Forward-backward asymmetry in $Z \rightarrow \mu \mu$ and determination of the effective weak mixing angle

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On behalf of the LHCb collaboration

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**LHCb detector**


- **LHCb** is a forward spectrometer designed for B physics.
- It covers a *unique acceptance* within the LHC experiments (2 < $\eta$ < 5).
- Momentum resolution: 0.4% at 5 GeV and 0.6% at 100 GeV.
- Impact parameter resolution of 13-20 $\mu$m at high $P_T$.
- Muon ID efficiency: 97% with 1-3% $\mu \rightarrow \pi$ mis-identification.
- Measurements in the *Electroweak* sector are possible (*Stephen's talk*).
Weinberg angle

- The Weinberg angle $\theta_w$ is a fundamental parameter of the electroweak lagrangian, not predicted by the theory:

\[
\mathcal{L}_{EW} = \sum_{\psi} \bar{\psi} \gamma^\mu \left( i\partial_\mu - g' \frac{1}{2} Y_W B_\mu - g \frac{1}{2} \tau W_\mu \right) \psi
\]

\[
\sin \theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}
\]

- The Z couplings differ for left- and right-handed fermions. This difference leads to an asymmetry in the angular distribution of negative and positive leptons.

- $\sin^2 \theta_{W}^{\text{eff}}$ is defined in function of the axial and vector-axial couplings of the Z to the fermions and it is proportional to $\sin^2 \theta_w$. 
**A bit of history**

- $\sin^2\theta_{\text{eff}}^W$ was precisely measured at **LEP** in the 90s, by studying the $Z$ asymmetry to fermions.
- Also another electron-positron collider, **SLAC**, performed the measurement with the detector **SLD**.
- A little puzzle appears at this point: these two measurements, the most precise in the world, differ for $3\sigma$.

![Graph showing measurements at different experiments](image)

- $\sin^2\theta_{\text{eff}}^W$ was also measured at hadron colliders by D0, CDF, ATLAS and CMS.
Measuring the $Z$ asymmetry at LHCb

- LHCb measured the $Z$ asymmetry in the process $q\bar{q} \rightarrow Z/\gamma^* \rightarrow \mu\mu$

  ![Diagram](image)

- The $Z$ angular distribution is given by

$$\frac{d\sigma}{d\cos\theta^*} = A(1 + \cos^2\theta^*) + B\cos\theta^*$$

- The forward-backward asymmetry:

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

  - $N_F$: number of forward decays ($\cos\theta^* > 0$)
  - $N_B$: number of backward decays ($\cos\theta^* < 0$)
At high rapidities $A_{FB}$ is enhanced, and there is an increased sensitivity to $\sin^2\theta_W$ respect to low rapidities: due to PDFs the high-x parton tend to be the quark and not the anti-quark.
Z $\rightarrow$ $\mu\mu$ selection

- **Inclusive Z $\rightarrow$ $\mu\mu$ cross section measurement paper:** arXiv:1505.07024

- **Trigger selection:** one muon with $P_T > 10$ GeV.

- **Offline selection:**
  - Two muons with $P_T > 20$ GeV and $2 < \eta < 4.5$

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**Dimuon mass (7 TeV data)**

**Dimuon mass (8 TeV data)**
Unfolding the asymmetry

- The raw asymmetry $A_{FB}^{raw}$ is corrected for:
  - Efficiency on trigger, track reconstruction and muon identification (almost negligible).
  - Detector mis-alignment → curvature/momentum bias that shifts the Z peak.

- The true asymmetry $A_{FB}$ is obtained from the measured asymmetry through a Bayesian unfolding technique.

- Finally data are corrected for background contaminations, by using the simulation (also this is negligible).

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\sqrt{s} = 7$ TeV</th>
<th>$\sqrt{s} = 8$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>curvature/momentum scale</td>
<td>0.0102</td>
<td>0.0050</td>
</tr>
<tr>
<td>data/simulation mass resolution</td>
<td>0.0032</td>
<td>0.0025</td>
</tr>
<tr>
<td>unfolding parameter</td>
<td>0.0033</td>
<td>0.0009</td>
</tr>
<tr>
<td>unfolding bias</td>
<td>0.0025</td>
<td>0.0025</td>
</tr>
</tbody>
</table>

Absolute experimental uncertainties on $A_{FB}$
True asymmetry $A_{FB}$ at 7 and 8 TeV compared to theory [JHEP 11 (2015) 190]:
Measuring $\sin^2\theta^\text{eff}_W$

- Simulation samples are generated with different values of $\sin^2\theta^\text{eff}_W$. The measured one is chosen by comparing the simulations with the measured $A^\text{FB}$, using a $X^2$.

- Simulation is produced using POWHEG-BOX interfaced with Pythia 8, using NNPDF2.3 and setting $\alpha_s(M_Z) = 0.118$. The result is compatible by using different generators.

- The systematics in the theoretical prediction are:
  - Uncertainties in the PDFs
  - Uncertainty in $\alpha_s$  
  - Uncertainty on the Final State Radiation
  - Renormalization and factorization scale uncertainty

| Uncertainty | average $\Delta |A^\text{pred}_{FB}|$ |
|-------------|-----------------|
| PDF         | 0.0062          |
| scale       | 0.0040          |
| $\alpha_s$  | 0.0030          |
| FSR         | 0.0016          |
The combined measurement of $\sin^2\theta_{\text{eff}}^W$ for the 7 TeV and the 8 TeV dataset is:

$\sin^2\theta_{\text{eff}}^W = 0.23142 \pm 0.00073 \text{ (stat.)} \pm 0.00052 \text{ (syst.)} \pm 0.00056 \text{ (th.)}$
The LHCb measurement is consistent with the world average, and it is one of the most precise at hadron colliders.
Conclusions and future

- $\sin^2\theta_{\text{eff}}^W$ has been measured by LHCb, by studying $A_{\mu\mu}^{\text{FB}}$:

  - $\sin^2\theta_{\text{eff}}^W = 0.2329 \pm 0.0015$ (7 TeV)
  - $\sin^2\theta_{\text{eff}}^W = 0.2307 \pm 0.0012$ (8 TeV)
  - $\sin^2\theta_{\text{eff}}^W = 0.2314 \pm 0.0011$ (combined)

- This is the most precise measurement of $\sin^2\theta_{\text{eff}}^W$ at LHC, thanks to LHCb forward acceptance.

- The uncertainty on $\sin^2\theta_{\text{eff}}^W$ can be reduced in the future:
  - By taking more data.
  - The errors on the PDFs will decrease with the new PDFs sets constrained with LHC data.
  - Events can be weighted (for example as a function of the Z boson rapidity) to increase the sensitivity to $\sin^2\theta_{\text{eff}}^W$.

- But with higher energy (14 TeV) the asymmetry dilution at LHCb increases by 5%, for imperfect knowledge of the initial state quark direction.
Thanks for your attention!
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