Updated Measurement of the Anomalous Like-sign Dimuon Asymmetry at D0

SUSY 2011: 19th International Conference on Supersymmetry and Unification of Fundamental Interactions

Fermilab, Illinois, USA

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The Tevatron (you are here!)

Collides protons and antiprotons at centre-of-mass energy 1.96 TeV;

Accelerator performance better than ever in 2011 – learning from the past;

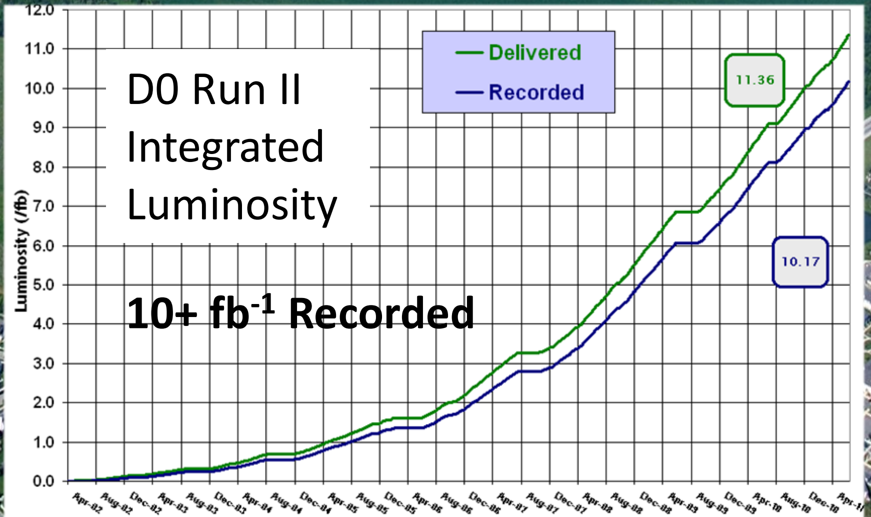
In final push before collisions stop at the end of September 2011.

CDF II

DØ

p

$\bar{p}$



SUSY Conference
30th August 2011

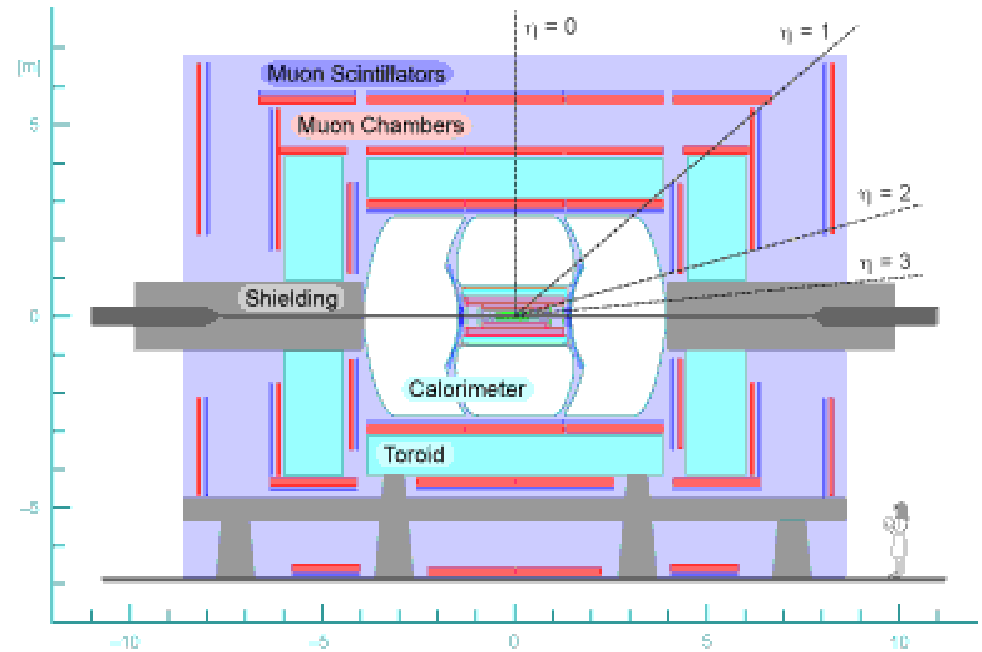
Experimental Strengths

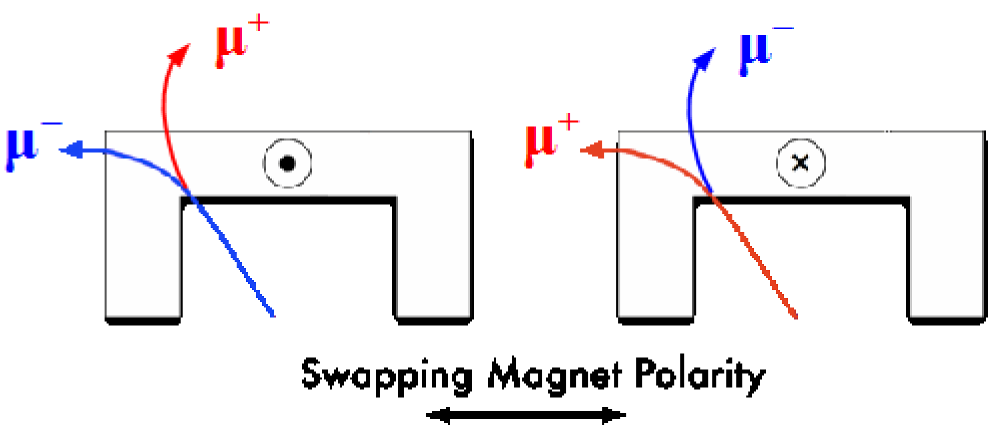
D0 Experiment

Central tracking detector (silicon, scintillating fibers): impact parameter (IP) resolution ~35μm;

Wide acceptance in three-layered muon system (|η| < 2.2);

Thick shielding before muon system – hadronic punch-though suppressed.

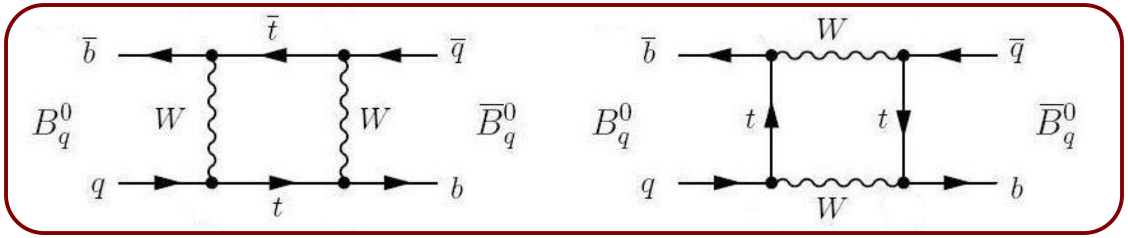




Regular reversal of toroid (muon-system) and solenoid (tracker) magnet polarities – cancels many detector asymmetries.

