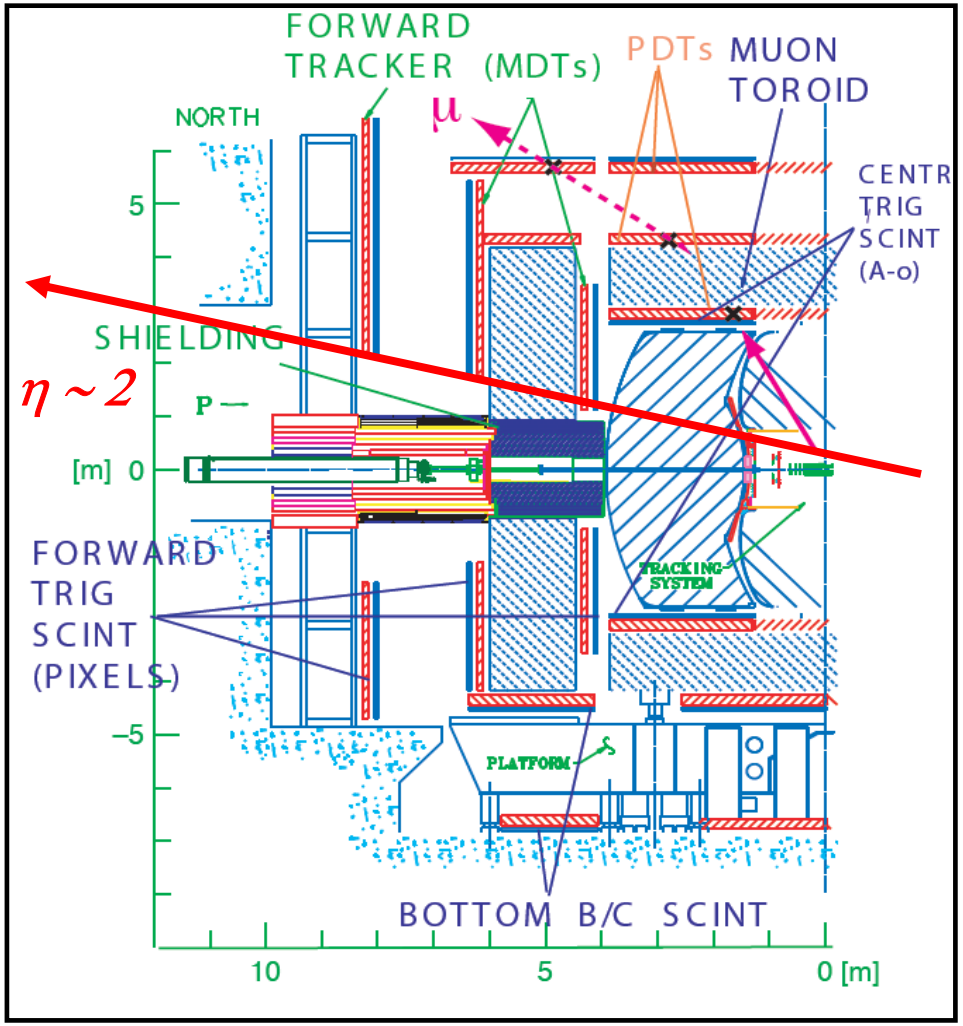
Heavy Flavor Physics Winter Results

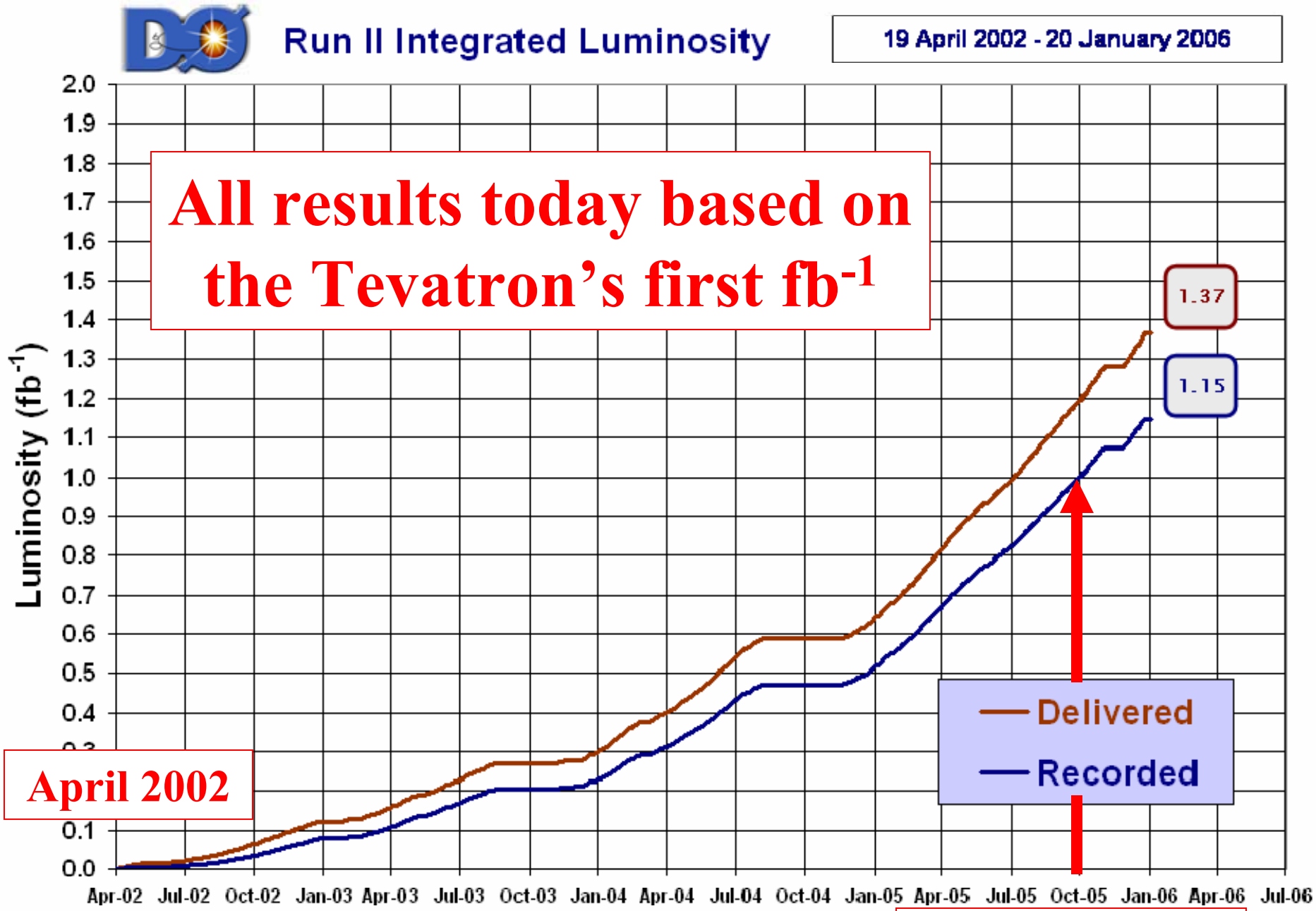
2.2 meters

DØ *B* Physics Program



Based on excellent performance of muon system

Good single and dimuon triggers



All results today based on the Tevatron's first fb^{-1}

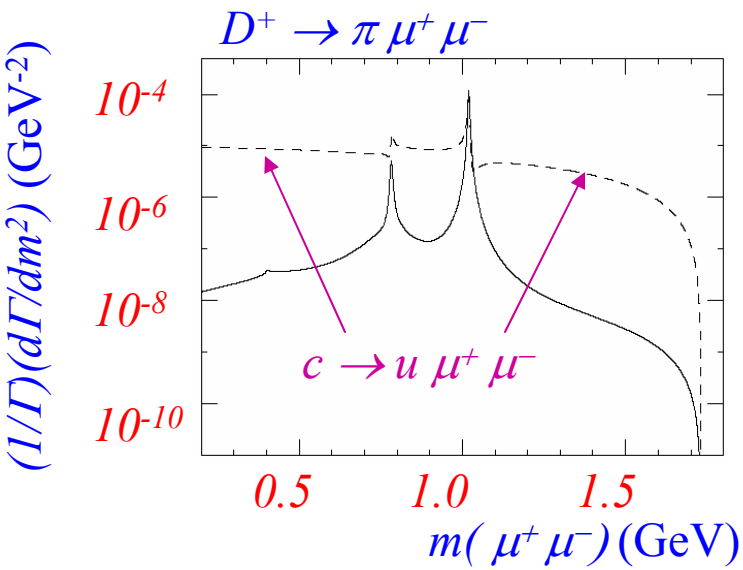
April 2002

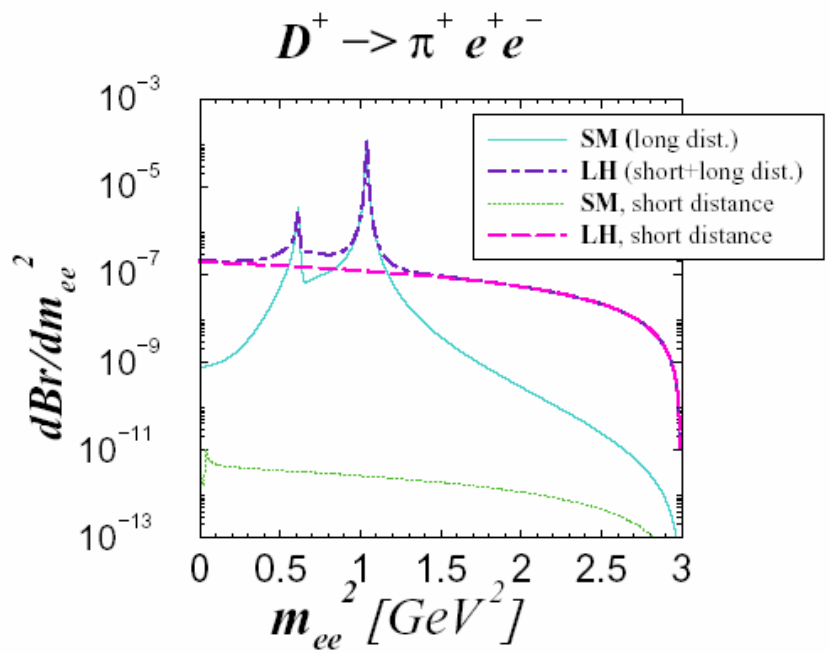
October 2005

Why FCNC Charm?

Strict limits from $b \to s$ and $s \to d$

Possible to have effects in up sector and not down sector





RPV in the up sector and not the down sector

Burdman et al. hep-ph/0112235

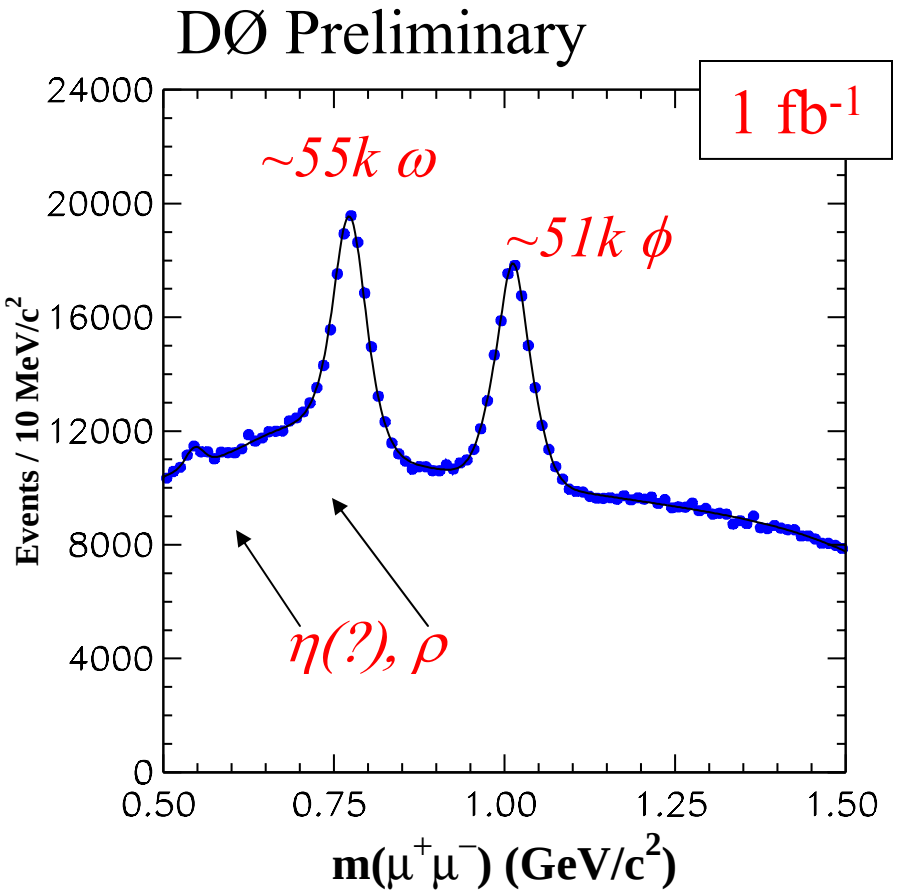
Little Higgs models with new up sector vector quark

Fajfer et al. hep-ph/0511048

factors of >1000 over SM not ruled out. Similar in magnitude to $B_s \to \mu\mu$ but orthogonal parameter space

