Forward-Backward asymmetry ($A_{FB}$) of Drell-Yan process

- $A_{FB}$ originate from the interference of vector and axial coupling
- $A_{FB}$ has strong dependence on dilepton mass ($M$)
  - $A_{FB}$ is close to zero near $Z$ boson mass peak
  - $A_{FB}$ is large and negative at low $M$, but large and positive at high $M$
- $A_{FB}(M)$ is sensitive to the electroweak mixing angle, $\sin^2\theta_W$
  - $A_{FB}(M)$ is used to extract the effective weak mixing angle

$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$

$\sigma_F$ denotes $\cos\theta > 0$ ($\sigma_B$ denotes $\cos\theta < 0$)
Differential cross section as a function of $\cos\theta^*$ in leading order (LO):

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

Asymmetric term

$A_{FB}$ is calculated in Collins-Soper (CS) frame

- CS frame reduces the uncertainties due to $p_T$ of the incoming quarks
- The quark direction (positive z-axis) is determined based on the rapidity direction

$$\cos\theta^*_{CS} \rightarrow \frac{|Q_z|}{Q_z} \cos\theta^*_{CS}$$

: where $Q_z$ is the longitudinal momentum of the dilepton

- In pp collision, the quark ($q$) and anti-quark ($q\bar{q}$) directions are not known
- $q$ carries more momentum than $q\bar{q}$ as $q\bar{q}$ must originate from the parton sea
- On average, Z boson is boosted into $q$ direction

The ambiguity in the quark direction increases at low rapidity

- $A_{FB}$ in LHC has strong rapidity dependence
- $A_{FB}$ is more pronounced at large rapidity due to better identification of $q$ direction
- Extending the measurement in higher rapidity is important

This talk will cover ATLAS and CMS measurements (LHCb result in Xabier’s talk)
ATLAS and CMS Detector

**ATLAS detector**
- Good muon coverage up to $|\eta|=2.4$
- EM calorimeter: $|\eta|<3$
- Forward calorimeter covers the region of $3.1<|\eta|<4.9$

**CMS detector**
- Muon coverage up to $|\eta|=2.4$
- Good tracking coverage
- EM calorimeter: $|\eta|<3$
- HF calorimeter extends $\eta$ coverage up to $|\eta|=5$

⇒ **Forward events have smaller dilution of $A_{FB}$**
ATLAS uses 7 TeV data, $\int L dt = 4.8 \ (4.6) \ fb^{-1}$ for electron (muon) channel

- Single lepton (electron or muon) trigger is used
  - $E_T(e)>20$ or $22$ GeV (depending on instantaneous luminosity), $p_T(\mu)>18$ GeV

Electron selection: $E_T>25$ GeV

- Central (C) electron ($|\eta|<2.47$) : candidates are matched to a track
  - ID selection is required based on shower shape and track quality cut
- Forward (F) electron ($2.5<|\eta|<4.9$) :
  - ‘medium’ quality criteria optimized for forward electron are required

Event topology :
- CC events : two central electrons passing ‘medium’ ID selection
  - Oppositely charged electrons
- CF events : one ‘tight’ central electron + one ‘medium’ forward electron
  - Required isolation energy cut ($<5$ GeV) on the central electron

Muon selection: $p_T>20$ GeV and $|\eta|<2.4$

- ID selection is required based on quality requirement in sub-detectors
- Fractional tracker isolation ($\frac{\sum p_T^{track}}{p_T^{\mu}} < 0.1$) is required
Data and Event selection : CMS

• CMS uses 8 TeV data, ∫Ldt = 19.7 fb^-1 for both electron and muon channels
  ✓ Dilepton (electron or muon) trigger or single electron trigger is used
    - Dilepton trigger : E_T(e) or p_T(μ) > 17 (leading), 8 (sub-leading) GeV with |η|<2.4
    - Single electron trigger for forward events : E_T(e)>27 GeV with |η|<2.4

• Electron selection :
  ✓ Central (C) electron (|η|<2.4) : E_T>20 or 30 GeV, candidates are matched to a track
    - ID selection and fractional PF isolation requirements are used
  ✓ Forward (F) electron (3<|η|<5) : E_T>20 GeV
    - Quality criteria (based on isolation) optimized for forward electron are required
  ✓ Event topology :
    - CC events : two central electrons with E_T>20 GeV, oppositely charged electrons
    - CF events : one central electron (E_T>30 GeV) + one forward electron (E_T>20 GeV)
      - Both electrons are required to be the same side of detector (η_{e1}·η_{e2} > 0)

