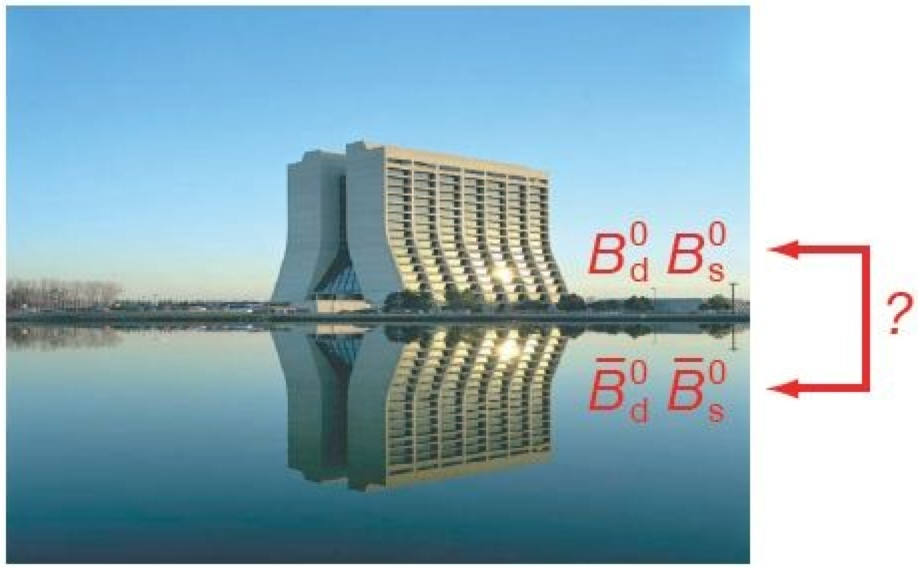
CPV and rare B_s decays at the Tevatron



LaThuile
March 2011
Marj Corcoran
for the CDF and D0 collaborations

Outline

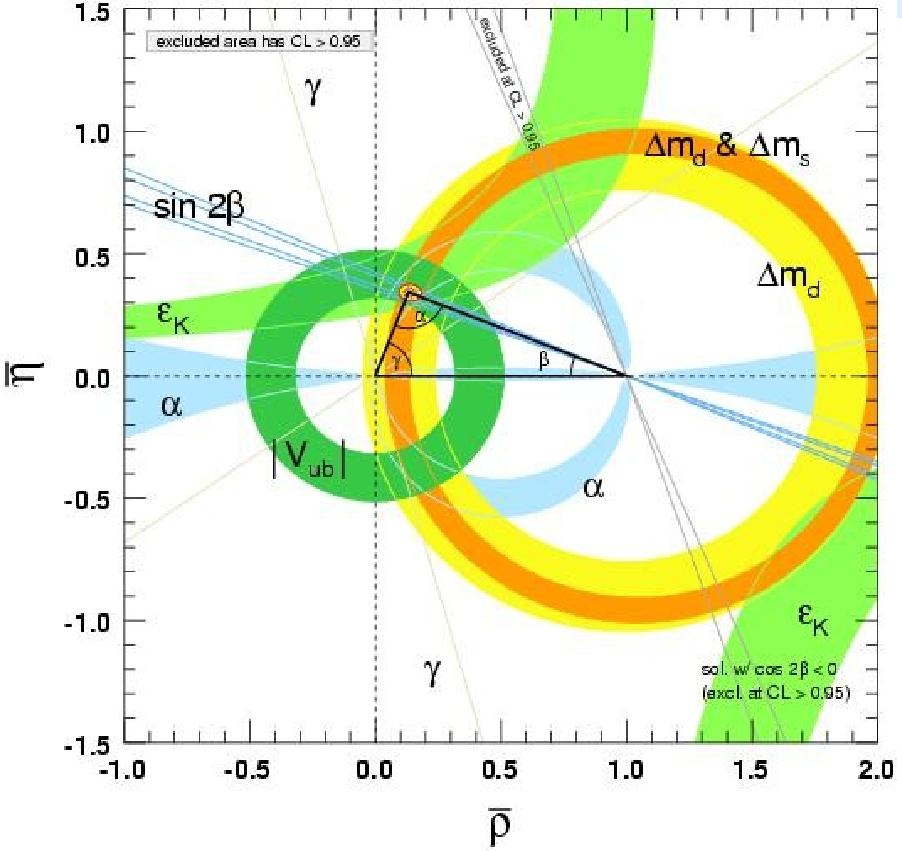
The B_s system and CPV phases

Dimuon charge asymmetry (D0)

$B_s \to J/\psi\ \phi$ (D0 and CDF)

$B_s \to \mu\mu$ (D0 and CDF)

CP violation the matter-antimatter asymmetry of the universe



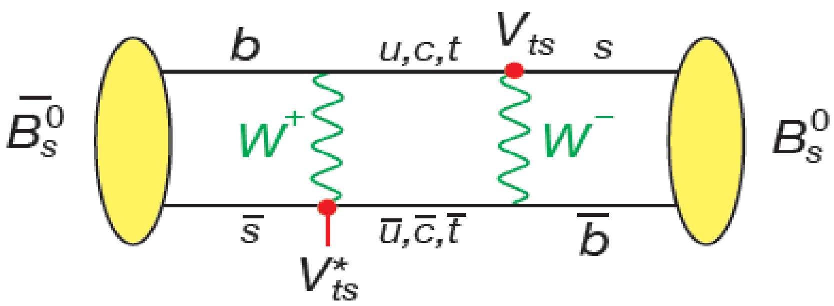
In 1968 Andrei Sakharov showed that CP violation is necessary to generate the matter-antimatter asymmetry of the universe.

The CKM matrix gives rise to CP violation through the complex phase.

But the amount of CP violation we see in the CKM matrix is too small by 10 orders of magnitude.

B_s meson

In the B_s system (as in the B^0_d and K^0 systems) CPV can arise through mixing via the box diagram:



or through interference of decay and mixing amplitudes through phases (ϕ_s),

or directly through the decay amplitudes (direct CPV).

B_s mixing

$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i\Gamma}{2} & M_{12} - \frac{i\Gamma_{12}}{2} \\ M_{12}^* - \frac{i\Gamma_{12}^*}{2} & M - \frac{i\Gamma}{2} \end{pmatrix}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}$$

The solution of the Schroedinger equation yields two mass eigenstates:

$B_s^H = p\,|B_s> - q\,|\bar{B}_s>$ and $B_s^L = p\,|B_s> + q\,|\bar{B}_s>$

If $p \neq q$, the mass eigenstates are not CP eigenstates, and $\bar{B} \rightarrow B \neq B \rightarrow \bar{B}$

B_s mixing parameters

$\Delta m_s = M_H - M_L = 2|M_{12}| = 17.77 \pm 0.12\ ps^{-1}$ (well measured by CDF)

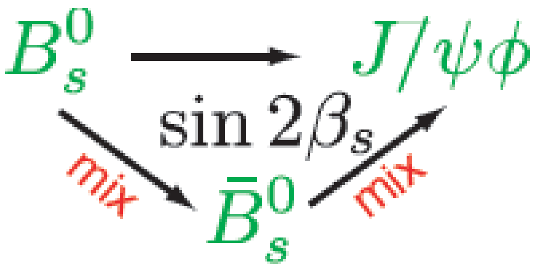
$\phi_s^{SM} = \arg[-M_{12}/\Gamma_{12}] = 0.0042 \pm 0.0014$ (SM expectation)

$\Delta\Gamma = \Gamma_L - \Gamma_H = 2|\Gamma_{12}| \cos\phi_s = 0.096 \pm 0.039\ ps^{-1}$ (SM expectation)

ϕ_s^{SM} is small, so measurements of ϕ_s are sensitive to new physics

$$\phi_s = \phi_s^{SM} + \phi_s^{NP}$$

$B_s \rightarrow J/\psi\phi$



For $B_s \rightarrow J/\psi\phi$, interference of direct decay and decay after mixing leads to a phase β_s or $\phi^{J/\psi\phi}$ which is also small in the SM.

$$\phi_s^{J/\psi\phi} = -2\beta_s = -2\arg[V_{ts} V^*_{tb}/V_{cs} V^*_{cb}] = 0.038 \pm 0.002$$

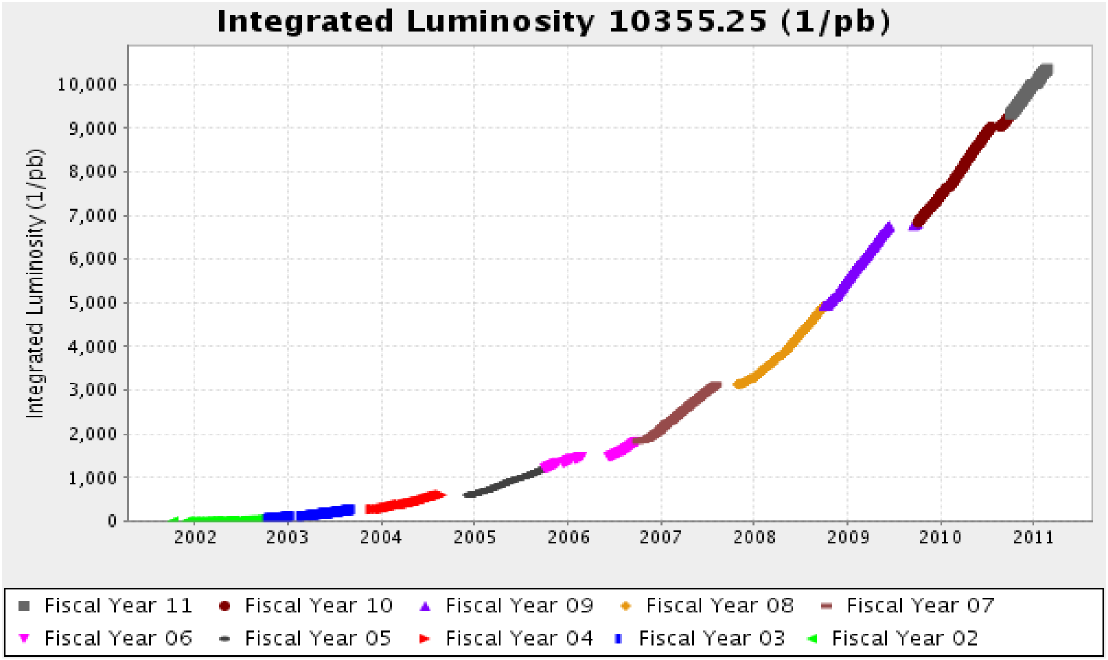
New physics could effect both ϕ_s and $\phi_s^{J/\psi\phi}$

$$\phi_s^{J/\psi\phi} = -2\beta_s^{SM} + \phi_s^{NP}$$

$$\phi_s = \phi_s^{SM} + \phi_s^{NP}$$

Note that CDF uses β_s and D0 uses $\phi_s^{J/\psi\phi}$

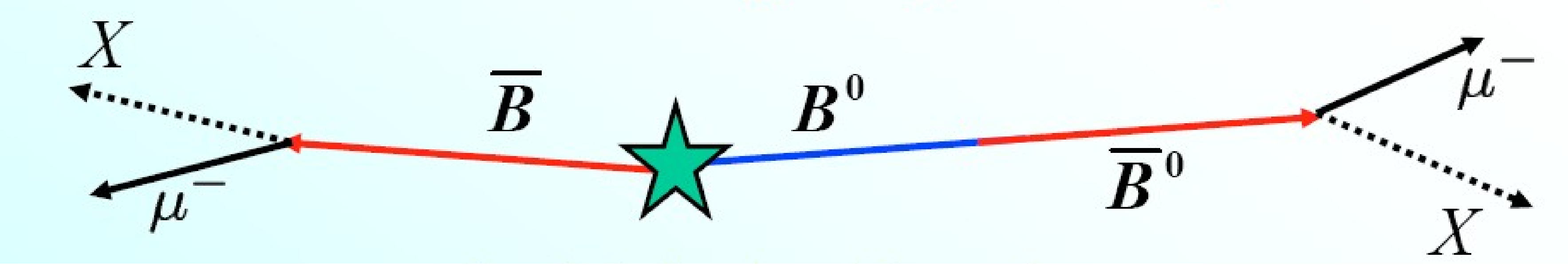
The Tevatron performs!



