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Search for new sources of CP violation with DØ experiment

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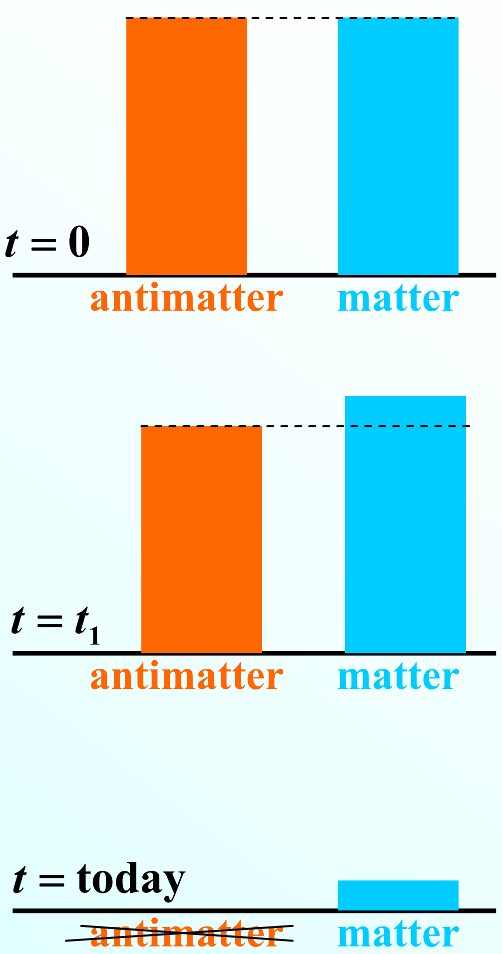
Matter – Antimatter Asymmetry

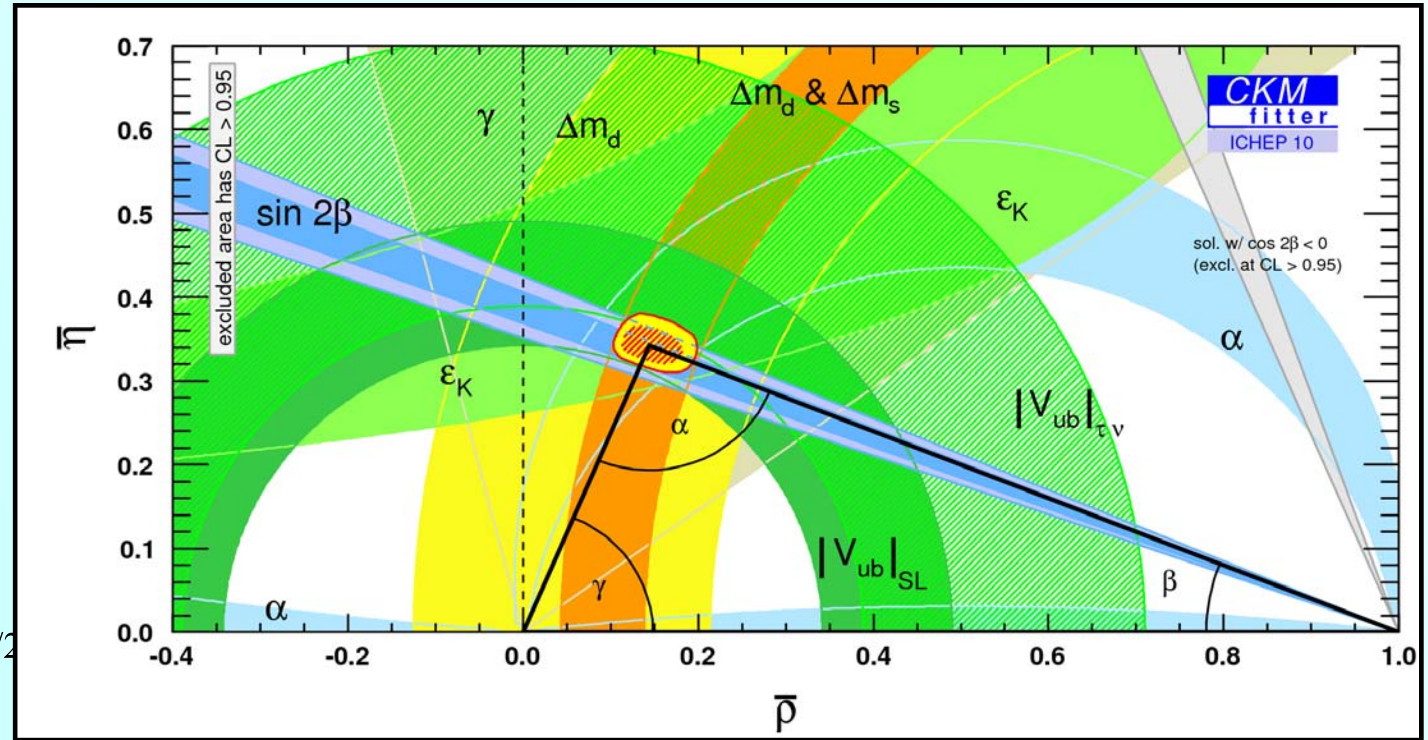
- One of major challenges of particle physics – explain the dominance of matter in our Universe
- Number of particles and antiparticles produced in the Big Bang is expected to be equal
- For some reason matter becomes more abundant in the early stages of Universe
- Antimatter completely annihilated
- Hence we're left only with matter today



One of conditions (A. Sakharov) required to explain this process – properties of particles and antiparticles must be different (*CP* violation)

CP violation in SM

- *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:
  - All measurements are consistent with a single apex of this unitarity triangle plot



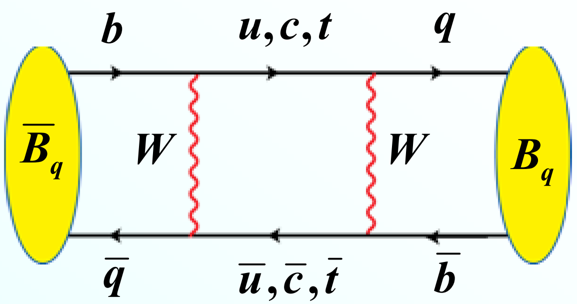
CP violation in SM

- The SM disagrees with one experimental fact – our existence
  - The SM source of *CP* violation is not sufficient to explain the imbalance between matter and antimatter
  - See e.g. P. Suet, E. Sather, Phys.Rev.D51, 379-394 (1995)
  - Some theoretical studies claim up to 10 orders of magnitude deficit of the CP violation provided by the SM
- New sources of *CP* violation are required to explain the matter dominance

Search for new sources of *CP* violation –
an important task of current and future experiments

CP violation in mixing

- A promising direction of the search for new sources of *CP* violation is the study of ***CP* violation in mixing** in the B_d and B_s systems
- This type of *CP* violation is described by a complex phase ϕ_q of B_q ($q=d,s$) mass matrix



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

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

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

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

SM prediction

- SM predicts very small values of ϕ_q:

$$\phi_d^{SM} = -0.091^{+0.026}_{-0.038}$$
$$\phi_s^{SM} = 0.0042 \pm 0.0014$$

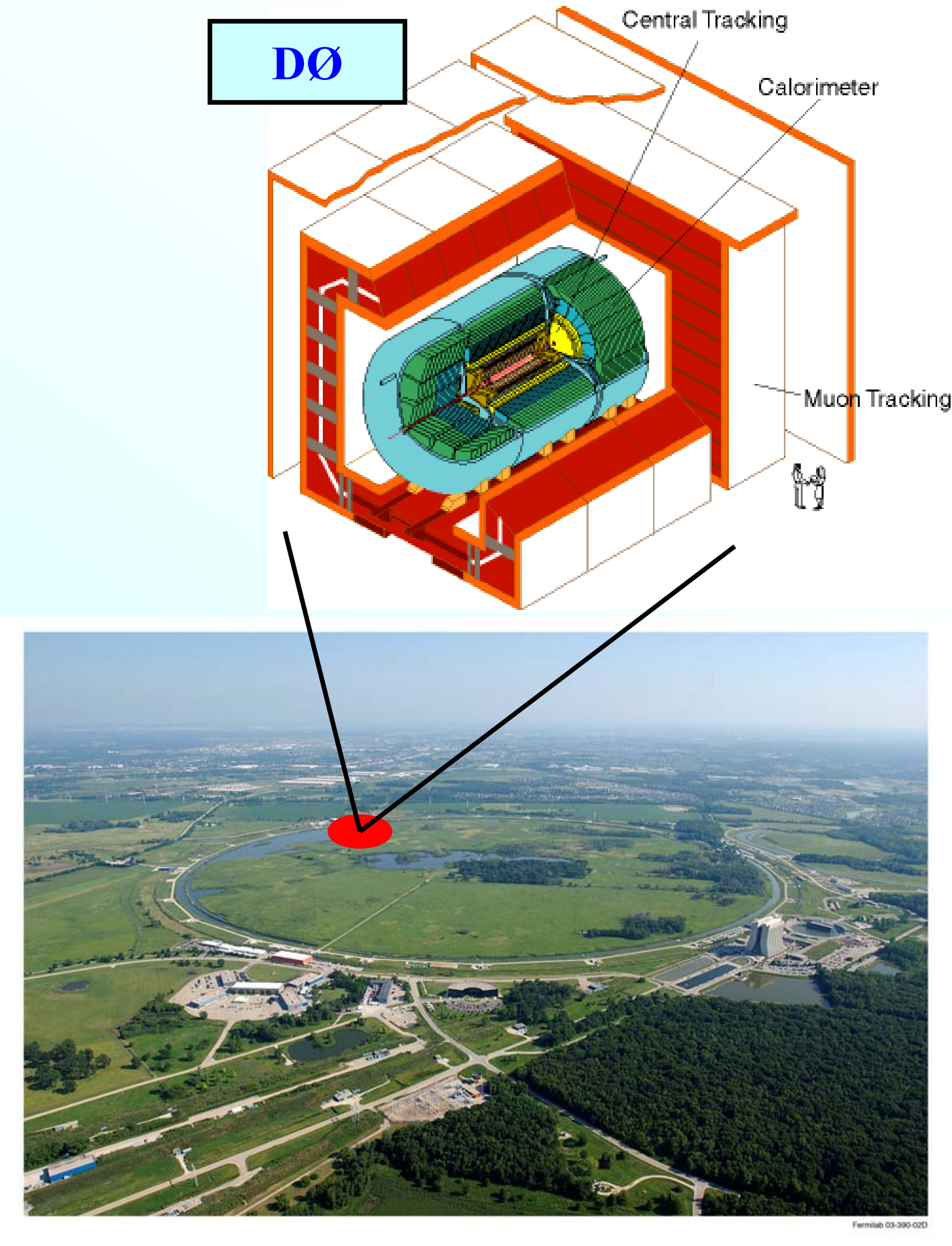
  - A. Lenz, U. Nierste, J. High Energy Phys. 0706, 072 (2007)
  - These values are below current experimental sensitivity
- New physics contribution can significantly change these values

$$\phi_d = \phi_d^{SM} + \phi_d^{NP}$$
$$\phi_s = \phi_s^{SM} + \phi_s^{NP}$$

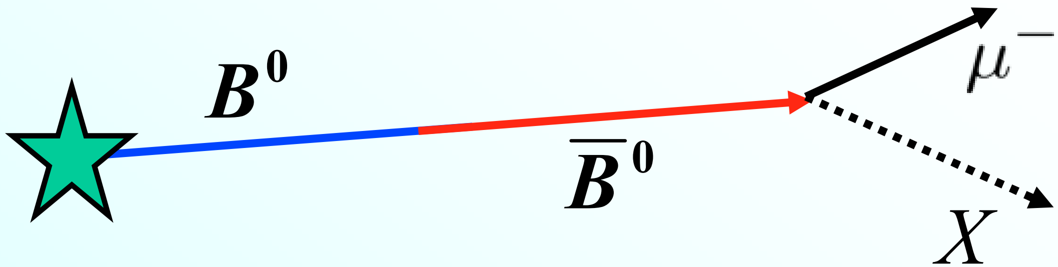
Large non-zero value of ϕ_q would indicate the presence of new physics

Measurement of ϕ_q

- The phase ϕ_q can be measured in several independent ways:
  - Charge asymmetry of semileptonic B_q decays;
  - Dimuon charge asymmetry;
  - Decay $B_s \to J/\psi\varphi$;
- DØ experiment at Fermilab performs all these measurements



Semileptonic charge asymmetry



- The charge asymmetry a^q_{sl} of "wrong sign" semileptonic B^0_q $(q = d,s)$ decays:

$$a^q_{sl} \equiv \frac{\Gamma(\overline{B}^0_q \to \mu^+ X) - \Gamma(B^0_q \to \mu^- X)}{\Gamma(\overline{B}^0_q \to \mu^+ X) + \Gamma(B^0_q \to \mu^- X)}; \quad q = d,s$$

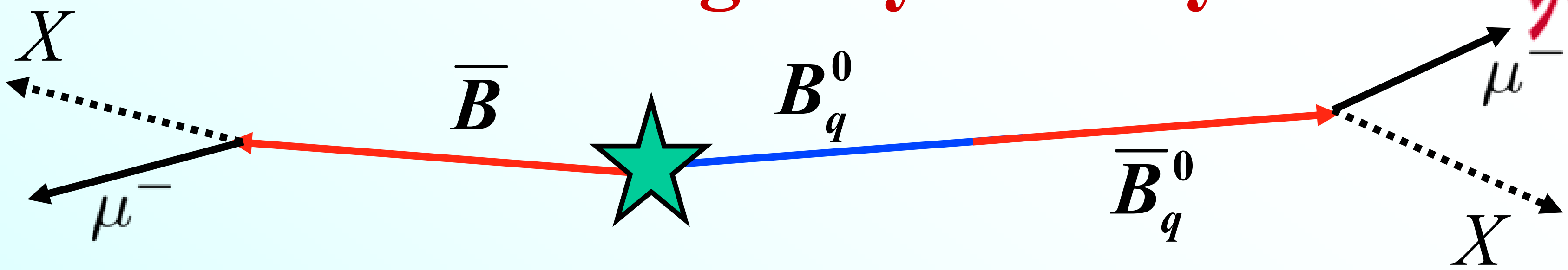
- This asymmetry is related with the phase ϕ_q as:

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

$$a^d_{sl}(SM) = (-4.8^{+1.0}_{-1.2}) \times 10^{-4}$$
$$a^s_{sl}(SM) = (2.1 \pm 0.6) \times 10^{-5}$$

- a^d_{sl} is measured by B factories : $a^d_{sl} = -0.0047 \pm 0.0046$
- a^s_{sl} is measured by DØ experiment: $a^s_{sl} = -0.0017 \pm 0.0091^{+0.0014}_{-0.0015}$

