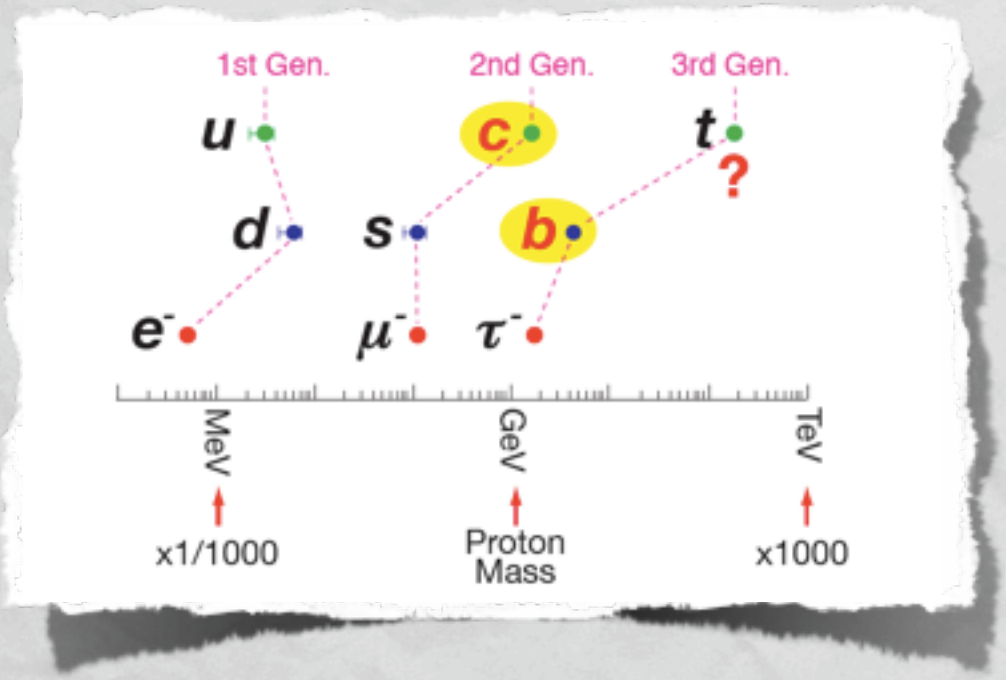
Heavy flavor at the Tevatron

D. Tonelli - Fermilab

Aspen , Feb 16, 2011

Flavor

The physics of matter at its most fundamental level. Deals with masses and mixings of fermions



$$V \approx \begin{array}{c} \\ \\ \\ \end{array}\begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix} \end{array}\begin{array}{c} \\ u \\ c \\ t \end{array}$$

$\lambda = 0.22$

Origin of mass? Why are masses so different across families? Why are couplings different?...

CP Violation

Physics laws are not invariant for mirror-reversal of the spatial arrangement and replacement of all particles with antiparticles

$$
\begin{array}{cc}
 & \begin{array}{ccc} d & s & b \end{array} \\
V \approx & \begin{pmatrix} 1 & \lambda & \lambda^3 e^{i\phi} \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 e^{-i\phi} & -\lambda^2 & 1 \end{pmatrix} \begin{array}{c} u \\ c \\ t \end{array}
\end{array}
$$

The standard model did not predict this. But has sufficient complexity to accommodate it in its framework.

CPV to probe New Physics

Profound implications that extend beyond particle physics

E.g. large CP violation could drive dynamic generation of matter-antimatter asymmetry in the Universe.

In many extensions of the standard model, additional sources of CP or flavor violation can arise from exchange of new particles.

The mantra

Multiple, precise, and redundant experimental tests of the CKM picture should reveal early signs of the presence of new particles exchanged in virtual transitions, or couplings.

State of the Art

Dedicated experiments over the past 10+ years.

Simultaneous theory and computational advancements

Formidable success.

Standard model CPV explains satisfactorily data in leading B transitions. 10-15% corrections from non-SM not excluded.

- New particles are much heavier than O(1) TeV
- New particles are O(1) TeV, but with fine-tuned dynamics
- New particles couple very weakly with ordinary ones

The end of the story?

"Now this is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning". W. Churchill.

Some of most powerful probes not yet fully exploited.

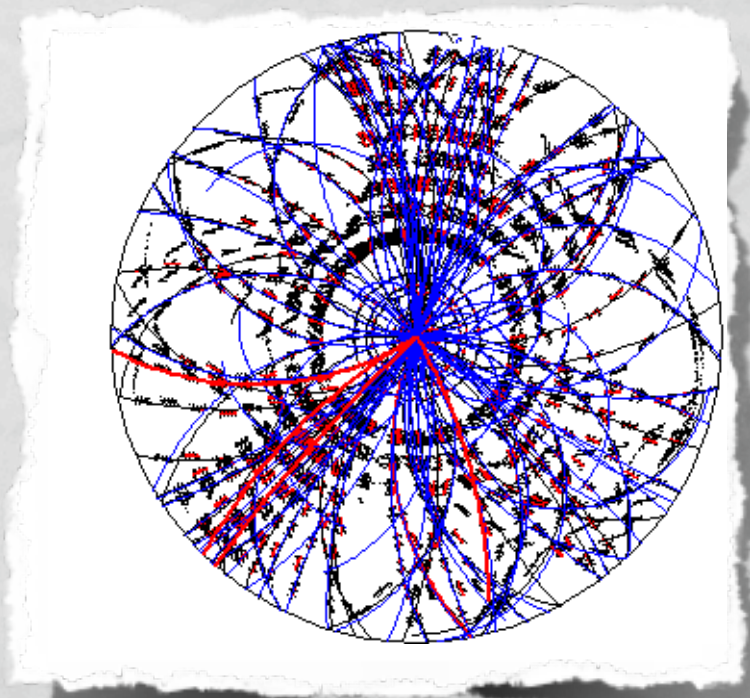
And many of them accessible with unprecedented precision at the Tevatron. Now.

- B_s mixing phase; this talk
- fully leptonic decays; this talk
- precision CPV in charm decays/mixing; this talk
- b->s penguins.
- ...

Interest supported by recent emergence of a few mild tensions in global CKM fits.

Tevatron Heavy Flavor

- 2 experiments.
- 10 years of 2 TeV $\bar{p}p$ collisions (10^{13} collisions)
- 0.1-1% of them yield B and D (of all kinds)
- Trigger + reconstruction keeps only 0.1-10% of them



- Collect B and D at higher rate than B factories.
- Only charged decay products are reconstructed
- Precise momentum and decay-position. Some PID.

new for ASPEN

CP violation in neutral charmed mesons

Neutral charmed

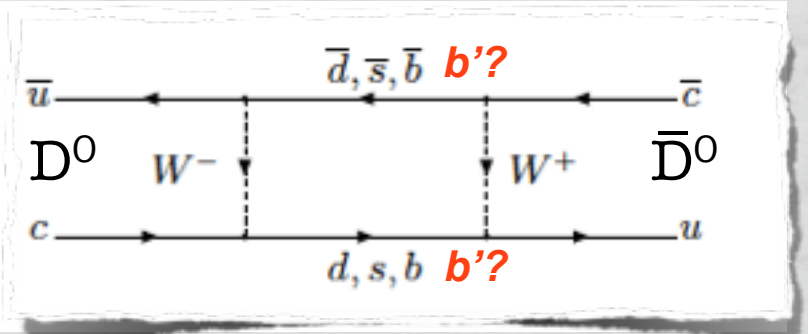
1000/s produced within CDF.

