Measurement of the Z^0 Forward-Backward Asymmetry in muon pairs with the ATLAS experiment at LHC

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Summary

- A brief introduction to the Standard Model of particle physics.
- The ATLAS experiment at LHC.
- The Forward-Backward asymmetry A_{FB} of $Z \rightarrow \mu^+\mu^-$ events.
- Data sample.
- Event selection.
- Raw A_{FB} measurement and unfolding procedure.
- Extraction of $\sin^2\theta_W^{eff}$.
    - The 1D fit method.
- Conclusions.

The Standard Model and the Electroweak theory

- The Standard Model is the theory that describes matter and its interactions in terms of elementary particles.
- The electroweak theory plays an important role in the Standard Model.
  - Is based on a symmetry group $SU(2)_L \times U(1)_Y$.
  - The invariance of the Lagrangian in reached with the introduction of four bosons, W_i^μ with $i = 1, 2, 3$ and B^μ.
  - The electroweak interactions, charged and neutral, are mediated by vector bosons that are a combination of the $\mathbf{W}^{\boldsymbol{\mu}}$ and of B^μ.

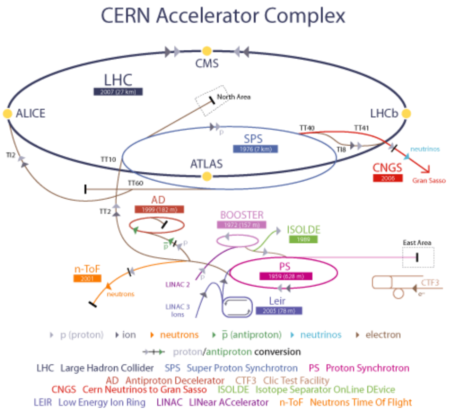
$$W^{\pm\mu} = \frac{1}{\sqrt{2}}\left(W_1^\mu \pm iW_2^\mu\right) \qquad \begin{pmatrix} Z^\mu \\ A^\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \\ \sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} W_3^\mu \\ B^\mu \end{pmatrix}$$

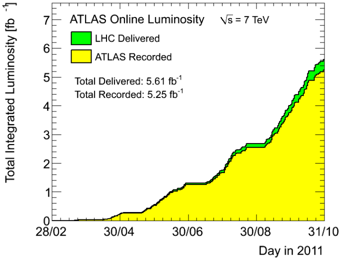
- The particles W^+, W^- and Z^0 were discovered at CERN by the UA1 and UA2 experiments in 1983 and studied at LEP and Tevatron.
  - Their mass values agree with the prediction from the SM.

$$M_Z = \frac{M_W}{\cos\theta_W}$$

The Large Hadron Collider at CERN

- The LHC is a proton-proton collider of 27 Km circumference.
  - Since March 2010 is collecting interactions at the energy of 7 TeV in the center of mass.

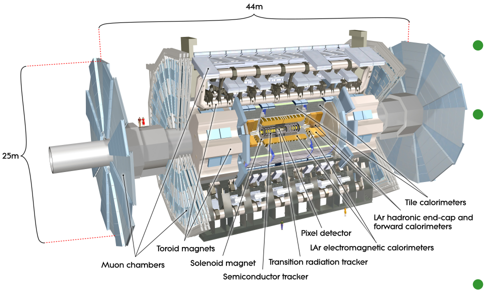




- Presently an integrated luminosity of about 5 fb^{-1} has been collected.
- Peak luminosity of 3.3×10^{33} cm^{-2} s^{-1}.

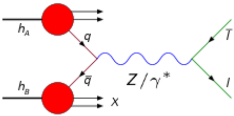
The ATLAS experiment

- General purpose detector to explore all proton-proton collisions.
- Main goals:
  - The discovery of the Higgs Bosons.
  - The discovery of physics Beyond Standard Model.