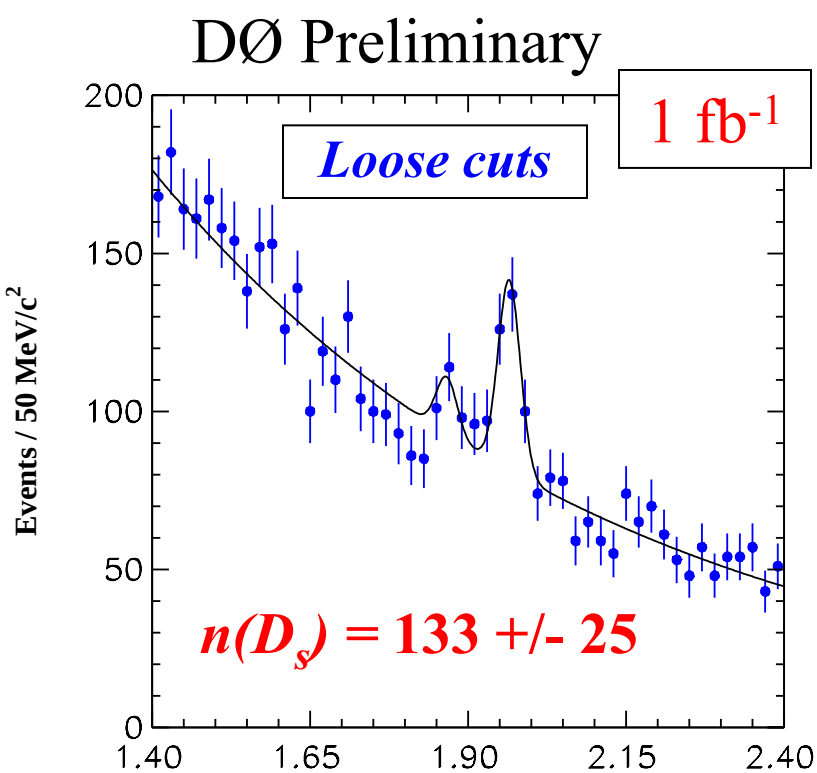
$c \rightarrow u\ \mu^+ \mu^-$ Analysis Strategy

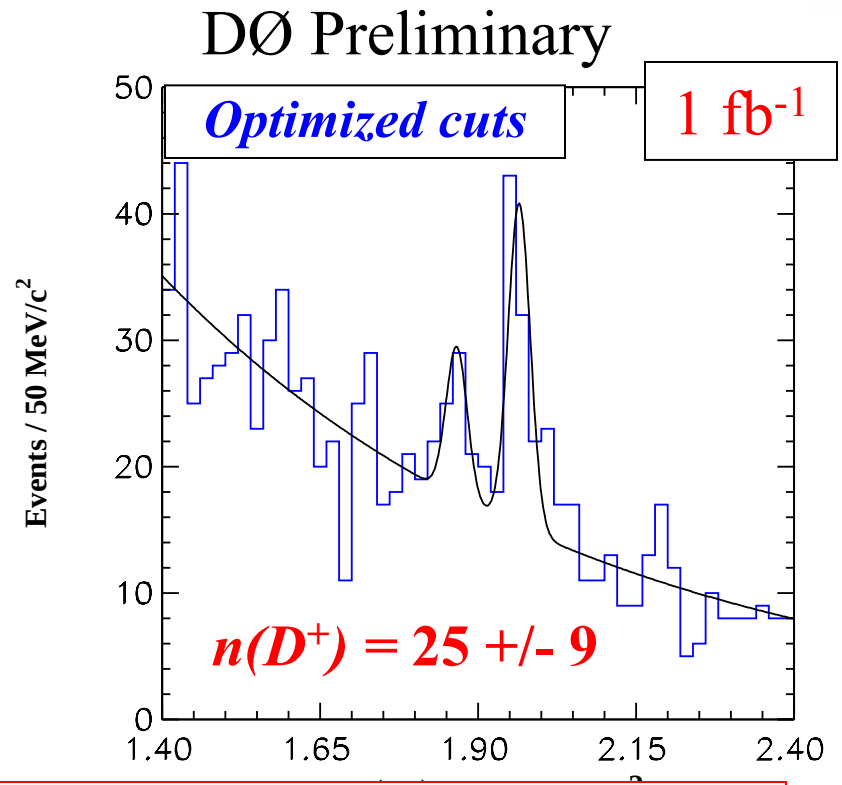
- First find $D_s \rightarrow \phi\ \pi$
  - BF($D_s \rightarrow \phi\ \pi$) = (3.6 +/– 0.9)%
  - BF($\phi \rightarrow \mu^+\mu^-$) = (2.85 +/- 0.19) x 10^{-4}
  - Product ~ 1 x 10^{-5}
- Then search for excess in the continuum region
  - $D^+ \rightarrow \pi^+\mu^+\ \mu^-$ with $m(\mu\mu)$!= ϕ
- Start with low mass dimuon candidate, add track to form D candidate
- Reduce background with lifetime and topological cuts



Dimuon invariant mass

Results for $D \to \phi\,\pi \to \pi\,\mu\,\mu$



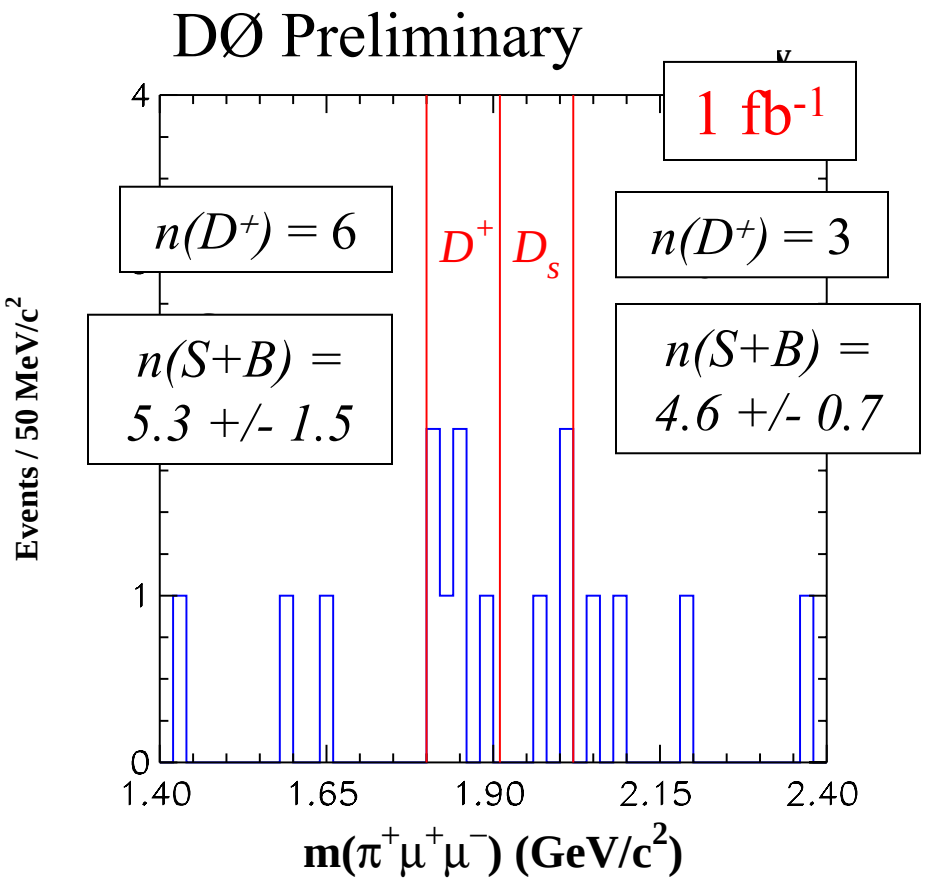


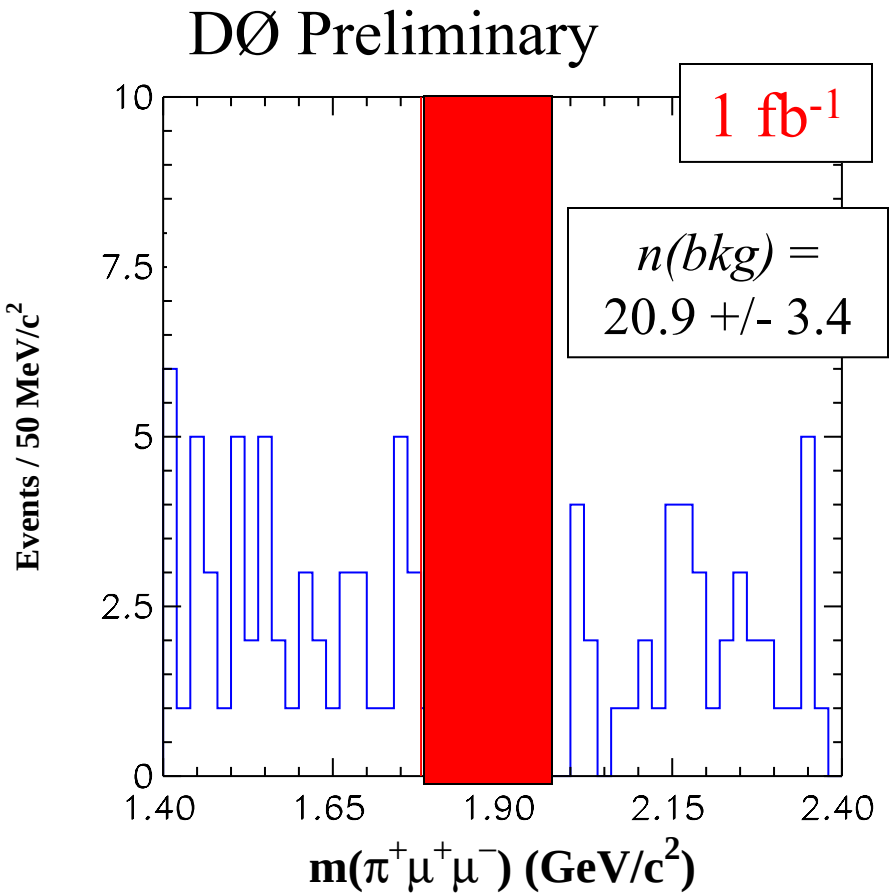
$m(\pi\mu\mu)$ GeV/c^2 for candidates with $0.96 < m(\mu\mu) < 1.06$ GeV/c^2

DØ: BF($D^+ \to \phi\,\pi \to \pi^+\,\mu^+\mu^-$) = (1.75 +/- 0.70 +/- 0.50) x 10^{-6}

CLEO-c: (2.7 +3.6 -1.8 +/- 0.2) x 10-6 Expected: 1.77 x 10-6

Results for $D^+ \rightarrow \pi^+\mu^+\mu^-$





$0.96 < m(\mu\mu) < 1.06$ GeV/c^2

$0.2 < m(\mu\mu) < 0.96$ GeV/c^2
$1.06 < m(\mu\mu) < 1.76$ GeV/c^2

Good agreement with expectations

Results for $D^+ \to \pi^+\mu^+\mu^-$

Branching fraction limit
$D^+ \to \pi^+ \mu^+\mu^-$:

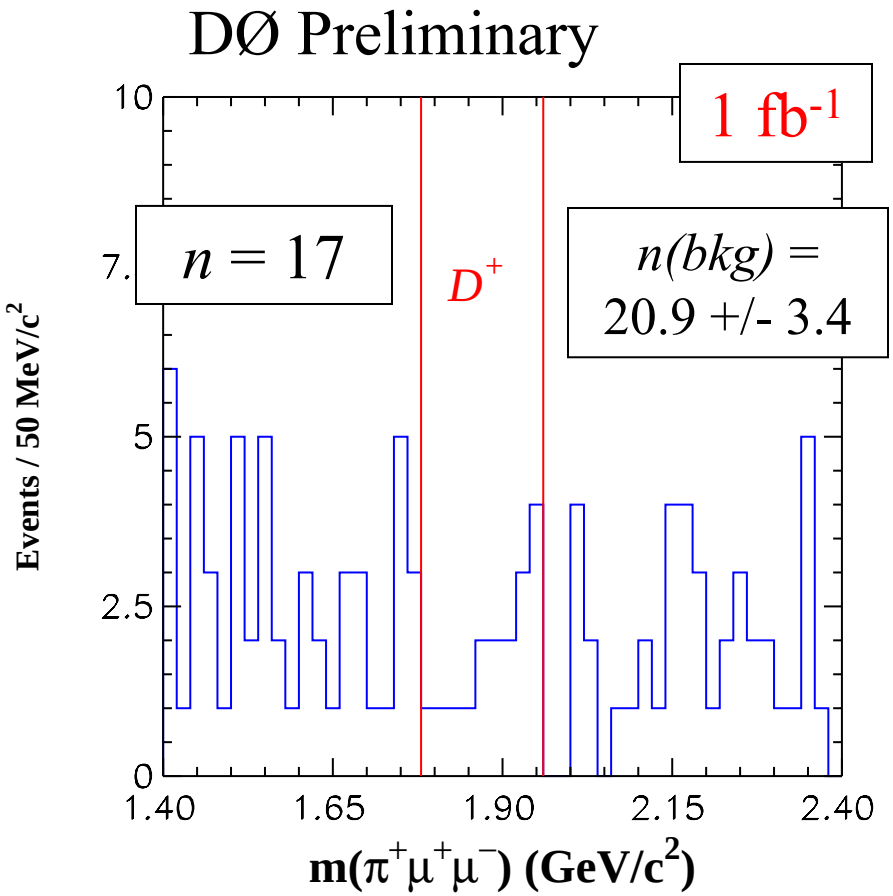
DØ: $< 4.7 \times 10^{-6}$ (at 90%)

CLEO-c(πe^+e^-): 7.4×10^{-6} at 90%

FOCUS: 8.8×10^{-6} at 90%

New limit on second generation RPV couplings

$$\bar{\lambda}_{22k}\bar{\lambda}_{21k} < 0.002$$



$0.2 < m(\mu\mu) < 0.96$ GeV/c^2
$1.06 < m(\mu\mu) < 1.76$ GeV/c^2

CP Violation in Mixing

$$\left|M_{CP\pm}\right\rangle = p\left|M^0\right\rangle \pm q\left|\overline{M^0}\right\rangle$$

Three phenomenological signatures

$$\lambda = \frac{|q|}{|p|}\frac{|\overline{A_{\bar{f}}}|}{|A_f|}e^{-i\varphi}$$

First in K

CPV in Mixing

ε_K: $K_L \to \pi\pi$ ✓

ε_B: $l^+l^+ - l^-l^-$?

