Evidence for an Anomalous Like-Sign Dimuon Charge Asymmetry

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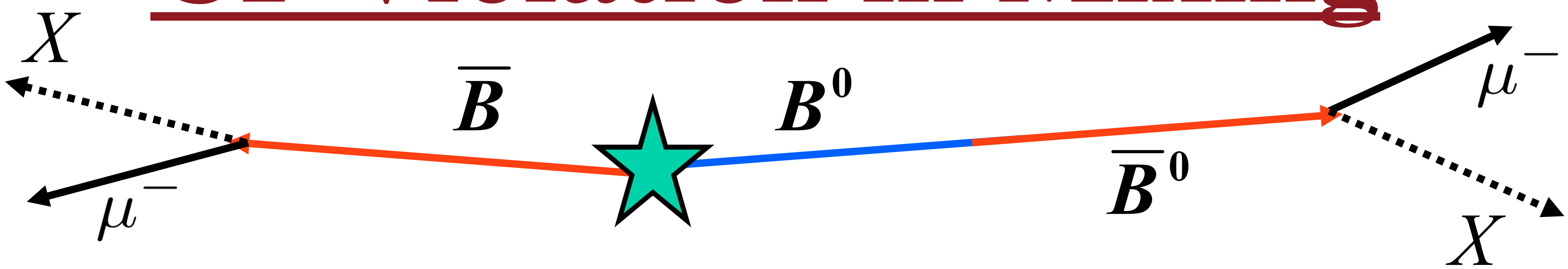
CP Violation in Mixing



- Asymmetry in "wrong charge" muons from decays of mixed B mesons:

$$a_{\rm sl}^b \equiv \frac{\Gamma(\bar{B} \to \mu^+ X) - \Gamma(B \to \mu^- X)}{\Gamma(\bar{B} \to \mu^+ X) + \Gamma(B \to \mu^- X)} = A_{\rm sl}^b$$

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

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

- Can be extracted multiple ways:
  - Time-dependent tagged decays (e.g. B_s: DØ **arXiv:0904.3907 [hep-ex]**)
  - Asymmetry in single muon, or same-sign dimuon events

At the Tevatron

- Proton-antiproton collisions ⇒ CP-symmetric!
- Inclusive, untagged analysis has contributions from both B_d and B_s: use measured production fractions (CDF) and mixing properties (Δm_q, $\Delta\Gamma_q$):

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

- Large B_s contribution!
- In terms of CP-violating mixing phase:

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

- In the SM: $A^b_{\rm sl}({\rm SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$

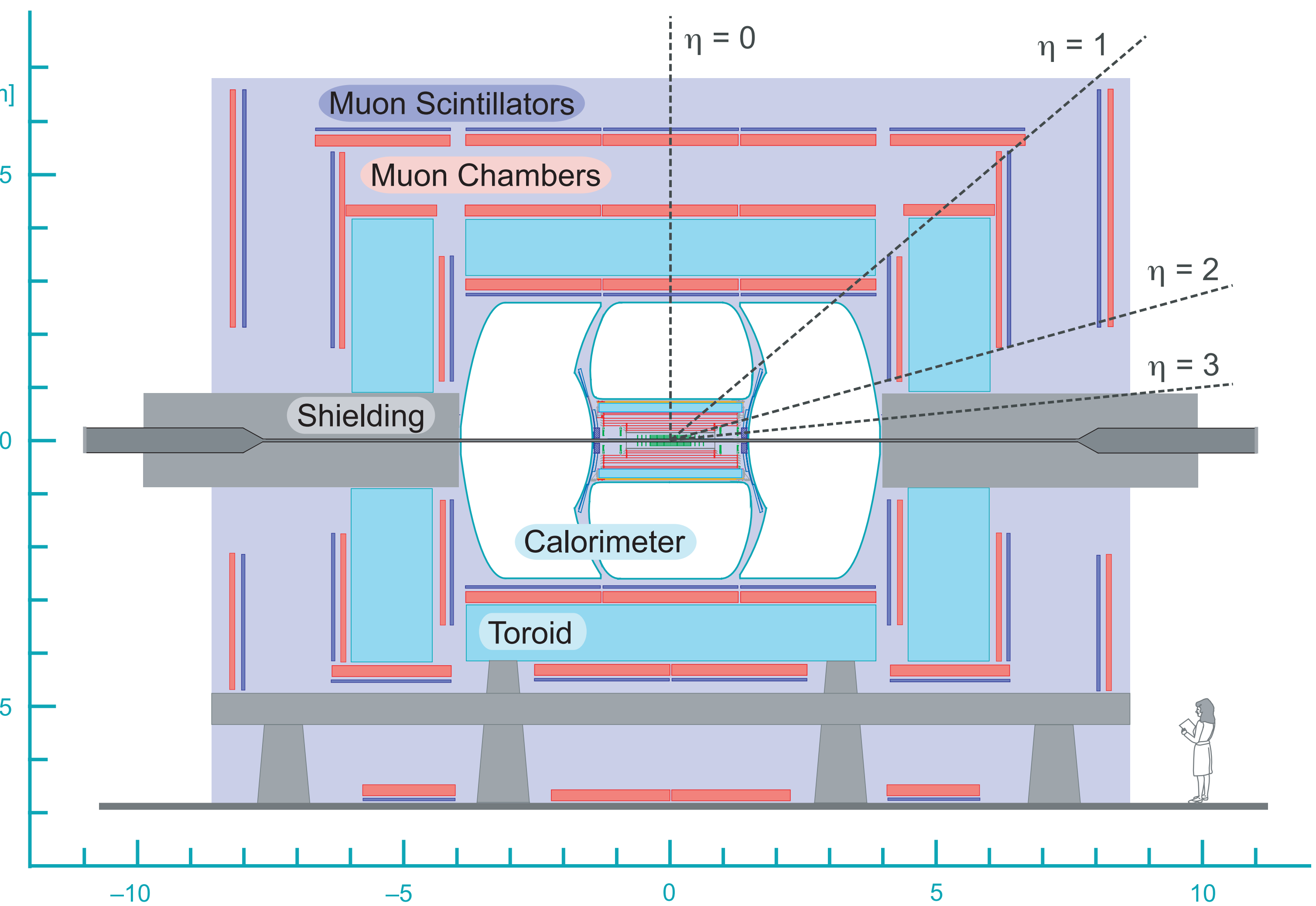
Lenz, Nierste, **JHEP 0706:072,2007**

Strategy

1. Measure both $A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$ and $a \equiv \frac{n^{+} - n^{-}}{n^{+} + n^{-}}$

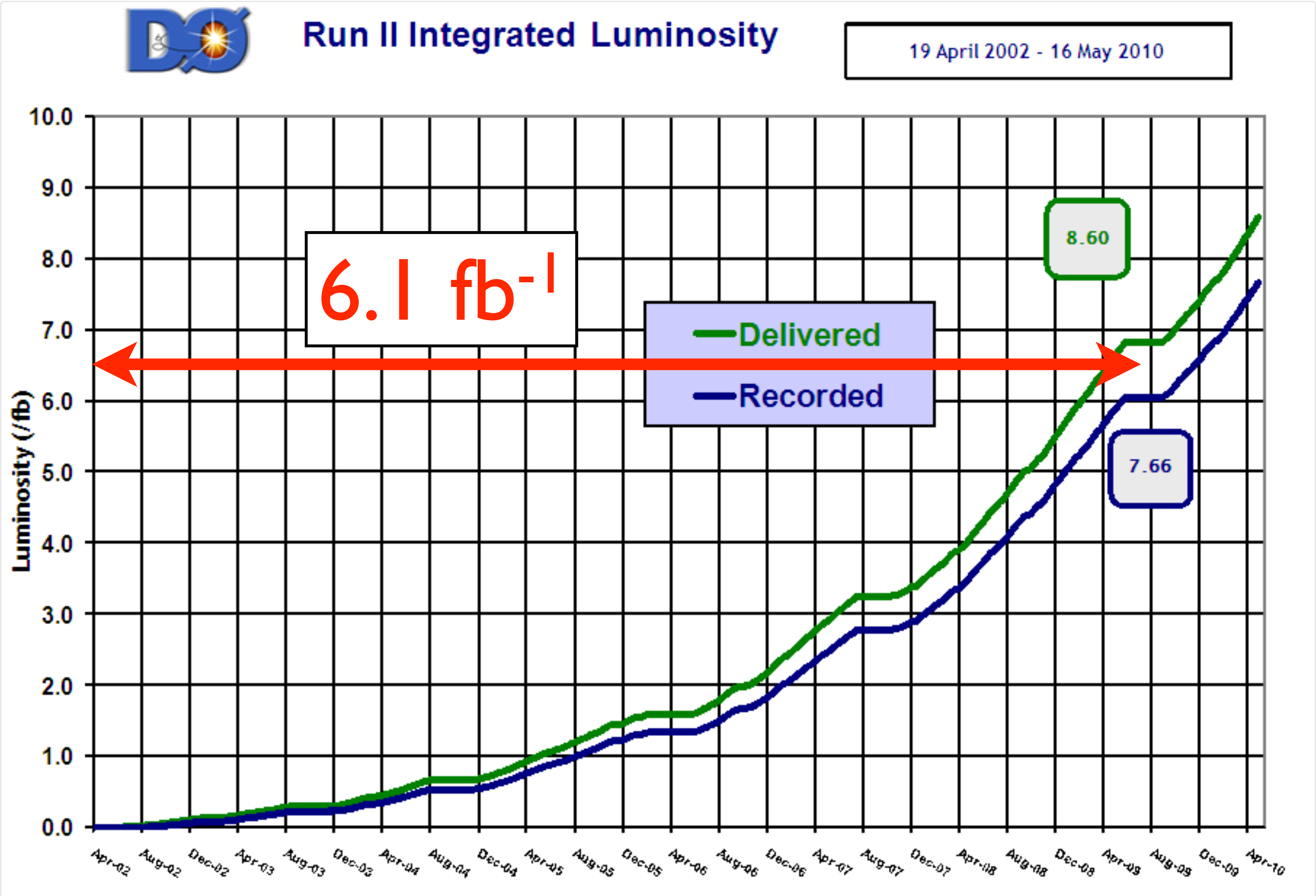
- Both have contributions from A^b_{sl}, other processes with prompt muons, as well detector-related backgrounds

