Status of the anomalous dimuon charge asymmetry in $p\bar{p}$ collisions

B. Hoeneisen

Universidad San Francisco de Quito
Representing the DØ Collaboration
FPCP 2014

The purpose of this talk

is to present the pieces of a puzzle

with the hope that we can solve it.

Outline:

1. What is measured and why
2. History
3. Final measurement with 10.4 fb^{-1}
4. Interpretation
5. Experimental constraints
6. Outlook
7. Measurements in progress

1. What is measured and why

CP violation in mixing of B^0 and 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)

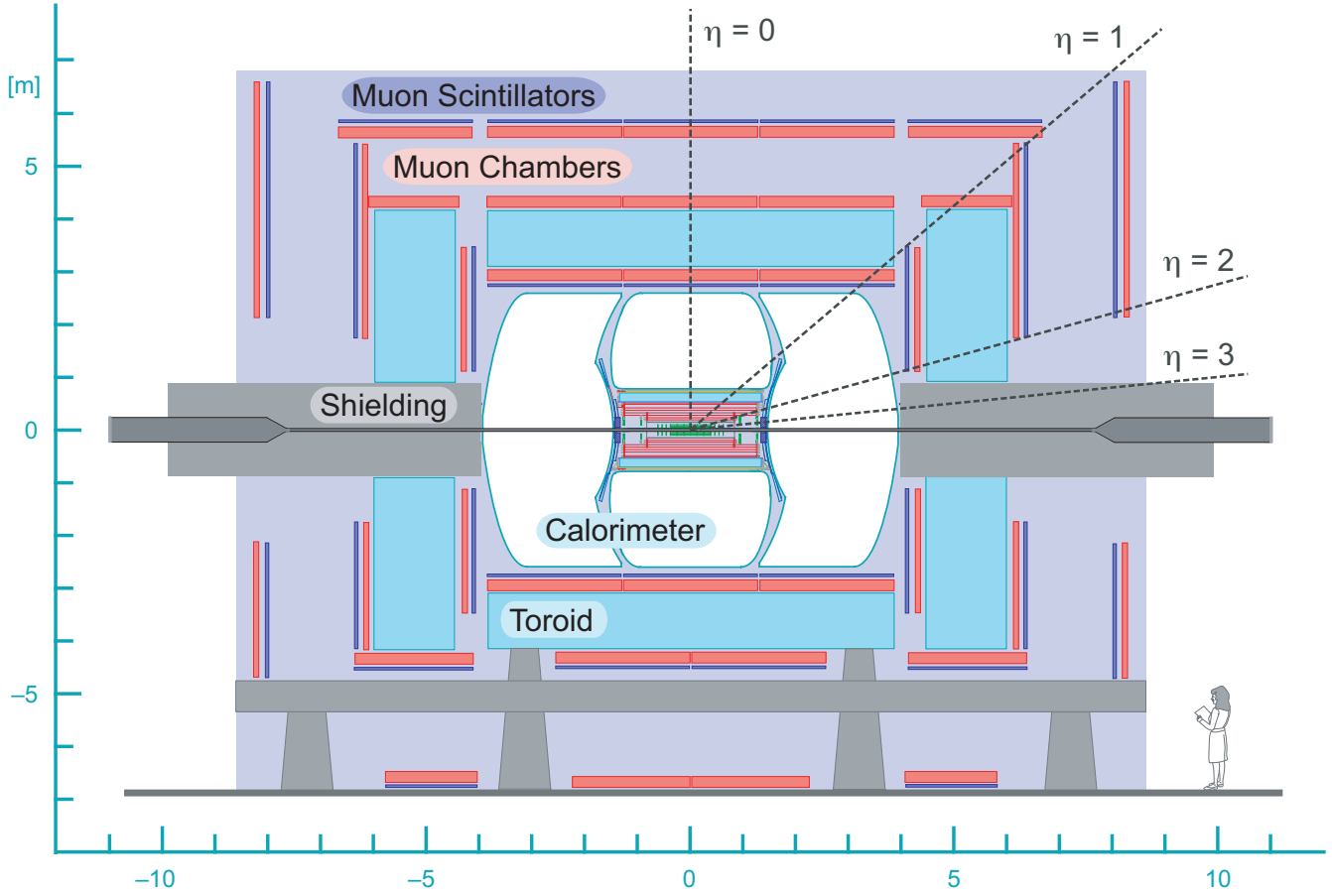
CP violation in interference of B^0 and B_s^0

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

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



The DØ detector.

What we measure:

- Raw asymmetries are obtained by counting:

$$a \equiv \frac{n(\mu^+) - n(\mu^-)}{n(\mu^+) + n(\mu^-)}, \qquad A \equiv \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)}.$$

- Model independent residual asymmetries due to CP violation:

$$a_{CP} = a - a_{\text{bkg}}, \qquad A_{CP} \equiv A - A_{\text{bkg}}.$$

- CP violating asymmetries normalized to signal muons (excluding muons from kaon and pion decay):

$$a_S \equiv \frac{a_{CP}}{f_S}, \qquad A_S \equiv \frac{A_{CP} - F_{SL} a_S}{F_{SS}}.$$

Background asymmetries are measured with the same data:

$$\begin{aligned} a_{CP} &= a - a_{\text{bkg}} \\ a_{\text{bkg}} &= a_\mu + f_K a_K + f_\pi a_\pi + f_p a_p \end{aligned}$$

- f_K 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 $K_S \to \pi^+\pi^-$.
- a_K measured with $K^{*0} \to K^+\pi^-$ or $\phi \to K^+K^-$, followed by $K^+ \to \mu^+\nu$.
- a_π measured with $K_S \to \pi^+\pi^-$ with $\pi \to \mu\nu$.
- a_μ measured with $J/\psi \to \mu^+\mu^-$ reconstructed from tracks only.
- Cross-check: $f_K + f_\pi$ measured from "central" vs. "muon" tracks.