Dimuon charge asymmetry



- Charge asymmetry of same sign dimuon pairs produced in a $p\bar{p}$ collision

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

N_b^{++} (N_b^{--}) – number of same-sign $\mu^+\mu^+$ ($\mu^-\mu^-$) events from $B \to \mu X$ decay

- Both B_d and B_s contribute in $A^b_{\rm sl}$ at Tevatron :

$$A_{sl}^b = (0.506 \pm 0.043) a_{sl}^d + (0.494 \pm 0.043) a_{sl}^s$$

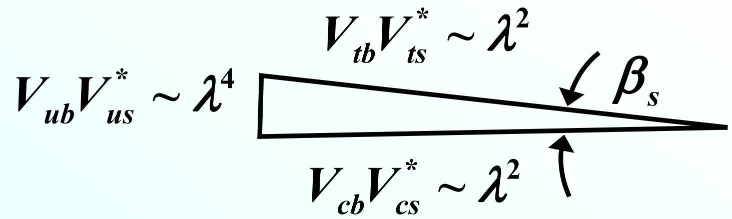
B_d contribution

B_s contribution

Decay $B_s \rightarrow J/\psi\ \varphi$

- CP violation in $B_s \rightarrow J/\psi\varphi$ decay is described by the phase $\phi^{J/\psi\varphi}$
- Within the SM $\phi^{J/\psi\varphi}$ is related to the angle β_s of the (bs) unitarity triangle:

$$\phi^{J/\psi\varphi,SM} = -2\beta_s = 2\arg\left(-\frac{V_{tb}V_{ts}^*}{V_{cb}V_{cs}^*}\right) = -0.038 \pm 0.002$$



- It can be significantly modified by the new physics contribution:

$$\phi^{J/\psi\varphi} = \phi^{J/\psi\varphi,SM} + \phi_s^{NP}$$

ϕ_s^{NP} is the same for $\phi^{J/\psi\varphi}$ and ϕ_s

Measuring the dimuon charge asymmetry

- Experimentally, we measure two quantities:
- **Like-sign dimuon charge asymmetry**:

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = (+0.564 \pm 0.053)\%$$

- **Inclusive muon charge asymmetry**:

$$a \equiv \frac{n^{+} - n^{-}}{n^{+} + n^{-}} = (0.955 \pm 0.053)\%$$

  - N^{++}, N^{--} – the number of events with two like-sign dimuons
  - n^{+}, n^{-} – the number of muons with given charge

Experimental observables and A^b_{sl}

- Semileptonic B decays contribute to both A and a;
- Both A and a linearly depend on the charge asymmetry A^b_{sl}

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

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

- In addition, there are detector related background contributions A_{bkg} and a_{bkg}

Our task is:

- Determine the background contributions A_{bkg} and a_{bkg}
- Find the coefficients K and k
- Extract the asymmetry A^b_{sl}

Background contribution

$$a = k\,A_{sl}^{b} + a_{bkg}$$
$$A = K\,A_{sl}^{b} + A_{bkg}$$

- Sources of background muons:
  - Kaon and pion decays $K^+ \to \mu^+ \nu$, $\pi^+ \to \mu^+ \nu$ or punch-through
  - proton punch-through
  - False track associated with muon track
  - Asymmetry of muon reconstruction

We measure all background contributions directly in data, with a reduced input from simulation

With this approach we expect to control and decrease the systematic uncertainties

Background description

$$a = k\, A_{sl}^{b} + a_{bkg}$$
$$A = K\, A_{sl}^{b} + A_{bkg}$$

- Background contribution a_{bkg} to **inclusive muon sample**:

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

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

Background description

$$a = k\, A_{sl}^{b} + a_{bkg}$$

$$A = K\, A_{sl}^{b} + A_{bkg}$$

- Background contribution A_{bkg} to **like-sign dimuon sample**:

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

  - F_K, F_π, and F_p are the fractions of kaons, pions and protons identified as a muon in the like-sign dimuon 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
  - $F_{bkg} = F_K + F_\pi + F_p$;

Background description

- We measure in data:
  - Asymmetries $a_K(p_T)$, $a_\pi(p_T)$, $a_p(p_T)$;
    - Using decays $K^{*0} \to K^+\pi^-$, $\varphi \to K^+K^-$, $K_S \to \pi^+\pi^-$, $\Lambda \to p\pi^-$;
  - Asymmetry of muon reconstruction $\delta(p_T)$;
    - Using decay $J/\psi \to \mu^+\mu^-$;
  - Fractions $f_K(p_T)$, $F_K(p_T)$;
    - Using decays $K^{*0} \to K^+\pi^-$, $K^{*+} \to K_S\pi^+$, $K_S \to \pi^+\pi^-$;
  - Ratio of probabilities $P(\pi \to \mu)/P(K \to \mu)$, $P(p \to \mu)/P(K \to \mu)$;
    - Using decays $\varphi \to K^+K^-$, $K_S \to \pi^+\pi^-$, $\Lambda \to p\pi^-$;
- We take from simulation:
  - Ratio of multiplicities n_π / n_K , n_p / n_K ;

Kaon detection asymmetry

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

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

- Interaction cross section of K^+ and K^- with the detector material is different
  - especially for kaons with low momentum
  - It happens because the reaction $K^- N \rightarrow Y\pi$ has no $K^+ N$ analogue
- K^+ meson travels further than K^- in the material, and has more chance of decaying to a muon
  - It also has more chance to punch-through and produce a muon signal
- Therefore, the asymmetries a_K, A_K **should be positive**
- All other background asymmetries are found to be about ten times less

Measurement of kaon asymmetry

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

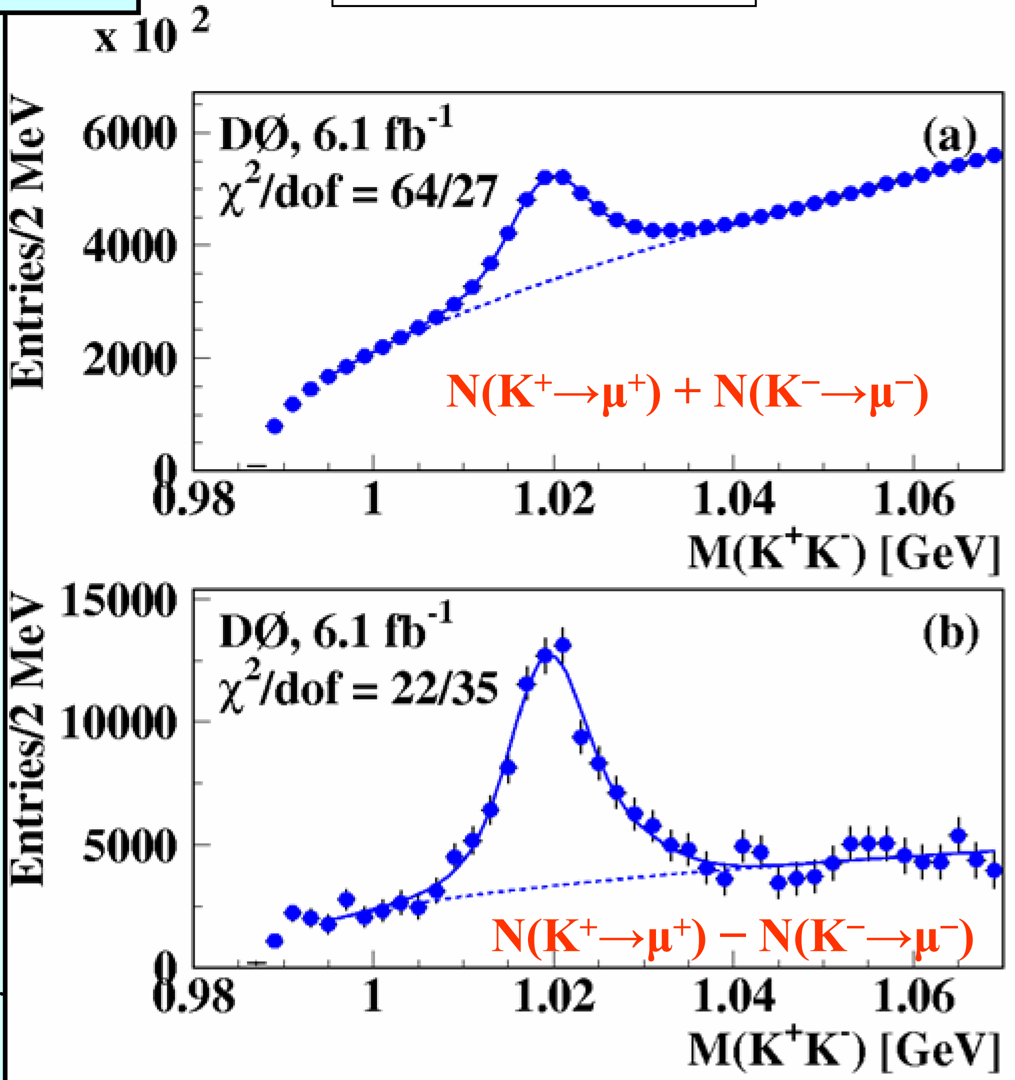
$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

- Define sources of kaons:

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

- Require that the kaon is identified as a muon
- Build the mass distribution separately for positive and negative kaons
- Compute asymmetry in the number of observed events

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



Measurement of a_π, a_p

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

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

- The asymmetries a_π , a_p are measured using the decays $K_S \to \pi^+ \pi^-$ and $\Lambda \to p \pi^-$ respectively
- Similar measurement technique is used

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

Summary of background composition

$$f_{bkg} = f_k + f_\pi + f_p$$

- We get the following background fractions in the inclusive muon events:

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

  – Uncertainties for both data and simulation are statistical
  – Simulation fractions are given as a cross-check only, and **are not used in the analysis**
  – Good agreement between data and simulation within the systematic uncertainties assigned

Summary of background contribution

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

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

- 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
- Notice that background contribution is similar for inclusive muon and dimuon sample: $A_{bkg} \approx a_{bkg}$

Signal – dimuon events

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}} \quad \Rightarrow \quad A_{sl}^{b} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

- We need to count dimuon events coming from $B \to \mu X$ decay
- Other decays of B mesons contribute to dimuon events
  - e.g. $(b \to c \to \mu^+ X)(\bar{b} \to \mu^+ X)$ + c.c.
- Only $(B \to \mu^+ X)(\bar{B} \to B \to \mu^+ X)$ decays produce asymmetry between N_b^{++} and N_b^{--} ;
- All other processes contribute in the denominator only;
- This dilution is taken into account by the coefficient K:

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

Signal – inclusive muon events

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

$$\Rightarrow$$

$$a_{sl}^q \equiv \frac{\Gamma(\bar{B}_q^0 \to \mu^+ X) - \Gamma(B_q^0 \to \mu^- X)}{\Gamma(\bar{B}_q^0 \to \mu^+ X) + \Gamma(B_q^0 \to \mu^- X)}; \quad q = d, s$$

- We need to count muon events coming from $B \to \bar{B} \to \mu^- X$ decay
- Other decays of *b*- and *c*- quarks contribute to muon events
  - e.g., $b \to \mu$ without oscillation
  - e.g., $c \to \mu$
- Only $B \to \bar{B} \to \mu^- X$ decays produce $a^q{}_{sl}$ asymmetry;
- All other processes contribute in the denominator only;
- This dilution is taken into account by the coefficient *k*:

$$a - a_{bkg} = k\, A_{sl}^b$$

Coefficients *k* and *K*

$$k\,A_{sl}^{b} = a - a_{bkg}$$
$$K\,A_{sl}^{b} = A - A_{bkg}$$

- Coefficients *k* and *K* are determined using the simulation of *b*- and *c*-quark decays
  - These decays are currently measured with a good precision, and this input from simulation produces a small systematic uncertainty
- Coefficient *k* is found to be much smaller than *K*, because many more non-oscillating *b*- and *c*-quark decays contribute to the asymmetry *a*:

$$k = 0.041 \pm 0.003$$
$$K = 0.342 \pm 0.023$$

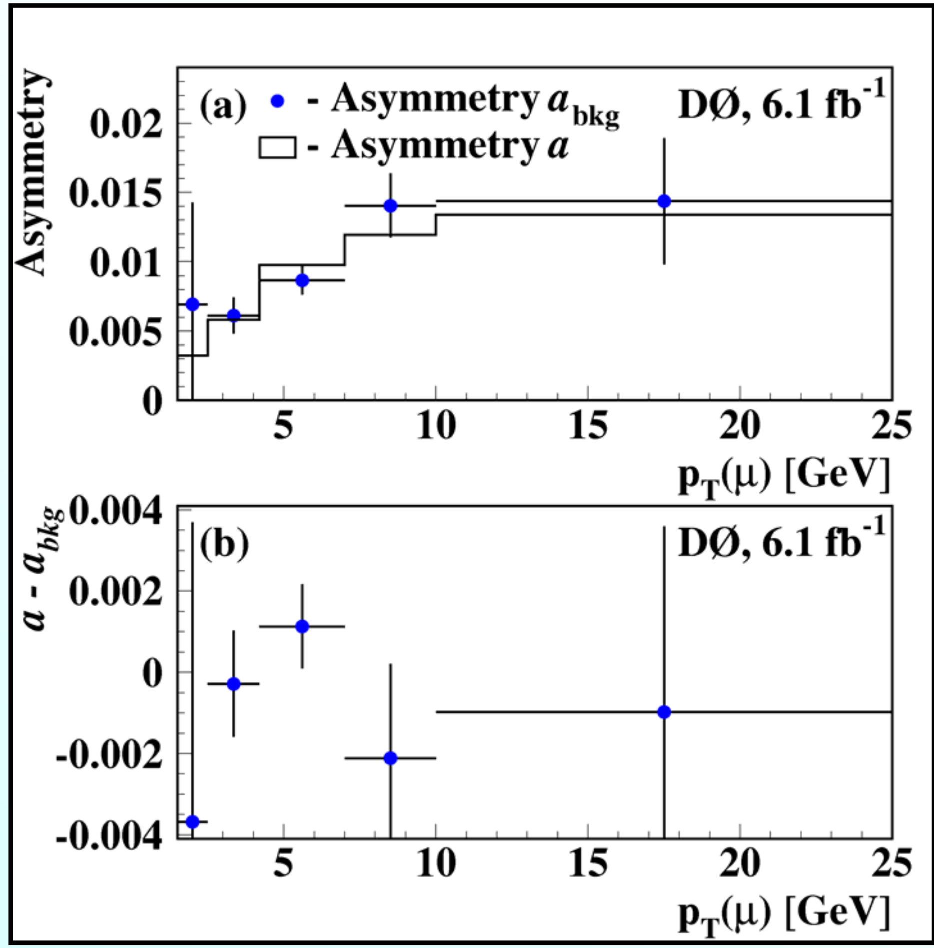
$$\frac{k}{K} = 0.12 \pm 0.01$$

Closure test

$$a = k\,A_{sl}^{b} + a_{bkg}$$

$$A = K\,A_{sl}^{b} + A_{bkg}$$

- The contribution of A^b_{sl} in the inclusive muon asymmetry a is suppressed by $k = 0.041 \pm 0.003$
- The value of a is mainly determined by the background asymmetry a_{bkg}
- We measure a_{bkg} in data, and we can verify how well does it describe the observed asymmetry a
- We compare a and a_{bkg} as a function of muon p_T
- We get $\chi^2/\mathrm{dof} = 2.4/5$ for the difference between these two distributions



