Evidence for an Anomalous like-sign dimuon charge asymmetry

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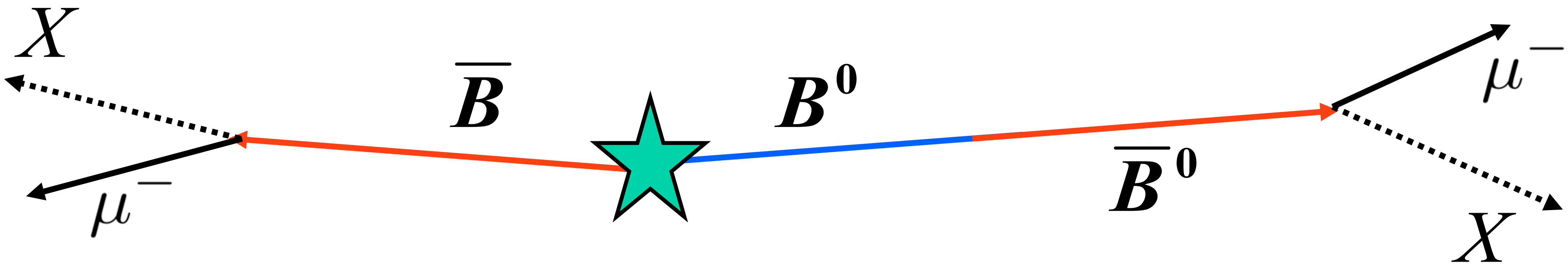
CP Violation in Mixing



- Asymmetry in "same-sign" muons from decays of mixed neutral B mesons:

$$a^b_{sl} \equiv \frac{\Gamma\left(\bar{B} \to \mu^+ X\right) - \Gamma\left(B \to \mu^- X\right)}{\Gamma\left(\bar{B} \to \mu^+ X\right) + \Gamma\left(B \to \mu^- X\right)}$$

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

Grossman, Nir, Raz, Phys.Rev.Lett.97:151801,2006.

- Extract in multiple ways
  - Time dependent tagged decays (e.g. DØ B_S semi-leptonic decays lifetime analysis arxiv.org:0904.3907)
  - asymmetry in single muon, or same sign dimuon events

At the Tevatron

- Inclusive, untagged analysis has contributions form both B_d and B_s. Take the measured production fractions (CDF) and mixing properties:

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

- Large contribution from B_s
- Can be written in terms of CP-violating mixing phase:

$$a^q_{sl} = \frac{\left|\Gamma^{12}_q\right|}{\left|M^{12}_q\right|} \sin\theta_q = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\theta_q$$

- and in the SM it is given by:

$$A^b_{sl}\,(\mathrm{SM}) = \left(-2.3^{+0.5}_{-0.6}\right) \times 10^{-4}$$

Lenz, Nierste, **JHEP 0706:072,2007**

Outline of Measurement

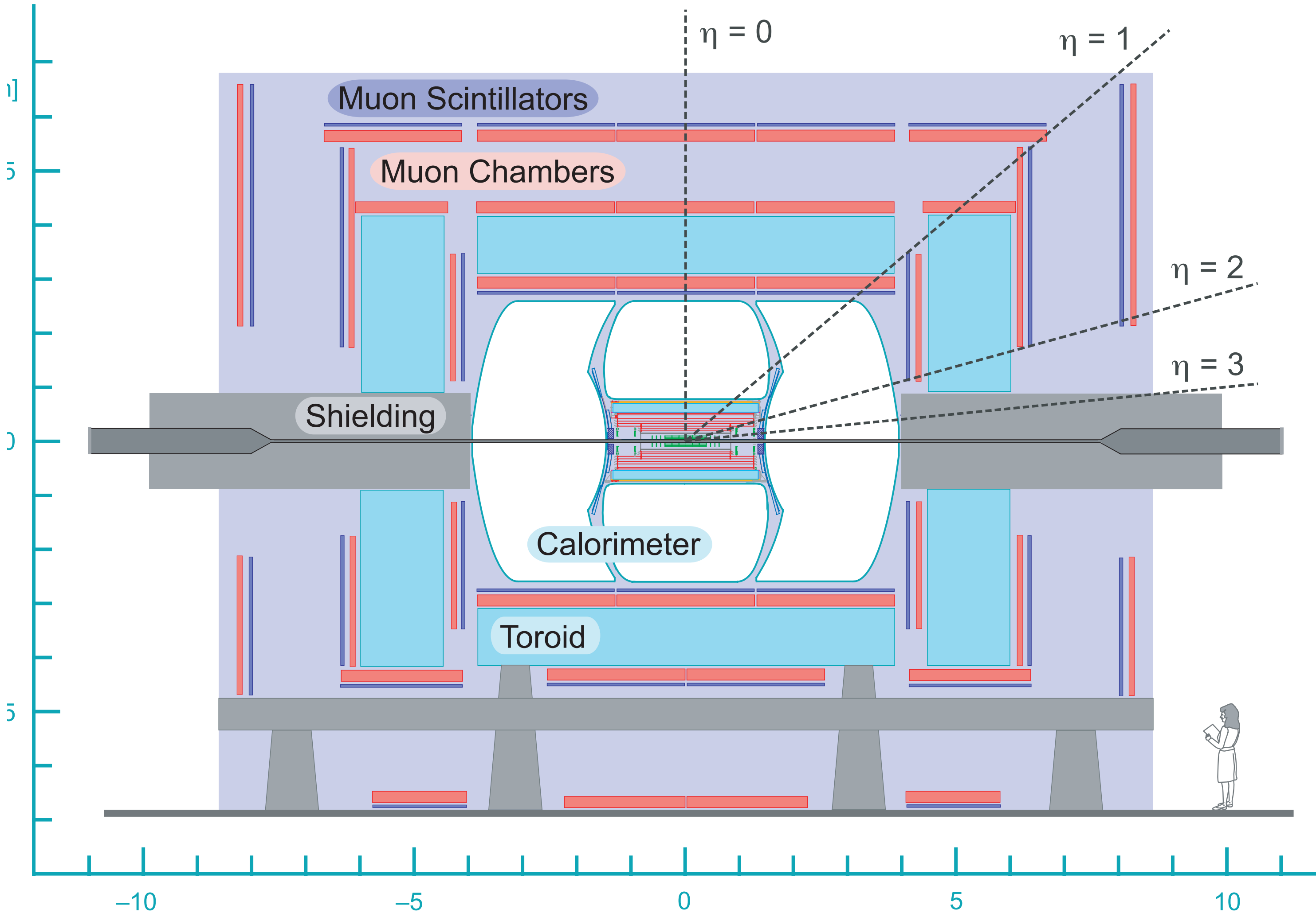
- Measure both dimuon asymmetry A and inclusive asymetry a:

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

- Both have contributions from A^{b}_{sl}, other process with muons and detector related background

