Lepton Asymmetry in B_s & B_d Decays

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FPCP 2009

Outline

- Mixing and Asymmetry in B_s & B_d
- Measurement Strategies
  - Dimuon Asymmetry
  - Untagged, time-integrated Asymmetry
  - Tagged, time-dependent Asymmetry
- Recent Results

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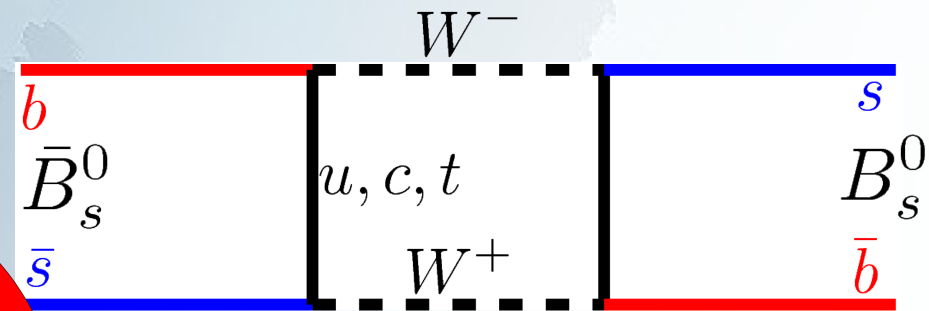
CP Violation in Mixing



Schrodinger Equation:

$$i\frac{d}{dt}\begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix} = \left(M - i\frac{\Gamma}{2}\right)\begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix}$$

Mass Eigenstates:

$$|B_L\rangle = p|B\rangle + q|\bar{B}\rangle$$
$$|B_H\rangle = p|B\rangle - q|\bar{B}\rangle$$

Solve the Schrodinger Equation to determine the time evolution of the B meson.

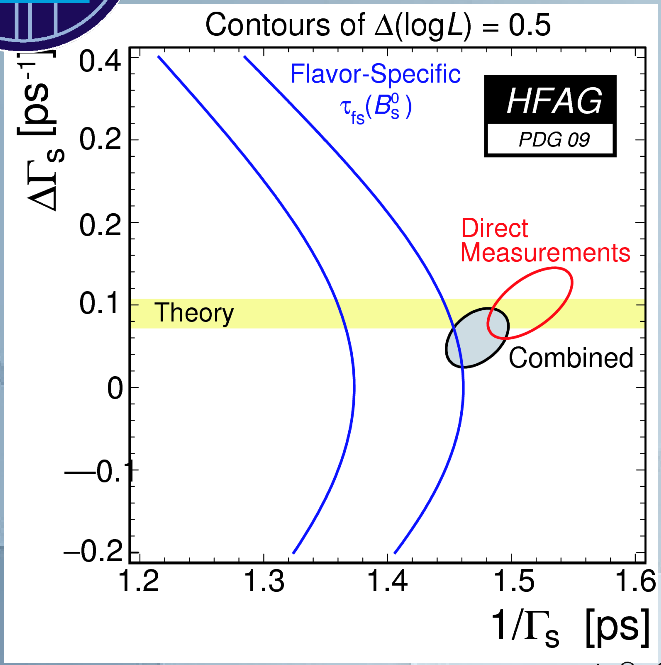
Solutions:

$$|B(t)\rangle = g_+(t)|B\rangle + \frac{q}{p}g_-(t)|\bar{B}\rangle$$
$$|\bar{B}(t)\rangle = \frac{p}{q}g_-(t)|B\rangle + g_+(t)|\bar{B}\rangle$$

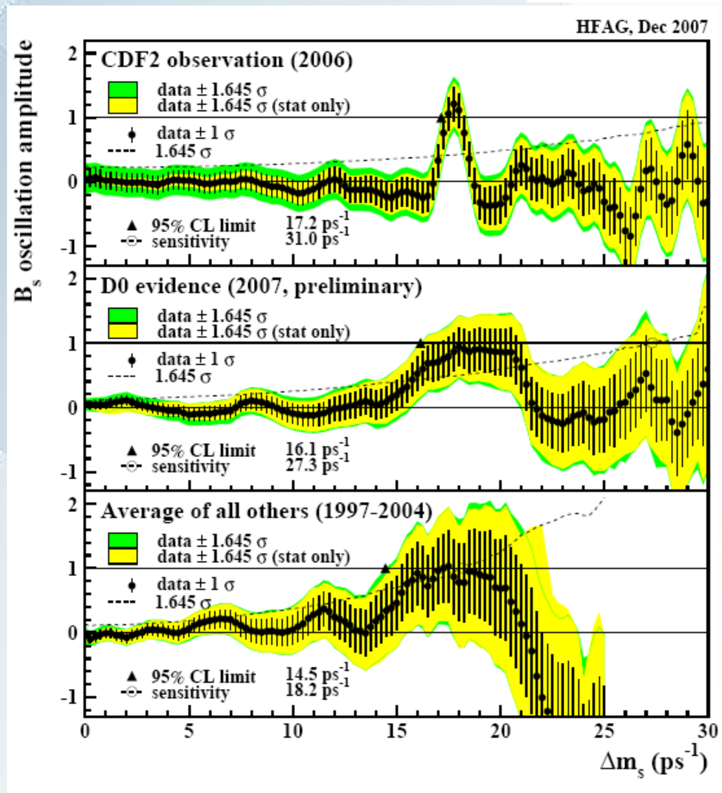
Find the probability of B decaying as B (nomix) or Bbar (mix)

$$P_{Mix}(t) \sim \cosh(\Delta\Gamma_s t/2) - \cos(\Delta m_s t)$$
$$P_{NoMix}(t) \sim \cosh(\Delta\Gamma_s t/2) + \cos(\Delta m_s t)$$

CP Violation in Mixing



HFAG
Apr 09



$$\Delta\Gamma_s \approx 2|\Gamma_{12}|\cos\phi_s = 0.062^{+0.034}_{-0.037}\ \mathrm{ps}^{-1}(*)$$

$$|B(t)\rangle = g_+(t)|B\rangle + \frac{q}{p}g_-(t)|\bar{B}\rangle$$
$$|\bar{B}(t)\rangle = \frac{p}{q}g_-(t)|B\rangle + g_+(t)|\bar{B}\rangle$$

$$\Delta m_s \approx 2|M_{12}| = 17.78 \pm 0.12 \quad \mathrm{ps}^{-1}$$

Mixing

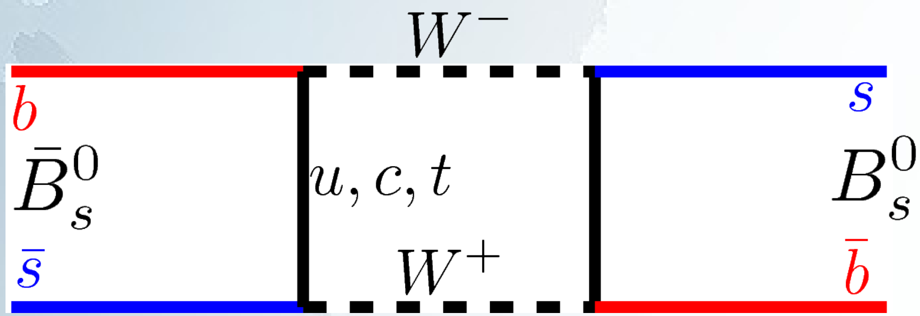
$$P_{Mix}(t) \sim \cosh(\Delta\Gamma_s t/2) \boxed{-\cos(\Delta m_s t)}$$
$$P_{NoMix}(t) \sim \cosh(\Delta\Gamma_s t/2) \boxed{+\cos(\Delta m_s t)}$$

*Assuming no CP violation

CP Violation in Mixing

Schrodinger Equation:

$$i\frac{d}{dt}\begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix} = \left(M - i\frac{\Gamma}{2}\right)\begin{pmatrix} |B(t)\rangle \\ |\bar{B}(t)\rangle \end{pmatrix}$$



Mass Eigenstates:

$$|B_L\rangle = p|B\rangle + q|\bar{B}\rangle$$
$$|B_H\rangle = p|B\rangle - q|\bar{B}\rangle$$

Different dependence on p/q gives a difference in the decay rates for B and Bbar mixed decays.

Solutions:

$$|B(t)\rangle = g_+(t)|B\rangle + \frac{q}{p}g_-(t)|\bar{B}\rangle$$
$$|\bar{B}(t)\rangle = \frac{p}{q}g_-(t)|B\rangle + g_+(t)|\bar{B}\rangle$$

$$P(B \to \bar{B}) \sim |q/p|^2$$
$$P(\bar{B} \to B) \sim |p/q|^2$$
$$\text{If } |q/p|^2 \neq 1 \text{ CP Violation}$$

unmixed terms are independent of p/q

$$P_{Mix}(t) \sim \cosh(\Delta\Gamma_s t/2) - \cos(\Delta m_s t)$$
$$P_{NoMix}(t) \sim \cosh(\Delta\Gamma_s t/2) + \cos(\Delta m_s t)$$

CP Asymmetry

Define an asymmetry in mixed decay rates: $B \to \bar{B} \to \mu^+ X$ $\bar{B} \to B \to \mu^- \bar{X}$

$$A_{sl}(t) = \frac{\Gamma^{\mu^+}_{Mix}(t) - \Gamma^{\mu^-}_{Mix}(t)}{\Gamma^{\mu^+}_{Mix}(t) + \Gamma^{\mu^-}_{Mix}(t)} = \frac{N^+_{Mix} - N^-_{Mix}}{N^+_{Mix} + N^-_{Mix}} = A_{sl} \ \text{(Constant)}$$

Time Integral
= Counting Experiment

Only works if you can isolate the mixed decays
Otherwise average mixed/unmixed decay rates:

$$A^{unt}_{sl}(t) = \frac{\Gamma^{\mu^+}(t) - \Gamma^{\mu^-}(t)}{\Gamma^{\mu^+}(t) + \Gamma^{\mu^-}(t)} = \frac{A_{sl}}{2}\left(1 - \frac{\cos(\Delta m_s t)}{\cosh(\Delta\Gamma_s t/2)}\right)$$

No longer time-independent!

CP Violation

The weak phase (ϕ_s) is the primary CP violating parameter for B_s

$$\phi_s = \arg\left[-\frac{M_{12}}{\Gamma_{12}}\right]$$

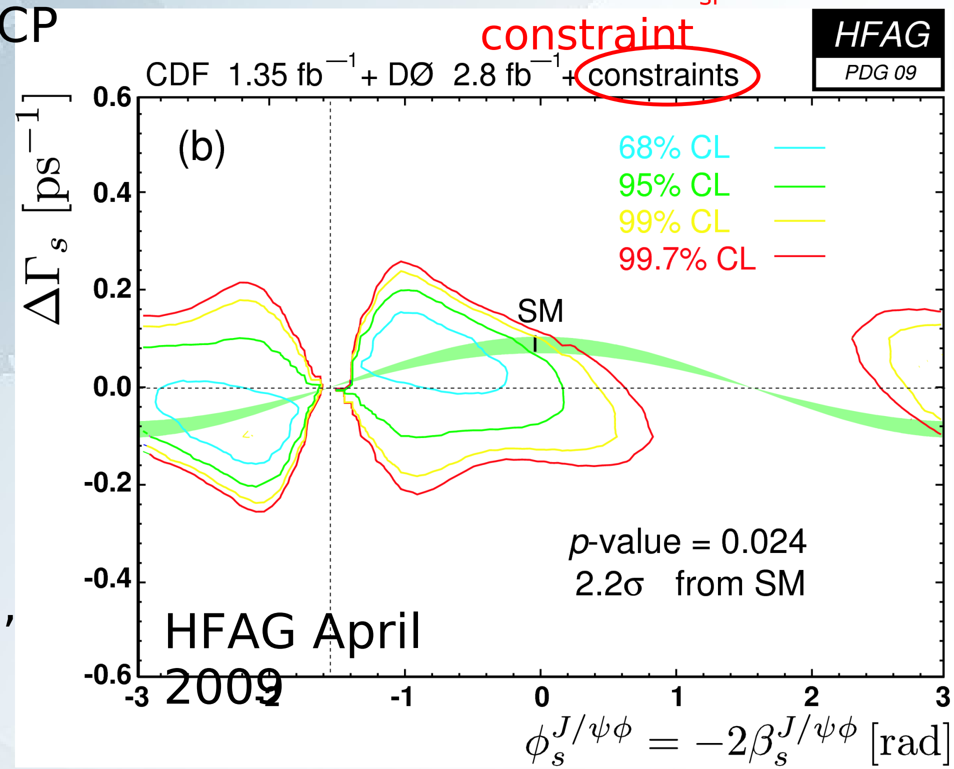
And is related to the asymmetry.