CPV in Mixing

Neutral $B^0_{(q=d,s)}$ mesons mix into their antiparticles via box diagrams:



Process **not CP symmetric** – $\mathbf{R(B^0_q \to \bar{B}^0_q) \neq R(\bar{B}^0_q \to B^0_q)}$ – due to complex phase $\varphi_{(d,s)}$ in quark mixing matrix, but…

…SM prediction of resulting asymmetry is **tiny**, much smaller than experimental precision. **New particles** entering loops can enhance this asymmetry significantly.

Measure CPV through asymmetry of decay products.

Flavor-specific semileptonic asymmetries defined for both B^0_s and B^0_d:

$$a^q_{sl} = \frac{\Gamma(\bar{\mathbf{B}}^0_q \to B^0_q \to \mu^+X) - \Gamma(\mathbf{B}^0_q \to \bar{B}^0_q \to \mu^-X)}{\Gamma(\bar{\mathbf{B}}^0_q \to B^0_q \to \mu^+X) + \Gamma(\mathbf{B}^0_q \to \bar{B}^0_q \to \mu^-X)} = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\varphi_q$$

Physical parameters characterizing B^0_q system

Measuring CPV in Mixing

D0 experiment measures an inclusive asymmetry, with contributions from both B^0_d and B^0_s:

$$a^b_{sl} = \frac{N(\bar{\mathbf{B}}^0 \to \mu^+ X) - N(\mathbf{B}^0 \to \mu^- X)}{N(\bar{\mathbf{B}}^0 \to \mu^+ X) + N(\mathbf{B}^0 \to \mu^- X)} = \underbrace{C_d a^d_{sl} + C_s a^s_{sl}}$$

More B^0_d produced, but most decay before mixing: $C_d \approx C_s \approx 0.5$

Challenge: separate signal (semileptonic *mixed* decays of B mesons) from the many other muon-producing backgrounds.

To suppress such backgrounds, require second muon of the same charge:

$$A^b_{sl} = \frac{N(b\bar{b} \to \mu^+\mu^+) - N(b\bar{b} \to \mu^-\mu^-)}{N(b\bar{b} \to \mu^+\mu^+) + N(b\bar{b} \to \mu^-\mu^-)} = a^b_{sl} \qquad (0.028 \pm 0.006)\% \textit{ in S.M.}$$

We therefore have two ways to extract a^b_{sl}, and take advantage of the correlated backgrounds by combining the two measurements.

Analysis Strategy

1) Measure 'raw' asymmetries by counting single muons ($n^{\pm}$) and dimuon events ($N^{\pm\pm}$);

2) Express in terms of a^b_{sl}:

$$a \equiv \underbrace{\frac{n^+ - n^-}{n^+ + n^-}}_{\text{Raw asymmetry (event counting)}} = \underbrace{\sum_{i=0}^{5} f^i_\mu}_{\text{Weighted average over bins of muon } p_T} \left\{ \underbrace{f_s^{\,i}\,(c_b \mathbf{a^b_{sl}} + \delta_i)}_{\text{Asymmetry from heavy-flavor decays}} + \underbrace{f_k^{\,i} a_k^{\,i} + f_\pi^{\,i} a_\pi^{\,i} + f_p^{\,i} a_p^{\,i}}_{\text{Asymmetries from backgrounds and detector effects}} \right\}$$

Raw asymmetry
(event counting)

Weighted average
over bins of muon p_T

Asymmetry
from heavy-
flavor decays

Asymmetries from
backgrounds and
detector effects

Analysis Strategy

1) Measure 'raw' asymmetries by counting single muons ($n^{\pm}$) and dimuon events ($N^{\pm\pm}$);

2) Express in terms of a^b_{sl}:

fraction

Charge asymmetry

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-} = \sum_{i=0}^{5} f^i_\mu \ \{ f_s{}^i \,(c_b \mathbf{a^b}_{sl} + \ \delta_i) + \underbrace{f_k{}^i a_k{}^i}_{\text{Kaon DIF and punch-through}} + \underbrace{f_\pi{}^i a_\pi{}^i}_{\text{Pion DIF and punch-through}} + \underbrace{f_p{}^i a_p{}^i}_{\text{...proton punch-through}} \}$$

Kaon DIF and punch-through

Pion DIF and punch-through

...proton punch-through

Asymmetries from backgrounds and detector effects

Residual muon reconstruction asymmetries (almost entirely cancelled by magnet polarity reversal)

Analysis Strategy

1) Measure 'raw' asymmetries by counting single muons ($n^{\pm}$) and dimuon events ($N^{\pm\pm}$);

2) Express in terms of a^b_{sl}:

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-} = \sum_{i=0}^{5} f^i_{\mu} \; \{ f_s{}^i \, (c_b a^b{}_{sl} + \delta_i) + f_k{}^i a_k{}^i + f_\pi{}^i a_\pi{}^i + f_p{}^i a_p{}^i \}$$

Asymmetry from heavy-flavor decays

Dilution factor (muons from charge symmetric HF processes)

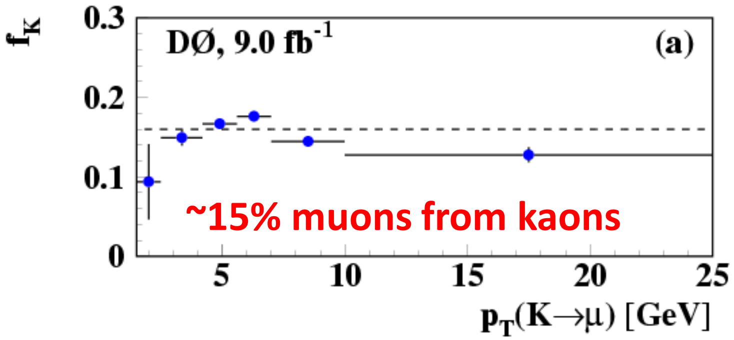
What we want to extract

Remaining fraction of muons after kaon, pion, proton components taken into account:
i.e. *"Heavy Flavor Fraction"*

Similar expression for dimuon case. Many BG quantities are the same, or highly correlated, e.g. presence of second muon doesn't change kaon asymmetry $a_k{}^i$.

