First measurement of the angular coefficients of Drell-Yan e+e- pairs in the Z boson mass region at the Tevatron

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for the CDF collaboration

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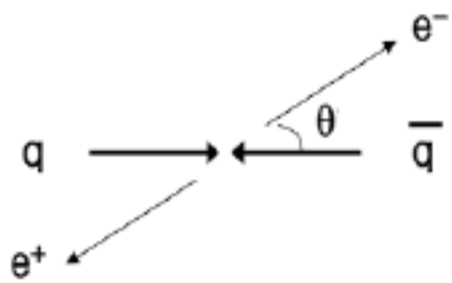
Differential cross section in cosθ and φ

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

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



If Pt of Z boson in lab is zero, Z direction of q-qbar in the CM is along the p and pbar axis

- Differential cross section

$$\frac{d\sigma}{dP_T^2 dy d\cos\theta d\phi} \propto \boxed{(1+\cos^2\theta)} + \boxed{A_4 \cos\theta}$$

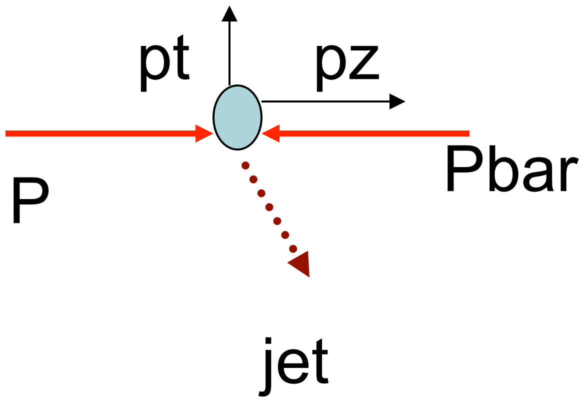
If Pt of the Z boson is not zero, the Z direction of the CM of q-qbar system is not known. It can only be defined on average.

Note: In addition to the q-qbar annihilation process, there is a q-Gluon Compton process.

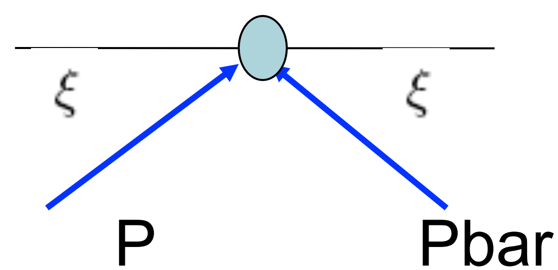
Collins Soper Frame: CM of Z or W Bosons

1. Z axis splits the angle of the incoming P and Pbar beam.
2. X axis along the Pt direction of the Z or W Boson

In lab frame: Z has Pt and Pz



Collins-Soper Frame: CM of Z or DY pair. We do not know if the jet came from a parton in the proton or in the antiproton. So the **q-qbar** axis can be either along the proton, or the **antiproton** direction



Angle of proton and antiproton direction with respsect to the z axis of Collins-Soper

$$\sin^2 \xi = \frac{P_T^2}{P_T^2 + M_{\ell\ell}^2}$$

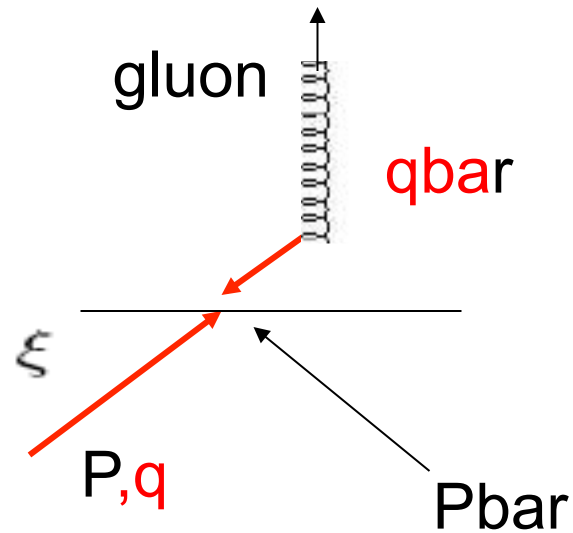
QCD spin 1 gluons (or QED spin 1 photons) quark helicity is conserved when a gluon or photon is emitted.

$$\frac{d\sigma}{d\cos(\theta)} = A\left[(1+\cos^2\theta') + \frac{B'}{A}\cos\theta'\right]$$

In q-qbar (Z boson) CM

$$\sin^2\ \xi = \frac{P_T^2}{P_T^2 + M_{\ell\ell}^2}$$

Angle of q-qbar Z axis with respect to Collins-Soper frame, there are two possibilities depending on where the gluon jet originated. We are in the CM of the q-qbar, but do not know the correct Z axis



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

Rotate from q-qbar CM to Collins Soper frame.

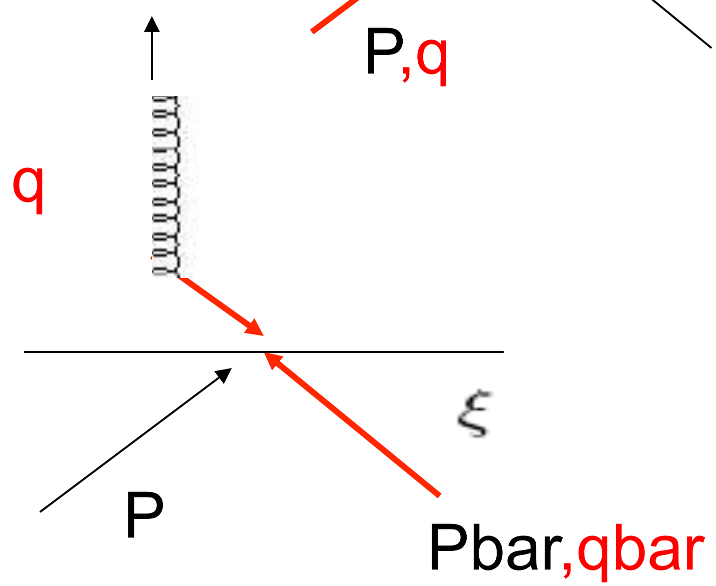
A0 $$+ \frac{\sin^2\xi}{2}(1-3\cos^2\theta)$$

$$+ \Delta P\ \cos\xi\sin\xi\ \sin 2\theta\cos\phi$$

A2 $$+ \frac{\sin^2\xi}{2}\ \sin^2\theta\cos^2\phi$$

$$+ \Delta P\frac{B'}{A}\ \sin\xi\ \sin\theta\cos\phi$$

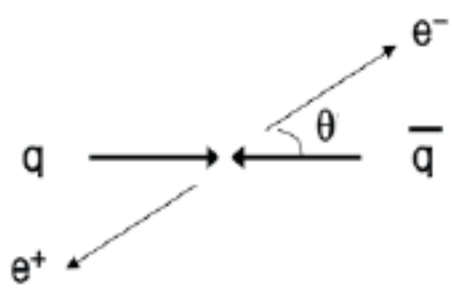
A4 $$+ \frac{B'}{A}\cos\xi\cos\theta]$$



Differential cross section in cosθ and ϕ

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

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



in lepton plane

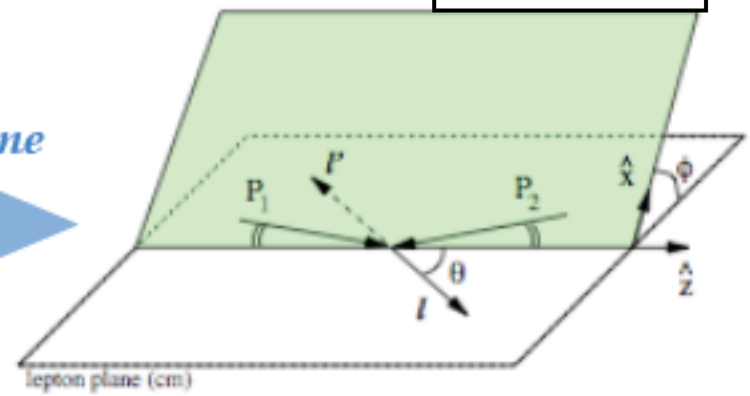


FIG. 1: The Collins-Soper frame.