2. History

Residual asymmetry $A_{CP} = A - A_{\text{bkg}}$ measured with different integrated luminosities $\int Ldt$.

$\int Ldt$	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}	$(-0.235 \pm 0.064 \pm 0.055)\%$	3.6σ **	**89**, 012002 (2014)

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

** Discrepancy with A_{CP}^{mix}(SM) and A_{CP}^{int}(SM).

For CPV in interference see Phys. Rev. D **87**, 074020 (2013).

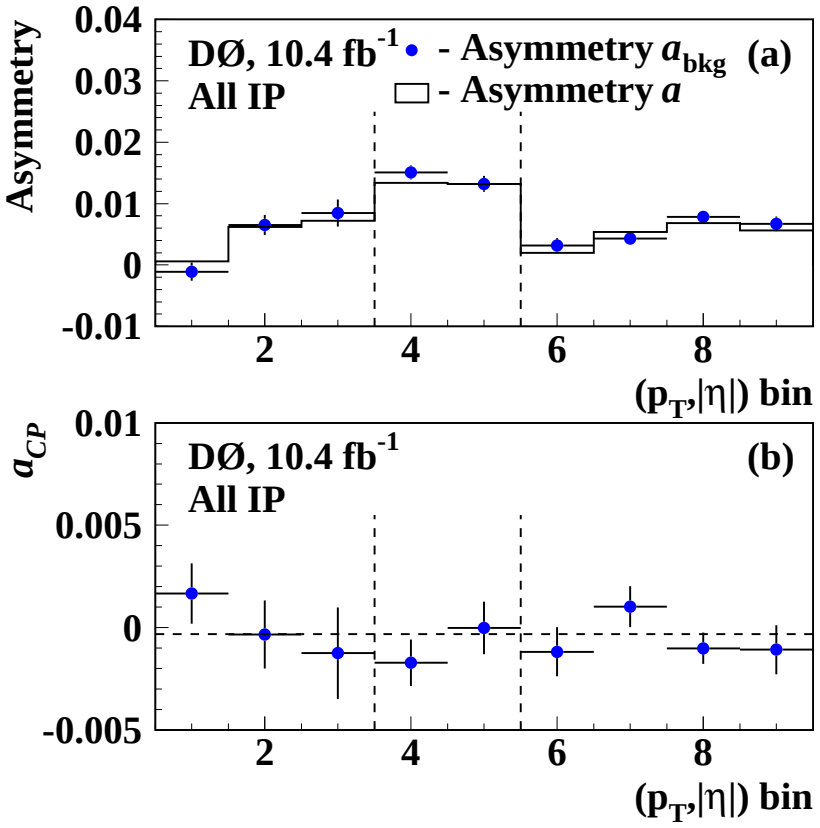
3. Final measurement with 10.4 fb^{-1} (2014)

- The inclusive muon charge asymmetry a_{CP} is measured in 27 bins: 9 bins of $(p_T, |\eta|)$ $\times$ 3 bins of impact parameter (IP).

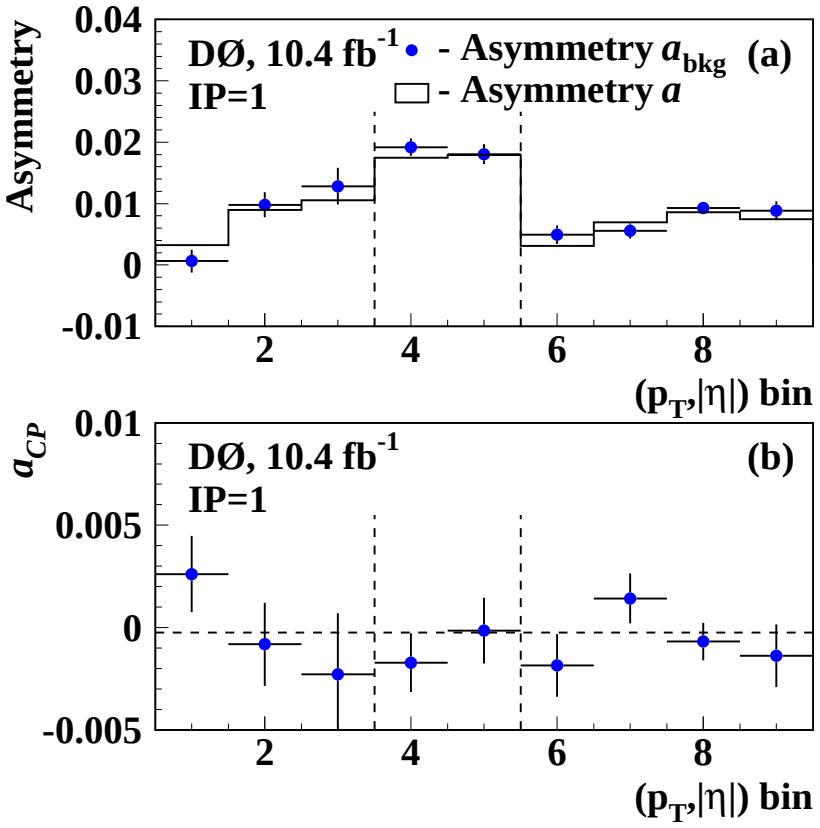
- The like-sign dimuons charge asymmetry A_{CP} is measured in 54 bins: 9 bins of $(p_T, |\eta|)$ $\times$ 6 bins of $(\mathrm{IP}_1, \mathrm{IP}_2)$.