Analysis Strategy

3) Measure all quantities $f_{k,\pi,p}{}^{i}$, $a_{k,\pi,p}{}^{i}$, δ_i in data, with limited input from simulation;



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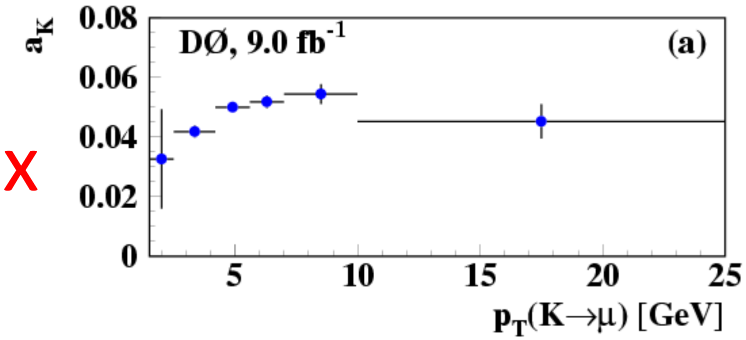

= +0.776 ± 0.021 % asymmetry from kaons

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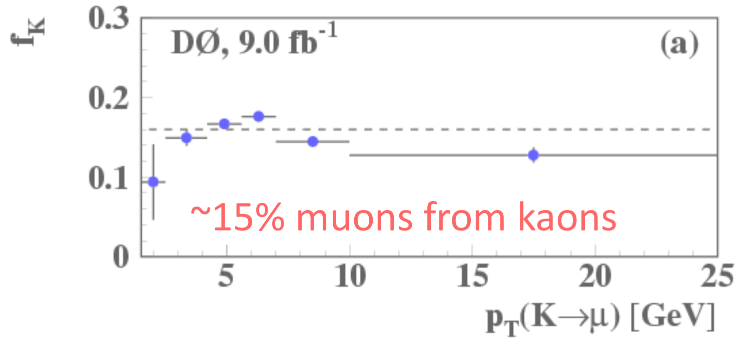

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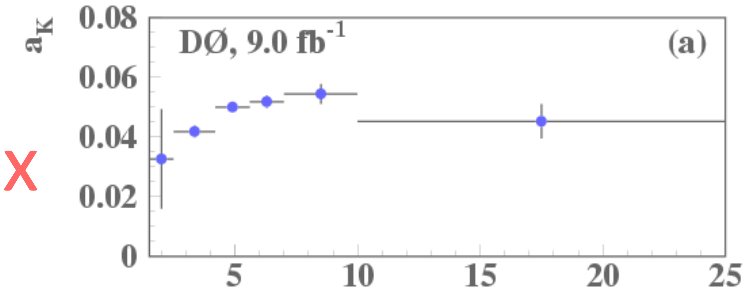

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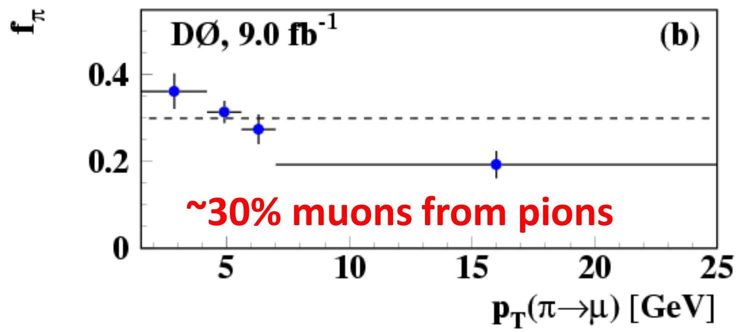

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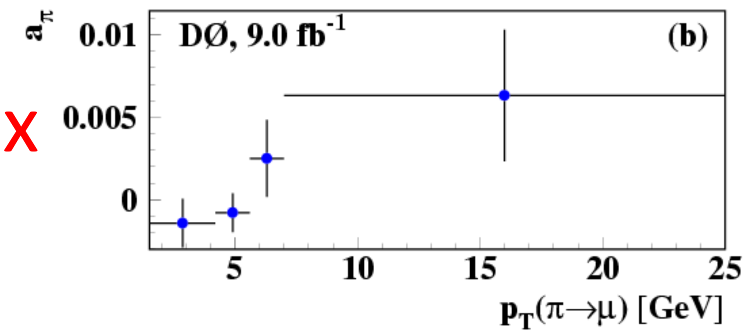

= +0.007 ± 0.027 % asymmetry from pions

Analysis Strategy

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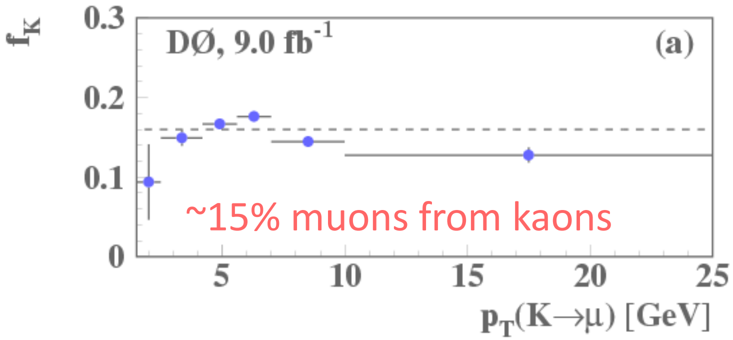

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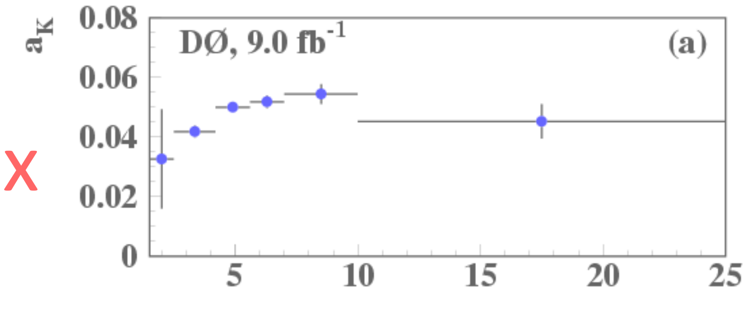

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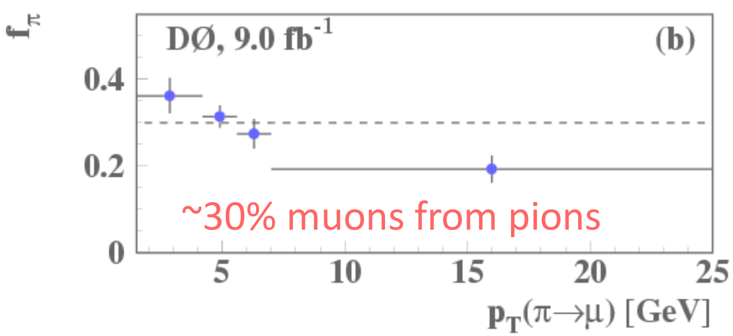

