Measurement of the Forward-Backward Charge Asymmetry(A_{FB}) in $p\bar{p} \to Z/\gamma^* \to ee$ at DØ

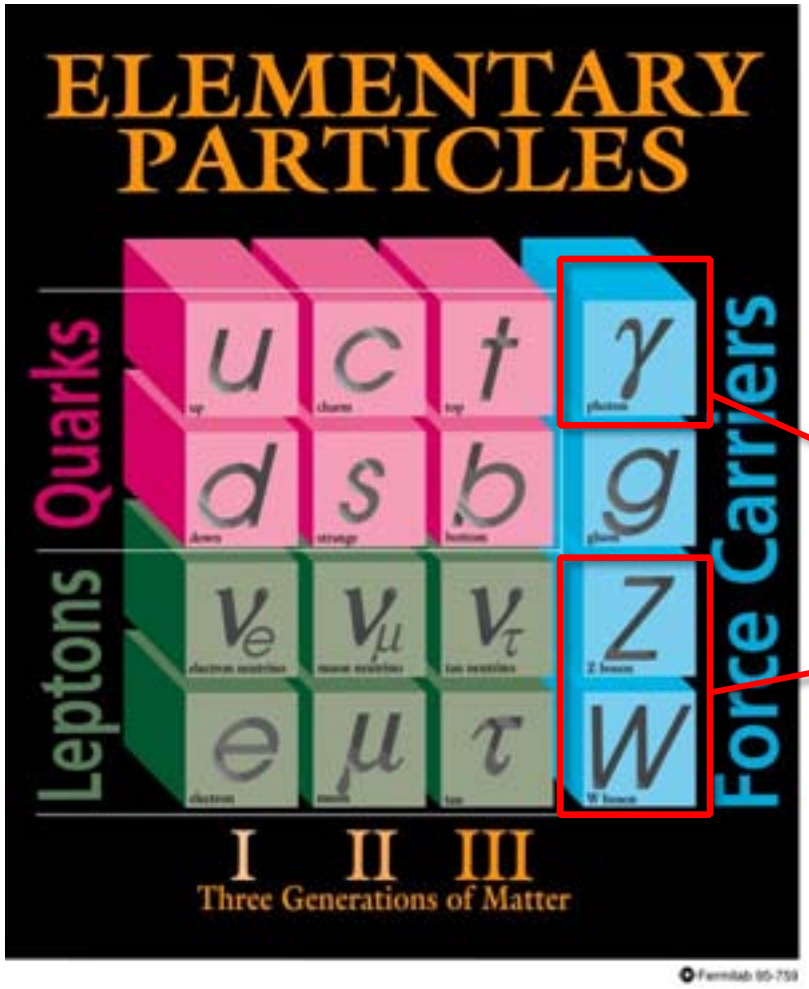
Hang Yin

University of Science and Technology of China(USTC)

Outline

- Introduction
- Tevatron and D∅ detector
- Event selection
- Analysis results
  1. Forward-Backward charge asymmetry measurement
  2. Weak mixing angle
  3. Z to light quark couplings
  4. Differential cross section
- Conclusion

Standard Model

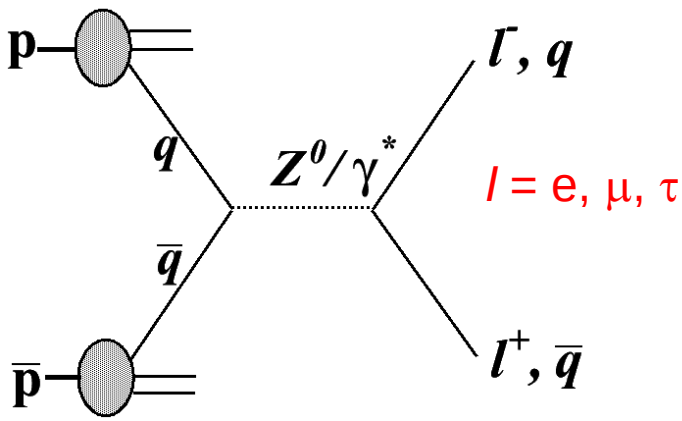


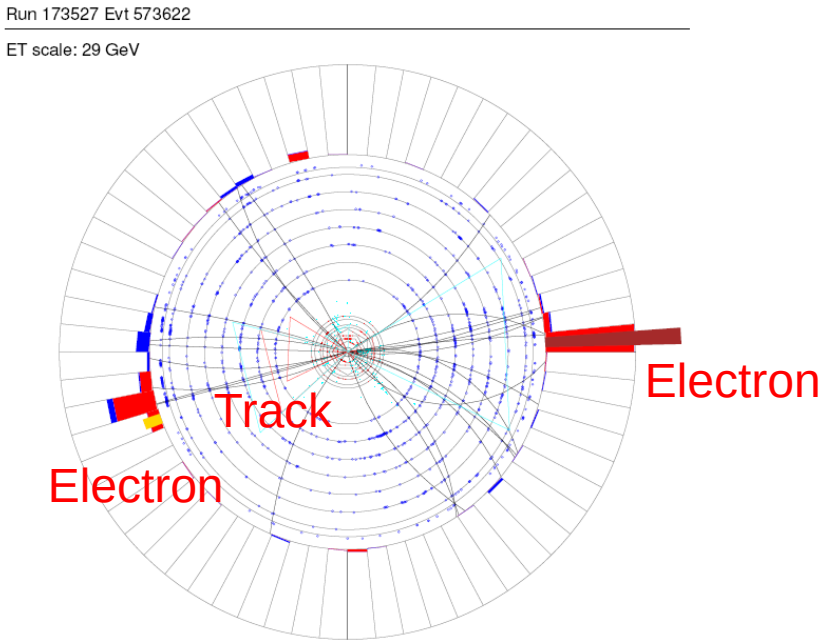
- Describes elementary particles and their interactions
  - Three generations of particles(quarks and leptons)
  - Gauge bosons mediate interactions
    - Strong → QCD theory
    - Electromagnetic
    - Weak

    } electroweak theory

Z boson

- Z boson production at Tevatron

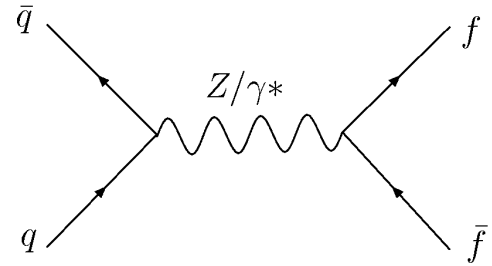


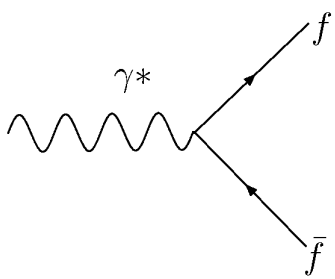


- Z (→ee, μμ) events are often used for detector calibration
- Z are backgrounds for many measurements and searches
- Physics with Z boson
  - Make precision measurements of electroweak parameters
  - Test high-order QED and QCD corrections
  - Search for physics beyond the SM

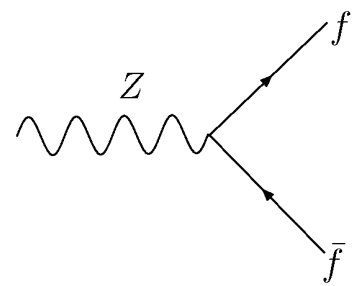
Drell-Yan

- Drell-Yan Procedure: annihilation of $q\bar{q}$ and the production of di-lepton or $q\bar{q}$ pair via a Z-boson or virtual photon





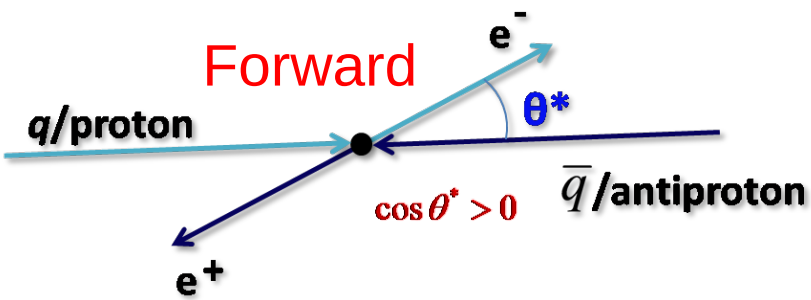
- Coupling of a virtual photon to fermions: vector coupling

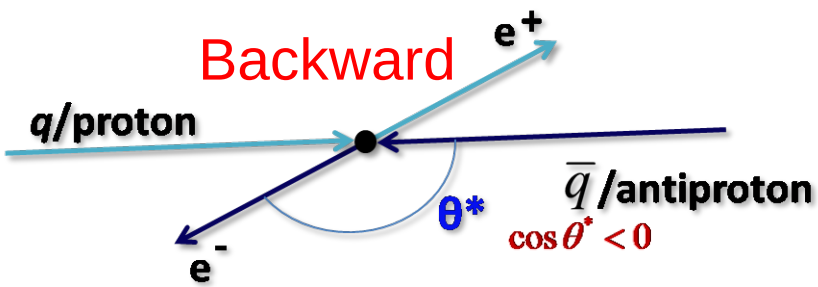


- Couplings of a Z-boson to fermions: vector and axial-vector couplings

Forward-Backward asymmetry

- The presence of both vector and axial vector couplings gives rise to non-zero A_{FB}.



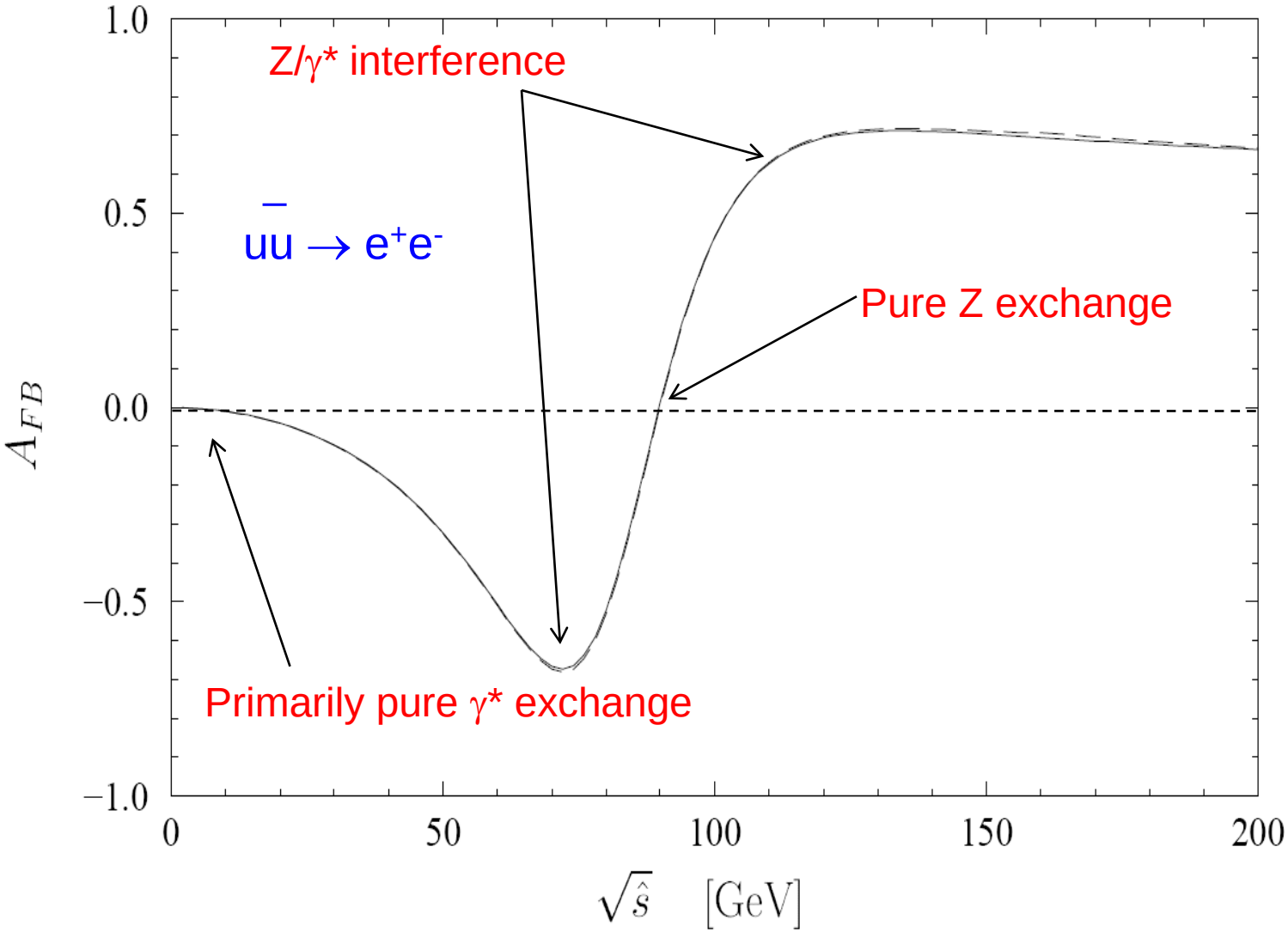


- The differential cross section: $\frac{d\sigma}{d\cos\theta^*} = A(1+\cos^2\theta^*) + B\cos\theta^*$

- Forward-backward asymmetry : $A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$

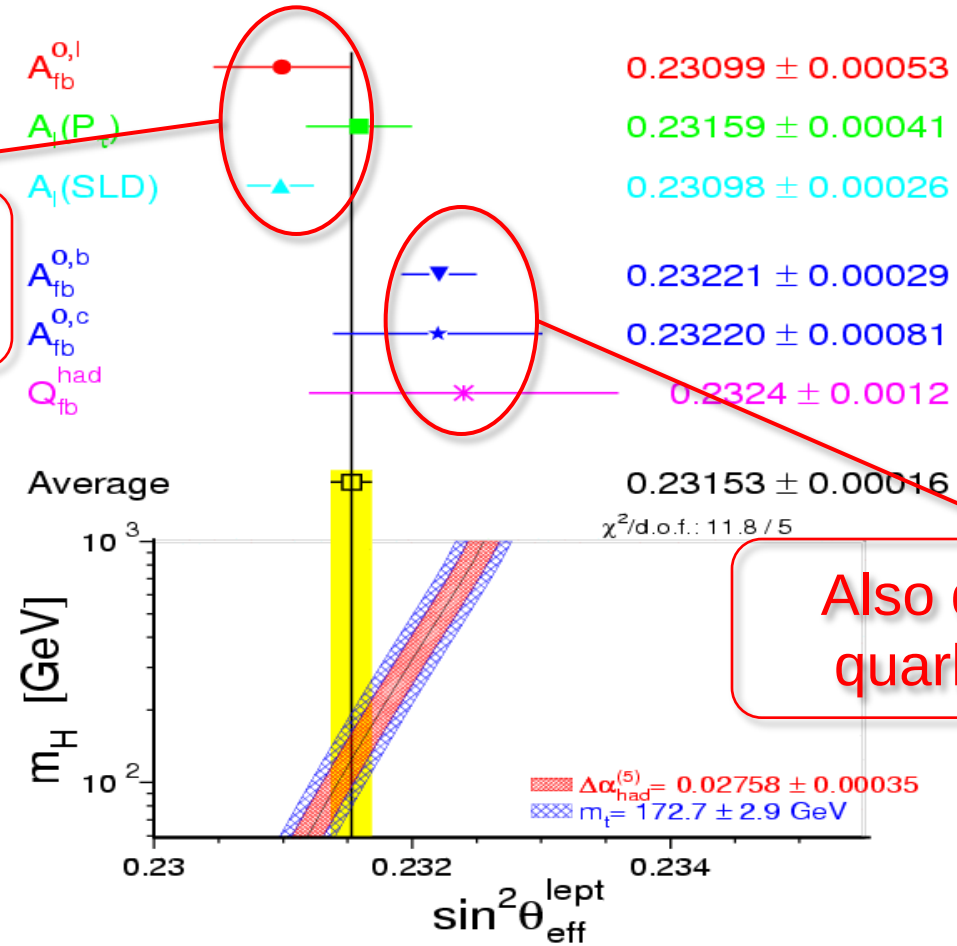
$$\sigma_F = \int_0^{+1} \frac{d\sigma}{d\cos\theta*} d\cos\theta*, \qquad \sigma_B = \int_0^{-1} \frac{d\sigma}{d\cos\theta*} d\cos\theta*$$