- In all cases the asymmetry does not vary significantly with $(p_T, |\eta|)$.

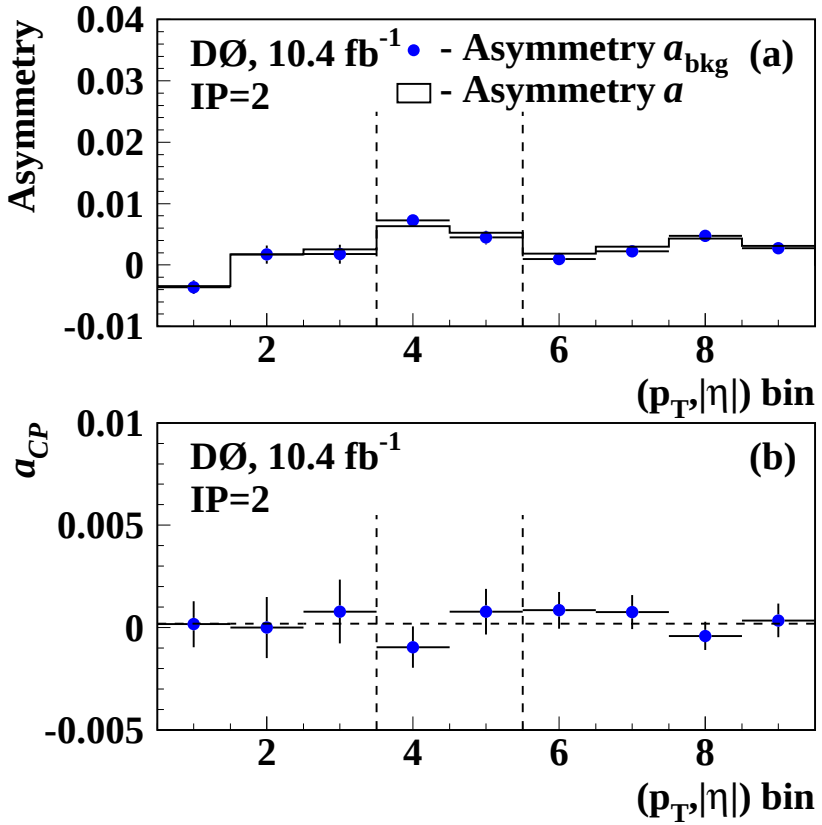
Closure test with inclusive muons: a_{CP} for all IP:



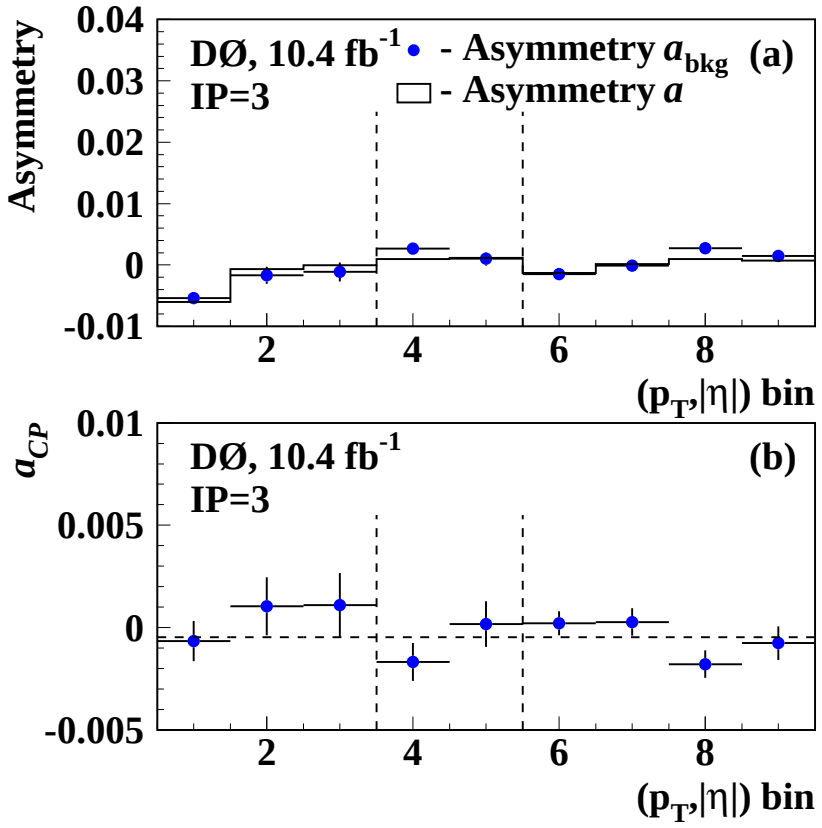
IP = 1 from 0 to 50 μm: (asymmetry from kaon decay dominates)



