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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on behalf of CDF collaboration

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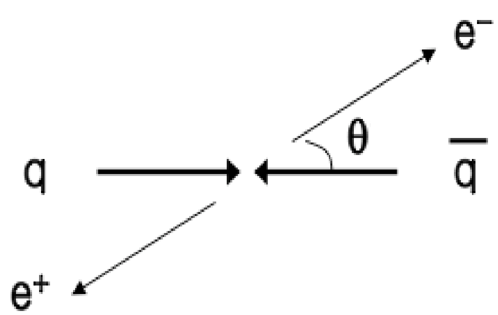
Angular Coefficients Measurement

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

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



in lepton plane

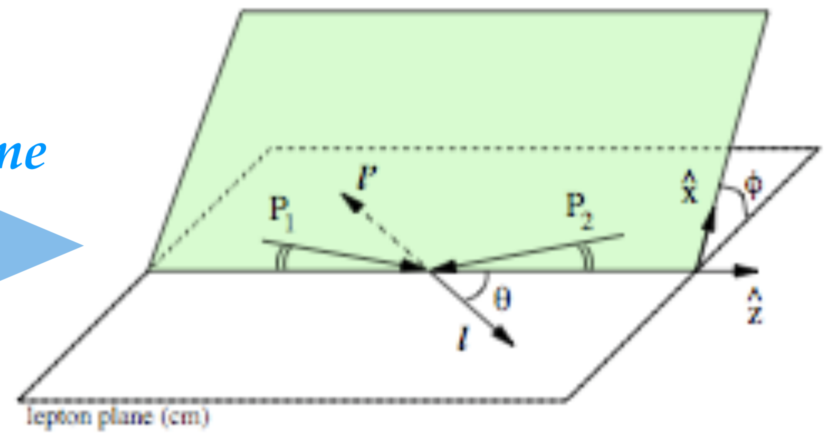


FIG. 1: The Collins-Soper frame.

- Differential cross section of cosθ and φ

$$\frac{\mathbf{d}\sigma}{\mathbf{dP_T^2 dy d}\cos\theta\,\mathbf{d}\phi} \propto \boxed{(1+\cos^2\theta)} \longrightarrow \textit{LO term}$$

$$+ \frac{1}{2}A_0(1-3\cos^2\theta) \longrightarrow \cos^2\theta \text{ : higher order term}$$

$$+ A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi \longrightarrow (\theta,\phi) \text{ terms}$$

$$+ \boxed{A_4\cos\theta} \longrightarrow \text{LO term : determine } A_{fb}$$

$$+ \boxed{A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi} \longrightarrow \text{very small terms}$$

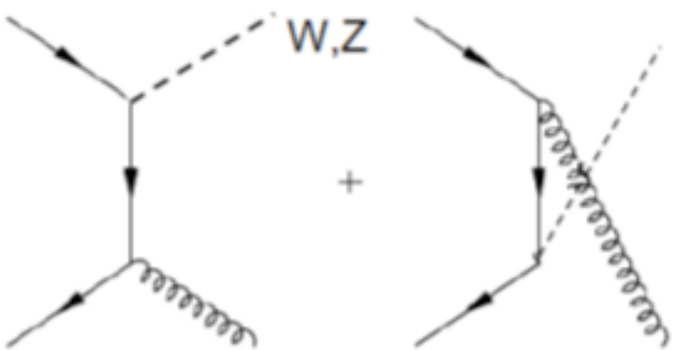
All higher order terms are zero at Pt=0

Physics Motivation : Drell-Yan Process

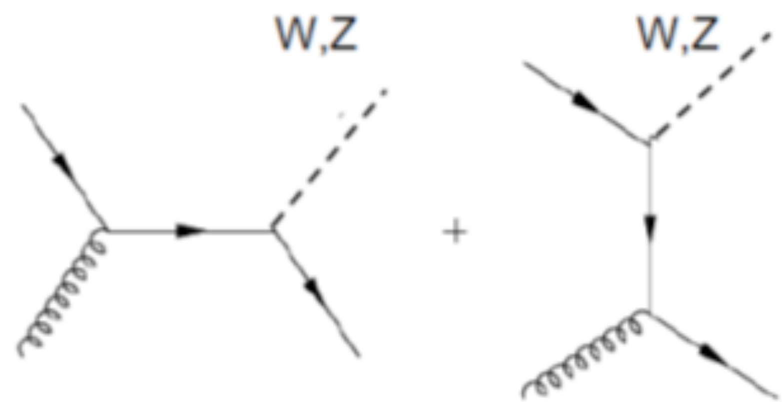
- The differential cross section for $q\bar{q} \to \gamma^*/Z \to e^+e^-$ in LO

$$\frac{d\sigma}{dM_{\ell\ell}dcos\theta} = C'[(1+cos^2\theta) + Bcos\theta]$$

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



Annihilation diagram $A_0^{q\bar{q}} = A_2^{q\bar{q}} = \frac{P_T^2}{M_{\ell\ell}^2 + P_T^2}$

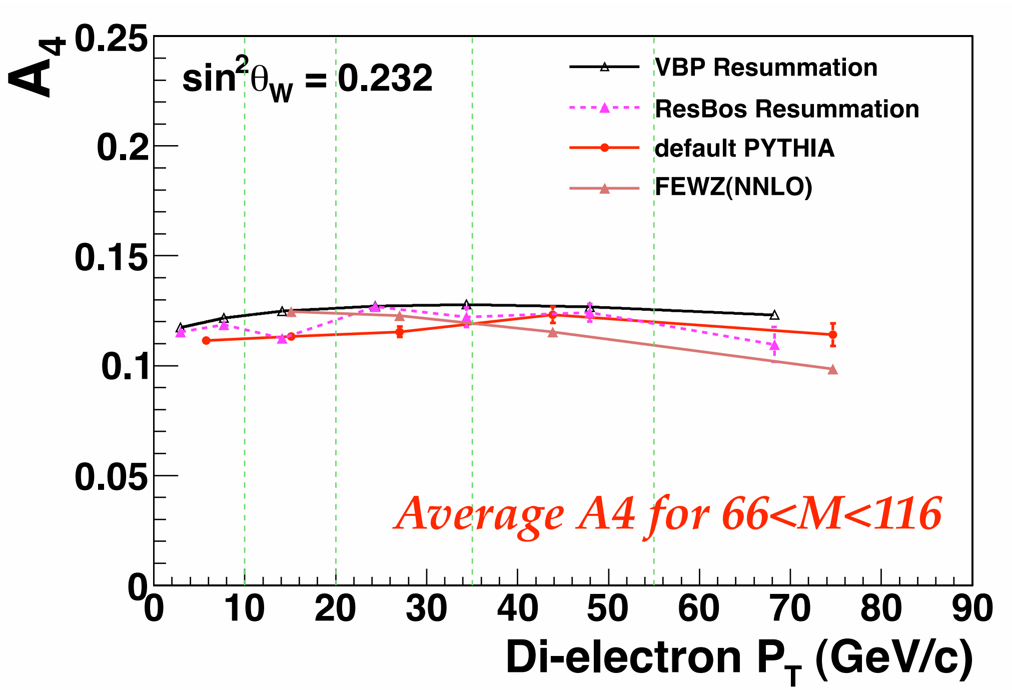


Compton diagram $A_0^{q\bar{q}} = A_2^{q\bar{q}} = \frac{5P_T^2}{M_{\ell\ell}^2 + 5P_T^2}$

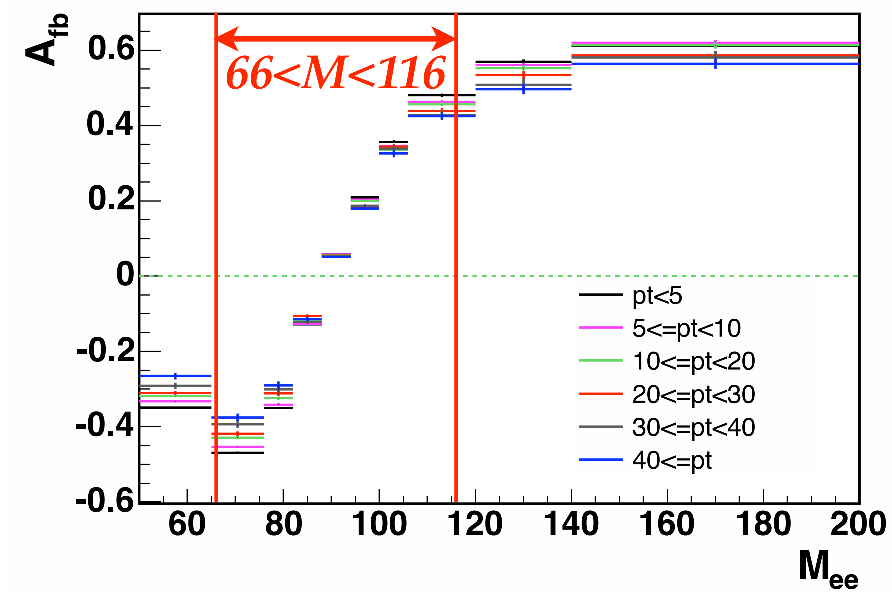
- The angular distribution of the final state e^+e^- is different for two processes
  : A_0 and A_2 prediction in Pt is different in each process
- A measurement of the angular distribution in Pt provide a detailed test of the production mechanism of gauge boson with finite Pt
- Standard model QCD in 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}