• Muon selection : p_T>20 GeV and |η|<2.4
  ✓ ID selection is required based on quality requirement in sub-detectors
  ✓ Fractional tracker isolation (Σp_T^{track} / p_T^μ < 0.1) is required
Simulations

- Signal MC sample (Z/γ* → ee or μμ)
  - ATLAS: PYTHIAv6.4 with MSTW2008(LO) PDFs with $\sin^2 \theta_{eff}^{lep} = 0.232$
    - FSR from QED is taken into account using PHOTOS
  - CMS: POWHEG with CT10(NLO) PDFs with $\sin^2 \theta_{eff}^{lep} = 0.2312$
    - Parton showering, hadronization are simulated using PYTHIA with Z2* tune

- Background MC samples
  - ATLAS:
    - Z/γ*→ττ (PYTHIA), Diboson (HERWIG), ttbar (MC@NLO)
    - multi-jet and W+jets background are estimated by data-driven method
  - CMS:
    - Z/γ*→ττ, ttbar, tW (POWHEG), inclusive W (MadGraph), Diboson (PYTHIA)
    - Z/γ*→ττ, ttbar, multi-jet background are also measured by data-driven method

- MC simulations are fully simulated for detector effect based on GEANT4
- MC simulations are tuned to describe data for
  - pileup distribution and efficiencies (trigger, ID, reconstruction)
  - Lepton energy/momentum scale and resolution
Background estimation

- Major backgrounds in low and high mass are $Z/\gamma^* \rightarrow \tau\tau$ and $t\bar{t}$ process
- Multi-jet background is one of dominant sources in electron channel
- Background measurement in ATLAS
  - $Z/\gamma^* \rightarrow \tau\tau$, $t\bar{t}$, and diboson ($WW/WZ/ZZ$) are measured using MC
  - Multi-jet background is estimated using a combination of data-driven technique
    - CC electron topology:
      - the reverse ID method in $M < 125$ GeV + fake-factor method in high mass
    - CF electron topology: only the reverse ID method is used
    - Muon channel: control region (anti-isolation) vs. signal region method used
- Background measurement in CMS
  - Multi-jet background for CC and muon channel: same charged events method used
  - Multi-jet background for CF events: Fitting of kinematic distributions used
  - $Z/\gamma^* \rightarrow \tau\tau$, $t\bar{t}$, $W_{jets}$, $tW$ for muon channel: $e\mu$ method is used
    - Overall rate for $\mu\mu$ background events is proportional to observed $e\mu$ events
  - Other remaining backgrounds are estimated using MC
Dilepton mass distributions

- Dilepton mass comparison between data and MC

**ee(CC) events**

- Data: 1.2 million
- Z\gamma\rightarrow\text{ee}: 0.35 million

**ee(CF) events**

- Data: 1.7 million
- Z\gamma\rightarrow\text{ee}: 0.35 million

**\mu\mu events**

- Data: 8 million

---

*** CMS mass spectrum is normalized by bin width
Unfolding $A_{FB}$

- The measured $A_{FB}$ in the reconstructed level is defined as

$$A_{FB} = \frac{N_{\cos \theta^*_CS \geq 0} - N_{\cos \theta^*_CS < 0}}{N_{\cos \theta^*_CS \geq 0} + N_{\cos \theta^*_CS < 0}}$$

ATLAS measures $A_{FB}$ in mass for $ee(CC)$, $ee(CF)$, $\mu\mu$

CMS measures $A_{FB}$ in mass, $\gamma$

- The measured $A_{FB}$ is unfolded using iterative Bayesian method for
  - Detector effect (efficiencies, detector resolution, acceptance (CMS only))
  - QED radiation corrections

- ATLAS result is further corrected for the dilution and acceptance effect
  - PYTHIA signal sample is used to estimate the correction factors
Unfolded $A_{FB}$ in CMS

- $A_{FB}$ is measured as a function of dilepton mass and rapidity
- CMS measures $A_{FB}$ for $ee$ and $\mu\mu$, then combines both channel up to $|y|=2.4$

Measured $A_{FB}$ in mass and rapidity agrees with POWHEG prediction with $\sin^2 \theta_{eff}^{lept} = 0.2312$.