Excellent agreement between the expected and observed values of a, including a p_T dependence

Background subtraction

- Many background uncertainties in the inclusive muon and in the like-sign dimuon samples are correlated
- We subtract the background using the linear combination:

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

  - The parameter α is selected such that the total uncertainty of $A^b{}_{sl}$ is minimized
- Since $A_{bkg} \approx a_{bkg}$ and the uncertainties of these quantities are correlated, we can expect the cancellation of background uncertainties in A' for $\alpha \approx 1$
- The signal asymmetry $A^b{}_{sl}$ does not cancel in A' for $\alpha \approx 1$ because: $k << K$

Result

- From $A' = A - \alpha a$ we obtain a value of A^b_{sl} :

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

- To be compared with the SM prediction:

$$A^b_{sl}(SM) = (-0.023^{+0.005}_{-0.006})\%$$

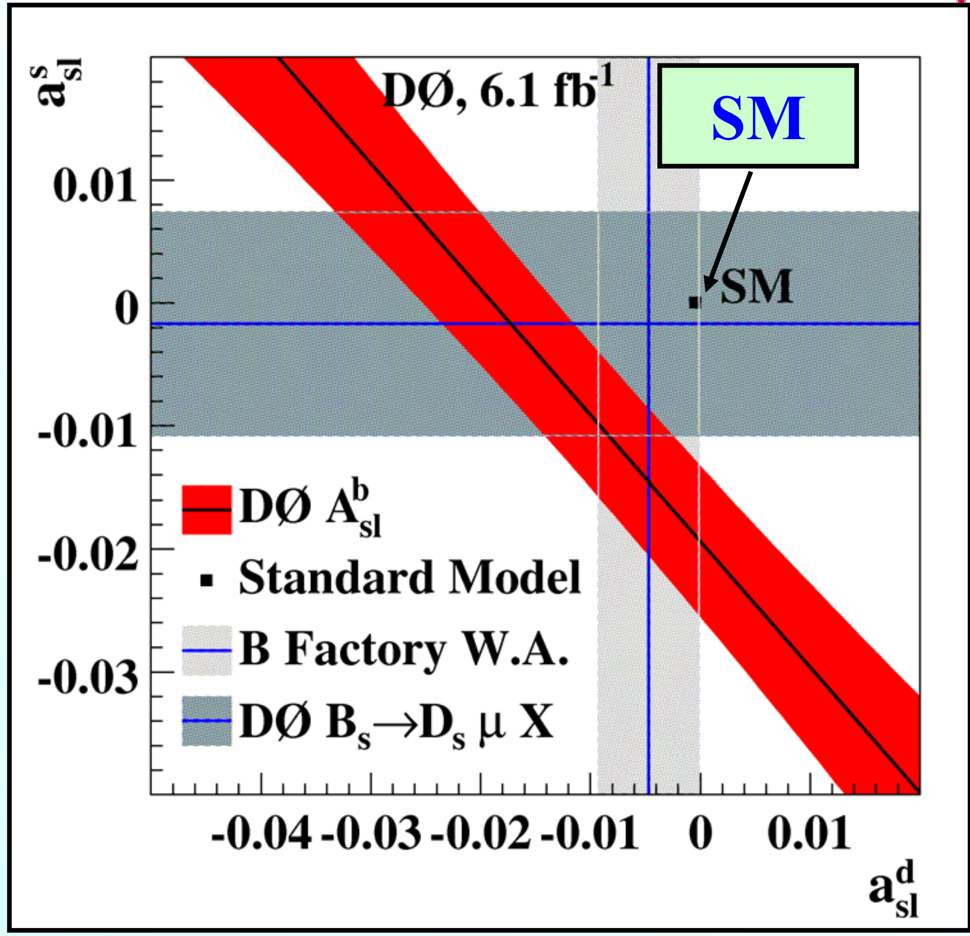
- This result differs from the SM prediction by ~3.2 σ

Comparison with other measurements

- A^b_{sl} is a linear combination of semileptonic charge asymmetries a^d_{sl} (for B_d meson) and a^s_{sl} (for B_s meson)

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

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

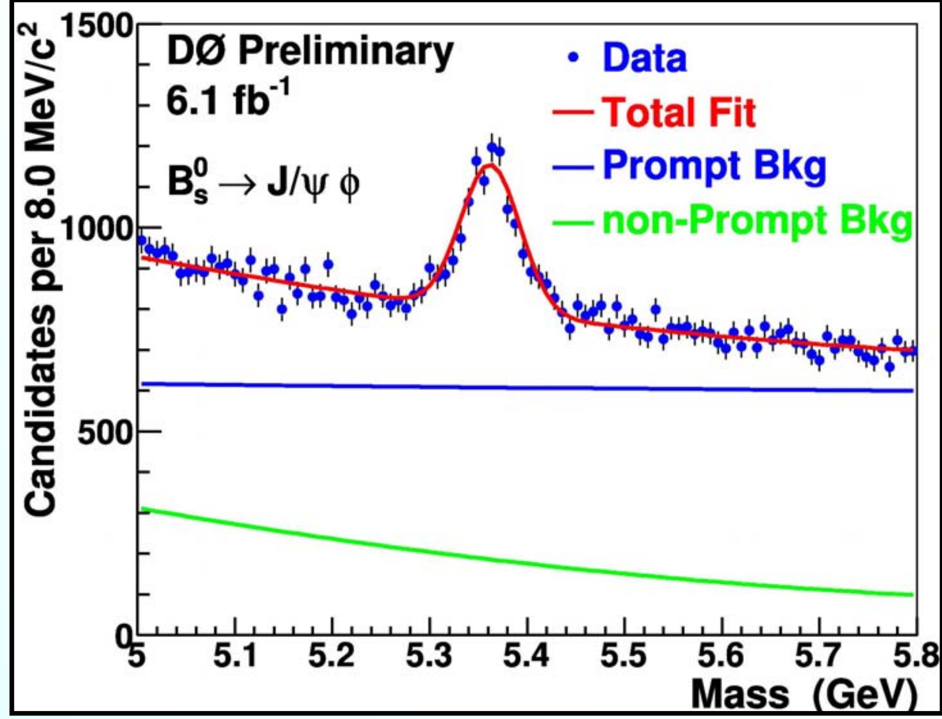


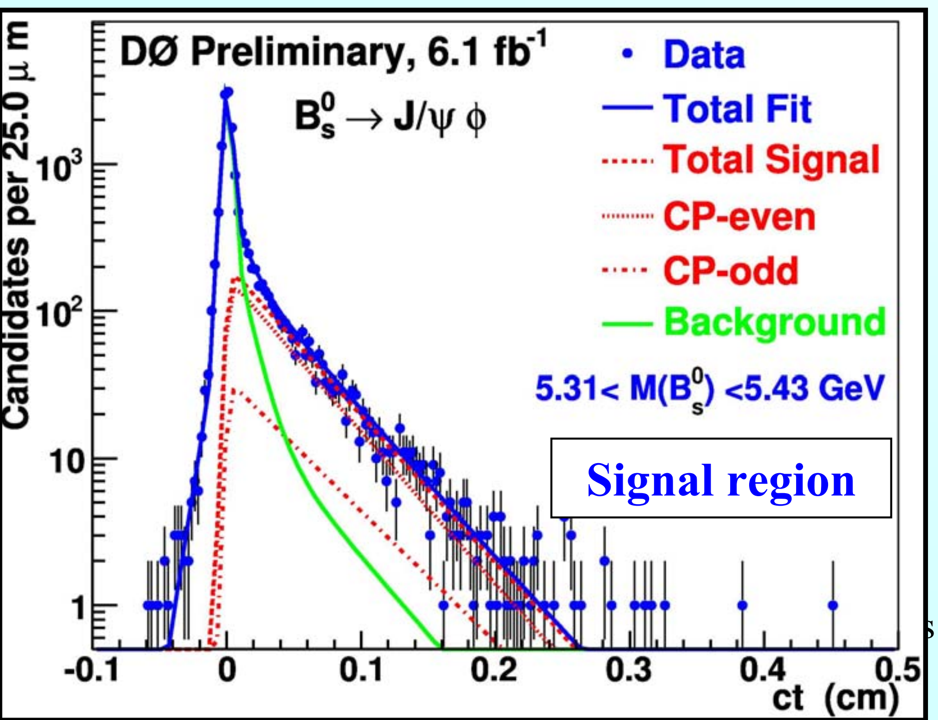
$$a^d_{sl} = -0.0047 \pm 0.0046 \ \ \text{(B-factories)}$$

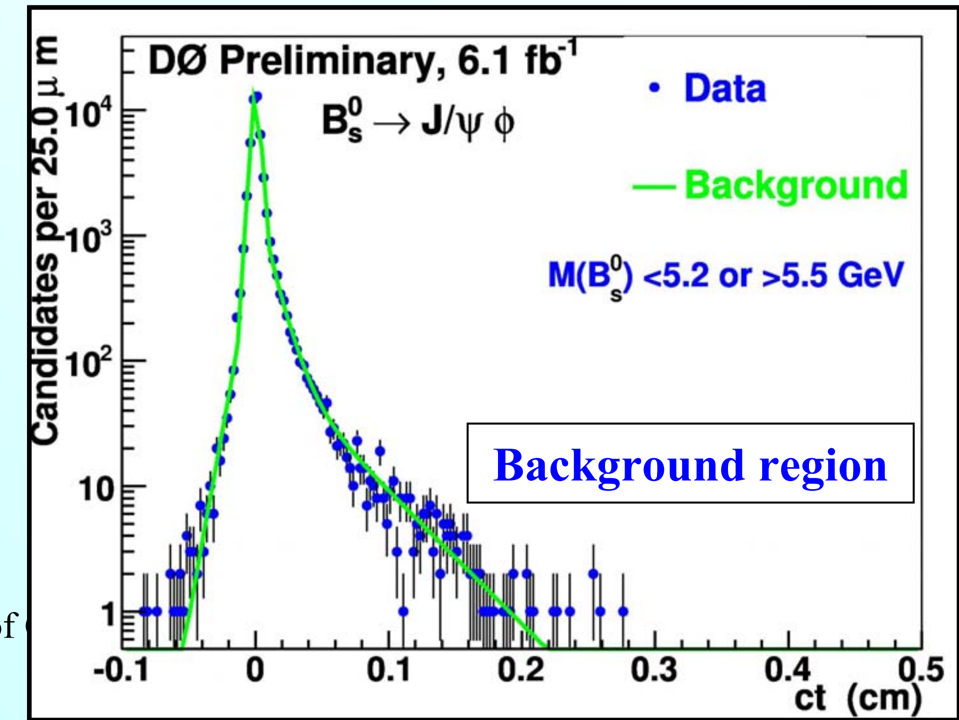
$$a^s_{sl} = -0.0017 \pm 0.0091^{+0.0014}_{-0.0015} \ \ \text{(DZero experiment)}$$

$B_s \rightarrow J/\psi\ \varphi$

- 6.1 fb^{-1} of data analyzed
- ~3400 signal $B_s \rightarrow J/\psi\ \varphi$ events
- Both $\Delta\Gamma$ and $\phi^{J/\psi\varphi}$ are extracted from the time evolution of angular distributions of decay products

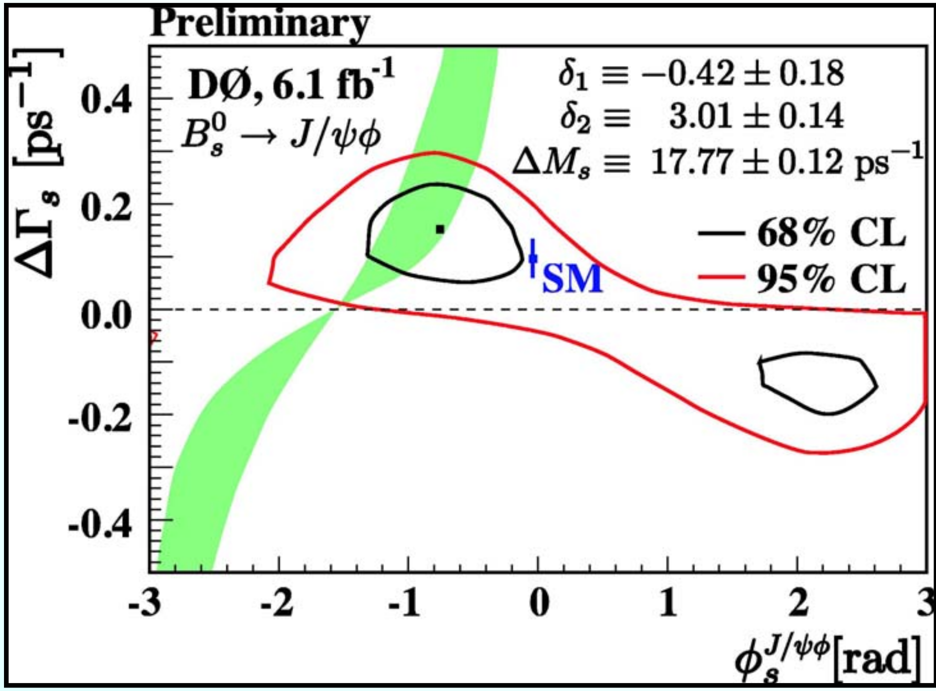






$B_s \to J/\psi\ \varphi$

- S-wave is found to be non-significant, not included
- Only the opposite flavour tagging is used
- Strong phases are constrained to the values from $B^0 \to J/\psi K^{*0}$
- $\tau(B_s)$ and $\Delta\Gamma_s$ are consistent with other measurements



$$\tau_s = 1.47 \pm 0.04 \pm 0.01\ \text{ps}$$
$$\Delta\Gamma_s = 0.15 \pm 0.06 \pm 0.01\ \text{ps}^{-1}$$
$$\phi_s = -0.76^{+0.38}_{-0.36} \pm 0.02$$

$$0.014 < \Delta\Gamma_s < 0.263\ \text{ps}^{-1}\quad (95\%\ \text{C.L.})$$
$$-1.65 < \phi^{J/\psi\varphi} < 0.24\quad (95\%\ \text{C.L.})$$