Asymmetry Prediction



$\sin^2\theta_W$

- A_{FB} is sensitive to $\sin^2\theta_W$

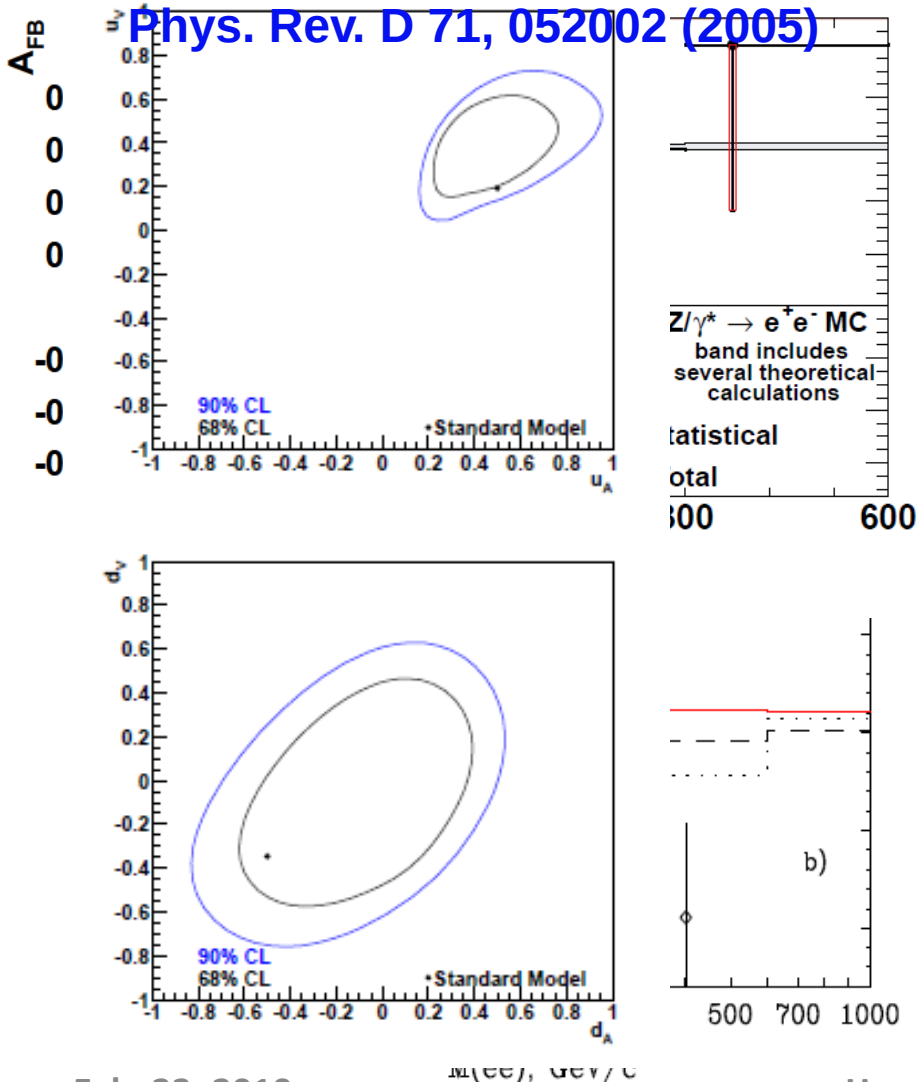


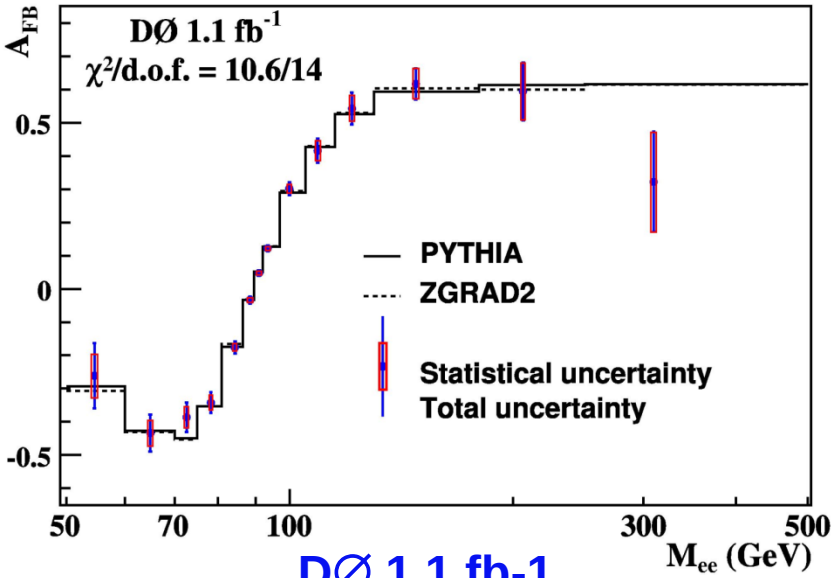
Only depends on lepton couplings

Also depends on quark couplings

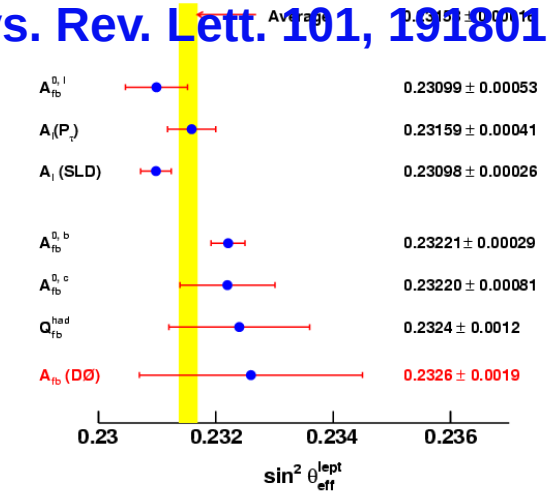
Previous Tevatron A_{FB} results

CDF RunII 72 pb-1,
Phys. Rev. D 71, 052002 (2005)





DØ 1.1 fb-1,
Phys. Rev. Lett. 101, 191801 (2008)



Measurement strategy

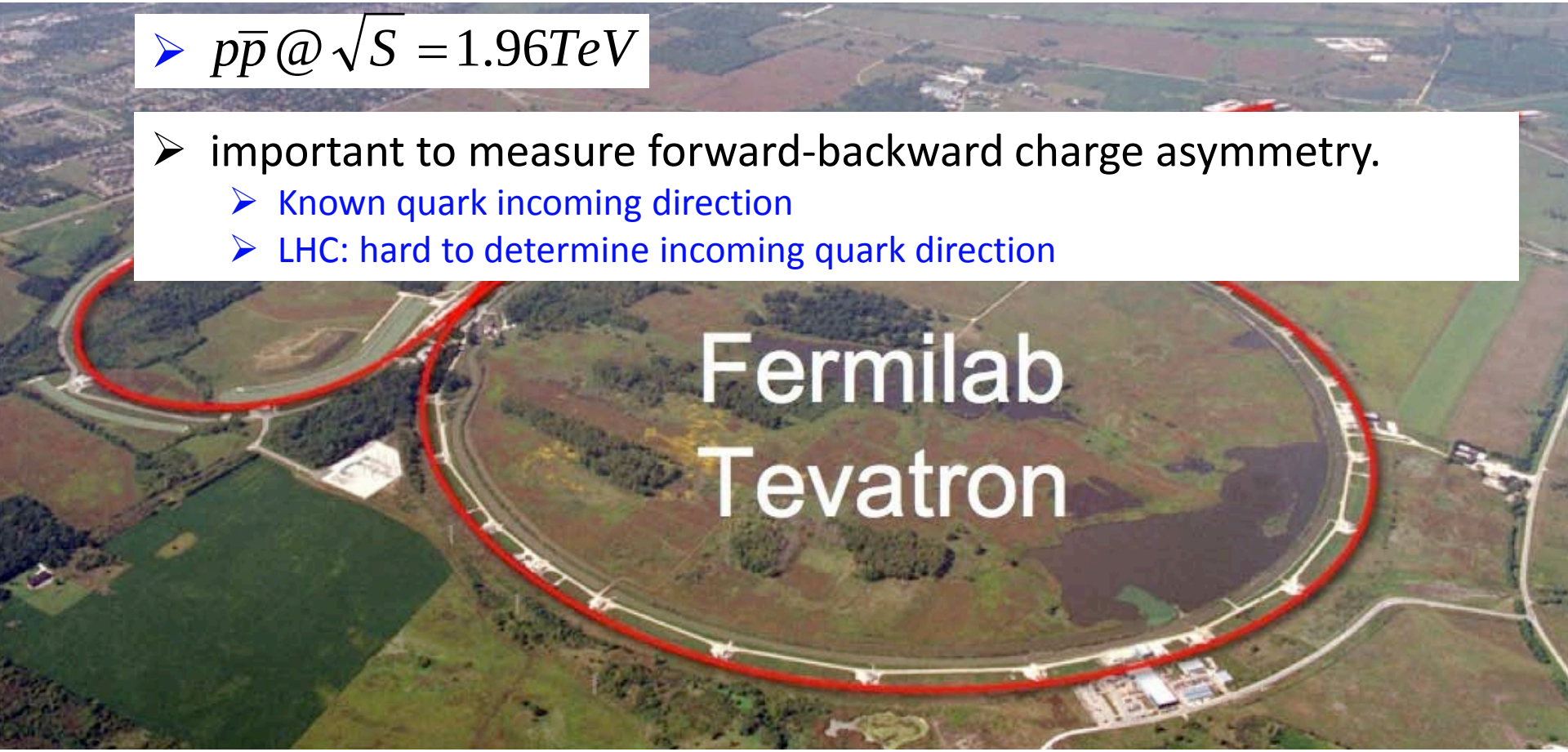
- Select *Z/γ** candidates from data
- Subtract backgrounds and measure A_{FB}^{raw} distribution
- After various Corrections:
  - Unfold data A_{FB}^{raw} and compare unfolded A_{FB} with theoretical prediction
  - Extract $\sin^2\theta_W^{eff}$ using the A_{FB}^{raw} distribution
  - Extract *Z to light quark* couplings using the unfolded A_{FB} distribution
  - Measure Drell-Yan normalized differential cross section: $\frac{1}{\sigma}\times\frac{d\sigma}{dM}$

TEVATRON AND DØ DETECTOR

Tevatron

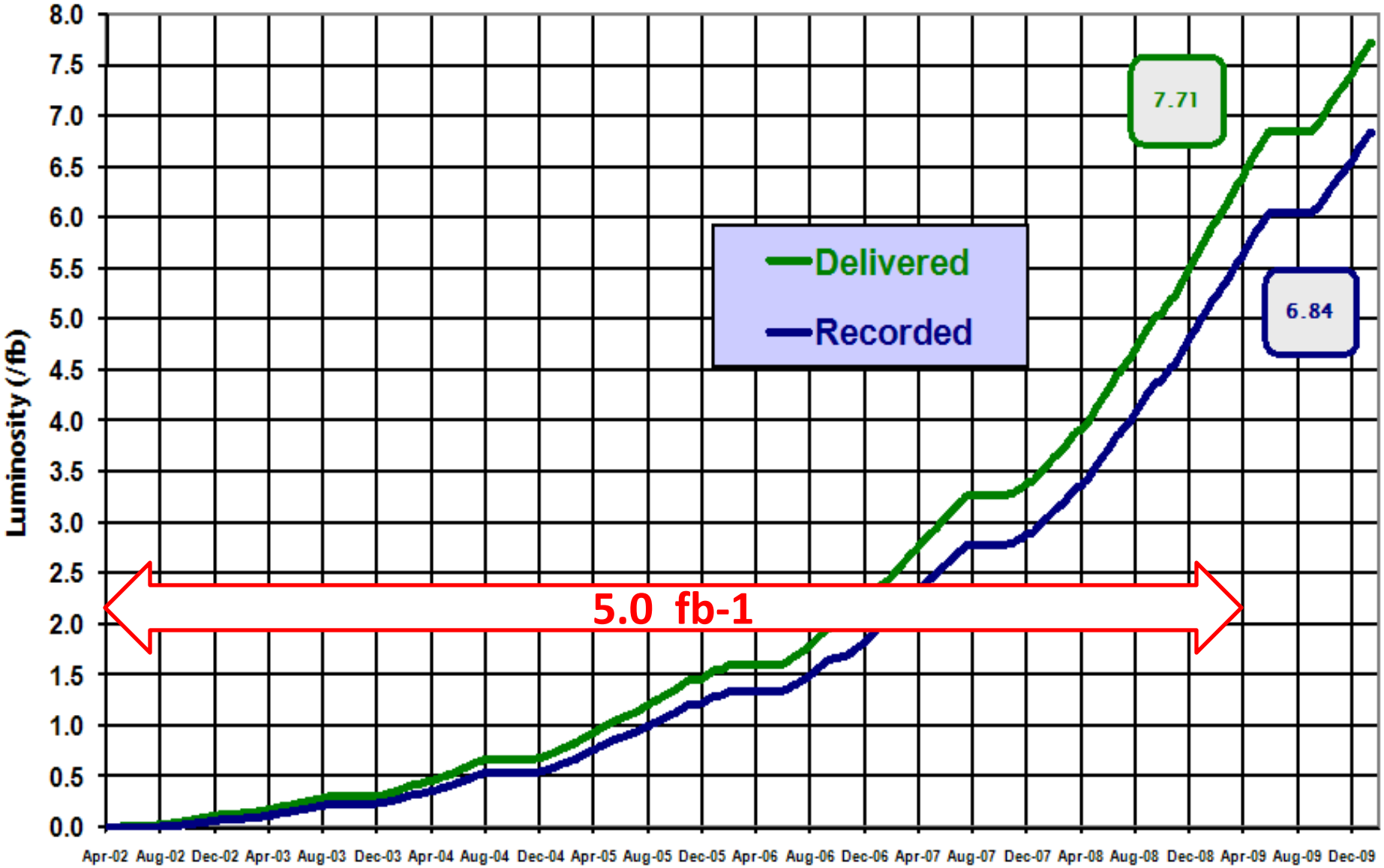
- $p\bar{p} @ \sqrt{S} = 1.96 TeV$

- important to measure forward-backward charge asymmetry.
  - Known quark incoming direction
  - LHC: hard to determine incoming quark direction



Run II Integrated Luminosity

19 April 2002 - 31 January 2010



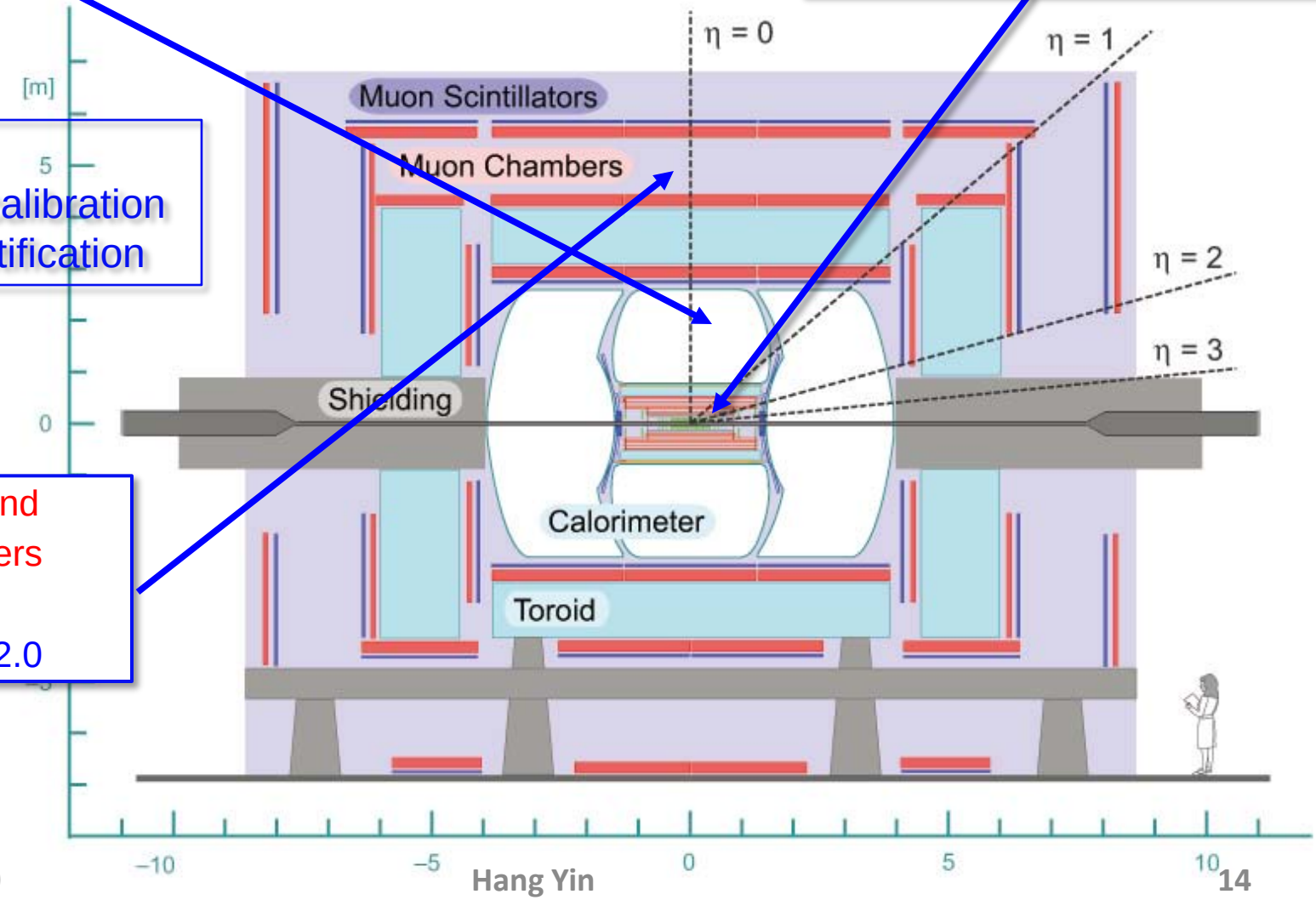
DØ detector

Uranium Liquid Argon calorimeters
Central (CC) and Endcap (EC)
Coverage: $|\eta| < 4.2$

