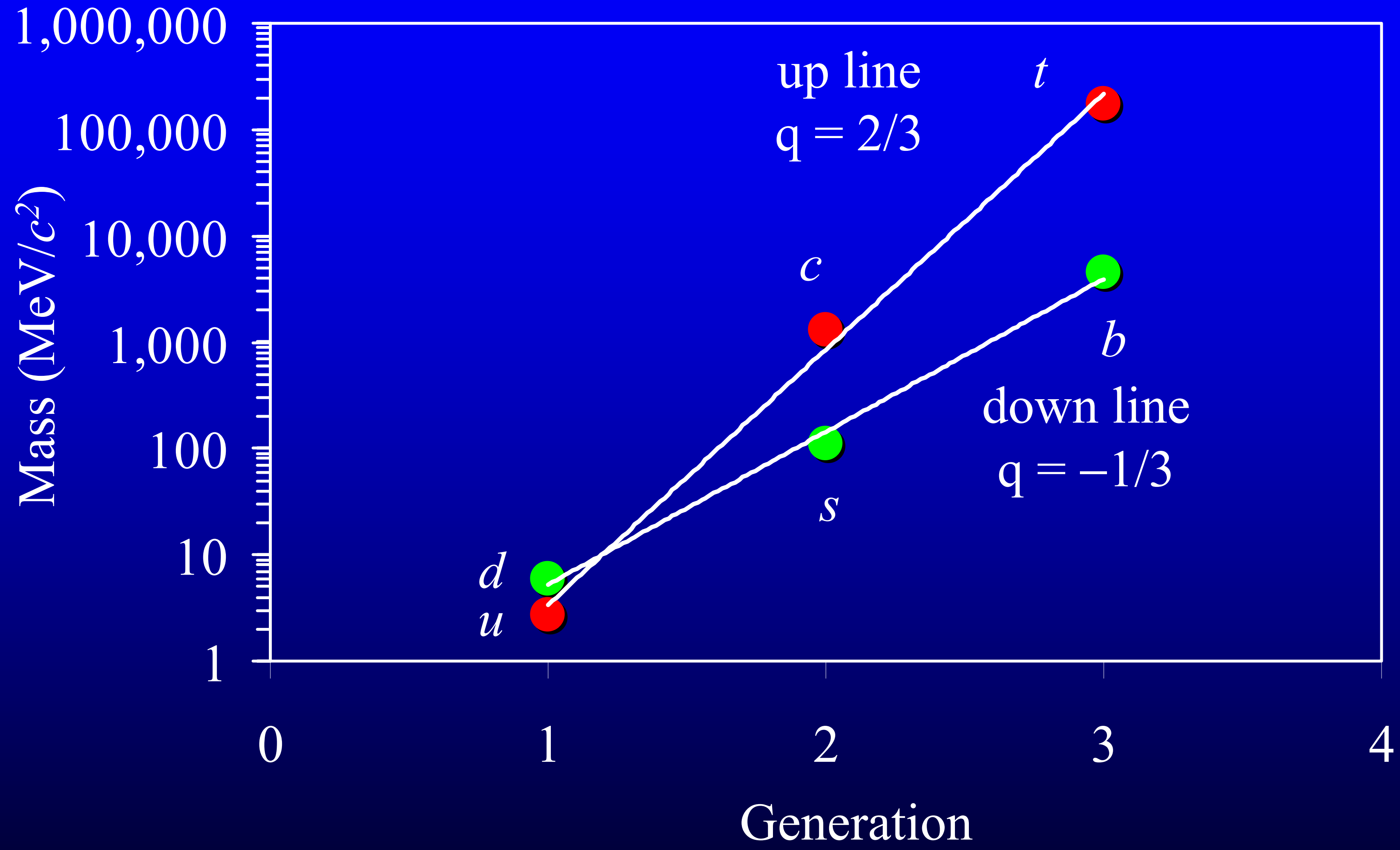
- Now reached SM level for one of our key indirect NP search modes, Δm_s.
  - No new physics.

- Not just a Tevatron problem, problem for *B* physics in general.

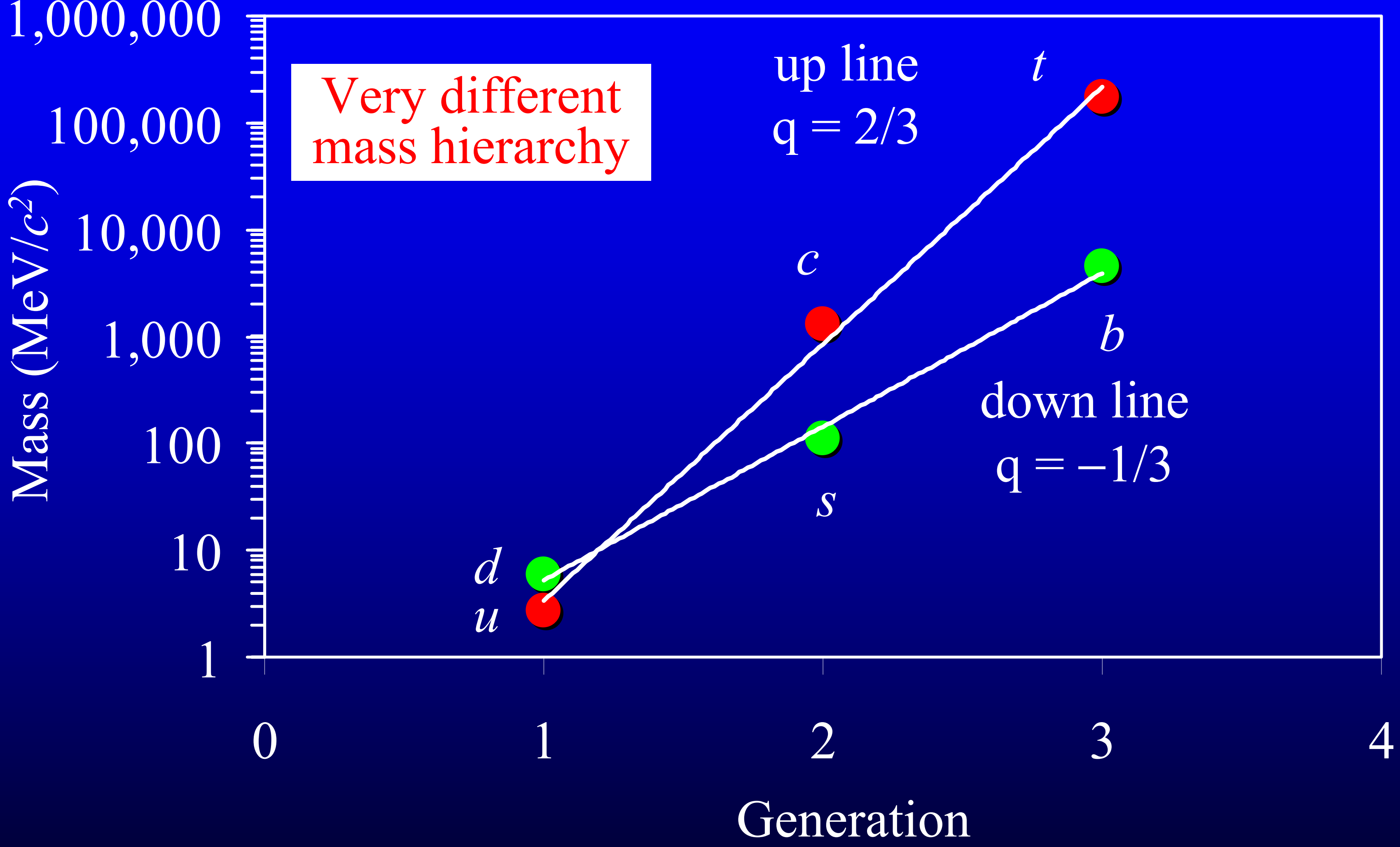
- Choice:
  - Wait for new energy frontier
  - Expand current physics program
    - beauty $\rightarrow$ charm