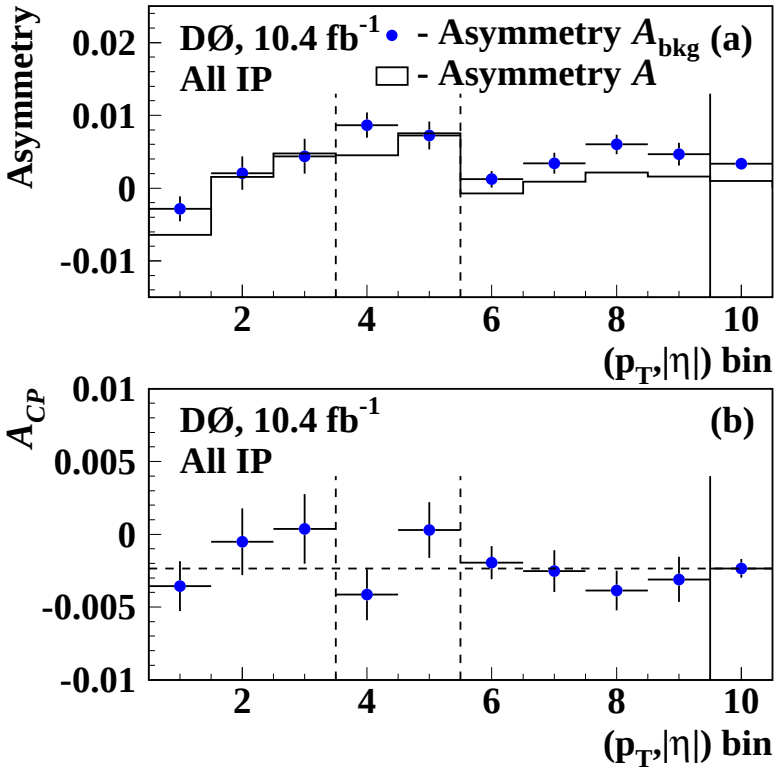
IP = 2 from 50 to 120 μm:

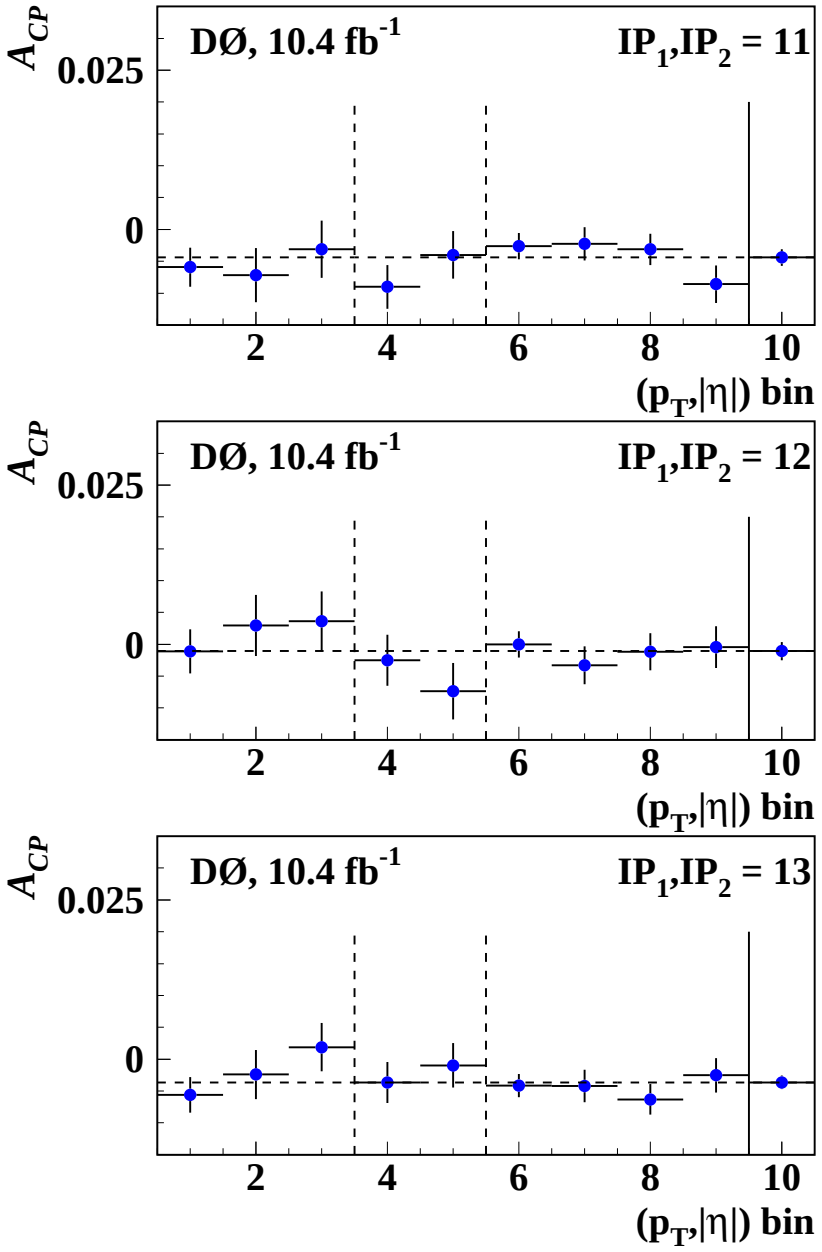


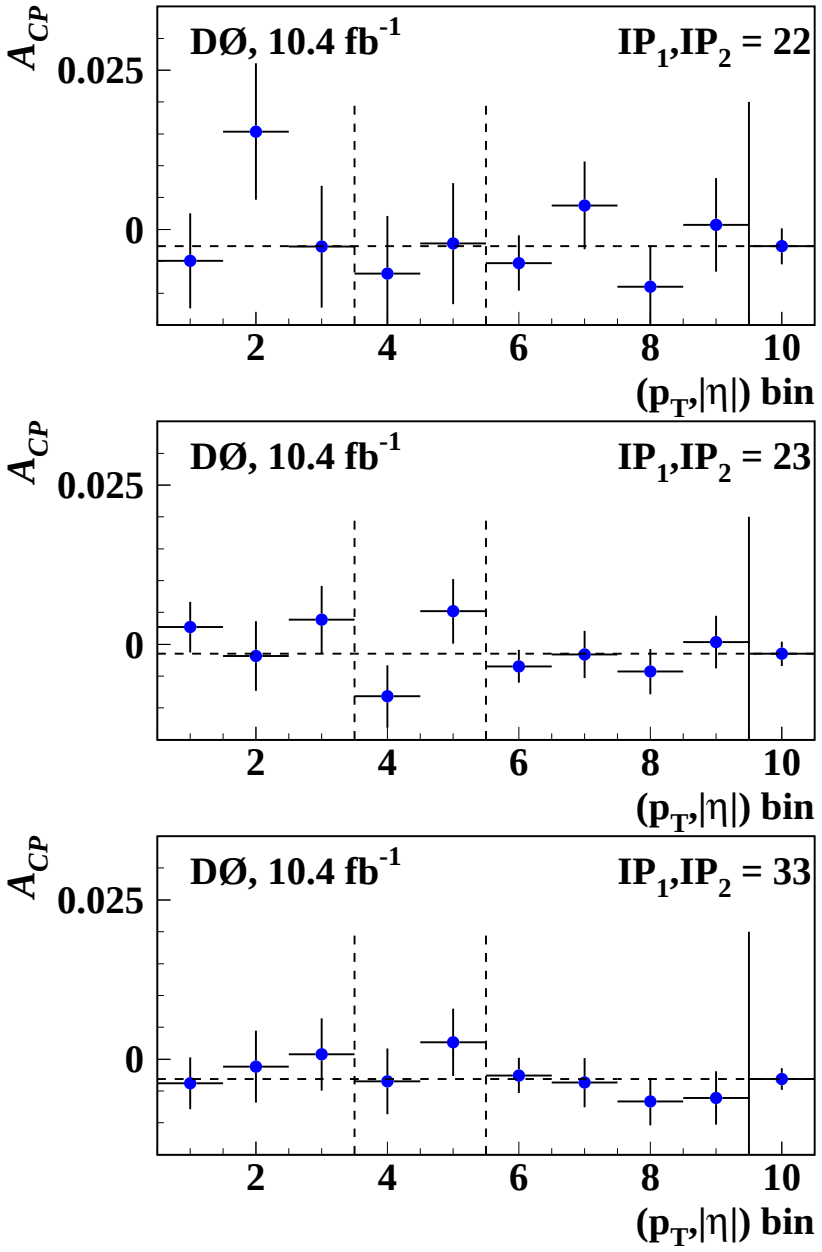
IP = 3 from 120 to 3000 μm: (detector asymmetry $a_\mu \approx -f_K a_K$)



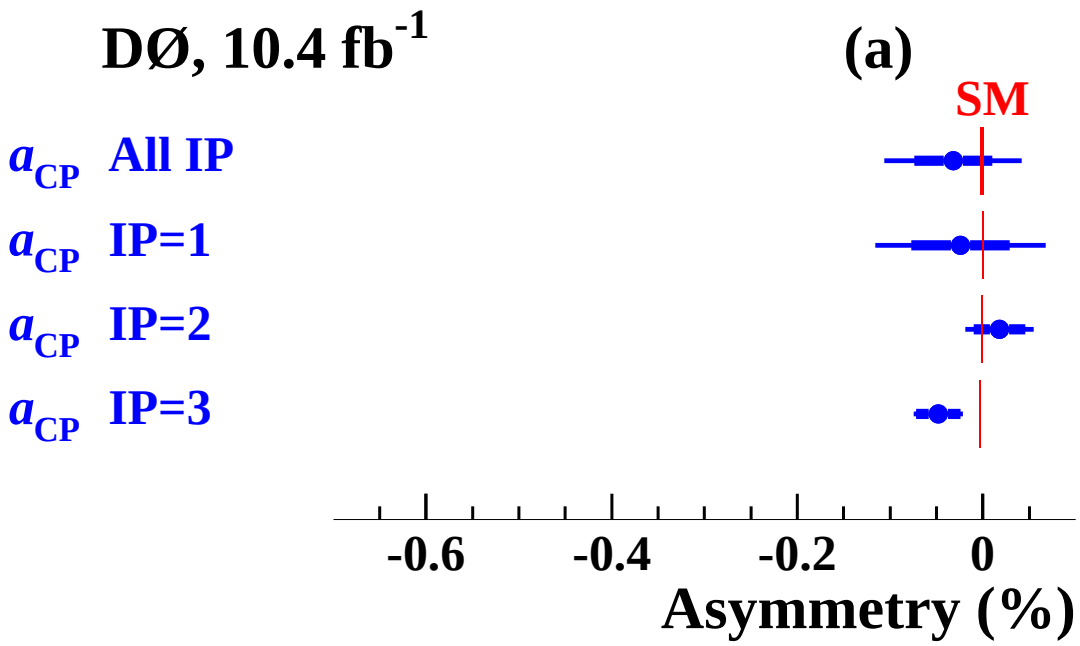
Residual charge asymmetry A_{CP} for like-sign dimuons:



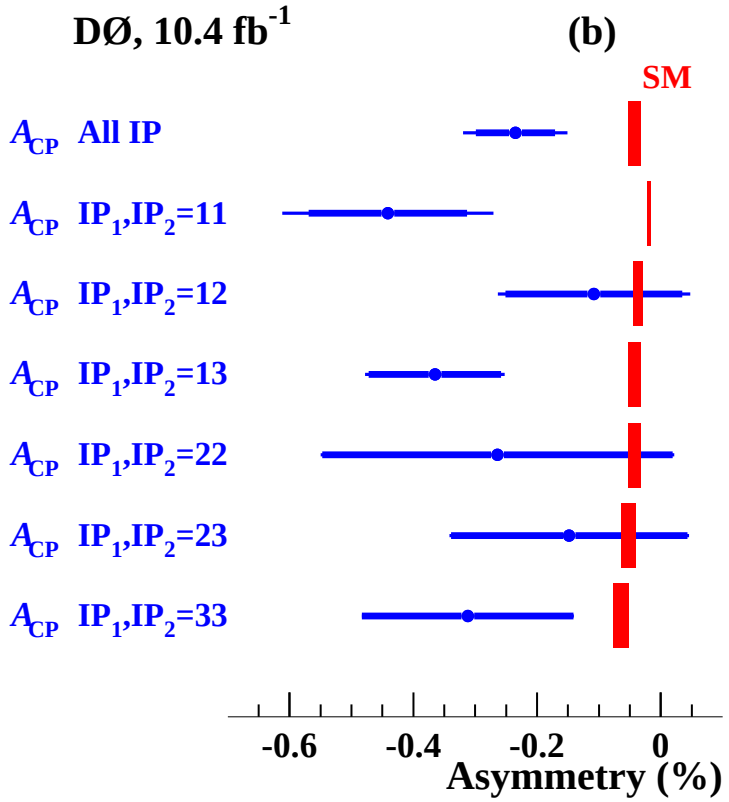

A_{CP}
DØ, 10.4 fb^{-1}
IP$_1$,IP$_2$ = 11
0.025
0
2
4
6
8
10
(p$_T$,|η|) bin
A_{CP}
DØ, 10.4 fb^{-1}
IP$_1$,IP$_2$ = 12
0.025
0
2
4
6
8
10
(p$_T$,|η|) bin
A_{CP}
DØ, 10.4 fb^{-1}
IP$_1$,IP$_2$ = 13
0.025
0
2
4
6
8
10
(p$_T$,|η|) bin


A_{CP}
DØ, 10.4 fb^{-1}
IP$_1$,IP$_2$ = 22
0.025
0
2
4
6
8
10
(p$_T$,|η|) bin
A_{CP}
DØ, 10.4 fb^{-1}
IP$_1$,IP$_2$ = 23
0.025
0
2
4
6
8
10
(p$_T$,|η|) bin
A_{CP}
DØ, 10.4 fb^{-1}
IP$_1$,IP$_2$ = 33
0.025
0
2
4
6
8
10
(p$_T$,|η|) bin

Residual asymmetry a_{CP} of inclusive muons:



Residual asymmetry A_{CP} of like-sign dimuons:



For all muons:

$$
\begin{aligned}
a_{CP} &= (-0.032 \pm 0.042 \text{ (stat)} \pm 0.061 \text{ (syst)})\%, \\
a_S &= (-0.064 \pm 0.148)\%, \\
A_{CP} &= (-0.235 \pm 0.064 \text{ (stat)} \pm 0.055 \text{ (syst)})\%, \\
A_S &= (-0.319 \pm 0.132)\%, \\
A_S^{\text{mix}}(SM) &= (-0.012 \pm 0.002)\%, \\
A_S^{\text{int}}(SM) &= (-0.050 \pm 0.012)\%.
\end{aligned}
$$

The measurements in 6 bins of $(\text{IP}_1, \text{IP}_2)$ differ from the SM prediction $A_S^{\text{int}} + A_S^{\text{mix}}$ by 3.6σ.

Most of the discrepancy with the SM prediction, i.e. 3.0σ, corresponds to muons with transverse impact parameter less than 50μm (IP $= 1$):

$$
\begin{aligned}
a_{CP}(1) &= (-0.024 \pm 0.053\ (\text{stat}) \pm 0.075\ (\text{syst}))\%, \\
a_S(1) &= (-0.063 \pm 0.241)\%, \\
A_{CP}(11) &= (-0.441 \pm 0.128\ (\text{stat}) \pm 0.113\ (\text{syst}))\%, \\
A_S(11) &= (-0.921 \pm 0.410)\%, \\
A_S^{\text{mix}}(11)(SM) &= (-0.005 \pm 0.001)\%, \\
A_S^{\text{int}}(11)(SM) &= (-0.036 \pm 0.008)\%.
\end{aligned}
$$

Is there an additional source of CP violation?