$$A_{sl}^s = \frac{\Delta\Gamma_s}{\Delta m_s}\tan\phi_s$$

SM predicts A_{sl}^s to be small ~$2\mathrm{x}10^{-5}$,

The currently favored ϕ_s gives a significantly larger asymmetry ~0.01

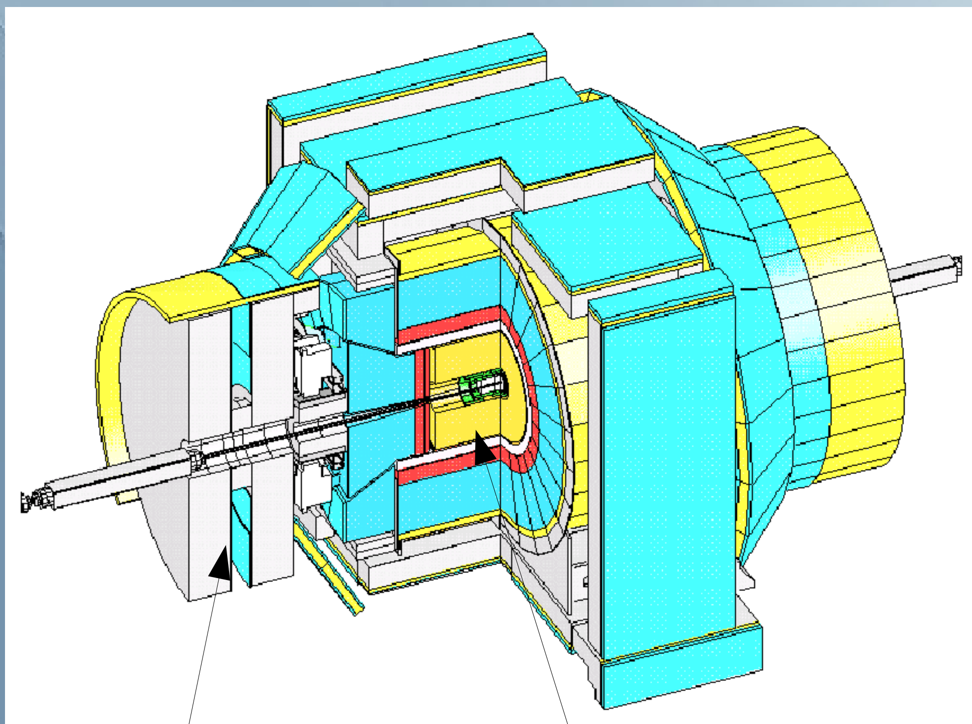
Includes A_{sl} constraint

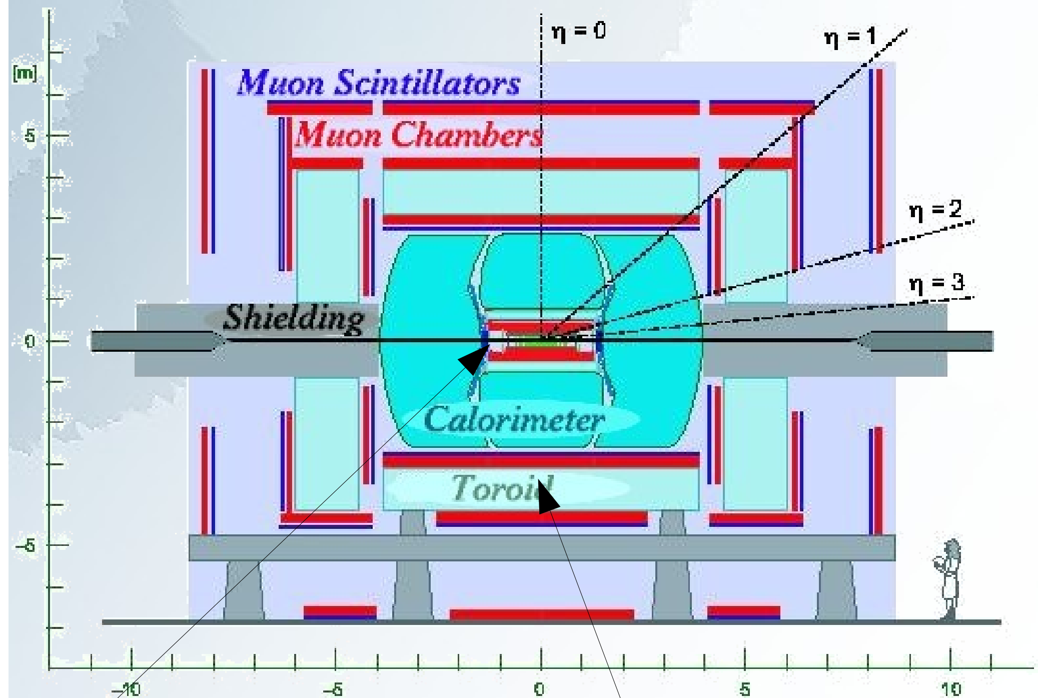


HFAG April 2009

Measuring A_{sl}^s provides a constraint on ϕ_s

Detectors





Full coverage of Toroid for Muon system up to η=2

Forward Muon Spectrometer

Tracking:

- D0 – Fiber Tracker & Silicon
- CDF – Wire Chamber & Silicon

Analysis Strategies - Overview

Three Strategies:

Old

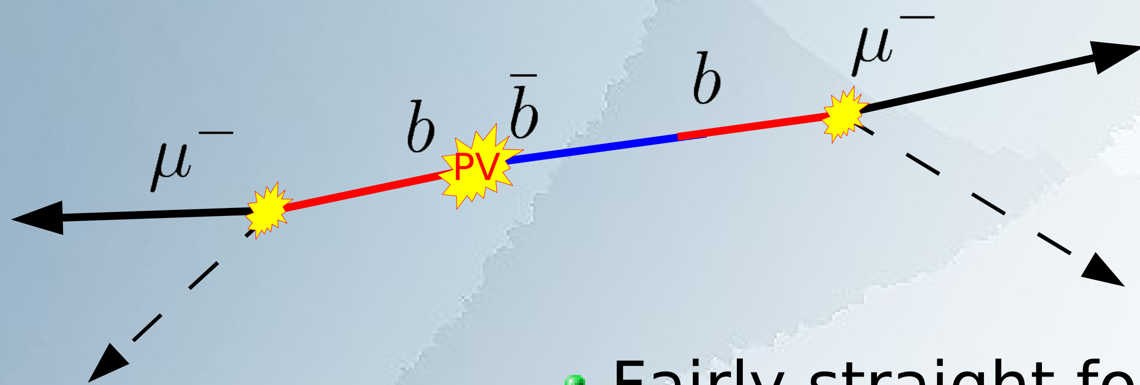
- Dimuon asymmetry (tagged)
  - Integrated charge asymmetry in inclusive dimuon events
  - D0 1.0fb^{-1} (2006) & CDF 1.6fb^{-1} (2007)
- Untagged, time integrated asymmetry
  - Integrated charge asymmetry in exclusive B_s decays
  - D0 1.3fb^{-1} (2007)

New

- Tagged, time dependent asymmetry
  - Time dependent charge asymmetry in exclusive B_s decays
  - D0 5.0fb^{-1} (2009)

Tagged vs. untagged – Makes use of mixing information
Time dependent vs. integrated – Counting experiment or fit to $A_{sl}^{s}(t)$

Analysis Strategy #1: Dimuon



Produce b-antib pairs, if both decay semileptonically, ++/-- indicated a mixed decay.

Measure Charge asymmetry in these events

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

Pros

- Fairly straight forward
  - No event reconstruction (inclusive)
  - No complex fitting – Counting exp.
- High confidence mixing information

Cons

- Low statistics, Br(b→μ)~10%
- No independent A_{sl}^{s}, A_{sl}^{d}

Analysis Strategy #1: Dimuon

Determine 'f' - contribution from 'fake' mixing processes & detector related asymmetries.

direct-direct	$b \to \mu^-,\ \bar{b} \to \mu^+$
direct-indirect	$b \to \mu^-,\ \bar{b} \to \bar{c} \to \mu^-$
direct-prompt	$b \to \mu^-,\ c \to \mu^+$
prompt-prompt	$c \to \mu^+,\ \bar{c} \to \mu^-$
$\mu - K^{\pm}$ decay	$K^- N \to Y\pi$
Detector Asym	

$$A^{\mu\mu} = \frac{1}{4f}\left[A^d_{sl} + \frac{f_s\langle\chi_s\rangle}{f_d\langle\chi_d\rangle}A^s_{sl}\right]$$

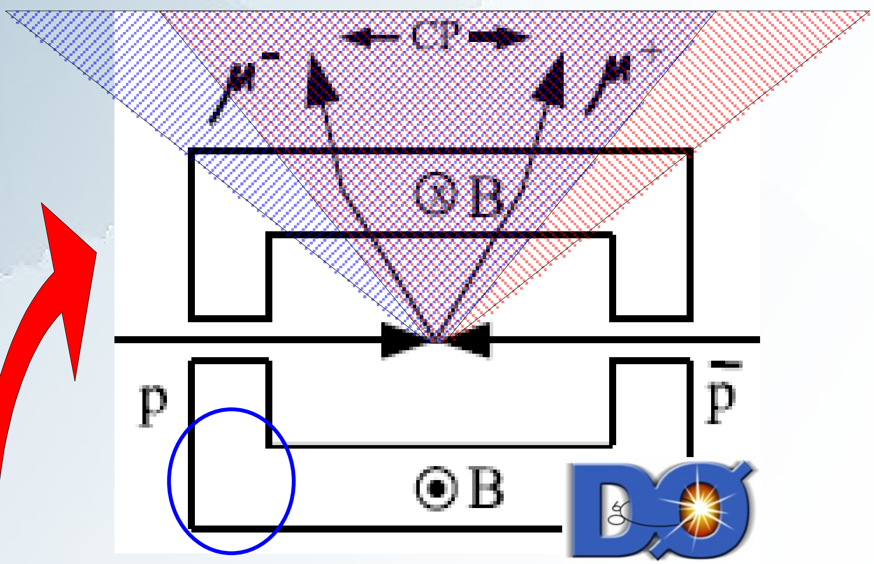
Mimics mixing

Background asymmetry

Acceptance of central muon system

μ^- acceptance

μ^+ acceptance



Low eff at corners

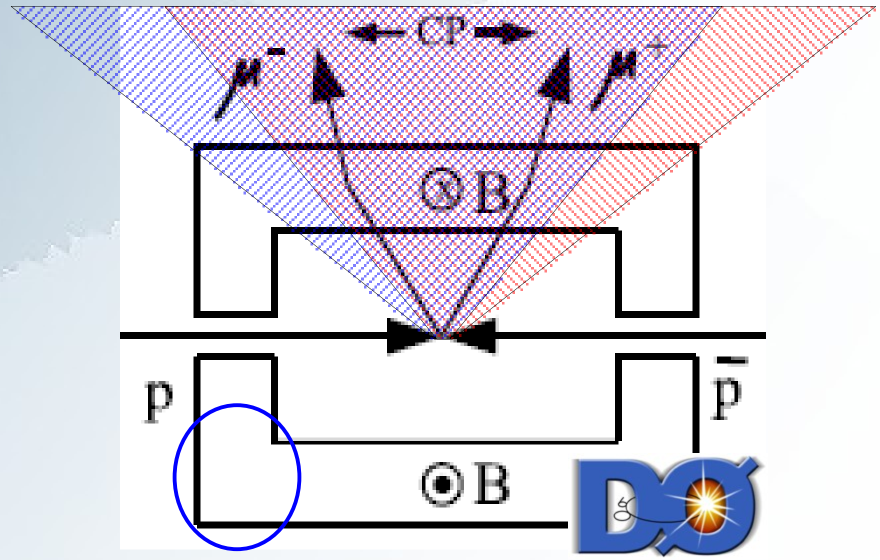
5 Detector asymmetries:

- Detector Asymmetry
- Forward-Backward Asymmetry
- Range Out Asymmetry
- Others expected to be zero