- Composed of different sub-detectors.
- Inner Detector. Three technologies:
  - Si pixel.
  - Si strips.
  - Straw tubes.
  - Central solenoid.
- Electromagnetic calorimeter.
  - Pb/LAr+Cu/LAr.
- Hadronic calorimeter.
  - Pb/Tiles.
- Muon spectrometer.
  - Precision muon tracking (MDT+CSC).
  - Dedicated trigger system (RPCs at $|\eta| < 1.05$ and TGCs at $1.05 < |\eta| < 2.7$)
- Magnet system.
  - Air-core toroidal magnets.

The Forward-Backward asymmetry A_{FB} in $pp \to Z/\gamma^* \to \mu^+\mu^-$ events



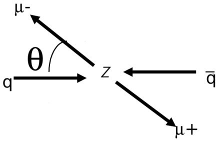
- It is due to the $V - A$ nature of the electroweak interaction.
- Neutral current coupling: $J_{Zf} = \bar{f}(g_V^f + g_A^f\gamma_5)f$.
  - Differential cross-section:

$$\frac{d\sigma}{d\cos\theta} = \frac{4\pi\alpha^2}{3s}\left[\frac{3}{8}A(1+\cos\theta^2) + B\cos\theta\right]$$

$$A = Q_l^2 Q_q^2 + 2Q_l Q_q g_V^q g_V^l Re(\chi(s)) + ({g_V^l}^2 + {g_A^l}^2)({g_V^q}^2 + {g_A^q}^2)|\chi(s)|^2 \qquad B = \frac{3}{2} g_A^q g_A^l (Q_l Q_q Re(\chi(s)) + 2g_V^q g_V^l |\chi(s)|^2)$$

- the $\cos\theta$ term gives rise to the forward-backward asymmetry

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{\int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta - \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta}{\int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta + \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta} = \frac{N_F - N_B}{N_F + N_B} = \frac{3B}{8A}$$

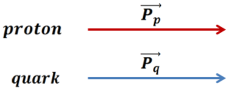


- Forward Event: $\cos\theta > 0$. Backward Event: $\cos\theta < 0$.

The Collins-Soper reference frame

- Consider the incoming quark. There are two possibilities

No transverse momentum



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θ is determined unambiguously from the four-momenta of the leptons.

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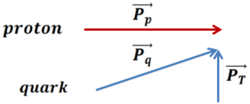
θ is the angle that the lepton makes with the proton beam in the center-of- mass frame of the lepton pair.

Significant transverse momentum



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exists an ambiguity in the four-momenta of the incoming quarks in the frame of the dilepton pair.

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The Collins-Soper formalism: the polar axis is defined as the bisector of the proton beam momentum and the negative of the anti-proton beam momentum when they are boosted into the center-of-mass frame of the dilepton pair.

$$\cos\theta^* = \frac{2}{Q\sqrt{Q^2 + Q_T^2}}(P_1^+ P_2^- - P_1^- P_2^+)$$

$\sin^2\theta_W^{eff}$ measurement from A_{FB}

$$A_{FB} = \frac{3B}{8A}$$

$$A = Q_l^2 Q_q^2 + 2Q_l Q_q g_V^q g_V^l Re(\chi(s)) + ({g_V^l}^2 + {g_A^l}^2)({g_V^q}^2 + {g_A^q}^2)|\chi(s)|^2$$

$$B = \frac{3}{2} g_A^q g_A^l (Q_l Q_q Re(\chi(s)) + 2 g_V^q g_V^l |\chi(s)|^2)$$

$$\frac{g_V^f}{g_A^f} = 1 - \frac{2Q_f}{I_f^3}\sin^2\theta_W^{eff}$$

- A_{FB} directly related with the value of the $\sin^2\theta_W^{eff}$.

