# Probing Partons with $W$ Charge Asymmetry at DØ

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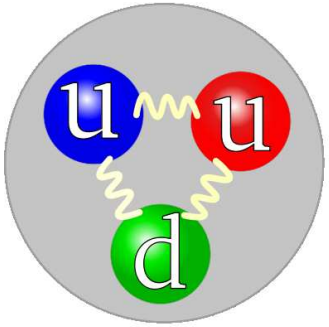
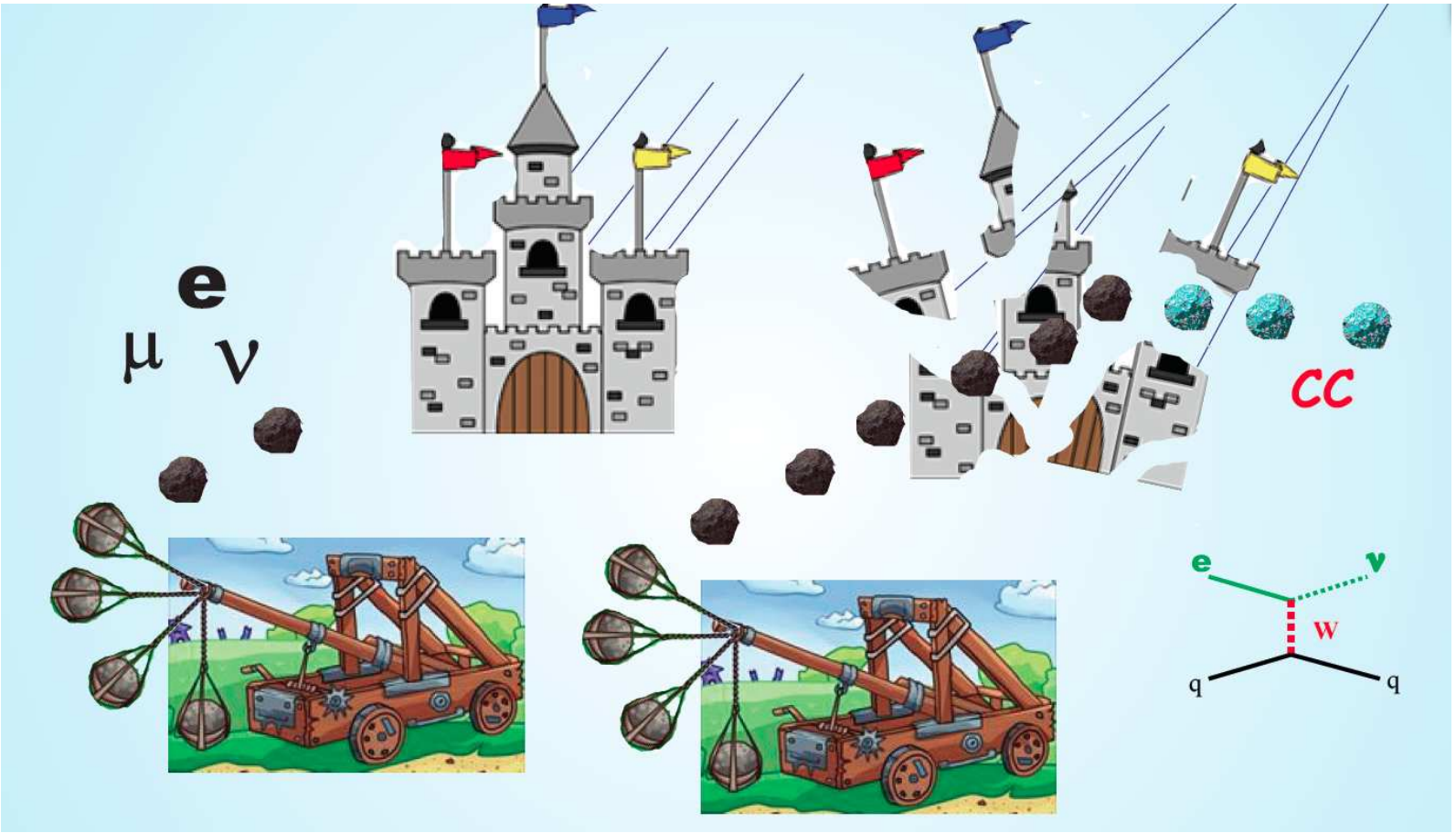
# What do we know about the proton?

- Composition: 2 $u$ quarks, 1 $d$ quark
- Mass: $1.672621777(74) \times 10^{-27}\ kg$, $938.272046(21)\ MeV/c^2$
- Lifetime: $> 5 \times 10^{33}$ years ($p \to \mu^+\pi^0$)
  - (older than universe $13.798 \times 10^9$ years)
- Charge: $+1\ e$, $1.602176565(35) \times 10^{-19}\ C$
- Spin: 1/2
- Charge radius: 0.8775(51) fm
- .....



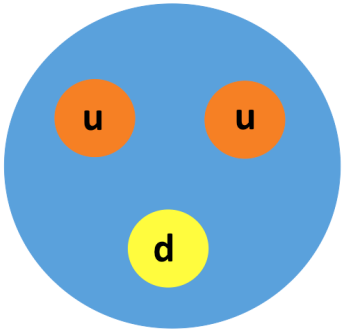
# The way to study proton structure?

- Deep Inelastic Scattering (DIS)

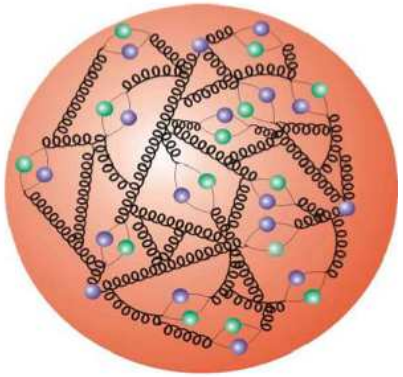


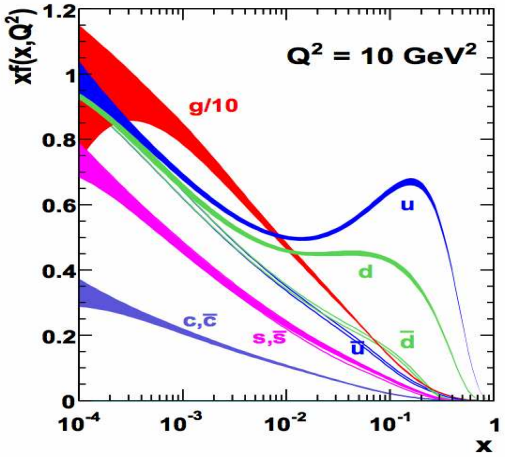

Taken from Iris Abt's PIC 2013 talk.

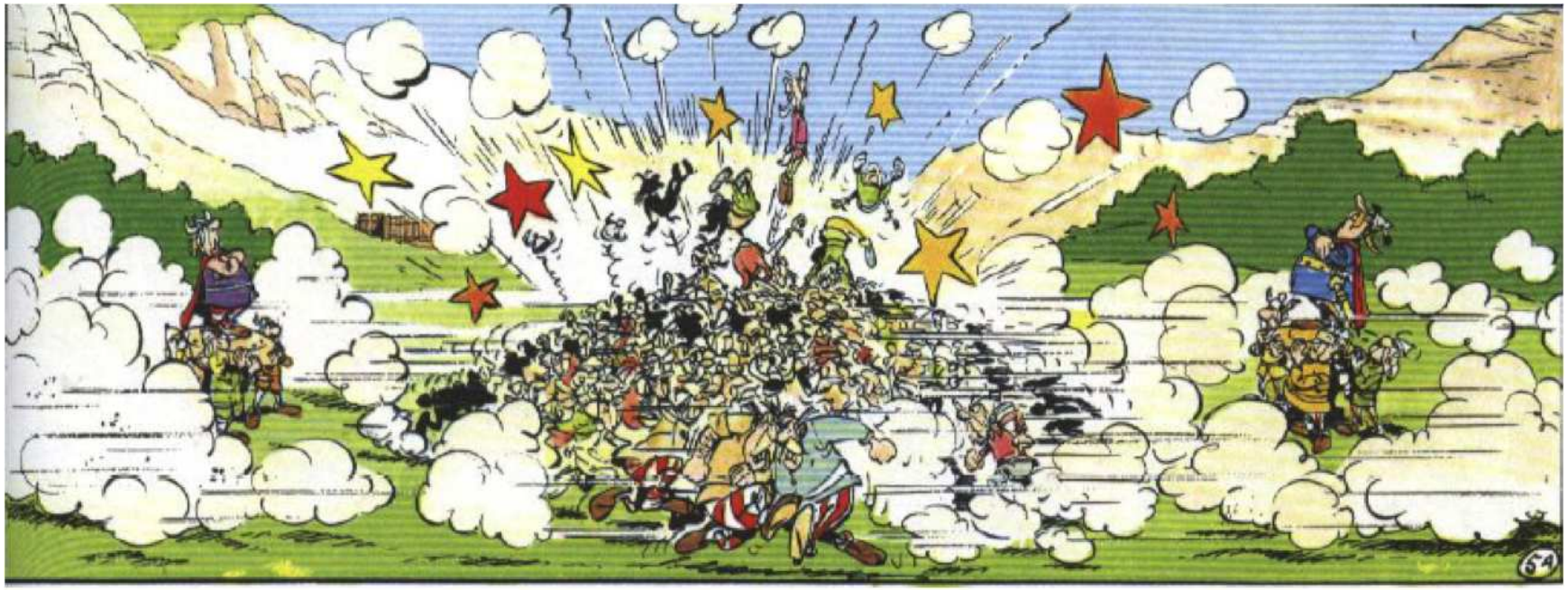
# Parton Distribution Functions at hadron colliders




proton

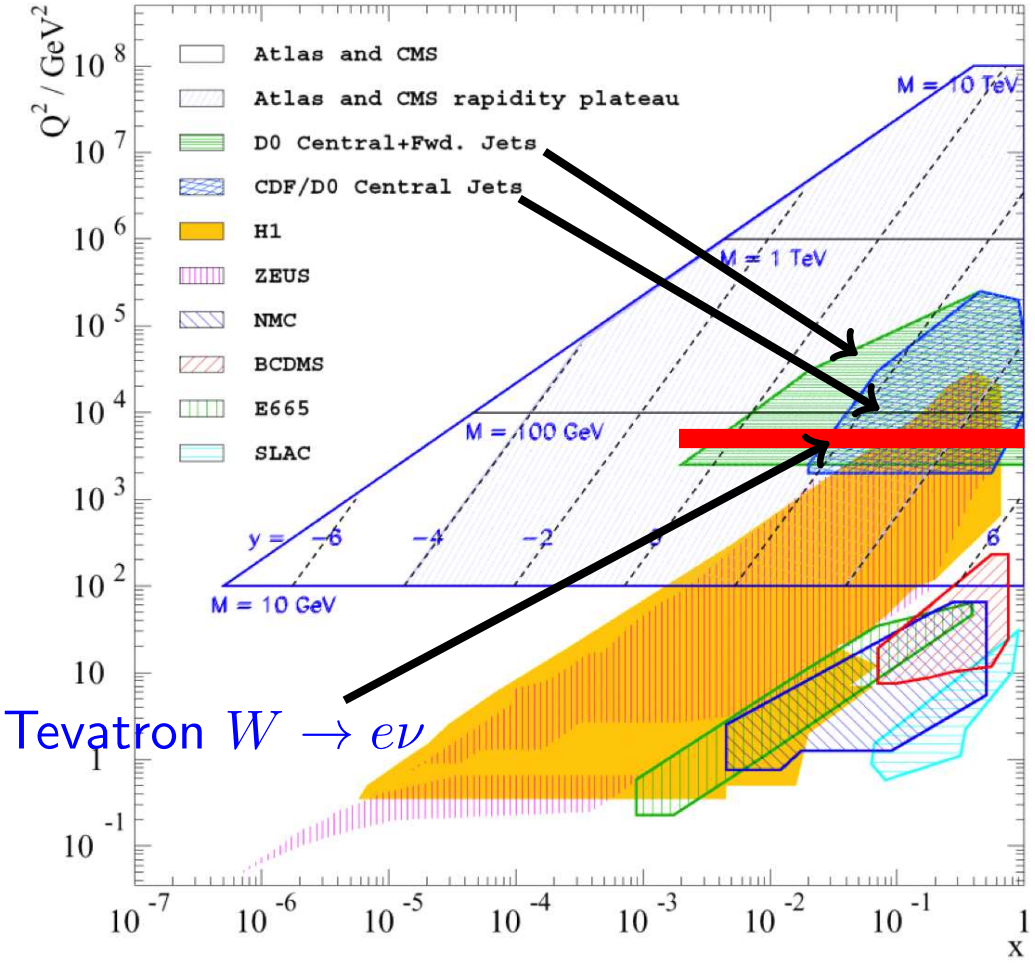




# $x \sim Q^2$ reach of DØ

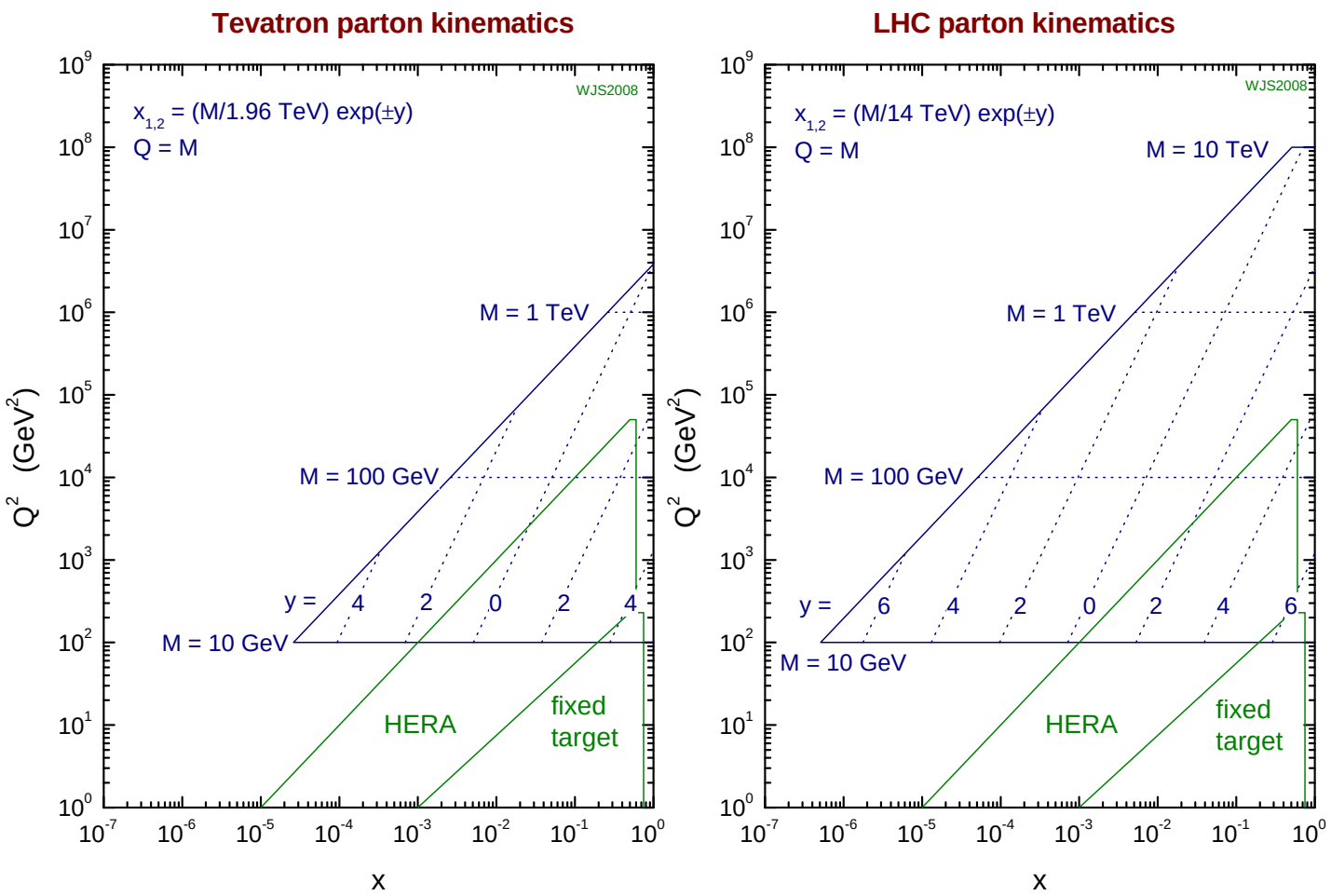
$x$ = momentum fraction of parton
$Q^2$ = squared momentum scale for the parton interactions




- $W$ charge asymmetry measurement:
  - $Q^2 \approx M_W^2$
  - $x = \frac{M_W}{\sqrt{s}} e^{\pm y_W}$
- $x$ range:
  - $|y_W| < 3.2 \sim$ $0.002 < x < 1.0$
- Complementary to central and forward jet measurements at Tevatron, and other scattering experiments

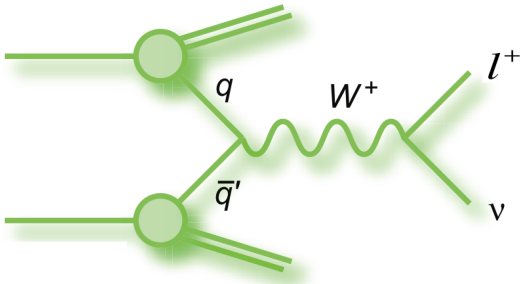
# Kinematic regions at the Tevatron and LHC

- For LHC data fixed $Q^2$ spans wider $x$ than the Tevatron



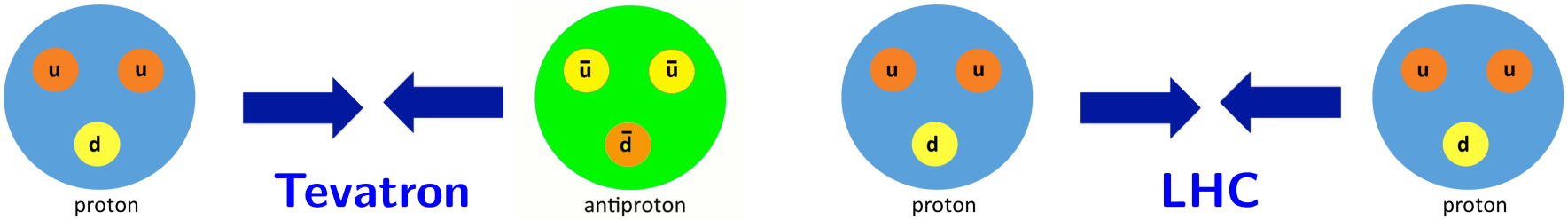
# $W$ production at: Tevatron and LHC

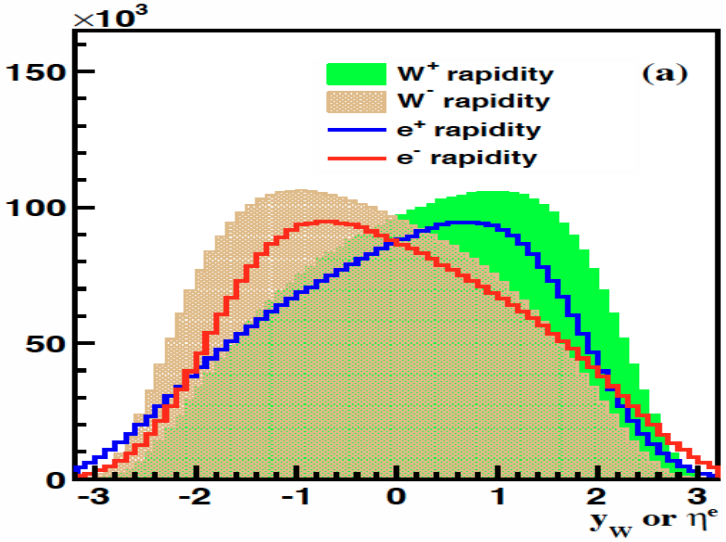
- Tevatron: dominated by valence quark production

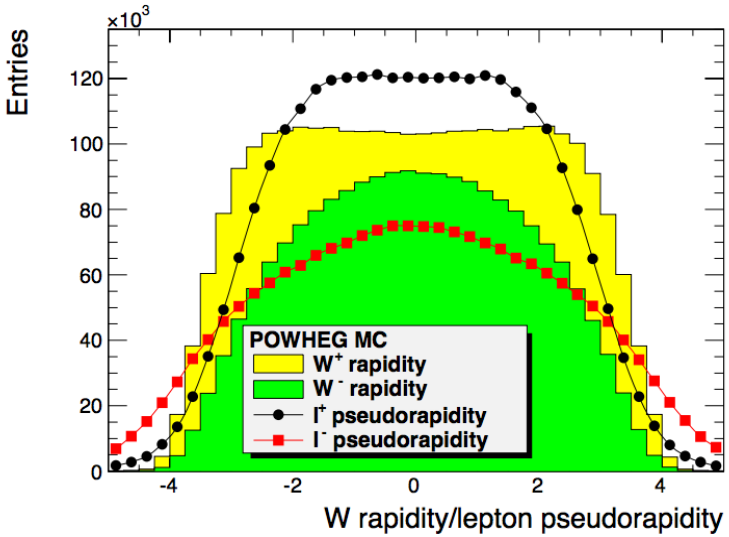



- LHC: dominated by sea quark and gluon production

**Measurement @Tevatron places stringent constraints on the PDFs**



# Impacts from PDFs

- Parton distribution functions are not directly calculable, must be determined using experimental inputs
- Many precision measurements are dominated by the PDF uncertainty

TABLE III. The input data used in the $M_W$ combination. All entries are in units of MeV.

| | CDF [8] | CDF [9] | CDF [10] | D0 [12–15] | D0 [16] | CDF [17] | D0 [18] |
|---|---|---|---|---|---|---|---|
| | (1988–1989) | (1992–1993) | (1994–1995) | (1992–1995) | (2002–2006) | (2002–2007) | (2006–2009) |
| | 4.4 $pb^{-1}$ | 18.2 $pb^{-1}$ | 84 $pb^{-1}$ | 95 $pb^{-1}$ | 1.0 $fb^{-1}$ | 2.2 $fb^{-1}$ | 4.3 $fb^{-1}$ |
| Mass and width | | | | | | | |
| $M_W$ | 79 910 | 80 410 | 80 470 | 80 483 | 80 400 | 80 387 | 80 367 |
| $\Gamma_W$ | 2 100 | 2 064 | 2 096 | 2 062 | 2 099 | 2 094 | 2 100 |
| $M_W$ uncertainties | | | | | | | |
| PDF | 60 | 50 | 15 | 8 | 10 | 10 | 11 |
| Radiative corrections | 10 | 20 | 5 | 12 | 7 | 4 | 7 |
| $\Gamma_W$ | 0.5 | 1.4 | 0.3 | 1.5 | | | |
| Total | 390 | 181 | 89 | 84 | | | |
| $M_W$ corrections | | | | | | | |
| $\Delta\Gamma_W$ | +1.2 | −4.2 | +0.6 | −4.5 | +1.1 | +0.3 | +1.2 |
| PDF | +20 | −25 | 0 | 0 | 0 | 0 | 0 |
| Fit method | −3.5 | −3.5 | −0.1 | 0 | 0 | 0 | 0 |
| Total | +17.7 | −32.7 | +0.5 | −4.5 | +1.1 | +0.3 | +1.2 |
| $M_W$ corrected | 79 927.7 | 80 377.3 | 80 470.5 | 80 478.5 | 80 401.8 | 80 387.3 | 80 368.6 |

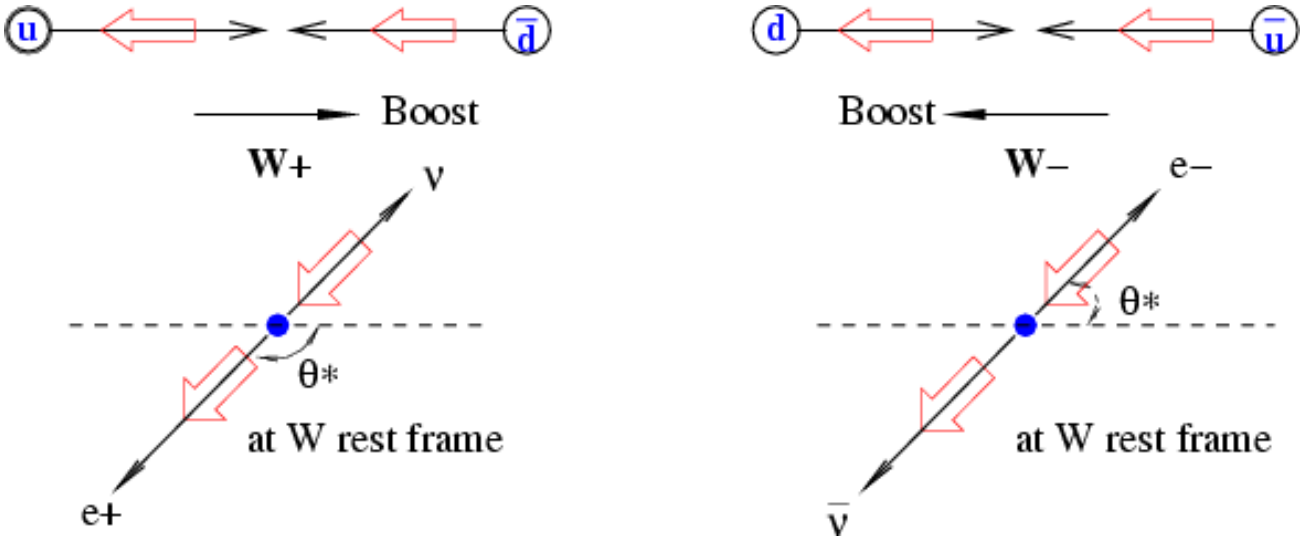
Stat.: 12 13 MeV

Phys. Rev. D **88**, 052018 (2013)

# $W$ charge asymmetry at the Tevatron

- $W$ charge asymmetry is sensitive to Parton Distribution Functions (PDFs).
  - *Tevatron* is $p\bar{p}$ collider, and $u$ quark has higher momentum.
  - $W^+$ boosted in $p$ direction, and $W^-$ boosted in $\bar{p}$ direction.
- $W$ asymmetry: In the leading order parton model

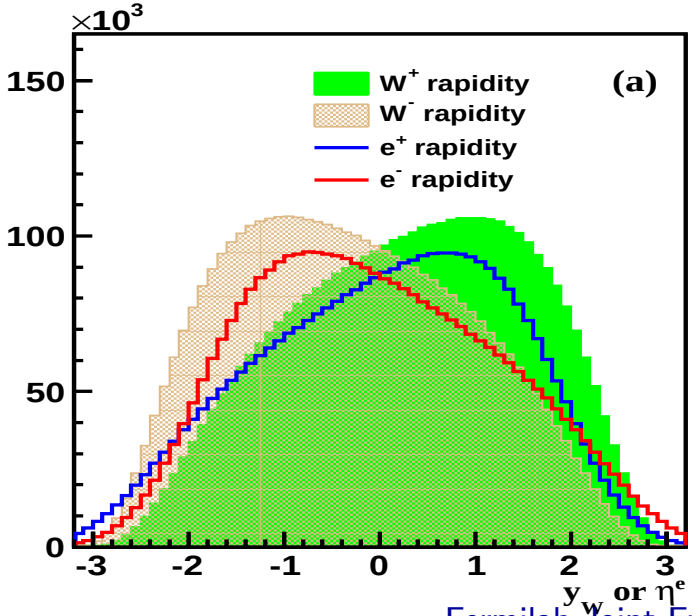
$$A(y_W) = \frac{\frac{d\sigma^+}{dy_W} - \frac{d\sigma^-}{dy_W}}{\frac{d\sigma^+}{dy_W} + \frac{d\sigma^-}{dy_W}} = \frac{u(x_p)\bar{d}(x_{\bar{p}}) - d(x_p)\bar{u}(x_{\bar{p}})}{u(x_p)\bar{d}(x_{\bar{p}}) + d(x_p)\bar{u}(x_{\bar{p}})}$$

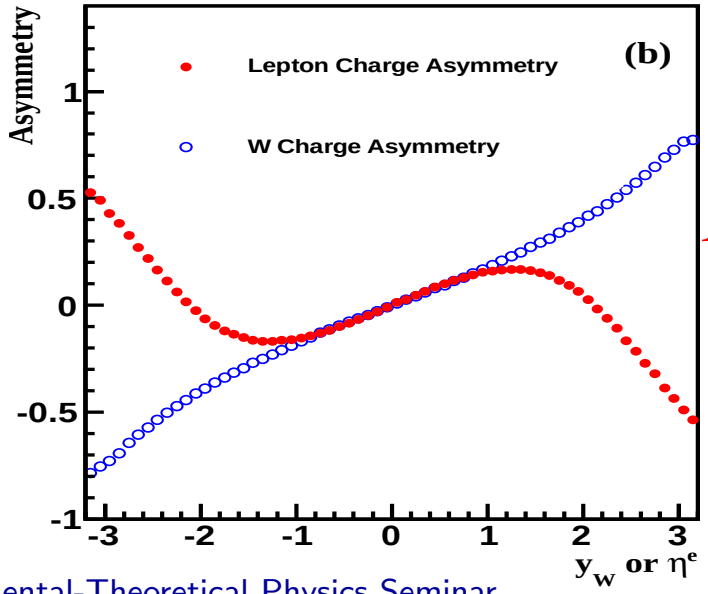


# Lepton and $W$ charge asymmetry

- Lepton asymmetry: convolution of the $W$ boson charge asymmetry and the $W$ $V-A$ decay
- $W$ asymmetry:
  - Advantage: Due to convolution leptons at a specific pseudorapidity ($\eta$) originate from a wide range of $W$ rapidities, and therefore from a wide range of parton $x$ values, making these asymmetries less useful in determining PDFs.
  - Challenge: With unknown neutrino $p_z^\nu$, difficult to determine the $W$ rapidity

