CP Violation in B_s Mixing

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On behalf of the
DØ collaboration

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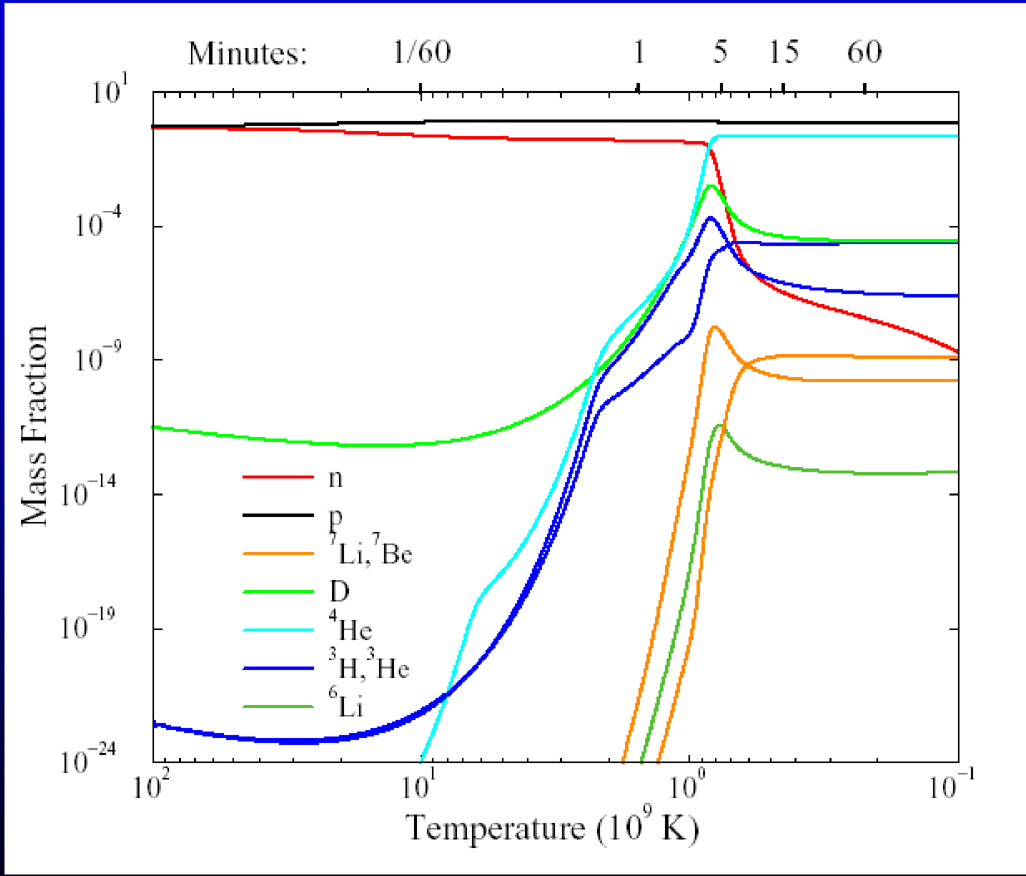
Role of CPV in the Universe

GR + Astro + Particle + Nuclear Physics = Big Bang Nucleosynthesis

Evolution of light elements in first hour of the universe



Burles, Nollett, Turner astro-ph/99003300

One of the greatest successes of modern phys.

<u>But:</u>

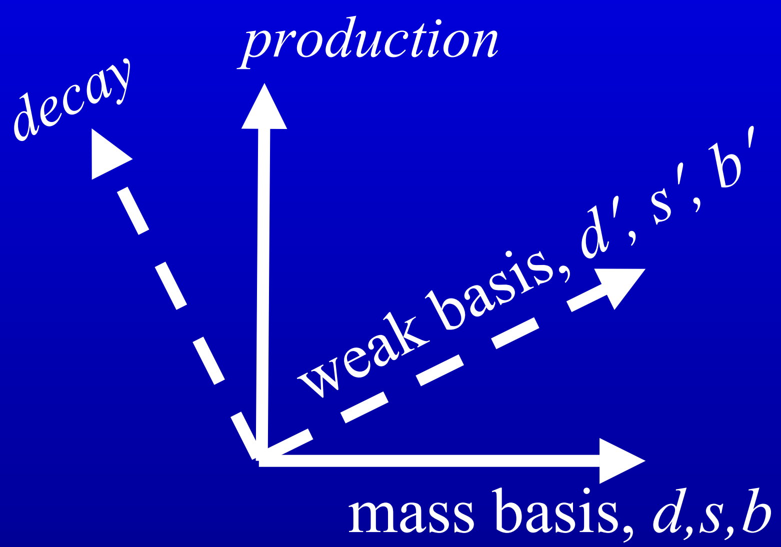
Small excess of baryons is an initial condition of BBN, not a prediction.

No explanation of the evolution of anti-elements

CP Violation necessary ingredient for our existence

one of the biggest obstacles in explaining the birth of our universe

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

$$V_{ub} \neq V_{ub}{}^*, \; V_{td} \neq V_{td}{}^* \Rightarrow \textbf{CPV}$$

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} ↑

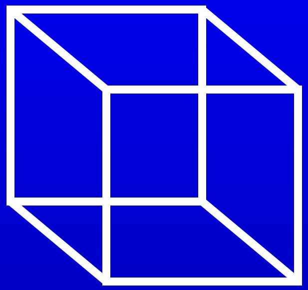
~15 orders of magnitude too small
Huet, Sather PRD51 379 (1995)

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

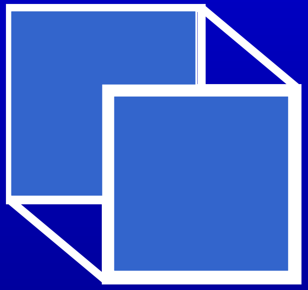
Jury still out

Need new sources of CPV!

Mesons, Mixing, and CPV



- Ideal laboratory for studying CPV
  - Mesons: matter – antimatter bound state
  - Neutral mesons: continuously transforming between matter and antimatter states



$$i\frac{\partial}{\partial t}\left|M(t)\right\rangle = \left(m - i\frac{\Gamma}{2}\right)\left|M(t)\right\rangle$$

$$i\frac{\partial}{\partial t}\left|\begin{matrix} M(t) \\ \overline{M}(t) \end{matrix}\right\rangle = \begin{pmatrix} m_{11} - i\frac{\Gamma_{11}}{2} & m_{12}e^{-i\phi} - i\frac{\Gamma_{12}}{2} \\ m_{21}e^{i\phi} - i\frac{\Gamma_{21}}{2} & m_{11} - i\frac{\Gamma_{11}}{2} \end{pmatrix}\left|\begin{matrix} M(t) \\ \overline{M}(t) \end{matrix}\right\rangle$$

Observables

$$|M(t)\rangle_1 = \left(g^+(t)|M\rangle + g^-(t)e^{-2i\phi}|\overline{M}\rangle\right)$$

$$|M(t)\rangle_2 = \left(g^-(t)e^{2i\phi}|M\rangle + g^+(t)|\overline{M}\rangle\right)$$

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

$$\Delta m = m_H - m_L = 2|m_{12}|$$

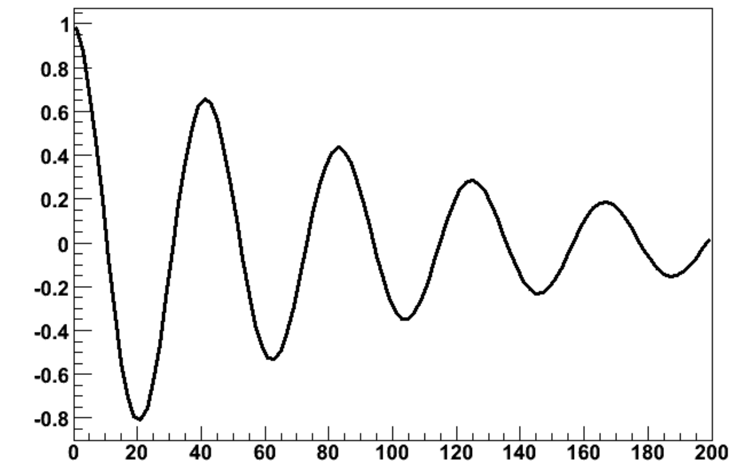
$$\Delta\Gamma = \Gamma_L - \Gamma_H = 2|\Gamma_{12}|\cos\phi$$

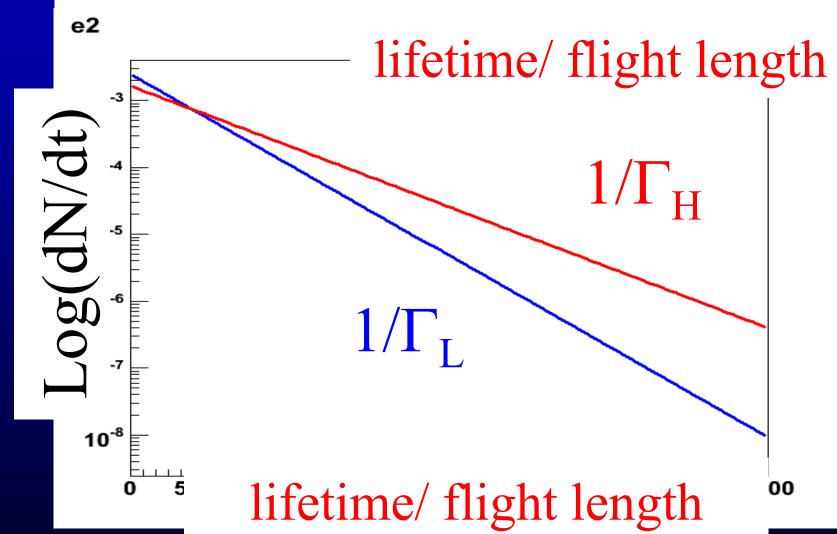
$$\phi = \arg\left(-\frac{m_{12}}{\Gamma_{12}}\right)$$

$$\overline{\Gamma} = \frac{1}{\overline{\tau}} = \frac{1}{2}(\Gamma_L + \Gamma_H)$$

$$\Delta\Gamma_{CP} = \Gamma_{even} - \Gamma_{odd} = 2|\Gamma_{12}|$$

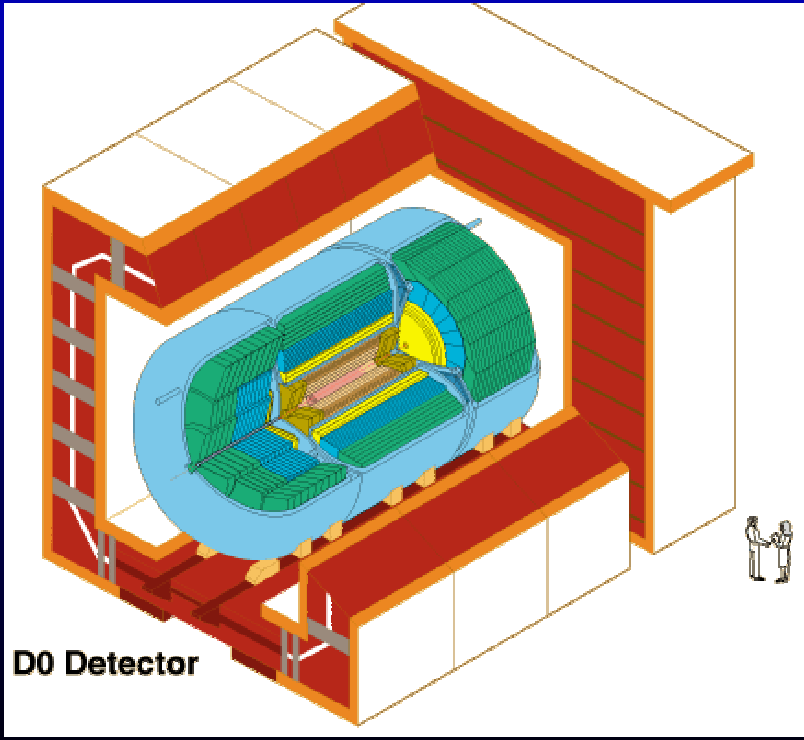
$$\frac{N(unmixed) - N(mixed)}{N(unmixed) + N(mixed)}$$





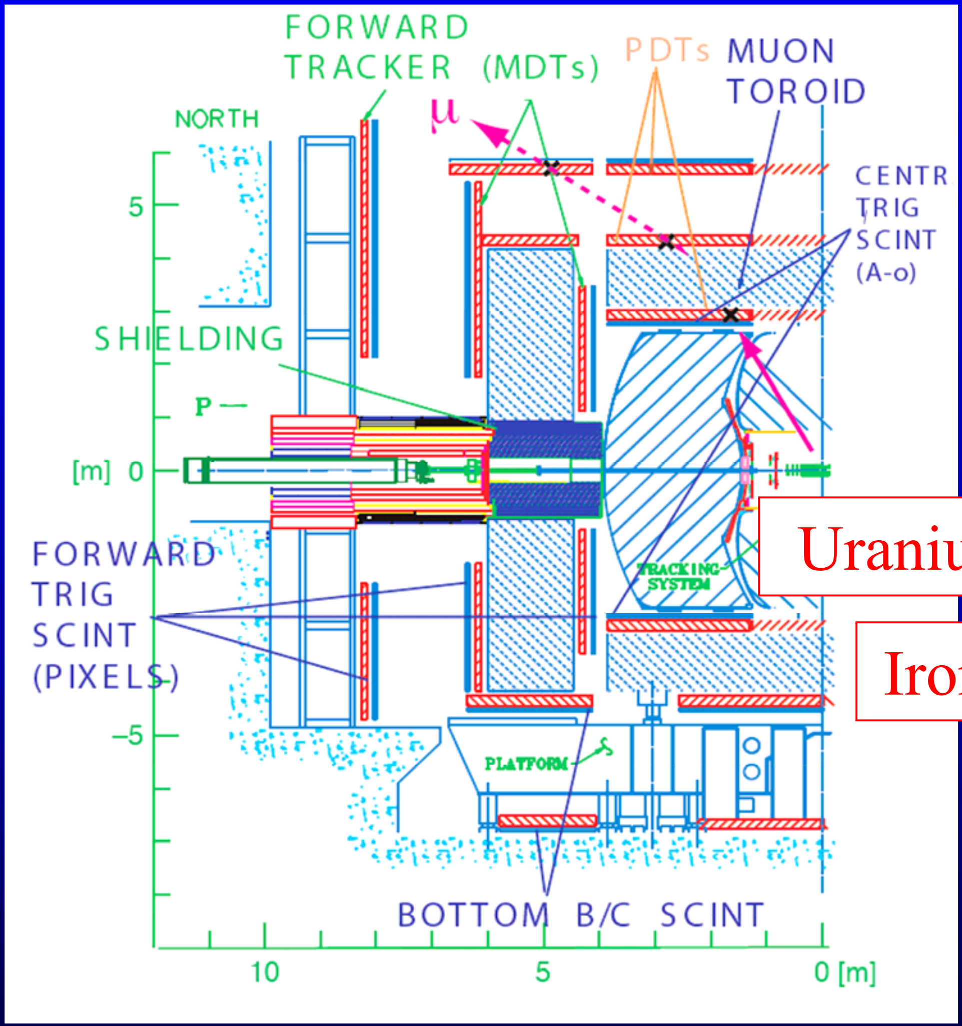
$$\Gamma(M \Rightarrow \overline{M}) \neq \Gamma(\overline{M} \Rightarrow M)$$