Last in B

CPV in Decay

ε'/ε: $K_L \to \pi^0\pi^0, \pi^+\pi^-$ ✓

A_{CP}: $K^+\pi^-, K^-\pi^+$ ✓

Mixing vrs Decay

η: $K_L \to \pi^0\nu\nu$?

β/ϕ_1: $J/\psi\, K_s$ ✓

Analysis Strategy

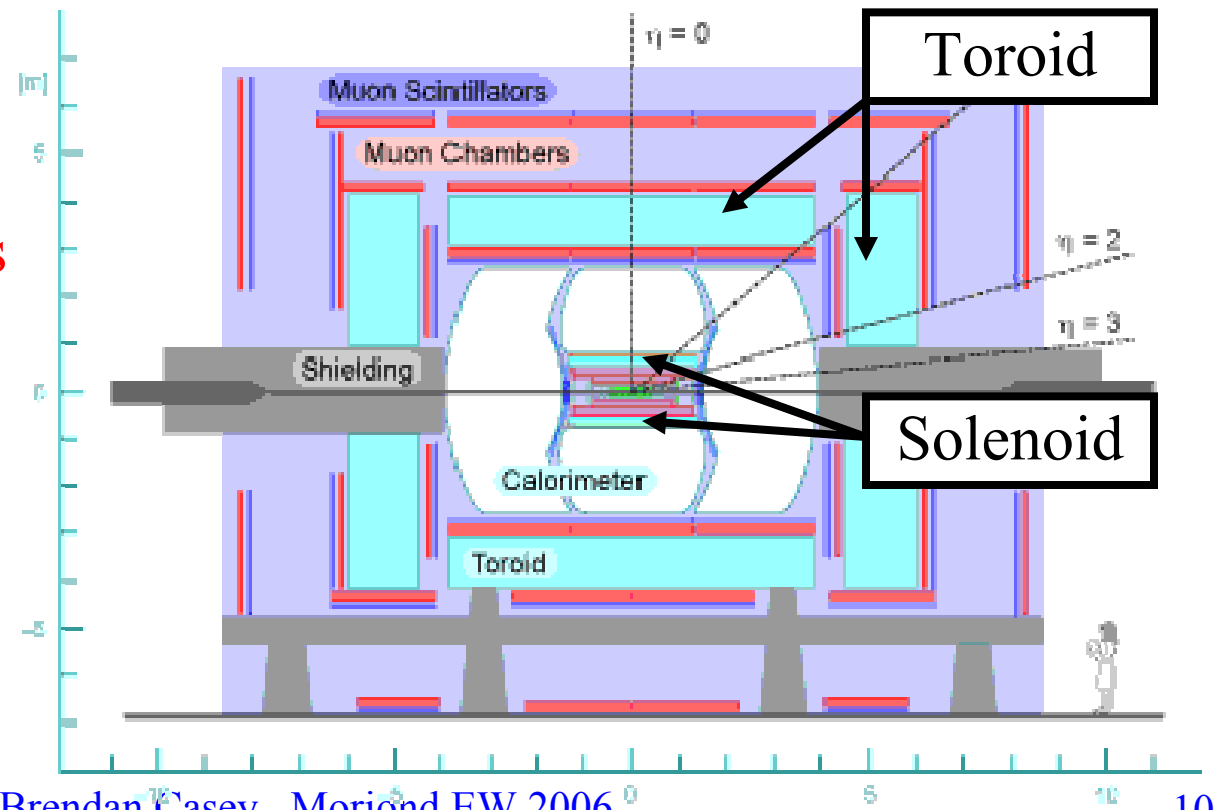
Goal is to measure ε_B with part per mil precision by looking for asymmetry in like-sign dimuons

$$A_{SL} = \frac{N(b\bar{b} \to \mu^+\mu^+X) - N(b\bar{b} \to \mu^-\mu^-X)}{N(b\bar{b} \to \mu^+\mu^+X) + N(b\bar{b} \to \mu^-\mu^-X)}$$

How?

Using independent spectrometers and reversing the polarities

Solenoid	Toroid
+	+
−	+
+	−
−	−



Raw Results

Tor*Sol polarity	-1	+1
N++	177,950	156,183
N--	176,939	156,148
N+-	1,175,547	1,029,604

After removing detector based asymmetries:

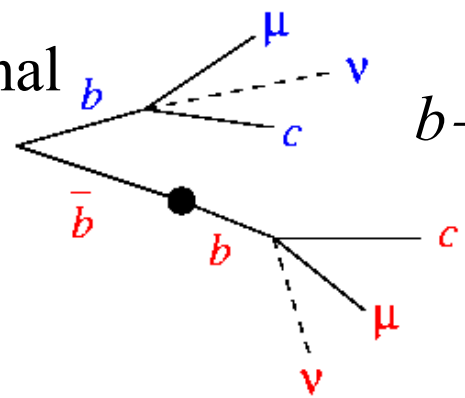
$$A = -0.0013 \pm 0.0012(stat) \pm 0.0008(syst)$$

Now need the fraction of μ from B

$$A_{SL} = f_B \times A$$

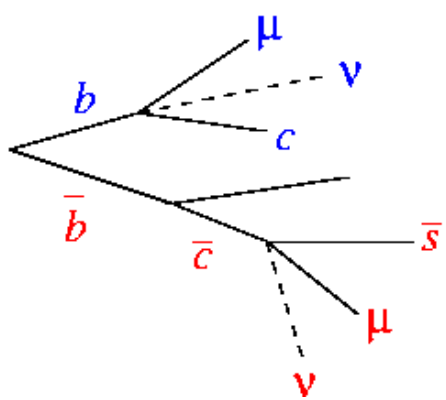
Sample Composition

signal

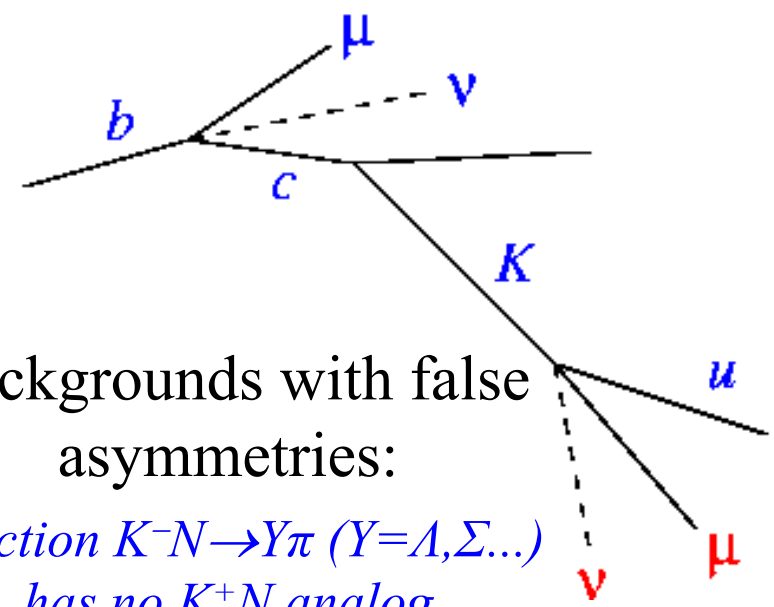


$b \to \mu^+;\ b \to b \to \mu^+$

$b \to \mu^+;\ b \to c \to \mu^+$



Backgrounds that dilute the asymmetry

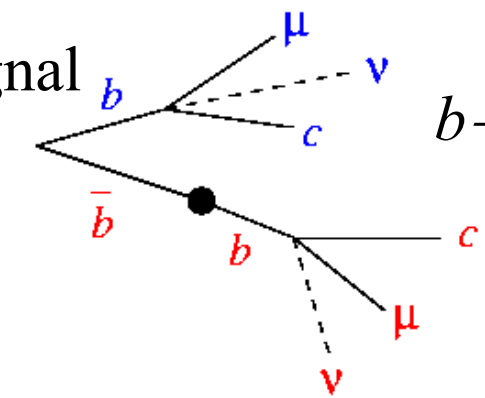


Backgrounds with false asymmetries:

Reaction $K^- N \to Y\pi$ ($Y=\Lambda,\Sigma$...) has no $K^+ N$ analog

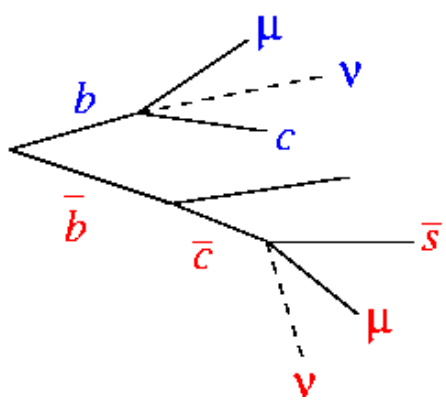
Sample Composition

signal

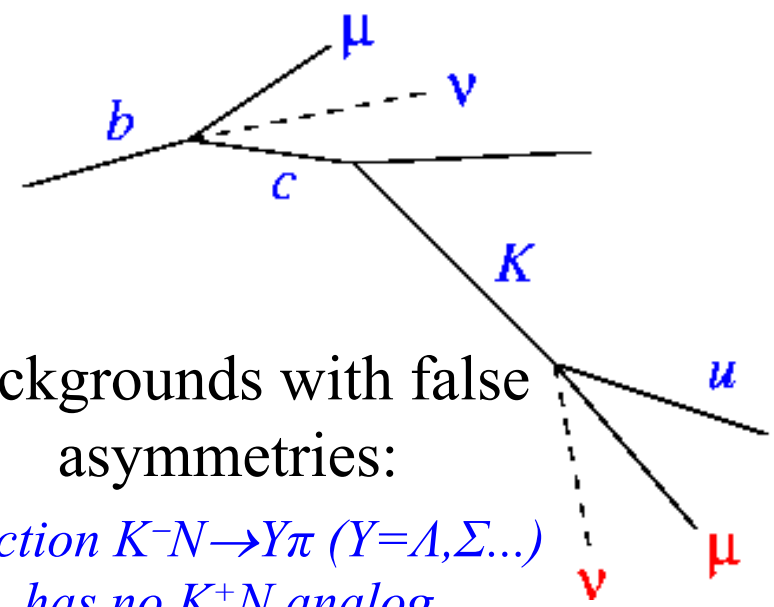


$b \to \mu^+;\ b \to b \to \mu^+$

$b \to \mu^+;\ b \to c \to \mu^+$



Backgrounds that dilute the asymmetry



Backgrounds with false asymmetries:

Reaction $K^-N \to Y\pi$ ($Y=\Lambda,\Sigma\ldots$) has no K^+N analog

Cross-check:

$$\chi(D0) = 0.136 \pm 0.001 \pm 0.024$$

$$\chi(PDG) = 0.1281 \pm 0.0076$$

Results

Raw Asymmetry:

$$A = -0.0013 \pm 0.0012(\text{stat}) \pm 0.0008(\text{syst})$$

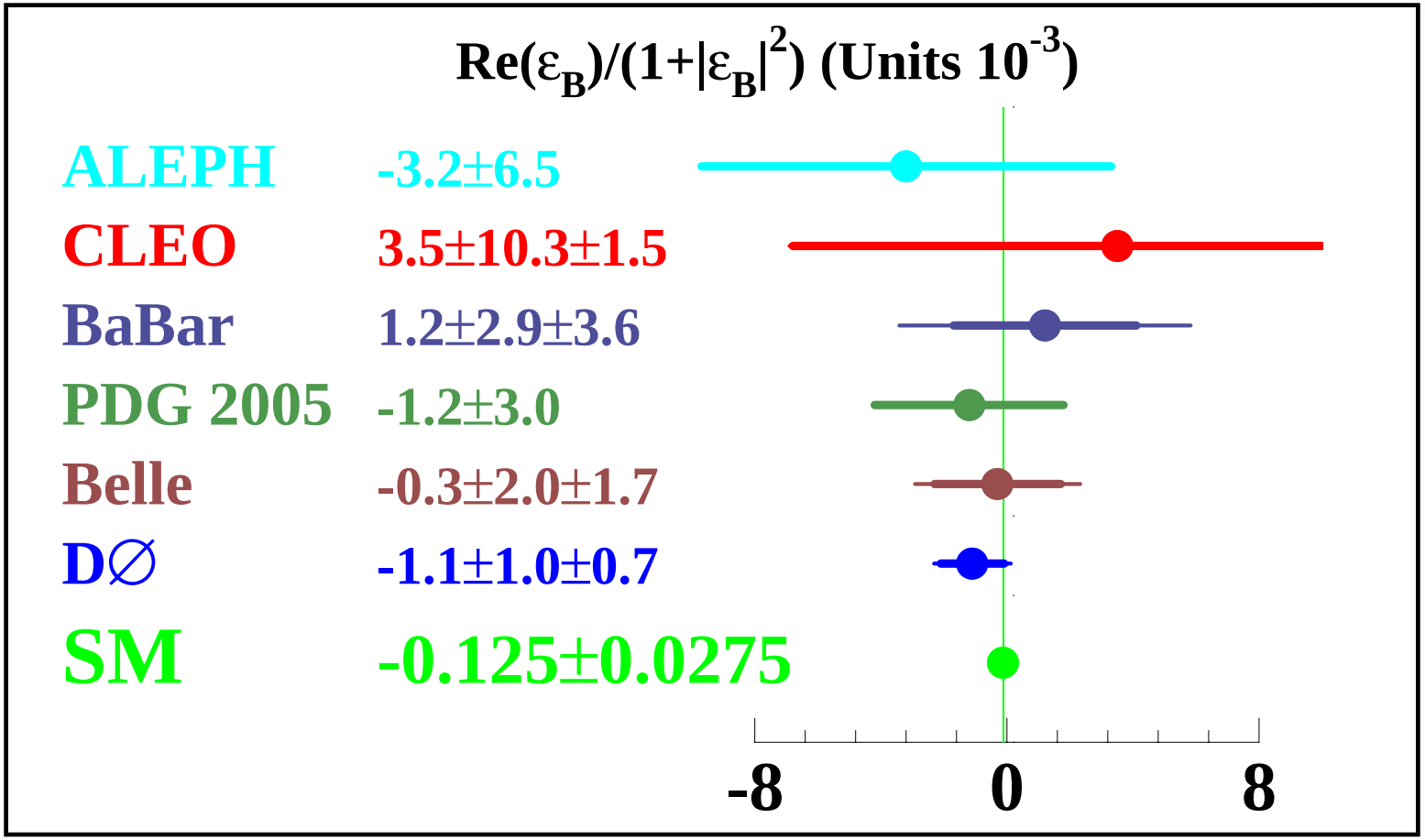
Asymmetry from Mixing:

$$A_{SL} = -0.0044 \pm 0.0040(\text{stat}) \pm 0.0028(\text{syst})$$

$$\frac{\text{Re}(\varepsilon_{B^0})}{1+\left|\varepsilon_{B^0}\right|^2} = \frac{A_{SL}}{4}$$

$$\frac{\text{Re}(\varepsilon_{B^0})}{1+\left|\varepsilon_{B^0}\right|^2} = -0.0011 \pm 0.0010(\text{stat}) \pm 0.0007(\text{syst})$$

