Evidence for an Anomalous Like-Sign Dimuon Charge Asymmetry

Rick Jesik
Imperial College London

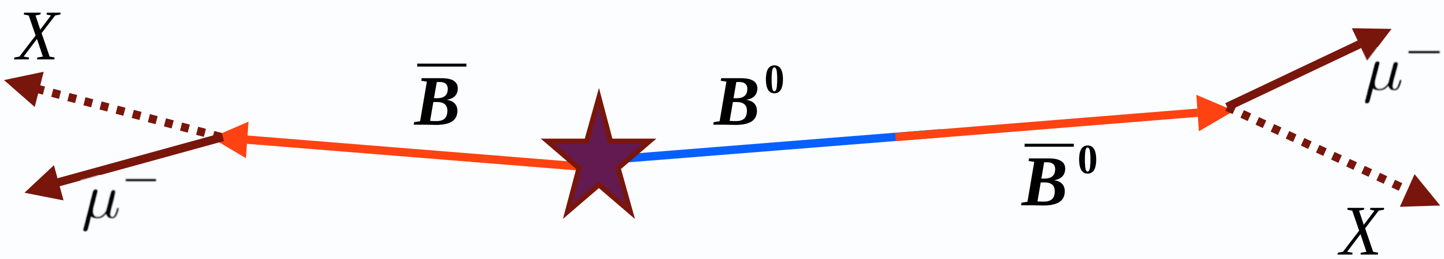
Representing the DØ Collaboration

Third Workshop on Theory, Phenomenology, and Experiments in Heavy Flavour Physics
Capri 5-7 July 2010

Matter dominance and CP violation

- Soon after the creation of the universe, matter and anti-matter were believed to be produced in equal amounts.
- Some peculiar properties of particles and their interactions produced a small preference for matter (CP violation) – on the order of one part per billion – which evolved into the present matter dominance of the universe.
- We have actually measured CP violation in weak quark decays in both the kaon and B_d meson systems, but at levels orders of magnitude too small to explain matter dominance.
- The CKM formalism of the Standard Model agrees very well with these measurement and predicts no other significant sources of CP violation.
- But we exist! So we continue to search for other sources.

CP violation in B meson mixing



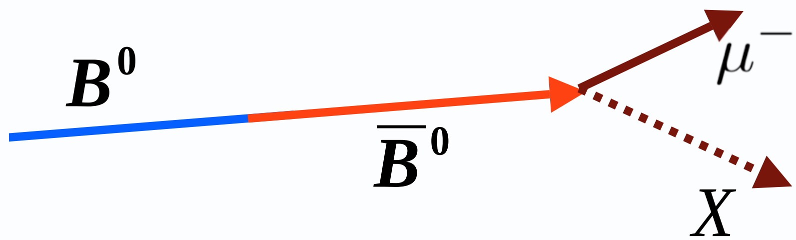
- We search for CP violation in mixing in the like-sign dimuon charge asymmetry of semileptonic B decays.

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

  - N_b^{++}, N_b^{--} – number of events with two *b* hadrons decaying semileptonically and producing two muons of the same charge
- Initial p anti-p collision state is CP symmetric
- B meson mixing is the dominant source of like-sign dimuon events

Semileptonic charge asymmetry

- A^b_{sl} is also equal to the charge asymmetry of "wrong sign" semileptonic B decays Y. Grossman, Y. Nir, G. Raz, PRL 97, 151801 (2006)



- "Right sign" decay is $B \to \mu^+ X$
- "Wrong sign" decays can happen only due to flavor oscillation in B_d and B_s mesons

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

A^b_{sl} at the Tevatron

- Since both B_d and B_s are produced at the Tevatron, A^b_{sl} is a linear combination of a^d_{sl} and a^s_{sl} :
  - Relies on mixing probability and production fractions measurements of B_d and B_s mesons.

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

  - 12% B_s production fraction (CDF), but large mixing probability leads to a significant B_s contribution.

A^b_{sl} and *CP* violation

- Non-zero value of A^b_{sl} means that the semileptonic decays of B and anti-B mesons are different
  - ***CP* violation in mixing!**
- It is quantitatively described by the CP violating phase ϕ_q of the B^0_q ($q = d,s$) mass matrix:

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

- The Standard Model predicts an extremely small value of A^b_{sl}:

$$\boxed{A_{sl}^b = (-2.3^{+0.5}_{-0.6})\times 10^{-4}}$$

A. Lenz, U. Nierste, hep-ph/0612167

- New physics contributions can, however, significantly increase this value

Measurement strategy

- Measure raw single and like-sign dimuon asymmetries:

$$a \equiv \frac{n^{+} - n^{-}}{n^{+} + n^{-}} \qquad A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

- Determine the contributions from mixed B decays
- Determine detector and reconstruction related backgrounds
  - Almost all from data - not simulation
- Two measurements of A^{b}_{sl}. The one from the single muon asymmetry is dominated by background so we do NOT take a weighted average. The background contributions to the two measurements are highly correlated, so we perform an effective background subtraction by measuring a linear combination of the two to extract A^{b}_{sl} with a signifcantly reduced systematic uncertainty.
- The Central value of A^{b}_{sl} for the full data sample was kept blind until all of the analysis methods and statistical and systematic uncertainties were finalized.