	$|\eta|$	$|\theta|$
Muon ID	~2	~15^{o}
tracking	~3	~5^{o}
EM and hadronic calorimetry	~4	~2^{o}



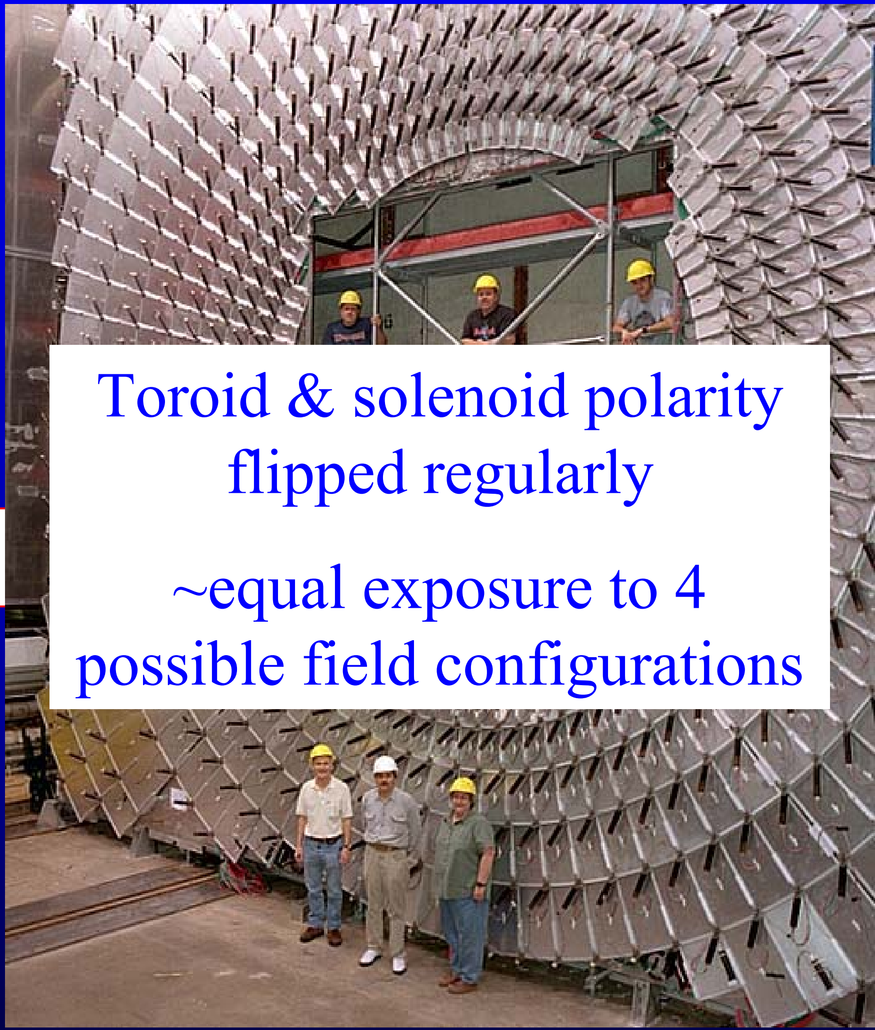
629 scientists, 81 institutions, 20 countries

Heart of the DØ Program



Uranium

Iron



Toroid & solenoid polarity flipped regularly

~equal exposure to 4 possible field configurations

Excellent, large angle, muon spectrometer and trigger

Large $B \rightarrow \mu$ semileptonic and $B \rightarrow J/\psi$ samples

Tevatron Data Set

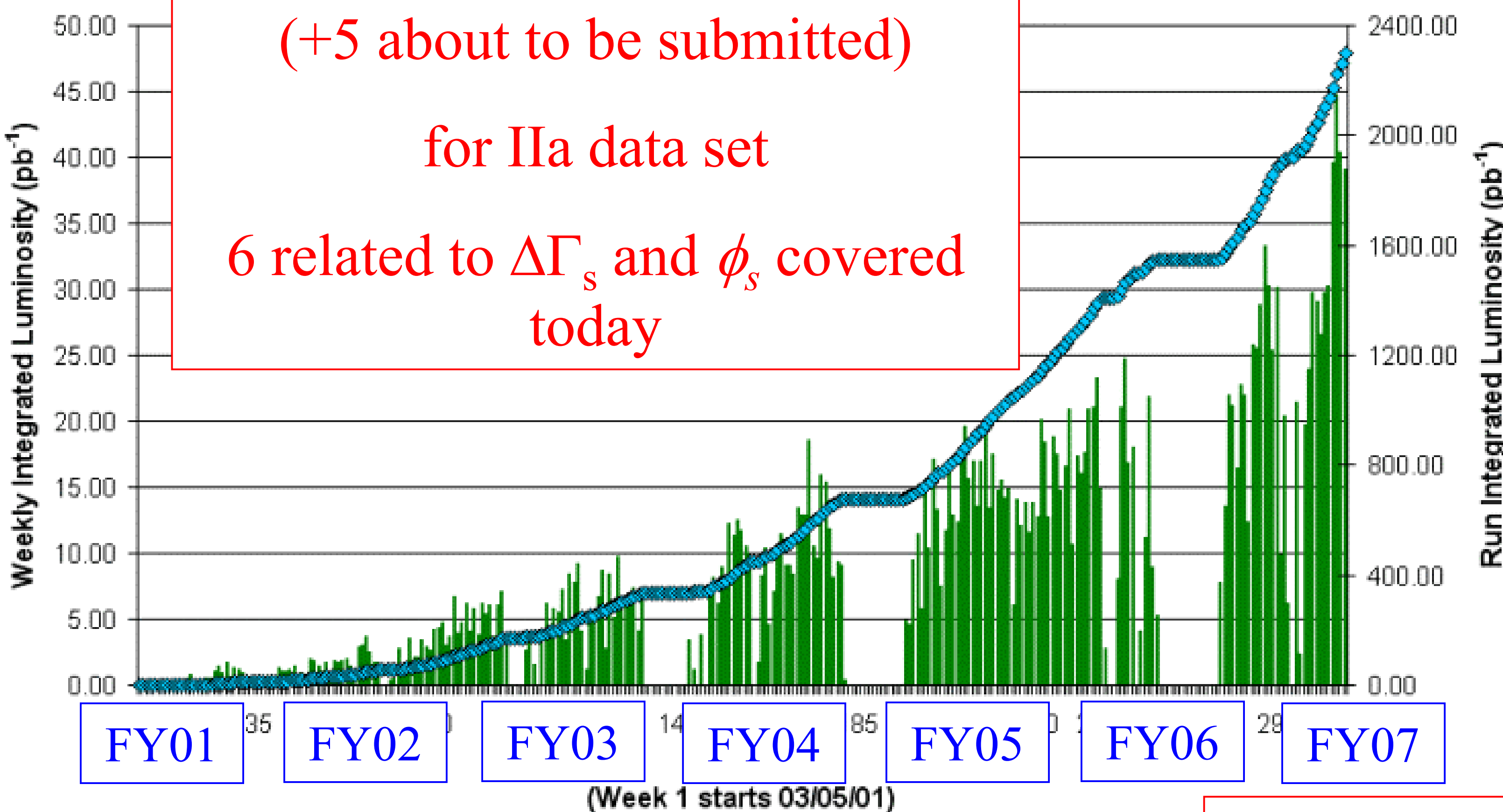
>2.3 fb^{-1} delivered

15 Heavy Flavor Publications

(+5 about to be submitted)

for IIa data set

6 related to $\Delta\Gamma_s$ and ϕ_s covered today

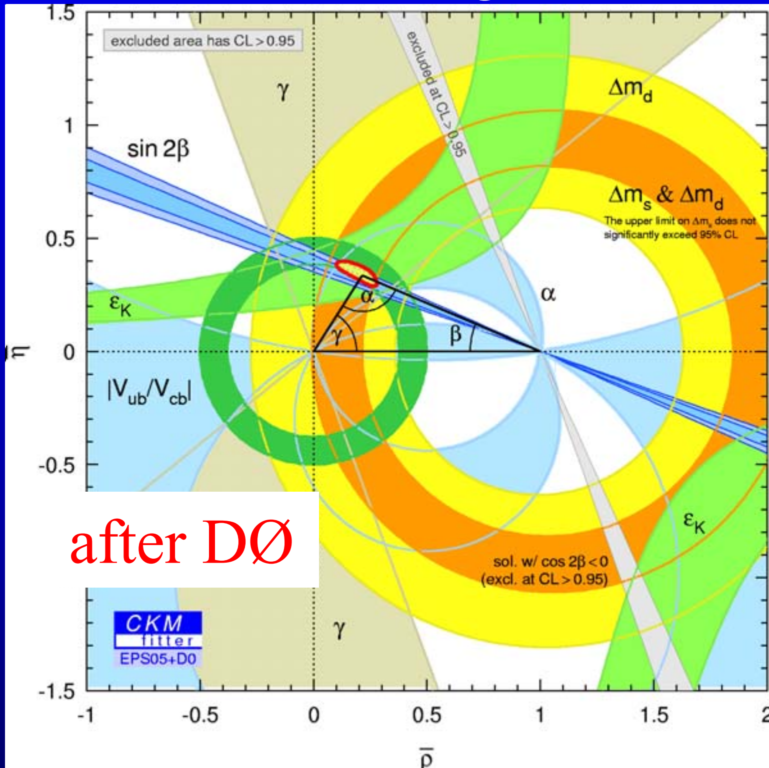


Run IIa: 1.3 fb^{-1} on tape

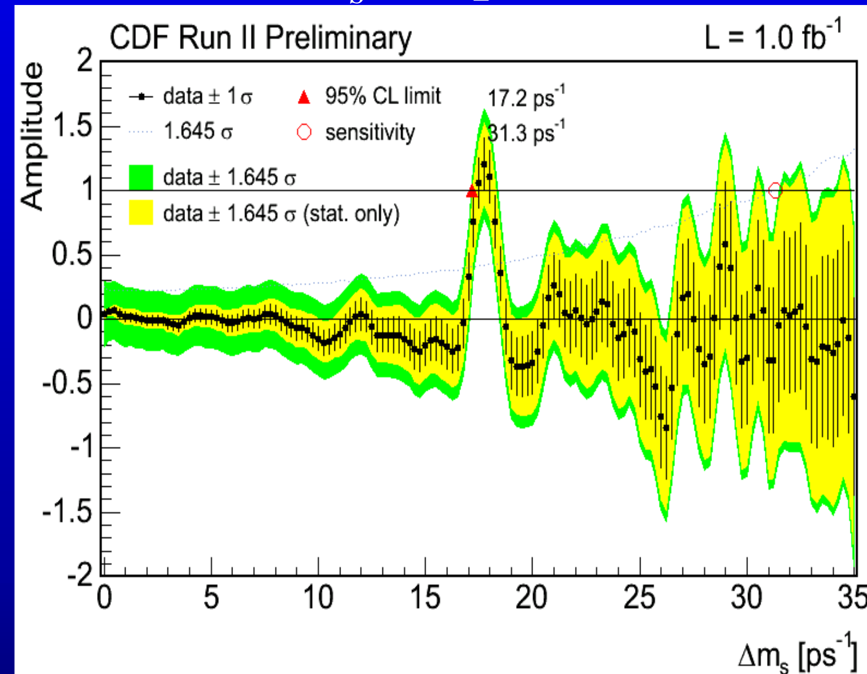
Run IIb: >700 pb^{-1} on tape

First Parameter: Δm_s

CKM triangle



CDF Δm_s Amplitude Scan



$$\frac{|V_{td}|}{|V_{ts}|} = 0.2060 \pm 0.0007(ex.)^{+0.0081}_{-0.0060}(theo.)$$

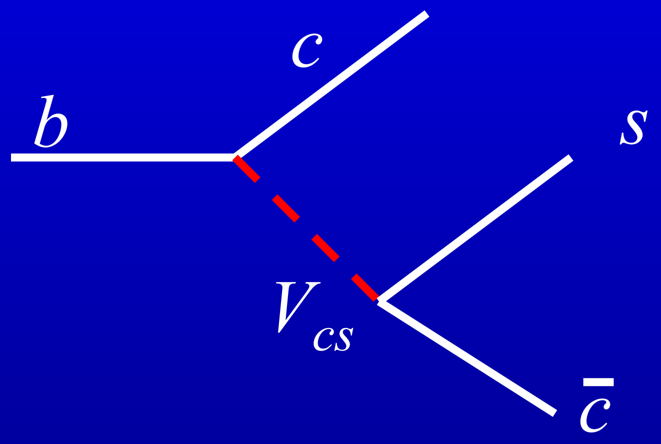
Rule out large new physics: DØ Collab. PRL 97 021802 (2006)

Precision SM measurement: CDF Collab. PRL 97 062003 (2006)

Two top cited experimental HEP papers of 2006

Second Parameter: $\Delta\Gamma$

Governed by decay rates to CP *eigenstates*



Tree process,

don't expect new physics

Importance: defines the phenomenology

$$\Gamma_L(t)+\Gamma_H(t)\approx\left[e^{-\Gamma_L t}-e^{-\Gamma_H t}\right]\sin\phi$$

Large $\Delta\Gamma$: CPV observables do not cancel out, info in all events

Small $\Delta\Gamma$: CP studies require initial state tagging $\varepsilon_{eff}\approx 2.5\%$

Second Parameter: $\Delta\Gamma$

- First step:
  - Determine $\Delta\Gamma$ assuming SM level CPV in B_s mixing: $\cos\phi_s \equiv 1$
  - $\Gamma_{\mathrm{L}} - \Gamma_{\mathrm{H}} = \Gamma_{\mathrm{CP+}} - \Gamma_{\mathrm{CP-}}$
- Three main channels:
  - $B_s \to D_s^{(*)} D_s^{(*)}$
  - Flavor specific B_s lifetime
  - $B_s \to J/\psi\, \phi$

$B_s \to D_s^{(*)} D_s^{(*)}$ and $\Delta\Gamma_{CP}$

- Three channels
  - $D_s D_s$ (PP), $D_s^* D_s$ (VP), $D_s^* D_s^*$ (VV)
- Heavy quark limit + factorization
  - $B_s^{odd} \to D_s^* D_s$ forbidden