2. We determine the detector and reconstruction-related backgrounds
   - With very little input from simulation
3. Determine the fraction of prompt single- and LS di-muons from mixed B decays
4. Exploit the different signal and (correlated) background contents of both samples to minimize the uncertainty on A^b_{sl}



- Two magnets: central solenoid + muon system toroid
    - Bi-weekly polarity changes ensures ~equal datasets with each
    - Helps cancel most detector-related asymmetries

Dataset



Run II Integrated Luminosity
19 April 2002 - 16 May 2010
6.1 fb-1
Delivered
Recorded
8.60
7.66
Luminosity (/fb)
10.0
9.0
8.0
7.0
6.0
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4.0
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Reference 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: $|dz| < 5$ 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. A and a

- $A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = (+\,0.564 \pm 0.053)\%$
  - 3.7×10^6 like-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: distinguish
  - Detector/reconstruction backgrounds
  - “Dilution” due to other sources of “prompt” muons

$A = KA^{b}_{sl} + A_{bkg}$ $\quad$ $a = kA^{b}_{sl} + a_{bkg}$

2. Detector-Related Backgrounds

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

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

(For dimuons, only linear terms in asymmetries are kept)

- f_K, f_π, f_p, F_K, F_π, F_p are the contributions 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

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

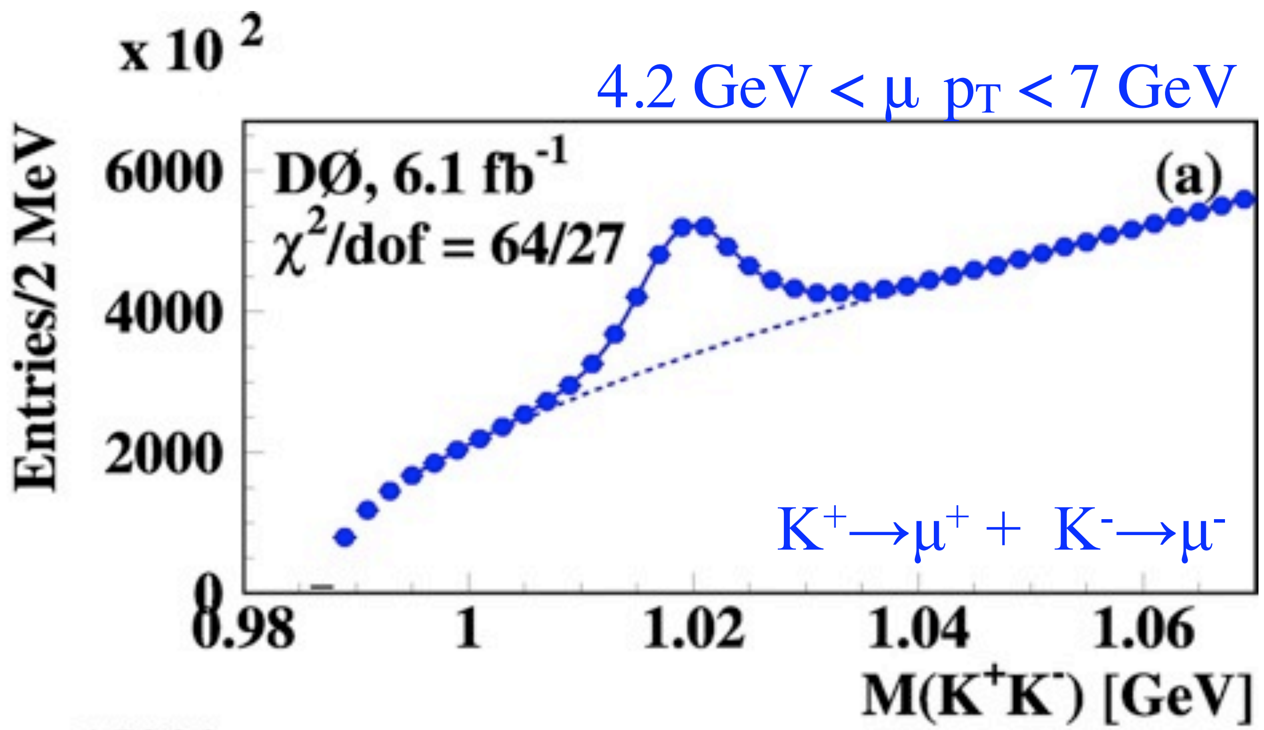
$$A_{bkg} = F_K A_K + F_\pi A_\pi + F_p A_p + (2-F_{bkg})\Delta$$

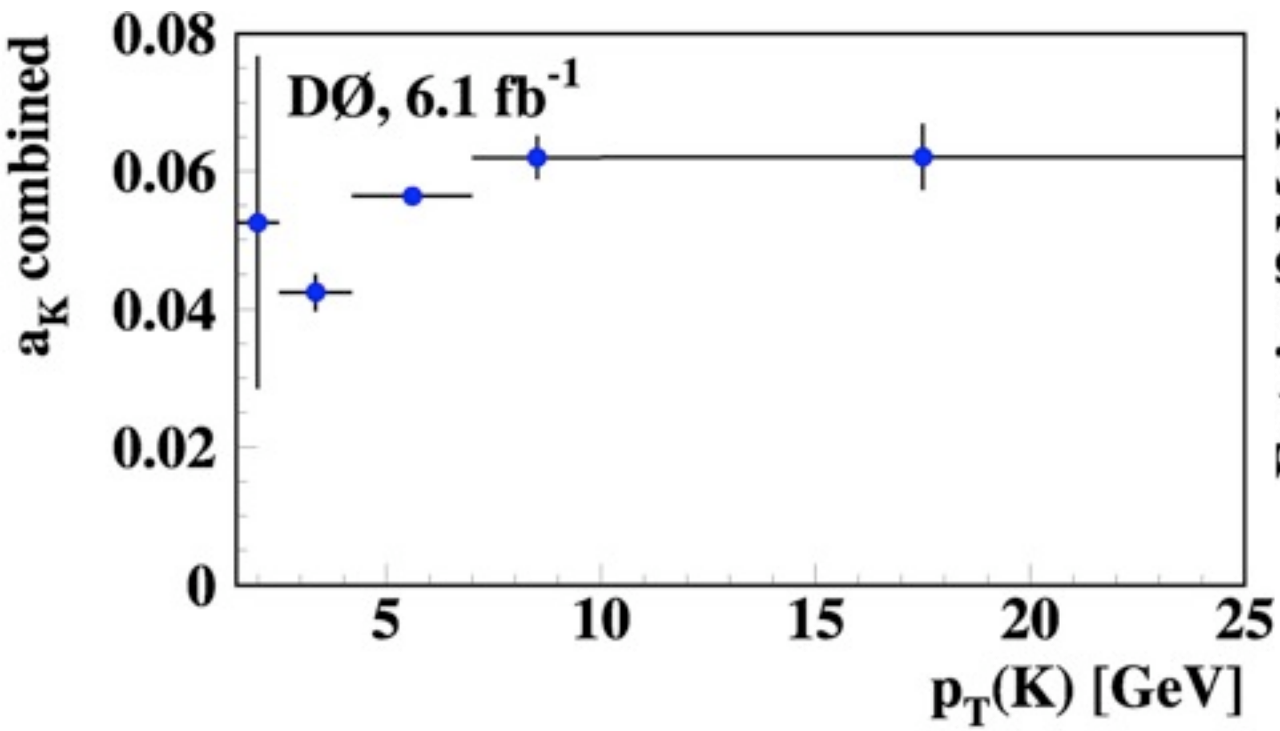
- Dominant contribution is kaon term:
  - Detector is made of matter
  - Different interaction cross-section for K^+ vs K^-
    - K^+ has substantially lower cross-section because no equivalent to $K^- N \rightarrow Y\pi$
    - ➡ Significant positive asymmetry from K decay in flight & punch-through
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

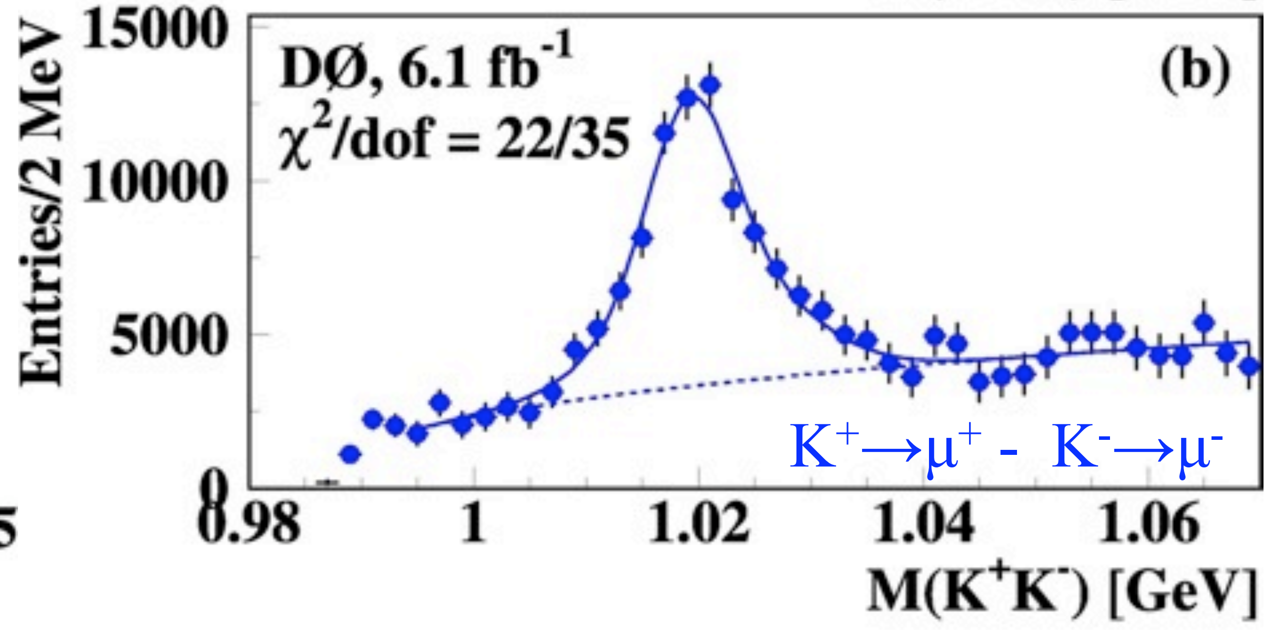
Kaon Asymmetry

- Source of kaons in single muon sample?
  - Find $\phi(1020) \to K^+K^-$ and $K^{*0} \to K^+\pi^-$ (with the K identified as a muon)