Analysis Strategy #1: Dimuon

Acceptance of central muon system

μ^- acceptance μ^+ acceptance



Low eff at corners

Average B_s^0/B_d^0 mixing probability

From B factories, LEP

Fraction of B_s^0/B_d^0 events

$$A^{\mu\mu} = \frac{1}{4f}\left[A^d_{sl} + \frac{f_s\langle\chi_s\rangle}{f_d\langle\chi_d\rangle}A^s_{sl}\right]$$

$$\text{Take} \quad A^d_{sl} = -0.0047 \pm 0.0046$$

CDF Results 1.6fb^{-1} (Public Note *)

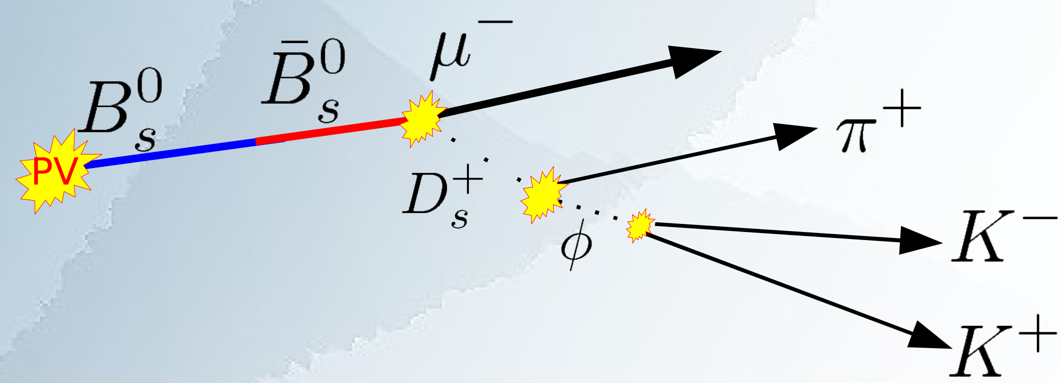
$$\begin{cases} A^{\mu\mu} = 0.0080 \pm 0.0090(\text{stat}) \pm 0.0068(\text{syst}) \\ A^s_{sl} = \boxed{0.026 \pm 0.021(\text{stat}) \pm 0.017(\text{syst})\ (\text{HFAG})} \end{cases}$$

D0 Results 1.0fb^{-1} (PRD 74 092001)

$$\begin{cases} A^{\mu\mu} = -0.0028 \pm 0.0013(\text{stat}) \pm 0.0090(\text{syst}) \\ A^s_{sl} = \boxed{-0.006 \pm 0.006(\text{stat}) \pm 0.008(\text{syst})\ (\text{HFAG})} \end{cases}$$

* www-cdf.fnal.gov/physics/new/bottom/070816.blessed-acp-bsemil/

Analysis Strategy #2:
untagged, time-integrated



Reconstruct the B decay, discounting the opposite side b hadron (IE untagged).

½ of B_s^0 decays will be mixed, unmixed events dilute asymmetry.

$$A/2 = \frac{N^+ - N^-}{N^+ + N^-}$$

Asymmetry diluted by unmixed events

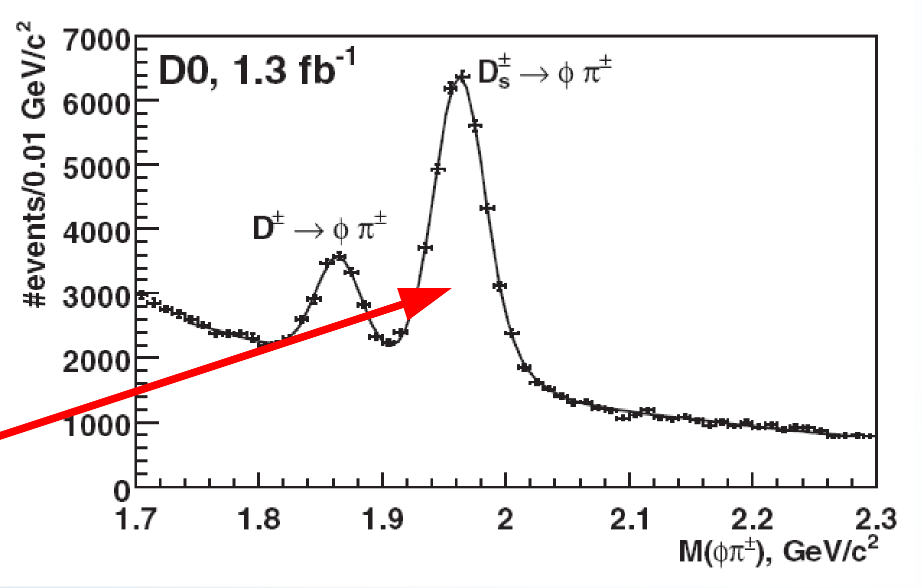
Pros
- Still a counting experiment
- Large sample
- Flavour specific (independent A_{sl}^s)

Cons
- No mixing information

“Coms”*
- Fit D_s^+ mass (sample composition)

* Coms = Complexities

Analysis Strategy #2: untagged, time-integrated



Determine N^+ / N^- from the fit to the D_s mass in +/- charged subsamples.

x4 to include detector asymmetries. 8 fits total.

$$N_{D_s}^{+/-} = \frac{N\epsilon^{\beta}}{4}(1 + qA_{physics})(1 + \ldots)$$

Solve 3 systems of 8 equations to determine the asymmetry in the D_s^+, D^+, and background.

Account for fraction of B_s^0

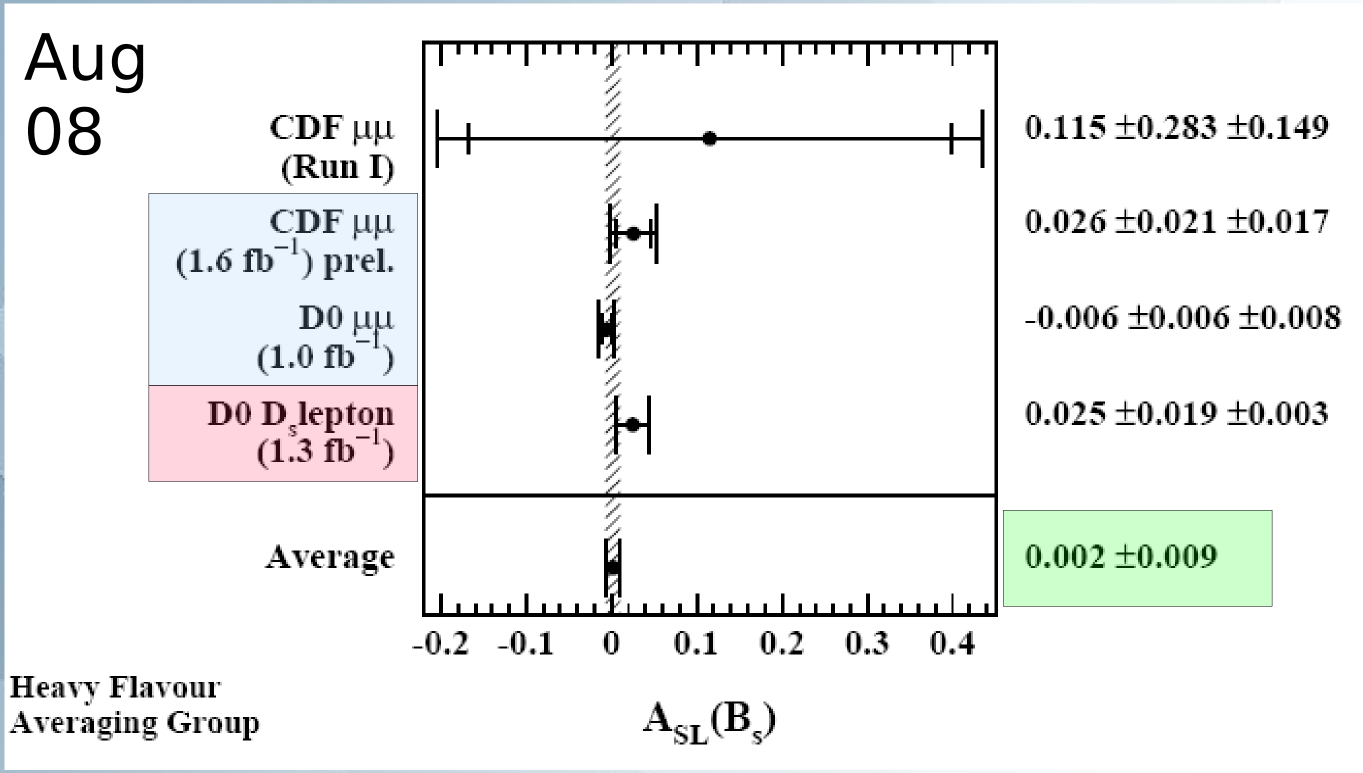
x2 for integrated

D0 Result (PRL 98 151801)

$$A_{D_s^+} = 0.0102 \pm 0.0081$$
$$A_{sl}^{s,unt} = 0.0123 \pm 0.0097(\mathrm{stat}) \pm 0.0017(\mathrm{syst})$$
$$A_{sl}^{s} = 0.0245 \pm 0.0193(\mathrm{stat}) \pm 0.0035(\mathrm{syst})$$

World Average

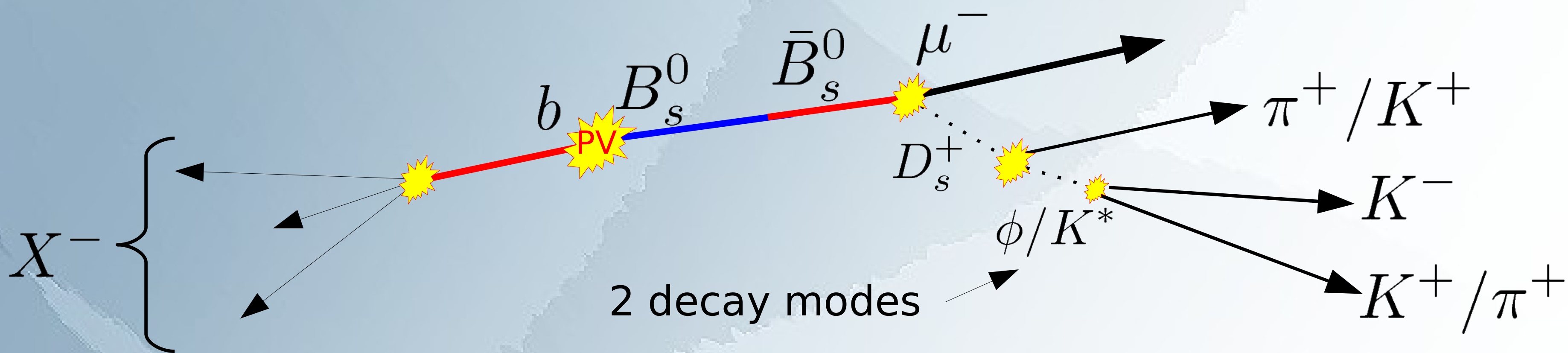
Aug 08



Apr 09 revised:

$$A_{sl}^{s} = -0.0037 \pm 0.0094 \text{ using } A_{sl}^{d} = -0.0005 \pm 0.0056$$

Analysis Strategy #3:
tagged, time-dependent



Likelihood fit allows time dependent asymmetry.