Silicon Microstrip Tracker (SMT)
Central Fiber Tracker (CFT)
2 T magnetic field
Coverage: $|\eta| < 3.0$

Service work:
- Calorimeter calibration
- Electron identification

Drift chambers and scintillator counters
1.8 T toroids
Coverage: $|\eta| < 2.0$



EVENT SELECTION

Event selection

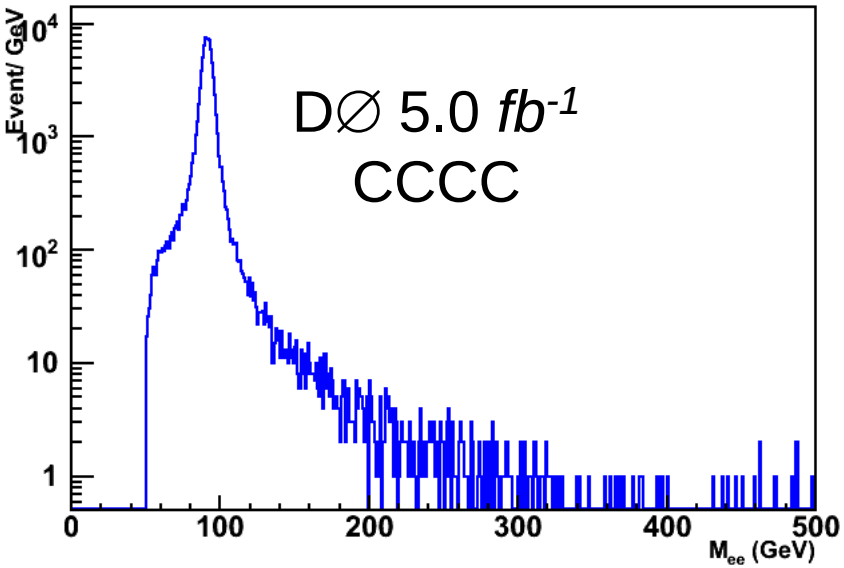
- DØ RunII, $\boldsymbol{L}$ = 5.0 fb^{-1}

- Primary vertex $|Z| < 40\ cm$
- Electron selections:
  - Very tight electron cuts based on calorimeter parameters
  - p_T > 25 GeV
  - Shower shape cut

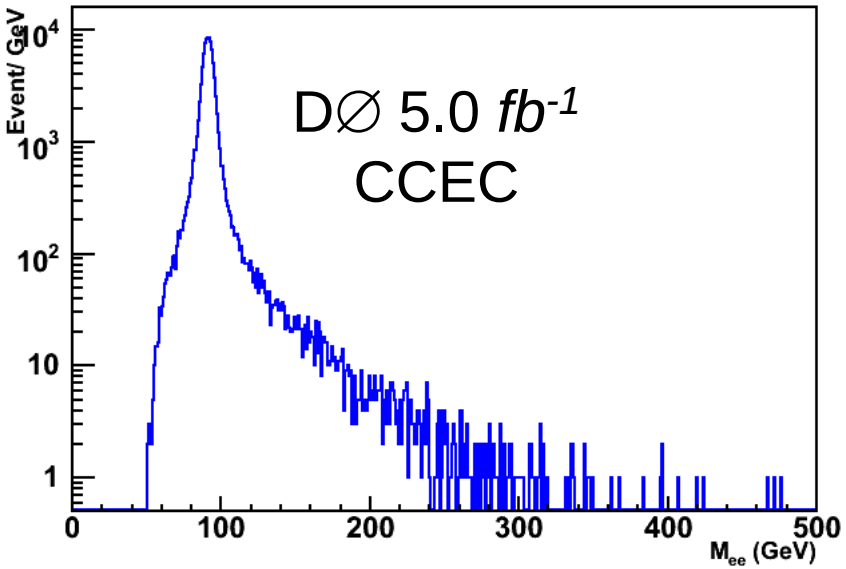
- Only look at CC-CC and CC-EC events
  - For CC-CC events, require two opposite track matches
  - For CC-EC events, require CC electron must have track match(use the charge of CC electron to determine forward/backward event)

  - Lower EC electron track match efficiency

InvMass distribution



74 k events



84 k events

Selected data

Mass region(GeV)	CC-CC		CC-EC	
	Forward	Backward	Forward	Backward
50 – 60	272	309	53	64
60 – 70	466	707	239	418
70 – 75	409	537	281	489
75 – 81	851	1054	768	1223
81 – 86.5	3309	3519	3760	4178
86.5 – 89.5	6672	6644	8323	7636
89.5 – 92	9323	8807	11123	9558
92 – 97	12138	11041	14278	11365
97 – 105	2861	2182	3698	2155
105 – 115	678	432	1137	400
115 – 130	407	188	766	228
130 – 180	436	151	844	269
180 – 250	137	61	252	73
250 - 500	63	45	84	24

Signals and Backgrounds

- Pythia Geant MC samples:
  - ***Z/γ*->ee*** samples: M_Z > 40 GeV
  - At generate level: applying Z-pT rapidity and Z Mass reweighting(NLO)
  - At reconstructed level: MC tuned to data by applying EM smearing, efficiencies scaling

- Backgrounds***: Z->ττ, W+X, WW, WZ, γγ, ttbar***
  - Backgrounds determined from MC.

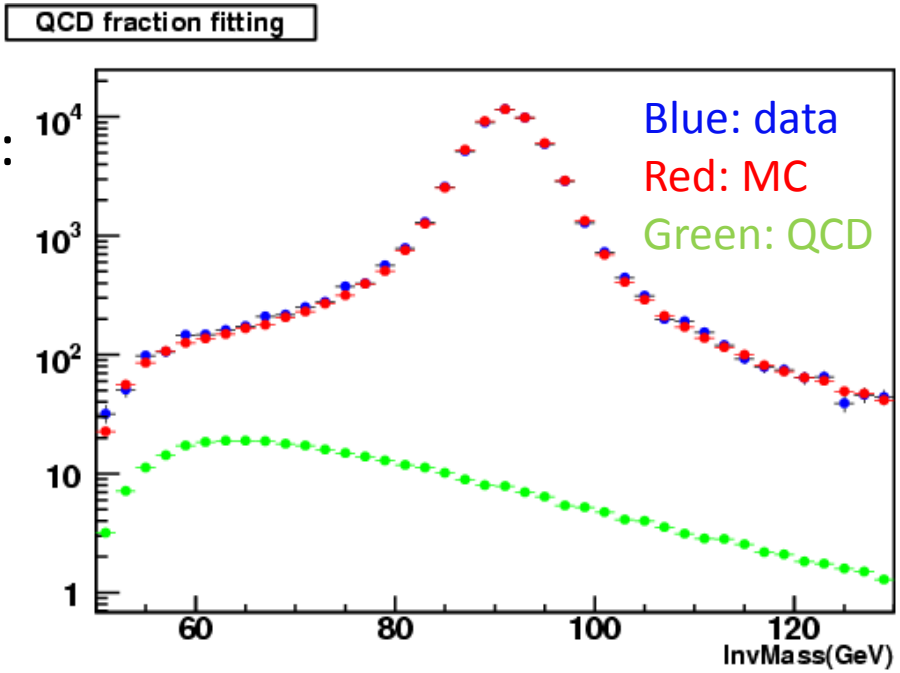
QCD Multijets background

- QCD background: jets are misidentified as electrons, estimated from data

- Shape of QCD background measured from real data: inverting electron shower shape requirement in CC and in EC

- Fraction of QCD background: using minimum χ2 fitting

$$N_{data} = \alpha \times N_{MC} + \beta \times N_{QCD}$$

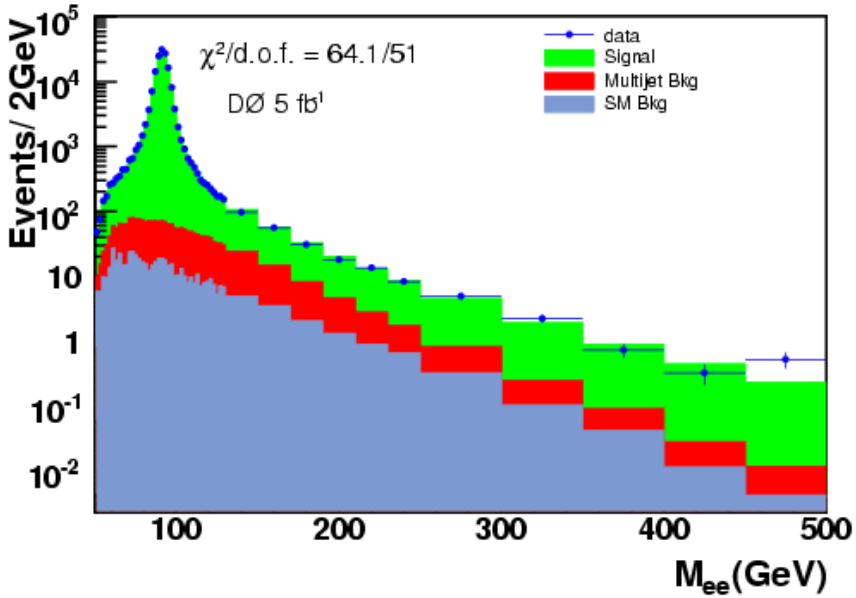


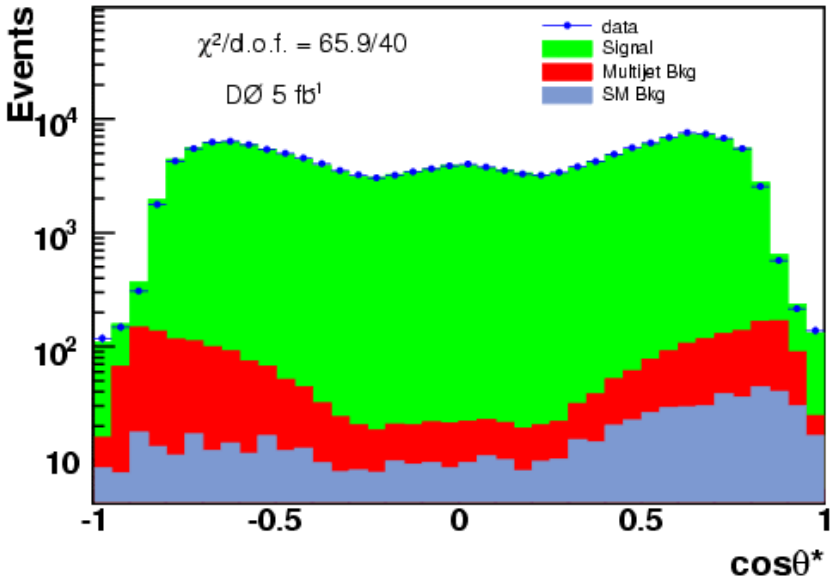
Background contributions

Mass Range(GeV)	Z->ττ	W+X	WW	WZ	γγ	ttbar	Multijet	Signal
50 – 60	20.0	15.3	4.6	0.3	2.2	2.4	38.7	600.1
60 – 70	55.6	24.1	7.0	0.5	6.5	3.9	106.5	1588.8
70 – 75	28.9	19.7	4.3	0.4	4.0	2.2	69.7	1451.5
75 – 81	19.6	18.3	4.2	0.7	4.3	2.6	85.8	3477.4
81 - 86.5	6.2	25.4	3.5	1.6	5.9	2.2	79.6	14148.1
86.5 - 89.5	1.6	11.4	2.8	3.3	3.5	1.0	40.0	29552.6
89.5 – 92	1.8	12.1	2.2	5.2	1.8	1.2	32.3	38507.8
92 – 97	1.3	19.2	3.7	6.8	6.8	2.0	63.4	48384.1
97 – 105	1.7	28.8	6.7	1.6	7.1	3.2	89.2	10734.7
105 – 115	1.5	25.3	6.1	0.7	8.3	2.8	95.9	2454.7
115 – 130	1.8	32.3	7.6	0.8	8.5	4.5	108.9	1422.4
130 – 180	3.1	50.9	15.5	1.5	16.9	8.0	172.0	1404.2
180 – 250	0.8	17.7	7.0	0.8	8.8	3.4	44.4	437.6
250 – 500	0.2	4.5	2.5	0.3	3.4	1.0	8.9	169.5

Data and MC comparisons

Work in Progress, 5.0 fb-1





Also compared other distributions, like: electron-E_t, Electron-η, vertex, cosΘ* in each mass bins

RESULTS

1. Unfolded AFB measurement
2. Weak Mixing angle measurement
3. Z to light quark couplings measurement
4. Differential cross section measurement

Unfolding procedure

- Unfolding: from reconstruction level to particle level
  - Detector resolution corrections
  - Acceptance * efficiency corrections
  - Charge Mis-identification corrections

Detector resolution unfolding: Response Matrices

- Due to the finite detector resolution, events migrate into other mass bins

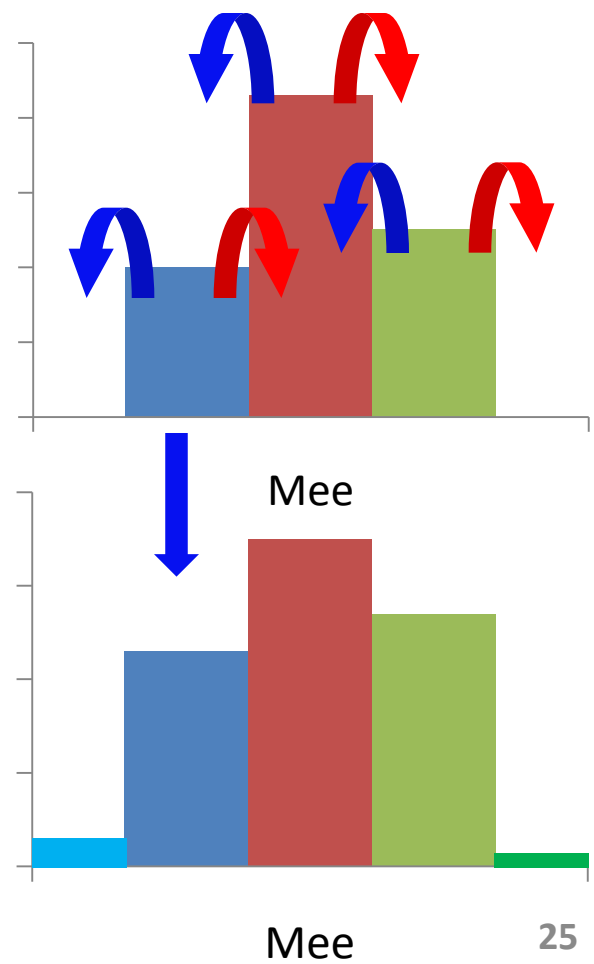
$$N^F_{gen} = R^{FF}_{i,j} \times N^F_{sel} + R^{FB}_{i,j} \times N^B_{sel}$$

$$N^B_{gen} = R^{BF}_{i.j} \times N^F_{sel} + R^{BB}_{i,j} \times N^B_{sel}$$

- At generate level: $N^F_{gen}[i]$ and $N^B_{sel}[i]$
- At selected level: $N^F_{sel}[i]$ and $N^B_{sel}[i]$

