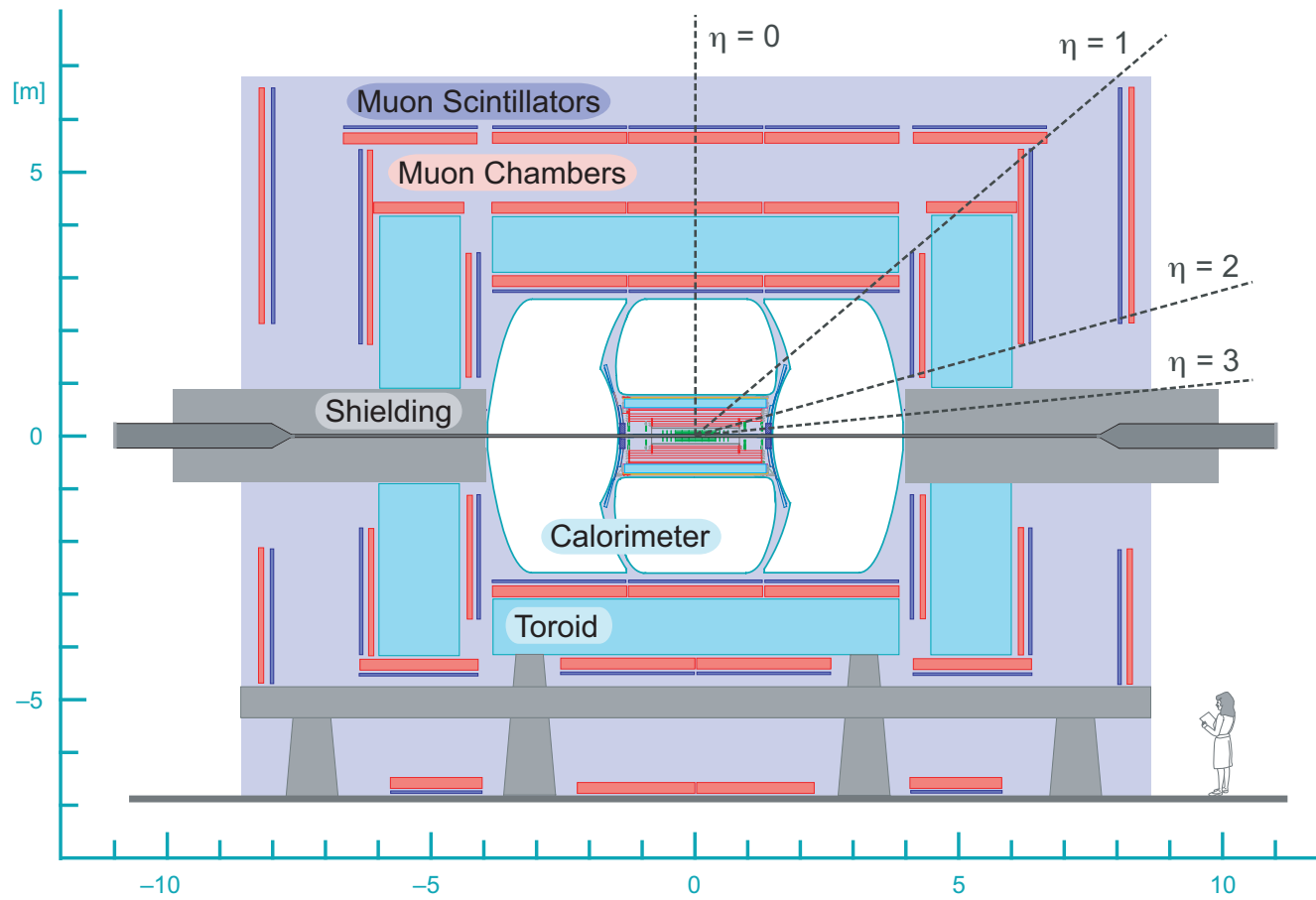# Study of the anomalous like-sign dimuon charge asymmetry in $p\bar{p}$ collisions

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The DØ detector.

1. Motivation: (in 1992!)
CP violation in mixing of $B^0 \leftrightarrow \bar{B}^0$ and $B_s^0 \leftrightarrow \bar{B}_s^0$

Example: $p\bar{p} \to b\bar{b}X$,

$b \to B^- \to \mu^-$ ("right sign" μ), $\bar{b} \to B^0 \to \bar{B}^0 \to \mu^-$ ("wrong sign" μ)

$\bar{b} \to B^+ \to \mu^+$ ("right sign" μ), $b \to \bar{B}^0 \to B^0 \to \mu^+$ ("wrong sign" μ)

2. Outline of the measurement:

Two data sets: Like-sign dimuons and inclusive muons.