- Differential cross section of cosθ and ϕ

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

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

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

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

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

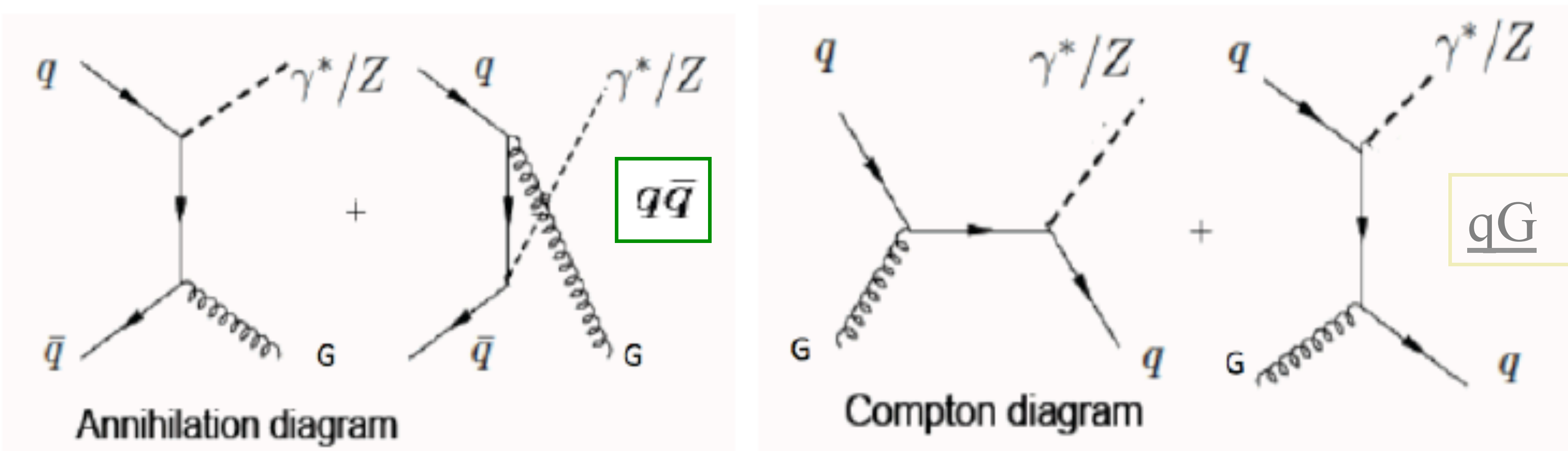
******All higher order terms are zero at Pt=0***

Physics Motivation : Drell-Yan Process

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

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

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



- The angular distribution of the final state e+e- is different for these two processes
- A measurement of the angular distribution in Pt provide a detailed test of the production mechanism of gauge boson with finite Pt

For spin 1 gluons QCD predictions:

$\boxed{\text{A0=A2 (Lam Tung relation)}}$

This holds for both annihilation and Compton diagrams

(For spin 0 gluons A0-A2 is large - about 2)

Annihilation process QCD prediction

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

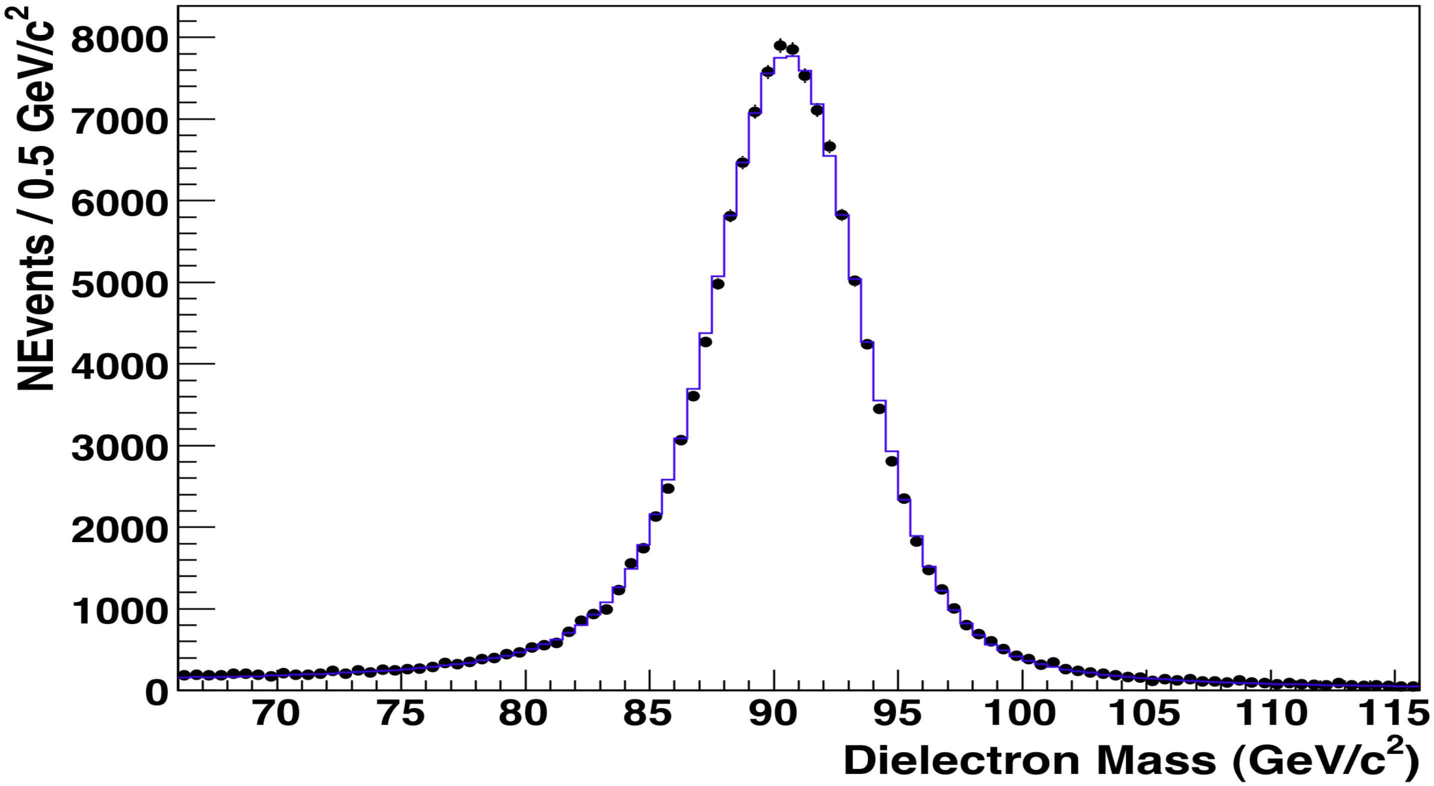
Compton process, A0 and A2 are approximated by

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

Therefore, a measurement of A0 and A2

(1) Tests the spin of the gluon,

(2) Determines the relative contributions of the two processes



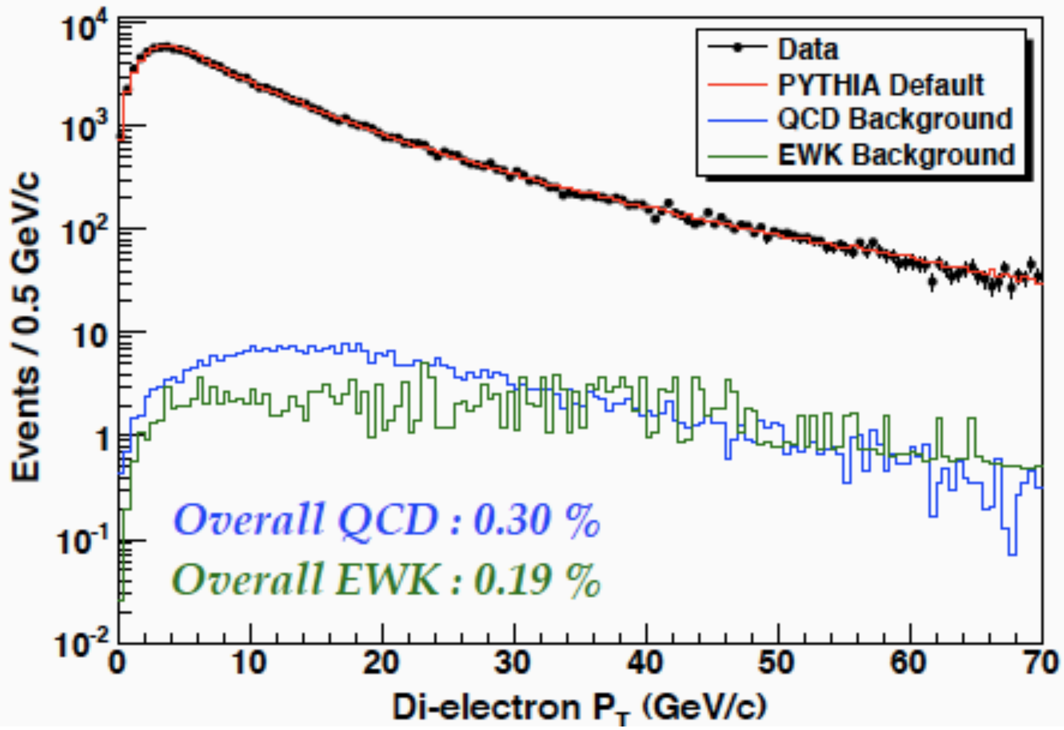
The sample, 140,000 Z’s (mass window 66 to 116)

Require that both leptons have a track, and that both leptons are isolated.

CDF has Central (C) and Plug (P) calorimeters. Use CC, CP and PP events.