Both CDF and D0 have received more than 10fb^{-1} of integrated luminosity, and both have been running at ~90% efficiency.

Dimuon Charge Asymmetry

Dimuon charge asymmetry



Decay of B tags its flavor

The quantity being measured is simple, and can be nonzero from B mixing.

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

If the rate of $B \rightarrow \overline{B}$ is the same as $\overline{B} \rightarrow B$, this quantity will be zero. The SM expectation is nearly zero.

Semileptonic muon charge asymmetry

We also measure the 'wrong sign' semileptonic charge asymmetry for inclusive muons:

$$a_{\mathrm{sl}}^{b} = \frac{\Gamma(\overline{B} \to \mu^{+} X) - \Gamma(B \to \mu^{-} X)}{\Gamma(\overline{B} \to \mu^{+} X) + \Gamma(B \to \mu^{-} X)} = A_{\mathrm{sl}}^{b}$$

The 'right sign' decays are $B \to \mu^{+} X$ and $\overline{B} \to \mu^{-} X$
The 'wrong sign' decays can only occur through mixing.

Semileptonic and dimuon asymmetries

We measure a linear combination of B_d and B_s decays

$$A^b_{\rm sl} = (0.506 \pm 0.043)a^d_{\rm sl} + (0.494 \pm 0.043)a^s_{\rm sl}$$

dimuon semileptonic B_d semileptonic B_s

The fractions of B_d and B_s are known from other measurements.

Upper case A refers to dimuon quantities; lower case to single muon inclusive quantities.

Analysis strategy

Measure the raw asymmetries

$$A = \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)}$$

3.7×10^6 events

$$a = \frac{n(\mu^+) - n(\mu^-)}{n(\mu^+) + n(\mu^-)}$$

1.5×10^9 events

Correct for backgrounds and detector related asymmetries

almost entirely from the data

Correct for non-B contributions and non-oscillating contributions

from simulation

Use the two independent measurements to cancel some systematics

Analysis strategy

$k=0.041\pm0.003$

$K=0.342\pm0.023$

Determine backgrounds from data

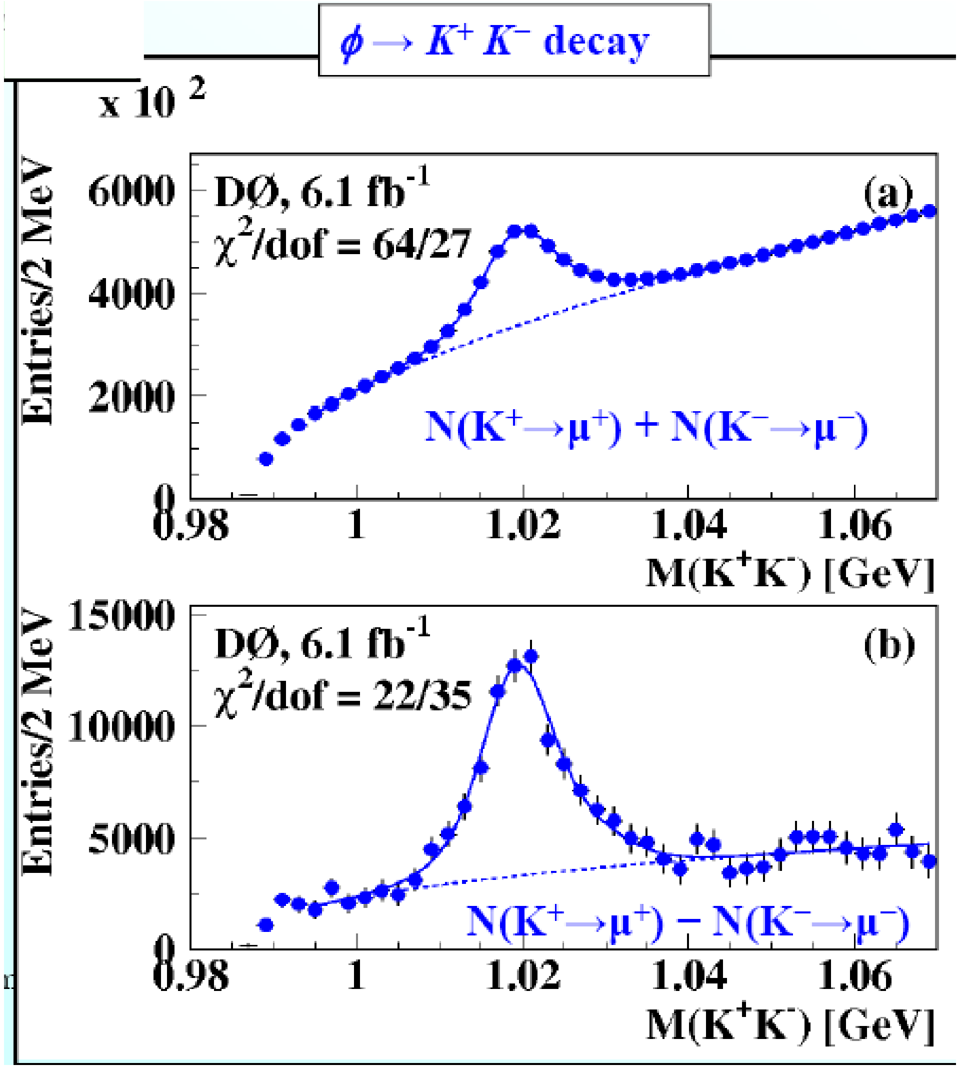
$$A=KA^{b}_{sl} + A_{bkg} \qquad a=kA^{b}_{sl} + a_{bkg}$$

Determine dilution factors from simulation

Blind analysis! The central value of A^{b}_{sl} from the full data set was not revealed until all the background subtraction and systematics had been finalized.

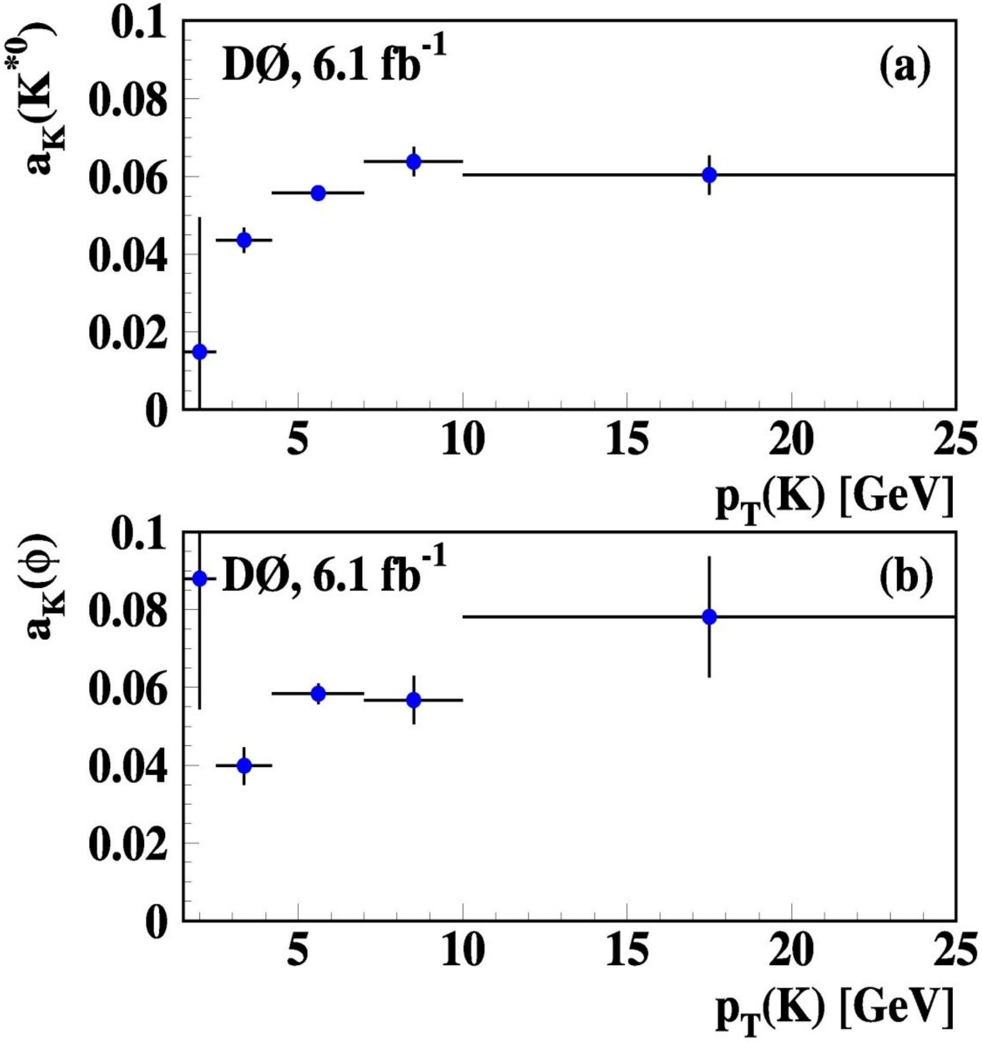
Kaon background

The largest background comes from $K \to \mu\nu$, which is asymmetric for K^+ / K^-. The resulting fake asymmetry is measured from the data, using $\phi \to KK$ and $K^{0*} \to K\pi$.



Processes such as $K^- p \to \Lambda\pi^0$ gives K^- a much larger cross section than K^+ . So more K^+ survive to decay.

Kaon asymmetry



The K asymmetry is measured two ways, in complete agreement. The average is used.

Background asymmetries from protons and pions are 20x smaller and are determined from $\Lambda \rightarrow p\pi$ and $K_S \rightarrow \pi\pi$.

Background fractions

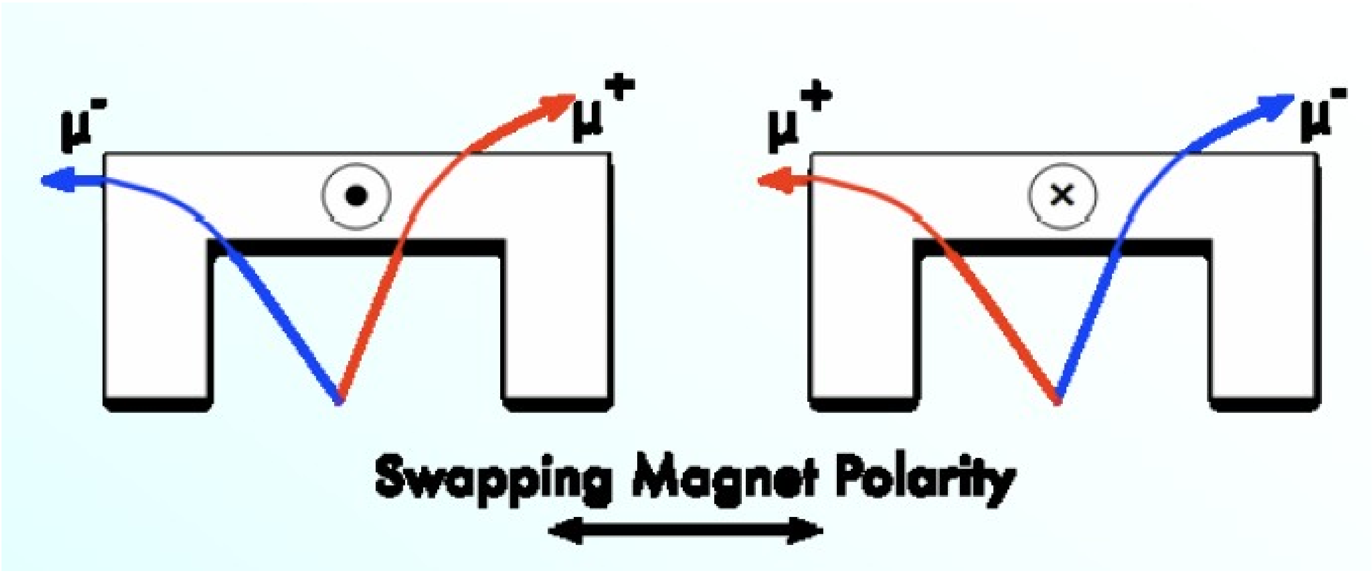
The background fractions are determined mainly from the data, but a comparison with MC truth gives us confidence that everything hangs together.