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







Kaon Contribution

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

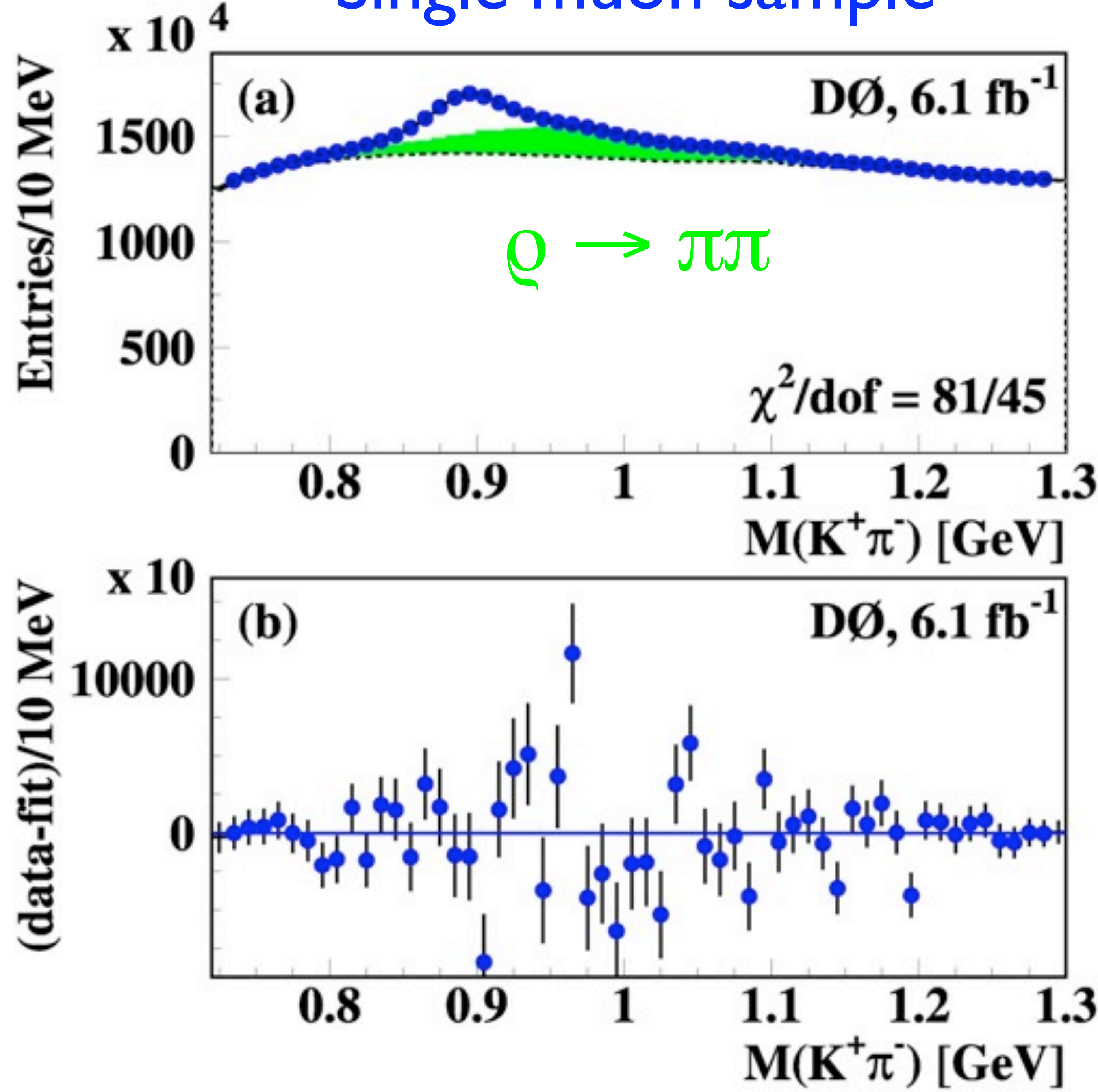
$$f_K = \frac{N(K_S)}{N(K^{*+} \to K_S \pi^+)} f_{K^{*0}}$$

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

$= f_K/f_{K^*}$

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

Single muon sample



Dominant systematic!

Other Background Asymmetries

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

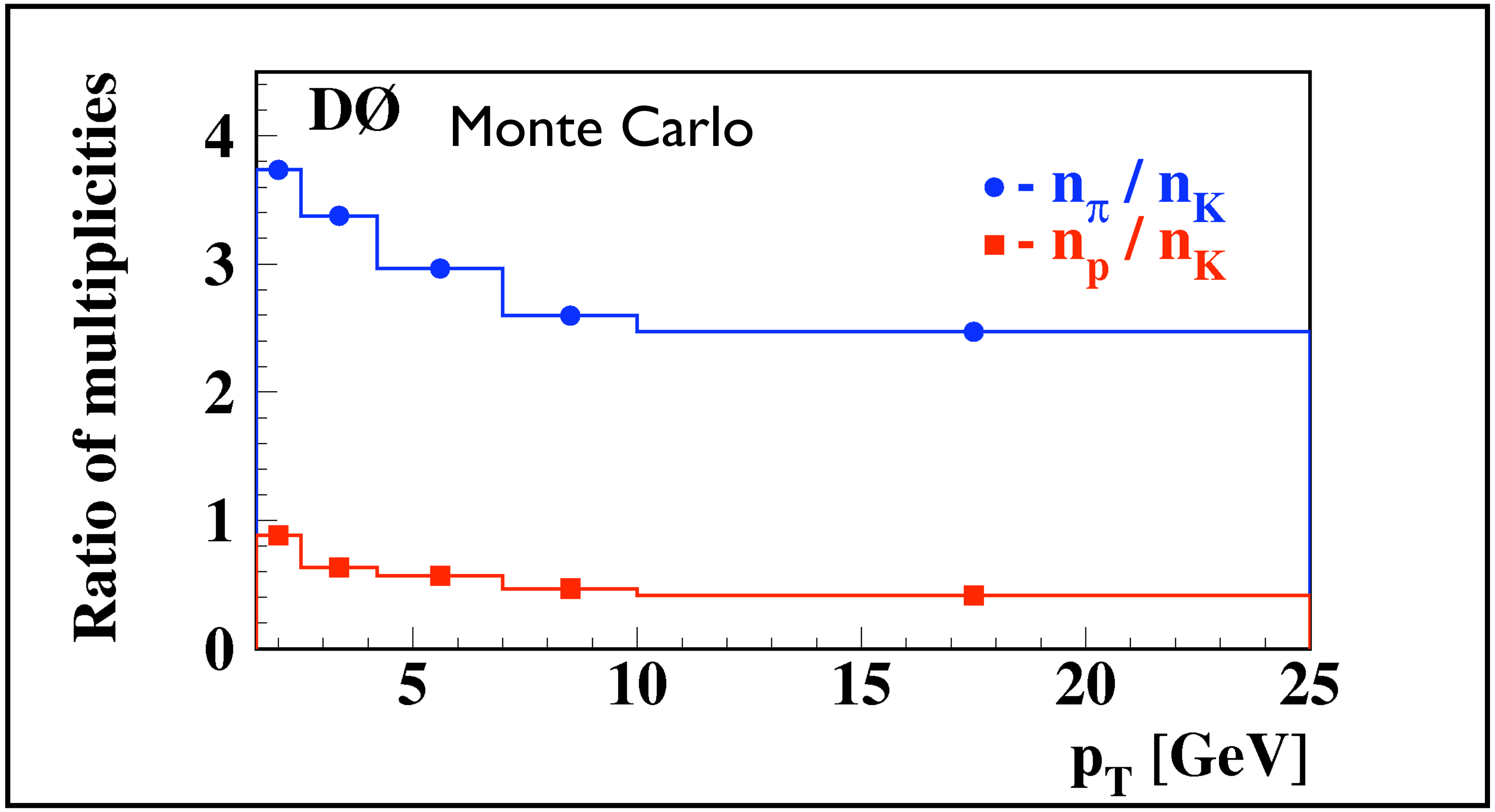
a_K	a_π	a_p
+0.0551±0.0011	+0.0025±0.0010	+0.023±0.028

- 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 Background Contributions

- 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 (not used) gives very similar results