$A_{FB}$ in forward region ($2.4<|y|<5$) is statistical uncertainty dominant.
Unfolded $A_{FB}$ in ATLAS

- ATLAS measures $A_{FB}$ for ee(CC), ee(CF), $\mu\mu$, respectively.
- $A_{FB}$ is corrected up to the Born level including the dilution and acceptance.
- Unfolding procedure and energy scale/resolution are leading source of syst. error.
  - Background is also dominant source for CF electrons.

- Measured $A_{FB}$ agrees with PYTHIA prediction with $\sin^2 \theta_{eff}^{lept} = 0.232$.
  - Muon channel shows more deviation in high mass, but within 2$\sigma$.
Measurement of $\sin^2 \theta_{\text{eff}}^{\text{lept}}$

- The extraction of effective weak mixing angle, $\sin^2 \theta_{\text{eff}}^{\text{lept}}$
  - The extraction is done using the detector level $A_{\text{FB}}$ (raw $A_{\text{FB}}$)
  - PYTHIA is used to produce the template of $A_{\text{FB}}$ for each $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ value
    - Varying $\sin^2 \theta_{\text{eff}}^{\text{lept}}$ in the region of $0.218 \leq \sin^2 \theta_{\text{eff}}^{\text{lept}} \leq 0.236$ : 17 MC samples
    - Weights are calculated in gen. level, in bins of dilepton mass and $\cos\theta^*_\text{CS}$
    - The $A_{\text{FB}}^{\text{raw}}$ values obtained from the reweighted sample are compared with data
      - $\chi^2$ test over the mass range of 70 ~ 250 GeV is used

<table>
<thead>
<tr>
<th>$\sin^2 \theta_{\text{eff}}^{\text{lept}}$</th>
<th>CC electron</th>
<th>CF electron</th>
<th>Muon</th>
<th>El. combined</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC electron</td>
<td>0.2302 ± 0.0009(stat.) ± 0.0008(syst.) ± 0.0010(PDF) = 0.2302 ± 0.0016</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CF electron</td>
<td>0.2312 ± 0.0007(stat.) ± 0.0008(syst.) ± 0.0010(PDF) = 0.2312 ± 0.0014</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muon</td>
<td>0.2307 ± 0.0009(stat.) ± 0.0008(syst.) ± 0.0009(PDF) = 0.2307 ± 0.0015</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>El. combined</td>
<td>0.2308 ± 0.0006(stat.) ± 0.0007(syst.) ± 0.0010(PDF) = 0.2308 ± 0.0013</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined</td>
<td>0.2308 ± 0.0005(stat.) ± 0.0006(syst.) ± 0.0009(PDF) = 0.2308 ± 0.0012</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

PDF uncertainty is dominant source:
ATLAS-epWZ12 LO PDFs is used as default

CF electron has smallest error even though less statistics due to smaller dilution effect
Summary

- Forward-Backward asymmetry of Drell-Yan process is measured using RunI data
  - ATLAS uses \( \sqrt{s} = 7 \) TeV data (4.8 fb\(^{-1}\)) and CMS uses \( \sqrt{s} = 8 \) TeV data (19.7 fb\(^{-1}\))
    - ATLAS measures \( A_{FB}(M) \) up to Born level including dilution correction
    - CMS measures \( A_{FB}(M) \) up to particle level as a function of rapidity
    - The measured \( A_{FB} \) shows a good agreement with predictions (PYTHIA, POWHEG)

- ATLAS \( A_{FB} \) measurement is used to extract the effective weak mixing angle
  - Combined result: \( \sin^2 \theta_{eff}^{lept} = 0.2308 \pm 0.0005(\text{stat.}) \pm 0.0006(\text{syst.}) \pm 0.0009(\text{PDF}) \)

World average is dominated by
the most precise measurements (LEP-1 and SLD)
Two most precise measurements differ by 0.00122 (3.2\(\sigma\))

LHC has already reached an impressive precision on \( \sin^2 \theta_W \),
but it still has large uncertainty to distinguish
the tension between LEP-1 and SLD
\( \Rightarrow \) We will improve the precision further