Flavor Changing Neural Current Charm Decay

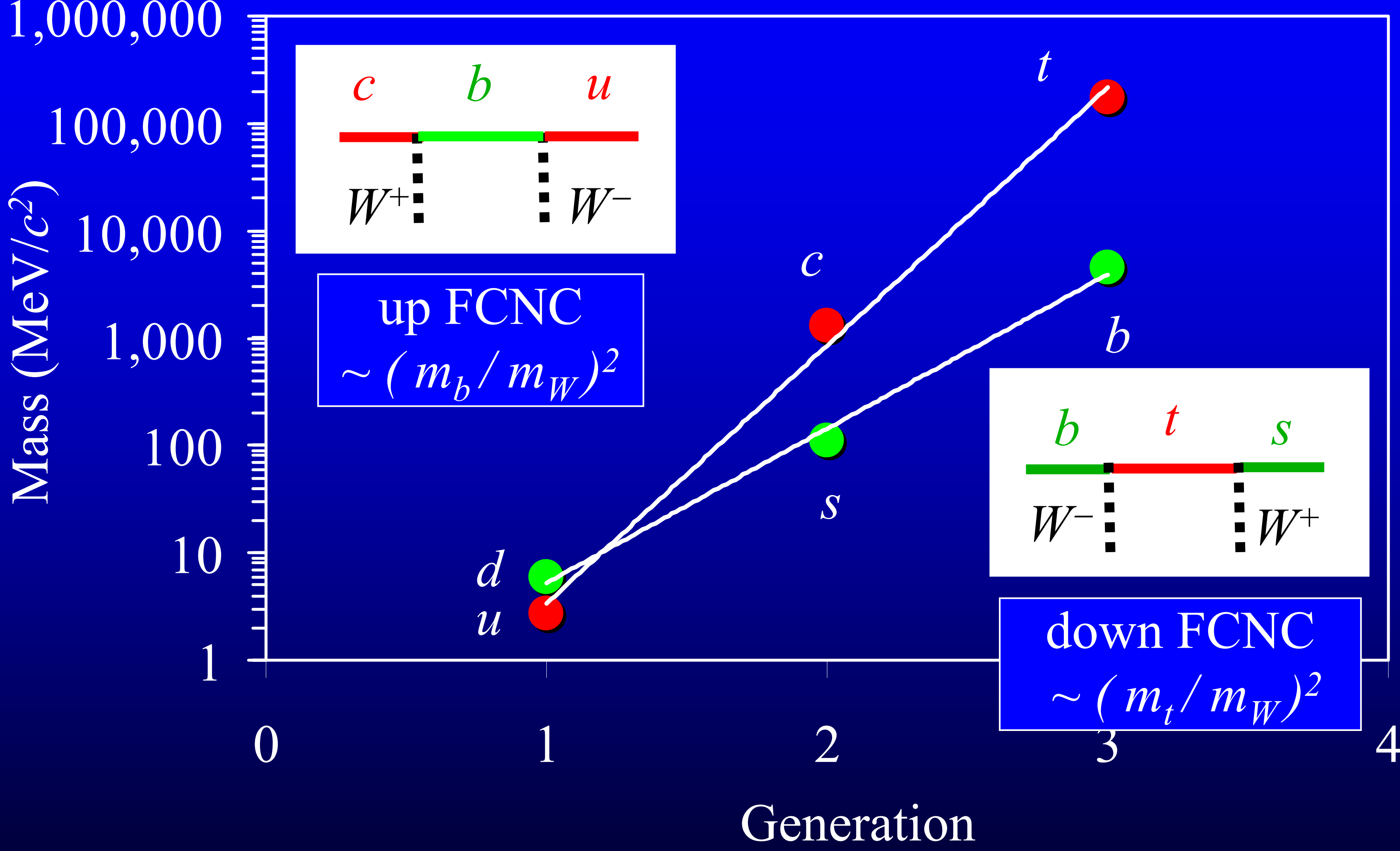
Up versus Down



Up versus Down



Up versus Down



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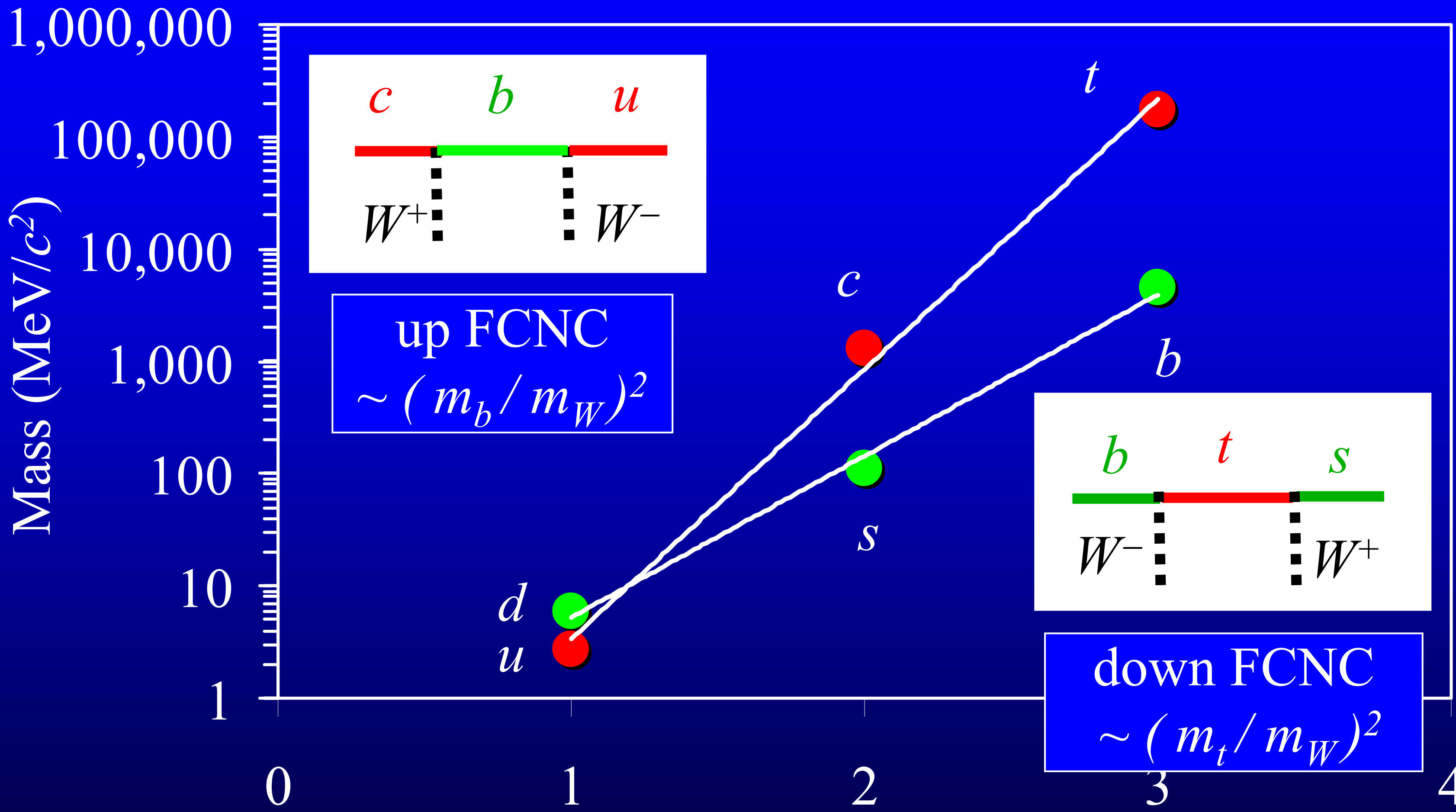