Measurement : Background

- Background Contribution
  - QCD background in data - measured by isolation and mass fit method
    - CC: 0.24 ± 0.03%, CP: 0.22 ± 0.03(stat.) ± 0.55(sys.)%, PP: 0.67 ± 0.12 ± 0.23%
    - Pt shape of background sample is normalized to overall background rate
  - EWK background - estimated using MC samples
    - WW / WZ, inclusive ttbar, inclusive W+jets, $Z \rightarrow \tau\tau$ are considered
  - Background in Z Pt (CC+CP+PP topology)



All background is subtracted in cosθ and φ

Background sample (data) used for QCD

Simulation sample used for EWK

Angular Distribution in Pt

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

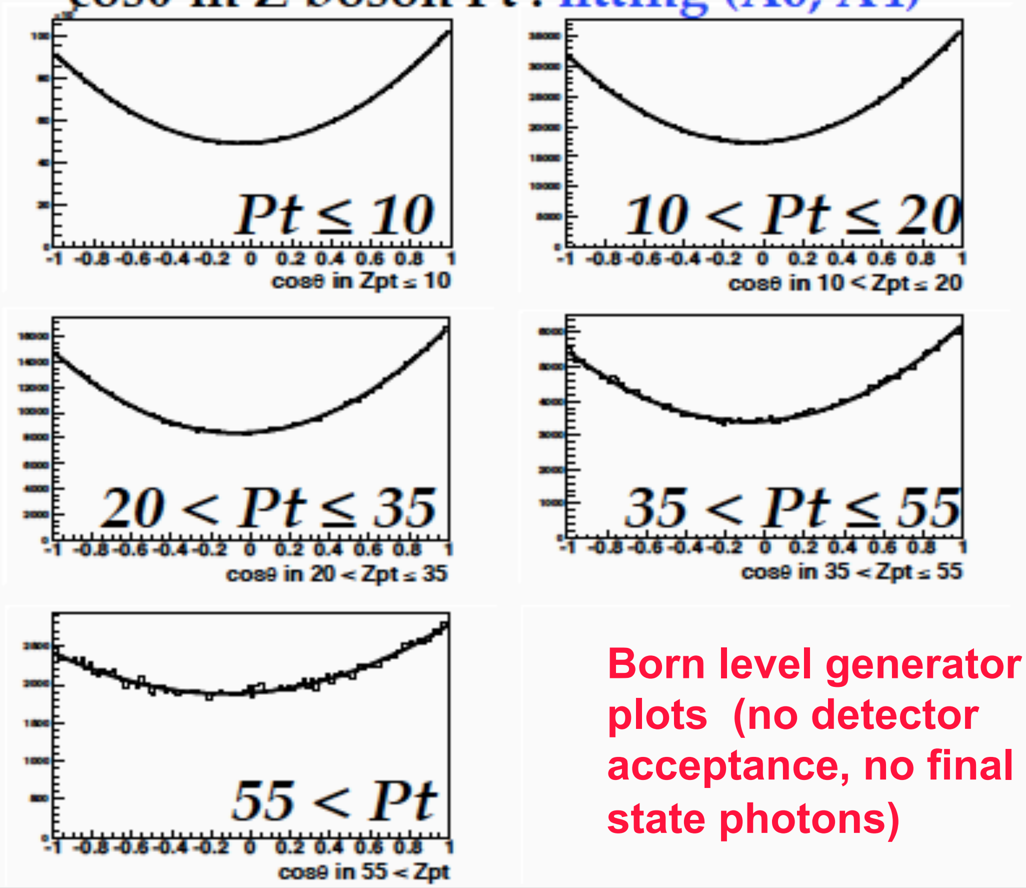
Integrate over all ϕ ,

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

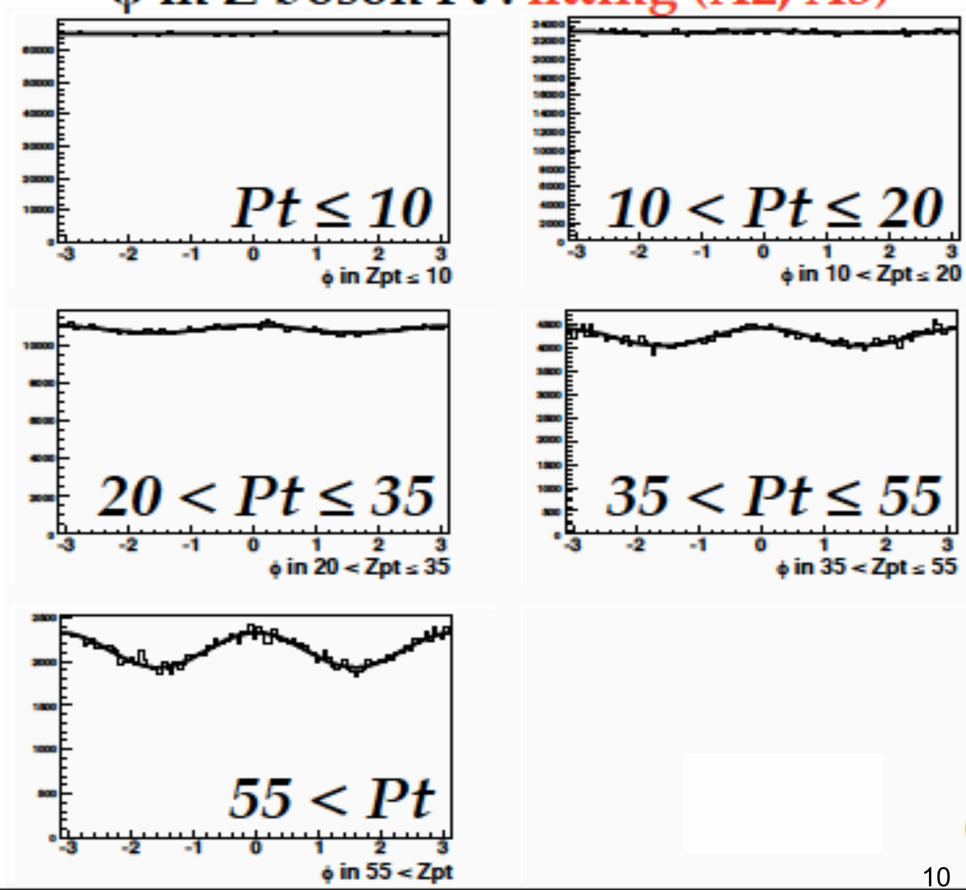
Integrate over all $\cos\theta$,

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

cosθ in Z boson Pt : fitting (A0, A4)



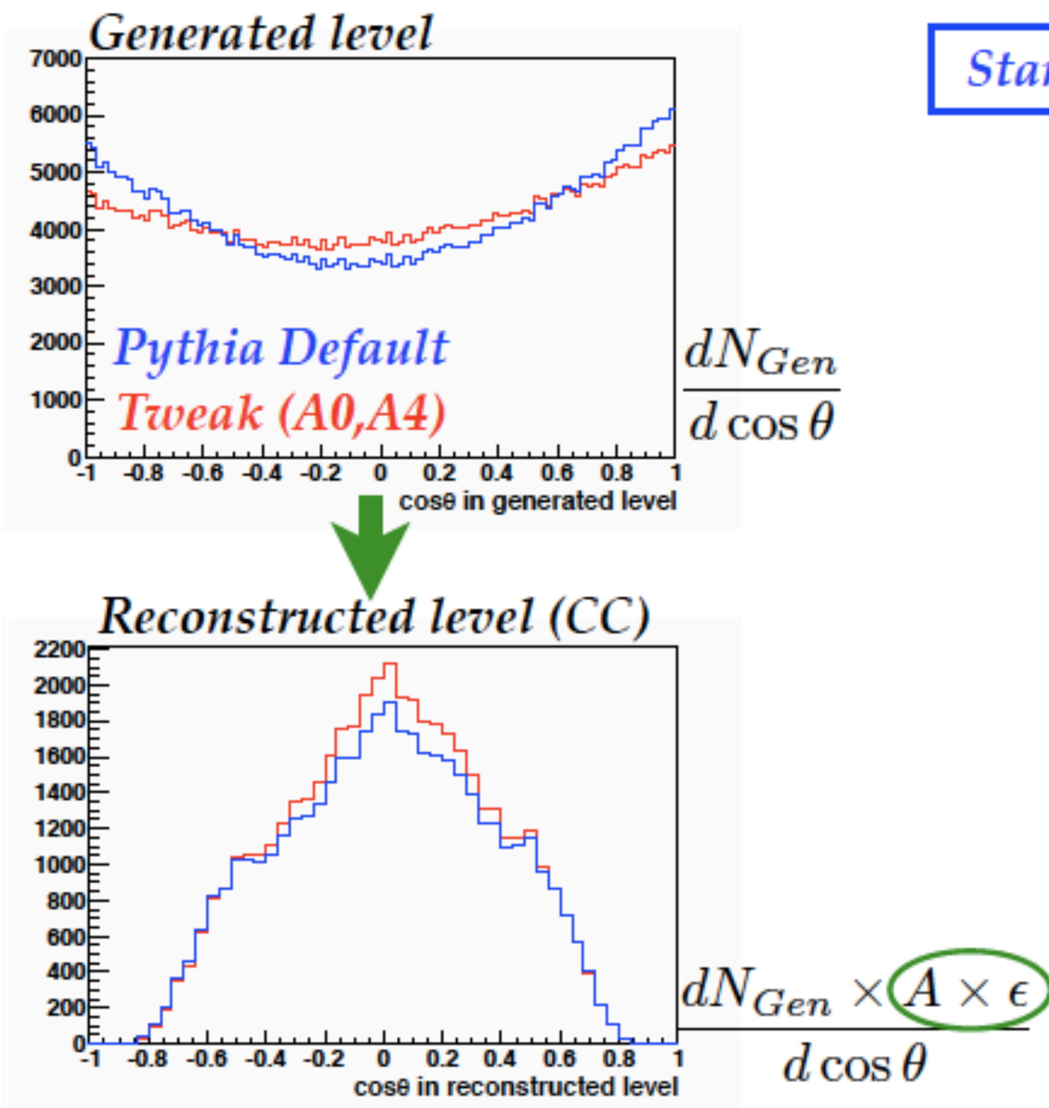
φ in Z boson Pt : fitting (A2, A3)