$$A_{sl}^s(t) = \frac{\Gamma^+(t) - \Gamma^-(t)}{\Gamma^+(t) + \Gamma^-(t)}$$

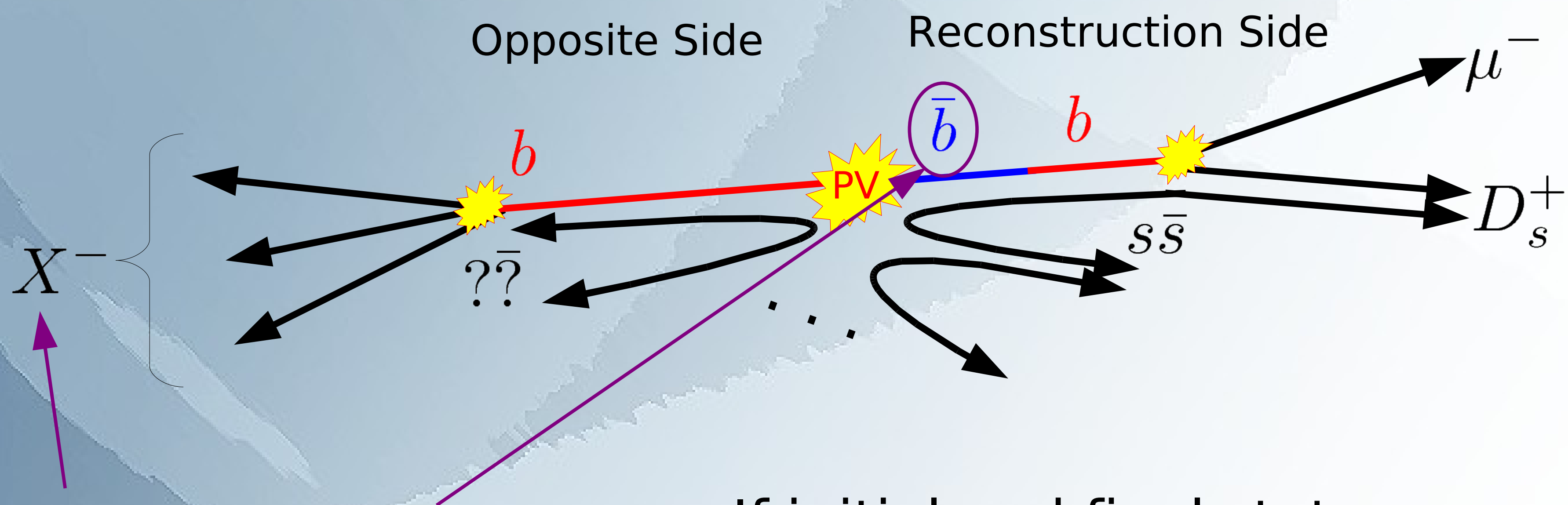
Pros

- Still large sample
- Flavour specific (independent A_{sl}^s)
- Using all available information

Coms

- Mixing info not 100% accurate
- Fit D_s^+ mass (sample composition)
- Fit B_s^0 lifetime (time evolution)
- Various other complexities

Flavour Tagging



Initial State Flavour

Decay of opposite side B hadron indicates initial flavour on Reco side.
As available, use:

- Lepton Charge
- Jet Charge
- Secondary Vertex Charge
- Event Charge

If initial and final state flavour do not agree, decay is mixed

About 20% of events are tagged, performance varies for each tagger, quantified by 'dilution' variable (D)

Log likelihood

Probability of measured parameters is determined event-by-event (i) for each channel (j).

$$P_i^j = P_i^j(\mathrm{lifetime}) \otimes P_i^j(\mathrm{resolution}) \times P_i^j(\mathrm{mass}) \times P_i^j(\mathrm{others})$$

Function of Asymmetry

Fit to data

From MC or data

Sum over all channels.

Sum ln P_i for all events.

Add Loglikelihood for two decay modes.

$$L_{\mathrm{mode}} = -2 \cdot \sum_i^{\mathrm{events}} \ln \left(\sum_j^{\mathrm{channels}} Fr^j P_i^j \right)$$

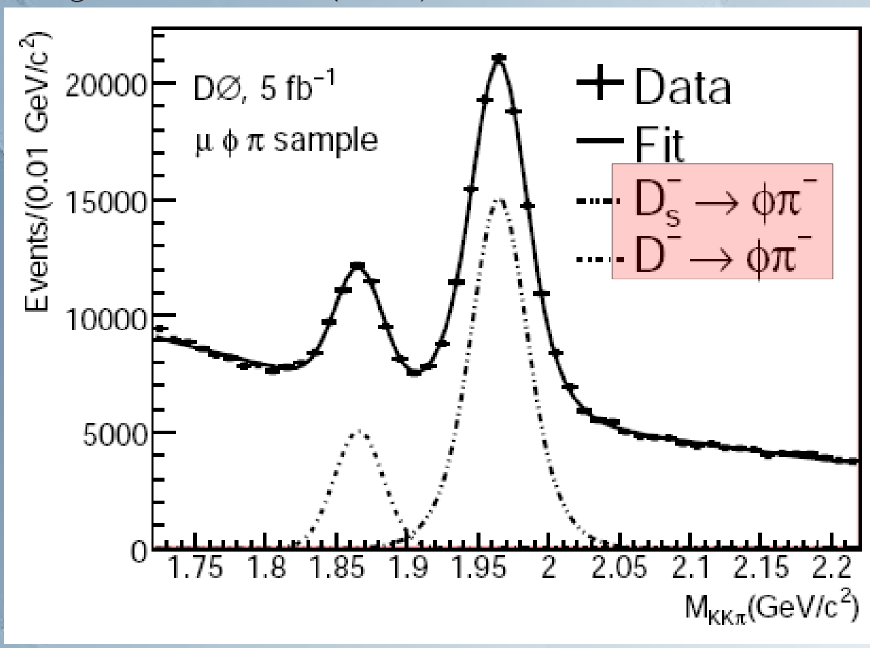
Minimize negative loglikelihood (L) by varying asymmetry parameters.

$$L = L_{K^*K} + L_{\phi\pi}$$

Mass Fit to D_s candidates

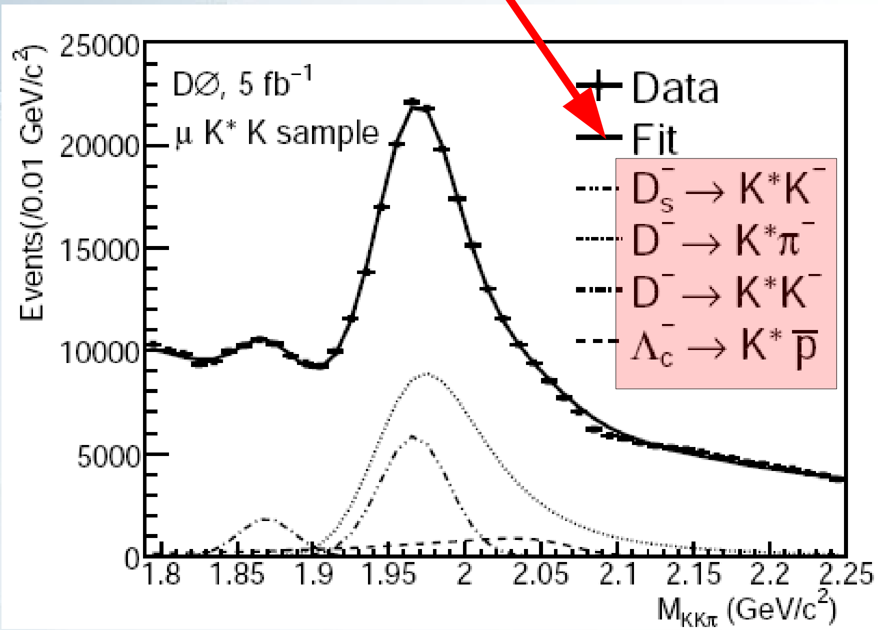
In addition to the mass pdf, the fit also determines the fractions for each channel

$B_s^0 \rightarrow \mu D_s(\phi\pi)$



$81,394 \pm 865\ D_s$ candidates

$B_s^0 \rightarrow \mu D_s(K^* K)$



$33,557 \pm 1200\ D_s$ candidates

~ 830k events total

Lifetime Function

Truth unmixed decay rate:

$$\Gamma(B_s \to \mu^+ X) \propto exp\left(-\Gamma t\right)\left[\cosh\left(\Delta\Gamma_s t/2\right) + \cos\left(\Delta m_s t\right)\right]$$
$$\Gamma(\bar{B}_s \to \mu^- X) \propto exp\left(-\Gamma t\right)\left[\cosh\left(\Delta\Gamma_s t/2\right) + \cos\left(\Delta m_s t\right)\right]$$

Truth mixed decay rate:

$$\Gamma(\bar{B}_s \to \mu^+ X) \propto \left(1 + A^s_{sl}\right) exp\left(-\Gamma t\right)\left[\cosh\left(\Delta\Gamma_s t/2\right) - \cos\left(\Delta m_s t\right)\right]$$
$$\Gamma(B_s \to \mu^- X) \propto \left(1 - A^s_{sl}\right) exp\left(-\Gamma t\right)\left[\cosh\left(\Delta\Gamma_s t/2\right) - \cos\left(\Delta m_s t\right)\right]$$

But initial state flavour is not 100% accurate:

Example

$$\Gamma^{++} = \Gamma\left(\bar{B}_s \to \mu^+\right)\frac{1+D}{2} + \Gamma\left(B_s \to \mu^+\right)\frac{1-D}{2}$$

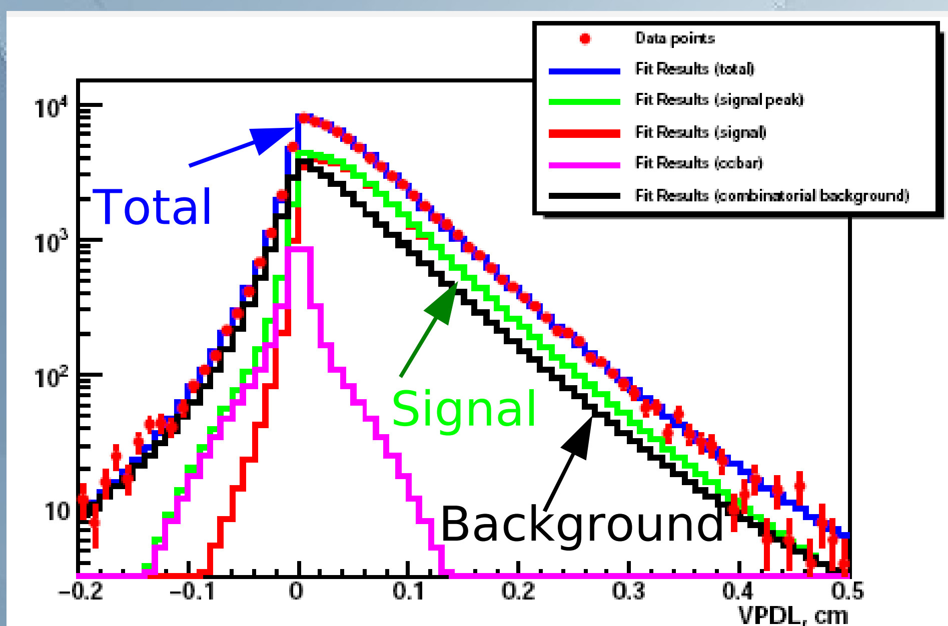
initial and final state tags

Weight the mixed/unmixed decay rate functions according to dilution

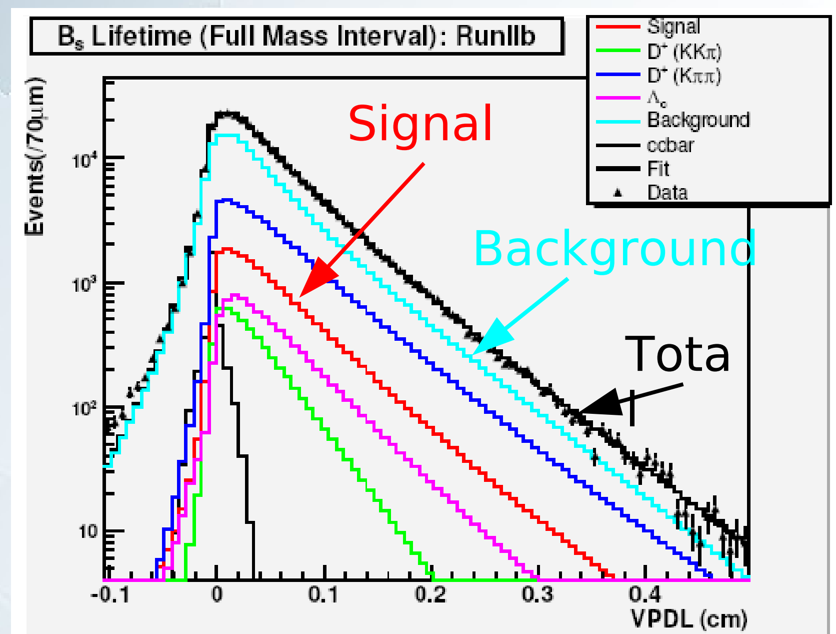
Lifetime Fit

Determine contributions to the background and $B_s{}^0$ lifetime

$$B_s^0 \to \mu D_s(\phi\pi)$$



$$B_s^0 \to \mu D_s(K^*K)$$



Detector Asymmetries

- Three non-CP conserving variables, μ charge (q), μ sign of the pseudorapidity (γ), sign of the toroid polarity (β).
- Seven possible asymmetries
  - A_q: Charge asymmetry, IE A_{sl}
  - A_β: Toroid asymmetry, determined from data (fixed)
  - A_γ: North/South Detector asymmetry (A_{det})
  - $A_{q\gamma}$: Beam related, forward-backward asymmetry (A_{fb})
  - $A_{q\beta}$: Possible efficiency changes related to toroid
  - $A_{\beta\gamma}$: Possible forward-backward asymmetry related to toroid
  - $A_{q\beta\gamma}$: Asymmetry due to muons in toroid bending towards/away from beam axis (range out asymmetry A_{ro}) - large