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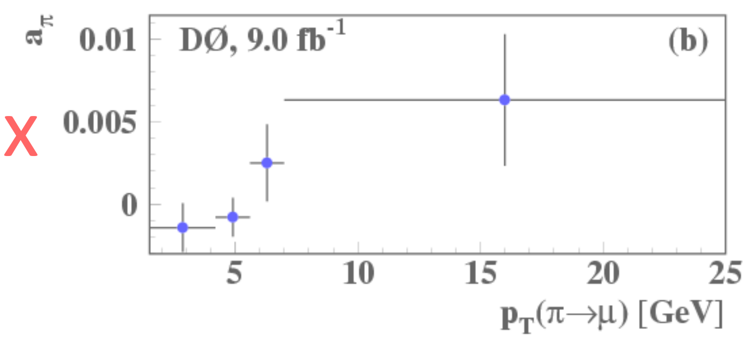

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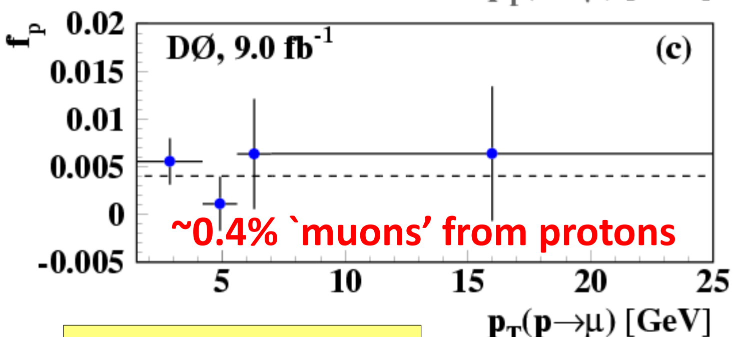

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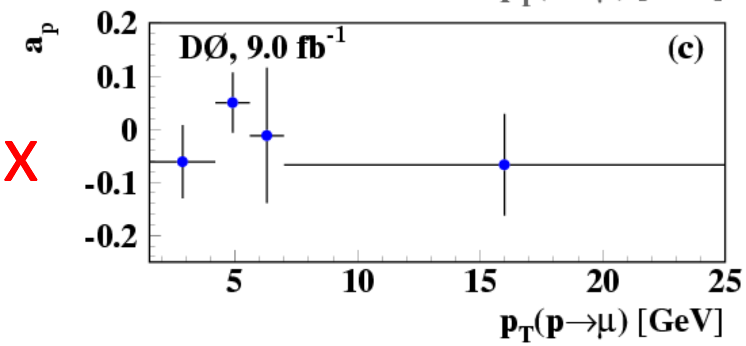
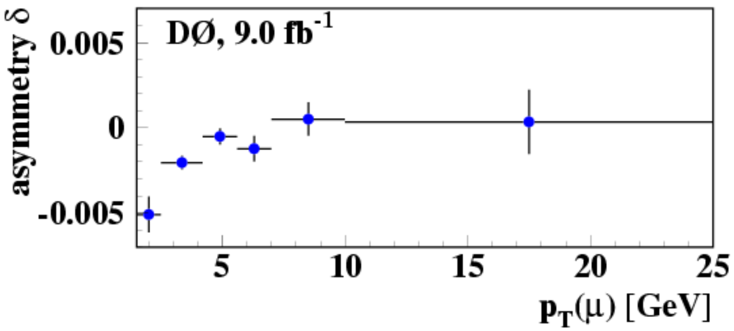


= -0.014 ± 0.022 % asymmetry from protons

Analysis Strategy

3) Measure all quantities $f_{k,\pi,p}^{\,i}$, $a_{k,\pi,p}^{\,i}$, δ_i in data, with limited input from simulation;



Contribution from residual muon reconstruction asymmetry:
$\sum_i (1 - f_k^{\,i} - f_\pi^{\,i} - f_p^{\,i})\delta_i$ = -0.047 ± 0.012 %

Source	inclusive muon	like-sign dimuon
$(f_K a_K$ or $F_K A_K) \times 10^2$	$+0.776 \pm 0.021$	$+0.633 \pm 0.031$
$(f_\pi a_\pi$ or $F_\pi A_\pi) \times 10^2$	$+0.007 \pm 0.027$	-0.002 ± 0.023
$(f_p a_p$ or $F_p A_p) \times 10^2$	-0.014 ± 0.022	-0.016 ± 0.019
$[(1 - f_{\rm bkg})\delta$ or $(2 - F_{\rm bkg})\Delta] \times 10^2$	-0.047 ± 0.012	-0.212 ± 0.030
$(a_{\rm bkg}$ or $A_{\rm bkg}) \times 10^2$	$+0.722 \pm 0.042$	$+0.402 \pm 0.053$
$(a$ or $A) \times 10^2$	$+0.688 \pm 0.002$	$+0.126 \pm 0.041$
$[(a - a_{\rm bkg})$ or $(A - A_{\rm bkg})] \times 10^2$	-0.034 ± 0.042	-0.276 ± 0.067

Background dominated

Significantly different from zero

Analysis Strategy

4) Account for dilution from charge-symmetric processes (i.e. determine coefficients c_b, C_b):

	Process	Weight
T_1	$b \to \mu^- X$	$w_1 \equiv 1.$
T_{1a}	$b \to \mu^- X$ (nos)	$w_{1a} = (1-\chi_0)w_1$
T_{1b}	$\bar{b} \to b \to \mu^- X$ (osc)	$w_{1b} = \chi_0 w_1$
T_2	$b \to c \to \mu^+ X$	$w_2 = 0.096 \pm 0.012$
T_{2a}	$b \to c \to \mu^+ X$ (nos)	$w_{2a} = (1-\chi_0)w_2$
T_{2b}	$\bar{b} \to b \to c \to \mu^+ X$ (osc)	$w_{2b} = \chi_0 w_2$
T_3	$b \to c\bar{c}q$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$w_3 = 0.064 \pm 0.006$
T_4	$\eta, \omega, \rho^0, \phi(1020), J/\psi, \psi' \to \mu^+\mu^-$	$w_4 = 0.021 \pm 0.002$
T_5	$b\bar{b}c\bar{c}$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$w_5 = 0.013 \pm 0.002$
T_6	$c\bar{c}$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$	$w_6 = 0.675 \pm 0.101$

Weights measured using simulation
This analysis uses LEP value for χ_0, following recent CDF update.