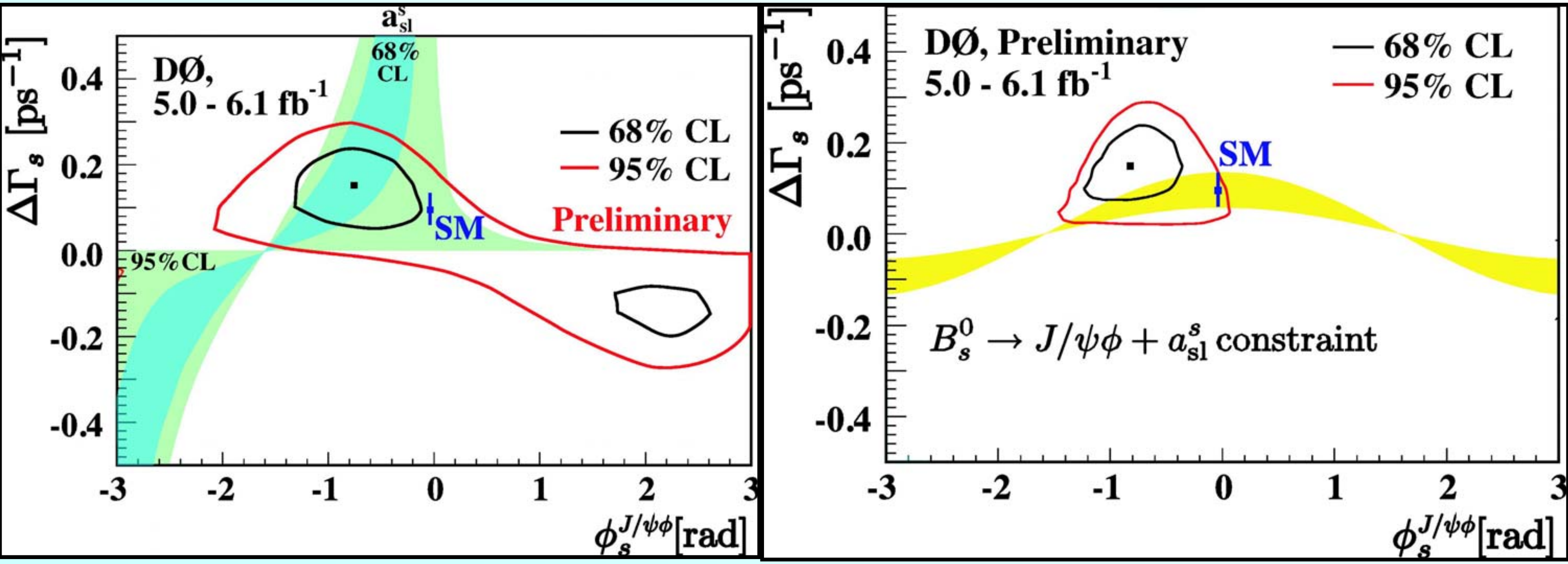
and

$$-0.235 < \Delta\Gamma_s < -0.040\ \text{ps}^{-1}\quad (95\%\ \text{C.L.})$$
$$1.14 < \phi^{J/\psi\varphi} < 2.93\quad (95\%\ \text{C.L.})$$

Combination of DØ results

- $B_s \to J/\psi\, \varphi$
- A^b_{sl}
- a^s_{sl} from $B_s \to D_s \mu \nu$
- p-value at SM point is 7.5%

$$a^s_{sl} = (-1.00 \pm 0.59)\% \;\; \text{(D0)}$$



$B_s \to J/\psi\ \varphi$ (CDF)

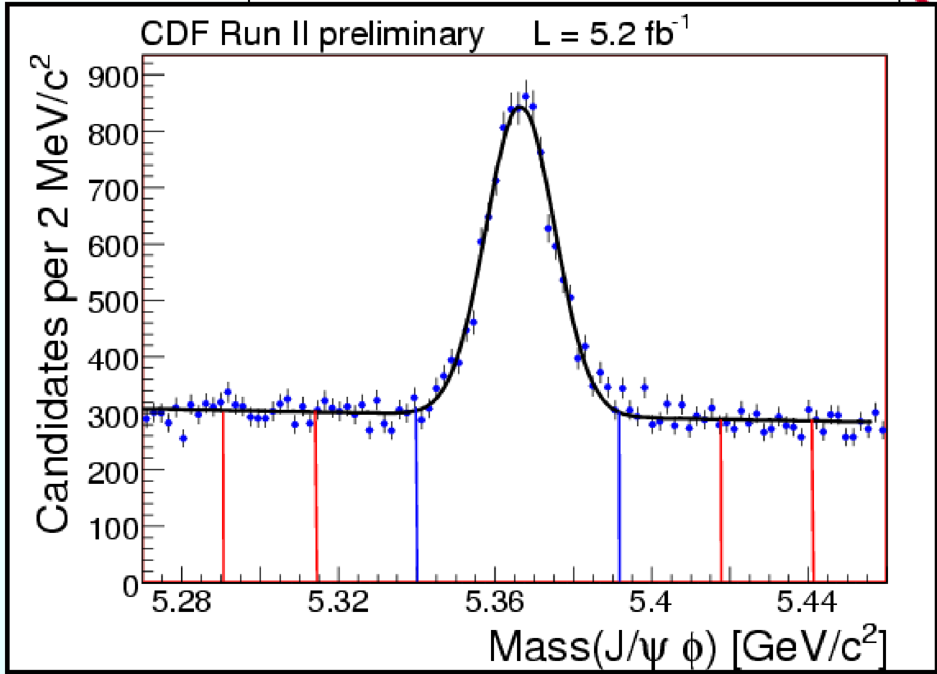
G. Giurgiu, ICHEP-2010,
CDF Public note 10206

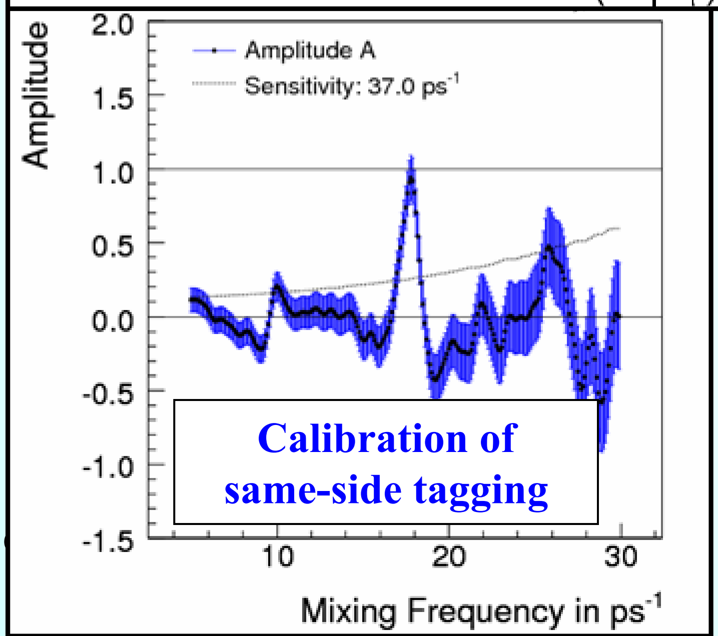
- 5.2 fb^{-1} of data analyzed
- ~6500 signal events
- Same side flavour tagging calibrated in data
- Strong phases are free
- S wave included in the fit

  < 6.5% at 95% CL

$$\tau_s = 1.529 \pm 0.025\,(\text{stat}) \pm 0.012\,(\text{syst})\ \text{ps}$$
$$\Delta\Gamma_s = 0.075 \pm 0.035\,(\text{stat}) \pm 0.01\,(\text{syst})\ \text{ps}^{-1}$$

Most precise measurements of $\tau(B_s)$ and $\Delta\Gamma_s$



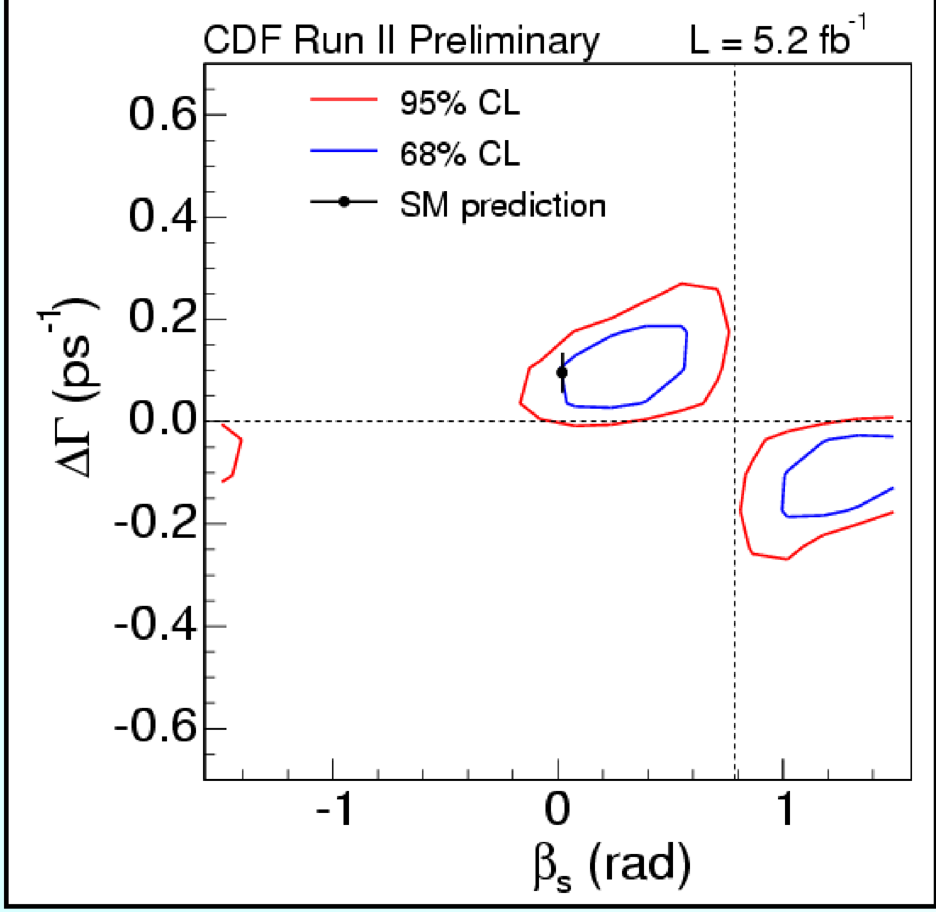


$B_s \to J/\psi\ \varphi$ (CDF)

G. Giurgiu, ICHEP-2010, CDF Public note 10206

- Result of angular analysis consistent with SM prediction
  - p-value is 44% (0.8 σ)

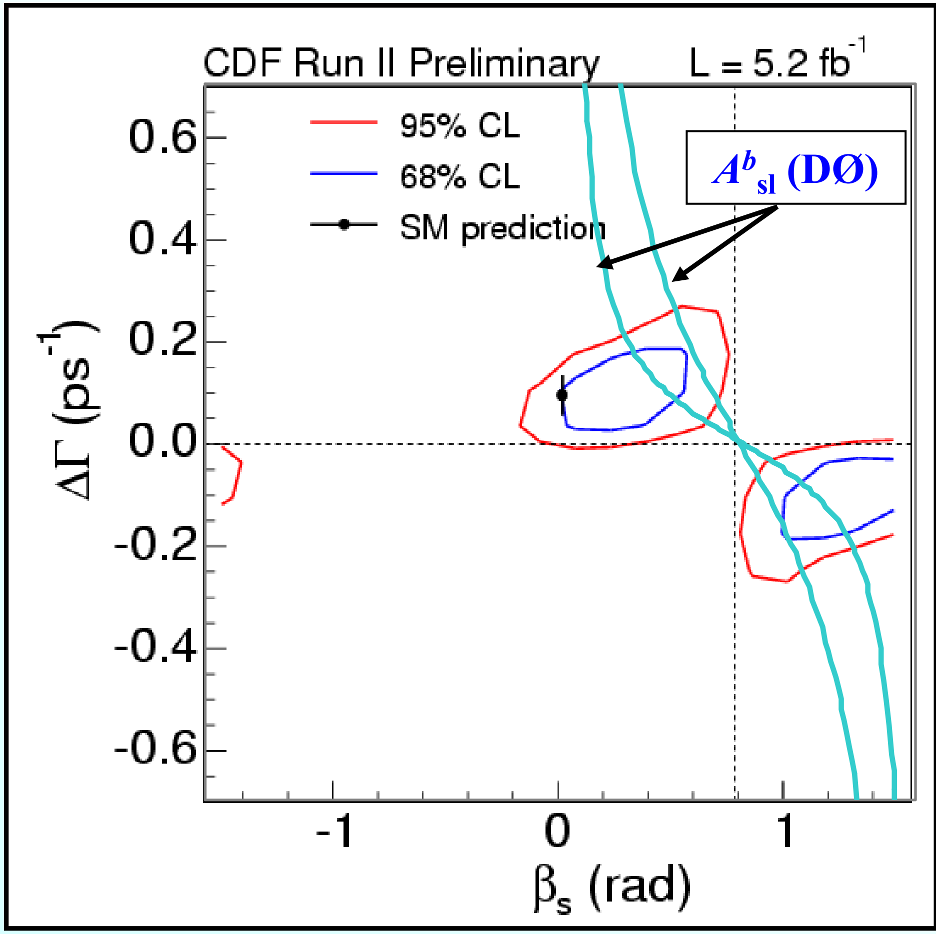
$$\phi^{J/\psi\varphi} = -2\beta_s$$



$B_s \to J/\psi\ \varphi$ (CDF)