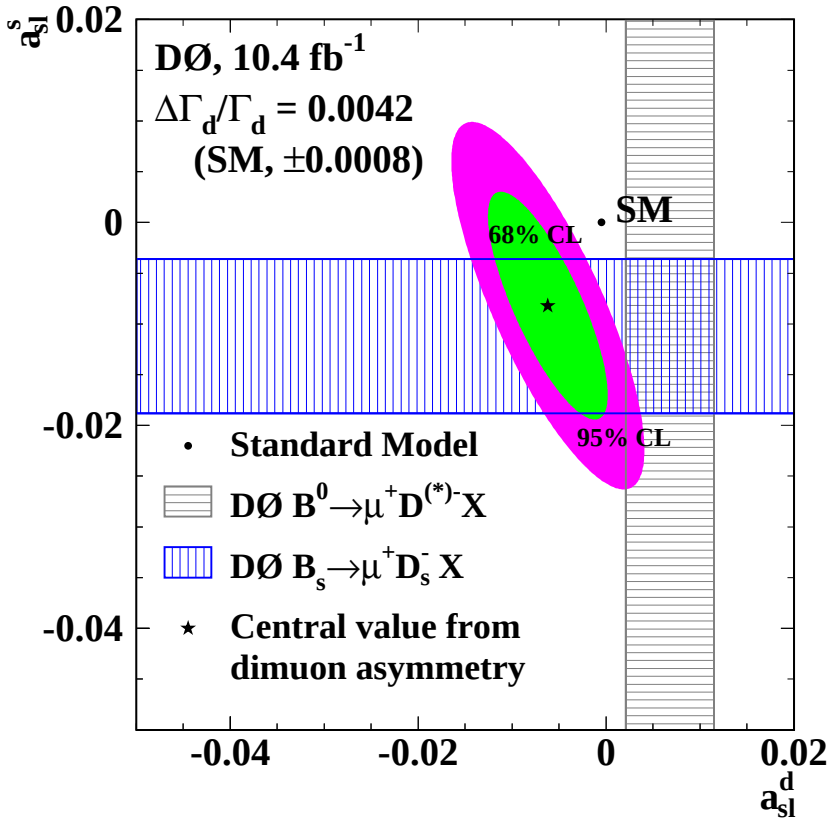
4. Interpretation

$$
\begin{aligned}
A_{CP} &= A_{CP}^{\text{int}} + A_{CP}^{\text{mix}} + ?, \\
A_{CP}^{\text{int}} &\propto \Delta\Gamma_d, \\
A_{CP}^{\text{mix}} &\propto C_d a_{\text{sl}}^d + C_s a_{\text{sl}}^s, \approx C_d a_{\text{sl}}^d \\
a_{\text{sl}}^d &\propto \Delta\Gamma_d,
\end{aligned}
$$

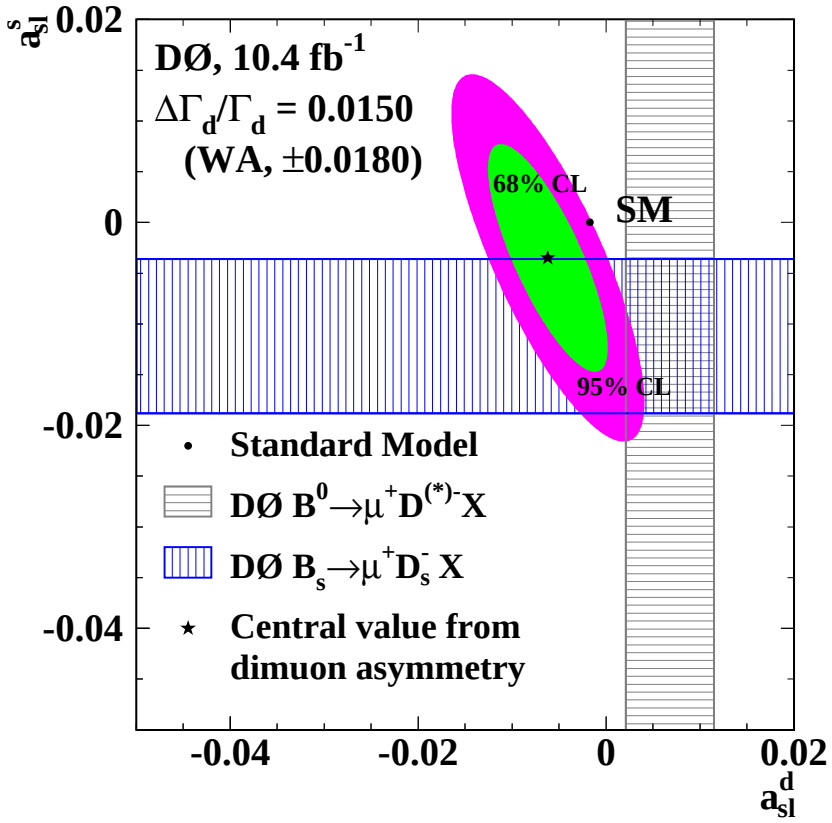
The measurements as a function of impact parameter constrain a_{sl}^d, a_{sl}^s and $\Delta\Gamma_d$ (and ?).

IF NO ? then:

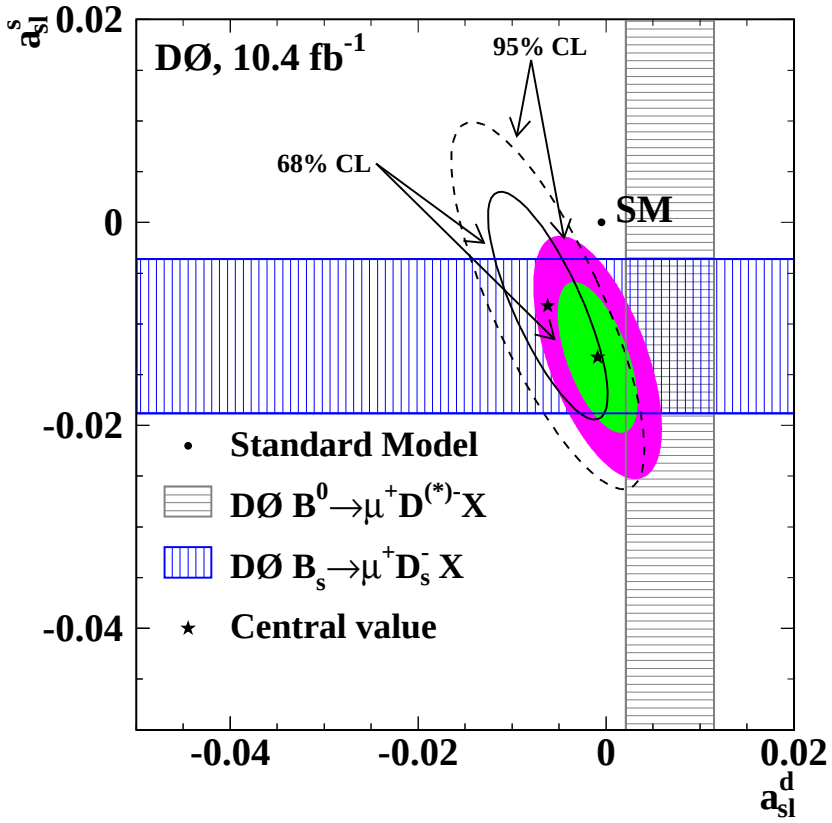
The 68% and 95% CL contours from fit with $\Delta\Gamma_d/\Gamma_d = 0.0042$ (expected SM value with uncertainty ± 0.0008):