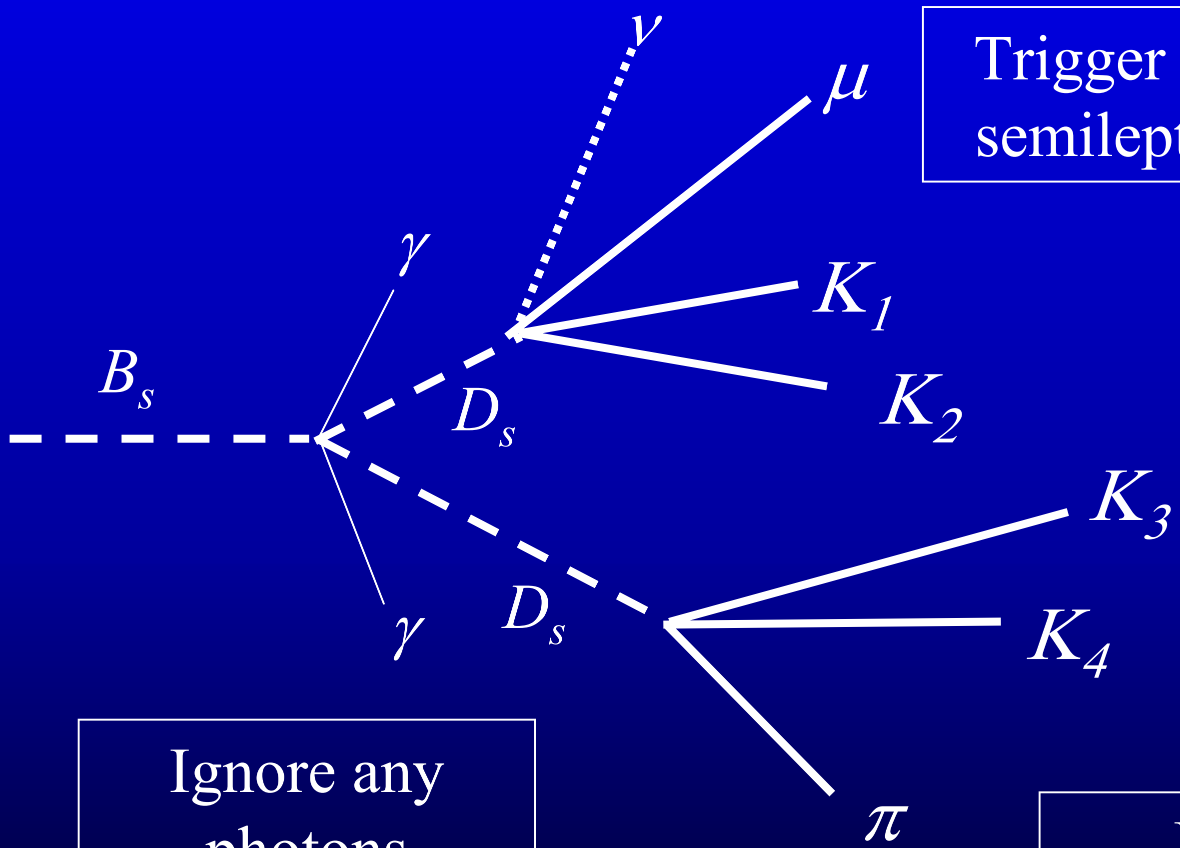
R. Alexan et al., PLB 316, 567 (1993) ~5% odd
Others: maybe as much as 30% odd

- $D_s^* D_s^*$ in S-wave

⇒ **$Ds^{(*)}Ds^{(*)}$ pure CP even**

$$BF(B_s \to D_s^{(*)} D_s^{(*)}) = \left(\frac{\Delta\Gamma_{CP}}{2\Gamma}\right)\left(1 + O\left(\frac{\Delta\Gamma}{\Gamma}\right)\right)$$

$B_s \rightarrow D_s^{(*)} D_s^{(*)}$

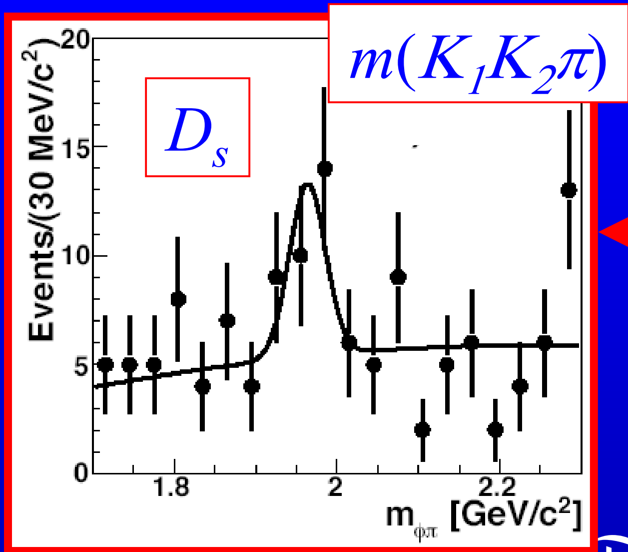


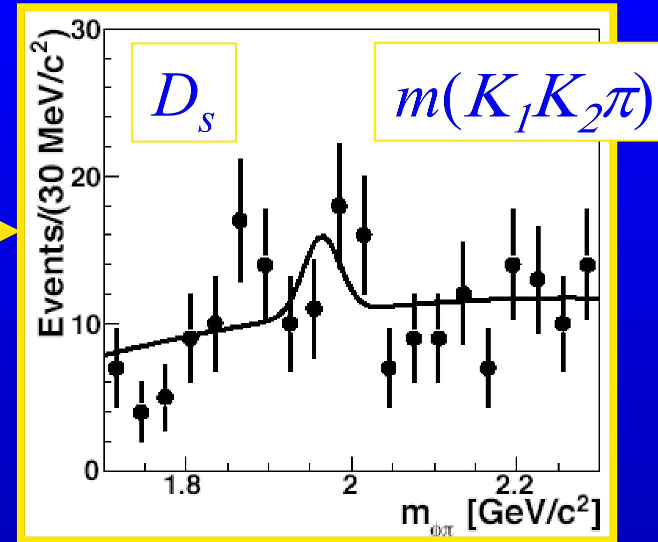
Trigger on muon from semileptonic D_s decay

Ignore any photons

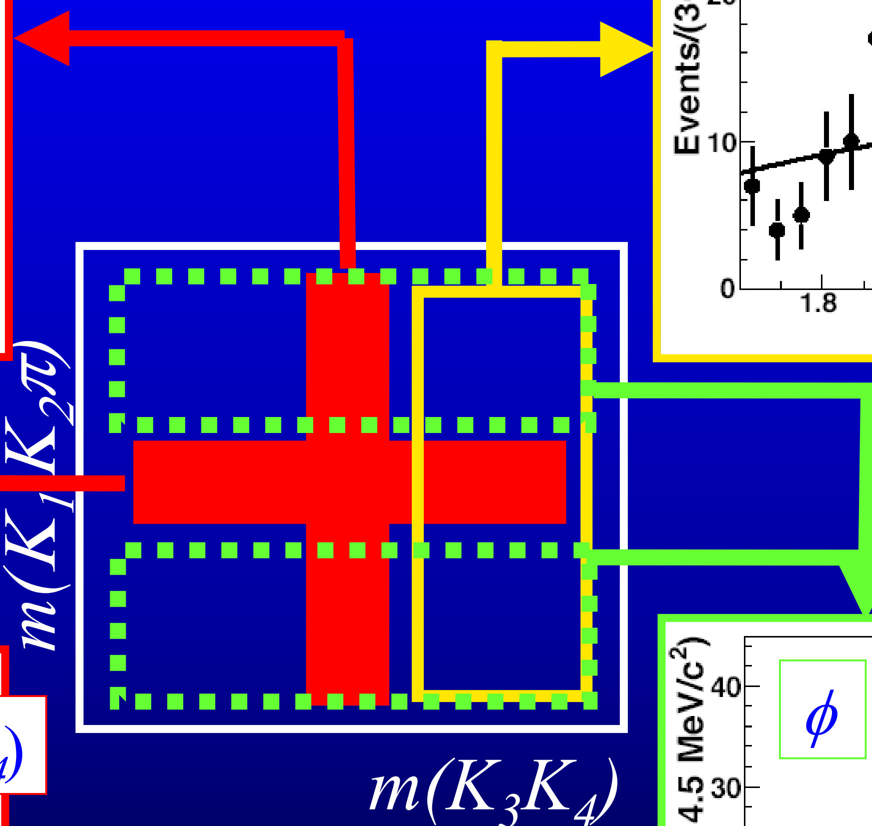
Look for correlated production of $D_s \rightarrow \phi\pi$ and $D_s \rightarrow \phi\mu$

$D_s\mu\phi$ candidates

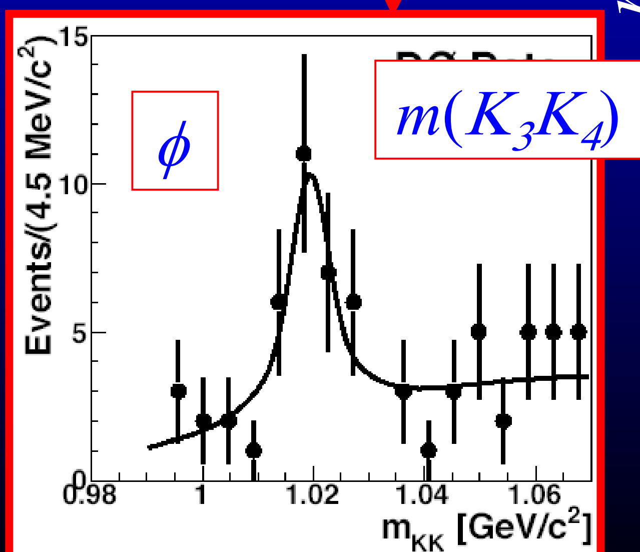




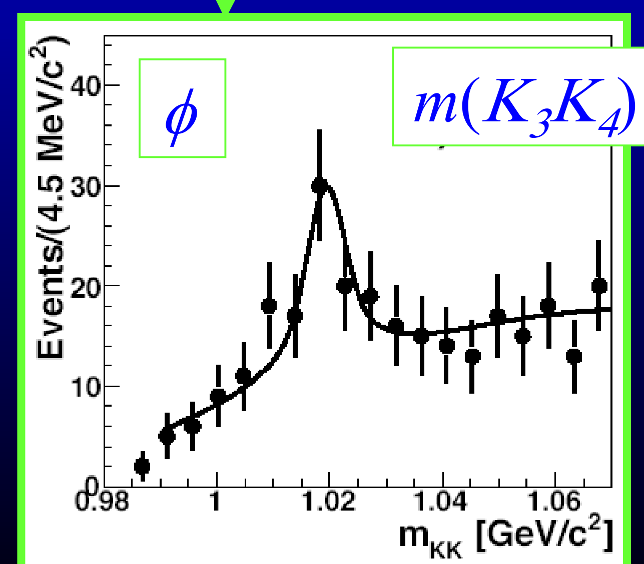
signal



sidebands



$$N(D_s^{(*)}D_s^{(*)}) = 13.4^{+6.6}_{-6.0}$$



$B_s \rightarrow D_s^{(*)} D_s^{(*)}$

$$BF(B_s \rightarrow D_s^{(*)} D_s^{(*)}) = \left(\frac{\Delta\Gamma_{CP}}{2\Gamma}\right)\left(1 + \mathrm{O}\left(\frac{\Delta\Gamma}{\Gamma}\right)\right)$$

$$BF(B_s \rightarrow D_s^{(*)} D_s^{(*)}) = 0.039^{+0.019}_{-0.017}{}^{+0.016}_{-0.015}$$

$$\frac{\Delta\Gamma_{CP}}{\Gamma} = 0.079^{+0.038}_{-0.035}{}^{+0.031}_{-0.030}$$

Flavor Specific B_s Lifetime

Flavor specific decays carry equal amounts of B_H and B_L

$$\left|B_s \to D_s \mu \nu\right\rangle = \frac{1}{\sqrt{2}}\left(\left|B_H\right\rangle + \left|B_L\right\rangle\right)$$

$$e^{-t/\tau_{FS}} \equiv \frac{1}{2}\left(e^{-t/\tau_H} + e^{-t/\tau_L}\right)$$

Get the flavor specific lifetime when you fit FS data with single exponential

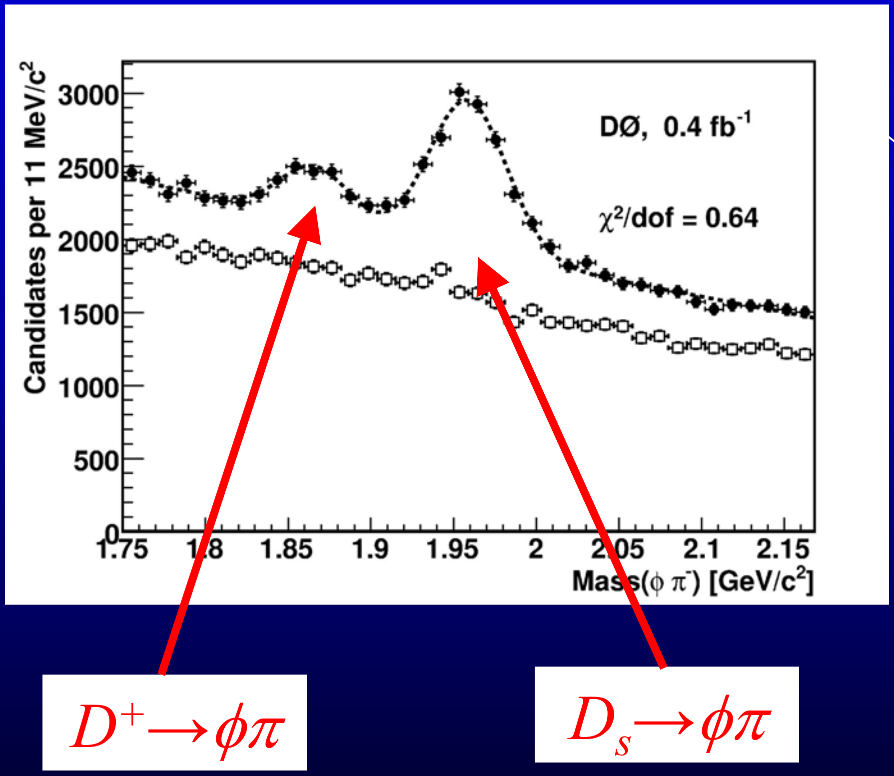
Maps out a 2-D constraint on the average width and the width difference