RESBOS+CTEQ6.6

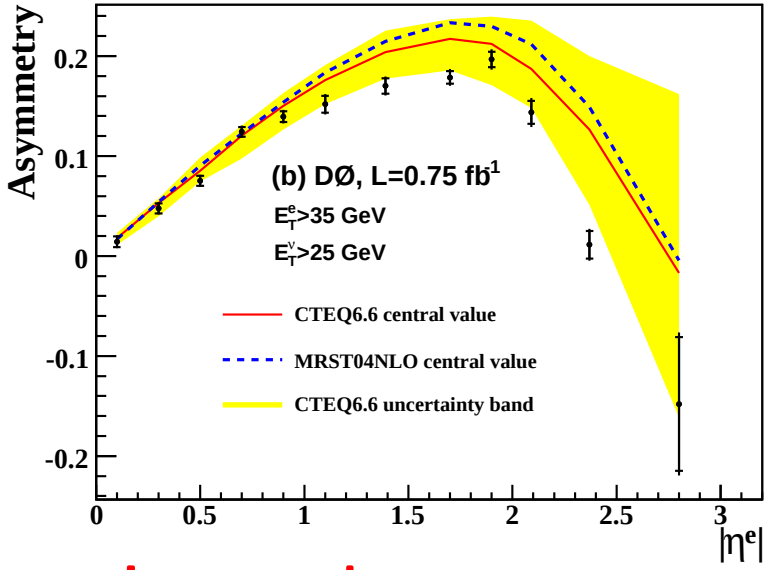



$$A = \frac{N^+ - N^-}{N^+ + N^-}$$

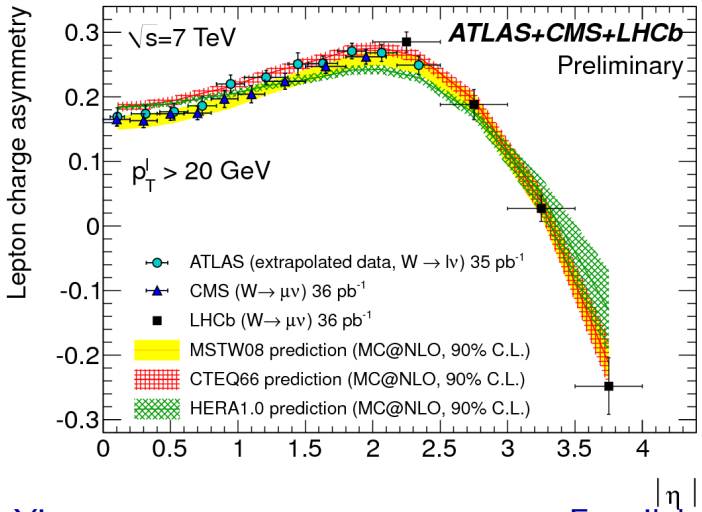
# Previous measurements

Phys. Rev. Lett. **101**, 211801 (2008)

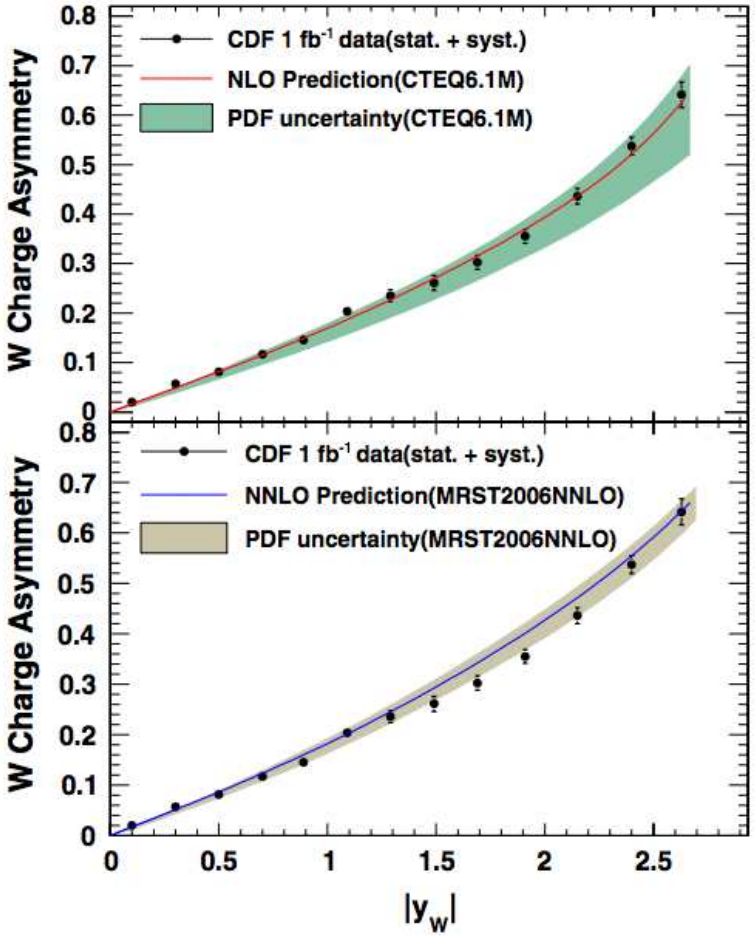



**Lepton charge asymmetry**

ATLAS-CONF-2011-129




Phys. Rev. Lett. **102**, 181801 (2009)




**$W$ charge asymmetry**

(symmetric distributions in $\eta^l$, $y_W$ are folded)

# Strategy and Measurements

- Select $W \to e\nu$ or $W \to \mu\nu$ candidates from data
- Subtract backgrounds: $QCD$, $Z \to ee/Z \to \mu\mu$, $Z \to \tau\tau$ and $W \to \tau\nu$
- Unfold to remove detector effects
- Compare corrected asymmetries with theoretical predictions using different PDF sets

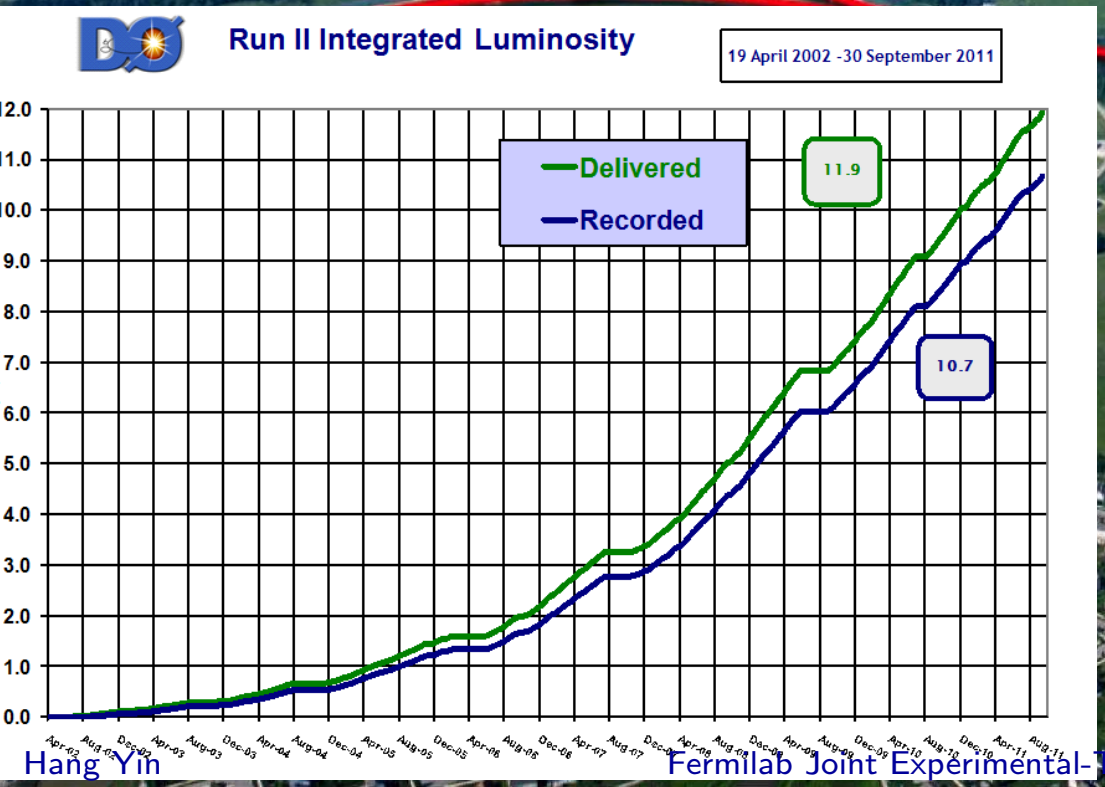
Measurements included in this talk:

- Muon charge asymmetry with 7.3 fb$^{-1}$ data: Phys. Rev. D **88**, 091102(R) (2013)
- Electron charge asymmetry with 9.7 fb$^{-1}$ data
- $W$ boson charge asymmetry in electron channel with 9.7 fb$^{-1}$ data

New!

# The Tevatron

**Thanks to Accelerator Division for the excellent running of Tevatron!!**

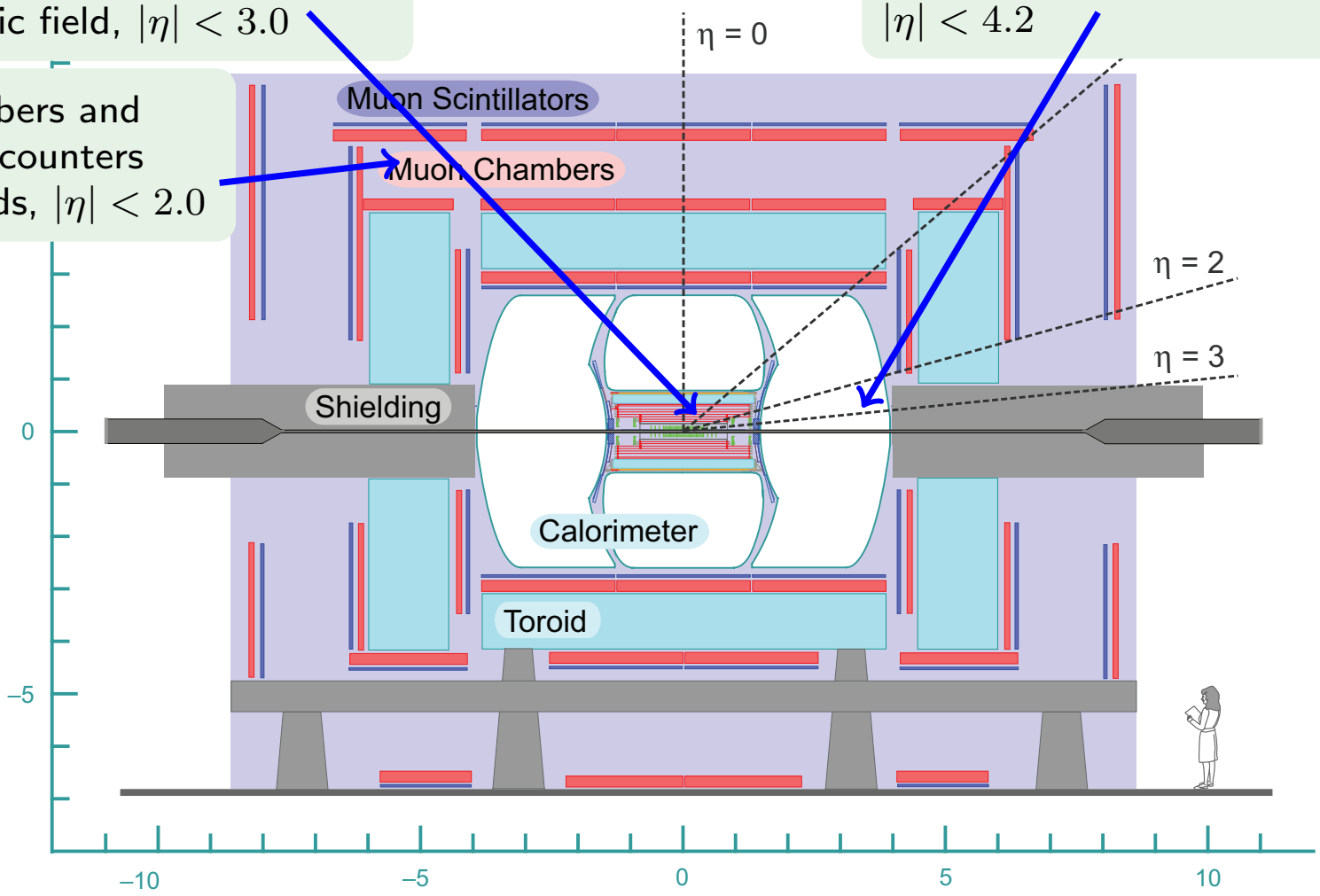


# DØ Detector

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

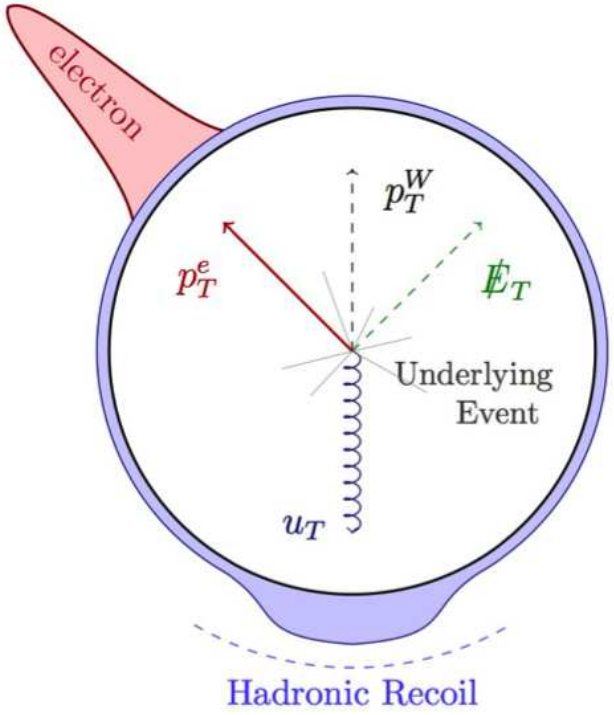
Uranium Liquid Argon calorimeters
Central (CC) and Endcap (EC)
$|\eta| < 4.2$

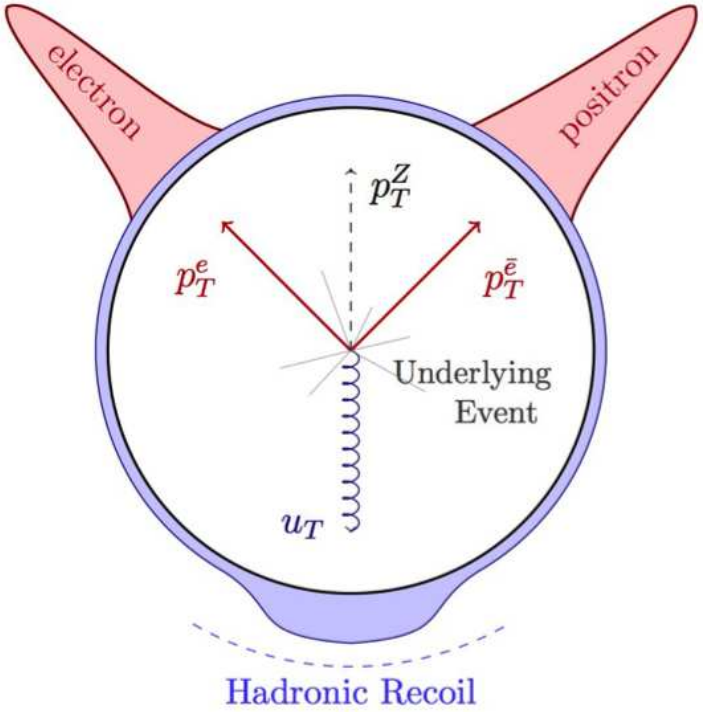
Drift chambers and
scintillator counters
1.8T Toroids, $|\eta| < 2.0$



# $W$ and $Z$ events

- $Z$ boson: two high $p_T$ charged leptons
  - Both charged leptons are detected and their momentum measured
- $W$ boson: one high $p_T$ charged lepton, one high $p_T$ neutrino
  - Charged lepton is detected and momentum measured, neutrino cannot be detected
  - $p_T^\nu$ is inferred by the missing $E_T$ "($\not{E}_T$)"



# Measurement of Muon charge asymmetry

# $W \to \mu\nu$ event selection

- Muon charge asymmetry:

$$A(\eta, p_T) = \frac{(1-g+kg)N^+ - (k-kg+g)N^-}{(1-g-kg)N^+ + (k-kg-g)N^-}$$

  - $g$: charge misidentification probability
  - $k$: relative efficiency correction

- Use $Z \to \mu\mu$ events for muon charge misidentification and relative efficiency correction

- DØ RunII 7.3 fb$^{-1}$ data, with single muon triggers
- Isolated muon matched to a tight central track
- $\not{E}_T > 25$ GeV and $W$ transverse mass $M_T > 50$ GeV

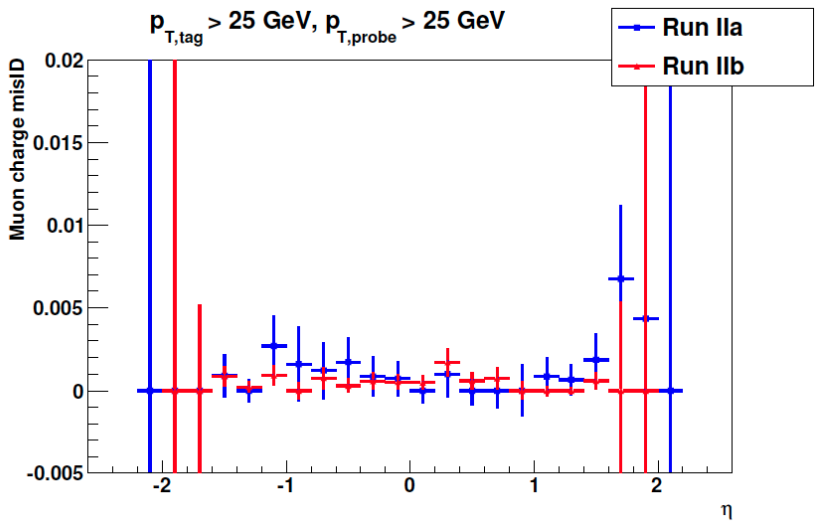
$$M_T = \sqrt{2E_T\not{E}_T(1-\cos\Delta\phi)}$$

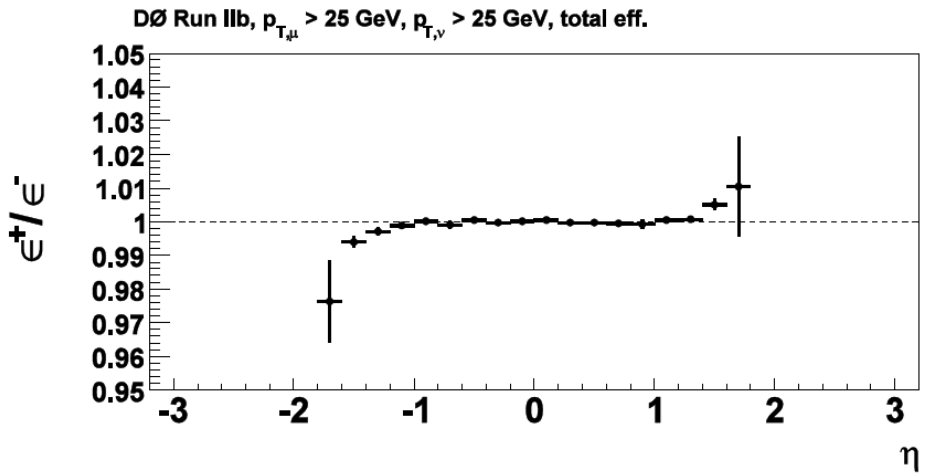
$\Delta\phi$ is the azimuthal angle between the electron and $\not{E}_T$

# QmisID and relative efficiency

- Charge mis-identification (QmisID) can dilute the asymmetry
- Use Tag-and-Probe method to study QmisID
- The average muon QmisID is $(0.06 \pm 0.01)\%$

- Muon efficiency should be independent of muon charge
- Positive/negative muon $p_T$ spectrum is different for a given $\eta$ bin
- Relative efficiency correction: $k = \langle \epsilon^+ \rangle / \langle \epsilon^+ \rangle$



# Effect of magnet polarity

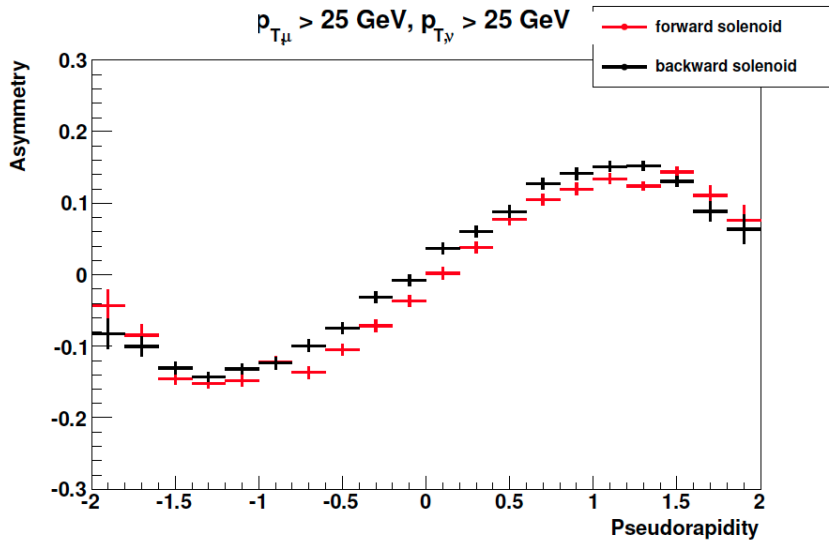
- The direction of DØ solenoid and toroid magnetic fields are were reversed during data taking, every 2 weeks on average: reduces detector charged particle reconstruction asymmetry in the detector
- Event categories:

| | Forward | Reversed |
|---|---|---|
| solenoid | 50.2% | 49.8% |
| toriod | 49.1% | 50.9% |

- There is a discrepancy in muon charge asymmetry between different solenoid polarities
- Weight the data so that all four polarity combination have the same integrated luminosity to correct for the magnet polarity effect

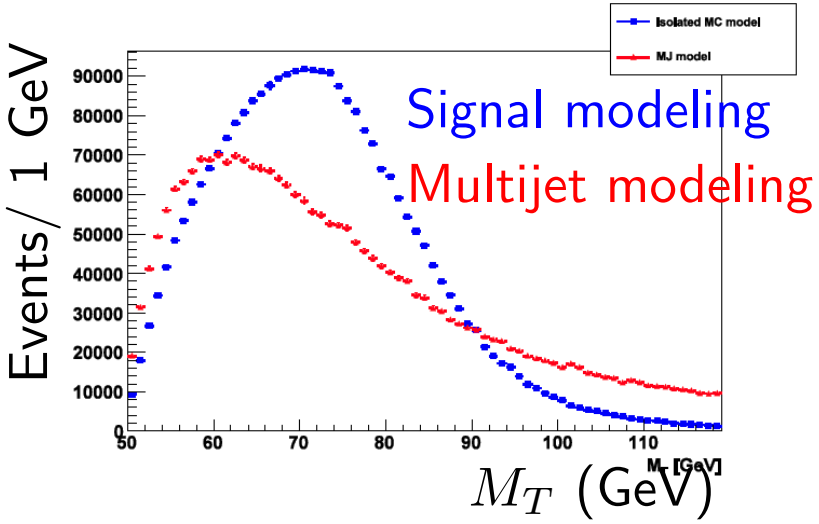
Forward Solenoid Polarities

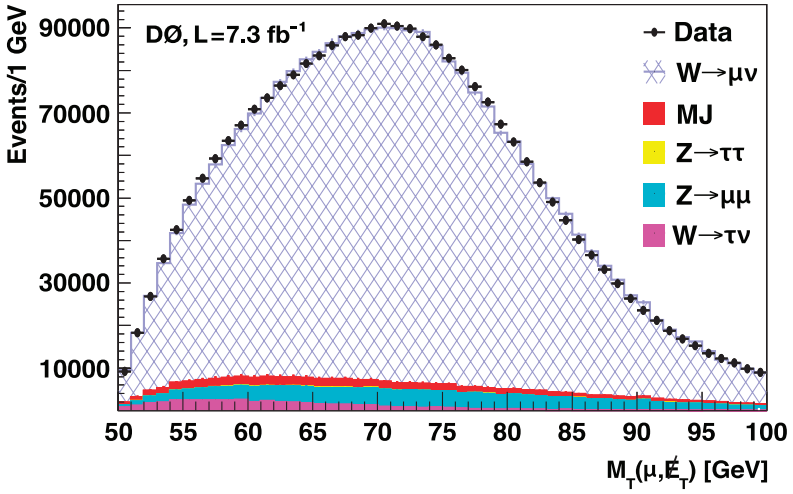
Reversed Solenoid Polarities



# Backgrounds

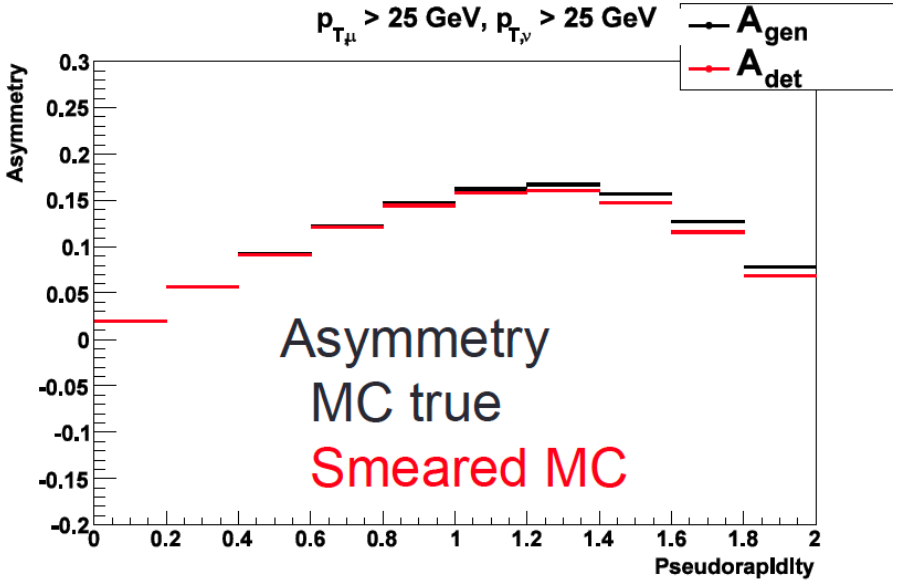
- Electroweak backgrounds:
  - $Z \to \mu\mu$, one muon is misidentified
  - $W \to \tau\nu$, with $\tau \to \mu\nu$
  - $Z \to \tau\tau$, one tau decays to a muon
  - Estimated using PYTHIA MC, with generator level and reconstruction level corrections
- Multijet background:
  - Estimated from data
  - Fit the $M_T$ distribution of data with the sum of signal and multi-jet background shape
  - The multi-jet shape is obtained from reversing the isolation criteria