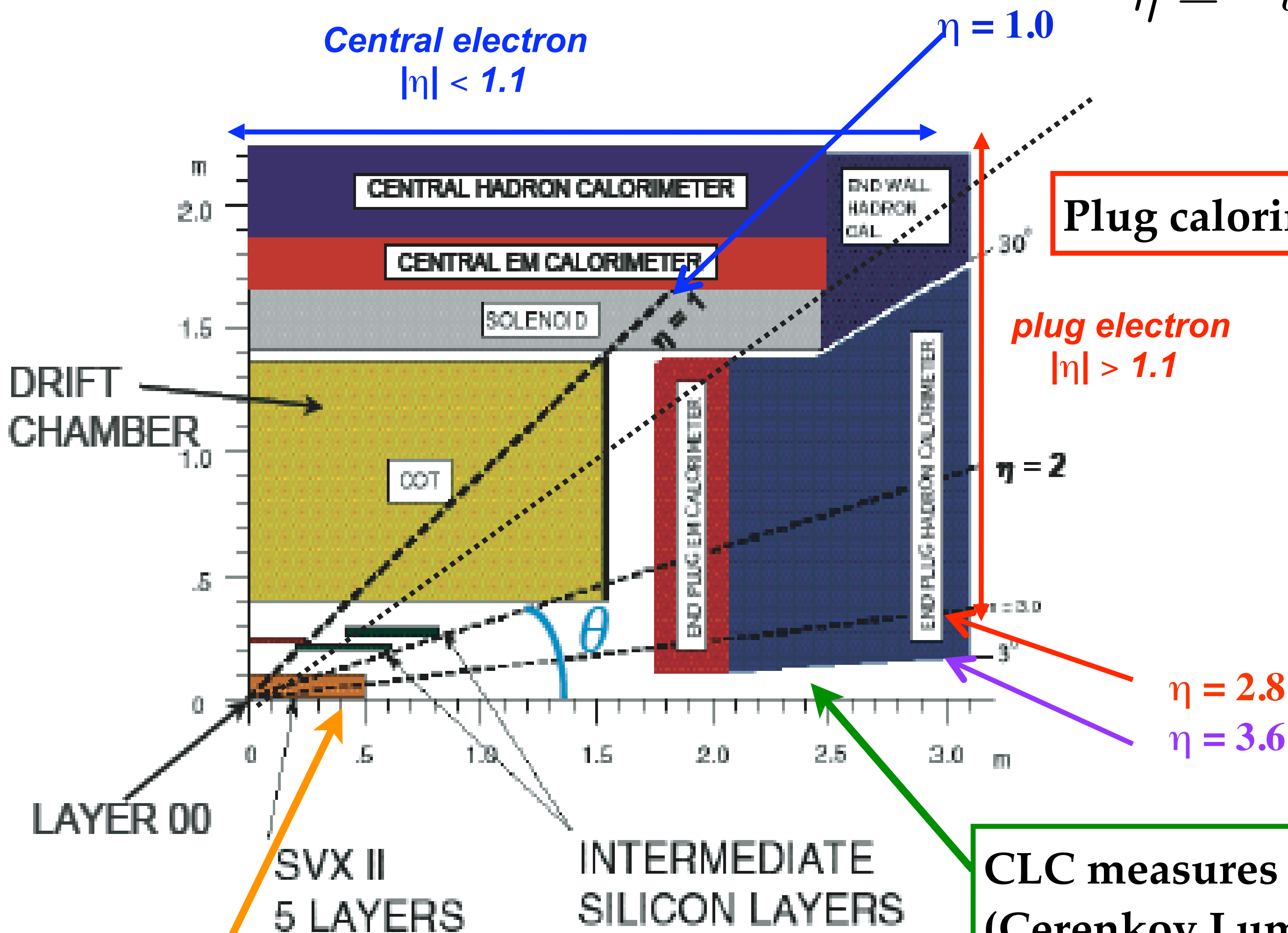
$$A_4 = \frac{8}{3} A_{fb}(M_{\ell\ell}, P_T, y)$$



- 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

$$\eta = -ln(tan(\theta/2))$$



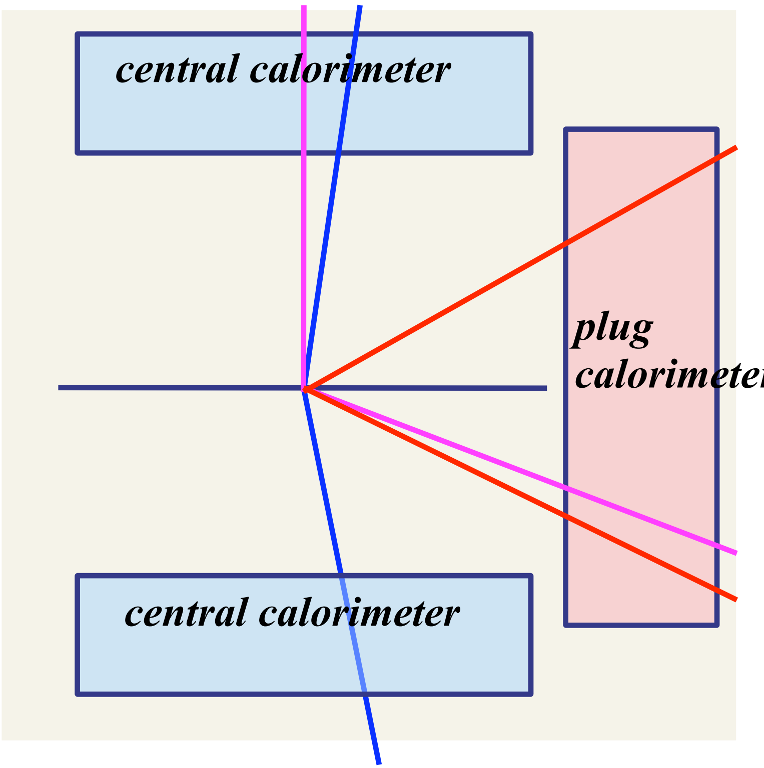
Plug calorimeter covers high η (~3.6)

CLC measures luminosity : |η|>3.6
(Cerenkov Luminosity Counter)

Silicon track covers |η|< 2.8
Silicon tracking reduces background contamination

Di-electron Selection : Angular Coefficients

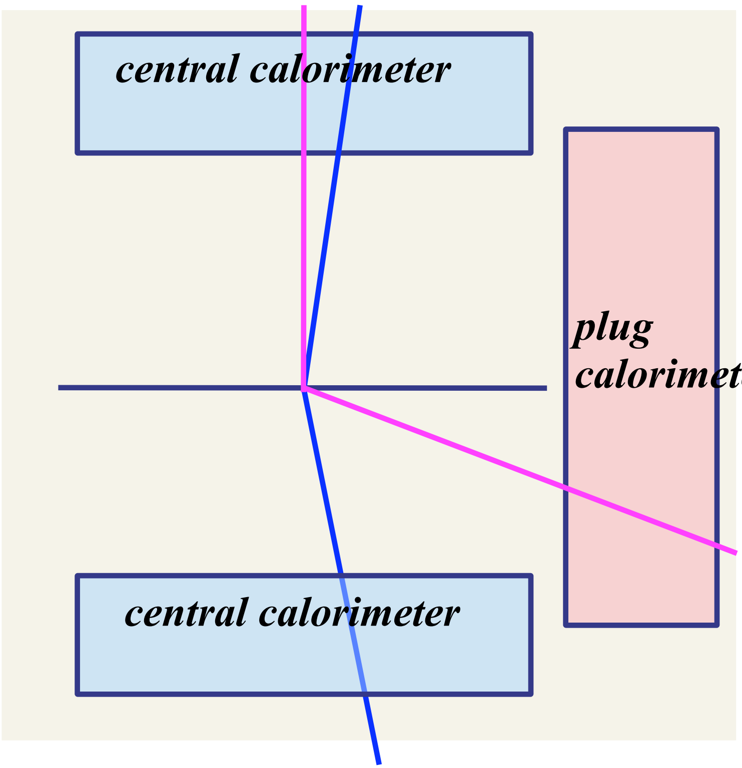
- **Data set** : integrated luminosity = 2.1 fb^{-1}
  - Inclusive single central / two electron trigger
    - Trigger efficiency is more than 99%
- The isolated electrons are selected passing ID cut
- Both electrons have a matching track
  - Track requirement reduces the background (~0.5%)
- **Di-electron 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***