Results: $c_b = 0.061 \pm 0.007$ $C_b = 0.474 \pm 0.032$

Inclusive muon sample dominated by charge-symmetric backgrounds (94%)

Dimuon sample has a large contribution (47%) from mixed B mesons (remember: around 50% each of B^0_d and B^0_s)

Results with 9fb^{-1}

Final asymmetry from both samples:

From inclusive muon sample: A^b_{sl} = [-1.04 ± 1.30 (stat.) ± 2.31 (syst.)] %
(2.041 x 10^9 muons)

From like-sign dimuon sample: A^b_{sl} = [-0.808 ± 0.202 (stat.) ± 0.222 (syst.)] %
(6.019 x 10^6 muons)

Now use **linear combination** of inclusive and dimuon asymmetries, **A' = A – αa** with **α=0.89** chosen to minimise total uncertainty on A^b_{sl}:

A^b_{sl} = [-0.787 ± 0.172 (stat.) ± 0.093 (syst.)] %

Systematic uncertainty reduces significantly due to extra information in (background dominated) inclusive muon sample

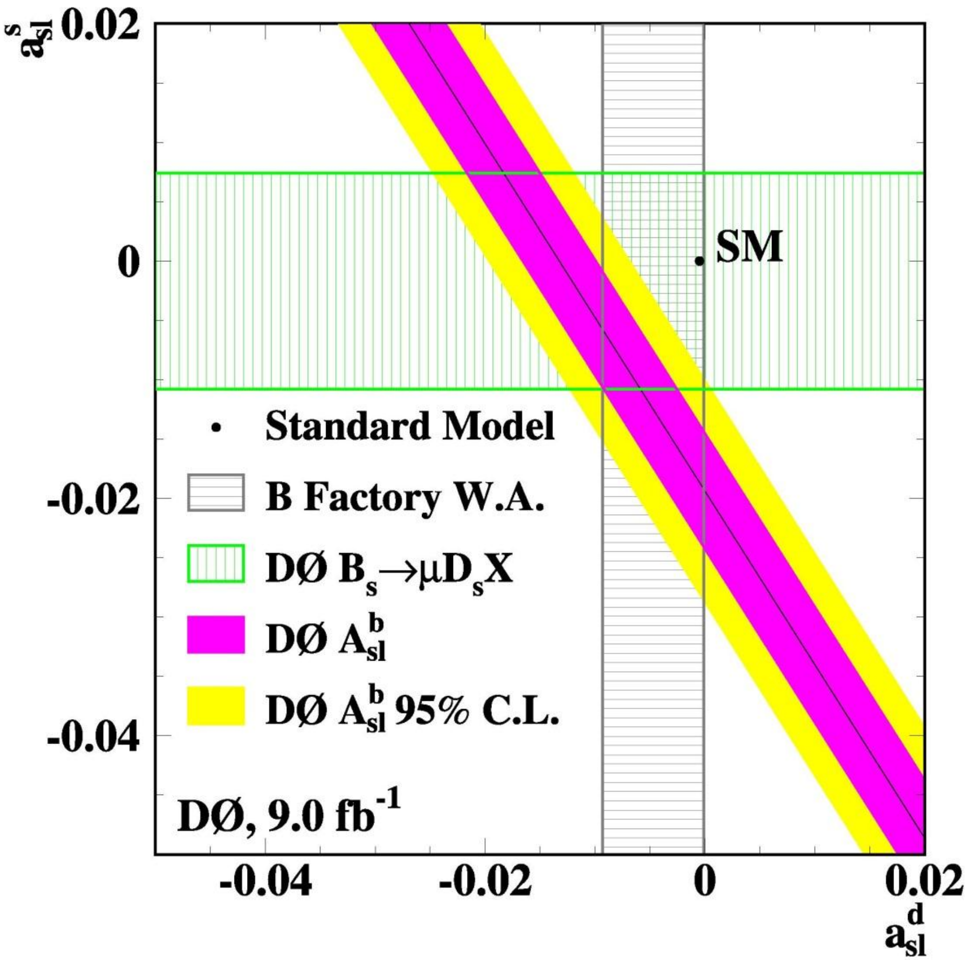
This result differs from the SM prediction by **3.9σ**

Results with 9fb^{-1}

$$A^b_{sl} = (0.594 \pm 0.022)\cdot a^d_{sl} + (0.406 \pm 0.22)\cdot a^s_{sl}$$

Use *sample composition* and *mixing probability* to express as constraint in (a^d_{sl}, a^s_{sl}) plane.

Results consistent with previous measurements of flavor-specific asymmetries.



Comparison with Previous Result

Previous D0 measurement
PRD 82, 032001 (2010) ($6.1 fb^{-1}$)

A^b_{sl} = [-0.957 ± 0.251 (stat.) ± 0.146 (syst.)] %

3.2σ

First $6.1 fb^{-1}$, new technique:

A^b_{sl} = [-0.891 ± 0.204 (stat.) ± 0.128 (syst.)] %

3.6σ

Final $2.9 fb^{-1}$, new technique:

A^b_{sl} = [-0.600 ± 0.335 (stat.) ± 0.188 (syst.)] %

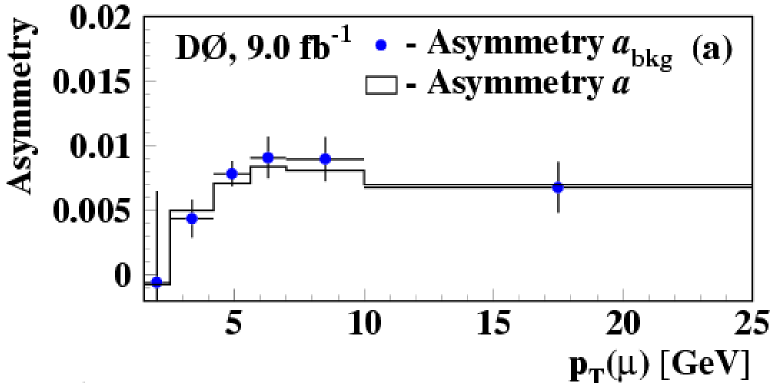
1.6σ

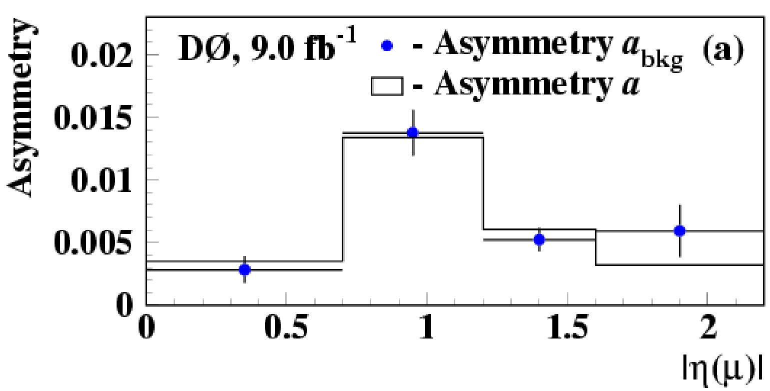
So what's new?

- Event selection optimized:
  - Looser minimum $|p_z|$ cut (6.4→5.4 GeV) based on new study of detector thickness;
  - Tighter match required between muon track and central track – reduces BG contribution from D.I.F.;
- New method to extract ratio of kaon fractions in two samples $\mathbf{R_k = F_k/f_k}$: eliminates dependence on mass resolution, and better quantifies correlations.
- Second, independent channel used to measure $\mathbf{R_k}$: consistent results found.