Muon Reconstruction Asymmetry

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

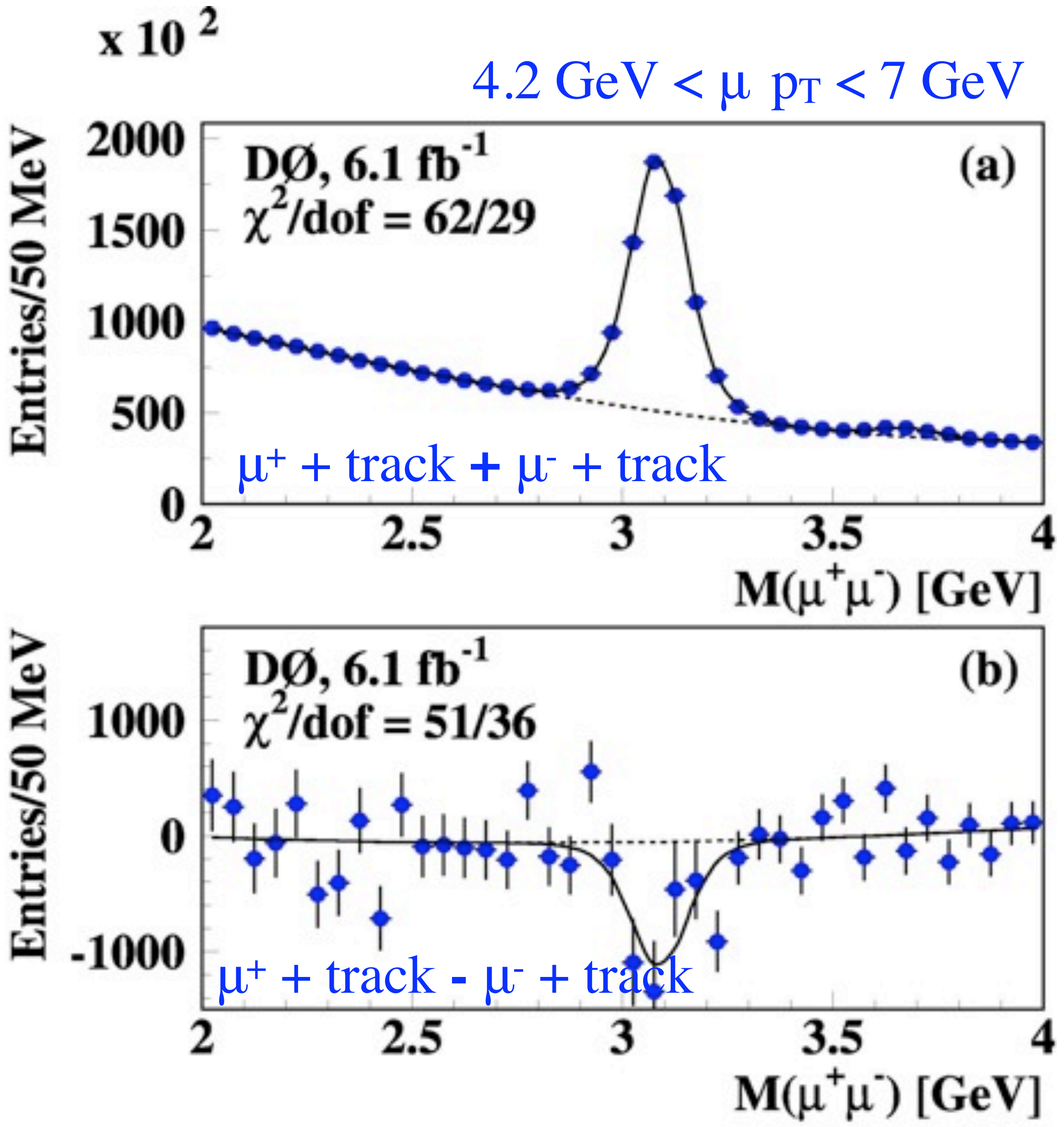
$$A_{bkg} = F_K A_K + F_\pi A_\pi + F_p A_p + (2-F_{bkg})\Delta$$

- Use dimuon triggers, exploit J/ψ
  - Measure asymmetry in μ + track & dimuon events

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

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

Direct benefit of regular magnet polarity reversal!



3. Dilution Factors

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

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

- Multiple processes contribute to the "physics" single- and LS dimuon samples in the denominator
  - Only the oscillating term produces an asymmetry
- k, K are determined using simulation
  - 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 $\bar{c} \to \mu^- X$

$$K = 0.342 \pm 0.023$$

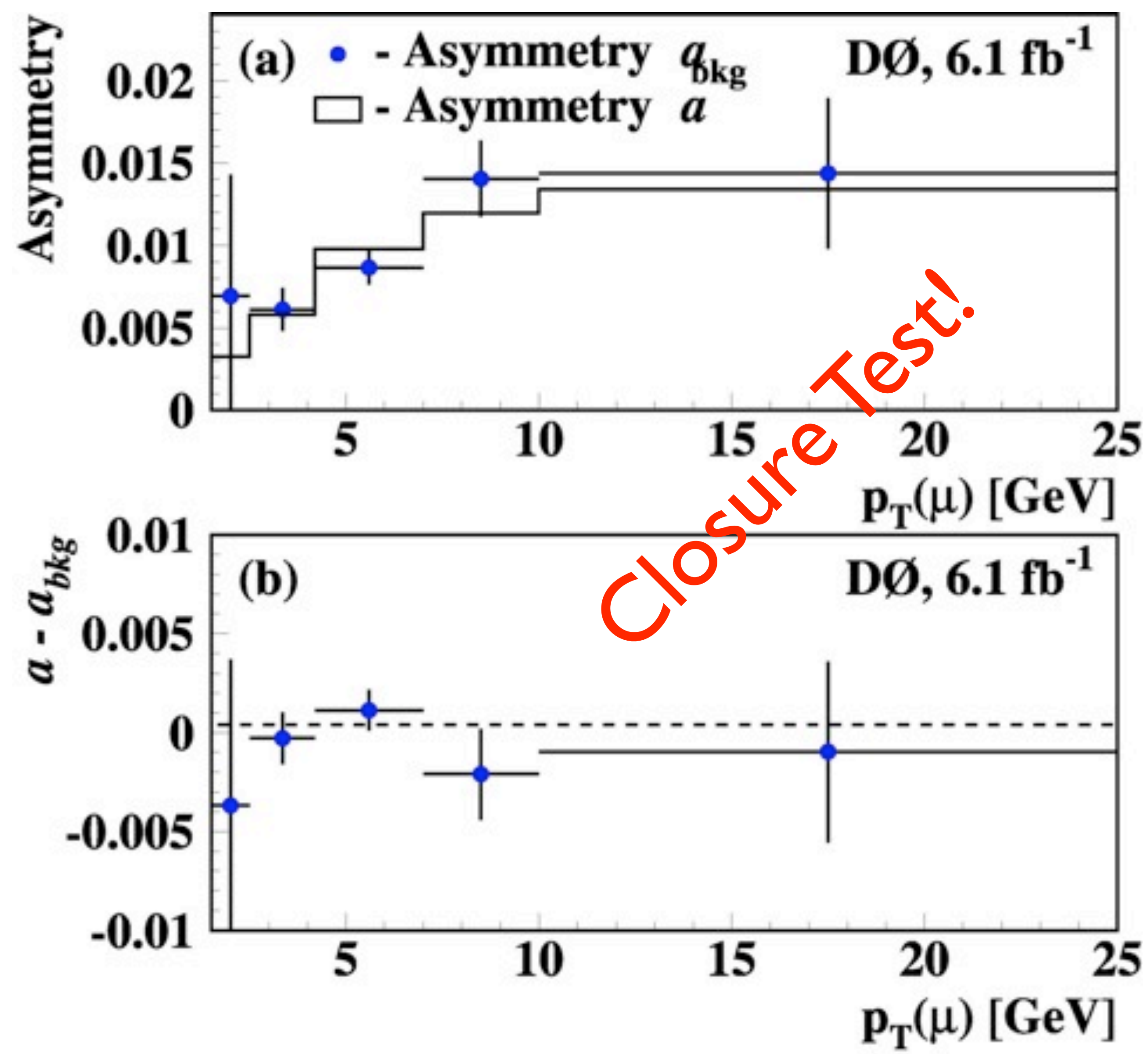
$$k = 0.041 \pm 0.003$$

Background Check

$a - a_{bkg} = kA^{b}_{sl}$ $k = 0.041 \pm 0.003$

$a = (+0.955 \pm 0.003)\%$ $a_{bkg} = (+0.917 \pm 0.045)\%$

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



4. Reducing the Uncertainty

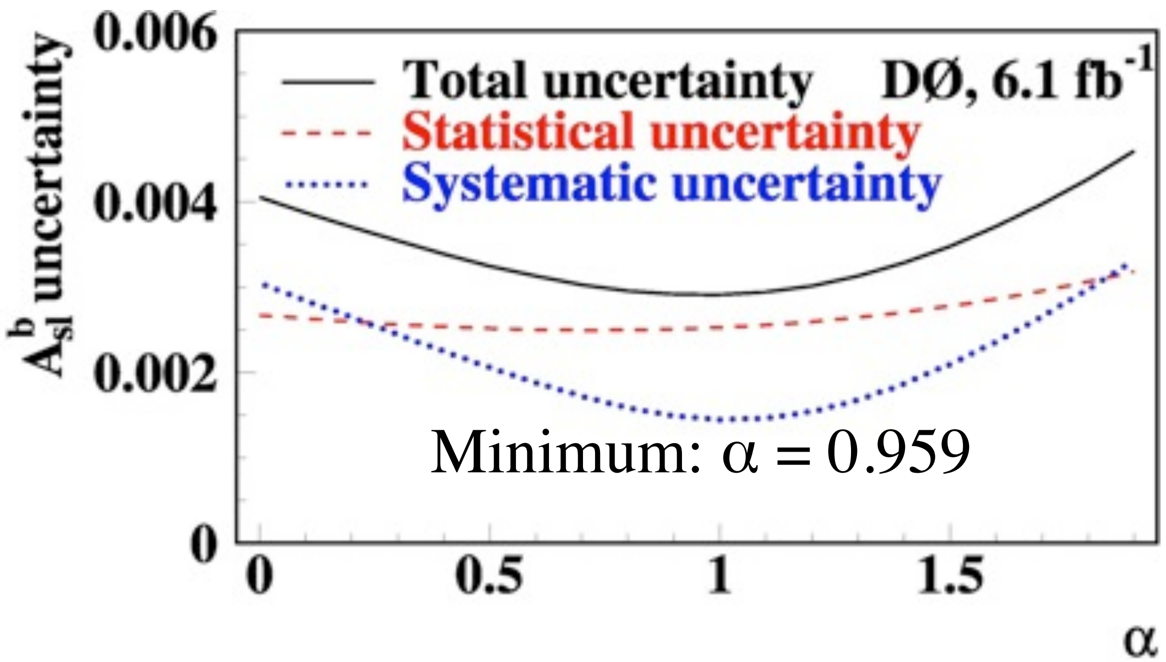
- Single muon asymmetry completely dominated by background, and background systematic is dominant
  - Use a to constrain background asymmetry uncertainty in dimuons