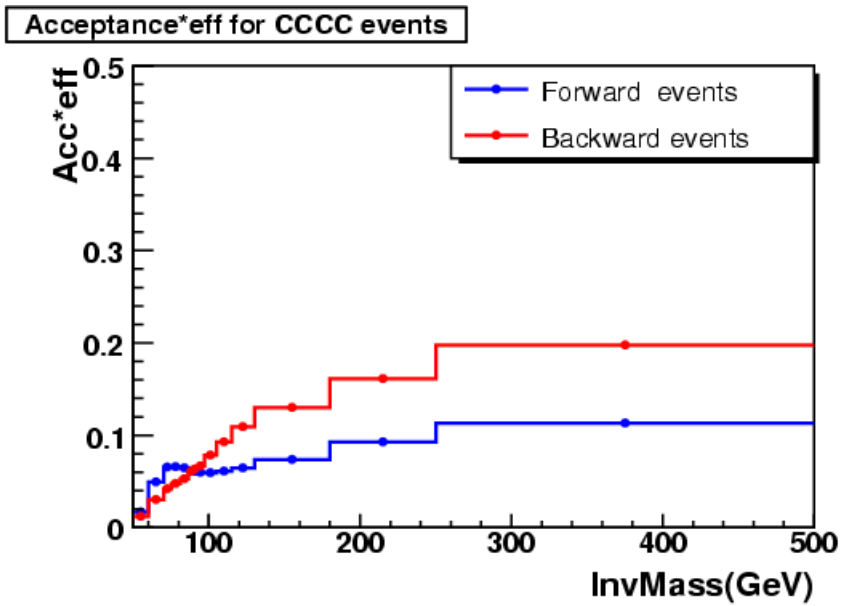
$$R^{FF}_{i,j} = \frac{N(gen_F[i], sel_F[j])}{N^F_{sel}[j]}; R^{FB}_{i,j} = \frac{N(gen_F[i], sel_B[j])}{N^B_{sel}[j]}$$

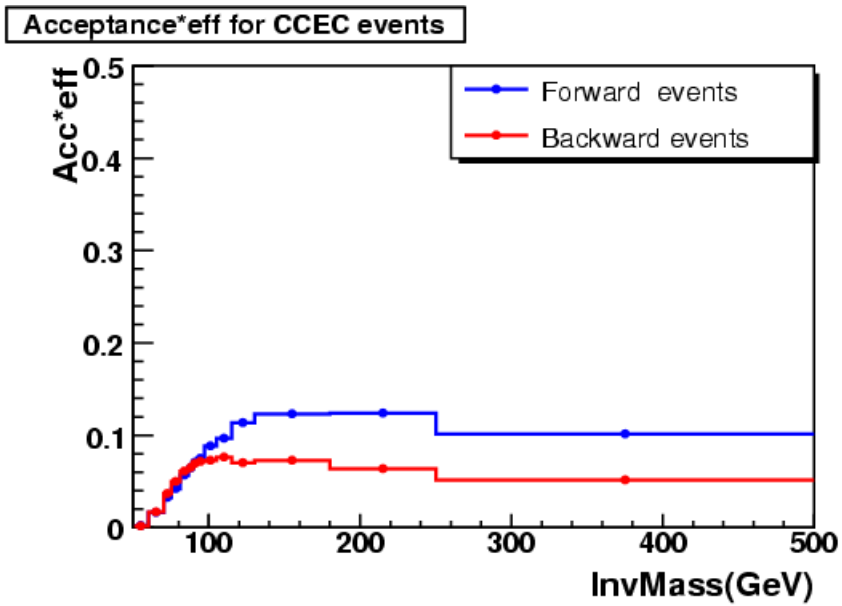
$$R^{BF}_{i,j} = \frac{N(gen_B[i], sel_F[j])}{N^F_{sel}[j]}; R^{BB}_{i,j} = \frac{N(gen_B[i], sel_B[j])}{N^B_{sel}[j]}$$



Acceptance*efficiency unfolding

- Acc*eff for CCCC and CCEC events





- To remove geometric and kinematic cuts effects

$$N_{Acc\times eff}^{F-unfolded}[i] = \frac{N_{detector-unfold}^{F}[i]}{Acc^{F}[i]\times eff[i]} \qquad N_{Acc\times eff}^{B-unfolded}[i] = \frac{N_{detector-unfold}^{B}[i]}{Acc^{B}[i]\times eff[i]}$$

Charge mis-ID correction

- f_Q : Charge mis-identification rate
- For CCCC events, we have

$$A^{true} = \frac{1 - 2 f_Q + 2 f_Q^2}{1 - 2 f_Q} A^{sel}$$

- For CCEC events, we have

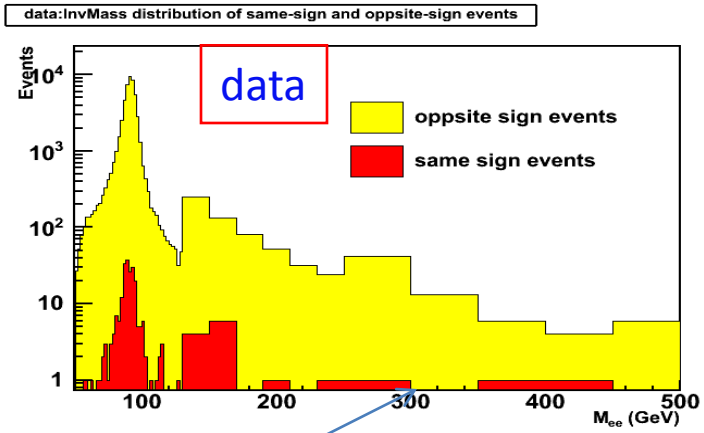
$$A^{true} = \frac{1}{1 - 2 f_Q} A^{sel}$$

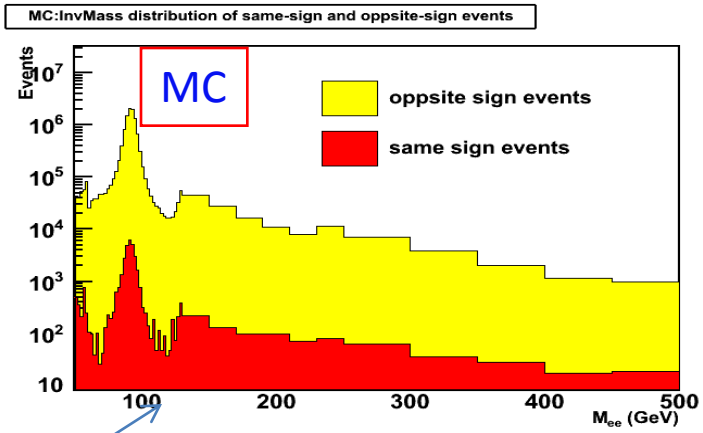
If f_Q = 50%, cannot measure charge asymmetry

- Measured f_Q vs. M_{ee} in analysis

Charge mis-ID rate

- The rate of same-sign events as a function of di-electron invariant mass



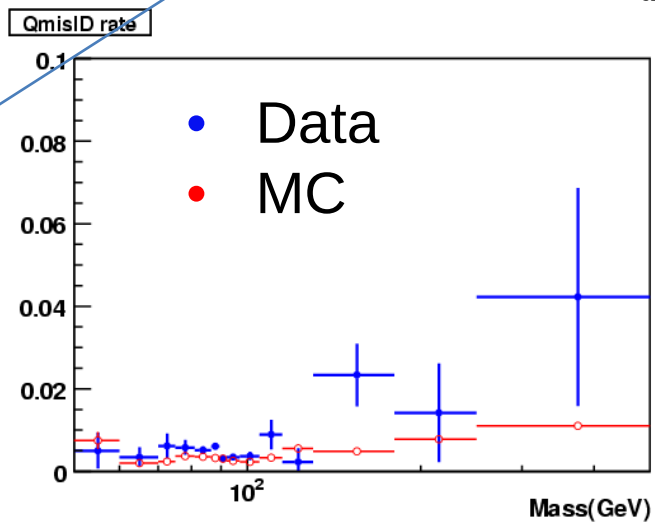


Very few events for M_{ee} > 200 GeV

Mis-ID rate shape determined from MC

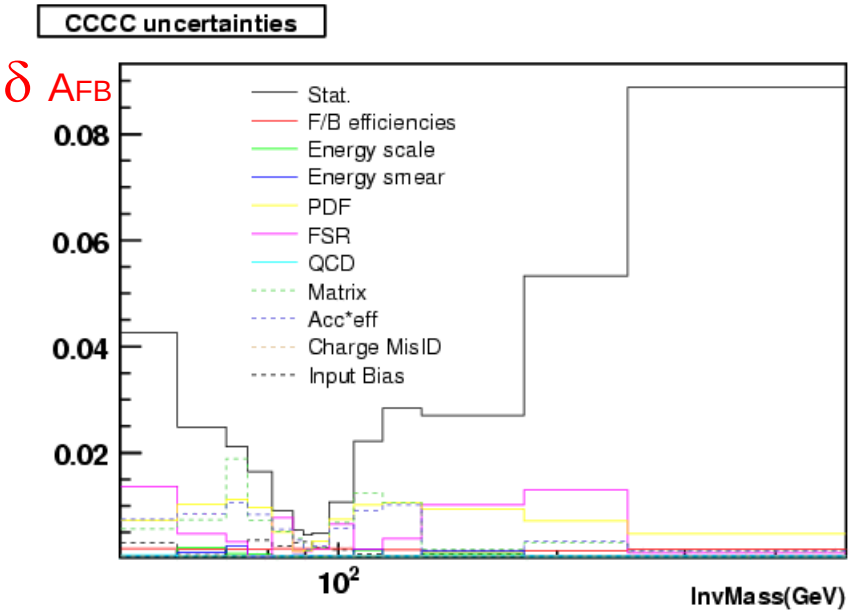
MC cannot describe the data for charge mis-ID rate:

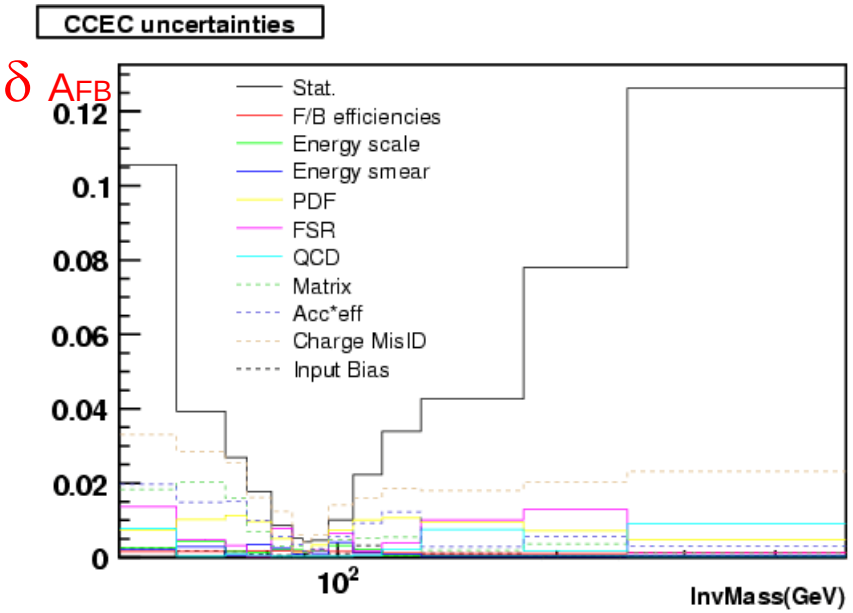
- normalized MC distribution to data in the Z peak region
- Use data statistical uncertainty



Source of systematic uncertainties

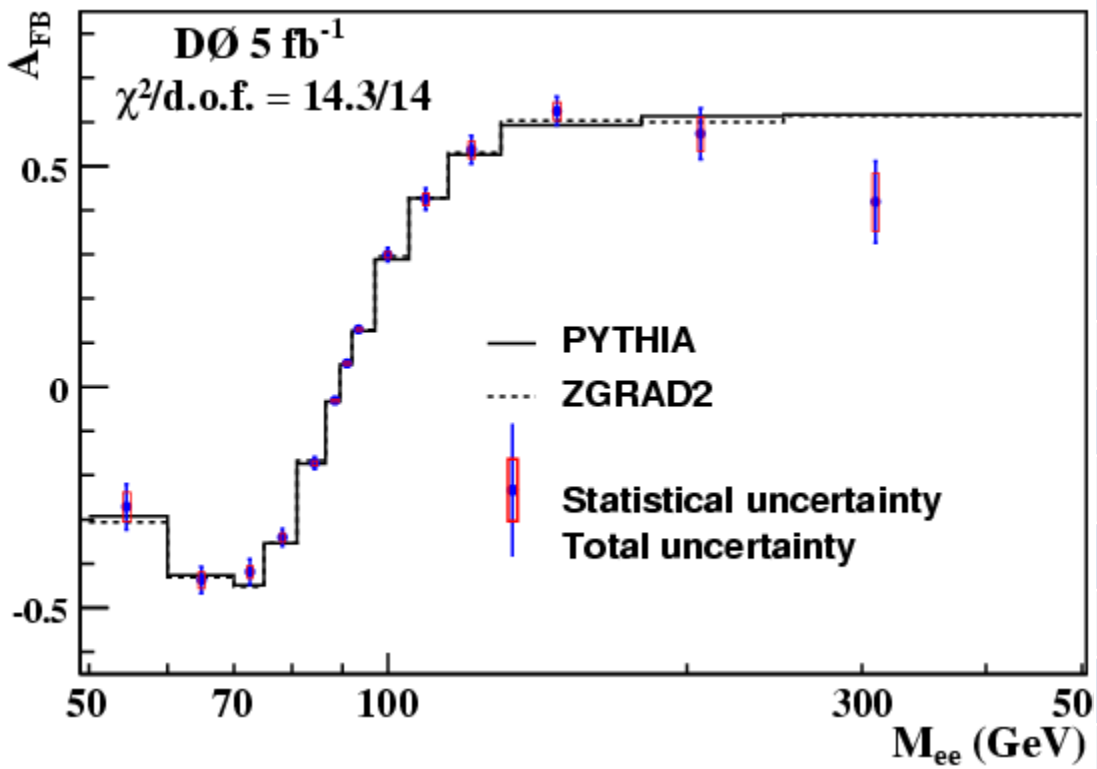
- Theoretical: PDF, QCD and EW corrections
- Electrons: energy scale, energy smear, difference between forward and backward efficiencies, charge mis-identification
- Other: background, Acc*eff, the input of $\sin^2\theta_W$, the unfolding method





Unfolded A_{FB}

Work in Progress, 5.0 fb-1



<Mee> GeV	Predicted AFB		Unfolded AFB
	PYTHIA	ZGRAD2	
54.5	-0.293	-0.307	-0.273±0.040±0.018
64.9	-0.426	-0.431	-0.442±0.021±0.016
72.6	-0.449	-0.452	-0.434±0.017±0.022
78.3	-0.354	-0.354	-0.342±0.012±0.014
84.4	-0.174	-0.166	-0.175±0.006±0.012
88.4	-0.033	-0.031	-0.033±0.004±0.006
90.9	0.051	0.052	0.054±0.003±0.004
93.4	0.127	0.129	0.133±0.003±0.006
99.9	0.289	0.296	0.301±0.007±0.013
109.1	0.427	0.429	0.428±0.016±0.016
121.3	0.526	0.530	0.539±0.022±0.017
147.9	0.593	0.603	0.634±0.023±0.014
206.4	0.613	0.600	0.570±0.044±0.016
310.5	0.616	0.615	0.443±0.073±0.006

RESULTS

1. Unfolded A_{FB} measurement
2. Weak Mixing angle measurement
3. Z to light quark couplings measurement
4. Differential cross section measurement

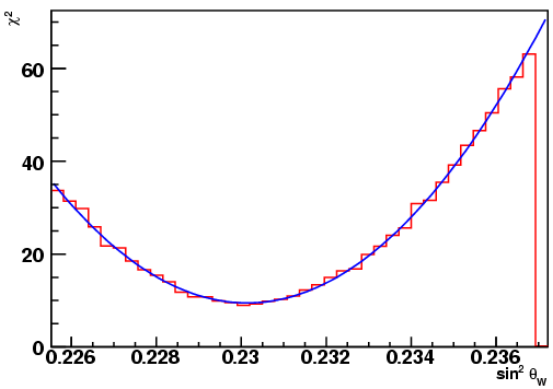
Weak mixing angle measurement

- Pythia samples generated with 40 $\sin^2 \Theta_w^{eff}$ inputs

- Geant MC files with different input values of $\sin^2 \Theta_w^{eff}$:
  - Reweight Geant MC generator-level distribution with different $\sin^2 \Theta_w^{eff}$ values (2D reweight) M_{Z/γ^*}-$\cos\Theta^*$
  - Checked the distributions like electron pT, electron η, Mee, $\cos\Theta^*$ and Z boson pT etc

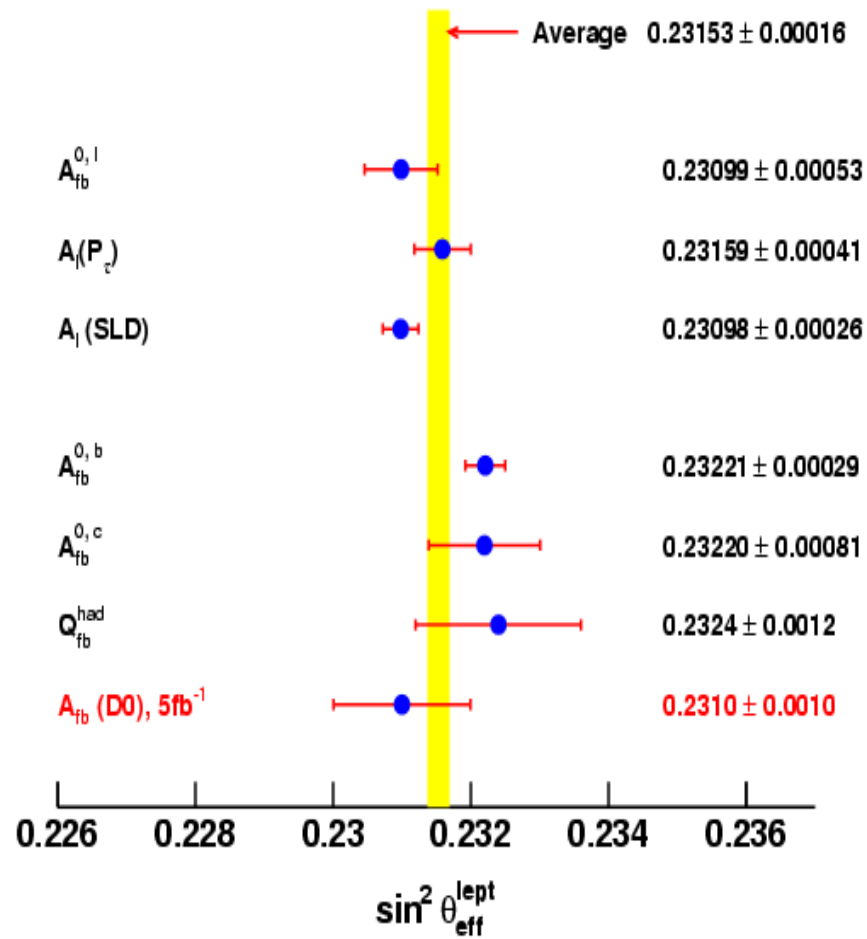
$\sin^2\theta_W^{eff}$ results

- Measured value
  $\sin^2\theta_W^{eff} = 0.2310 \pm 0.0009(Stat.) \pm 0.0006(Syst.)$
- Using minimum χ2 fitting method



- Main systematic uncertainty comes from PDFs
- With more data, combined with muon channel , Tevatron precision will be comparable with the world-average.

