Evidence for an anomalous like-sign dimuon charge asymmetry

Bruce Hoeneisen

Universidad San Francisco de Quito

representing the

DØ Collaboration

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Outline

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- 3. Result

- Appendix A: Details

- Appendix B: Theory

1. Motivation

- Symmetries shape theories.

- At the FERMILAB Tevatron the initial $p\bar{p}$ state is invariant with respect to CP.

- Is the final state invariant with respect to CP?

- The matter in the Universe requires new sources of CP violation beyond the Standard Model.

- Muon identification with the DØ detector has low background due to 5500 tonnes of shielding.

- Very few processes contribute to like-sign dimuons.

- Most muons at the Tevatron come from the decay of heavy quarks b or c.

- Our signal is the direct semi-leptonic decay of B hadrons: $B \rightarrow \mu X$.

- Our signal in the like-sign dimuon sample requires $B_d \leftrightarrow \bar{B}_d$ and/or $B_s \leftrightarrow \bar{B}_s$ mixing: $B \rightarrow \mu^+ X, \bar{B}_q^0 \rightarrow B_q^0 \rightarrow \mu^+ X$.

- Mixing is due to "box" Feynman diagrams that probe new heavy virtual particles not directly accessible at the Tevatron.

Example: the 2 Higgs Doublet Model.
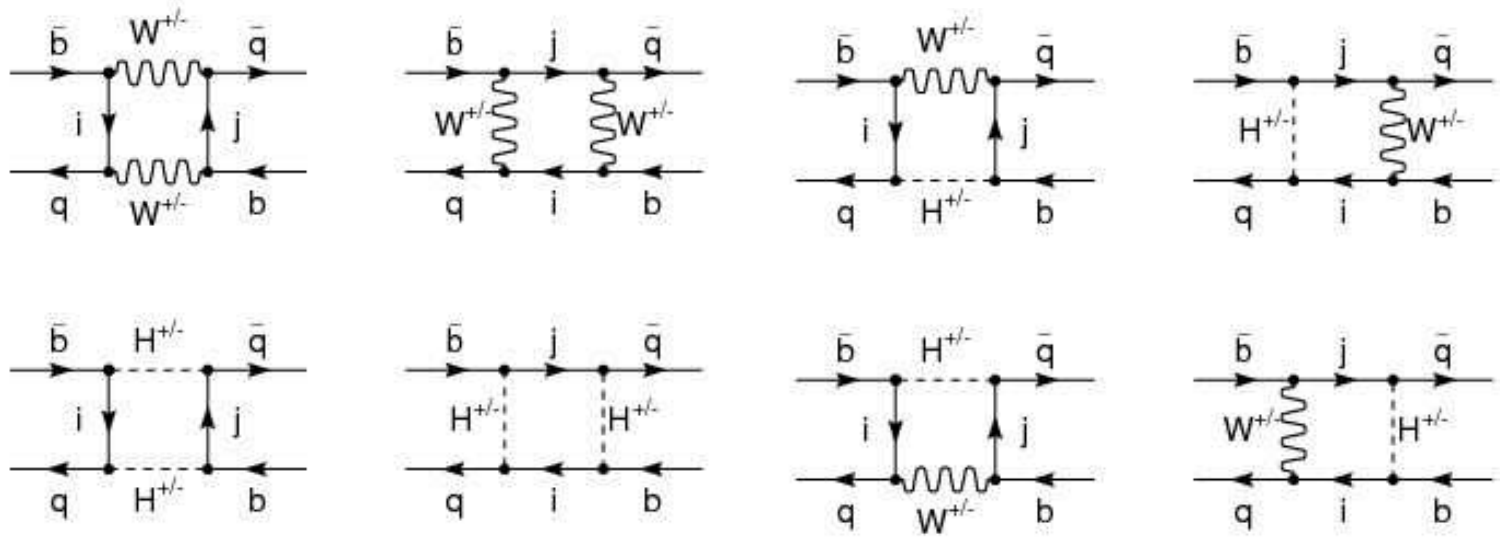
- New Physics may compete, or even dominate M_{12}.

- At the Tevatron, the dimuon charge asymmetry is the most sensitive probe of some extensions of the Standard Model.

We measure the like-sign dimuon charge asymmetry of semileptonic B decays in $p\bar{p}$ collisions:

$$A^b_{\mathsf{sl}} \equiv \frac{N^{++}_{b\bar{b}} - N^{--}_{b\bar{b}}}{N^{++}_{b\bar{b}} + N^{--}_{b\bar{b}}} = \frac{f_d \chi_{d0} a^d_{\mathsf{sl}} + f_s \chi_{s0} a^s_{\mathsf{sl}}}{f_d \chi_{d0} + f_s \chi_{s0}}$$

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

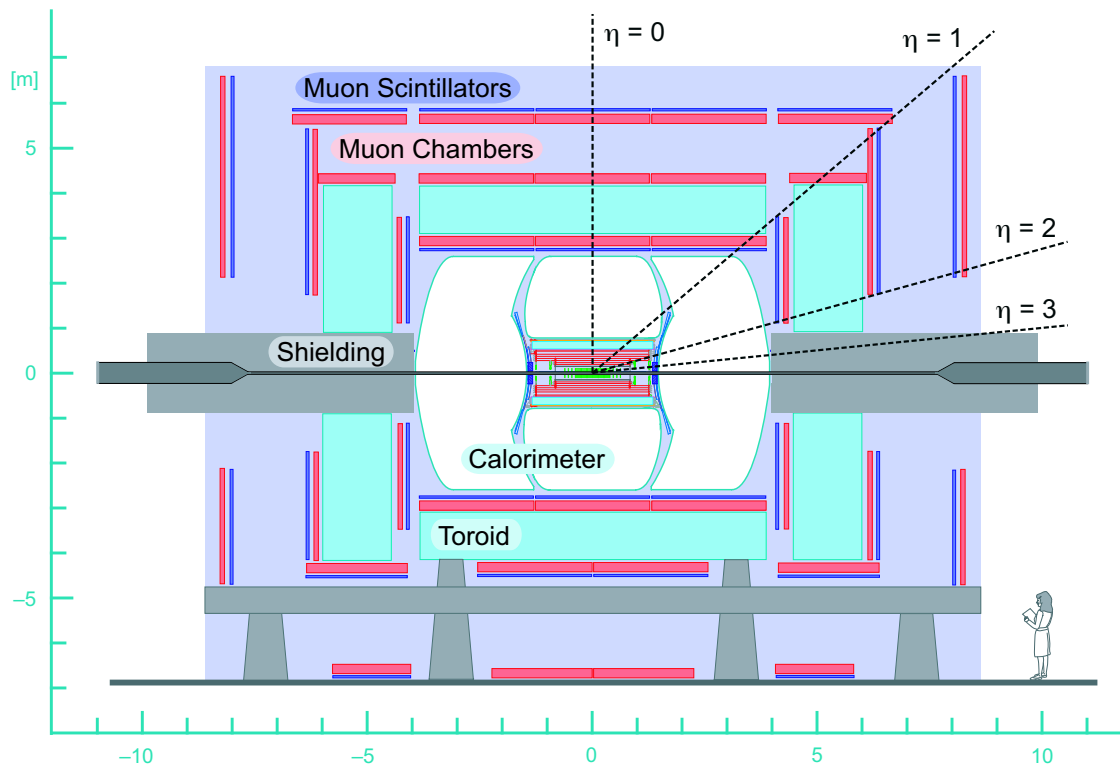$$a^s_{\mathsf{sl}} = \frac{\Delta \Gamma_s}{\Delta M_s} \tan \phi_s$$

A^b_{sl} is obtained from the like-sign dimuon charge asymmetry

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

- In the Standard Model $\phi_s \approx 0$ and $A_{\text{sl}}^b \approx 0$.

- Any significant deviation of the dimuon charge asymmetry A_{sl}^b from zero is unambiguous evidence of New Physics.