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

- Choose α to minimize uncertainty on A^b_{sl}
  - α will be close to 1 since the backgrounds are highly correlated

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

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



Result

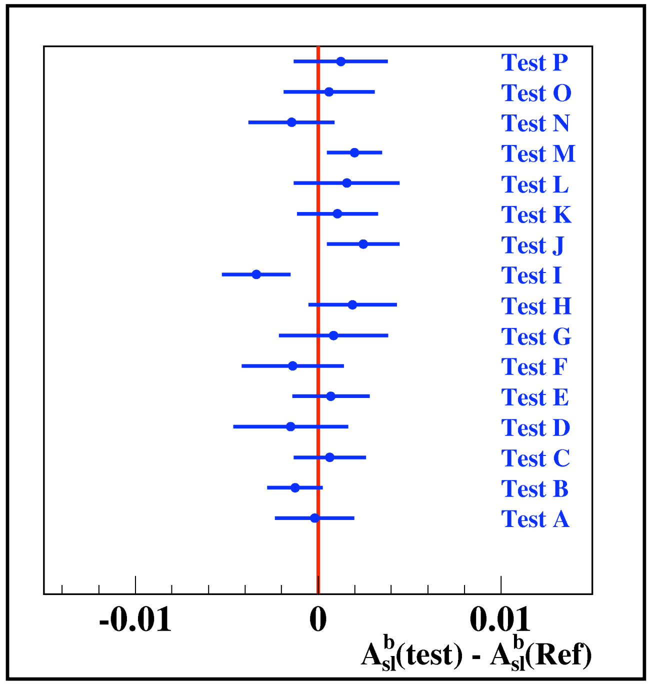
A^b_{sl} = (- 0.957 ± 0.251 (stat) ± 0.146 (syst)) %

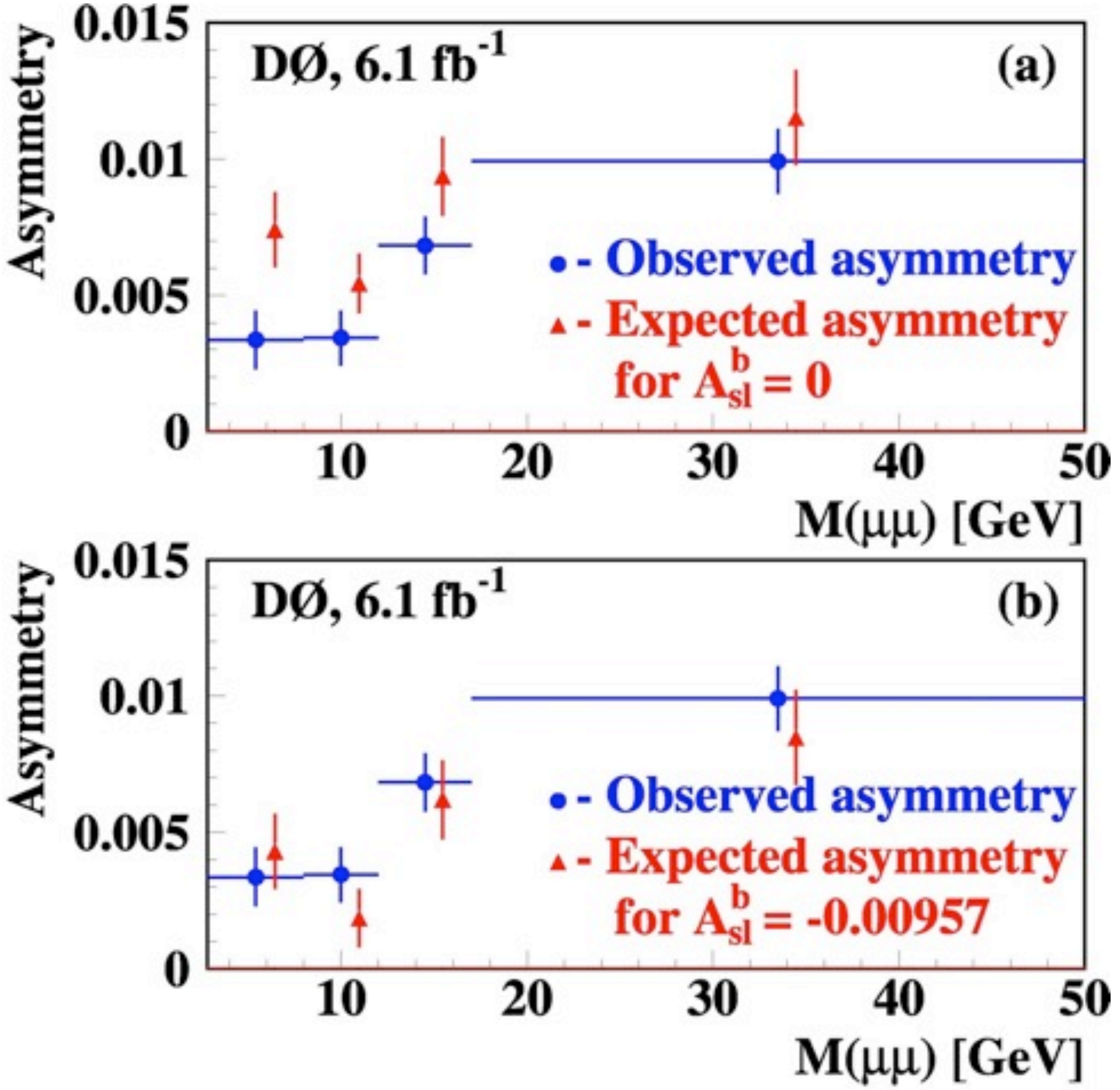
$$A^b_{\rm sl}({\rm SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$$

Result is ~3.2 σ from SM

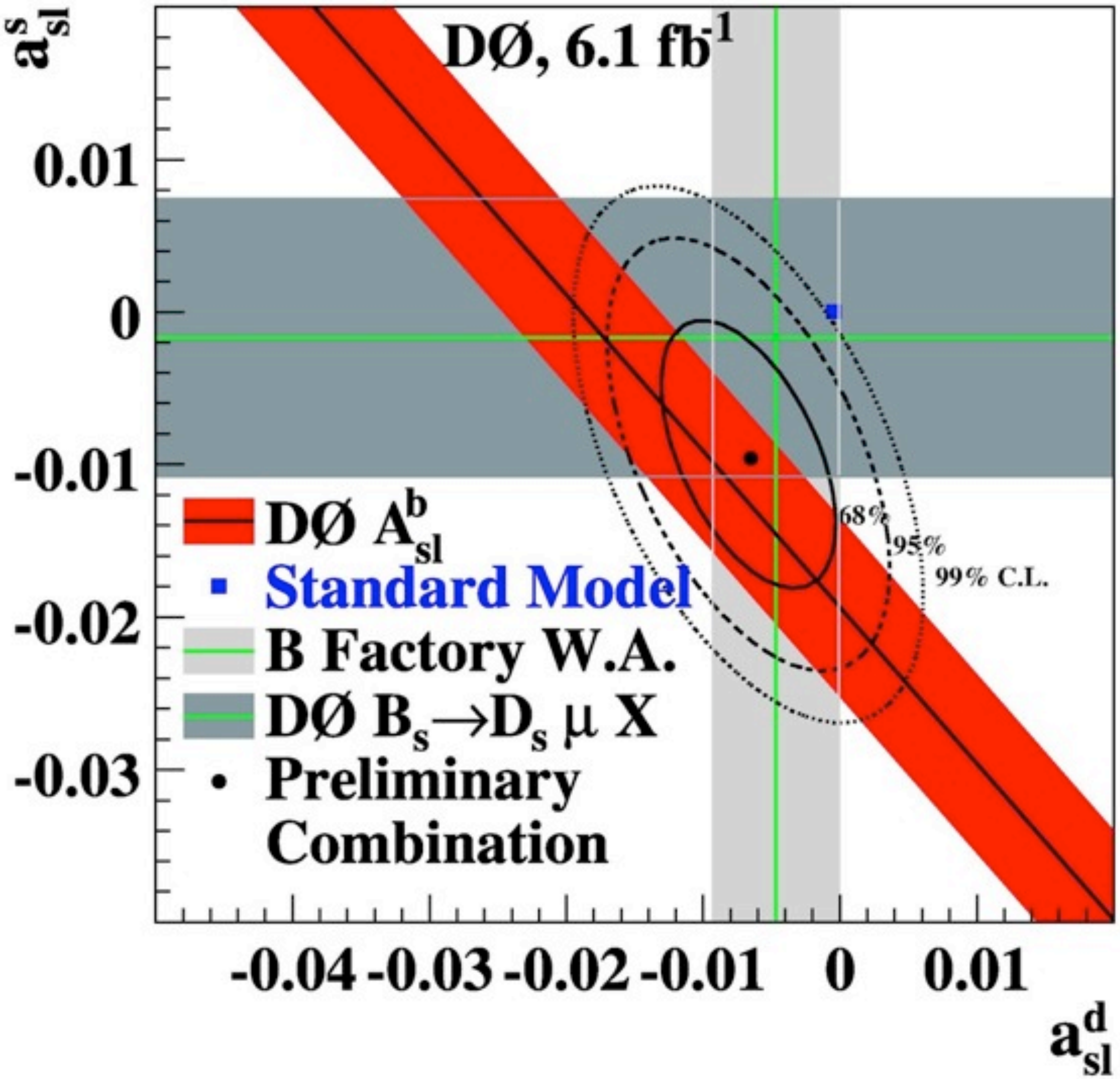
Notes

- No tagging, so cannot *guarantee* it comes from B
  - But it very much looks like it!
- Many consistency tests done, good agreement seen in $A^b{}_{sl}$
  - With large variations in A (140%)