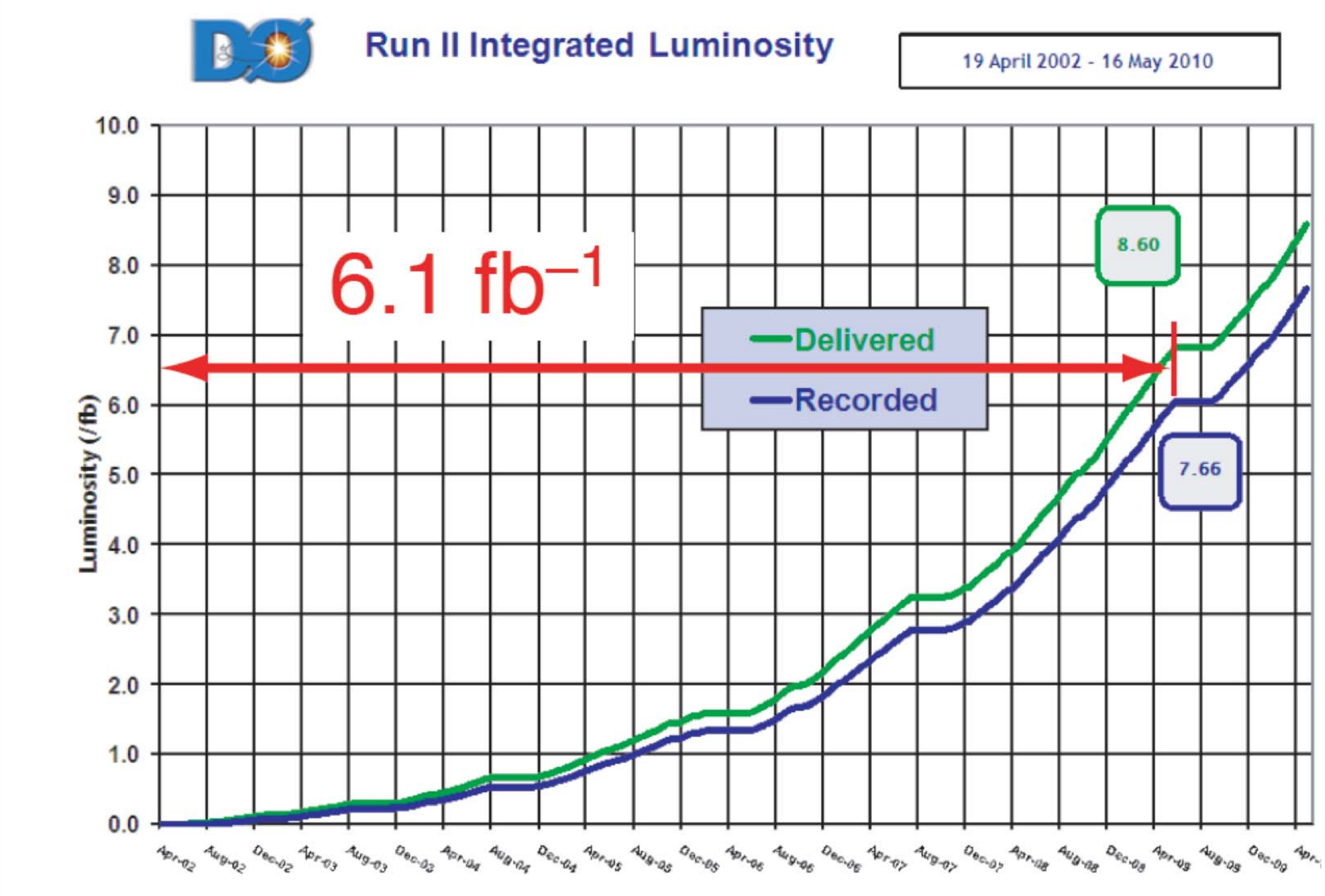
Experimental observables and A^b_{sl}

- Semileptonic *B* decays contribute to both *A* and *a*
  - Only mixing contributes to the asymmetries (numerator), many muon sources dilute the effect (denominator)
- Both *A* and *a* linearly depend on the charge asymmetry A^b_{sl}

$$\boxed{\begin{aligned} a &= k\, A^b_{sl} + a_{bkg} \\ A &= K\, A^b_{sl} + A_{bkg} \end{aligned}}$$

  - recall that $A^b_{sl} = a^b_{sl}$
- In addition, there are detector related background contributions A_{bkg} and a_{bkg}

6.1 fb^{-1} of data used in this analysis



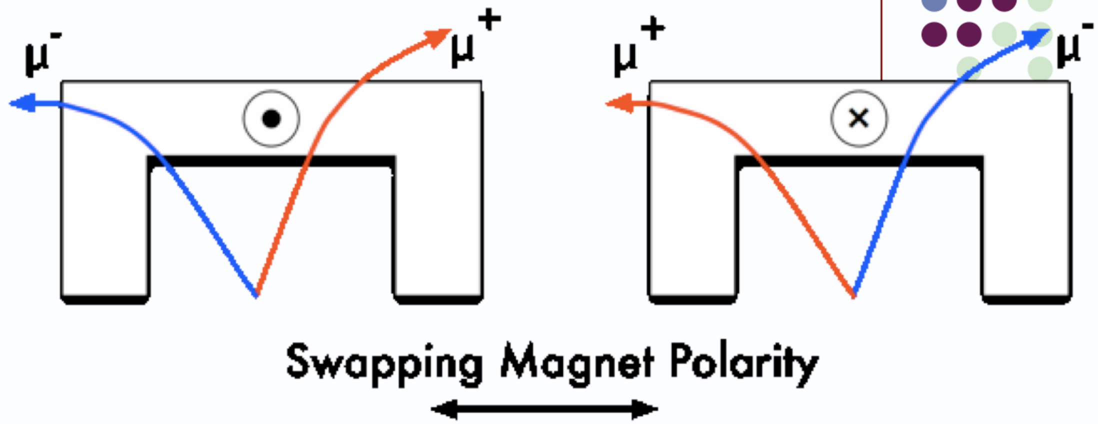
This measurement brought to you by the continued excellent performance of the Tevatron!

The DØ Run II Detector

- Silicon vertex detector
  - $|\eta| < 3.0$
- Central fiber tracker
  - $|\eta| < 2.5$
- 2 T solenoid magnet
- Three layer muon system with dedicated toroid magnet and 5500 tons of shielding
- Excellent muon purity and coverage:
  - $p_T > 1.5$ GeV, $|\eta| < 2.2$

Reversal of Magnet Polarities

- Polarities of DØ solenoid and toroid magnets 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 magnet polarities is an important feature of the DØ detector, which significantly reduces the systematic uncertainty in charge asymmetry measurements

Event selection

- **Inclusive muon sample**:
  - Charged particle identified as a muon
  - $1.5 < p_T < 25$ GeV (suppress EW contribution)
  - muon with $p_T < 4.2$ GeV must have $|p_Z| > 6.4$ GeV (penetrate iron)
  - $|\eta| < 2.2$
  - 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
  - Both muons associated to same primary vertex
  - $M(\mu\mu) > 2.8$ GeV to suppress events with two muons from the same *B* decay

Raw asymmetries

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

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

- We select:
  - 1.495×10^{9} events in the inclusive muon sample
  - 3.731×10^{6} events in the like-sign dimuon sample
- Raw asymmetries:

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

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

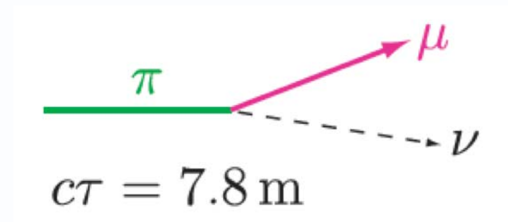
$$a = (+0.955 \pm 0.003)\%$$

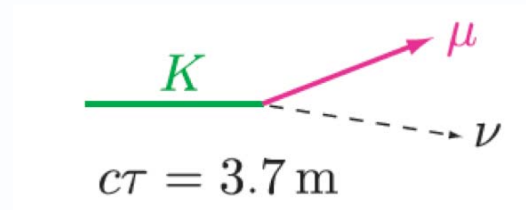
$$A = (+0.564 \pm 0.053)\%$$

Background contributions

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

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





- Sources of background muons:
  - kaon and pion decays in flight into muons $K^+ \to \mu^+ \nu$, $\pi^+ \to \mu^+ \nu$
  - K, pi, proton “punch-through” particles which make it through the muon system
  - charge asymmetry of muon reconstruction
- We measure all background contributions directly in data, with minimal input from simulation

Background details

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

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

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

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

- 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
- $f_{bkg} = f_K + f_\pi + f_p$
- Corresponding capitalized terms for the dimuon sample

Kaon detection asymmetry

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

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

- The largest background asymmetry, and the largest background contribution comes from the charge asymmetry of kaon track identified as a muon (a_K, A_K)
- Our detector is made of matter. The Interaction cross section of K^+ and K^- with the detector material is different, especially for kaons with low momentum (because the reaction $K^- N \rightarrow Y\pi$ has no $K^+ N$ equivalent)
- K^+ travel further in our detector
  - more chance to decay into a muon
  - more chance of “punching through”
- All other backgrounds 10x less, but we measured them nonetheless.

