Evidence for Anomalous Like-sign Dimuon Asymmetry At the D0 Experiment

Mark Williams

Fermilab International Fellow

Lancaster University, UK

Why the Big Fuss?

The New York Times
A New Clue to Explain Existence

TIME
Big News About Small Particles. And Why You Care

SCIENTIFIC AMERICAN

FORTE
Teadlased avastasid aine ja antiaine ebasümmeetria

Fermilab Finds New Mechanism for Matter's Dominance over Antimatter

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SİZİN HABERCİNİZ BİZİZ

Noi descoperiri în misterul antimateriei

RL *România liberă.ro*

Telegraph
Haber: Evrendeki Dengelere Yeni Denklem

Atom smasher offers new clue to mystery of universe's formation

Почему мы существуем: как материя побеждает антиматерию
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САМАРА сегодня
Ежедневная интернет-газета

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宇宙何以充斥物质而不是反物质？

europapress.es
El Tevatrón halla una pista para entender la composición del Universo

Matter Dominance and CP Violation

The universe that we observe is matter dominated, **but** we expect that the Big Bang produced matter/antimatter **equally**.

$\rightarrow$ At some point a small asymmetry developed. **CP Violation** (CPV) is required in order to generate such an asymmetry (*Sakharov*).

CP violation is naturally included in the standard model through the quark mixing (CKM) matrix;

Many different measurements of *CP* violation phenomena are in excellent agreement with the SM:
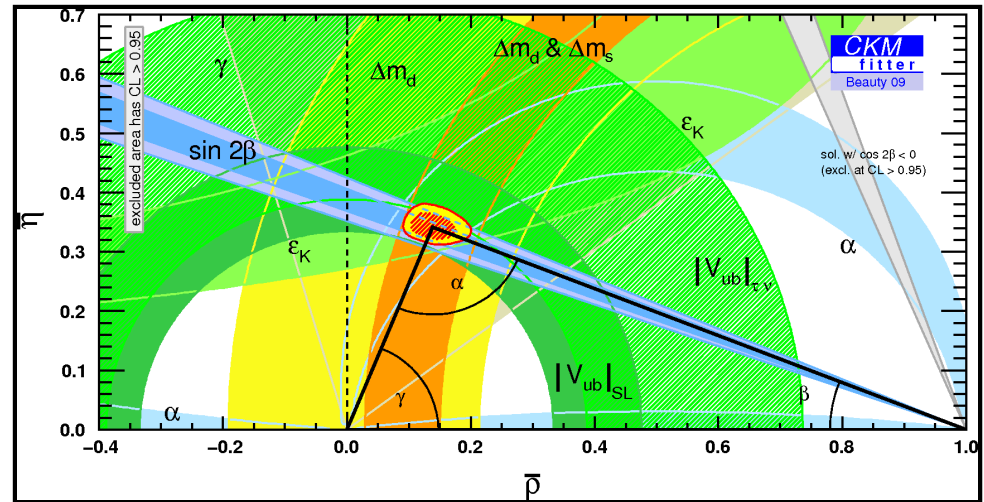
However, the level of CPV predicted by the SM is far **too small** to explain the observed matter dominance.
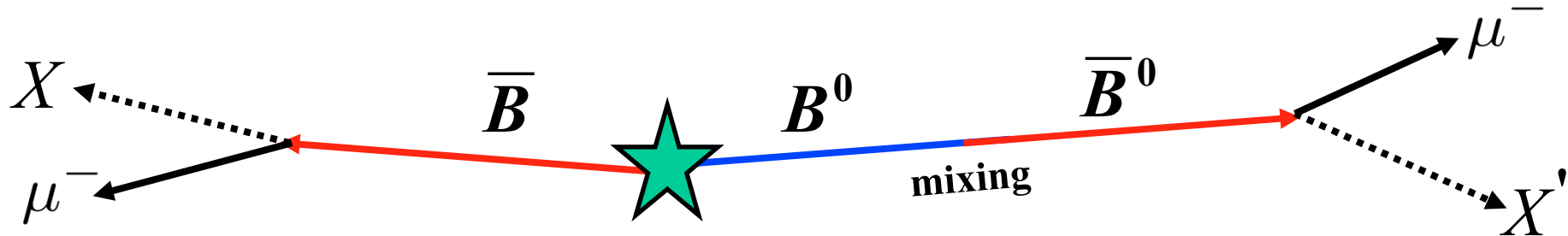
It is important to look for new sources of CPV

Dimuon Charge Asymmetry

We measure *CP* violation in neutral B meson mixing using the **same-sign** dimuon charge asymmetry of **semileptonic *B* decays**:

$$A_{sl}^{b} \equiv \frac{N_{b}^{++} - N_{b}^{--}}{N_{b}^{++} + N_{b}^{--}}$$

X

$\bar{B}$ B^0 $\bar{B}^0$

μ^-

mixing

μ^-

X'

One muon comes from direct semileptonic decay $b \rightarrow \mu^- X$

Second muon comes from direct semileptonic decay after neutral *B* meson mixing: $B^0 \rightarrow \bar{B}^0 \rightarrow \mu^- X$

Asymmetry can occur if mixing rates are different: $\mathbf{R(B_{(s)}^{0} \rightarrow \bar{B}_{(s)}^{0}) \neq R(\bar{B}^0 \rightarrow B^0)}$
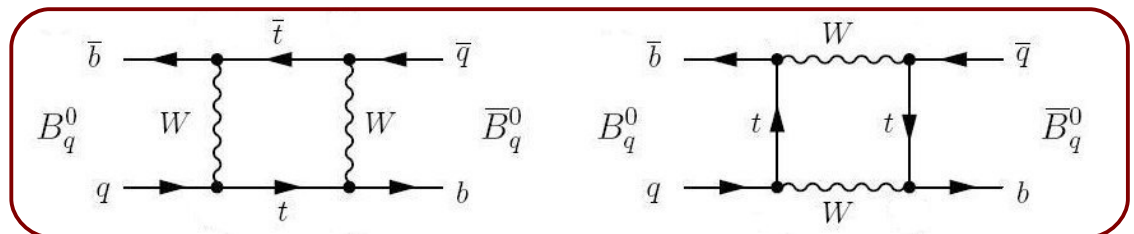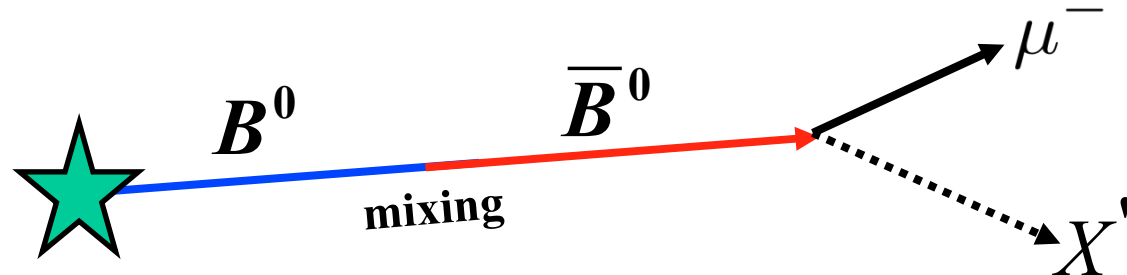
Inclusive Muon Charge Asymmetry

Because any dimuon asymmetry arises from the meson mixing, A^b_{sl} is equal to the charge asymmetry a^b_{sl} of "wrong sign" (i.e. oscillated) semileptonic B decays:

No 'opposite side' muon requirement: more events, more background processes.

$$B^0 \quad \overline{B}^0 \quad \mu^-$$

mixing

$$X'$$

$$a^b_{sl} \equiv \frac{\Gamma(\overline{B} \to \mu^+X) - \Gamma(B \to \mu^-X)}{\Gamma(\overline{B} \to \mu^+X) + \Gamma(B \to \mu^-X)} = A^b_{sl}$$

We therefore have two ways of measuring A^b_{sl}:

➢ **Via dimuon charge asymmetry;**   *(upper-case symbols in this talk)*

➢ **Via inclusive muon charge asymmetry.**   *(lower-case symbols)*

A^b_{sl} at the Tevatron

The inclusive muon charge asymmetry can also be defined separately for specific flavors, $B^0_{(d)}$ and B^0_s, and related to the meson mixing parameters ΔM, $\Delta \Gamma$, φ:

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

Both B^0_d and B^0_s are produced at the Tevatron, so both contribute to A^b_{sl}, yielding the SM prediction:

$$A^b_{sl} = (0.506 \pm 0.043)a^d_{sl} + (0.494 \pm 0.043)a^s_{sl} = (-0.023^{+0.005}_{-0.006})\,\%$$

SM prediction is negligible compared to current experimental precision – **any significant deviation from zero is an unambiguous signal of new physics**.

Experimental Environment

D0 records p$\bar{\text{p}}$ collisions at 1.96 TeV: **matter-antimatter symmetric** (by design)

Inner **tracking** (silicon sensors + scintillation fibers) **within 2T solenoid magnet**;

Muon tracking detector: multiple planes of drift chambers on either side of **1.8T toroid magnet**;

Muon scintillators provide time resolution of 2-3 ns;

Detector is made of matter – therefore has **inherent matter-antimatter asymmetry**!

Asymmetries due to magnet polarities are mitigated by **regularly reversing currents**...

Muon Scintillators
Muon Chambers
$\eta = 0$ $\eta = 1$ $\eta = 2$ $\eta = 3$
[m]
Shielding
Calorimeter
Toroid
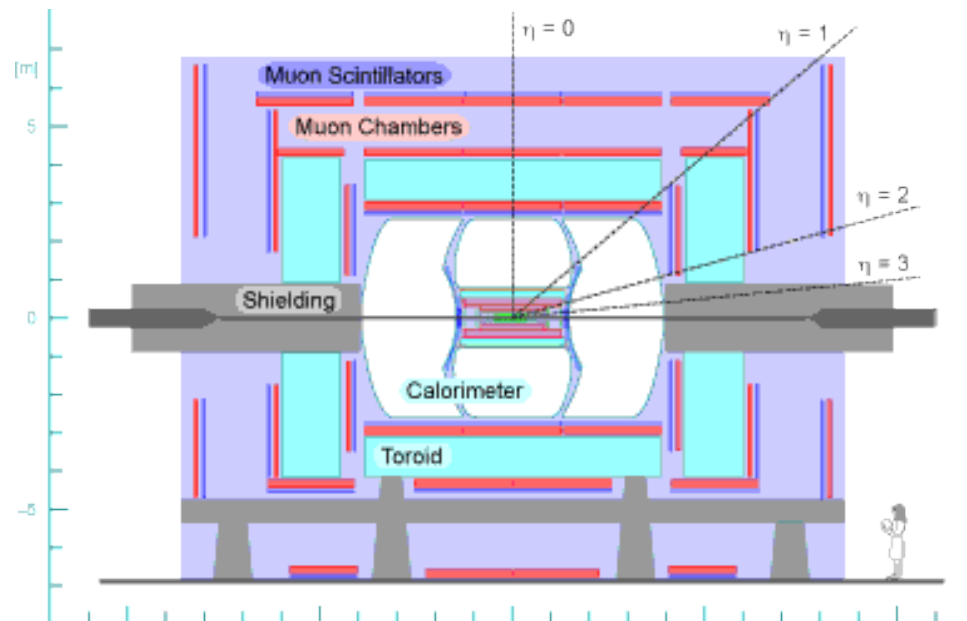
Run II Integrated Luminosity   19 April 2002 - 9 May 2010