- The measurement of the dimuon charge asymmetry complements studies with $B_s \rightarrow J/\psi\phi$: they both obtain ϕ_s.

See Appendix B: Theory.

2. Overview

The DØ detector.

This analysis uses two data sets:

The inclusive muon set contains all events which have at least one muon candidate (passing a given set of single muon triggers and selection cuts).
1.495×10^9 muons.

The like-sign dimuon set contains all events with 2 muon candidates with equal charges (passing a given set of dimuon triggers and selection cuts).
3.731×10^6 events.

Origin of muons:

"Short S" muons (fraction f_S) created within a few mm of the primary vertex:

- decay of b quark, $b \to \mu X$;

- decay of c quark, $c \to \mu X$;

- decays of J/ψ, η, ω, τ etc.;

"Long L" muons:

- kaon decay $K \to \mu\nu$, punch-through or fake (fraction f_K);

- pion decay $\pi \to \mu\nu$, punch-through or fake (fraction f_π);

- proton identified as a muon: punch-through or fake (fraction f_p);

Analysis in a nut shell

1.
   - Count n^+ and n^- and obtain $a = (n^+ - n^-)/(n^+ + n^-)$.
   - Correct for L muons and obtain a_S.
   - Correct for non-direct semileptonic b decays: $A_{\text{sl}}^b = a_S/(0.07 \pm 0.006)$.

2.
   - Count N^{++} and N^{--} and obtain $A = (N^{++} - N^{--})/(N^{++} + N^{--})$.
   - Correct for L muons and obtain A_S.
   - Correct for non-direct semileptonic b decays: $A_{\text{sl}}^b = A_S/(0.486 \pm 0.032)$.

3. Combine A and a to cancel correlated uncertainties and reduce the uncertainty of A_{sl}^b.

The inclusive muon charge asymmetry

$$a = f_S(a_S + \delta) + f_K a_K + f_\pi a_\pi + f_p a_p,$$

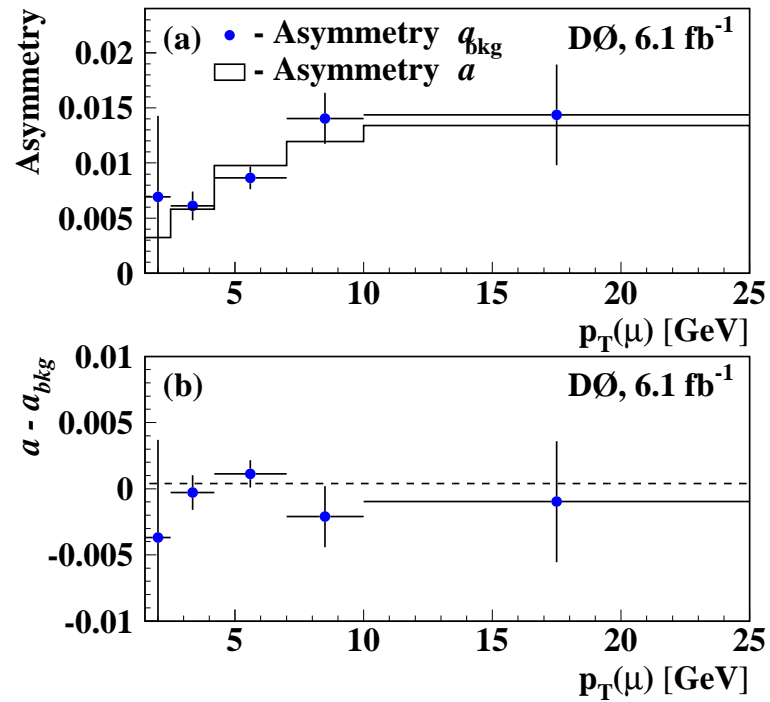and the like-sign dimuon charge asymmetry

$$A = F_{SS}A_S + F_{SL}a_S + (2 - F_{\text{bkg}})\Delta + F_K A_K + F_\pi A_\pi + F_p A_p$$
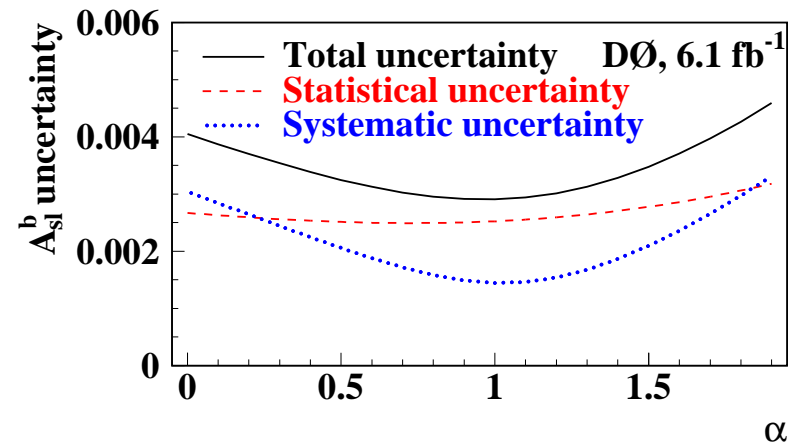
have common sources of backgrounds. These can be (partially) cancelled in $A - \alpha a$, resulting in a minimum total uncertainty of A_S.

All parameters are measured with data as a function of p_T by reconstructing exclusive decays:

- f_K: $K^{*+} \rightarrow K_S \pi^+$, $K^{*0} \rightarrow \pi^- K^+ \rightarrow \mu^+$ and $K_S \rightarrow \pi^+ \pi^-$.

- f_π: f_K, $K_S \rightarrow \pi^+ \pi^- \rightarrow \mu$, $\phi \rightarrow K^+ K^- \rightarrow \mu$ and n_π / n_K from MC.

- f_p: f_K, $\Lambda \rightarrow \pi^- p^+ \rightarrow \mu$, $\phi \rightarrow K^+ K^- \rightarrow \mu$ and n_p / n_K from MC.

- a_K: $K^{*0} \rightarrow \pi^- K^+ \rightarrow \mu^+$ and $\phi \rightarrow K^+ K^- \rightarrow \mu$.

- a_π: $K_S \rightarrow \pi^+ \pi^- \rightarrow \mu$.

- a_p: $\Lambda \rightarrow \pi^- p \rightarrow \mu$.

- δ: $J/\psi \rightarrow$ track track $\rightarrow \mu$.

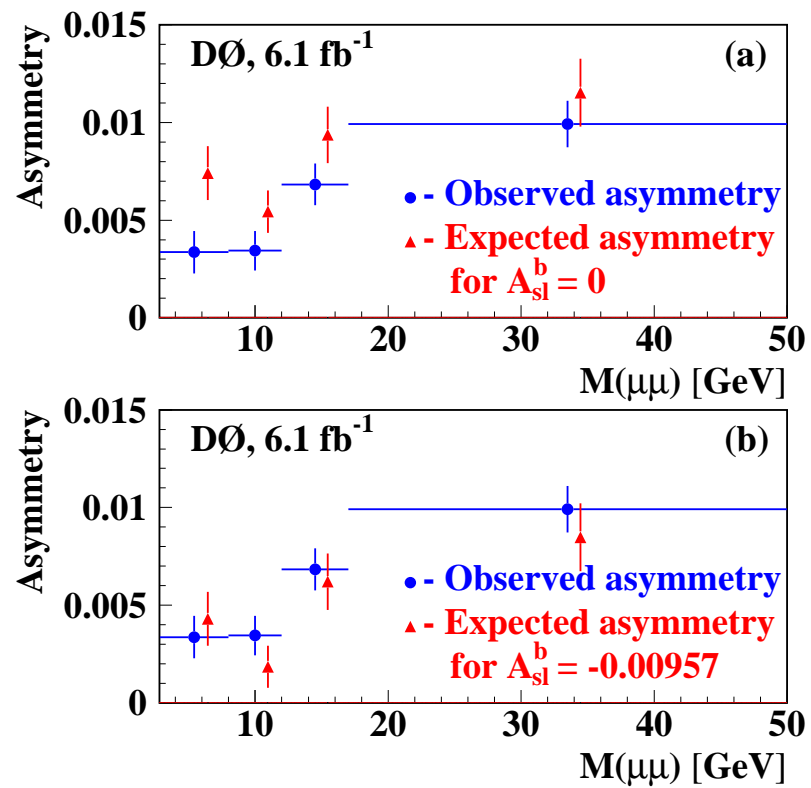Closure test: $a = f_S(a_S + \delta) + f_K a_K + f_\pi a_\pi + f_p a_p \equiv f_S a_S + a_{\mathsf{bkg}}$.

