Transverse single-spin asymmetries in $W^{\pm}$ and Z^{0} bosons production in p+p collisions at RHIC

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for the STAR Collaboration

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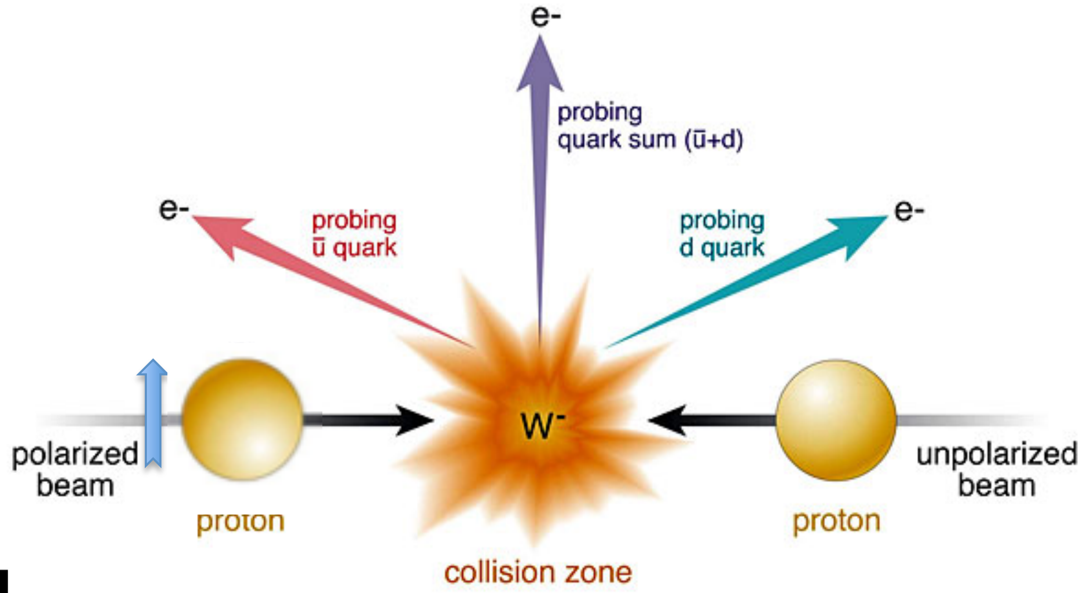

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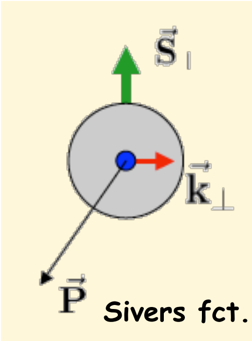
Plan of the talk

- ✧ Physics motivations
- ✧ The $W^{\pm}$ selection and A_N measurement
- ✧ The Z^0 selection and A_N measurement
- ✧ Future plans
- ✧ Conclusions

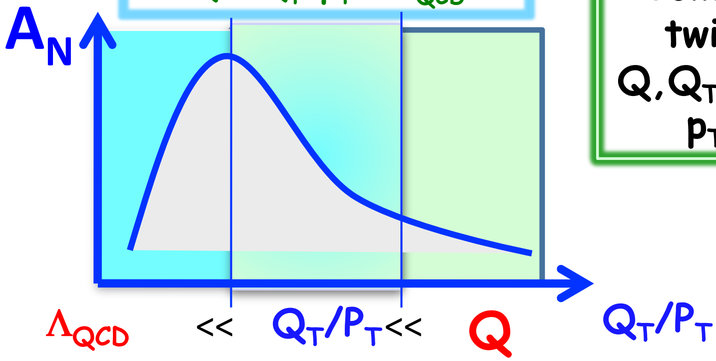
Motivations

$$A_N \approx \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

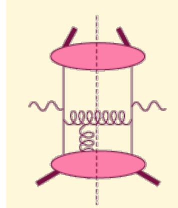


Transverse momentum dependent
$Q >> Q_T >= \Lambda_{QCD}$
$Q >> p_T$

Intermediate Q_T
$Q >> Q_T/p_T >> \Lambda_{QCD}$



Collinear/ twist-3
$Q, Q_T >> \Lambda_{QCD}$
$p_T \sim Q$

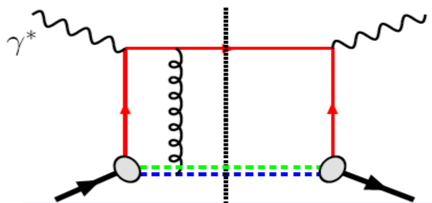


Efremov, Teryaev; Qiu, Sterman

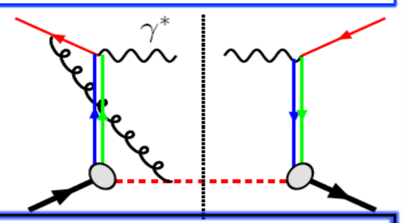
QCD:

TMDs
need 2 scales
Q^2 and p_t
Remember pp:
most observables one scale
Exception: DY, W/Z, Collins

DIS: γq scattering
attractive FSI



pp: $q/\bar{q}$ annihilation
repulsive ISI



Sivers_{DIS} = − Sivers (DY or W or Z)

Twist-3
needs only 1 scale
Q^2 or p_t
But
should be of reas. size.
Applicable to most pp observables $A_N(\pi^0/\gamma/\text{jet})$

The much discussed sign change of the Sivers' function
critical test for our understanding of TMD's and TMD factorizati

Goal: ***measure sign change and pin down TMD-evolution*** *by measuring A_N for* γ, $W^{\pm}$, Z^0, DY

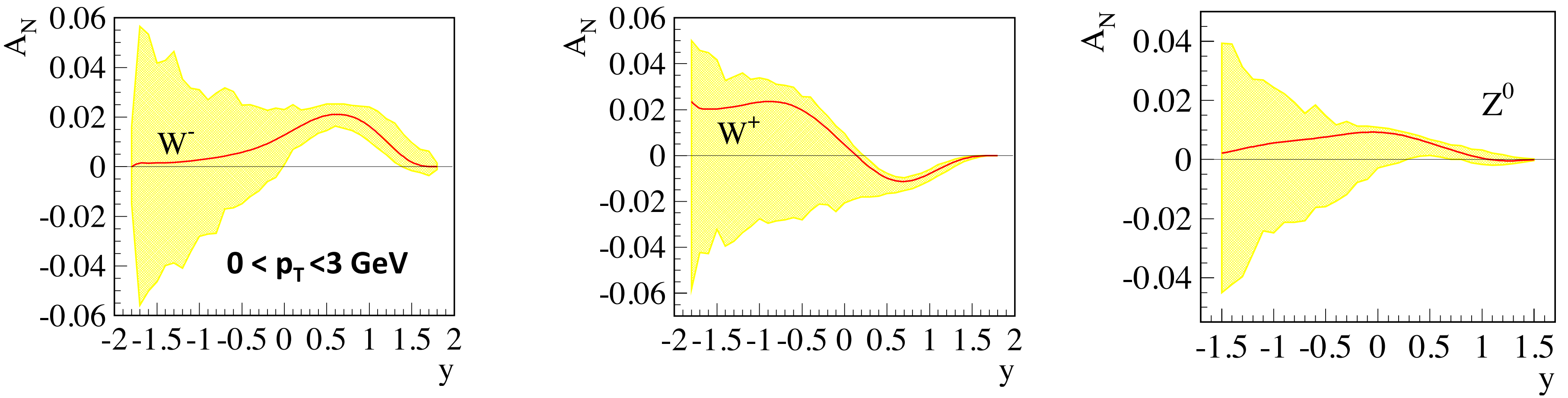
Motivations

- Very high Q^2-scale (~ W/Z boson mass)
- No fragmentation function
- Asymmetry from lepton-decay is diluted → Full kin. reconstruction of the boson needed
  - > Z^0 easy to reconstruct (but small cross-section)
  - > W kin. can be reconstructed from the hadronic recoil (first time at STAR)

***Sea quarks are mostly unconstrained... but* they can give a relevant contribution!**

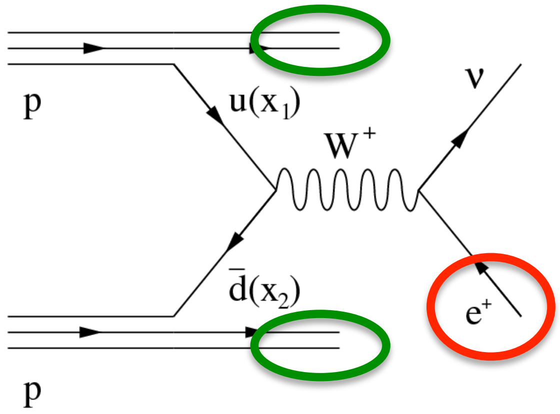
M. G. Echevarria, A. Idilbi, Z-B Kang, and I. Vitev arXiv:1401.5078

Revised error bands (private communication) use positivity bounds for the sea quarks