These results 6.1 fb^{-1}

— Delivered
— Recorded

8.54
7.60

Luminosity (/fb)
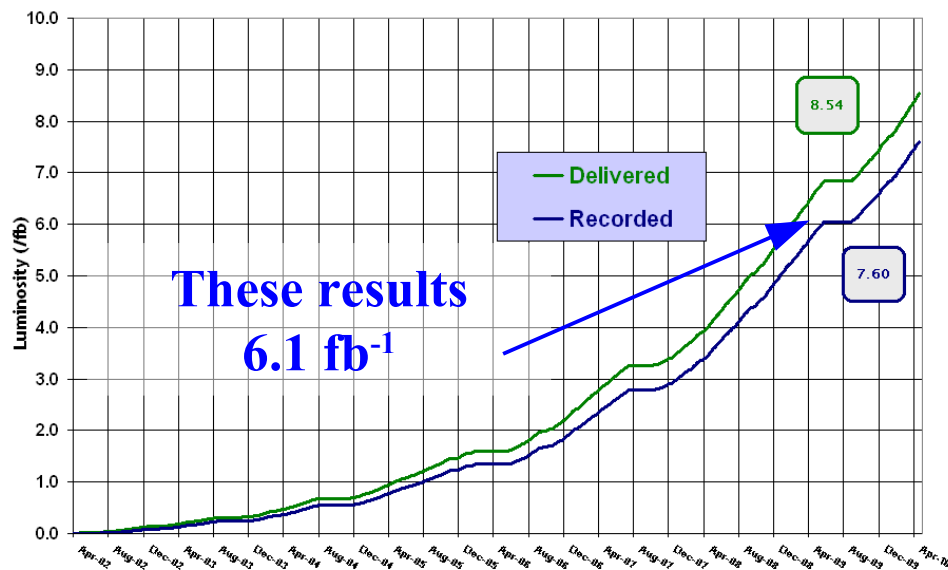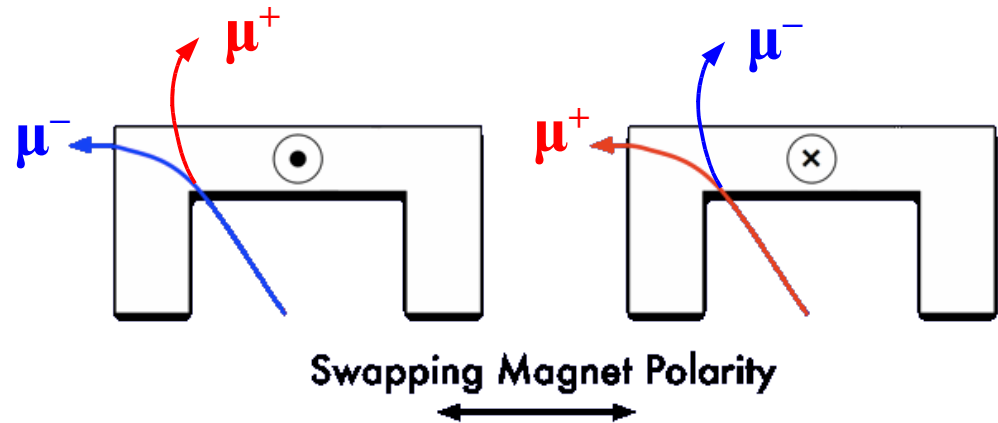
Reversal of Magnet Polarities

For a given magnet polarity, there is a charge asymmetry, e.g. from muons bending out of the muon detector acceptance;

Swapping Magnet Polarity

The trajectory of a *negative* particle in a given polarity is exactly the same as the trajectory of the *positive* particle with the magnet polarity reversed;

By separately analyzing four samples corresponding to the different solenoid/toroid polarities **(++, −−, +−, −+)** the overall difference in the reconstruction efficiency between positive and negative particles is minimized.

Changing polarities is an important feature of the DØ detector, which significantly reduces systematics in charge asymmetry measurements.

Raw Asymmetries

Experimentally, we measure two quantities (by event counting):

Inclusive muon charge asymmetry

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-}$$

Like-sign dimuon charge asymmetry

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

Event Selection:

- Track-matched muon ($|\eta| < 2.2$);
- $1.5 < pT < 25$ GeV;
- $p_T > 4.2$ GeV *or* $|p_z| > 6.4$ GeV;
- Distance to primary vertex < **3mm** **(5mm)** in transverse (beam) direction.

- Both muons must pass inclusive muon selection;
- Same charge, same PV;
- **M(μμ) > 2.8** GeV to suppress events where muons are from same B decay.

Results:

a = (+0.955 ± 0.003) %

(from 1.495 x 10^9 muons)

A = (+0.564 ± 0.053) %

(from 3.731 x 10^6 dimuon events)

Extracting A^b_{sl}

Both A and a linearly depend on the charge asymmetry A^b_{sl}

$$a = kA^b_{sl} + a_{bkg}$$

$$A = KA^b_{sl} + A_{bkg}$$

(recall that $A^b_{sl} = a^b_{sl}$)

➢ A_{bkg} and a_{bkg} are detector-related background contributions to the measured asymmetry;

➢ Coefficients K and k are small (< 1) due to the effect of charge symmetric background processes diluting the semileptonic asymmetry.

Our task is to:

1) Determine the background contributions A_{bkg} and a_{bkg};

2) Find the coefficients K and k;
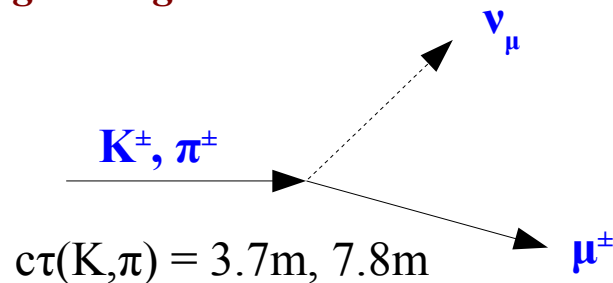
3) Extract the asymmetry A^b_{sl}.

Final result was blinded until all analysis methods were fixed

Detector Asymmetries A_{bkg}, a_{bkg}

$$a = kA^b_{sl} + a_{bkg}$$

$$A = KA^b_{sl} + A_{bkg}$$

ν_μ

$K^\pm, \pi^\pm$

$\mu^\pm$

$c\tau(K,\pi) = 3.7m, 7.8m$

These terms account for effects from :

➢ Decays $K^\pm \rightarrow \mu^\pm \nu$, $\pi^\pm \rightarrow \mu^\pm \nu$;

➢ Hadronic punch-through to the muon detector;

➢ Muon reconstruction asymmetries;

➢ Asymmetries in tracks wrongly associated with muons.

Measured directly in data, with a reduced input from simulation

e.g. for inclusive muon case:

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

kaon

pion

Proton
(+ 'fakes')

Muon reconstruction
asymmetry

fraction

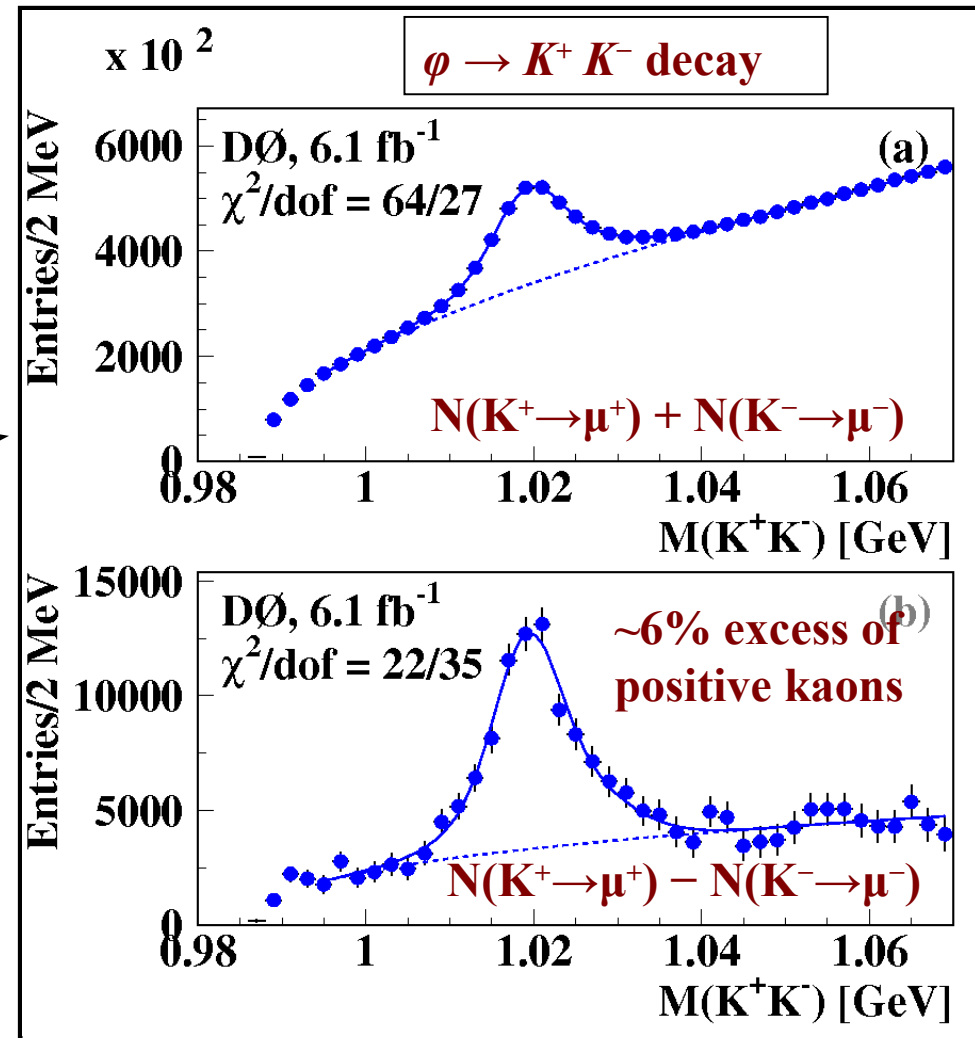asymmetry

Example: Asymmetry from Kaons

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

To determine a_{bkg} and A_{bkg}, we need to know the 7 parameters $a_{K,\pi,p}$, $f_{K,\pi,p}$, δ, and the corresponding dimuon parameters.

These are measured in bins of muon p_T.

Example: Kaon asymmetry measured using decays $\varphi \to K^+ K^-$ and $K^{*0} \to K^+ \pi^-$ by fitting mass peaks to find asymmetry.

It is positive, because **'antimatter'** kaons (K^-) are more likely to interact with **matter** in the detector, so have less chance of decaying to muons before interaction.