Data and Monte Carlo samples

- An integrated luminosity of 4.8 fb^{-1} were analyzed corresponding to about 1.3M $Z/\gamma^* \to \mu^+\mu^-$ events.
- Pythia Monte Carlo sample used for signal events and background events (QCD, $Z \to \tau\tau$, $W \to \mu\nu$, $W \to \tau\nu$).
- Mc@NLO sample used for background events (WW, WZ, ZZ).
- PowHeg_Pythia sample used for $t\bar{t}$ channel.

MC statistic used

Channel	Number of Events	Cross Section (nb)
$Z \to \mu\mu$	4999129	0.85525
$Z \to \tau\tau$	1998042	0.854
$W \to \mu\nu$	6965567	8.9379
$W \to \tau\nu$	998368	8.9291
$WW \to ll\nu\nu$	1399724	0.000505
$W^+Z \to l\nu ll$	24995	0.011126
$W^+Z \to l\nu qq$	24989	0.011231
$W^-Z \to l\nu ll$	99972	0.0060414
$W^-Z \to l\nu qq$	24993	0.0060842
$ZZ \to llqq$	24990	0.0056683
$ZZ \to llll$	99982	0.0056757
$ZZ \to ll\nu\nu$	99978	0.0056702
cc	1499511	28.0305
bb	4482783	72.6217
tt	998771	0.1458

$Z/\gamma^* \to \mu^+\mu^-$ event selection

- Single muon trigger.
  - $p_T^\mu > 18$ GeV.
- Vertex:
  - $N_{tracks} > 3$.
  - $z_{vertex} < 150$ mm.
- Preselection:
  - $p_T > 20$ GeV.
  - Muon reconstructed using both ID and MS.
- $\eta < 2.4$.
- $(z_0 - z_{vertex}) < 10$ mm.
- Isolation:
  - $\frac{\sum p_T}{p_T^\mu} < 0.2$ in a cone of $\Delta R < 0.4$
- Opposite charge.
- Z mass window:
  - $66 < M_{\mu\mu} < 110$ GeV.
- 1.282M Z/γ^* candidates found in data sample.

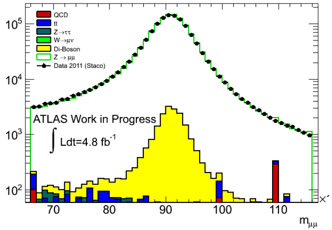
$$p_T = \sqrt{p_x^2 + p_y^2}$$

$$\eta = -\log \tan \frac{\theta}{2}$$

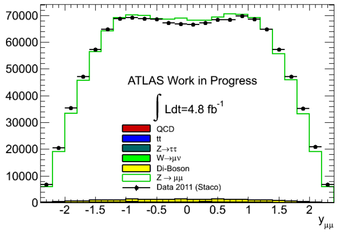
$$y = \frac{1}{2} \log \frac{E + p_z}{E - p_z}$$

$$M = \sqrt{(\sum E_i)^2 - (\sum p_{Ti})^2}$$

$Z/\gamma^* \to \mu^+\mu^-$ invariant mass distribution



$Z/\gamma^* \to \mu^+\mu^-$ rapidity distribution

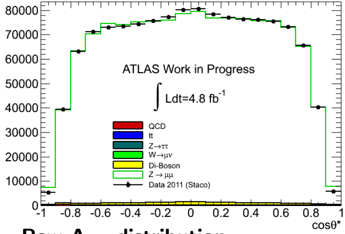


Raw A_{FB} measurement

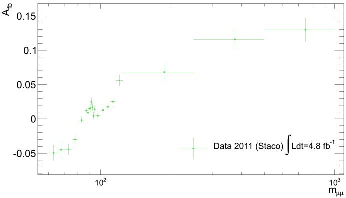
- Divide the mass spectrum in bins.
- In each bin count the number of forward and backward events.
- Subtract the number of forward and backward events due to the background estimated by MC.
- Compute the raw A_{FB} value using the relation:

$$A_{FB} = \frac{N^F - N^B}{N^F + N^B}$$

$\cos\theta^*$ distribution of the μ^-

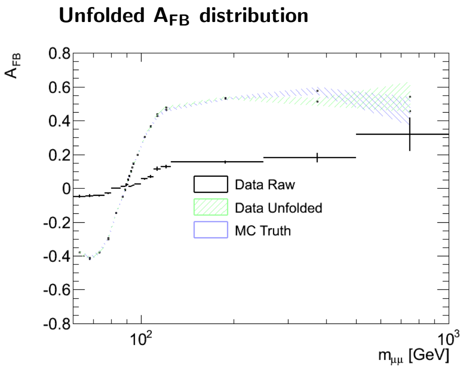


Raw A_{FB} distribution



Unfolding of the A_{FB} distribution.

- Two effects to be taken into account:
- *Z* **Mass migration**.
  - Final state radiation (FSR) of muons and detector resolution.
- **Dilution**.
  - Lack of knowledge on which of the beam contributes with a quark to the interaction.
- Corrections are applied by means of response matrices.
  - Matrices are built using Monte Carlo truth information.
- After the unfolding perfect agreement with Standard Model prediction.
  - A deviation from SM could be a signal for new physics.



Extraction of $\sin^2\theta_W^{eff}$

- We use an expansion of A_{FB} around the Z pole in terms of the center-of-mass energy s.

$$A_{FB}(s) \simeq A_{FB}\left(m_Z^2\right) + \frac{\left(s-m_Z^2\right)}{s}\frac{3\pi\alpha(s)}{\sqrt{2}G_F m_Z^2}\frac{2Q_q Q_f g_{Aq} g_{A\mu}}{\left(g_{Vq}^2+g_{Aq}^2\right)\left(g_{V\mu}^2+g_{A\mu}^2\right)} \qquad \frac{g_V^f}{g_A^f} = 1 - \frac{2Q_f}{I_f^3}\sin^2\theta_W^{eff}$$

- To extract $\sin^2\theta_W^{eff}$ fit the A_{FB} vs. $M_{\mu\mu}$ distribution with the expression:

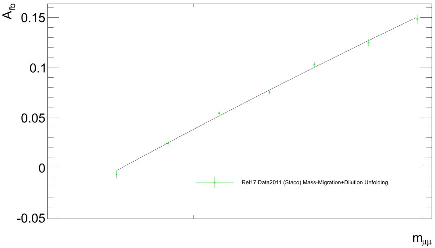
$$\begin{aligned} A_{FB}(s) &\simeq A_{FB}\left(m_Z^2\right) + \frac{s-m_Z^2}{s}\frac{3\pi\alpha(s)}{\sqrt{2}G_F m_Z^2}\cdot \\ &\cdot\left[\frac{2\left(x_u+x_c+x_t\right)}{1+\left(1-\frac{8}{3}\sin^2\theta_W^{eff}\right)^2} + \frac{x_d+x_s+x_b}{1+\left(1-\frac{4}{3}\sin^2\theta_W^{eff}\right)^2}\right]\cdot\left[\frac{1}{1+\left(1-4\sin^2\theta_W^{eff}\right)^2}\right] \end{aligned} \quad (1)$$

- A logarithmic expansion is used for the running of the electromagnetic coupling.

$$\alpha(s) = \frac{\alpha}{1-\Delta\alpha-\frac{\alpha}{3\pi}\frac{38}{9}\log\frac{s}{m_Z^2}}$$

$\sin^2 \theta_W^{eff}$ measurement

- The mass range chosen to perform the fit is 88.5 $< M_{\mu\mu} <$ 94.5 GeV.
- Need to fit the fully unfolded A_{FB} vs. $M_{\mu\mu}$ distribution.
- Results in agreement with Pythia Monte Carlo prediction.