Results



$$\frac{\mathrm{Re}(\varepsilon_{B^0})}{1+\left|\varepsilon_{B^0}\right|^2} = -0.0011 \pm 0.0010(\mathrm{stat}) \pm 0.0007(\mathrm{syst})$$

Beyond the Frontier

What we've learned from mixing:

- Kaon mixing
  - CP is violated in weak interactions!
  - Only logical solution is a third generation!
- B_d mixing
  - The top quark is heavy! $m_t >> m_W$
  - The top quark has CP violating couplings! $\mathrm{Arg}(V_{td}) \sim 24^{O}$
- Neutrino mixing
  - Neutrinos have mass! (CPV in lepton sector?)

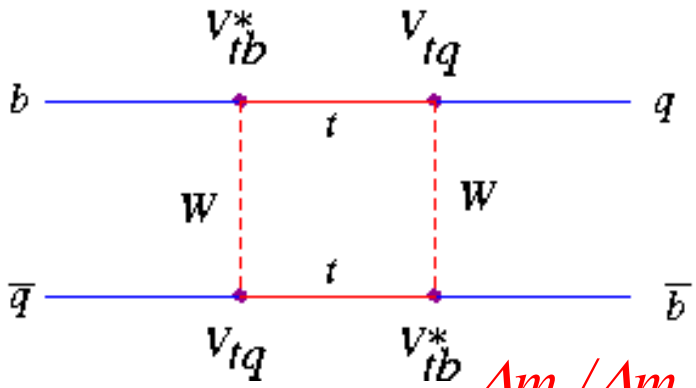
Every flavor mixing measurement has led to a new discovery!

Almost always involving particles inaccessible at the energy frontier.

Why B_s Mixing?

#1:

error in V_{td}



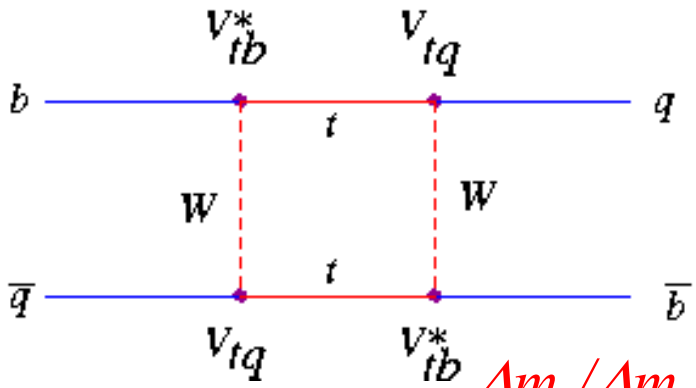
$\Delta m_d \sim$ (lots of QCD)x$|V_{td}|$

$\Delta m_s \sim$ (lots of QCD)x$|V_{ts}|$

$\Delta m_s/\Delta m_d \sim$ (much less QCD)x$|V_{ts}|/|V_{td}|$

Why B_s Mixing?

#1: It's a QCD thing

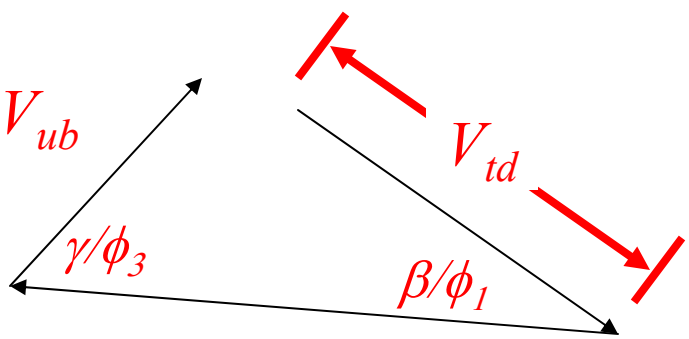


$\Delta m_d \sim$ (lots of QCD)x$|V_{td}|$

$\Delta m_s \sim$ (lots of QCD)x$|V_{ts}|$

$\Delta m_s/\Delta m_d \sim$ (much less QCD)x$|V_{ts}|/|V_{td}|$

#2: why V_{td}?
New sources of CPV



2 fundamental CKM relations:

$|V_{ub}|$ constrains $\beta/\phi_1 = Arg(V_{td})$ ✓

$|V_{td}|$ constrains $\gamma/\phi_3 = Arg(V_{ub})$ **?**

Disagreement = new source of CPV

Why B_s Mixing?

#3: What else?

(Almost) any NP scenario that is not flavor blind should show up somewhere in the $b \to s$ sector

But with no smoking gun, need to measure as many processes as possible:

$$B_d \to J/\psi\, \phi,$$

$$B \to K^* l^+ l^-,$$

$$B_s \to \mu^+ \mu^-,$$

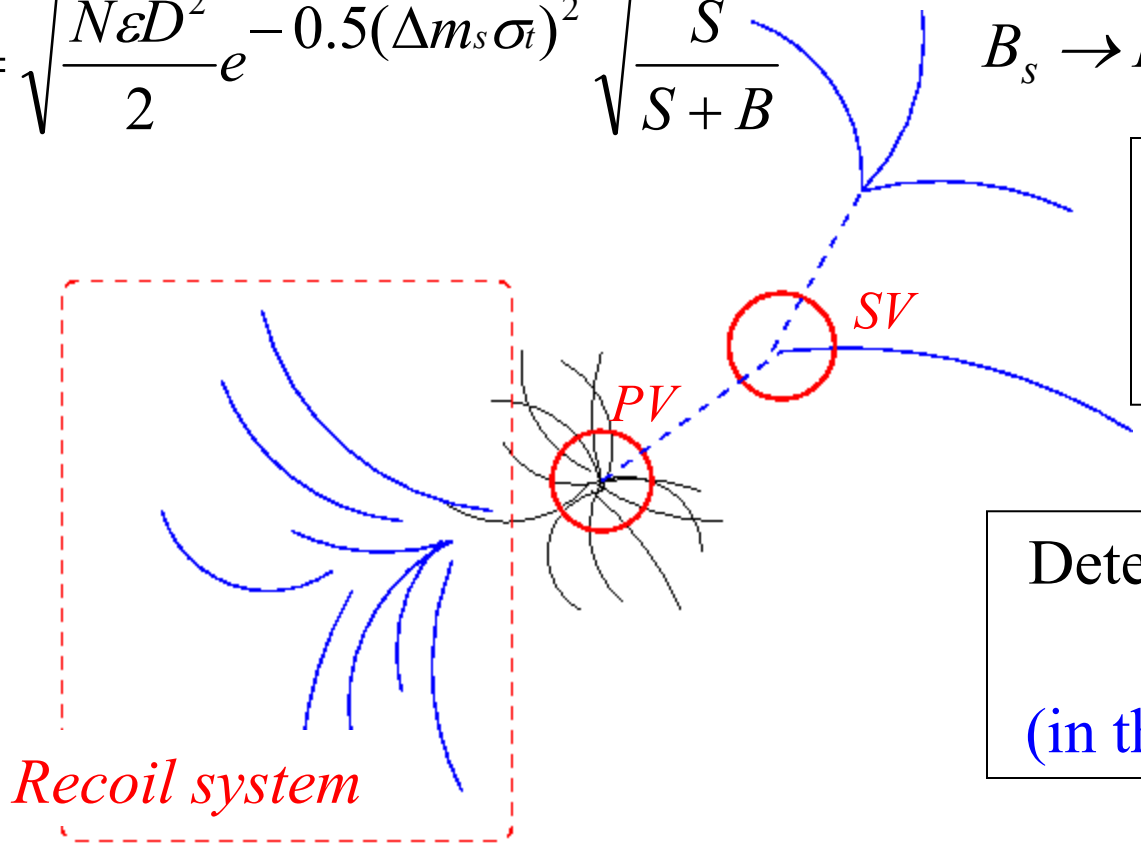
$$B_s \text{ mixing}....$$

Combination of these three factors makes B_s mixing one of the highest priority analyses for the Tevatron and all HEP

Analysis Overview

$$FOM = \sqrt{\frac{N\varepsilon D^2}{2}} e^{-0.5(\Delta m_s \sigma_t)^2} \sqrt{\frac{S}{S+B}}$$

$$B_s \to D_s \mu^+ \nu$$



Reconstruct the decay of a B_s

(final flavor)

Determine how long the B_s lived

(in the B_s rest frame)

Determine the B_s initial flavor from the recoil system

(recoil flavor is opposite initial B_s flavor)

$$FOM = \sqrt{\frac{N\varepsilon D^2}{2}} e^{-0.5(\Delta m_s \sigma_t)^2} \sqrt{\frac{S}{S+B}}$$

Reco

↓

Proper time

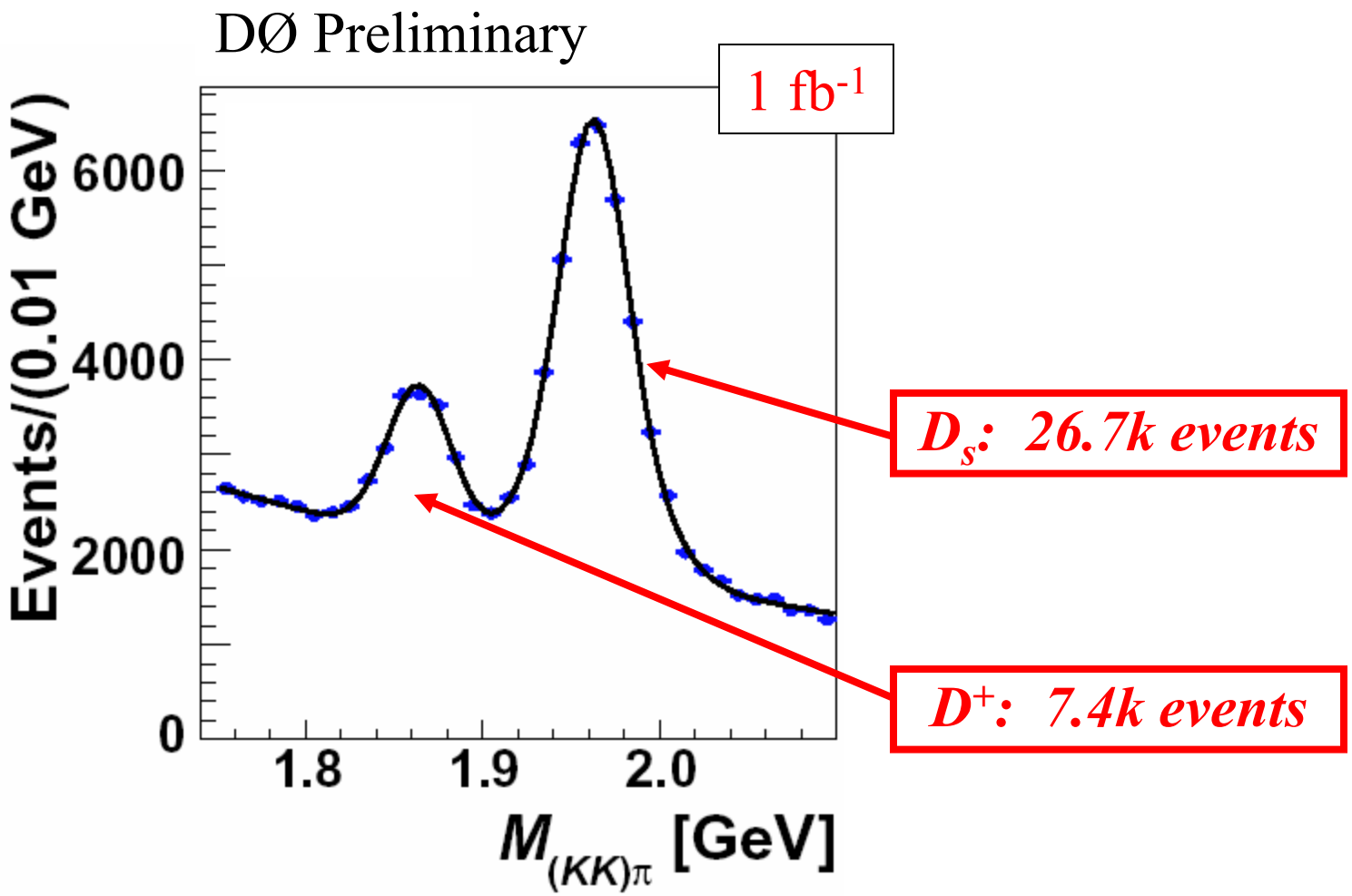
↓

Flavor tagging

↓

Δm_s

Bs Reconstruction



$$FOM = \sqrt{\frac{N\varepsilon D^2}{2}} e^{-0.5(\Delta m_s \sigma_t)^2} \sqrt{\frac{S}{S+B}}$$