Most precise hadron collider result is Tevatron combination

Tevatron and LHCb talks will follow after this talk !!
(See Willis’ and Xabier’s talk)
Backup Slides
$A_{FB}$ in ATLAS: raw $A_{FB}$

**Full mass**

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>$s = 7$ TeV, 4.8 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC electron</td>
<td>$p_T &gt; 25$ GeV, $</td>
</tr>
<tr>
<td>Data</td>
<td>Data</td>
</tr>
<tr>
<td>PYTHIA, $Z/\gamma \rightarrow ee$</td>
<td>PYTHIA, $Z/\gamma \rightarrow ee$</td>
</tr>
<tr>
<td>POWHEG, $Z/\gamma \rightarrow ee$</td>
<td>POWHEG, $Z/\gamma \rightarrow ee$</td>
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</tbody>
</table>

**Near Z peak**

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>$s = 7$ TeV, 4.8 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC electron</td>
<td>$p_T &gt; 25$ GeV, $</td>
</tr>
<tr>
<td>Data</td>
<td>Data</td>
</tr>
<tr>
<td>PYTHIA, $Z/\gamma \rightarrow ee$</td>
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</tr>
<tr>
<td>POWHEG, $Z/\gamma \rightarrow ee$</td>
<td>POWHEG, $Z/\gamma \rightarrow ee$</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>$s = 7$ TeV, 4.6 fb$^{-1}$</th>
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<tbody>
<tr>
<td>muon electron</td>
<td>$p_T &gt; 20$ GeV, $</td>
</tr>
<tr>
<td>Data</td>
<td>Data</td>
</tr>
<tr>
<td>PYTHIA, $Z/\gamma \rightarrow \mu\mu$</td>
<td>PYTHIA, $Z/\gamma \rightarrow \mu\mu$</td>
</tr>
<tr>
<td>POWHEG, $Z/\gamma \rightarrow \mu\mu$</td>
<td>POWHEG, $Z/\gamma \rightarrow \mu\mu$</td>
</tr>
</tbody>
</table>
Unfolded $A_{FB}$ in fiducial region
Systematic uncertainty summary: ATLAS

- Summary table for the systematic uncertainties

<table>
<thead>
<tr>
<th></th>
<th>CC electrons</th>
<th>CF electrons</th>
<th>Muons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncertainty</td>
<td>66–70 GeV</td>
<td>70–250 GeV</td>
<td>250–1000 GeV</td>
</tr>
<tr>
<td>Unfolding</td>
<td>~1×10⁻²</td>
<td>(2–5)×10⁻³</td>
<td>~4×10⁻⁴</td>
</tr>
<tr>
<td>Energy scale/resolution</td>
<td>~7×10⁻³</td>
<td>(0.5–2)×10⁻³</td>
<td>~2×10⁻²</td>
</tr>
<tr>
<td>MC statistics</td>
<td>~5×10⁻³</td>
<td>(0.1–1)×10⁻³</td>
<td>(3–20)×10⁻³</td>
</tr>
<tr>
<td>PDF</td>
<td>~2×10⁻³</td>
<td>(1–8)×10⁻⁴</td>
<td>(0.7–3)×10⁻³</td>
</tr>
<tr>
<td>Other</td>
<td>~1×10⁻³</td>
<td>(0.1–2)×10⁻³</td>
<td>(5–9)×10⁻³</td>
</tr>
</tbody>
</table>

- Major contributions are unfolding and background
- Systematic uncertainty of unfolding procedure is estimated using a partially data-driven method (modeling effect in mass and cosθ*)
• Summary table for the systematic uncertainties: maximum deviation in mass

**Muon channel**

| Systematic uncertainty          | $|y|$ bins |
|--------------------------------|-----------|
|                                | 0–1       | 1–1.25    | 1.25–1.5  | 1.5–2.4 |
| Background                     | 0.062     | 0.080     | 0.209     | 0.051   |
| Momentum correction            | 0.006     | 0.015     | 0.020     | 0.022   |
| Unfolding                      | 0.001     | 0.003     | 0.004     | 0.003   |
| Pileup reweighting             | 0.002     | 0.004     | 0.003     | 0.004   |
| Efficiency scale factors       | <0.001    | 0.002     | 0.003     | 0.005   |
| PDFs                           | 0.001     | 0.004     | 0.008     | 0.047   |
| FSR                            | <0.001    | 0.001     | 0.001     | 0.002   |