Five Detector Asymmetries to be measured

Asymmetry Results

	$\mu^+\phi\pi^-$	$\mu^+K^{*0}K^-$	Combined
$a^s_{fs} \times 10^3$	-7.0 ± 9.9	20.3 ± 24.9	-1.7 ± 9.1
$a^d_{fs} \times 10^3$	-21.4 ± 36.3	50.1 ± 19.5	40.5 ± 16.5
$a_{bg} \times 10^3$	-2.2 ± 10.6	-0.1 ± 13.5	-3.1 ± 8.3
$A_{\rm fb} \times 10^3$	-1.8 ± 1.5	-2.0 ± 1.5	-1.9 ± 1.1
$A_{\rm det} \times 10^3$	3.2 ± 1.5	3.1 ± 1.5	3.1 ± 1.1
$A_{\rm ro} \times 10^3$	-36.7 ± 1.5	-30.2 ± 1.5	-33.3 ± 1.1
$A_{\beta\gamma} \times 10^3$	1.1 ± 1.5	0.2 ± 1.5	0.6 ± 1.1
$A_{q\beta} \times 10^3$	4.3 ± 1.5	2.0 ± 1.5	3.1 ± 1.1

Detector Asymmetries

$$A^s_{sl} = -0.0017 \pm 0.0091(\text{stat})^{+0.0012}_{-0.0023}(\text{syst})$$

Systematic Uncertainties

- Calibration of the Opposite Side Tagger
  - 'Turn off' tagger, shift in A_{sl}^{s} = -0.0022
- Large Shift in A_{sl}^{d} (from SM), A_{sl}^{s}, A_{sl}^{d} and A_{sl}^{bg} correlated
  - Fix A_{sl}^{d}=0, shift in A_{sl}^{s}= +0.0012

Small
- Fraction of Signal/Background from mass fit
- Parameters from lifetime fit
- $\Delta\Gamma_{s}$, Δm_{s}
- Branching fractions

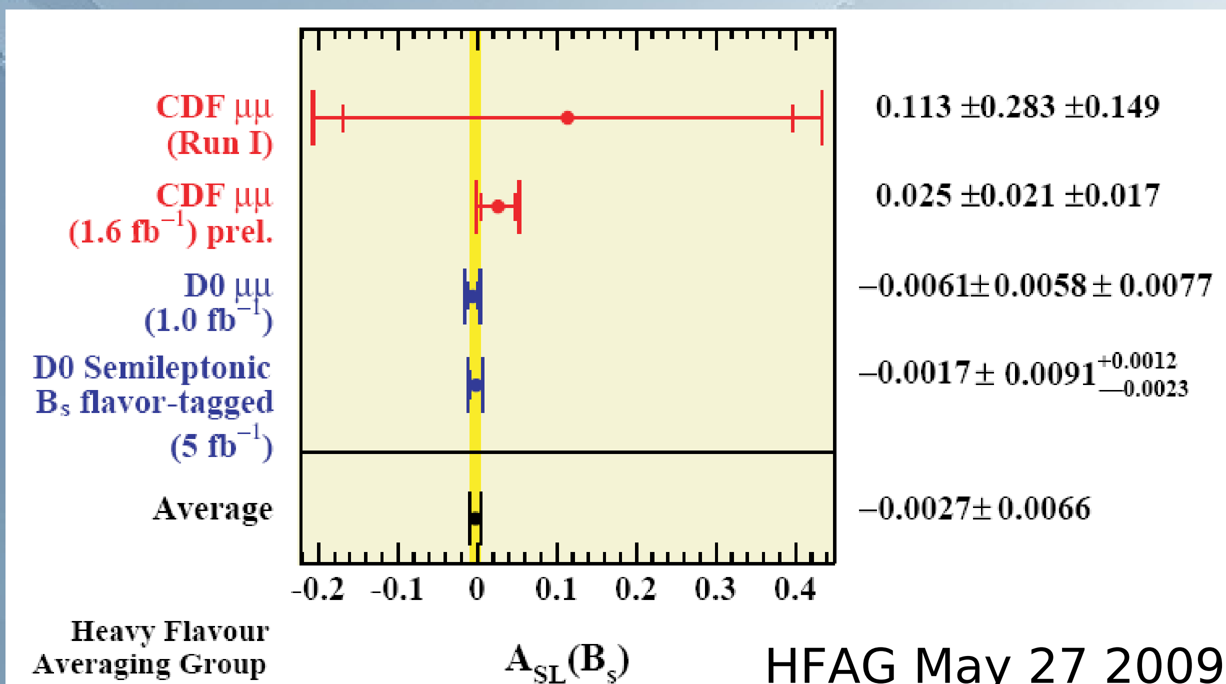
$$A_{sl}^{s} = -0.0017 \pm 0.0091(\mathrm{stat})^{+0.0012}_{-0.0023}(\mathrm{syst})$$

Conclusions

The B_s^0 semileptonic asymmetry has been measured with a $5fb^{-1}$ data sample to be:

$$-0.0017 \pm 0.0091(\text{stat})^{+0.0012}_{-0.0023}(\text{syst})$$

Submitted to PRL
arXiv: 0904.3907



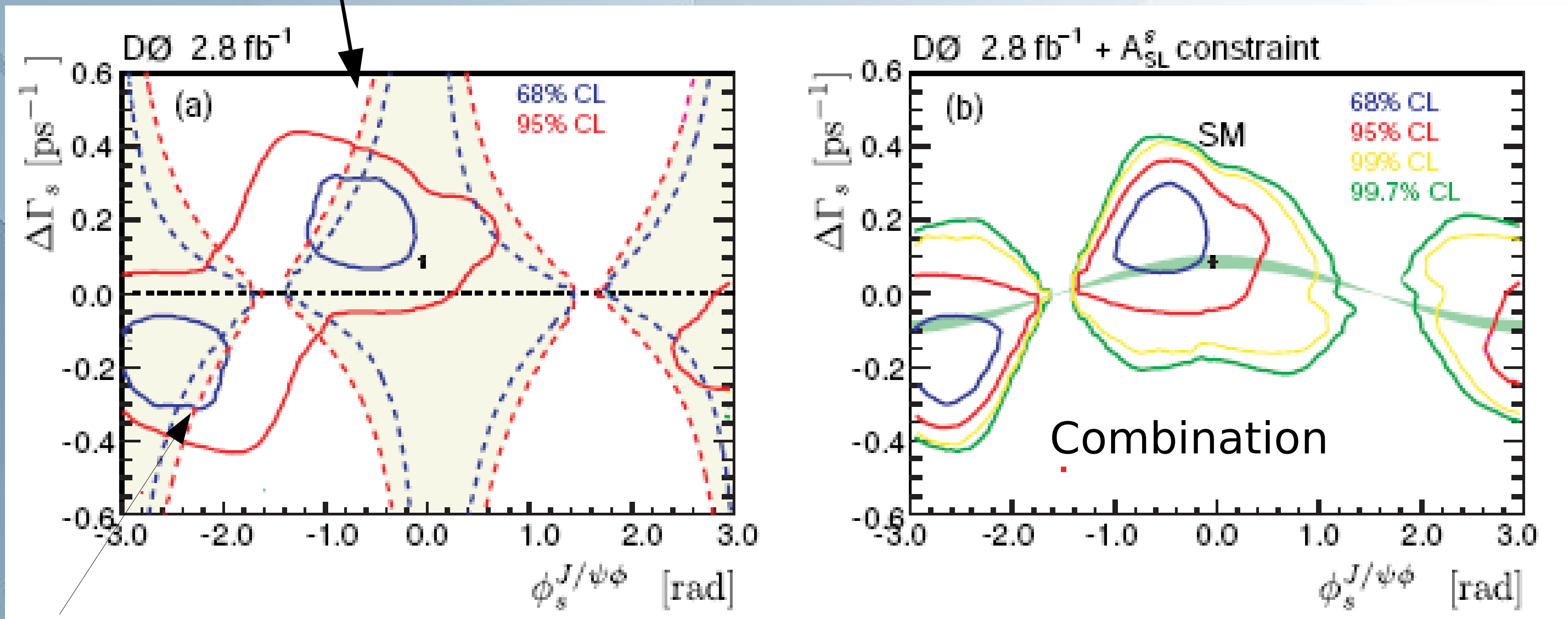
This analysis supersedes the previous semileptonic CP asymmetry at D0, and improves statistical uncertainty by ~2x

Compare, Apr 09: $A^s_{sl} = -0.0037 \pm 0.0094$

Conclusions

Impact of A_{sl}^{s} constraint on $\Delta\Gamma_s$ & ϕ_s
(only D0 results)

World average
A_{sl}^{s} constraint



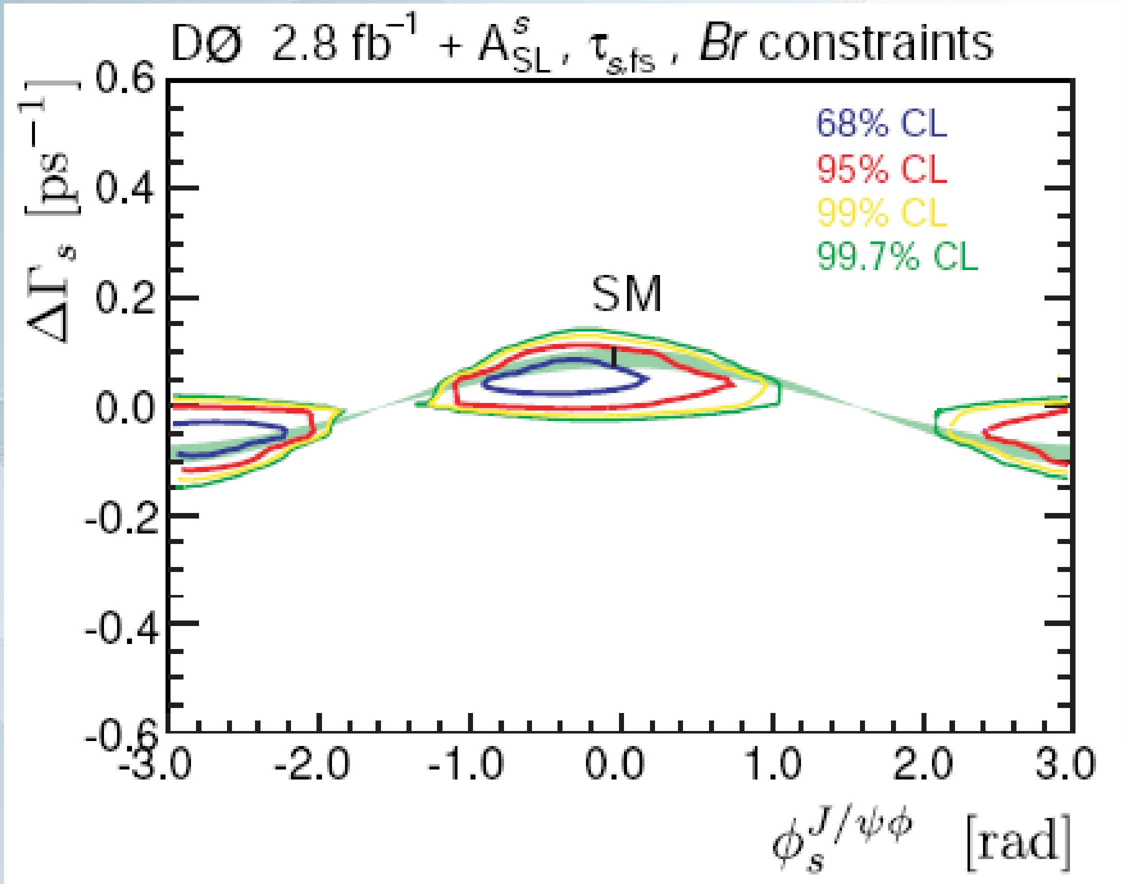
Direct D0 2.8fb
($B_s \rightarrow J/\psi\phi$)