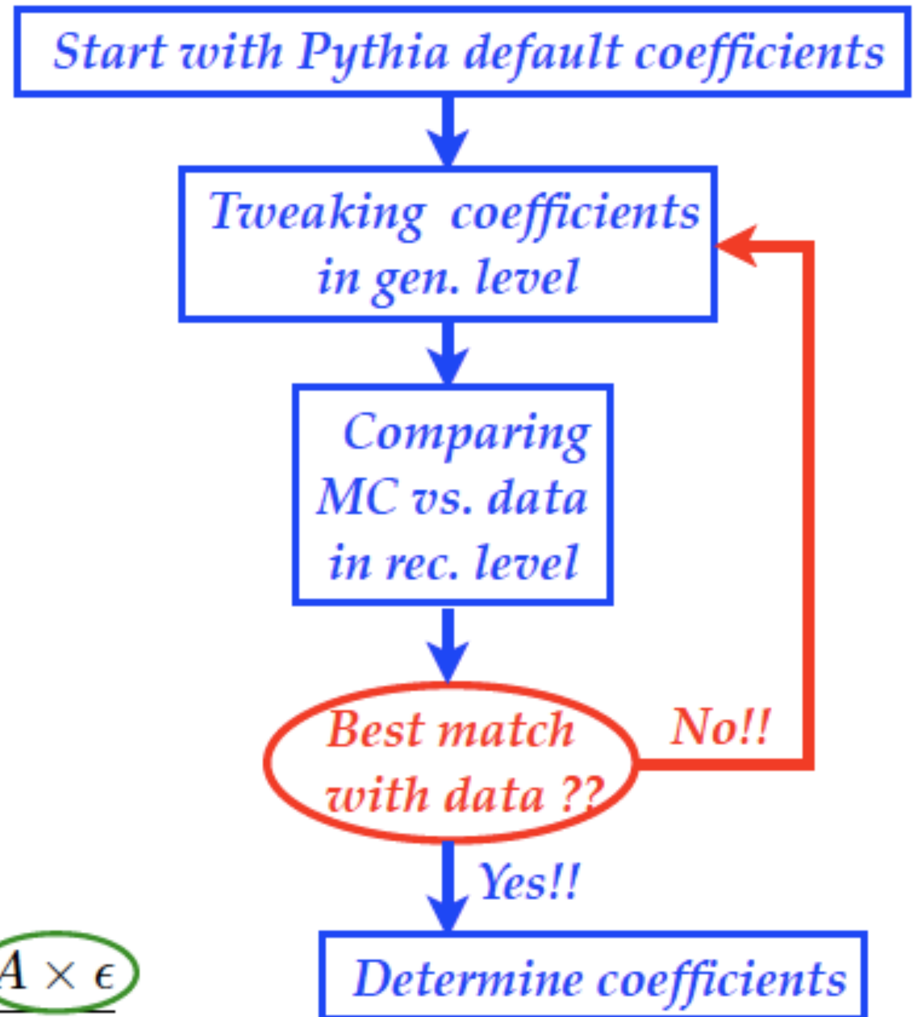


Born level generator plots (no detector acceptance, no final state photons)

Extracting Coefficients : Fitting Method (general)

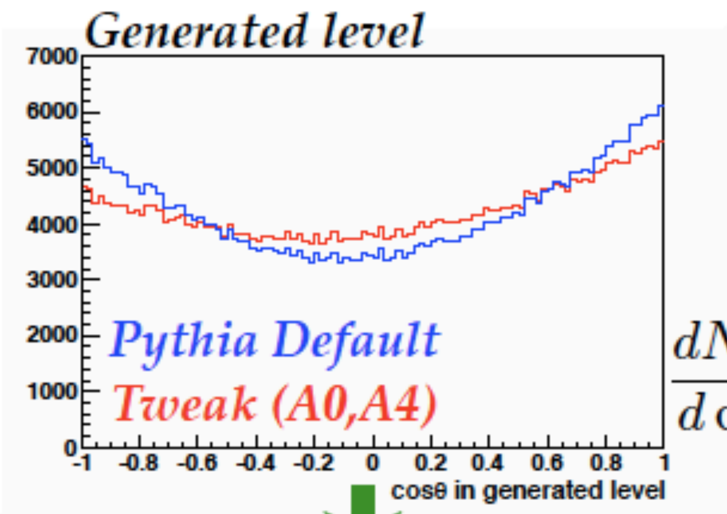
- Extraction the coefficients using the fitting method
  - Tune CDF MC (Pythia) to match with data in the reconstructed level



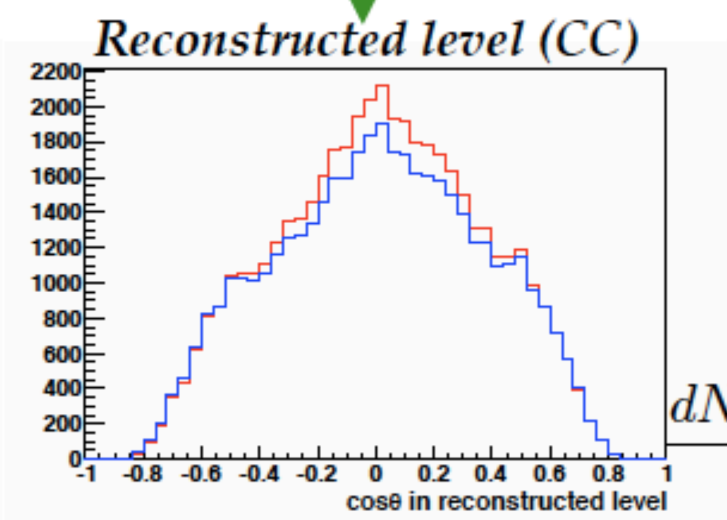


Extracting Parameters : Fitting Method (details)

- Extraction the parameters using the fitting method
  - Tune CDF MC (Pythia) to match with data in the reconstructed level



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



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

Integrate over all ϕ ,

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

(A0,A4) change makes different cosθ shape

***Change is not same between Gen. vs. Rec. level because of Axε effect*

Makes (A0,A4) grid points

***Other parameters are same as Pythia default*

***Each grid point has a different cos**θ** shape*

*Calculate $\mathcal{L}$ of cos**θ**(Rec.) in each (A0,A4) point*

Find (A0,A4) point which maximizes $\mathcal{L}$

Extract values for (A0,A4)

Same procedure for ϕ distribution except (A0,A4) → (A2,A3) and

$$\frac{d\sigma}{d\phi} \propto 1 + \frac{3\pi A_3}{16}\cos\phi + \frac{A_2}{4}\cos 2\phi$$