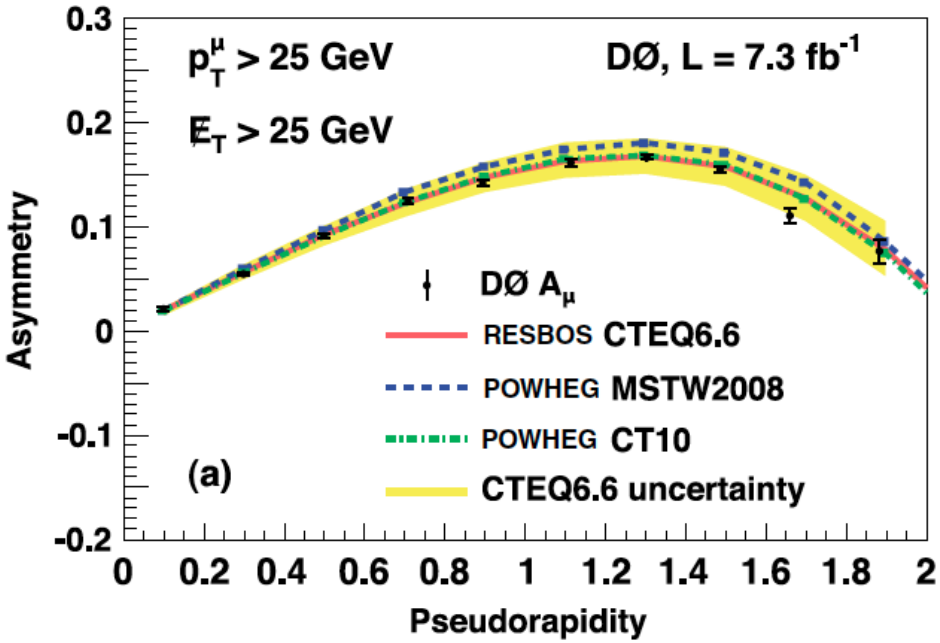



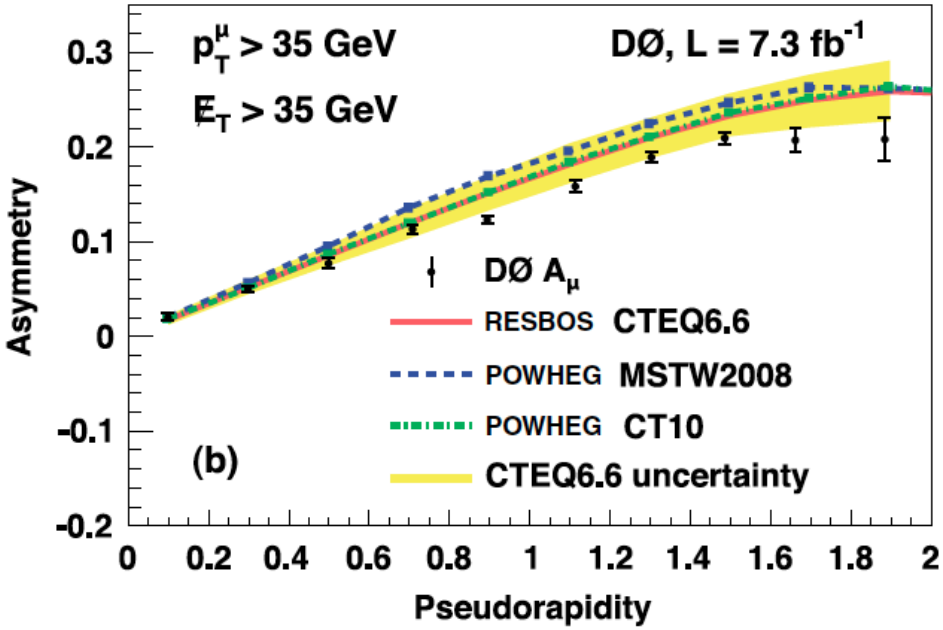
# Resolution correction

- Muon $p_T$ and $\not{E}_T$ resolution correction:
  - Estimated using REBOS and PYTHIA MC
  - Muon $p_T$ and recoil are smeared to same resolution as in data
  - $\Delta\mathcal{A} = \mathcal{A}_{\text{true}}$ - $\mathcal{A}_{\text{reco}}$: from 0 to 0.01
- Measured data asymmetry is corrected to generator level



# Muon charge asymmetry




**Measured uncertainties are significantly smaller than that of predictions for $|\eta^\mu| < 1.5$, can be used to improve PDFs**

# Measurement of Electron charge asymmetry

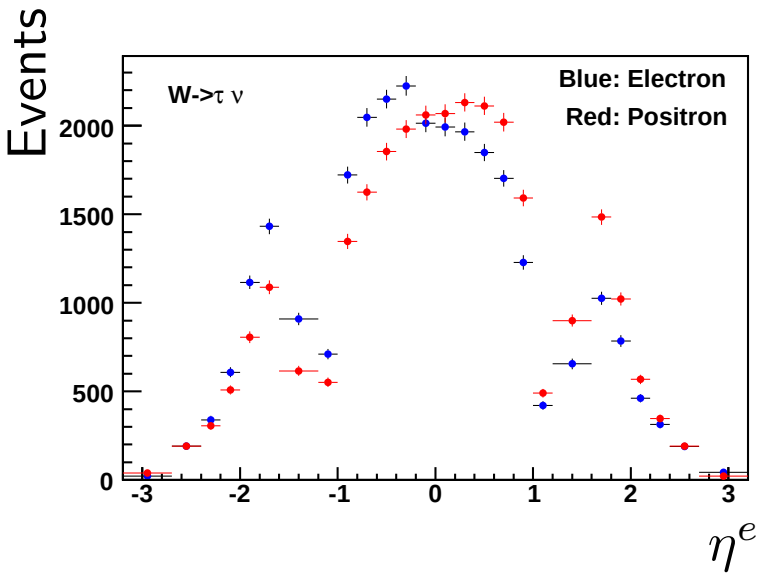
# Event selection

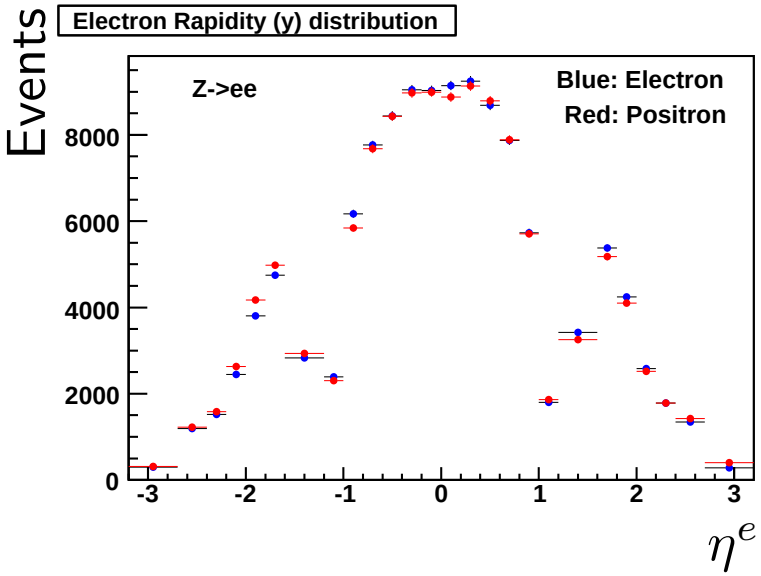
- Entire DØ RunII data, $\mathcal{L} = 9.7$ fb$^{-1}$ with all single EM triggers
- Electron requirements:
  - $25 < p_T < 100$ GeV, isolation and shower shape requirements
- Missing transverse momentum: $\not{E}_T > 25$ GeV
- $W$ selection: $50 < M_T < 130$ GeV, $U_T < 60$ GeV, low *SET*
- Track matching requirements

- $U_T$: vector sum of the transverse components of the energy deposited in the calorimeter
- *SET*: the scalar sum of all transverse energies measured by calorimeter

# Backgrounds

- SM backgrounds from PYTHIA samples:
  - $Z \to ee$: $15 < M_Z < 250$ GeV
  - $Z \to \tau\tau$: $15 < M_Z < 250$ GeV
  - $W \to \tau\nu$: $\tau \to e\nu$
  - $QCD$ bkgs: estimate from the data



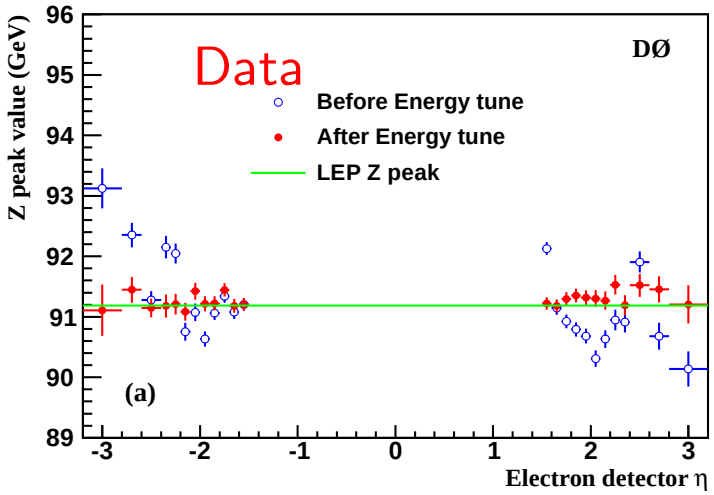



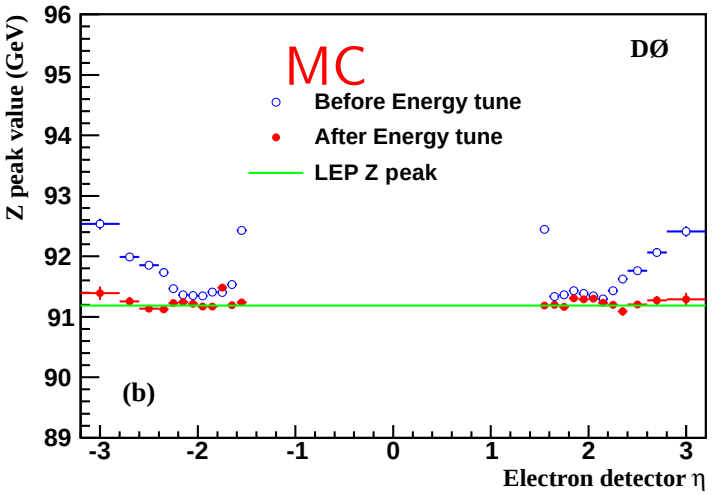
# MC tunings

- Generator: $p_T$ and rapidity of $W$ to NLO
- Electron identification (EMID) corrections: Pre-Selection, EMID, Track-match, trigger, charge mis-identification
- Correction of Positron/electron efficiencies
- Electron energy tuning: scale, smear, non-linearity
- Recoil tuning: $U_T$ and $\phi$ tuning
- Vertex and calorimeter activity tuning

# Electron energy modeling

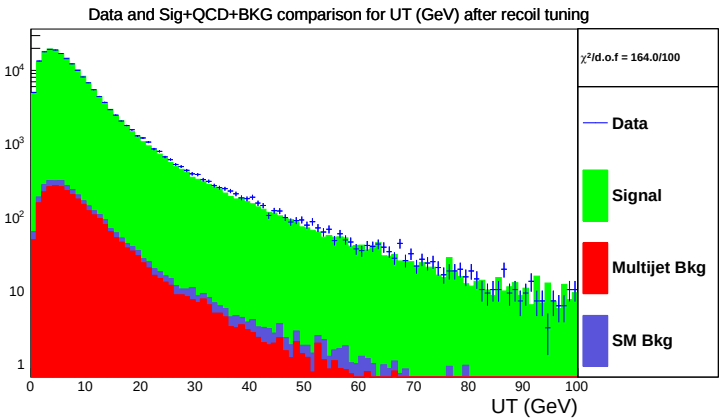
- EC electron energy modeling is very important for this analysis
- Due to detector effects and high instantaneous luminosity, electron energy has strong $\eta$ and luminosity dependences
- The background energy in calorimeter deposits in an EM cluster is also correlated with *SET*, which is related to the total activity in the event.
- We developed an iterative method to remove these three dependences ($\eta$, instlum, and *SET*)

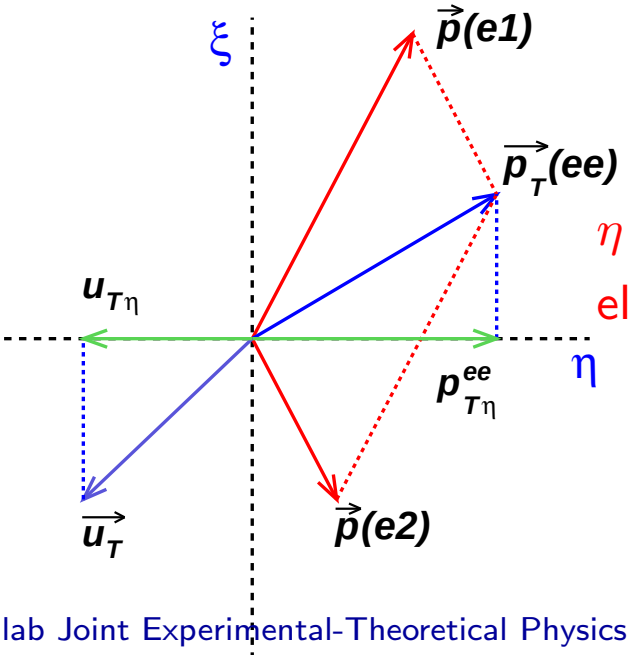


# Recoil modeling

- In $W$ events, the $\not{E}_T$ is calculated as: $\overrightarrow{\not{E}_T} = -1 * (\overrightarrow{p_T}(e) + \overrightarrow{p_T}(recoil))$
- Use $Z \to ee$ events to model the recoil
  - The particle distribution in the $W$ and $Z$ recoil distributions should be very similar
  - In $Z \to ee$ events, there is no $\not{E}_T$: any observed $\not{E}_T$ arises from energy mismeasurement in calorimeter
  - Use orthogonal basis $\eta$, $\xi$ to describe recoil
  - The $Z$ $p_T$ should equal the recoil $u_T$, in the $\eta$ direction
- After tuning the $Z$ MC recoil system in both $\eta$ and $\xi$ direction, recoil in MC describes the data

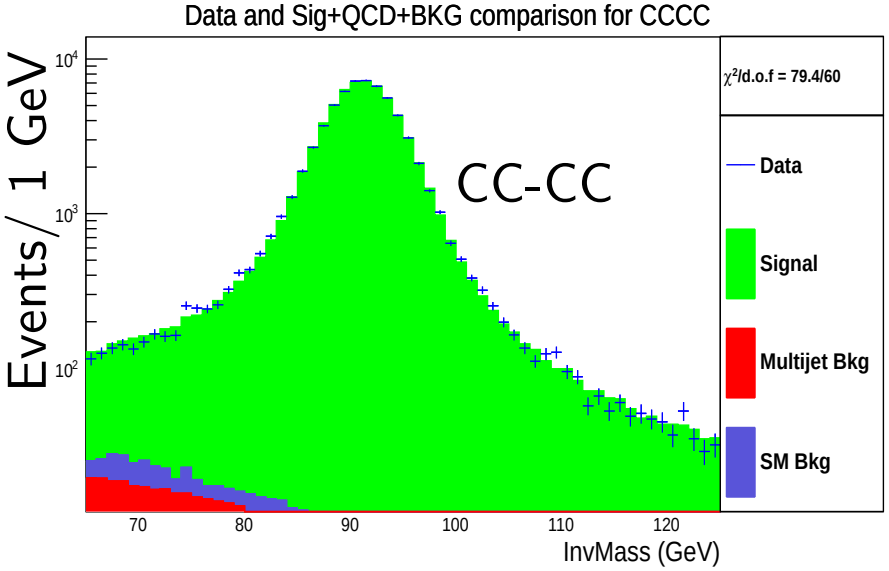


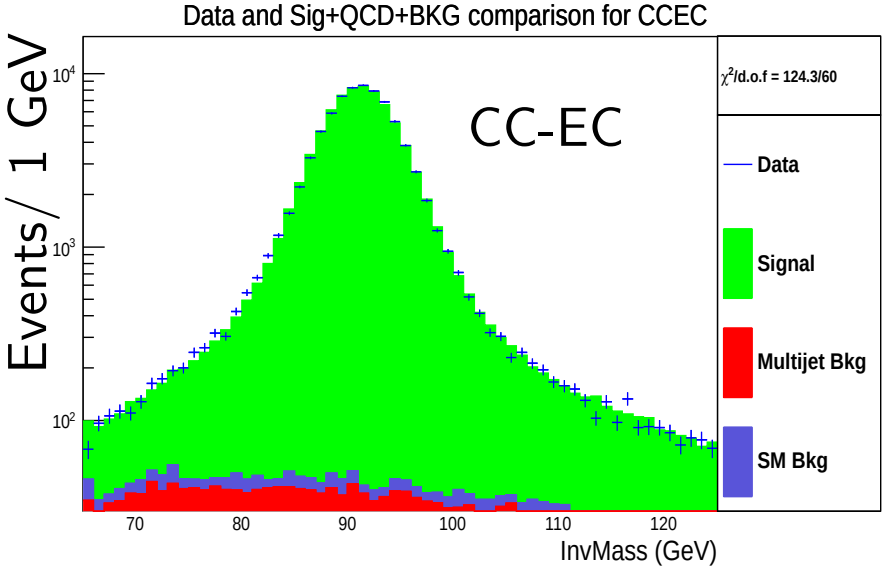



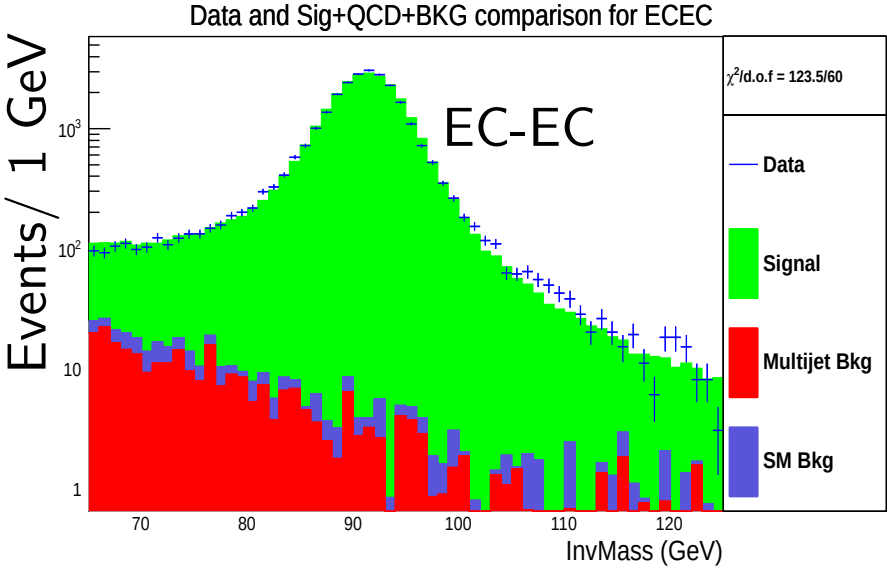

$\eta$ is defined by bisector of two electron momentum vectors

# $Z$ event comparisons

## Invariant mass of two electrons

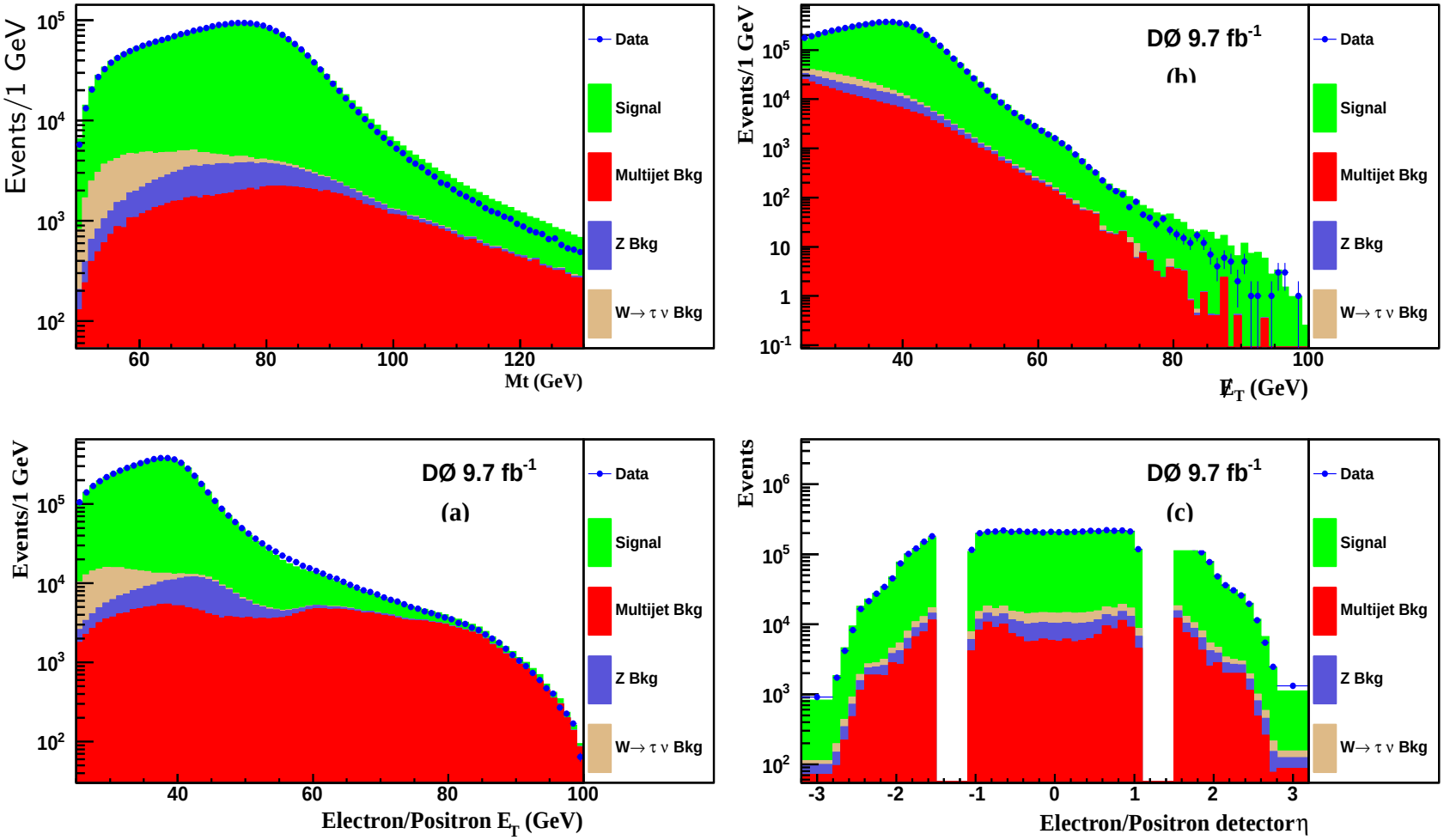


# $W$ event comparisons

- Reasonable agreement between data and MC
  **Statistical uncertainty only**



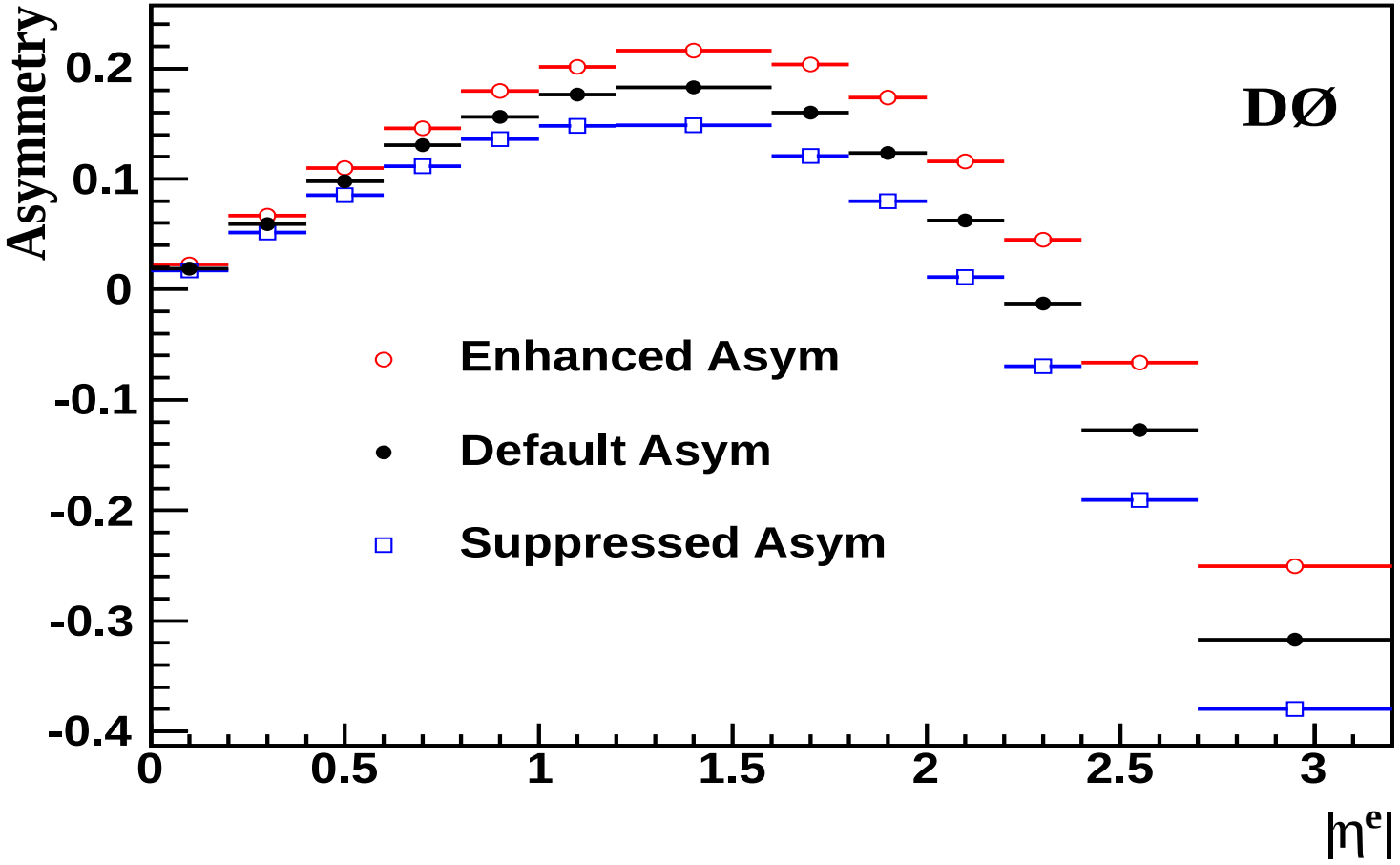
# Unfolding: Three steps

- Migration matrix: used to remove detector resolution effects
  - Electron and positron are expected to have same detector response
  - Study migration matrices for all events (elec+posi): no input bias
- $K^{\pm}_{eff}$: relative efficiency for positrons and electrons
  - Use $Z \to ee$ events to study $K^{\pm}_{eff}$: track bias from alignment + solenoid polarity
  - Only study $K^{\pm}_{eff}$ for track cuts, do not expect calorimetry cuts to have such effects
- Acc $\times$ Eff: to remove kinematic and geometric cut effects

# Closure tests: different input asymmetry

**Test 1: Enhanced Asym**

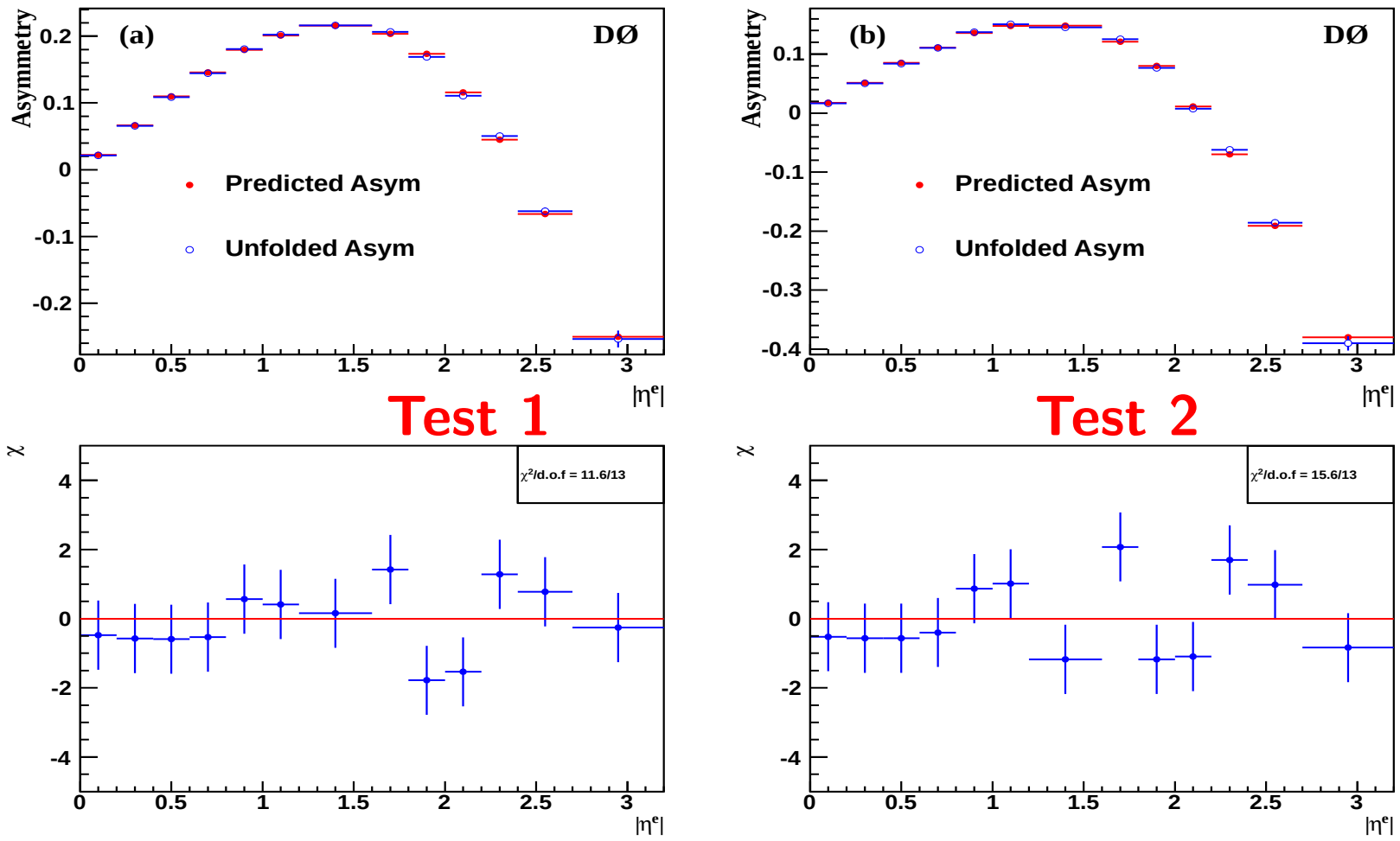
**Test 2: Suppressed Asym**



# Closure tests (1, 2): results

## Test 1: Enhanced Asym

## Test 2: Suppressed Asym



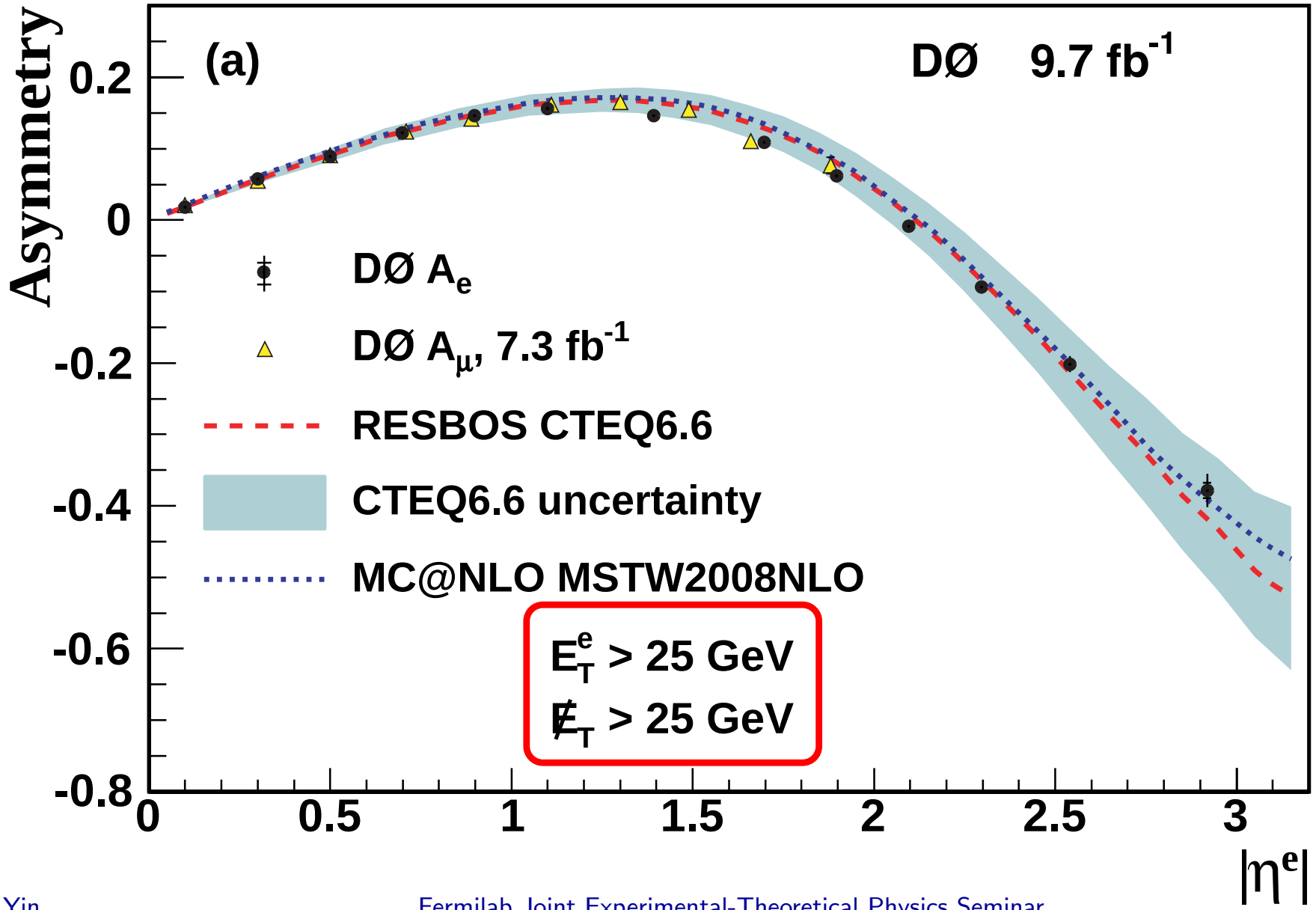
# Systematic uncertainties

Table: Summary of systematic uncertainties from different sources for lepton *CP* folded asymmetries, with $p_T^e > 25$ GeV, $\not{E}_T > 25$ GeV. The uncertainties are presented in permille (‰).