$\varphi \to K^+ K^-$ decay

(a)

DØ, 6.1 fb^{-1}
χ^2/dof = 64/27

x 10^2

Entries/2 MeV

$N(K^+ \to \mu^+) + N(K^- \to \mu^-)$

M(K^+K^-) [GeV]

(b)

DØ, 6.1 fb^{-1}
χ^2/dof = 22/35

~6% excess of positive kaons

Entries/2 MeV

$N(K^+ \to \mu^+) - N(K^- \to \mu^-)$

M(K^+K^-) [GeV]

Summary of Background Contributions

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

We obtain:

	$f_K a_K$ (%) or $F_K A_K$ (%)	$f_\pi a_\pi$ (%) or $F_\pi A_\pi$ (%)	$f_p a_p$ (%) or $F_p A_p$ (%)	$(1-f_{bkg})\delta$ (%) or $(2-F_{bkg})\Delta$ (%)	a_{bkg} or A_{bkg}
Inclusive	0.854 ± 0.018	0.095 ± 0.027	0.012 ± 0.022	-0.044 ± 0.016	**0.917 ± 0.045**
Dimuon	0.828 ± 0.035	0.095 ± 0.025	0.000 ± 0.021	-0.108 ± 0.037	**0.815 ± 0.070**

- All uncertainties are statistical only;
- Dominant effect comes from kaons, as expected;
- Notice that background contribution is similar for inclusive muon and dimuon sample: $A_{bkg} \approx a_{bkg}$

Dilution by Non-Contributing Processes

$$a - a_{bkg} = k\, A^b_{sl}$$

$$A - A_{bkg} = K\, A^b_{sl}$$

*Factors k and K account for muons from sources which are fully symmetric, and **only contribute to the denominator in A^b_{sl}**.*

Decays contributing to the muon sample include:

- **$b \rightarrow \mu^- X$**   (including possible oscillations)
- **$b \rightarrow c \rightarrow \mu^+ X$**   (including possible oscillations)
- **$b \rightarrow c\bar{c}q$**
- **$c\bar{c}$** and **$b\bar{b}c\bar{c}$** production
- **$\eta, \omega, \rho^0, \varphi(1020), J/\psi, \psi'$** decaying to **$\mu^+\mu^-$**

These decays are currently measured with a good precision (see PDG), and this input from simulation produces a small systematic uncertainty.

$$k = 0.041 \pm 0.003$$

$$K = 0.342 \pm 0.023$$

k is found to be much smaller than K, because many more non-oscillating b- and c-quark decays contribute to the inclusive asymmetry.

Closure Test

The contribution of A^b_{sl} in the inclusive muon asymmetry a is suppressed by:

$$k = 0.041 \pm 0.003;$$

therefore a is mainly determined by the background asymmetry $a \approx a_{bkg}$;

We measure a_{bkg} in data, and we can verify how well it describes the observed asymmetry a, as a function of muon p_T;

We get $\chi^2/\text{d.o.f.} = 2.4/5$ for the difference between these two distributions;

(a) • - Asymmetry a_{bkg} □ - Asymmetry a DØ, 6.1 fb^{-1}

(b)   DØ, 6.1 fb^{-1}
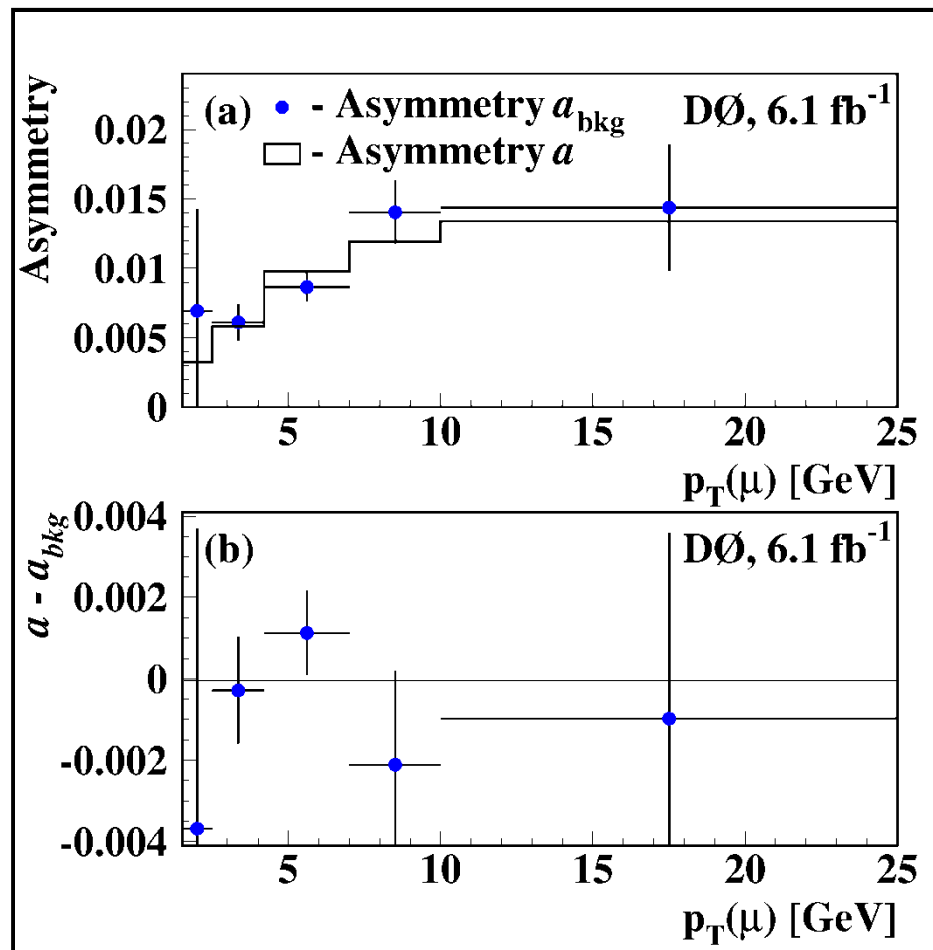
Excellent agreement between the expected and observed values of a , including p_T dependence

Results: Part I

A^b_{sl} is extracted separately from both inclusive muon (a) and dimuon (A) methods:

From a:

$$A^b_{sl} = [\ +0.94\ \pm 1.12\ (\text{stat.})\ \pm 2.14\ (\text{syst.})\ ]\ \%$$

From A:

$$A^b_{sl} = [\ -0.736 \pm 0.266\ (\text{stat.}) \pm 0.305\ (\text{syst.})\ ]\ \%$$

Here's the clever part...

The background fractions a_{bkg} and A_{bkg} are strongly correlated (same sources contribute to both), so we can construct a linear combination such that the total uncertainties are minimised:

$$\mathbf{A' \equiv A - \alpha \cdot a} \ = \ (\mathbf{K} - \mathbf{\alpha \cdot k})\mathbf{A}^b_{sl} + (\mathbf{A}_{bkg} - \mathbf{\alpha \cdot a}_{bkg})$$

We can expect optimal uncertainties for $\alpha \approx 1$, since background asymmetries are similar. **We retain sensitivity to A^b_{sl}, because the dilution coefficient K >> k.**
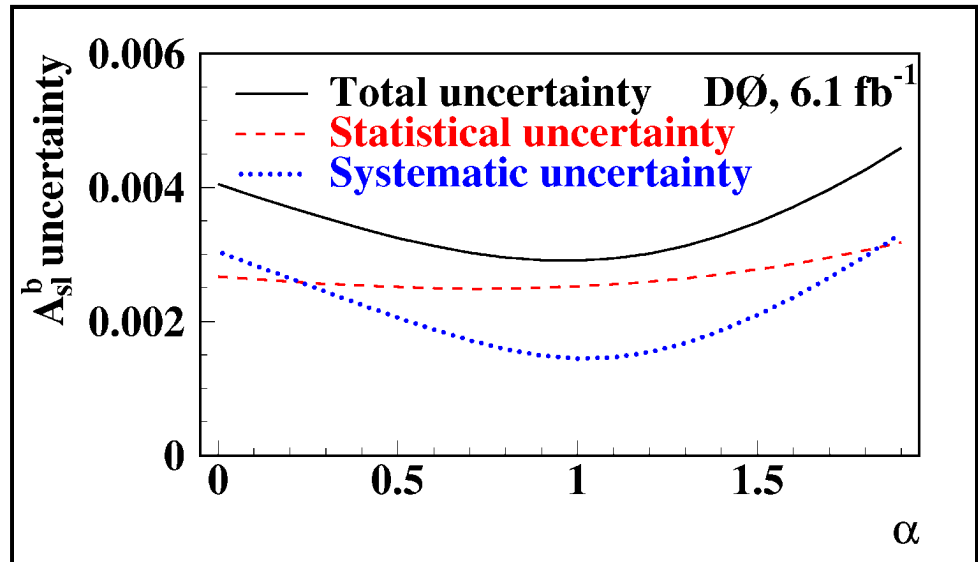
Results: Part II

Scan over total uncertainty on final measurement, yields $\alpha = 0.959$.

Reduces overall systematic uncertainty – precision is now **statistically limited**.

From $A' = A - \alpha\, a$ we obtain:

$$A^b_{sl} = [-0.957 \pm 0.251 \text{ (stat.)} \pm 0.146 \text{ (syst.)}]\ \%$$

This result differs from the SM prediction, $[-0.023 \pm 0.006]\ \%$, by $\sim 3.2\ \sigma$.

Measured asymmetry **favours the production of matter over antimatter** in semileptonic decays of oscillated neutral B mesons.

Minimising Uncertainties...

Source	A^b_{sl} Inclusive $\sigma(A^b_{sl})(59)$	A^b_{sl} Dimuon $\sigma(A^b_{sl})(60)$	A^b_{sl} Combined $\sigma(A^b_{sl})(62)$
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

Dominant uncertainties

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Dominant uncertainty changes from systematic → statistical

Comparison with other Measurements

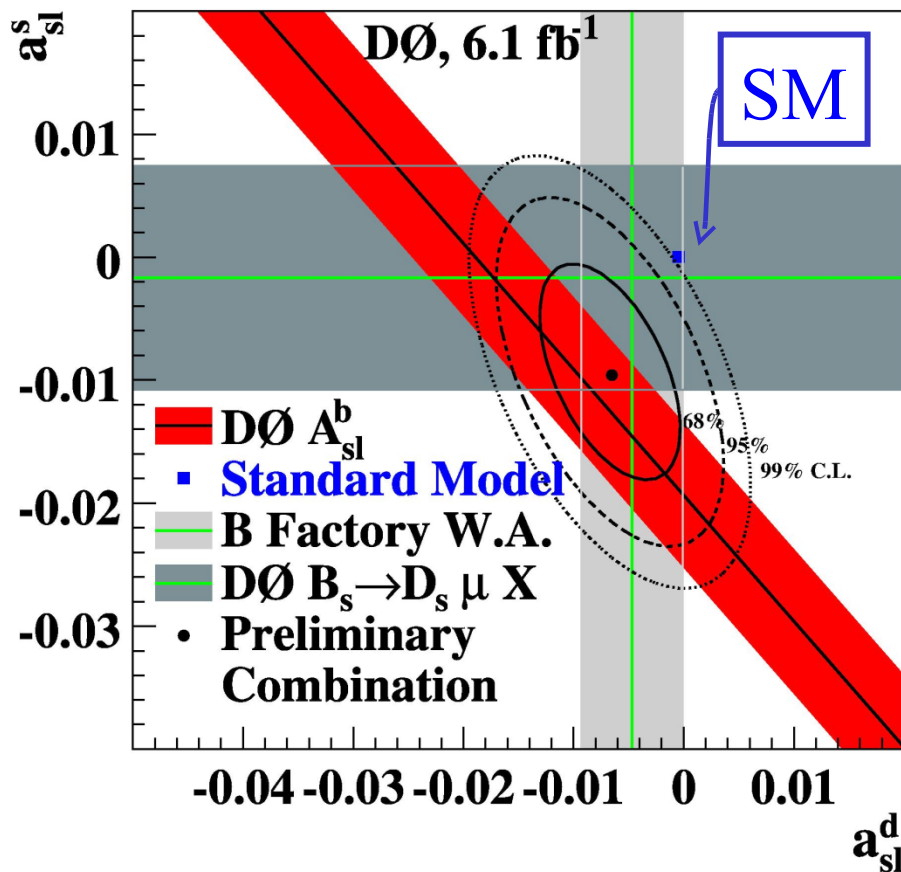In this analysis we measure a linear combination of a^d_{sl} and a^s_{sl}:

$$A^b_{sl} = 0.506\, a^d_{sl} + 0.494\, a^s_{sl}$$

Obtained result agrees well with other measurements of a^d_{sl} and a^s_{sl}.