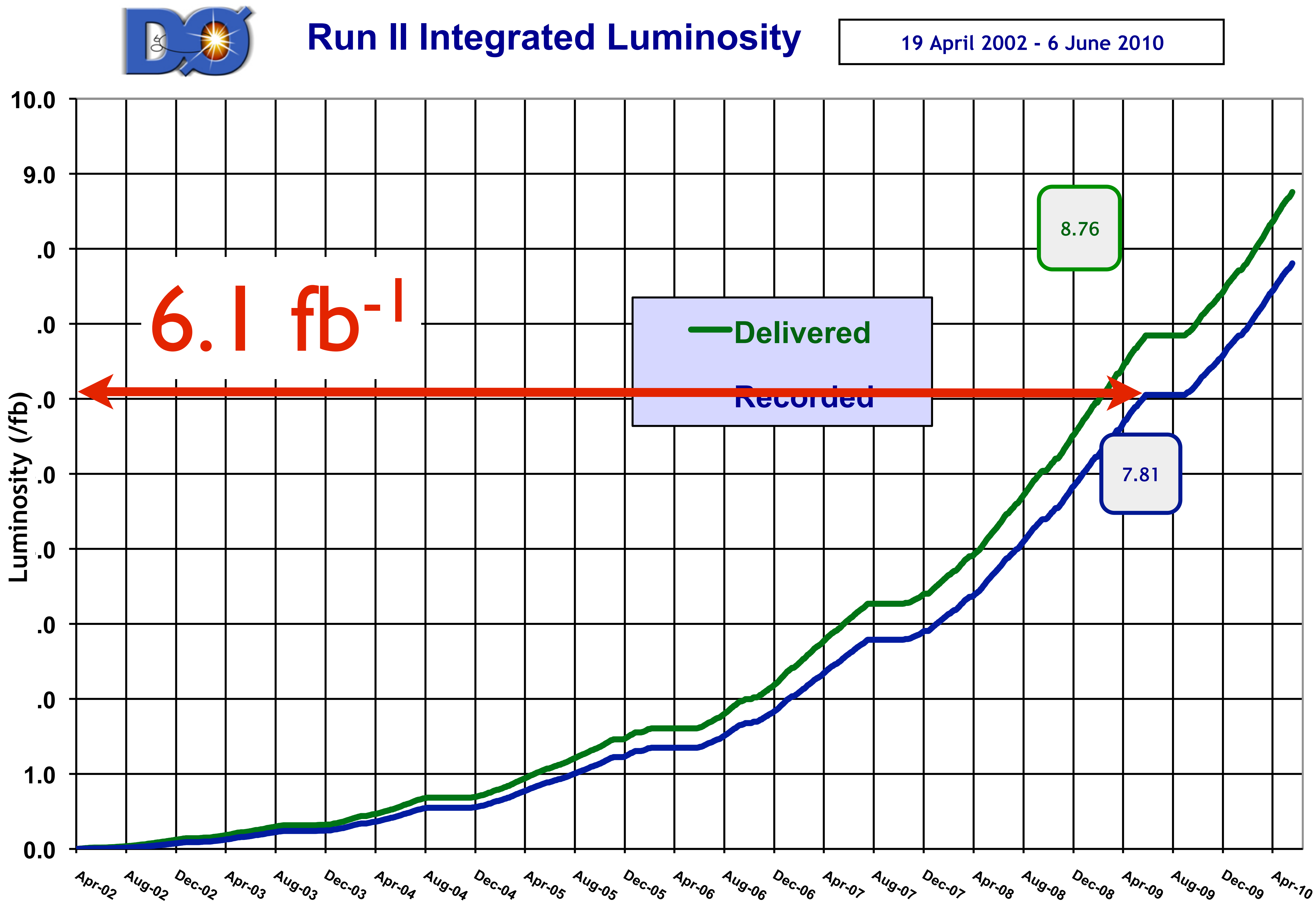
1. Determine the detector and reconstruction backgrounds
   - minimal input from simulation
2. Determine the fraction of prompt single and same-sign di-muons from mixed B decays
3. Exploit the correlations in the backgrounds to minimise the systematic uncertainties of A^{b}_{sl}

DØ Experiment



- Key facts:
  - Extensive muon coverage - high statistics
  - Reversal of magnetic field every two weeks - cancellation of most detector related asymmetries

Dataset



Run II Integrated Luminosity
19 April 2002 - 6 June 2010
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Luminosity (/fb)
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Apr-08
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Aug-09
Dec-09
Apr-10
Delivered
8.76
7.81
6.1 fb-1

Event Selection

- Single muon selection:
  - Good muon: reconstructed tracks in central tracker and muon system match well, $|\eta| < 2.2$
  - $1.5 < p_T < 25$ GeV (suppress EWK contributions)
  - If $p_T < 4.2$ GeV, require $p_z > 6.4$ GeV (get through toroid)
  - Good match to primary vertex: $|d_z| < 5$ mm, axial dca < 3 mm
- Dimuon selection:
  - Two like-sign muons satisfying all criteria above
  - Match same primary vertex
  - $M(\mu\mu) > 2.8$ GeV (suppress muons from same B)

1: Measure A and a

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

- 3.7×10^6 same-sign dimuon events

$$a \equiv \frac{n^{+} - n^{-}}{n^{+} + n^{-}} = (+0.955 \pm 0.003)\,\%$$

- 1.5×10^9 single muon events

- These have significant background contributions:
  We need to distinguish between

  - Detector/reconstruction backgrounds

$$A = K \times A^b_{sl} + A_{\mathrm{bkg}}, \quad a = k \times A^b_{sl} + a_{\mathrm{bkg}}$$

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- These have significant background contributions: We need to distinguish between
  - Detector/reconstruction backgrounds
  - "Dilution" due to other sources of "prompt" muons

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

2. Detector related Backgrounds

$$a_{\text{bkg}} = f_K a_K + f_\pi a_\pi + f_p a_p + \left(1 - f_{\text{bkg}}\right) \delta$$
$$A_{\text{bkg}} = F_K A_K + F_\pi A_\pi + F_p A_p + \left(1 - F_{\text{bkg}}\right) \Delta$$

(For dimuons we only consider linear terms in the asymmetry)

- f_K, f_π, fp, F_K, F_π, F_p are the fractions of kaons, pions and protons identified as muons in the single and dimuon samples
- a_K, a_π, a_p, A_K, A_π, A_p are their reconstructed charge asymmetries
- f_{bkg} = $f_K + f_\pi + f_p$, and $F_{bkg} = F_K + F_\pi + F_p$
- δ and Δ are the muon reconstruction charge asymmetries

The Importance of Kaons

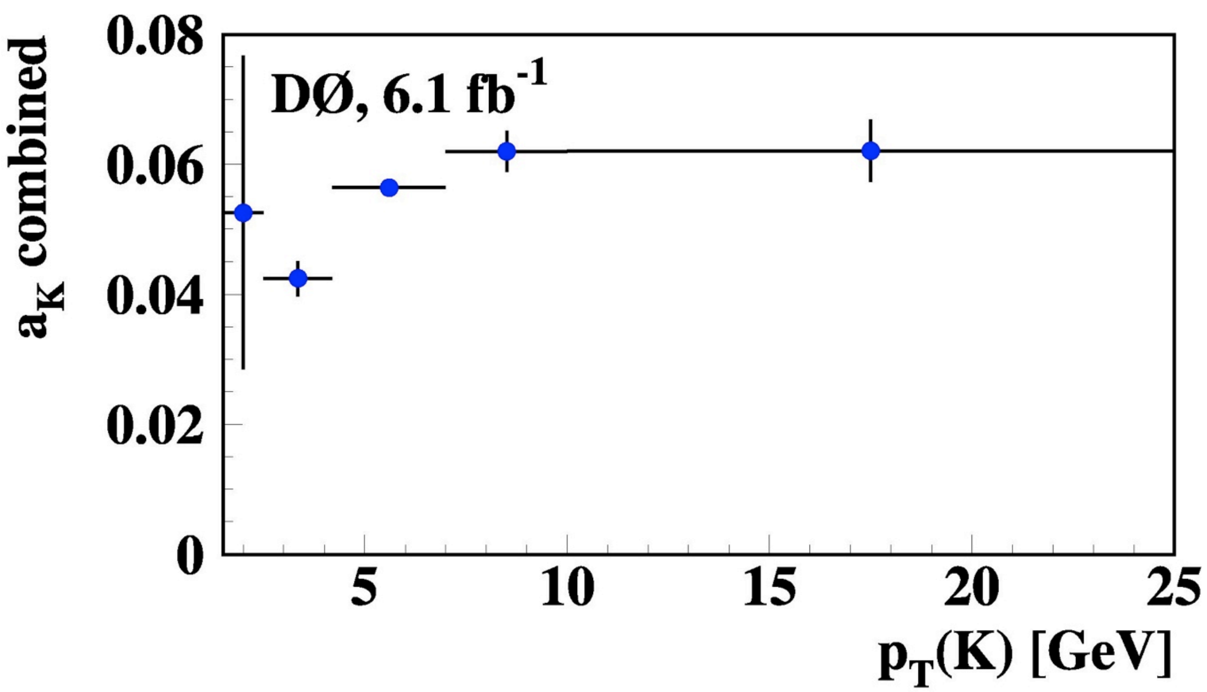
$$a_{\text{bkg}} = f_K a_K + f_\pi a_\pi + f_p a_p + \left(1 - f_{\text{bkg}}\right)\delta$$
$$A_{\text{bkg}} = F_K A_K + F_\pi A_\pi + F_p A_p + \left(1 - F_{\text{bkg}}\right)\Delta$$

- Dominant contribution is kaon term:
  - Detector is made of matter
  - Different interaction cross-section for K^+ vs K^-
    - K^+ has substantially lower cross-section because no equivalent to $K^-N \rightarrow Y\pi$
  - ➡ Large positive asymmetry from K decay in flight & punch-through
  - Need to measure in data!
- Other asymmetries are ~10x smaller (but measure as well!)