Then oscillate and decay after few hundred microns flight (0.5 ps)

Oscillation strength seen O(1)%, Much larger than most predictions.

New physics in loop?

If so, enhanced CP violation may be there as well.



up-type quark carries flavor. Sensitivity to NP complementary to K, B

$$A_{CP}(D^0 \to h^+h^-) = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\overline{D}^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) + \Gamma(\overline{D}^0 \to h^+h^-)}.$$

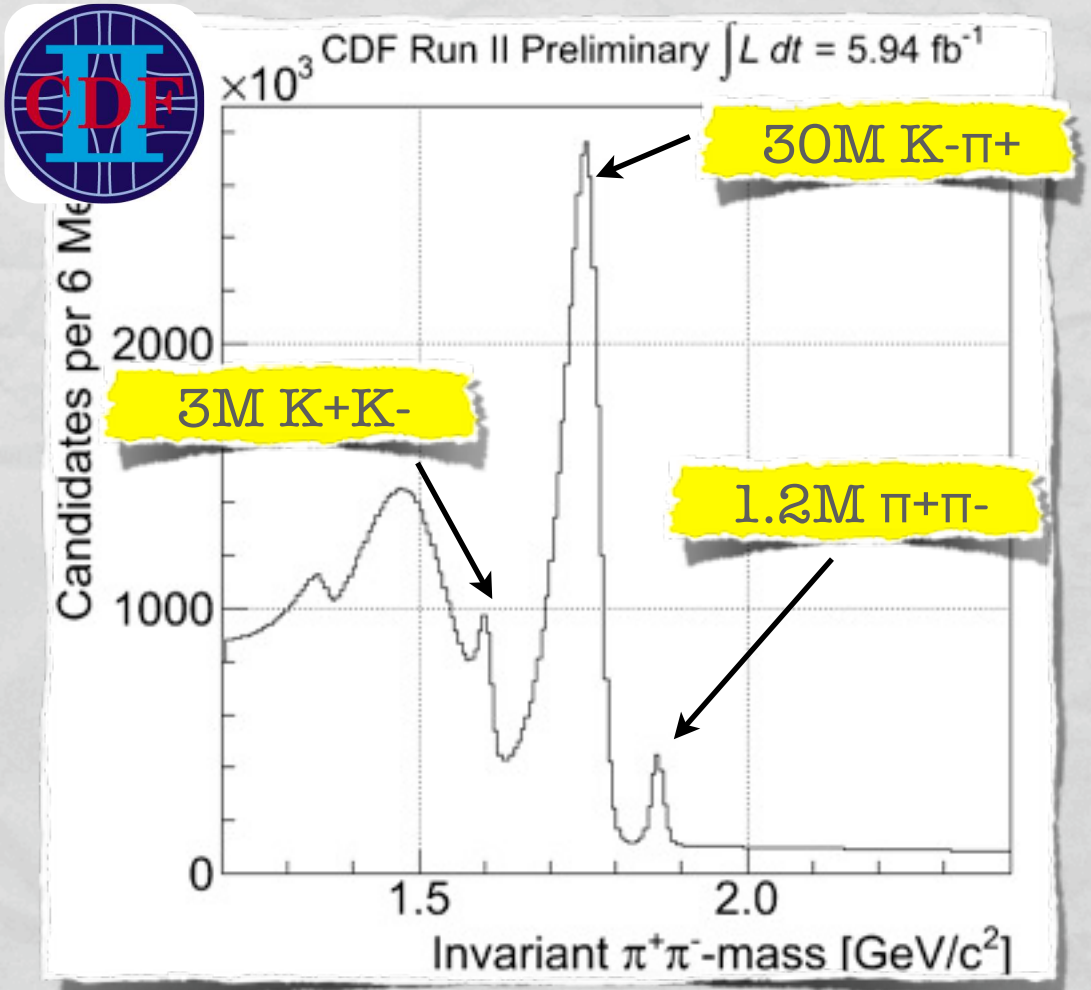
Charm Decay Factory

$$V \approx \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 1 & \lambda & \lambda^3 e^{i\phi} \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 e^{i\theta} & -\lambda^2 & 1 \end{pmatrix} \end{array} \begin{array}{c} u \\ c \\ t \end{array}$$

c->s, c->d real in the SM.

Expect CPV small, < 0.1%

Large samples and tight control on systematics



World's largest sample.

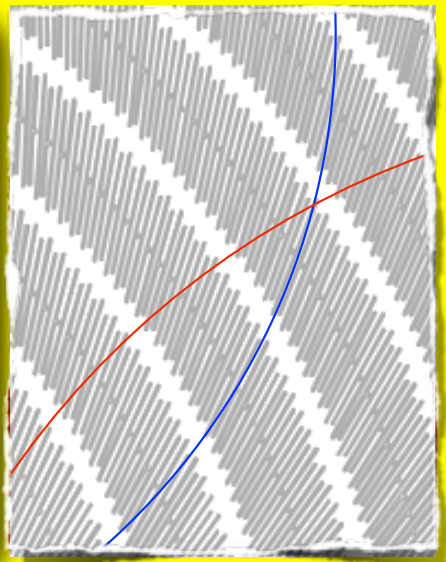
D->hh at a glance

Trigger on two tracks displaced from primary vertex

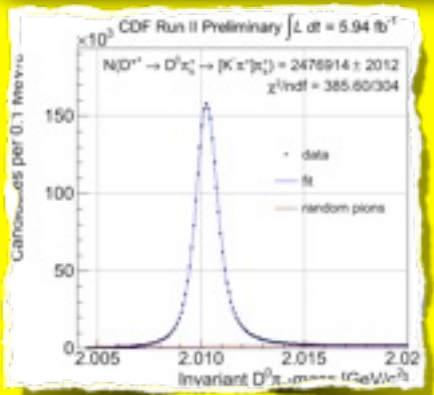
Reconstruct D^0-->π+π- and D^0-->K+K- decays

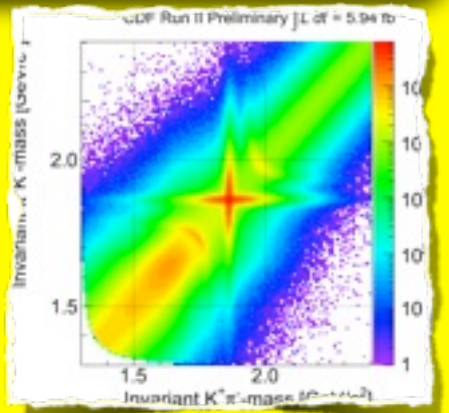
Count $\bar{D}^0$ and D^0 by requiring D^{*+}-->$D^0\pi^+$