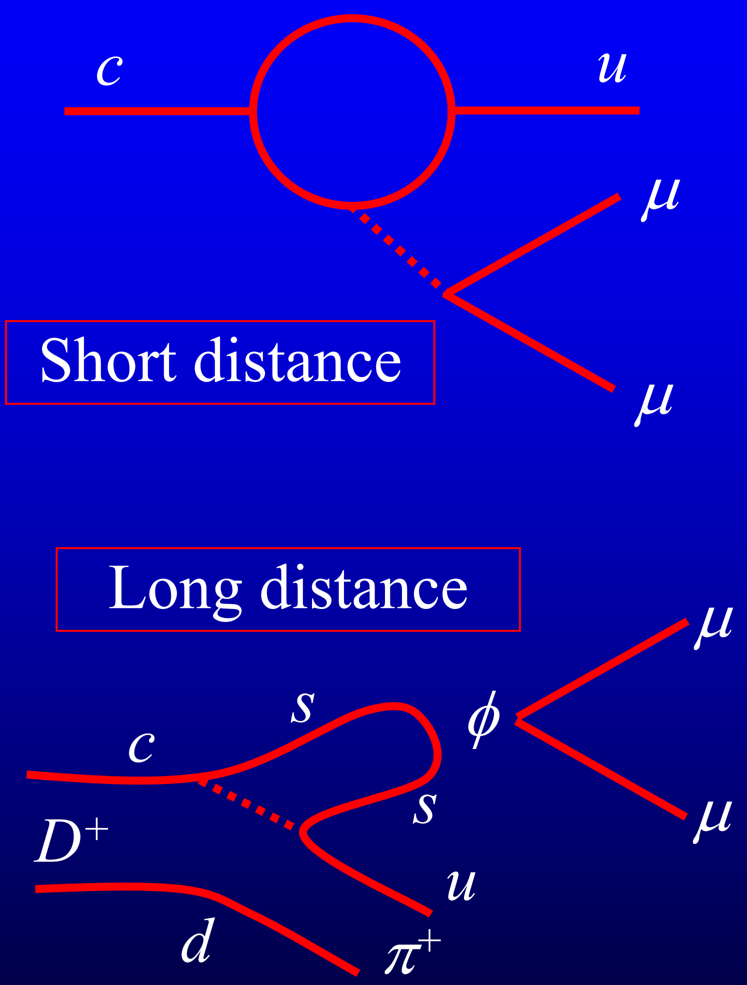


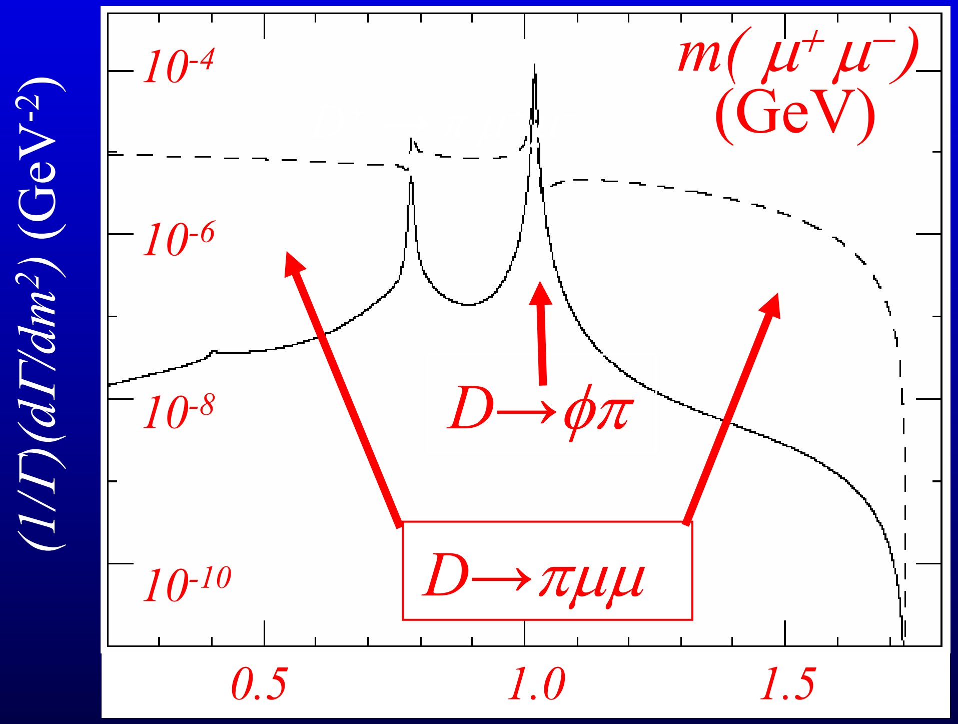
Down the down line: suppressed but measurable (eg. mixing)

Down the up line: almost impossible for SM ⇒ unambiguous signal of NP

Why 3 body FCNC charm?