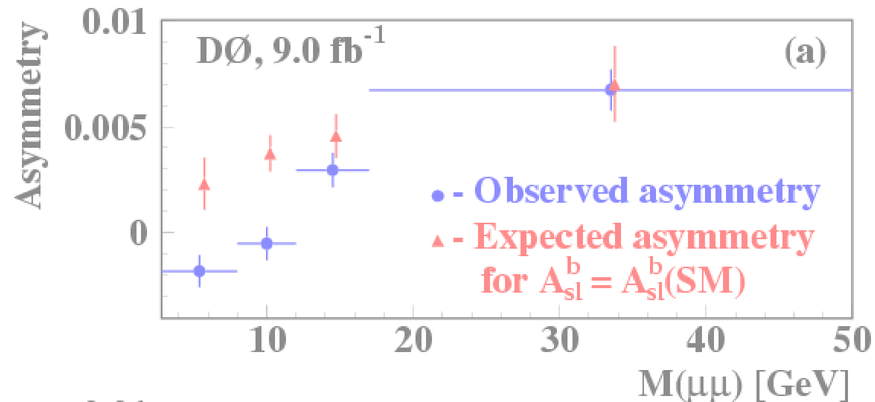
Cross-Checks

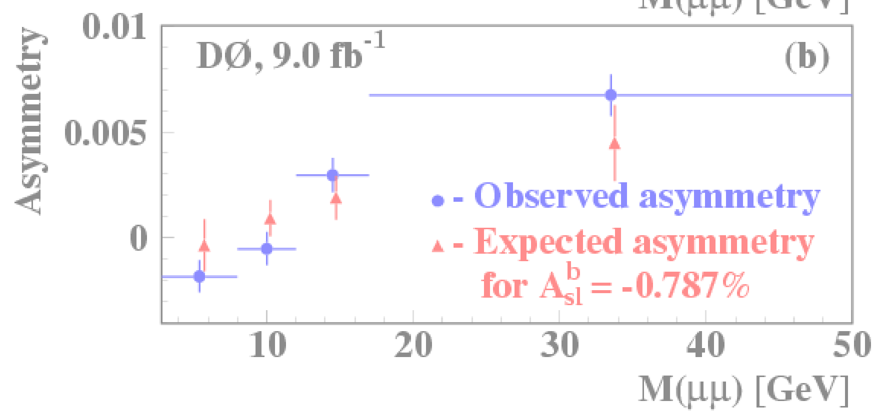
Measured inclusive muon asymmetry *a* is dominated by background: should match a_{bkg}:





Dimuon asymmetry versus M(μμ) – inconsistent with SM, but consistent with measured A^b_{sl}.





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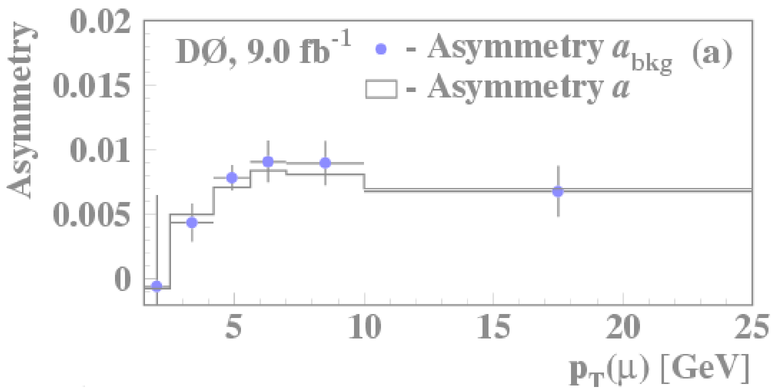

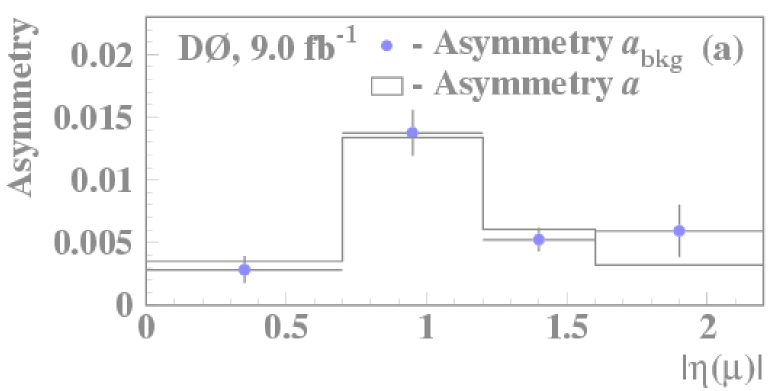

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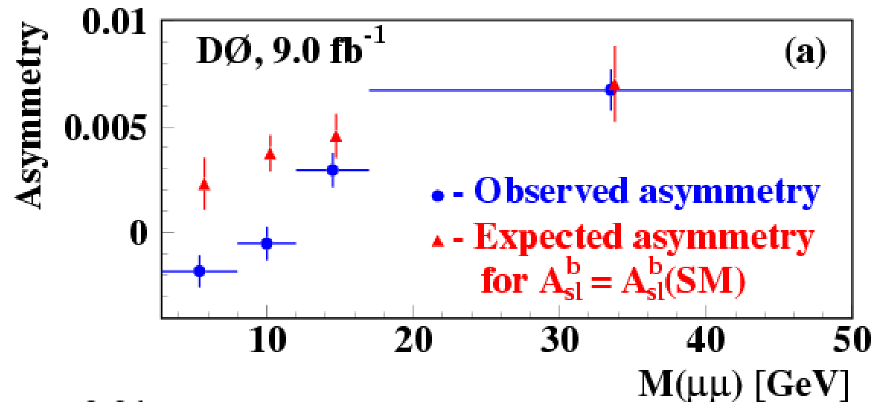