	$(1-f_{bkg})$	f_K	f_π	f_p
MC	(59.0±0.3)%	(14.5±0.2)%	(25.7±0.3)%	(0.8±0.1)%
Data	(58.1±1.4)%	(15.5±0.2)%	(25.9±1.4)%	(0.7±0.2)%

The fractions of single muons coming from background sources, comparing data and Monte Carlo 'truth'.

Many other cross-checks were done.

Track reconstruction

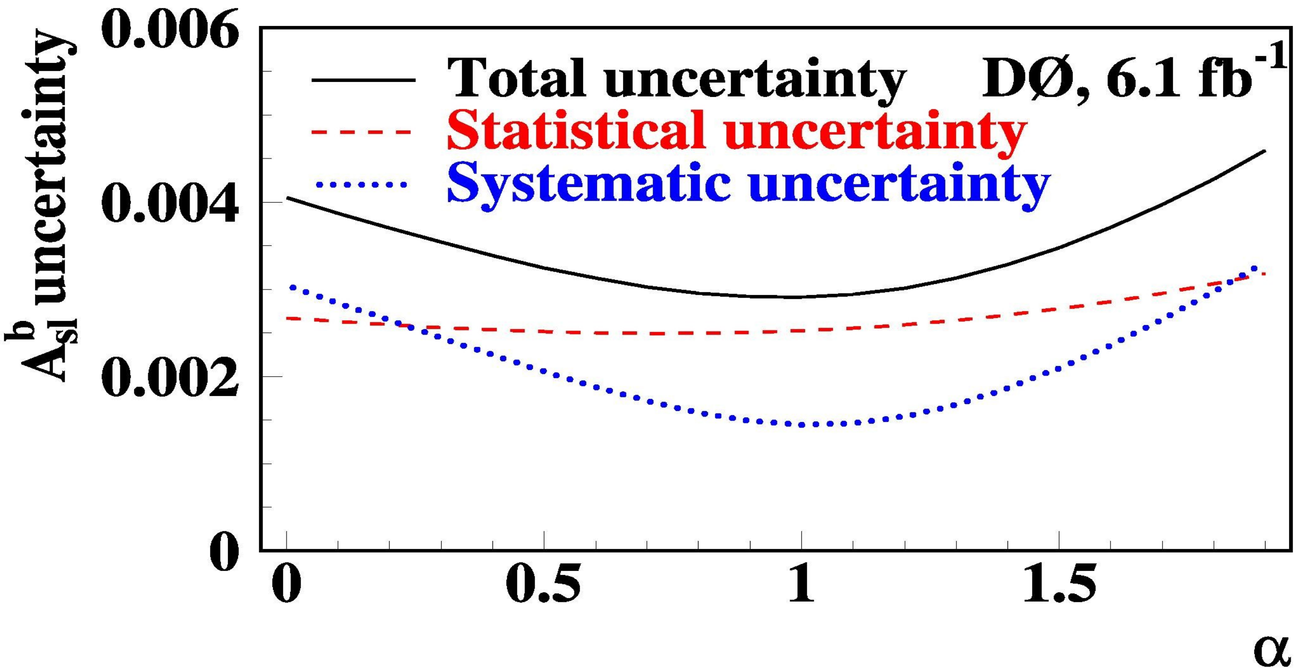


The detector can give a fake asymmetry. Reversal of the magnet polarities is important for cancelling these instrumental asymmetries.

Cancellation of systematics

There are two measurements of the charge asymmetry—one from dimuons and one from single inclusive muons

Reduce the systematic uncertainties by a cancellation using the dimuon and the single muon charge asymmetries.



$$A' \equiv A - \alpha a,$$

Dimuon charge asymmetry

Measurement

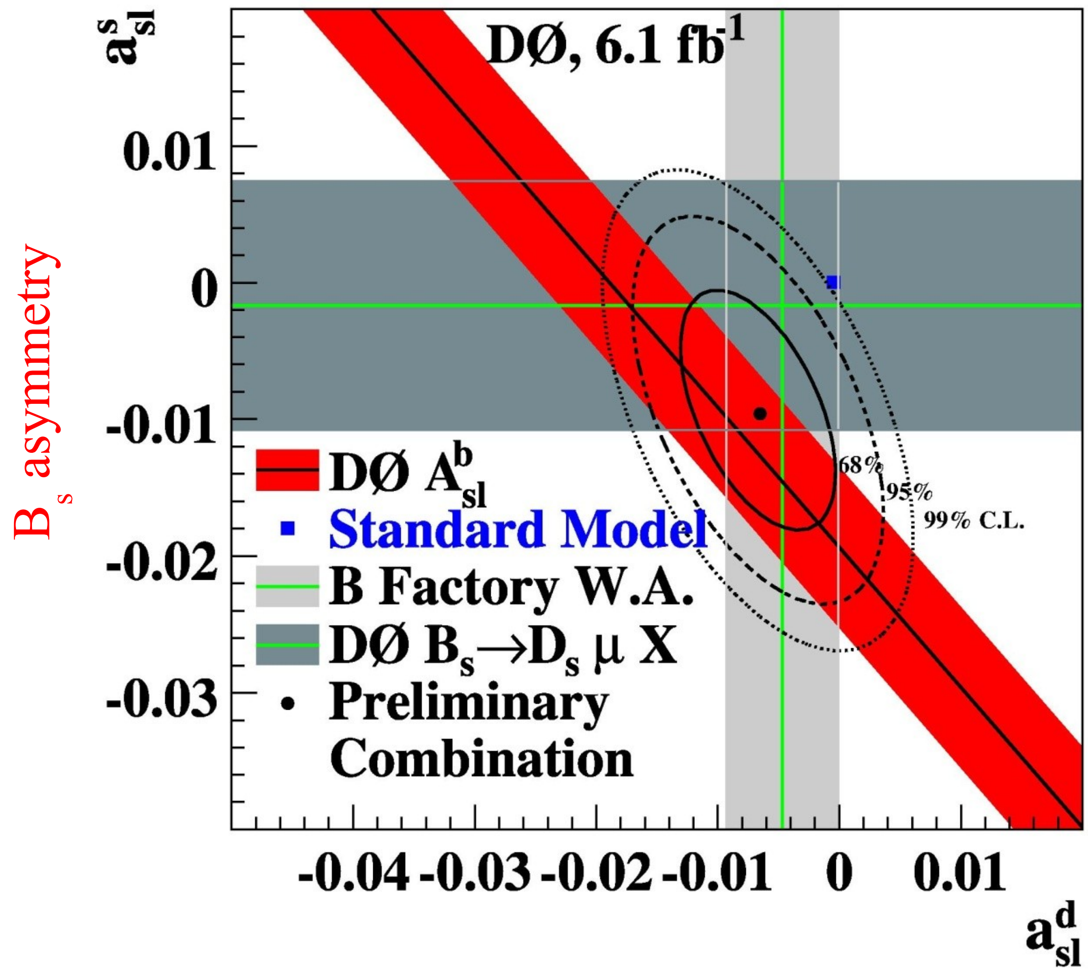
$$A^b_{sl} = [\,-0.957 \pm 0.251\,(\text{stat.}) \pm 0.146\,(\text{syst.})\,]\ \%$$

Expectation

$$A^b_{sl}\,(\text{SM}) = [\,-0.023\,^{+0.005}_{-0.006}\,]\ \%$$

The final result is 3.2 σ from the SM expectation.

CDF is working on a similar analysis (we eagerly await...)
D0 is working on an update with more data, better background treatment, and asymmetry vs. impact parameter.



B_d asymmetry

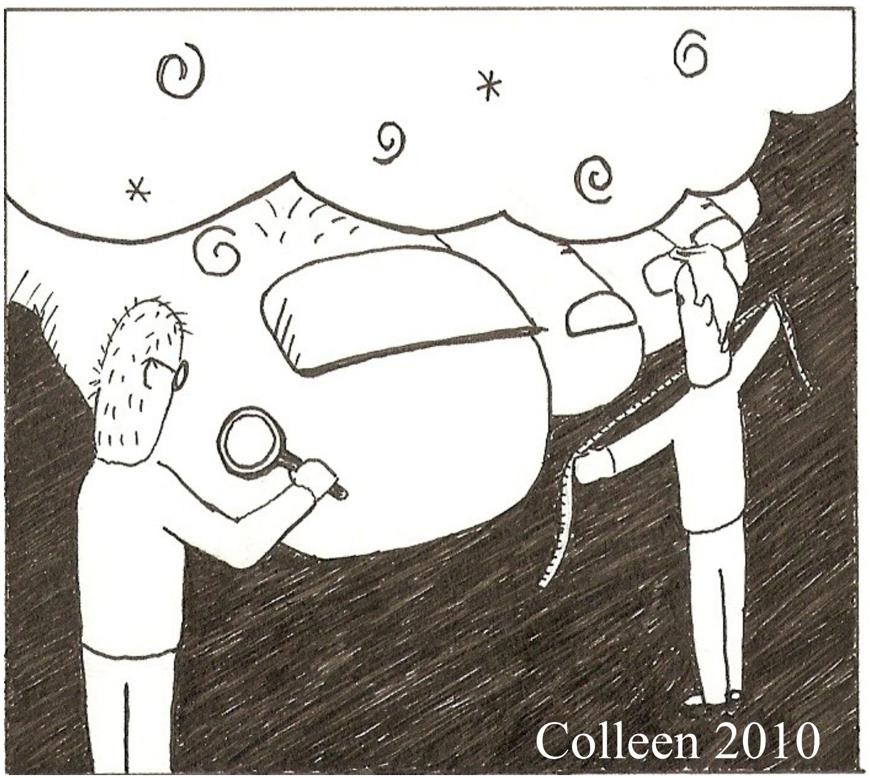
Comparing to other measurements

The quantity we measure is a linear combination of the asymmetry from B_d and B_s mesons.

$$A_{\mathrm{sl}}^{b} = (0.506 \pm 0.043) a_{\mathrm{sl}}^{d} + (0.494 \pm 0.043) a_{\mathrm{sl}}^{s}.$$

“A New Clue to Explain Existence” New York Times

Joe Lykken, a theorist at Fermilab, said, “So I would not say that this announcement is the equivalent of seeing the face of God, but it might turn out to be the toe of God.”