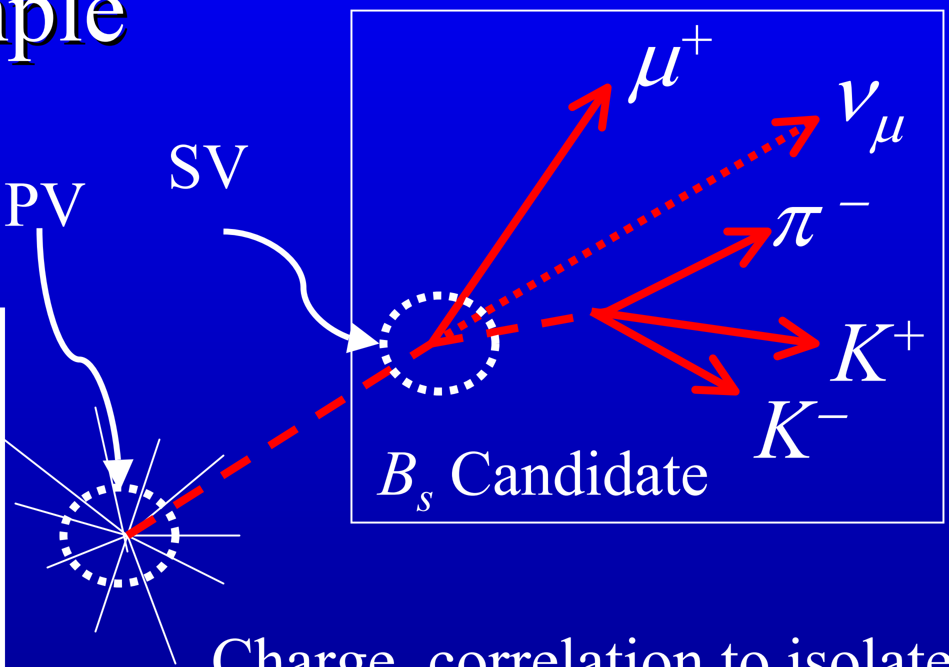
$$\tau_{FS} = \frac{1}{\overline{\Gamma}_s}\left(\frac{1+y^2}{1-y^2}\right)$$

$$y = \frac{\Delta\Gamma}{2\Gamma}$$

hep-ph/0201071

B_s Semileptonic Sample





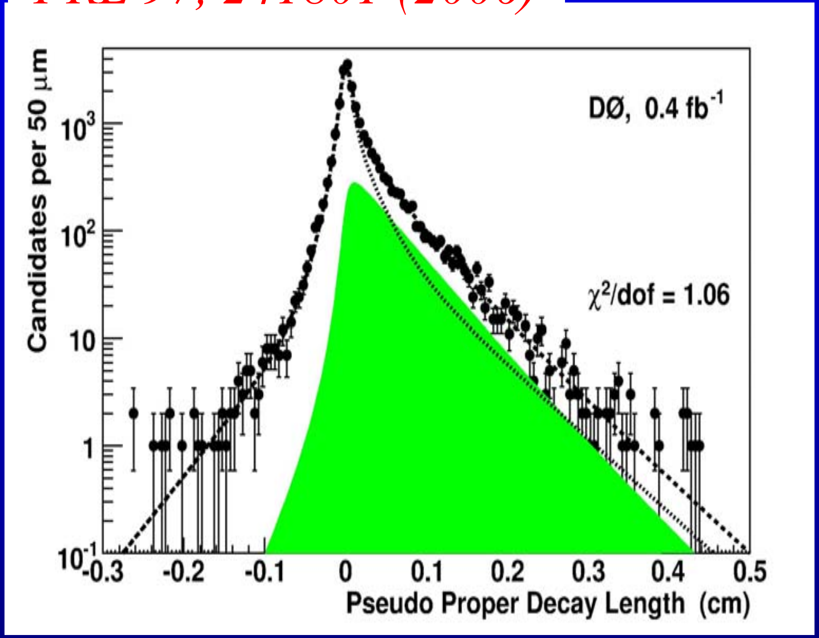
Charge correlation to isolate B_s sample

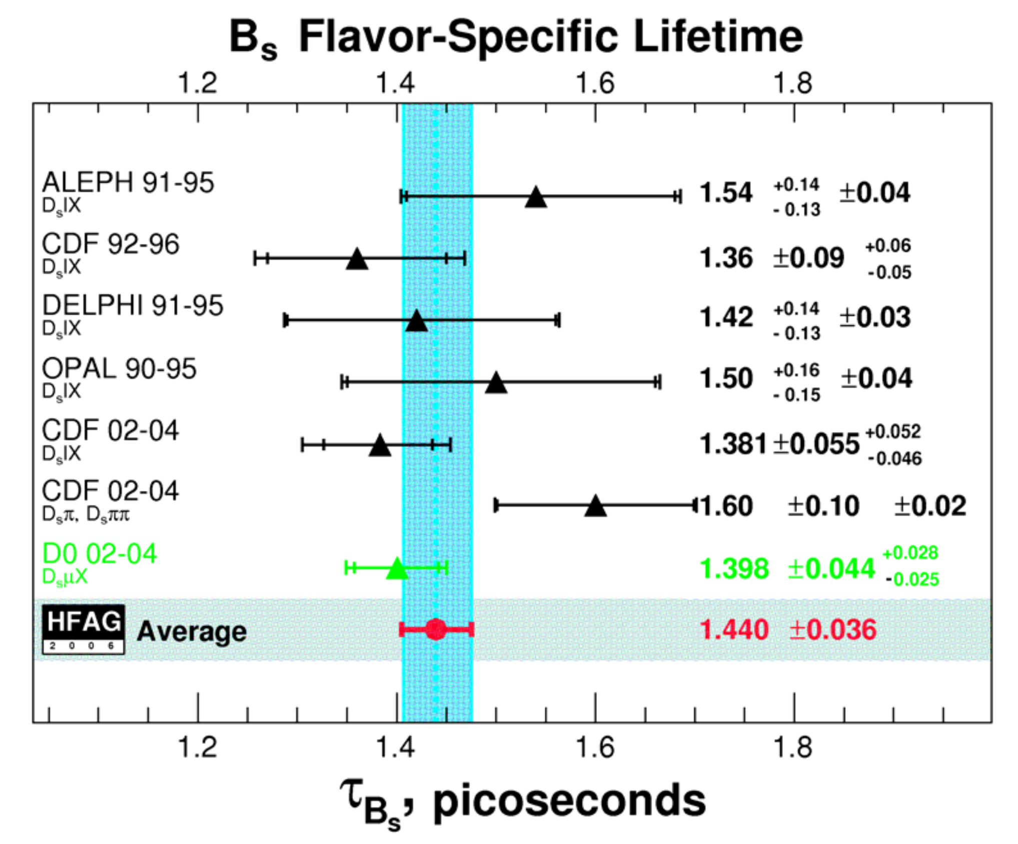
Transverse decay length determined in lab frame

Boost back using MC to estimate neutrino momentum

B_s Flavor Specific Lifetime

PRL 97, 241801 (2006)





$$\tau_{FS}(B_s) = 1.398 \pm 0.044^{+0.028}_{-0.025}\, ps$$

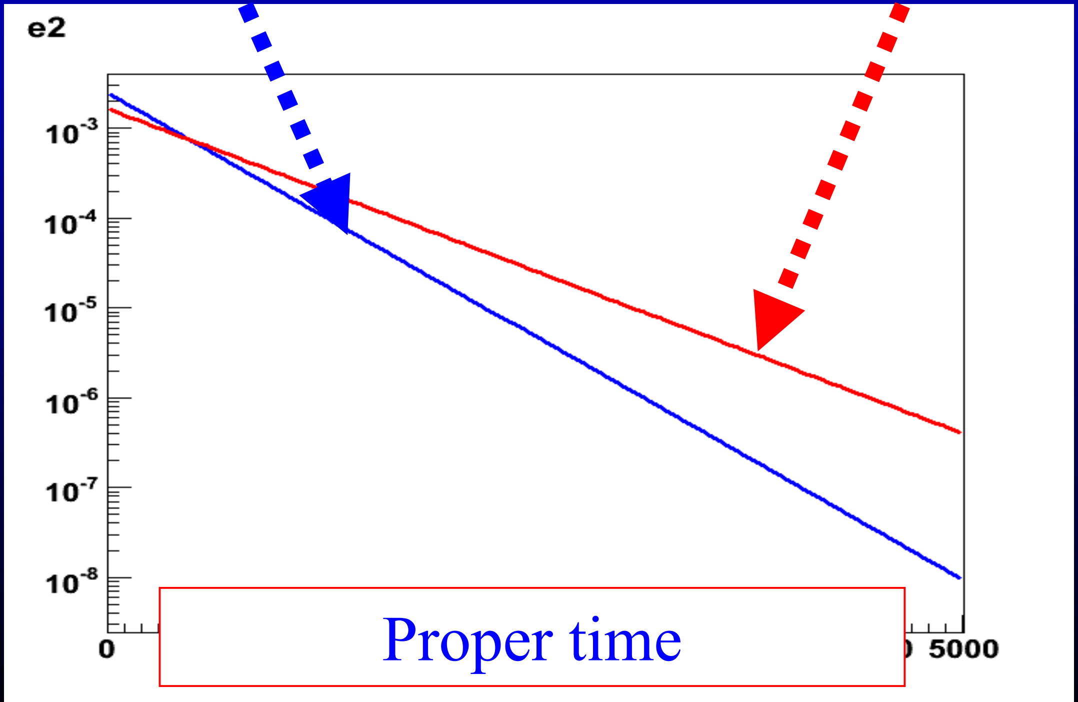
$$\tau_{FS}(B_s, WA) = 1.440 \pm 0.036\, ps$$

$B_s \to J/\psi\, \phi$: $P \to VV$

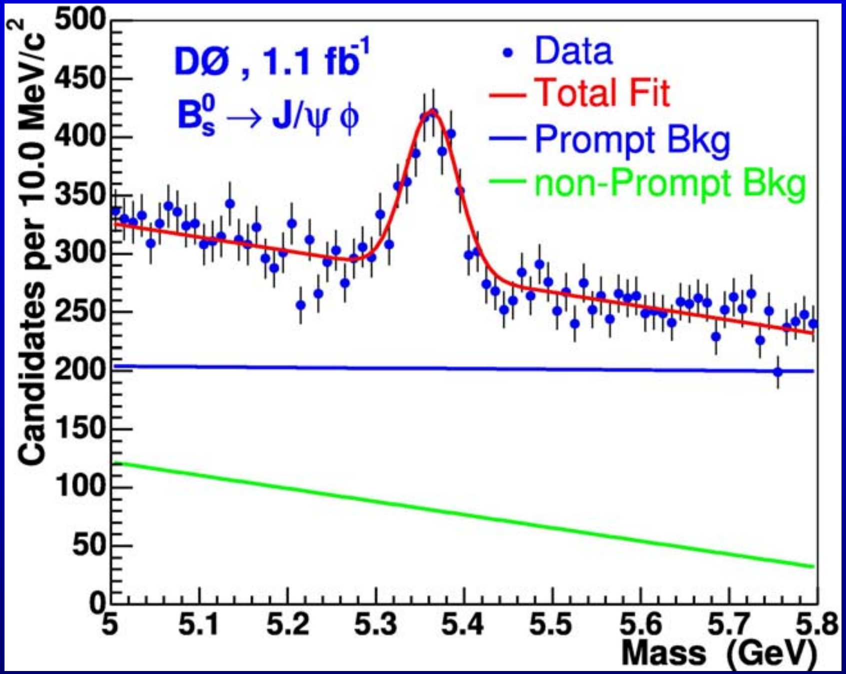
Even and odd paths distinguishable with angular analysis of final state particles