Consistency with Other Results

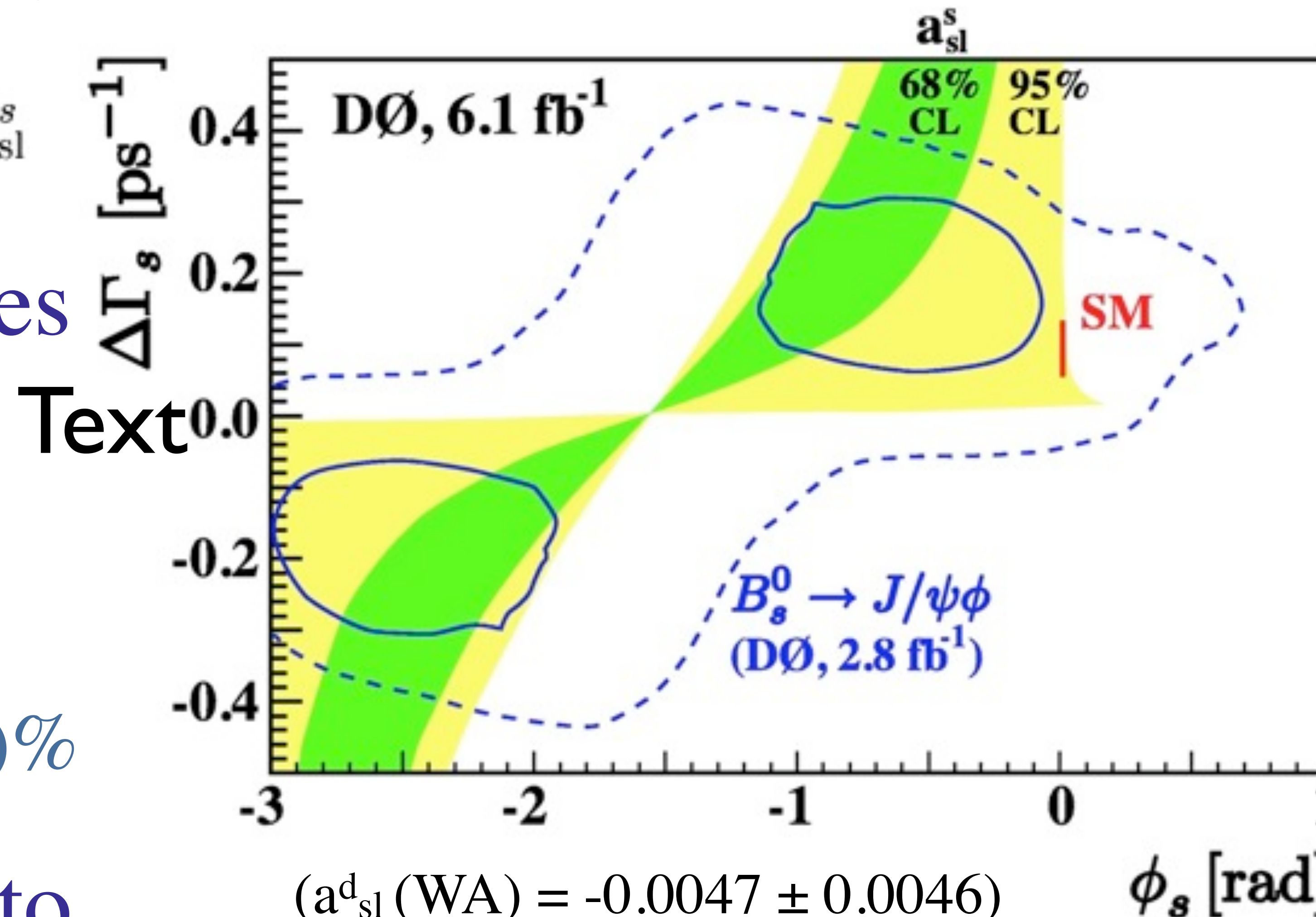


Consistency with Other Results

- 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}:
  - $a^s_{sl} = (-1.46 \pm 0.75)\%$
  - $a^s_{sl}(SM) = (+0.0021 \pm 0.0006)\%$
- a^s_{sl} can then be translated into constraints on ϕ_s, $\Delta\Gamma_s$



(a^d_{sl} (WA) = -0.0047 ± 0.0046)

Conclusions

- We made a new measurement of the like-sign dimuon asymmetry which is significantly different from 0
  - Under the assumption it is due to B-physics, we extract

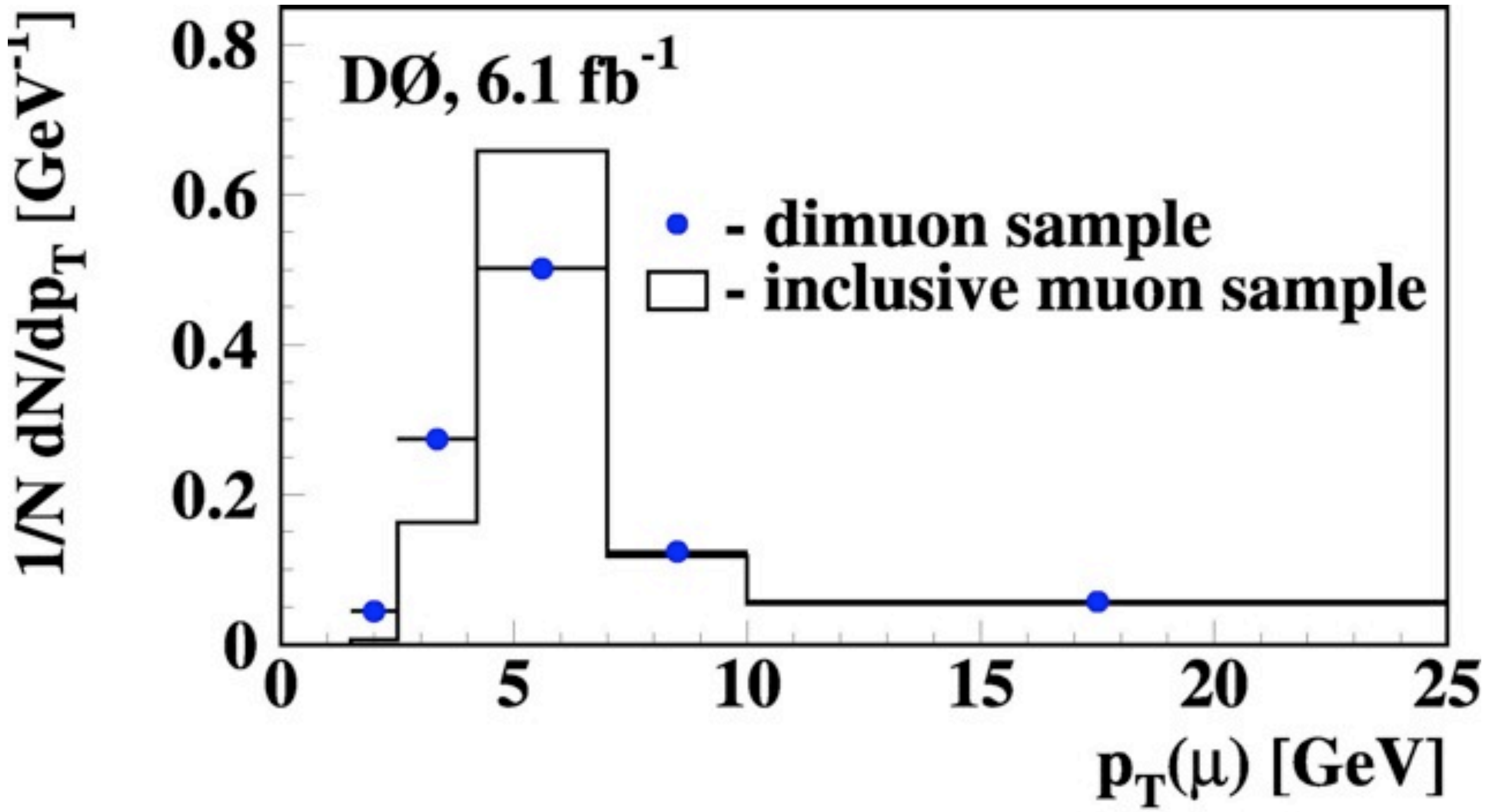
$$A^{b}_{sl} = (-\,0.957 \pm 0.251\ \text{(stat)} \pm 0.146\ \text{(syst)})\ \%$$

- 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

Backup

Muon p_T Spectra

Bin	Muon p_T range (GeV)	f_μ^i	F_μ^i
0	1.5 − 2.5	0.0055	0.0442
1	2.5 − 4.2	0.1636	0.2734
2	4.2 − 7.0	0.6587	0.5017
3	7.0 − 10.0	0.1175	0.1238
4	10.0 − 25.0	0.0547	0.0569