Interested in short distance (weak scale) but also need to worry about long distance (QCD scale)



Clear separation of long distance and short distance components
New Physics only effects short distance. (rare clean channel)

New Phenomena in $c \rightarrow u\, \mu^+ \mu^-$

Strict limits from $b \rightarrow s$, interesting scenarios effect up sector quarks and not down sector quarks.

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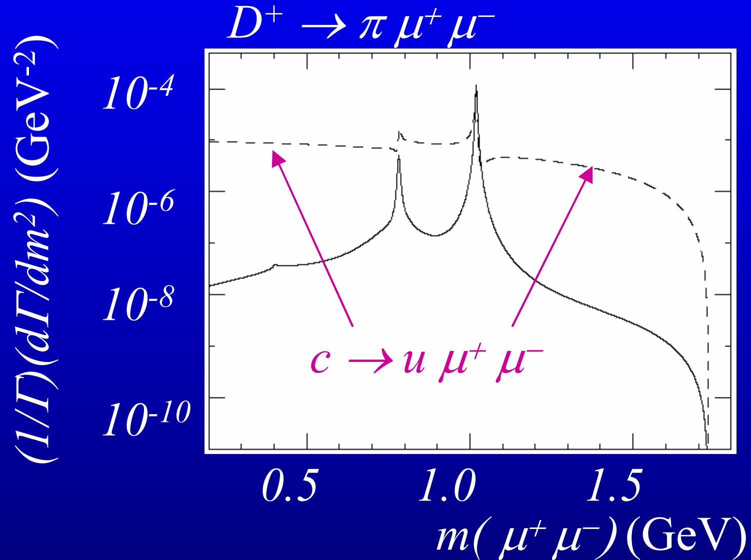
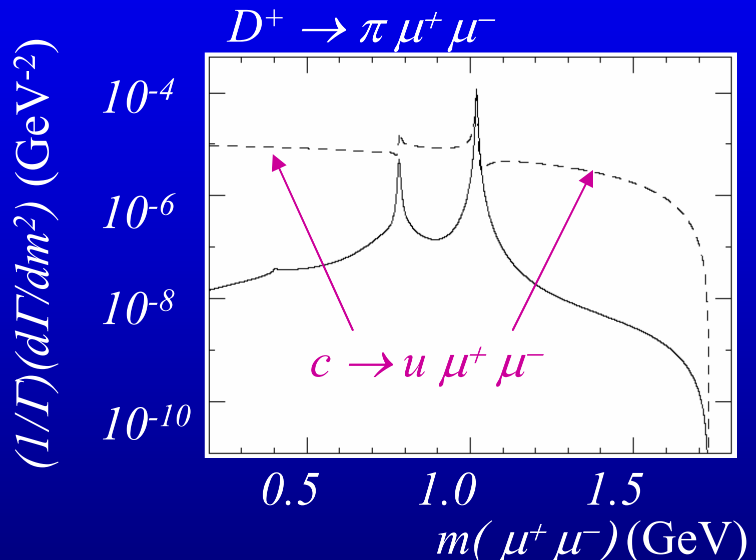


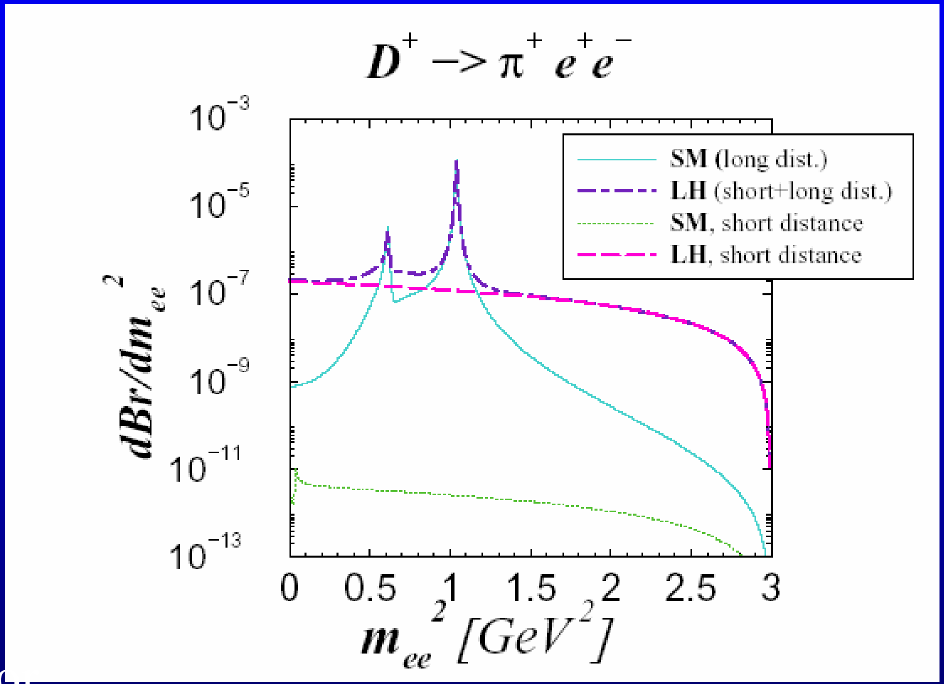
RPV in the up sector and not the down sector

Burdman et al. hep-ph/0112235

New Phenomena in $c \rightarrow u\, \mu^+ \mu^-$

Strict limits from $b \rightarrow s$, interesting scenarios effect up sector quarks and not down sector quarks.