Central electron: $|\eta|<1.1$
Plug electron : $1.2<|\eta|<2.8$

Di-electron Selection : A_{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/c² mass range is used***



Central electron: $|\eta|<1.1$

Plug electron : $1.2<|\eta|<2.8$

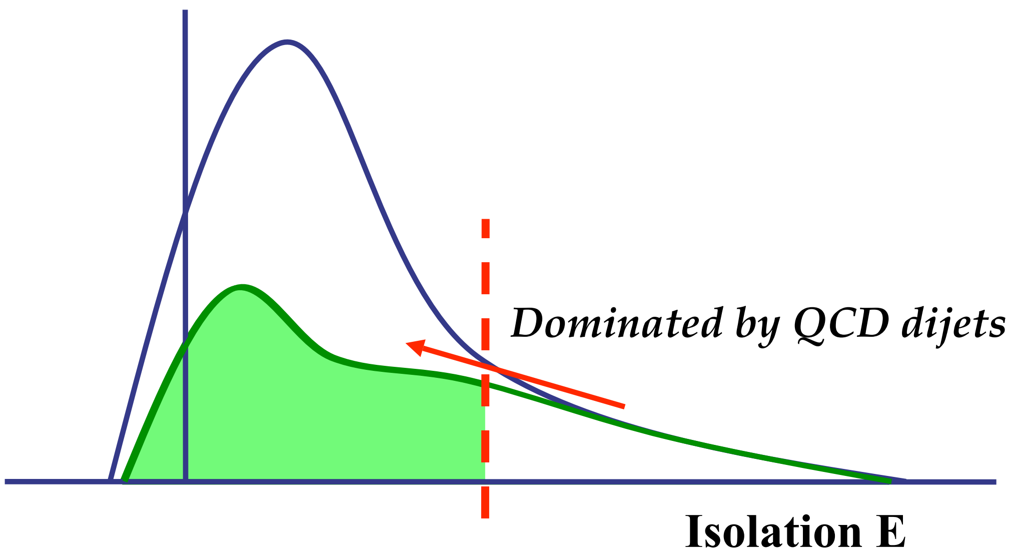
CDF Simulation for Drell-Yan

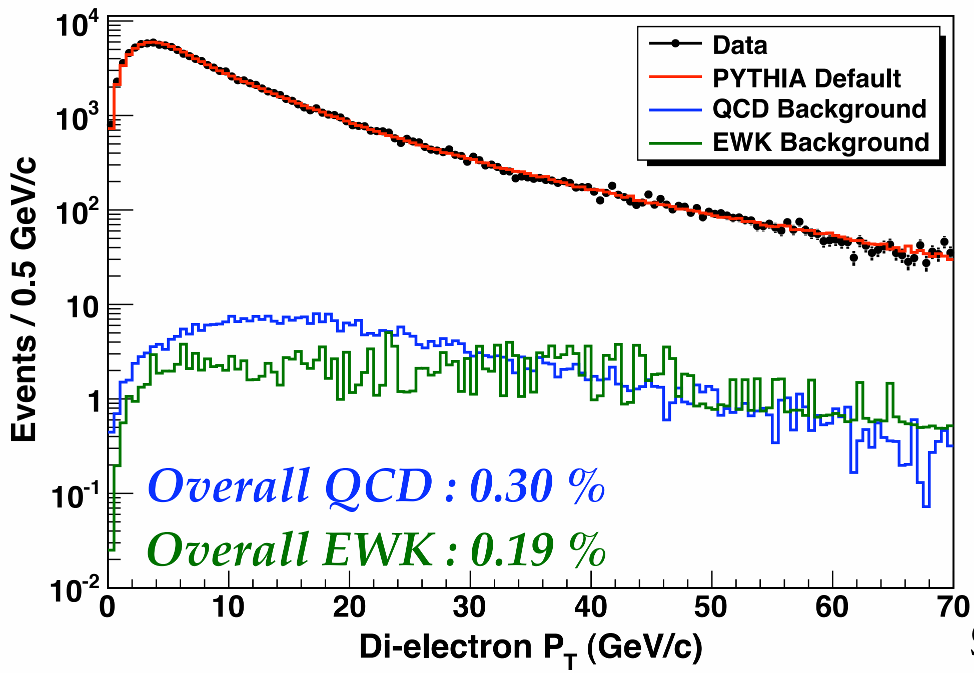
- Simulation of data is necessary to determine acceptance and efficiency
  - Simulation must describe data(physics + detector) as closely as possible
  - MC is tuned to describe the data for physics and also detector effect
- Physics simulation
  - Pythia Drell-Yan LO $\mathbf{p} + \bar{\mathbf{p}} \rightarrow \gamma^*/\mathbf{Z} \rightarrow \mathbf{ee}$ generator (CTEQ5L PDFs)
  - γ^*/Z P_T tweaked to match CDF Run I measurement
    - Additional tuning is applied to match γ^*/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 η 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 : ~90 %, CP efficiency : ~62 %, PP efficiency : ~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 cosθ and ϕ, M(ee) for A_{fb}*





