The Angular Coefficients / $A_{fb}$ of Drell-Yan $e^+e^-$ pairs in the Z mass Region from ppbar Collisions at $\sqrt{s} = 1.96$ TeV

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Angular Coefficients Measurement

- Collins-Soper frame: the center of mass frame of dilepton

\[ q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^- \]

in lepton plane

- Differential cross section of \(\cos \theta\) and \(\phi\)

\[
\frac{d\sigma}{dP_T^2 dy d\cos \theta d\phi} \propto (1 + \cos^2 \theta) + \frac{1}{2} A_0 (1 - 3 \cos^2 \theta) + A_1 \sin 2\theta \cos \phi + \frac{1}{2} A_2 \sin^2 \theta \cos 2\phi + A_3 \sin \theta \cos \phi + A_4 \cos \theta + A_5 \sin^2 \theta \sin 2\phi + A_6 \sin 2\theta \sin \phi + A_7 \sin \theta \sin \phi
\]

LO term: determine \(A_{fb}\)

\(\cos^2 \theta\): higher order term

(\(\theta, \phi\)) terms

**very small terms**

***All higher order terms are zero at \(P_T=0\)***

Jiyeon Han/Univ. of Rochester (CDF)
Physics Motivation: Drell-Yan Process

- The differential cross section for $q\bar{q} \rightarrow \gamma^*/Z \rightarrow e^+e^-$ in LO:
  $$\frac{d\sigma}{dM_{\ell\ell}d\cos\theta} = C'[1 + \cos^2\theta + B\cos\theta]$$

- $p\bar{p} \rightarrow \gamma^*/Z \rightarrow e^+e^-X$ process in NLO: Process has a finite boson Pt

- The angular distribution of the final state $e^+e^-$ is different for two processes:
  $A_0$ and $A_2$ prediction in Pt is different in each process

- A measurement of the angular distribution in Pt provide a detailed test of the production mechanism of gauge boson with finite Pt

- Standard model QCD in all order predicts $A_0 = A_2$: Lam-Tung relation
  : Lam-Tung relation is only valid for vector gluons (spin 1)
A_4 vs. A_{fb}

- A_4 has a direct relation with A_{fb}
- A_4 is sensitive to weak mixing angle, \( \sin^2 \theta_W \)
- A_{fb} has the mass, \( P_T \), and \( y \) dependence
  - \( P_T \) and \( y \) dependence is much smaller than the mass dependence
  - A_{fb} in mass gives more sensitivity to extract the physics quantities
    - Physics quantities: \( \sin^2 \theta_W \), quark couplings
Tracker and Calorimeter

\[ \eta = -\ln(\tan(\theta/2)) \]

- Central electron \( |\eta| < 1.1 \)
- Plug electron \( |\eta| > 1.1 \)
- Plug calorimeter covers high \( \eta \) (~3.6)
- CLC measures luminosity: \( |\eta| > 3.6 \)
  (Cerenkov Luminosity Counter)
- Silicon track covers \( |\eta| < 2.8 \)
- Silicon tracking reduces background contamination
Di-electron Selection : Angular Coefficients

- **Data set**: integrated luminosity = 2.1 fb$^{-1}$
  - Inclusive single central/two electron trigger
  - Trigger efficiency is more than 99%
- The isolated electrons are selected passing ID cut
- Both electrons have a matching track
  - Track requirement reduces the background (~0.5%)
- **Di-electron topology**:
  - **Z(CC)** topology: two central electrons
    - Kinematic selection: $E_T \geq 25, 15$ GeV
    - Opposite charged electrons
  - **Z(CP)** topology: central and plug electron
    - Kinematic selection: $E_T \geq 20$ GeV
  - **Z(PP)** topology: two plug electrons
    - Kinematic selection: $E_T \geq 25$ GeV
    - Two isolated electrons are found in the same end-plug calorimeter
- ~ 140k events are selected in mass window, 66 < $M(ee)$ < 116 GeV/c$^2$
Di-electron Selection: $A_{\text{fb}}$

- **Data set**: integrated luminosity = 4.1 fb$^{-1}$
  - Inclusive single central:
    - Trigger efficiency is more than ~94%
- The isolated electrons are selected passing ID cut
- Both electrons have a matching track
  - Track requirement reduces the background (~0.5%)