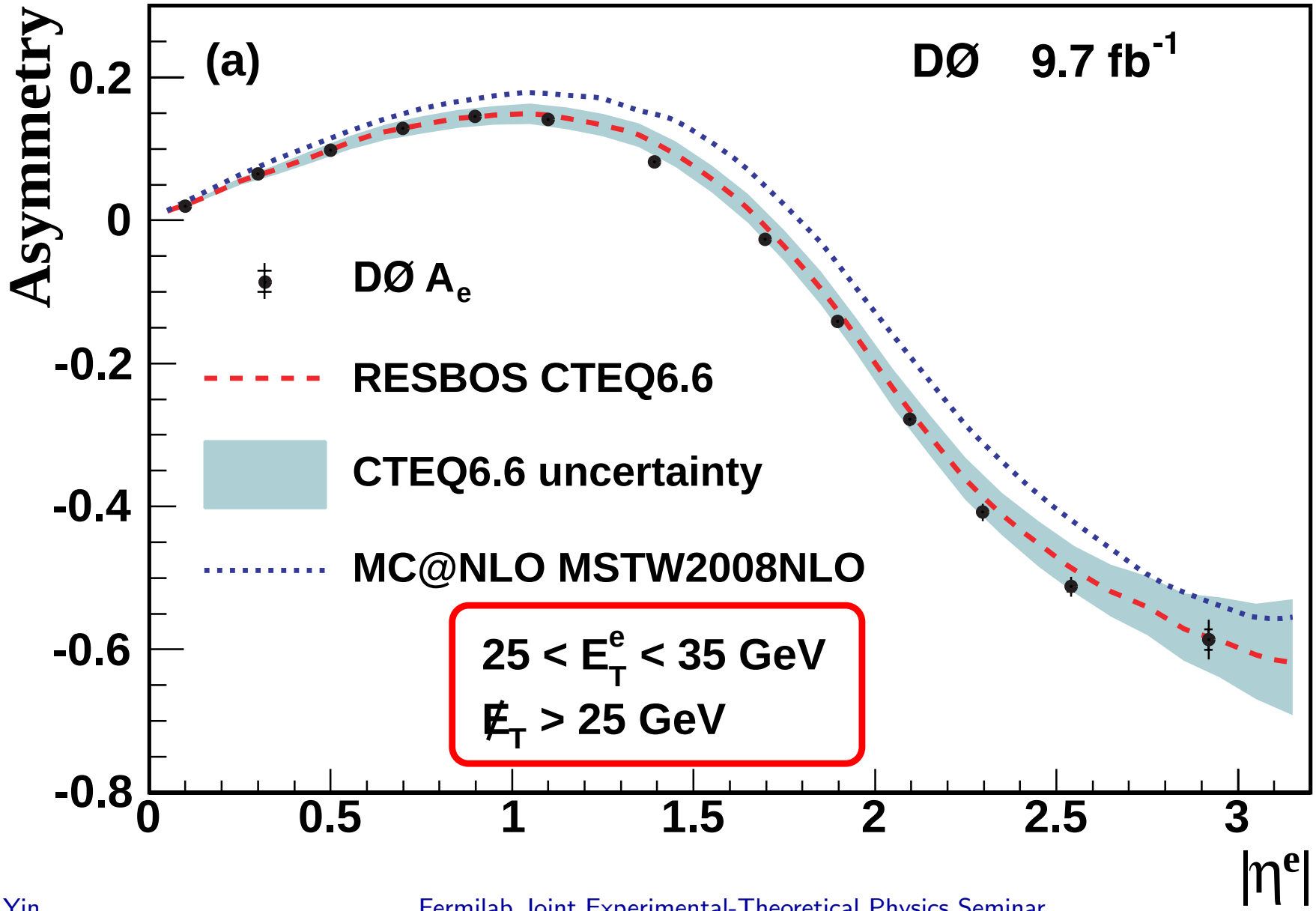
| $\eta$ bin | Gen | EMID | Energy | Recoil | Bkgs | Model | Unfolding | Qmis | $K_{eff}^{+/-}$ |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.08 | 0.02 | 0.03 | 0.04 | 0.26 | 0.12 | 0.82 | 0.54 | 0.00 |
| 2 | 0.23 | 0.18 | 0.18 | 0.26 | 0.54 | 0.27 | 0.81 | 0.56 | 0.00 |
| 3 | 0.18 | 0.24 | 0.25 | 0.35 | 0.87 | 0.58 | 0.80 | 0.59 | 0.00 |
| 4 | 0.36 | 0.34 | 0.34 | 0.49 | 1.81 | 1.03 | 0.80 | 0.60 | 0.00 |
| 5 | 0.33 | 0.36 | 0.36 | 0.53 | 2.37 | 1.33 | 0.85 | 0.76 | 0.00 |
| 6 | 0.17 | 0.37 | 0.37 | 0.55 | 2.71 | 1.20 | 1.17 | 1.20 | 0.00 |
| 7 | 0.08 | 0.42 | 0.39 | 0.58 | 3.94 | 2.63 | 1.04 | 1.67 | 0.00 |
| 8 | 0.15 | 0.28 | 0.22 | 0.34 | 1.37 | 2.66 | 0.95 | 1.53 | 0.00 |
| 9 | 0.10 | 0.36 | 0.05 | 0.10 | 1.43 | 2.61 | 1.13 | 2.46 | 0.00 |
| 10 | 0.09 | 0.36 | 0.04 | 0.07 | 1.75 | 2.15 | 1.47 | 4.37 | 0.00 |
| 11 | 0.17 | 0.30 | 0.02 | 0.05 | 1.54 | 2.29 | 1.93 | 7.15 | 0.01 |
| 12 | 0.08 | 0.43 | 0.29 | 0.48 | 2.16 | 4.43 | 2.36 | 8.65 | 0.01 |
| 13 | 0.15 | 0.87 | 0.81 | 1.30 | 3.99 | 3.48 | 5.48 | 18.85 | 0.02 |

# Lepton asymmetry (1)

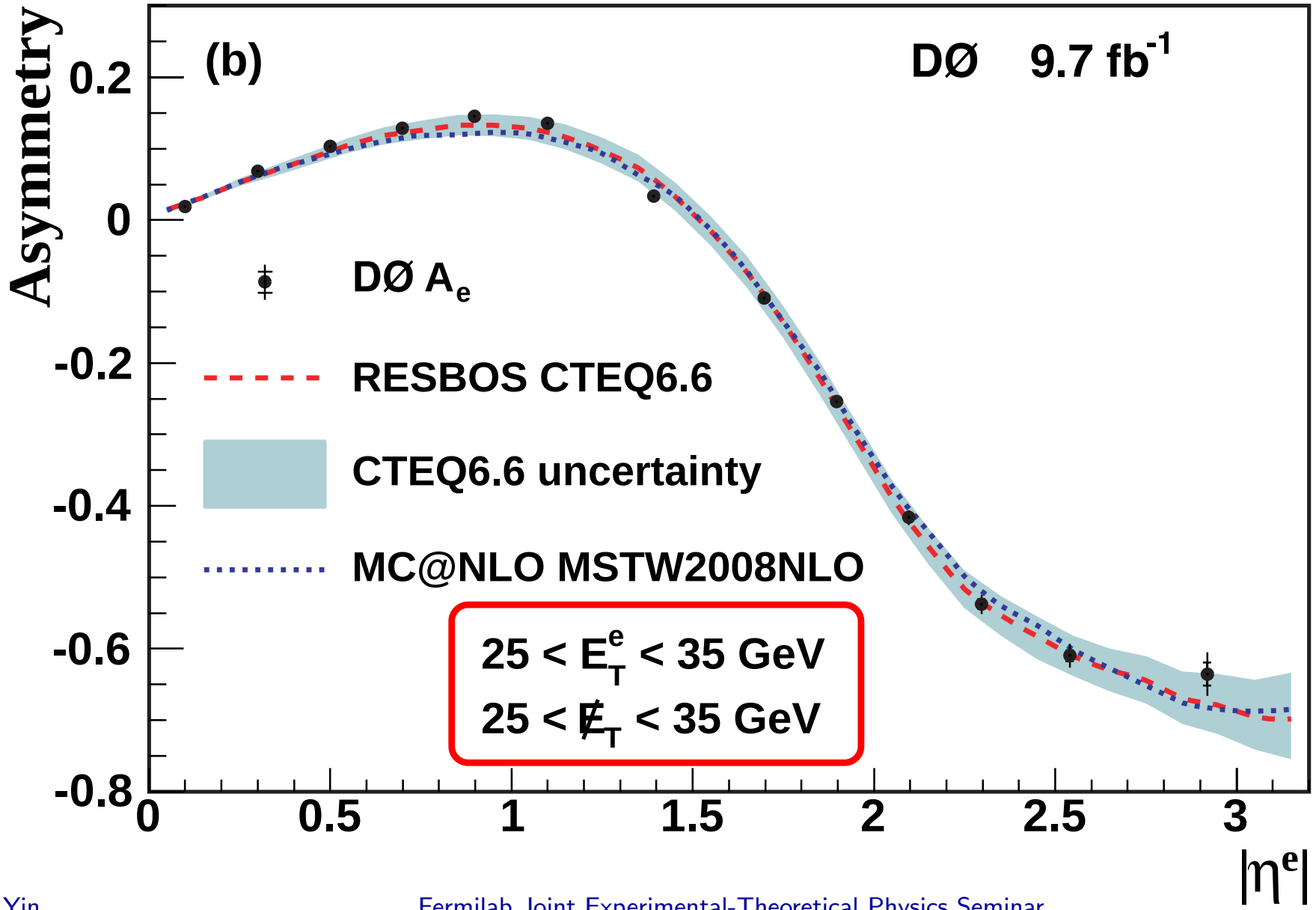
**New results supersede previous electron charge asymmetry!**



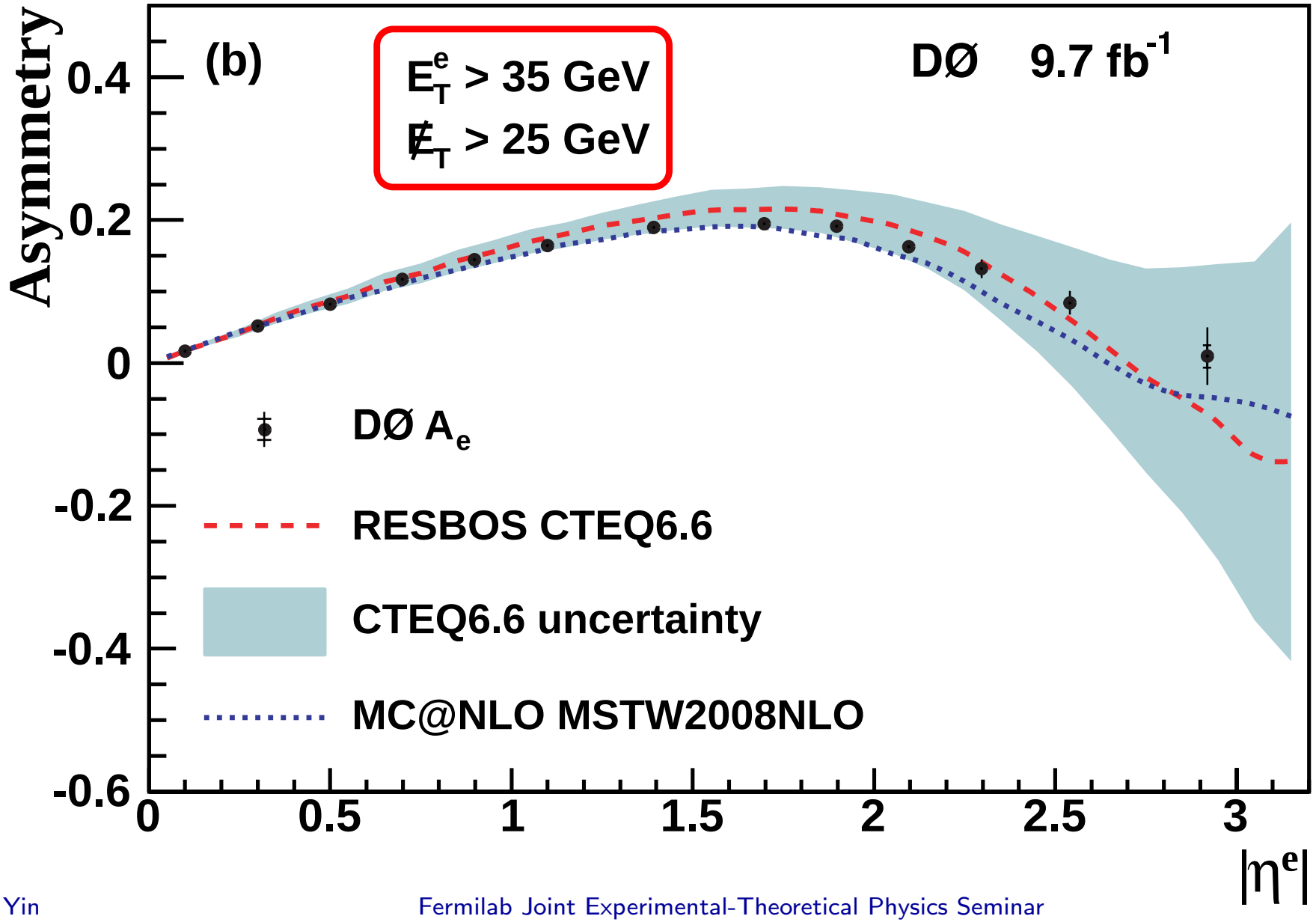
# Lepton asymmetry (2)



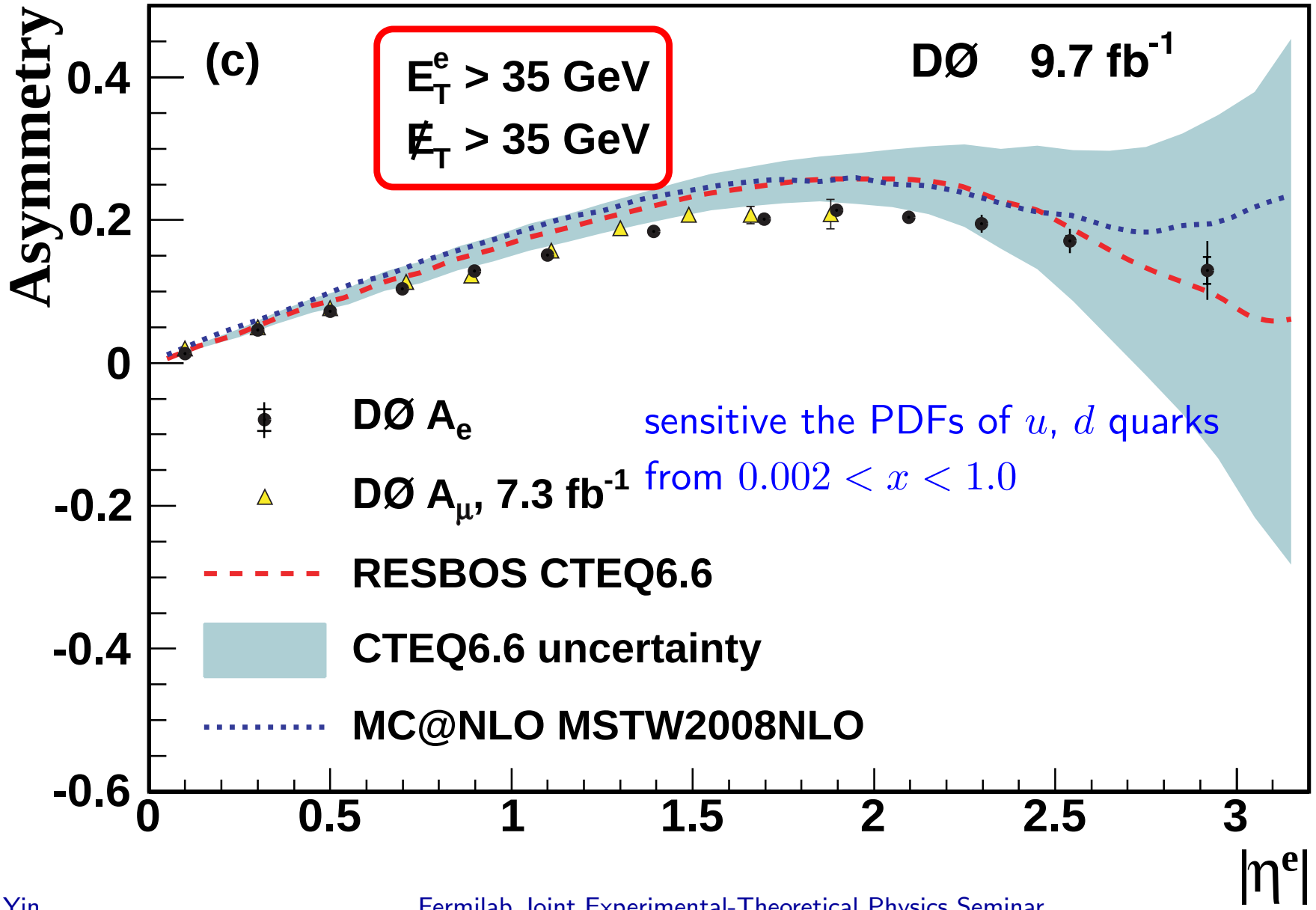
# Lepton asymmetry (3)



# Lepton asymmetry (4)



# Lepton asymmetry (5)

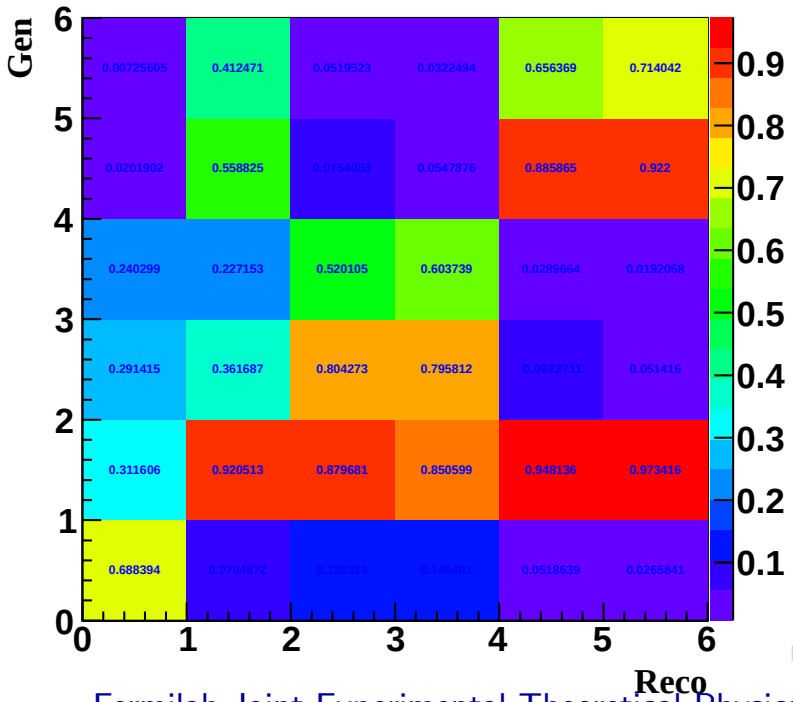



sensitive the PDFs of $u$, $d$ quarks from $0.002 < x < 1.0$

# Kinematic types fraction

Table: Fractions of events in each reconstruction level kinematic bin that come from different generator level kinematic bins.

| Reco \ Gen | $[20, 25]$ \|\| $[20, 25]$ | $[25, \infty]$ & $[25, \infty]$ | $[25, 35]$ & $[25, \infty]$ | $[25, 35]$ & $[25, 35]$ | $[35, \infty]$ & $[25, \infty]$ | $[35, \infty]$ & $[35, \infty]$ |
|---|---|---|---|---|---|---|
| $[20, 25]$ \|\| $[20, 25]$ | 0.69 | 0.31 | 0.29 | 0.24 | 0.02 | 0.01 |
| $[25, \infty]$ & $[25, \infty]$ | 0.08 | 0.92 | 0.36 | 0.23 | 0.56 | 0.41 |
| $[25, 35]$ & $[25, \infty]$ | 0.12 | 0.88 | 0.80 | 0.52 | 0.08 | 0.05 |
| $[25, 35]$ & $[25, 35]$ | 0.15 | 0.85 | 0.80 | 0.60 | 0.05 | 0.03 |
| $[35, \infty]$ & $[25, \infty]$ | 0.05 | 0.95 | 0.06 | 0.03 | 0.89 | 0.66 |
| $[35, \infty]$ & $[35, \infty]$ | 0.03 | 0.97 | 0.05 | 0.02 | 0.92 | 0.71 |

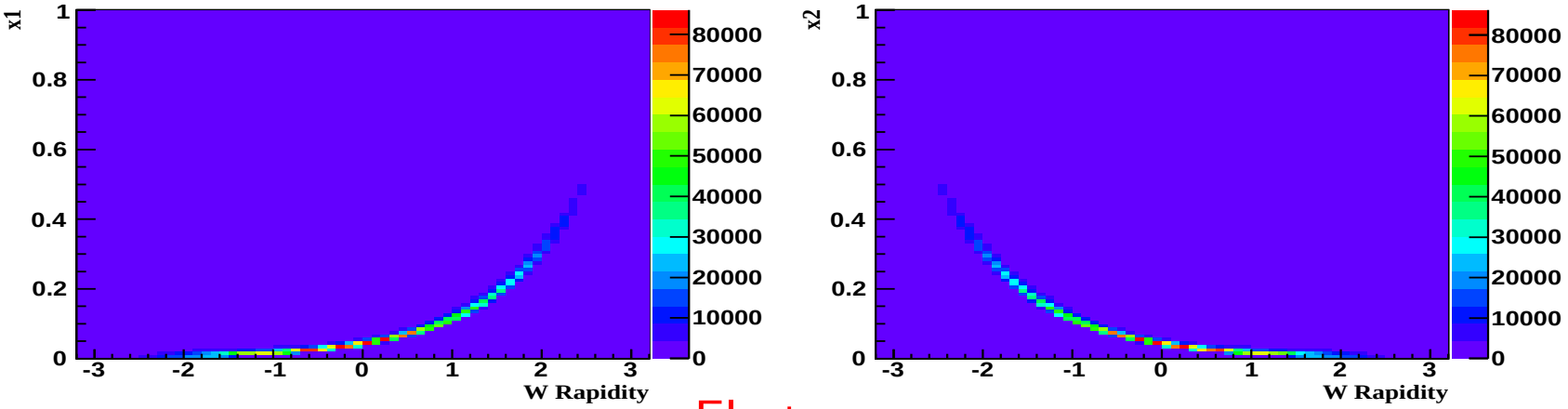


# Measurement of $W$ boson production charge asymmetry in the electron channel

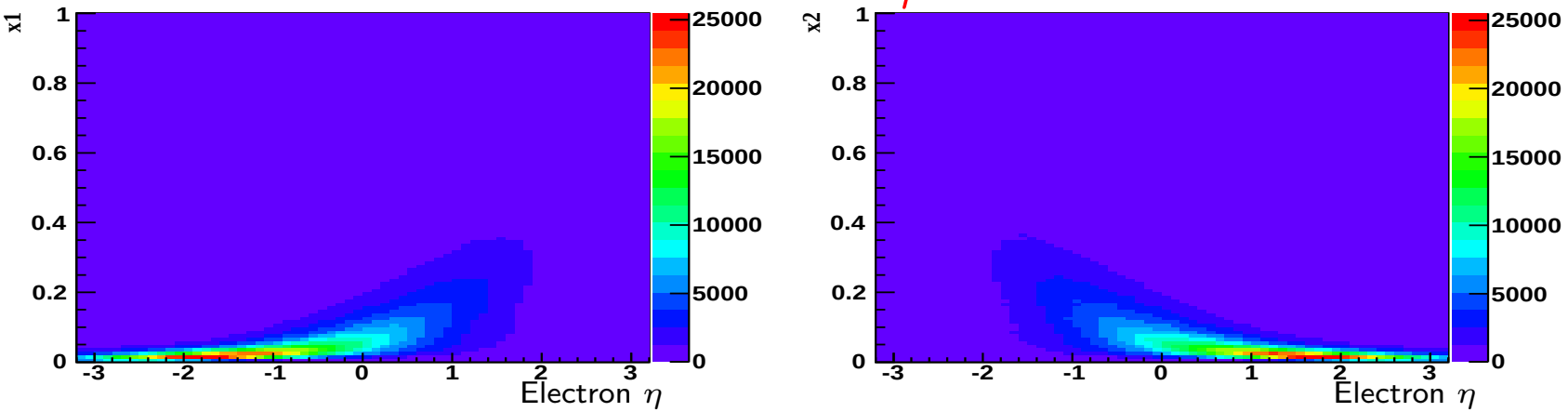
# $y_W/\eta$ vs. $x$

- Asymmetry and $x$ : lepton asymmetries are from a larger range of parton $x$ values compared with $W$ asymmetry
- The $W$ asymmetry is expected to be more sensitive to the $u/d$ ratio