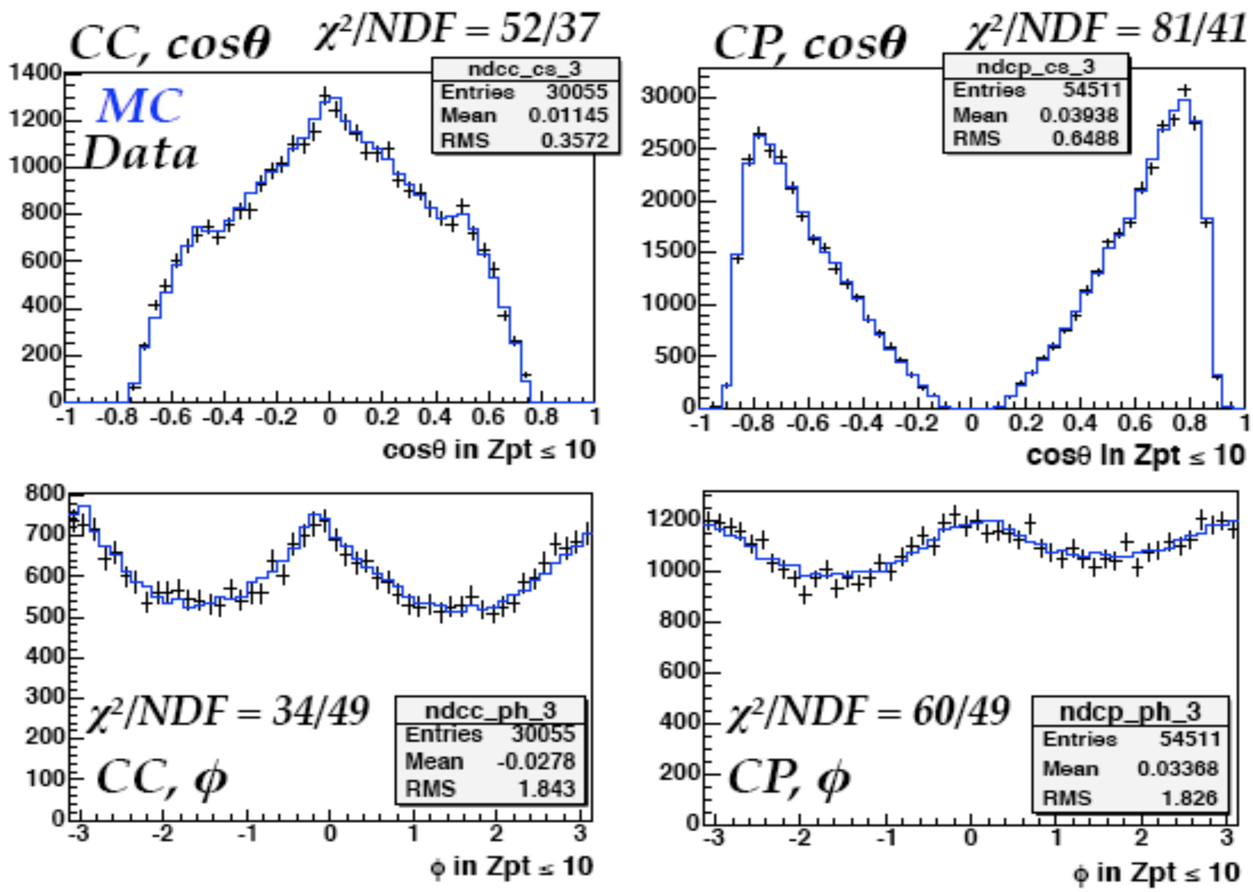
Data vs. MC in cosθ and ψ

Example at low Z PT

- cosθ and φ distribution in data and MC - Pt < 10 GeV/c

Example: Central-Central and Central-Plug leptons Z PT<10

- Calculate χ^2 in each topology and combine χ^2 to extract data values



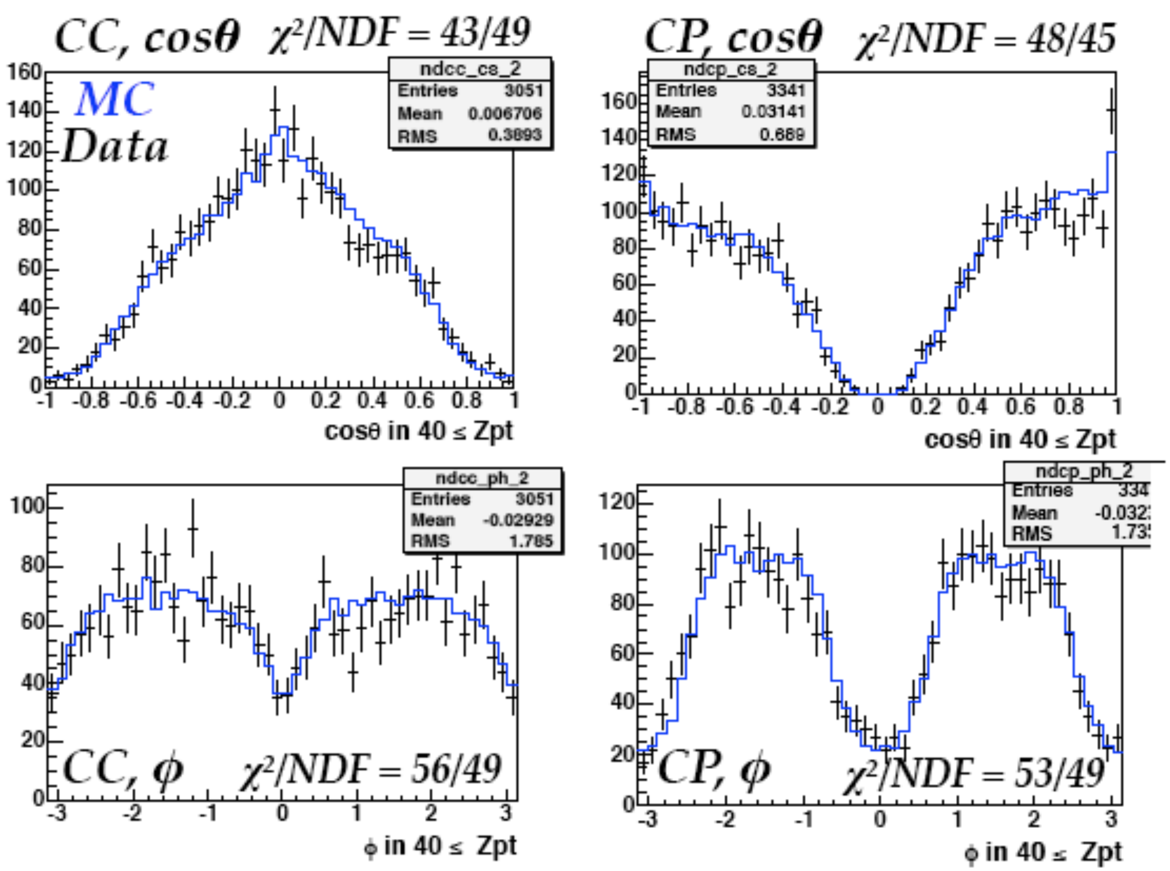
Central-Plug topology yields acceptance at large cos(θ)

Data vs. MC in cosθ and ψ in high Pt

- cosθ and ϕ distribution in data and MC - Pt > 40 GeV / c

Example: Central-Central and Central-Plug leptons Z PT>40

- Calculate χ^2 in each topology and combine χ^2 to extract data values



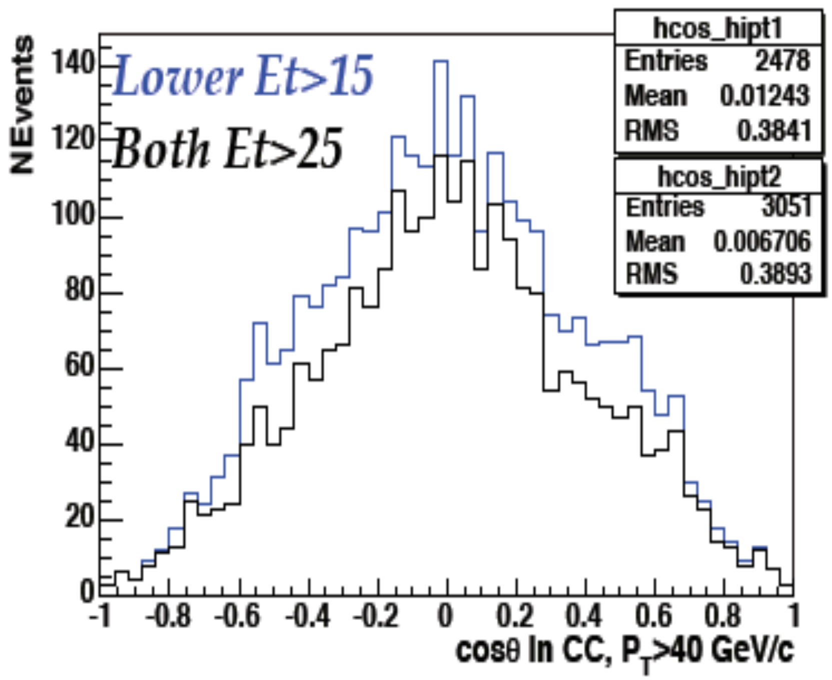
Example at high Z PT. Central Plug topology yields acceptance at large cos(θ).

However, Lepton Et cut of 25 GeV --- limits acceptance at ϕ=0

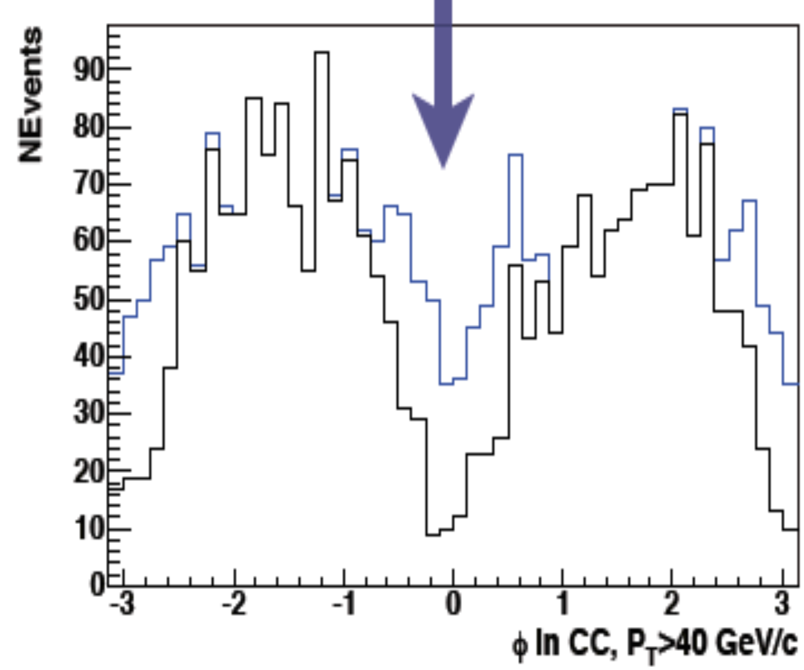
Acceptance effects are important: Previous CDF analysis required lepton Et> 25 GeV for each lepton. This lepton Et cut limits acceptance for high Pt Z bosons.

