Banff BIRS Statistics July 14 2010

Evidence for an anomalous like-sign dimuon charge asymmetry:

Combining Correlated Measurements (not a physics talk!)

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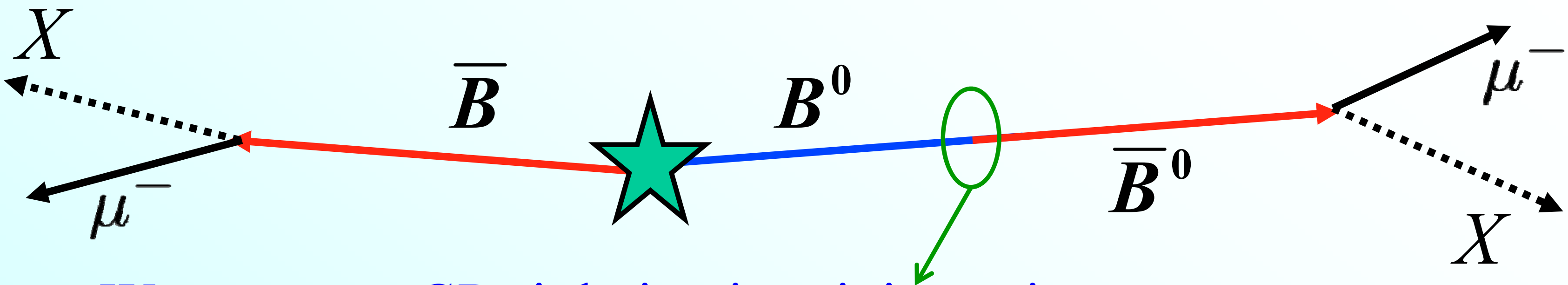
Many Thanks to G.Borissov, D0

Many slides from his Wine & Cheese at Fermilab

Dimuon charge asymmetry



- We measure *CP* violation in mixing using **the 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
  - One muon comes from direct semileptonic decay $b \to \mu^- X$
  - Second muon comes from direct semileptonic decay after neutral *B* meson mixing: $B^0 \to \overline{B}^0 \to \mu^- X$

CP violation in mixing

- Main goal: study ***CP* violation in mixing** of B_d and B_s
  - Expected SM magnitude of this *CP* violation is small

A measurement of *CP* violation significantly different from zero would be unambiguous evidence of new physics

Raw asymmetries

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

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

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

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

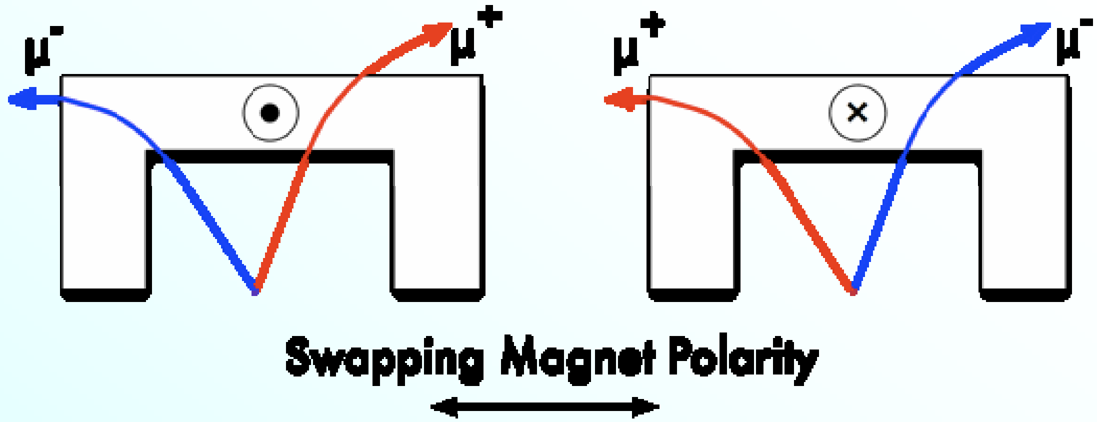
$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

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

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

Measure all backgrounds contribution directly in data, with a reduced input from simulation

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

Background contributions

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

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

- We obtain:

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

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

Kaon detection asymmetry

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

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

- The largest background asymmetry, and the largest background contribution comes from the charge asymmetry of kaon track identified as a muon (a_K, A_K)
- Interaction cross section of K^+ and K^- with the detector material is different, especially for kaons with low momentum
  - e.g., for $p(K)$ = 1 GeV:

$$\sigma(K^- d) \approx 80\ \text{mb}$$
$$\sigma(K^+ d) \approx 33\ \text{mb}$$

- It happens because the reaction $K^- N \to Y\pi$ has no $K^+ N$ analogue

Kaon detection asymmetry

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

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

- K^+ meson travels further than K^- in the material, and has more chance of decaying to a muon
  - And 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 about x 10 less

This asymmetry is difficult to model:
measure it from data

Coefficients *k* and *K*

$$x_1 = A_{sl}^b = \frac{a - a_{bkg}}{k}$$

$$x_2 = A_{sl}^b = \frac{A - A_{bkg}}{K}$$

- Coefficients *k* and *K* take into account dilution of "raw" asymmetries *a* and *A*
- Determined using simulation of *b*- and *c*-quark decays
  - Well measured: simulation produces a small systematic uncertainty

$$k < K$$

more non-oscillating decays contribute to *a* *(1 muon)*

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

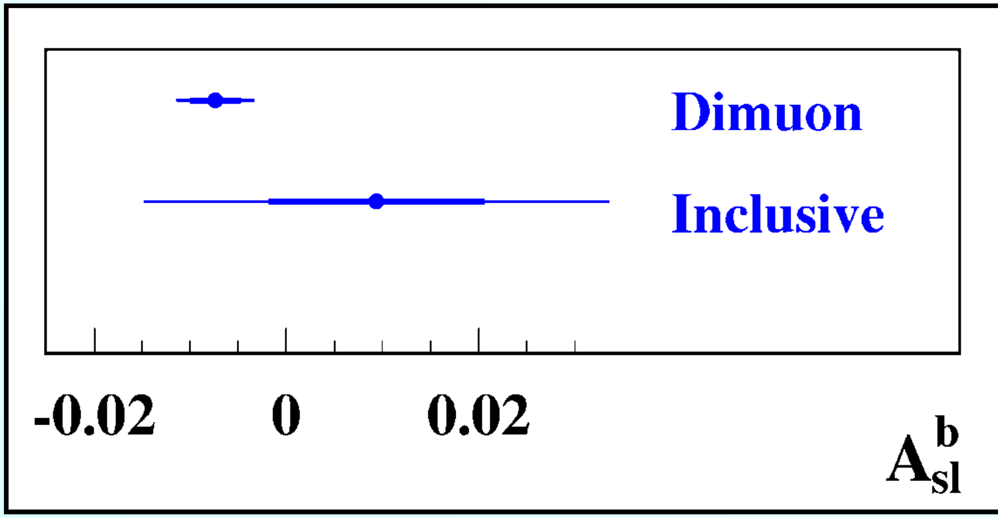
$$\frac{k}{K} = 0.12 \pm 0.01$$

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:

$$x_1 = A^b_{sl} = (+0.94 \pm 1.12\,(\text{stat}) \pm 2.14\,(\text{syst}))\% \quad (\text{from inclusive})$$
$$x_2 = A^b_{sl} = (-0.736 \pm 0.266\,(\text{stat}) \pm 0.305\,(\text{syst}))\% \quad (\text{from dimuon})$$

  - Uncertainties of x_1 larger because k small
  - Dominant systematic uncertainty from f_K and F_K fractions



Correlated background uncertainties

- Same background processes contribute to *both* A_{bkg} and a_{bkg}

  Therefore, they are correlated
- Take advantage and obtain A^b_{sl} from the linear combination:

$$A' \equiv A - \alpha\, a$$

α selected to minimize the total uncertainty of A^b_{sl}

Combination of measurements

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

$k << K$

$A_{bkg} \approx a_{bkg}$ so cancellation for $\alpha \approx 1$

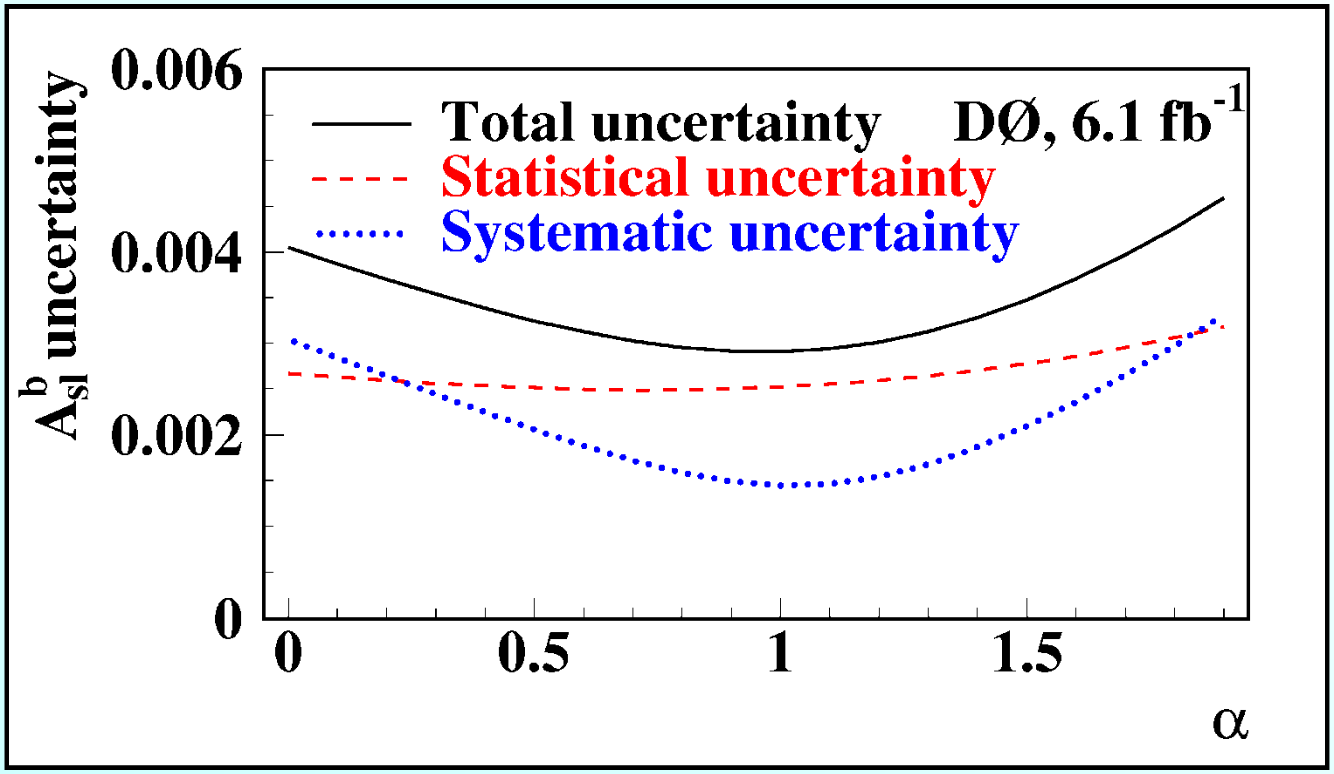
signal asymmetry $A^b{}_{sl}$ doesn't cancel

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

Combination of measurements

- scan total uncertainty of A^b_{sl} from A'

α =0.959 is selected



Final result

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

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

- To be compared with the SM prediction:

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

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

How can that be?

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

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

a_{bkg} or A_{bkg}
0.917±0.045
0.815±0.070

$$k = 0.041 \pm 0.003$$
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$$X(\alpha) = A_{sl}^{b} = (-0.957 \pm 0.251\,(\text{stat}) \pm 0.146\,(\text{syst}))\%$$

Final Result

Why isn't Final value between inclusive and dimuon?

Analysis Method: Subtraction

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

Why is this better than standard weighted average?

- Xwavg = $(WA^{b}_{sl} + wA^{b}_{sl})/(W + w)$
  - Standard weighting according to $w = 1/\sigma^2$ of each channel
  - "minimum variance unbiased estimator": how can we do better?
  - Corresponds to $\alpha \sim -.47 = (K/k)\ (\sigma_A / \sigma_a)^2$
- **Xwavg would give -.65**, 2.5 SD stat from zero
  - This is indeed between the values from separate channels
- **Instead: X(α) = -.94**, 3.8 SD stat from zero (3.2 including syst)
  - Corresponds to $\alpha \sim +.96$

Some Interesting Facts

Can write final estimator $X(\alpha)$ in terms of individual estimates x_1 and x_2

$X(\alpha) = (x_2 - \beta\ x_1) / (1 - \beta)$ **$\beta = \alpha\ k/K$**

Quite peculiar: for $\alpha > 0$, $X(\alpha)$ is always outside (x1, x2)!