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Angular Distribution in Pt

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

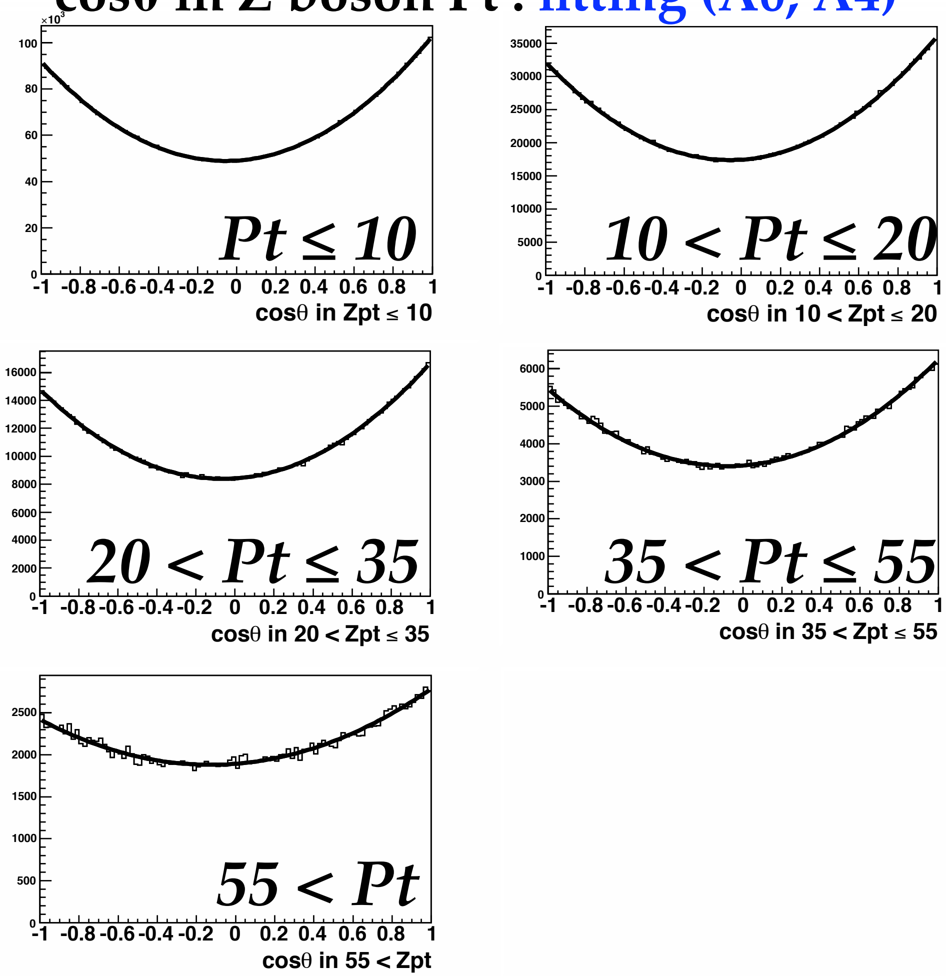
Integrate over all ϕ ,

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

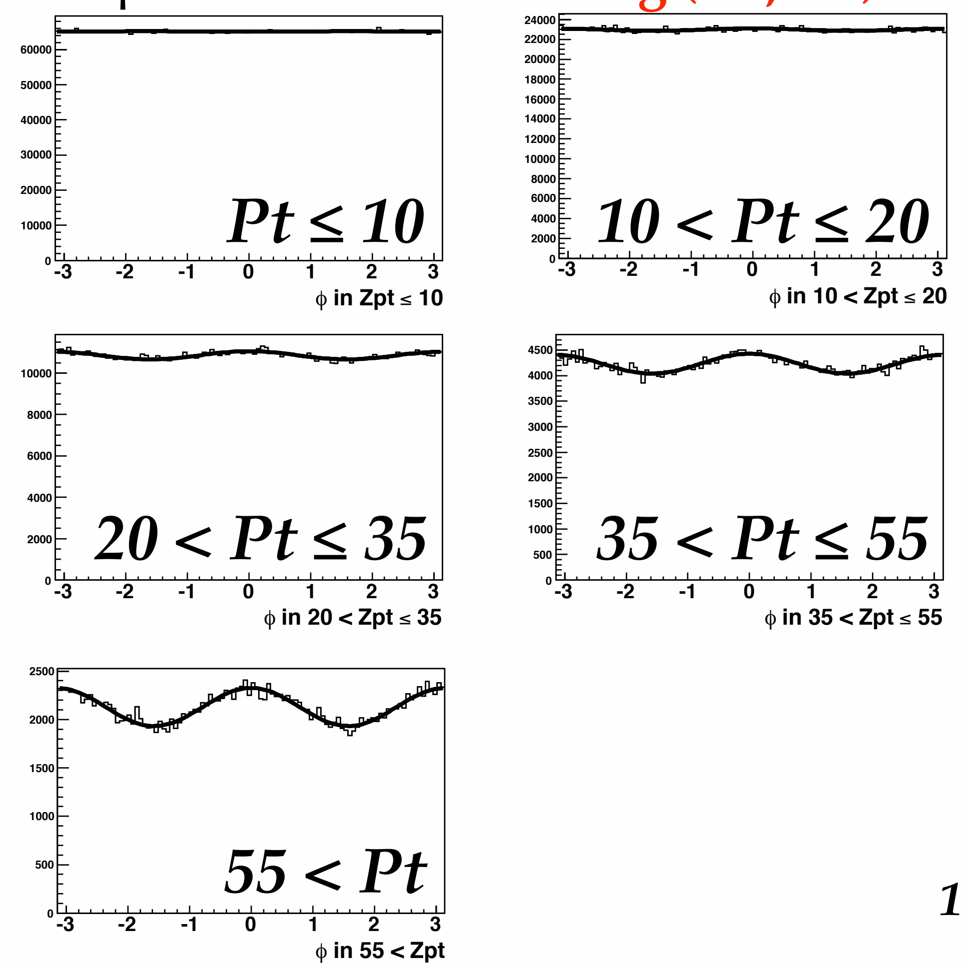
Integrate over all cosθ ,

$$\frac{d\sigma}{d\phi} \propto 1 + \frac{3\pi A_3}{16}\cos\phi + \frac{A_2}{4}\cos 2\phi + \underbrace{\frac{3\pi A_7}{16}\sin\phi}_{=0} + \underbrace{\frac{A_5}{4}\sin 2\phi}_{=0}$$

cosθ in Z boson Pt : fitting (A0, A4)

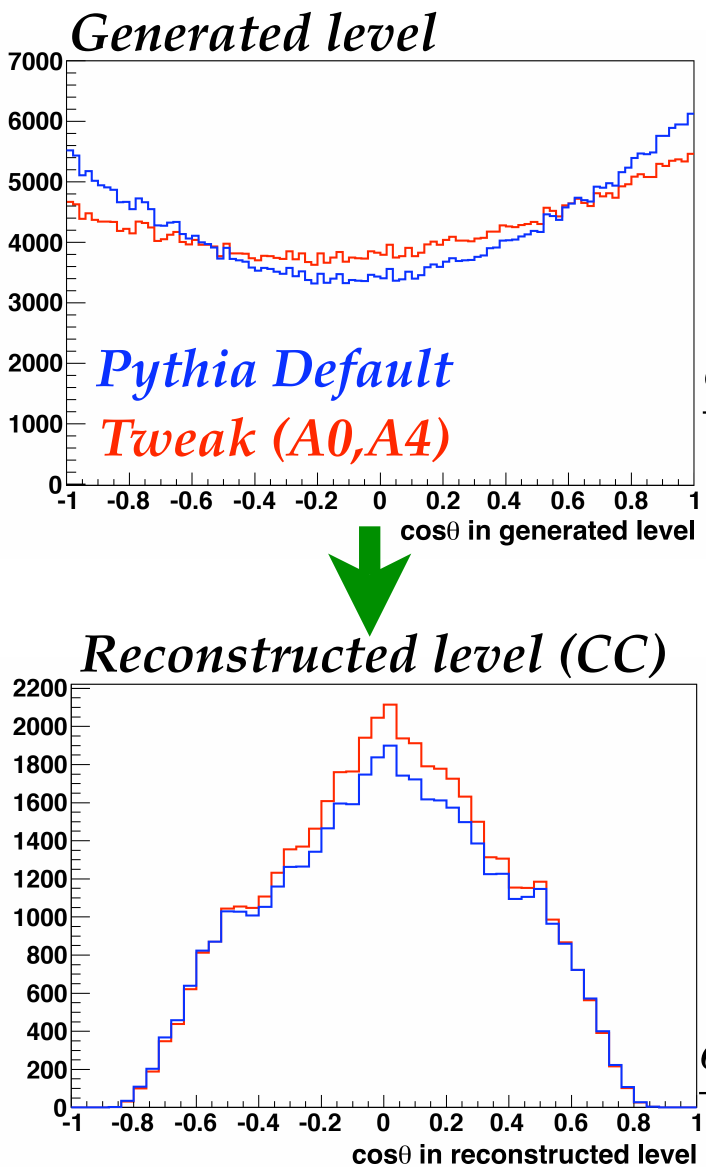


φ in Z boson Pt : fitting (A2, A3)



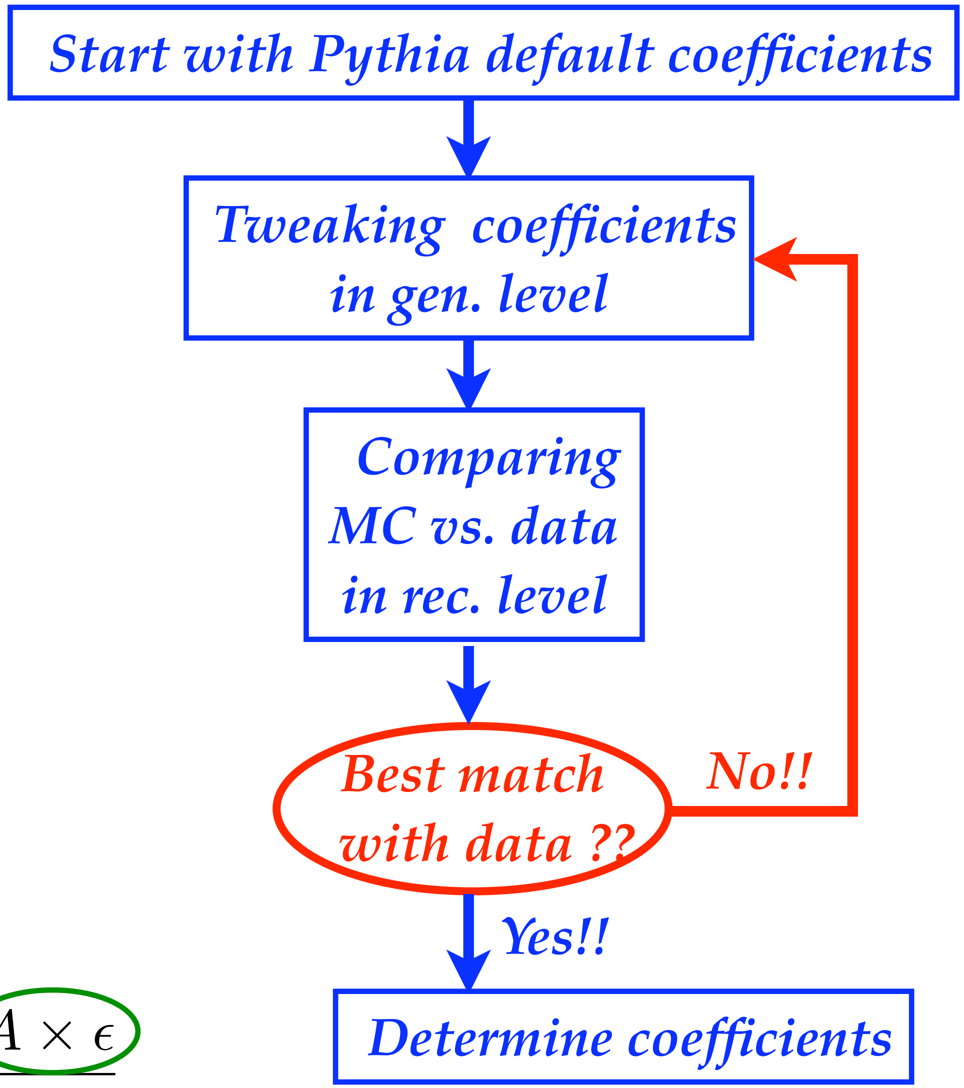
Extracting Coefficients : Fitting Method (general)