- 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***

Central-Central

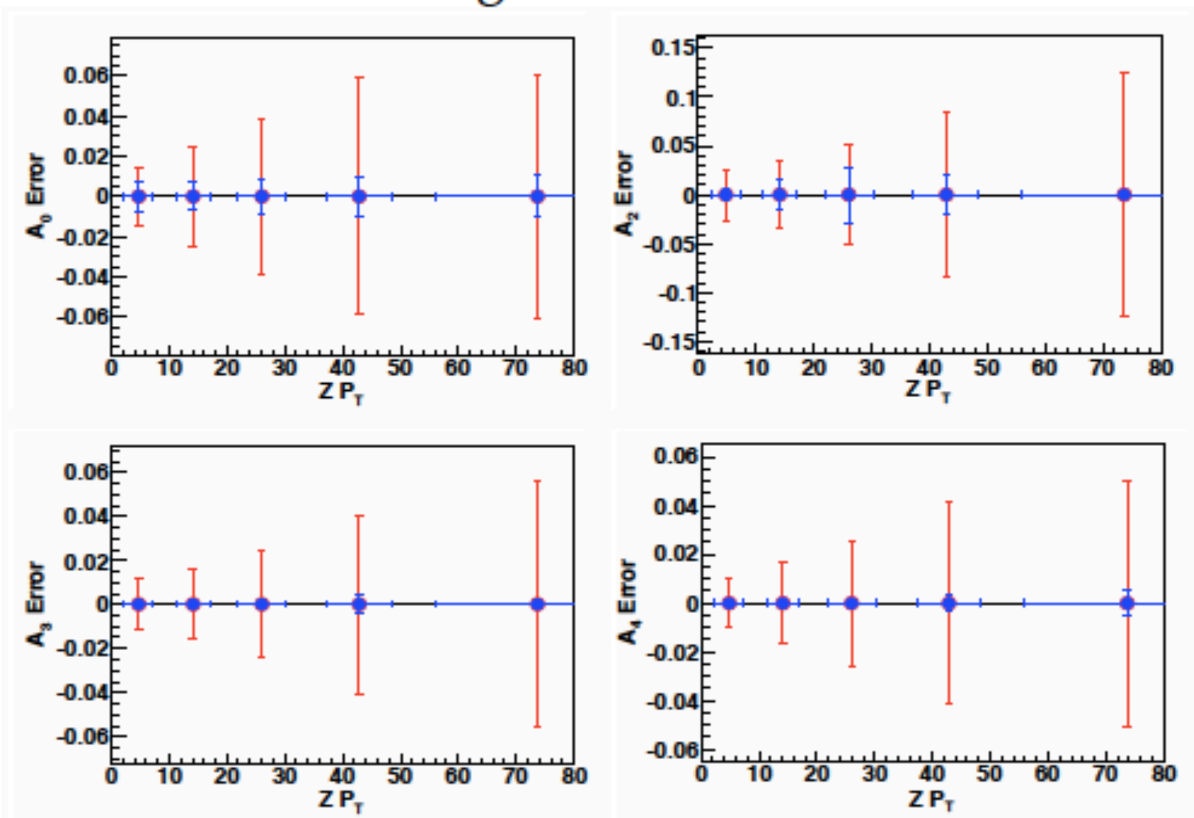


Central – Central



Systematic Uncertainties

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

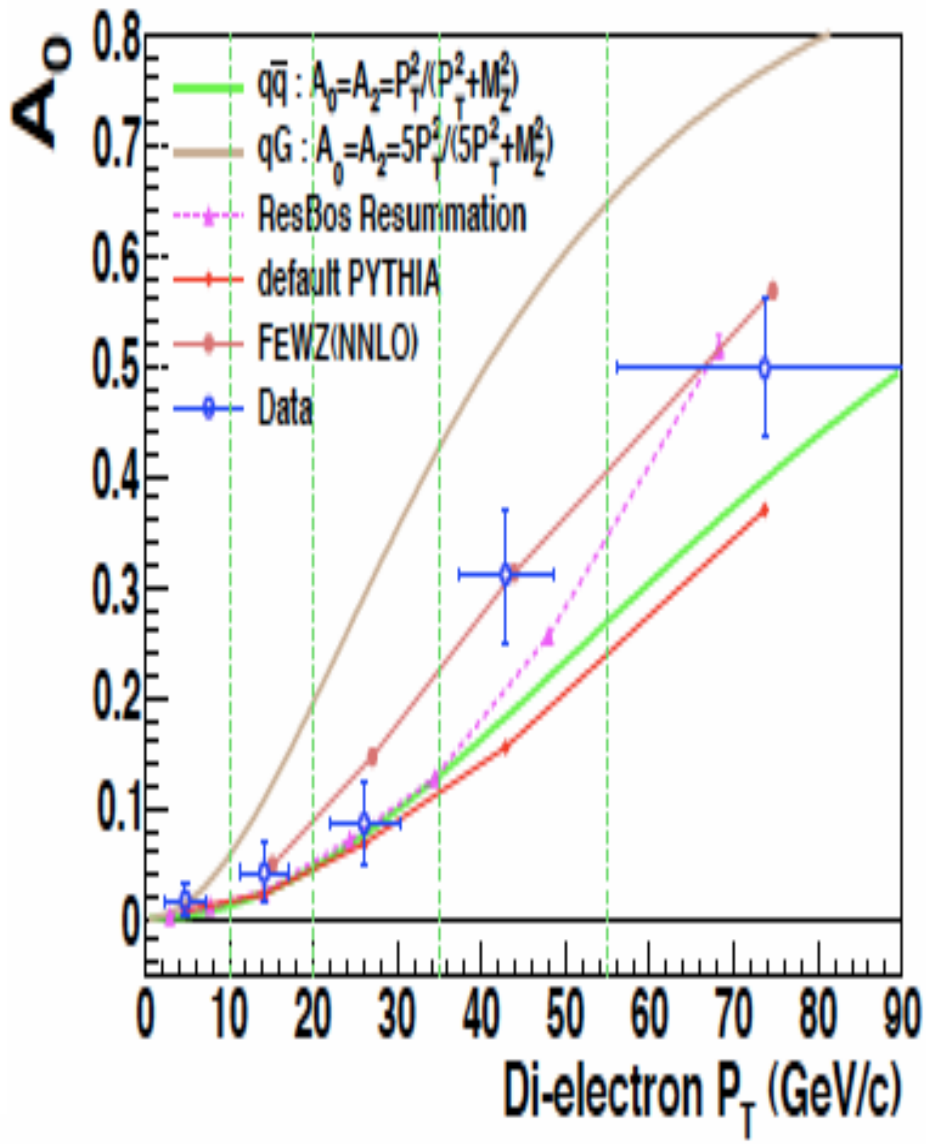


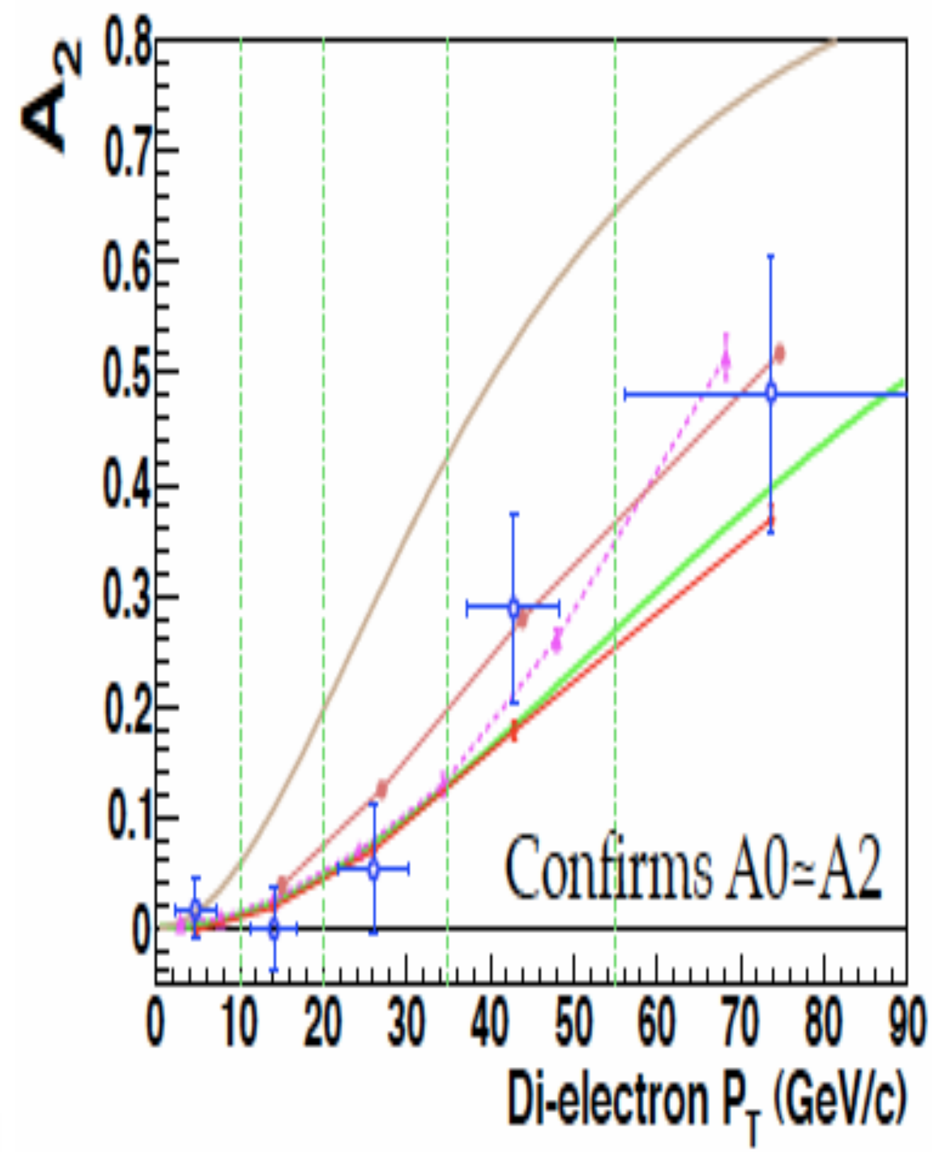
Systematic vs. Statistical

Systematic uncertainty is negligible compared to statistical uncertainty

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

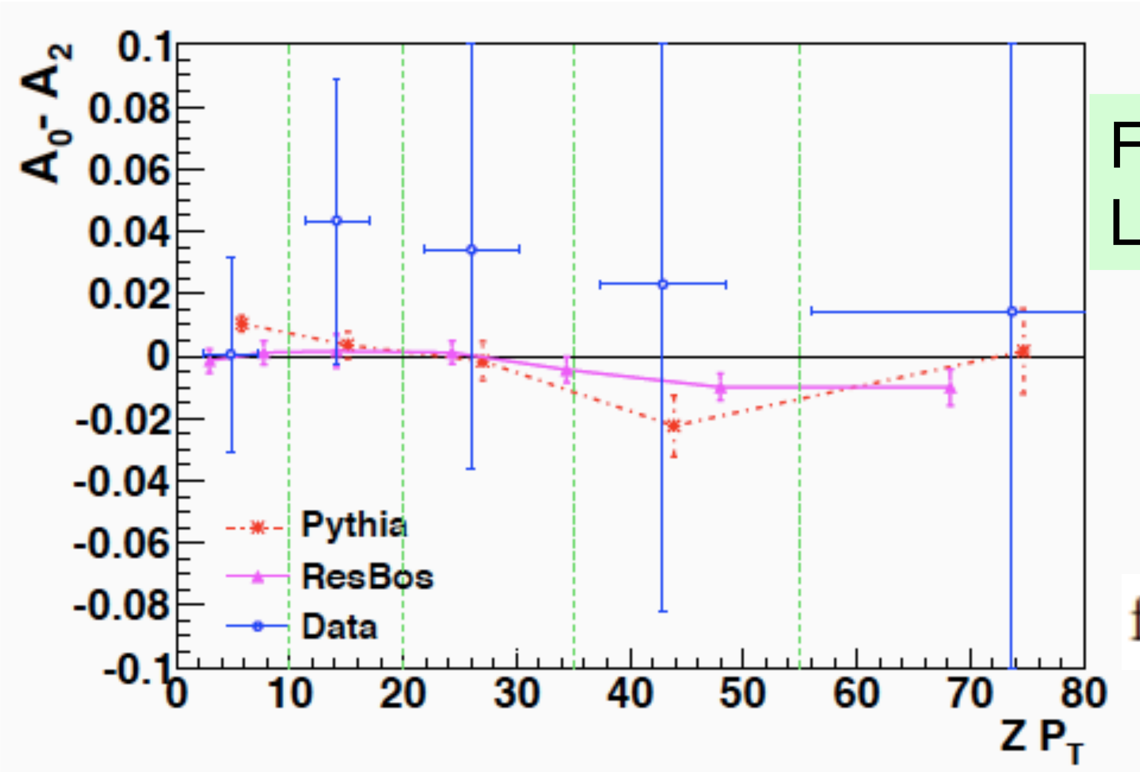
- Parameters in Z Pt : stat. ⊕ syst. error are shown (stat. error is dominant)





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



First definitive test of the Lam Tung Relation.

Agrees with Spin 1 gluons.

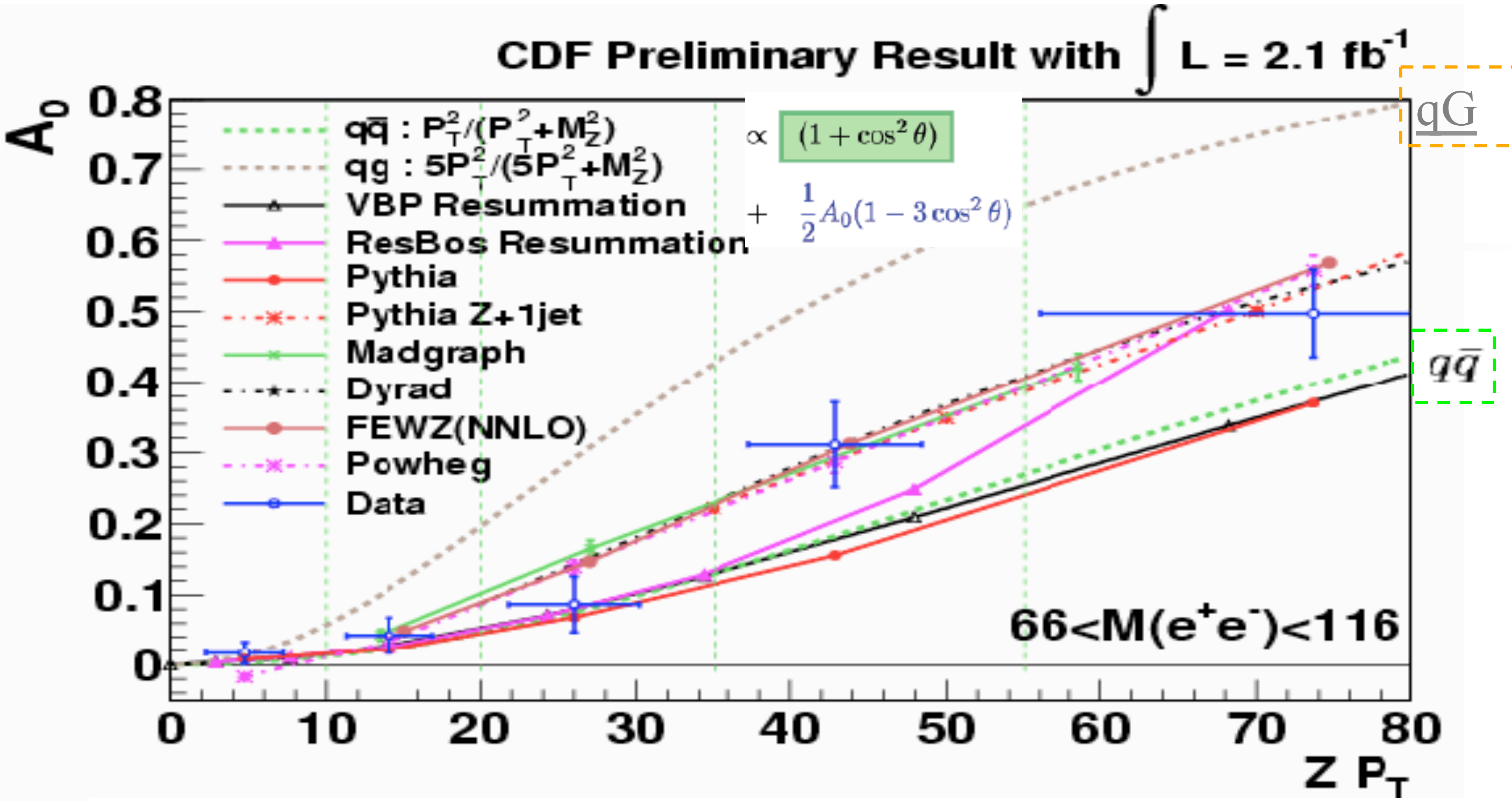
Previous test of the gluon spin were done at PETRA from a study of 3-jet events

$(e^+e^- \rightarrow q\bar{q}\ G)$

First definitive experimental test of the Lam Tung relation A0=A2, as expected for spin 1 gluons.

What about previous results in Drell-Yan experiments?

Previous fixed target tests of the Lam Tung relation at low Pt and low dilepton mass were inconclusive because of issues of non-perturbative effects at low Pt and low mass, some experiments were consistent with the Lam Tung relations and some were not. All had large errors.



A0 agrees with fixed order perturbation theory:

FEWZ(NNLO), DYRAD, MADGRAPH, Pythia Z+1jet, POWHEG (expect at PT=0, negative A0 is unphysical)

Consistent with RESBOS but disagree with Default Pythia (q-qbar only), or VBP.

