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 $b \rightarrow \mu^{-}X$
- Second muon comes from direct semileptonic decay after neutral $B$ meson mixing: $B^{0} \rightarrow B^{0} \rightarrow \mu^{-}X$
Main goal: study \textit{CP violation in mixing} of $B_d$ and $B_s$

- Expected SM magnitude of this \textit{CP} violation is small

\textbf{A measurement of \textit{CP} violation significantly different from zero would be unambiguous evidence of new physics}
Raw asymmetries

\[ a = k A^b_{sl} + a_{bkg} \]
\[ A = K A^b_{sl} + A_{bkg} \]

• We select:
  – \( 1.495 \times 10^9 \) muon in the inclusive muon sample
  – \( 3.731 \times 10^6 \) events in the like-sign dimuon sample

• Raw asymmetries:

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

\[ a \equiv \frac{n^+ - n^-}{n^+ + n^-} \]

\[ A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}} \]
Blinded analysis

The central value of $A_{sl}^b$ 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

\[ a = k A^b_{sl} + a_{bkg} \]

\[ A = K A^b_{sl} + A_{bkg} \]

- Sources of background muons:
  - Kaon and pion decays \( K^+ \rightarrow \mu^+ \nu, \pi^+ \rightarrow \mu^+ \nu \) 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:

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

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

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

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

• 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 \(K^- N \rightarrow Y\pi\) has no \(K^+ N\) analogue
Kaon detection asymmetry

\[ a_{\text{bkg}} = f_k a_k + f_\pi a_\pi + f_p a_p + (1 - f_{\text{bkg}}) \delta \]
\[ A_{\text{bkg}} = F_k A_k + F_\pi A_\pi + F_p A_p + (2 - F_{\text{bkg}}) \Delta \]

- \( K^+ \) 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 $K$

$$
x_1 = A^b_{sl} = \frac{a - a_{bkg}}{k}
$$

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

- 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 $A_{sl}^b$ from inclusive and like-sign dimuon samples:

\[
x_1 = A_{sl}^b = (+0.94 \pm 1.12 \text{ (stat)} \pm 2.14 \text{ (syst)})\% \quad \text{(from inclusive)}
\]
\[
x_2 = A_{sl}^b = (-0.736 \pm 0.266 \text{ (stat)} \pm 0.305 \text{ (syst)})\% \quad \text{(from dimuon)}
\]

– 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 $A_{sl}^b$ from the linear combination:

$$A' = A - \alpha a$$

$\alpha$ selected to minimize the total uncertainty of $A_{sl}^b$
Combination of measurements

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

\[ A_{bkg} \approx a_{bkg} \text{ so } \]
\[ \alpha \approx 1 \]

signal asymmetry \( A_{sl}^b \) doesn’t cancel

\[ X(\alpha) = A_{sl}^b = \frac{(A - \alpha a) - (A_{bkg} - \alpha a_{bkg})}{K - \alpha k} \]
Combination of measurements

- scan total uncertainty of $A_{sl}^b$ from $A'$
  $\alpha = 0.959$ is selected
Final result

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

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

• To be compared with the SM prediction:

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

• This result differs from the SM prediction by $\sim 3.2 \sigma$
How can that be?

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

\[
\begin{array}{c|c}
\text{a}_{bkg} & \text{0.917±0.045} \\
\text{or A}_{bkg} & \text{0.815±0.070} \\
\end{array}
\]

\[
\begin{array}{c|c}
k & 0.041±0.003 \\
K & 0.342±0.023 \\
\end{array}
\]

\[
x_1 = A_{sl}^b = (+0.94±1.12 \text{ (stat) } ± 2.14 \text{ (syst)})\% \text{ (from inclusive)}
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x_2 = A_{sl}^b = (−0.736±0.266 \text{ (stat) } ± 0.305 \text{ (syst)})\% \text{ (from dimuon)}
\]

\[
X(\alpha) = A_{sl}^b = (−0.957±0.251 \text{ (stat) } ± 0.146 \text{ (syst)})\%
\]

Final Result

Why isn’t Final value between inclusive and dimuon?
Analysis Method: Subtraction

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

Why is this better than standard weighted average?

\[ X_{\text{wavg}} = (WA_{sl}^b + wA_{sl}^b)/(W + w) \]

Standard weighting according to \( w = 1/\sigma^2 \) of each channel

“minimum variance unbiased estimator”: how can we do better?

Corresponds to \( \alpha \sim -0.47 = (K/k) \left( \sigma_A/\sigma_a \right)^2 \)

\( X_{\text{wavg}} \) would give \(-0.65\), 2.5 SD stat from zero

This is indeed between the values from separate channels

Instead: \( X(\alpha) = -0.94 \), 3.8 SD stat from zero (3.2 including syst)

Corresponds to \( \alpha \sim +0.96 \)
Some Interesting Facts

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

$$X(\alpha) = \frac{(x_2 - \beta x_1)}{(1 - \beta)}$$

$\beta = \alpha k/K$

Quite peculiar: for $\alpha > 0$, $X(\alpha)$ is always outside $(x_1, x_2)$!

Though $x_1, x_2$ 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 $X_{wavg}$: see below

Key fact: $x_1$ and $x_2$ correlated

$$x_2 = \frac{(A - A_{bkg})}{K} \quad x_1 = \frac{(a - a_{bkg})}{k}$$

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

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

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

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

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

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

$\sqrt{\text{Var}} = .26$ for $X_{wavg} = X(\alpha = -.47)$

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

$\rho > 0$ means $\text{Var}$ is lowered for $\beta > 0$ : min. $\text{Var}$ estimator w/ correlation correctly included
A nice way to think of it

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

\[
k A^b_{sl} = a - a_{bkg} \\
K A^b_{sl} = A - A_{bkg}
\]

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

\[
A^b_{sl} = (-0.957 \pm 0.251 \text{ (stat)} \pm 0.146 \text{ (syst)})\% \\
A^b_{sl} = (+0.94 \pm 1.12 \text{ (stat)} \pm 2.14 \text{ (syst)})\% \quad \text{(from inclusive)} \\
A^b_{sl} = (-0.736 \pm 0.266 \text{ (stat)} \pm 0.305 \text{ (syst)})\% \quad \text{(from dimuon)}
\]

Final Result

Biggest Improvement: cancellation of systematics in background
An Extended $\alpha$ 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:
  \[ K^{0} \rightarrow K^+ \pi^- \]
  \[ \phi(1020) \rightarrow K^+ K^- \]

- 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

\[ \phi \rightarrow K^+ K^- \text{ decay} \]

\[ \chi^2/\text{dof} = 64/27 \]

\[ \chi^2/\text{dof} = 22/35 \]

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