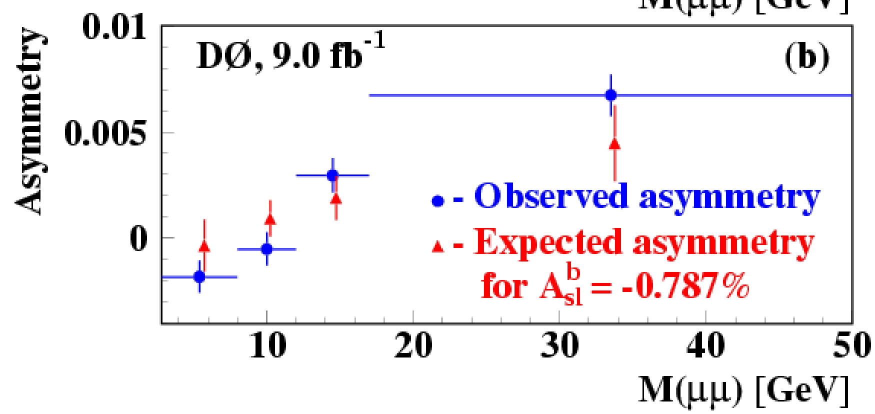

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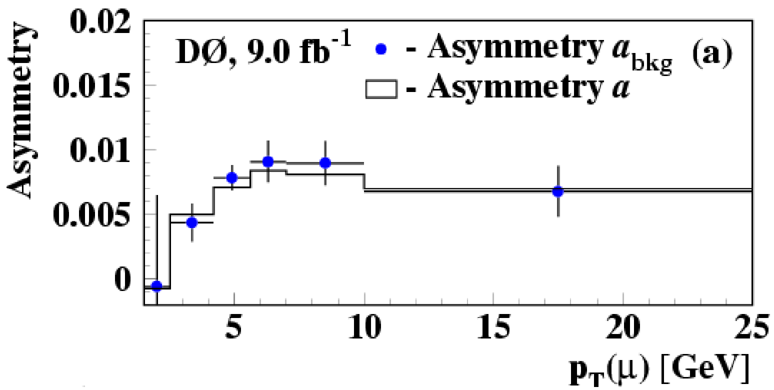
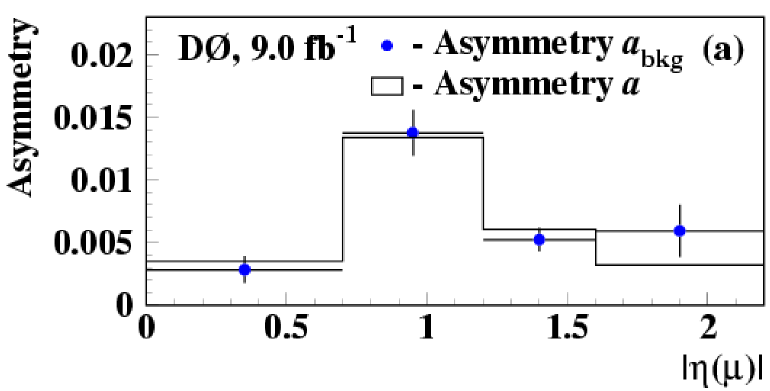
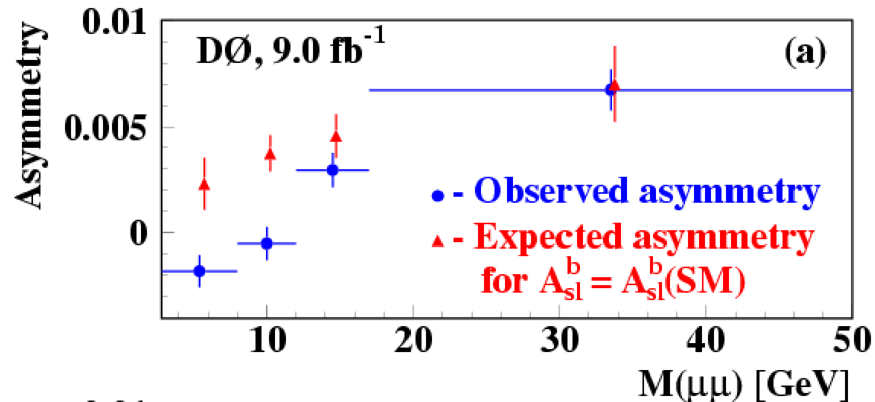
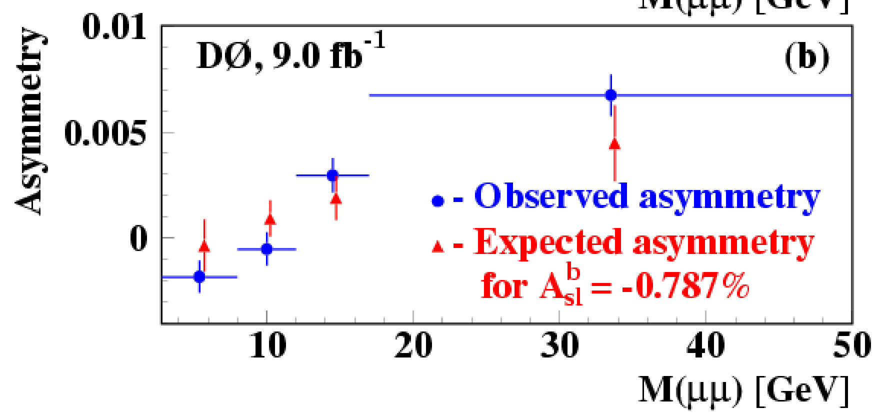




Dimuon asymmetry versus M(μμ) – inconsistent with SM, but consistent with measured A^b_{sl}.



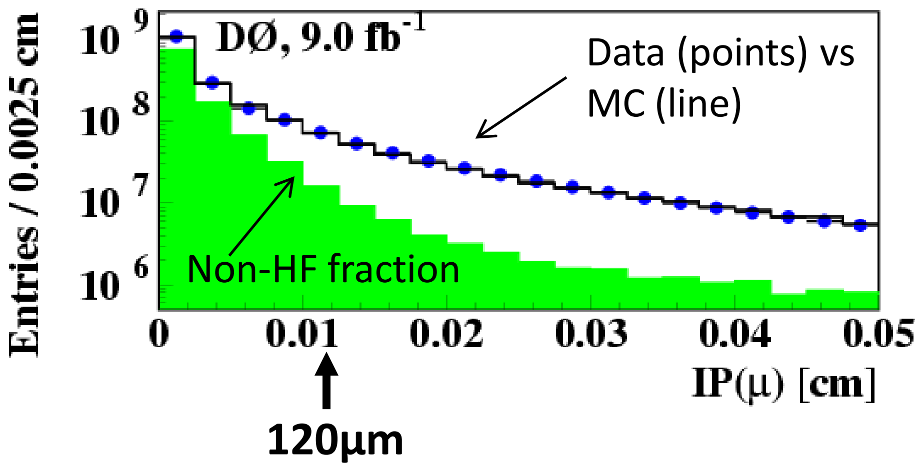


Measurement also repeated with many different requirements to enhance/suppress backgrounds. Final A^b_{sl} consistent in all samples (Total χ^2 = 16 for 18 different tests)