Uncertainties of A_{sl}^{b} for different values of parameter α. We set $\alpha = 0.959$ for minimum total uncertainty.

Final result from $A - \alpha a$ for 6.1 fb^{-1}:

$A_{sl}^{b} = -0.00957 \pm 0.00251(\text{stat}) \pm 0.00146(\text{syst})$

Observed and expected like-sign dimuon charge asymmetries A in bins of dimuon invariant mass. The expected asymmetry is shown for (a) $A_{sl}^b = 0.0$ and (b) $A_{sl}^b = -0.00957$.

Breakdown of uncertainties of A^b_{sl}

| Source	From a	From A	From $A - \alpha a$
A or a (stat)	0.00066	0.00159	0.00179
f_K or F_K (stat)	0.00222	0.00123	0.00140
$P(\pi \to \mu)/P(K \to \mu)$	0.00234	0.00038	0.00010
$P(p \to \mu)/P(K \to \mu)$	0.00301	0.00044	0.00011
A_K	0.00410	0.00076	0.00061
A_π	0.00699	0.00086	0.00035
A_p	0.00478	0.00054	0.00001
δ or Δ	0.00405	0.00105	0.00077
f_K or F_K (syst)	0.02137	0.00300	0.00128
π, K, p multiplicity	0.00098	0.00025	0.00018
c_b or C_b	0.00080	0.00046	0.00068
Total statistical	0.01118	0.00266	0.00251
Total systematic	0.02140	0.00305	0.00146
Total	**0.02415**	**0.00405**	**0.00290**

Tests. Measured asymmetry A_{sl}^b with reference and several modified selections (see Appendix A). The raw parameters change in a wide range, while the resulting asymmetry A_{sl}^b is stable. This is a strong confirmation of the method.

| Test:	Ref	A	B	C	D	E	F
$N(\mu\mu) \times 10^{-6}$	3.731	1.809	2.733	1.809	1.785	2.121	1.932
$a \times 10^2$	+0.955	+0.988	+0.791	+0.336	+1.057	+0.950	+1.029
$A \times 10^2$	+0.564	+0.531	+0.276	-0.229	+0.845	+0.543	+0.581
α	0.959	0.901	0.942	1.089	1.083	0.902	0.915
$[(2 - F_{bkg})\Delta - \alpha f_S \delta] \times 10^2$	-0.065	-0.072	-0.143	-0.200	-0.074	-0.075	-0.069
F_{bkg}	0.409	0.372	0.401	0.303	0.384	0.385	0.426
$A_{sl}^b \times 10^2$	-0.957	-0.976	-1.084	-0.892	-1.107	-0.888	-1.096
$\sigma(A_{sl}^b) \times 10^2$ (stat)	0.251	0.330	0.293	0.315	0.402	0.328	0.375
Significance		0.090	0.846	0.324	0.478	0.326	0.498

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- Details in Appendix A.

- Theory in Appendix B.

- Full details in arXiv:1005.2757 (16 May 2010).

3. Result

- This measurement (6.1 fb^{-1}):
  $A^b_{\text{sl}} = -0.00957 \pm 0.00251(\text{stat}) \pm 0.00146(\text{syst})$.

- 3.2 standard deviation discrepancy with the Standard Model

- This is a precision measurement: $F_{SS}A_S = -0.00309 \pm 0.00090$.

- This result is in agreement with the DØ publication of 2006 (1 fb^{-1}) and superseeds it.
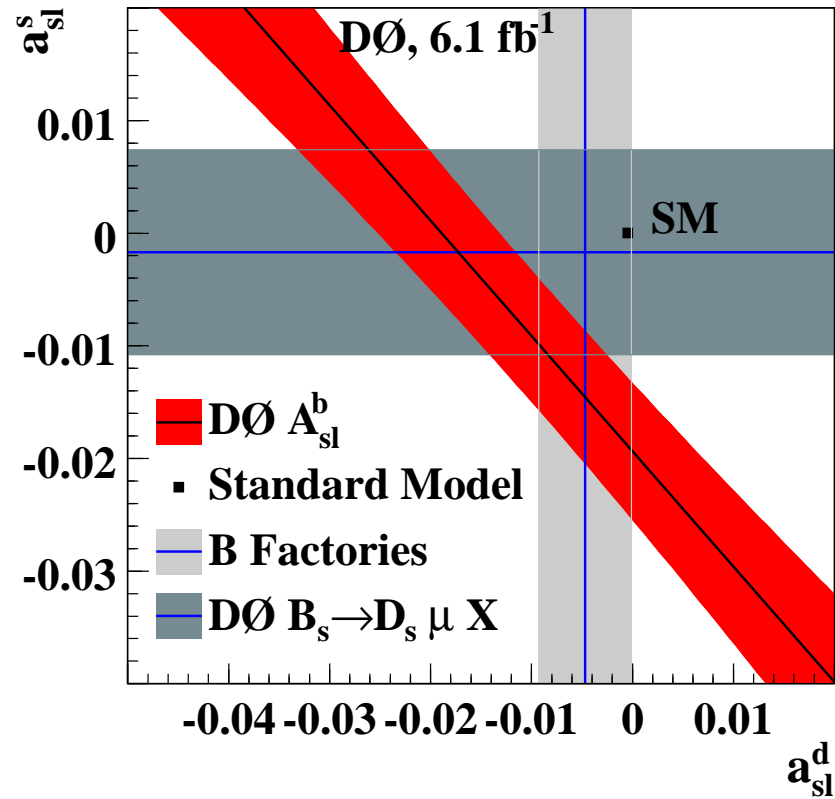
Comparison of the A_{sl}^b measurement with the standard model (SM) prediction for a_{sl}^d and a_{sl}^s.
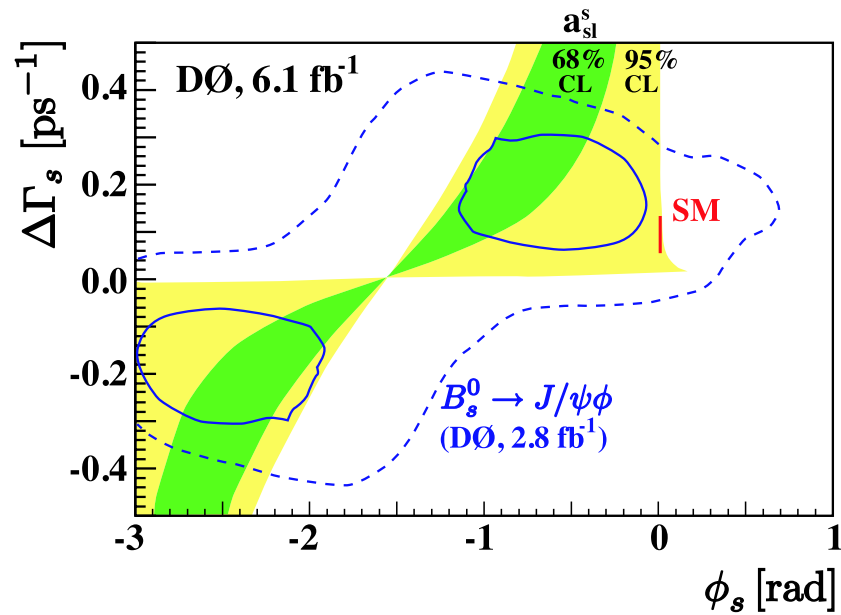
The 68% and 95% C.L. regions of $\Delta\Gamma_s$ and ϕ_s obtained from this measurement, and from $B_s \to J/\psi\phi$ at DØ . Also shown is the standard model (SM) prediction.
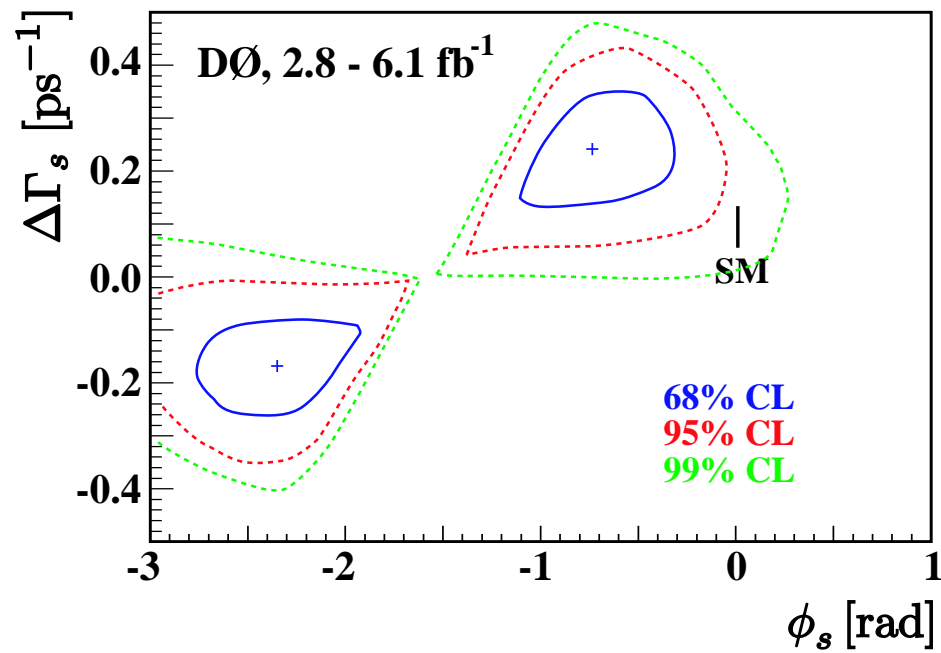
Confidence level contours in the ϕ_s–$\Delta\Gamma_s$ plane for the combination of this measurement and $B_s \to J/\psi\phi$ at DØ.