- **Di-electron topology**:
  - **Z(CC) topology**: two central electrons
    - Kinematic selection: $E_T \geq 25$ GeV for both legs
    - Opposite charged electrons
  - **Z(CP) topology**: central and plug electron
    - Kinematic selection: $E_T \geq 20$ GeV
  - **Z(PP) topology** is not included
    - The charge fake rate is increased in Z(PP) topology
- $40 < M(ee) < 600$ GeV/c$^2$ mass range is used
Simulation of data is necessary to determine acceptance and efficiency
- Simulation must describe data (physics + detector) as closely as possible
- MC is tuned to describe the data for physics and also detector effect

Physics simulation
- Pythia Drell-Yan LO $p + \bar{p} \rightarrow \gamma^*/Z \rightarrow ee$ generator (CTEQ5L PDFs)
- $\gamma^*/Z$ $P_T$ tweaked to match CDF Run I measurement
  - Additional tuning is applied to match $\gamma^*/Z$ $P_T$ and $y$ correlation

CDF detector simulation
- Detector geometric modeling is good
- Detector energy response (Calorimeter):
  - Tweak energy response in the simulation considering $\eta$ dependence
- Efficiencies: Trigger, electron selection, and tracking efficiency
  - Efficiencies are measured considering geometry and inst. luminosity effect
  - The measured efficiencies in data is applied into the simulation
  - CC efficiency: $\sim 90\%$, CP efficiency: $\sim 62\%$, PP efficiency: $\sim 67\%$
Measurement: Background

- Background Contribution
  - QCD background: measured by isolation extrapolation method in data
    - Isolation E: the energy contained in $\Delta R=0.4$ cone outside of the electron shower
    - Electron is the isolated object, distinguished from jet object in isolation E shape
    - Fit isolation distribution for both signal and background contributions
    - Extrapolate the background from the high isolation tail into the signal region
  - EWK background - estimated using MC samples
    - WW/WZ, inclusive ttbar, inclusive W+jets, $Z\rightarrow\tau\tau$ are considered

*** All backgrounds are subtracted in $\cos\theta$ and $\phi$, $M(ee)$ for $A_{fb}$

![Graph showing isolation E distribution with QCD dijets dominance](image)

- Overall QCD: 0.30%
- Overall EWK: 0.19%
Angular Distribution in Pt

- **cosθ and φ distribution in Z boson Pt**: Pythia MC (gen. level)

**Integrate over all φ**,

\[
\frac{d\sigma}{d\cos\theta} \propto (1 + \cos^2 \theta) + \frac{1}{2} A_0 (1 - 3 \cos^2 \theta) + A_4 \cos \theta
\]

- **cosθ in Z boson Pt**: fitting (A0, A4)

- **φ in Z boson Pt**: fitting (A2, A3)
Extracting Coefficients: Fitting Method (general)

- Extraction the coefficients using the max. log-likelihood fitting method
- Tune CDF MC (Pythia) to match with data in the reconstructed level

**Generated level**

![Graph showing the comparison of generated level with Pythia default coefficients and tweaked (A0,A4) coefficients.](image1)

**Reconstructed level (CC)**

![Graph showing the comparison of reconstructed level with MC vs data.](image2)

Start with Pythia default coefficients

Tweaking coefficients in gen. level

Comparing MC vs. data in rec. level

Best match with data ??

No!!

Yes!!

Determine coefficients
Systematic Uncertainties

- Systematic uncertainties are considered for:
  - Background Estimation: dominant source
  - Z Pt vs. y Correction
  - ID and Tracking Efficiencies
  - Energy Scale
  - Material Modeling

Systematic vs. Statistical

Systematic uncertainty is small compared to statistical uncertainty
Angular Coefficients: $A_{0,2,3,4}$ in $P_T$

- Parameters in $Z$ $P_T$: stat. $\oplus$ syst. error are shown (stat. error is dominant)

*PRL 106, 241801 (2011)*
A_{fb} Measurement

• $A_{fb}$ is measured using the event counting in mass

$$A_{fb} = \frac{N_{sig}(\cos \theta > 0) - N_{sig}(\cos \theta < 0)}{N_{sig}(\cos \theta > 0) + N_{sig}(\cos \theta < 0)}$$