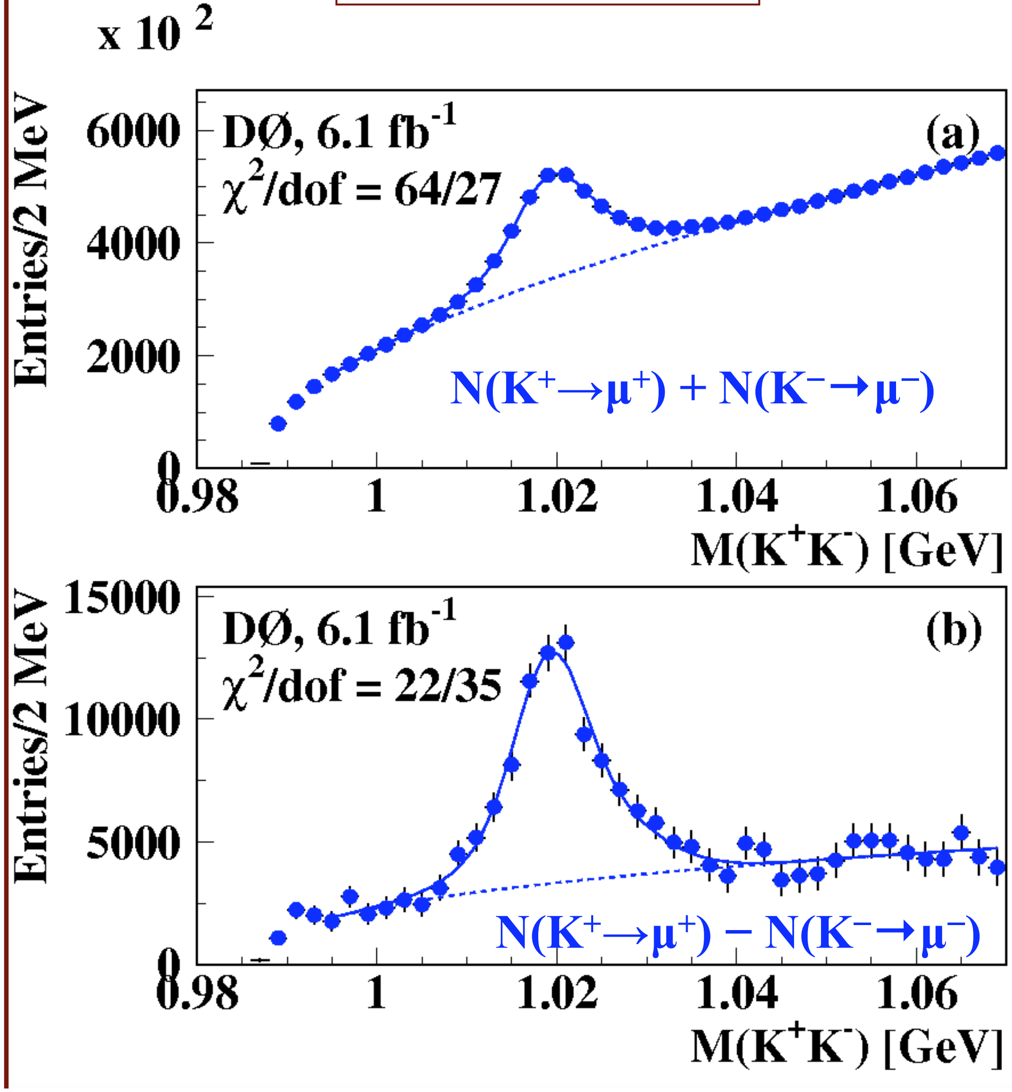
Measurement of kaon asymmetry

- Reconstruct sources of kaons:

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

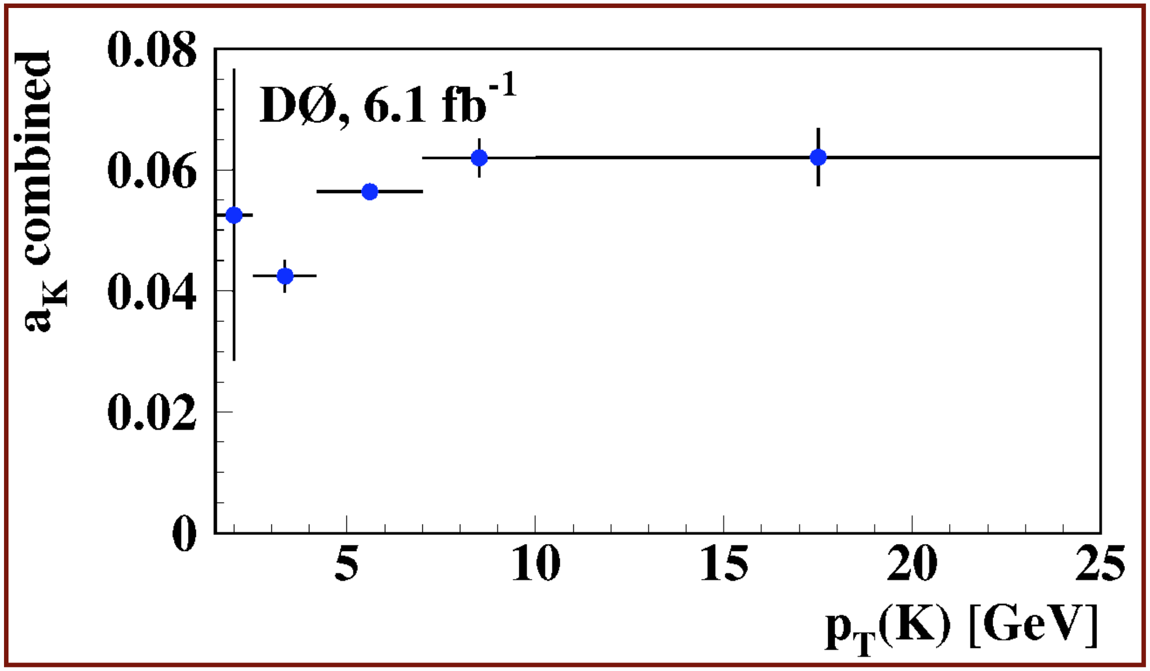
- Require that one of the kaon's is identified as a muon
  - punch through or decay
- Build the mass distribution separately for positive and negative kaons
- Compute asymmetry in the number of observed events
- Apply correction factor for track reconstruction efficiency loss due to kink in the track from decay in flight

$\phi \rightarrow K^{+} K^{-}$ decay



Measurement of kaon asymmetry

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



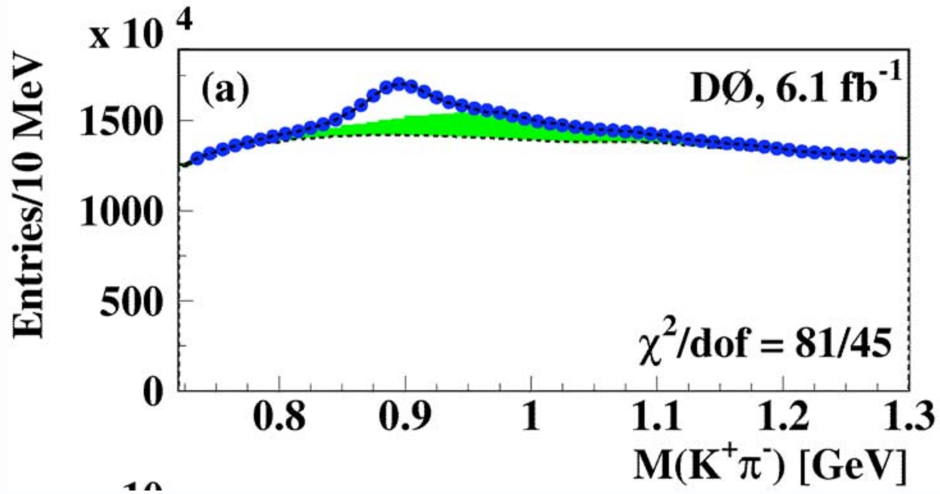
Measurement of a_π, a_p

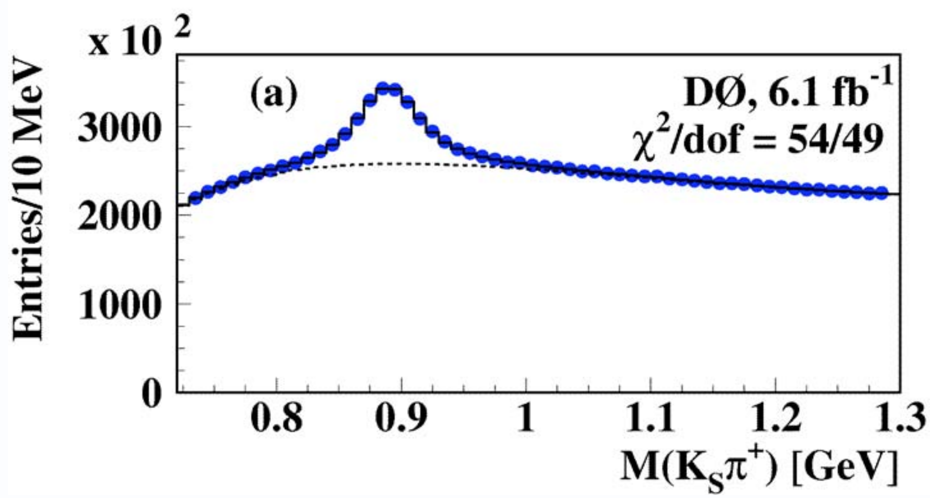
- The asymmetries a_π , a_p are measured using the decays $K_S \to \pi^+ \pi^-$ and $\Lambda \to p\, \pi^-$ respectively
- Similar measurement technique is used