Requiring soft charged track induces O(%) instrumental asymmetry

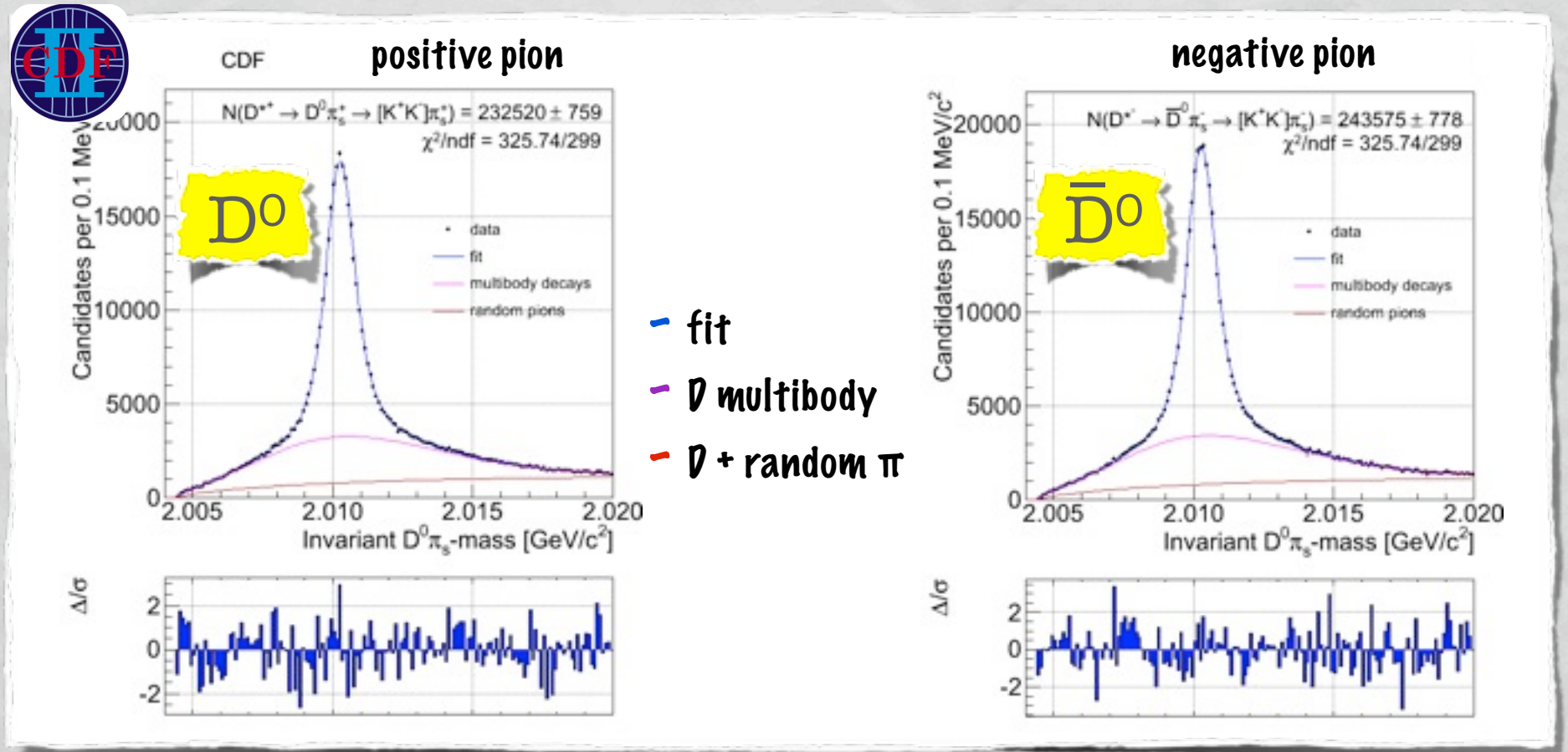


Data-driven correction using D*-tagged and untagged D->Kπ





$D^0 \rightarrow KK$ from D^*



Permille

new for ASPEN

$A_{CP}(D^0 \to K^+K^-) = (-0.24 \pm 0.22 \pm 0.10)\%$

BaBar '08 $= (0.00 \pm 0.34 \pm 0.13)\%$

Belle '08 $= (-0.43 \pm 0.30 \pm 0.11)\%$

$A_{CP}(D^0 \to \pi^+\pi^-) = (+0.22 \pm 0.24 \pm 0.11)\%$

BaBar '08 $= (-0.24 \pm 0.52 \pm 0.22)\%$

Belle '08 $= (0.43 \pm 0.52 \pm 0.12)\%$

No evidence for CP violation (larger than 0.2%).

World's most precise measurements (for years to come)