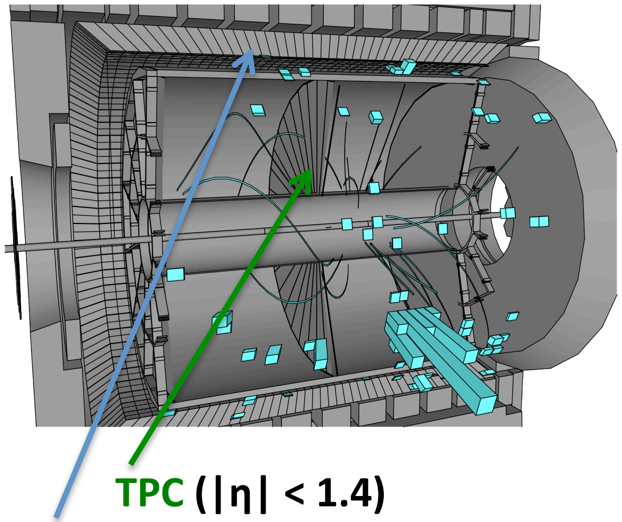


$W^{\pm}$ data can constrain the sea-quark Sivers function

Strategy



The STAR detector @ RHIC



TPC (|η| < 1.4)
Barrel EMCAL (|η| < 1)

Ingredients for the analysis
- **Isolated electron**
- **neutrino (not measured directly)**
- Hadronic recoil

- **Select events with the W-signature**
  - Isolated high P_T > 25 GeV electron
  - Hadronic recoil with total P_T > 18 GeV

- **Neutrino transverse momentum is reconstructed from missing P_T**

$$\vec{P}_T^{\nu} \approx -\sum_{i\in \substack{tracks \\ clusters}} \vec{P}_T^{i}$$

- **Neutrino's longitudinal momentum is reconstructed from the decay kinematics**

$$M_W^2 = \left(E_e + E_\nu\right)^2 - \left(\vec{p}_e + \vec{p}_\nu\right)^2$$

Data & MC

Monte Carlo

→ **PYTHIA** reconstructed trough GEANT simulated STAR detector

→ **Perugia tune** with hard P_T > 10 GeV

→ PYTHIA **embedded** into real zero-bias pp events

Data sample

- **pp – transverse** (collected in 2011) @ √500 GeV
- Integrated luminosity: **~ 25 pb^{-1}**
- Events triggered in Barrel EMCAL

Signal

$W \rightarrow e\nu_e$

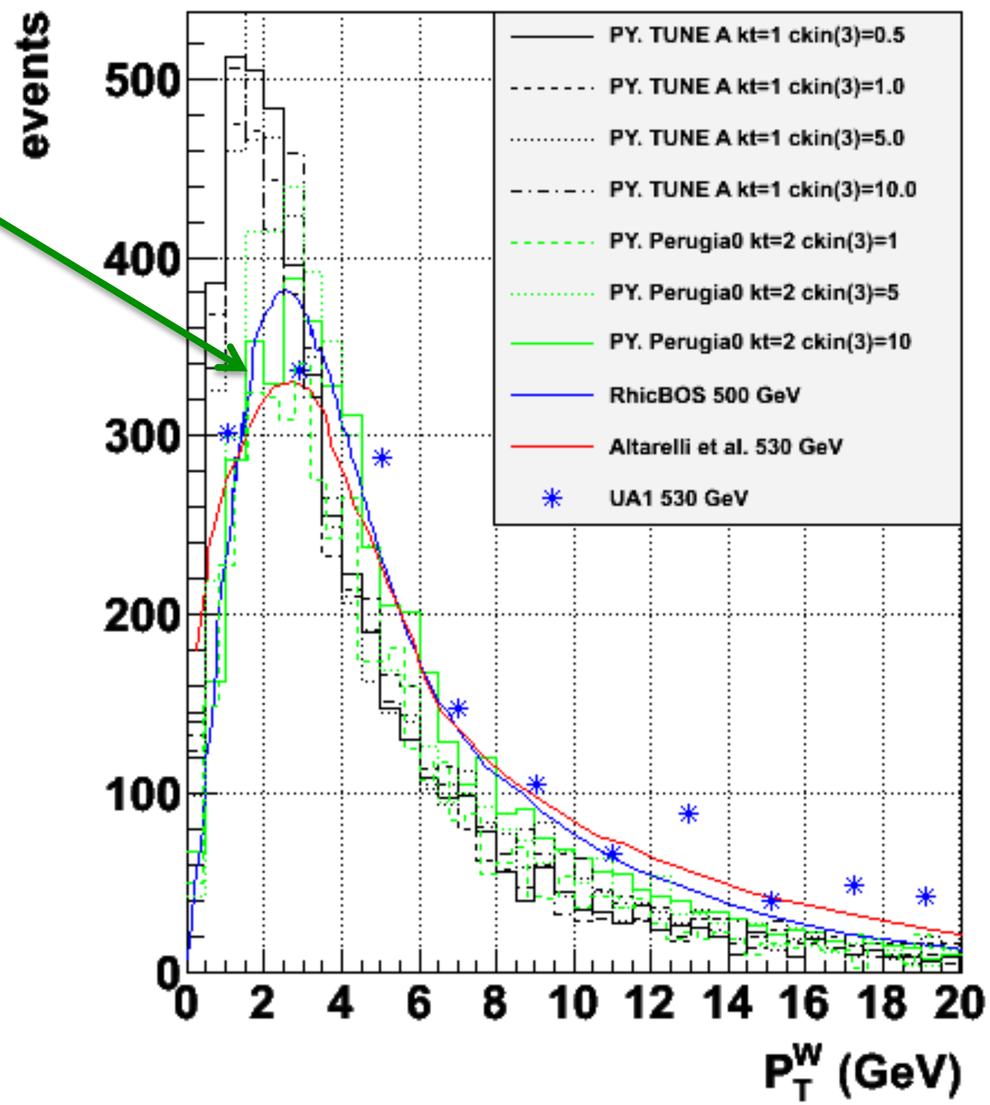
Background

$W \rightarrow \tau\nu_\tau \rightarrow e\nu_e\nu_\tau$

$Z \rightarrow ee$

QCD events

PYTHIA tuning

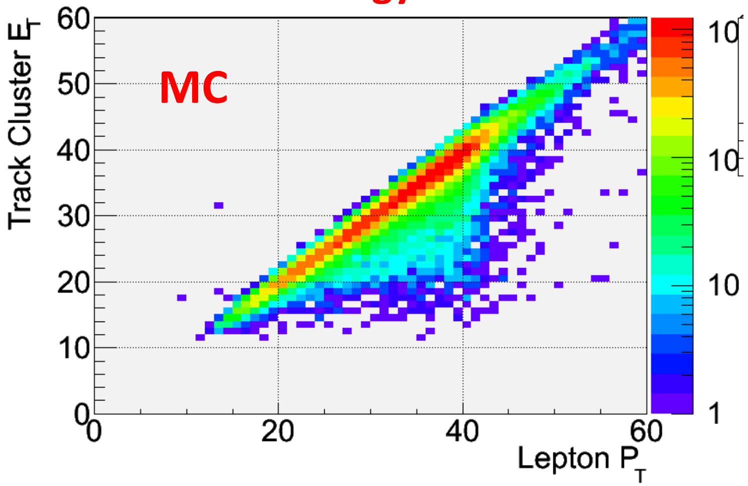


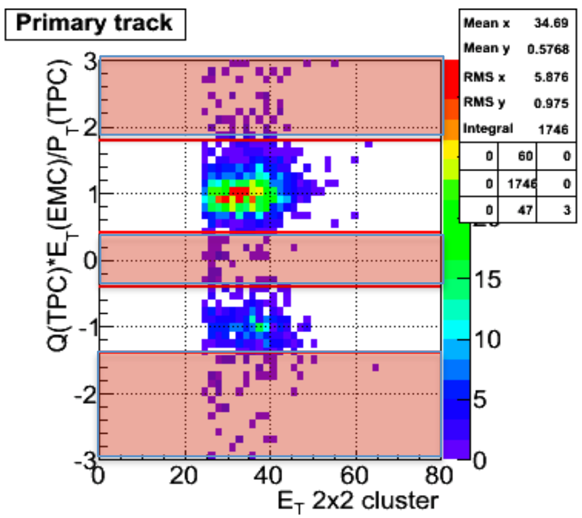
Electron identification

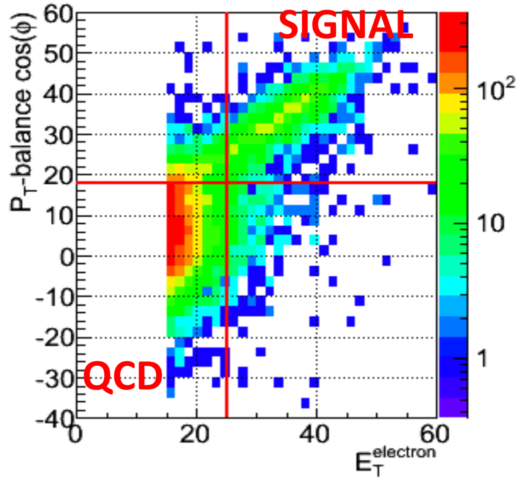
- **Isolation:** $(P^{track}+E^{cluster}) / \Sigma[P^{tracks}$ in R=0.7 cone] > 0.8
- **Imbalance:** no energy in opposite cone (E<20 GeV)
- **E_T > 25 GeV**
- Track |η| < 1
- |Z-vertex|<100 cm
- **Charge separation** (avoids charge misidentification):