	a_K	a_π	a_p
Data	**(+5.51 ± 0.11)%**	**+(0.25 ± 0.10)%**	**(+2.3 ± 2.8)%**

Measurement of f_K, F_K

- We actually measure $f_{K^{*0}}$, $F_{K^{*0}}$ using the decays $K^{*0} \to K^+\pi^-$ with kaons which are identified as muons
- To convert these fractions to f_K, F_K we need to know the fraction $R(K^{*0})$ of kaons which come from $K^{*0} \to K^+\pi^-$ and the efficiency to reconstruct an additional pion ε_0
- Using isospin invariance, we measure the fraction of Ks mesons which come from $K^{*+} \to K_S\pi^+$ and equate this to $R(K^{*0})$
- The pion reconstruction efficiency is the same for both channels





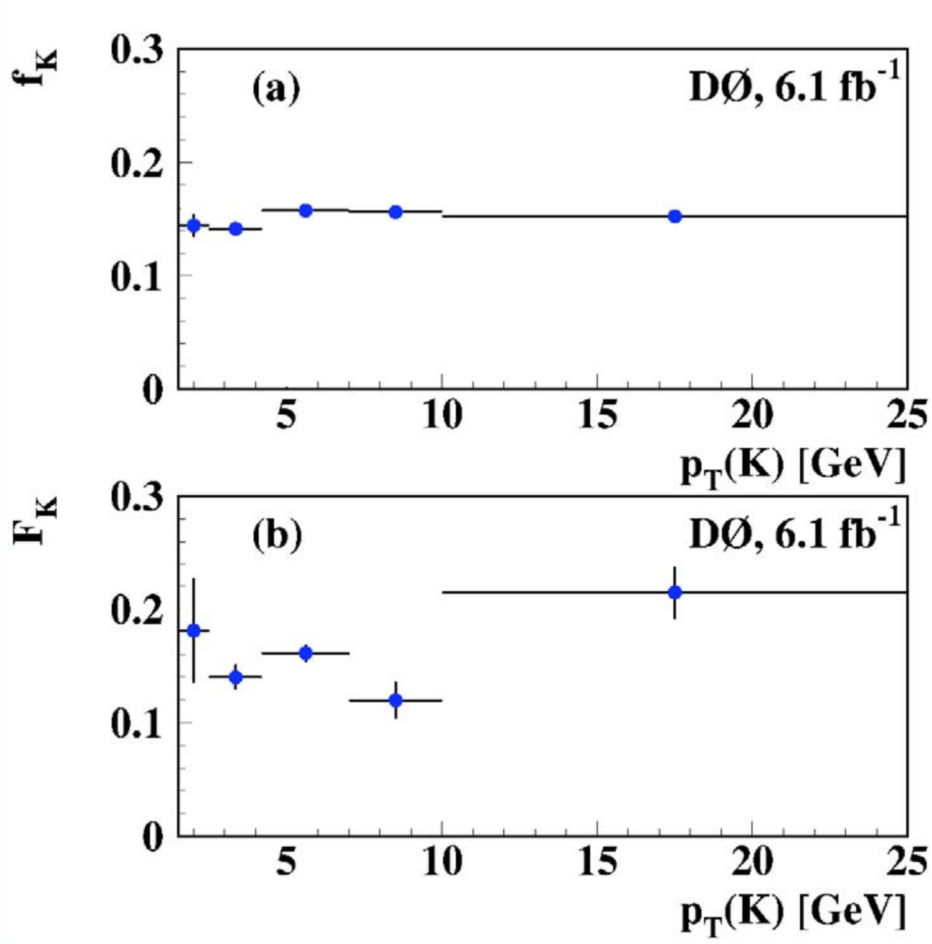
19

Measurement of f_K , F_K

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

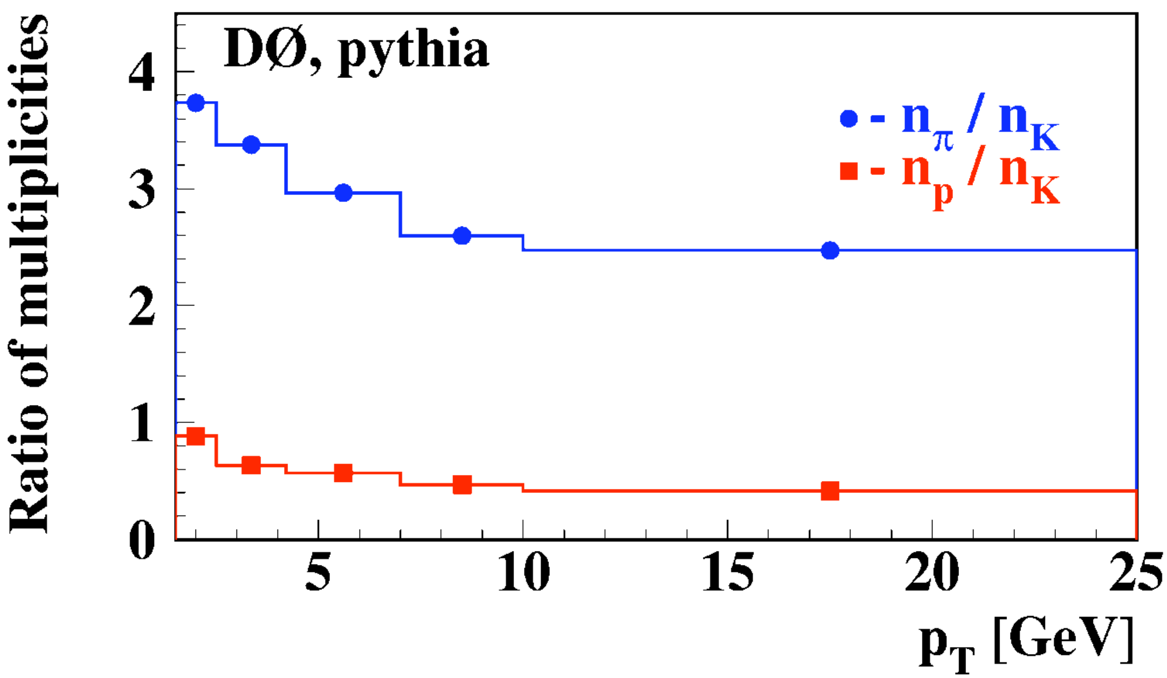
$$F_K = \frac{N(K_S)}{N(K^{*+})} F_{K^{*0}}$$

- This method agrees with an alternative method (which could improve errors in the future) and simulation
- One of the largest sources of systematic uncertainty.