The value of a^s_{sl} can also be extracted, using additional input from a^d_{sl}:

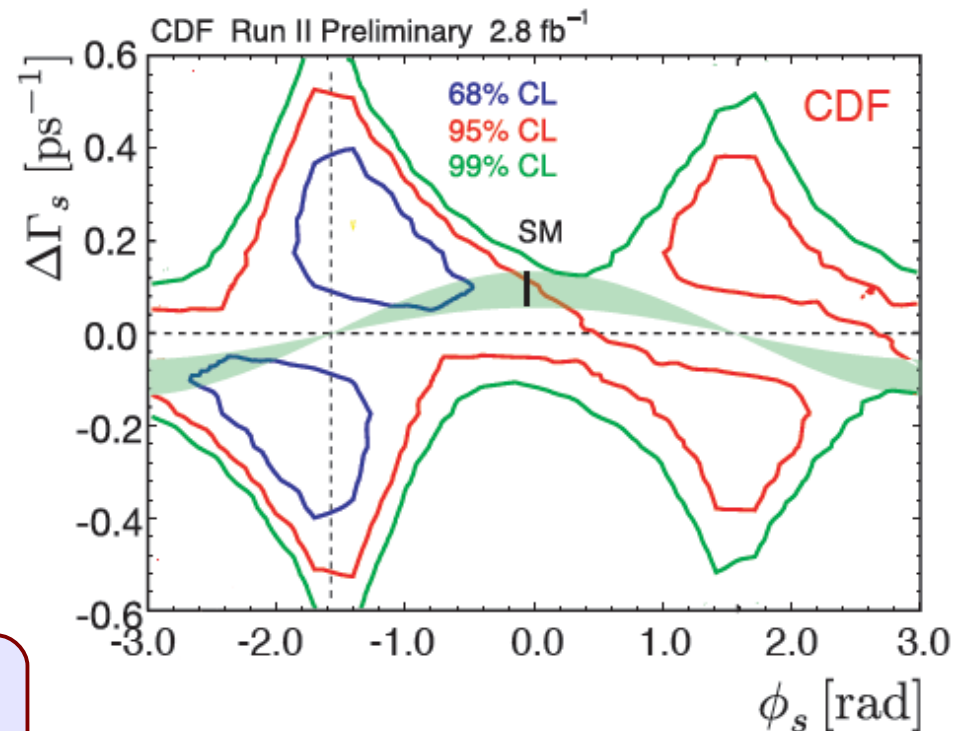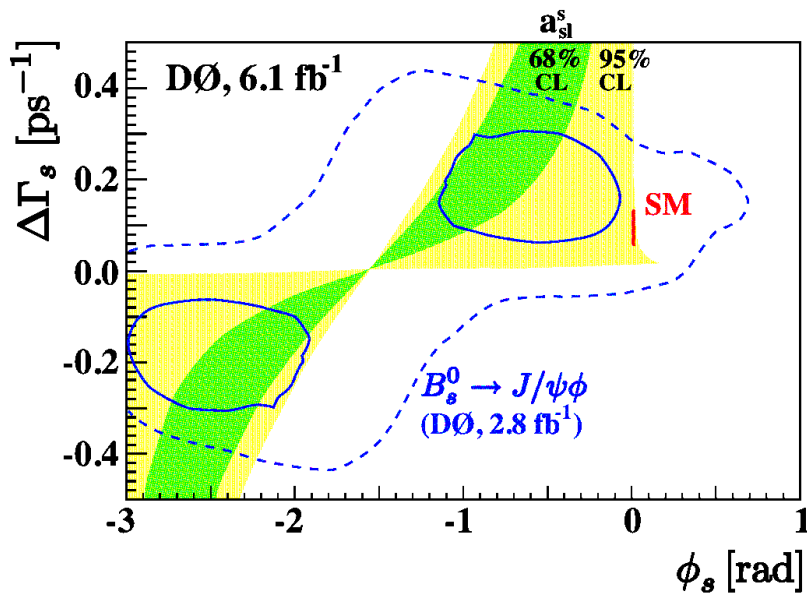$$a^s_{sl} = (\,-1.46 \pm 0.75\,)\,\%$$

SM value is (+0.0021 ± 0.0006)%

Constraining B^0_s Mixing Parameters

- The value of a^s_{sl} can be further translated into a 2D constraint on the CP violating phase φ_s and $\Delta\Gamma_s$;

- The contours are in excellent agreement with independent measurements of φ_s and $\Delta\Gamma_s$ in $B_s \rightarrow J/\psi\varphi$ decay (CDF and D0);
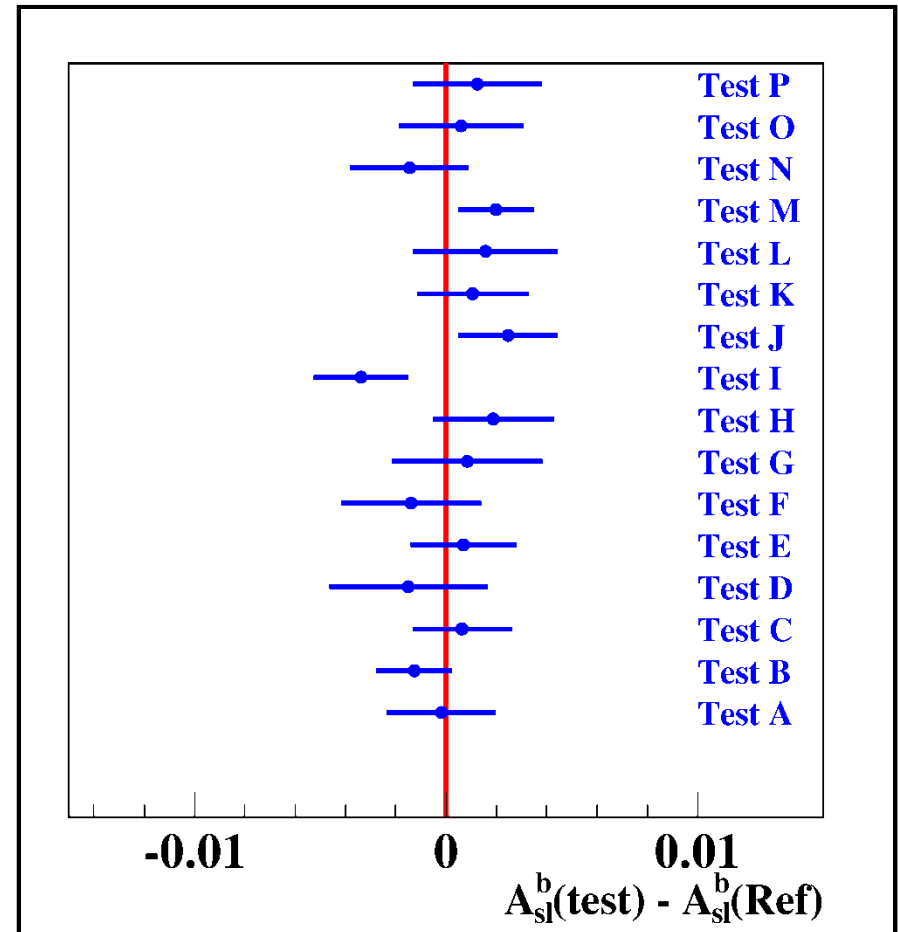

$$a^q_{sl} = \frac{\Delta\Gamma_q}{\Delta M_q}\, tan(\varphi_q)$$

Consistency Tests

We modify the selection criteria, or use a sub-set of the data, to test the stability of the final result:

- 16 tests in total are performed;

- There is significant variation of the raw asymmetries A and a (up to 140%) due to changes in the background composition;

- However, A^b_{sl} remains stable in all tests.

The developed method is stable and gives a consistent result after modifying selection criteria over a wide range.

Conclusions

- We find evidence for CP violation in B meson mixing;

  ➤ **Inconsistent with the SM** at a 3.2σ level;

  ➤ **Favours the production of matter over antimatter**;

- Final measurement is robust against changes in event selection;

- Backgrounds are well-understood, and can explain the p_T dependence of raw inclusive muon asymmetry *a*.

- Measurement is *statistically limited* – precision will improve as more data is collected;

- Also many new ideas to further reduce uncertainties, and to investigate other aspects of the measurement.

Further reading: **arXiv:1005.2575**
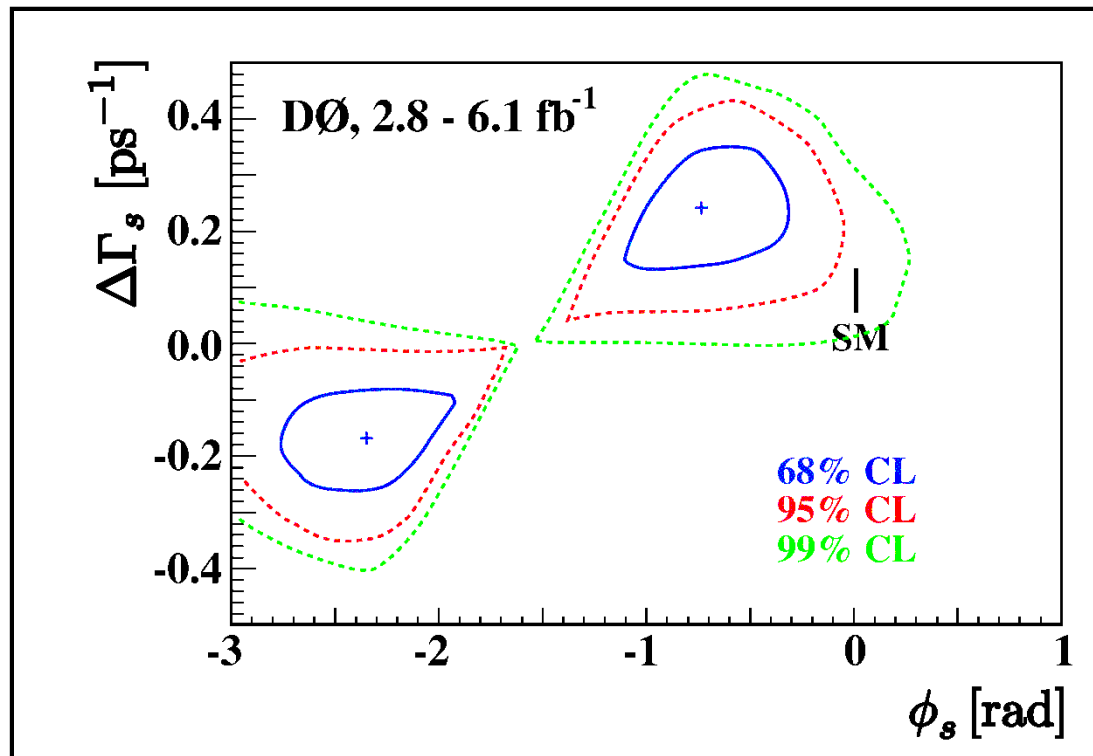*submitted to PRD (PRL in preparation)*

Backup Slides:

➢ *D0 Combination of $(\Delta\Gamma_s, \varphi_s)$;*

➢ *Mass dependence of asymmetry;*

➢ *Theory slide;*

➢ *Additional details on measurement;*

Combination of Results

- This measurement and the result of the DØ analysis in $B_s \rightarrow J/\psi\varphi$ can be combined together;
- This combination excludes the SM value of φ_s at more than 95% C.L.