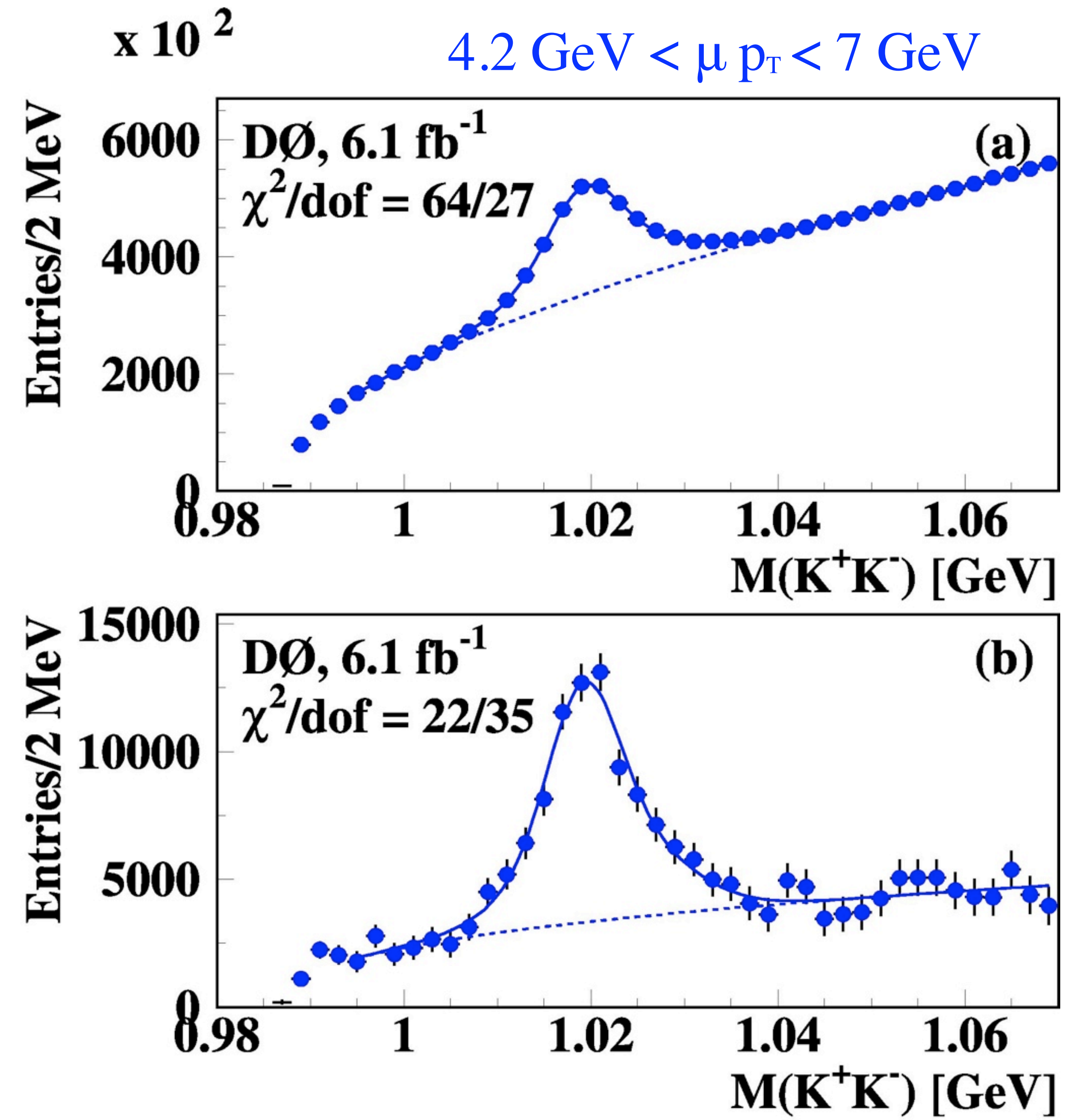
Kaon Asymmetry Background

- Sources of Kaon in single muon sample
  - Kaon decays, punch through, tracking overlap, etc.
  - Find $\Phi(1020) \rightarrow K^+K^-$, and $K^{*0} \rightarrow K^+\pi^-$ where K identified as a muon

Compare K^+ and K^- and subtract.
Results from ϕ and K^* agree well, combine



4.2 GeV < μ p_T < 7 GeV



Fraction of Kaons in Sample

- Can measure $f_{K^{*0}}$, $F_{K^{*0}}$
- Extract f_K, F_K from

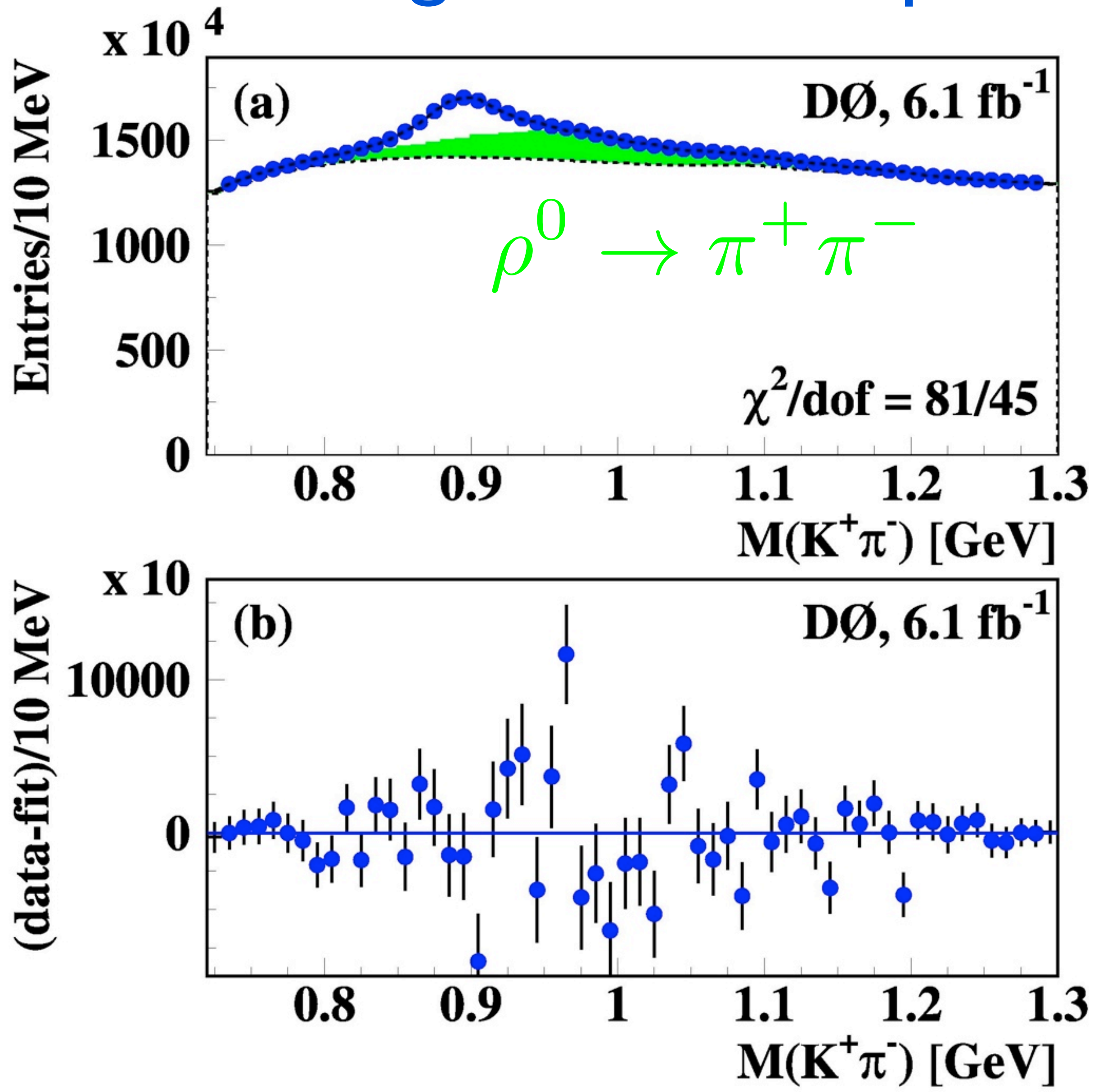
$$f_K = \frac{N(K_S)}{N\left(K^{*+} \to K_S \pi^+\right)} f_{K^{*0}}$$

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

$= f_K/f_{K^*}$

- Use simulation to confirm pion reconstruction ε is the same for K^{*+} and K^{*0} if K^+/K_S is reconstructed