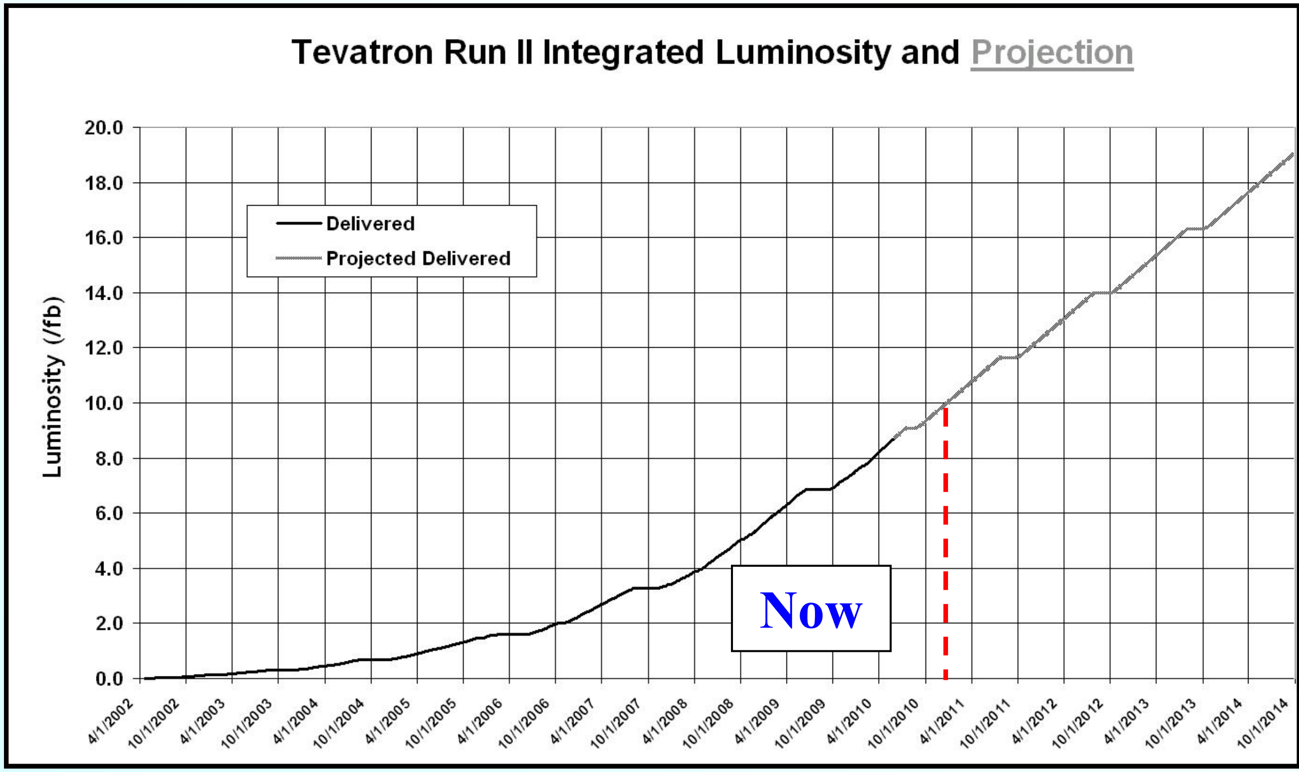
- Result of angular analysis consistent with SM prediction
  - p-value is 44% (0.8 σ)
- Results of CDF and DØ are consistent within ~1σ

$$\phi^{J/\psi\varphi} = -2\beta_s$$



Not the final word yet

- Tevatron experiments now collect >2 fb^{-1} / year
- By the end of 2011 run, the statistics of all measurements will be almost doubled
- Uncertainties of all measurements are statistically dominated



Tevatron experiments have excellent prospects to make a strong statement on the contribution of new physics in *B* decays

Conclusions

- DØ collaboration performs extensive study of CP violation in B_s system;
- Evidence for an anomalous dimuon charge asymmetry A^b_{sl} at 3.2σ is obtained
- New results in $B_s \rightarrow J/\psi\ \varphi$ demonstrate a better consistency with the SM
- All measurements of the CP violating phase ϕ_q are consistent;
- Combination of all DØ results for B_s system gives
  p-value = 6.0% of the SM
- Excellent prospects for the future improvement of precision

Backup slides

Event selection

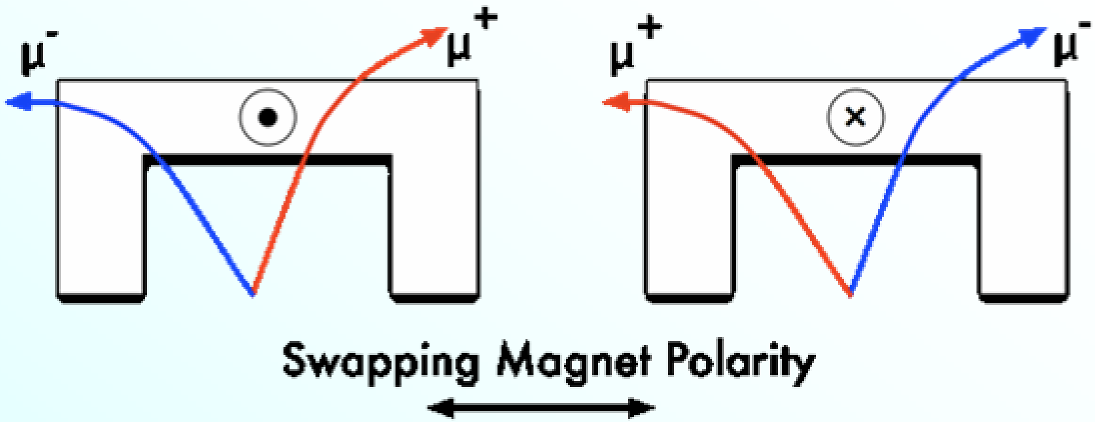
- **Inclusive muon sample**:
  - Charged particle identified as a muon
  - $1.5 < p_T < 25$ GeV
  - muon with $p_T < 4.2$ GeV must have $|p_Z| > 6.4$ GeV
  - $|\eta| < 2.2$
  - Distance to primary vertex: <3 mm in axial plane; < 5 mm along the beam
- **Like-sign dimuon sample**:
  - Two muons of the same charge
  - Both muons satisfy all above conditions
  - Primary vertex is common for both muons
  - $M(\mu\mu) > 2.8$ GeV to suppress events with two muons from the same *B* decay

Blinded analysis

The central value of A^b_{sl} was extracted from the full data set only after the analysis method and all statistical and systematic uncertainties had been finalized

Reversal of Magnet Polarities

- Polarities of DØ solenoid and toroid are reversed regularly
- Trajectory of the negative particle becomes exactly the same as the trajectory of the positive particle with the reversed magnet polarity



- By analyzing 4 samples with different polarities (++, −−, +−, −+) the difference in the reconstruction efficiency between positive and negative particles is minimized

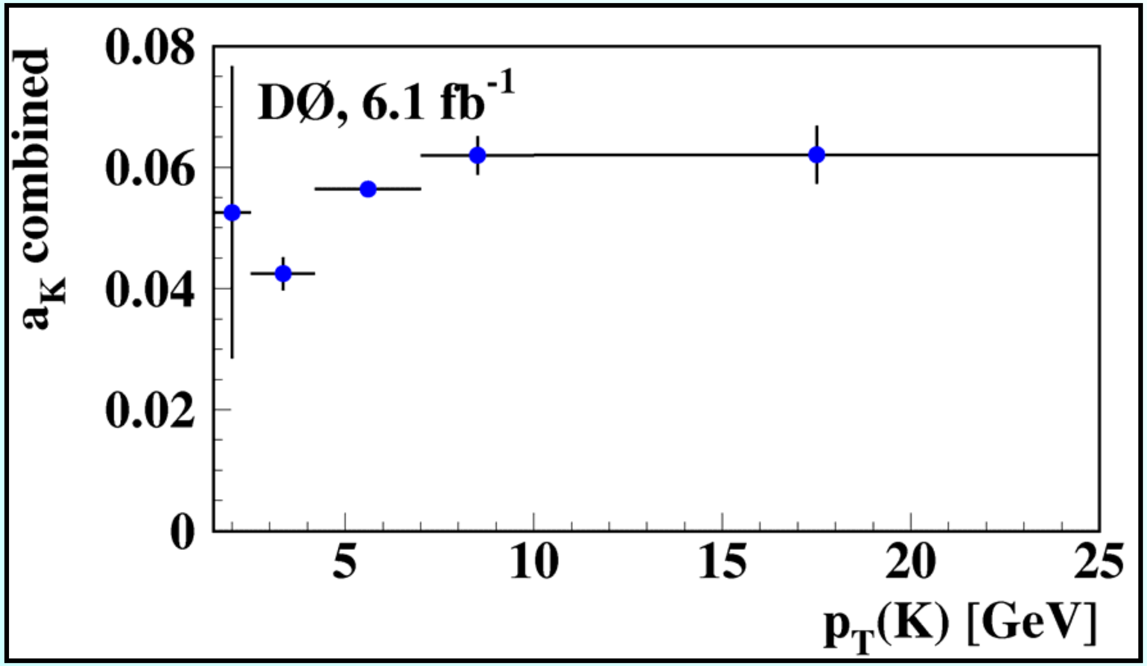
Changing polarities is an important feature of DØ detector, which reduces significantly systematics in charge asymmetry measurements

Measurement of kaon asymmetry

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

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

- Results from $K^{*0} \to K^+\pi^-$ and $\phi(1020) \to K^+K^-$ agree well
  - For the difference between two channels: $\chi^2/dof = 5.4 / 5$
- We combine the two channels together:

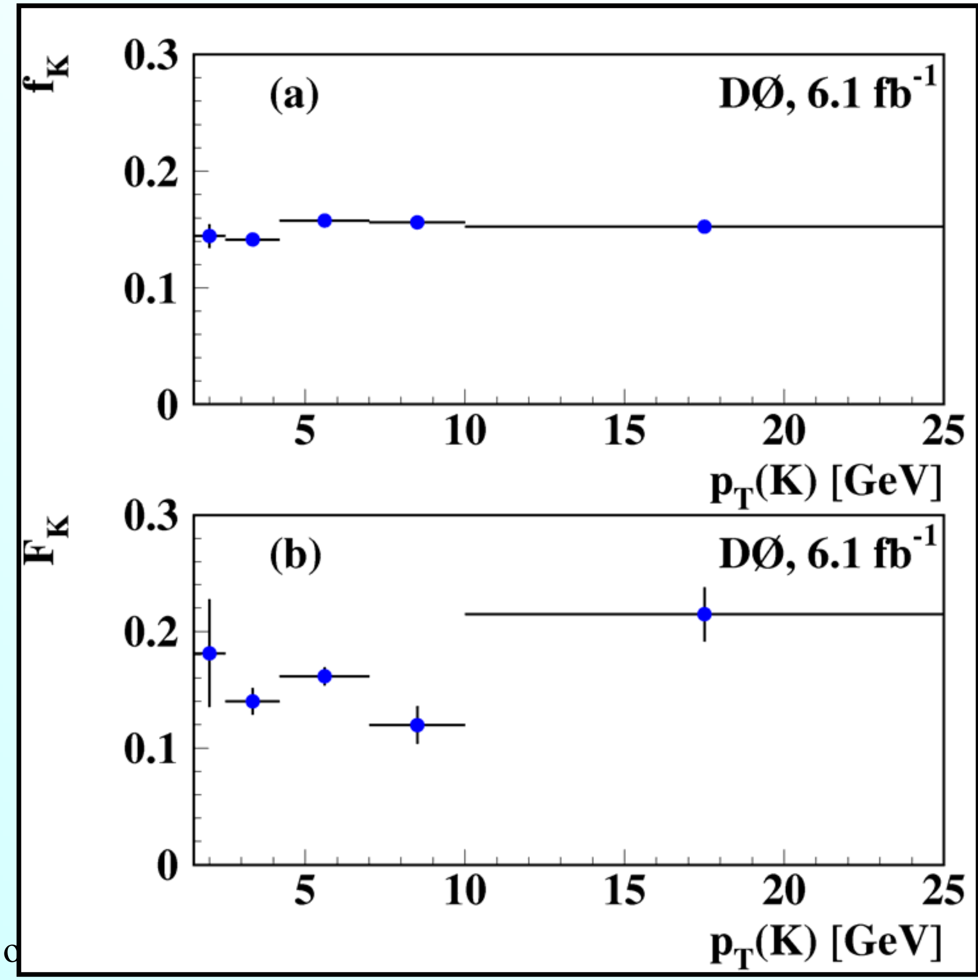


Measurement of f_K, F_K

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

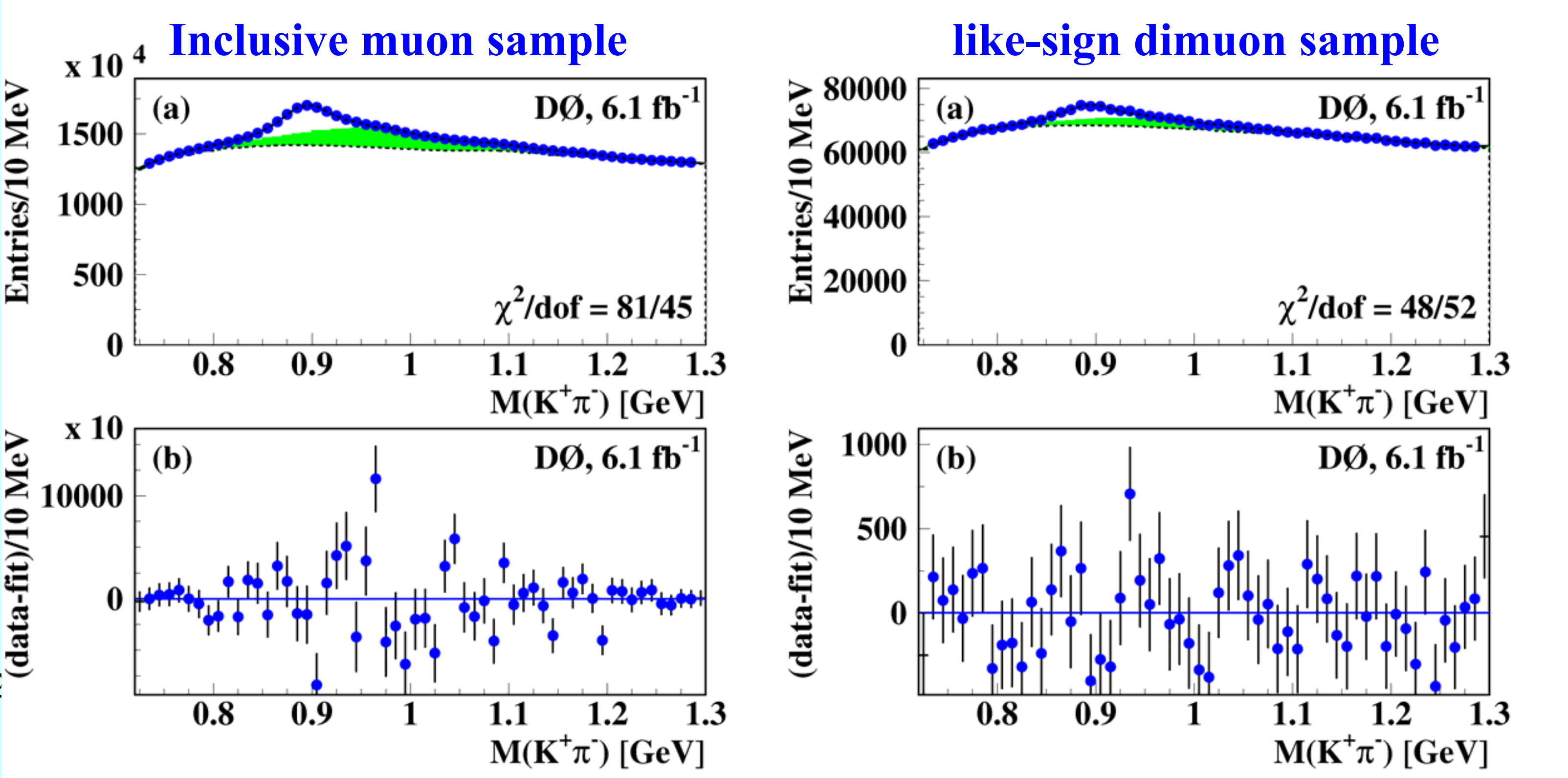
$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