25 citations of arXiv:1005.2757 from 16 May to 10 July 2010:

- arXiv:1006.0432, Title: Implications of the dimuon CP asymmetry in B_d,s decays, Authors: Zoltan Ligeti, Michele Papucci, Gilad Perez, Jure Zupan.

- arXiv:1005.5310, Title: Higgs-mediated FCNCs: Natural Flavour Conservation vs. Minimal Flavour Violation, Authors: Andrzej J. Buras, Maria Valentina Carlucci, Stefania Gori, Gino Isidori.

- arXiv:1005.4582, Title: Axigluon on like-sign charge asymmetry $\mathcal{A}^b\_s\ell$, FCNCs and CP asymmetries in B decays, Authors: Chuan-Hung Chen, Gaber Faisel.

- arXiv:1005.4238, Title: CP violation in B_s mixing from heavy Higgs exchange, Authors: Bogdan A. Dobrescu, Patrick J. Fox, Adam Martin.

- arXiv:1005.4051, Title: Enhanced $B_S\bar{B}_S$ lifetime difference and anomalous like-sign dimuon charge asymmetry from new physics in $B\_s \to \tau^+\tau^-$, Authors: Amol Dighe, Anirban Kundu and, Soumitra Nandi.

- arXiv:1005.3505, Title: Less space for a new family of fermions, Authors: Otto Eberhardt, Alexander Lenz, Jrgen Rohrwild. ... etc

This is the first evidence of anomalous CP-violation in the mixing of neutral B mesons.

Appendix A: Details

- **Test A:** Part of data sample corresponding to the first 2.8 fb^{-1} (RunIIa) is used.

- **Test B:** Tight muon selection. In addition to the *reference* selection cuts, we require at least three hits in wire chamber layers B or C, and the χ^2 of the local track fit in the muon detector less than 8.

- **Test C:** Since the background muons are produced by decays of kaons and pions, their track parameters measured by the central tracker and by the muon system are different. Therefore, the fraction of background strongly depends on the χ^2 of the difference between these two measurements. The cut on this χ^2 is changed from 40 to 4 in this test.

- **Test D:** The cut on the transverse impact parameter is changed from 0.3 to 0.05 cm, and the cut on the longitudinal distance between the point of closest approach to the beam and the associated vertex is changed from 0.5 to 0.05 cm.

- **Test E:** Select low-luminosity events by selecting events with less than three primary interactions.

- **Test F:** Events with the same polarities of solenoid and toroid magnet are used.

- **Test G:** The cut on the mass of the two muons is changed from 2.8 GeV to 12 GeV.

- **Test H:** Require that the muon transverse momentum $p_T > 4.2$ GeV.

- **Test I:** Require that the muon transverse momentum $p_T < 7.0$ GeV.

- **Test J:** Require that the muon momentum azimuthal angle ϕ be in the ranges $0 < \phi < 4$ or $5.7 < \phi < 2\pi$. This selection excludes muons directed to the region of lower muon identification efficiency.

- **Test K:** Require that the muon pseudorapidity η be in the range $|\eta| < 1.6$.

- **Test L:** Require that the muon pseudorapidity η be in the range $|\eta| < 1.2$ or $1.6 < |\eta| < 2.2$.

- **Test M:** Require that the muon pseudorapidity η be in the range $|\eta| < 0.7$ or $1.2 < |\eta| < 2.2$.

- **Test N:** Require that the muon pseudorapidity η be in the range $0.7 < |\eta| < 2.2$.

- **Test O:** Like-sign dimuon events passing at least one single muon trigger are used, while the request of a dimuon trigger for these events is dropped.

- **Test P:** Like-sign dimuon events passing both single muon and dimuon triggers are used.
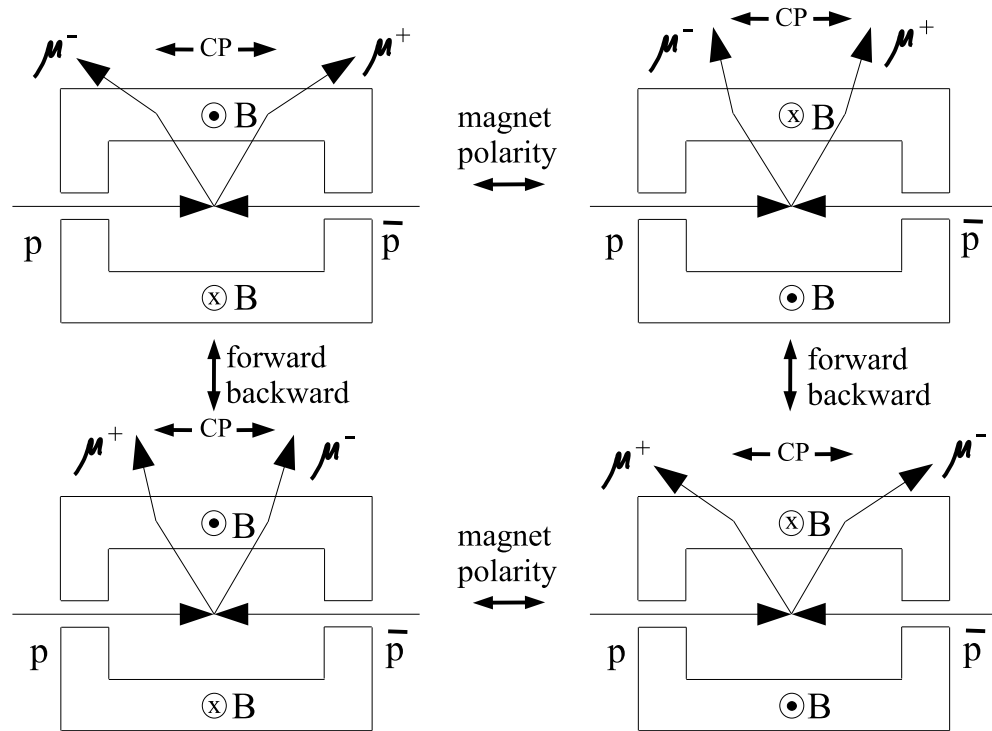
Reversal of magnetic fields cancels first order detector asymmetries.