CDF Note 10296

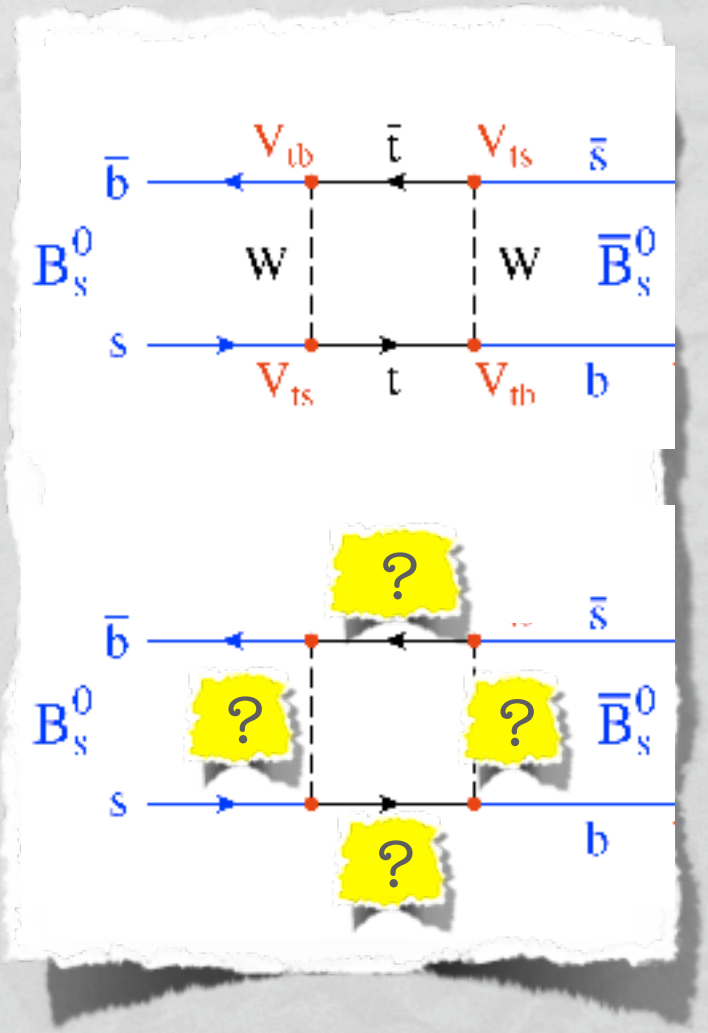
The B_s mixing phase

The phase

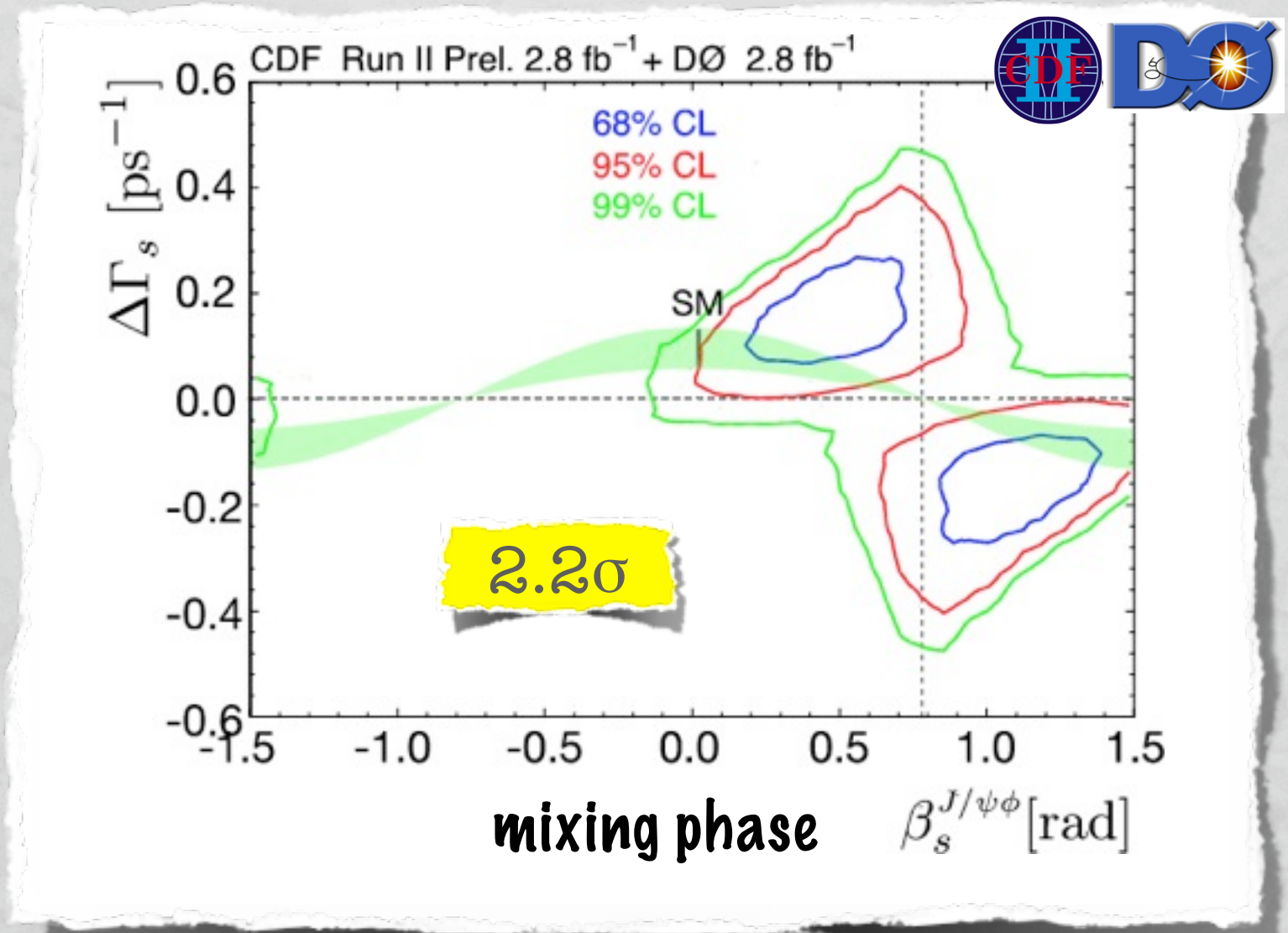
New physics accessible through flavor oscillations and decay, after 0.1-1 mm flight (1.5 ps).

CDF/D0, 2006: mixing strength consistent with SM (within lattice uncertainties)

Mixing phase unconstrained - large NP contributions still possible



The (mild) excitement



CDF Note 9787/ D0 Note 5928

J/ψφ at a glance

Trigger on two muons consistent with J/ψ decay

Unbiased optimization of signal selection

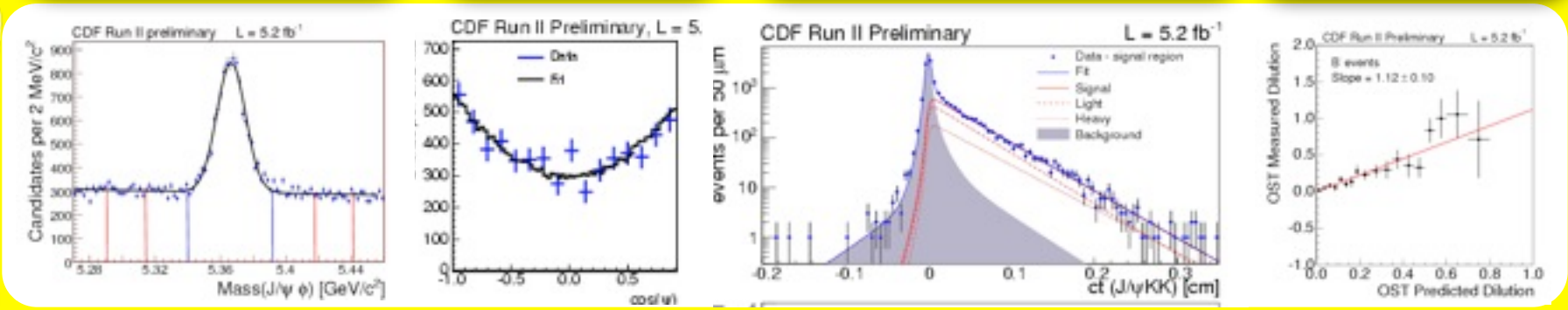
Joint fit to mass, angles, decay time, production flavor