Work on progress, 5.0 fb-1



RESULTS

1. Unfolded AFB measurement
2. Weak Mixing angle measurement
3. Z to light quark couplings measurement
4. Differential cross section measurement

How?

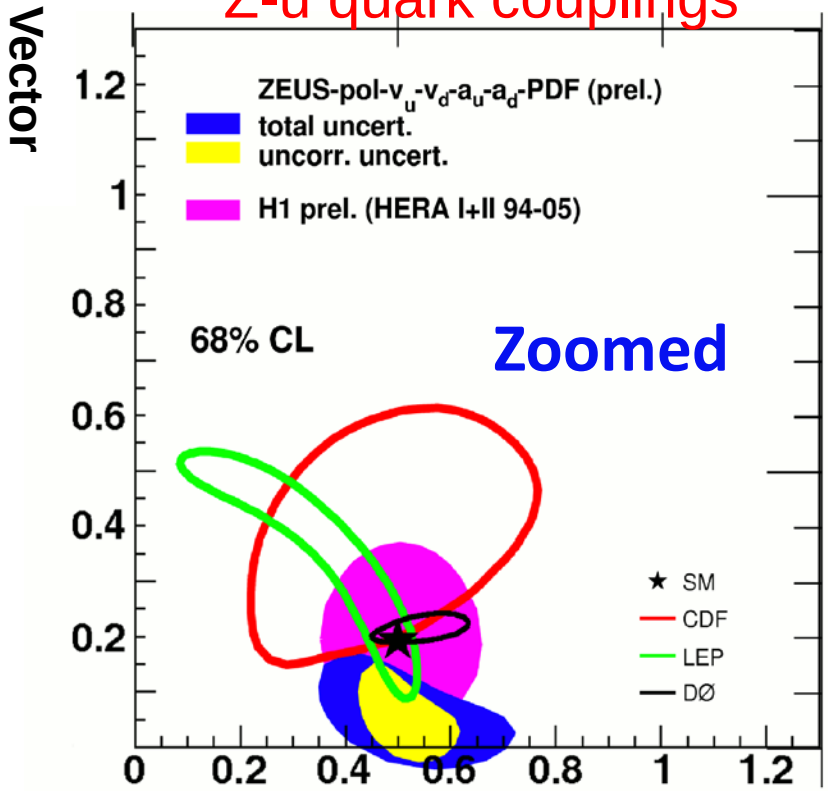
Fermion	g_V	g_A
u	0.196	0.5
d	-0.346	-0.5
e	-0.08	-1.0

- Generator ZGRAD2, 5M events for each points
- Using unfolded A_{FB} to extract couplings
  - 16*16 grids with Vu step size of 0.008 and Au step size of 0.03
  - 16*16 grids with Vd step size of 0.024 and Ad step size of 0.034
- Fix Z-u(Z-d) quark couplings to SM values for the determination of Z-d(Z-u) quark couplings

Z to light quark couplings

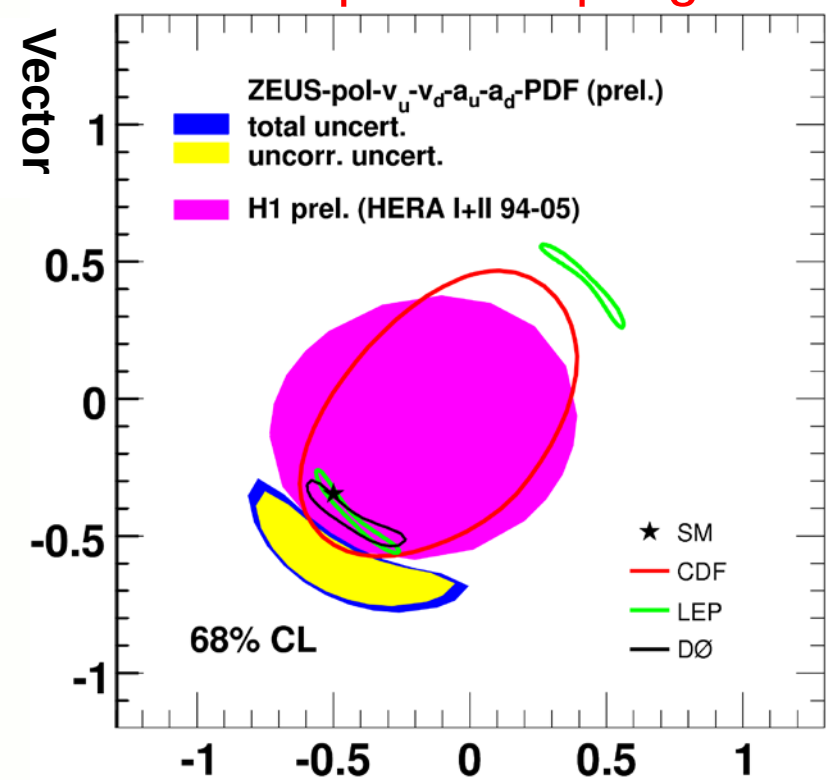
Work in Progress, 5.0 fb-1

Z-u quark couplings



Axial-vector coupling

Z-d quark couplings



Axial-vector coupling

RESULTS

1. Unfolded AFB measurement
2. Weak Mixing angle measurement
3. Z to light quark couplings measurement
4. Differential cross section measurement

Normalized differential cross section

- Normalized differential cross section:

$$\frac{1}{\sigma}\times\frac{d\sigma}{dM}=\frac{1}{\sigma}\times\frac{N-B}{\varepsilon\times\beta\times L\times\Delta M}$$

Number of selected events

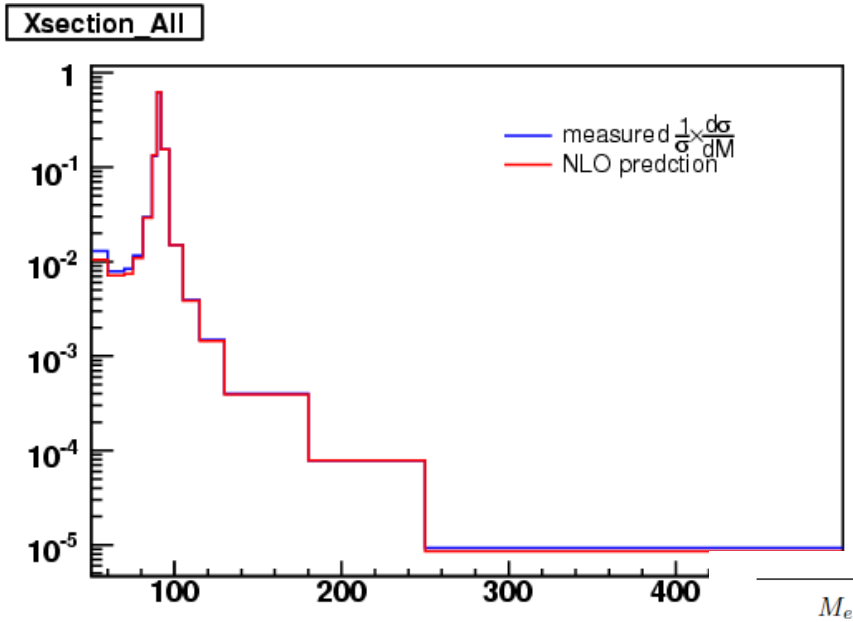
Number of background events

Bin width

Integrated luminosity

Acceptance * efficiency effects

Results



Work in Progress, 5.0 fb-1

M_{ee} (GeV)	Prediction PYTHIA	Prediction NLO	$\frac{1}{\sigma}\times\frac{d\sigma}{dM}$	measured/NLO
$50.0 < M_{ee} < 60.0$	0.0109	0.0105	$0.0132 \pm 0.0005 \pm 0.0004$	1.262
$60.0 < M_{ee} < 70.0$	0.0073	0.0072	$0.0078 \pm 0.0001 \pm 0.0002$	1.094
$70.0 < M_{ee} < 75.0$	0.0076	0.0075	$0.0082 \pm 0.0001 \pm 0.0001$	1.101
$75.0 < M_{ee} < 81.0$	0.0110	0.0109	$0.0117 \pm 0.0001 \pm 0.0002$	1.074
$81.0 < M_{ee} < 86.5$	0.0293	0.0291	$0.0300 \pm 0.0001 \pm 0.0006$	1.032
$86.5 < M_{ee} < 89.5$	0.1342	0.1340	$0.1303 \pm 0.0003 \pm 0.0015$	0.972
$89.5 < M_{ee} < 92.0$	0.6249	0.6254	$0.6246 \pm 0.0033 \pm 0.0056$	0.999
$92.0 < M_{ee} < 97.0$	0.1543	0.1547	$0.1534 \pm 0.0004 \pm 0.0017$	0.992
$97.0 < M_{ee} < 105.0$	0.0149	0.0150	$0.0148 \pm 0.0001 \pm 0.0003$	0.988
$105.0 < M_{ee} < 115.0$	0.0038	0.0039	$0.0039 \pm 0.0001 \pm 0.0001$	1.009

M_{ee} (GeV)	PYTHIA($\times 10^{-3}$)	NLO($\times 10^{-3}$)	$\frac{1}{\sigma}\times\frac{d\sigma}{dM}(\times 10^{-\beta})$	measured/NLO
$115.0 < M_{ee} < 130.0$	1.4118	1.4383	$1.5053 \pm 0.0335 \pm 0.0328$	1.047
$130.0 < M_{ee} < 180.0$	0.3811	0.3920	$0.4012 \pm 0.0107 \pm 0.0076$	1.024
$180.0 < M_{ee} < 250.0$	0.0757	0.0786	$0.0779 \pm 0.0037 \pm 0.0017$	0.991
$250.0 < M_{ee} < 500.0$	0.0083	0.0086	$0.0096 \pm 0.0007 \pm 0.0003$	1.125

Conclusion

- Measured A_{FB} with 5.0 fb^{-1} data
  - Agrees with PYTHIA prediction
  - 5 times more data than the previous result (DØ, Phys. Rev. Lett. 101, 191801 (2008)), will be the most precise measurement at the Tevatron.
- Measured $\sin^2\theta_W^{eff} = 0.2310 \pm 0.0009(Stat.) \pm 0.0006(Syst.)$
  - Precision is better than the uncertainty of LEP(HAD combination) , still dominated by statistical uncertainty
  - With 8-10 fb^{-1} combine both electron and muon channel with CDF, the expected precision will be comparable with WA
- Measured *Z to light quark* couplings
  - Will be world's most precise measurement of those couplings
- Measured Drell-Yan normalized differential cross section: $\frac{1}{\sigma} \times \frac{d\sigma}{dM}$
  - First measurement in Tevatron Run II
- DØ RunII 1.1 fb^{-1} has been published in Phys. Rev. Lett. 101, 191801 (2008)
- DØ RunII 5.0 fb^{-1} paper is under review for publication.

BACKUP

Gamma cross section

$$q\bar{q} \to e^- e^+ \Rightarrow$$

$$\{$$

$$q_{\Rightarrow}\bar{q}_{\Leftarrow} \Rightarrow J^{e,i}_{RL} = \bar{v}_L \gamma^\mu u_R;$$

$$q_{\Rightarrow}\bar{q}_{\Rightarrow} \Rightarrow J^{e,i}_{RR} = \bar{v}_R \gamma^\mu u_R;$$

$$q_{\Leftarrow}\bar{q}_{\Leftarrow} \Rightarrow J^{e,i}_{LL} = \bar{v}_L \gamma^\mu u_L;$$

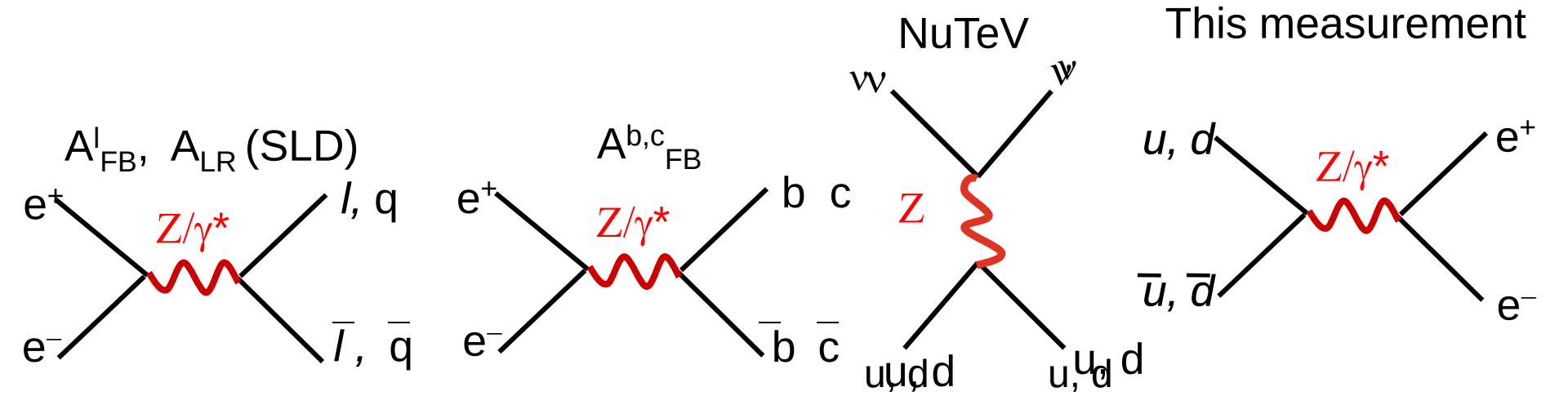
$$q_{\Leftarrow}\bar{q}_{\Rightarrow} \Rightarrow J^{e,i}_{LR} = \bar{v}_R \gamma^\mu u_L$$