Dependence on Dimuon Mass

- We compare the expected and observed raw dimuon charge asymmetry A for different invariant masses $M(\mu\mu)$;

- The expected and observed asymmetries agree well for $A^b_{sl} = -0.00957$;

- Agreement is over the entire $M(\mu\mu)$ range – supports B physics as the source of anomalous asymmetry.
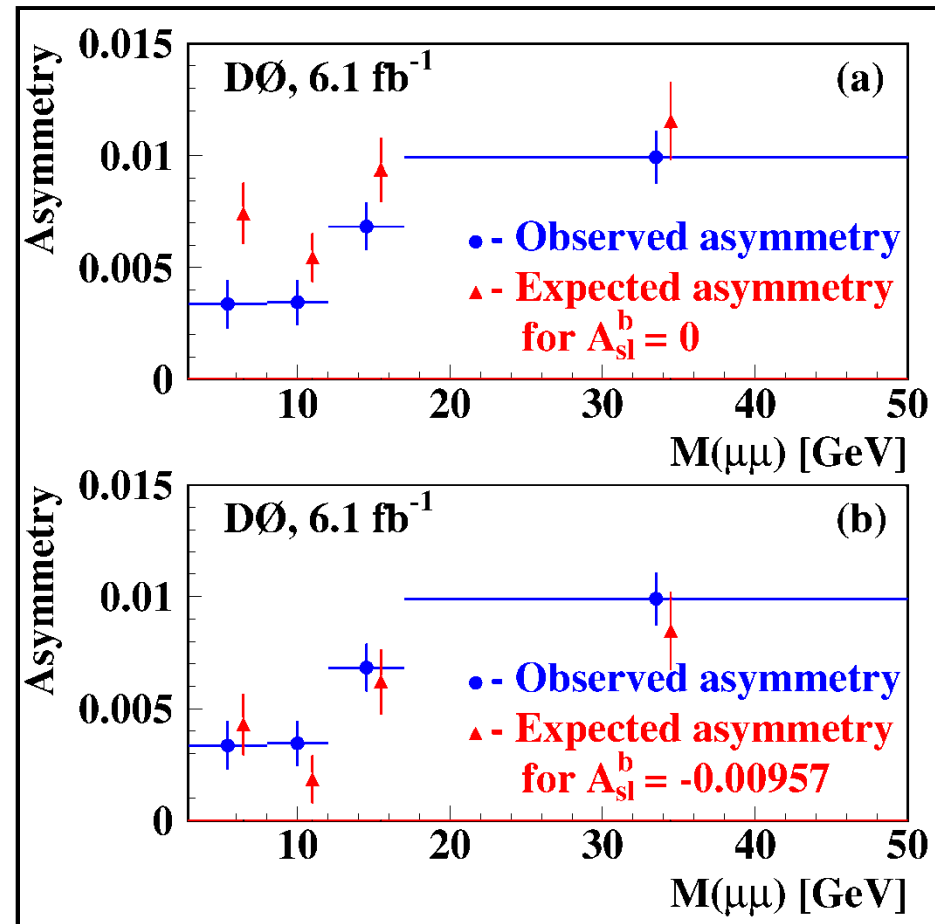
Dependence on the dimuon mass is well described by the analysis method.

Consistency Tests A-C

- Test A: Using only the part of the data sample corresponding to the first 2.8 fb^{-1}.

- Test B: In addition to the reference selections, requiring at least three hits in muon wire chamber layers B or C, and the χ^2 for a fit to a track segment reconstructed in the muon detector to be 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 requirement on this χ^2 is changed from 40 to 4 in this study.

Consistency Tests D-F

- Test D: The requirement on the transverse impact parameter is changed from 0.3 to 0.05 cm, and the requirement on the longitudinal distance between the point of closest approach to the beam and the associated primary vertex is changed from 0.5 to 0.05 cm (this test serves also as a cross-check against the possible contamination from muons from cosmic rays in the selected sample).

- Test E: Using only low-luminosity events with fewer than three primary vertices.

- Test F: Using only events with the same polarities of the solenoidal and toroidal magnets.

Consistency Tests G-J

- Test G: Changing the requirement on the invariant mass of the two muons from 2.8 GeV to 12 GeV.

- Test H: Using the same muon p_T requirement, $p_T > 4.2$ GeV, over the full detector acceptance.

- Test I: Requiring the muon p_T to be $p_T < 7.0$ GeV.

- Test J: Requiring the azimuthal angle ϕ of the muon track be in the range $0 < \phi < 4$ or $5.7 < \phi < 2\pi$. This selection excludes muons directed to the region of poor muon identification efficiency in the support structure of the detector.

Consistency Tests K-N

- Test K: Requiring the muon η be in the range $|\eta| < 1.6$ (this test serves also as a cross-check against the possible contamination from muons associated with the beam halo).

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

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

- Test N: Requiring the muon η be in the range $0.7 < |\eta| < 2.2$.

$A^b{}_{sl}$ and *CP* violation

A non-zero value of $A^b{}_{sl}$ means that the semileptonic decays of $B_q{}^0$ and $\bar{B}_q{}^0$ are different;

It implies ***CP* violation in mixing**;

> ➢ This occurs only due to mixing in the B_d and B_s systems;
> ➢ i.e. meson spends more time in $\bar{B}^0{}_q$ state ($b\bar{s}$) than $B^0{}_q$ ($\bar{b}s$);

Quantity describing *CP* violation in mixing is the complex phase ϕ_q of the $B^0{}_q$ ($q = d,s$) mass matrix:

$$\|M_q\| = \begin{bmatrix} M_q & M_q^{12} \\ (M_q^{12})^* & M_q \end{bmatrix} - \frac{i}{2}\begin{bmatrix} \Gamma_q & \Gamma_q^{12} \\ (\Gamma_q^{12})^* & \Gamma_q \end{bmatrix}$$

$$\Delta M_q = M_H - M_L \approx 2\left|M_q^{12}\right|$$

$$\Delta \Gamma_q = \Gamma_L - \Gamma_H \approx 2\left|\Gamma_q^{12}\right|\cos\phi_q$$

$$\phi_q = \arg\left(-\frac{M_q^{12}}{\Gamma_q^{12}}\right)$$

$a^q{}_{sl}$ is related with the CP violating phase ϕ_q as:

$$a_{sl}^q = \frac{\Delta\Gamma_q}{\Delta M_q}\tan(\phi_q)$$

Background Contributions

$$a = kA^b{}_{sl} + \boxed{a_{bkg}}$$

$$A = KA^b{}_{sl} + \boxed{A_{bkg}}$$

Several background processes contribute to a_{bkg} and A_{bkg}:

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

Total 'fraction' of muons in each **dimuon** event is 2

- f_K, f_π, and f_p are the fractions of kaons, pions and protons identified as a muon in the inclusive muon sample;

- a_K, a_π, and a_p are the charge asymmetries of kaon, pion, and proton tracks;

- δ is the charge asymmetry of muon reconstruction;

- $f_{bkg} = f_K + f_\pi + f_p$

Uppercase variables are the same quantities defined in the **same-sign dimuon sample**

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Muon Reconstruction Asymmetry

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

Final piece of the equation needed to determine a_{bkg} and A_{bkg};

• Reversal of toroid and solenoid polarities cancels 1st-order detector effects;

• Quadratic terms in detector asymmetries still can contribute into the muon reconstruction asymmetry;

• Detector asymmetries for a given magnet polarity $a_{det} \approx O(1\%)$;

• Therefore, we can expect the residual reconstruction asymmetry :