Mass separates signal from background

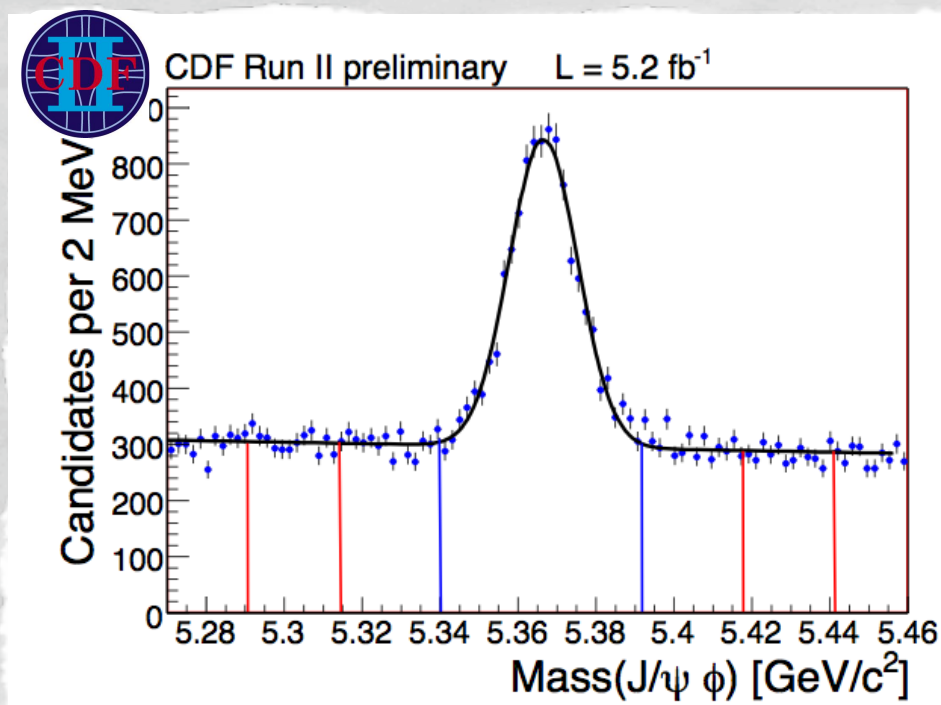
Angles: CP-even from from CP-odd

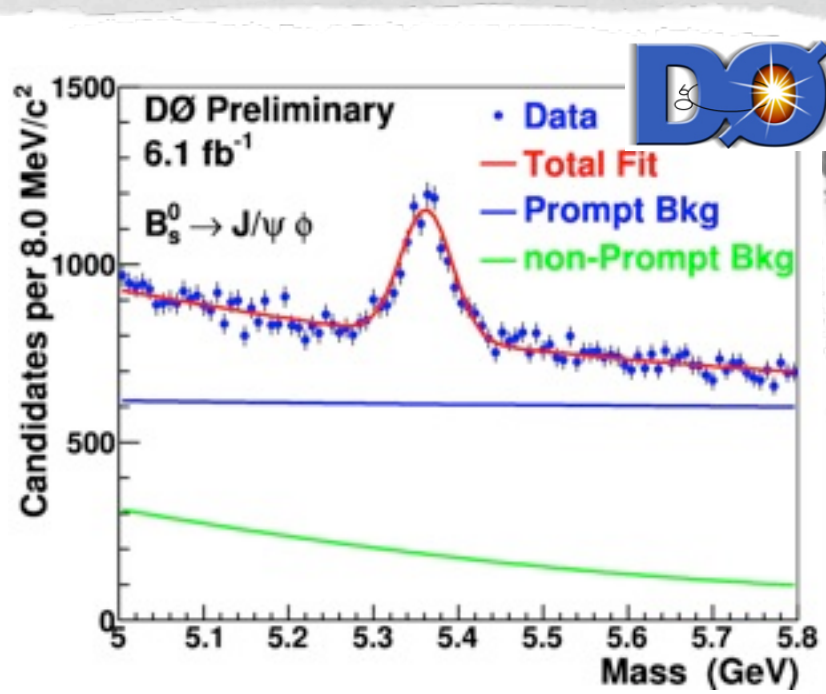
Decay-time to know time evolution

Flavor: Bs from Bsbar



Signals



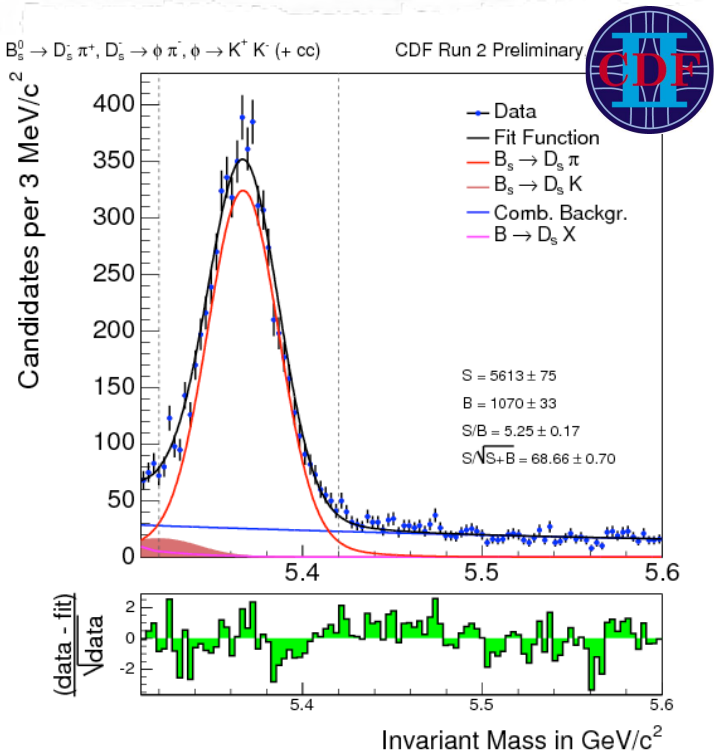


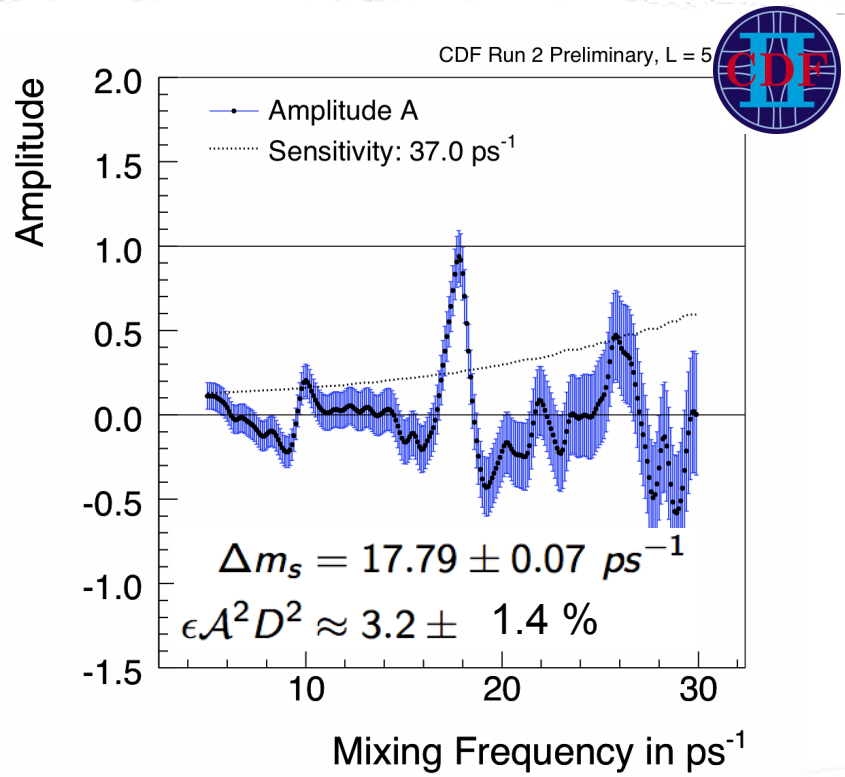
6500 events in 5.2 fb^{-1}

3400 events in 6.1 fb^{-1}

The headache

Sensitivity to phase depends on how well we know whether a Bs or a $\bar{B}$s was produced