$W$ Rapidity vs. $x$



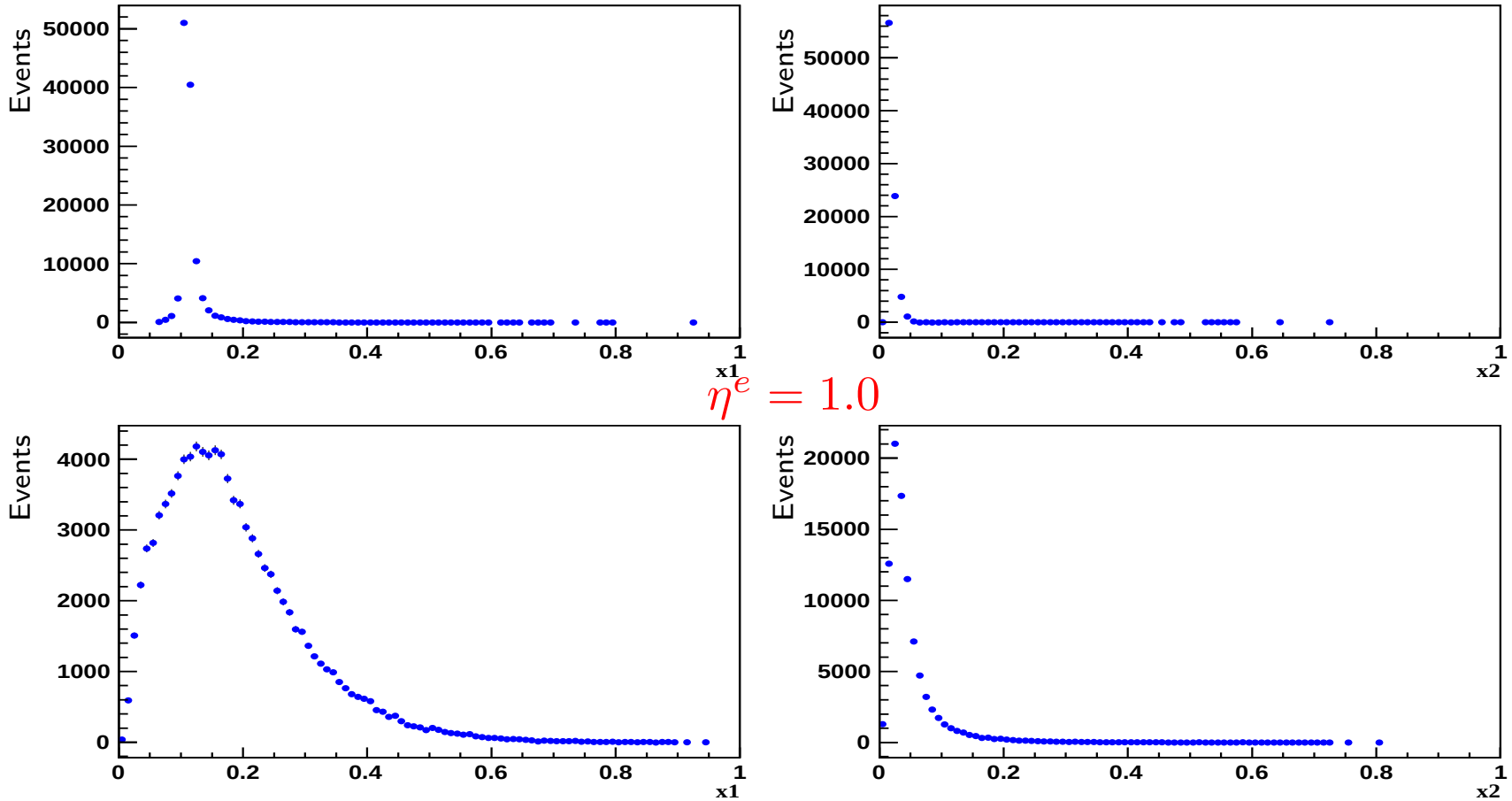

Electron $\eta$ vs. $x$



# Asymmetries vs. $x$: projected

- Asymmetry and $x$ : lepton asymmetry comes from a larger range of parton $x$ values compared with $W$ asymmetry
- The $W$ asymmetry is expected to a more sensitive on the $u/d$ ratio

$y_W = 1.0$




$\eta^e = 1.0$

# $W$ boson asymmetry: Neutrino $p_z^\nu$

A. Bodek, *et. al.* Phys. Rev. D **77**, 111301(R) (2008).

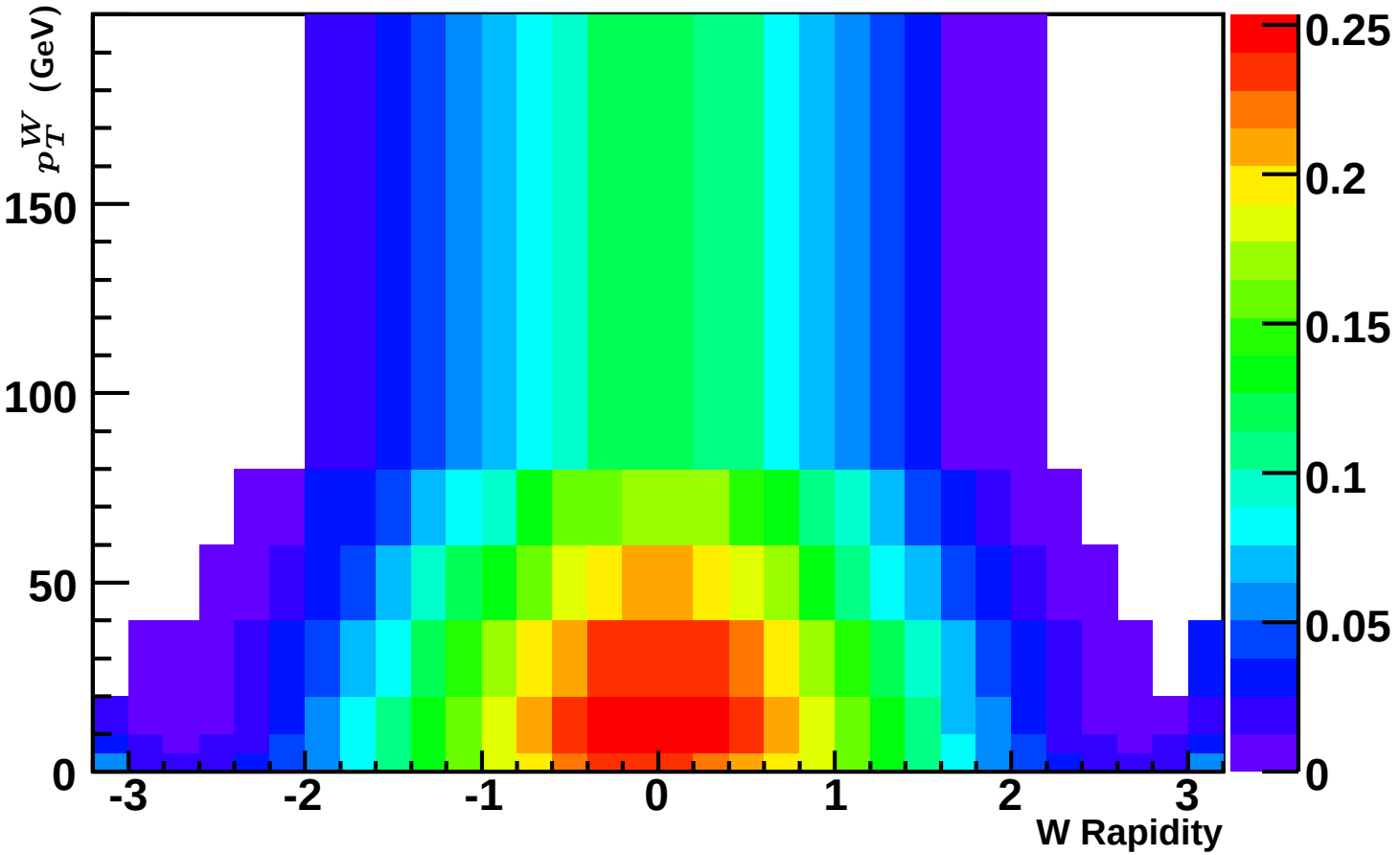
- $W$ rapidity:
  - Massive particle rapidity: $y = \frac{1}{2} ln \frac{E+P_z}{E-P_z}$
  - Fix $M_W$ to 80.385 GeV, $M_W^2 = (E_\ell + E_\nu)^2 - (\overrightarrow{P_\ell} + \overrightarrow{P_\nu})^2$
- Obtain neutrino $p_z^\nu$ solutions, with given mass of $W$:
  - If there are two complex solutions, which means $\not{E}_T$ is not measured 'properly', we scale the $\not{E}_T$ to set the imaginary part to 0
  - If two solutions, give each solution a weight factor, according to $W$ $p_T$, Collins angle, and rapidity of $W$ boson:

$$P_\pm\left(\cos\theta^*, y_W, p_T^W\right) = \left(1 \mp \cos\theta^*\right)^2 + Q\left(y_W, p_T^W\right)\left(1 \pm \cos\theta^*\right)^2$$

$$w_{1,2}^\pm = \frac{P_\pm\left(\cos\theta_{1,2}^*, y_{1,2}, p_T^W\right) d\sigma^\pm\left(y_{1,2}\right)}{P_\pm\left(\cos\theta_1^*, y_1, p_T^W\right) d\sigma^\pm\left(y_1\right) + P_\pm\left(\cos\theta_2^*, y_2, p_T^W\right) d\sigma^\pm\left(y_2\right)}$$

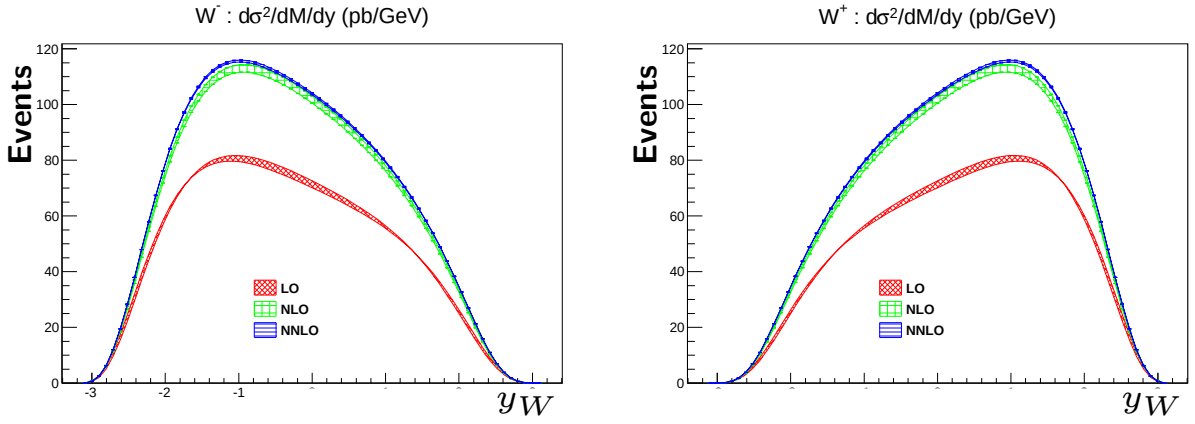
# Ratio: sea-quark/valence-quark

- Generator level sea-quark/valence-quark ratio: $\mathcal{Q}(y_W, p_T^W)$
- Get from MC@NLO

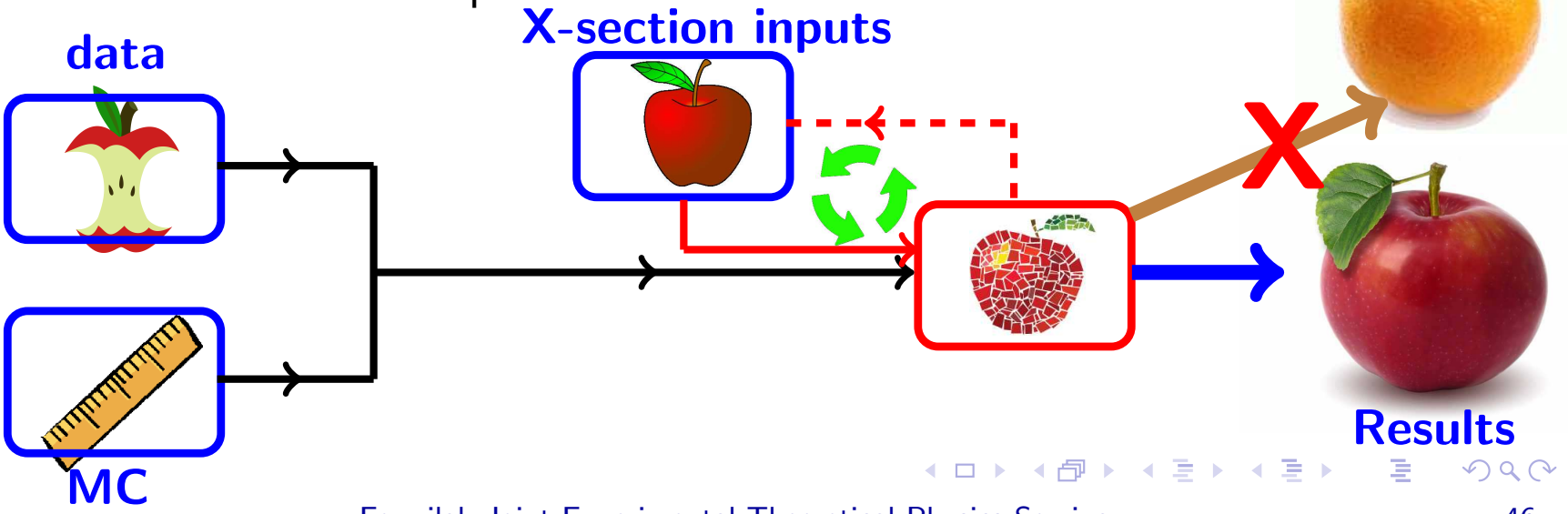


# NNLO differential cross section

- Using VRAP NNLO generator to predict the differential cross section

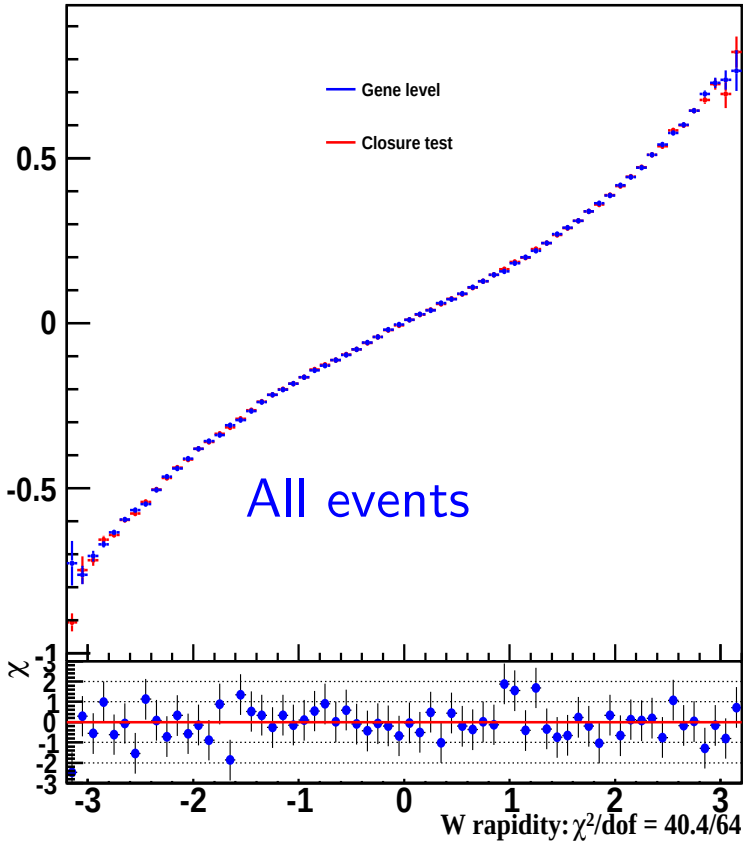


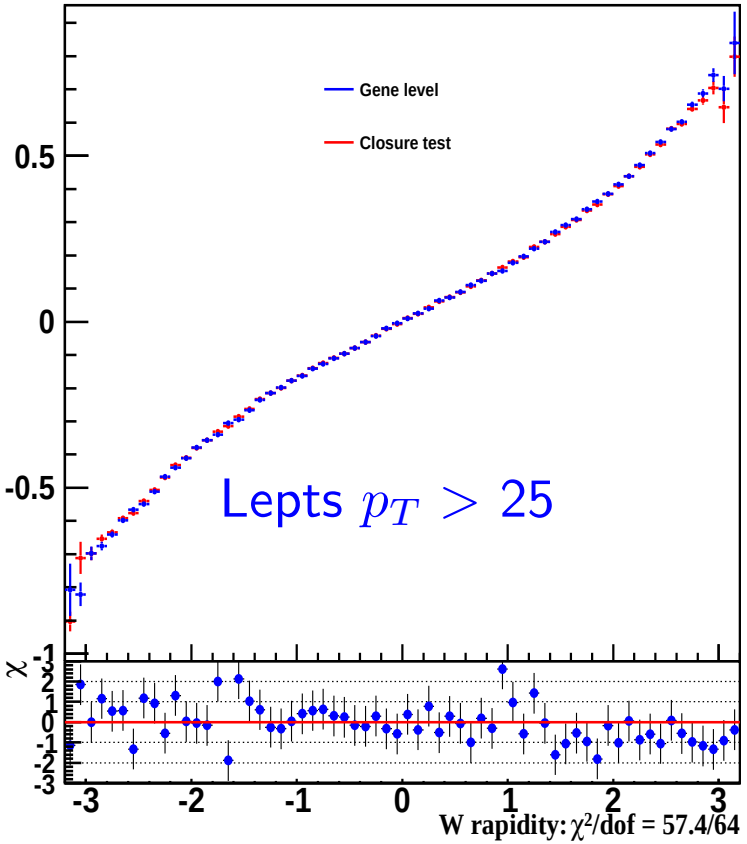

- Iterative method to remove input bias:



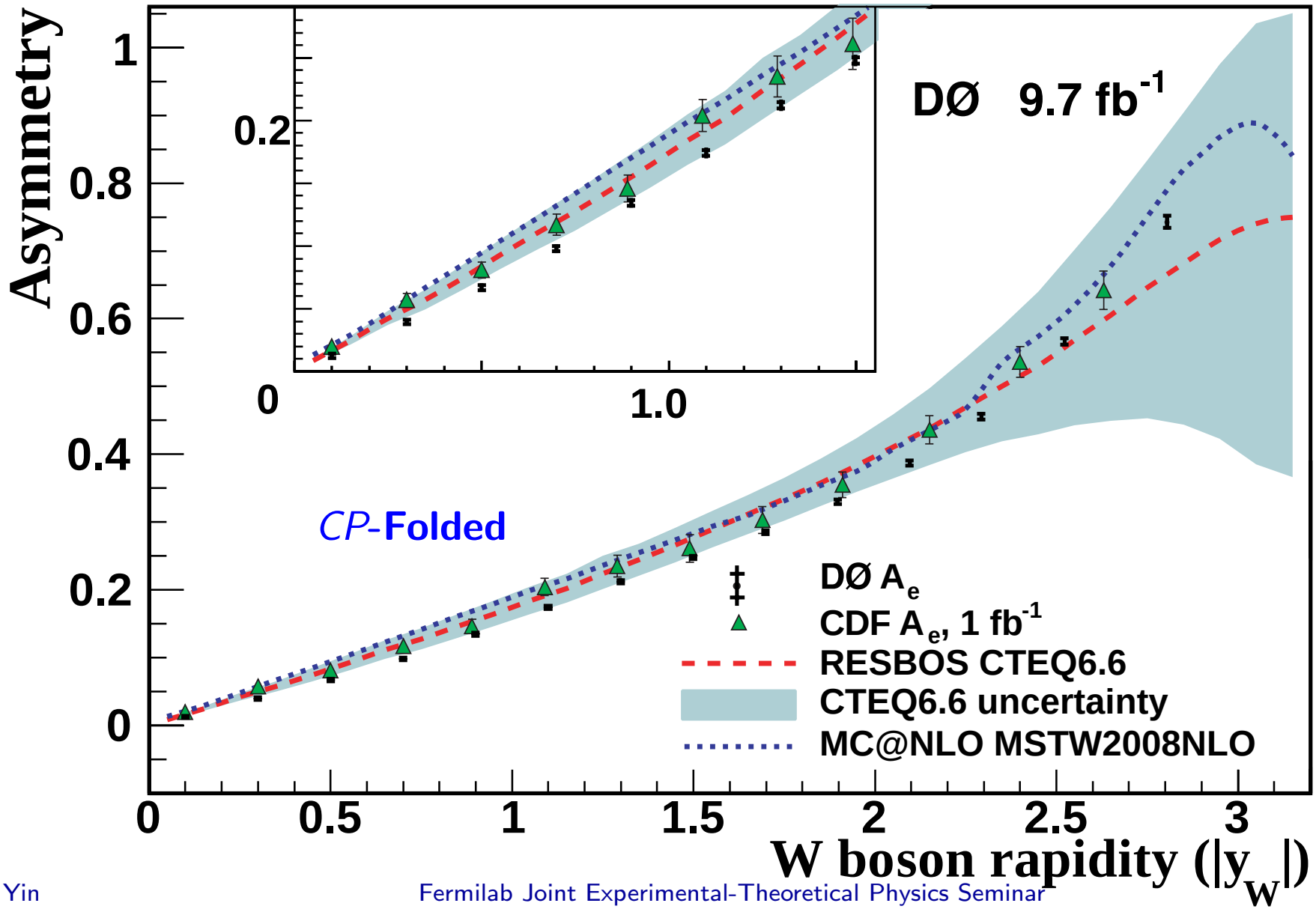
# Closure test

- Using 10 M MC@NLO events as pseudo data
- Using 100 M MC@NLO events to generate the sea/valence quark ratio



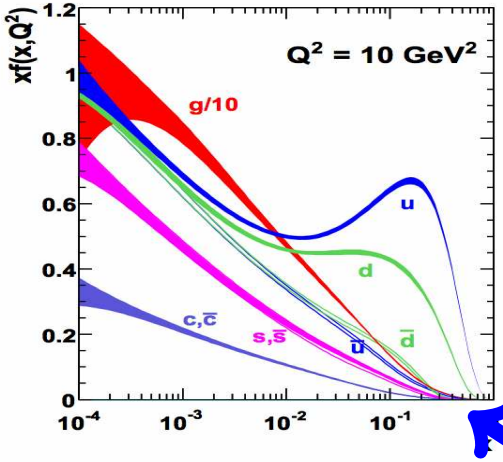
# $W$ charge asymmetry

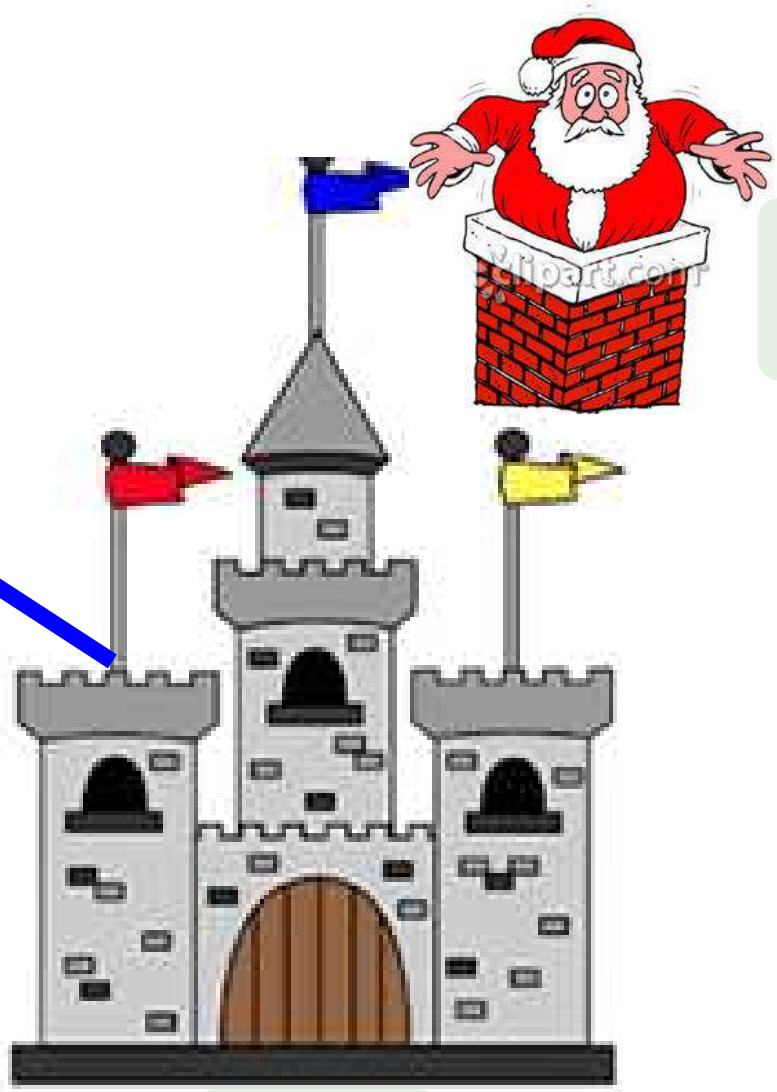


# Summary

- Measurements of $W$ charge asymmetry with DØ RunII full data-set (electron and muon channels), with extended $\eta$ coverage to 3.2
  - Both the $W$ boson production charge asymmetry and the lepton charge asymmetry measurements have been performed
  - Most precise measurement of lepton charge asymmetry to date
  - First and most precise direct measurement of $W$ boson production asymmetry from DØ
  - Provide correlation matrix between different kinematic bins (for the first time at the Tevatron)
- Benefit all the hadronic physics analyses!
  - Potential improvement of PDF models in the $x - Q^2$ region of interest for $W$ production at the Tevatron is estimated to reduce the PDF uncertainty in the DØ $M_W$ measurement by approximately 30% (2-3 MeV)

New!