Conclusions

$2.8 fb^{-1}$ D0 results from $B_s \rightarrow J/\psi\varphi$

constraints from A_{sl}, fs lifetime and $Br(B_s \rightarrow D_s D_s)$

Combination with CDF results coming soon!



p-value at SM point is 10%

Backup Slides

Untagged time integrated

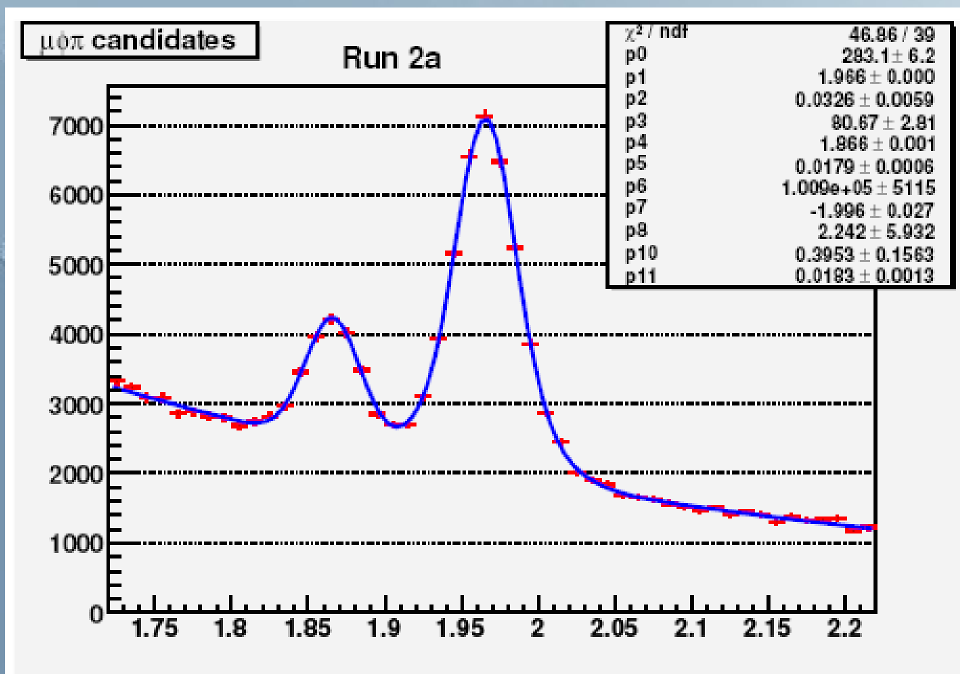
TABLE I. The numbers of events $n_q^{\beta\gamma}(D_s)$ [$n_q^{\beta\gamma}(D)$] in the D_s [D] mass peak and in the background $n_q^{\beta\gamma}$(bkg) for eight subsamples.

Subsample: $\beta\gamma q$	$n_q^{\beta\gamma}(D_s)$ (events)	$n_q^{\beta\gamma}(D)$ (events)	$n_q^{\beta\gamma}$(bkg) (events)
$+ + +$	3216 ± 76	907 ± 55	9797 ± 124
$+ - +$	3586 ± 79	965 ± 56	$10\,387 \pm 127$
$+ + -$	3391 ± 78	1037 ± 57	$10\,390 \pm 127$
$+ - -$	3225 ± 76	963 ± 55	9832 ± 124
$- + +$	3616 ± 80	1003 ± 57	$10\,508 \pm 128$
$- - +$	3370 ± 77	801 ± 54	9987 ± 125
$- + -$	3353 ± 77	831 ± 55	$10\,215 \pm 125$
$- - -$	3532 ± 79	1116 ± 59	$10\,701 \pm 129$

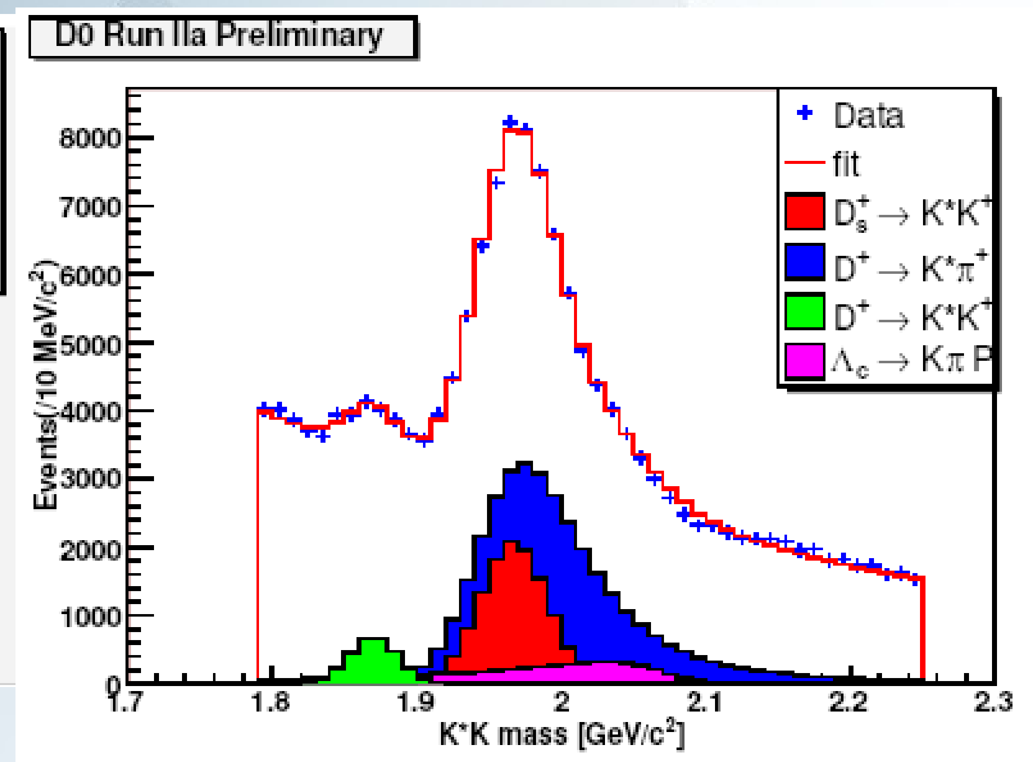
TABLE II. The physics and detector asymmetries for (μD_s), (μD), and background events. Uncertainties are statistical.

	(μD_s)	(μD)	Background
N	$27\,289 \pm 220$	7623 ± 162	$81\,817 \pm 357$
ϵ^+	0.492 ± 0.004	0.510 ± 0.011	0.494 ± 0.002
A	0.0102 ± 0.0081	-0.0345 ± 0.0211	-0.0056 ± 0.0045
A_{fb}	-0.0046 ± 0.0081	0.0480 ± 0.0210	-0.0020 ± 0.0043
A_{det}	-0.0051 ± 0.0081	-0.0072 ± 0.0212	0.0001 ± 0.0044
A_{ro}	-0.0352 ± 0.0081	-0.0819 ± 0.0209	-0.0263 ± 0.0044
$A_{\beta\gamma}$	-0.0097 ± 0.0081	0.0104 ± 0.0213	-0.0010 ± 0.0044
$A_{q\beta}$	0.0030 ± 0.0081	0.0014 ± 0.0212	0.0046 ± 0.0044

Mass RunIIa

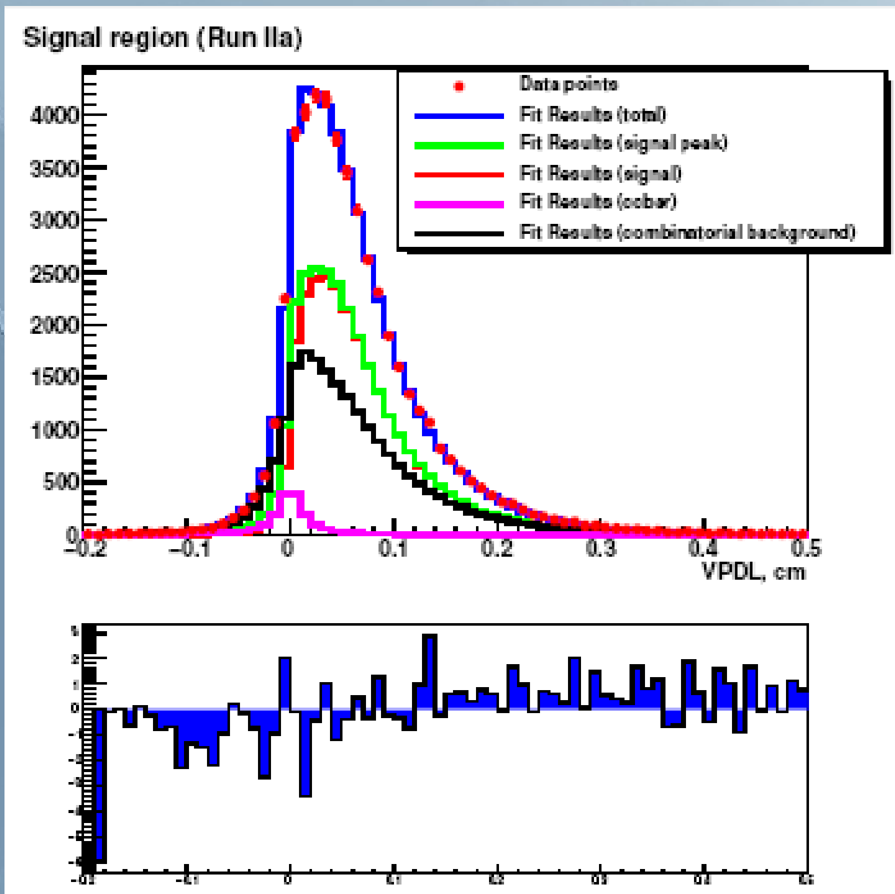


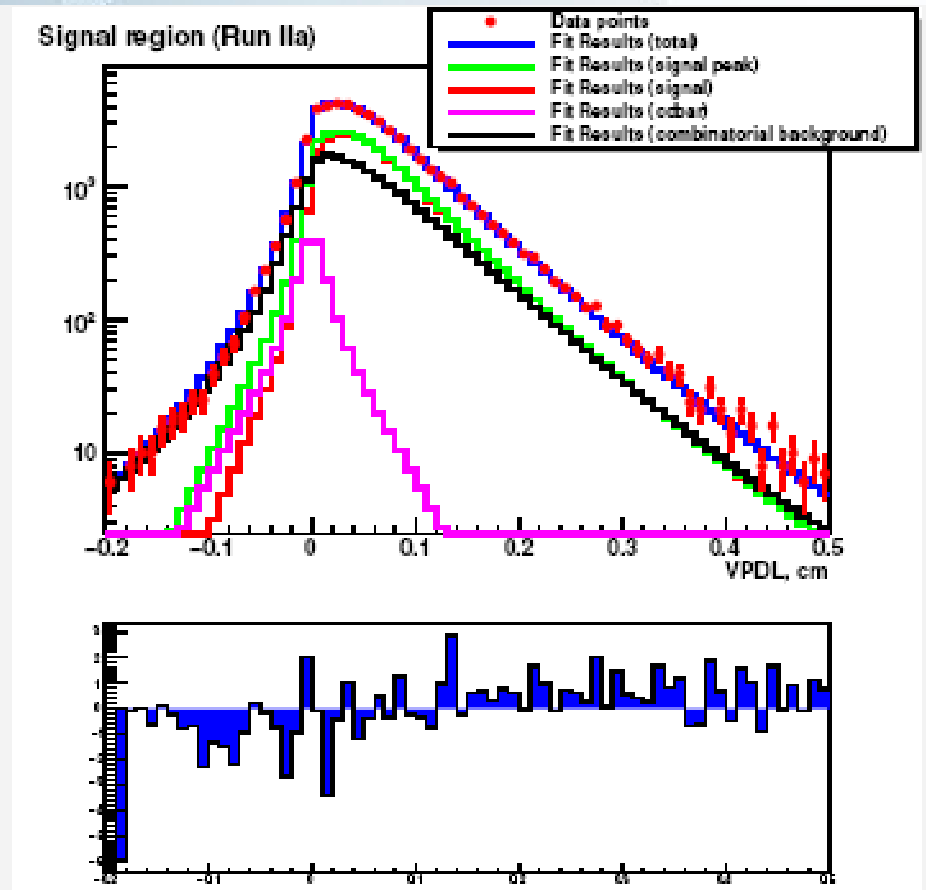
μφπ candidates
Run 2a
χ² / ndf 46.86 / 39
p0 283.1 ± 6.2
p1 1.966 ± 0.000
p2 0.0326 ± 0.0059
p3 80.67 ± 2.81
p4 1.866 ± 0.001
p5 0.0179 ± 0.0006
p6 1.009e+05 ± 5115
p7 -1.996 ± 0.027
p8 2.242 ± 5.932
p10 0.3953 ± 0.1563
p11 0.0183 ± 0.0013