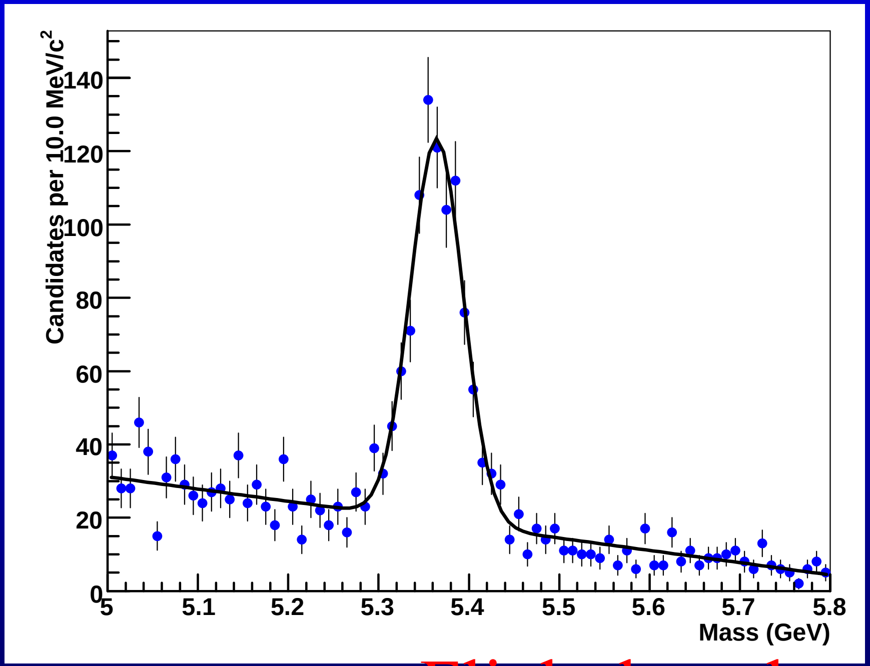
A_0 $A_{||}$ — Even waves

$A_\perp$ — Odd waves



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

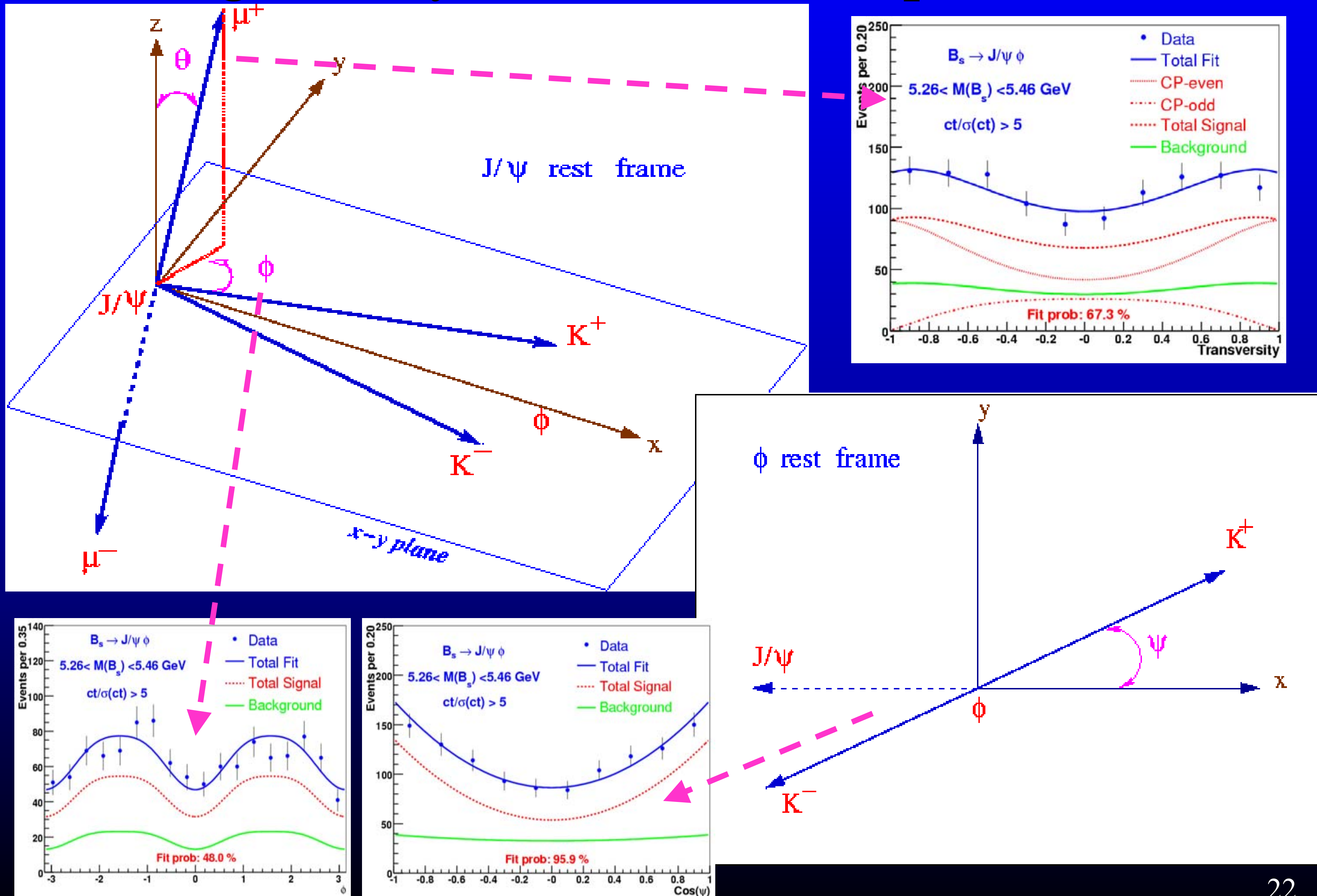




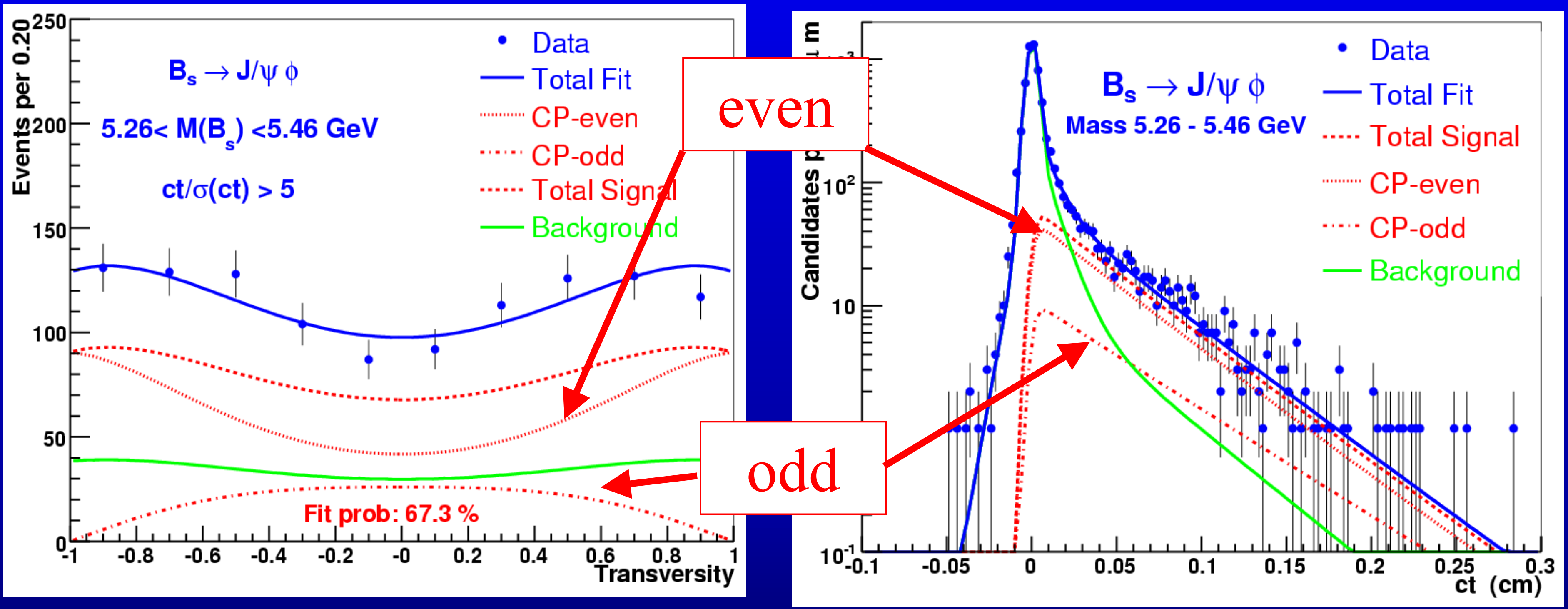
Flight length significance > 5

1039±45 B_s Candidates

3 angle analysis to determine polarization



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

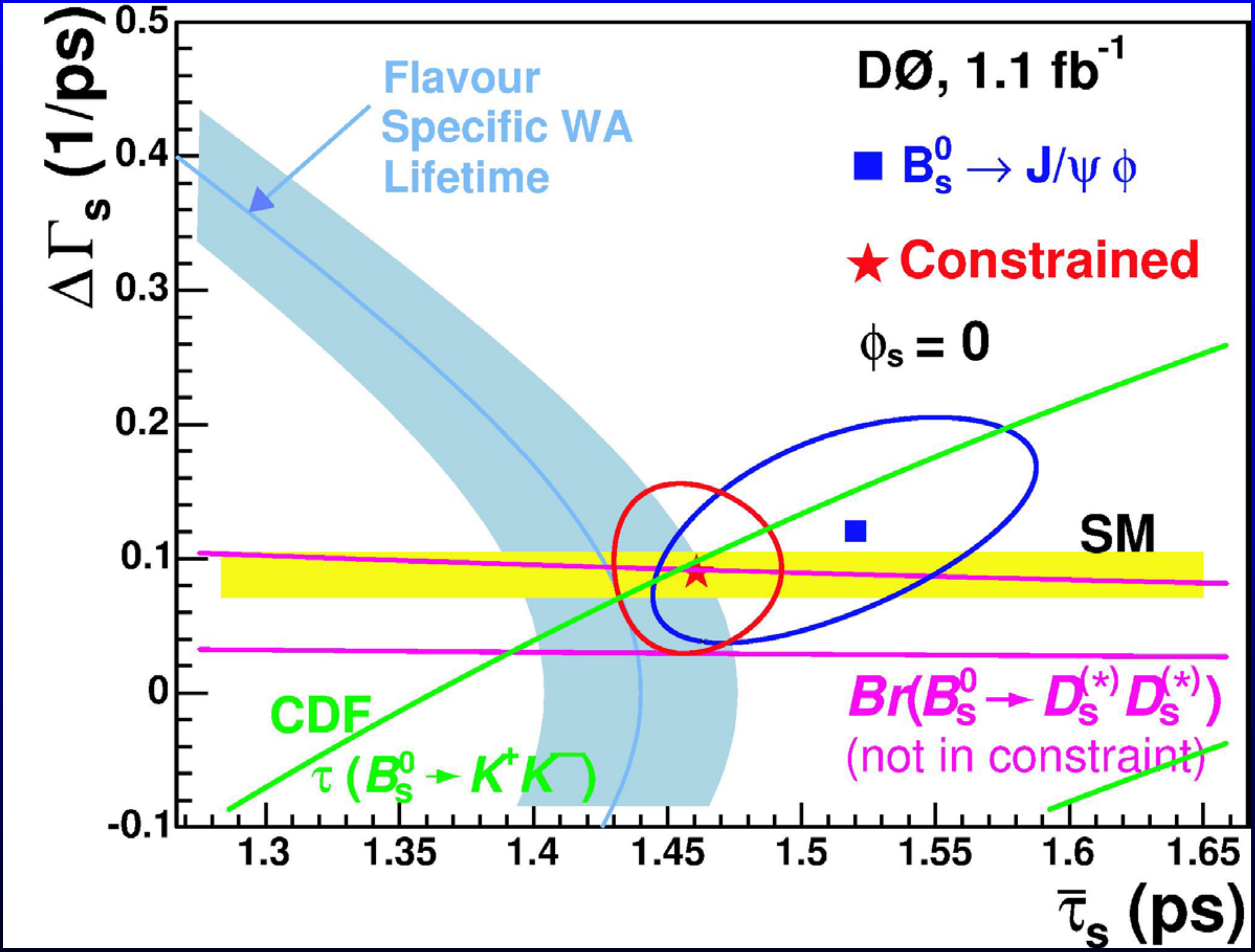


$$\Delta\Gamma_s = 0.12^{+0.08}_{-0.10} \pm 0.02\, ps^{-1}$$

$$\bar{\tau}_s = 1/\Gamma_s = 1.52 \pm 0.08^{+0.01}_{-0.03}\, ps$$

hep-ex/0701012 submitted to PRL

Combined $\Delta\Gamma$ ($\cos\phi_s \equiv 1$)

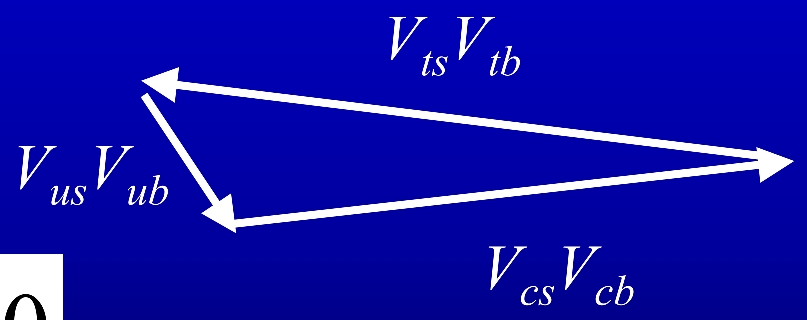


Third Parameter: ϕ_s

In Standard Model: $\phi_s \approx \arg(-V_{ts})$

Size limited by unitarity of CKM matrix

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



$$V_{us}V_{ub}^{*} + V_{cs}V_{cb}^{*} + V_{ts}V_{tb}^{*} = 0$$

Standard Model $\phi_s \approx 0.004$ rad.

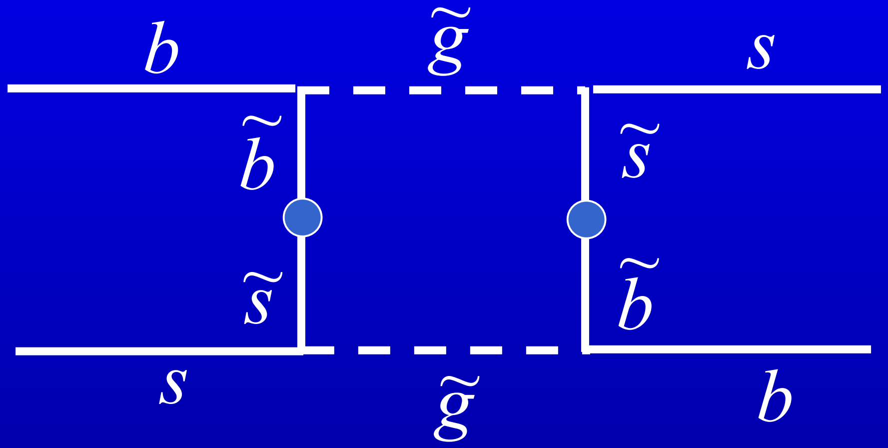
A. Lenz, U. Nierste hep-ph/0612167

<u>Observables:</u>

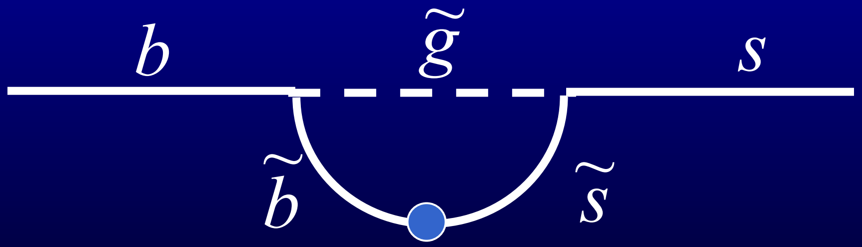
Semileptonic asymmetries, interference in decays to CP eigenstates

ΔB = 2 versus ΔB = 1

We are looking for something like this



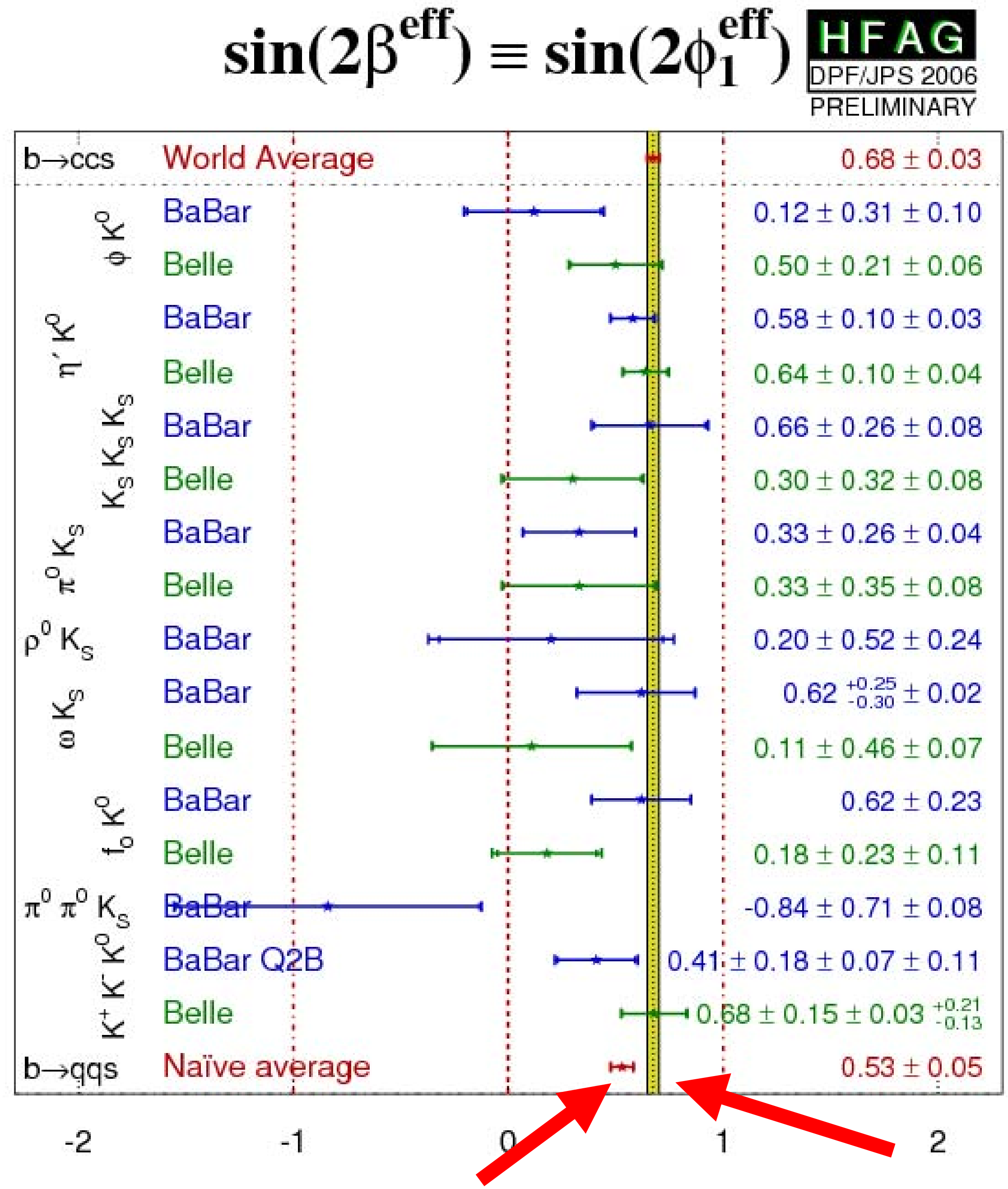
B factories are looking for something like this