$$\delta \approx \Delta \approx O\ (0.01\%)$$

Muon Reconstruction Asymmetry

x 10²

(a) DØ, 6.1 fb⁻¹
$\chi^2/\text{dof} = 62/29$

$n(\mu^+ t^-) + n(\mu^- t^+)$

(b) DØ, 6.1 fb⁻¹
$\chi^2/\text{dof} = 51/36$

$n(\mu^+ t^-) - n(\mu^- t^+)$

We measure the muon reconstruction asymmetry using $J/\psi \rightarrow \mu\mu$ events, where a muon is combined with any track of opposite charge:
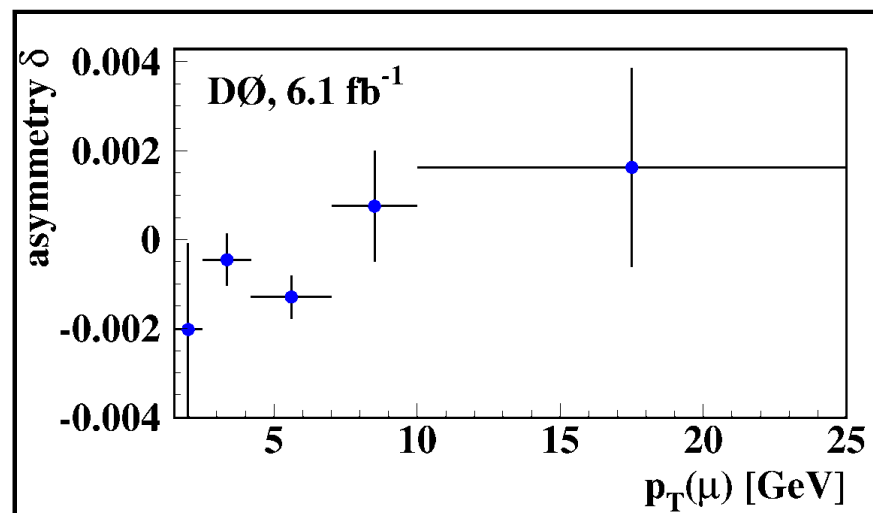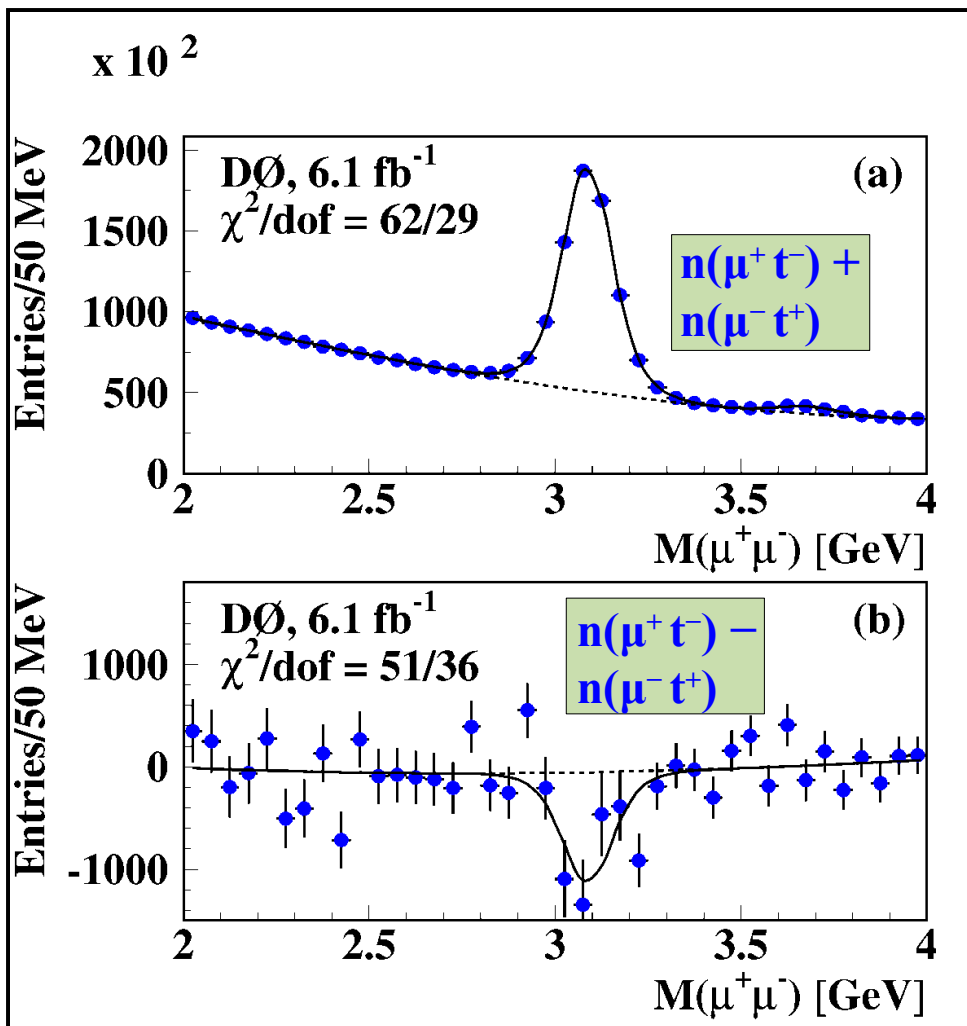
$$\delta = (- 0.076 \pm 0.028)\ \%$$

$$\Delta = (- 0.068 \pm 0.023)\ \%$$

To be compared with:

$$a = (+ 0.955 \pm 0.003)\ \%$$

$$A = (+ 0.564 \pm 0.053)\ \%$$

DØ, 6.1 fb⁻¹

Kaon Detection Asymmetry

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

- The largest background asymmetry comes from the charge asymmetry of kaon tracks identified as muons (a_K, A_K);

- Interaction cross section of K^+ and K^- with the detector material is different, especially for kaons with low momentum:

  @ $p(K) = 1$ GeV: $\sigma(K^-d) \approx 80$ mb $\sigma(K^+d) \approx 33$ mb

  This is because the reaction $K^- N \rightarrow Y\pi$ has no $K^+ N$ analogue;

- Hence K^+ mesons travel further in the detector on average, having a greater probability of decaying to muons, or punching through to the muon system – **the asymmetries a_K and A_K should be positive**.

Measuring Kaon Asymmetry
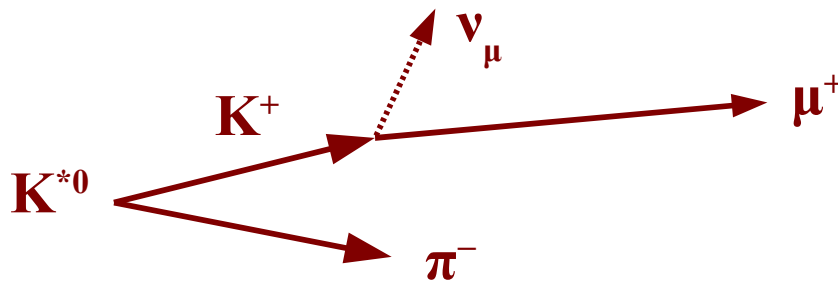
Starting from the inclusive muon sample...

1) Define sources of kaons from resonances which can be fitted to extract signal size (two independent samples):

$$K^{*0} \to K^+\pi^- \qquad\qquad \varphi(1020) \to K^+K^-$$

2) Require that the kaon is identified as a muon, e.g.:

kaon usually decays outside tracking detector – so momentum is correctly measured.

3) Build the mass distribution separately for positive and negative kaons;

4) Compute asymmetry in the number of observed events;

Measuring Kaon Asymmetry

$\varphi \rightarrow K^+ K^-$ decay

DØ, 6.1 fb⁻¹
$\chi^2/\text{dof} = 64/27$

(a)

$N(K^+ \rightarrow \mu^+) + N(K^- \rightarrow \mu^-)$

Entries/2 MeV

x 10²

M(K⁺K⁻) [GeV]

DØ, 6.1 fb⁻¹
$\chi^2/\text{dof} = 22/35$

(b)

Excess of positive kaons

$N(K^+ \rightarrow \mu^+) - N(K^- \rightarrow \mu^-)$

Entries/2 MeV

M(K⁺K⁻) [GeV]

For each channel, K^{*0} and $\varphi(1020)$, the asymmetry is determined is bins of kaon transverse momentum.

The results for both channels agree (χ^2 of difference is 5.4/5 degrees-of-freedom), so they are combined to produce $\mathbf{a_K}$.

The same-sign dimuon asymmetry $\mathbf{A_K}$ is then determined algebraically from a_K, based on the two p_T values of the muons.

DØ, 6.1 fb⁻¹

a_K combined

Typical kaon asymmetry is ~ **4-6%**

$p_T(K)$ [GeV]
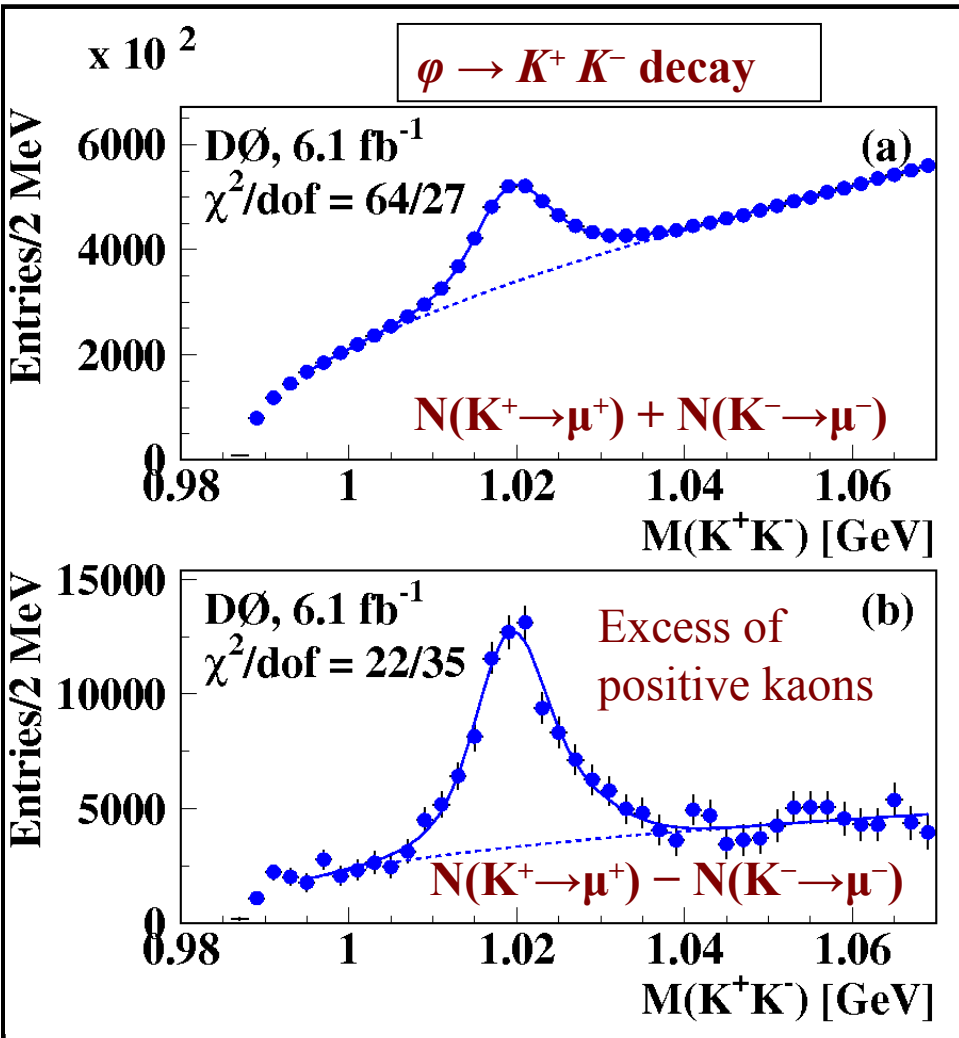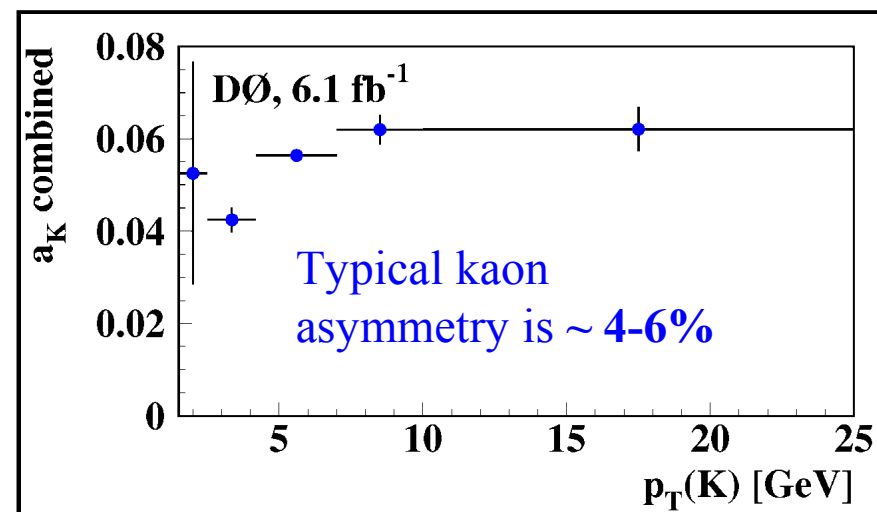
Pion and Proton Asymmetry

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

The same strategy is used to determine a_π, a_p, A_π and A_p.