"Raw" charge asymmetries:

$$A \equiv \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)}; \quad a \equiv \frac{n(\mu^+) - n(\mu^-)}{n(\mu^+) + n(\mu^-)}$$

"Residual" charge asymmetries:

$$A_{CP} \equiv A - A_{\mathsf{bkg}}; \quad a_{CP} = a - a_{\mathsf{bkg}}.$$

Model independent asymmetries: A_{CP} and a_{CP} are normalized to all muons. The corresponding asymmetries A_S and a_S have normalizations that exclude muons from kaon and pion decay.

$$a_{CP} = a - a_{\mathsf{bkg}}$$

$$a_{\mathsf{bkg}} = a_\mu + f_K a_K + f_\pi a_\pi + f_p a_p$$

- The fraction of muons from kaon decay f_K is measured with $K^{*0} \to K^+\pi^-$ and $K^+ \to \mu^+\nu$. $f_{K^{*0}}$ converted to f_K with $K^{*+} \to K_S\pi^+$ and $K_S \to \pi^+\pi^-$.

- The charge asymmetry of muons from kaon decay a_K is measured with $K^{*0} \to K^+\pi^-$ or $\phi \to K^+K^-$, followed by $K^+ \to \mu^+\nu$.

- The muon detector charge asymmetry a_μ is measured with $J/\psi \to \mu^+\mu^-$ reconstructed from tracks only.

- New cross-check: The background fraction $f_K + f_\pi$ is also measured from "central" vs. "muon" tracks.

3. History

Residual asymmetry $A_{CP} = A - A_{\mathsf{bkg}}$ measured with different
integrated luminosities $\int L dt$.

$\int L dt$	asymmetry A_{CP}		(DØ), Phys.Rev. D
1.0 fb^{-1}	$(-0.28 \pm 0.13 \pm 0.09\ )\%$	1.7σ *	**74**, 092001 (2006)
6.1 fb^{-1}	$(-0.252 \pm 0.088 \pm 0.092)\%$	3.2σ *	**82**, 032001 (2010)
9.0 fb^{-1}	$(-0.276 \pm 0.067 \pm 0.063)\%$	3.9σ *	**84**, 052007 (2011)
10.4 fb^{-1}	$(? \pm 0.064 \pm 0.055)\%$	$?\sigma$ &	# (2013)

* Discrepancy with $A_{CP}^{\mathsf{mix}}(\mathsf{SM})$ only.

& Discrepancy with $A_{CP}^{\mathsf{mix}}(\mathsf{SM})$ and $A_{CP}^{\mathsf{int}}(\mathsf{SM})$.

In DØ Collaboration review. Preliminary.

4. CPV in interference of B^0

Example: $p\bar{p} \to b\bar{b}X$,

$b \to B^- \to \mu^-$ ("right sign" μ), $\bar{b} \to B^0(\to \bar{B}^0) \to D^+D^-$, $D^- \to \mu^-$ ("wrong sign" μ)

$\bar{b} \to B^+ \to \mu^+$ ("right sign" μ), $b \to \bar{B}^0(\to B^0) \to D^+D^-$, $D^+ \to \mu^+$ ("wrong sign" μ)

D^+D^- is CP-even.

$$\frac{d\Gamma(\bar{B}^0 \to D^+D^-)}{dt} \propto \exp\left(-\Gamma_d t\right)\left[1 - \sin\left(2\beta\right)\sin\left(\Delta m_d t\right)\right],$$

$$\frac{d\Gamma(B^0 \to D^+D^-)}{dt} \propto \exp\left(-\Gamma_d t\right)\left[1 + \sin\left(2\beta\right)\sin\left(\Delta m_d t\right)\right].$$

For this decay $\bar{B}^0(B^0) \to D^+ D^-$:

$$A_S^{\text{int}} = -\sin{(2\beta)}\frac{x_d}{1 + x_d^2}.$$

This asymmetry is numerically LARGE because
$\sin(2\beta) = 0.679 \pm 0.020$ and $x_d \equiv \Delta m_d/\Gamma_d = 0.770 \pm 0.008$.

CPV in interference does not contribute to a_{CP}: because $D^+ \to \mu^+$
cancels $D^- \to \mu^-$.