Reco

↓

Proper time

↓

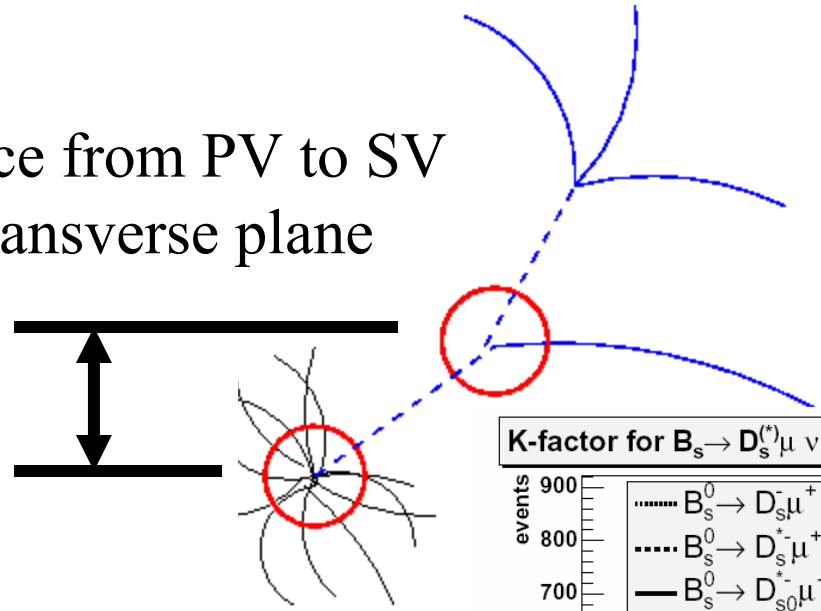
Flavor tagging

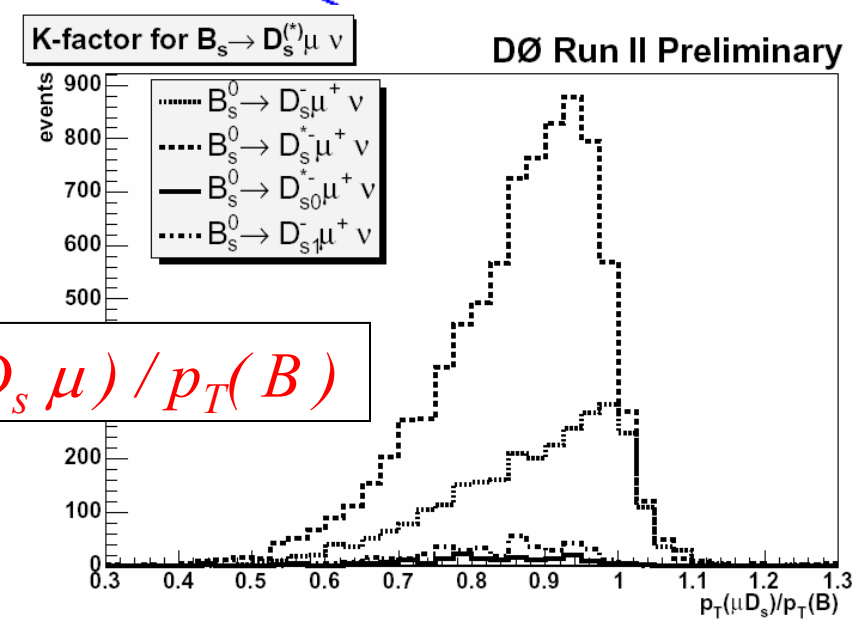
↓

Δm_s

Proper time determination

Distance from PV to SV in transverse plane





$p_T(D_s \mu) / p_T(B)$

For boost:

Correct for missing neutrino using MC

$$FOM = \sqrt{\frac{N\varepsilon D^2}{2}} e^{-0.5(\Delta m_s \sigma_t)^2} \sqrt{\frac{S}{S+B}}$$

Reco

↓

Proper time

↓

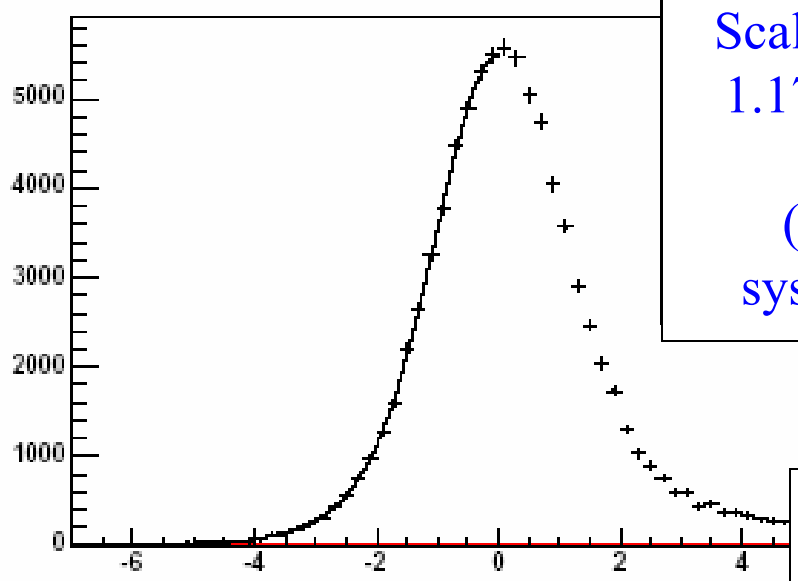
Flavor tagging

↓

Δm_s

Proper Time Resolution

Best estimate of errors used in track fitting, any additional scaling determined from data



Scale factor = 1.17 +/- 0.02

(largest systematic)

decay length / σ(decay length)

Pull of J/ϕ vertex from the primary vertex for prompt J/ϕ s

$$FOM = \sqrt{\frac{N\varepsilon D^2}{2}} e^{-0.5(\Delta m_s \sigma_t)^2} \sqrt{\frac{S}{S+B}}$$

Reco → Proper time → Flavor tagging → Δm_s

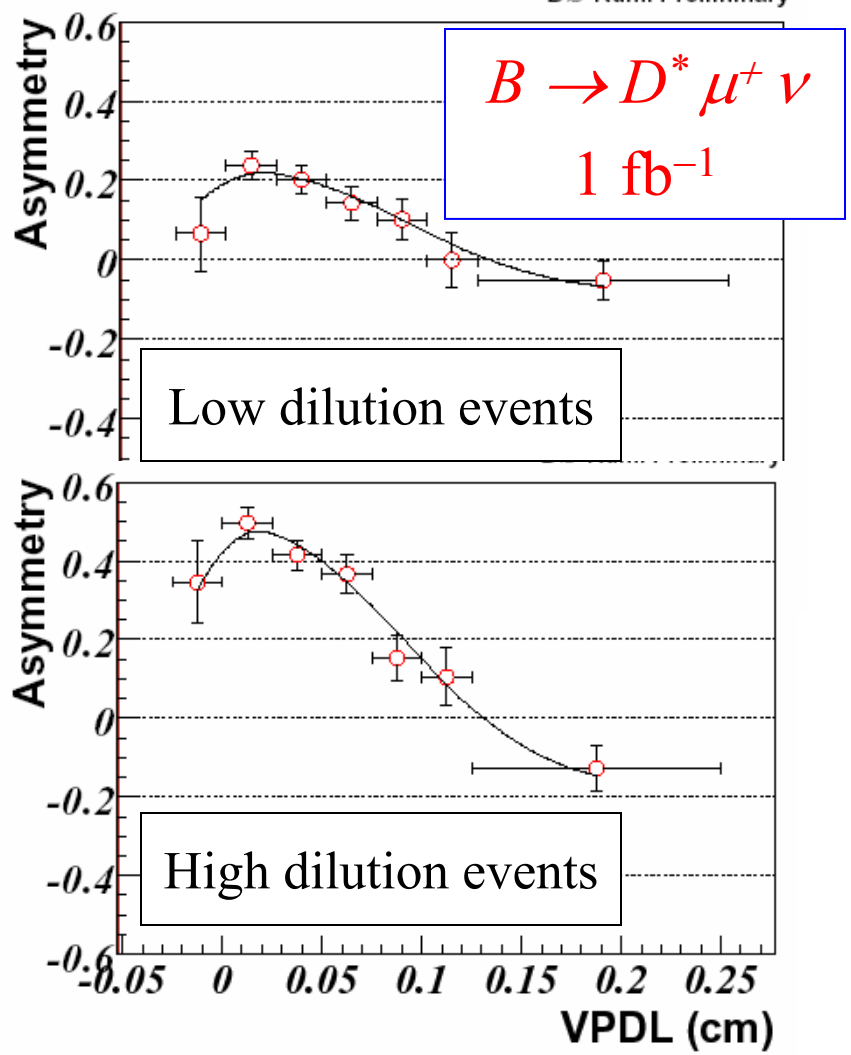
Flavor Tagging

DØ Preliminary

Inputs:

- Jet charge centered on lepton (e or μ)
- Secondary vertex charge
- Recoil charge

Tuned using B_d mixing



Combined opposite side tag:

$$\varepsilon D^2 = (2.48 \pm 0.21^{+0.08}_{-0.06})\%$$

$$FOM = \sqrt{\frac{N\varepsilon D^2}{2} e^{-0.5(\Delta m_s \sigma_t)^2}} \sqrt{\frac{S}{S+B}}$$

Reco → Proper time → Flavor tagging → Δm_s

Mixing Analysis

$$p_s^{nos}(x, K, d_{pr}) = \frac{K}{c\tau_{B_s}} \exp(-\frac{Kx}{c\tau_{B_s}}) \cdot 0.5 \cdot (1 + \mathcal{D}(d_{pr}) \cos(\Delta m_s \cdot Kx/c))$$

unmixed sample

$$p_s^{osc}(x, K, d_{pr}) = \frac{K}{c\tau_{B_s}} \exp(-\frac{Kx}{c\tau_{B_s}}) \cdot 0.5 \cdot (1 - \mathcal{D}(d_{pr}) \cos(\Delta m_s \cdot Kx/c))$$

mixed sample

<u>Components:</u>

Peaking:

- Signal
- $B \rightarrow D_s D$
- *Prompt* $D_s D$

combinatorial:

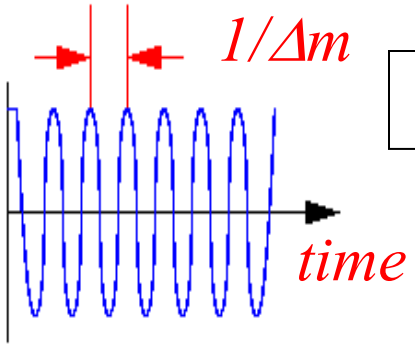
- Random light flavor
- $B+$
- B_d

$$FOM = \sqrt{\frac{N\varepsilon D^2}{2}} e^{-0.5(\Delta m_s \sigma_t)^2} \sqrt{\frac{S}{S+B}}$$

Reco → Proper time → Flavor tagging → Δm_s

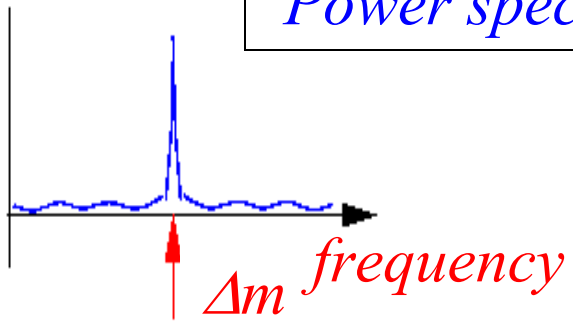
Amplitude Method

$$P(\Delta m_s) \approx 1 \pm \cos \Delta m_s t \Rightarrow P(A) \approx 1 \pm A \cos \Delta m_s t$$