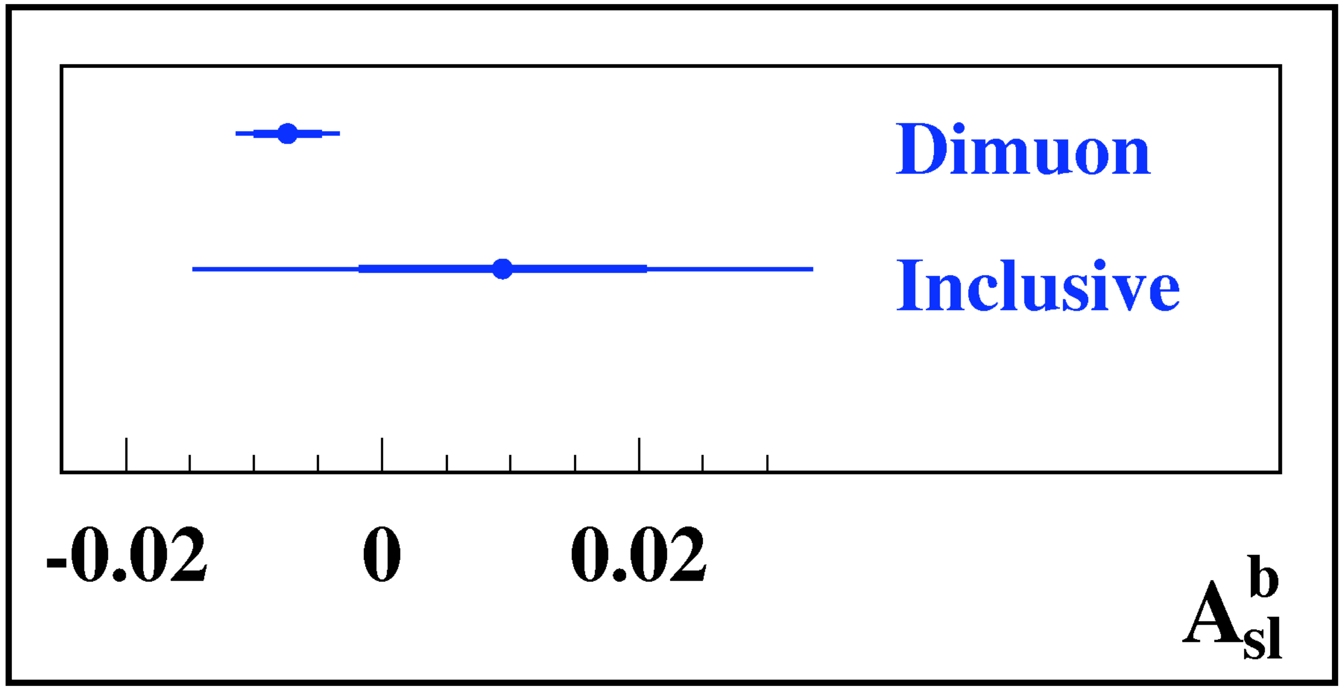
Individual Results

- Single muon channel:
  - $A^b_{sl} = (+ 0.94 \pm 1.12 \text{ (stat)} \pm 2.14 \text{ (syst)})$ %
- Dimuon channel:
  - $A^b_{sl} = (- 0.736 \pm 0.266 \text{ (stat)} \pm 0.305 \text{ (syst)})$ %

Good agreement with main result!

Small k kills single muon channel sensitivity (as expected)

Dominant systematics from f_K and F_K



Systematic Uncertainties

Source	Single muon $\delta\sigma(A^b_{sl})(62)$	Dimuon $\delta\sigma(A^b_{sl})(63)$	Main $\delta\sigma(A^b_{sl})(65)$
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

Background Summary

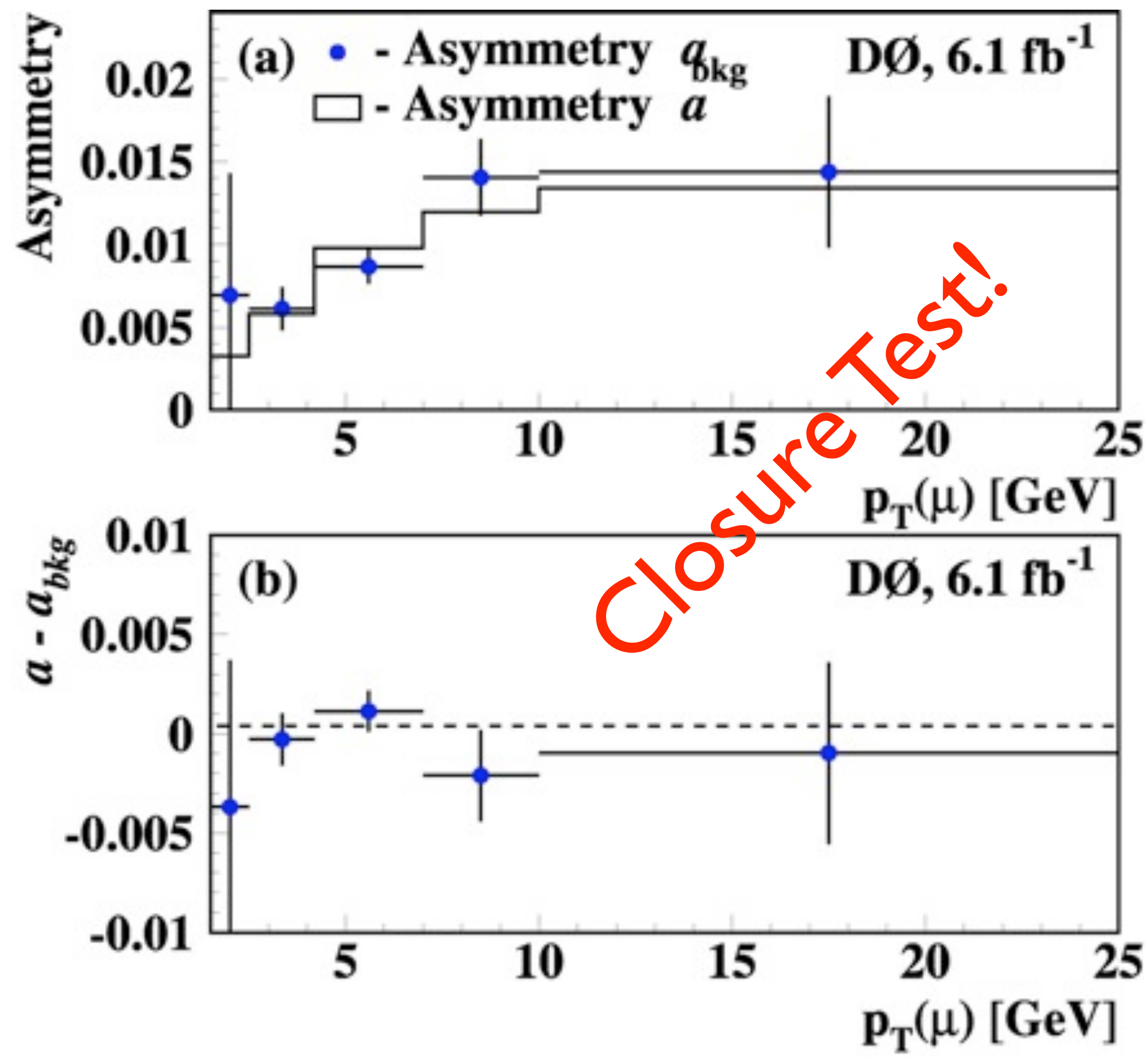
$A = KA^b_{sl} + A_{bkg}$　　$K = 0.342 \pm 0.023$

$a = kA^b_{sl} + a_{bkg}$　　$k = 0.041 \pm 0.003$

$A = (+0.564 \pm 0.053)\%$　　$A_{bkg} = (+0.815 \pm 0.070)\%$

$a = (+0.955 \pm 0.003)\%$　　$a_{bkg} = (+0.917 \pm 0.045)\%$

- Substantial correction
  - Cancels out single muon asymmetry.... as it should!



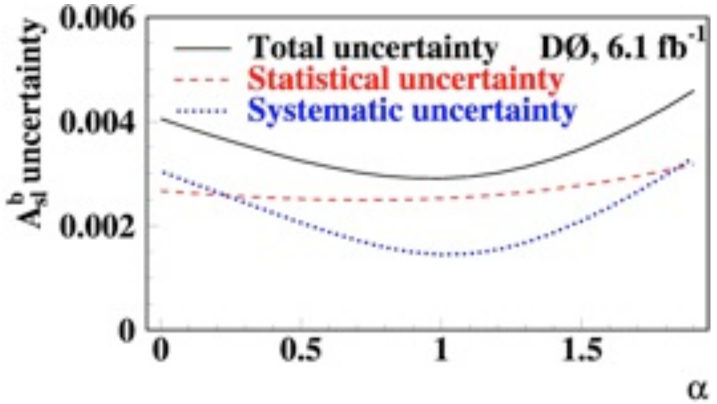
Choosing α

- Single muon asymmetry completely dominated by background
  - Use it to constrain background asymmetry uncertainty in dimuons

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

- Choose α to minimize uncertainty on A^b_{sl}

Minimum: α = 0.959



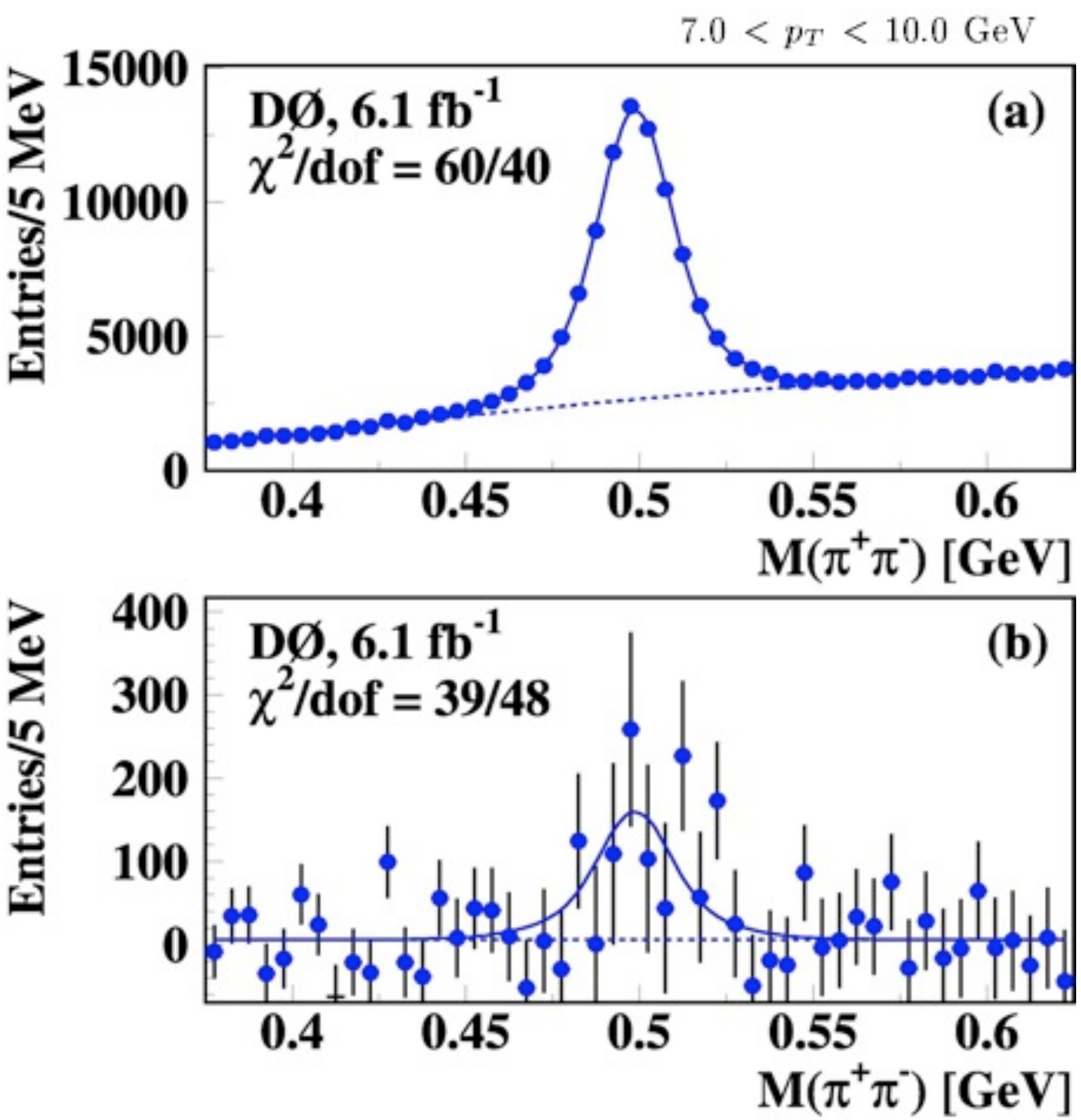
- If take α to minimize main uncertainty, i.e. $\alpha = \frac{F_K A_K}{f_K a_K}$
  - Get α = 0.970