- $K_S \rightarrow \pi^+ \pi^-$ is used to measure pion asymmetry;
- $\Lambda \rightarrow p\,\pi^-$ is used to measure proton asymmetry.

a_K	a_π	a_p
$(+5.51 \pm 0.11)\%$	$+(0.25 \pm 0.10)\%$	$(+2.3 \pm 2.8)\%$

In fitting with expectations, the kaon asymmetry is positive, and forms the largest contribution.
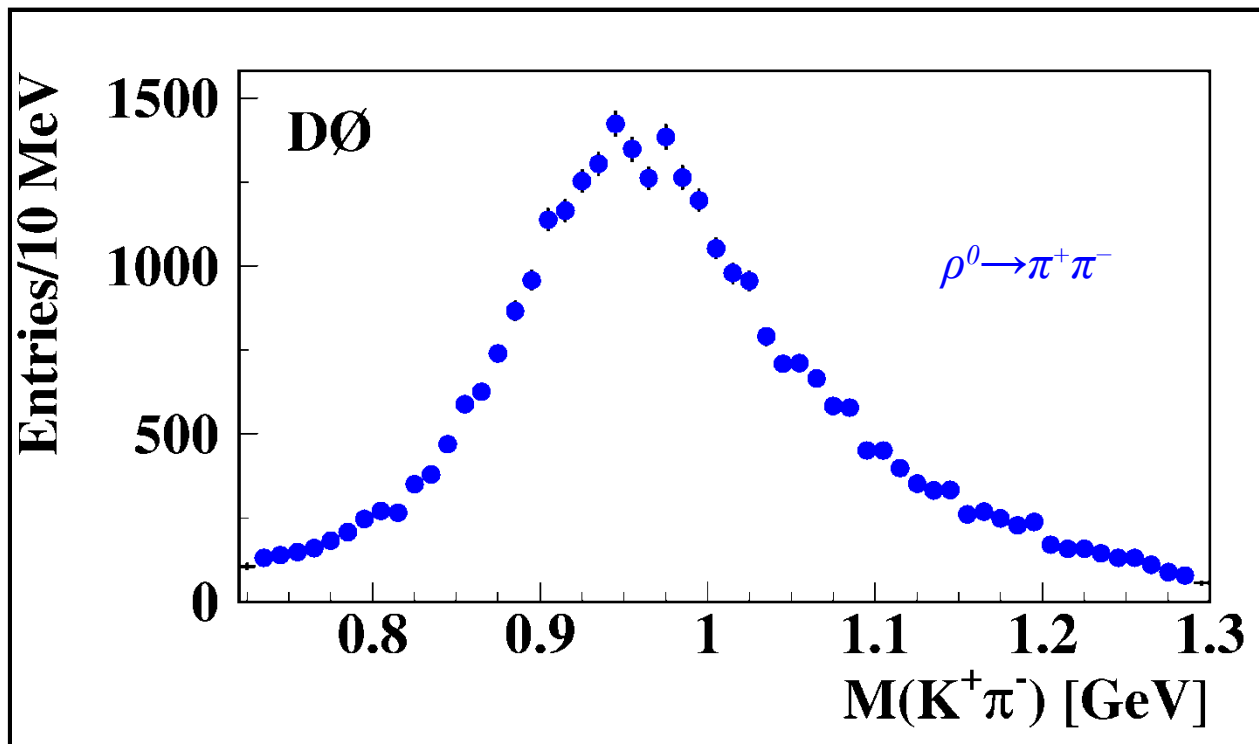
Measurement of f_K, F_K

- Fractions f_K, F_K are measured using the decays $K^{*0} \to K^+\pi^-$ selected in the inclusive muon and like-sign dimuon samples respectively;

- Kaon is required to be identified as a muon;

- We measure fractions f_{K*0}, F_{K*0};
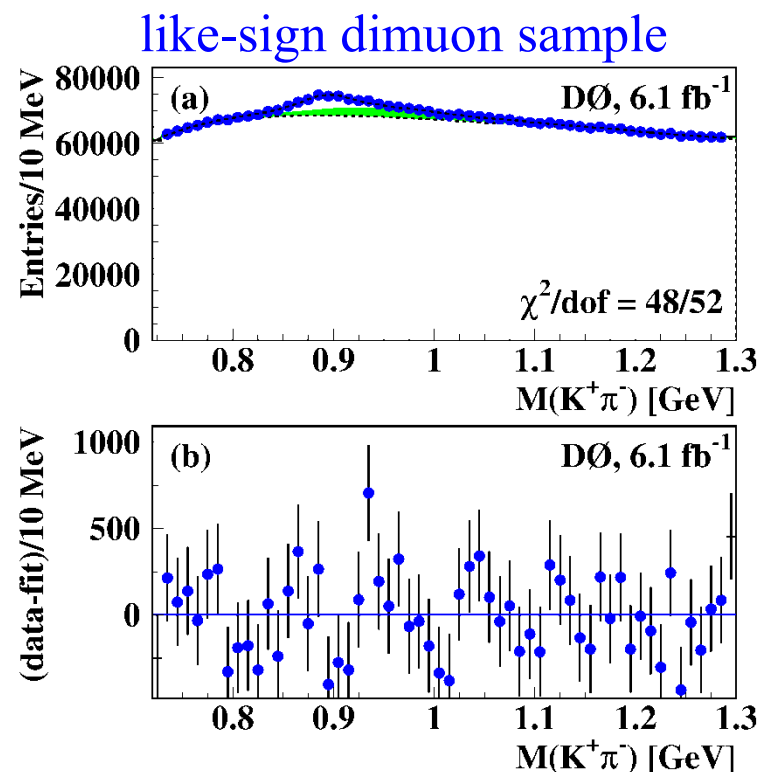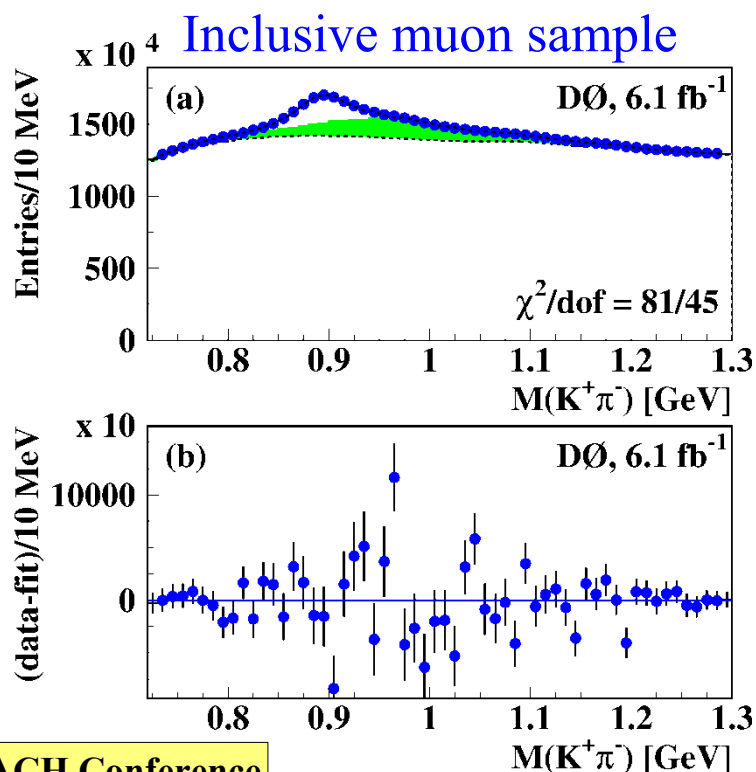
Peaking background contribution

- Decay $\rho^0 \rightarrow \pi^+\pi^-$ produces a peaking background in the $(K\pi)$ mass, because one pion can be misidentified as a kaon;

- The mass distribution from $\rho^0 \rightarrow \pi^+\pi^-$ is taken from simulation.

Measurement of f_K, F_K

To convert these fractions to f_K, F_K, we need to know the fraction $R(K^{*0})$ of charged kaons from $K^{*0} \rightarrow K^+\pi^-$ and the efficiency to reconstruct an additional pion ε_0 :

$$f_{K*0} = f_K R(K^{*0})\varepsilon_0; \quad F_{K*0} = F_K R(K^{*0})\varepsilon_0$$

What we measure

What we need

Fraction of kaons which originate from K*0 decay

Efficiency to reconstruct an additional charged pion track
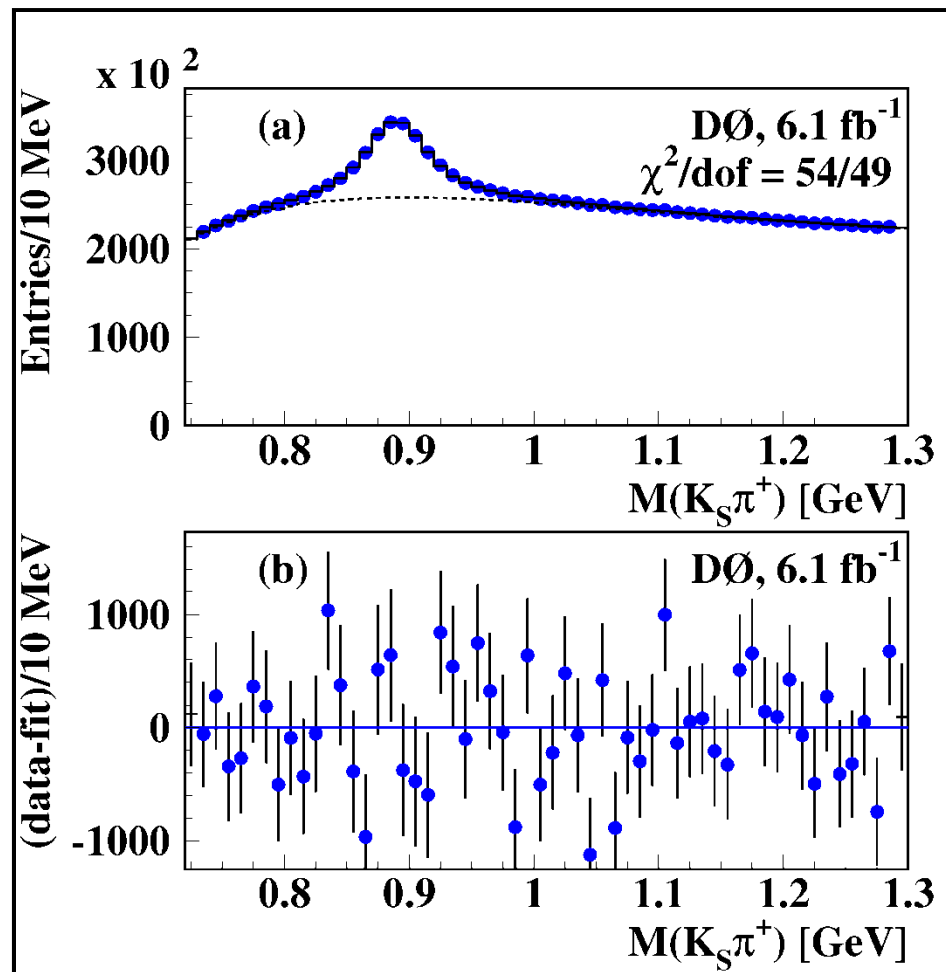
Measurement of f_K, F_K

We also select decay $K^{*+} \rightarrow K_S \pi^+$;