5. Status with 9.0 fb^{-1} (2011):

Comparison between experiment and the standard model:

$$
\begin{aligned}
a_{CP}(\text{data}) &= (-0.034 \pm 0.042 \pm 0.073)\%, \\
a_{CP}^{\text{mix}}(\text{SM}) &= (-0.0007 \pm 0.0002)\%, \\
a_{CP}^{\text{int}}(\text{SM}) &= (-0.000 \pm 0.000)\%, \\
A_{CP}(\text{data}) &= (-0.276 \pm 0.067 \pm 0.063)\%, \\
A_{CP}^{\text{mix}}(\text{SM}) &= (-0.008 \pm 0.002)\%, \\
A_{CP}^{\text{int}}(\text{SM}) &= (-0.035 \pm 0.008)\%.
\end{aligned}
$$

What is the cause of this discrepancy?

From DØ , Phys. Rev. D **84** 052007 (2010), and

G. Borissov and B. Hoeneisen, Phys. Rev. D **87**, 074020 (2013).

6. Experimental constraints

Contributions to A_S allowed by experiments:
(compare with $A_S = (-0.383 \pm 0.092 \pm 0.102)\%$ PRD (2011))

Process	Allowed A_S
Mixing of B^0	$(+0.062 \pm 0.073)\%$
Mixing of B^0_s	$(-0.111 \pm 0.093)\%$ *
Interference of B^0	$(-0.045 \pm 0.016)\%$ (SM)
Interference of B^0_s	$(-0.0009 \pm 0.0003)\%$ (SM)
CPV in $b \to c\bar{c}\bar{q}$ decays	$(+0.000 \pm 0.001)\%$
$a_{(b)}$ in $b \to \mu X$ decays	$(-0.17 \pm 0.43)\%$
$a_{(c)}$ in $c \to \mu X$ decays	$(-0.07 \pm 0.19)\%$

G. Borissov and B. Hoeneisen, Phys. Rev. D **87**, 074020 (2013)
*From $B^0_s \to J/\psi\phi$ at LHCb, assuming that new physics CPV is not cancelled by penguin contributions, $a^s_{sl} = (-0.01 \pm 0.05)\%$, and this entry becomes negligible.

7. Preview of measurement with 10.4 fb^{-1}
(preliminary 2013)

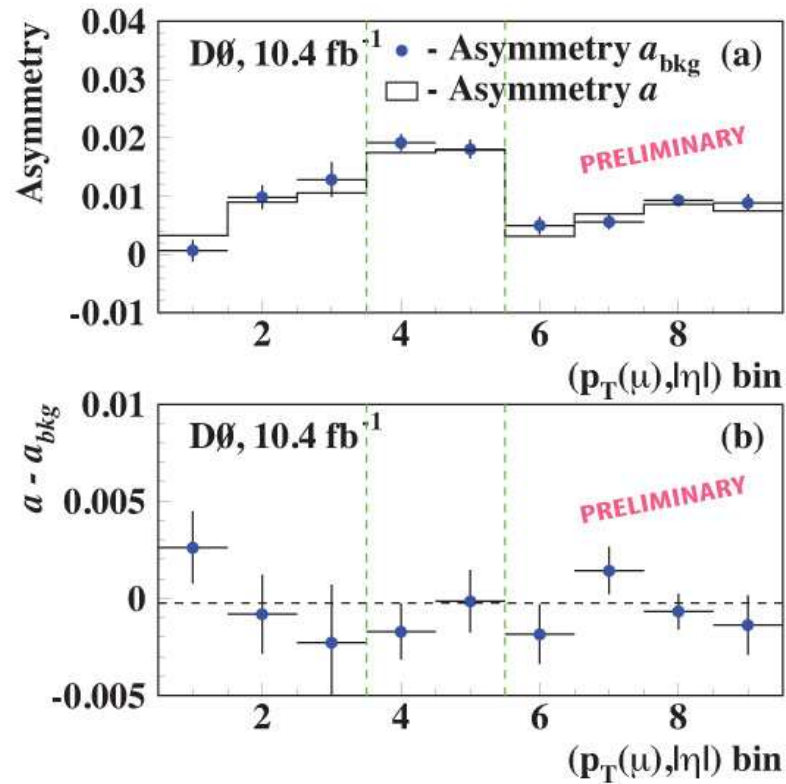All measurements are done in 9 exclusive bins of $(p_T, |\eta|)$:

3 p_T bins for "central" muons with $|\eta| < 0.7$
2 p_T bins for "corner" muons with $0.7 < |\eta| < 1.2$
4 p_T bins for "forward" muons with $1.2 < |\eta| < 2.2$
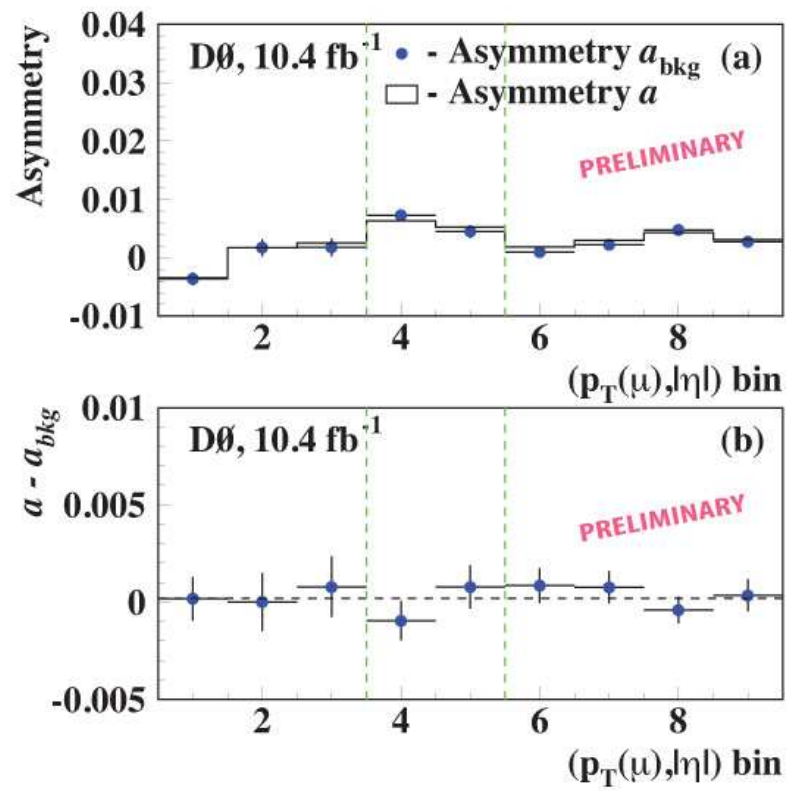
Closure test with inclusive muons: a_{CP} for all IP:
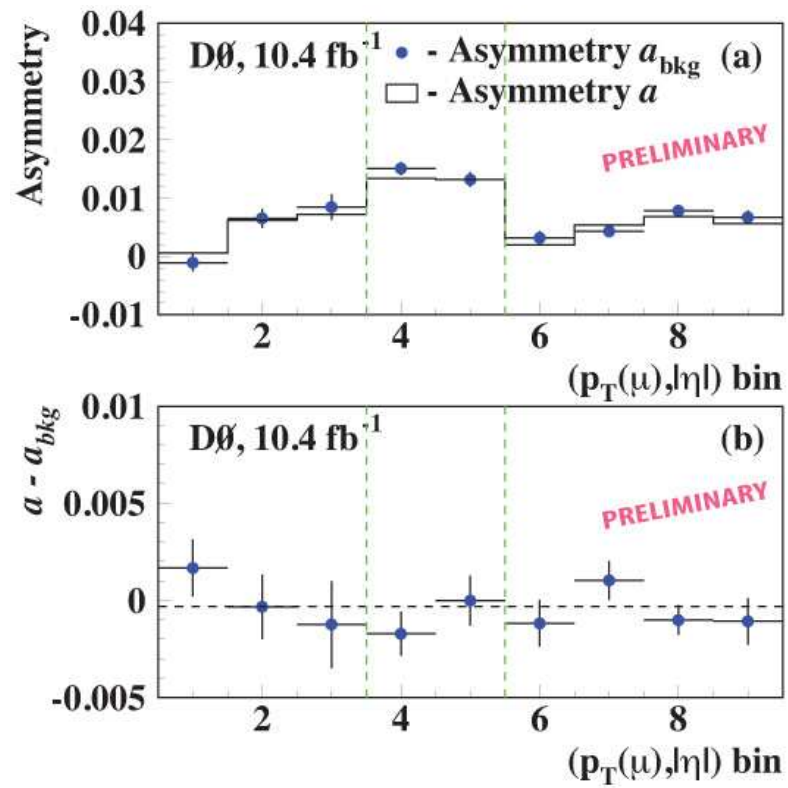
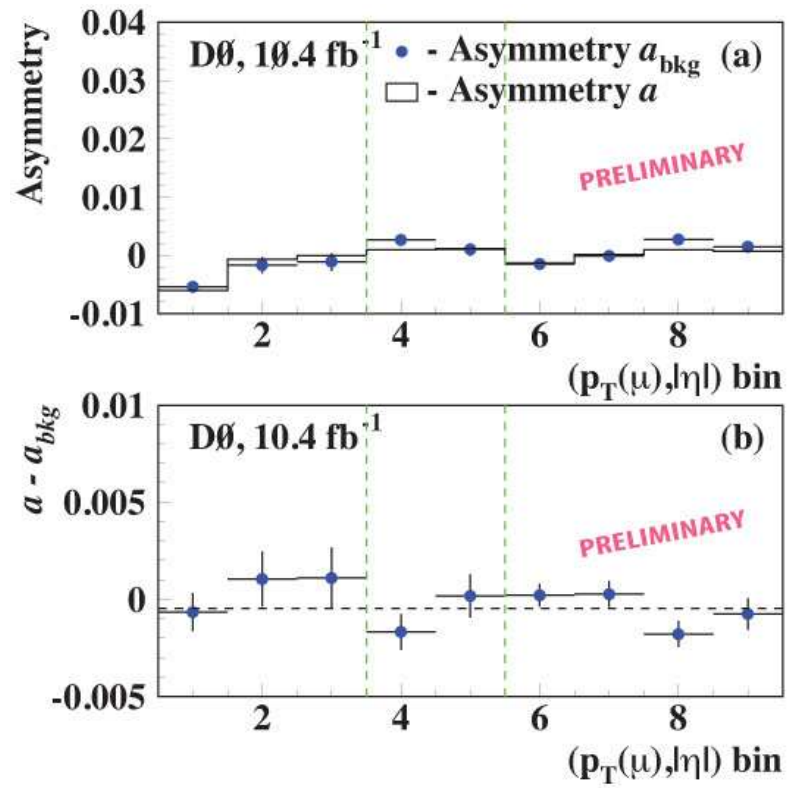Same for 27 exclusive bins of p_T, η and IP