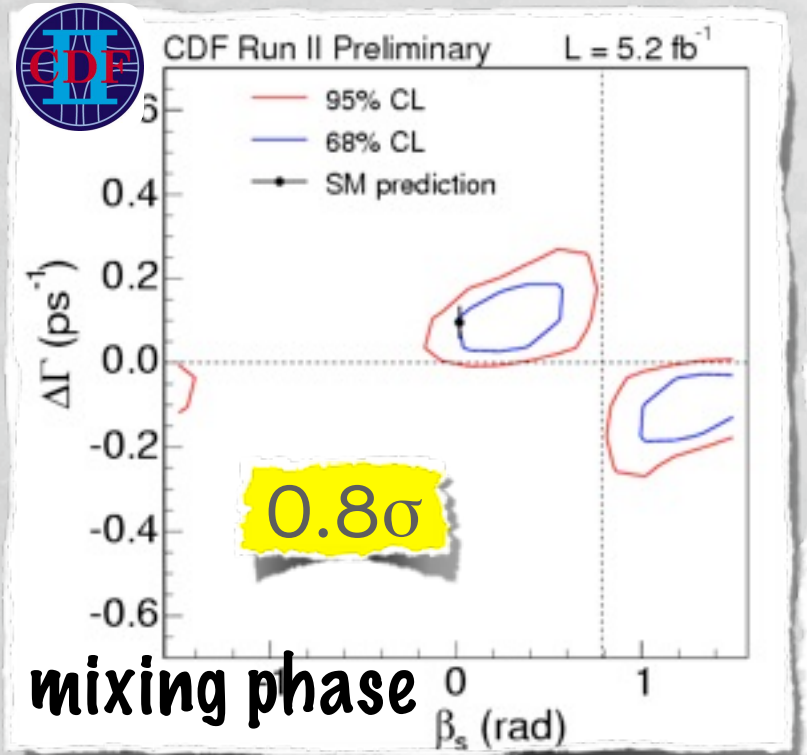


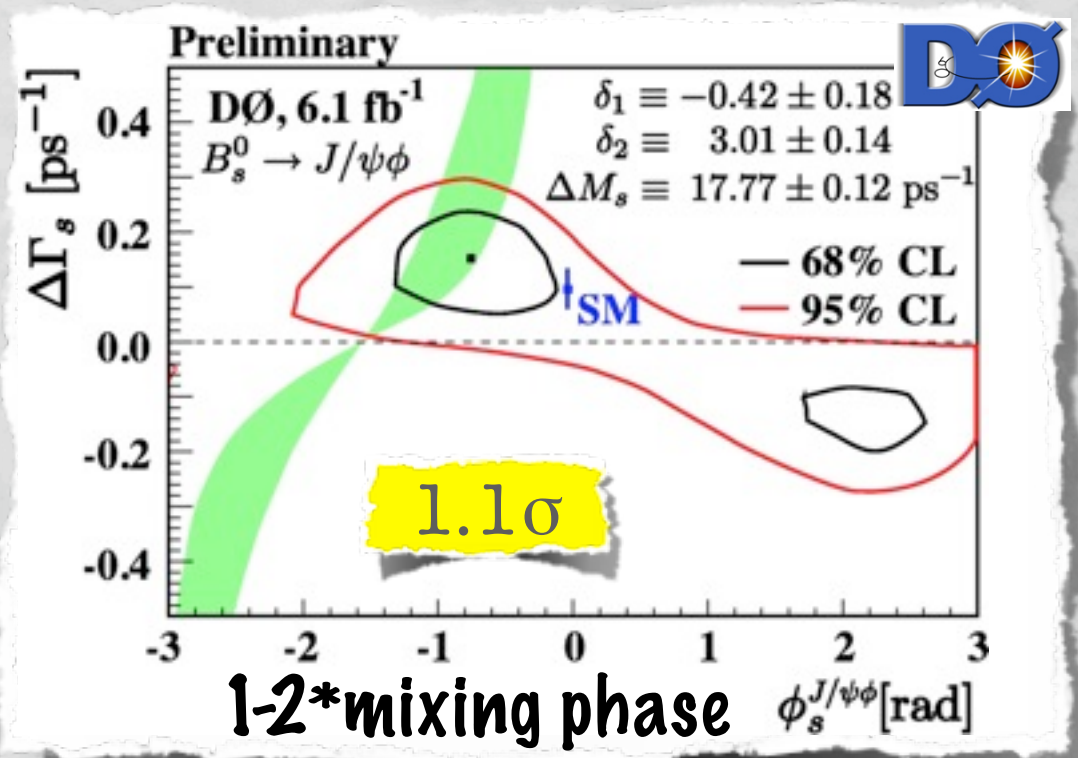
Calibration of flavor-tag only in data: repeat B_s mixing analysis

CDF Note 10108

The de-excitement

ICHEP10





CDF Note 10206

D0 Note 6098

Another way to look at it

Semileptonic asymmetry

- flavor-symmetric $p\bar{p}$->$b\bar{b}$ production, N(b)=N($\bar{b}$)
- 50% of b and $\bar{b}$ dress into neutral B^0 or B_s mesons.
  - they can undergo oscillations before decaying
- 1.3% of times both $\bar{b}$ and b decay into muons.
  - Muons tag flavor: - come from b, + come from $\bar{b}$.
- $\mu^\pm \mu^\pm$ pairs from B mean oscillations occurred
- N++ = N-- if oscillation probability is same for $\bar{b}$ and b
- if N++ ≠ N-- then CPV in mixing
- CPV is 10^{-4} in SM. Any enhancement due to NP

A_{SL} in one slide

two samples: 1.5 billion single μ and 3.7 million di-μ in 6.1 fb^{-1}. p_T > 1.5-4.2 GeV/c

Measure +/- asymmetry in both samples

Asymmetry washed by muons from non-oscillating sources (from MC)

Asymmetry biased by background asymmetries from instrumental effects

Kaon contribution measured in data, pion one extrapolated using MC.

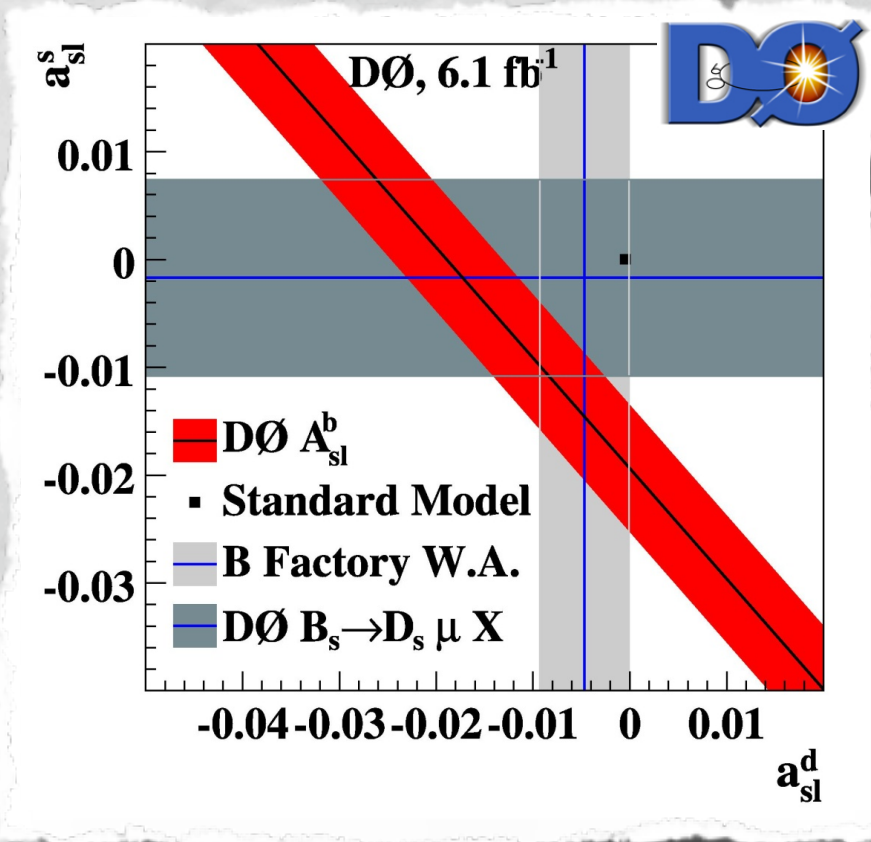
Combine asymmetries from single-μ and di-μ samples to subtract common backgrounds