  0.4 < |Charge (TPC) x E_T (EMC) / P_T (TPC)| < 1.8
- Signed P_T balance > 18 GeV (**rejects QCD Background**)

We calculate energy from the cluster



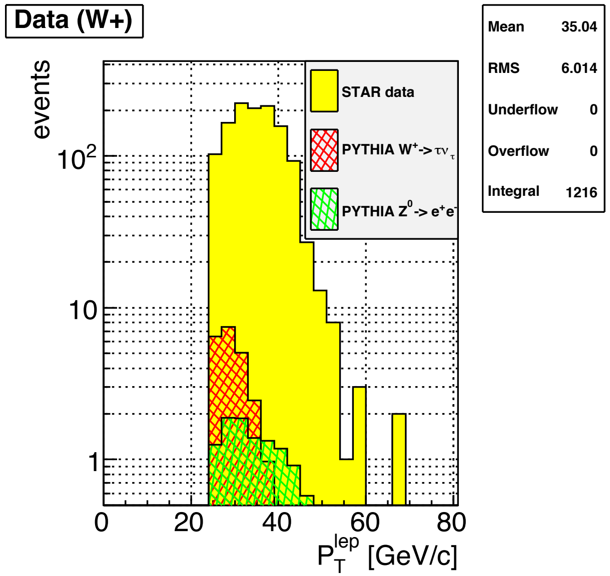


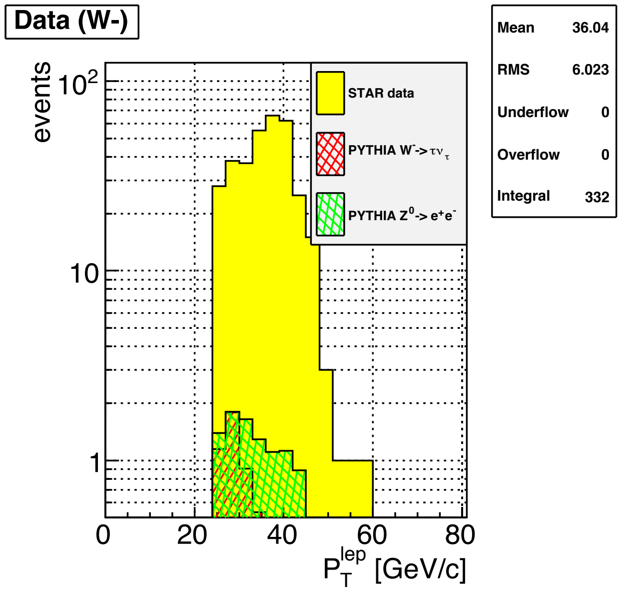


$$\vec{P}_T^{bal} = \vec{P}_T^{e} + \sum \vec{P}_T^{recoil}$$

Background estimation

Background estimated via MC normalized to recorded data luminosity





- Positive-charge signal **1216 events**
- *Z → ee*
- *W^+ → tv_t*

W^+ sample

***Z^0 -> ee* = 10.71 events [B/S = 0.88%]**

***W^+ -> tv_t* = 22.92 events [B/S = 1.88%]**

- Negative-charge signal **332 events**
- *Z → ee*
- *W^- → tv_t*

W^- sample

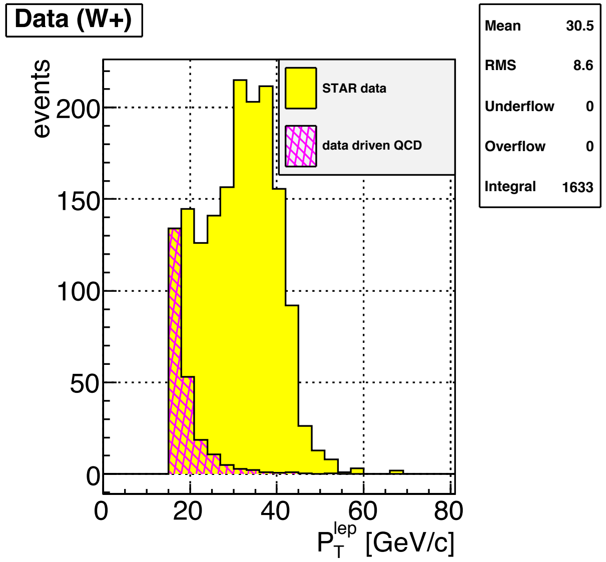
***Z^0 -> ee* = 9.77 events [B/S = 2.94%]**

***W^- -> tv_t* = 4.62 events [B/S = 1.39%]**

QCD background estimation

Data-driven QCD background estimation

- **Reverse of P_T-balance cut [PT-balance < 15 GeV] → Selects QCD events**
- **Plot lepton-P_T > 15 GeV**
- **QCD sample normalized to the first P_T-bin [15-19 GeV]**



W⁺ sample

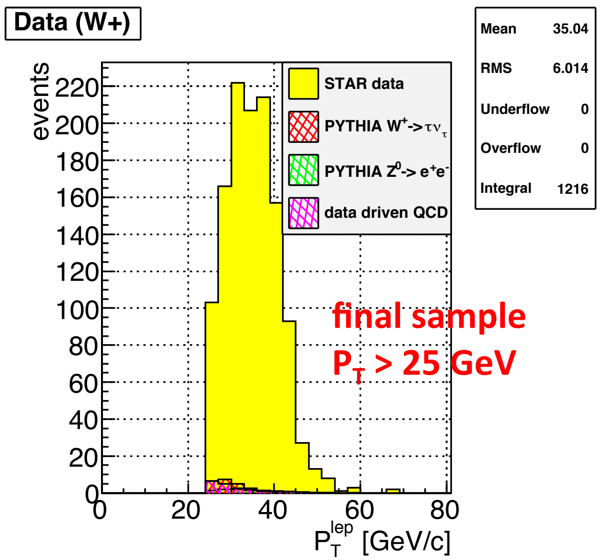
***QCD* = 19.37 events**

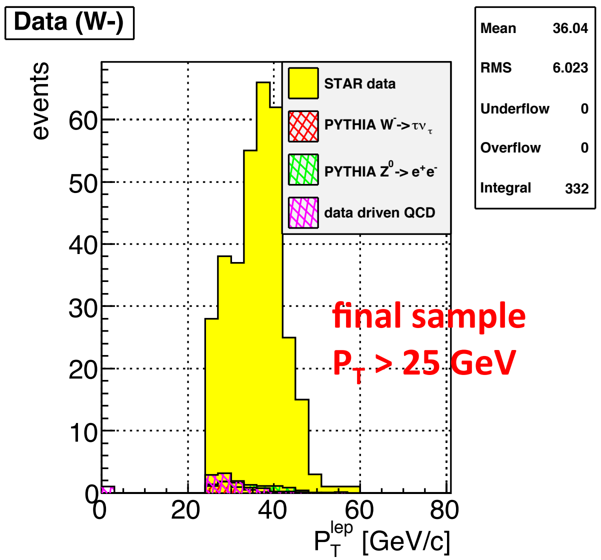
[B/S = 1.59%]

W⁻ sample

***QCD* = 11.30 events**

[B/S = 3.40%]





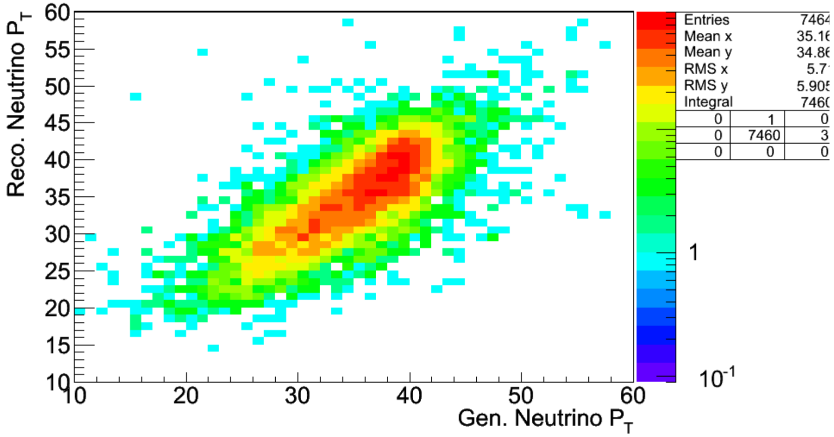
COMMENTS:

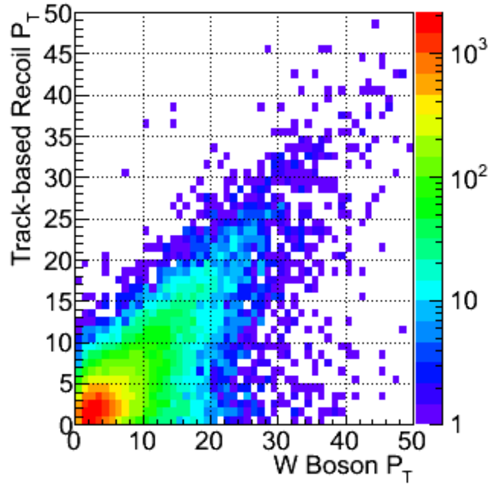
- Backgrounds under control!
- Z -> $e^+ e^-$ expected to have a comparable asymmetry