Guennadi Borissov
Lancaster Univ.
UK

Bruce Hoeneisen
Universidad San Francisco de Quito
Ecuador

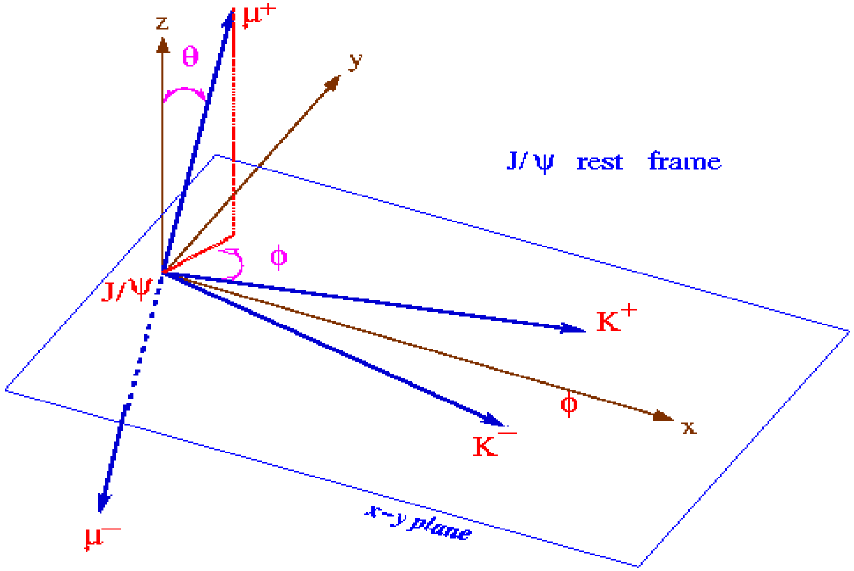
V. A. Abazov et al, Phys. Rev. D **82**, 032001 (2010)
V. A. Abazov et al, Phys. Rev. Lett. **105**, 081801 (2010)

$$B_s \rightarrow J/\psi\phi$$

A previous CDF/D0 combination had a 2.1σ discrepancy with the SM.

See CDF public note 10206
See D0 public note 6098

$B_s \to J/\psi\phi$

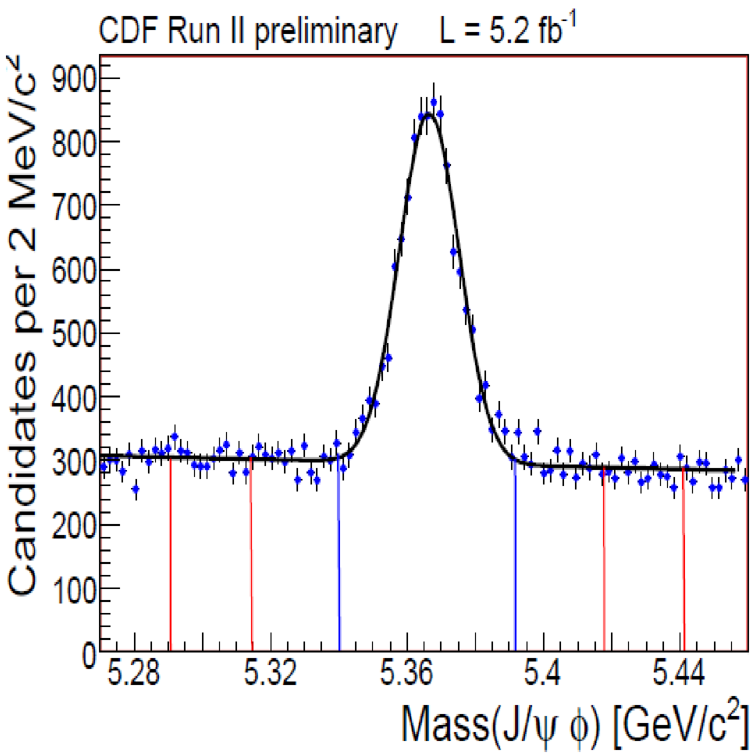


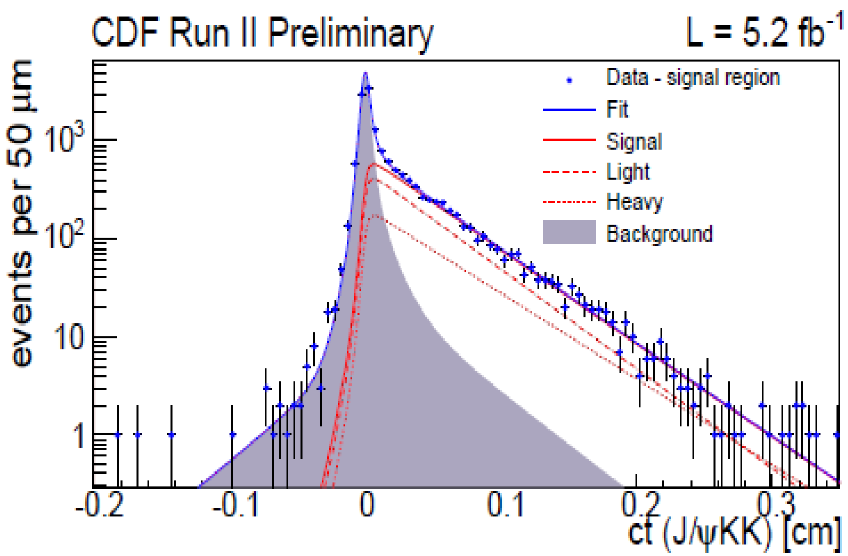
$$\frac{d^3\Gamma\left[B_s^0(t) \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)\right]}{d\cos\theta \;\; d\varphi \;\; d\cos\psi} \propto$$

$$\begin{aligned}
& 2\cos^2\psi(1-\sin^2\theta\cos^2\varphi) && |A_0(t)|^2 \\
+\; & \sin^2\psi(1-\sin^2\theta\sin^2\varphi) && |A_\parallel(t)|^2 \\
+\; & \sin^2\psi\sin^2\theta && |A_\perp(t)|^2 \\
+\; & \frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\varphi && Re(|A_0^*(t)||A_\parallel(t)|) \\
+\; & \frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\varphi && Im(|A_0^*(t)||A_\perp(t)|) \\
-\; & \sin^2\psi\sin 2\theta\sin\varphi && Im(|A_\parallel(t)||A_\perp(t)|)
\end{aligned}$$

Scalar → two vectors, L=0,1,2 allowed
Complicated fit to time-dependent angular distributions.

$B_s \to J/\psi\phi$

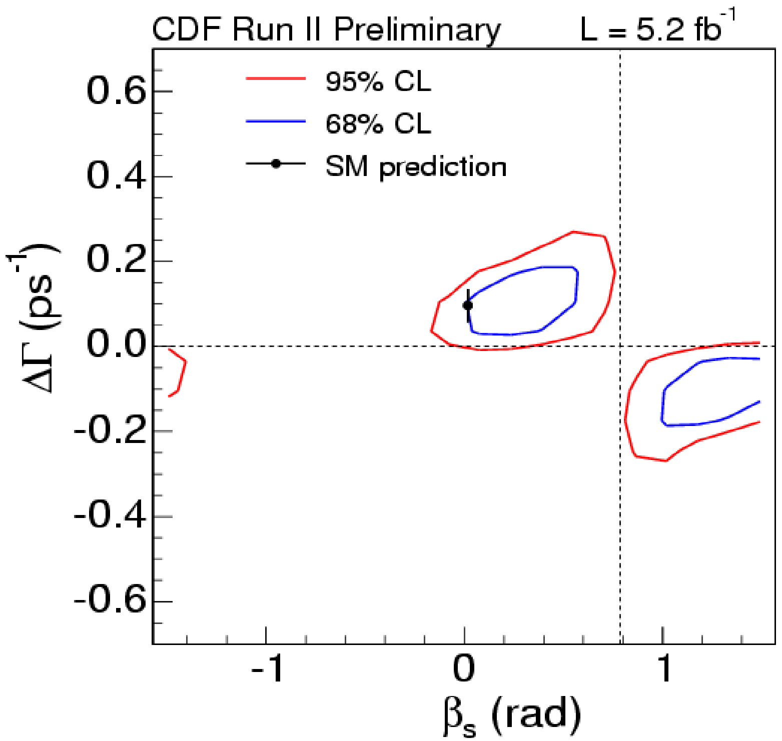


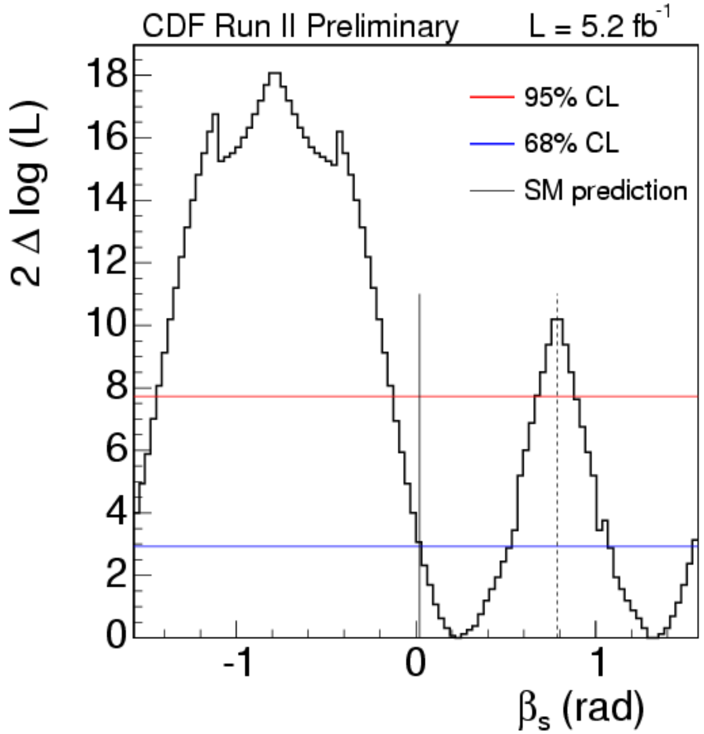


6504± 85 signal events

CDF has uses both same-side and opposite-side tagging.
A neural net is used for signal selection, and a multidimensional max-likelihood fit extracts the parameters.

$B_s \to J/\psi\phi$





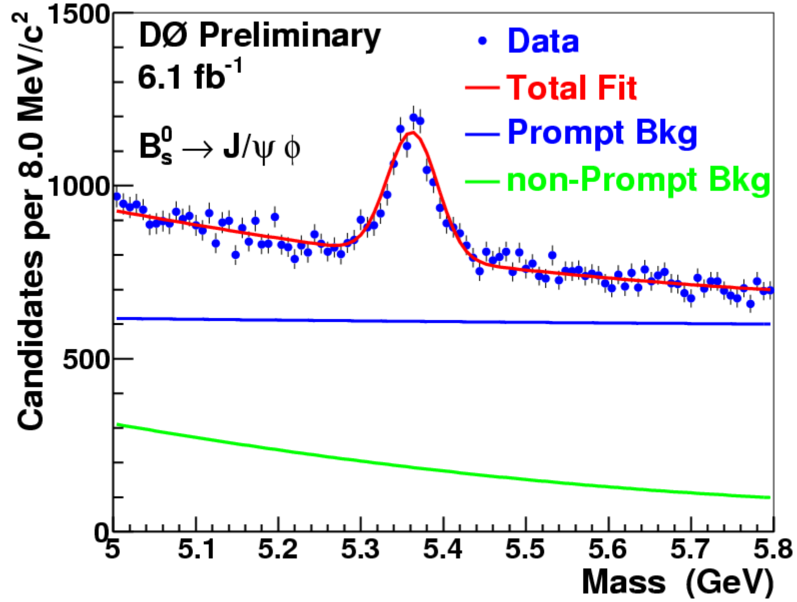
New CDF result agrees with the SM at about 1 σ

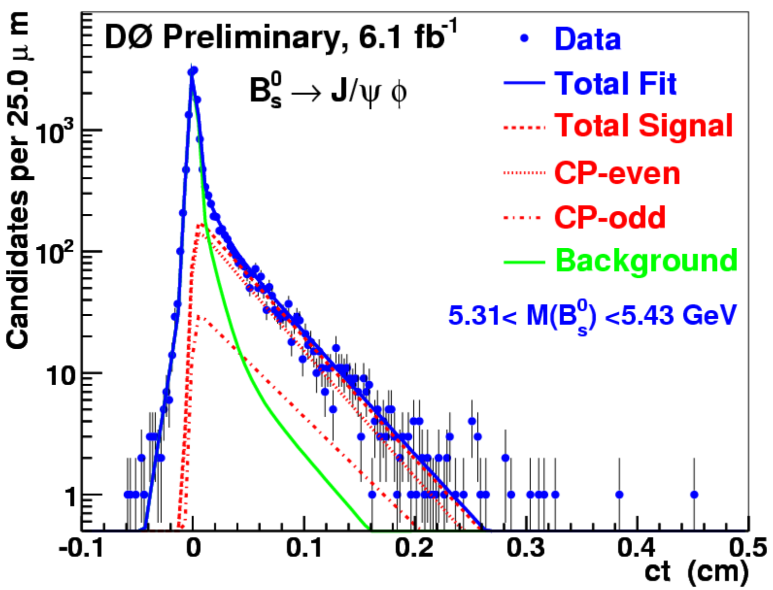
They also have excellent measurements of B_s lifetime, $\Delta\Gamma_s$ and the polarization amplitudes. S-wave contribution in KK < 6.7% at 95% CL.