$W$ charge asymmetry

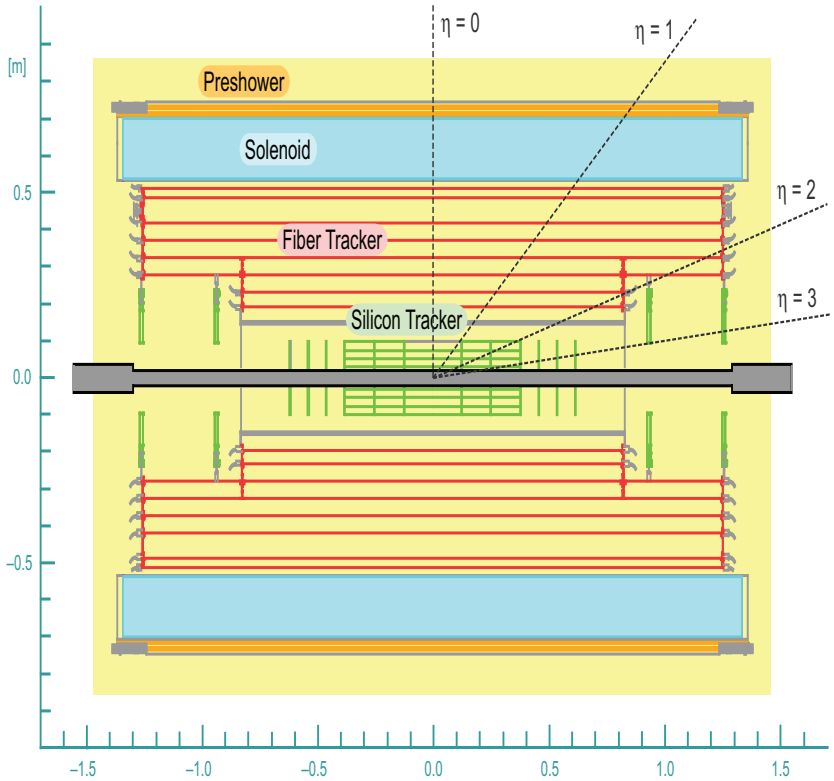
DIS

Proton

# Backup

# Track requirements

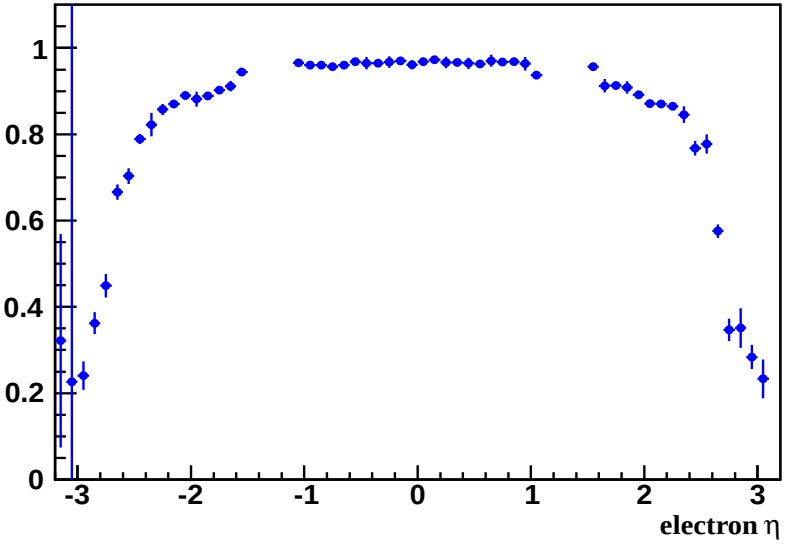
## Tracking Detector

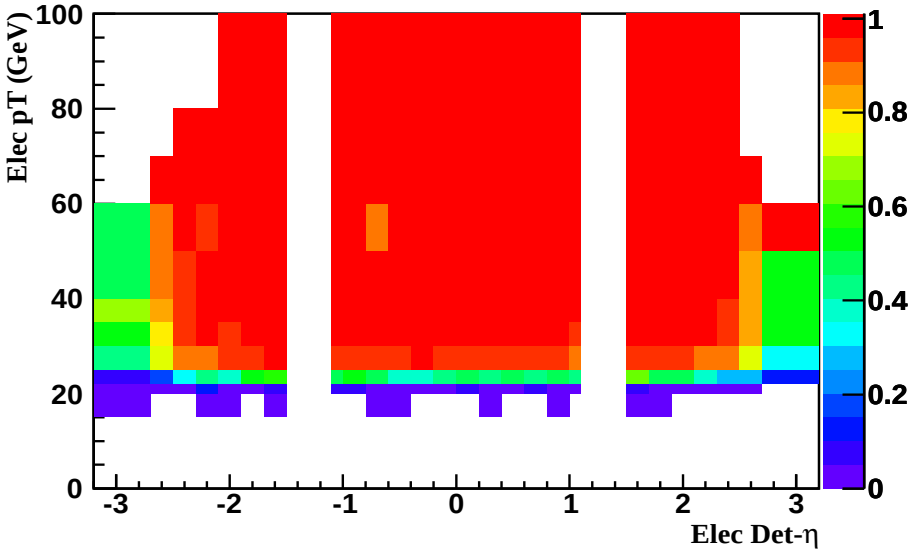



- Four electron categories:
  - Type 1: Central calorimeter and full CFT coverage
  - Type 2: End cap and full CFT coverage
  - Type 3: End cap and partial CFT coverage
  - Type 4: End cap and NO CFT
- Four track requirements:
  - Overall cuts: track $p_T$ >10, $P(\chi^2)$ >0.00, $\chi^2 < 9.95$, rdca $< 0.02$
  - Type 1: NCFT >9, NSMT >2
  - Type 2: NCFT >9, NSMT >2
  - Type 3: NCFT >3, NSMT >2
  - Type 4: NSMT >8, track-significant-cut > 1

# Trigger modeling

- All Calorimeter EM triggers is used to select events
- Study the trigger match efficiencies using tag and probe method
- Apply 2-D trigger correction to MC: electron det-$\eta$ and electron $p_T$

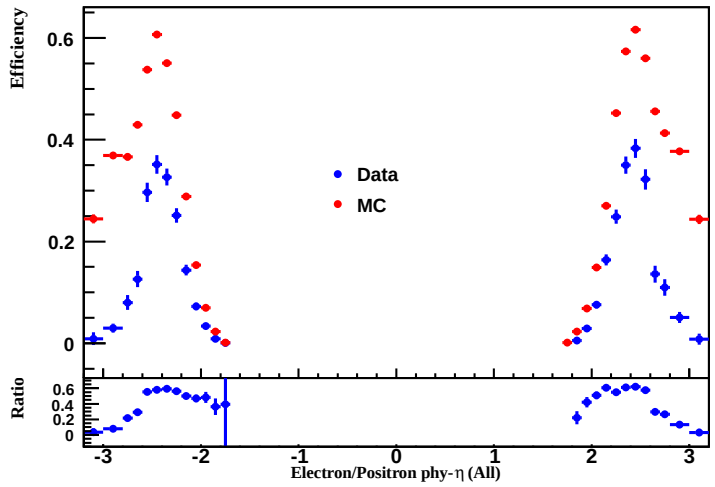


# Electron Efficiencies modeling

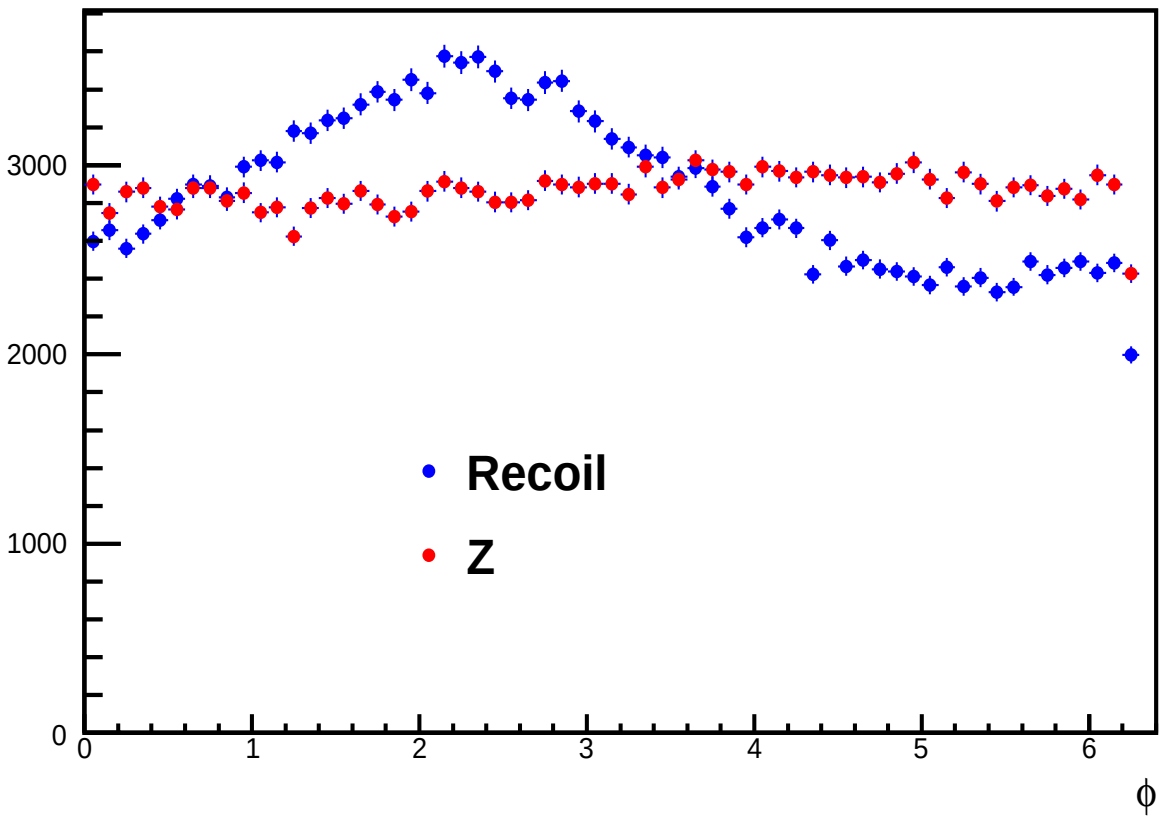
- Since $Z$ boson can be taken as a candle, all electron modelings are based on $Z \to ee$ event
  - EMID efficiencies, electron energy tuning, trigger efficiencies
- EMID efficiencies corrections: 4-steps corrections

| Step | Pre-Selection | Cal-ID | Track-Match |
|---|---|---|---|
| 1 | $\eta_{\text{phy}}$ | $\eta_{\text{det}}$ & $E_T$ | $\eta_{\text{det}}$ & $E_T$ |
| 2 | | $\eta_{\text{phy}}$ & $vtx_z$ | $\eta_{\text{phy}}$ & $vtx_z$ |
| 3 | | $\phi$ & $lumi$ | $\phi$ & $lumi$ |
| 4 | | $SET$ & $E_T$ | $SET$ & $E_T$ |



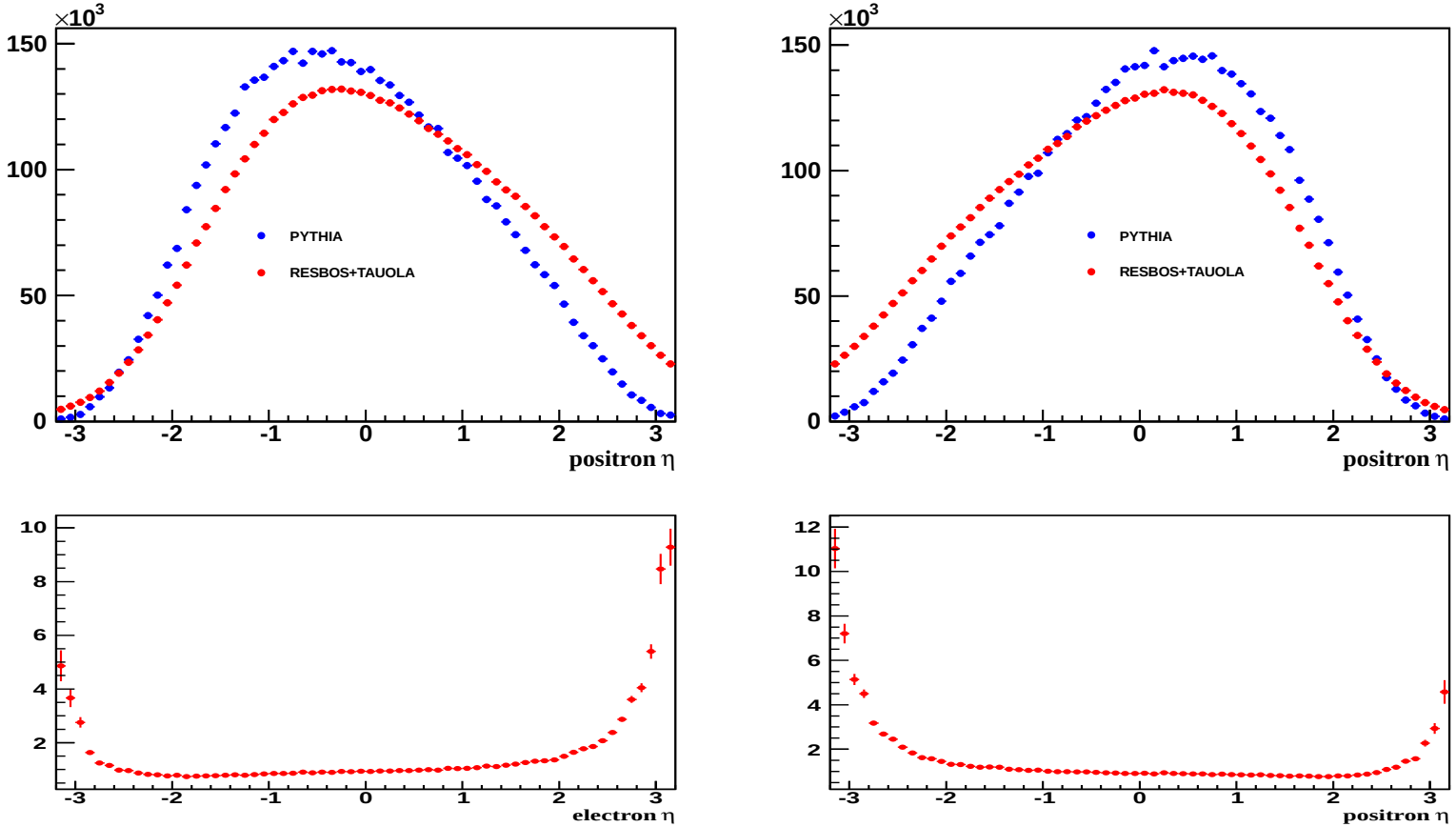
# Recoil $\phi$ modeling

- In the calorimeter, there is a top-bottom asymmetry, which will bias the $\phi$ distribution
- In order to get the correct $\phi$ distribution, a recoil $\phi$ tuning is applied



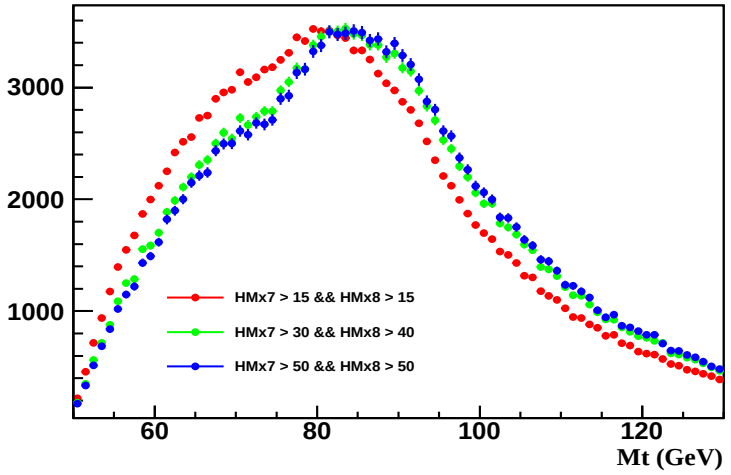
# $W \to \tau\nu$ background

- $W \to \tau\nu$ background contribution is estimated from PYTHIA MC
- Based on $W$ mass group study, PYTHIA $v6$ cannot describe $\tau$ decay phase
- TAUOLA is used in $W$ mass group to simulate the decay of $\tau$



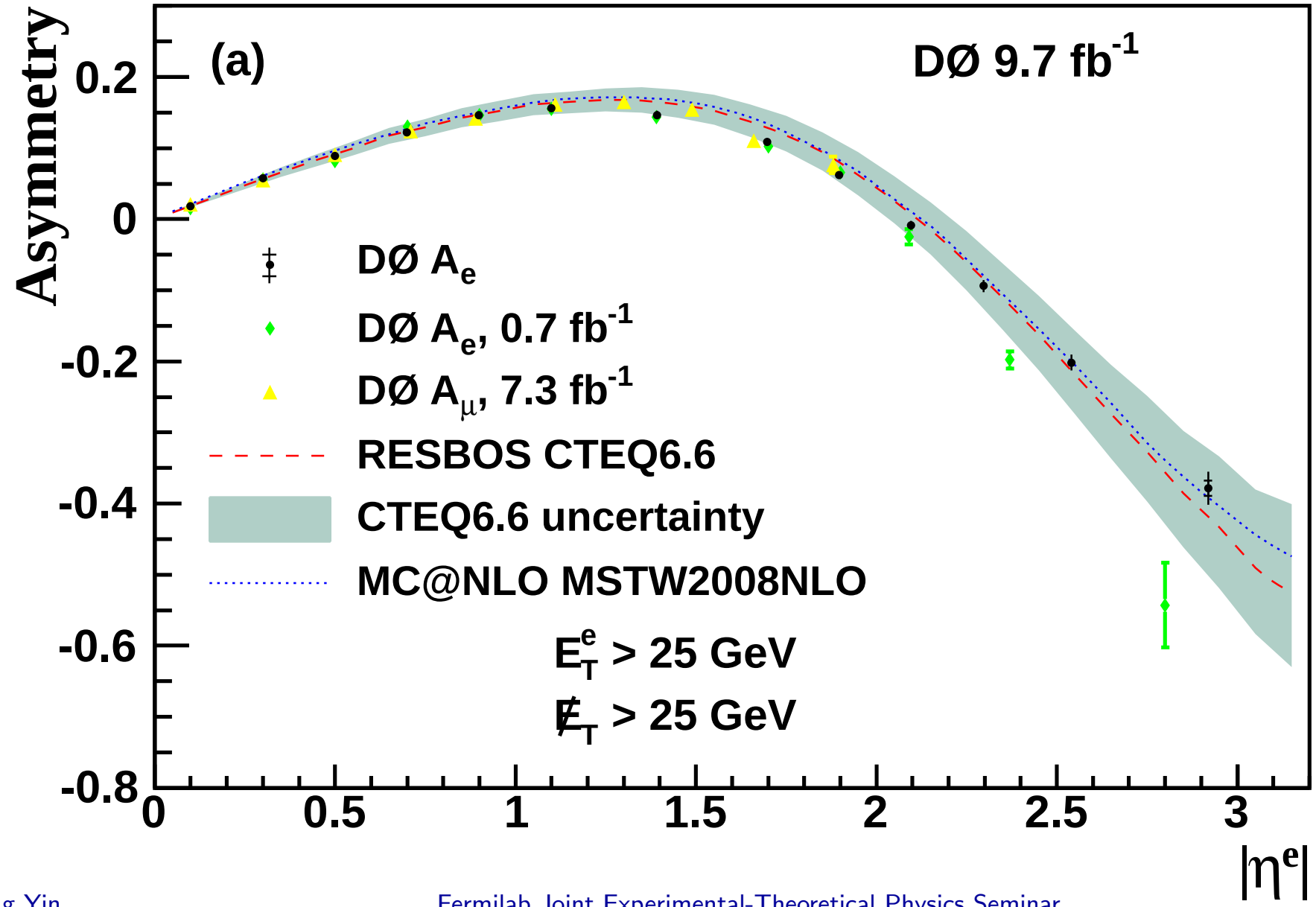
# QCD: Template method

- Template fitting method
  - Use signal shape and QCD shape to fit data
  - $QCD$ shape: reverse the electron cuts: HMX7 for CC electron events, HMX8 for EC electron events.
  - $QCD$ contribution: fitting for CC and EC events separately (the HMX cuts are different for CC and EC electron)

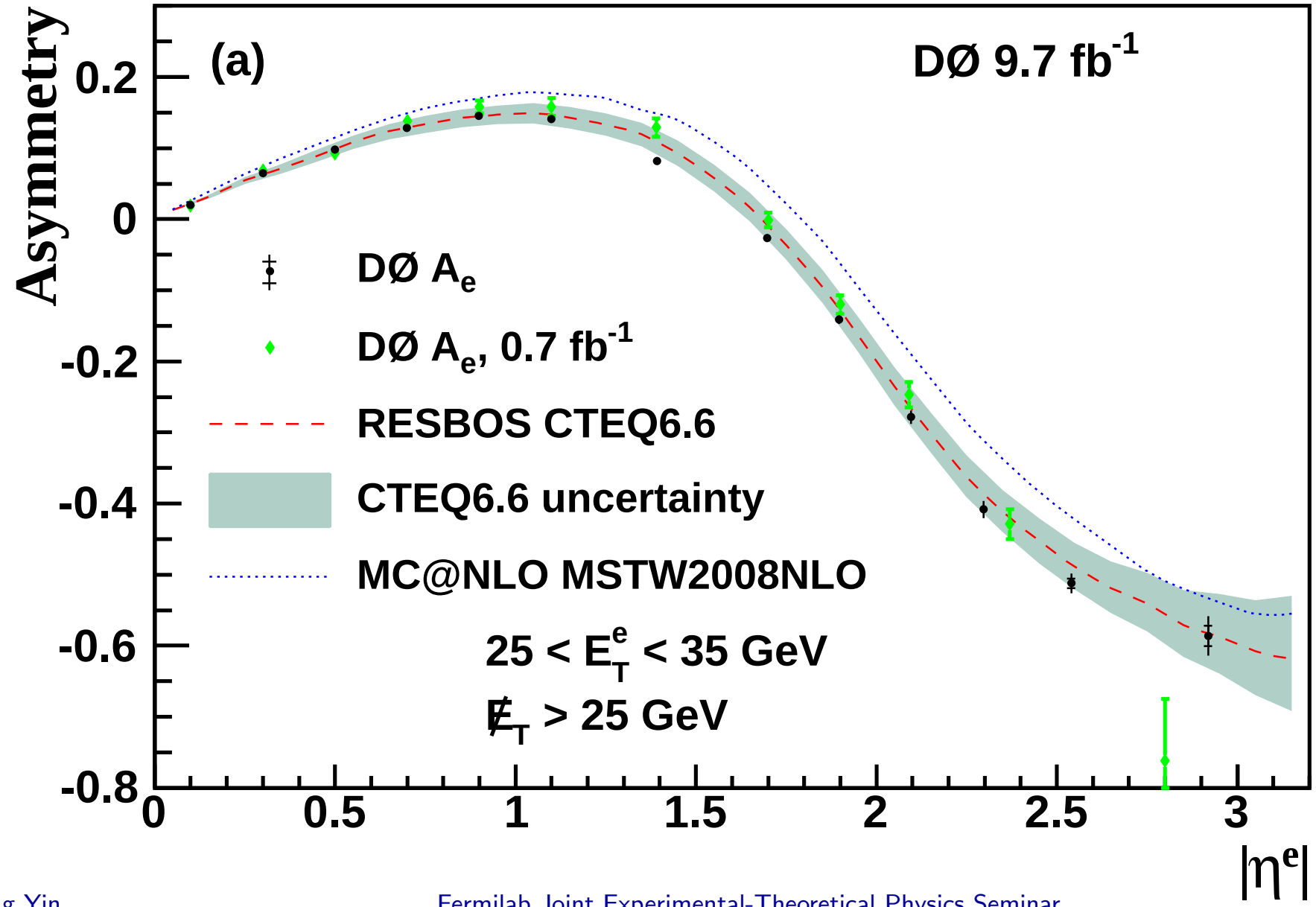


# Lepton asymmetry (1)

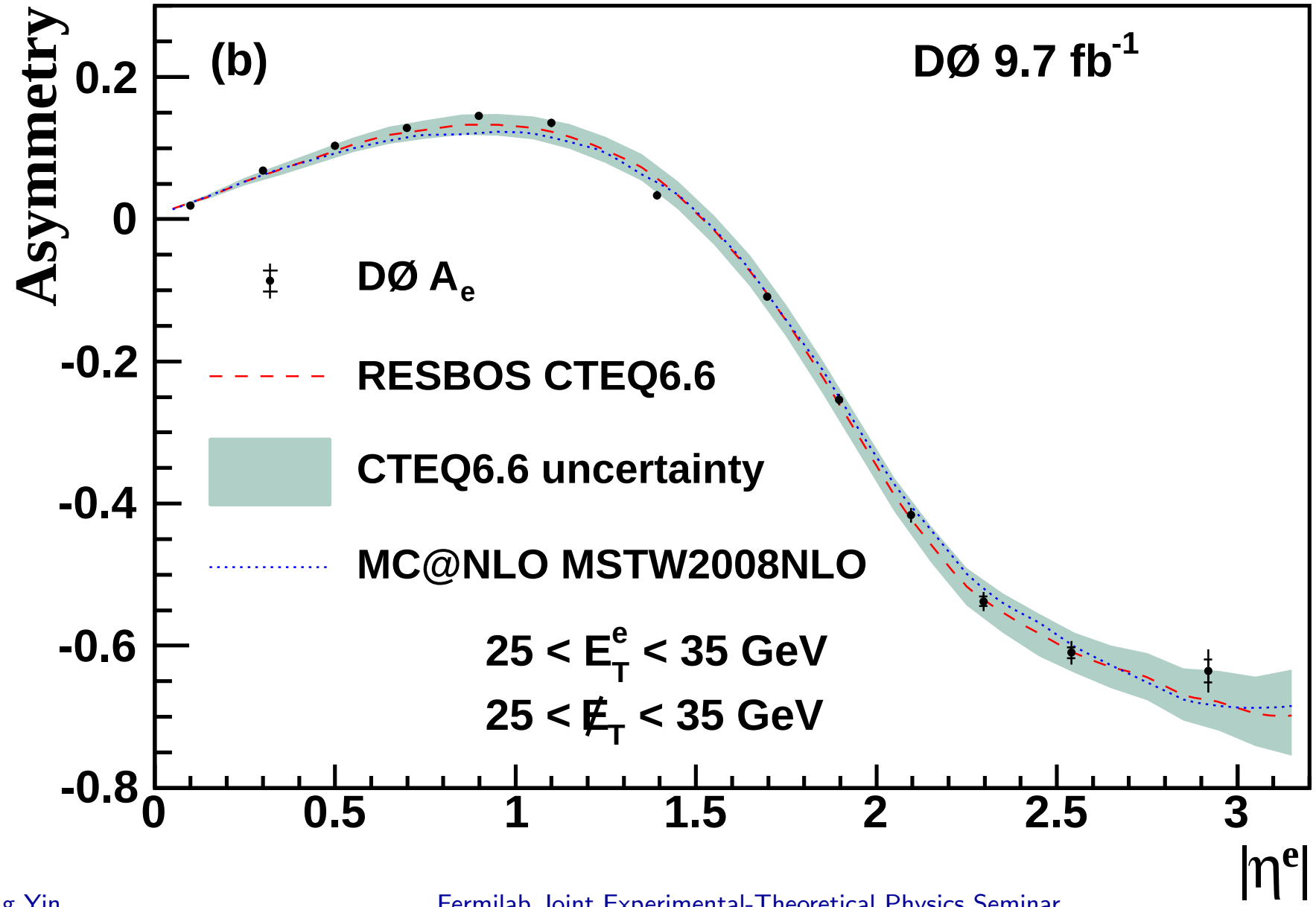
**New results supersede previous electron charge asymmetry!**



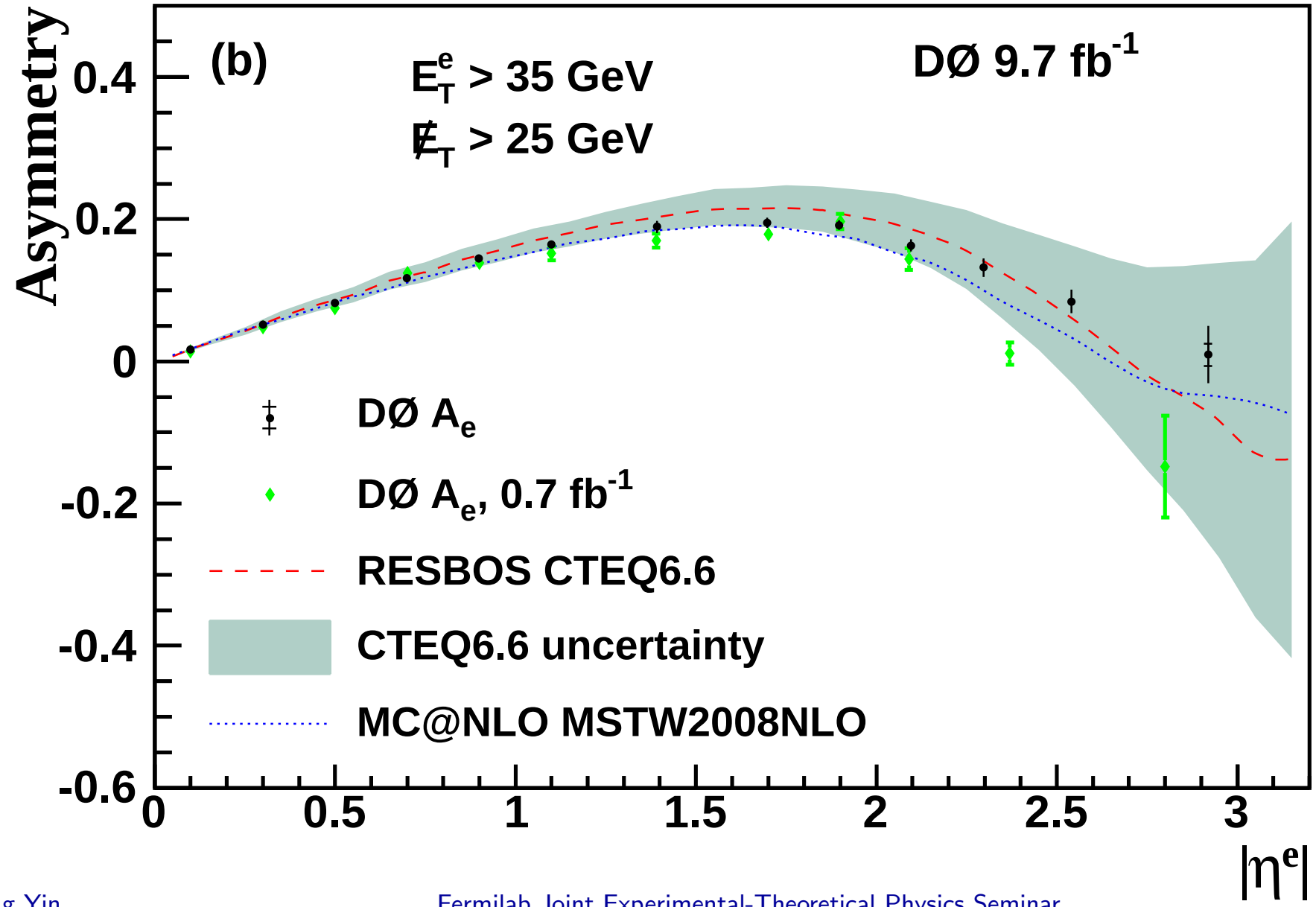
# Lepton asymmetry (2)