- Fractions f_K , F_K are measured using the decays $K^{*0} \to K^+\pi^-$
- We measure f_{K*0} , F_{K*0}
- We find f_{K*0}/f_K using the similar decay $K^{*+} \to K_S\pi^-$
  - In this decay we measure f_{K*+}/f_{Ks} and convert it into f_{K*0}/f_K



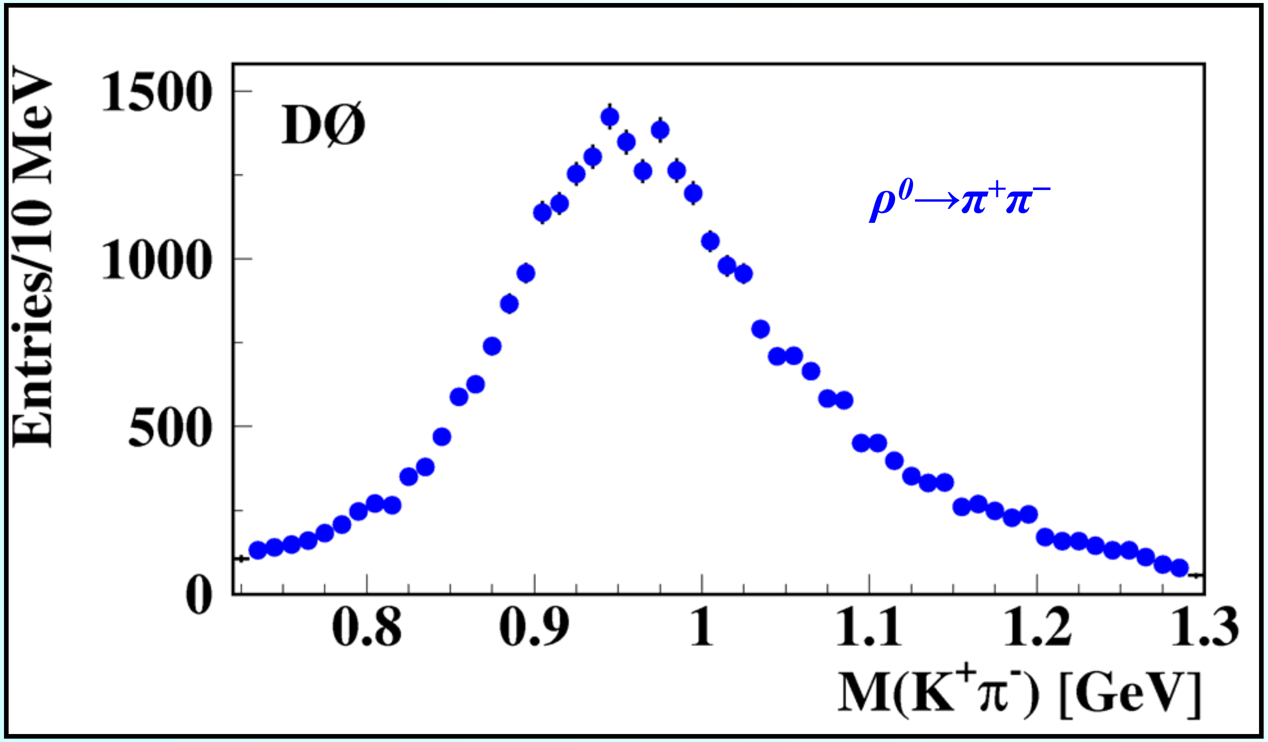
Measurement of f_K, F_K

- 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 $\rho^0 \to \pi^+\pi^-$ produces a peaking background in the (Kπ) mass
- The mass distribution from $\rho^0 \to \pi^+\pi^-$ 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 $K^{*0} \to K^+\pi^-$ and the efficiency to reconstruct an additional pion ε_0 :

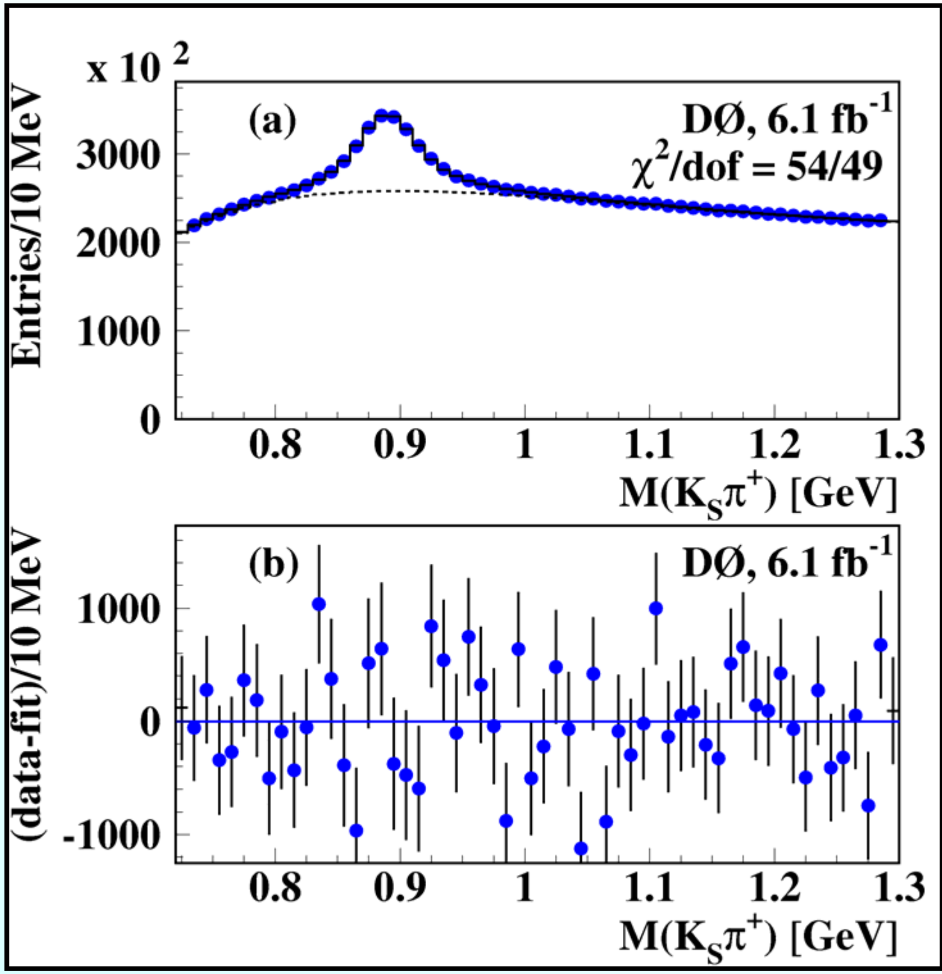
$$f_{K^*0} = f_K R(K^{*0})\varepsilon_0; \quad F_{K^*0} = F_K R(K^{*0})\varepsilon_0$$

Measurement of f_K, F_K

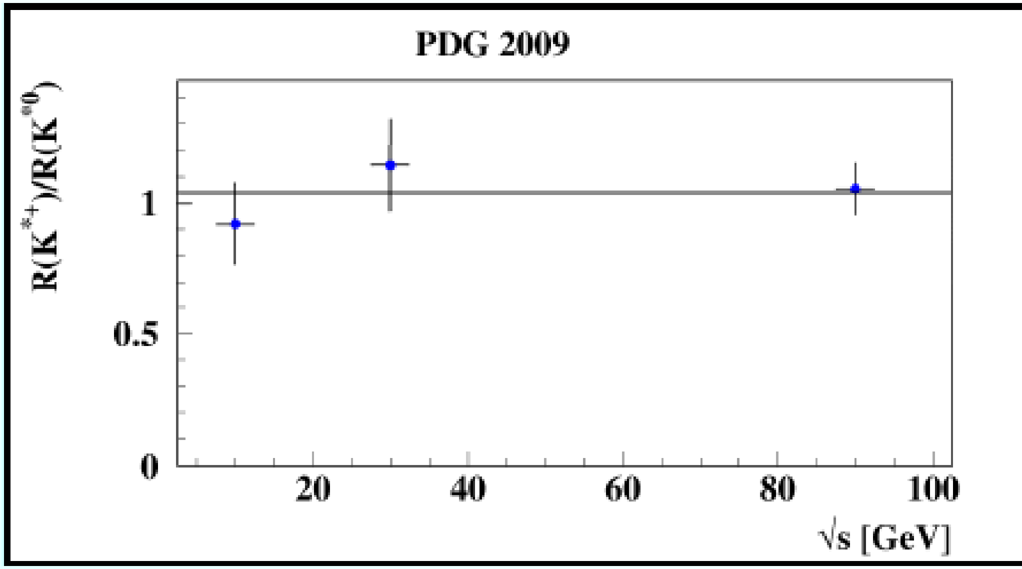
- We also select decay $K^{*+} \to K_S \pi^+$;
- We have:

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

  - $R(K^{*+})$ is the fraction of K_S mesons from $K^{*+} \to K_S \pi^+$ decay;
  - ε_c is the efficiency to reconstruct an additional pion;



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:

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

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

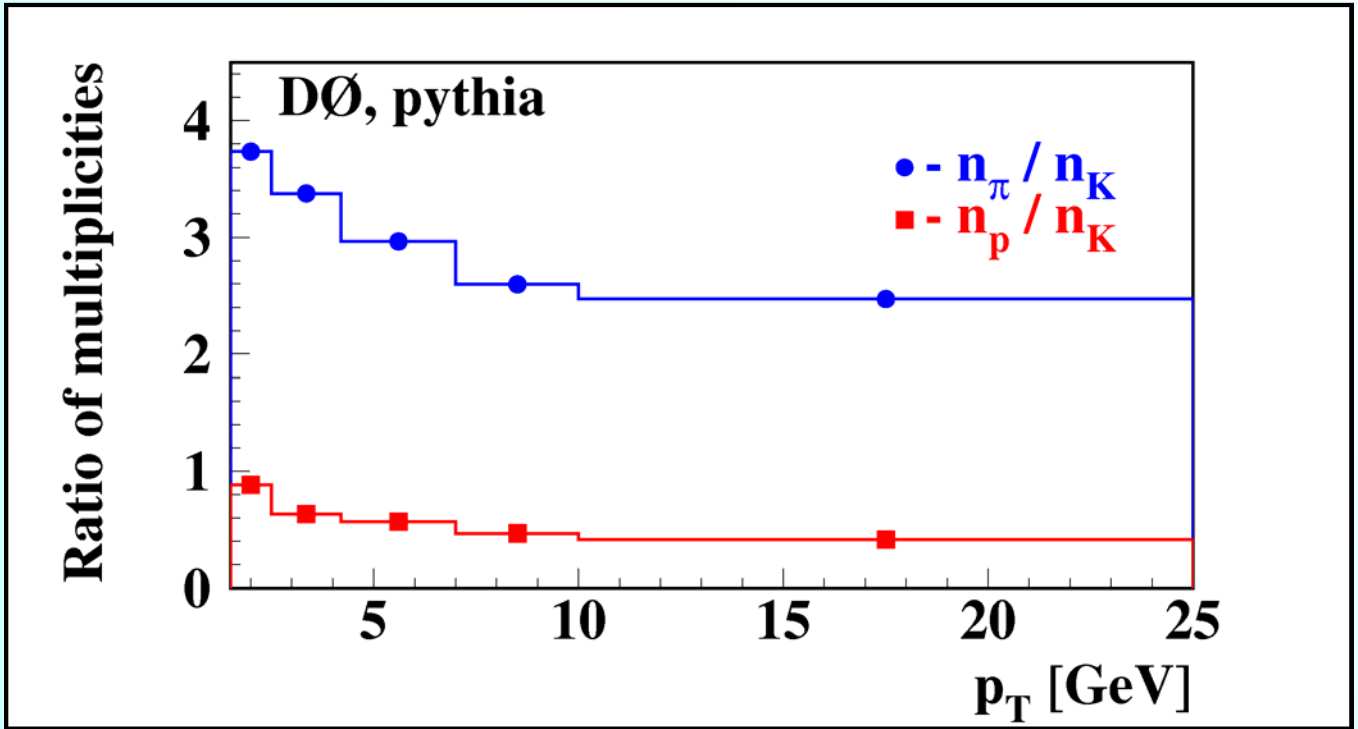
  - The same values $N(K_S)$, $N(K^{*+})$ are used to measure f_K , F_K ;
- • We assume that the fraction $R(K^{*0})$ of charged kaons coming from $K^{*0} \rightarrow K^+\pi^-$ decay is the same in the inclusive muon and like-sign dimuon sample;
  - We verified this assumption in simulation;
- We assign the systematic uncertainty 3% due to this assumption;

Measurement of $f_\pi , f_p , F_\pi , F_p$

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

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

- Fractions f_π , f_p, F_π , F_p are obtained using f_K , 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:

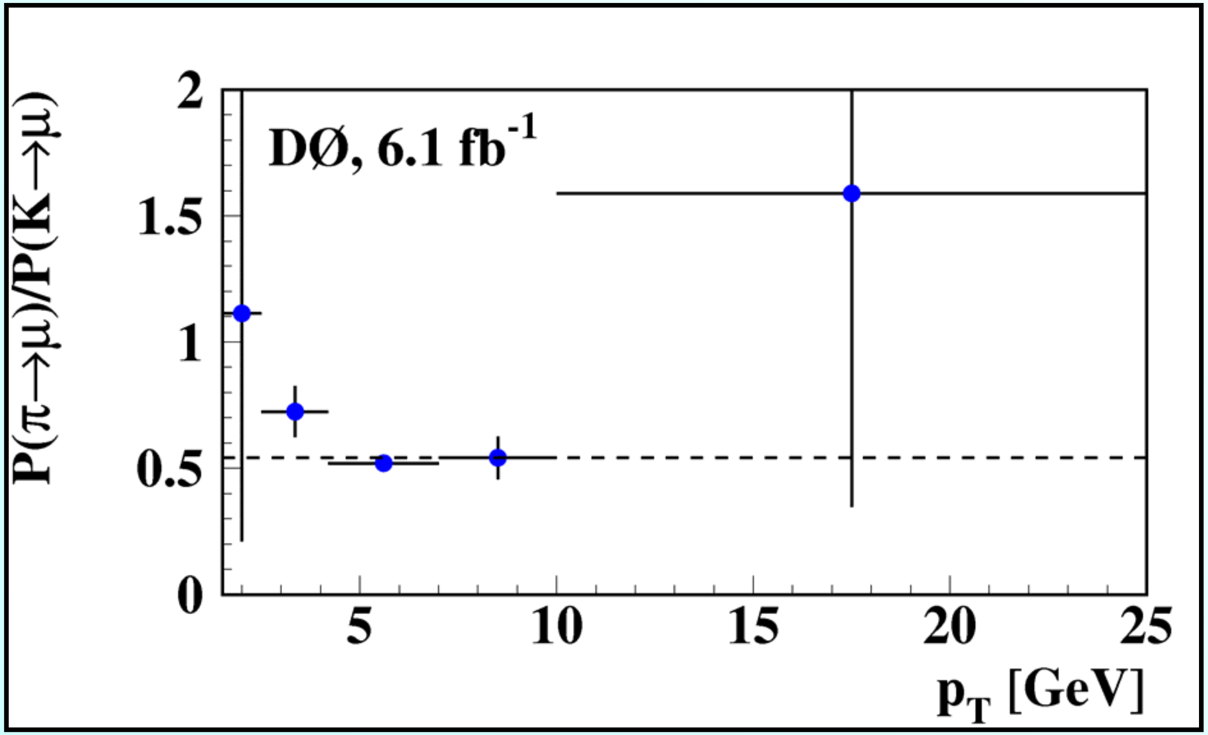
$$f_\pi = f_K \frac{P(\pi \to \mu)}{P(K \to \mu)} \frac{n_\pi}{n_K}$$

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

Measurement of P(π→μ)/ P(K→μ)

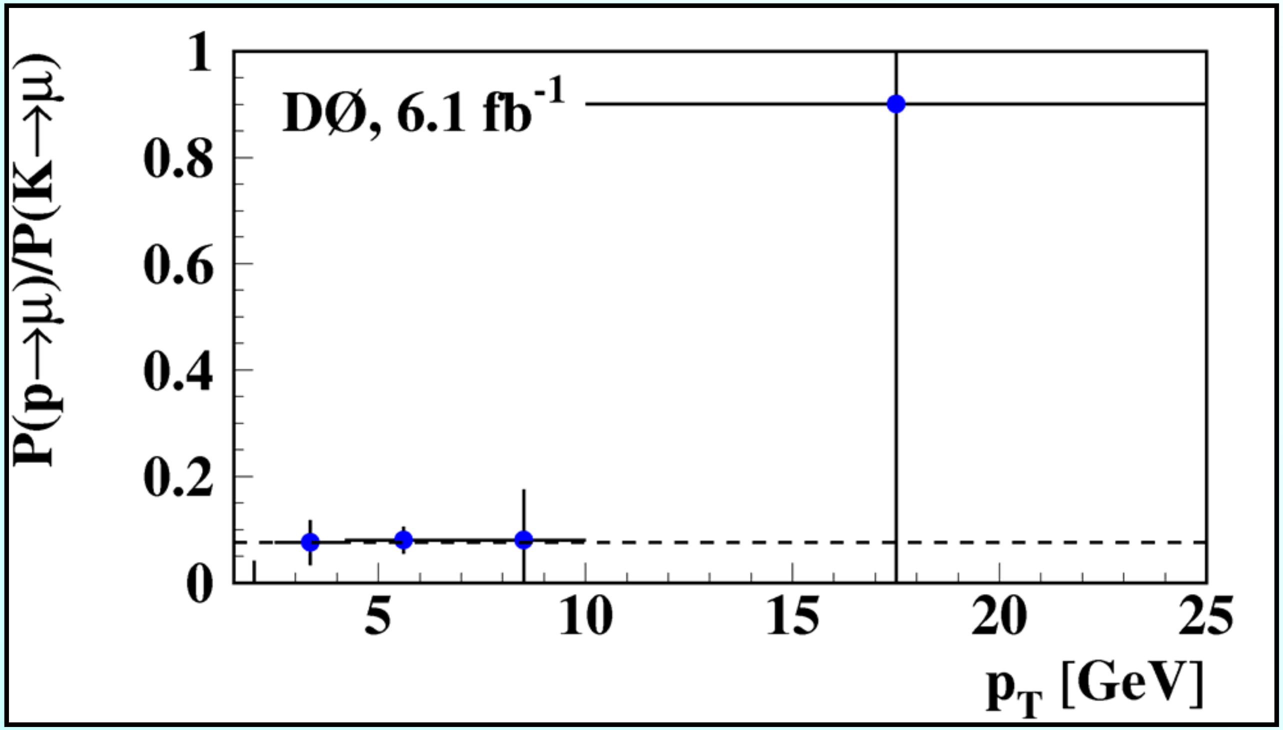
- The ratio of these probabilities is measured using decays $K_S \to \pi^+ \pi^-$ and $\phi(1020) \to K^+ K^-$;
- We obtain:

$$P(\pi \to \mu) / P(K \to \mu) = 0.540 \pm 0.029$$



Measurement of f_p, F_p

- Similar method is used to measure the fractions f_p , F_p ;
- The decay $\Lambda \to p\pi^-$ is used to identify a proton and measure $P(p\to\mu)/P(K\to\mu)$;
- We obtain: $P(p \to \mu)/P(K \to \mu) = 0.076 \pm 0.021$



Muon reconstruction asymmetry

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

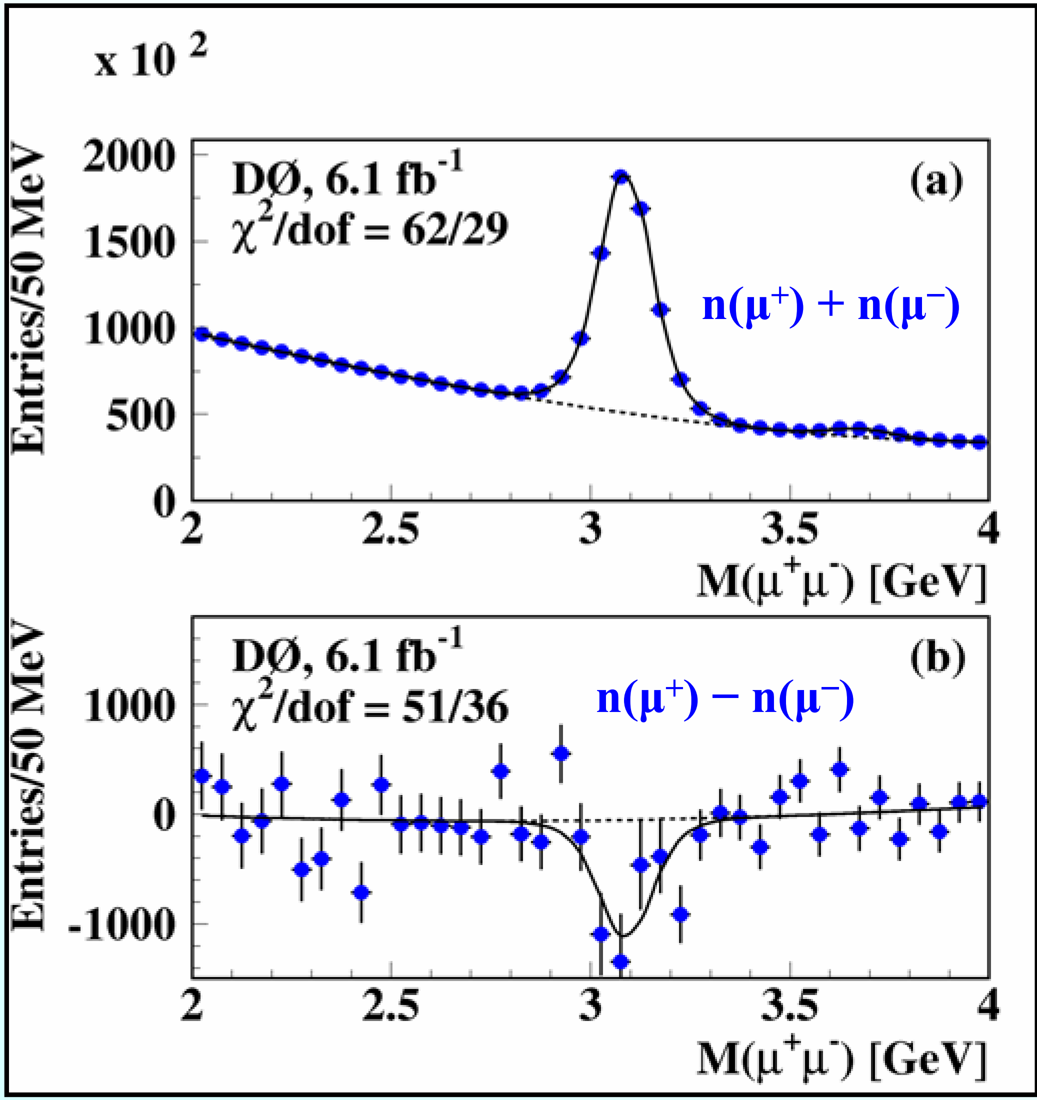
$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

- Reversal of toroid and solenoid polarities cancel the first-order detector effects
- Quadratic terms in detector asymmetries still can contribute into the muon reconstruction asymmetry
- Detector asymmetries for a given magnet polarity $a_{det} \approx O(1\%)$
- We can expect the residual reconstruction asymmetry :

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

Muon reconstruction asymmetry

- We measure the asymmetry of muon reconstruction using decays $J/\psi \to \mu^+\mu^-$;
  - Select events with only one identified muon and one additional track;
  - Build J/ψ meson in these events;
  - Extract muon reconstruction asymmetry from the asymmetry in the number of events with positive and negative muon;



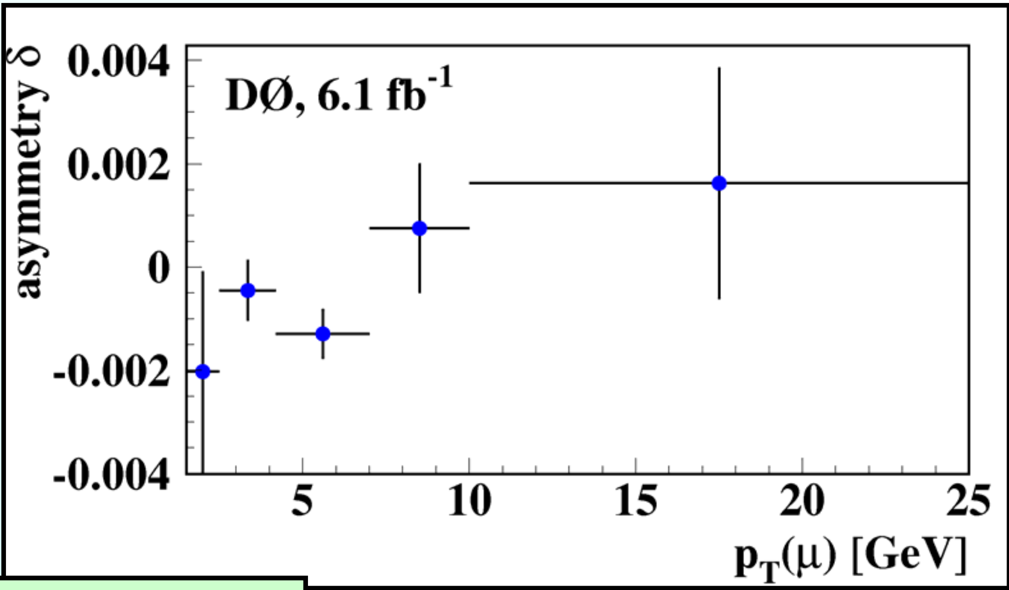
Muon reconstruction asymmetry

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

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

- We measure the muon reconstruction asymmetry using $J/\psi \to \mu\mu$ events
- Average asymmetries δ and Δ are:

$$\delta = (-0.076 \pm 0.028)\%$$
$$\Delta = (-0.068 \pm 0.023)\%$$



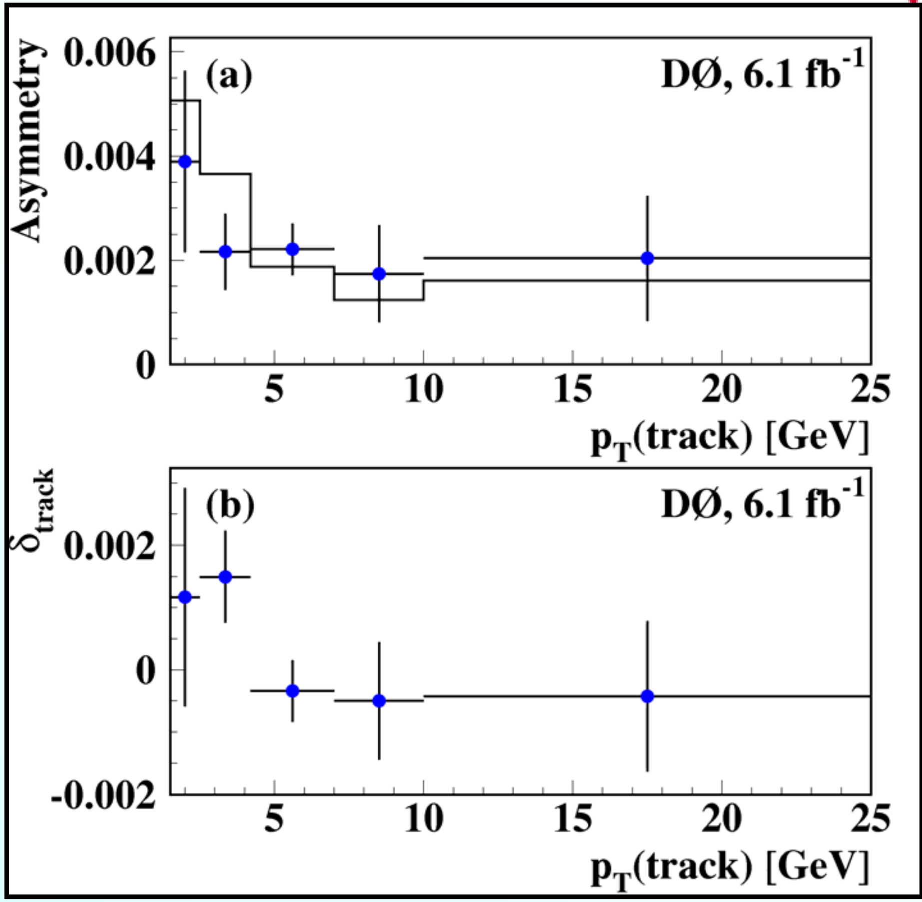
- To be compared with:

$$a = (+0.955 \pm 0.003)\%$$
$$A = (+0.564 \pm 0.053)\%$$

Such small values of reconstruction asymmetries are a direct consequence of the regular reversal of magnet polarities during data taking