• The measured $A_{fb}$ is unfolded using the response matrix (R_{ij}) inversion
  • The response matrix includes smearing, $A \times \varepsilon$, and FSR effect
  • $\mu = R^{-1}(\nu - \beta)$ where $\mu$ (true value), $\nu$ (observation), and $\beta$ (background)
**$A_{fb}$ Result**

- $A_{fb}$ before and after unfolding

**Forward-Backward Asymmetry, $A_{FB}$**

![Graph showing $A_{fb}$ before unfolding](image1)

- Only stat. error considered

![Graph showing $A_{fb}$ after unfolding](image2)

- stat. error and syst. error

- The measured $A_{fb}$ is compared with PYTHIA prediction
  - The measurement shows a good agreement with the prediction
  - The stat. error is dominant than the syst. error except low and high mass bin
**Weinberg angle ($\sin^2 \theta_W$) vs. $A_4$**

- $A_4$ is very sensitive to weak mixing angle, $\sin^2 \theta_W$
- $A_4$ measurement is translated into $\sin^2 \theta_W$ using various predictions
  - $A_4$ in $P_T$ is integrated over $P_T$ in $66 < M(ee) < 116$ GeV/$c^2$
  - Pythia, ResBos, VBP, Powheg(NLO), FEWZ(NNLO) are used
  - Theory band includes the order difference of the calculation, PDFs(CTEQ, MSTW)
  - Variation in predictions is assigned as the uncertainty for QCD theory

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**CDF Preliminary Result with $\int L = 2.1$ fb$^{-1}$**

$$\sin^2 \theta_W = 0.2329 \pm 0.0008(\text{A}_4 \text{ error})\pm 0.0009(\text{QCD})$$

- $A_4$ Measurement
- Total Error of $A_4$
- Systematic (QCD Theory)

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**D0 measurement (PRD 84, 012007)**:

$$\sin^2 \theta_W = 0.2309 \pm 0.0008(\text{stat.})$$

$$\pm 0.0006(\text{syst.})$$

extracted from $A_{fb}$ with 5.0 fb$^{-1}$ in $70 < M(ee) < 130$ GeV
Conclusion and Summary

• We present the first measurement of the angular coefficients in the production of $\gamma^*/Z$ bosons at large transverse momentum
  • At low $P_t$, $A_0$ and $A_2$ are well described by the annihilation function, $P_T^2/(P_T^2+M_{ll}^2)$
  • At high $P_t$, both the annihilation and Compton processes contribute to the cross section
  • The results are in agreement with fixed-order perturbation theory calculation
    • DYRAD, MADGRAPH, PYTHIA Z+1 jet, POWHEG, and FEWZ
  • $A_3$ and $A_4$ are in agreement with the predictions of all models

• We present the first test of the Lam-Tung relation at high $P_t$
  • The Lam-Tung relation ($A_0 - A_2 = 0$) is confirmed: average of $A_0 - A_2 = 0.02 \pm 0.02$
  • $A_{fb}$ in mass also measured and compared with PYTHIA prediction
    • The measurement shows a good agreement with PYTHIA
  • An analysis with larger samples in both ee and $\mu\mu$ channels is under way
  • A comparison of these results with the measurement at LHC would provide additional tests of production mechanisms
    • The contribution of Compton process at LHC is expected to be larger

*** The angular coefficients result: PRL 106, 241801 (2011)
Back-Up Pages
Expectation for Angular Coefficients

- Standard model QCD in all order predicts $A_0 = A_2$ : **Lam-Tung relation**
  - Lam-Tung relation is a fundamental prediction of QCD for spin 1 vector gluons
- $q \bar{q}$ annihilation process: dominant at the Tevatron
- No rapidity ($y$) dependence or PDFs dependence of $A_0$, $A_2$
- $A_0$ and $A_2$ only depend on the ratio, $P_T/M$

\[
A_0^{q\bar{q}} = A_2^{q\bar{q}} = \frac{P_T^2}{M_{\ell\ell}^2 + P_T^2} \quad A_1(+y) = -A_1(-y)
\]
\[
A_3(+y) = -A_3(-y) \quad A_5 = A_6 = A_7 = 0
\]