Measurement of f_π , f_p , F_π , F_p

- 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
  - With a cross check that the simulation produces the same n_K as found in data



Summary of background composition

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

- 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

Muon reconstruction asymmetry

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

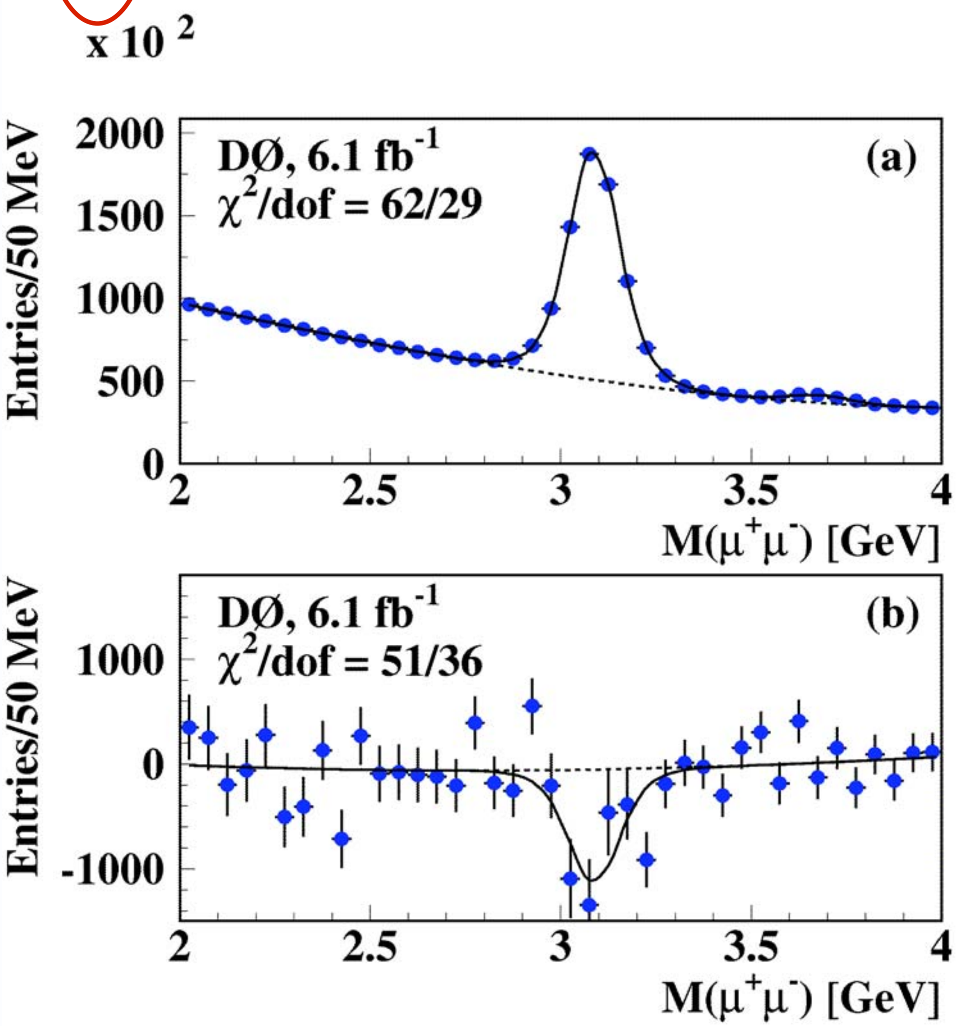
$$A_{bkg} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{bkg})\Delta$$

- We measure the muon reconstruction asymmetry using J/ψ events where one muon is not reconstructed

$$\delta = (-0.076 \pm 0.028)\%$$

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

Such small values of reconstruction asymmetries are a direct consequence of the regular reversal of magnet polarities during data taking, they would be 10x higher without switching



Summary of background contributions

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

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

	$f_K a_K$ (%) $F_K A_K$ (%)	$f_\pi a_\pi$ (%) $F_\pi A_\pi$ (%)	$f_p a_p$ (%) $F_p A_p$ (%)	$(1-f_{bkg})\delta$ (%) $(2-F_{bkg})\Delta$ (%)	a_{bkg}(%) 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 the single muon and dimuon samples: $A_{bkg} \approx a_{bkg}$

Signal contribution

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

- K factors take into account the dilution of "raw" asymmetries from real physics processes
- They 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 single muon sample

	Process
T_1	$b \to \mu^- X$
T_{1a}	$b \to \mu^- X$ (non-oscillating)
T_{1b}	$\bar{b} \to b \to \mu^- X$ (oscillating) $\longrightarrow A$
T_2	$b \to c \to \mu^+ X$ $\longrightarrow A$
T_{2a}	$b \to c \to \mu^+ X$ (non-oscillating)
T_{2b}	$\bar{b} \to b \to c \to \mu^+ X$ (oscillating)
T_3	$b \to c\bar{c}q$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$
T_4	$\eta, \omega, \rho^0, \phi(1020), J/\psi, \psi' \to \mu^+\mu^-$
T_5	$b\bar{b}c\bar{c}$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$
T_6	$c\bar{c}$ with $c \to \mu^+ X$ or $\bar{c} \to \mu^- X$

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

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

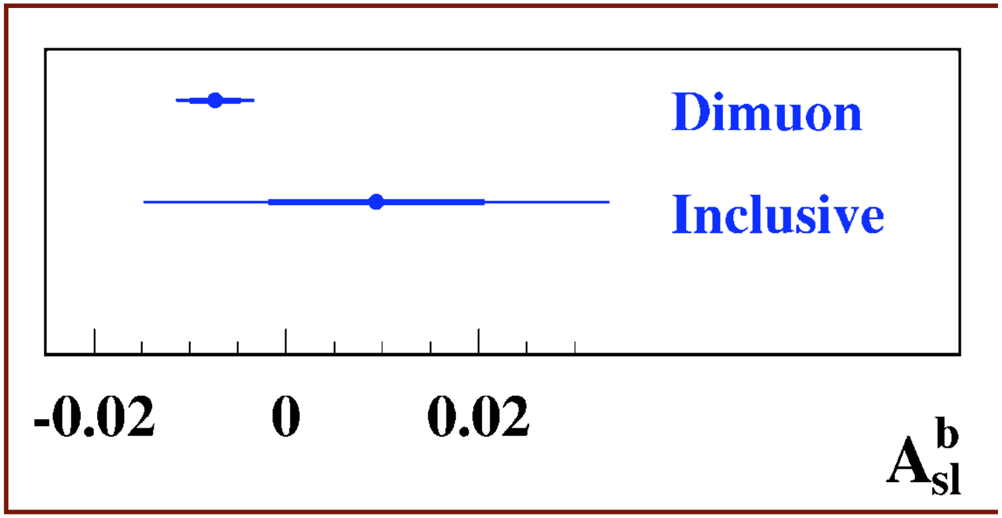
Bringing everything together

- Using all results on background and signal contribution we get two separate measurements of A^b_{sl} from inclusive and like-sign dimuon samples:

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

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

- Uncertainties of the single muon measurement are much larger, because of the small coefficient $k = 0.041 \pm 0.003$ (background dominates)
- Dominant contribution into the systematic uncertainty comes from the measurement of f_K and F_K fractions