Single Muon Sample



Pion and Proton Background Asymmetry

- a_π, a_p, A_π and A_p are measured using $K_S \rightarrow \pi\pi$ and $\Lambda \rightarrow p\pi$

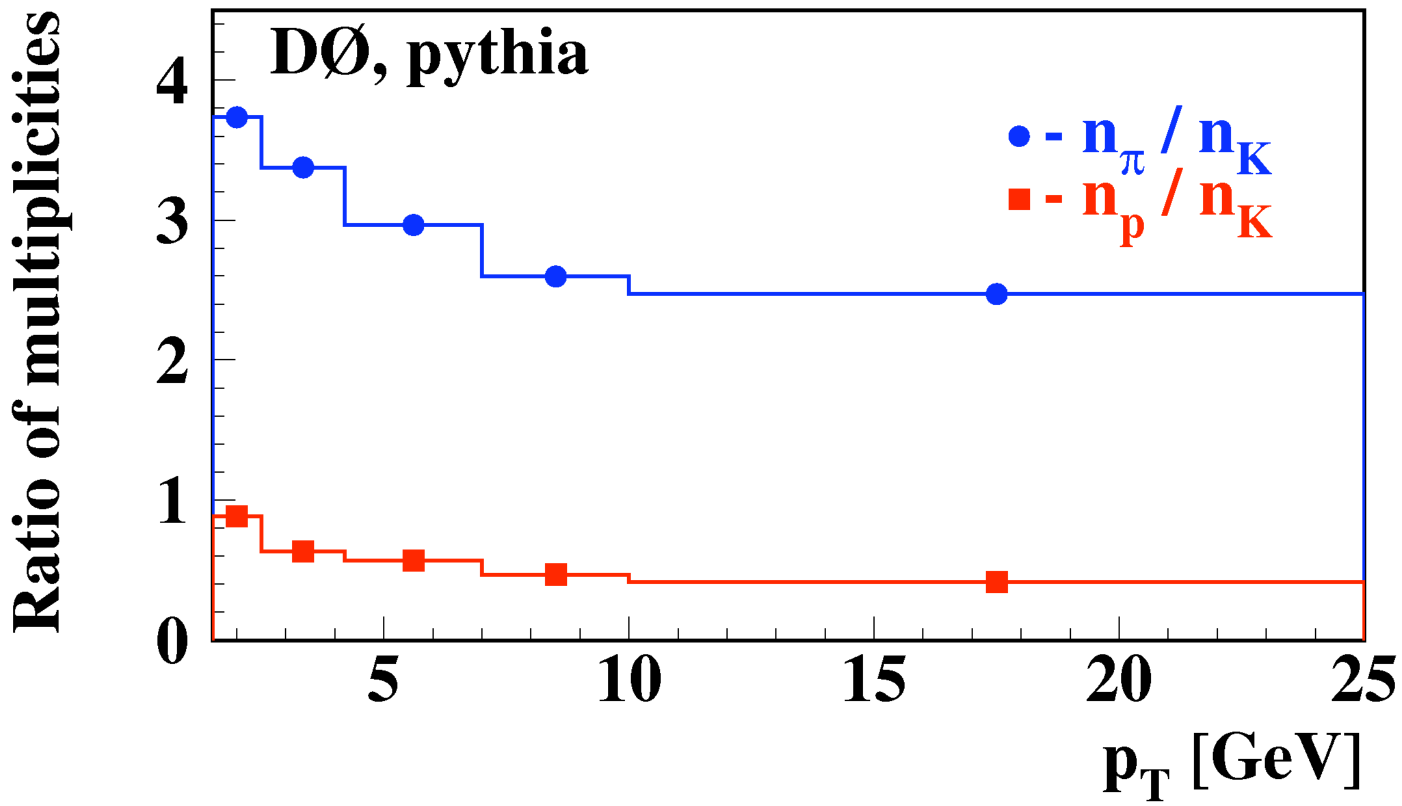
a_K	a_π	a_p
(5.51 ± 0.11)%	(0.25 ± 0.10)%	(2.3 ± 2.8)%

- These are all determined in "muon" p_T bins.
- Asymmetries in the dimuon sample are derived taking into account the slightly different muon p_T distributions:

$$F_K A_K = \sum_{i=0}^{4} F_\mu^i F_K^i a_K^i$$

Other Backgrounds

- Use n_π/n_K and n_p/n_K from simulation to derive f_π, f_p, F_π and F_p from f_K and F_K (with a check on n_K in data to evaluate uncertainties)
  - Also adjust for the probabilities for a π, p, K to be reconstructed as a muon (from φ, K_S, Λ decays)



Background Summary

- Putting everything together, the detector & reconstruction backgrounds are:

$(1-f_{bkg})$	f_K	f_π	f_p
(58.1±1.4)%	(15.5±0.2)%	(25.9±1.4)%	(0.7±0.2)%
	$a_K f_K$	$a_\pi f_\pi$	$a_p f_p$
	(+0.854 ± 0.018)%	(+0.095 ± 0.027)%	(+0.012 ± 0.022)%
	$A_K F_K$	$A_\pi F_\pi$	$A_p F_p$
	(+0.828 ± 0.035)%	(+0.095 ± 0.025)%	(+0.000 ± 0.021)%

(Statistical uncertainties only)

Simulation gives similar results (not used)

Muon Reconstruction Asymmetry

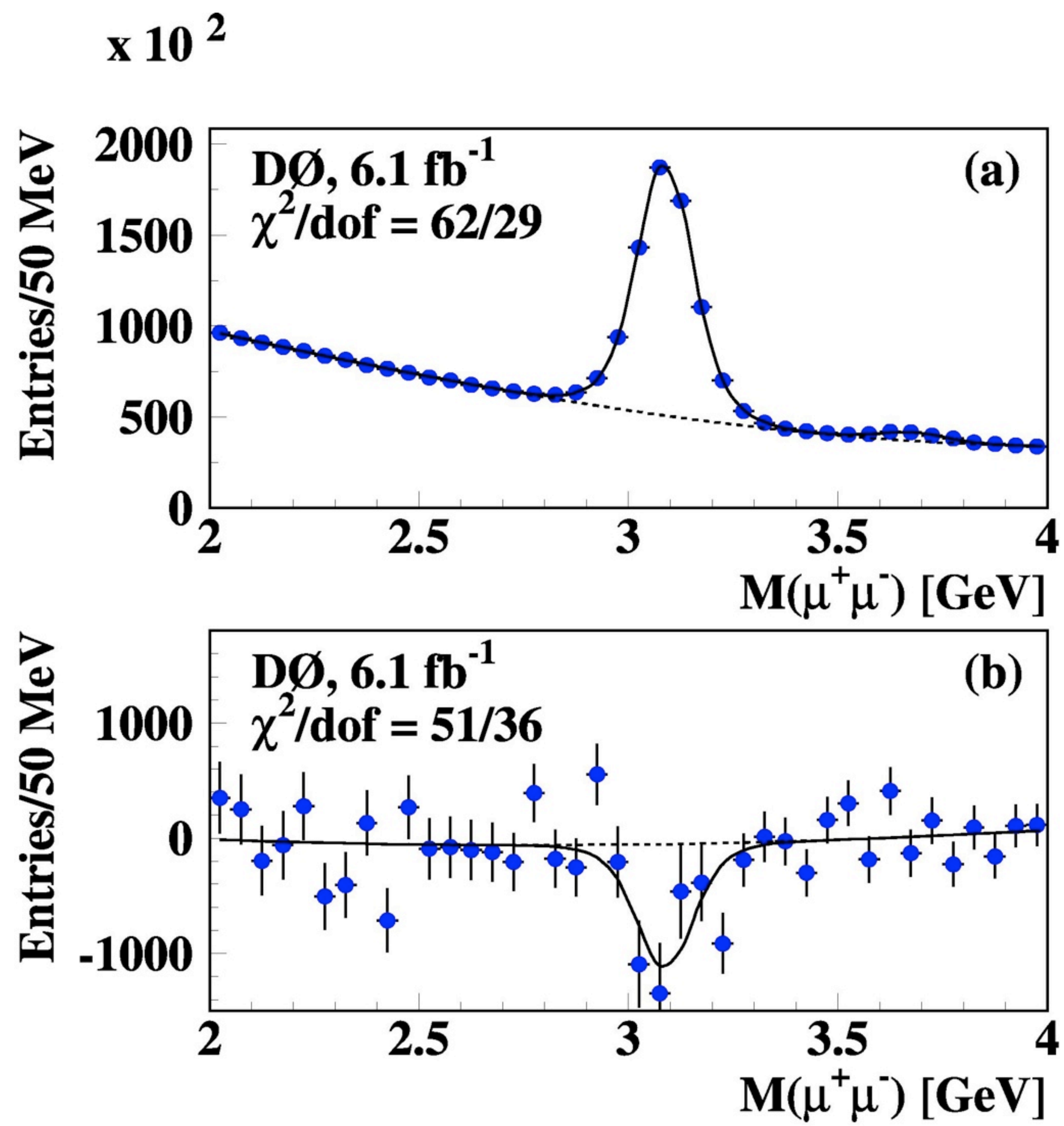
$$a_{\text{bkg}} = f_K a_K + f_\pi a_\pi + f_p a_p + \left(1 - f_{\text{bkg}}\right)\delta$$

$$A_{\text{bkg}} = F_K A_K + F_\pi A_\pi + F_p A_p + \left(1 - F_{\text{bkg}}\right)\Delta$$