**Electron channel**

| Systematic uncertainty          | $|y|$ bins |
|--------------------------------|-----------|
|                                | 0–1       | 1–1.25    | 1.25–1.5  | 1.5–2.4 | 2.4–5 |
| Background                     | 0.064     | 0.015     | 0.008     | 0.004   | 0.033 |
| Energy correction              | 0.011     | 0.015     | 0.012     | 0.012   | 0.123 |
| Unfolding                      | 0.005     | 0.007     | 0.006     | 0.004   | 0.001 |
| Pileup reweighting             | 0.003     | 0.002     | 0.002     | 0.001   | 0.007 |
| Efficiency scale factors       | <0.001    | <0.001    | <0.001    | <0.001  | 0.008 |
| Forward $\eta$ scale factor    | —         | —         | —         | —       | 0.002 |
| Forward $\eta$ asymmetry       | —         | —         | —         | —       | 0.029 |
| Global normalization factor    | —         | —         | —         | —       | 0.060 |
| PDFs                           | 0.002     | 0.004     | 0.005     | 0.008   | 0.014 |
| FSR                            | <0.001    | 0.001     | 0.001     | 0.001   | 0.002 |

Major contributions are background and $p_T, E_T$ scale/resolution. The table summarizes the maximum deviation in $A_{FB}(M)$. Some of the contribution comes from the high mass region due to the fluctuation effect.
Weak mixing angle

- In Drell-Yan process,
  ✓ Virtual photon coupling: fermions(f) couple to $\gamma^*$ via vector coupling, $Q_f \gamma_\mu$
  ✓ $Z$ boson coupling: fermion coupling to $Z$ boson has $g^f_V \gamma_\mu + g^f_A \gamma_\mu \gamma_5$
    Born couplings: $g^f_V = T^f_3 - 2Q_f \sin^2 \theta_W$, $g^f_A = T^f_3 \rightarrow$ affect angular distributions
  ✓ Asymmetry in $\cos \theta$ distribution is induced from
    - $\gamma^*$ and $Z$ interference: depends on $g_A(T_3)$
    - $Z$ boson vector and axial-vector interference: includes $g_V$
      $\Rightarrow A_4$ contribution is proportional to $g_V \gamma g_V^q$

- Loop and vertex electroweak radiative correction modify $\sin^2 \theta_W$ by few %
  $\Rightarrow$ “effective” coupling ($\sin^2 \theta_{\text{eff, lept}}$) is observed
    - $A_4$ is most sensitive to the effective lepton-$Z$ coupling ($\sin^2 \theta_{\text{eff, lept}}$)
Electroweak mixing angle measurement

World average is dominated by the average of two most precise measurements (LEP-1, SLD).

Two most precise measurements of $\sin^2 \theta_W$ differ by 0.00122 which is 3.2 $\sigma$.

LHC result (ATLAS and LHCb) still has larger error, more than factor of 2 than Tevatron.

Most precise hadron collider measurements (CDF and D0) have a errors of 0.00047.
Electroweak mixing angle results

- Electroweak mixing angle measurements at Hadron collider

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Data</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS (μ)</td>
<td>1.1/fb</td>
<td>0.22870 ± 0.00200(stat) ± 0.00250(syst+pdf)</td>
</tr>
<tr>
<td>ATLAS (e+μ)</td>
<td>4.5/fb</td>
<td>0.23080 ± 0.00050(stat) ± 0.00060(syst) ± 0.00090(pdf)</td>
</tr>
<tr>
<td>D0 (e)</td>
<td>9.7/fb</td>
<td>0.23138 ± 0.00043(stat) ± 0.00008(syst) ± 0.00017(pdf)</td>
</tr>
<tr>
<td>CDF (e+μ)</td>
<td>9.7/fb</td>
<td>0.23221 ± 0.00043(stat) ± 0.00018(syst+pdf)</td>
</tr>
<tr>
<td>LHCb(μ)</td>
<td>7&amp;8TeV</td>
<td>0.23142 ± 0.00073(stat) ± 0.00052(syst) ± 0.00017(theo)</td>
</tr>
</tbody>
</table>

- PDF uncertainty is already dominant source at LHC
  - PDF error in ATLAS result is already ~2 times of statistical error
- CDF measurement used $\chi^2$ weighting technique to reduce PDFs error