Results

May '10

$$A_{sl}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}},$$

$$A_{sl}^b(\mathrm{SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4},$$



$A_{sl}^b = (-96 \pm 25 \pm 15) \times 10^{-4}$

Assuming the muons come from B decays this is a

3.2σ discrepancy

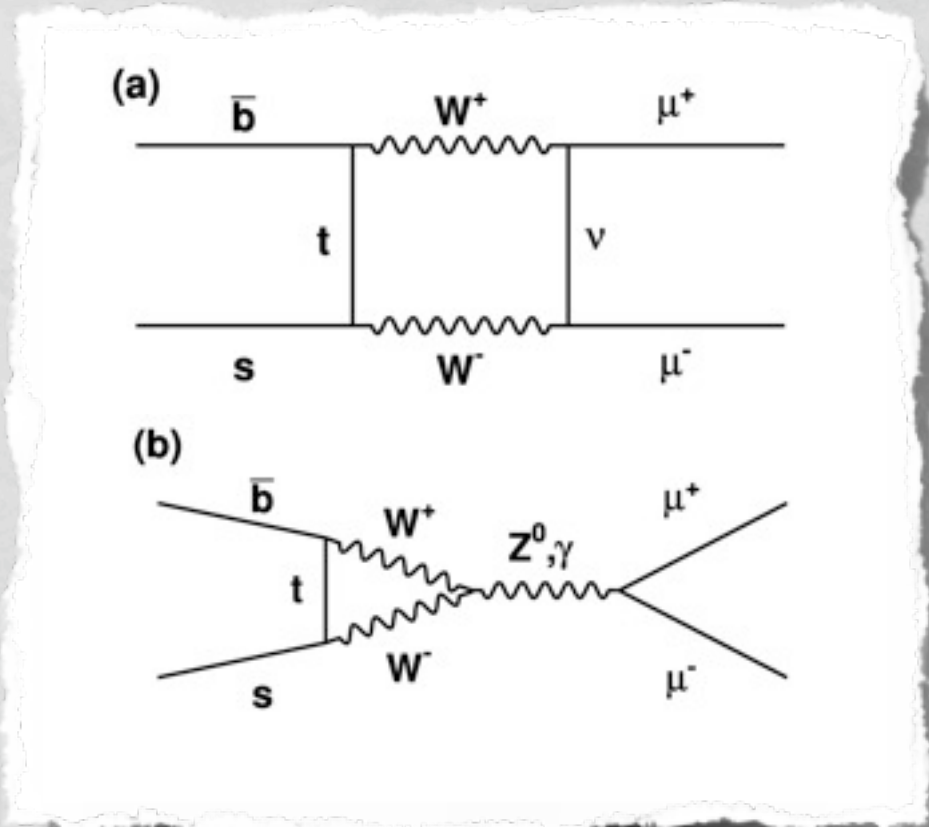
Extremely interesting. Same direction as J/ψφ.
Crucial to have independent cross-check measurement.

PRD 82, 032001 (2010)

Search for B-->μμ

The physics

- SM rate is well understood
- SM rate is small, 3.6×10^{-9}
- Broad class of NP models enhance it by O(1-100)
- Experimental signature clean.
- Backgrounds are wild



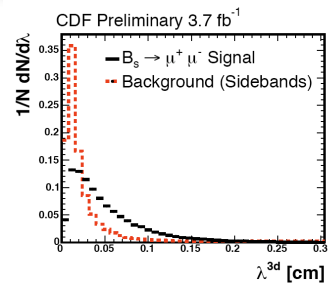
Challenge: reject 10^6 larger bckg. Keep signal efficiency high

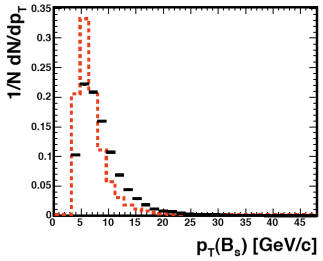
The analysis

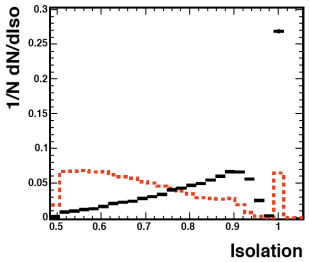
Trigger on two muons with $p_T > 1.5 - 2$ GeV/c

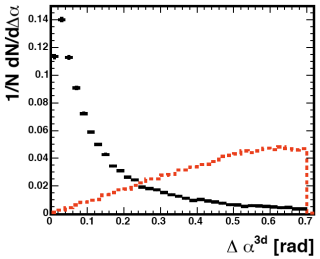
NN classifier separates S from B

lifetime | transverse momentum | Isolation | Pointing









Bckg predictions checked on many control samples

Look at search region in bins of mass and NN.

Rate determined using $B^+ \to J/\psi K^+$ as reference

The results

May '10

D0, 6.1 fb^{-1}

$Br < 5.1 \times 10^{-8}$ at 95% CL

14 times the SM rate

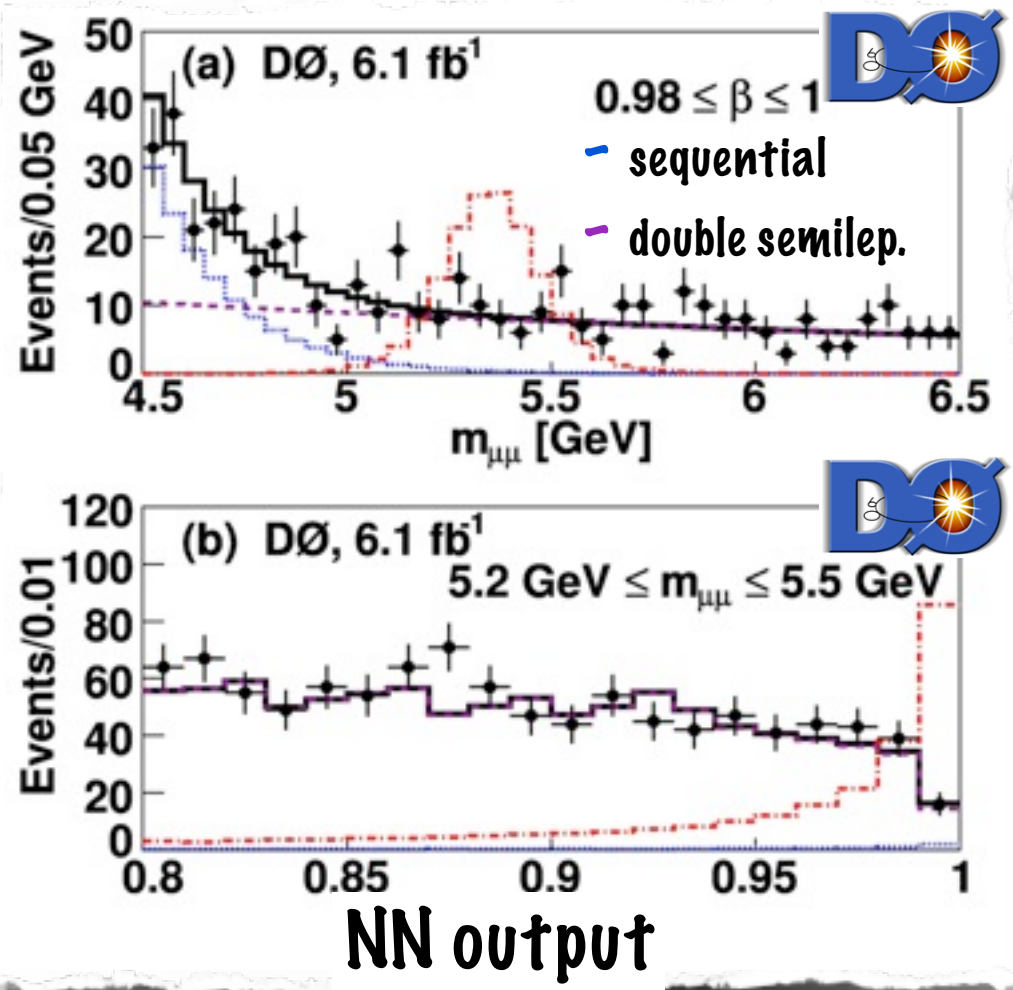
PLB 693, 539 (2010)