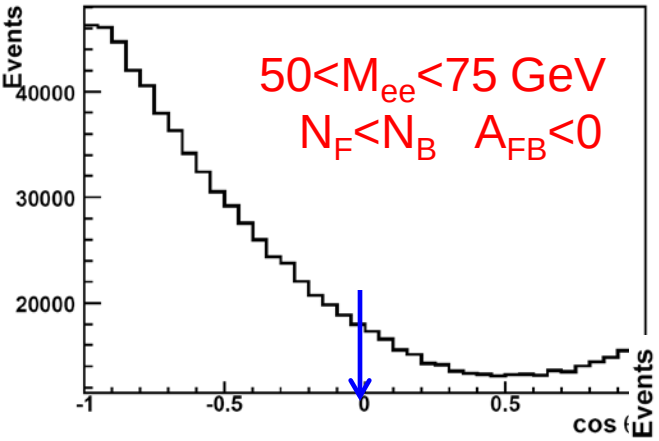
$$\}$$

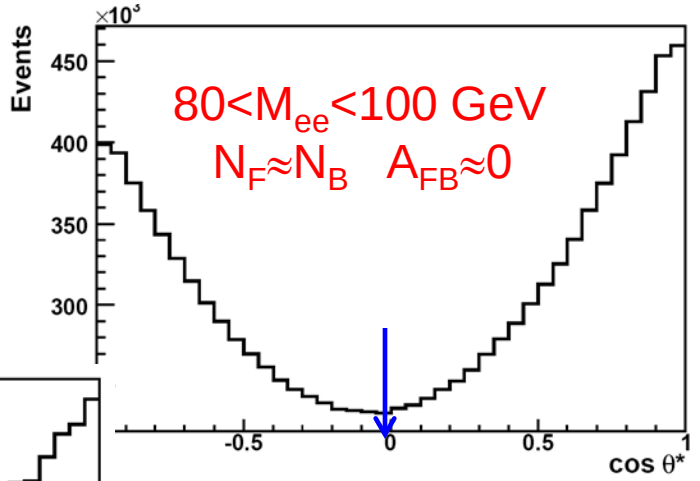
$$\frac{d\sigma_{LL}}{d\Omega}(\theta) = \frac{d\sigma_{RR}}{d\Omega}(\theta) = \frac{\alpha^2}{S}\left(\frac{1+\cos\theta}{2}\right)^2$$

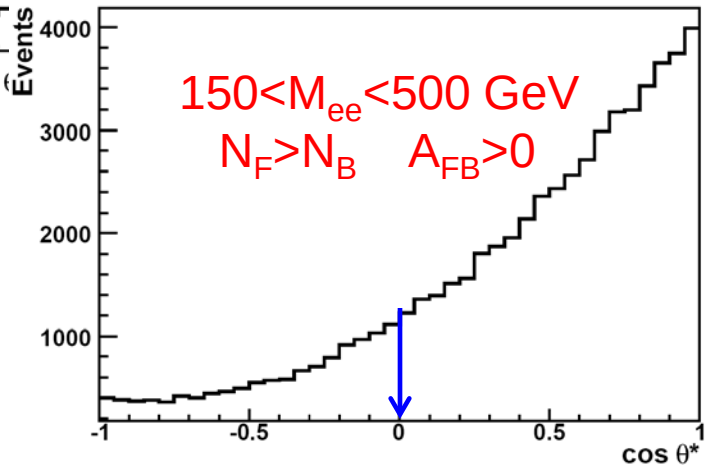
$$\frac{d\sigma_{LR}}{d\Omega}(\theta) = \frac{d\sigma_{RL}}{d\Omega}(\theta) = \frac{\alpha^2}{S}\left(\frac{1-\cos\theta}{2}\right)^2$$

$$\frac{d\sigma}{d\Omega} = \frac{1}{4}\left[\frac{d\sigma_{LL}}{d\Omega} + \frac{d\sigma_{RR}}{d\Omega} + \frac{d\sigma_{LR}}{d\Omega} + \frac{d\sigma_{RL}}{d\Omega}\right] = \frac{1}{4}\frac{\alpha^2}{S}\left(1+\cos\theta^2\right)$$


A^{l}_{FB}, A_{LR} (SLD)
e^+
e^-
Z/γ^*
l, q
$\bar{l}$, $\bar{q}$
$A^{b,c}_{FB}$
e^+
e^-
Z/γ^*
b c
$\bar{b}$ $\bar{c}$
NuTeV
ν
$\bar{\nu}$
Z
u, d
u, d
u, d
u, d
This measurement
u, d
$\bar{u}$, $\bar{d}$
Z/γ^*
e^+
e^-


Events
40000
30000
20000
-1
-0.5
0
0.5
cos θ*
$50<M_{ee}<75$ GeV
$N_F<N_B$ $A_{FB}<0$


$\times 10^3$
Events
450
400
350
300
-0.5
0
0.5
1
cos θ*
$80<M_{ee}<100$ GeV
$N_F \approx N_B$ $A_{FB} \approx 0$


Events
4000
3000
2000
1000
-1
-0.5
0
0.5
1
cos θ*
$150<M_{ee}<500$ GeV
$N_F>N_B$ $A_{FB}>0$

Z

$$\frac{d\sigma}{d\Omega} = \frac{1}{4}\left[\frac{d\sigma_{LL}}{d\Omega} + \frac{d\sigma_{RR}}{d\Omega} + \frac{d\sigma_{LR}}{d\Omega} + \frac{d\sigma_{RL}}{d\Omega}\right]$$

$$= \frac{1}{16}\frac{S}{D_Z(S)}\frac{e^4}{s_W^4 c_W^4} \times \left\{ \begin{array}{l} \left[1+\cos^2\theta\right]\left[(g_{Lq}^2 + g_{Rq}^2)(g_{Ll}^2 + g_{Rl}^2)\right] \\ +2\cos\theta\left[(g_{Lq}^2 - g_{Rq}^2)(g_{Ll}^2 - g_{Rl}^2)\right] \end{array} \right\}$$

$$D_Z = \left(S - M_Z^2\right)^2 + M_Z \Gamma_Z^2 (S)$$

$$\frac{d\sigma_{LL}}{d\Omega}(\theta) = g_{Lq}^2 g_{Ll}^2 \frac{S}{D_Z(S)}\left(\frac{1+\cos\theta^2}{2}\right)^2 \frac{e^4}{s_W^4 c_W^4},$$

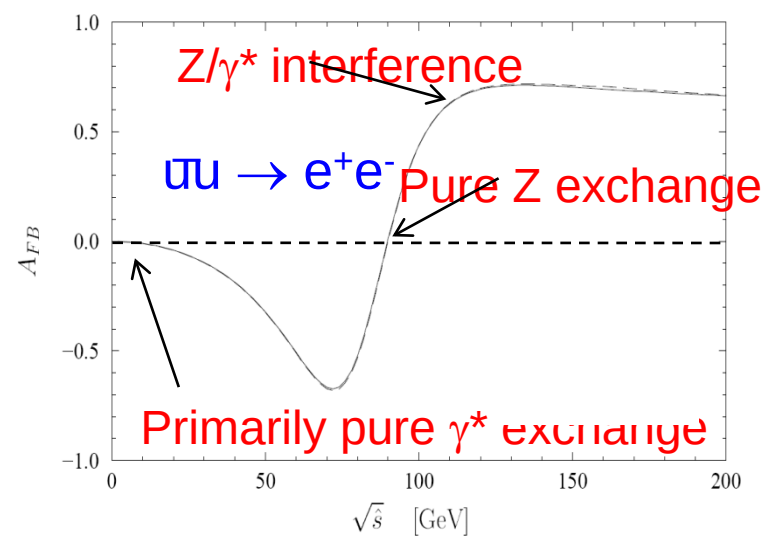
$$\frac{d\sigma_{RR}}{d\Omega}(\theta) = g_{Rq}^2 g_{Rl}^2 \frac{S}{D_Z(S)}\left(\frac{1+\cos\theta^2}{2}\right)^2 \frac{e^4}{s_W^4 c_W^4},$$

$$\frac{d\sigma_{LR}}{d\Omega}(\theta) = g_{Lq}^2 g_{Rl}^2 \frac{S}{D_Z(S)}\left(\frac{1-\cos\theta^2}{2}\right)^2 \frac{e^4}{s_W^4 c_W^4},$$

$$\frac{d\sigma_{RL}}{d\Omega}(\theta) = g_{Rq}^2 g_{Ll}^2 \frac{S}{D_Z(S)}\left(\frac{1-\cos\theta^2}{2}\right)^2 \frac{e^4}{s_W^4 c_W^4}$$

If $g_{Lq}^2 = g_{Rq}^2$

NO asymmetry.



$$\frac{d\sigma(q\bar{q}\to l^+l^-)}{d\cos\theta} = C\frac{\pi\alpha^2}{2S}\Big\{Q_l^2Q_q^2\left(1+\cos^2\theta\right)$$ γ exchange

$$+Q_lQ_q\,\mathrm{Re}\left(\chi(S)\right)\left(2g_V^q g_V^l\left(1+\cos^2\theta\right)+4g_A^q g_A^l\cos\theta\right)$$ Interference

$$+\left|\chi(S)\right|^2\left(\left(g_V^{q\,2}+g_A^{q\,2}\right)\left(g_V^{l\,2}+g_A^{l\,2}\right)\left(1+\cos^2\theta\right)+8g_V^q g_A^q g_V^l g_A^l\cos\theta\right)\Big\}$$ Z exchange

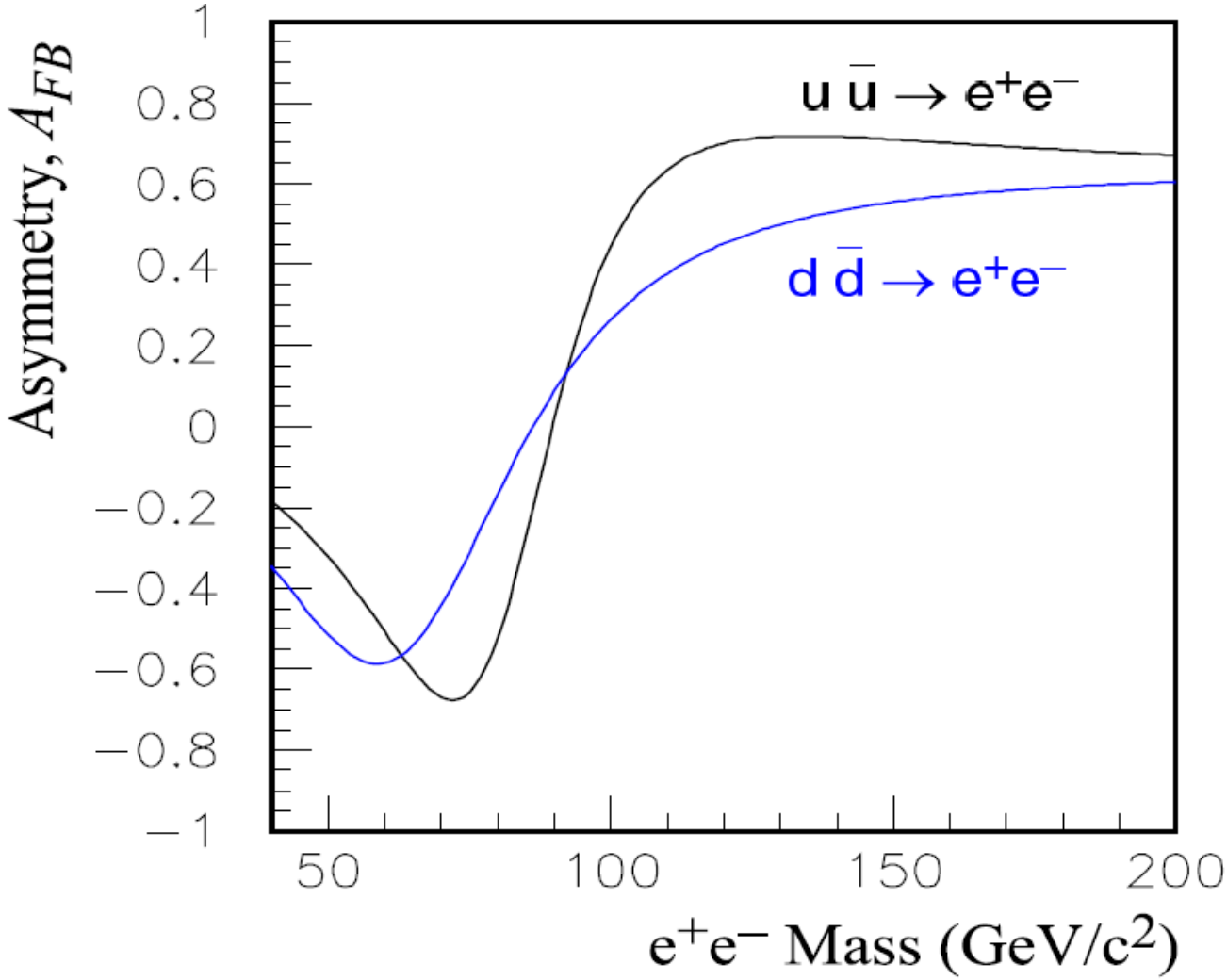
$$C=\begin{cases}1 & \text{for leptons}\\ 3 & \text{for quarks}\end{cases}$$

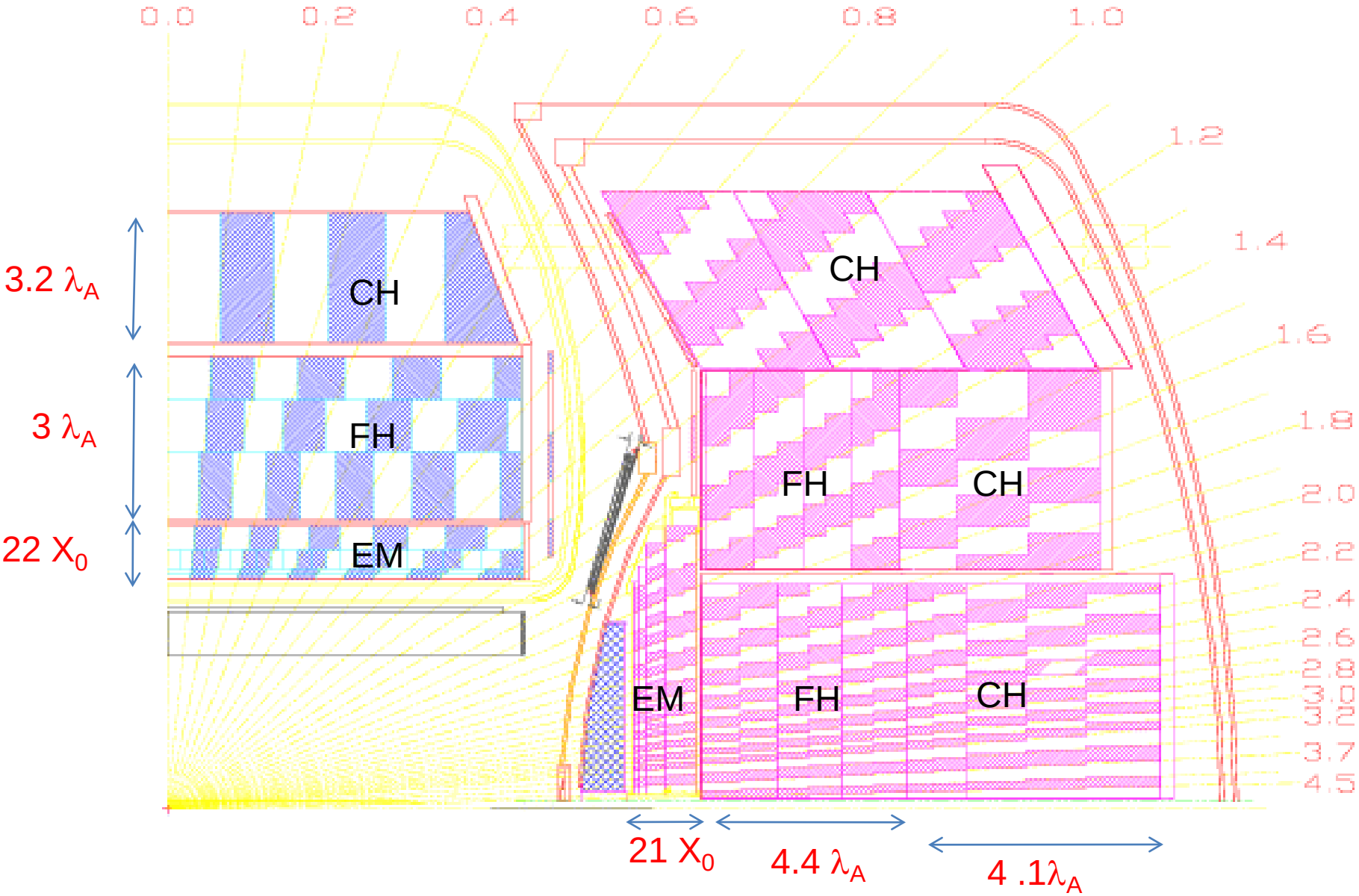
$$\chi=\frac{1}{4\sin^2\theta_W\cos^2\theta_W}\frac{S}{S-m_Z^2+i\Gamma_Z m_Z}$$

$$A_{\mathrm{FB}}^{\mathrm{f}}(s) = \frac{3}{8}\frac{-4\,Q_{\mathrm{f}}\,g_A^{\mathrm{e}}g_A^{\mathrm{f}}\,\Re\{\chi\}+8\,g_A^{\mathrm{e}}g_V^{\mathrm{e}}g_A^{\mathrm{f}}g_V^{\mathrm{f}}\,|\chi|^2}{Q_{\mathrm{f}}^2-2\,Q_{\mathrm{f}}\,g_V^{\mathrm{e}}g_V^{\mathrm{f}}\,\Re\{\chi\}+[(g_A^{\mathrm{e}})^2+(g_V^{\mathrm{e}})^2]\,[(g_A^{\mathrm{f}})^2+(g_V^{\mathrm{f}})^2]\,|\chi|^2}$$

$$A_{\mathrm{FB}}^{\mathrm{f}}(\sqrt{s}=m_{\mathrm{Z}}) = 3\,\frac{g_{\mathrm{V}}^{\mathrm{e}}\,g_{\mathrm{A}}^{\mathrm{e}}}{(g_{\mathrm{V}}^{\mathrm{e}})^2+(g_{\mathrm{A}}^{\mathrm{e}})^2}\,\frac{g_{\mathrm{V}}^{\mathrm{f}}\,g_{\mathrm{A}}^{\mathrm{f}}}{(g_{\mathrm{V}}^{\mathrm{f}})^2+(g_{\mathrm{A}}^{\mathrm{f}})^2} \qquad (21)$$

u/d AFB


Asymmetry, A_{FB}
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
50
100
150
200
e^+e^- Mass (GeV/c^2)
$u\bar{u} \to e^+e^-$
$d\bar{d} \to e^+e^-$


0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.7
4.5
3.2 λA
3 λA
22 X0
CH
FH
EM
CH
FH
CH
EM
FH
CH
21 X0
4.4 λA
4 .1λA

Calorimeter calibration: basic idea

ICD: similar techniques; technically different/separate implementation

Factorise (roughly) into two parts:

- calibration of the calorimeter electronics,
- calibration of the device itself.