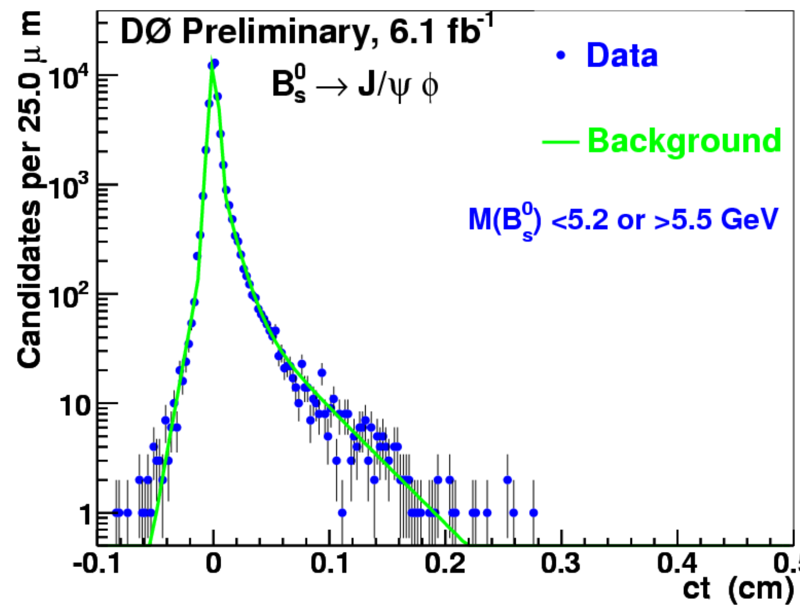
$B_s \rightarrow J/\psi\phi$

D0 analysis is similar: multidimensional unbinned likelihood fit, opposite- side tagging, strong phases fixed to B_d values

3435 ± 84 signal events

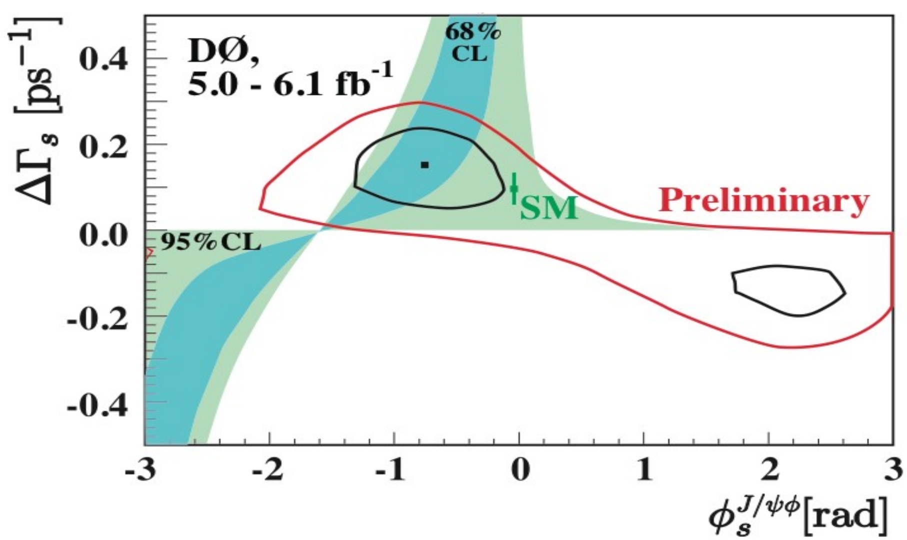


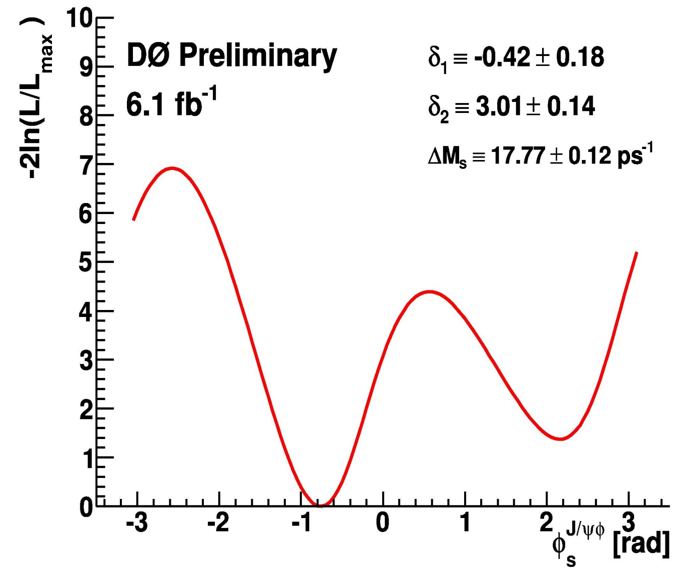




$B_s \rightarrow J/\psi\phi$

green bands show expectation from a^s_{sl}

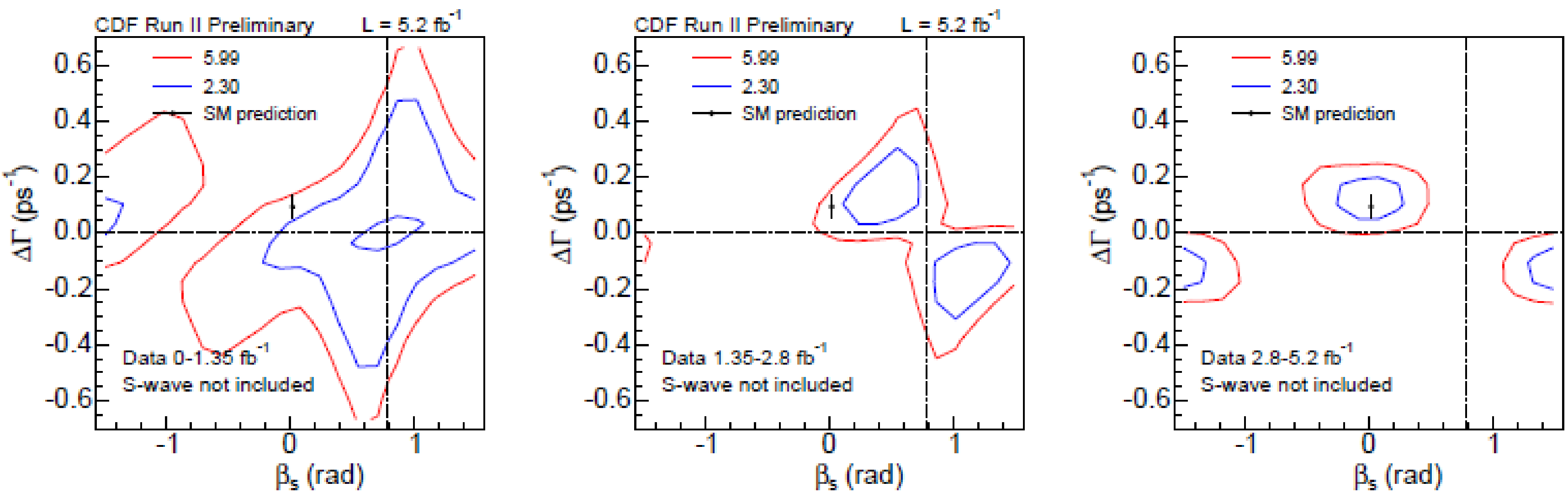




D0s new result is a bit further from the SM than the older result, and in good agreement with the dimuon charge asymmetry.

$B_s \rightarrow J/\psi\phi$

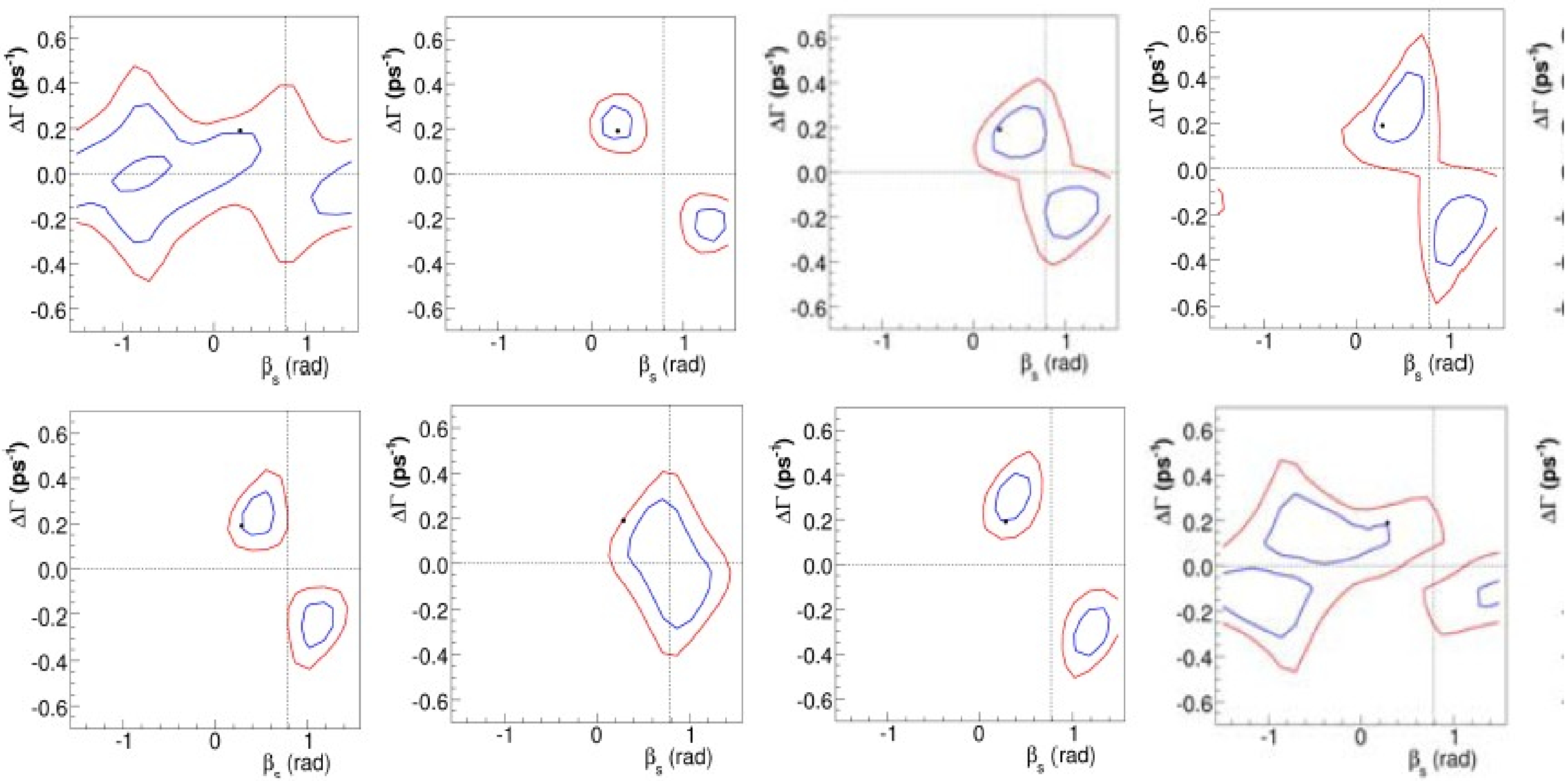
Both experiments agree that results can vary a lot, even with data sets of the same size!