CDF, 3.7 fb^{-1}

$Br < 4.3 \times 10^{-8}$ at 95% CL

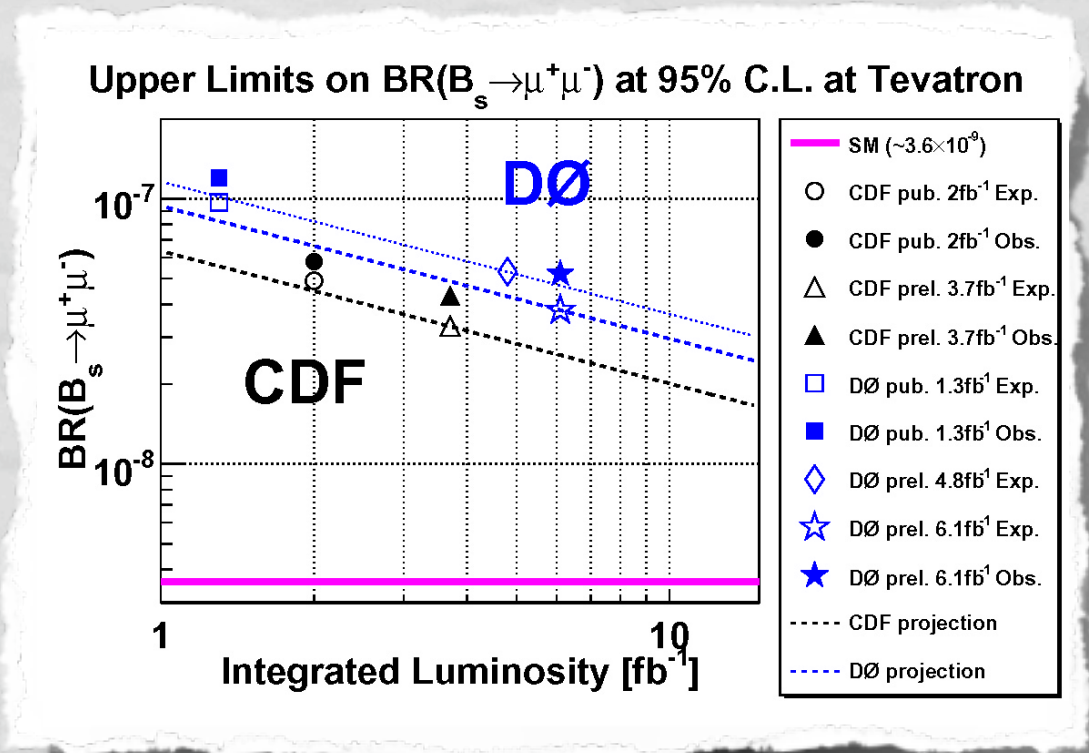
12 times the SM rate

CDF Note 9892



A star in "NP-exclusion hall of fame"

- No NP seen yet
- 2 orders of magnitude since 10 years ago. Ate huge portions of parameters space
- Both CDF and DO analyses being updated
- Aiming at 5×SM

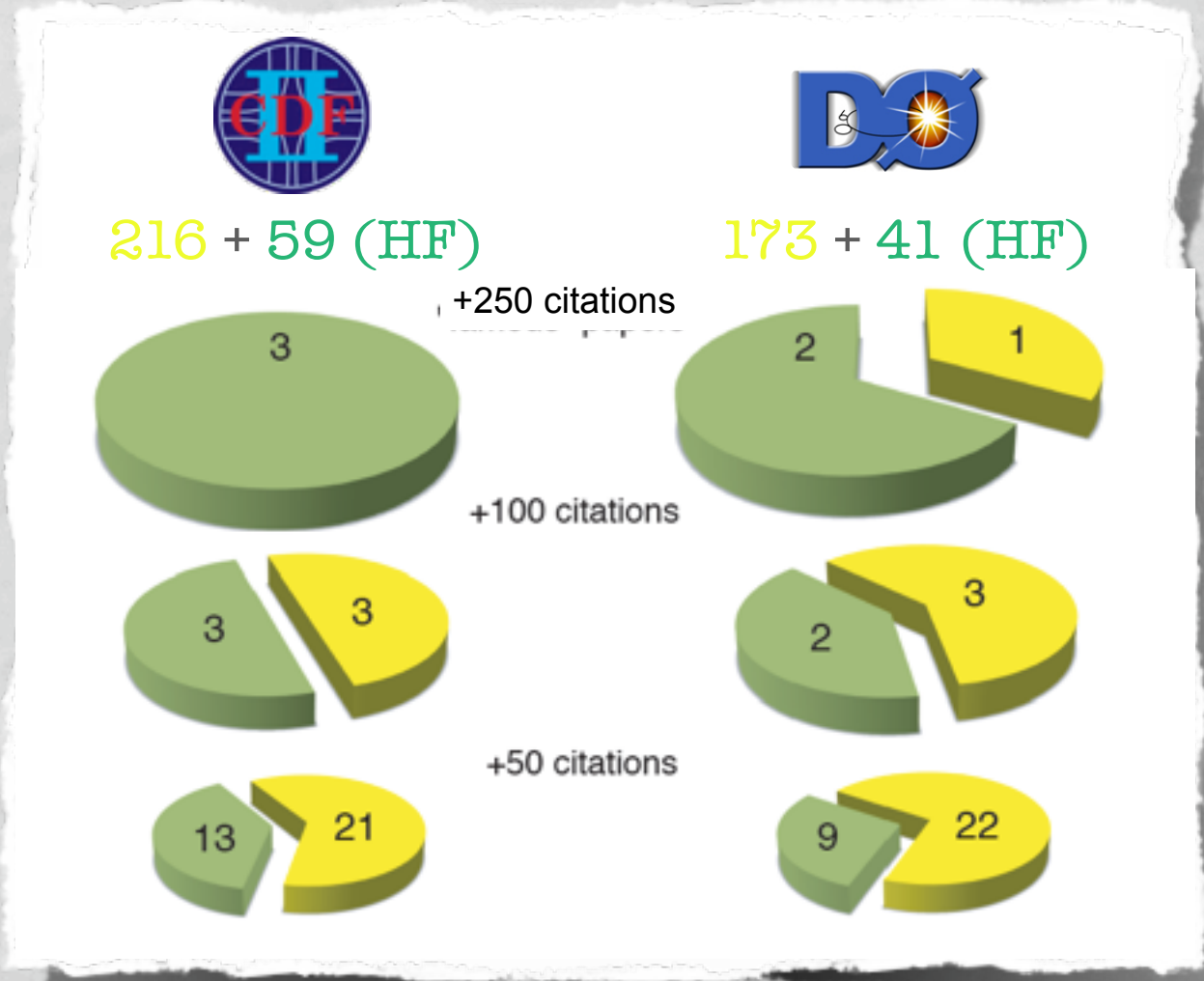


Conclusions

The impact

Heavy flavor, a key player in Tevatron Run II program

- world-leading rare decays
- unique access to B_s physics
- world leading masses/lifes
- b-baryons breakthrough
- exotic XYZ



Final remarks

- Many open questions on current understanding of matter and interactions are closely related to flavor.
- CKM picture success doesn't preclude chance of detectable effects from new particles. Soon.
- Rare decays, bottom-strange, precision charm, ...yet to be fully explored.
- Tevatron: then pioneers - now crucial players.
- Few recent, world-leading results shown. A sampler from extensive and successful ongoing program
- Paving the way for future experiments is no fun - we are still working to be the party-crashers.

WHO ARE THE DELINQUENTS —
KIDS OR THEIR "RESPECTABLE" PARENTS?

PARAMOUNT PRESENTS

THE PARTY CRASHERS

CONNIE STEVENS · ROBERT DRISCOLL · MARK DAMON · FRANCES FARMER · DORIS DOWLING

PRODUCED BY WILLIAM ALLAND · DIRECTED BY BERNARD GIRARD

SCREENPLAY BY BERNARD GIRARD AND DAN LUNDBERG