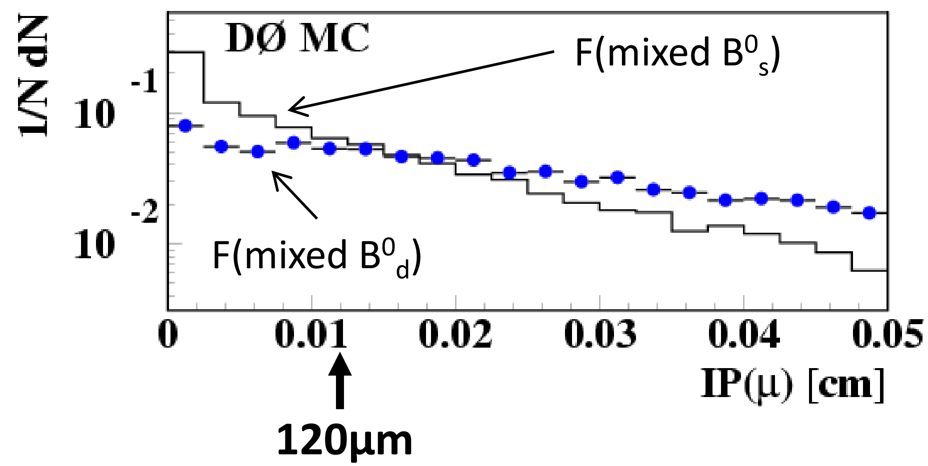
Dependence on Impact Parameter

Muon impact parameter strongly influences:

Heavy flavor fraction



Fraction of `oscillated' B^0_q mesons



By dividing into two samples corresponding to **IP(μ) < 120μm** and **IP(μ) > 120μm**, we can:

1) Confirm stable measurement in background enhanced and suppressed samples;
2) Test for larger asymmetry from B^0_d or B^0_s mesons:

for IP(μ) < 120μm: $A^b_{sl} = (0.397 \pm 0.053)a^d_{sl} + (0.603 \pm 0.053)a^s_{sl}$

IP(μ) > 120μm: $A^b_{sl} = (0.728 \pm 0.030)a^d_{sl} + (0.272 \pm 0.030)a^s_{sl}$

Dependence on Impact Parameter

Quantity	$IP_{>120}$	$IP_{<120}$
$f_K \times 10^2$	5.19 ± 0.37	17.64 ± 0.27
$f_\pi \times 10^2$	5.65 ± 0.40	34.72 ± 1.86
$f_p \times 10^2$	0.05 ± 0.03	0.45 ± 0.20
$F_K \times 10^2$	4.48 ± 4.05	21.49 ± 0.62
$F_\pi \times 10^2$	4.43 ± 3.95	40.47 ± 2.26
$F_p \times 10^2$	0.03 ± 0.05	0.59 ± 0.23
$f_S \times 10^2$	89.11 ± 0.88	47.18 ± 2.03
$F_{\rm bkg} \times 10^2$	8.94 ± 8.26	62.56 ± 3.07
$F_{SS} \times 10^2$	91.79 ± 7.65	53.66 ± 2.68
$a \times 10^2$	-0.014 ± 0.005	$+0.835 \pm 0.002$
$a_{\rm bkg} \times 10^2$	$+0.027 \pm 0.023$	$+0.864 \pm 0.049$
$A \times 10^2$	-0.529 ± 0.120	$+0.555 \pm 0.060$
$A_{\rm bkg} \times 10^2$	-0.127 ± 0.093	$+0.829 \pm 0.077$

Kaon and pion fractions much lower in IP>120μm sample

HF fraction increases from ~50% → ~90%

Even inclusive muon asymmetry significantly different from BG expectation for IP>120μm

Dependence on Impact Parameter

Quantity	$IP_{>120}$	$IP_{<120}$
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$F_{\text{bkg}} \times 10^2$	8.94 ± 8.26	62.56 ± 3.07
$F_{SS} \times 10^2$	91.79 ± 7.65	53.66 ± 2.68
$a \times 10^2$	-0.014 ± 0.005	$+0.835 \pm 0.002$
$a_{\text{bkg}} \times 10^2$	$+0.027 \pm 0.023$	$+0.864 \pm 0.049$
$A \times 10^2$	-0.529 ± 0.120	$+0.555 \pm 0.060$
$A_{\text{bkg}} \times 10^2$	-0.127 ± 0.093	$+0.829 \pm 0.077$

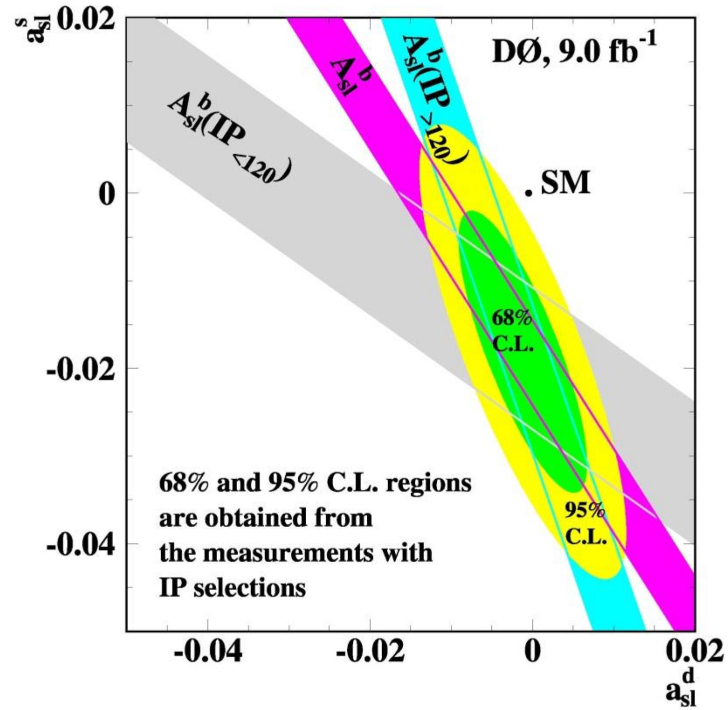
Kaon and pion fractions much lower in IP>120µm sample

HF fraction increases from ~50% → ~90%

Even inclusive muon asymmetry significantly different from BG expectation for IP>120µm

Measured asymmetry larger in B^0_d suppressed sample, but too early to make strong conclusions.

$IP < 120\mu$m	1μ	-1.654	2.774	4.962
	2μ	-1.175	0.439	0.590
	comb.	-1.138	0.366	0.323
$IP > 120\mu$m	1μ	-0.422	0.240	0.121
	2μ	-0.818	0.342	0.067
	comb.	-0.579	0.210	0.094



Conclusions

- **Dimuon asymmetry** offers a tantalizing possibility for BSM physics in B meson mixing:
  - Current measurement **inconsistent with SM** at the ~4σ level
  - D0 already planning next update with more use of IP information
  - Need independent confirmation from other experiments.
- Further studies ongoing in exclusive decay modes to extract *flavor-specific asymmetries* in B^0 and B^0_s systems.
- We thank the community for their interest and ideas.

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