Pythia Monte Carlo prediction		
$\sin^2 \theta_W^{eff}$	$x_u + x_c + x_t$	$x_d + x_s + x_b$
0.232	0.430	0.570

$\sin^2 \theta_W^{eff}$ measurement				
$\sin^2 \theta_W^{eff}$	$\sin^2 \theta_W^{eff}$ PDG value	$x_u + x_c + x_t$	$x_d + x_s + x_b$	$\Delta\alpha$
0.23200±0.00043(stat.)	0.23153±0.00016	0.3131±0.0095(stat.)	0.471±0.011(stat.)	0.020±0.013(stat.)

$\sin^2\theta_W^{eff}$ systematics

- Also studied some systematic errors.
- Use of different PDF sets $\mathbf{\Delta \sin^2\theta_W^{eff}=0.0003}$
- Use of different unfolding algorithm $\mathbf{\Delta \sin^2\theta_W^{eff}=0.0042}$
- Other systematic error studies are ongoing

$$\mathbf{\sin^2\theta_W^{eff} = 0.2320 \pm 0.0045(sys.) \pm 0.0004(stat.)}$$

Conclusions

The ATLAS experiment at LHC is collecting proton-proton collisions at 7 TeV and successfully remeasuring SM processes

- Analyzed ∼1.3M Z→ $\mu\mu$ events collected in 2010-2011 and measured the A_{FB}
  - This is an important test to search for new physics BSM
- From the A_{FB} extracted, at the Z pole, a preliminary measurement of the $\sin^2\theta_W^{eff}$.
  - Result in agreement with the SM expectation and precision measurement at Tevatron
  - Some systematics studies already done.
- Goal is to produce a paper in February.

Backup slides

A_{FB} expansion

- On the Z pole

$$A_{FB} = \frac{3}{4}\mathcal{A}_q\mathcal{A}_\mu \qquad \mathcal{A}_{q,\mu} = \frac{2\frac{g_V^{q,\mu}}{g_A^{q,\mu}}}{1+\left(\frac{g_V^{q,\mu}}{g_A^{q,\mu}}\right)^2}$$

- For a pp collider

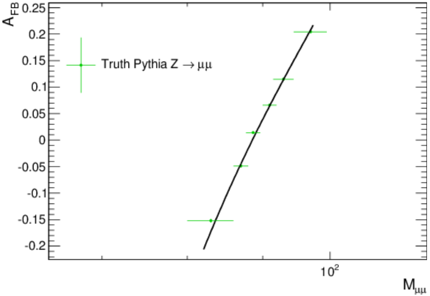
$$A_{FB} = \sum_{q=u,d,s,c,t,b} x^q A_{FB}^q \qquad x^q = \frac{N_q^+ + N_q^-}{N^+ + N^-} \qquad A_{FB}^q = \frac{N_q^+ - N_q^-}{N_q^+ + N_q^-}$$

$$\Downarrow$$

$$A_{FB} = \frac{3}{4}\left[\frac{2\left(1-\frac{8}{3}\sin^2\theta_W^{eff}\right)}{1+\left(1-\frac{8}{3}\sin^2\theta_W^{eff}\right)^2}\cdot(x_u+x_c+x_t)+\frac{2\left(1-\frac{4}{3}\sin^2\theta_W^{eff}\right)}{1+\left(1-\frac{4}{3}\sin^2\theta_W^{eff}\right)^2}\cdot(x_d+x_s+x_b)\right]\frac{2\left(1-4\sin^2\theta_W^{eff}\right)}{1+\left(1-4\sin^2\theta_W^{eff}\right)^2}$$

Monte Carlo closure test (1D fit)

- The mass range chosen to perform the fit is $82 < M_{\mu\mu} < 97.5$ GeV.
- Need to fit the fully unfolded A_{FB} vs. $M_{\mu\mu}$ distribution.
- Results in agreement with Pythia true values.



Fit Results(Monte Carlo truth)			
$\sin^2\theta_W^{eff}$	$x_u + x_c + x_t$	$x_d + x_s + x_b$	b
0.2328±0.0033	0.31±0.24	0.50±0.12	0.00497±0.00088