Additional Comments about QCD Monte Carlos

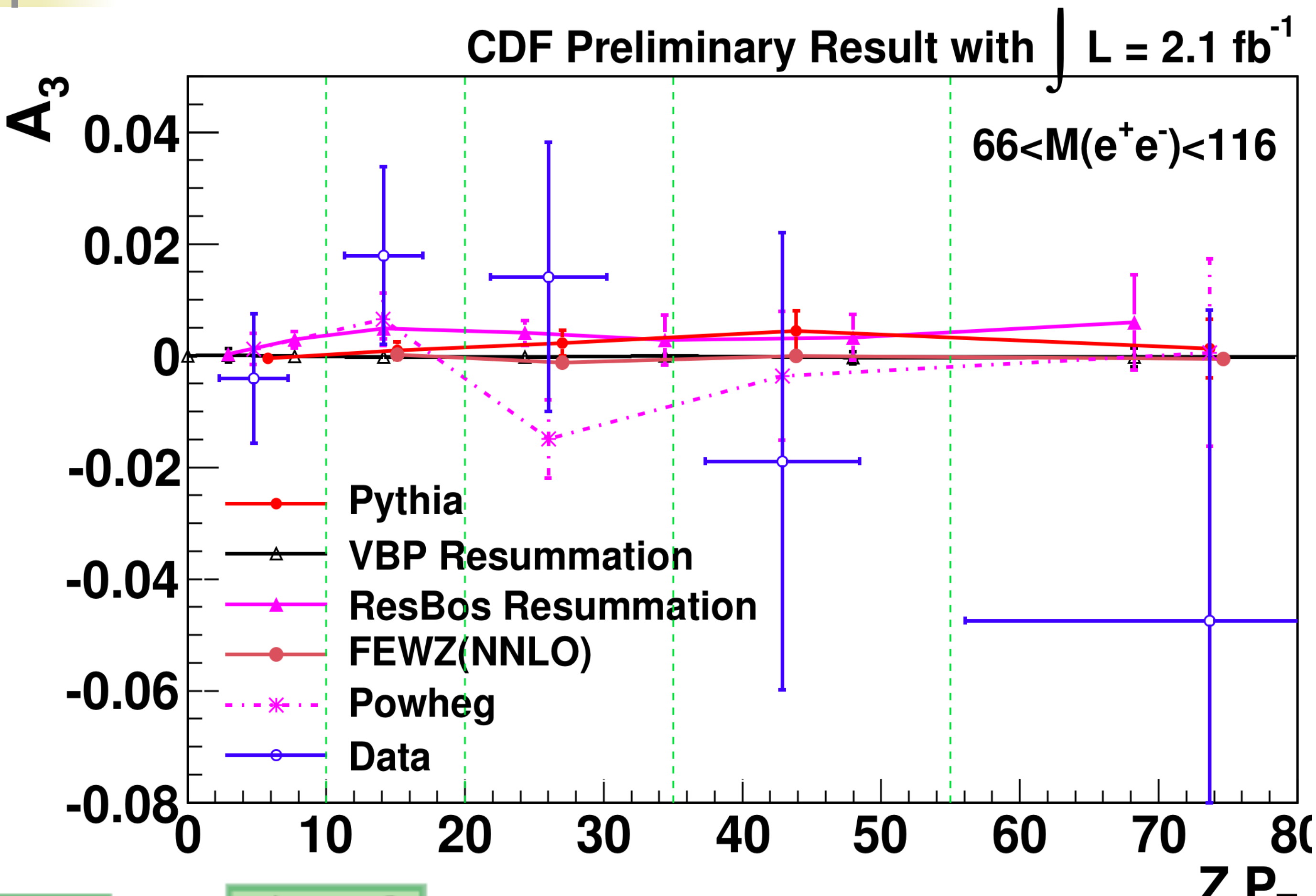
At high Pt: A0 and A2 show that there is a significant contribution from the Compton (qG) process as expected from fixed order perturbation theory.

Therefore, default standard Pythia, and VPB which only have the q-qbar process do not agree with data)

Powheg has both q-qbar and qG, so it works at high Pt, but has unphysical (negative) prediction for A0 at Pt=0

- A3 is expected to be small (~A4 x A1)

This result is over all y, so expect 0 average because for q-qbar → $A_3(+y) = -A_3(-y)$



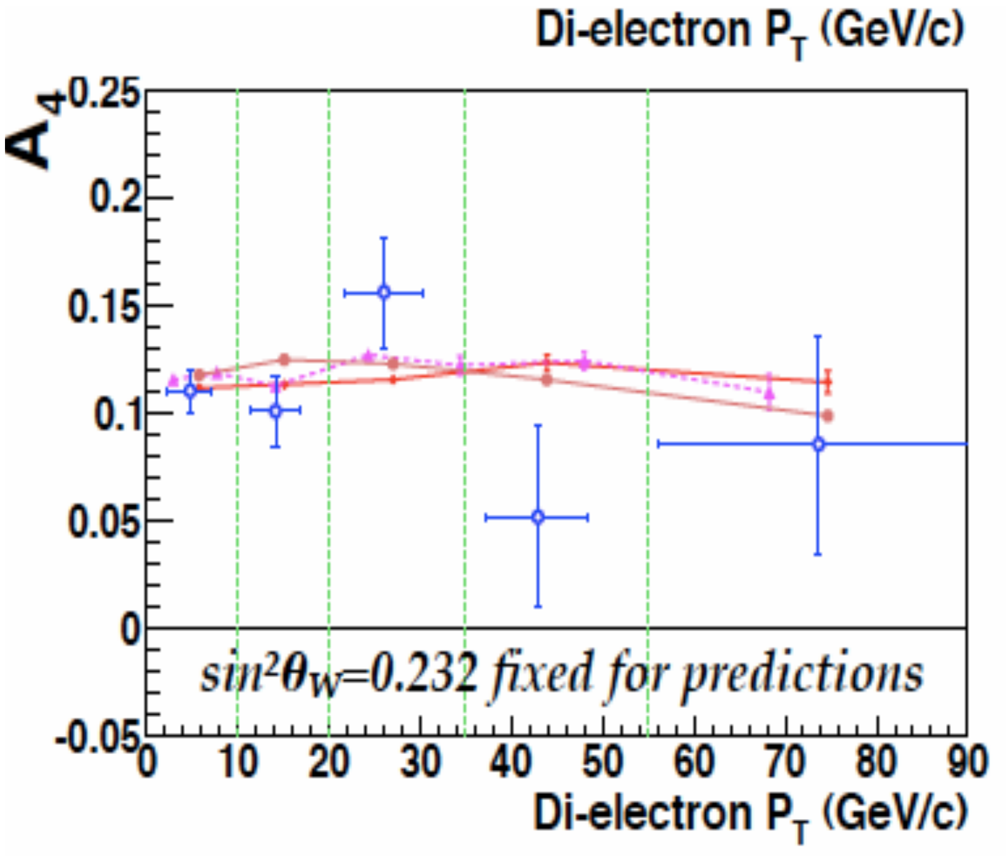
$$\propto \boxed{(1+\cos^2\theta)} + \boxed{A_4 \cos\theta}$$

$$+ \frac{1}{2}A_0(1-3\cos^2\theta) + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi$$

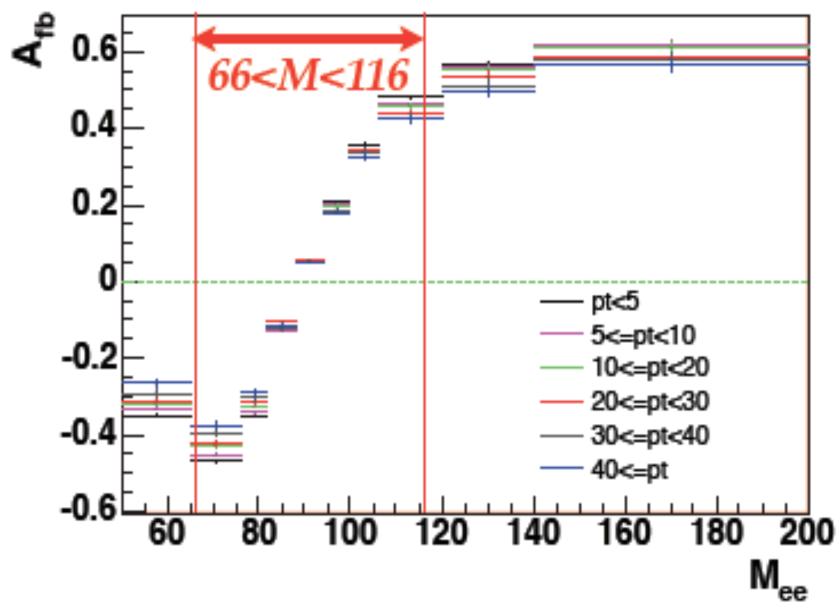
Analysis for positive and negative y, in progress,

Tevatron Measurement : A4 $\propto (1+\cos^2\theta) + A_4 \cos\theta$

A4 is related to the Average Forward Backward Asymmetry In the Z region. It can be used for a precision measurement of the EW mixing angle. This analysis is under way.



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



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, $P_T^2/(P_T^2+M_{\mu}^2)$
  - *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*

Gluon spin = 1

- 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

Ongoing Work

1. These CDF results are based on 2.1 fb-1 of e+e- sample (150K events)
2. We are currently looking at factor of 3 larger samples: 6 fb-1 e+e sample, and 6 fb-1 dimuon sample.
3. Working towards a precision measurement of EW mixing angle using A4 (=Afb) with larger data sample
4. CDF Analysis to be expanded to investigate A1 as a function of y.

- A1(Pt,y) : Pt and y dependence measures the difference in the probability of emission of gluons by low x and high x partons

•We are also doing this analysis with current 35 pb-1 CMS data sample at LHC (Note: 1 fb-1 expected by Aug, 2011)