- We have:

$$N_{K^{*+}} = N_{K_S} R(K^{*+}) \varepsilon_c$$

Fraction of K_S mesons which originate from K^{*+} decay

Efficiency to reconstruct an additional charged pion track

(a) DØ, 6.1 fb^{-1}
χ^2/dof = 54/49

(b) DØ, 6.1 fb^{-1}

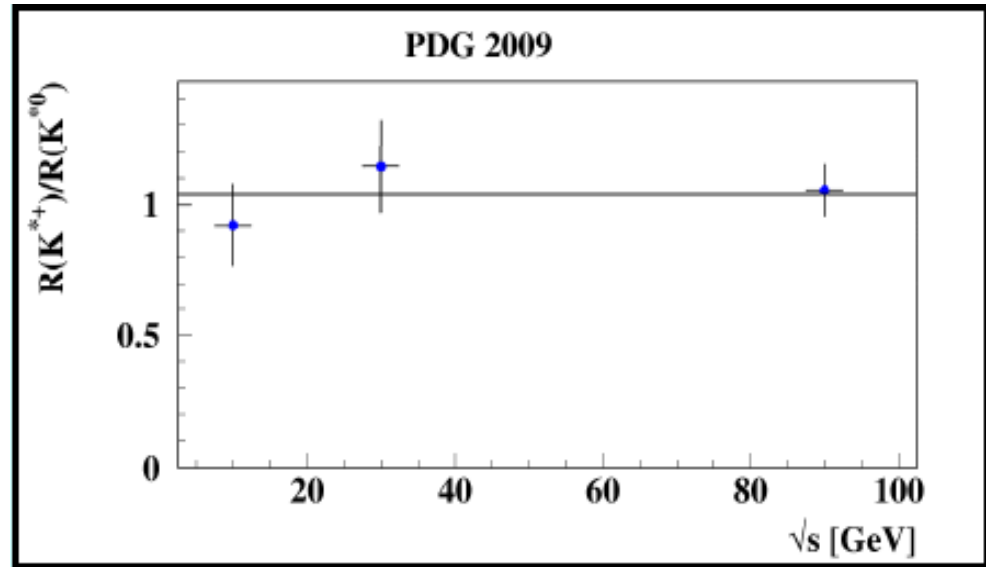# Measurement of f_K, F_K

R(K*+) = R(K*0) due to isospin invariance:

➤ Verified with the available data on production of K*+ and K*0 in jets at different energies (PDG);

➤ Also confirmed by simulation;

➤ Related systematic uncertainty 7.5%

$\varepsilon_0 = \varepsilon_c$ because the same criteria are used to select the pion in

$K^{*+} \rightarrow K_S \pi^+$ and $K^{*0} \rightarrow K^+ \pi^-$

➤ Verified in simulation;

➤ Related systematic uncertainty 3%;

Measurement of f_K, F_K

With these conditions applied, we obtain f_K , F_K as:

$$f_K = \frac{N(K_S)}{N(K^{*+})} f_{K^{*0}}$$

$$F_K = \frac{N(K_S)}{N(K^{*+})} F_{K^{*0}}$$

➢ **The same values $N(K_S)$, $N(K^{*+})$ are used to measure f_K , F_K ;**

We assume that the fraction $R(K^{*0})$ of charged kaons coming from $K^{*0} \rightarrow K^{+}\pi^{-}$ decay is the same in the inclusive muon and like-sign dimuon sample;

➢ **We verified this assumption in simulation;**

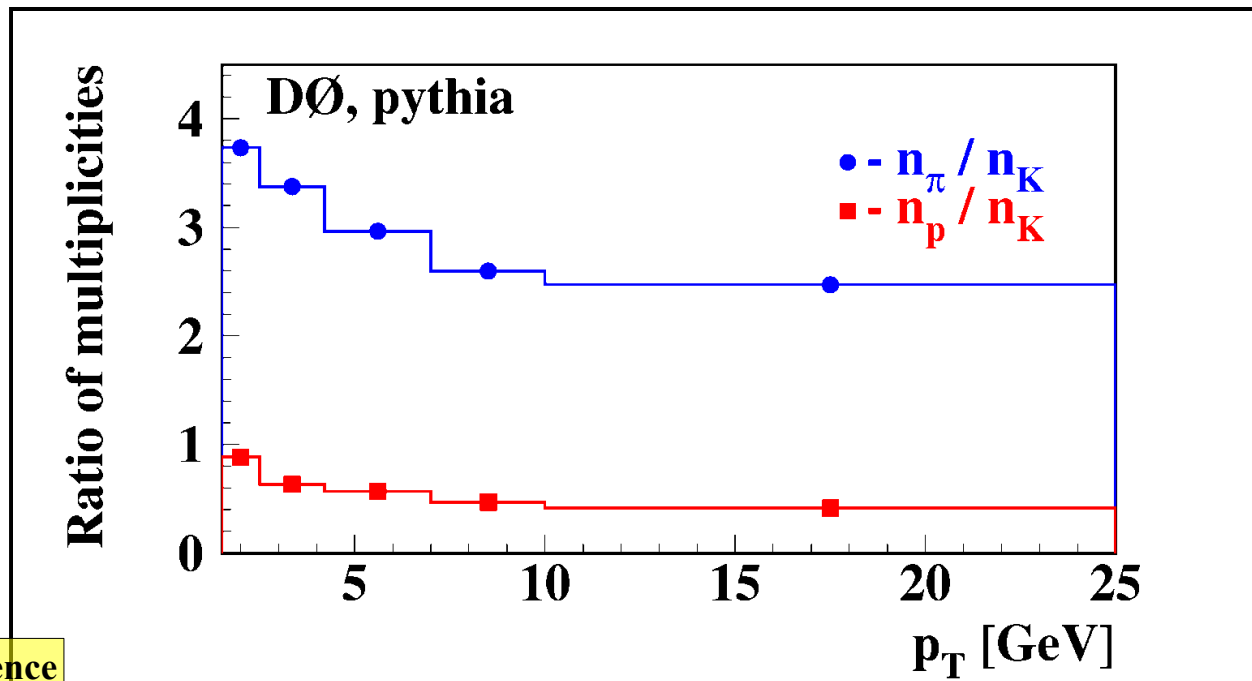We assign a 3% systematic uncertainty due to this assumption;

Measurement of f_π, f_p, F_π, F_p

$$a_{bkg} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{bkg})\delta$$

$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

Fractions f_π, f_p, F_π, F_p are obtained using f_K and F_K with an additional input from simulation on the ratio of multiplicities n_π/n_K and n_p/n_K:

Measurement of f_π, F_π

- We use as an input:
  - Measured fractions f_K, F_K;
  - Ratio of multiplicities of pion and kaon n_π / n_K in QCD events taken from simulation;
  - Ratio of multiplicities of pion and kaon N_π / N_K in QCD events with one additional muon taken from simulation;
  - Ratio of probabilities for charged pion and kaon to be identified as a muon: $P(\pi \to \mu) / P(K \to \mu)$;
  - Systematic uncertainty due to multiplicities: 4%
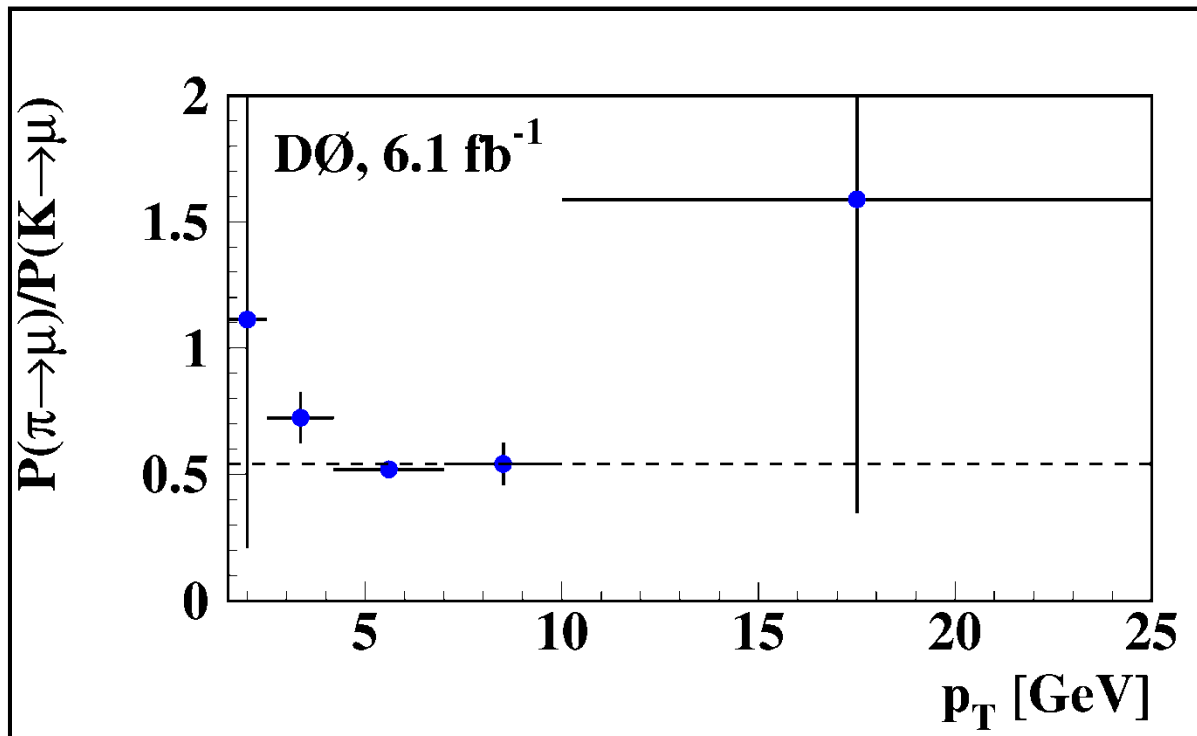
- We obtain f_π, F_π as:

$$f_\pi = f_K \frac{P(\pi \to \mu)}{P(K \to \mu)} \frac{n_\pi}{n_K}$$

$$F_\pi = F_K \frac{P(\pi \to \mu)}{P(K \to \mu)} \frac{N_\pi}{N_K}$$

Measurement of P($\pi\rightarrow\mu$)/ P(K$\rightarrow\mu$)

The ratio of these probabilities is measured using decays $K_S \rightarrow \pi^+ \pi^-$ and $\phi(1020) \rightarrow K^+ K^-$;

- We obtain: $P(\pi \rightarrow \mu)/P(K \rightarrow \mu) = 0.540 \pm 0.029$

Summary of Background Composition

$$f_{\text{bkg}} = f_K + f_\pi + f_p$$

We get the following background fractions in the inclusive muon sample:

	$(1 - f_{bkg})$	f_K	f_π	f_p
MC	$(59.0 \pm 0.3)\%$	$(14.5 \pm 0.2)\%$	$(25.7 \pm 0.3)\%$	$(0.8 \pm 0.1)\%$
Data	$(58.1 \pm 1.4)\%$	$(15.5 \pm 0.2)\%$	$(25.9 \pm 1.4)\%$	$(0.7 \pm 0.2)\%$

➢ Uncertainties for both data and simulation are statistical only;

➢ Simulation fractions are given as a cross-check only, and **are not used in the analysis**;

➢ Good agreement is found between data and simulation, within the systematic uncertainties assigned;

➢ Fractions for same-sign dimuon sample are extracted similarly.