Though x1, x2 unbiased Gaussians, X never between them!

However, sum of 2 Gaussian variables is **also Gaussian**

Distribution of $X(\alpha)$ is Gaussian: no hole around 0 despite "repulsion"

That makes you wonder why tails are not worse than Xwavg: see below

Key fact: x_1 and x_2 correlated

$x_2 = (A - A_{bkg}) / K$ **$x_1 = (a - a_{bkg}) / k$**

Because A_{bkg} and a_{bkg} are correlated: Kaon decays!

From General Eqn for Variance: (stat error only!)

$\mathrm{Var}[\ ax + by\ ] = a^2\,\mathrm{Var}[x] + b^2\,\mathrm{Var}[y] + 2ab\,\mathrm{Cov}[xy]$

$\mathrm{Var}[\ X(\alpha)\ ] = \mathrm{Var}[\ (x_2 - \beta\ x_1) / (1 - \beta)\ ]$

$\mathrm{Var}[\ X(\alpha)\ ]\,(1-\beta)^2 = \sigma_2^{\,2} + \beta^2\,\sigma_1^{\,2} - 2\,\beta\,\rho\,\sigma_2\sigma_1 \quad -1 < \rho < 1$

$\rho = 0$ means Var is lowest for $\beta < 0$ (the standard weighted average)

$\sqrt{\mathrm{Var}}$ = .26 for Xwavg = $X(\alpha = -.47)$

.33 for $X(\alpha = .96)$ **so yes the tails are worse—if uncorrelated**

$\rho > 0$ means Var is *lowered* for β **>** 0 : min. Var estimator w/ correlation correctly included

A nice way to think of it

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

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

a_{bkg} or A_{bkg}
0.917±0.045
0.815±0.070

Assuming SM, *a* measurement is 10x improved background estimate

even though not much of a measurement of A^b_{sl}

Note: it's higher than independent a_{bkg} estimate

Therefore, pushes up A_{bkg} estimate (correlated)

And pushes down dimuon-based asymmetry value

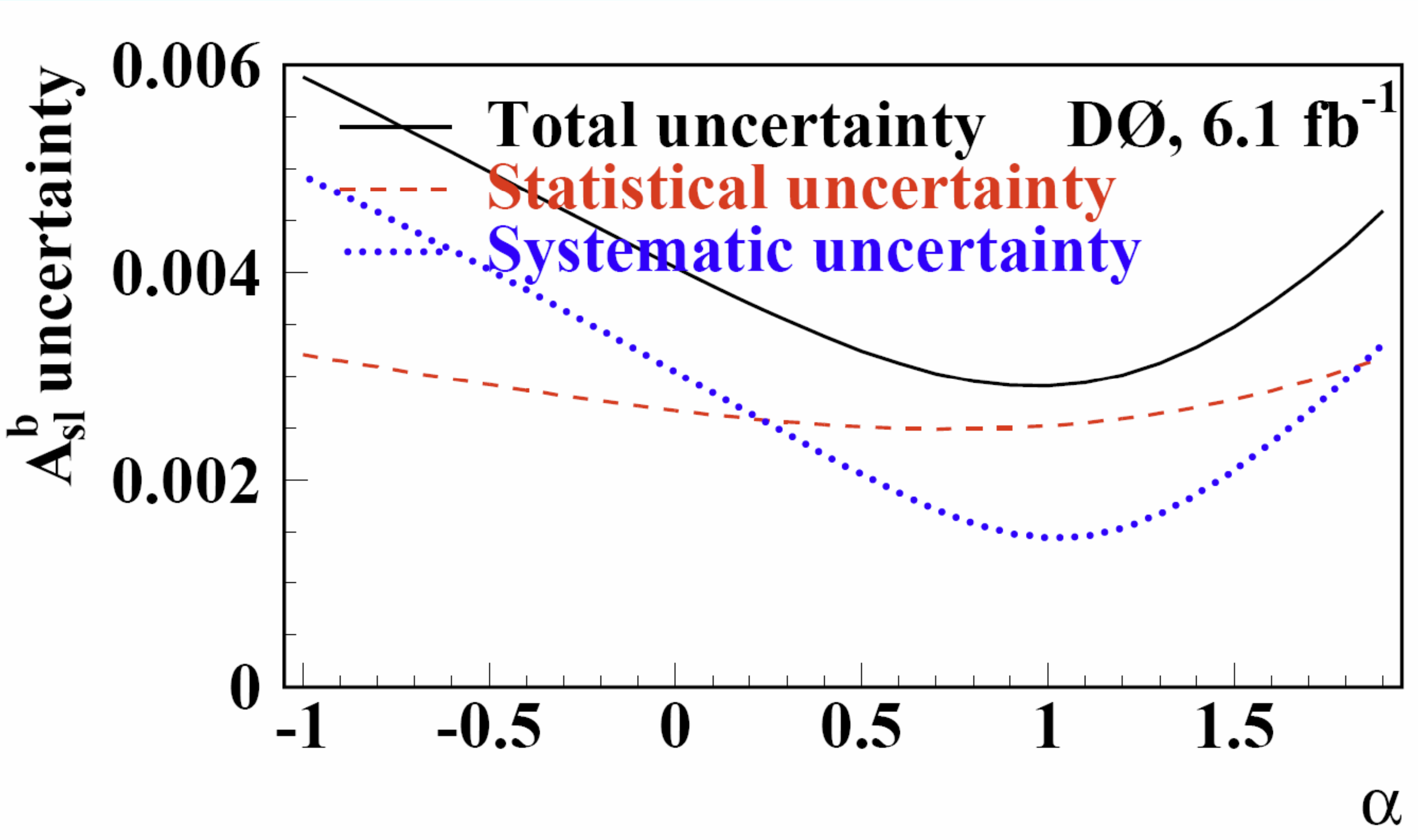
$$A^b_{sl} = (-0.957 \pm 0.251\,(\text{stat}) \pm 0.146\,(\text{syst}))\%$$ **Final Result**