This factor can absorb any imperfection in the electronics calibration that leads to a multiplicative miscalibration that is independent of the gain path and stable in time.

Electronics calibrated using pulsers.

Calibration of the device itself:

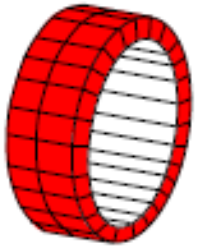
Determine energy scale (i.e. multiplicative correction factor), ideally per cell.

Use phi intercalibration to "beat down the number of degrees of freedom" as much as possible. Done in EM and HAD.

EM: use $Z \rightarrow e^+ e^-$ to get access to the remaining degrees of freedom, as well as the absolute scale.

HAD: use dijet events (and criterion of "best energy resolution") to get access to the remaining degrees of freedom, as well as the HAD scale relative to the EM scale.

ϕ-intercalibration: basic method

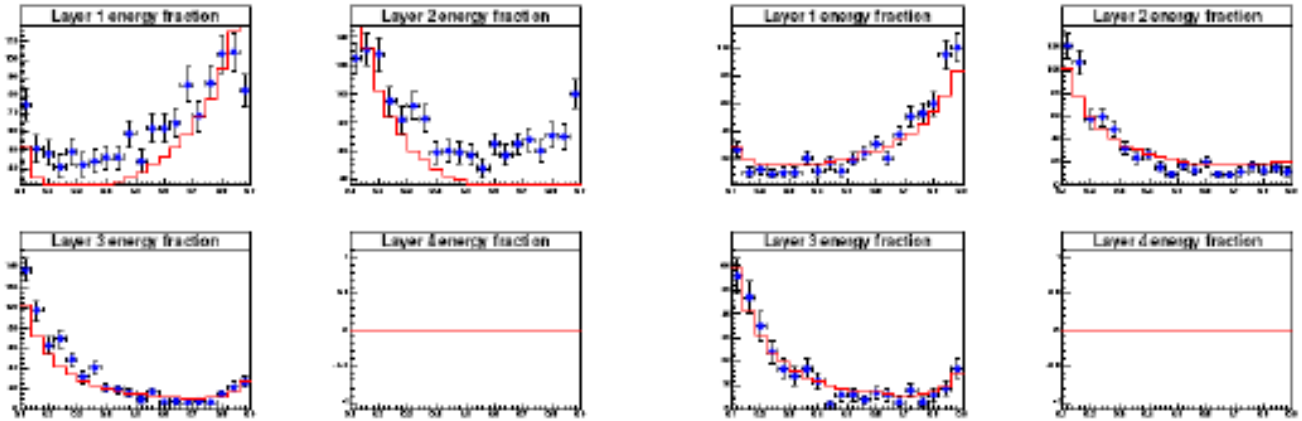


- Due to the unpolarized Tevatron beams physics is ϕ symmetric at DØ
  ➡ Energy flow in the direction transverse to the beams should not have any azimuthal dependence. Any ϕ dependence must be the result of instrumental effects

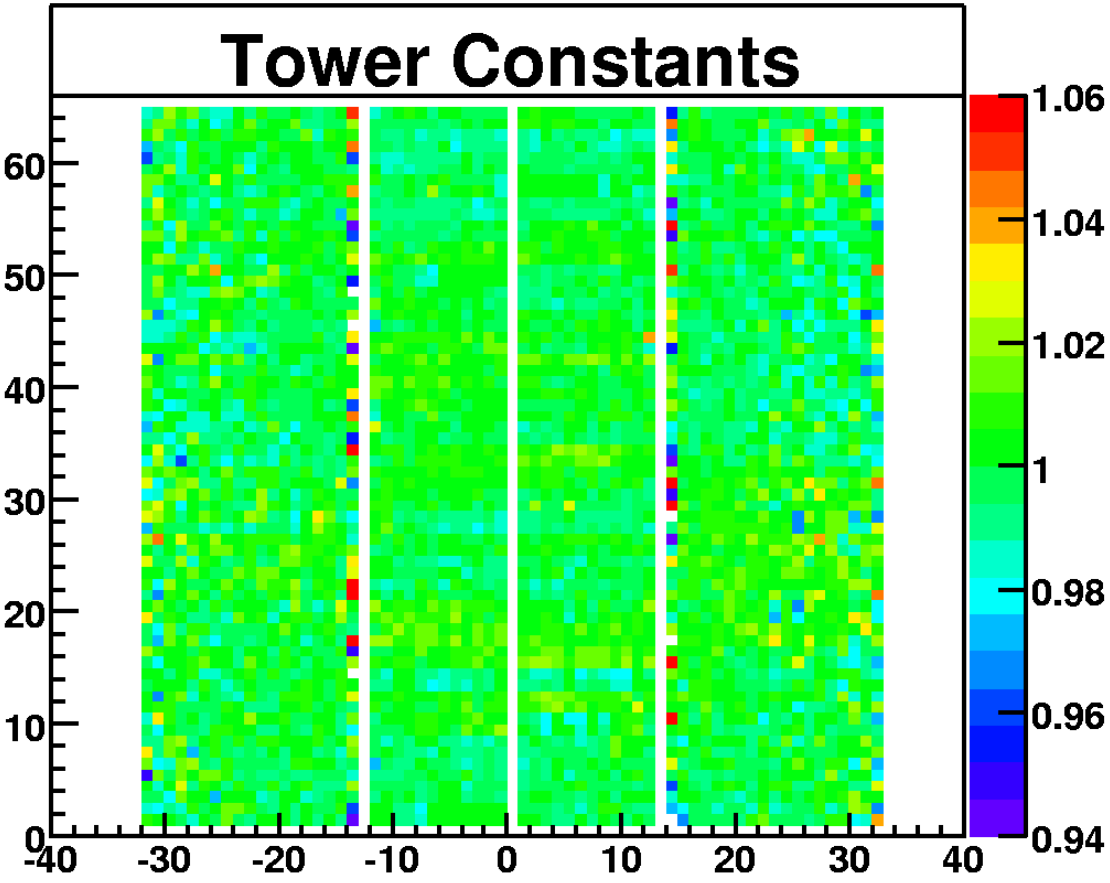
- Energy flow method: at a given η bin of the CAL measure the density of calorimeter objects above a given E_T threshold as a function of ϕ. With a perfect detector, this density would be flat in ϕ. Assuming that any ϕ-non-uniformities are due to energy scale variations, the uniformity of the detector can be improved by applying multiplicative calibration factors to the energies of calorimeter objects in each ϕ region in such a way that the candidate density becomes flat in ϕ

ϕ-intercalibration: in practice

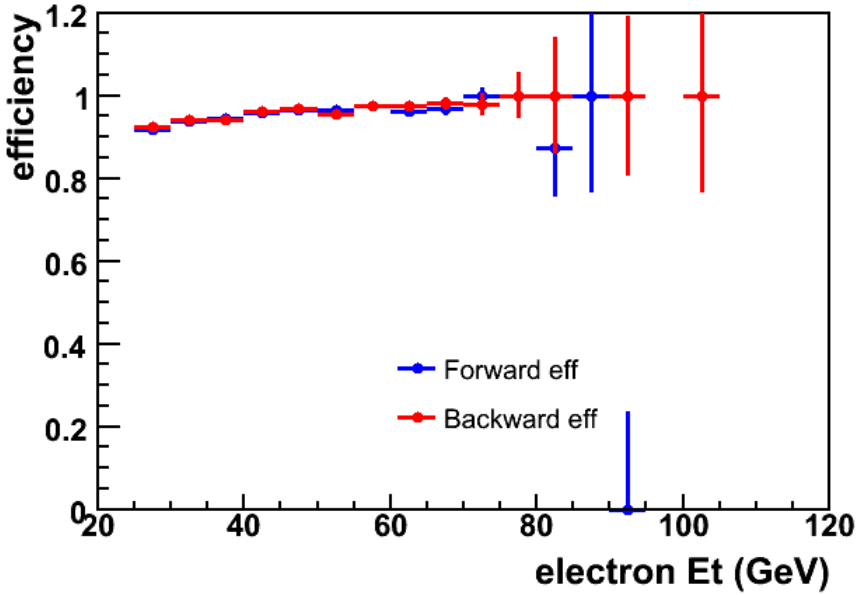
- In practice: calibration on tower and layer level
  - Tower level: count events in CAL towers above some E_T cut. Vary the cut so that each tower at given η gives the ϕ averaged number of events.
  - Layer level: intercalibrate cells inside the tower. Energy fraction distributions in ϕ are compared to the average for each layer, the set of layer constants within a tower is adjusted to obtain the best match

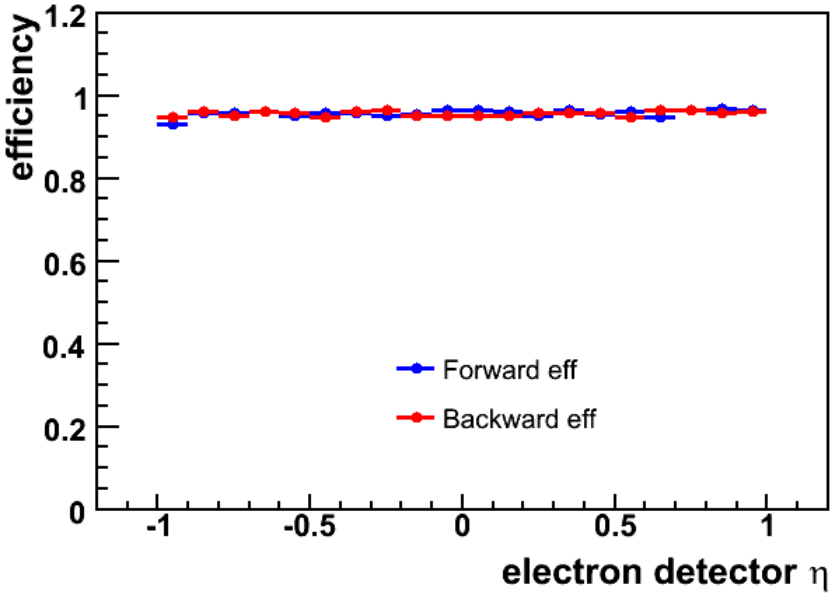


  - This is done by computing individual layer χ_i^2's and minimize $\chi^2_{\text{all}} \equiv \sum_i \chi_i^2$ using `Minuit`
- Iterate procedure of layer and tower calibration until stability is reached
- Final ϕ-intercalibration constants products of layer and tower constants


Tower Constants
60
50
40
30
20
10
0
-40
-30
-20
-10
0
10
20
30
40
1.06
1.04
1.02
1
0.98
0.96
0.94

Forward and Backward efficiency





There is no big difference between forward electron efficiencies and backward electron efficiencies

Will take the difference between forward electron and backward electron efficiencies as one of systematic uncertainties.

A_{FB} measurement at LEP and SLD

- Left- and right-handed couplings: $g_V = g_L + g_R$, $g_A = g_L - g_R$
- Fermion asymmetry parameter: $A_f = 2g_V g_A/(g^2_V + g^2_A)$
- At e^+e^- collider:
  - Forward-backward asymmetry:

    $A^f_{FB} = (\sigma^f_F - \sigma^f_B)/(\sigma^f_F + \sigma^f_B) = 0.75 A_e A_f$
  - Left-right asymmetry:

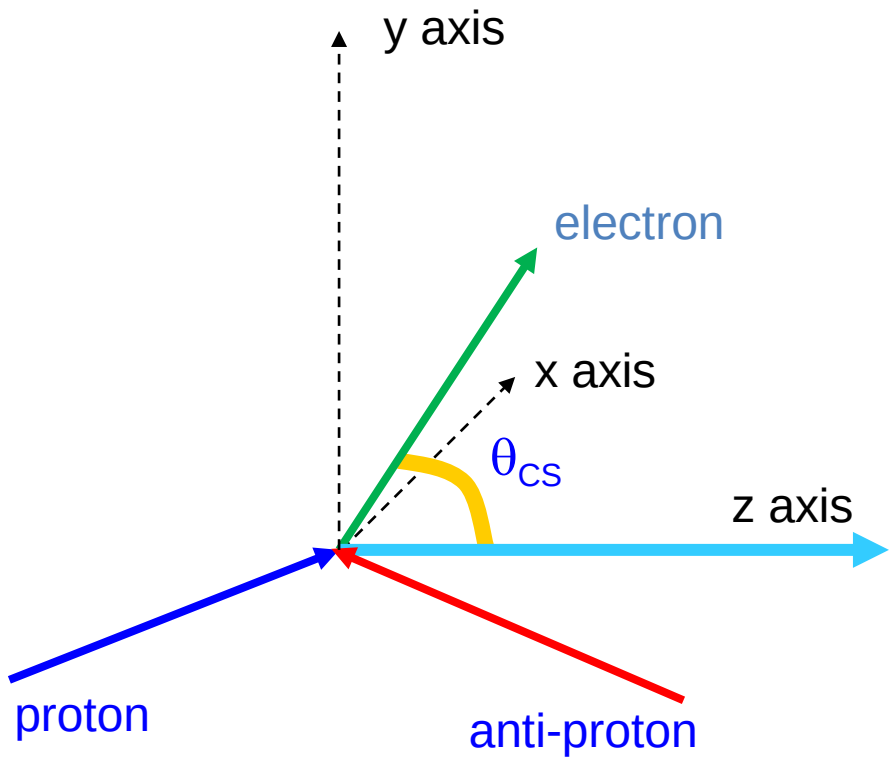
    $A_{LR} = (\sigma_L - \sigma_R)/(\sigma_{L+} \sigma_R) = P_e A_e$
  - Left-right F/B asymmetry (direct measurement of final-state coupling)

    $A^{LR}_{FB} = [(\sigma^L_F - \sigma^R_F) - (\sigma^L_B - \sigma^R_B))]/[(\sigma^L_{F+} \sigma^R_F) + (\sigma^L_{F+} \sigma^R_F)] = 0.75 P_e A_f$

Measurement Techniques used at SLD and LEP

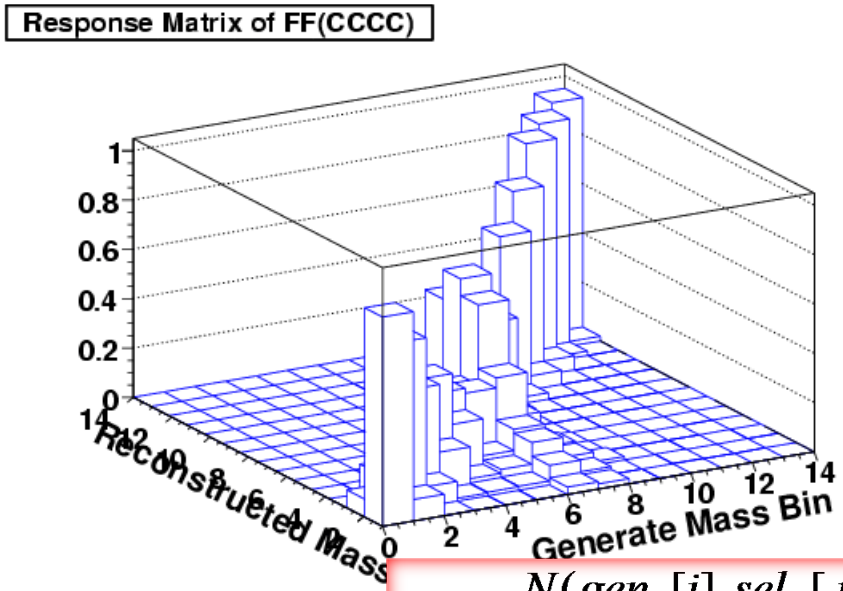
- Measurement of A_{LR}, A^{FB}_{LR}, A^{l}_{FB} at SLD:
  - Excludes electron mode to avoid the added complexity of correcting for t-channel interference
  - Determination of the beam polarization
- Measurement of A^{l}_{FB} at LEP
- Measurement of P^{τ} (τ polarization)
- Measurement of A^{b}_{FB}, A^{c}_{FB}
  - Use lepton tag: P and P_T of leptons can be used to assign a probability that the lepton is a *b* or a *c* quark
  - Sign of the lepton tags the quark charge
- Measurement of Q^{had}_{FB}:
  - Use momentum-weighted jet charge to tag the quark charge
  - Relies on MC to determine the relative abundance of the different quark species