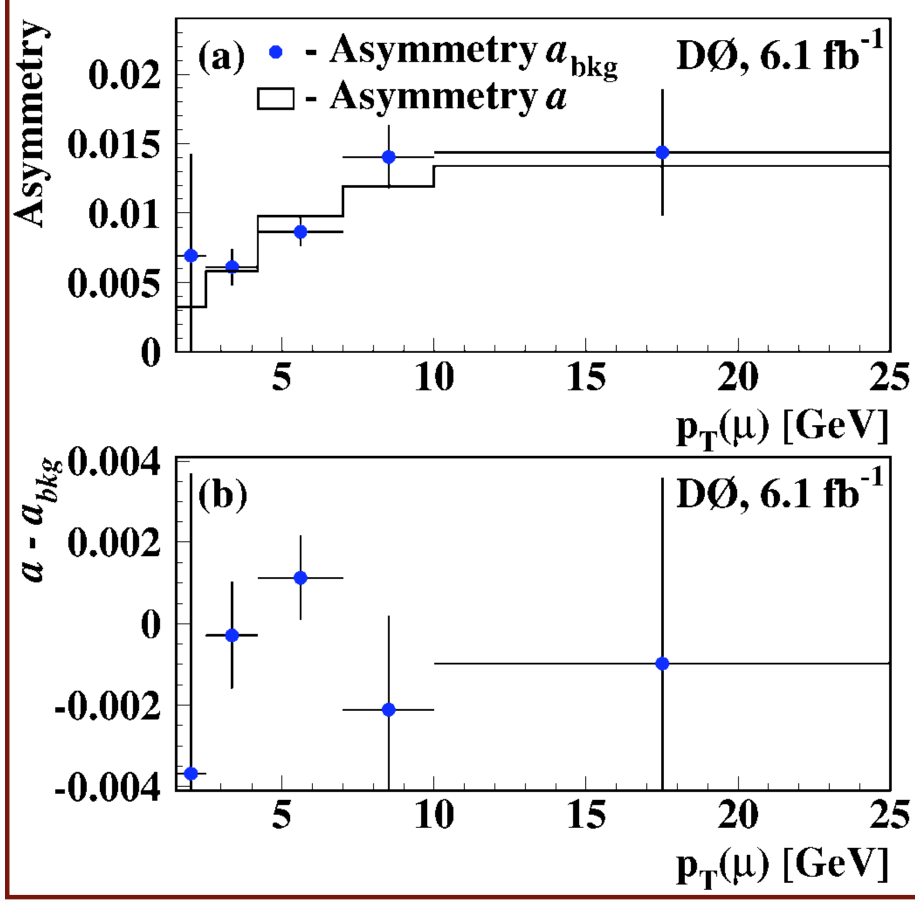


Closure test

- The contribution of A^b_{sl} in the inclusive muon asymmetry a is suppressed by k = 0.041±0.003
- The value of a is mainly determined by the background asymmetry a_{bkg}
- We compare

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

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



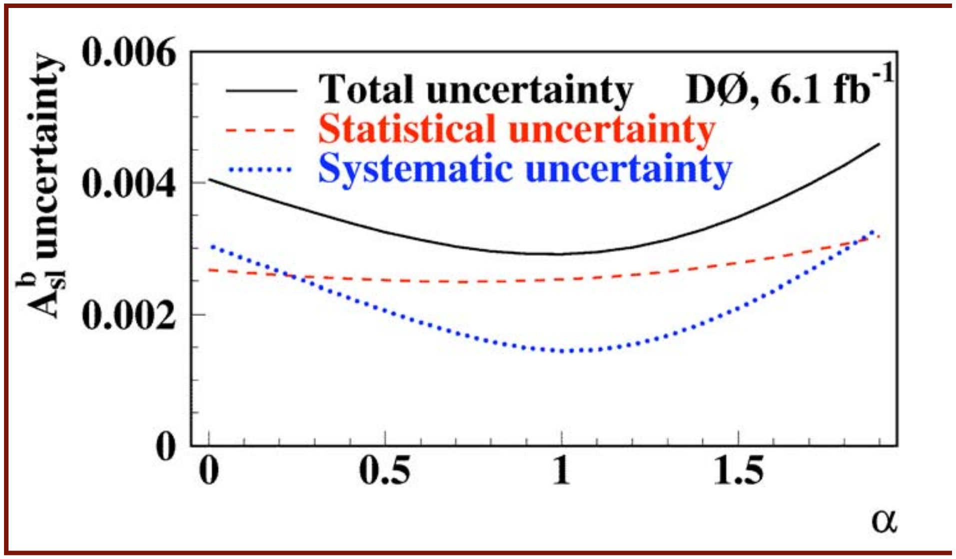
Excellent agreement between the expected and observed values of *a* , including its p_T dependence

Combination of measurements

- We use the inclusive muon measurement to constrain the background contributions and obtain the final "background subtracted" result using the linear combination:

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

- α is selected such that the total uncertainty of A^b_{sl} is minimized: α=0.959
- 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 $k << K$



Final result

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

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

- To be compared with the SM prediction:

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

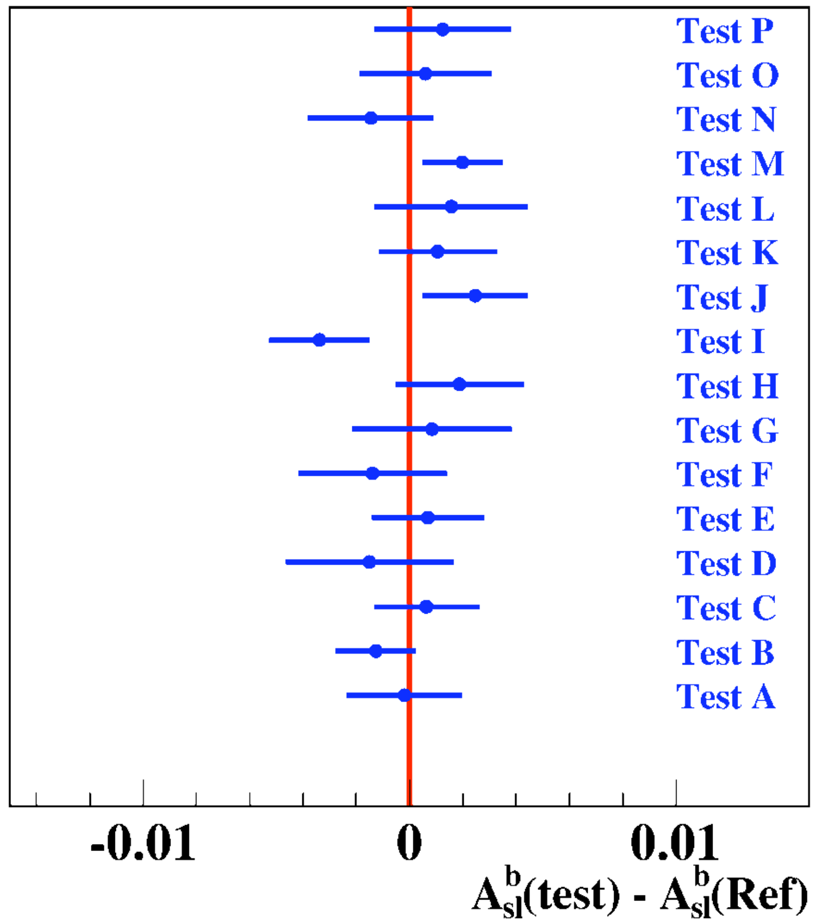
- This result differs is two orders of magnitude larger than the SM prediction; ~3.2 σ away from it.