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



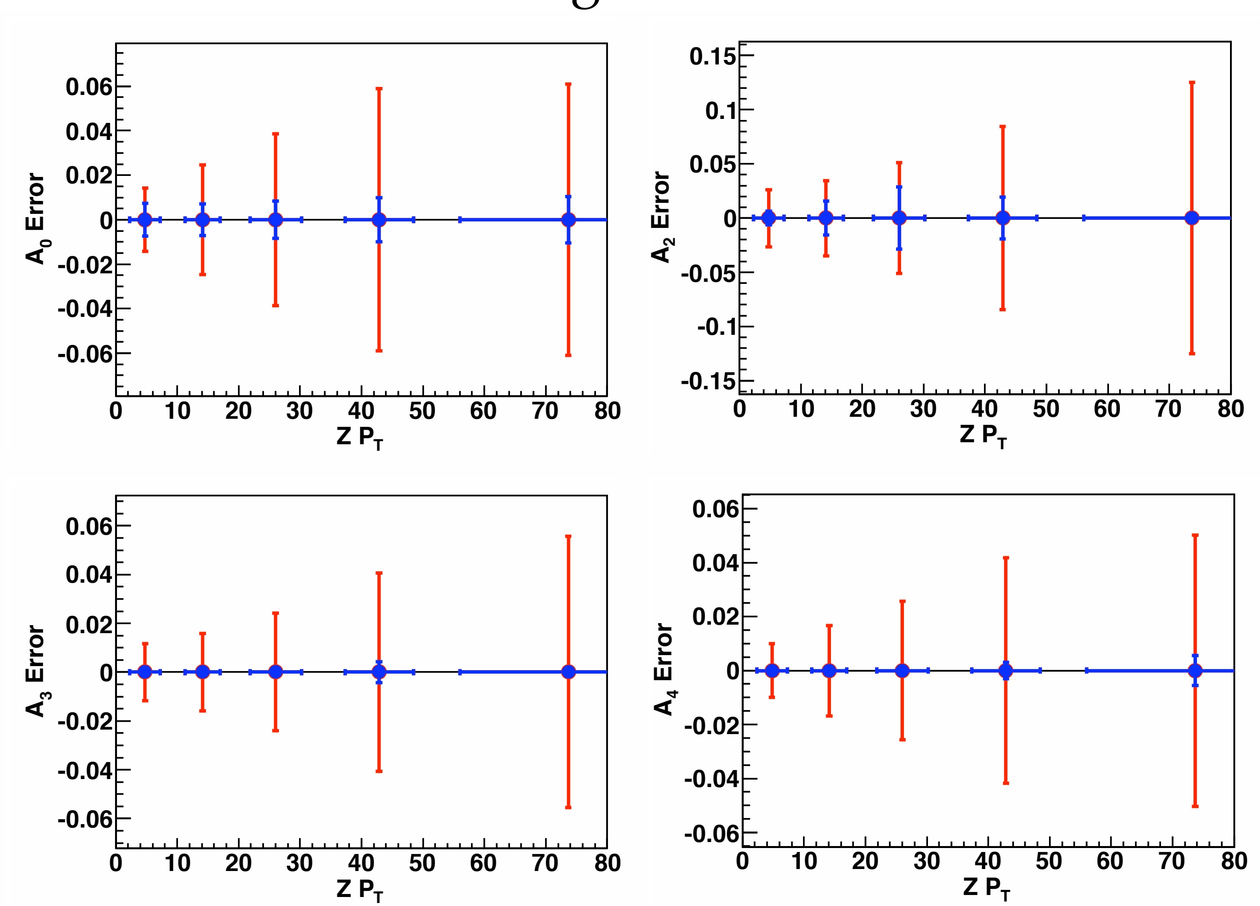
$$\frac{dN_{Gen}}{d\cos\theta}$$

$$\frac{dN_{Gen} \times A \times \epsilon}{d\cos\theta}$$



Systematic Uncertainties

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



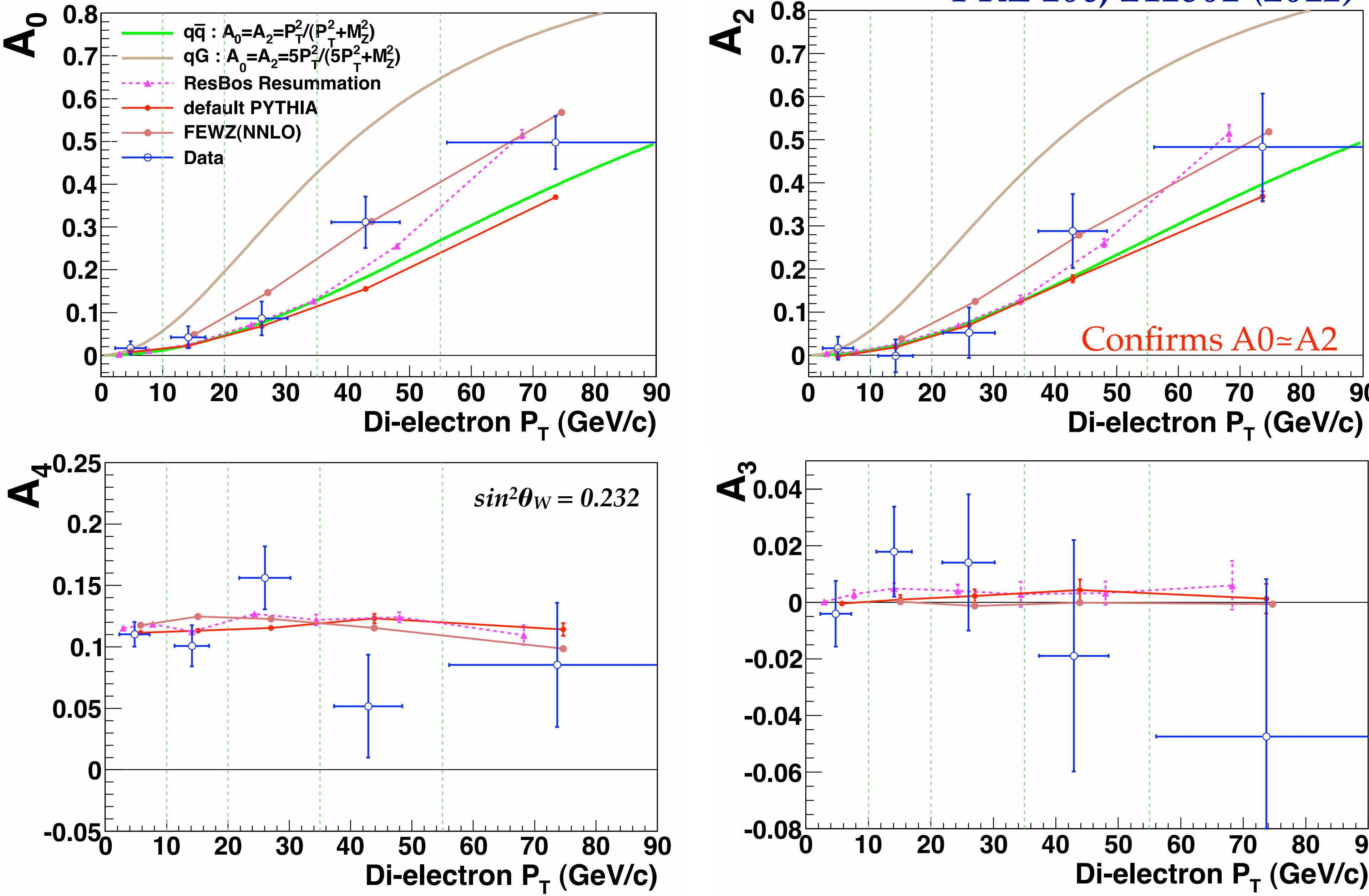
Systematic vs. Statistical

Systematic uncertainty is small compared to statistical uncertainty

Angular Coefficients : $A_{0,2,3,4}$ in Pt

- Parameters in Z Pt : stat. ⊕ syst. error are shown (stat. error is dominant)

PRL 106, 241801 (2011)