In absence of super-weak models, we are looking at the same thing

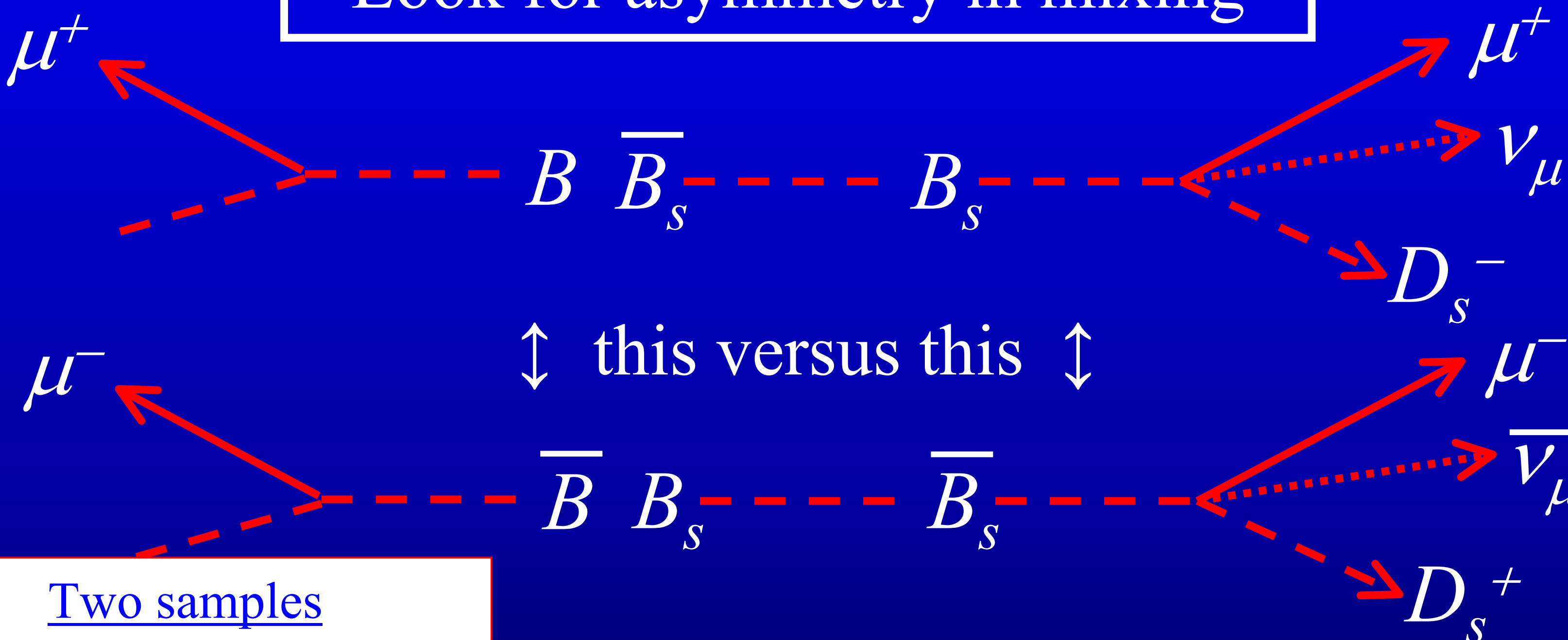
Hints from ΔB=1

Comparison of CPV in b→c and b→s,d



Semileptonic Asymmetry Measurements

Look for asymmetry in mixing



<u>Two samples</u>

Exclusive untagged $D_s\mu$

Inclusive like-sign $\mu\mu$

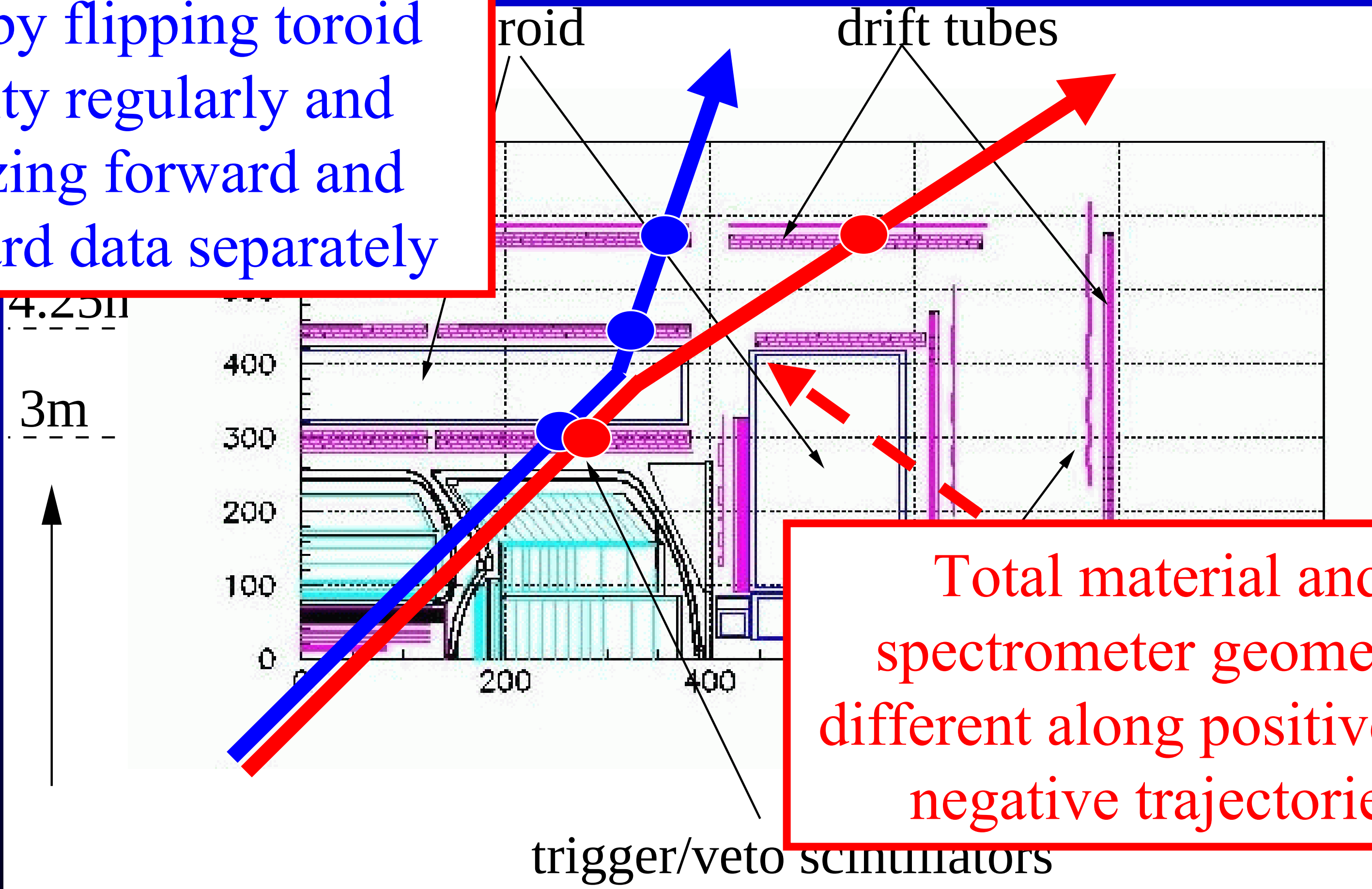
$$\frac{N(D_s\mu^+)-N(D_s\mu^-)}{N(D_s\mu^+)+N(D_s\mu^-)} = A_{SL}(untagged) \approx \frac{\Delta\Gamma}{\Delta m}\tan\phi$$

$$\frac{N(\mu^+\mu^+)-N(\mu^-\mu^-)}{N(\mu^+\mu^+)+N(\mu^-\mu^-)} = A_{SL}(tagged) = 2A_{SL}(untagged)$$

Detector Systematics

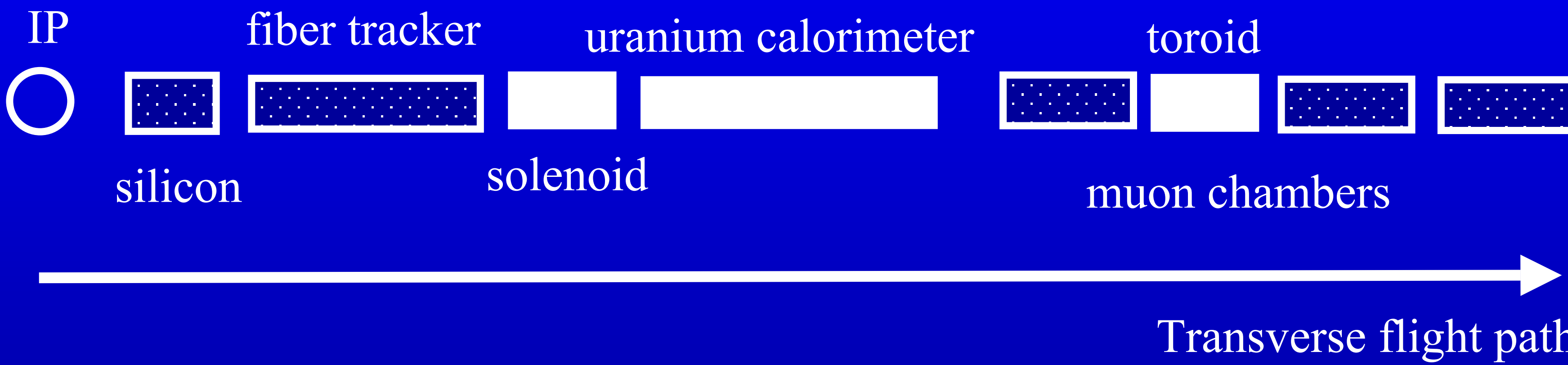
Main detector related systematic is due to geometry in muon spectrometer

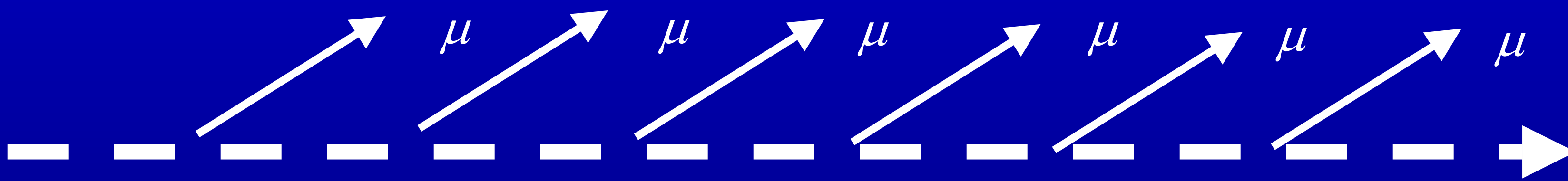
Solve by flipping toroid polarity regularly and analyzing forward and backward data separately



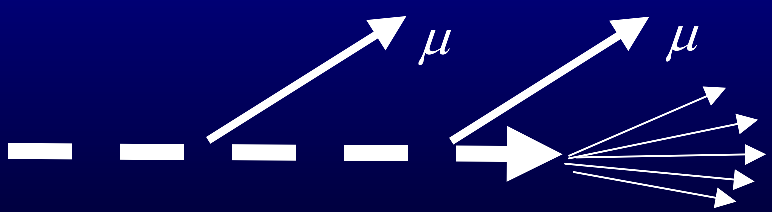
Total material and spectrometer geometry different along positive and negative trajectories

Physics Systematics





K^+ produce μ^+ from weak decay $N(\mu^+) \sim exp(-x/c\tau(K))$



Measured directly in data using kaons tagged from D* decay

K^- stop more frequently in calorimeter from $K^- + N \rightarrow Y + \pi$ nuclear interactions

Like-sign Dimuons

N(same sign) ≈ 310K

$$A_{SL} = -0.0092 \pm 0.0044 \pm 0.0032$$

PRD 74, 092001 (2006)

~60/40 mix of B_d and B_s

$$A_{SL} = A_{SL}(B_d) + \frac{f_s Z_s}{f_d Z_d} A_{SL}(B_s)$$

$Z \sim 2\chi$

$A_{SL}(B_d)$ from B-factories:

$A_{SL}(B_d) = -0.0047 \pm 0.0046$ (HFAG)

$$A_{SL}(B_s, \mu\mu) = -0.0064 \pm 0.0101$$

20 years of like-sign dileptons

- 1987: excess of like-sign dileptons first seen at a hadron collider (UA1)
  - Input from ϒ(4S) allows extraction of B_s mixing parameters

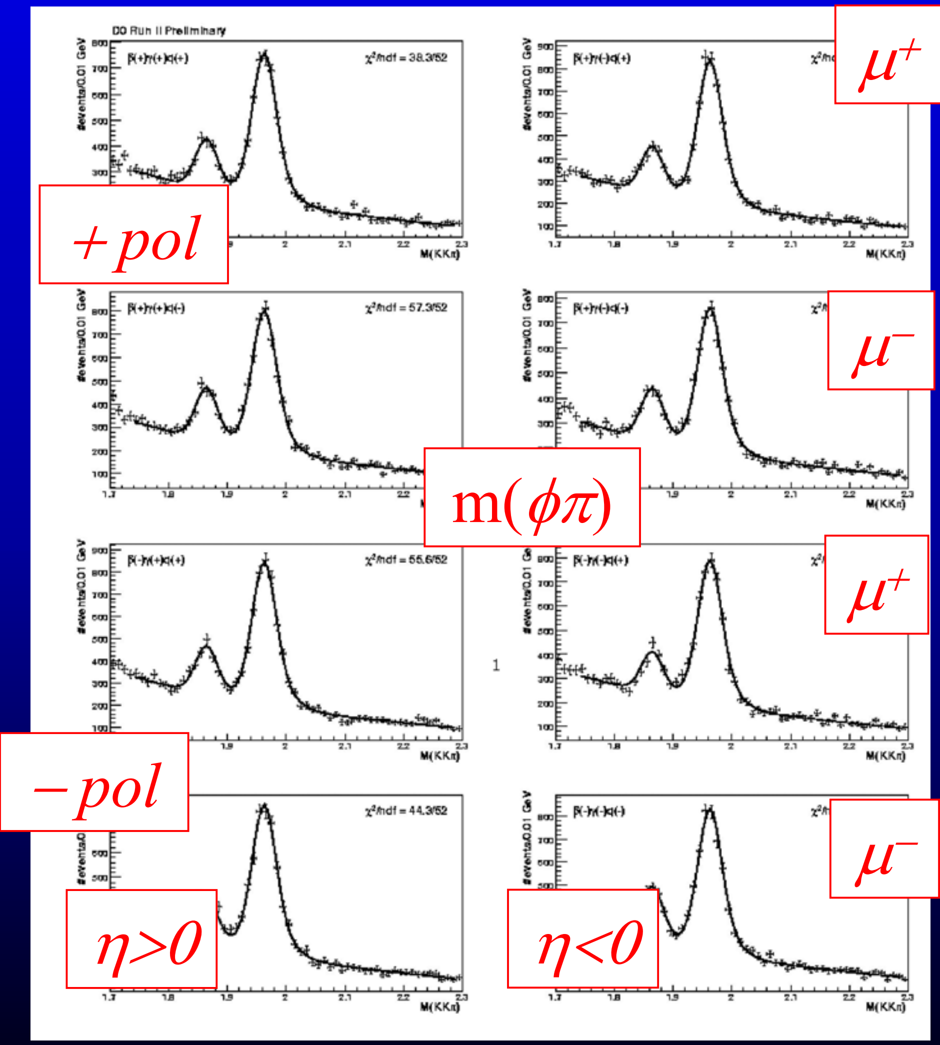
$$\chi = f_d \chi_d + f_s \chi_s$$

- 2006: best limits on CPV in like-sign dileptons determined at the next generation hadron collider
  - Input from next generation ϒ(4S) experiments allows extraction of CPV parameters in B_s mixing

$$A_{SL} = A_{SL}(B_d) + \frac{f_s Z_s}{f_d Z_d} A_{SL}(B_s)$$

Exclusive $B_s \rightarrow D_s^{\pm} \mu \nu$ Results

Exclusive $D_s \mu$



$$A_{SL}(B_s, D_s\mu) =$$
$$0.0245 \pm 0.0193 \pm 0.0035$$

hep-ex/0701007 submitted to PRL

Combined:

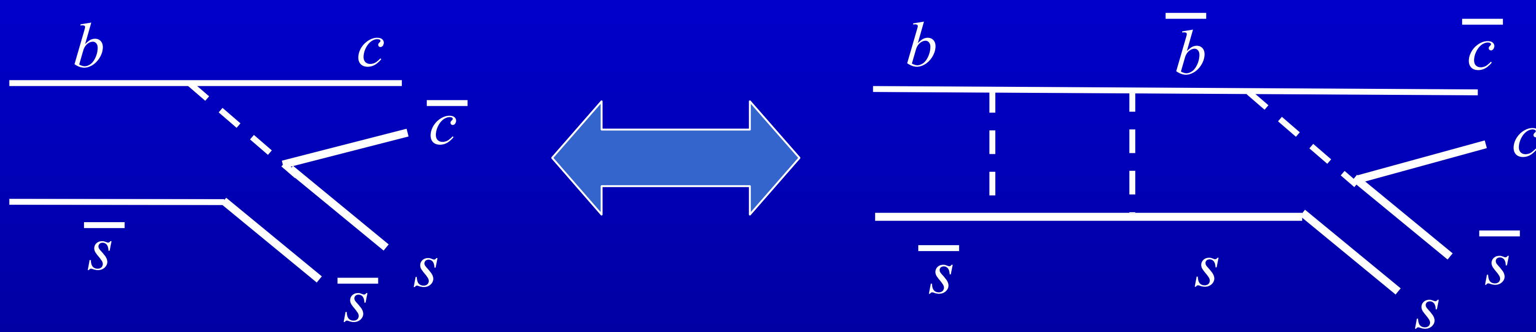
$$A_{SL}(B_s, \mu\mu + D_s\mu) =$$
$$0.0001 \pm 0.0090$$

Using Δm_s from CDF:

$$\Delta\Gamma_s \cdot \tan\phi_s = 0.02 \pm 0.16\, ps^{-1}$$

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

Analog to $B^0 \rightarrow J/\psi\, K_S$ but VV instead of VP



$J/\psi\ +\ \phi$	$J/\psi\ +\ \phi$
Even waves	Odd waves

$B_s \to J/\psi\ \phi$

Time dependent angular analysis of untagged sample

Time evolution: pure even case

$$\Gamma(t) \approx \left| A_{even}(\theta, \psi, \varphi, t) \right|^2$$

$$f(t, even) \approx e^{-\Gamma_L t}$$

$B_s \to J/\psi\ \phi$

Time dependent angular analysis of untagged sample

Time evolution: even plus odd components

$$\Gamma(t) \approx \left|A_{even}(\theta,\psi,\varphi,t)\right|^2 + \left|A_{odd}(\theta,\psi,\varphi,t)\right|^2$$

$$+ A^* A(CPC)$$

CP conserving interference

$$f(t,even) \approx e^{-\Gamma_L t}$$

$$f(t,odd) \approx e^{-\Gamma_H t}$$

CP states = heavy, light states

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

Time dependent angular analysis of untagged sample

Time evolution: even plus odd plus CPV

$$\Gamma(t) \approx \left|A_{even}(\theta,\psi,\varphi,t)\right|^2 + \left|A_{odd}(\theta,\psi,\varphi,t)\right|^2$$

$$+ A^* A(CPC)$$

CP conserving interference

$$+ A^* A(CPV)(e^{-\Gamma_L t} - e^{-\Gamma_H t})\sin\phi_s$$

CP violating interference between two paths

$$f(t,even) \approx (1+\cos\phi_s)e^{-\Gamma_L t} + (1-\cos\phi_s)e^{-\Gamma_H t}$$

$$f(t,odd) \approx (1+\cos\phi_s)e^{-\Gamma_H t} + (1-\cos\phi_s)e^{-\Gamma_L t}$$

Heavy and light states are mixed CP

$B_s \to J/\psi\ \phi$

Time dependent angular analysis of untagged sample

Time evolution: even plus odd plus CPV

$$\Gamma(t) \approx \left|A_{even}(\theta,\psi,\varphi,t)\right|^2 + \left|A_{odd}(\theta,\psi,\varphi,t)\right|^2$$

$$+ A^* A(CPC)$$

CP conserving interference

$$+ A^* A(CPV)(e^{-\Gamma_L t} - e^{-\Gamma_H t}) \sin\phi_s$$

CP violating interference between two paths

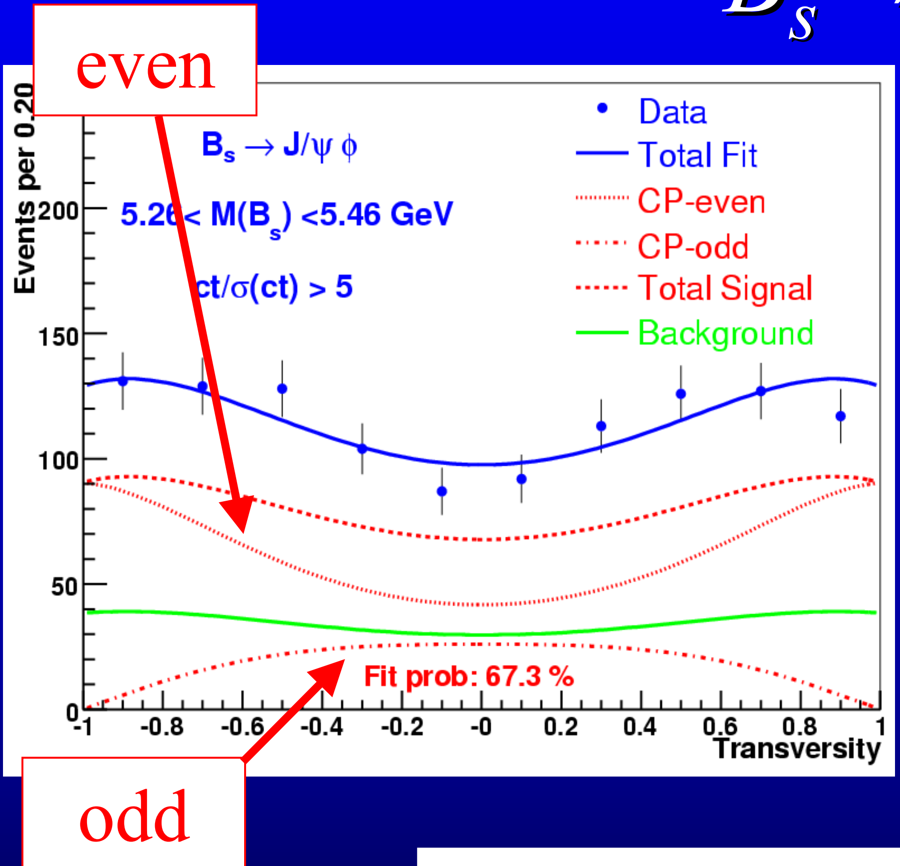
$$f(t,even) \approx (1+\cos\phi_s)e^{-\Gamma_L t} + (1-\cos\phi_s)e^{-\Gamma_H t}$$

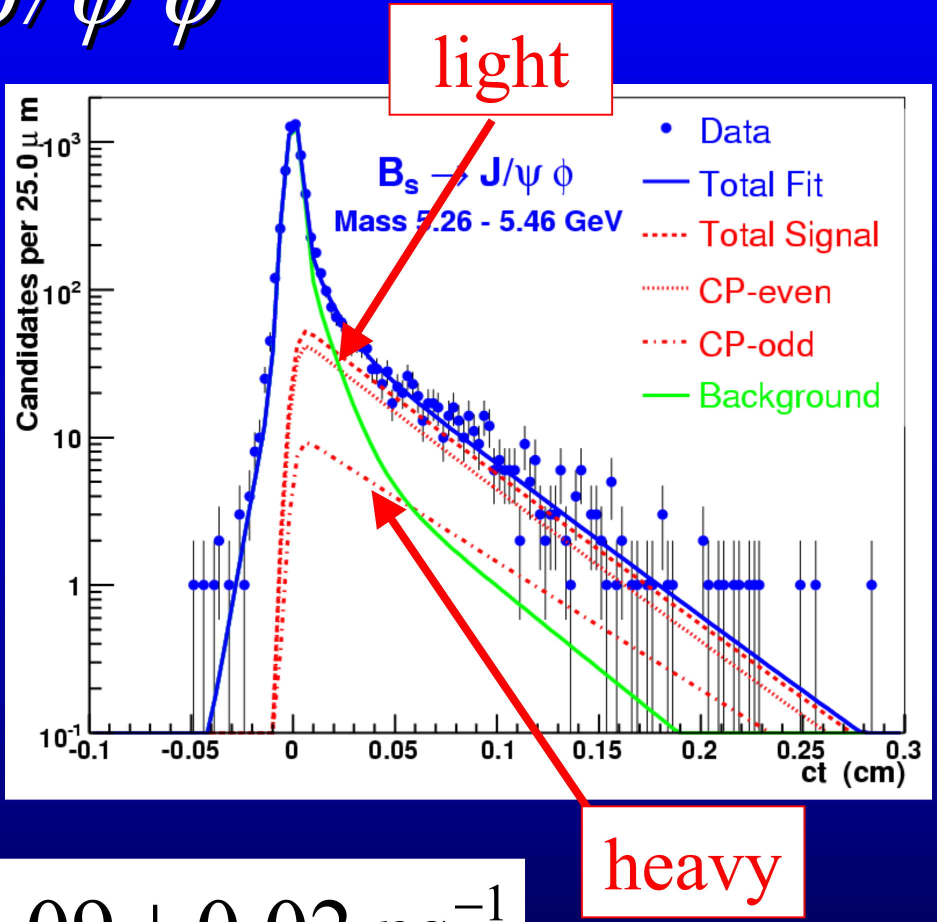
$$f(t,odd) \approx (1+\cos\phi_s)e^{-\Gamma_H t} + (1-\cos\phi_s)e^{-\Gamma_L t}$$

Heavy and light states are mixed CP

Same as seeing $K_L \to \pi^+\pi^-$

$B_s \to J/\psi\ \phi$



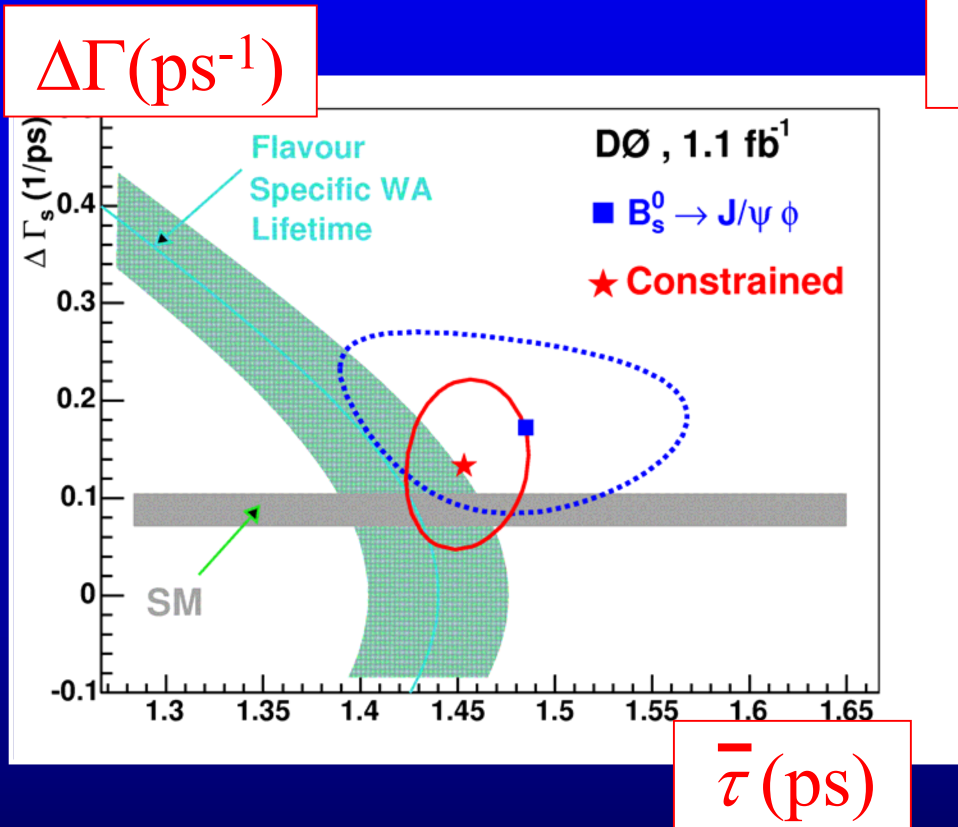


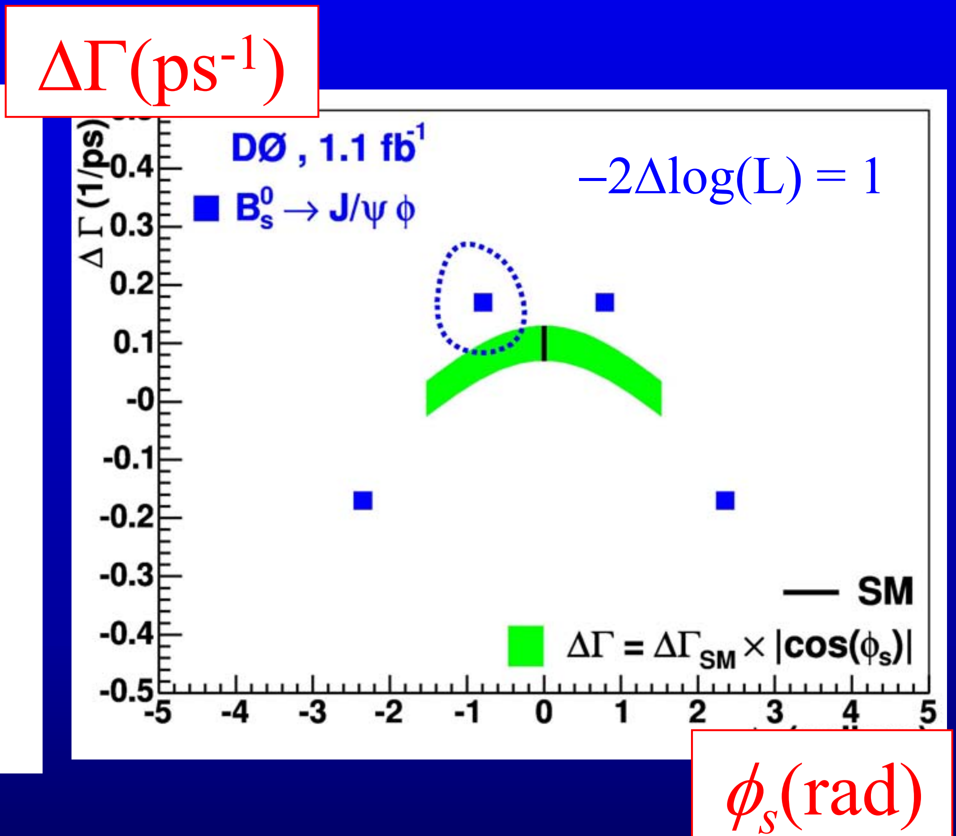
$$\Delta\Gamma_s = 0.17 \pm 0.09 \pm 0.02\, ps^{-1}$$