- Use dimoun triggers, and examine J/Ψ
  - Measure Asymmetry in muon & track and in dimuon events

    δ = (-0.076 ± 0.028)%
    Δ = (-0.068 ± 0.023)%

  - Direct benefit of reversing polarity of magnet



3 Dilution Factors

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

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

- Many processes contribute to the "physics single and same sign dimuon samples in the denominator
  - Only the oscillating term produces a signal
- k, K are determined with simulations
  - Decay processes are well measured

	Process
T_1	$b \to \mu^- X$
T_{1a}	$b \to \mu^- X$ (nos)
T_{1b}	$\bar{b} \to b \to \mu^- X$ (osc)
T_2	$b \to c \to \mu^+ X$
T_{2a}	$b \to c \to \mu^+ X$ (nos)
T_{2b}	$\bar{b} \to b \to c \to \mu^+ X$ (osc)
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 $\bar{c} \to \mu^- X$

$$K = 0.342 \pm 0.023$$

$$k = 0.041 \pm 0.003$$

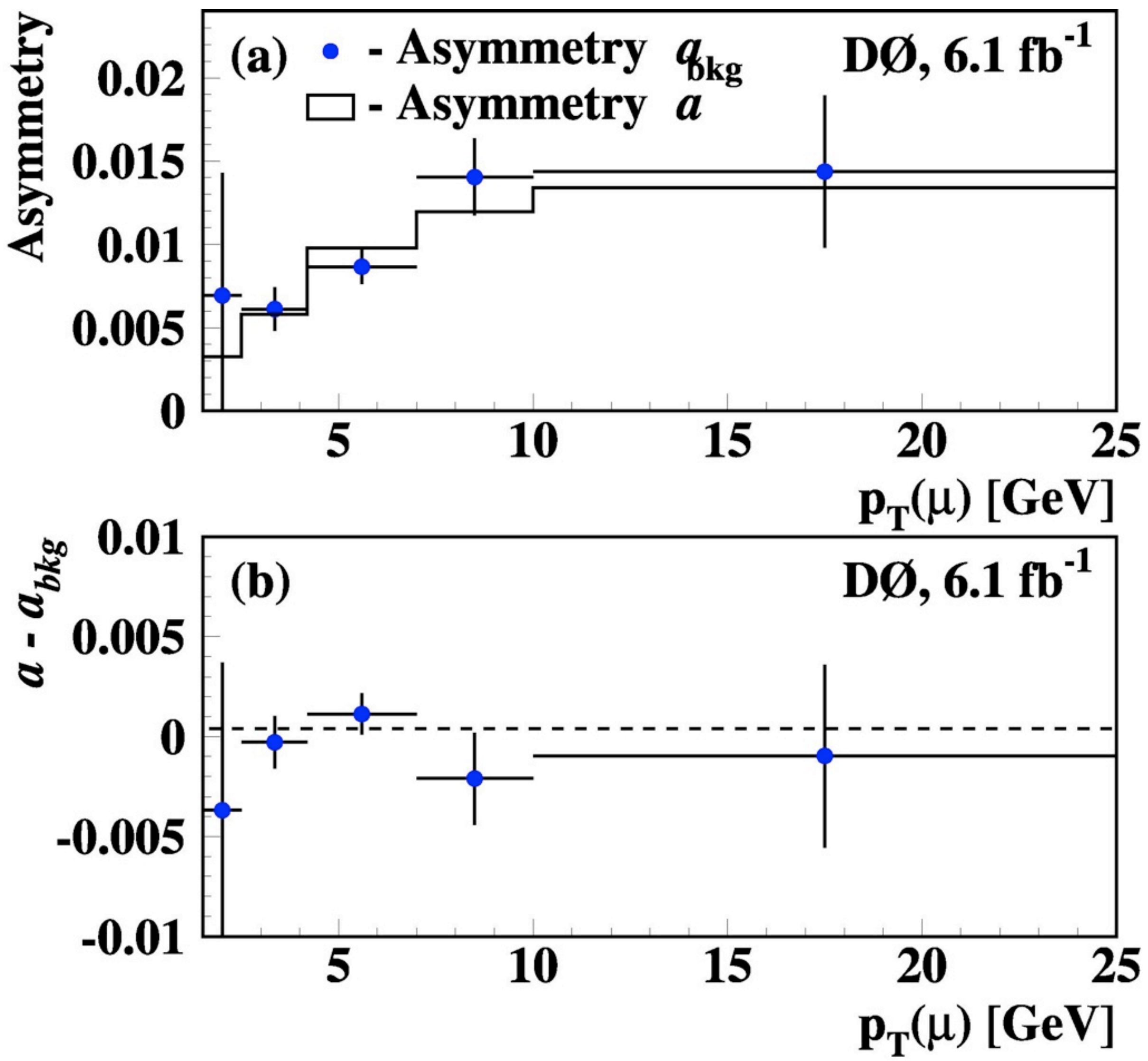
Closure Test

$$a \equiv \frac{n^+ - n^-}{n^+ + n^-} = (+0.955 \pm 0.003)\,\%$$

$$a - a_{\text{bkg}} = k \times A^b_{sl} \qquad k = 0.041 \pm 0.003$$

$$a_{\text{bkg}} = (0.917 \pm 0.45)\,\%$$

- a is dominated by background
- Use it as a closure test:
  - Do we reproduce the p_T dependence of the background asymmetry
  - ✔ YES!



Minimising the Uncertainty

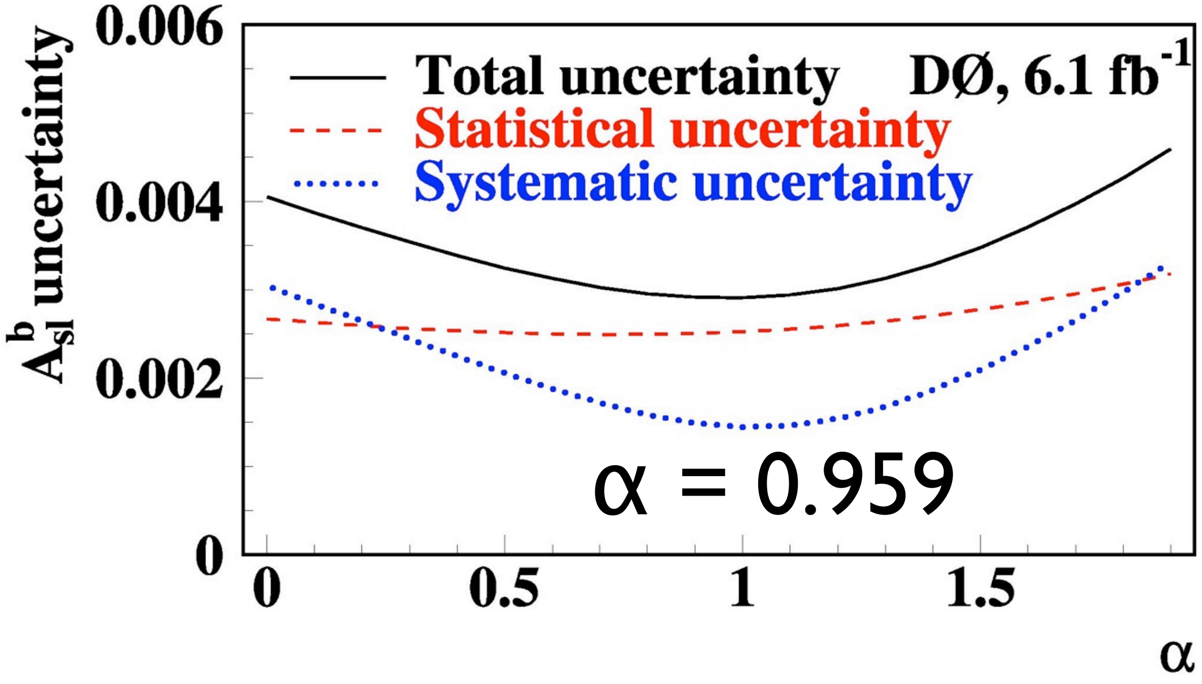
- The single muon asymmetry dominated by background, and background systematic is dominant.
  - Use a to constrain background