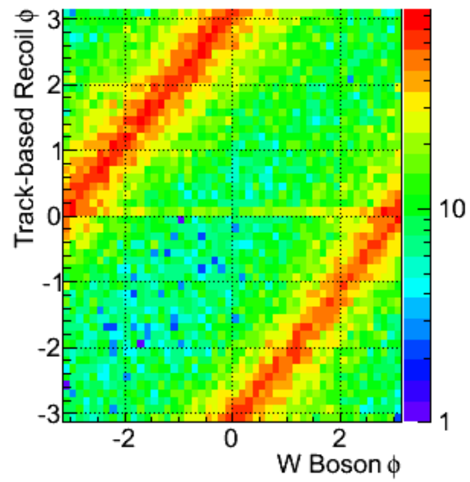
W P_T reconstruction

We calculate the recoil summing up all tracks and trackless electromagnetic clusters

- Matching track is a track which extends to the BEMC and matches a firing tower (< 7 cm)
- Trackless tower is a firing tower in the BEMC with no matching tracks and Energy > 200 MeV
- Recoil is calculated summing the momenta of all tracks which do not belong to the electron candidate + all firing trackless towers





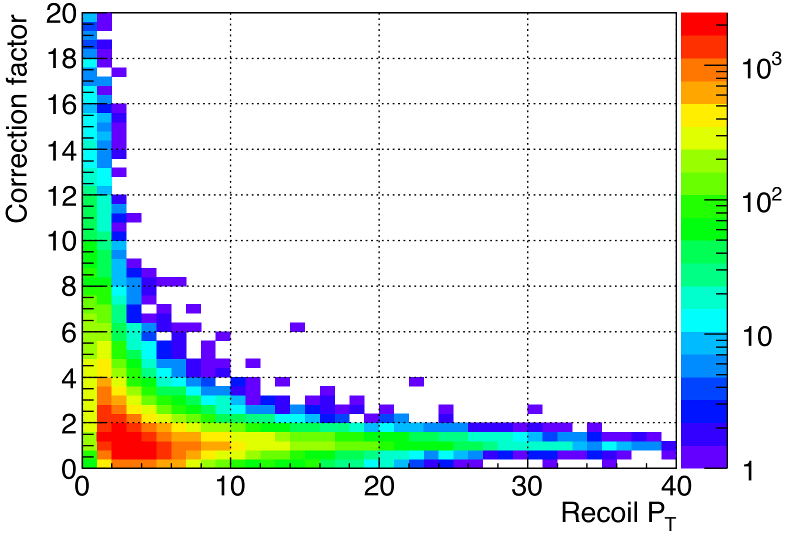


✓In transverse plane: $\vec{P}_T^{W} = \vec{P}_T^{e} + \vec{P}_T^{\nu} = -\vec{P}_T^{recoil}$

✓Recoil reconstructed using tracks and towers: $\sum_{i \in {tracks \atop clusters}} \vec{P}_T^{i}$

✓Part of the recoil not within STAR acceptance → MC correction applied

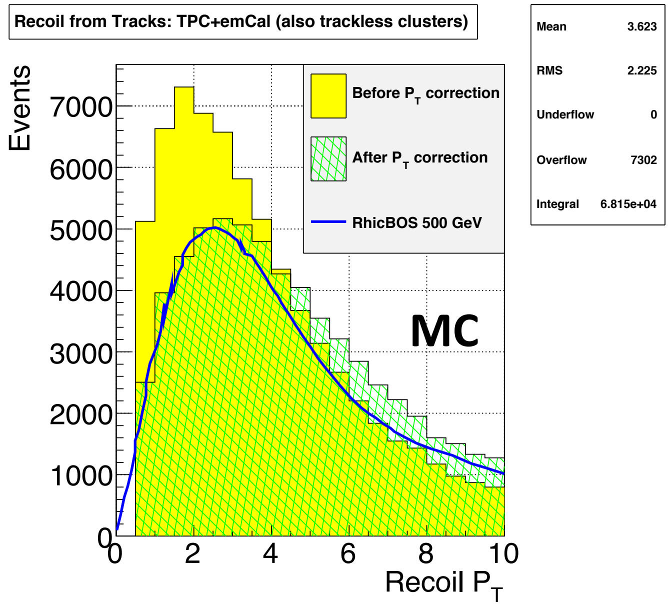
Monte Carlo correction

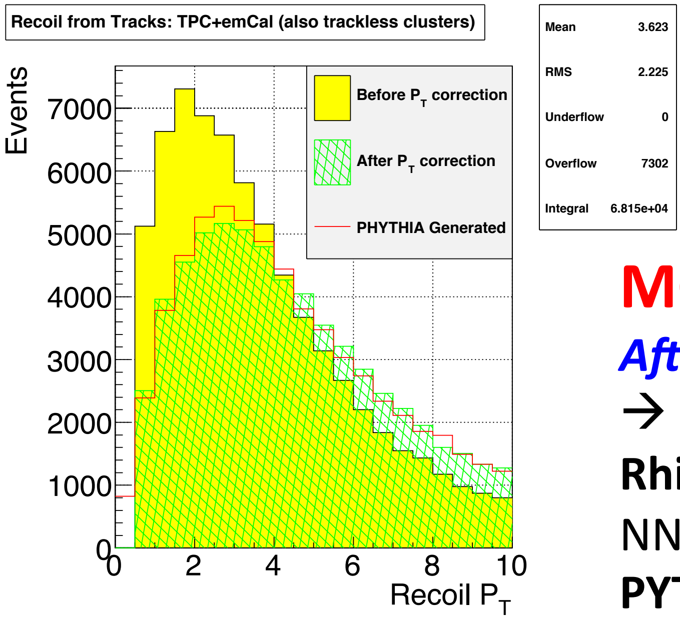


$$k_i = \frac{P^W_{T,i}(true)}{P^{Recoil}_{T,i}(reconstructed)}$$

The Correction method –

- ✓ **Read recoil P_T bin from data**
- ✓ **Project correction factor for corresponding P_T-bins**
- ✓ **Normalize the projection distribution to 1**
- ✓ **Pick a correction value sampled from the projection distribution**





MC test:

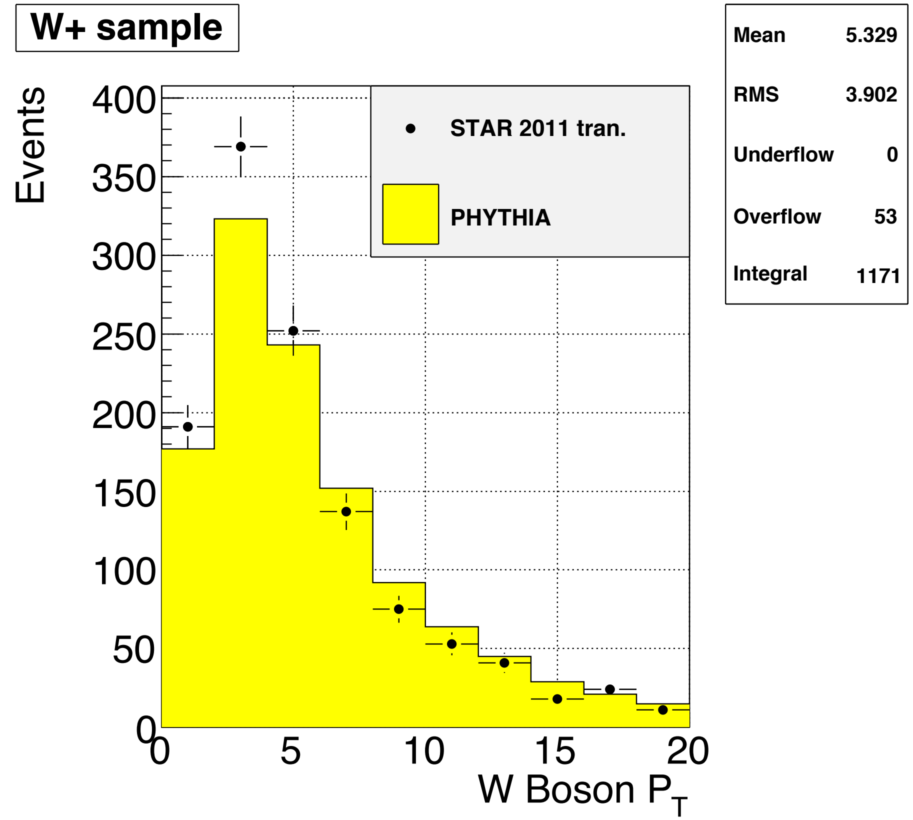
After MC correction

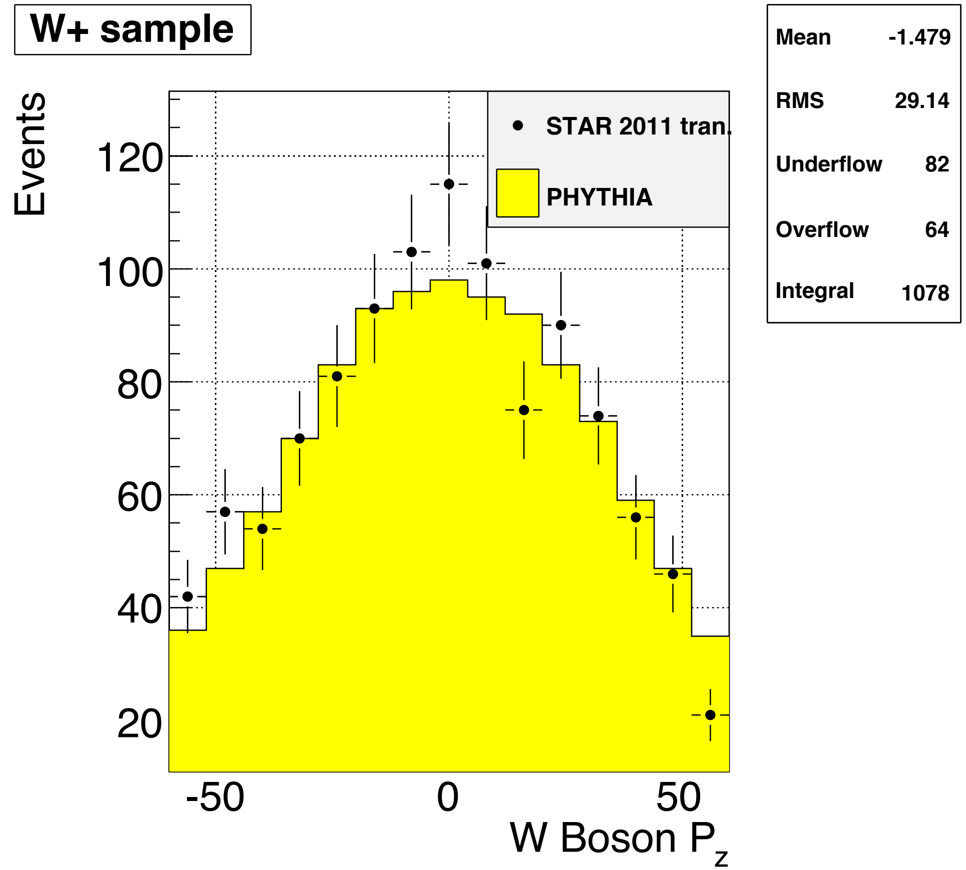
→ very good agreement with **RhicBOS** (fully re-summed NNL/NLO calculation) and **PYTHIA** predictions

W P_T – Data/MC

We add to our selection:

- Track-P_T in the recoil > 0.2 GeV
- Total recoil-P_T > 0.5 GeV





GOOD data/MC agreement after P_T correction

W P_Z reconstruction

- ✓ W longitudinal momentum (along z) can be calculated from the invariant mass. Currently we assume constant M_W (for W produced on shell)

$$M_W^2 = \left(E_e + E_\nu\right)^2 - \left(\vec{p}_e + \vec{p}_\nu\right)^2$$

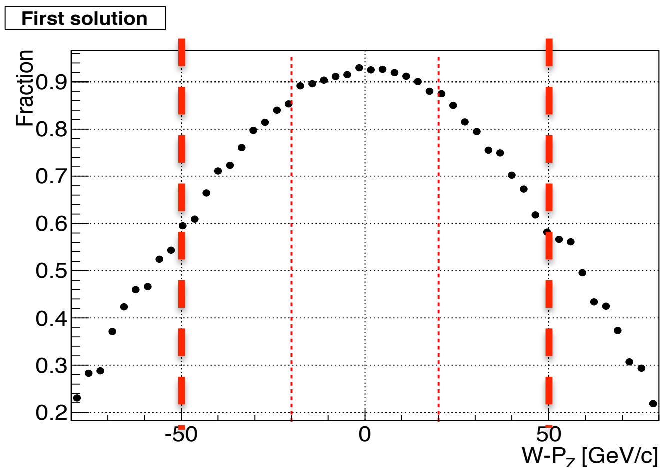
- ✓ Neutrino longitudinal momentum component from quadratic equation

$$\left|\vec{p}_T^{\,e}\right|^2 \left(p_z^\nu\right)^2 - 2Ap_z^e p_z^\nu + \left|\vec{p}_T^{\,\nu}\right|^2 \left|\vec{p}^{\,e}\right|^2 - A^2 = 0, \quad where \quad A = \frac{M_W^2}{2} + \vec{P}_T^e \cdot \vec{P}_T^\nu$$

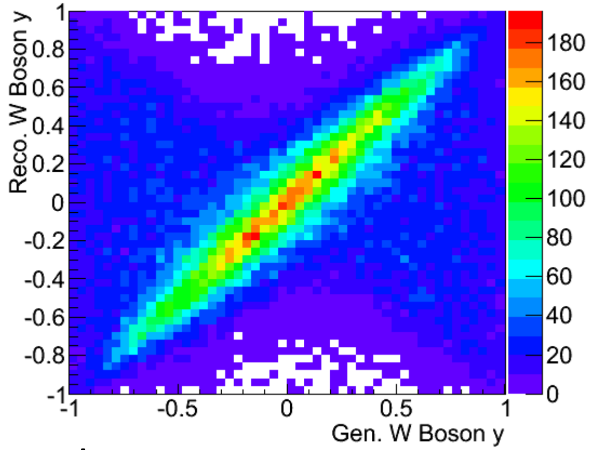
✓ **Two solutions!**

Smaller |Pz| → first solution
Larger |Pz| → other solution

We select **the first solution →** better ***Fraction of correctly reconstructed events***
(Pz is reconstructed within +/- 30 GeV)



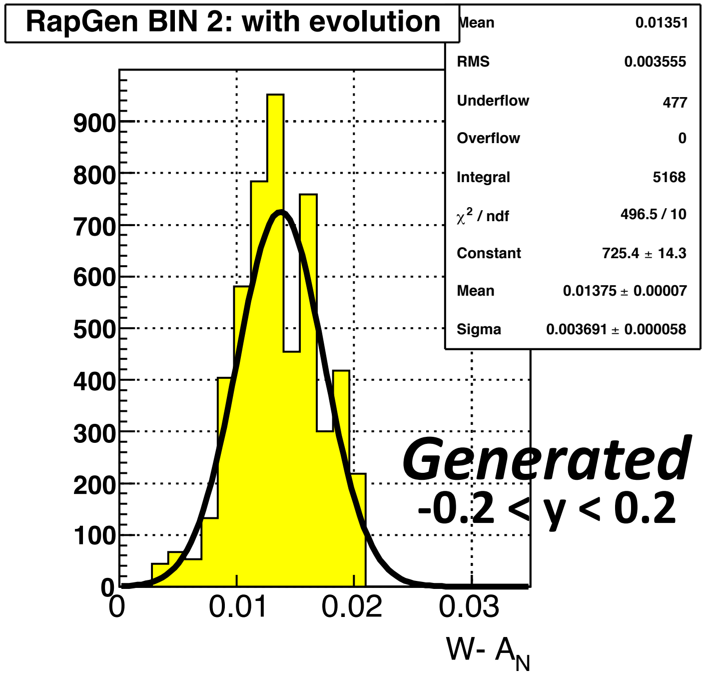
We cut at
|Pz| < 50 GeV → |W-y| < 0.6
to minimize misreconstructions

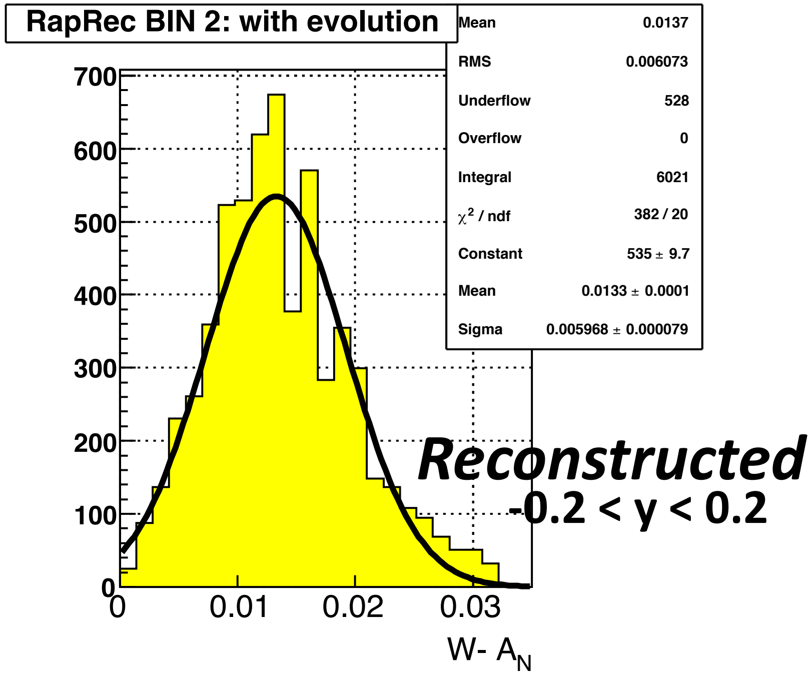


NOTE: We **only** use the first solution. This can be improved at a later stage.