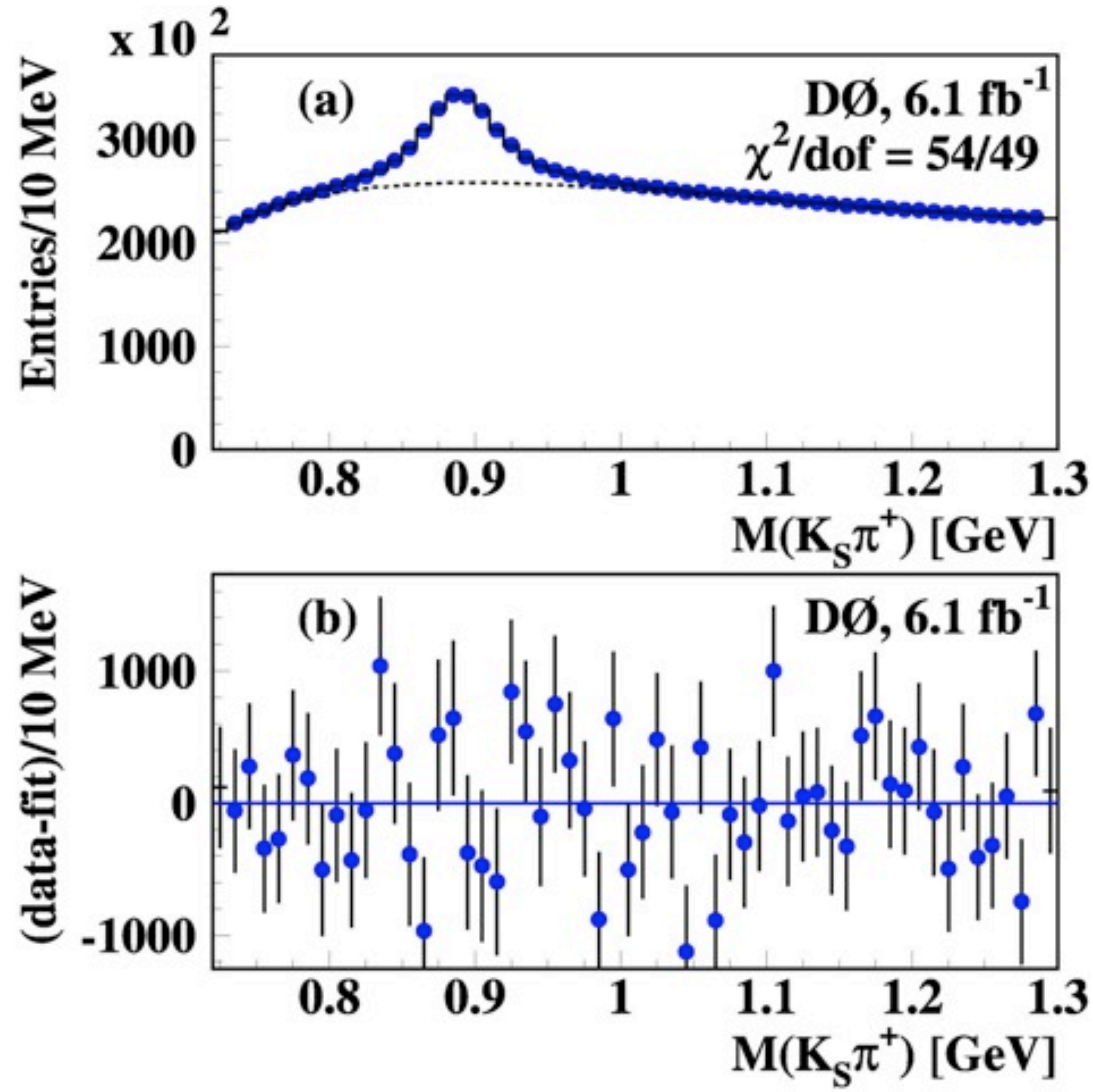
Consistency Tests

- 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.
- Test D: The maximum value of 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 interaction 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 interaction vertices.
- Test F: Using only events corresponding to two of the four possible configurations of the magnets, for which the solenoid and toroid polarities are identical.
- 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 $<$ 7.0 GeV.
- Test J: Requiring the azimuthal angle ϕ of the muon track to 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.
- Test K: Requiring the muon η to 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 to be in the range $|\eta| < 1.2$ or $1.6 < |\eta| < 2.2$.
- Test M: Requiring the muon η to be in the range $|\eta| < 0.7$ or $1.2 < |\eta| < 2.2$.
- Test N: Requiring the muon η to be in the range $0.7 < |\eta| < 2.2$.

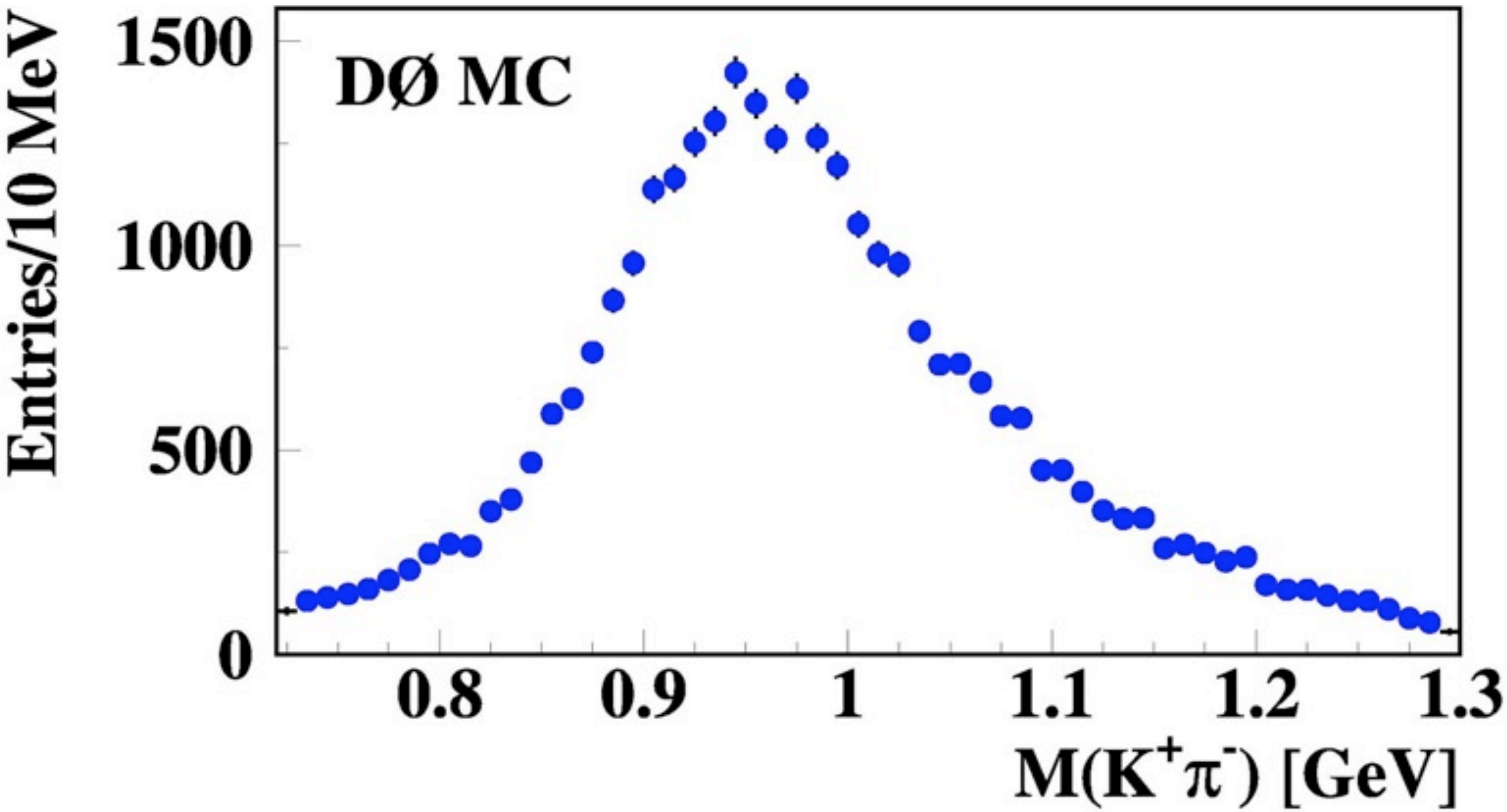
- Test O: Using like-sign dimuon events passing at least one single muon trigger, while ignoring the requirement of a dimuon trigger for these events.
- Test P: Using like-sign dimuon events passing both single muon and dimuon triggers.

$K^{*+} \rightarrow K_S\ \pi$





$\rho \rightarrow \pi\pi$



Kaon and Proton Asymmetry