- Approximation for the $qg$ Compton process
  - Angular coefficients are functions of $y$ and depend on PDFs
  - Average value of $A_0$, $A_2$ approximated by

\[
A_0^{qg} = A_2^{qg} = \frac{5P_T^2}{M_{\ell\ell}^2 + 5P_T^2}
\]
Measurement: Et cut in CC topology

- Event selection: same as for dσ/dy except Et cut in CC topology
  - At high Z Pt, one electron has high Et and another low Et (second leg)
  - The lower Et leg is rejected by the acceptance selection (Et > 25)
  - Release Et cut on the second leg (Et > 15) to increase the acceptance
  - Acceptance increase: ~ 23% → make φ distribution flatter
### Total number of the selected events and signal yield in Pt

<table>
<thead>
<tr>
<th>Pt bin</th>
<th># of selected (CC+CP+PP)</th>
<th># of background</th>
<th># of signal yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 10</td>
<td>84422 (30055+40303+14064)</td>
<td>120 (0.14%)</td>
<td>84302 ± 290</td>
</tr>
<tr>
<td>10 - 20</td>
<td>31615 (12173+14230+5212)</td>
<td>180 (0.57%)</td>
<td>31435 ± 177</td>
</tr>
<tr>
<td>20 - 35</td>
<td>13952 (5723+6042+2187)</td>
<td>177 (1.27%)</td>
<td>13775 ± 117</td>
</tr>
<tr>
<td>35 - 55</td>
<td>5342 (2470+2119+753)</td>
<td>132 (2.47%)</td>
<td>5210 ± 72</td>
</tr>
<tr>
<td>55 and above</td>
<td>2841 (1530+1058+253)</td>
<td>71 (2.50%)</td>
<td>2770 ± 53</td>
</tr>
</tbody>
</table>

- Total selected events = 138,172
- Total signal yield = 137,492 ± 371
- Total background rate = 0.49 %
Lam-Tung Relation

- Lam-Tung (LT) Relation ($A_0 = A_2$)
  - LT relation is only valid for vector gluons (spin 1): $A_0 - A_2 = 0$
  - Scalar gluons (spin 0): $A_0 - A_2 = -2$
  - We measure the average of $A_0 - A_2 = 0.02 \pm 0.02$ (total error)
  - Lam-Tung Relation in $p_T$ is also consistent with zero within uncertainty

$A_0 - A_2$ is consistent with zero
Confirms Lam-Tung Relation
Systematic Uncertainties: Angular Coefficients

- Systematic uncertainties are considered for
  - Background Estimation: dominant source
    - Extract parameters with / without background subtraction
    - Assign the difference as a systematic uncertainty
  - Z Pt vs. y Correction
    - Vary the correction with $\pm 1\sigma$ error and assign the difference as systematics
  - ID and Tracking Efficiencies
    - Vary the efficiency with $\pm 1\sigma$ error and assign the difference as systematics
  - Energy Scale
    - Shift the energy scale in $\pm 1\sigma$ error and assign the difference as systematics
  - Material Modeling: estimate using extra material MC samples
    - MC for central: include an additional 1% of $X_0$ of material in central region
    - MC for plug: include an additional $1/6$ $X_0$ of material in plug region
    - Estimate the deviation from the default sample
    - Assign the deviation as a systematic uncertainty for material modeling
Z(\text{ee}) mass distribution with 4.1 \text{ fb}^{-1} \text{ data}

- Reconstructed di-electron mass distribution with 4.1 \text{ fb}^{-1} \text{ data}

\textit{M(\text{ee}) above 300 GeV/c}^2 \text{ has only } \sim 100 \text{ events}
Systematic Uncertainties : $A_{fb}$

- Systematic uncertainties are considered for:
  - Background estimation
  - Energy scale
  - ID efficiency
  - Tracking efficiency
  - Response matrix
  - PDFs errors

- The syst. error is smaller than stat. error except first and last bin.

- The stat. error is dominant in the high mass above 120 GeV/c$^2$:
  - The stat. error is more than twice of syst. error
  - The last bin, $300 < M(\text{ee}) < 600$ GeV/c$^2$, has a large error: only $\sim 100$ events
\[ \sin^2 \theta_W (CDF) = 0.2329 \pm 0.0008 (A_4 \text{ error})^{+0.0010}_{-0.0009} (QCD) \]