MC challenge - systematics

- Tables (W rapidity-P_T bins) for A_N prediction with evolution given by Z-B Kang [arXiv:1401.5078]
- Use PYTHIA MC prediction for W^- (the A_N prediction is always positive)
- Assign each prediction value from the tables according to the generated values of W-rapidity and P_T
- After the event is fully reconstructed we look at the P_T distributions of A_N





- We fit a Gaussian distribution and compare the means
- We rely on the fact that the input asymmetry has the same dependence as the data

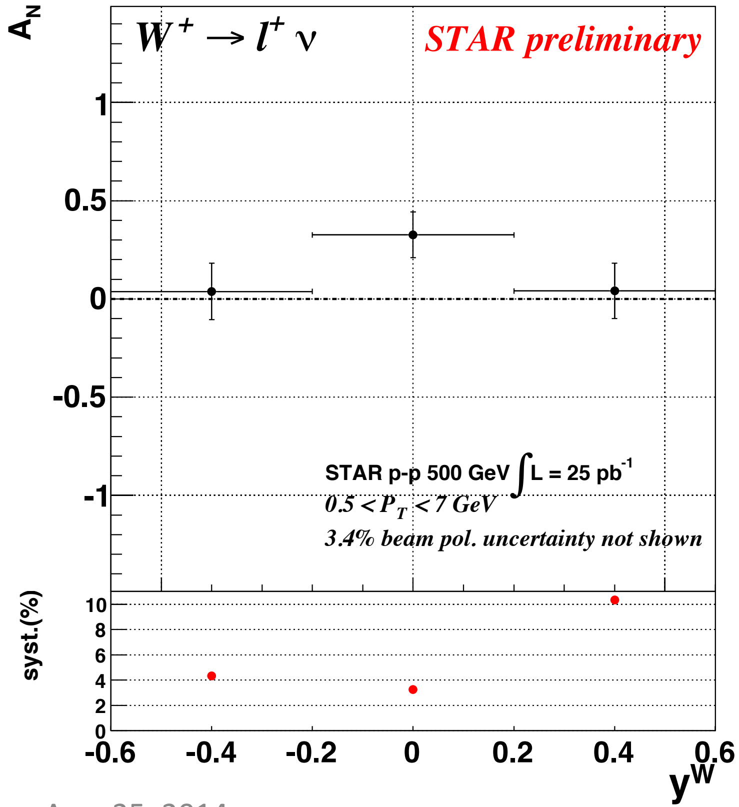
The same is done for W-P_T

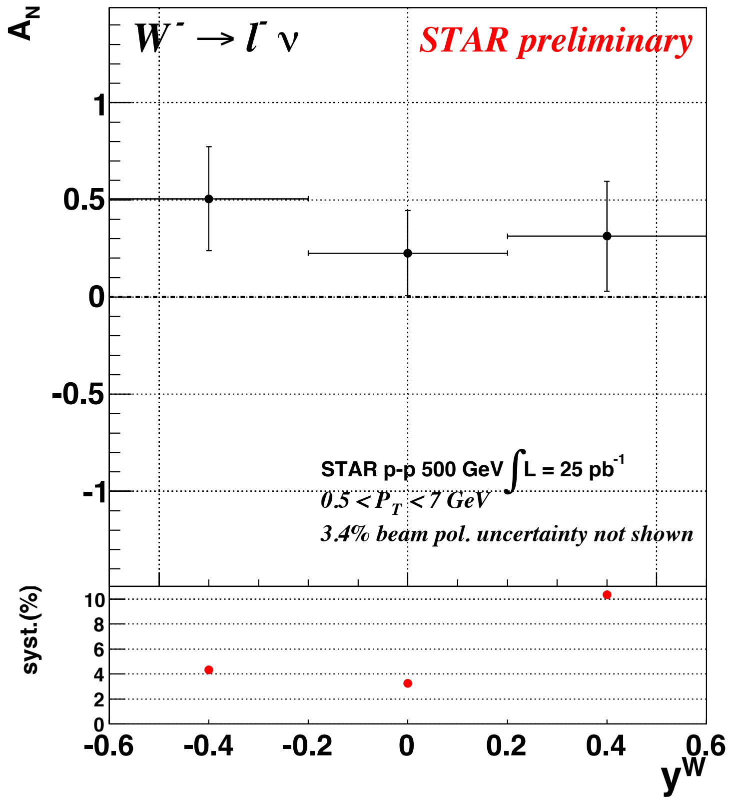
A_N vs W-rapidity

- ✓ We fit sin(ϕ) modulation with phase = π/2
- ✓ **Average RHIC polarization** for 2011 transverse p-p data → **P = 53%**

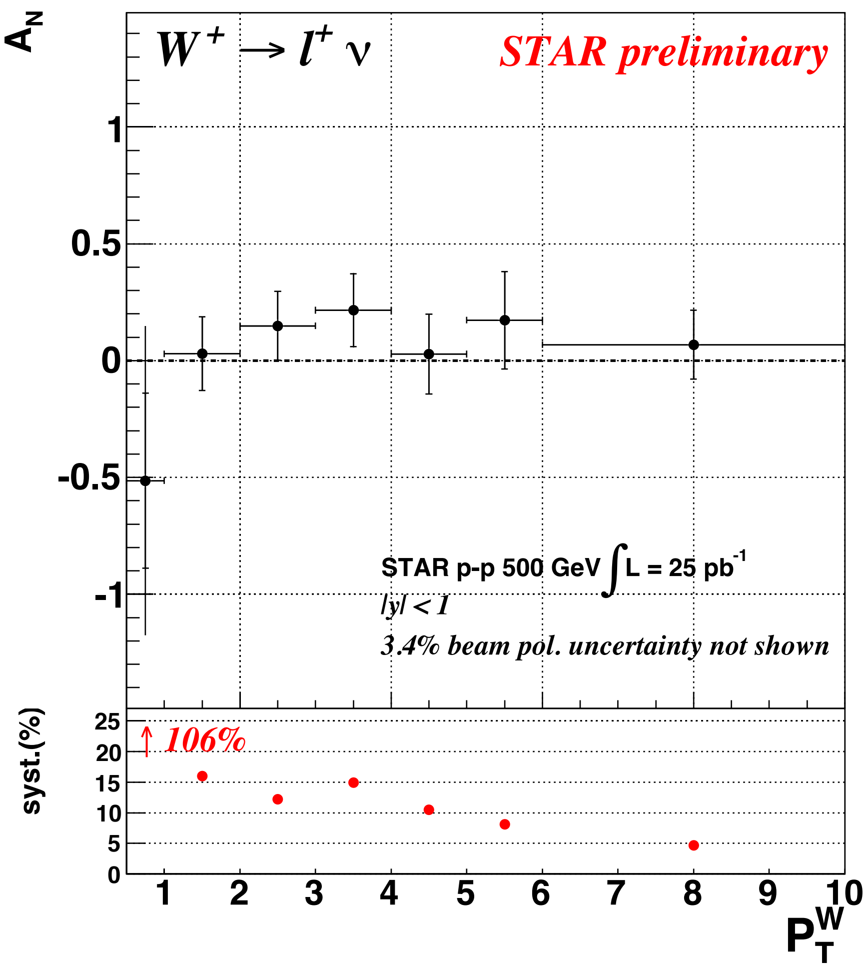
We use the "left-right" formula to cancel dependencies on geometry and luminosity (in backup slides)

$$A_N \approx \frac{1}{P}\frac{\sqrt{N_R^{\uparrow}N_L^{\downarrow}} - \sqrt{N_L^{\uparrow}N_R^{\downarrow}}}{\sqrt{N_R^{\uparrow}N_L^{\downarrow}} + \sqrt{N_L^{\uparrow}N_R^{\downarrow}}}$$

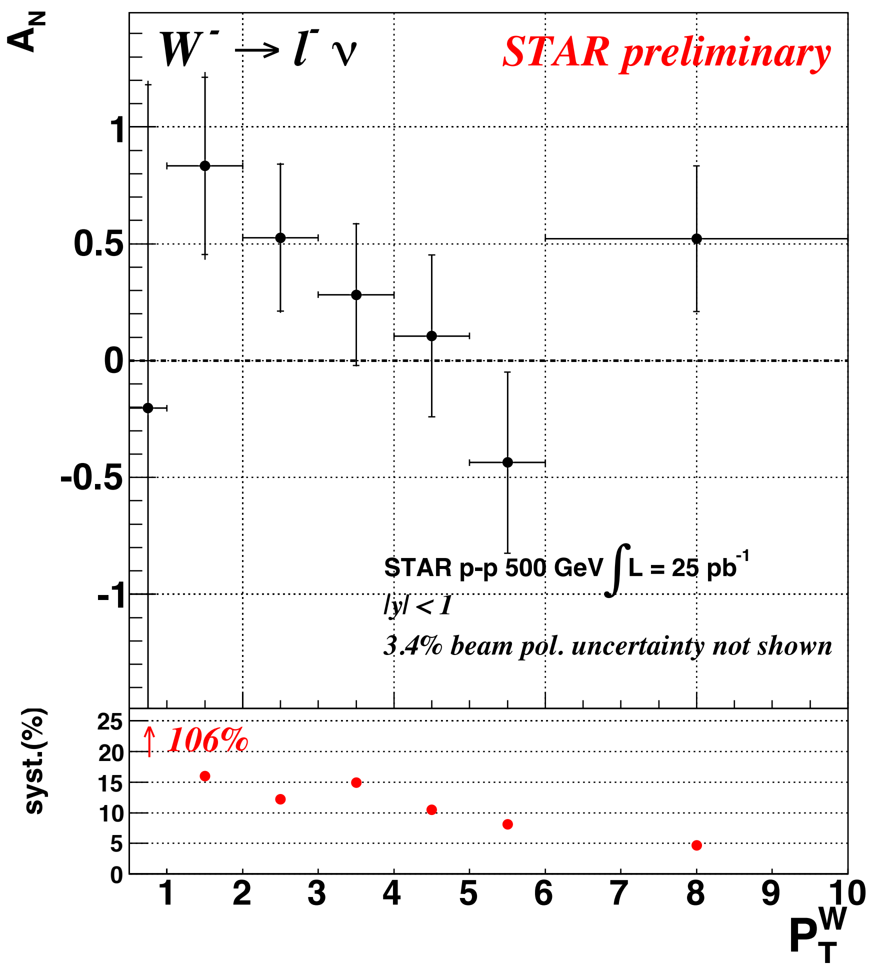




A_N vs W-P_T



$W^+ \rightarrow l^+ \nu$
STAR preliminary
STAR p-p 500 GeV $\int L = 25\ pb^{-1}$
$|y| < 1$
3.4% beam pol. uncertainty not shown
↑ 106%
A_N
syst.(%)
P_T^W