IP from 0 to 50 μm: (asymmetry from kaon decay dominates)

IP from 50 to 120 μm:

IP from 120 to 3000 μm: (detector asymmetry $a_\mu \approx -f_K a_K$)

- For inclusive muons the charge asymmetry a_{CP} is measured in 27 exclusive bins: 9 bins of $(p_T, |\eta|)$ times 3 bins of IP.

- For like-sign dimuons the charge asymmetry A_{CP} is measured in 54 exclusive bins: 9 bins of $(p_T, |\eta|)$ times 6 bins of $(\text{IP}_1, \text{IP}_2)$.

- In all cases the asymmetries a_{CP} and A_{CP} do not vary significantly with $(p_T, |\eta|)$.

8. Interpretation

$$
\begin{aligned}
A_S &= A_S^{\text{int}} + A_S^{\text{mix}} + ?, \\
A_S^{\text{int}} &\propto \frac{\Delta\Gamma_d}{\Gamma_d}, \\
A_S^{\text{mix}} &= C_b A_{\text{sl}}^b, \\
A_{\text{sl}}^b &= C_d a_{\text{sl}}^d + C_s a_{\text{sl}}^s, \\
a_{\text{sl}}^q &= \frac{\Delta\Gamma_q}{\Delta m_q} \tan(\phi_q^{12}),
\end{aligned}
$$

The measurements of a_{CP} and A_{CP} as a function of impact parameter obtain a_{sl}^d, a_{sl}^s and $\Delta\Gamma_d/\Gamma_d$ (and ?).

$\phi_q^{12} \equiv \arg\left(-m_q^{12}/\Gamma_q^{12}\right)$ is the phase of the hamiltonian of $B_q^0 \leftrightarrow \bar{B}_q^0$ mixing and decay.

9. Questions (instead of Conclusions!)

- $\Delta\Gamma_d/\Gamma_d(\text{SM})$ is predicted to be $(0.42 \pm 0.08)\%$. Is it possible that $\Delta\Gamma_d/\Gamma_d \approx 1\%$ or 2% due to low energy, non-perturbative contributions?

- Is it possible that we are still missing other significant standard model contributions to A_{CP}?

- Are we seeing hints of new physics? Confirmation by other experiments is necessary.