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

- Choose α to minimise uncertainty of A^b_{sl}
  - α will be close to 1 since uncertainty highly correlated

$A_{bkg} = (+0.815 \pm 0.070)\%$

$a_{bkg} = (+0.917 \pm 0.045)\%$



Result

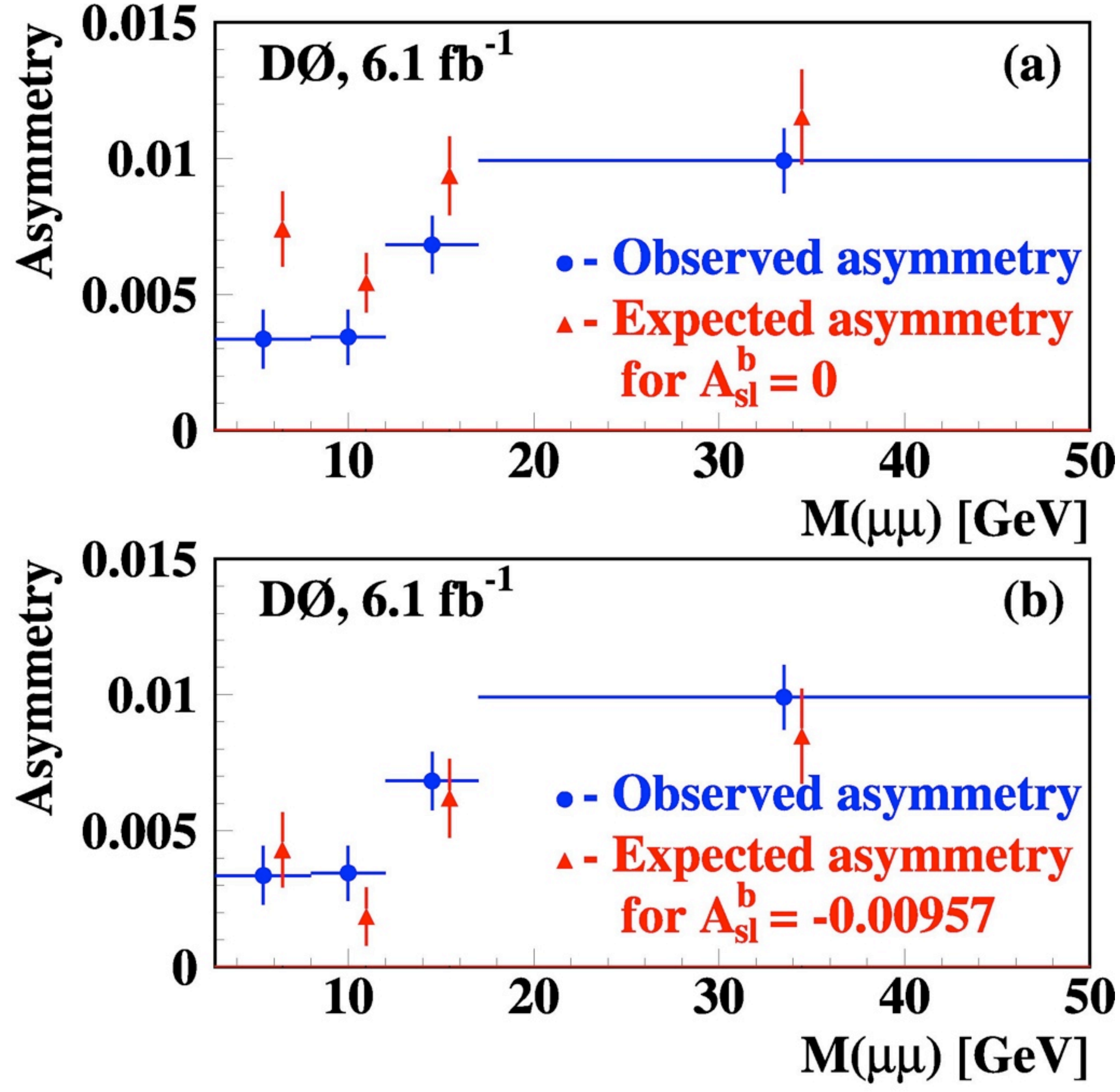
$$A^b_{sl} = (-0.957 \pm 0.251\,(\text{stat}) \pm 0.146\,(\text{syst}))\,\%$$

$$A^b_{sl}\,(\text{SM}) = \left(-2.3^{+0.5}_{-0.6}\right) \times 10^{-4}$$

- Systematic uncertainty reduced by more than two!
- Result is ~3.2 σ from SM

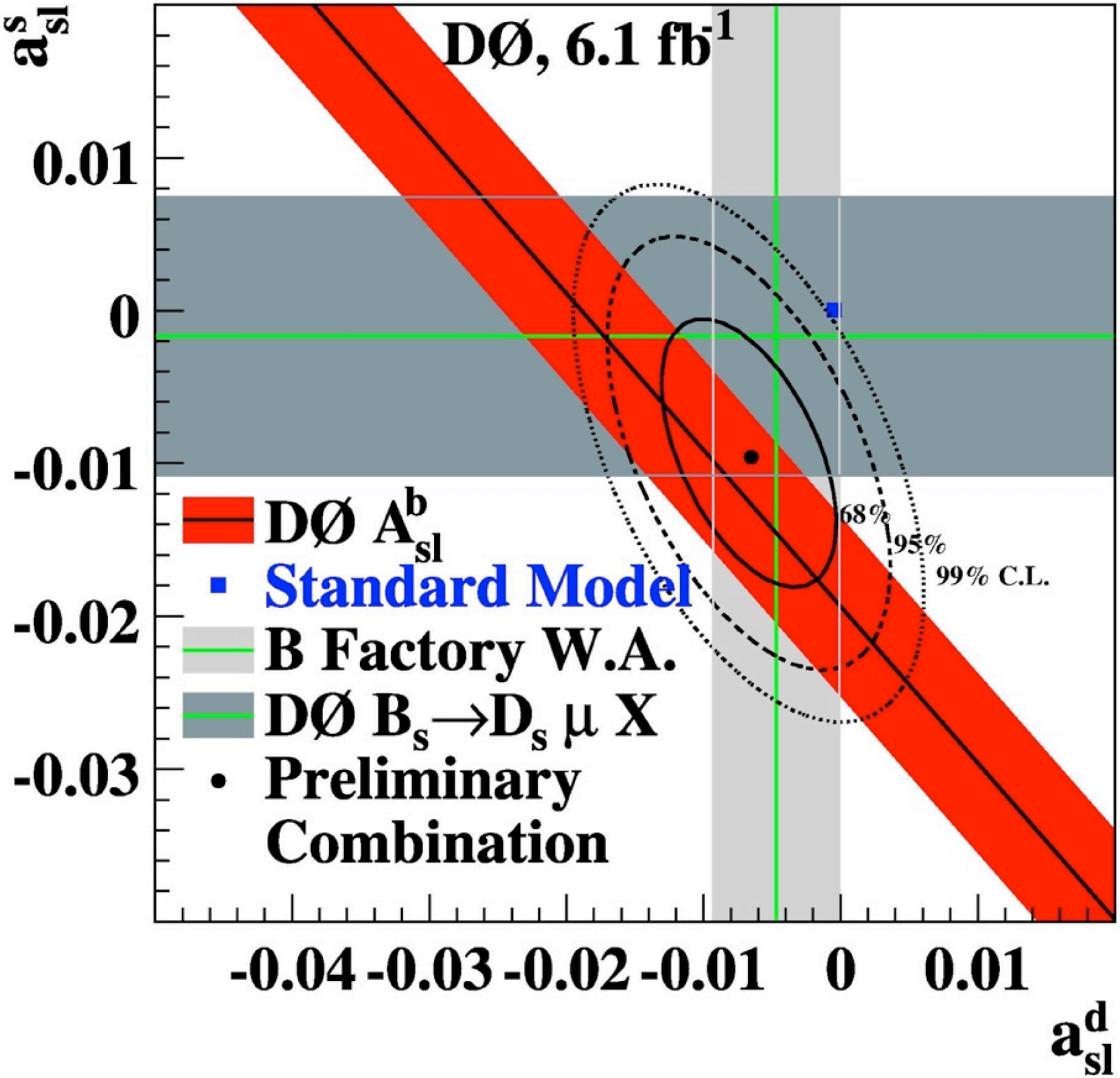
Cross Check - dimuon Mass

- Compare the expected and observed dimuon charge asymmetry for different dimuon mass bins
- Completely different background distribution
- data inconsistent with $A^b_{sl} = 0$
- No sign of "bump" in distribution