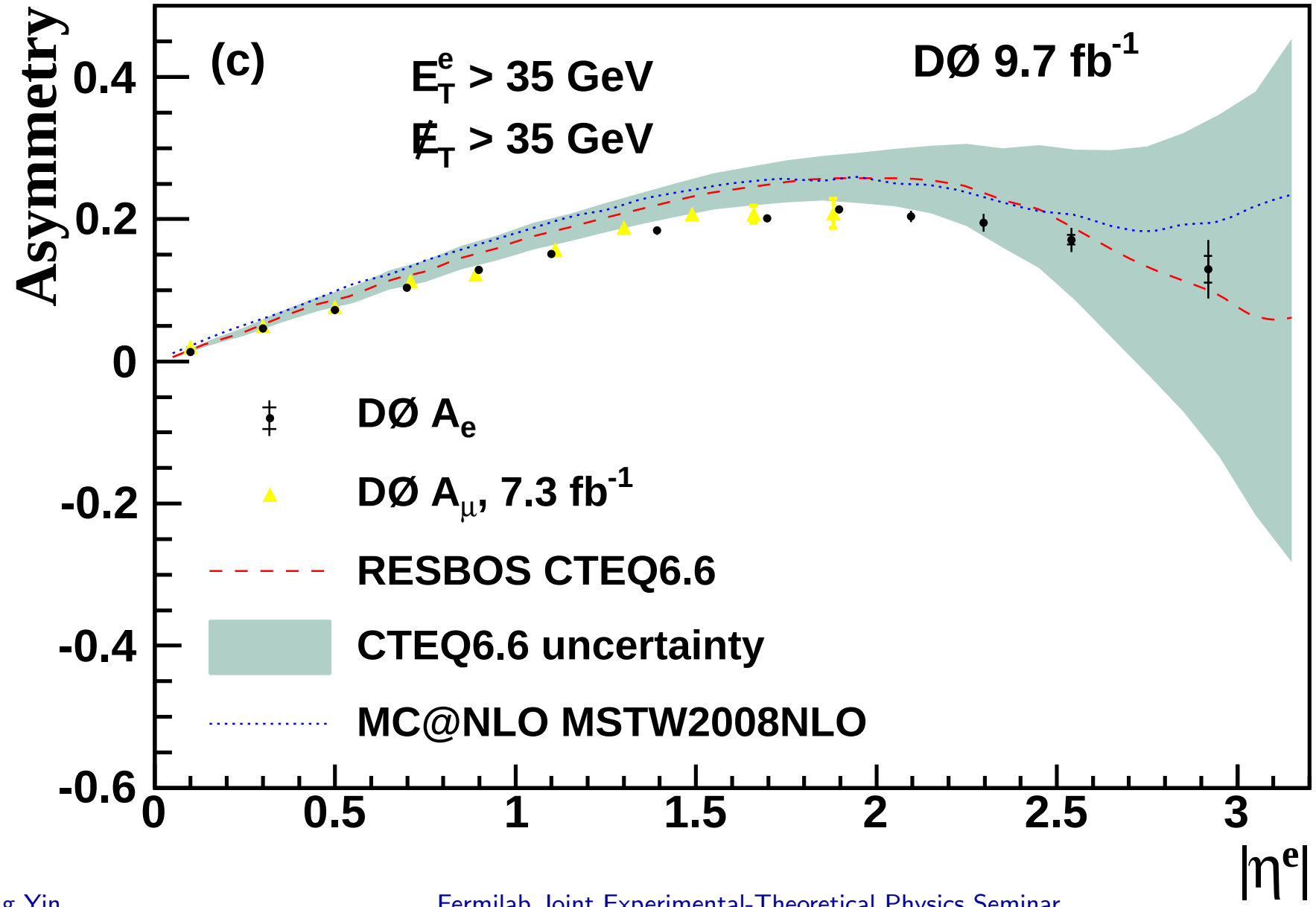
# Lepton asymmetry (3)



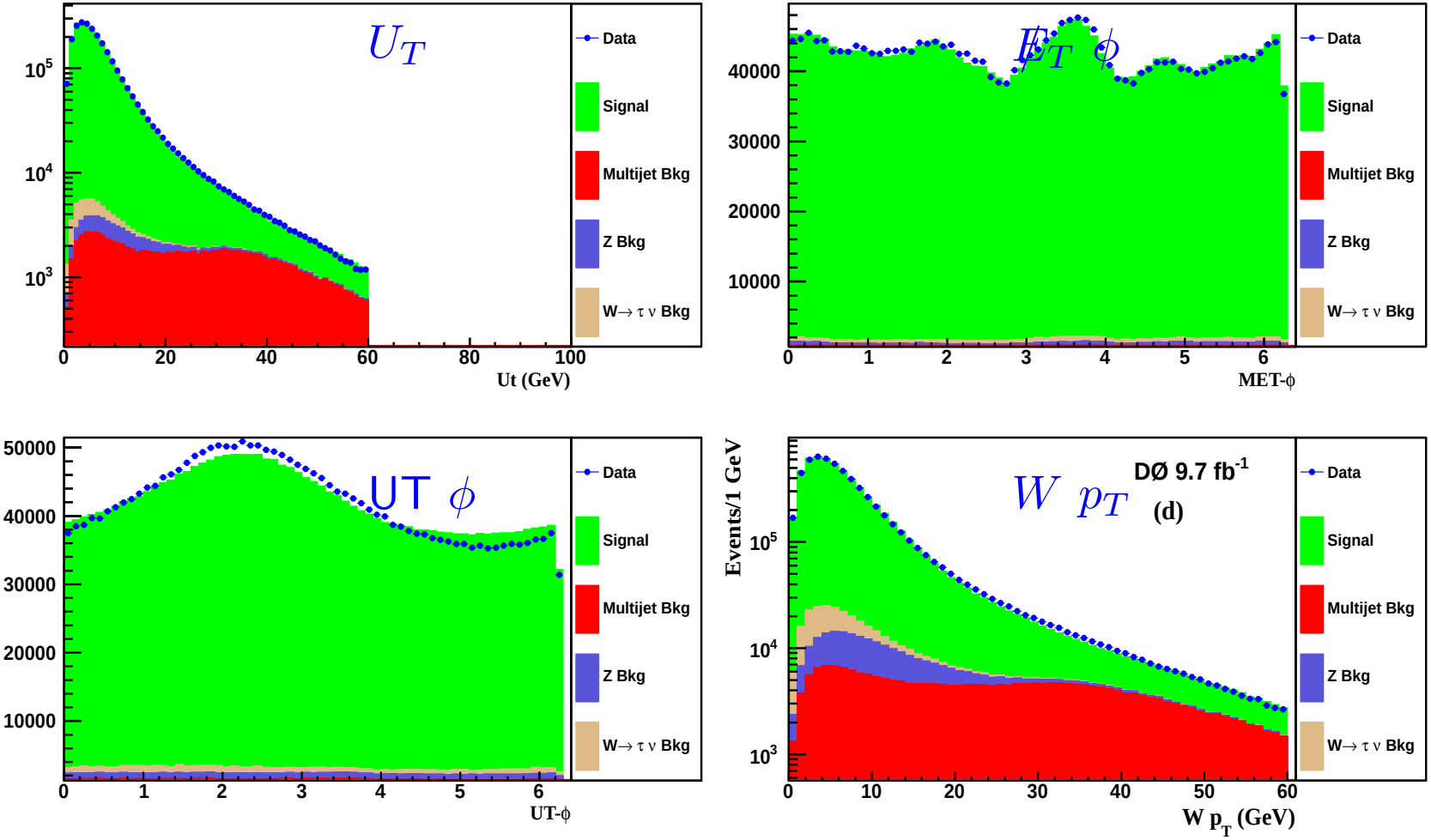
# Lepton asymmetry (4)



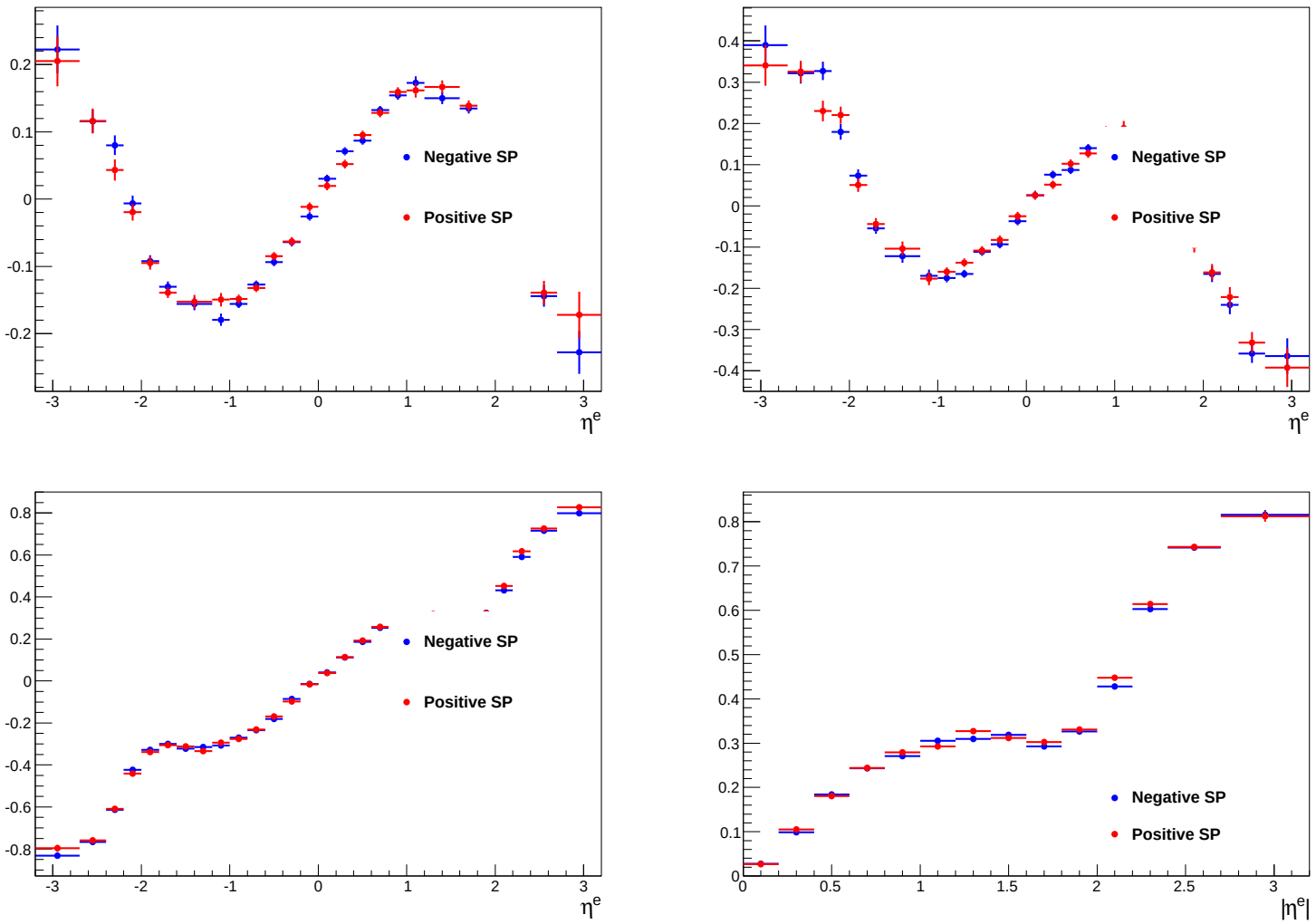
# Lepton asymmetry (5)



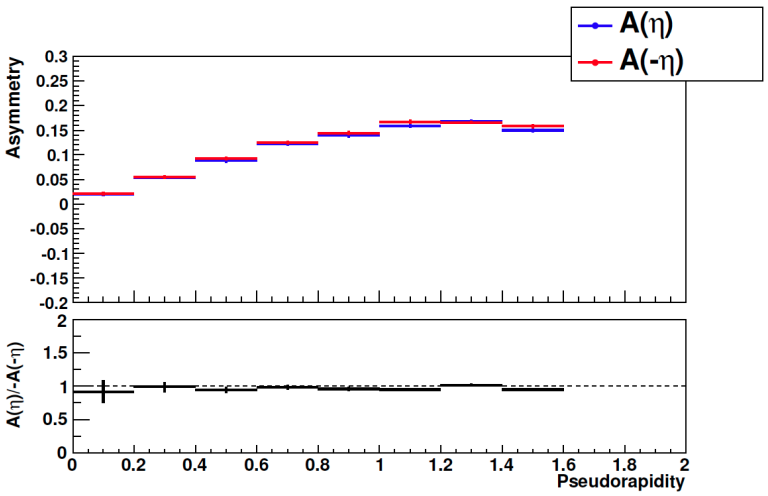
# $W$ events: $U_T$, $\not{E}_T$ $\phi$, UT $\phi$, $W$ $p_T$

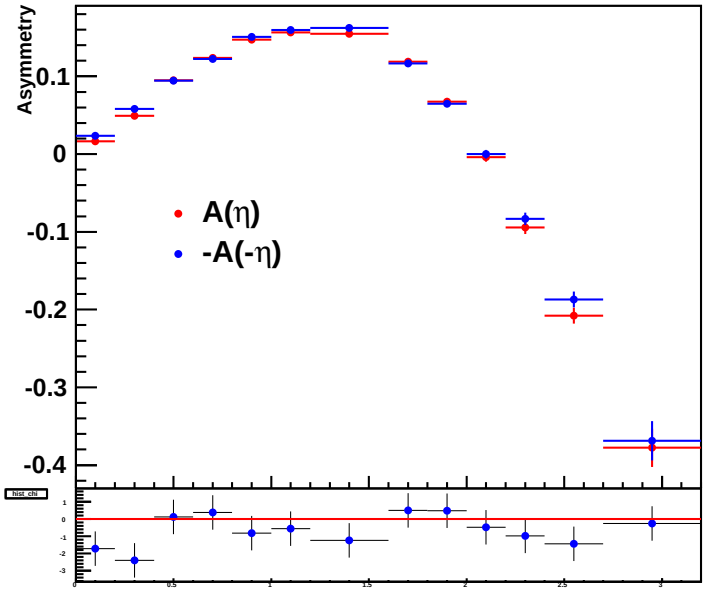


# Solenoid polarity in electron channel

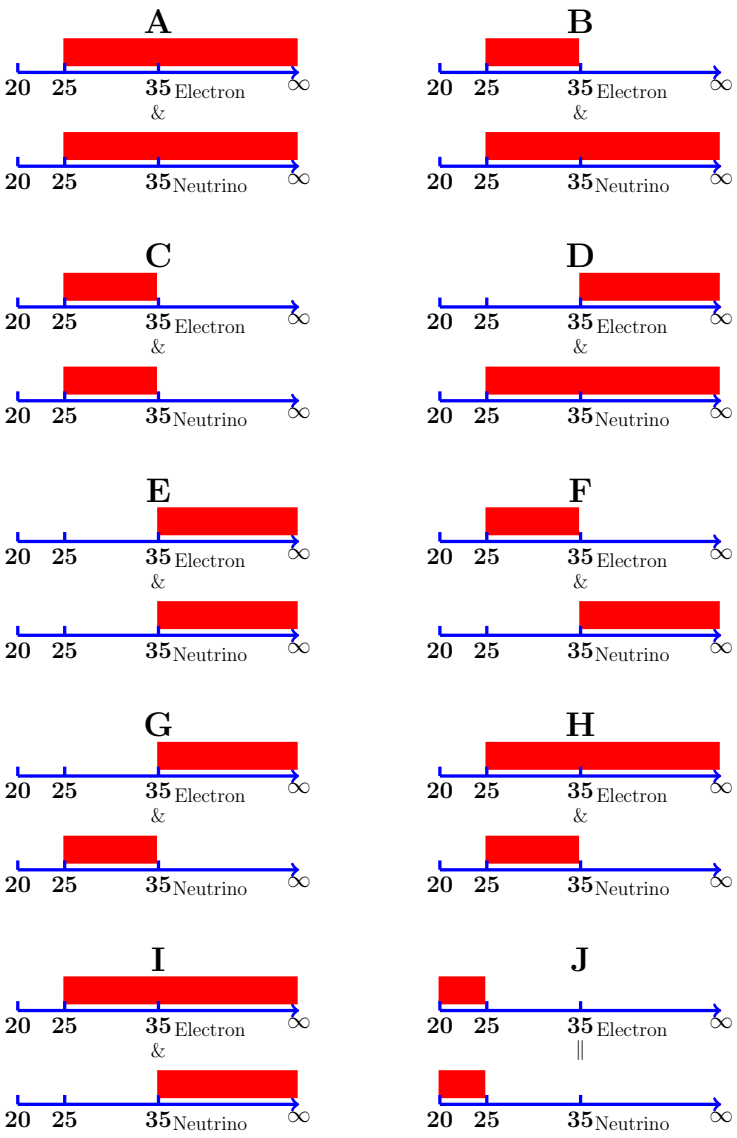


# *CP* fold



# Migration unfolding



# Migration unfolding formulas

- $N_A^{\text{Gene}} = N_A^{\text{Reco}} \times M^{\text{Reco(A),Gene(A)}} + N_J^{\text{Reco}} \times M^{\text{Reco(J),Gene(A)}}$
- $N_B^{\text{Gene}} = N_B^{\text{Reco}} \times M^{\text{Reco(B),Gene(B)}}$
  $+N_D^{\text{Reco}} \times M^{\text{Reco(D),Gene(B)}} + N_J^{\text{Reco}} \times M^{\text{Reco(J),Gene(B)}}$
- $N_C^{\text{Gene}} = N_C^{\text{Reco}} \times M^{\text{Reco(C),Gene(C)}}$
  $+N_E^{\text{Reco}} \times M^{\text{Reco(E),Gene(C)}} + N_F^{\text{Reco}} \times M^{\text{Reco(F),Gene(C)}}$
  $+N_G^{\text{Reco}} \times M^{\text{Reco(G),Gene(C)}} + N_J^{\text{Reco}} \times M^{\text{Reco(J),Gene(C)}}$
- $N_D^{\text{Gene}} = N_D^{\text{Reco}} \times M^{\text{Reco(D),Gene(D)}}$
  $+N_B^{\text{Reco}} \times M^{\text{Reco(B),Gene(D)}} + N_J^{\text{Reco}} \times M^{\text{Reco(J),Gene(D)}}$
- $N_E^{\text{Gene}} = N_E^{\text{Reco}} \times M^{\text{Reco(E),Gene(E)}}$
  $+N_C^{\text{Reco}} \times M^{\text{Reco(C),Gene(E)}} + N_F^{\text{Reco}} \times M^{\text{Reco(F),Gene(E)}}$
  $+N_G^{\text{Reco}} \times M^{\text{Reco(G),Gene(E)}} + N_J^{\text{Reco}} \times M^{\text{Reco(J),Gene(E)}}$

# Correlation matrix (1)

$$\mathcal{A}[i] = \frac{N^{+}_{\text{Gene}}[i] - N^{-}_{\text{Gene}}[i]}{N^{+}_{\text{Gene}}[i] + N^{-}_{\text{Gene}}[i]} \tag{1}$$

$$\begin{aligned} \mathcal{A}[i] &= \frac{N^{+}_{\text{unfold2}}[i] - N^{-}_{\text{unfold2}}[i]}{N^{+}_{\text{unfold2}}[i] + N^{-}_{\text{unfold2}}[i]} \\ &= \frac{\frac{N^{+}_{\text{unfold1}}[i]}{Acc^{+}[i]} - \frac{N^{-}_{\text{unfold1}}[i]}{Acc^{-}[i]}}{\frac{N^{+}_{\text{unfold1}}[i]}{Acc^{+}[i]} + \frac{N^{-}_{\text{unfold1}}[i]}{Acc^{-}[i]}} \end{aligned} \tag{2}$$

$$\begin{aligned} N^{-}_{\text{Gene}}(A)[i] &= \sum_{j} N^{-}_{\text{raw}}(A)[j] \times M^{\text{AA}}_{SS,-}[i][j] + N^{-}_{\text{raw}}(J)[j] \times M^{\text{JA}}_{SS,-}[i][j] + \\ & \sum_{j} N^{+}_{\text{raw}}(A)[j] \times M^{\text{AA}}_{OS,+}[i][j] + N^{+}_{\text{raw}}(J)[j] \times M^{\text{JA}}_{OS,+}[i][j] \end{aligned}$$

# Correlation matrix (2)

$$\Delta\mathcal{A}[i] = \sqrt{\left(\sum_j \left(\frac{\partial\mathcal{A}[i]}{\partial N^+_{A,raw}[j]}\Delta N^+_{A,raw}[j]\right)^2 + \sum_j \left(\frac{\partial\mathcal{A}[i]}{\partial N^-_{A,raw}[j]}\Delta N^-_{A,raw}[j]\right)^2 + \sum_j \left(\frac{\partial\mathcal{A}[i]}{\partial N^+_{J,raw}[j]}\Delta N^+_{J,raw}[j]\right)^2 + \sum_j \left(\frac{\partial\mathcal{A}[i]}{\partial N^-_{J,raw}[j]}\Delta N^-_{J,raw}[j]\right)^2\right)} \quad (3)$$

$$\frac{\partial\mathcal{A}[i]}{\partial N^+_{A,raw}[j]} = \frac{2\times N^-_{\text{unfold2}}[i]\times M^{AA}_{SS,-}[i][j]}{Acc^+[i]\times(N^+_{unfold2}[i]+N^-_{unfold2}[i])^2} - \frac{2\times N^+_{\text{unfold2}}[i]\times M^{AA}_{OS,+}[i][j]}{Acc^-[i]\times(N^+_{\text{unfold2}}[i]+N^-_{\text{unfold2}}[i])^2} \quad (4)$$

$$\frac{\partial\mathcal{A}[i]}{\partial N^-_{A,raw}[j]} = \frac{-2\times N^+_{\text{unfold2}}[i]\times M^{AA}_{SS,+}[i][j]}{Acc^-[i]\times(N^+_{unfold2}[i]+N^-_{unfold2}[i])^2} + \frac{2\times N^-_{\text{unfold2}}[i]\times M^{AA}_{OS,-}[i][j]}{Acc^+[i]\times(N^+_{\text{unfold2}}[i]+N^-_{\text{unfold2}}[i])^2} \quad (5)$$

$$\frac{\partial\mathcal{A}[i]}{\partial N^+_{J,raw}[j]} = \frac{2\times N^-_{\text{unfold2}}[i]\times M^{JA}_{SS,-}[i][j]}{Acc^+[i]\times(N^+_{unfold2}[i]+N^-_{unfold2}[i])^2} - \frac{2\times N^+_{\text{unfold2}}[i]\times M^{JA}_{OS,+}[i][j]}{Acc^-[i]\times(N^+_{\text{unfold2}}[i]+N^-_{\text{unfold2}}[i])^2} \quad (6)$$

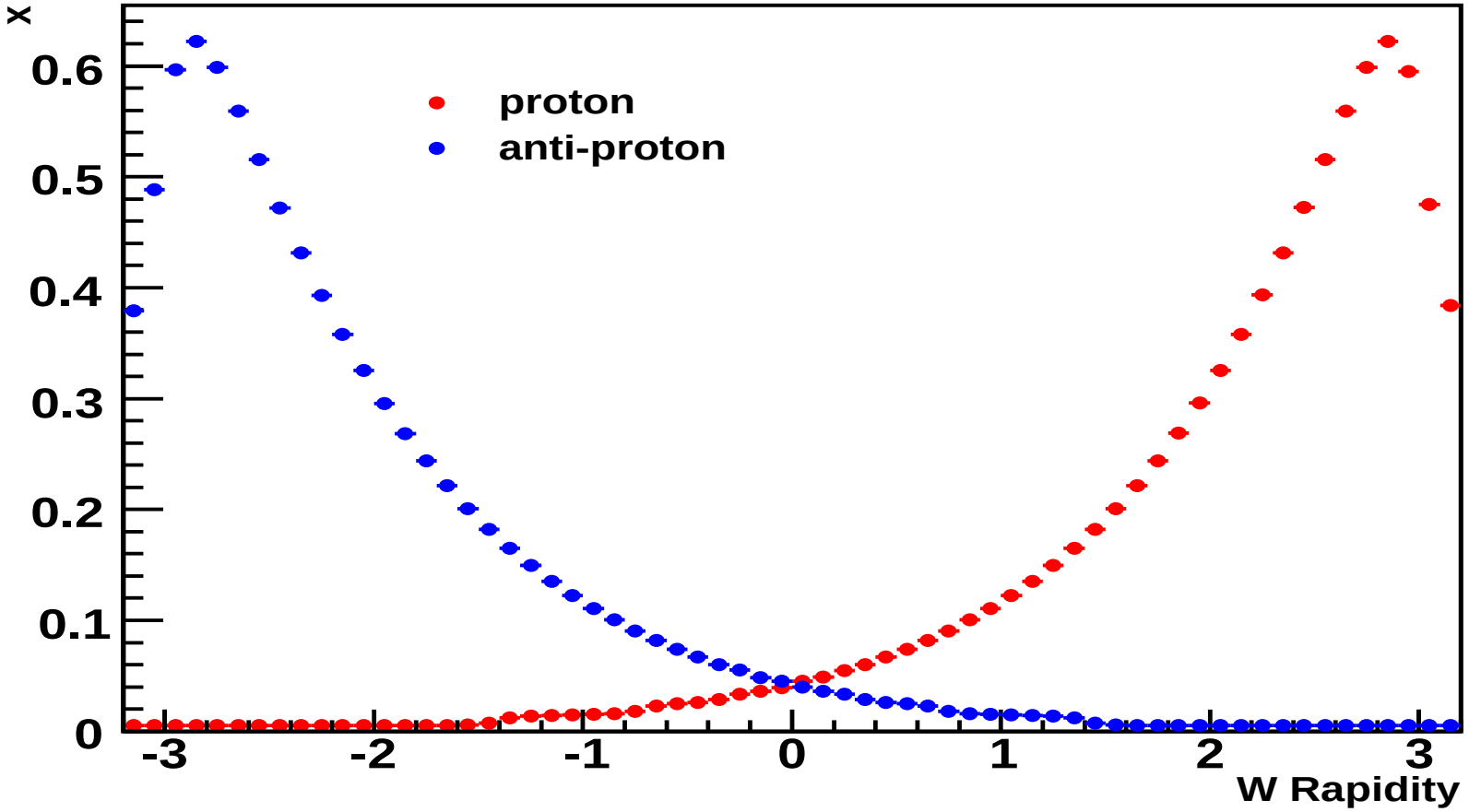
$$\frac{\partial\mathcal{A}[i]}{\partial N^-_{J,raw}[j]} = \frac{-2\times N^+_{\text{unfold2}}[i]\times M^{JA}_{SS,+}[i][j]}{Acc^-[i]\times(N^+_{unfold2}[i]+N^-_{unfold2}[i])^2} + \frac{2\times N^-_{\text{unfold2}}[i]\times M^{JA}_{OS,-}[i][j]}{Acc^+[i]\times(N^+_{\text{unfold2}}[i]+N^-_{\text{unfold2}}[i])^2} \quad (7)$$

# Correlation matrix (3)

$$
\begin{aligned}
\mathcal{E}[i][j] \quad = \quad & \sum_{m=1}^{\eta\ bins} \frac{\partial \mathcal{A}[i]}{\partial N^{+}_{A,raw}[m]} \cdot \frac{\partial \mathcal{A}[j]}{\partial N^{+}_{A,raw}[m]} \cdot (\Delta N^{+}_{A,raw}[m])^2 + \\
& \sum_{m=1}^{\eta\ bins} \frac{\partial \mathcal{A}[i]}{\partial N^{-}_{A,raw}[m]} \cdot \frac{\partial \mathcal{A}[j]}{\partial N^{-}_{A,raw}[m]} \cdot (\Delta N^{-}_{A,raw}[m])^2 + \\
& \sum_{m=1}^{\eta\ bins} \frac{\partial \mathcal{A}[i]}{\partial N^{+}_{J,raw}[m]} \cdot \frac{\partial \mathcal{A}[j]}{\partial N^{+}_{J,raw}[m]} \cdot (\Delta N^{+}_{J,raw}[m])^2 + \\
& \sum_{m=1}^{\eta\ bins} \frac{\partial \mathcal{A}[i]}{\partial N^{-}_{J,raw}[m]} \cdot \frac{\partial \mathcal{A}[j]}{\partial N^{-}_{J,raw}[m]} \cdot (\Delta N^{-}_{J,raw}[m])^2
\end{aligned}
$$

$$
\mathcal{C}[i][j] = \mathcal{E}[i][j] / \sqrt{\mathcal{E}[i][i] \times \mathcal{E}[j][j]}
$$