$$A^b_{sl} = (+0.94 \pm 1.12\,(\text{stat}) \pm 2.14\,(\text{syst}))\% \quad (\text{from inclusive})$$
$$A^b_{sl} = (-0.736 \pm 0.266\,(\text{stat}) \pm 0.305\,(\text{syst}))\% \quad (\text{from dimuon})$$

Biggest Improvement: cancellation of systematics in background

An Extended α Scan
(Thanks Guennadi !)

- Consistent with analysis above
- X(.96) is indeed better than X(-.47)



The End

So, yes,

after a few days of thinking

I believe the final combination of results is correct

Very interesting: beyond SM is rare these days!

Still: only 3.2 std deviations from SM

this is why it's "evidence for"

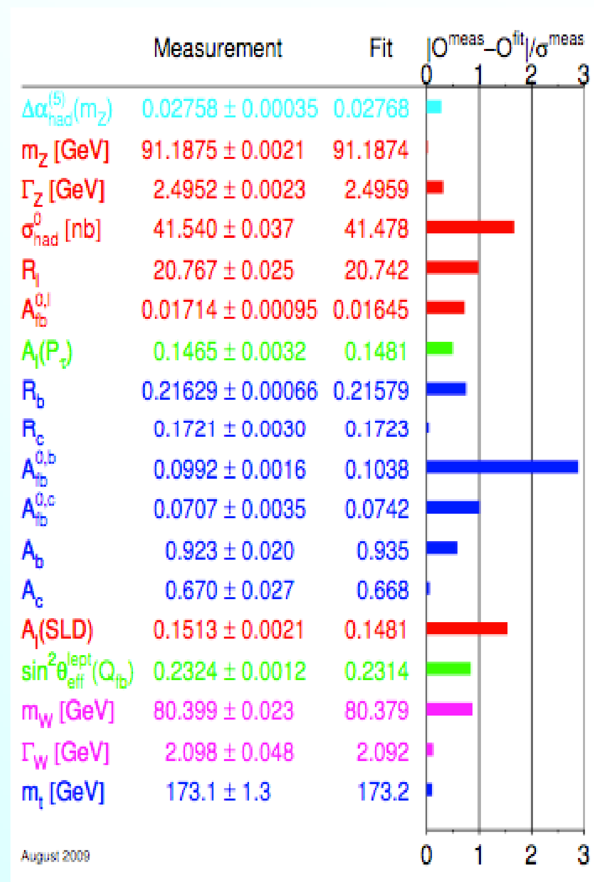
not "discovery"

we typically ask for 5 std deviations from SM

Also: there are many tests of SM

Pr{*one* > 3 std deviations} >> .005

20 x from this list…



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