No tagging, so cannot guarantee it comes from B - it is consistent though

Consistency



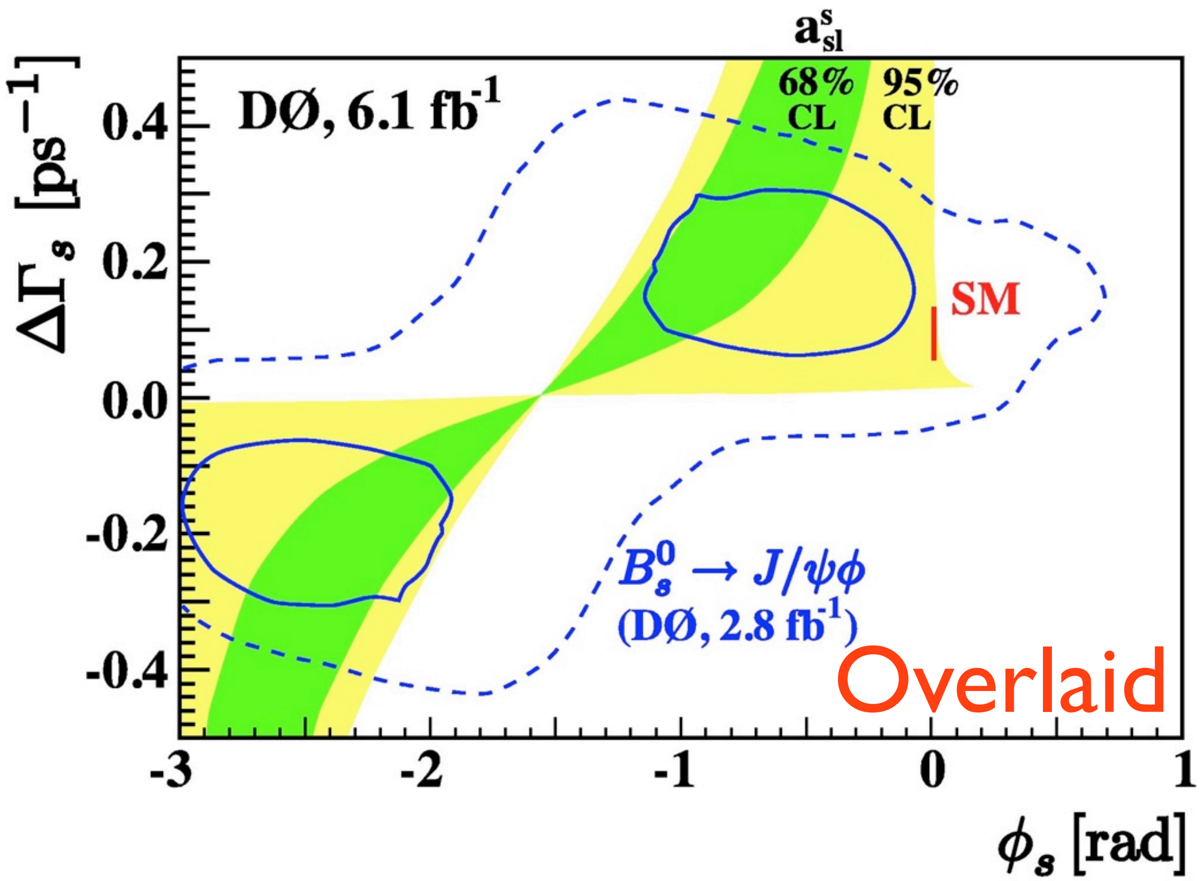
Consistency

- This measurement has contributions from B_d and B_s

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

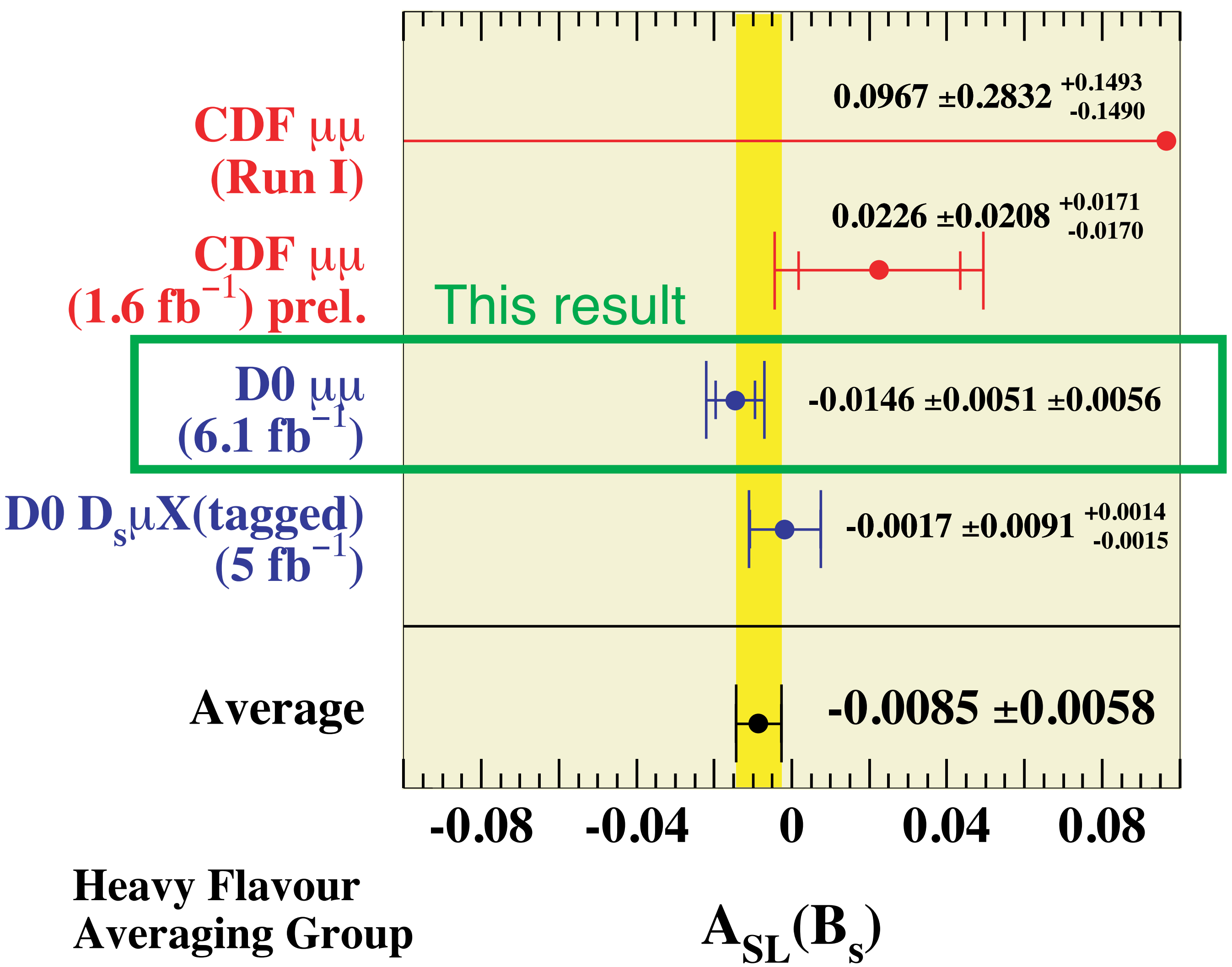
- Can take a^d_{sl} from B factories and extract a^s_{sl}:

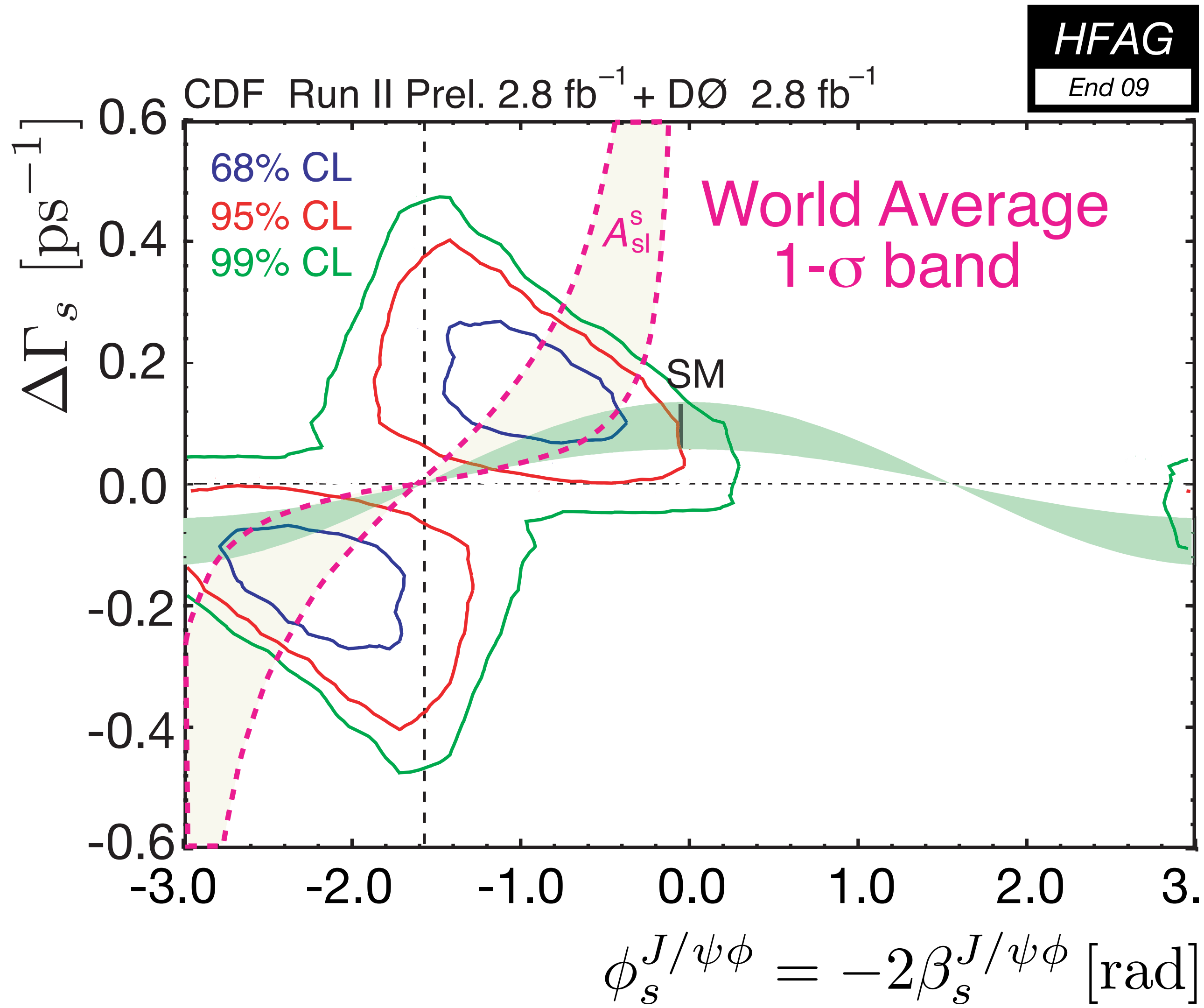
$$a^s_{sl} = (-1.46 \pm 0.75)\,\%$$
$$a^s_{sl}(\mathrm{SM}) = (+0.0021 \pm 0.0006)\,\%$$



- a^s_{sl} can then be translated into constraints on φ_s, $\Delta\Gamma_s$

World Average a^s_{sl}





Conclusions

- We have made a new measurement of the like sign dimuon asymmetry which is significantly different from zero!
  - Assuming the source of the asymmetry is B-physics, we obtain

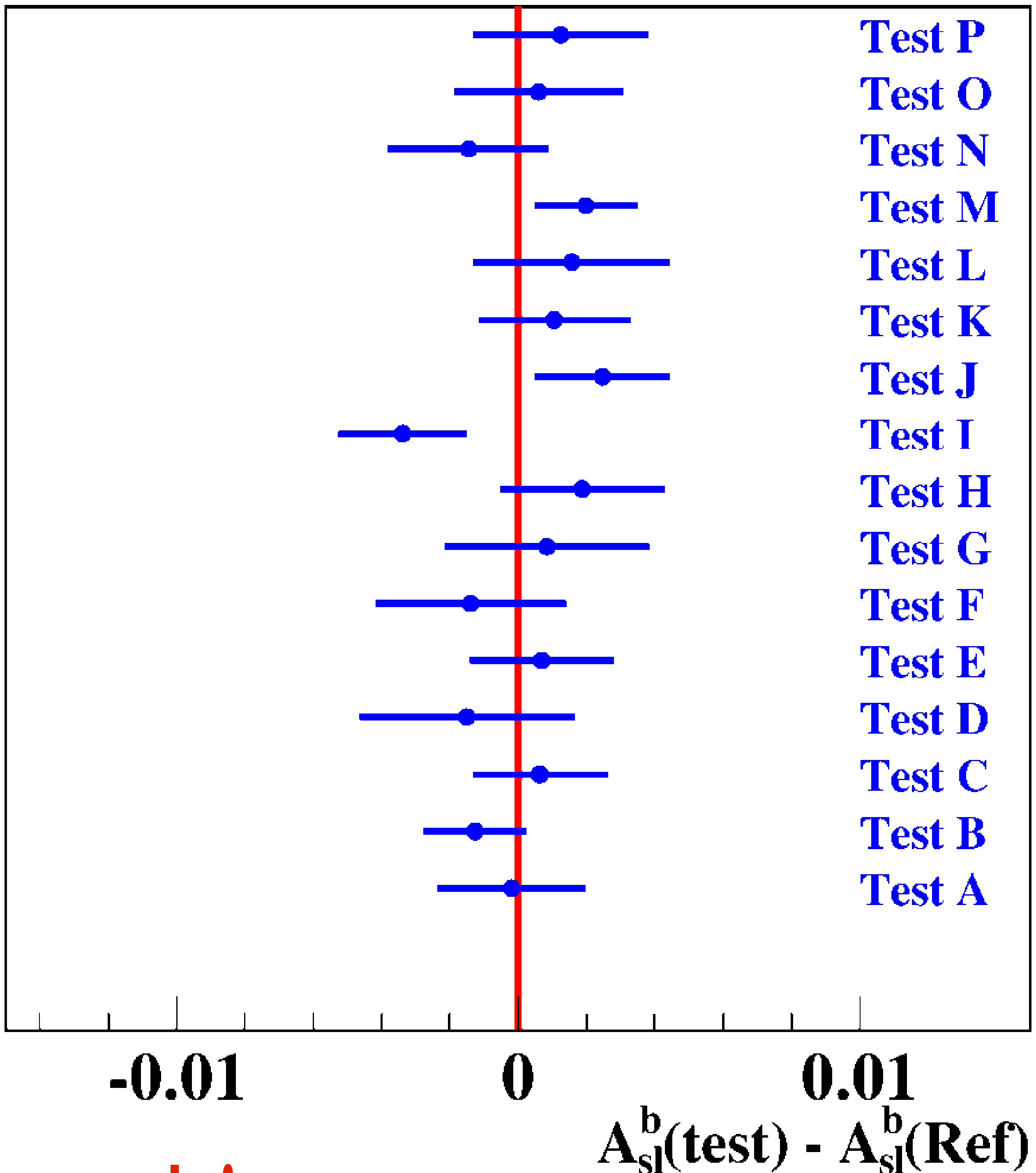
$$A^b_{sl} = (-0.957 \pm 0.251\,(\mathrm{stat}) \pm 0.146\,(\mathrm{syst}))\,\%$$

- This result is consistent with all other measurements of CP violation in B mixing, but inconsistent with the SM at 99.8% CL (3.2 σ)
- It was obtained using very little input from simulation, and all tests show excellent consistency

Extras

Consistency Checks

- We modify selection criteria, or use a part of sample to test the stability of result
- 16 tests in total are performed
- Large variation of raw asymmetry A (up to 140%) due to variation of background!



Stability of result!

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

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Reversing Magnetic Field