Statistical and systematic uncertainties

	1. Inclusive muon sample	2. Like-sign dimuon sample	1 constraining 2 (Final)
Source	$\delta\sigma(A_{\rm sl}^b)(62)$	$\delta\sigma(A_{\rm sl}^b)(63)$	$\delta\sigma(A_{\rm sl}^b)(65)$
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

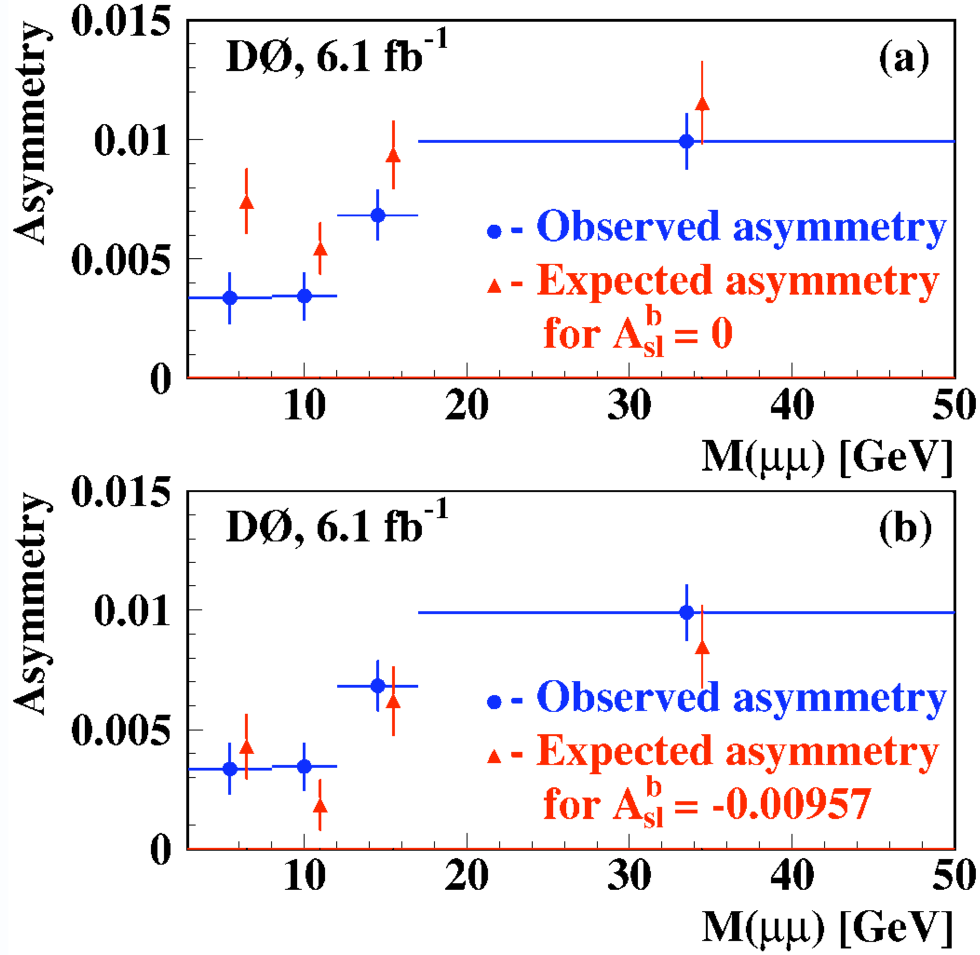
Consistency tests

- We modify selection criteria, or use partial of samples to test the stability of the 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



Dependence on dimuon mass

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

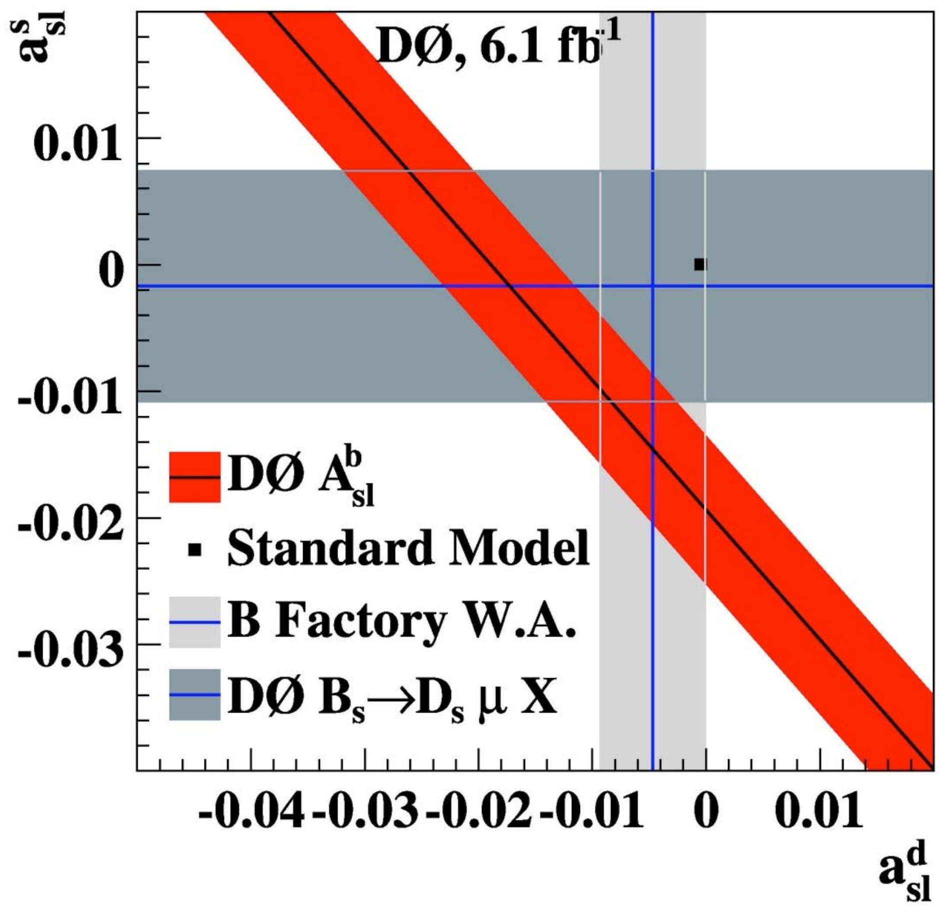


Comparison with other measurements

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

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

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



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 $a^d_{sl} = -0.0047 \pm 0.0046$ measured at B factories
- We obtain:

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

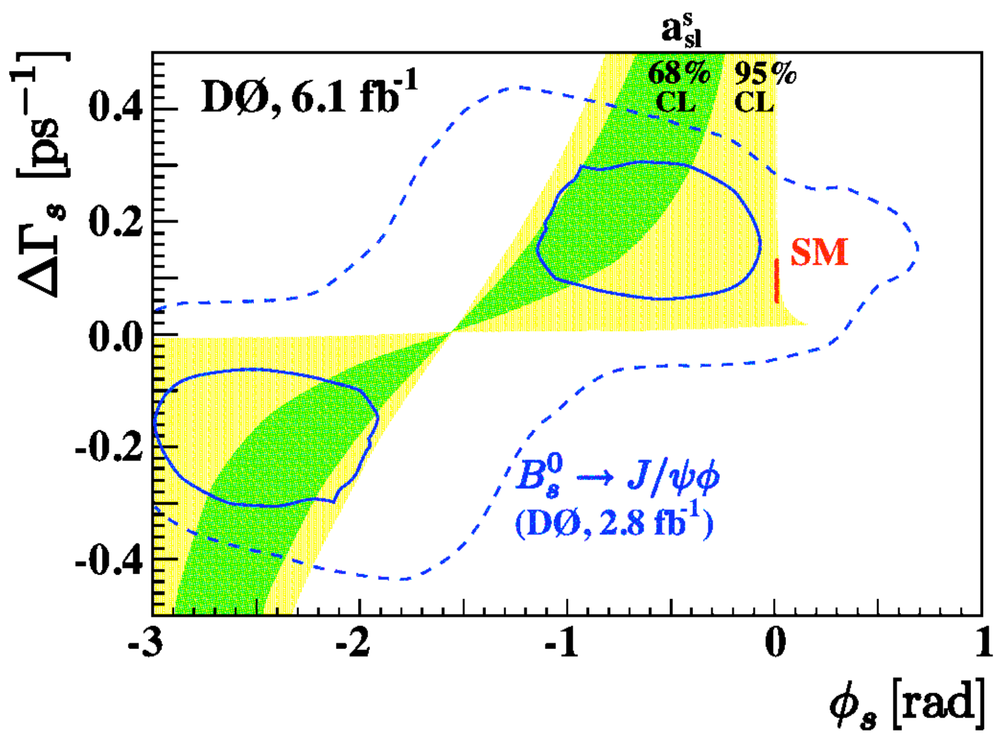
- To be compared with the SM prediction:

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

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

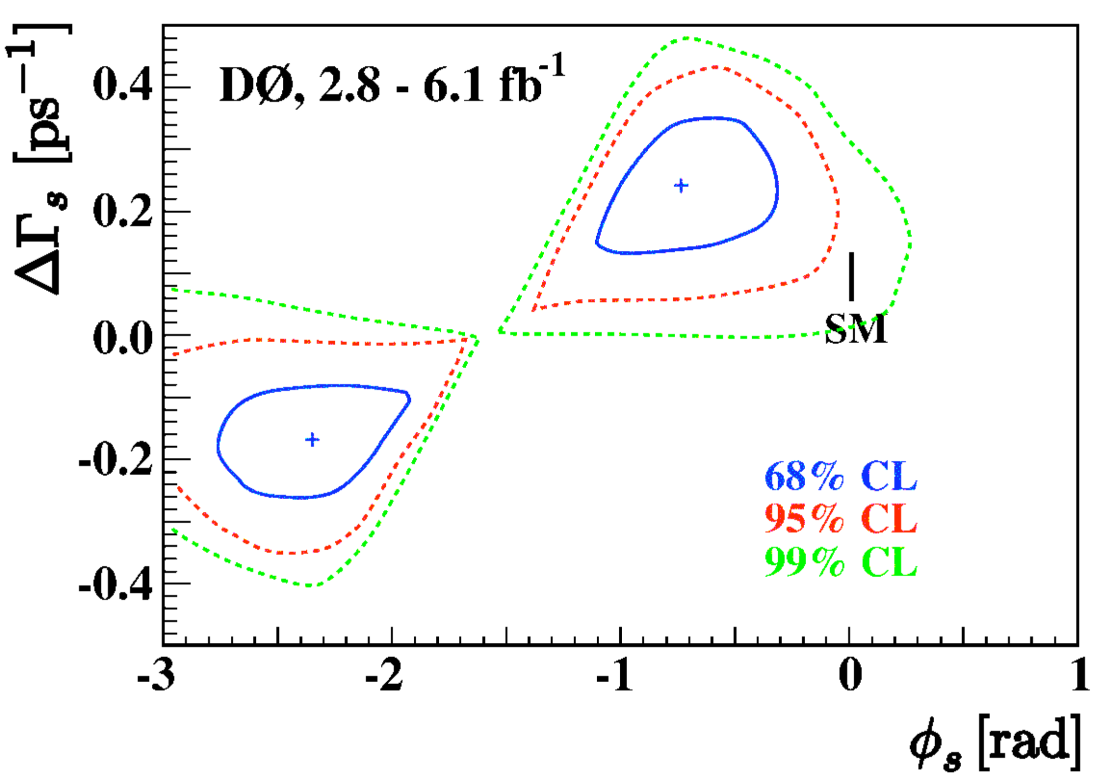
Comparison with other measurements

- Obtained value of a^s_{sl} can be translated into the measurement of the CP violating phase ϕ_s and $\Delta\Gamma_s$
- This constraint is in excellent agreement with an independent measurement of ϕ_s and $\Delta\Gamma_s$ in $B_s \to J/\psi\phi$ decay
- This result is also consistent with the CDF measurement in this channel



Combination of results

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

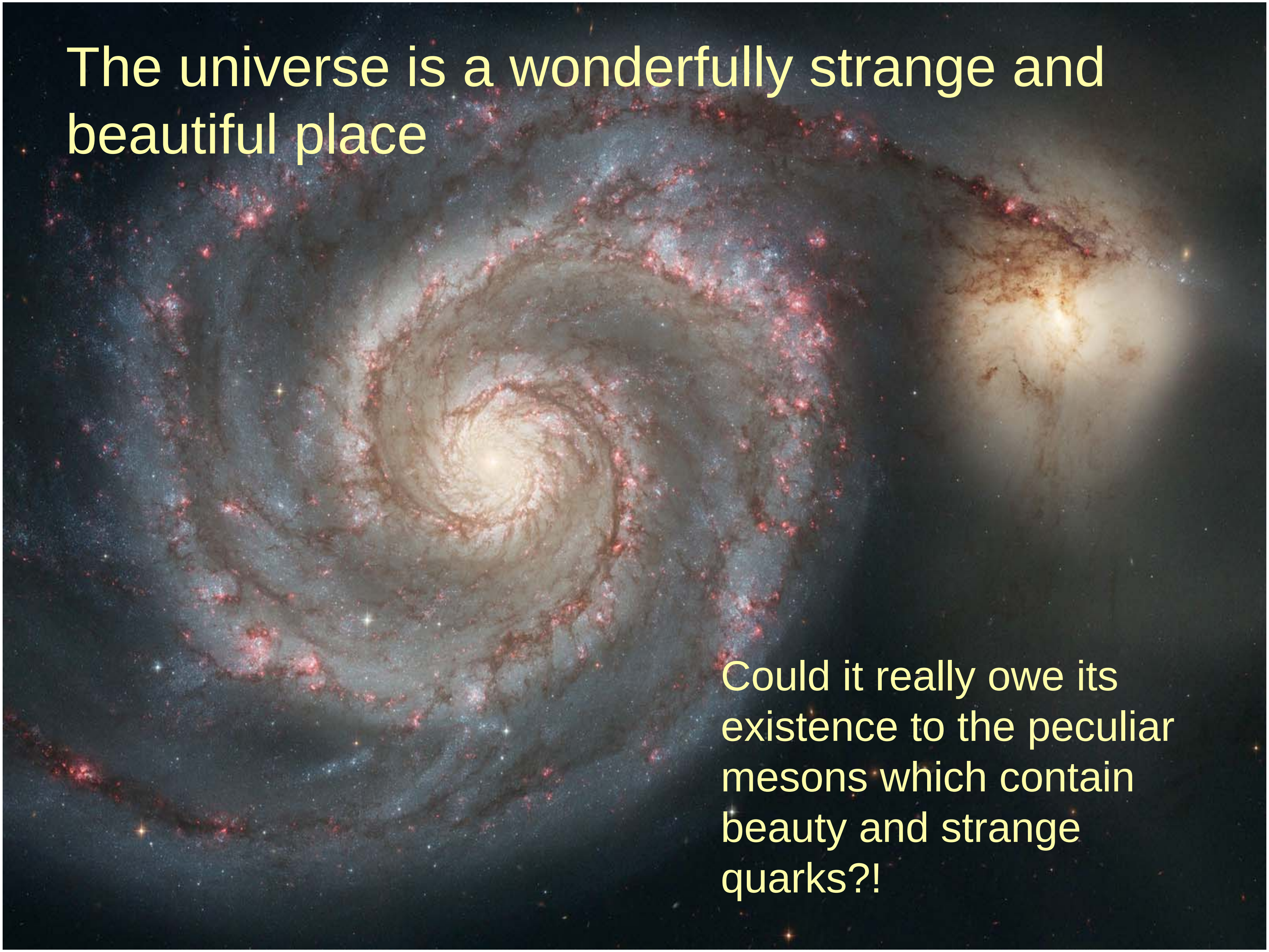


Conclusion

- We have found evidence of an anomalous charge asymmetry in the number of like-sign dimuons produced in the initially *CP* symmetric p anti-p interaction:

$$\boxed{A_{sl}^{b} = (-0.957 \pm 0.251\,(\text{stat}) \pm 0.146\,(\text{syst})\,)\%}$$

- This asymmetry is two orders of magnitude larger than the SM prediction and disagrees with it at a 3.2σ level
- This new result is consistent with other measurements
- We observe that the number of produced particles of matter (negative muons) is larger than the number of produced particles of antimatter
- The sign of observed asymmetry is consistent with the sign of *CP* violation required to explain the abundance of matter in our Universe


The universe is a wonderfully strange and beautiful place
Could it really owe its existence to the peculiar mesons which contain beauty and strange quarks?!