Data selection

Track selection:

$p_T > 1.5$ GeV,

$p_T > 4.2$ or $|p_z| > 6.4$ GeV dictated by detector geometry,

$p_T < 25$ GeV,

at least 3 hits in the silicon microstrip tracker,

at least 6 hits in the central fiber tracker,

vertex match,

transverse impact parameter < 0.3 cm,

longitudinal impact parameter < 0.5 cm,

$|\eta| < 2.2$,

track χ^2/d.f. < 6.

Muon selection:
Track with matching muon,
local fit converged,
global $\chi^2 < 40$,
at least one scintillator hit on track with $|\Delta t| < 5$ ns,
at least 2 hits in drift chambers A,
at least 2 hits in drift chambers B or C.

Triggers: single muon or dimuon.

Dimuons: Two muons, same vertex, same charge, $m(\mu\mu) > 2.8$ GeV.

Details in a backup slide.

1. The observed charge asymmetry
of the inclusive muon data set is

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-} = f_S(a_S + \delta) + f_K a_K + f_\pi a_\pi + f_p a_p.$$

To obtain a_S, we measure all other parameters
in data as a function of the muon p_T.

Results from a for 6.1 fb^{-1}:
$a = +0.00955 \pm 0.00003$ ("raw" asymmetry from muon counts),
$f_K a_K = 0.00854 \pm 0.00018$(stat) (largest correction),
$f_S = 0.581 \pm 0.014$(stat) ± 0.039(syst) (fraction of S muons),
$a_S = (0.070 \pm 0.005) A_{\text{sl}}^b$,
$A_{\text{sl}}^b = +0.0094 \pm 0.0112$(stat) ± 0.0214(syst).

2. Some definitions for like-sign dimuons:

$$N = N^{++} + N^{--} = N_{SS} + N_{SL} + N_{LL}.$$

N_{SS} - both muons are S

N_{SL} - one muon is S and one is L

N_{LL} - both muons are L, i.e. from K, π or p

$$F_{SS} \equiv N_{SS}/N; \qquad F_{LL} \equiv N_{LL}/N; \qquad F_{SL} \equiv N_{SL}/N;$$

$$F_{\mathsf{bkg}} \equiv F_K + F_\pi + F_p = F_{SL} + 2F_{LL}.$$

Like-sign dimuon charge asymmetry:

$$A = F_{SS}A_S + F_{SL}a_S + (2 - F_{\mathsf{bkg}})\Delta + F_K A_K + F_\pi A_\pi + F_p A_p.$$

To obtain A_S, we measure all other parameters in the data as a function of the muon p_T.

From MC:

$$A_S = (0.486 \pm 0.032)A_{\mathsf{sl}}^b$$

Results from A for 6.1 fb^{-1}:

- $A = +0.00564 \pm 0.00053$ ("raw" asymmetry from dimuon counts)

- $F_K A_K = 0.00828 \pm 0.00035$(stat) (largest correction)

- $F_{SS} = 0.665 \pm 0.016$(stat) ± 0.033(syst)

- $A_{\text{sl}}^b = -0.00736 \pm 0.00266$(stat) ± 0.00305(syst)
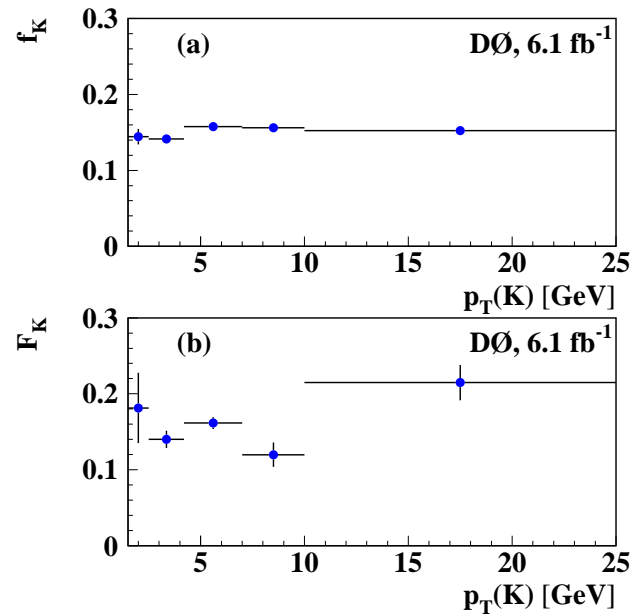
Fraction of $K \to \mu$ tracks in the inclusive muon sample (upper plot) and like-sign dimuon sample (lower plot) versus the muon transverse momentum.