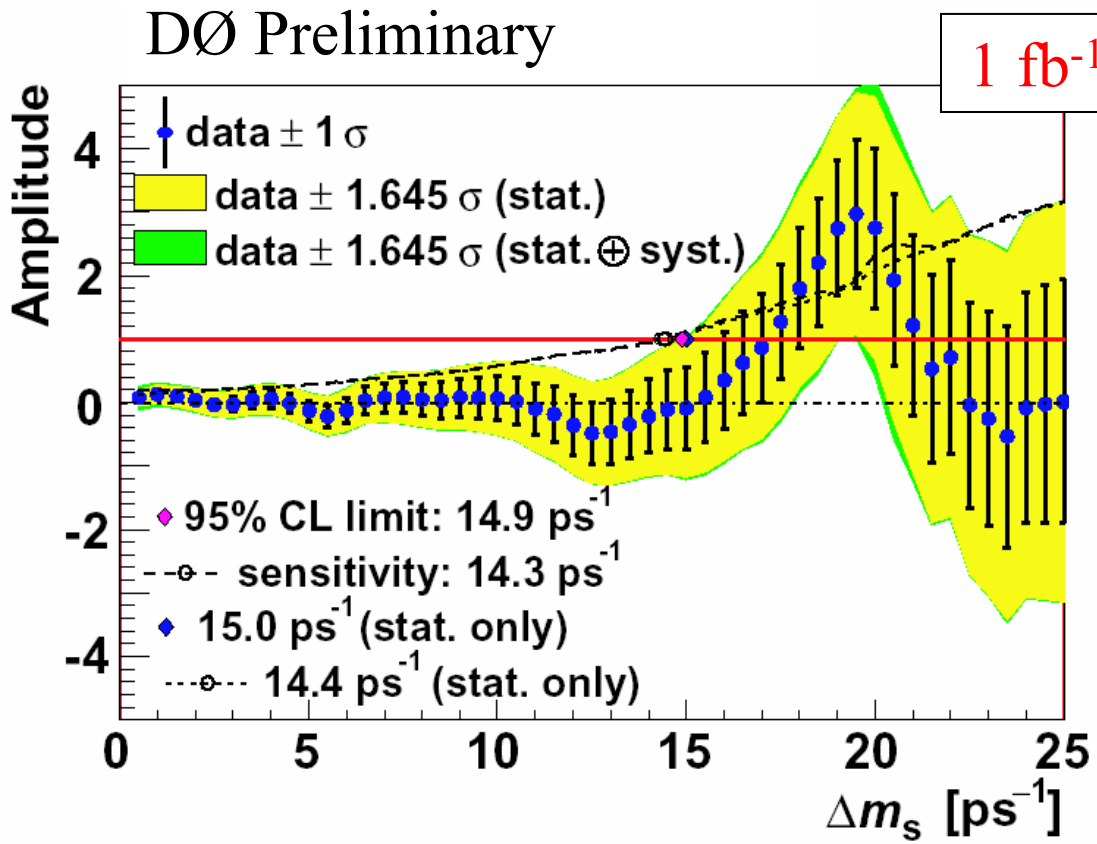
Asymmetry

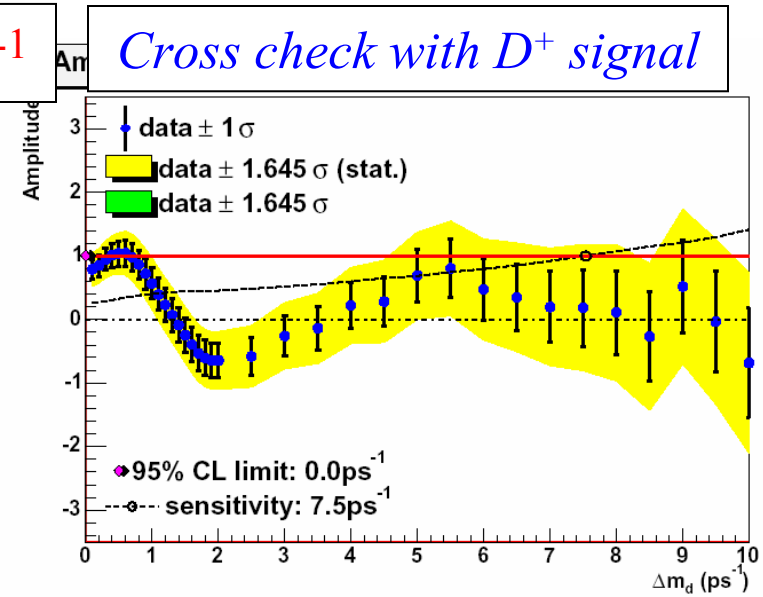
Power spectrum



Motivation is to simplify combining results with other experiments

Amplitude Method Results



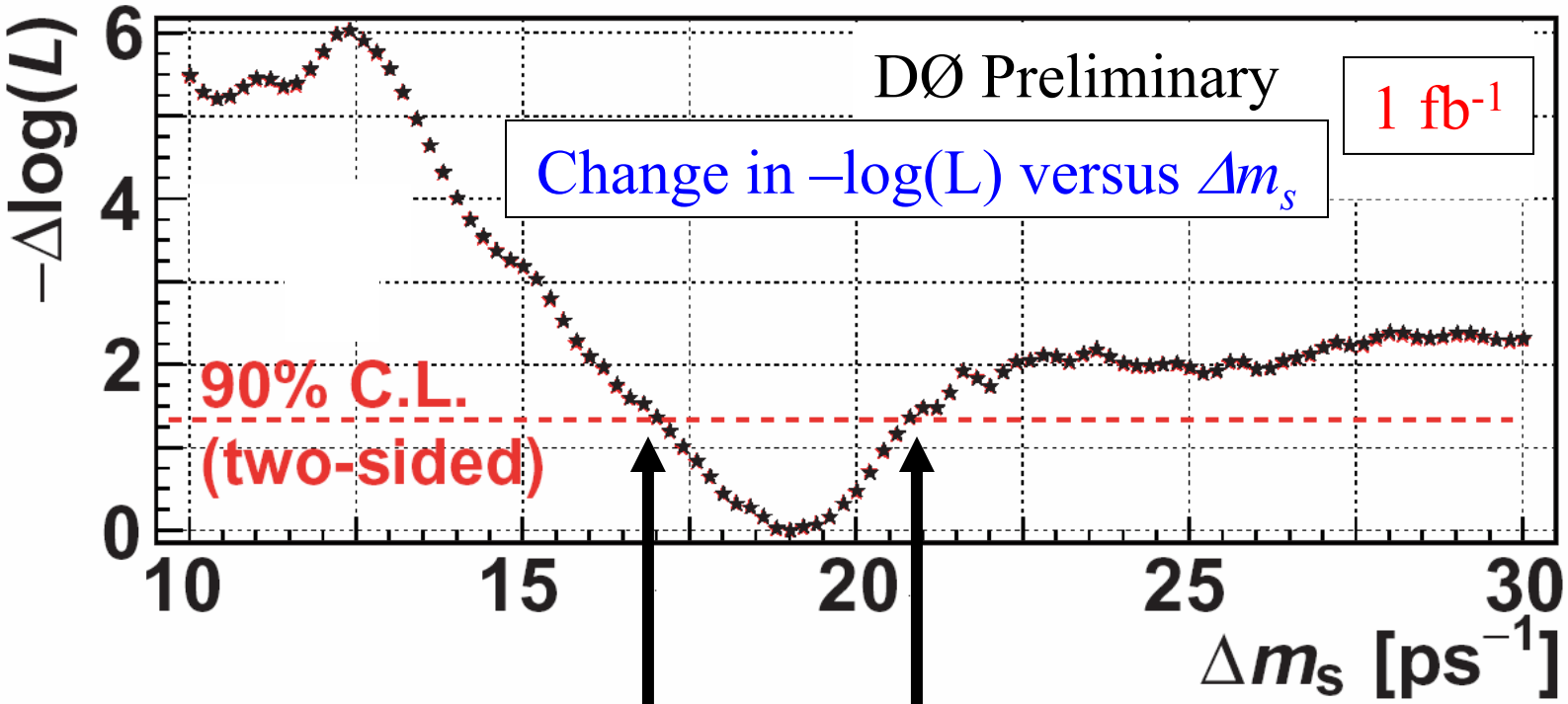


$\Delta m_s > 14.9\ ps^{-1}$ @ 95% CL

Deviation from zero clearly visible near $\Delta m_s \sim 19\ ps^{-1}$.

Difficult to quantify with amplitude method

Switch Back to Likelihood Fit

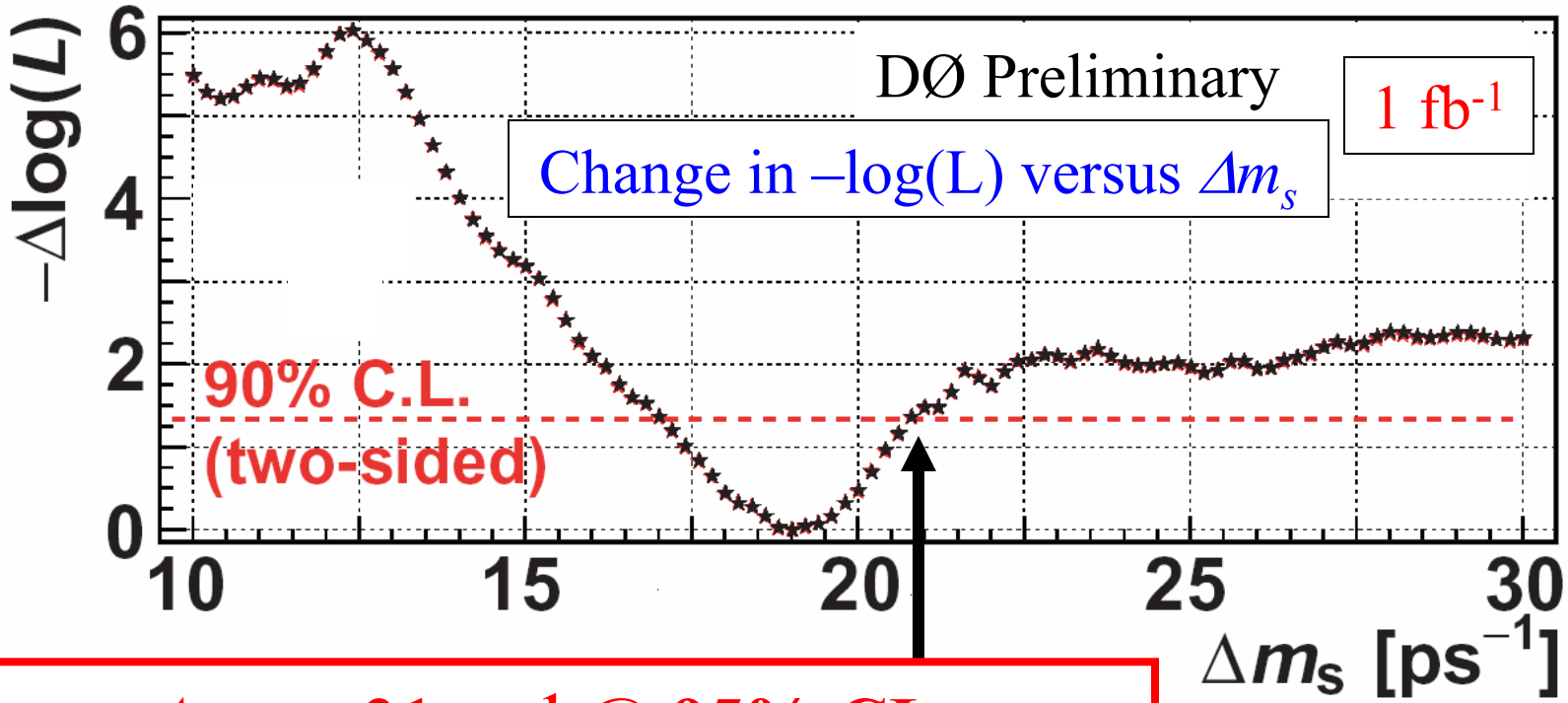


17 < Δm_s < 21 ps^{-1} @ 90% CL

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

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

Switch Back to Likelihood Fit



$\Delta m_s < 21\ ps^{-1}$ @ 95% CL

For one sided limit

5% probability for Δm_s to lie anywhere between 21 ps^{-1} and infinity

Significance Tests

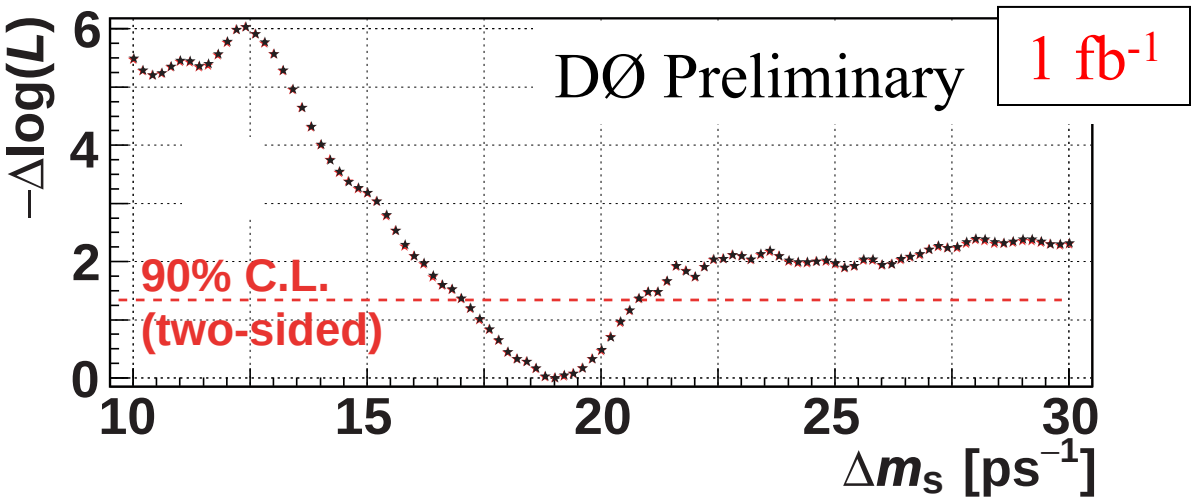
Probability for this measurement to lie in the range