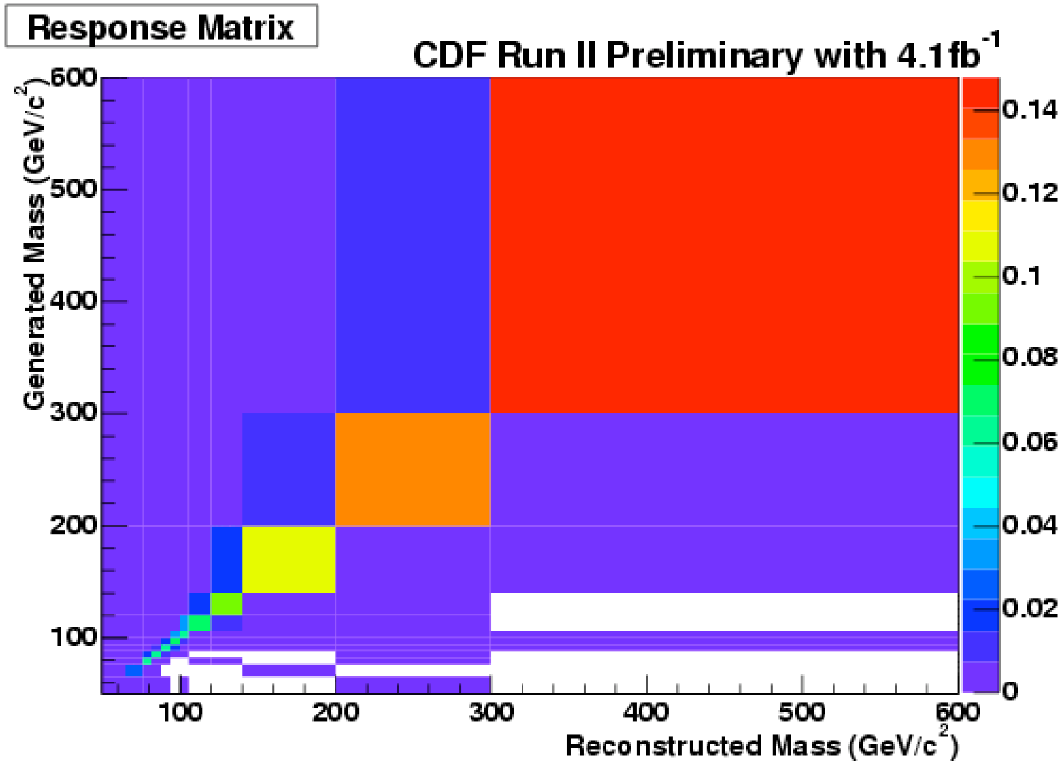


A_{fb} Measurement

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

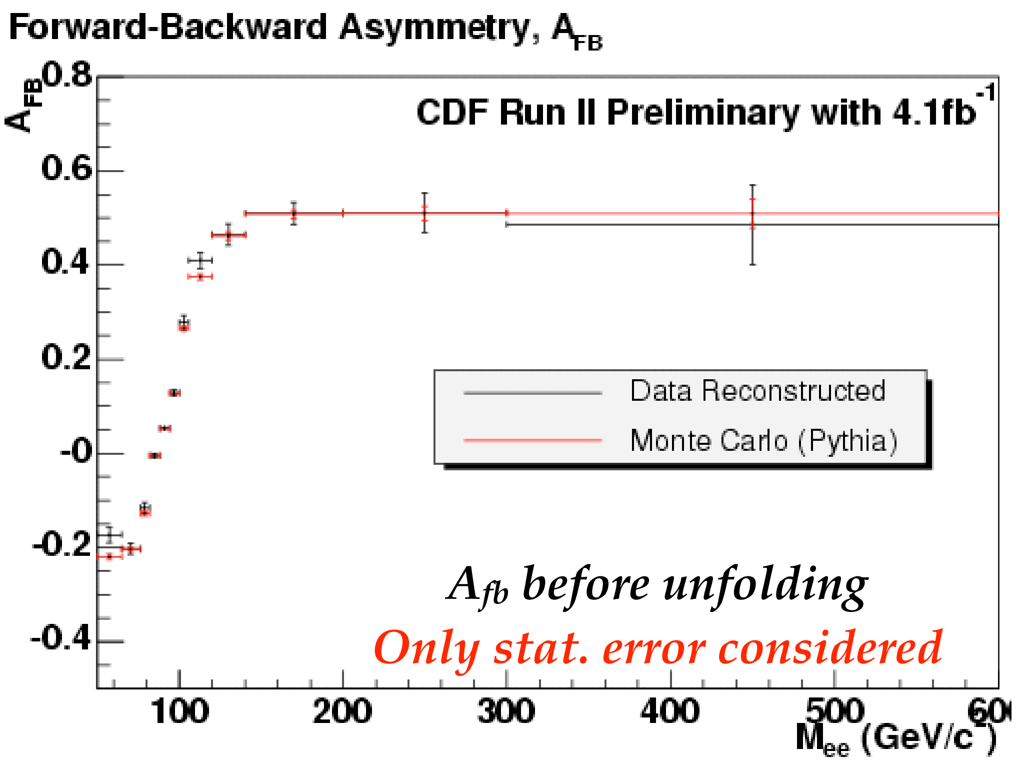
$$A_{fb} = \frac{N_{sig}(\cos\theta > 0) - N_{sig}(\cos\theta < 0)}{N_{sig}(\cos\theta > 0) + N_{sig}(\cos\theta < 0)}$$

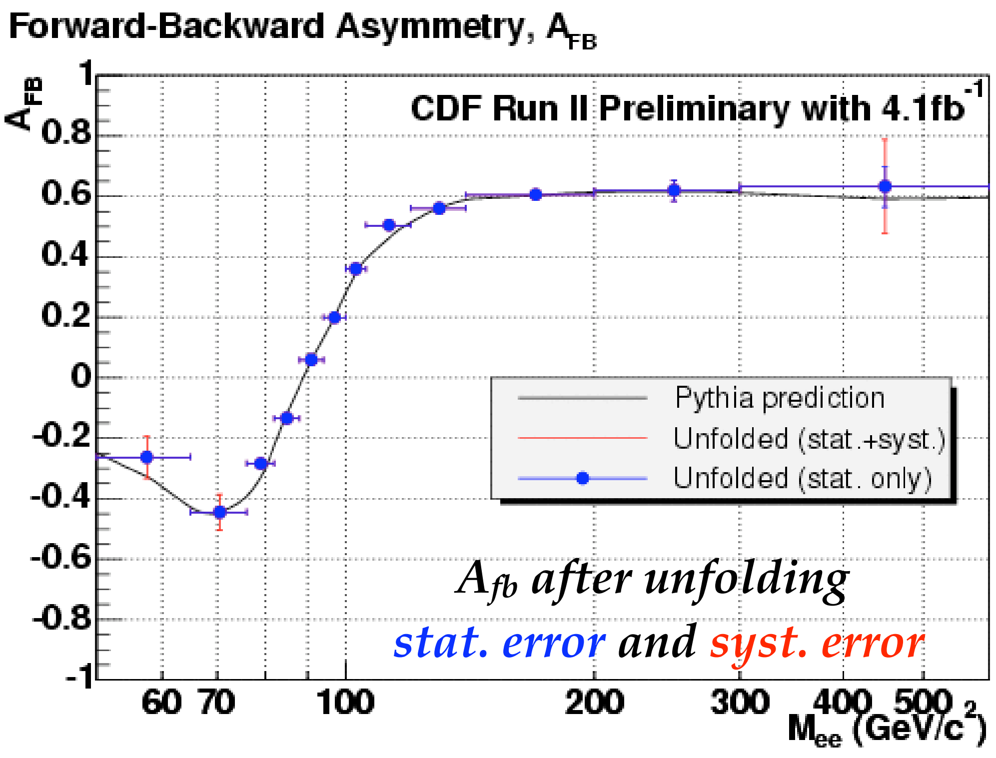
- The measured A_{fb} is unfolded using the response matrix(R_{ij}) inversion
  - The response matrix includes smearing, A×ε, and FSR effect
  - $\mu = R^{-1} (\upsilon - \beta)$ where μ (true value), ν (observation), and β (background)