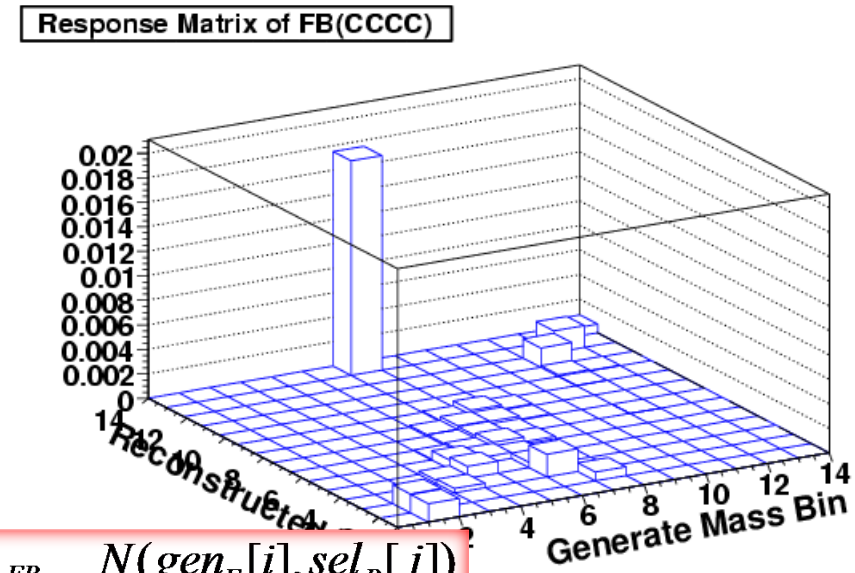
Collins-Soper frame



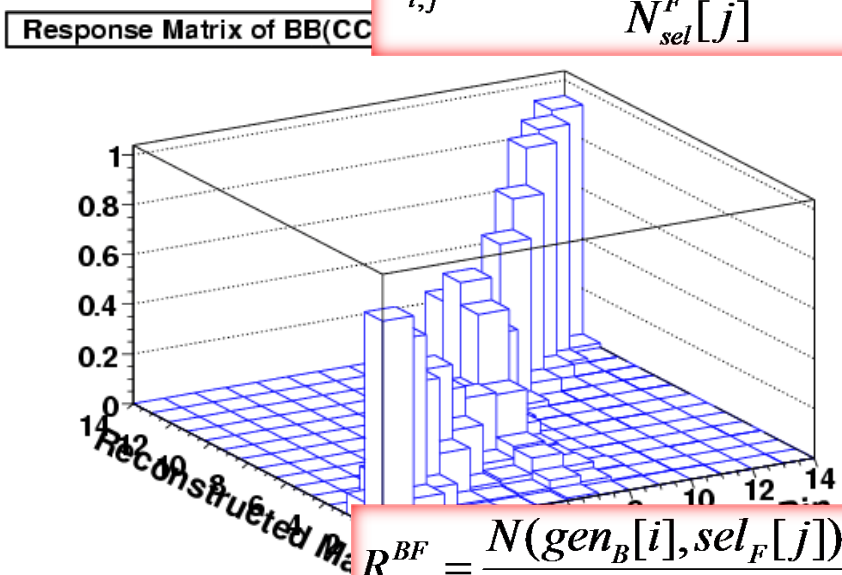
Viewed from di-electron rest frame

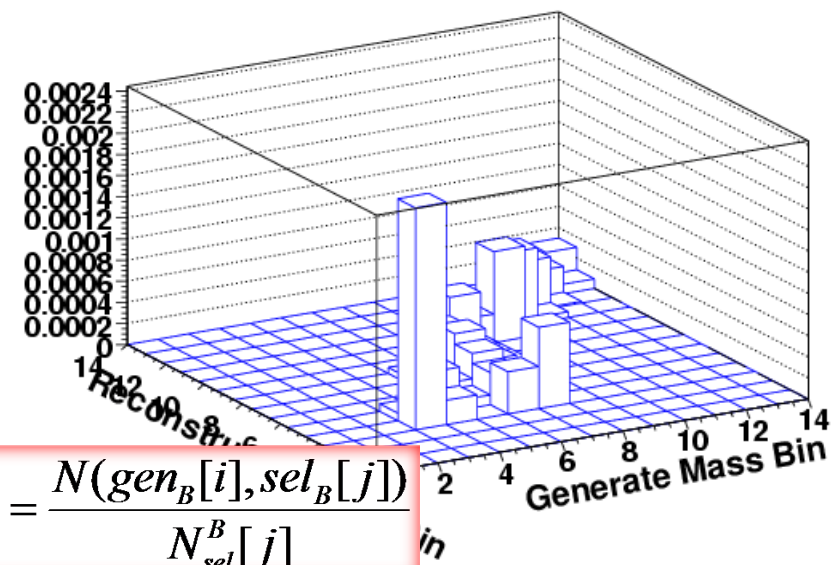
Z axis defined as the bisector of the proton beam momentum and the negative of the anti-proton beam momentum in the dilepton rest frame





$$R_{i,j}^{FF} = \frac{N(gen_F[i], sel_F[j])}{N_{sel}^F[j]}; R_{i,j}^{FB} = \frac{N(gen_F[i], sel_B[j])}{N_{sel}^B[j]}$$

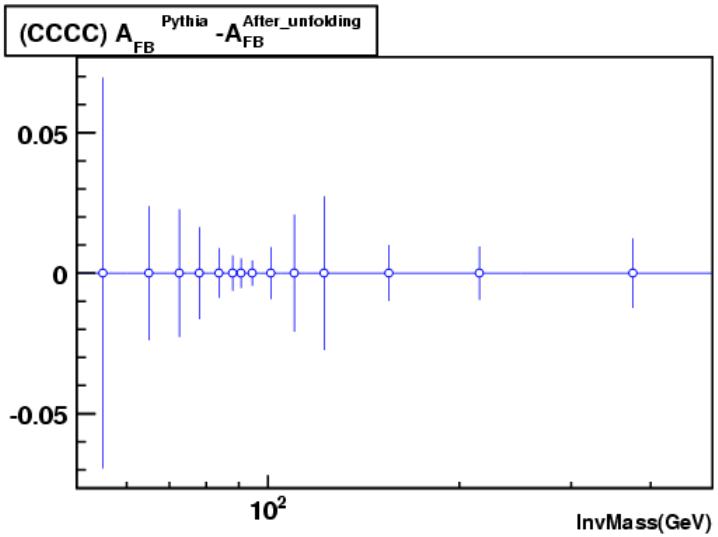


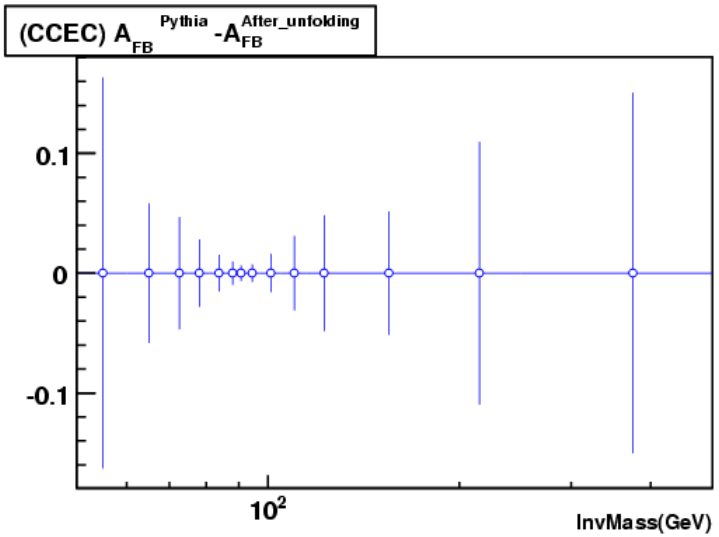


$$R_{i,j}^{BF} = \frac{N(gen_B[i], sel_F[j])}{N_{sel}^F[j]}; R_{i,j}^{BB} = \frac{N(gen_B[i], sel_B[j])}{N_{sel}^B[j]}$$

Closure tests

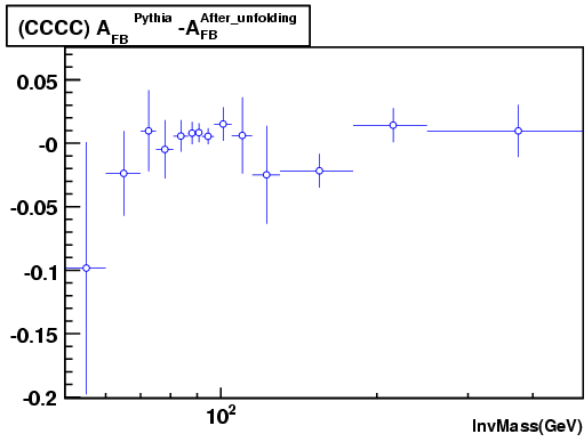
- Apply same analysis procedure on GEANT MC and compare the unfolded AFB with truth
- Three closure tests have been done:
  1. Raw A_{FB} and all corrections measured using the same GEANT MC files

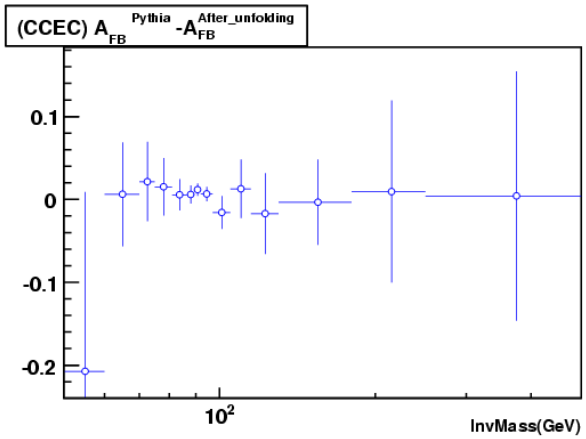




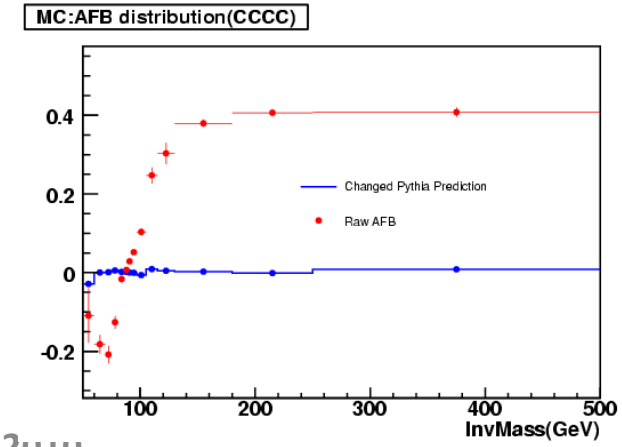
Closure tests(Cont.)

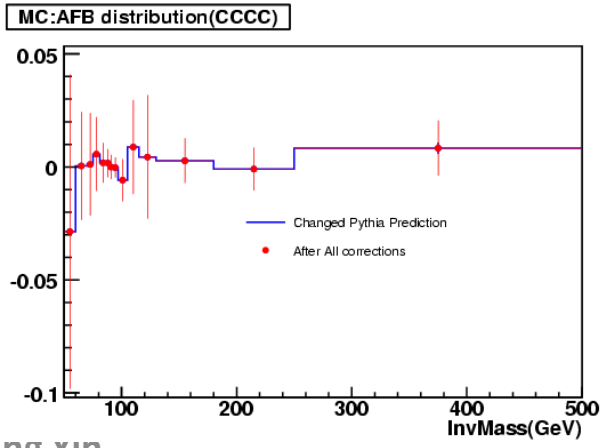
2. Use half of GEANT files to measure raw A_{FB} and other half to measure all correction





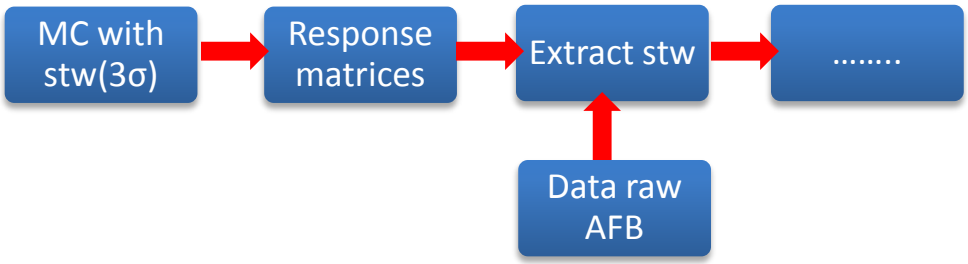
3. Randomly flip the charge to make generator level A_{FB} flat and then measure A_{FB} and all corrections



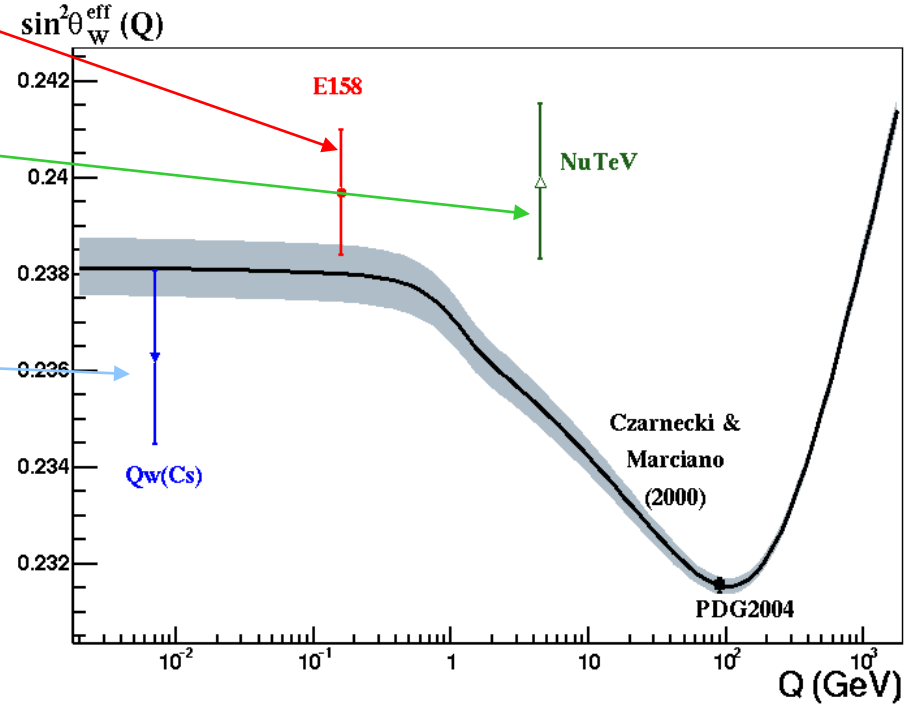


Bias due to the unfolding method

- Use Geant MC to get the response matrices and acc*eff corrections. Those corrections depends on the input AFB and may bias the unfolded results.



- Do an iterative unfolding to remove this bias:
  1. Use response matrices measured from a MC sample(with different $\sin^2\theta_W^{eff}$) to unfold the raw A_{FB}(start with 3σ(3*0.001) away from the measured $\sin^2\theta_W^{eff}$)
  2. Compare unfolded AFB with AFB generated with difference input $\sin^2\theta_W^{eff}$ using χ2 fitting method to get best $\sin^2\theta_W^{eff}$
  3. Use corrections measured from a MC sample(with $\sin^2\theta_W^{eff}$ from step 2) to unfold the raw AFB
  4. Repeat step 1 – 3 , until $\sin^2\theta_W^{eff}$ is stable

Stw depends on scale

- Moller scattering
- ν-nucleon scattering
- Atomic parity violation in Cesium