Track reconstruction asymmetry

- We measure track reconstruction asymmetry using events with one muon and 1 additional track;
- We compute the expected track asymmetry using the same method as in the main analysis, and we compare it with the observed asymmetry;
- The difference $\delta = a_{trk} - a_{exp}$ corresponds to a possible residual track reconstruction asymmetry;



- We find the residual track reconstruction asymmetry consistent with zero:

$$\delta = (+0.011 \pm 0.035)\%$$

Processes contributing to *a* and *A*

$$k\,A_{sl}^{b} = a - a_{bkg}$$
$$K\,A_{sl}^{b} = A - A_{bkg}$$

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

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

Process	a	A
$\overline{B}_q^0 \to B_q^0 \to \mu^+ X$	Yes	Yes
$b \to c \to \mu^+ X$	Yes	Yes
$B \to \mu^+ X$ (without oscillation)	Yes	No
$c \to \mu^+ X$	Yes	No

- All processes except $\overline{B}_q^0 \to B_q^0 \to \mu^+ X$ don't produce any charge asymmetry, but rather dilute the values of a and A by contributing in the denominator of these asymmetries;

Processes contributing to *a* and *A*

	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	$b \to c \to \mu^+ X$	$w_2 = 0.113 \pm 0.010$
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 $\bar{c} \to \mu^- X$	$w_3 = 0.062 \pm 0.006$
T_4	$\eta, \omega, \rho^0, \phi(1020), J/\psi, \psi' \to \mu^+\mu^-$	$w_4 = 0.021 \pm 0.001$
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 $\bar{c} \to \mu^- X$	$w_6 = 0.660 \pm 0.077$

Inclusive muon sample

- Using all results on background and signal contribution we get a measurement of A^b_{sl} in the inclusive muon sample:

$$A^b_{sl} = (+0.94 \pm 1.12\,(\mathrm{stat}) \pm 2.14\,(\mathrm{syst}))\%$$

  - Uncertainties are very large, because of a small coefficient $k = 0.041 \pm 0.003$
  - Dominant contribution into the systematic uncertainty comes from the measurement of f_K and F_K fractions

A^b_{sl} from like-sign dimuon and inclusive muon samples

- Using the like-sign dimuon sample only we obtain:

$$A^b_{sl} = (-0.736 \pm 0.266\,(\text{stat}) \pm 0.305\,(\text{syst}))\% \quad (\text{from like-sign dimuon})$$

- Using the inclusive muon sample only we obtain:

$$A^b_{sl} = (+0.94 \pm 1.12\,(\text{stat}) \pm 2.14\,(\text{syst}))\% \quad (\text{from inclusive muon})$$

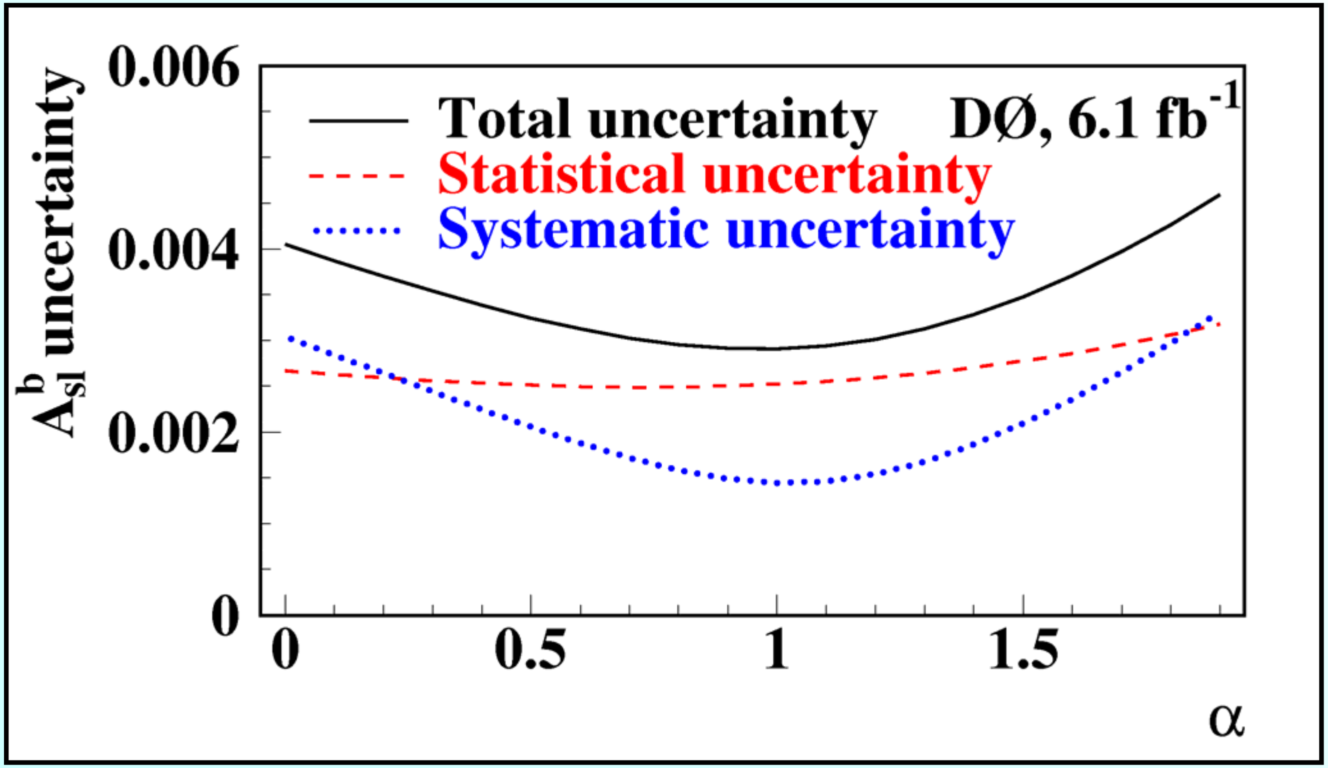
- These results are consistent with our main measurement:

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

  - Precision of these cross-check measurements is worse because of larger background uncertainties;

Background subtraction

- Optimal value of α is obtained by the scan of the total uncertainty of A^b_{sl} obtained from A'
- • The value $\alpha = 0.959$ is selected:



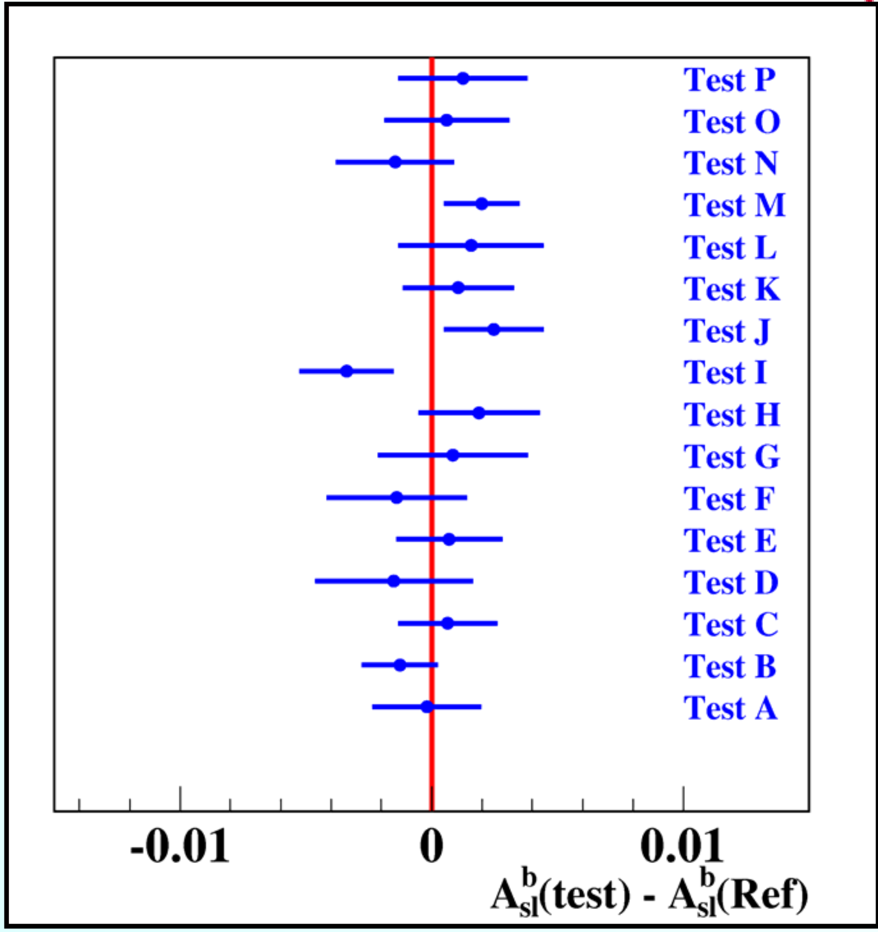
Statistical and systematic uncertainties

Source	A^b_{sl} inclusive muon	A^b_{sl} dimuon	A^b_{sl} combined
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

Consistency tests

- We modify selection criteria, or use a part of sample to test the stability of result
- 16 tests in total are performed
- Very big variation of raw asymmetry A (up to 140%) due to variation of background, but A^b_{sl} remains stable



Developed method is stable and gives consistent result after modifying selection criteria in a wide range

Consistency tests

- 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 (cont.)

- 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 (cont.)

- 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 (cont.)

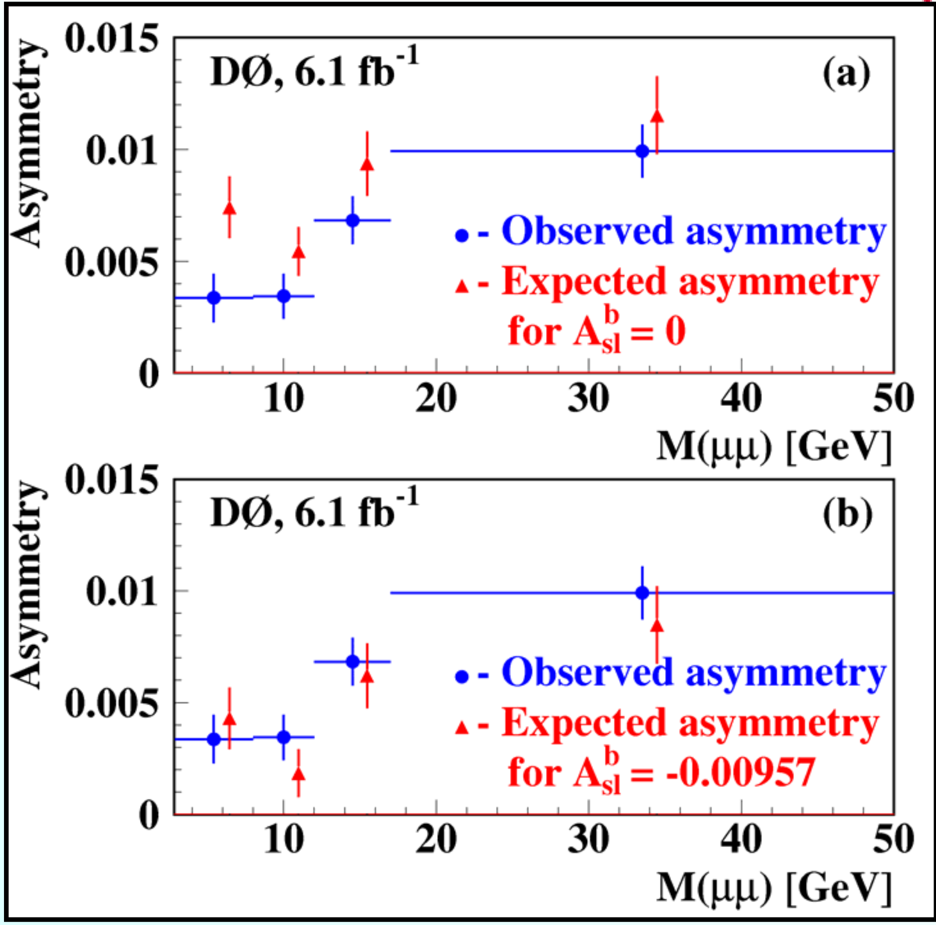
- Test K: Requiring the muon η be in the range $|\eta| < 1.6$ (this test serves also as a cross-check against the possible contamination from muons associated with the beam halo).
- Test L: Requiring the muon η be in the range $|\eta| < 1.2$ or $1.6 < |\eta| < 2.2$.
- Test M: Requiring the muon η be in the range $|\eta| < 0.7$ or $1.2 < |\eta| < 2.2$.
- Test N: Requiring the muon η be in the range $0.7 < |\eta| < 2.2$.

Consistency tests (cont.)

- Test O: Using like-sign dimuon events passing at least one single muon trigger, while ignoring the requirement of a dimuon trigger for these events.
- Test P: Using like-sign dimuon events passing both single muon and dimuon triggers.

Dependence on dimuon mass

- We compare the expected and observed dimuon charge asymmetry for different masses of $\mu\mu$ pair
- The expected and observed asymmetries agree well for $A^b_{\text{sl}} = -0.00957$
- No singularity in the $M(\mu\mu)$ shape supports B physics as the source of anomalous asymmetry



$$A^b_{sl} = (-0.873 \pm 0.388\,(\text{stat}) \pm 0.173\,(\text{syst}))\% \quad M(\mu\mu) > 12 \text{ GeV}$$

Dependence on the dimuon mass is well described by the analysis method

Value of a^s_{sl}

- Obtained A^b_{sl} value can be translated to the semileptonic charge asymmetry of B_s meson
- We need additional input of $a^d_{\text{sl}} = -0.0047 \pm 0.0046$ measured at B factories
- We obtain:

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

- To be compared with the SM prediction:

$$a^b_{sl}(SM) = (+0.0021 \pm 0.0006)\%$$

- Disagreement with the SM is reduced because of additional experimental input of a^d_{sl}

This result at a glance

- Evidence of an anomalous charge asymmetry in the number of muons produced in the initially *CP* symmetric $p\bar{p}$ interaction
- The number of produced particles of matter (negative muons) is larger than the number of produced particles of antimatter
- Therefore, the sign of observed asymmetry is consistent with the sign of *CP* violation required to explain the abundance of matter in our Universe
- This asymmetry is not consistent with the SM prediction at a 3.2σ level
- This new result is consistent with other measurements

This result may provide an important input for explaining the matter dominance in our Universe