A_{fb} Result

- A_{fb} before and after unfolding

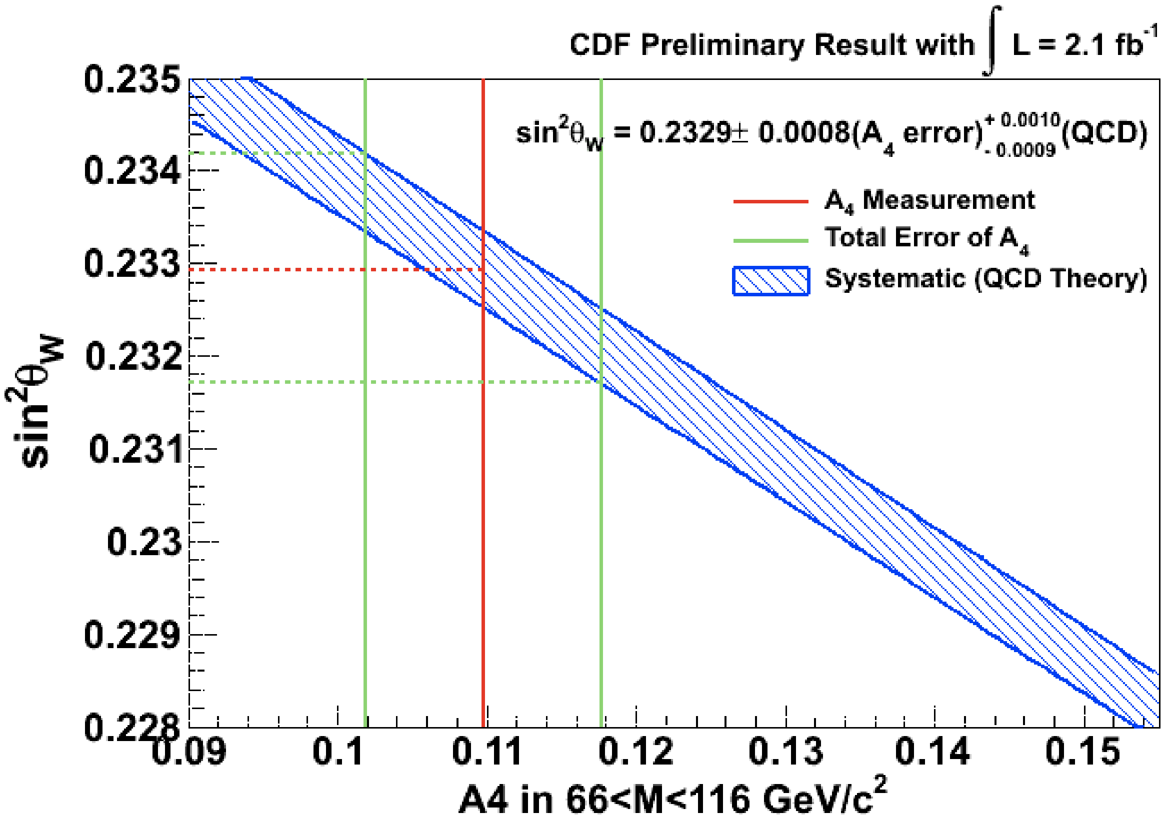




- The measured A_{fb} is compared with PYTHIA prediction
  - The measurement shows a good agreement with the prediction
  - The stat. error is dominant than the syst. error except low and high mass bin

Weinberg angle ($\sin^2\theta_W$) vs. A_4

- A4 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



D0 measurement (PRD 84, 012007) :
$\sin^2\theta_W = 0.2309 \pm 0.0008$(stat.)
$\pm\ 0.0006$(syst.)
extracted from Afb 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 γ^*/Z bosons ***at large transverse momentum***
  - At low Pt, A_0 and A_2 are well described by the annihilation function, $P_T^2/(P_T^2+M_{\mu\mu}^2)$
  - ***At high Pt, 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 Pt***
  - ***The Lam-Tung relation (A_0 - A_2 = 0) is confirmed*** : average of A_0-A_2 = 0.02 ± 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 μμ 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 A0 = A2 : ***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 A0, A2
  - A0 and A2 only depend on the ratio, Pt/Mll

$$A_0^{q\bar{q}} = A_2^{q\bar{q}} = \frac{P_T^2}{M_{\ell\ell}^2 + P_T^2}$$

$$A_4 = \frac{8}{3} A_{fb}(M_{\ell\ell}, P_T, y)$$

$$A_1(+y) = -A_1(-y)$$

$$A_3(+y) = -A_3(-y)$$

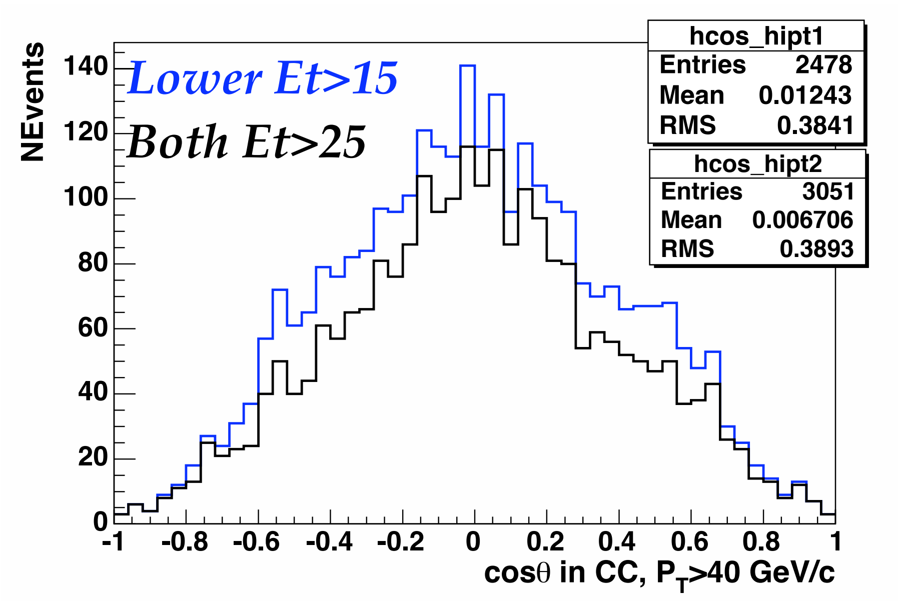
$$A_5 = A_6 = A_7 = 0$$

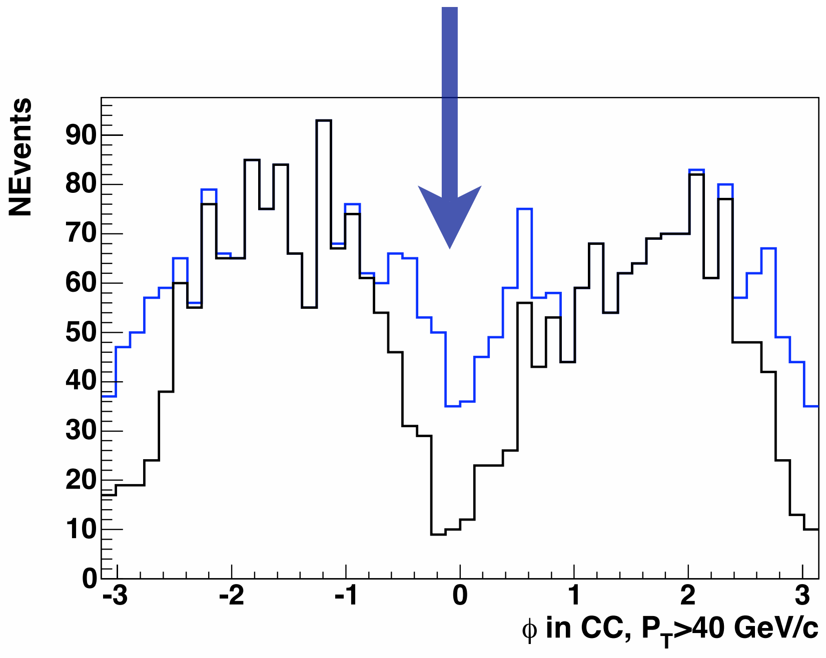
- Approximation for the qg Compton process
  - Angular coefficients are functions of y and depend on PDFs
  - Average value of A0, A2 approximated by

$$A_0^{qg} = A_2^{qg} = \frac{5P_T^2}{M_{\ell\ell}^2 + 5P_T^2}$$

Measurement : Et cut in CC topology

- Event selection : same as for $d\sigma/dy$ 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***





Measurement : Total number of events in Z Pt

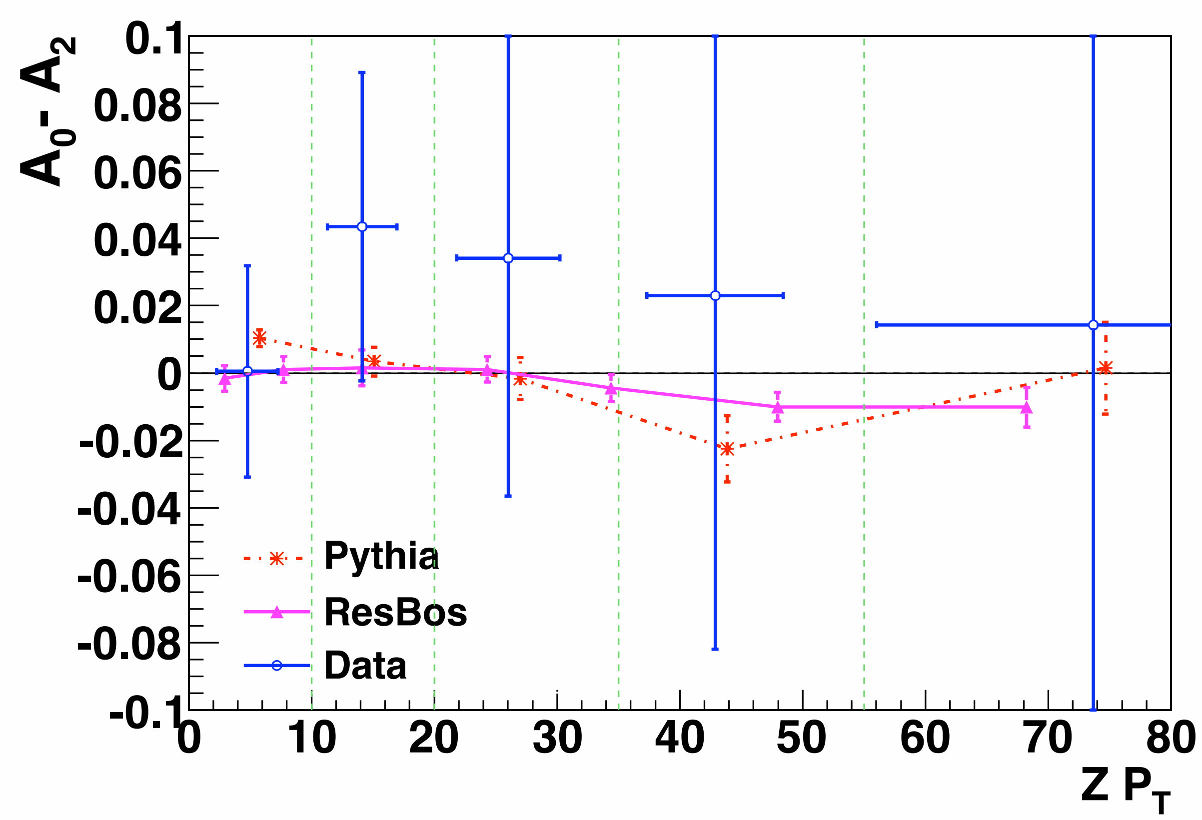
- Total number of the selected events and signal yield in Pt