Measured with $K^{*+} \to K_S \pi^+$, $K^{*0} \to \pi^- K^+ \to \mu$ and $K_S \to \pi^+ \pi^-$.
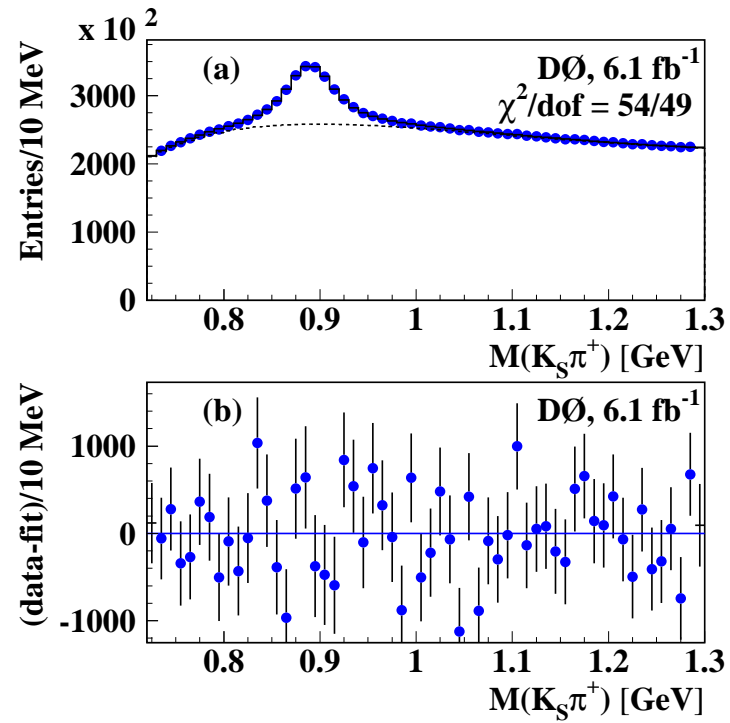
The $K_S\pi^+$ invariant mass distribution of K^{*+} candidates (upper plot). The lower plot shows the difference between data and the fit result.
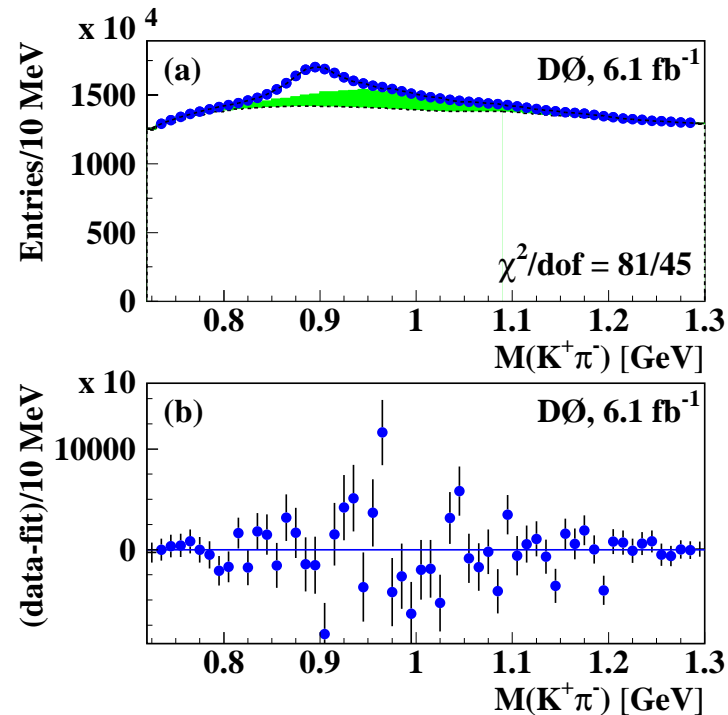
The $K^+\pi^-$ invariant mass distribution of K^{*0} candidates (upper plot) in the inclusive muon sample. The filled histogram shows the contribution of $\rho^0 \to \pi^+\pi^-$ events. The lower plot shows the difference between data and the fit result. 10^7 entries per bin!!!
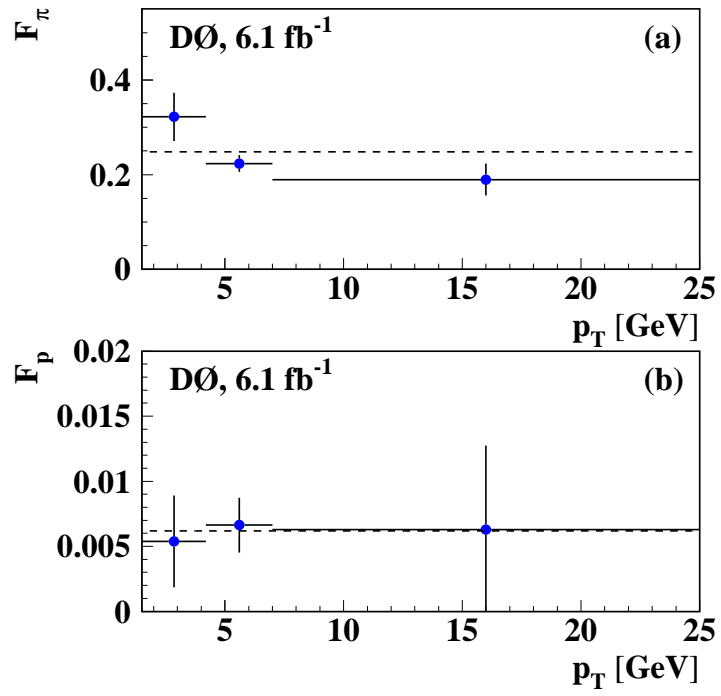
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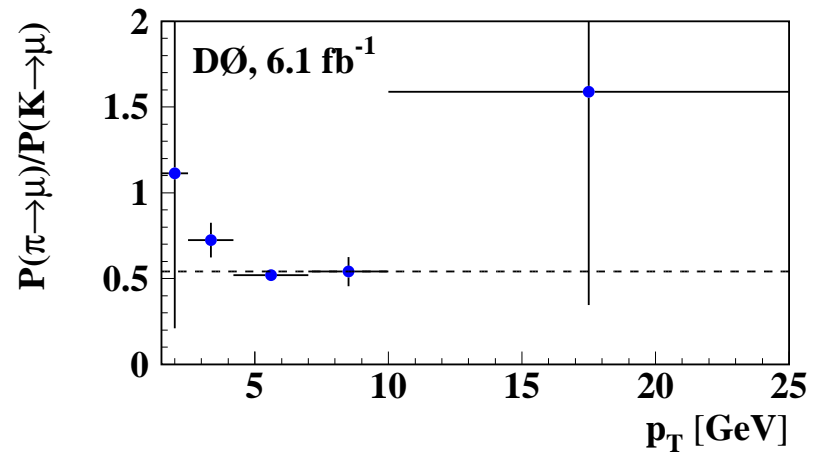
Ratio $P(\pi \rightarrow \mu)/P(K \rightarrow \mu)$ versus the particle transverse momentum. Measured with $K_S \rightarrow \pi^+\pi^- \rightarrow \mu$ and $\phi \rightarrow K^+K^- \rightarrow \mu$.
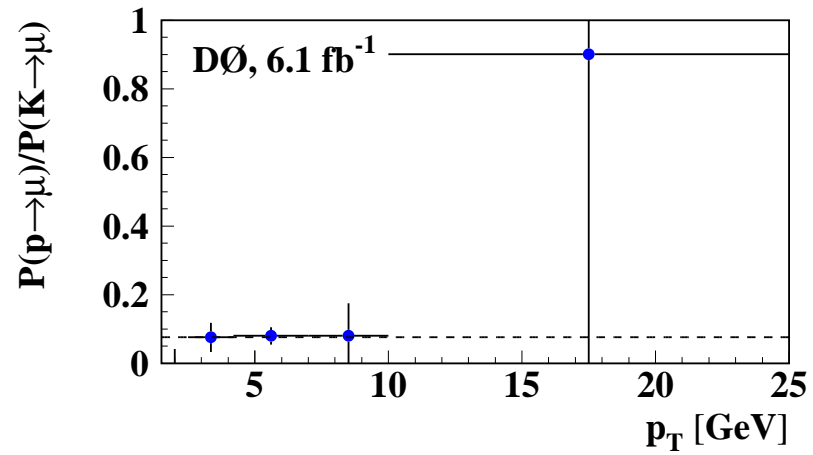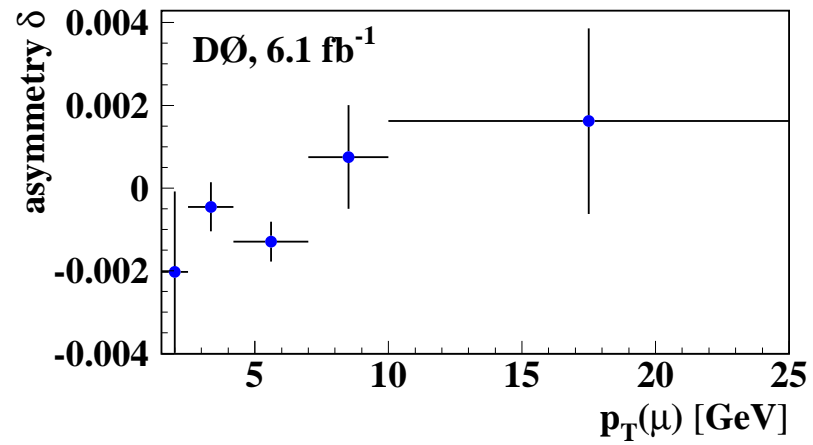
Ratio $P(p \to \mu)/P(K \to \mu)$ versus the particle transverse momentum. Measured with $\Lambda \to \pi^- p^+ \to \mu^+$ and $\phi \to K^+ K^- \to \mu$.
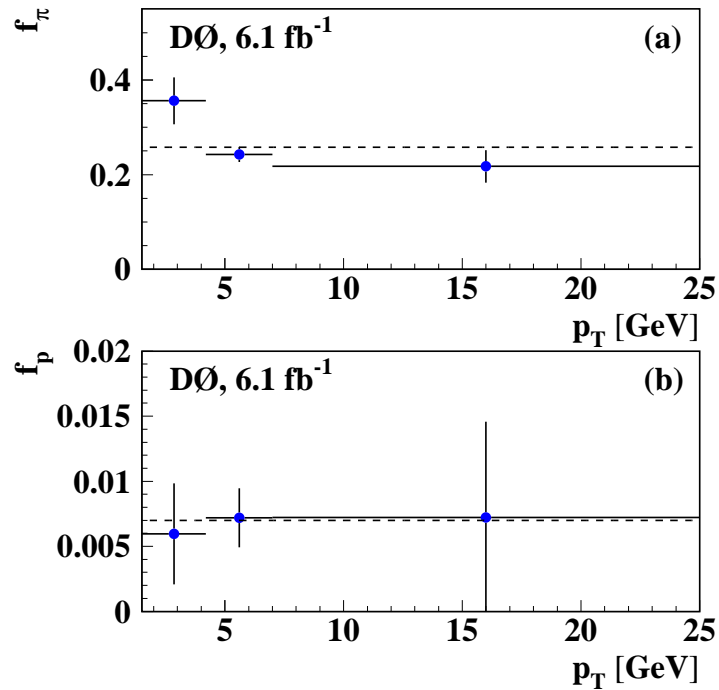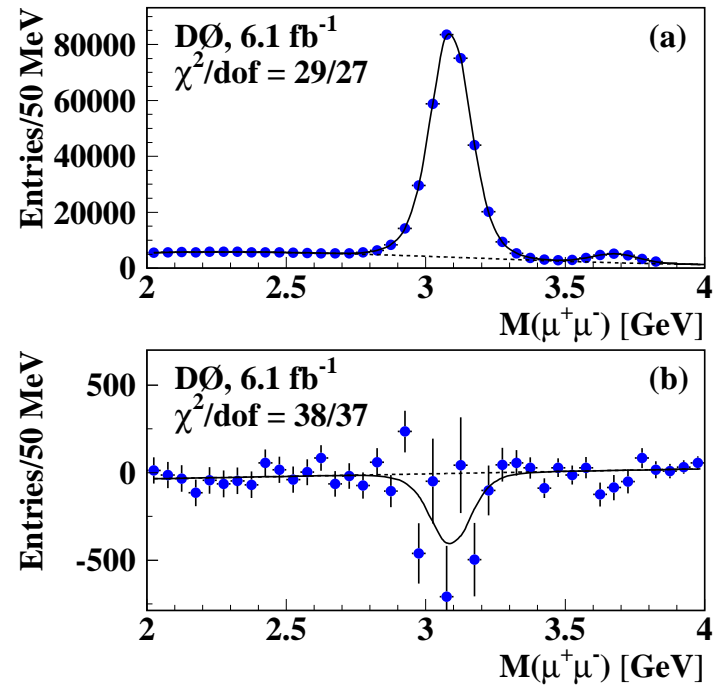
Fraction of $\pi \to \mu$ tracks (upper plot) and $p \to \mu$ tracks (lower plot) in the inclusive muon sample versus the muon transverse momentum.