The 68% and 95% CL contours from fit with $\Delta\Gamma_d/\Gamma_d = 0.0150$ (world average value with uncertainty ± 0.0180):



The 68% and 95% CL contours from fit with $\Delta\Gamma_d/\Gamma_d = 0.0050$ (corresponding to the best fit value), and combination of all DØ measurements (filled areas):



5. Experimental constraints

CP violation in	ΔA_S allowed by exp.	Comments
mixing $B^0 \leftrightarrow \bar{B}^0$	$(+0.021 \pm 0.083)\%$	from exp. $a^d_{\rm sl}$
mixing $B^0_s \leftrightarrow \bar{B}^0_s$	$(-0.374 \pm 0.124)\%$	from exp. $a^s_{\rm sl}$
interference $B^0 \to (\bar{B}^0) \to c\bar{c}d\bar{d}$	$(-0.050 \pm 0.012)\%$	from SM theory $\Delta\Gamma_d$
interference $B^0_s \to (\bar{B}^0_s) \to c\bar{c}s\bar{s}$	$(-0.0009 \pm 0.0003)\%$	from exp. $\Delta\Gamma_s$
direct decays $b \to c\bar{c}d$	$(+0.003 \pm 0.013)\%$	from exp. Br & CPV
direct decays $b \to c\bar{c}s$	$(+0.000 \pm 0.043)\%$	from exp. Br
direct decays $b \to \mu X$	$(-0.17 \pm 0.39)\%$	from a_{CP}
direct decays $c \to \mu X$	$(-0.07 \pm 0.17)\%$	from a_{CP}
weak production $p\bar{p} \to b\bar{c}X$	$(-0.15 \pm 0.35)\%$	from a_{CP}
neutrinoless double β decay	$(-0.12 \pm 0.29)\%$	from a_{CP}
b to "right sign" μ	$(-0.13 \pm 0.30)\%$	from a_{CP}
b to "wrong sign" μ	$(-0.46 \pm 1.07)\%$	from a_{CP}

Ranges of A_S allowed by experiments (with $\pm 1\sigma$ confidence).
Compare with the measured $A_S = (-0.319 \pm 0.132)\%$.

Update of Table II of Phys. Rev. D 87, 074020 (2013).

6. Outlook

Some possible solutions to the puzzle:

- $\mathrm{Re}(\Gamma_{12}^d)$ is larger than predicted. This would increase $\Delta\Gamma_d$ and A_S^{int} without changing significantly Δm_d, a_{sl}^d or $S_{J/\psi K_S}$.

- A large CP violating asymmetry in direct decays $b \to c\bar{c}s$.

- A large CP violating asymmetry in the weak production $p\bar{p} \to b\bar{c}X$.

- An experimental issue.

- Or something else.

7. Measurements in progress

What is the cause of the measured like-sign dimuon charge asymmetry? To help answer this question, we measure A_{CP} of sub-samples of the data:

- Like-sign dimuon events with one of the muons from J/ψ.
- Events with $\mu^+\mu^+\mu^-$, $\mu^+\mu^+K_S$, or $\mu^+\mu^-\Lambda$ in the final state.
- We measure A_{CP} as a function of $\Delta\phi$, $\Delta\eta$, $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$, p_{T2}/p_{T1}, $m(\mu_1, \mu_2)$, p_T, η, ϕ.

- These measurements are done for all muons, muons with low impact parameter, and isolated muons.

- Events with the two muons in different jets (3/4 of the data).

- Events with the two muons in the same jet (1/4 of the data).

In summary, we have added more pieces to the puzzle, and keep analyzing the data to try to solve it.

Backup slides

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.

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

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

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}:
$D^+ \to \mu^+$ cancels $D^- \to \mu^-$.

Experimental constraints

Contributions to A_S allowed by experiments:
(compare with $A_S = (-0.319 \pm 0.087 \pm 0.075)\%$)

Process	Allowed A_S
Mixing of B^0	$(+0.062 \pm 0.073)\%$
Mixing of B_s^0	$(-0.111 \pm 0.093)\%$ *
Interference of B^0	$(-0.045 \pm 0.016)\%$ (SM)
Interference of B_s^0	$(-0.0009 \pm 0.0003)\%$ (SM)
CPV in $b \to c\bar{c}q$ 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 $B_s^0 \to J/\psi\phi$, assuming that new physics CPV is not cancelled by penguin contributions, $a_{\mathrm{sl}}^s = (-0.01 \pm 0.05)\%$, and this entry becomes negligible.

9 bins of $(p_T, |\eta|)$:

$(p_T, \|\eta\|)$ bin	$\|\eta\|$	p_T (GeV)
1	0 to 0.7	1.5 to 5.6
2	0 to 0.7	5.6 to 7.0
3	0 to 0.7	7.0 to 25
4	0.7 to 1.2	1.5 to 5.6
5	0.7 to 1.2	5.6 to 25
6	1.2 to 2.2	1.5 to 3.5
7	1.2 to 2.2	3.5 to 4.2
8	1.2 to 2.2	4.2 to 5.6
9	1.2 to 2.2	5.6 to 25

Most $p\bar{p}$ collisions produce no muons, a few produce one recorded muon, very few produce two recorded muons, and fewer still produce two *like-sign* recorded muons, i.e. 4×10^{14} (mostly not recorded), 2.2×10^{9}, 2.8×10^{7} and 6.2×10^{6} respectively in the final data set of 10.4 fb^{-1}.