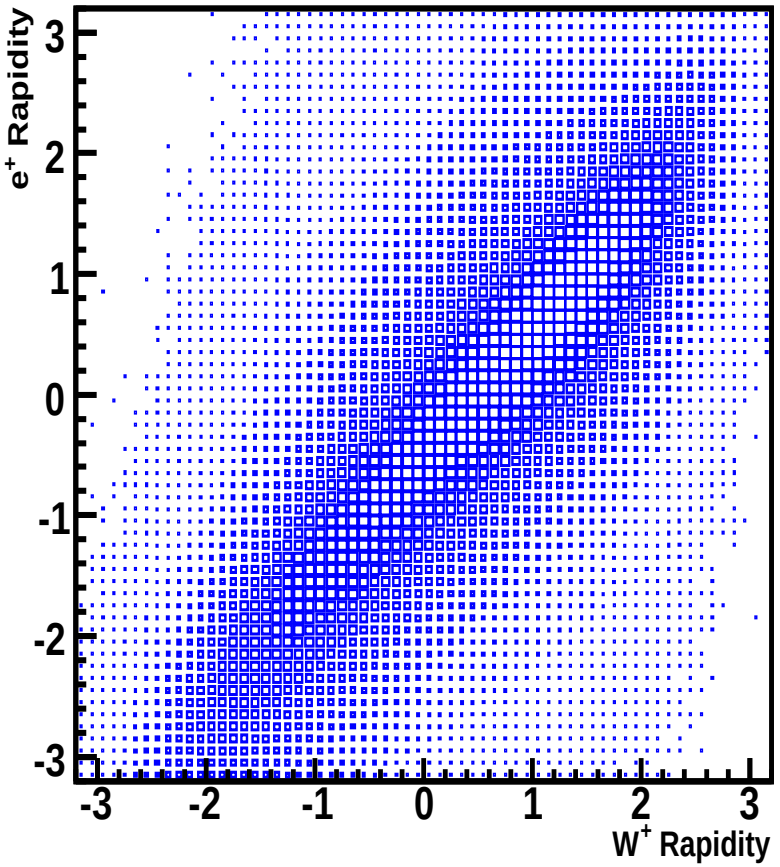
# x distribution

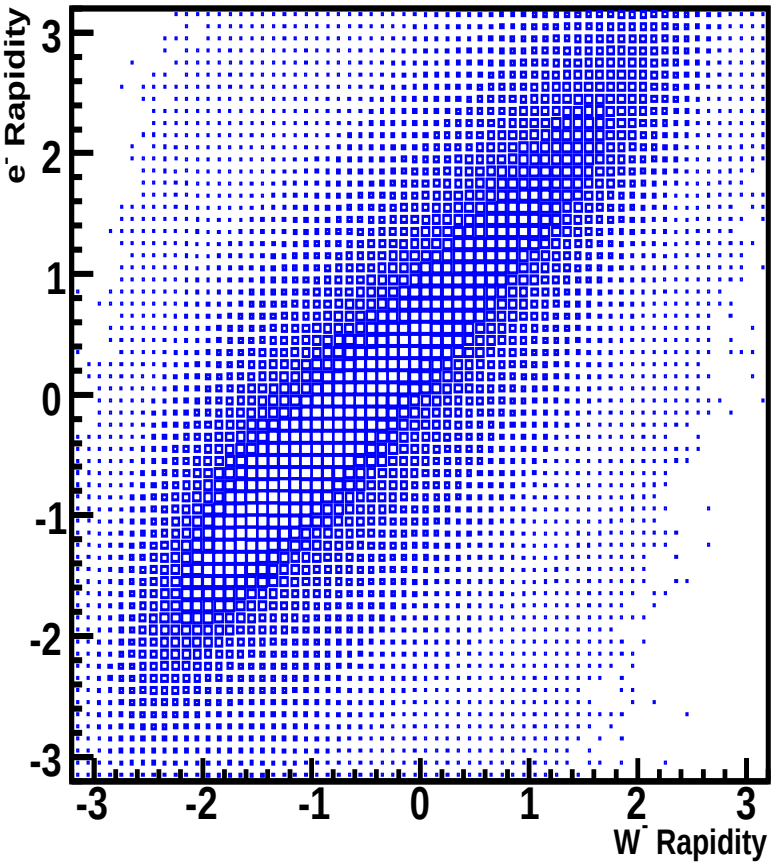


# Rapidity distribution

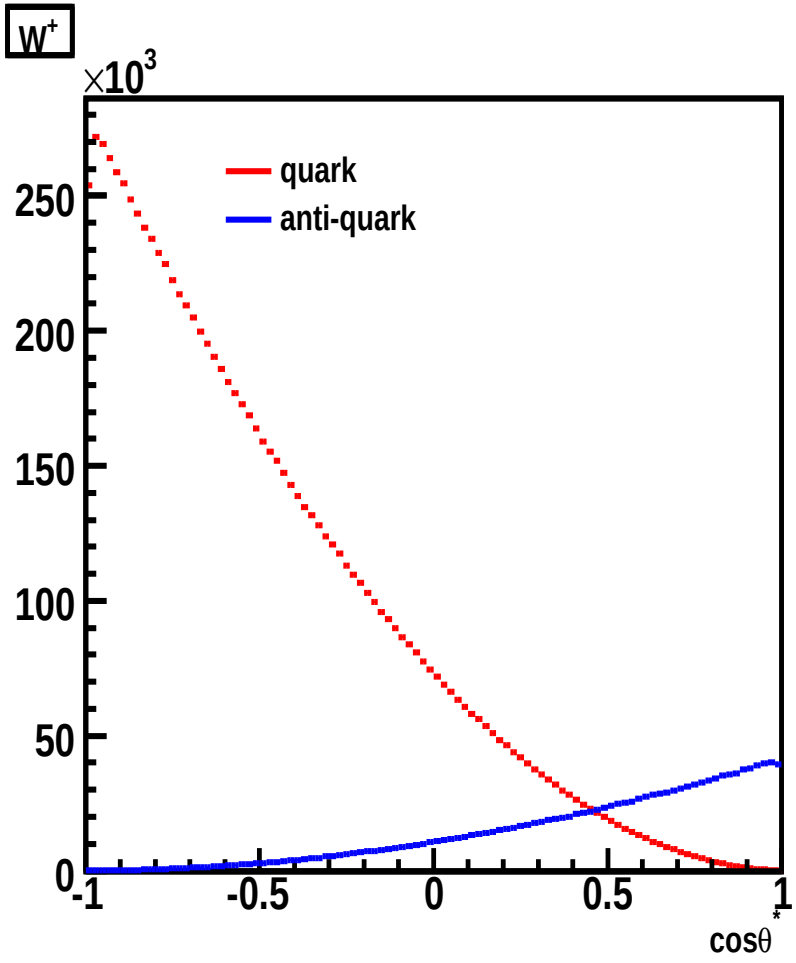
- Generator level $W$ $y$ vs. electron $\eta$

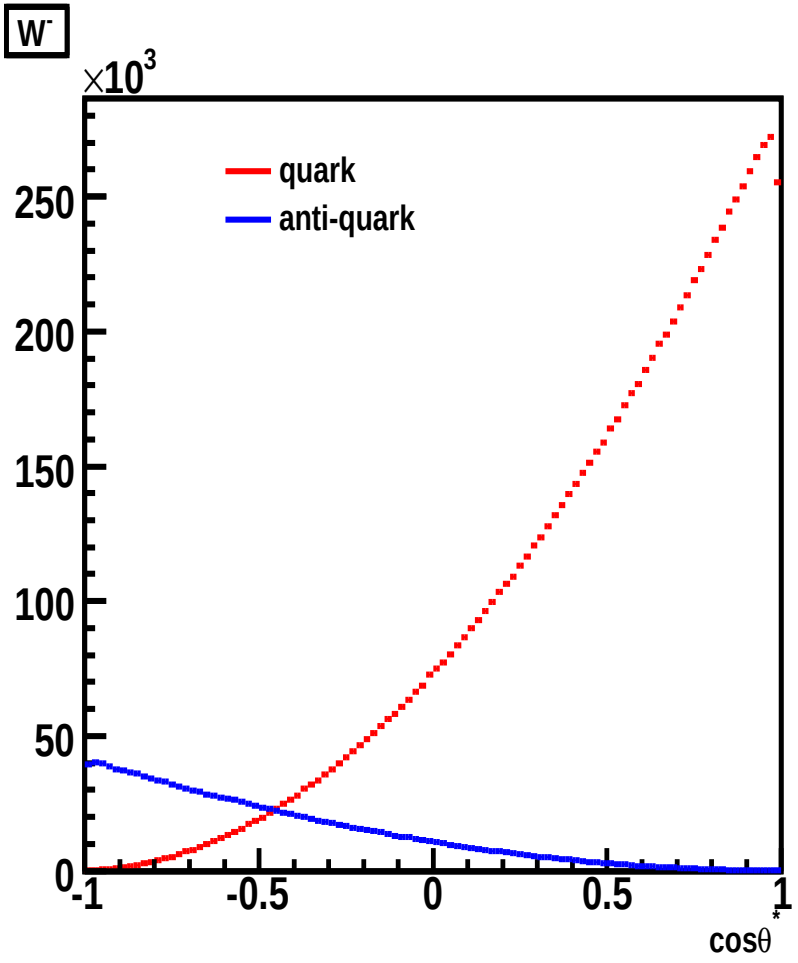
MC@NLO+MSTW2008NLO



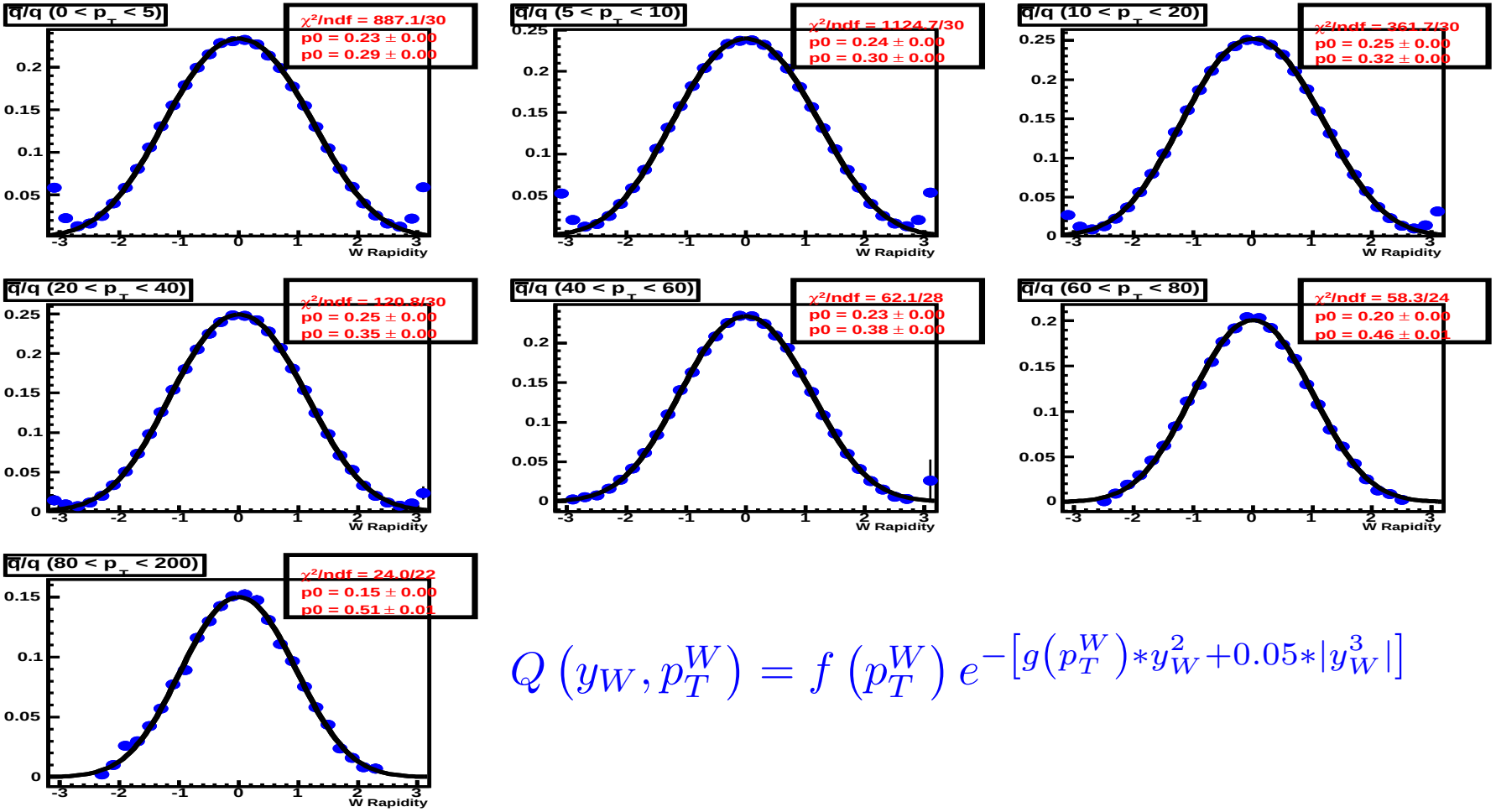
# Collins angle distribution



# Collins angle in each $p_T$ bin

- $W$ $y$ vs. $W$ $p_T$

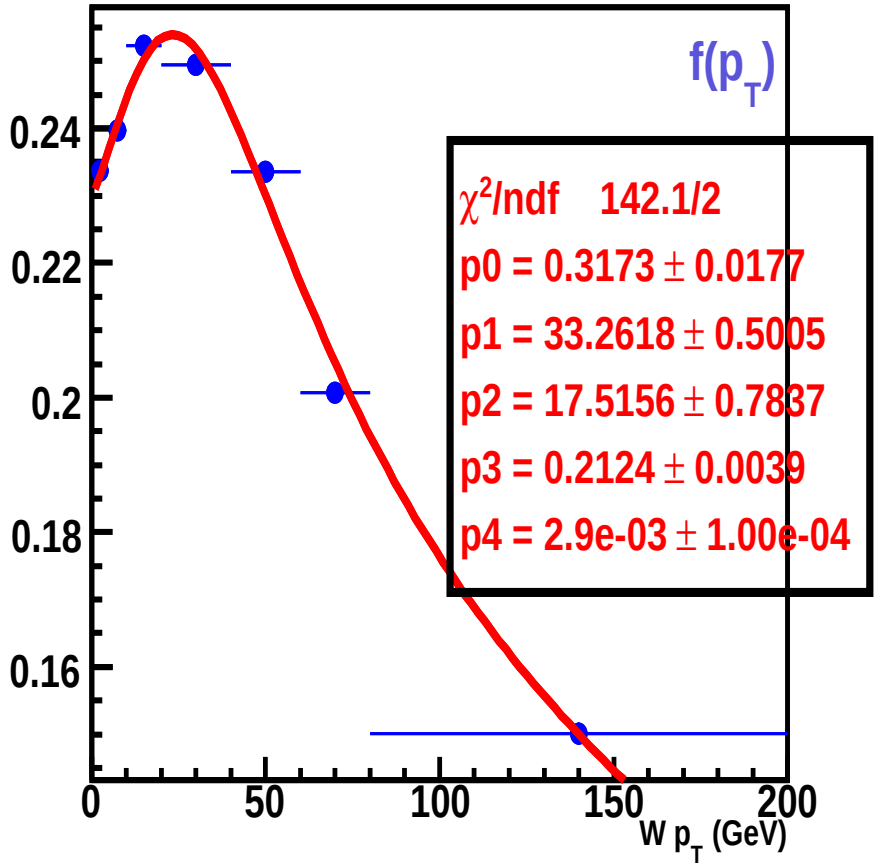


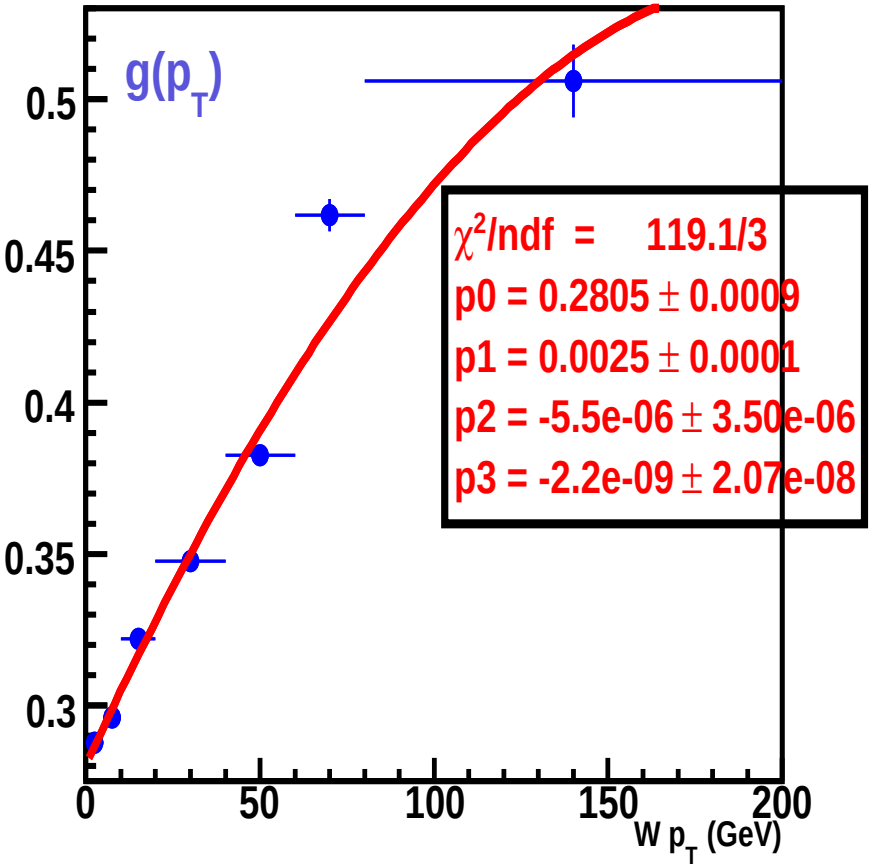

$$Q\left(y_W, p_T^W\right) = f\left(p_T^W\right) e^{-\left[g\left(p_T^W\right) * y_W^2 + 0.05 * \left|y_W^3\right|\right]}$$

# Fit results

$$f\left(p_T^W\right) = p0 * L(p_T^W, \mu, \sigma) + p1 * e^{-\left(p2 * p_T^W\right)}$$

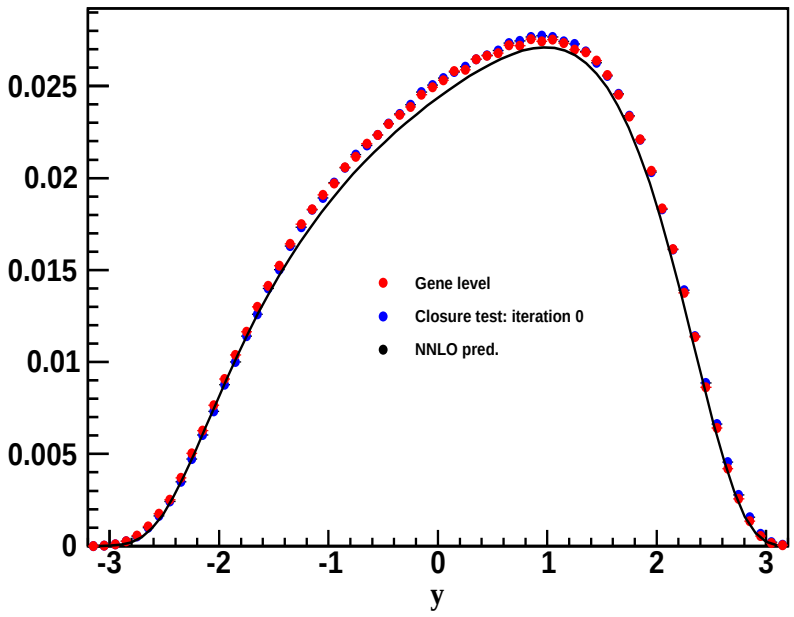
$$g\left(p_T^W\right) = p0 * +p1 * p_T^W + p2 * {p_T^W}^2 + p3 * {p_T^W}^3$$

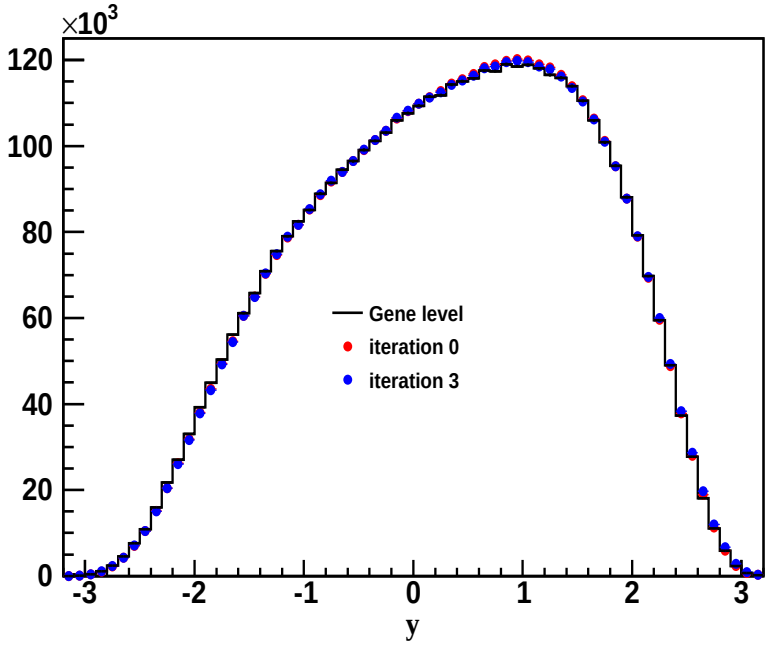


# Input bias

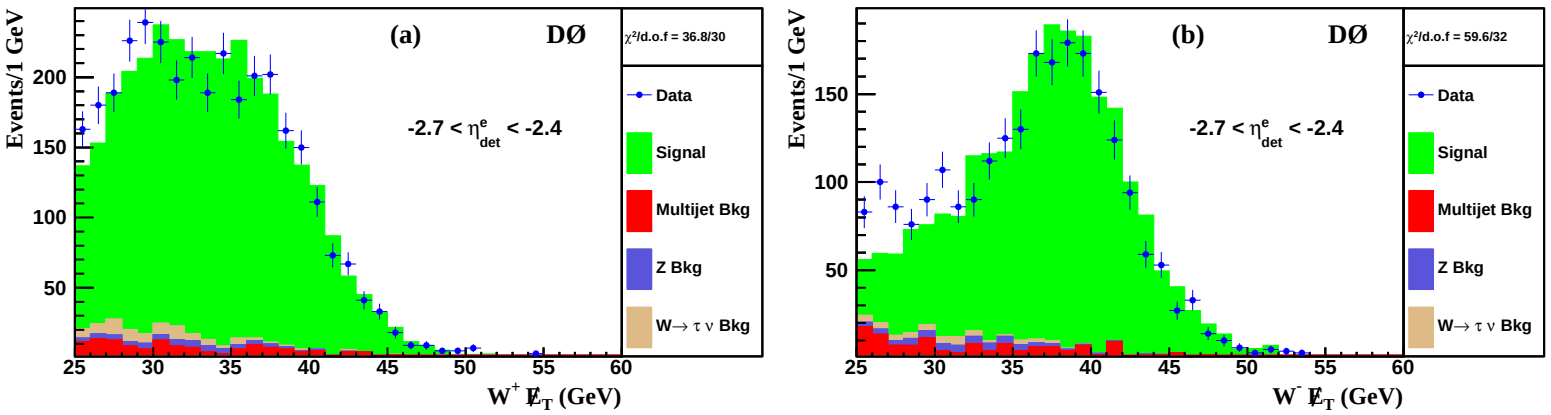
- The NNLO differential cross section predictions are taken as inputs, which will bias the results
- An iterative method is performed to remove this bias
  - Take the measured cross section as input ...



## Systematic uncertainty from MC modeling imperfections

- Reweight the $W^+$ and $W^-$ events separately with the data/MC ratio (obtained from $W^+$ and $W^-$ events) in each $\eta$ bin
- Take the asymmetry deviation between the samples with and without reweighing factor applying
- The uncertainties from $M_T$, electron $E_T$ and $\not{E}_T$, are combined to arrive at one total MC modeling uncertainty



# Lepton correlation matrix

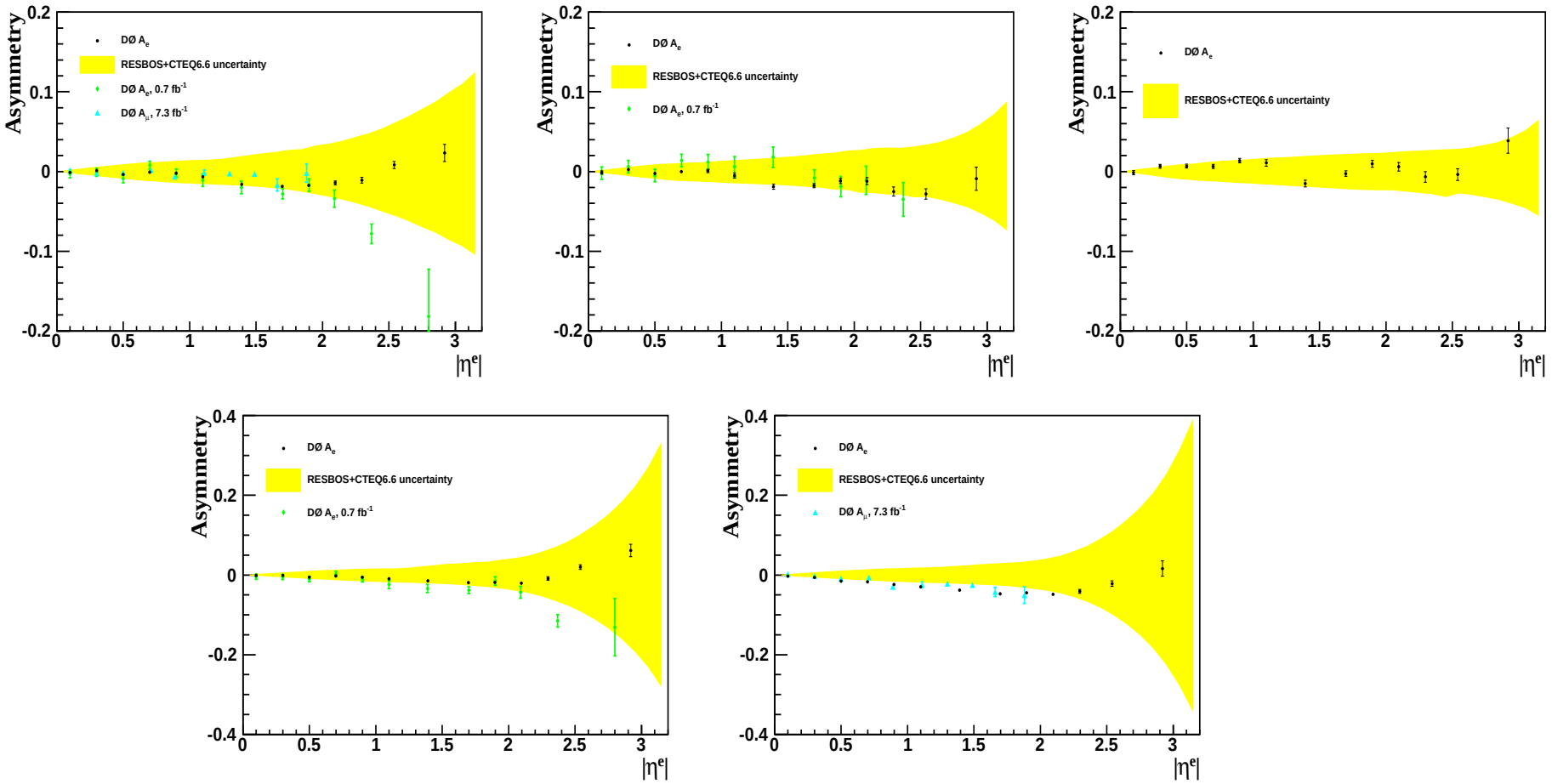
Table: Correlation coefficients between different $\eta$ bins for $p_T^e > 25$ GeV and $\not{E}_T > 25$ GeV. Only half of the symmetric correlation matrix is presented. And the elements of matrix are presented in percent (%).

| $\eta$ bin | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 100 | 0.73 | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2 | | 100 | 0.66 | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 3 | | | 100 | 0.64 | 0.03 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 4 | | | | 100 | 0.65 | 0.02 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 5 | | | | | 100 | 0.63 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 6 | | | | | | 100 | 0.38 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 7 | | | | | | | 100 | 0.54 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 8 | | | | | | | | 100 | 0.29 | 0.00 | 0.00 | 0.00 | 0.00 |
| 9 | | | | | | | | | 100 | 0.32 | 0.00 | 0.00 | 0.00 |
| 10 | | | | | | | | | | 100 | 0.50 | 0.00 | 0.00 |
| 11 | | | | | | | | | | | 100 | 0.16 | 0.00 |
| 12 | | | | | | | | | | | | 100 | 0.29 |
| 13 | | | | | | | | | | | | | 100 |

# $W$ boson charge asymmetry correlation matrix

Table: Correlation coefficients between different $\eta$ bins for $p_T^e > 25$ GeV and $\not{E}_T > 25$ GeV. Only half of the symmetric correlation matrix is presented. And the elements of matrix are presented in percent (%).

| $\lvert y_W \rvert$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.00 | 0.84 | 0.57 | 0.38 | 0.29 | 0.25 | 0.21 | 0.16 | 0.10 | 0.06 | 0.04 | 0.03 | 0.02 |
| 2 | | 1.00 | 0.85 | 0.58 | 0.39 | 0.29 | 0.24 | 0.16 | 0.11 | 0.07 | 0.04 | 0.04 | 0.03 |
| 3 | | | 1.00 | 0.85 | 0.58 | 0.38 | 0.26 | 0.16 | 0.10 | 0.06 | 0.05 | 0.06 | 0.05 |
| 4 | | | | 1.00 | 0.83 | 0.52 | 0.29 | 0.16 | 0.09 | 0.07 | 0.08 | 0.10 | 0.09 |
| 5 | | | | | 1.00 | 0.78 | 0.42 | 0.19 | 0.11 | 0.10 | 0.13 | 0.15 | 0.14 |
| 6 | | | | | | 1.00 | 0.74 | 0.37 | 0.22 | 0.19 | 0.22 | 0.22 | 0.20 |
| 7 | | | | | | | 1.00 | 0.76 | 0.50 | 0.38 | 0.34 | 0.31 | 0.29 |
| 8 | | | | | | | | 1.00 | 0.84 | 0.62 | 0.47 | 0.38 | 0.34 |
| 9 | | | | | | | | | 1.00 | 0.87 | 0.65 | 0.48 | 0.40 |
| 10 | | | | | | | | | | 1.00 | 0.89 | 0.67 | 0.51 |
| 11 | | | | | | | | | | | 1.00 | 0.89 | 0.66 |
| 12 | | | | | | | | | | | | 1.00 | 0.86 |
| 13 | | | | | | | | | | | | | 1.00 |
| 14 | | | | | | | | | | | | | |

# Lepton asymmetries

(data-RESBOS)/RESBOS