RPV in the up sector and not the down sector

Burdman et al. hep-ph/0112235

Little Higgs models with new up sector vector quark

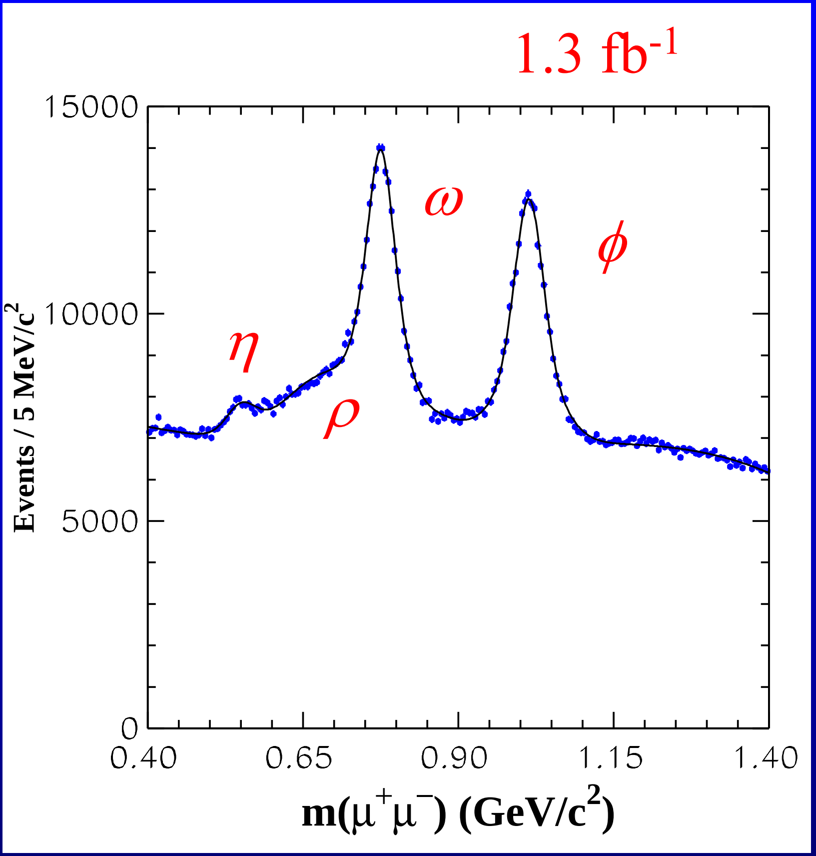
Fajfer et al. hep-ph/0511048

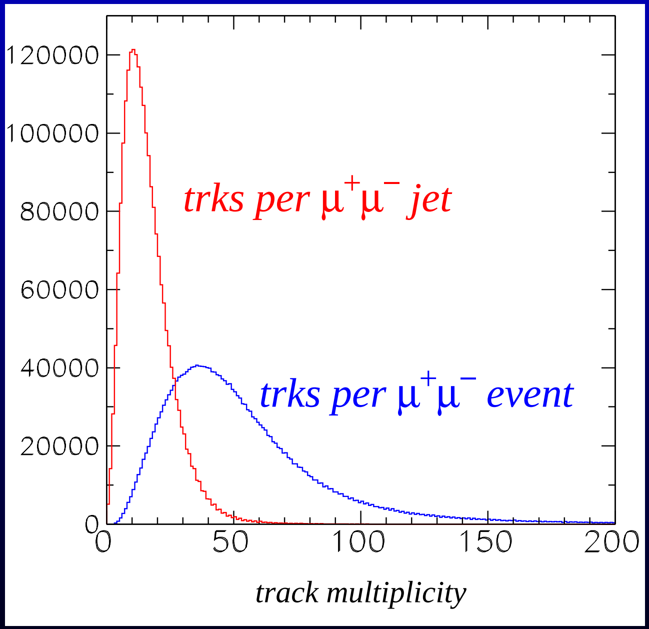
factors of >1000 over SM not ruled out.

D Selection

Require well reconstructed track in the muon spectrometer matched to a central track with $p_T > 2$ GeV , $p > 3$ GeV

First select $\phi \rightarrow \mu^+ \mu^-$
$0.96 < m(\mu\mu) < 1.06$ GeV

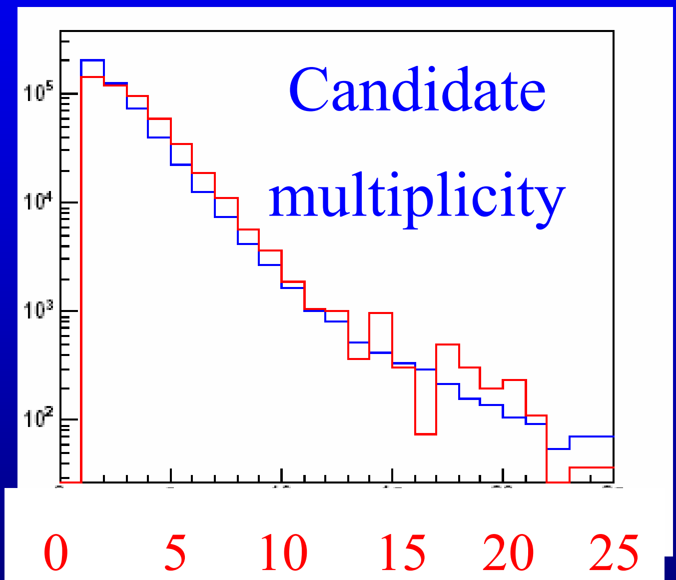




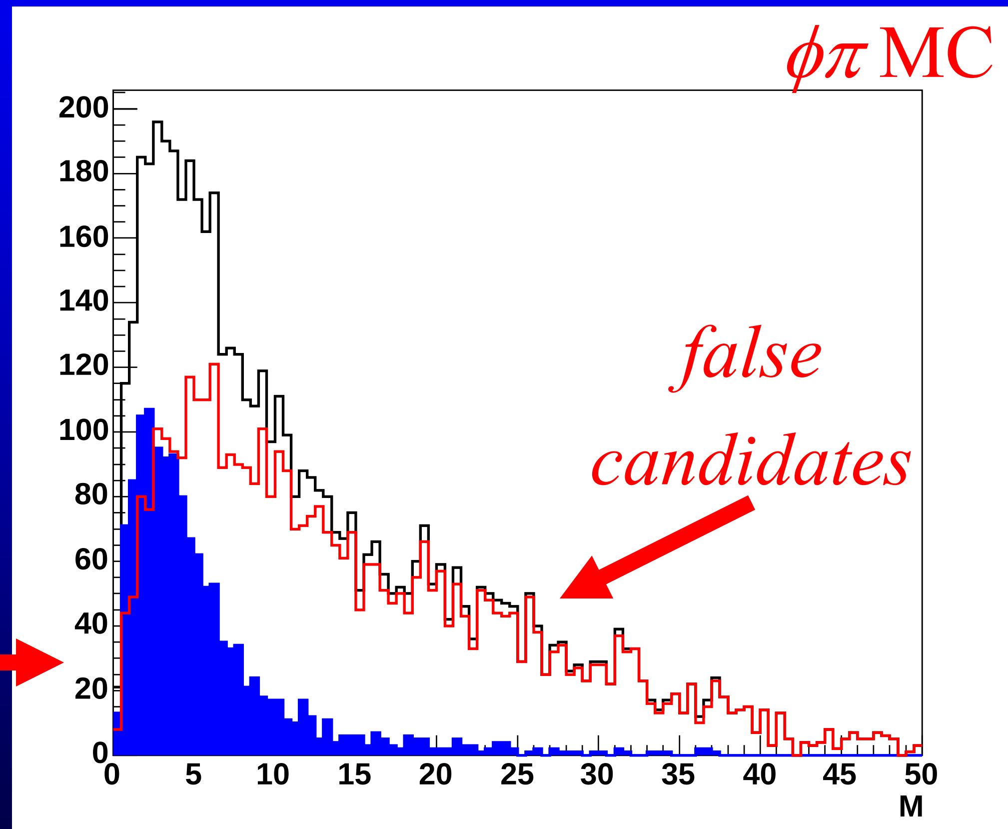
Combine $\mu^+ \mu^-$ with a track in the same jet and select *D* candidate
$1.4 < m(\pi\mu\mu) < 2.4$ GeV