CDF results for different data periods—significant variation

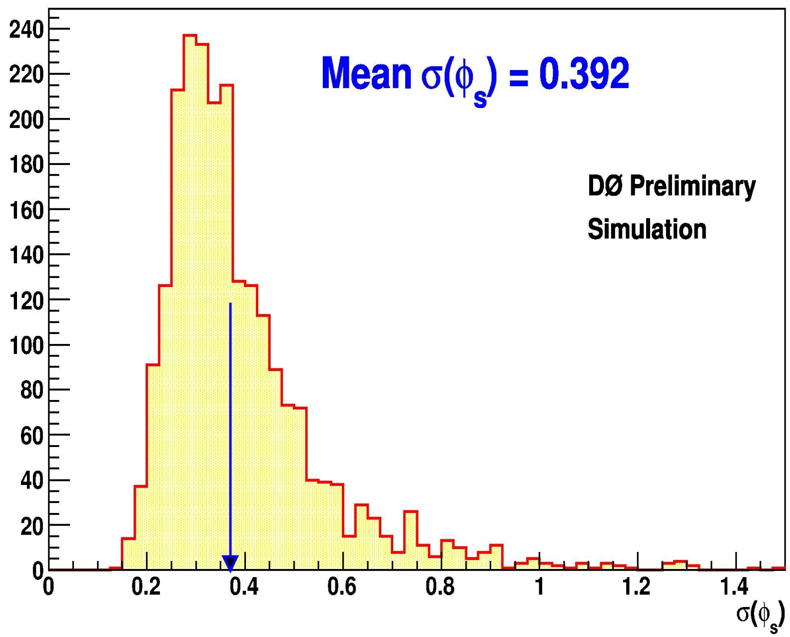
Pseudoexperiments

CDF pseudoexperiments equivalent to 1.4 fb^{-1}, all with the same initial parameters—a lot of variation.



From Gavril Giurgui's talk at ICHEP2010

D0 pseudoexperiments



Distribution of errors from 2000 pseudoexperiments with the same statistics as the data.

The two experiments are consistent.

$\phi_s^{J/\psi\phi}$ from full sample = -0.76 ± 0.37

first 2.8 fb^{-1} = -0.86 ± 0.33

last 3.3 fb^{-1} = -0.37 ± 0.81

D0 is working on finalizing the 2010 result with BDT selection and including s-wave in the KK system.

CDF result (translated to $\phi_s^{J/\psi\phi}$)

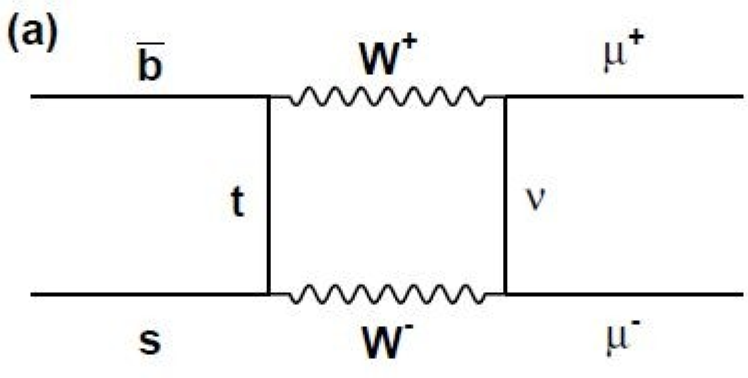
[-0.04, -1.04] U [-2.16,-3.10] at 68% CL

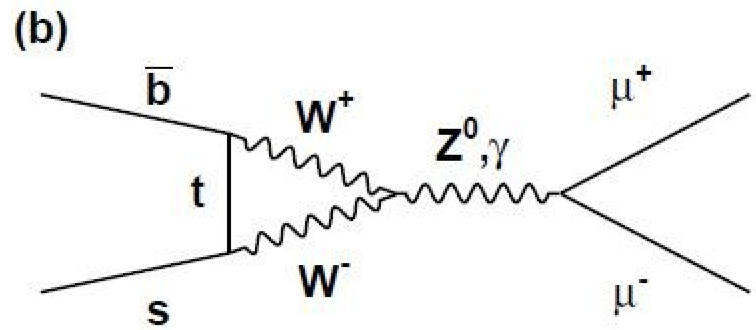
$B_s \rightarrow \mu\mu$

D0 has a result from 2010 on 6.1 fb^{-1}

CDF has a result from 2009 on 3.7fb^{-1}

$B_s \rightarrow \mu\mu$

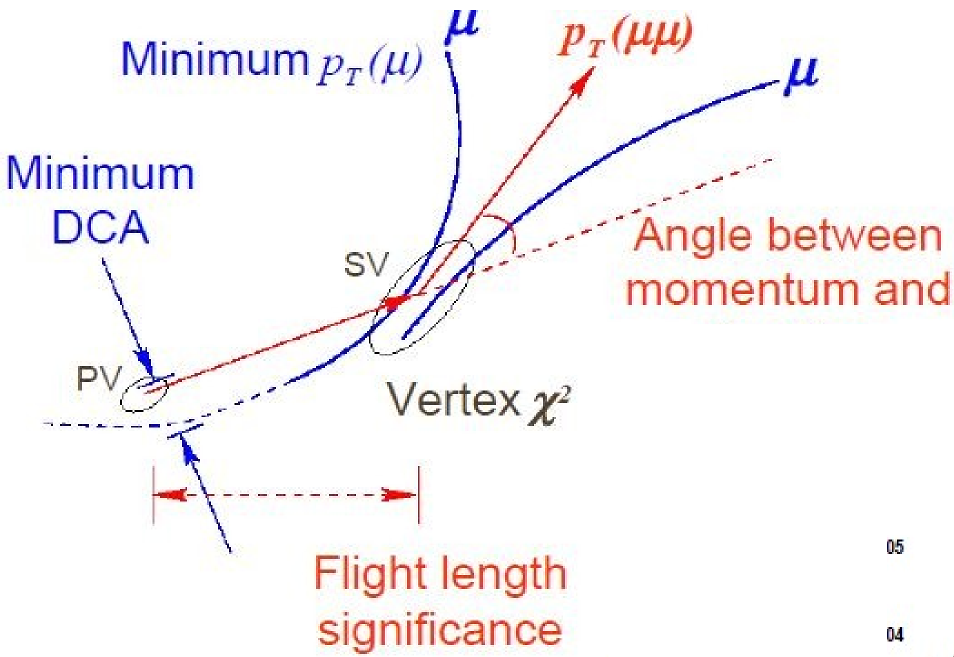




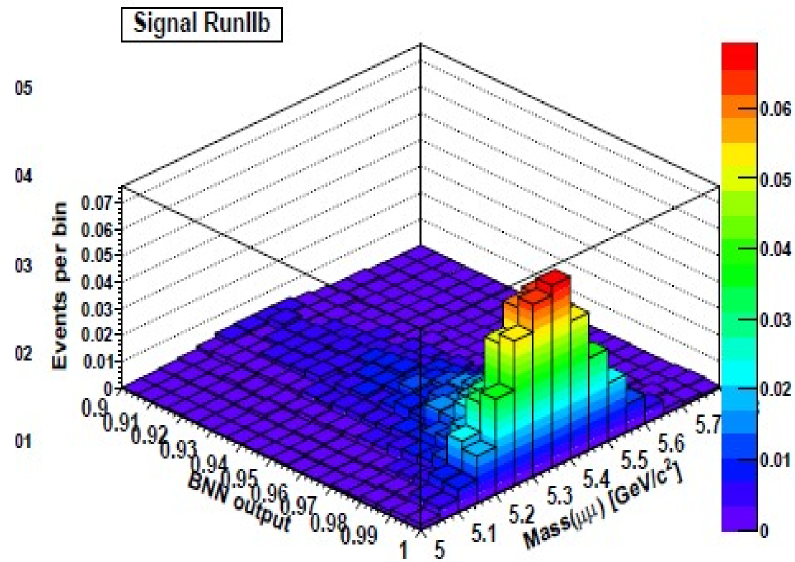
SM expected branching ratio is well known, BR=3.6 ± 0.3 x 10^{-9}
Many models of physics beyond the SM enhance this BR by large factors, lots of room for new physics.
Some models that lead to new physics in B_s mixing also enhance this decay .

Background suppression

Primary background is double semileptonic decays



Construct a Baysean Neural Net with six variables.



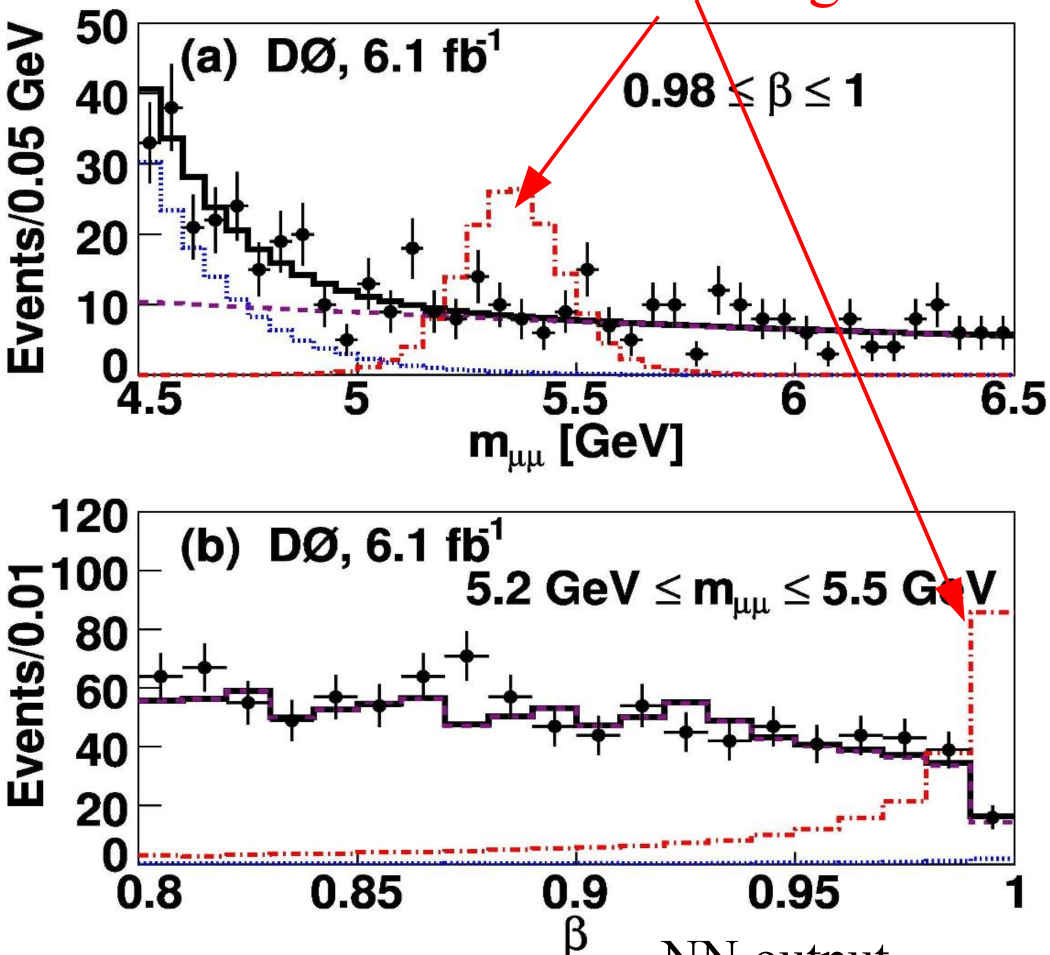
$B_s \rightarrow \mu\mu$

In highest sensitivity region, 51±4 bkgnd expected, 55 events seen.