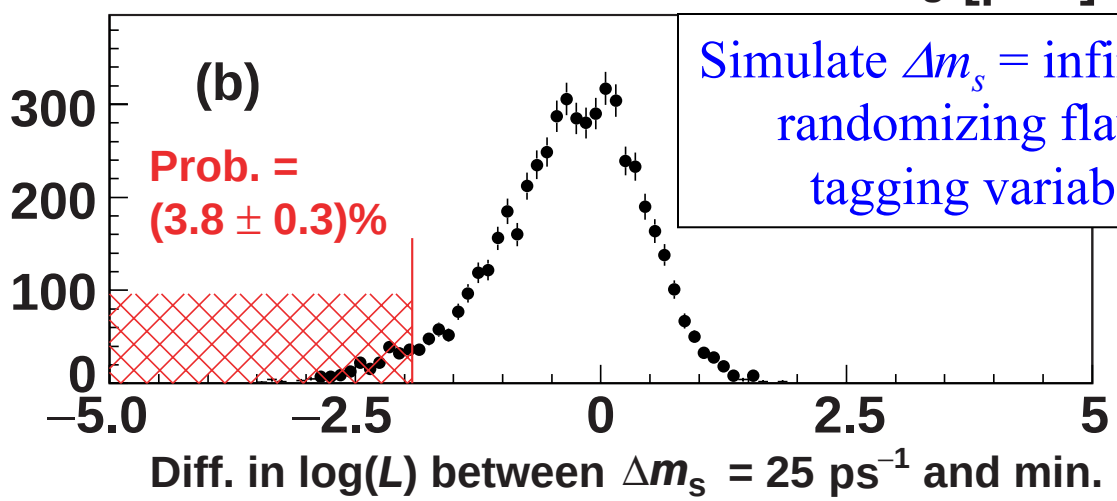
$16 < \Delta m_s < 22 ps^{-1}$

Given a true value:

Δm_s = infinity: 3.8%

$\Delta m_s = 19\ ps^{-1}$: 15%

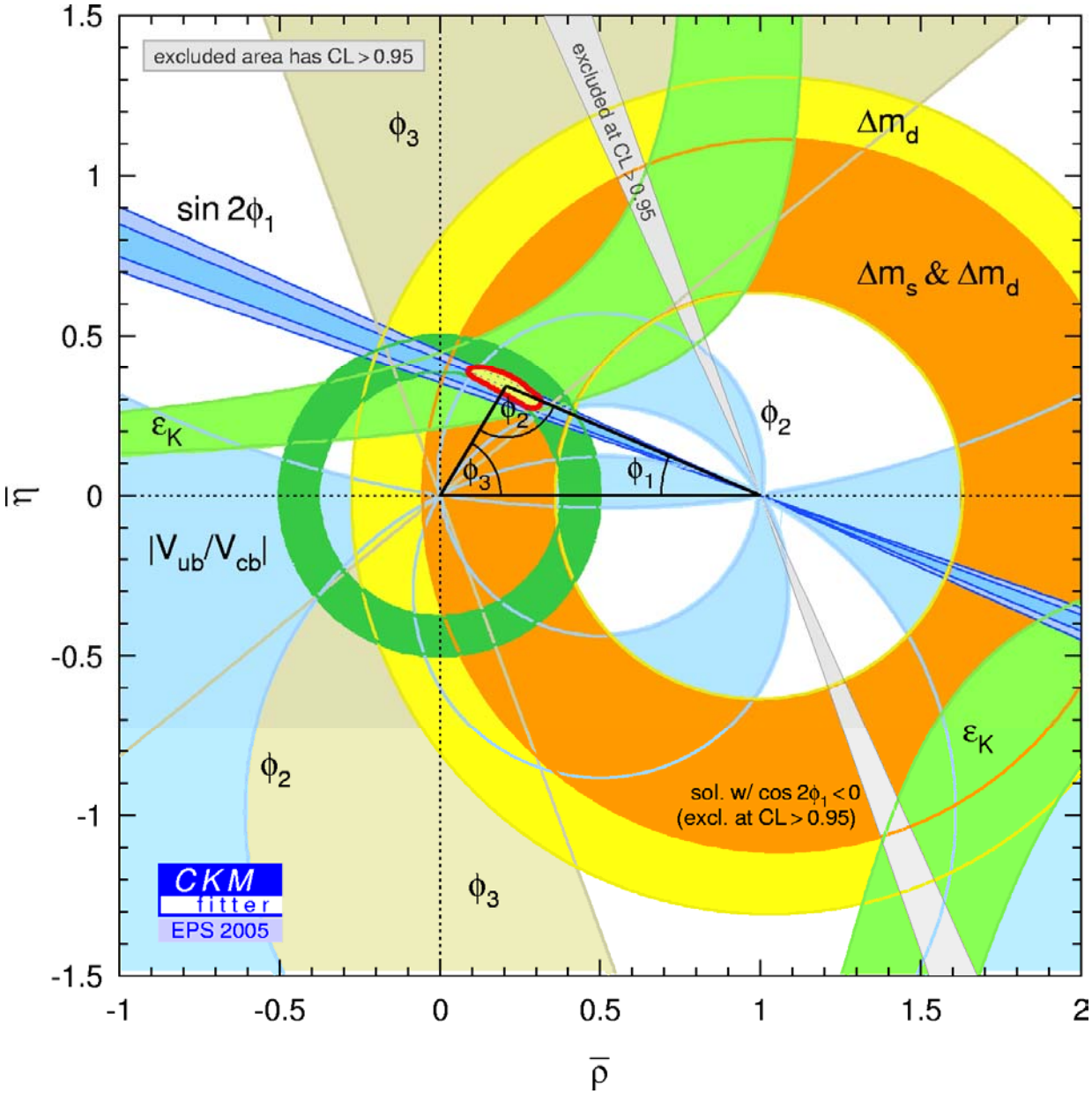




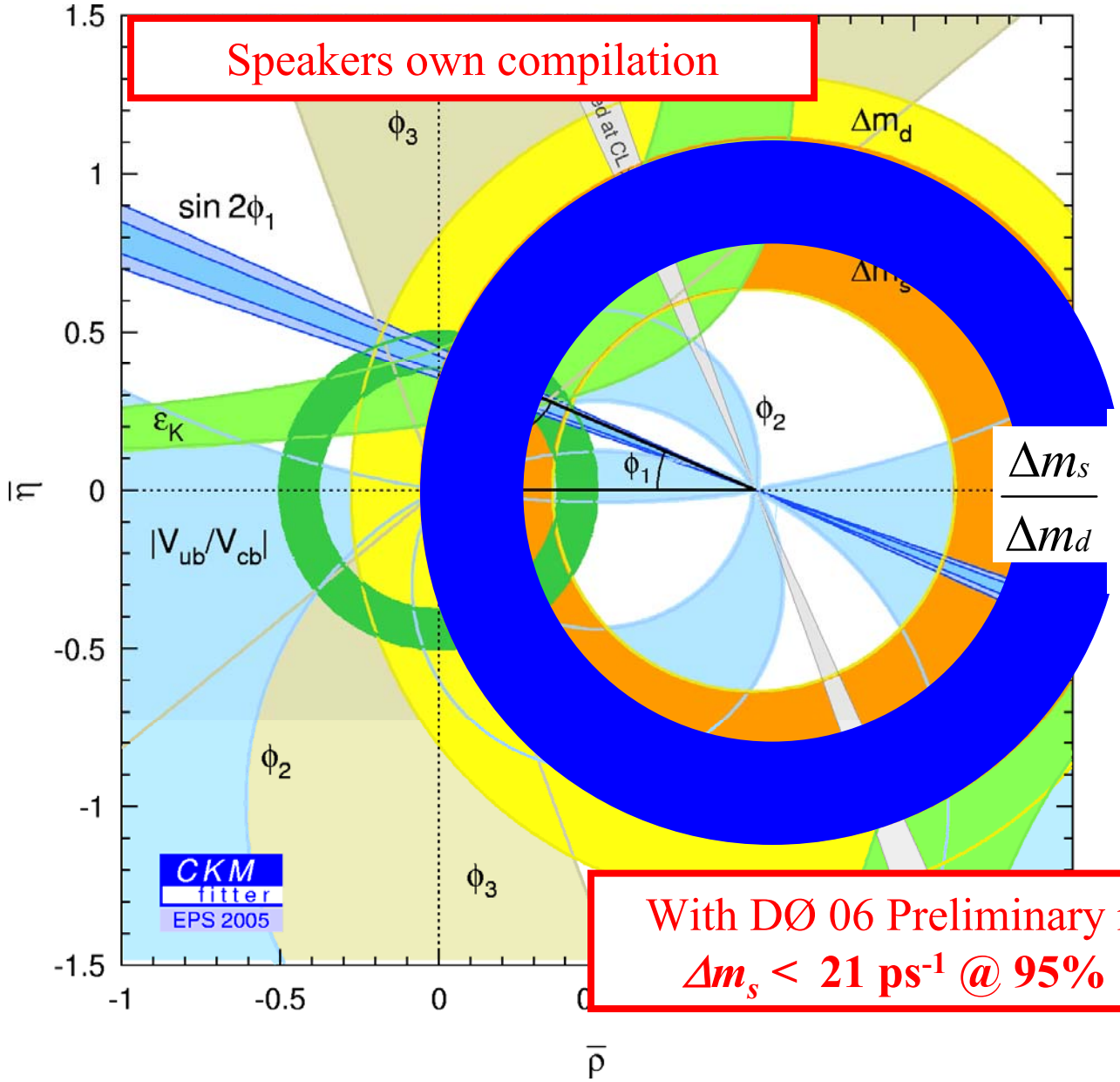
Simulate Δm_s = infinity by randomizing flavor tagging variable

Consistent results from parameterized MC studies

New CKM Triangle



New CKM Triangle



$\frac{\Delta m_s}{\Delta m_d}$

95% CL upper bound

With DØ 06 Preliminary result

$\Delta m_s < 21\ ps^{-1}$ @ 95% CL

Conclusions

- Tevatron's first fb^{-1} opening up several new opportunities in flavor physics

- Today, 3 world's best results
  - *Rare FCNC charm decays*
  - *CPV in B mixing*
  - *First direct upper bound on Δm_s.*

19 years after the observation of B_d mixing and 12 years after the first lower limit on Δm_s, we now have first direct upper bound on the B_s oscillation frequency.

DØ Preliminary

$$17 < \Delta m_s < 21\ ps^{-1}\ @\ 90\%\ CL$$

St. Valentine's Day 2006

Katie, 21 mo. *Pono, 4 yrs.*

Backup Slides

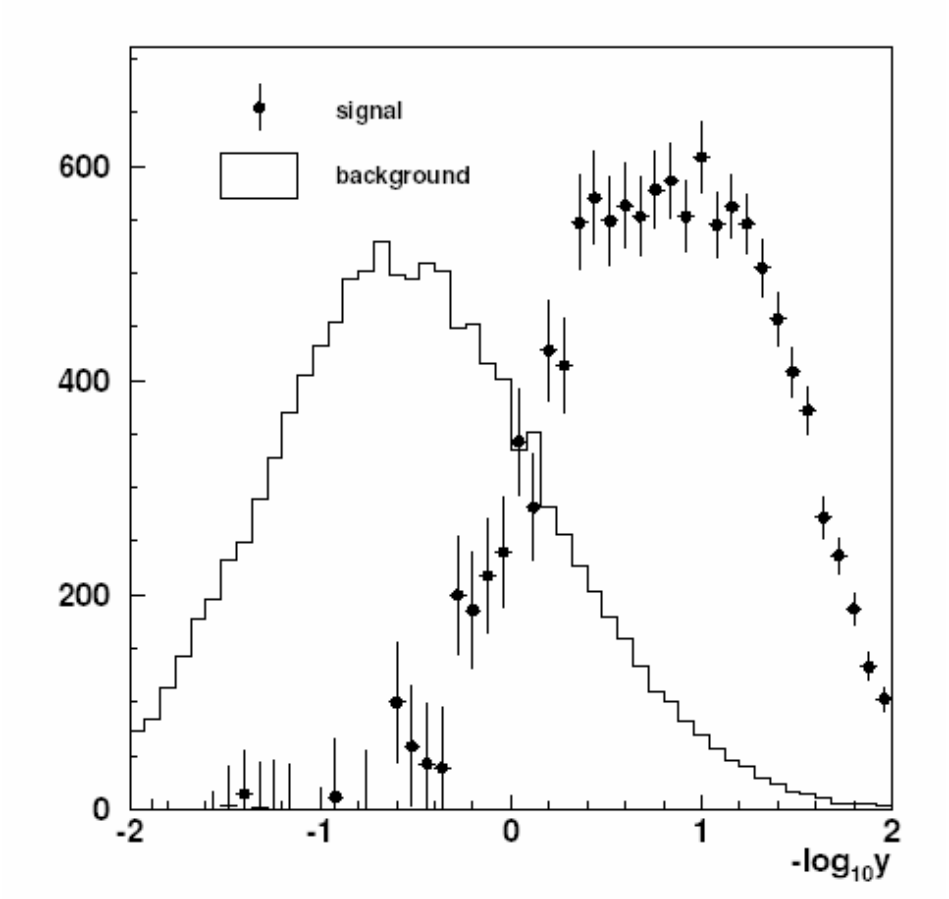
Systematic Errors

Source of error	ΔA
detector	0.00015
Polarity exposure	0.00018
muon and $K^{\pm}$ decay	0.00068
dimuon cosmic rays	0.00010
prompt μ and cosmic μ	0.00001
Wrong charge sign	0.00015
punch-through	0.00001
Total	0.00074

$$\frac{\mathrm{Re}(\varepsilon_{B^0})}{1+\left|\varepsilon_{B^0}\right|^2} = -0.0011 \pm 0.0010(\mathrm{stat}) \pm 0.0007(\mathrm{syst})$$

Signal Extraction

- Likelihood based using
  - *helicity*
  - *isolation*
  - $p_T(KK)$
  - $m(KK)$
  - $m(\mu D_s)$
  - $\cdot\ \chi^2_D$