$$\phi_s = -0.79 \pm 0.56^{+0.14}_{-0.01}$$

hep-ex/0701012 submitted to PRL

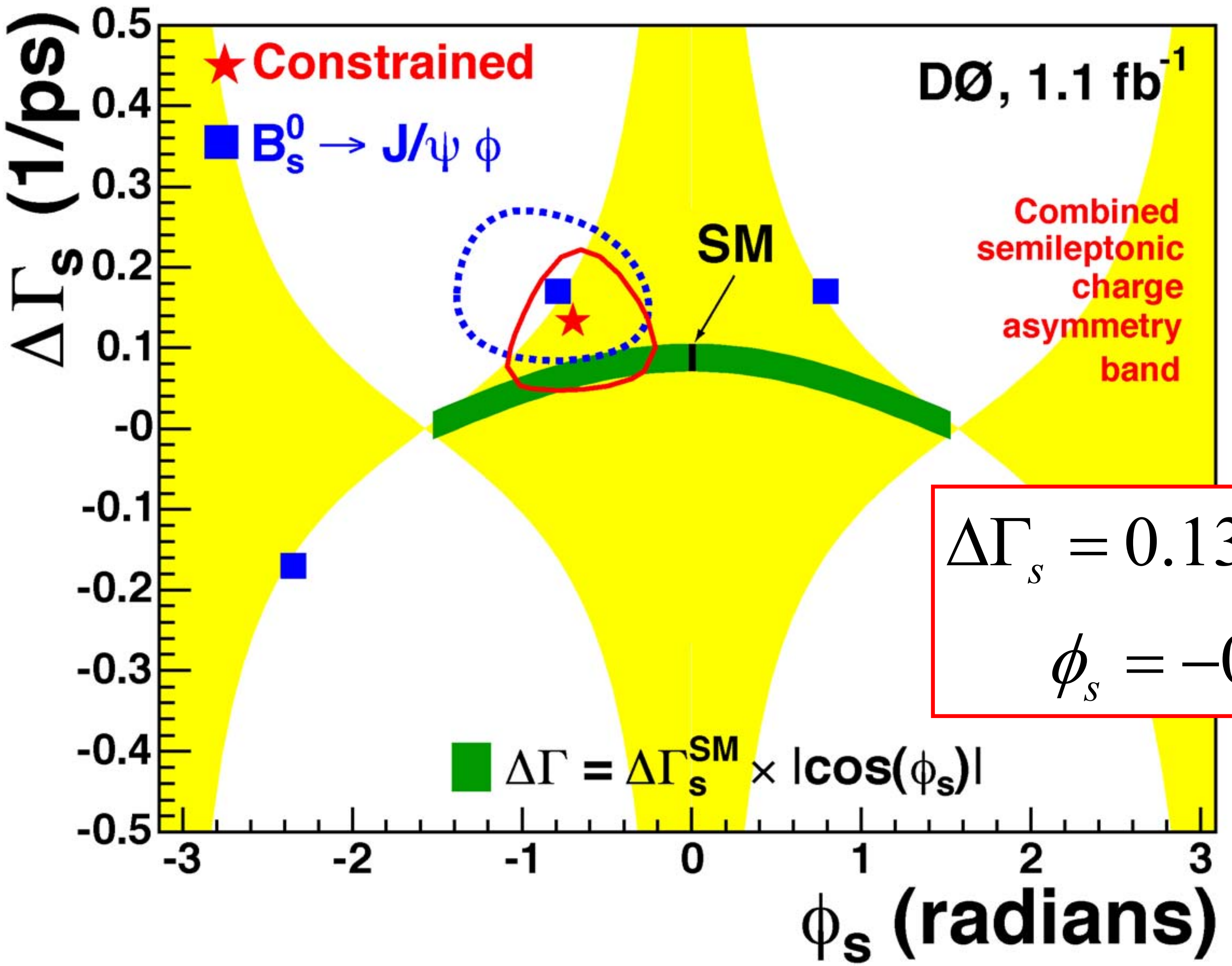
$B_s \rightarrow J/\psi\ \phi$ Results





Likelihood invariant to simultaneous flip of sign of ΔΓ and even-odd strong phase difference ⇒ 4-fold ambiguity

ϕ_s Results



$$\Delta\Gamma_s = 0.13 \pm 0.09\, ps^{-1}$$

$$\phi_s = -0.70^{+0.47}_{-0.39}$$

Outlook

- Right now: Pioneering measurements of CPV parameters in B_s mixing
  - Agreement with SM expectations at 1.2 sigma
- With more luminosity, we will clearly be able to probe for large new physics effects $\Rightarrow$ very interesting
- Goal: beat √Lum
  - $J/\psi\ \phi$: still use full sample but include initial flavor information in likelihood for tagged events
  - Like-sign $\mu\mu \Rightarrow$ like-sign $\mu\mu\phi$: enhance Bs component, reduce systematics
- If something is there, we want to find it before the LHC
- But need LHCb to reach SM level

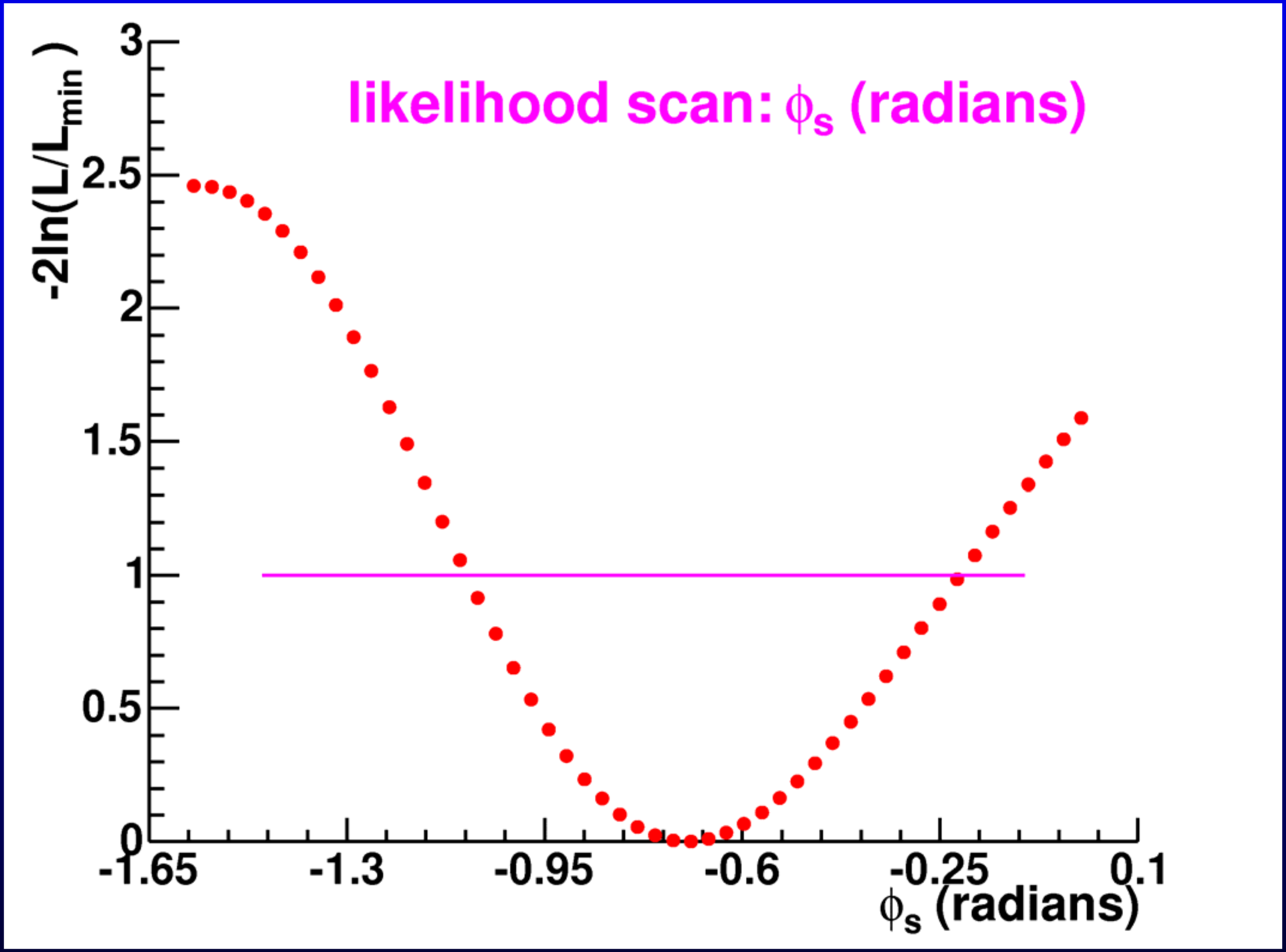
Conclusions

- Now have information on all B_s mixing parameters from the DØ.
  - Very diverse program giving consistent results:
    - Δm_s consistent with SM/CKM expectations
    - $\Delta\Gamma$ consistent with SM calculations
    - Interesting ϕ_s parameter space accessible at the Tevatron

- Expect rapid improvements in precision on ϕ_s
  - Doubling data set
  - Results from both experiments based on full data set
  - New modes and new techniques

Backup Slides

Likelihood Scan



Angular Distribution

Decay amplitude

$$\frac{d^3\Gamma(t)}{dt\, d\cos\theta\, d\varphi\, d\cos\psi} \propto$$

$$2|A_0(0)|^2\, \mathcal{T}_+\, \cos^2\psi(1-\sin^2\theta\cos^2\varphi)$$

$$+\ |A_\parallel(0)|^2\, \mathcal{T}_+\, \sin^2\psi(1-\sin^2\theta\sin^2\varphi)$$

$$+\ |A_\perp(0)|^2\, \mathcal{T}_-\, \sin^2\psi\sin^2\theta$$

$$+\ \frac{1}{\sqrt{2}}|A_0(0)||A_\parallel(0)|\cos(\delta_2-\delta_1)\, \mathcal{T}_+\, \sin 2\psi\sin^2\theta\sin 2\varphi$$

$$+\ \left\{\frac{1}{\sqrt{2}}|A_0(0)||A_\perp(0)|\cos\delta_2\, \sin 2\psi\sin 2\theta\cos\varphi\right.$$

$$\left.-|A_\parallel(0)||A_\perp(0)|\cos\delta_1\, \sin^2\psi\sin 2\theta\sin\varphi\right\}\frac{1}{2}\left(e^{-\Gamma_H t}-e^{-\Gamma_L t}\right)\sin(\delta\phi)$$

$$\mathcal{T}_+ = \tfrac{1}{2}\left\{(1+cos\delta\phi)e^{-\Gamma_L t} + (1-cos\delta\phi)e^{-\Gamma_H t}\right\}$$

$$\mathcal{T}_- = \tfrac{1}{2}\left\{(1-cos\delta\phi)e^{-\Gamma_L t} + (1+cos\delta\phi)e^{-\Gamma_H t}\right\}$$

- ✓ $\delta\phi$ → **CP-violating weak phase ; in SM ~ 0.004**
- ✓ $\delta_1\ \delta_2$ → **CP-conserving strong phase ; ~ |π| and 0**
- ✓ $A_0(0)$, $A_{||}(0)$ → **CP-even linear polarization amplitude at t=0**
- ✓ $A_\perp(0)$ → **CP-odd linear polarization amplitude at t=0**

Correlations

- Statistical: < 1%
- Systematic:
  - Usually 1 dominant systematic
  - Different for all analysis
    - Kaon decay in flight for $\mu\mu$
    - m($\phi\pi$) fitting for $D_s\mu$
- All combinations done assuming no correlations
  - No change when correlations included

Ambiguities

$$\frac{d^3\Gamma(t)}{d\cos\theta\ d\varphi\ d\cos\psi} \propto 2|A_0(0)|^2\,\mathcal{T}_+\ \cos^2\psi(1-\sin^2\theta\cos^2\varphi)+\sin^2\psi\{|A_\parallel(0)|^2\,\mathcal{T}_+\ (1-\sin^2\theta\sin^2\varphi)+|A_\perp(0)|^2\,\mathcal{T}_-\ \sin^2\theta\}$$

$$+\frac{1}{\sqrt{2}}\sin 2\psi|A_0(0)||A_\parallel(0)|\cos(\delta_2-\delta_1)\ \mathcal{T}_+\ \sin^2\theta\sin 2\varphi$$

$$+\left\{\frac{1}{\sqrt{2}}|A_0(0)||A_\perp(0)|\cos\delta_2\sin 2\psi\sin 2\theta\cos\varphi\right.$$

$$\left.-|A_\parallel(0)||A_\perp(0)|\cos\delta_1\sin^2\psi\sin 2\theta\sin\varphi\right\}\frac{1}{2}\left(e^{-\Gamma_H t}-e^{-\Gamma_L t}\right)\sin\phi_s\ . \qquad (2)$$

$$\mathcal{T}_{+/-}=\tfrac{1}{2}\left((1\pm\cos\phi_s)e^{-\Gamma_L t}+(1\mp\cos\phi_s)e^{-\Gamma_H t}\right)$$

$\Delta\Gamma$	$\cos\delta_1$	$\cos\delta_2$	ϕ_s
> 0	< 0	>0	-0.79
< 0	< 0	>0	2.35
>0	>0	< 0	0.79
< 0	>0	< 0	-2.35

Systematic Errors: dimuons

TABLE VI: Systematic uncertainties of the dimuon charge asymmetry A for standard cuts.

Source of error	ΔA
detector	0.00015
$e = \epsilon^+/\epsilon^-$	0.00018
prompt $\mu + K^\pm$ decay	0.00083
dimuon cosmic rays	0.00010
prompt μ + cosmic μ	0.00001
wrong charge sign	0.00018
punch-through	0.00001
Total	0.00089

TABLE VII: Systematic uncertainties of f.

Source of error	Δf
P_2	0.084
P_7	0.002
P_8'	0.056
χ_{d0}	0.012
f_d	0.014
χ_{s0}	0.0002
f_s	0.019
ρ'	0.008
P_{13}	0.0007
Total	0.105

Systematic Errors: $J/\psi\ \phi$

Observable	CP conserved	free ϕ_s
$\Delta\Gamma$ (ps^{-1})	$0.12^{+0.08}_{-0.10}$	$0.17^{+0.09}_{-0.09}$
$\frac{1}{\bar{\Gamma}} = \bar{\tau}$ (ps)	$1.52^{+0.08}_{-0.08}$	1.49 ± 0.08
ϕ_s	$\equiv 0$	-0.79 ± 0.56
$\lvert A_0(0)\rvert^2 - \lvert A_\parallel(0)\rvert^2$	0.38 ± 0.05	0.37 ± 0.06
$A_\perp(0)$	0.45 ± 0.05	0.46 ± 0.06
$\delta_1 - \delta_2$	2.6 ± 0.4	2.6 ± 0.4
δ_1	–	3.3 ± 1.0
δ_2	–	0.7 ± 1.1

TABLE II: Sources of systematic uncertainty in the results of the analysis of the decay $B_s^0 \to J/\psi\phi$.

Source	$c\tau(B_s^0)$ μm	$\Delta\Gamma$ ps^{-1}	$R_\perp$	ϕ_s
Procedure test	±2.0	±0.02	±0.01	–
Acceptance	±0.5	±0.001	±0.003	±0.01
Reco. algorithm	$-8.0,+1.3$	$+0.001$	±0.01	-0.01
Background model	$+1.0$	$+0.01$	-0.01	$+0.14$
Alignment	±2.0	–	–	–
Total	$-8.8, +3.3$	±0.02	±0.02	$-0.01, +0.14$