BF < 51 x 10^{-9} at 95% CL
Expected limit 38 x 10^{-9}
PLB 695, 539 (2010)

CDF preliminary 2009
43 x 10^{-9} observed
33 x 10^{-9} expected

100x signal



NN output

Both CDF and D0 are working on updates.

Summary

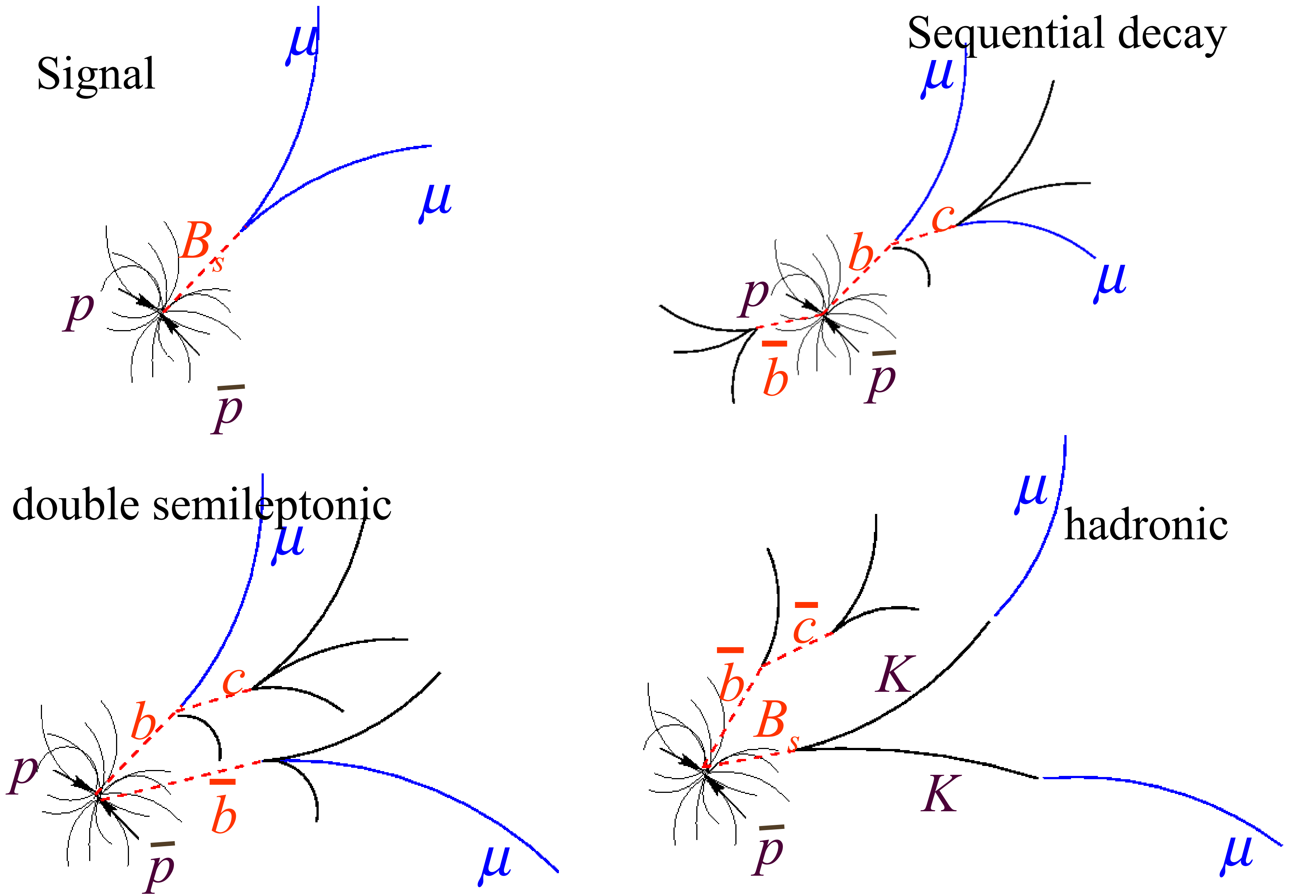
D0 has measured the dimuon charge asymmetry and finds a 3.2σ discrepancy with the SM. D0 is working on an update, and CDF is working on a similar result.

Both CDF and D0 have updated results for the CP violating phase in $B_s \rightarrow J/\psi\phi$. CDF is closer to the SM, D0 is a bit further from the SM, but within errors there is no discrepancy. Errors do not seem to scale with $1/\sqrt{N}$.

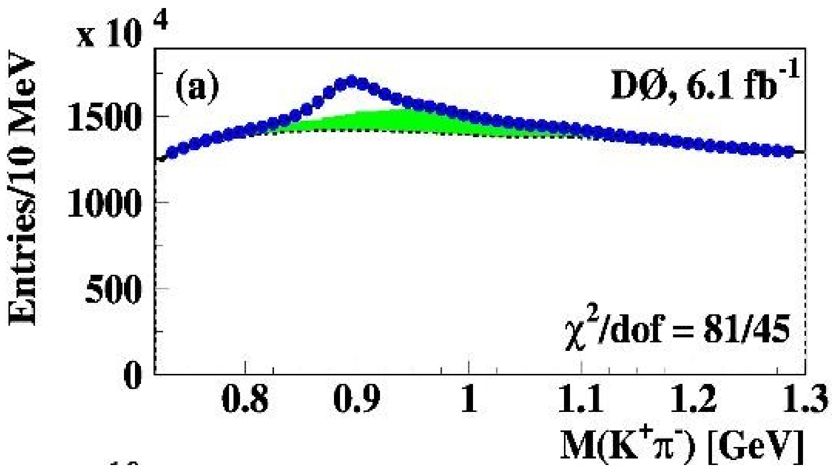
The current limit on $B_s \rightarrow \mu\mu$ is about 10x SM expectation. Both CDF and D0 are working on updates for this decay.

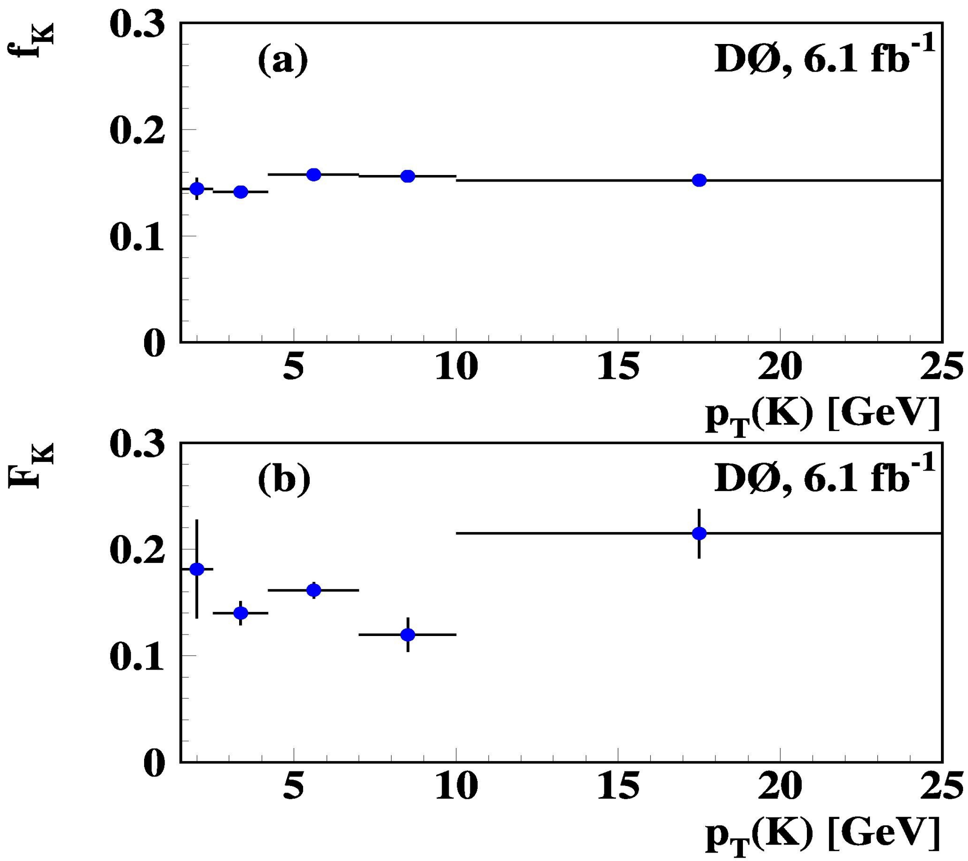

Backup slides

$B_s \to \mu\mu$ Signal and backgrounds



Background K fractions





The fraction of K→μ background is determined from data using K^{*0} and K^{*+} decays. The K fraction along with MC is used to determine the π and p fractions.

Final background determination

(statistical uncertainties only)

$(1 - f_{\mathrm{bkg}})$	f_K	f_π	f_p
$(58.1 \pm 1.4)\%$	$(15.5 \pm 0.2)\%$	$(25.9 \pm 1.4)\%$	$(0.7 \pm 0.2)\%$
	$a_K f_K$	$a_\pi f_\pi$	$a_p f_p$
	$(+0.854 \pm 0.018)\%$	$(+0.095 \pm 0.027)\%$	$(+0.012 \pm 0.022)\%$
	$A_K F_K$	$A_\pi F_\pi$	$A_p F_p$
	$(+0.828 \pm 0.035)\%$	$(+0.095 \pm 0.025)\%$	$(+0.000 \pm 0.021)\%$

Dilution Factors

The physics...

$$a - a_{\text{bkg}} = kA^b_{\text{sl}}$$
$$A - A_{\text{bkg}} = KA^b_{\text{sl}}$$

- Multiple physics processes contribute to the inclusive and like-sign dimuon samples