Best Track Selection

Large track multiplicity leads to several candidates per event.
Select best track based on the D vertex χ^2, and distance between the track and the dimuon system

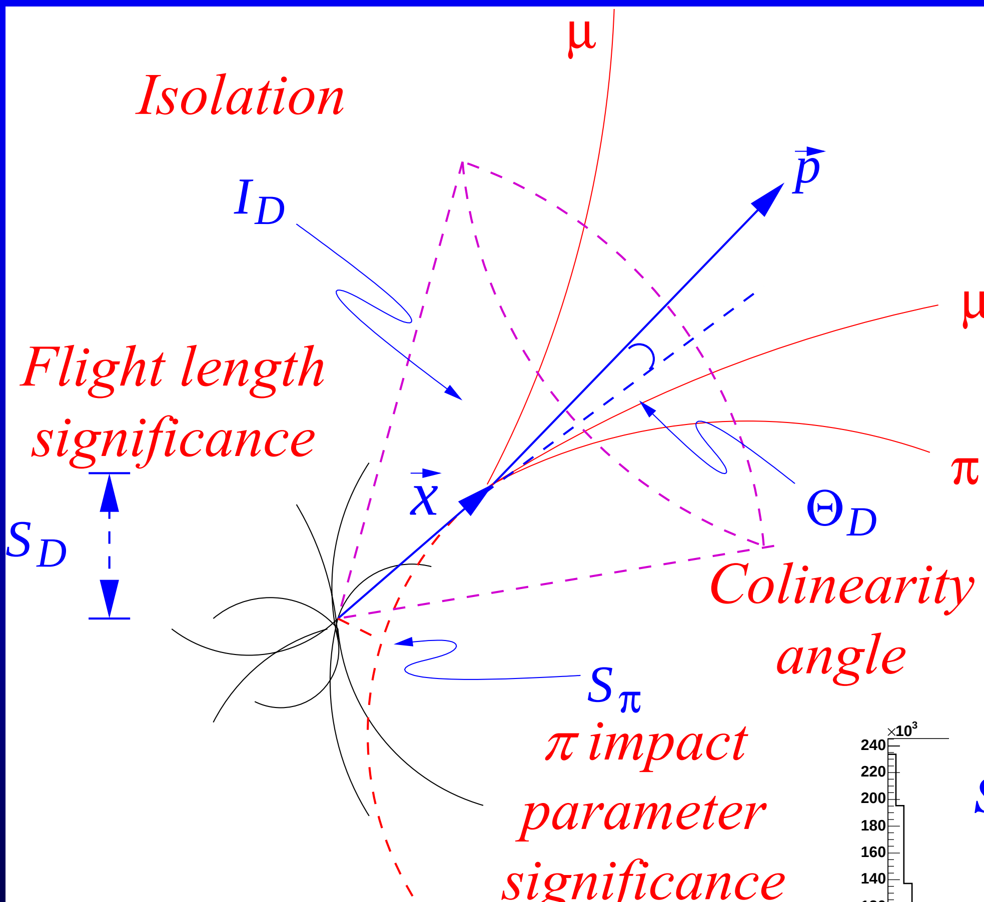


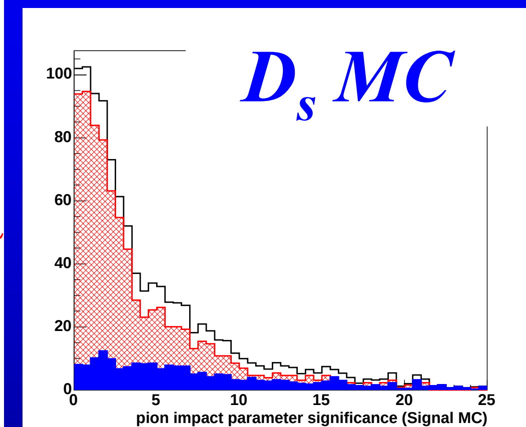
correct candidate



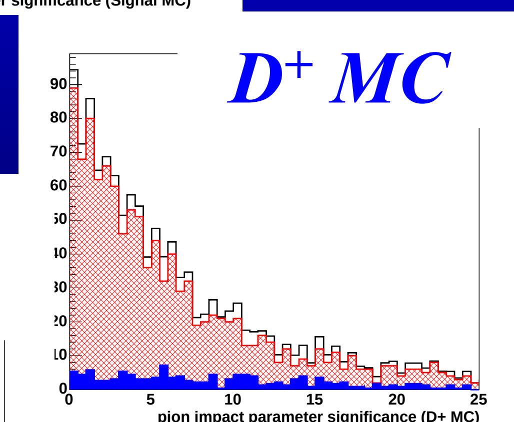
$$M = \chi^2 + \Delta R^2$$

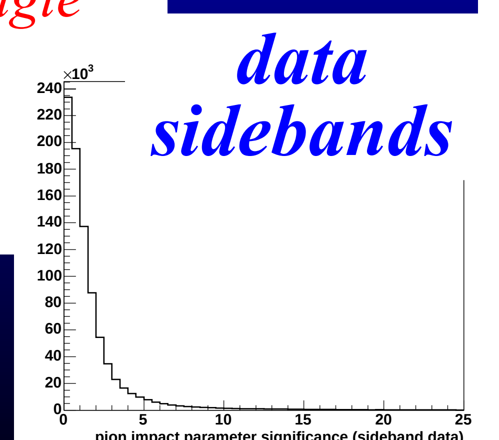
Background Suppression