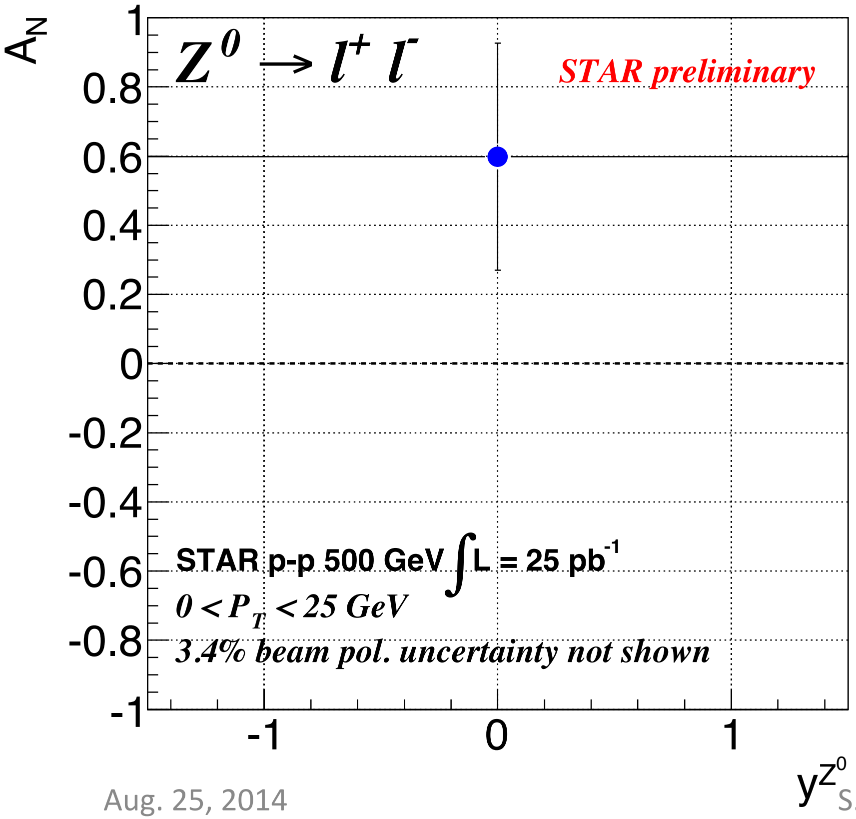


$W^- \rightarrow l^- \nu$
STAR preliminary
STAR p-p 500 GeV $\int L = 25\ pb^{-1}$
$|y| < 1$
3.4% beam pol. uncertainty not shown
↑ 106%
A_N
syst.(%)
P_T^W

Z^0 Asymmetry $pp \rightarrow Z^0 \rightarrow e^+e^-$

- Clean experimental momentum reconstruction
- Negligible background
- electrons rapidity peaks within tracker accept. ($|\eta|< 1$)
- Statistics limited

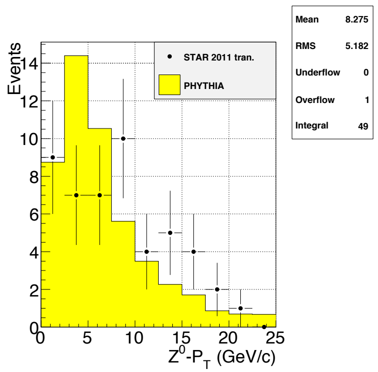
A_N measured in a single y, P_T bin

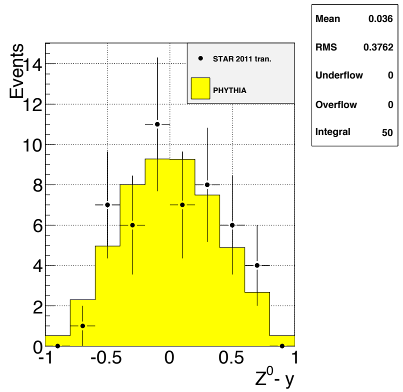


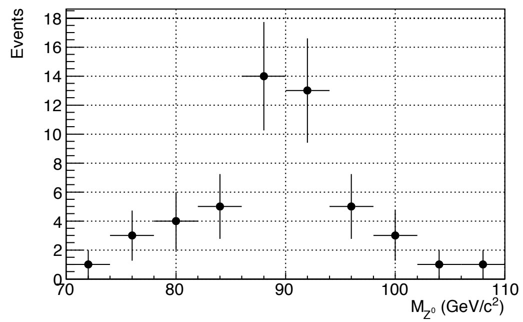
Z^0 boson selection criteria

- Two tracks each pointing to a cluster (no isolation requirements)
- $E_T > 25$ GeV for both candidates
- The two candidate tracks have opposite charge
- |Zvertex|< 100 cm
- Invariant Mass within ± 20% from the nominal M_Z

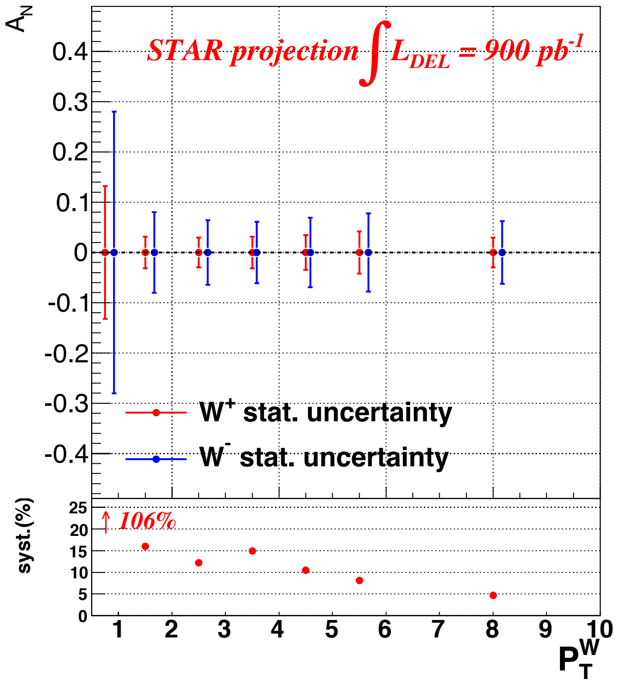
2011 pp-tran. ~25 pb^{-1}: **50 events** pass selection

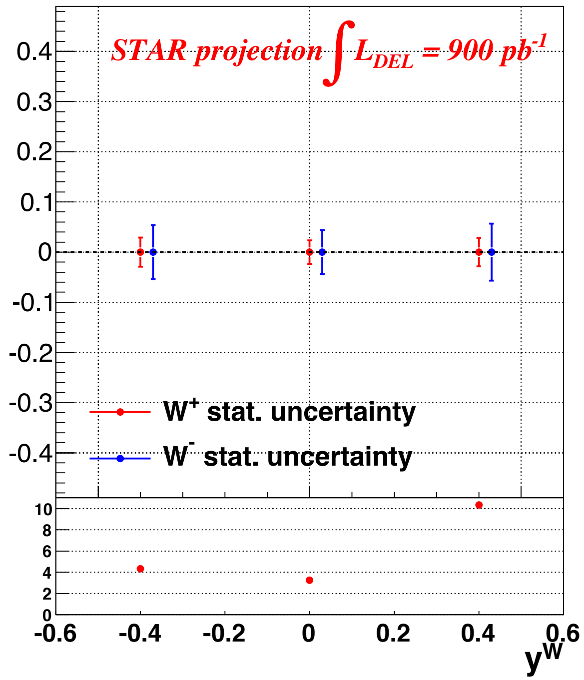






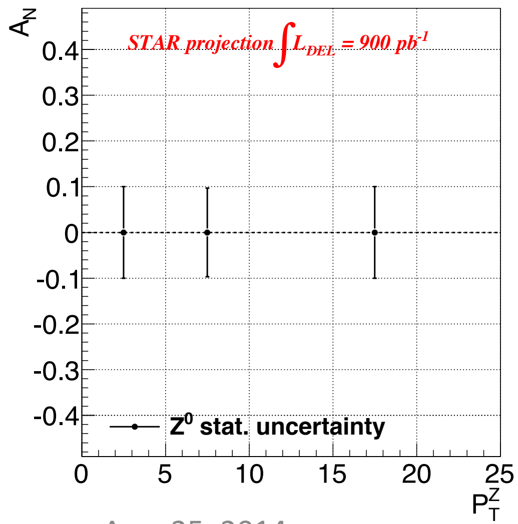
...and the future?