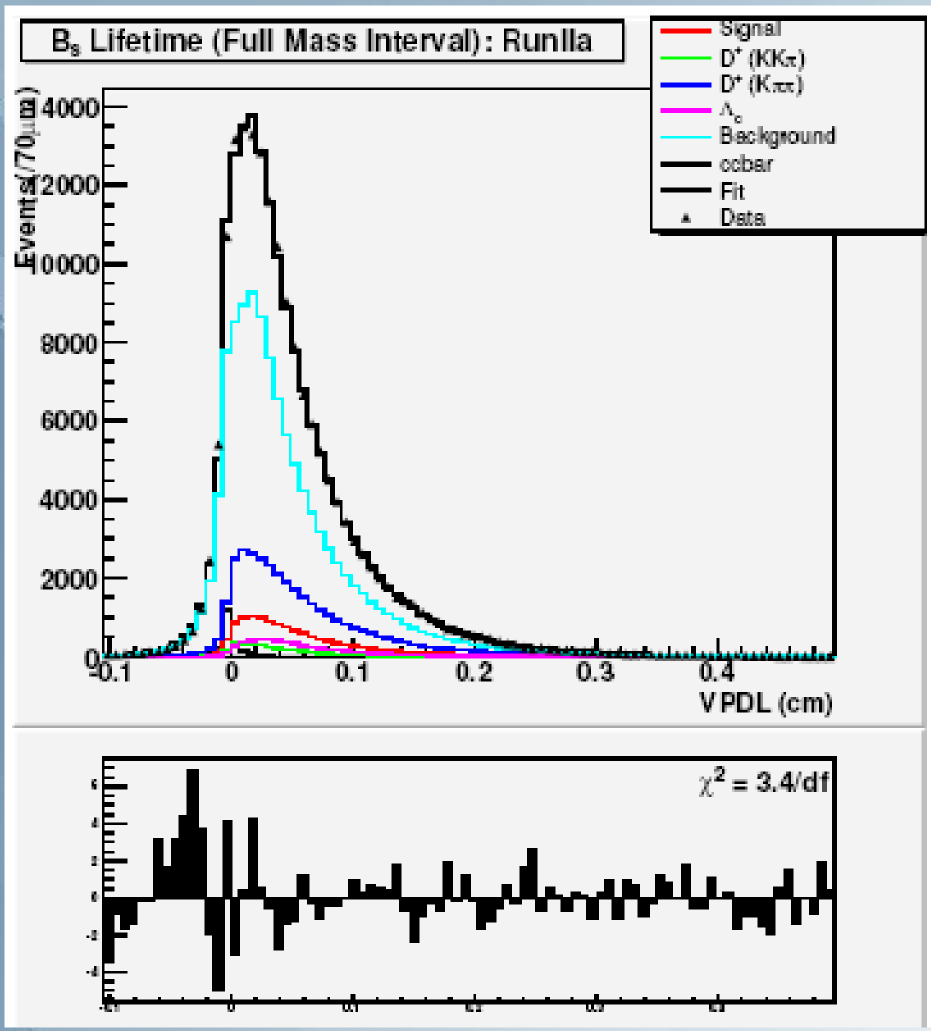
D0 Run IIa Preliminary
Data
fit
Events(/10 MeV/c²)
K*K mass [GeV/c²]