Signal-like PDFs

$$p_s^{nos}(x,K,d_{pr}) = \frac{K}{c\tau_{B_s^0}} \exp(-\frac{Kx}{c\tau_{B_s^0}}) \cdot 0.5 \cdot (1 + \mathcal{D}(d_{pr}) \cos(\Delta m_s \cdot Kx/c))$$

$$p_s^{osc}(x,K,d_{pr}) = \frac{K}{c\tau_{B_s^0}} \exp(-\frac{Kx}{c\tau_{B_s^0}}) \cdot 0.5 \cdot (1 - \mathcal{D}(d_{pr}) \cos(\Delta m_s \cdot Kx/c))$$

$$p_{DsDs}^{osc}(x,K) = \frac{K}{c\tau_{B_s^0}} \exp(-\frac{Kx}{c\tau_{B_s^0}}) \cdot 0.5$$

$$p_{DsDs}^{nos}(x,K) = \frac{K}{c\tau_{B_s^0}} \exp(-\frac{Kx}{c\tau_{B_s^0}}) \cdot 0.5$$

$$p_u^{nos}(x,K,d_{pr}) = \frac{K}{c\tau_{B^+}} \exp(-\frac{Kx}{c\tau_{B^+}}) \cdot 0.5 \cdot (1 - \mathcal{D}(d_{pr}))$$

$$p_u^{osc}(x,K,d_{pr}) = \frac{K}{c\tau_{B^+}} \exp(-\frac{Kx}{c\tau_{B^+}}) \cdot 0.5 \cdot (1 + \mathcal{D}(d_{pr}))$$

$$p_d^{nos}(x,K,d_{pr}) = \frac{K}{c\tau_{B_d^0}} \exp(-\frac{Kx}{c\tau_{B_d^0}}) \cdot 0.5 \cdot (1 - \mathcal{D}(d_{pr}) \cos(\Delta m_d \cdot Kx/c))$$

$$p_d^{osc}(x,K,d_{pr}) = \frac{K}{c\tau_{B_d^0}} \exp(-\frac{Kx}{c\tau_{B_d^0}}) \cdot 0.5 \cdot (1 + \mathcal{D}(d_{pr}) \cos(\Delta m_d \cdot Kx/c)).$$

Background PDFs

$$P_{bkg}(x^M, \sigma_{x^M}, \mathcal{D}) = \left(\mathcal{F}_{peak_bkg} G(x^M, \sigma_{peak_bkg}) + (1 - \mathcal{F}_{peak_bkg}) \cdot P^{res}_{bkg}(x^M, \sigma_{x^M})\right),$$

$$P^{res}_{bkg}(x^M, \sigma_{x^M}, \mathcal{D}) = \frac{Eff(x^M)}{N} \int_0^\infty dx \left(\mathcal{F}_0 G(x - x^M, s_{bkg}\sigma_{x^M})\delta(x) + (1 - \mathcal{F}_0) G(x - x^M, \sigma_{x^M}) \cdot p^{long}_{bkg}\right),$$

$$p^{long,osc/nos}_{bkg}(x, \mathcal{D}) = e^{\left(-\frac{x}{c\tau_{bkg}}\right)} \left((1 - \mathcal{F}_{tsens}) + \mathcal{F}_{tsens}\left((1 \pm \mathcal{D})(1 - \mathcal{F}_{osc}) + (1 \pm \mathcal{D}\cos(\Delta m_d \cdot x/c)) \cdot \mathcal{F}_{osc}\right)\right),$$

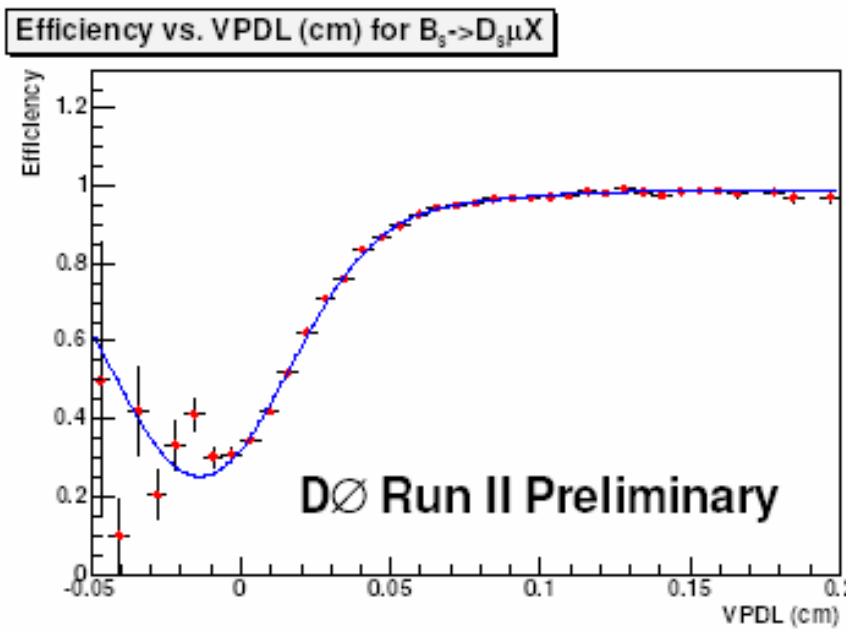
Backgrounds:

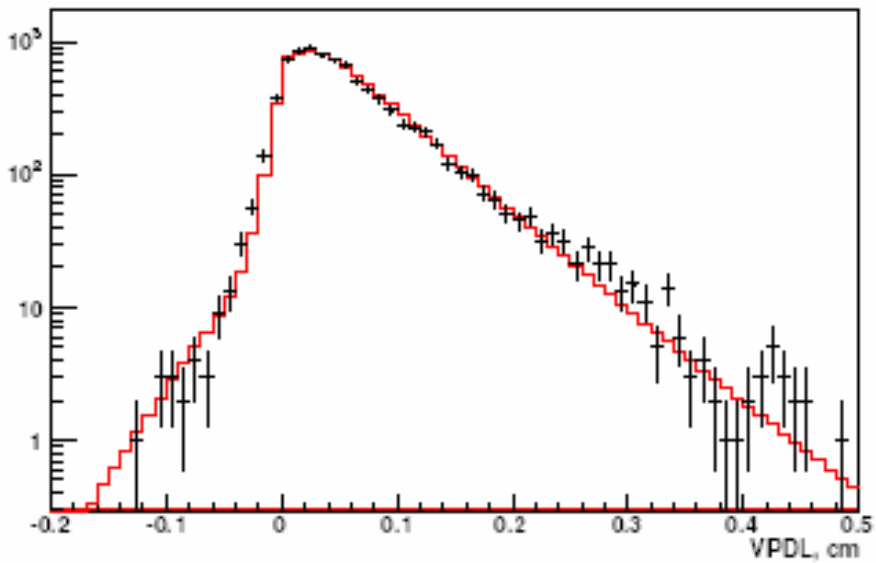
- *Zero lifetime prompt*
- *Long lived prompt (c cbar…) with Ds not associated with μ*
- *Long lived and D is associated with μ*
  - *Non B: independent of tagging.*
  - *B^+: offset from tagging but no oscillation.*
  - *B_d: oscillates at Δm_d*

Resolution and Efficiency

$$P_j^{osc,\ nos}(x^M, \sigma_{x^M}, d_{pr}) =$$

$$\int_{K_{min}}^{K_{max}} dK\ D_j(K) \cdot \frac{Eff_j(x^M)}{N_j(K, \sigma_{x^M}, d_{pr})} \int_0^{\infty} dx\ G(x - x^M, \sigma_{x^M}) \cdot p_j^{osc,\ nos}(x, K, d_{pr}).$$



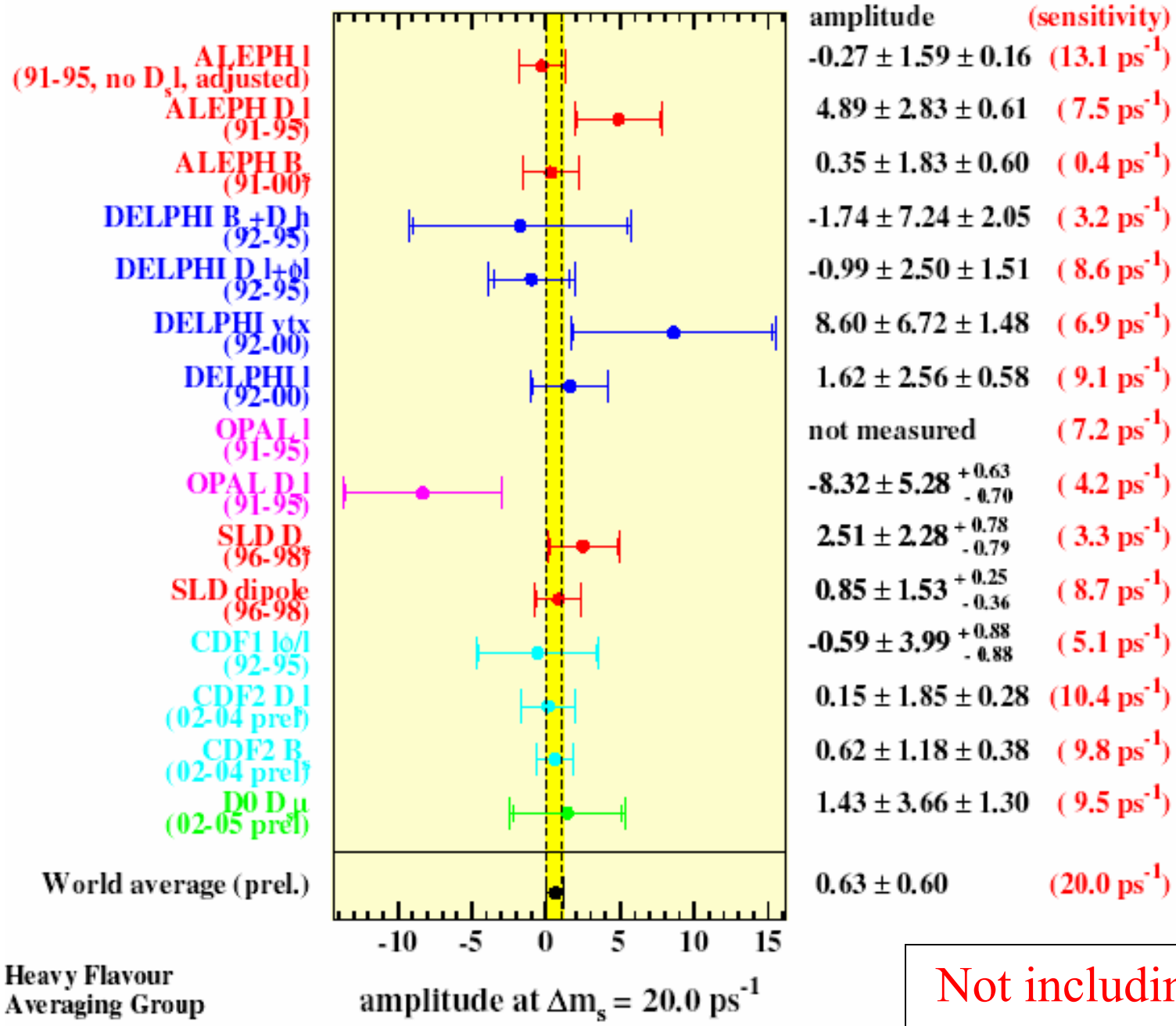


$c\tau(Bs) = 404 +/- 9\ \mu m(stat)$

Systematics

Osc. frequency		19 ps^{-1}
$\mathcal{A}$		2.356
Stat. uncertainty		1.188
$Br(D_s D_s) = 4.7\%$	$\Delta\mathcal{A}$	−0.053
	$\Delta\sigma$	−0.025
$Br(D_s \mu X) = 6.7\%$	$\Delta\mathcal{A}$	+0.036
	$\Delta\sigma$	+0.022
$p_{T_\mu} > 6$ GeV/c	$\Delta\mathcal{A}$	−0.094
	$\Delta\sigma$	−0.059
K-factor variation 2%	$\Delta\mathcal{A}$	+0.177
	$\Delta\sigma$	+0.054
K-factor distribution smoothed	$\Delta\mathcal{A}$	−0.010
	$\Delta\sigma$	+0.005
K-factor from measured momenta	$\Delta\mathcal{A}$	−0.024
	$\Delta\sigma$	+0.006
Fraction of peaking bkg. (combinatorial bkg.)	$\Delta\mathcal{A}$	+0.017
	$\Delta\sigma$	+0.003
Fraction of peaking bkg. (signal)	$\Delta\mathcal{A}$	+0.074
	$\Delta\sigma$	+0.016
$c\tau_{B_s^0}$	$\Delta\mathcal{A}$	+0.035
	$\Delta\sigma$	+0.011

uncertainty in reflection	$\Delta\mathcal{A}$	+0.005
	$\Delta\sigma$	+0.001
Stat. fluctuation of $N_{D_s^-}$	$\Delta\mathcal{A}$	+0.019
	$\Delta\sigma$	+0.008
resolution (signal)	$\Delta\mathcal{A}$	+0.056
	$\Delta\sigma$	+0.052
resolution (bkg.)	$\Delta\mathcal{A}$	+0.010
	$\Delta\sigma$	+0.000
dilution	$\Delta\mathcal{A}$	−0.042
	$\Delta\sigma$	−0.006
Fr_{tscns}	$\Delta\mathcal{A}$	+0.008
	$\Delta\sigma$	+0.001
Fr_{osc}	$\Delta\mathcal{A}$	+0.005
	$\Delta\sigma$	−0.000
Total syst.	σ_{tot}^{sys}	0.146
Total	σ_{tot}	1.197



Not including this result