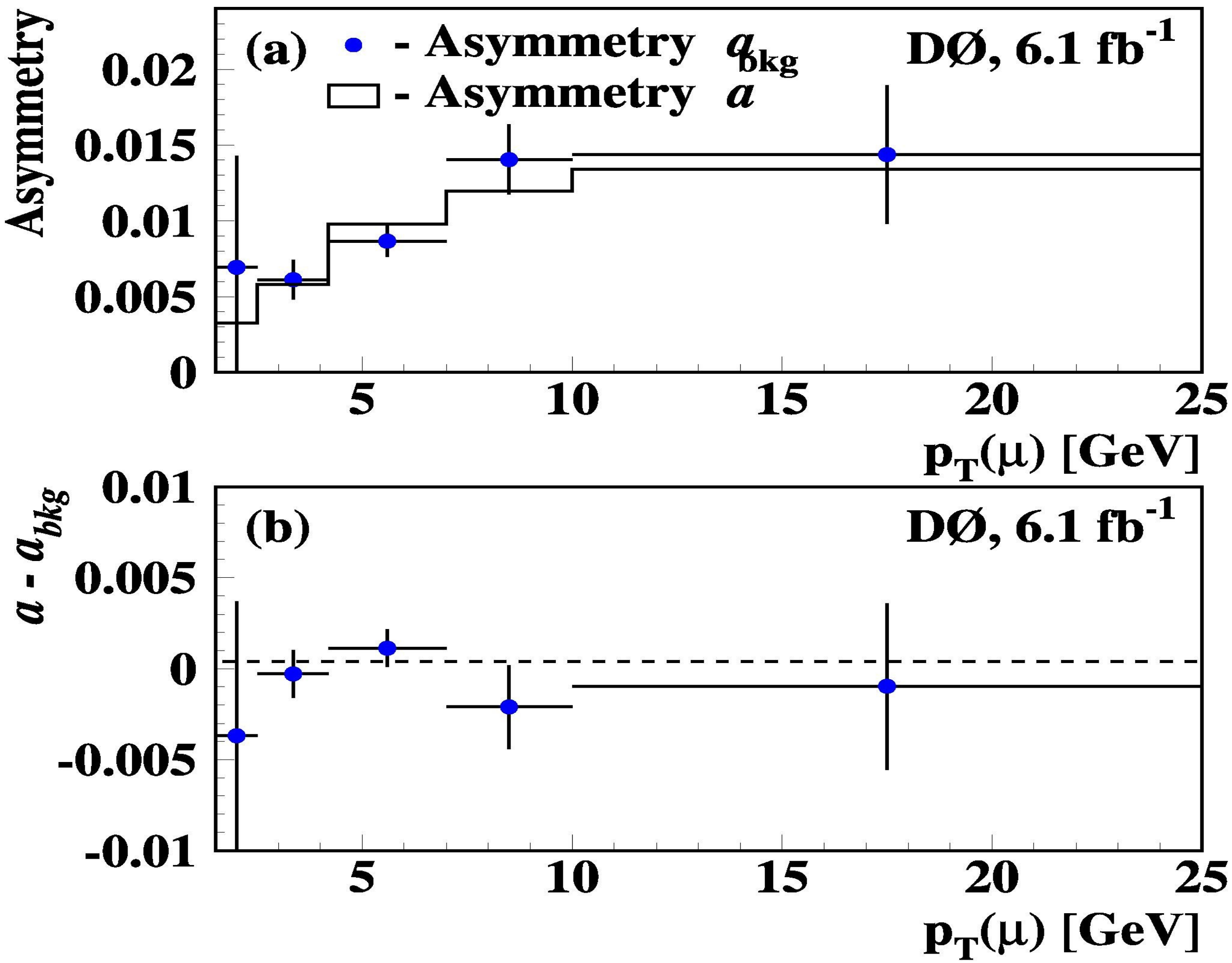
- Use simulation to determine dilution factors k and K

  (decay processes are well measured)

$$k = 0.041 \pm 0.003$$
$$K = 0.342 \pm 0.023$$

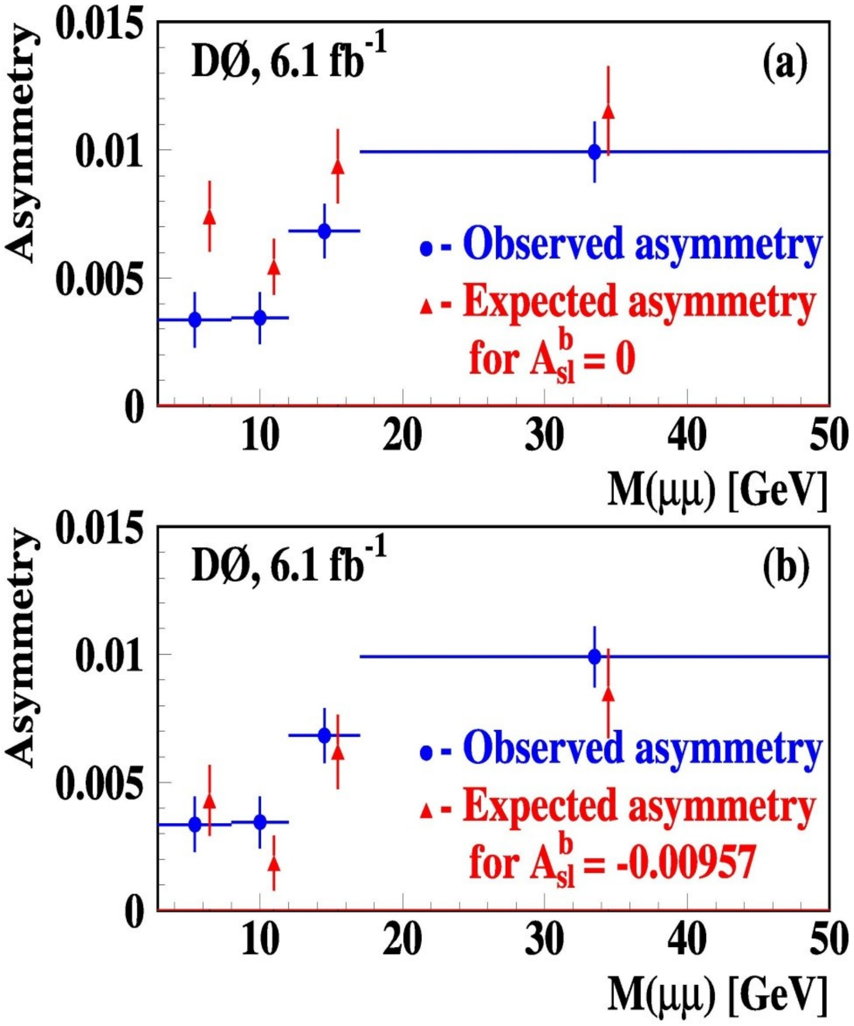
	Process		
T_1	$b \to \mu^- X$		
T_{1a}	$b \to \mu^- X$ (non-oscillating)		
T_{1b}	$\bar{b} \to b \to \mu^- X$ (oscillating)	$\longrightarrow A$	A^b_{sl}
T_2	$b \to c \to \mu^+ X$	$\longrightarrow A$	
T_{2a}	$b \to c \to \mu^+ X$ (non-oscillating)		
T_{2b}	$\bar{b} \to b \to c \to \mu^+ X$ (oscillating)		A^b_{sl}
T_3	$b \to c\bar{c}q$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$		
T_4	$\eta, \omega, \rho^0, \phi(1020), J/\psi, \psi' \to \mu^+\mu^-$		
T_5	$b\bar{b}c\bar{c}$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$\longrightarrow A$	
T_6	$c\bar{c}$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$		

Sanity check



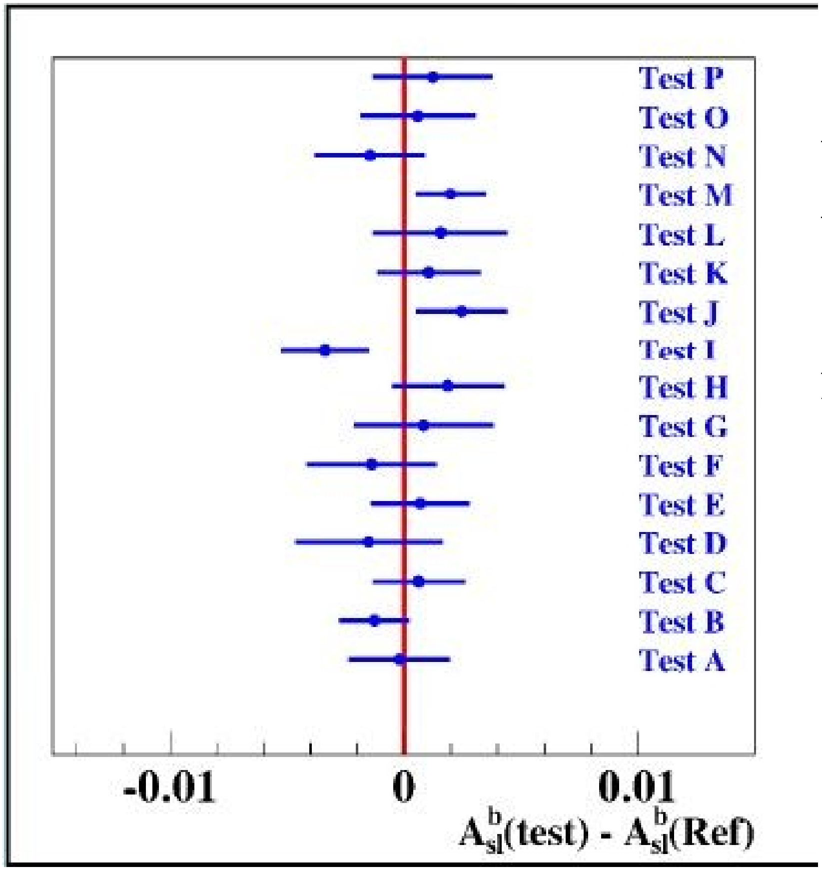
The measured raw inclusive asymmetry should be dominated by background, which it is.

Asymmetry vs mass



Measured and expected uncorrected asymmetry vs dimuon mass. The expected (red) values uses all the measured background contributions.

Systematic checks

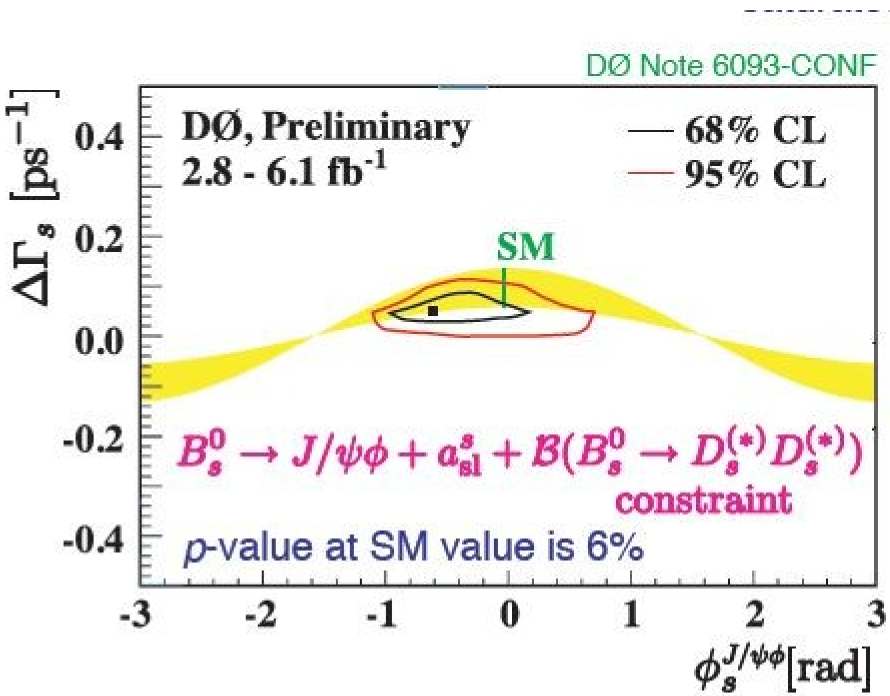


This plot shows the difference from the central value for 16 analysis variations.

The raw asymmetries changed by as much as 150% with these variations.

The variations include:

- more stringent muon selection
- variations in trigger requirements
- different angular regions
- different μμ mass cuts



D0 combination

$$\bar{\tau}_s = 1.45 \pm 0.04 \pm 0.01\,\mathrm{ps}$$

$$\Delta\Gamma_s = 0.15 \pm 0.06 \pm 0.01\,\mathrm{ps}^{-1}$$

$$\phi_s^{J/\psi\phi} = -0.76^{+0.38}_{-0.36} \pm 0.02$$