Fraction of $\pi \to \mu$ tracks (upper plot) and $p \to \mu$ tracks (lower plot) in the like-sign dimuon sample versus the muon transverse momentum.

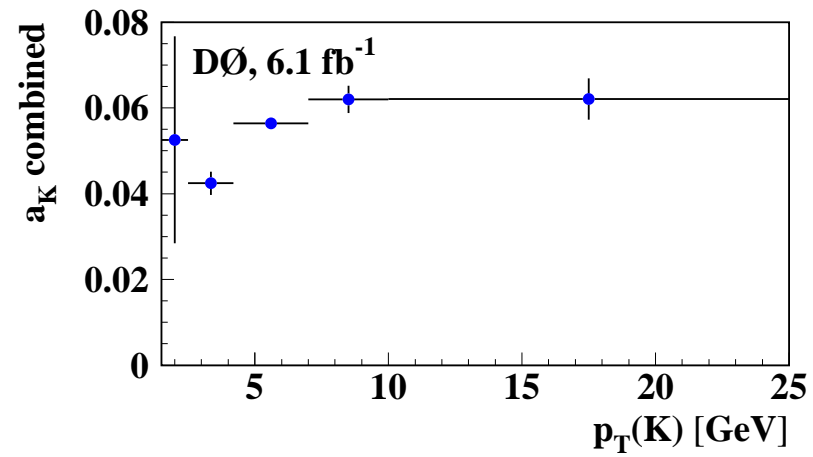Muon identification asymmetry δ versus the muon transverse momentum. Measured using $J/\psi \rightarrow$ track track $\rightarrow \mu$.
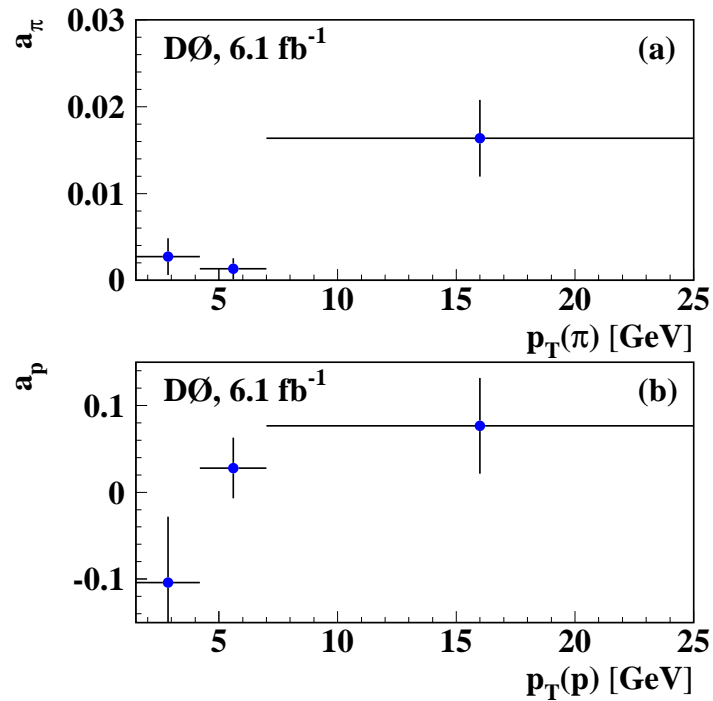
The detector efficiency asymmetry δ is measured with J/ψ's (two tracks and at least one of them matches a muon). Two examples of invariant mass histograms are shown: $N_{23} + N_{32}$ and $N_{23} - N_{32}$.

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Asymmetry a_K versus the $K \to \mu$ transverse momentum. Measured with $K^{*0} \to \pi^- K^+ \to \mu^+$ and $\phi \to K^+ K^- \to \mu$.

Asymmetries a_π (upper plot) and a_p (lower plot) versus the transverse momentum of pion or proton respectively. Measured with $K_S \to \pi^+\pi^- \to \mu$ and $\Lambda \to \pi^- p \to \mu$ respectively.

Heavy quark decays contributing to the inclusive muon and like-sign dimuon samples.