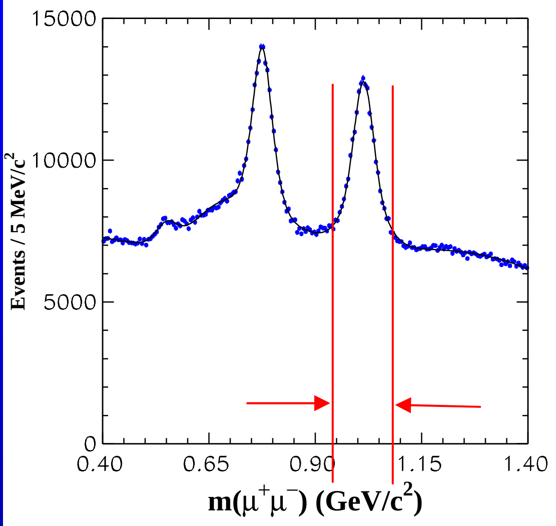
S_π

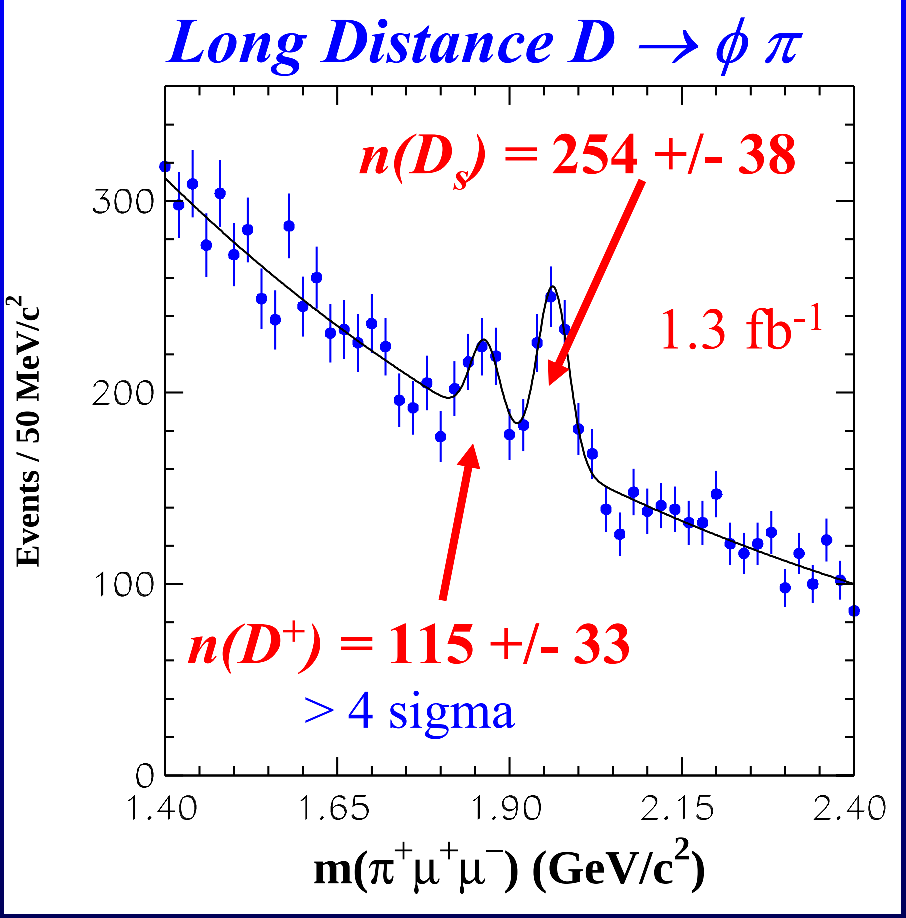




Results for Resonance Production

Dimuon invariant mass





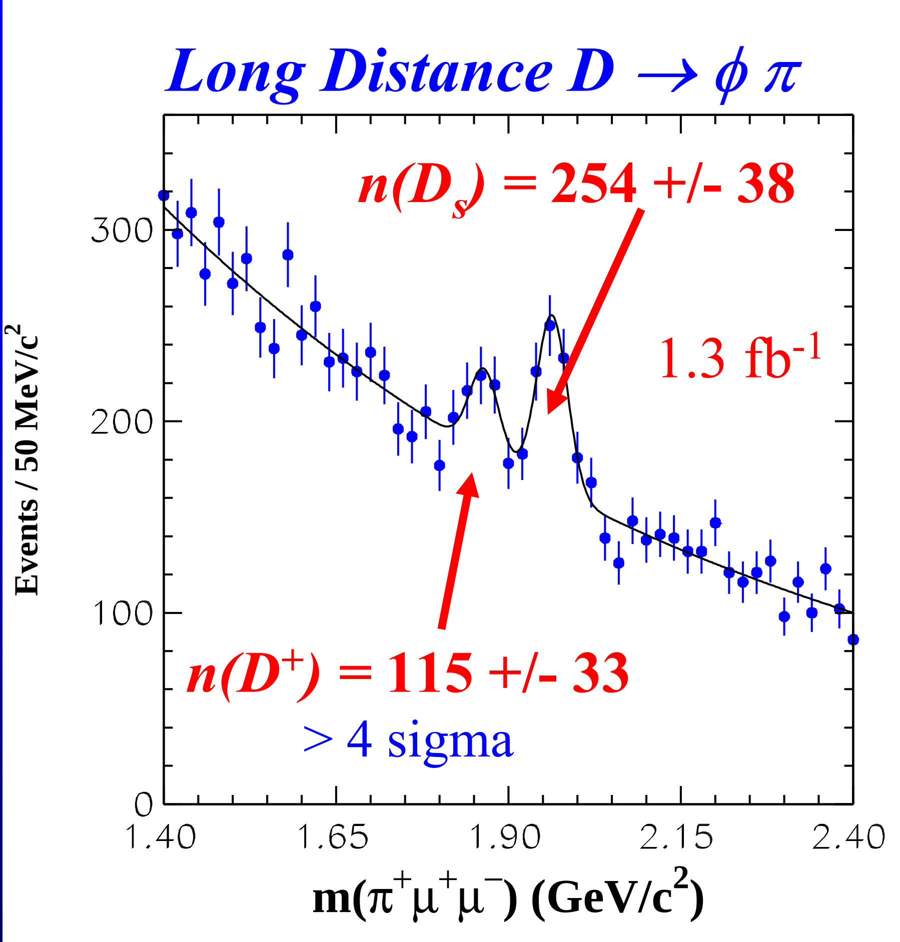
D significance > 5

Pion IP significance > 0.5

$$\mathrm{BF}(D^+ \to \phi\, \pi \to \pi^+ \mu^+\mu^-) = (1.41 \text{ +/- } 0.40 \text{ +/- } 0.46) \times 10^{-6}$$

(PRL for 1.3 fb^{-1} result about to be released.)