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

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

Lam-Tung Relation

- Lam-Tung (LT) Relation (A0 = A2)
  - LT relation is only valid for vector gluons (spin 1) : A0 - A2 = 0
  - Scalar gluons (spin 0) : A0 - A2 = -2
  - We measure the average of A0-A2 = 0.02 ± 0.02 (total error)
  - Lam-Tung Relation in Pt is also consistent with zero within uncertainty



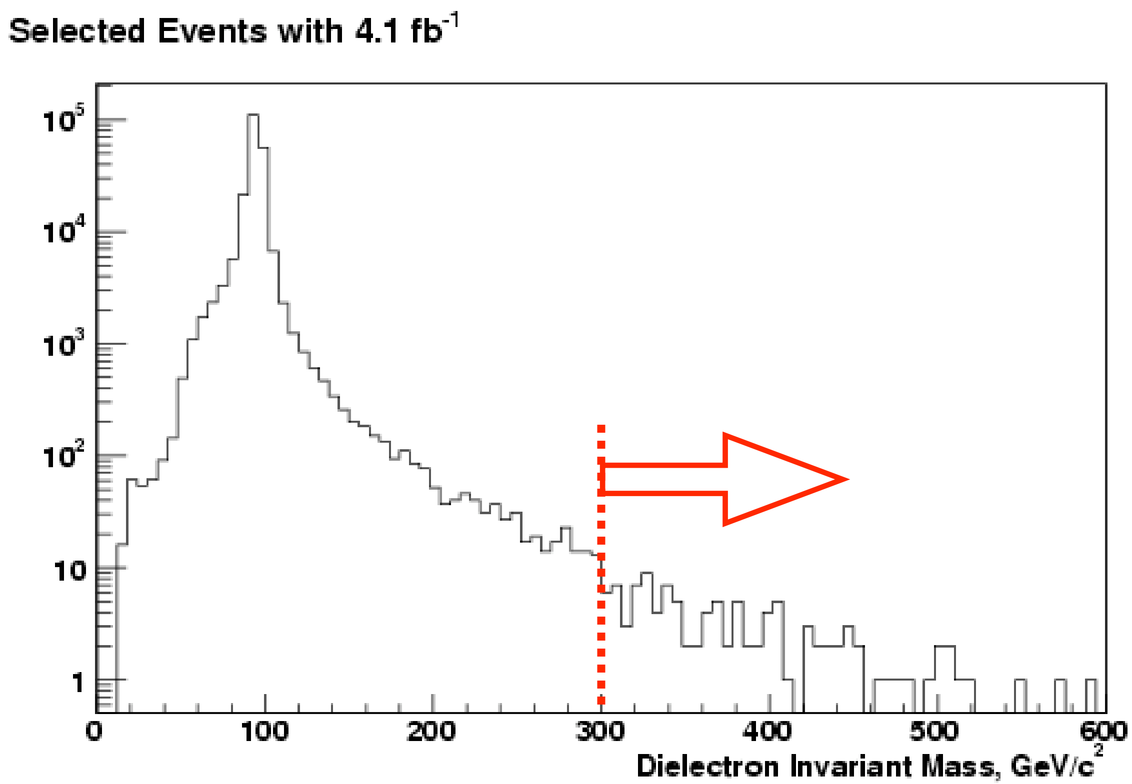
A0 - A2 is consistent with zero
Confirms Lam-Tung Relation

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 X0 of material in central region
    - MC for plug : include an additional 1/6 X0 of material in plug region
    - Estimate the deviation from the default sample
    - Assign the deviation as a systematic uncertainty for material modeling

Z(ee) mass distribution with 4.1 fb^{-1} data

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



M(ee) above 300 GeV/c^2 has only ~ 100 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, $300 < M(ee) < 600$ GeV/c^2, has a large error : only ~ 100 events

$\sin^2\theta_W$ Measurement

$$sin^2\theta_W(CDF) = 0.2329 \pm 0.0008(A_4\ error)^{+0.0010}_{-0.0009}(QCD)$$

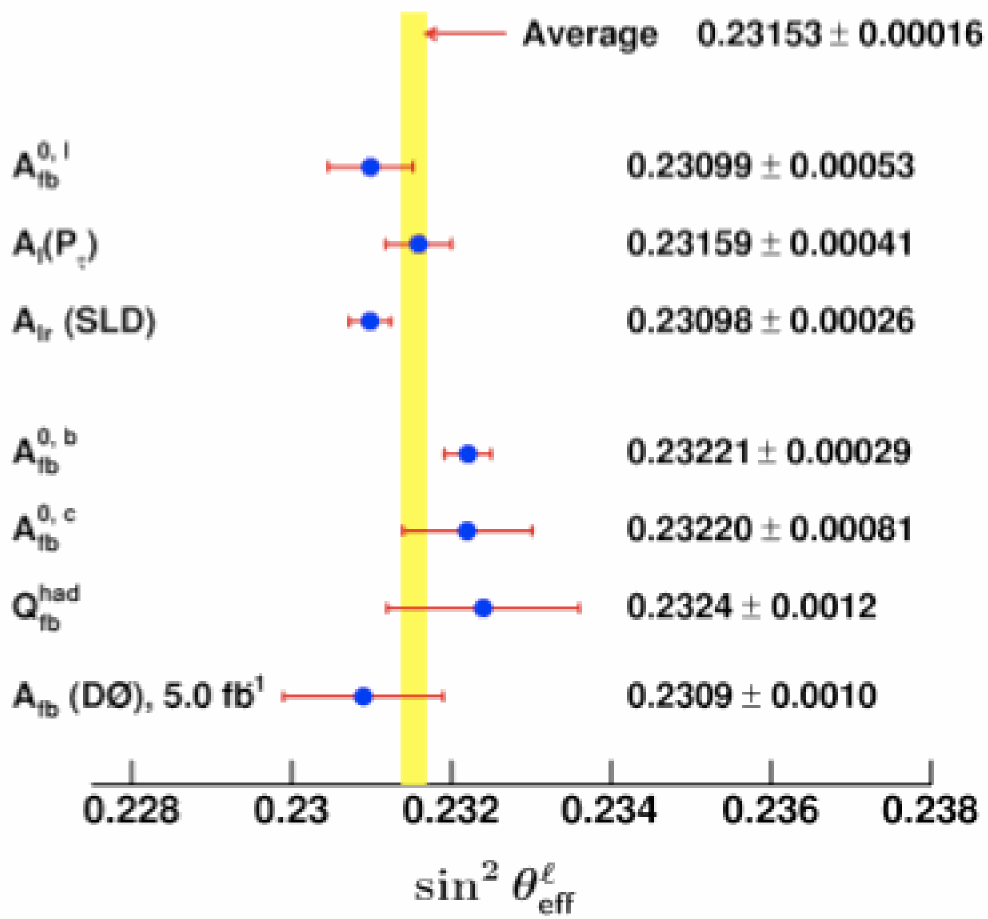


FIG. 6: Comparison of measured $\sin^2\theta^\ell_{eff}$ with results from other experiments. The average is a combination of $A^{0,\ell}_{FB}$, $A_l(P_\tau)$, A_{lr}(SLD), $A^{0,b}_{FB}$, $A^{0,c}_{FB}$, and Q^{had}_{FB} measurements from the LEP and SLD Collaborations.