Name	description	weight
T_1	$b \to \mu^-$	$p_1 \equiv 1.$
T_{1a}	$b \to \mu^-$ (nos)	$p_{1a} = (1 - \chi_0)p_1$
T_{1b}	$\bar{b} \to b \to \mu^-$ (osc)	$p_{1b} = \chi_0 p_1$
T_2	$b \to c \to \mu^+$	$p_2 = 0.113 \pm 0.007$
T_{2a}	$b \to c \to \mu^+$ (nos)	$p_{2a} = (1 - \chi_0)p_2$
T_{2b}	$\bar{b} \to b \to c \to \mu^+$ (osc)	$p_{2b} = \chi_0 p_2$
T_3	$b \to c\bar{c}q$ with $c \to \mu^+$ or $\bar{c} \to \mu^-$	$p_3 = 0.062 \pm 0.004$
T_4	$\eta, \omega, \rho^0, \phi(1020), J/\psi, \psi' \to \mu^+\mu^-$	$p_4 = 0.021 \pm 0.001$
T_5	$b\bar{b} + c\bar{c}$ with $c \to \mu^+$ or $\bar{c} \to \mu^-$	$p_5 = 0.013 \pm 0.001$
T_6	$c\bar{c}$ with $c \to \mu^+$ or $\bar{c} \to \mu^-$	$p_6 = 0.660 \pm 0.040$

Comparison with the previous DØ measurement

- This measurement for first 1.3 fb^{-1} of data:
  $F_{SS}A_S = -0.00267 \pm 0.00133$,
  $A_{\text{sl}}^b = -0.00816 \pm 0.00432$.
  1.9 σ significance.

- DØ Collab., Phys. Rev. D **74**, 092001 (2006) (Run IIa, 1 fb^{-1}):
  $F_{SS}A_S = -0.0028 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$, Eq. (11)
  $A_{\text{sl}}^b = -0.0053 \pm 0.0031$.
  1.7 σ significance.

Appendix B: Theory

If CPT is a symmetry,

$$i\frac{d}{dt}\left(\begin{array}{c} B_s(t) \\ \bar{B}_s(t) \end{array}\right) = \left(\left[\begin{array}{cc} m & M^s_{12} \\ M^{s*}_{12} & m \end{array}\right] - \frac{i}{2}\left[\begin{array}{cc} \Gamma & \Gamma^s_{12} \\ \Gamma^{s*}_{12} & \Gamma \end{array}\right]\right)\left(\begin{array}{c} B_s(t) \\ \bar{B}_s(t) \end{array}\right).$$

The eigenvalues are

$$M_s + \frac{1}{2}\Delta M_s - \frac{i}{2}(\Gamma_s - \frac{1}{2}\Delta\Gamma_s),$$

$$M_s - \frac{1}{2}\Delta M_s - \frac{i}{2}(\Gamma_s + \frac{1}{2}\Delta\Gamma_s),$$

where $\Delta M_s > 0$ by definition.

The CP-violating phase is

$$\phi_s \equiv \arg\left(-\frac{M^s_{12}}{\Gamma^s_{12}}\right).$$

The observables are M_s, Γ_s, ϕ_s,

$$\Delta M_s = 2\left|M_{12}^s\right|, \qquad \Delta\Gamma_s = 2\left|\Gamma_{12}^s\right|\cos\phi_s,$$

$$a_{\mathsf{sl}}^s = \Im\frac{\Gamma_{12}^s}{M_{12}^s} = \frac{\left|\Gamma_{12}^s\right|}{\left|M_{12}^s\right|}\sin\phi_s = \frac{\Delta\Gamma_s}{\Delta M_s}\tan\phi_s.$$

The semileptonic charge asymmetry is

$$a_{\mathsf{sl}}^s \equiv \frac{N(\bar{B}_s \to f) - N(B_s \to \bar{f})}{N(\bar{B}_s \to f) + N(B_s \to \bar{f})},$$

where f is a flavor specific final state to which only B_s can decay.

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

$$A_{\mathsf{sl}}^b = \frac{f_d \chi_d a_{\mathsf{sl}}^d + f_s \chi_s a_{\mathsf{sl}}^s}{f_d \chi_d + f_s \chi_s} = (0.506 \pm 0.043) a_{\mathsf{sl}}^d + (0.494 \pm 0.043) a_{\mathsf{sl}}^s.$$

New Physics may change the Standard Model $M_{12}^{SM,s}$ to:

$$M_{12}^s \equiv M_{12}^{SM,s} \cdot \Delta_s = M_{12}^{SM,s} \cdot |\Delta_s| \, e^{i\phi_s^\Delta}.$$

$$\phi_s = \phi_s^{SM} + \phi_s^\Delta = 0.0042 \pm 0.0014 + \phi_s^\Delta,$$

$$\Delta M_s = \Delta M_s^{SM} \cdot |\Delta_s| = (19.30 \pm 6.74) \text{ ps}^{-1} \cdot |\Delta_s|$$

$$\Delta\Gamma_s = 2 \, |\Gamma_{12}^s| \cos\phi_s = (0.096 \pm 0.039) \text{ ps}^{-1} \cdot \cos\phi_s,$$

$$\frac{\Delta\Gamma_s}{\Delta M_s} = \frac{|\Gamma_{12}^s|}{\left|M_{12}^{SM,s}\right|} \cdot \frac{\cos\phi_s}{|\Delta_s|} = (4.97 \pm 0.94) \cdot 10^{-3} \cdot \frac{\cos\phi_s}{|\Delta_s|},$$

$$a_{sl}^s = \frac{|\Gamma_{12}^s|}{\left|M_{12}^{SM,s}\right|} \cdot \frac{\sin\phi_s}{|\Delta_s|} = (4.97 \pm 0.94) \cdot 10^{-3} \cdot \frac{\sin\phi_s}{|\Delta_s|}.$$

From Alexander Lenz and Ulrich Nierste, hep-ph/0612167, November 2007.

The ϕ_s obtained from fits to $B_s \to J/\psi\phi$ is slightly different:

$$\phi_s = -2\beta_s^{SM} + \phi_s^{\triangle},$$

where

$$\beta_s^{SM} \equiv \arg \frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} = 0.019 \pm 0.001.$$

Backup slides

Track selection:
$p_T > 1.5$ GeV,
$p_T > 4.2$ or $|p_z| > 6.4$ GeV,
$p_T < 25$ GeV,
nSMTAx ≥ 2,
nSMTSt ≥ 1,
nCFTAx ≥ 3,
nCFTSt() ≥ 3,
vertex match,
transverse impact parameter < 0.3 cm,
longitudinal impact parameter < 0.5 cm,
$|\eta| < 2.2$,
track $\chi^2/$d.f. < 6.

Muon tag:
Matching muon with nseg ≥ 3

Loose muon selection:
nshita1 + nshitb1 + nshitc1 ≥ 1,
global $\chi^2 > -0.1$,
global $\chi^2 < 40$,
sctimeA < 5.0 or sctimeB < 5.0 or sctimeC < 5.0 ns,

Standard muon selection:
nwhita1 ≥ 2,
nwhitb1 + nwhitc1 ≥ 2,
local $\chi^2 > -0.1$ and categoryloc $= 1$,

Triggers: single muon or dimuon.

1. The number of observed μ^+ (upper signs) or μ^- (lower signs) candidates is

$$n^{\pm} \propto f_S(1 \pm a_S)(1 \pm \delta) + f_K(1 \pm a_K) + f_{\pi}(1 \pm a_{\pi}) + f_p(1 \pm a_p).$$

δ is the charge asymmetry of the detector efficiency,
a_S is the single muon charge asymmetry of S muons,
$f_S = 1 - f_K - f_{\pi} - f_p$ is the fraction of S muons,
f_K is the fraction of muons from charged kaon decay or punch-through and a_K is their measured charge asymmetry,
and similarly for f_{π}, a_{π}, f_p, a_p for pion decay or punch-through or proton punch-through.

3. Experimentally we find:

$$\frac{F_K}{f_K} \approx \frac{F_\pi}{f_\pi} \approx \frac{F_p}{f_p} \approx 1.$$

Note that

$$
\begin{aligned}
a &= f_S(a_S + \delta) + f_K a_K + f_\pi a_\pi + f_p a_p, \\
A &= F_{SS} A_S + F_{SL} a_S + (2 - F_{\text{bkg}})\Delta + F_K A_K + F_\pi A_\pi + F_p A_p,
\end{aligned}
$$

have common sources of backgrounds. These can be (partially) cancelled in $A - \alpha a$, resulting in a minimum total uncertainty of A_S for $\alpha \approx 1$.