Long Distance to Short Distance



<u>Long distance:</u>

ϕ mass cut removes most background

<u>Short distance:</u>

Now need to make an anti ϕ cut

Now have ~150k background events to remove

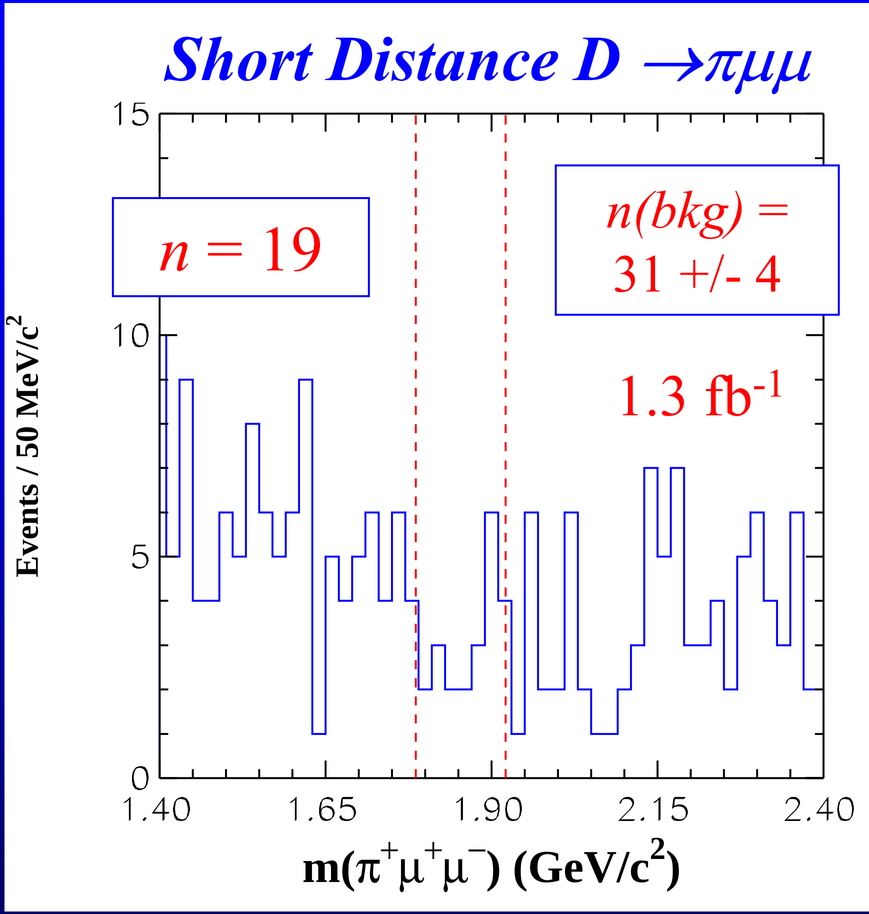
More Background Reduction

Next step: continuum production. Much larger dimuon phase space requires more stringent requirements

TABLE I: Final requirements for the background suppression variables along with the number of candidates surviving each requirement.

	requirement	surviving candidates
preselection		154203
ΔR_π	< 2.6	154131
$p_T(\pi)$	> 0.4 GeV/c	127027
$\mathcal{S}_D$	> 9.4	69817
$\mathcal{S}_\pi$	> 1.8	51736
$\mathcal{I}_D$	> 0.7	24742
Θ_D	< 7 mrad	962
χ^2_{vtx}	< 2.6	212
signal window	$\pm 2\sigma$	19

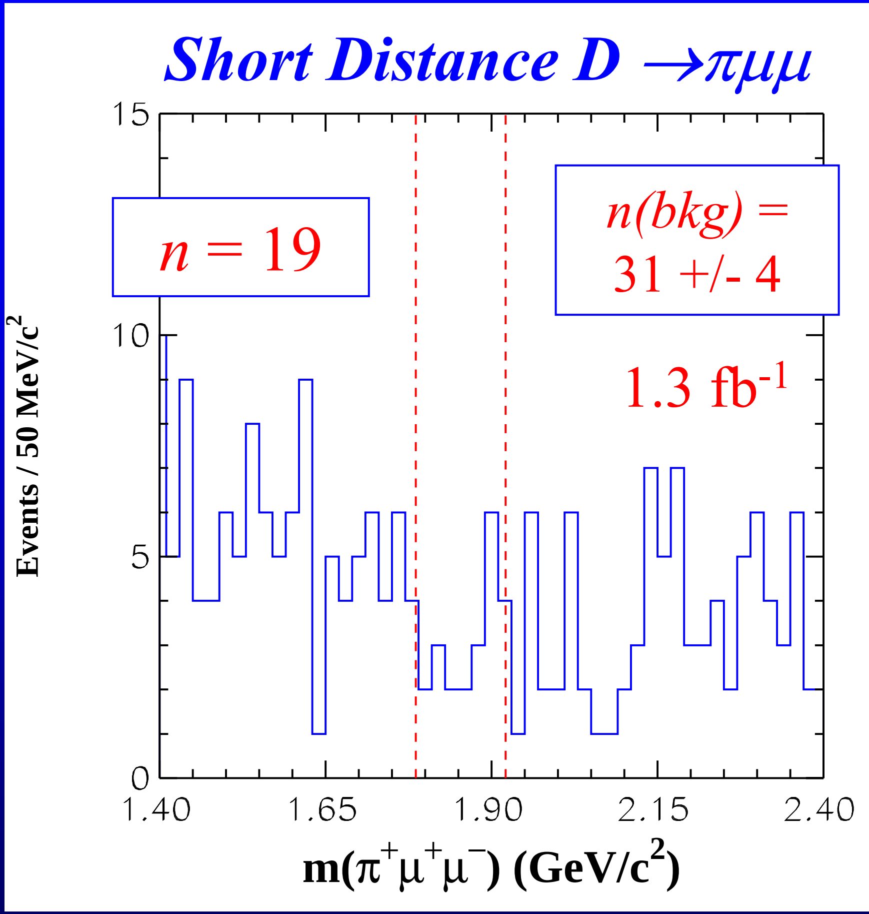
Continuum Results



$$BF(D \to \pi\mu\mu) < 2.85 \times 10^{-6}$$
@90% CL

(PRL for 1.3 fb^{-1} result about to be released.)

Continuum Results



How are we doing?

factor of ~4 better than dedicated charm experiments

Factor of ~10 better than *B* factories

$$BF(D \to \pi\mu\mu) < 2.85 \times 10^{-6}$$
@90% CL

(PRL for 1.3 fb^{-1} result about to be released.)

Conclusions

Conclusions

- DØ Heavy Flavor program producing several *world's first* or *world's best* results
  - 4 years ago prevailing opinion was that you don't do B physics at DØ
- Presented today:
  - First upper limit on the B_s mixing frequency
    - no smoking gun for new physics in Δm_s
  - Best limits on new physics in rare charm decays.
    - Basically rules out possibility of finding a smoking gun in charm.
- Results:
  - Demonstrated a lack of enhancement in almost all low energy FCNC processes.
    - Tells you that the next theory beyond the standard model must have mechanisms that supress FCNC
- Next steps:
  - Go find these new particles directly at the LHC