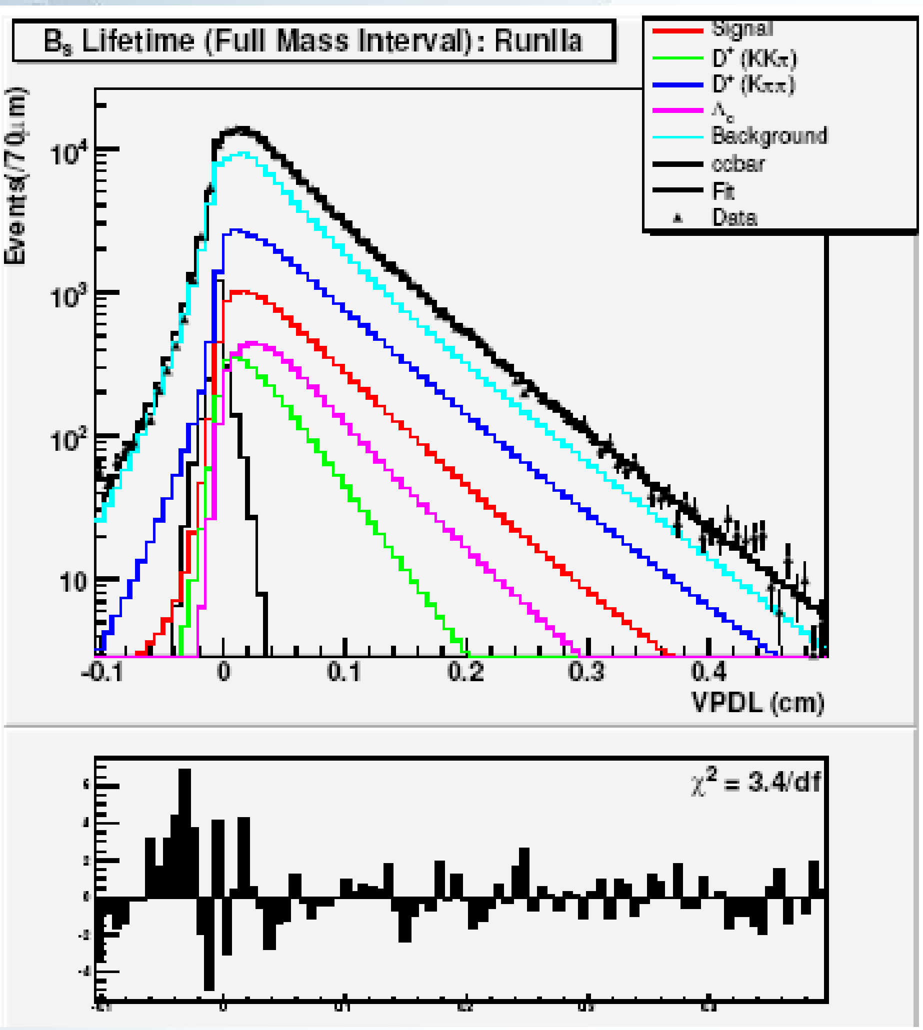
Lifetime RunIIa phipi



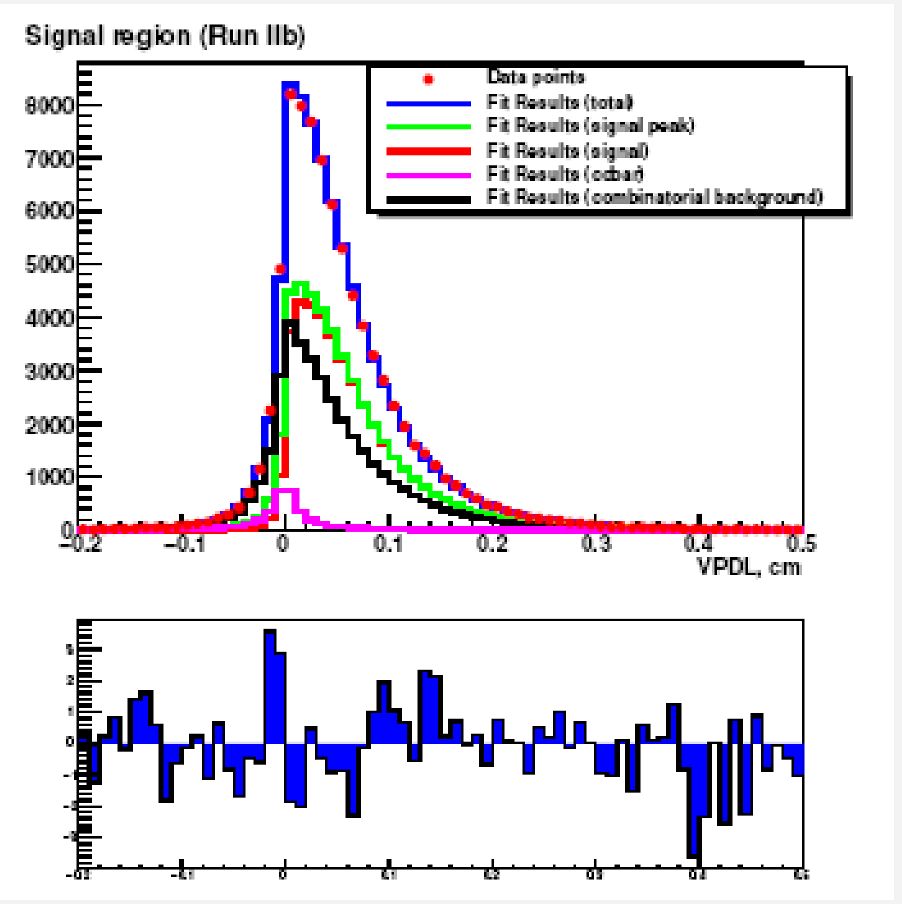


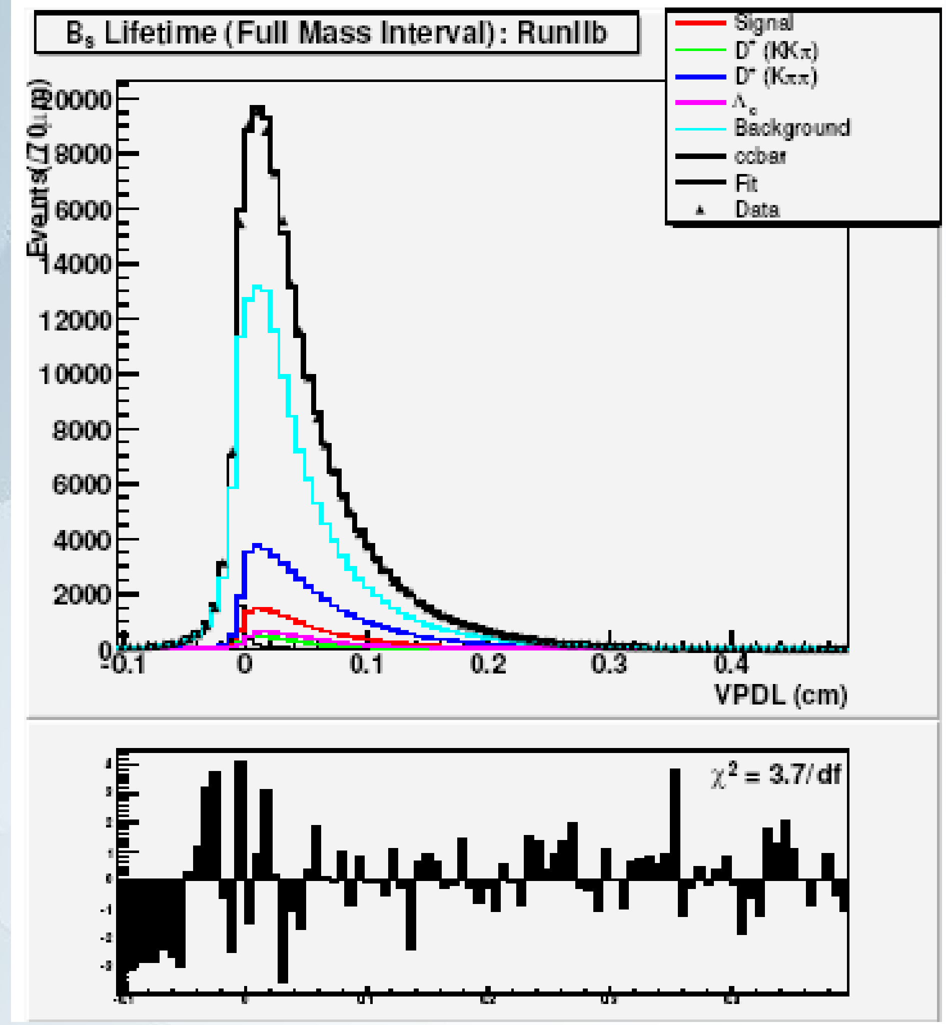
Lifetime RunIIa KstK



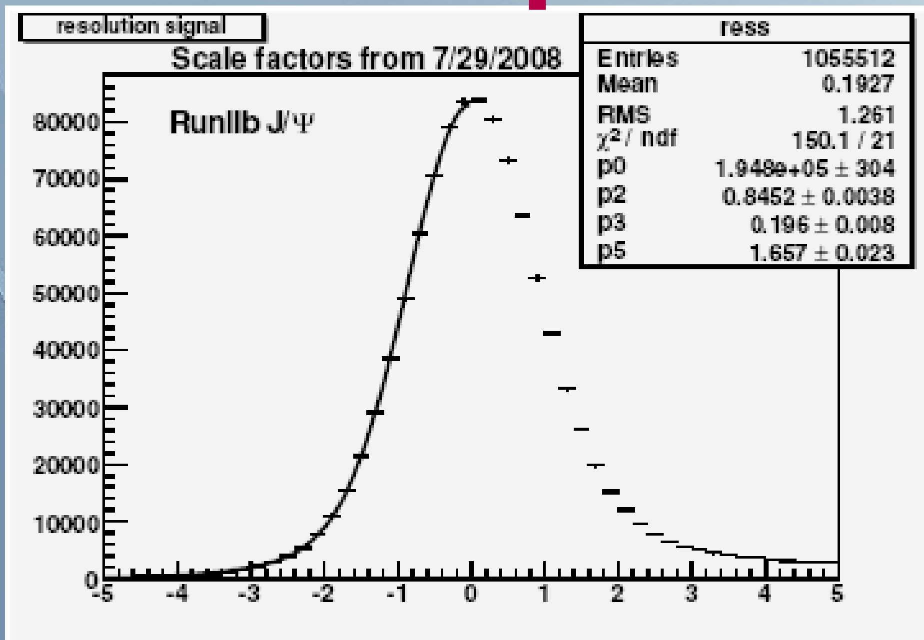


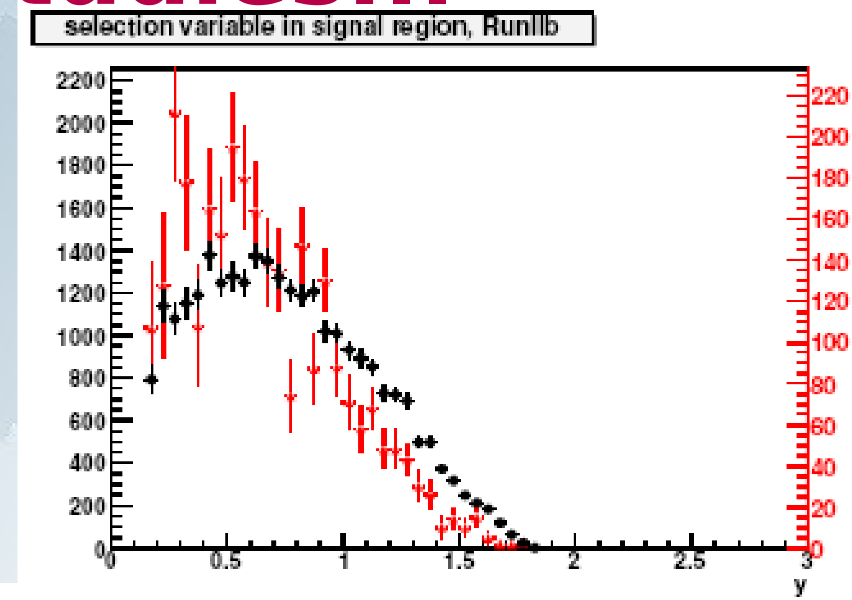
Lifetime RunIIb (linear)

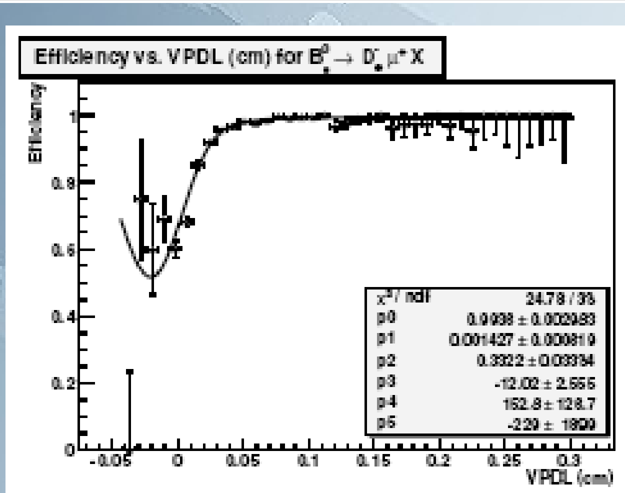


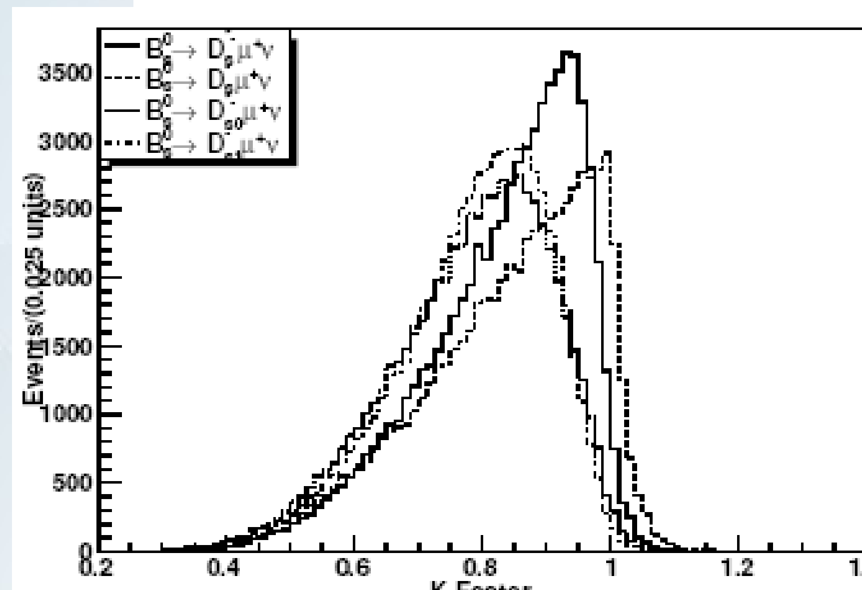


Various other inputs and studies…





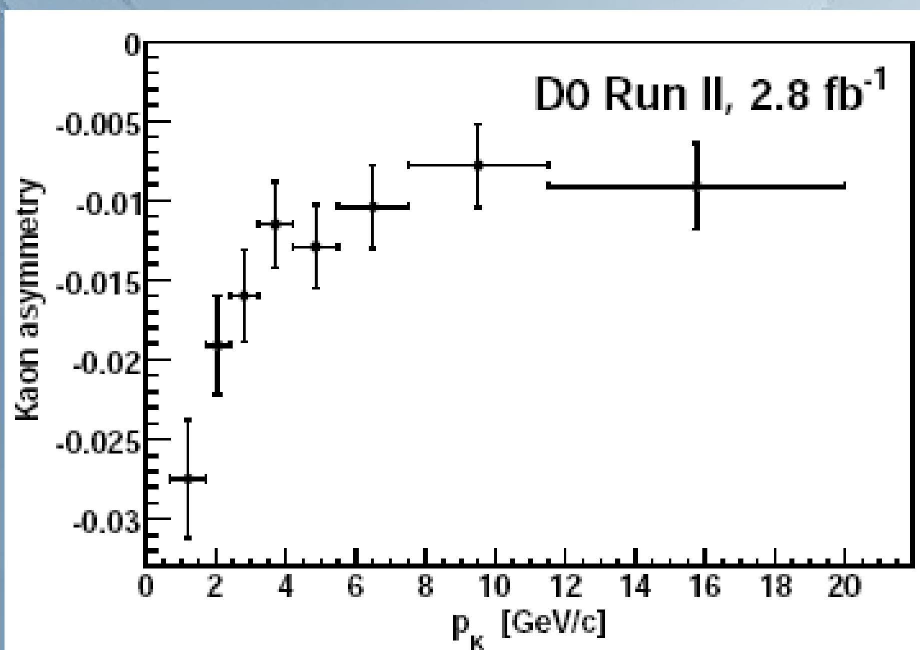




Kaon asymmetry

$$K^- N \to Y\pi$$

Efficiency for K^+ is higher than K^- due to interactions with detector material that do not occur for K^+. Causes momentum dependent asymmetry.



Only an issue in K^*K decay mode:

Kaons asymmetric

$$D_s^+ \to K^* K^+ \to (\pi^+ \boxed{K^-)K^+}$$

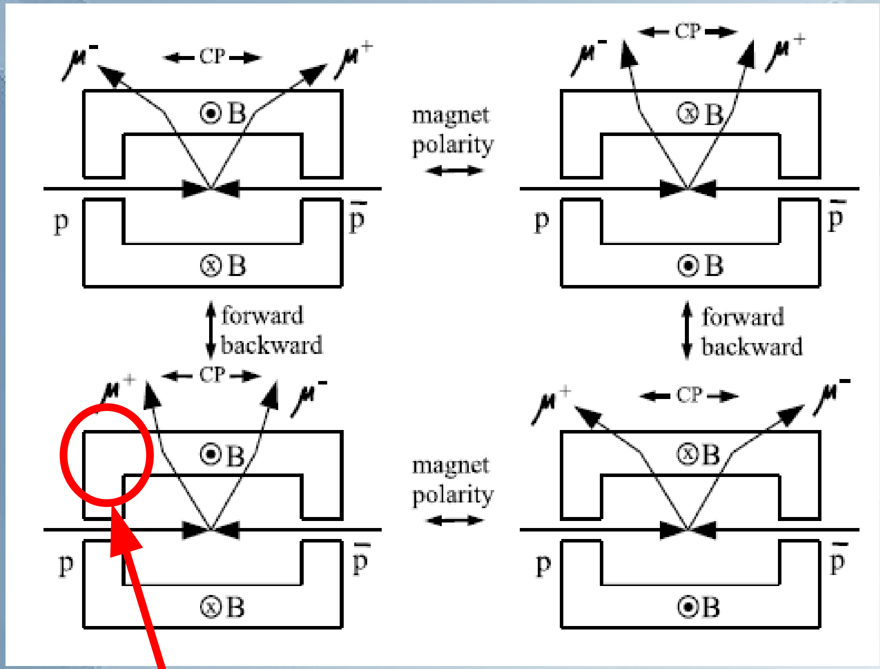
vs.

$$D_s^+ \to \phi\pi^+ \to \boxed{(K^+K^-}\,)\pi^+$$

Kaons symmetric

Detector Asymmetry

D0 flips muon toroid polarity regularly.
Approx 50% of the data is β=+1, β=-1.

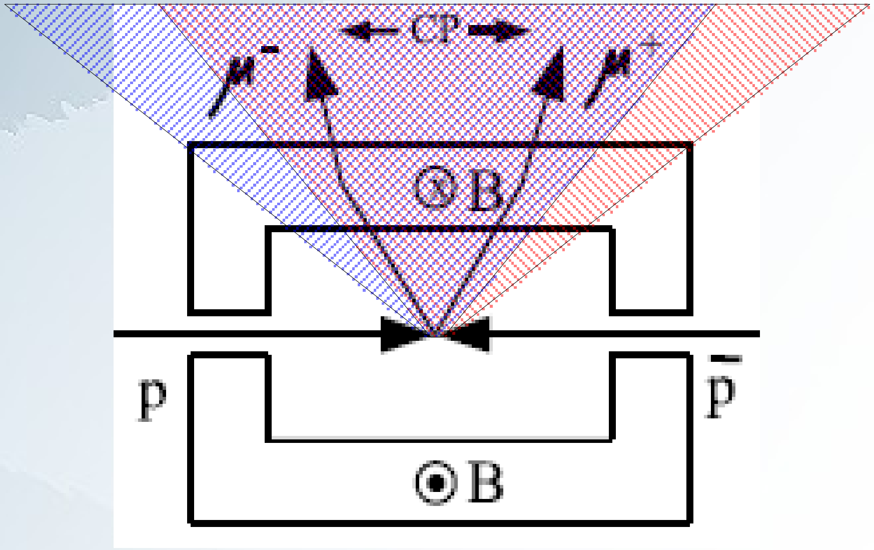


Low efficiency where forward and central toroid meet

Acceptance of central muon system

μ^- acceptance

μ^+ acceptance



Gives an asymmetry of ~3%
'range out asymmetry' A_{ro}