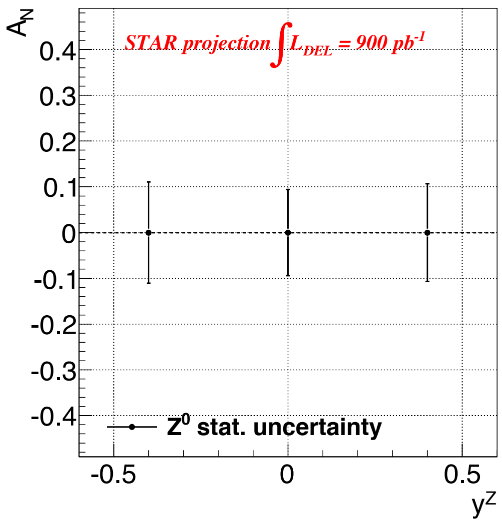




RHIC is capable of delivering ~900 pb^{-1} transverse p-p in 2016

- Possibility for **significantly measure A_N for Ws within a few %** in several W-P_T, y bins.
- Syst. from 2011 analysis rely on predictions and can be improved with more data
- Possibility to measure the very clean **Z^0 channel**.





Goal: *measure sea-quark Sivers and pin down TMD-evolution*

How?

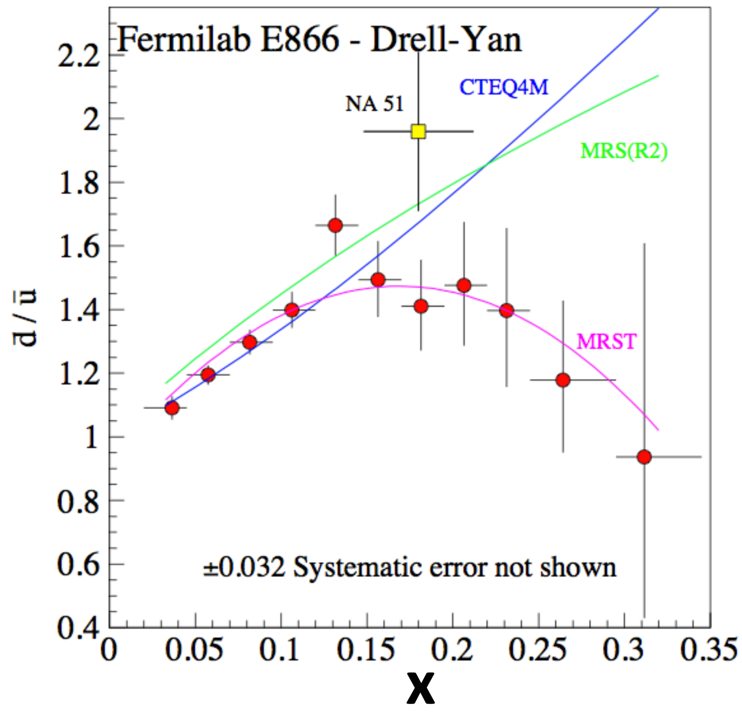
→ Measure A_N for γ, $W^\pm$, Z^0, DY
→ DY and $W^\pm$, Z^0 give Q^2 evolution
→ $W^\pm$ give sea-quark Sivers
→ All three A_N give sign change

Summary

- **First measurement of A_N for $W^{\pm}$ and Z^0 production at RHIC by reconstruction of the boson kinematics, using a sample of 25 pb^{-1} transverse p-p data @ √500 GeV collected by STAR**
- **Systematic uncertainties are constrained within < 15%**
- **A_N in the Z^0 boson channel → clean & background free, but need lumi**
- **We have a proof-of principle → A_N for Ws can be measured at STAR, new RHIC data (we requested to deliver up to L~900 pb^{-1}) can give statistical significance to test the Sivers' sign change and pin down TMD evolution**
- **RHIC run 2016: STAR can have access to A_N for γ, $W^{\pm}$, Z^0, DY in a single experiment, simultaneously!**

BACKUP

Motivations



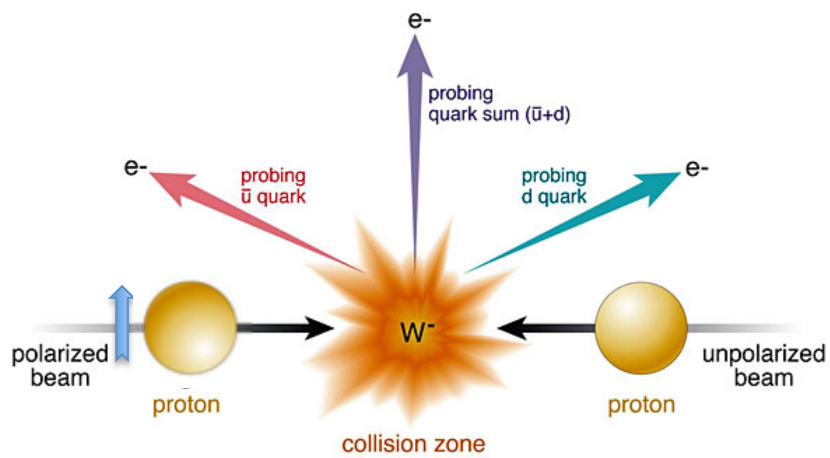
✧ **Unpolarized asymmetries:** Quantitative calculation of Pauli blocking does not explain $\bar{d}/\bar{u}$ ratio
→ Non-pQCD effects are large for sea quarks

✧ **Polarized asymmetries:** valence quarks distributions well determined from DIS measurements

The $W^{\pm}/Z^{0}$ transverse asymmetry:

- Very high Q^2-scale (~ W/Z boson mass)
- No fragmentation function
- Asymmetry from lepton-decay is diluted

→ <u>Full kin. reconstruction of the boson needed</u>



Processes:

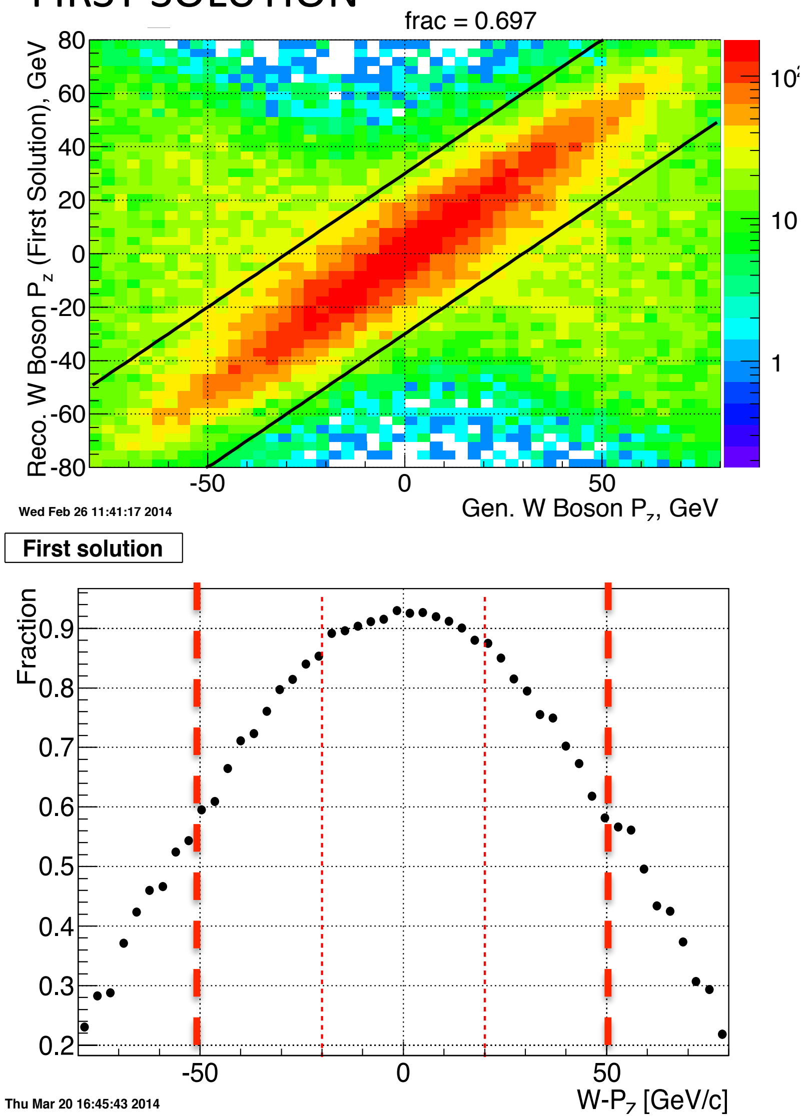
$W \rightarrow e\, \nu_e$

$Z^0 \rightarrow e^+ e^-$

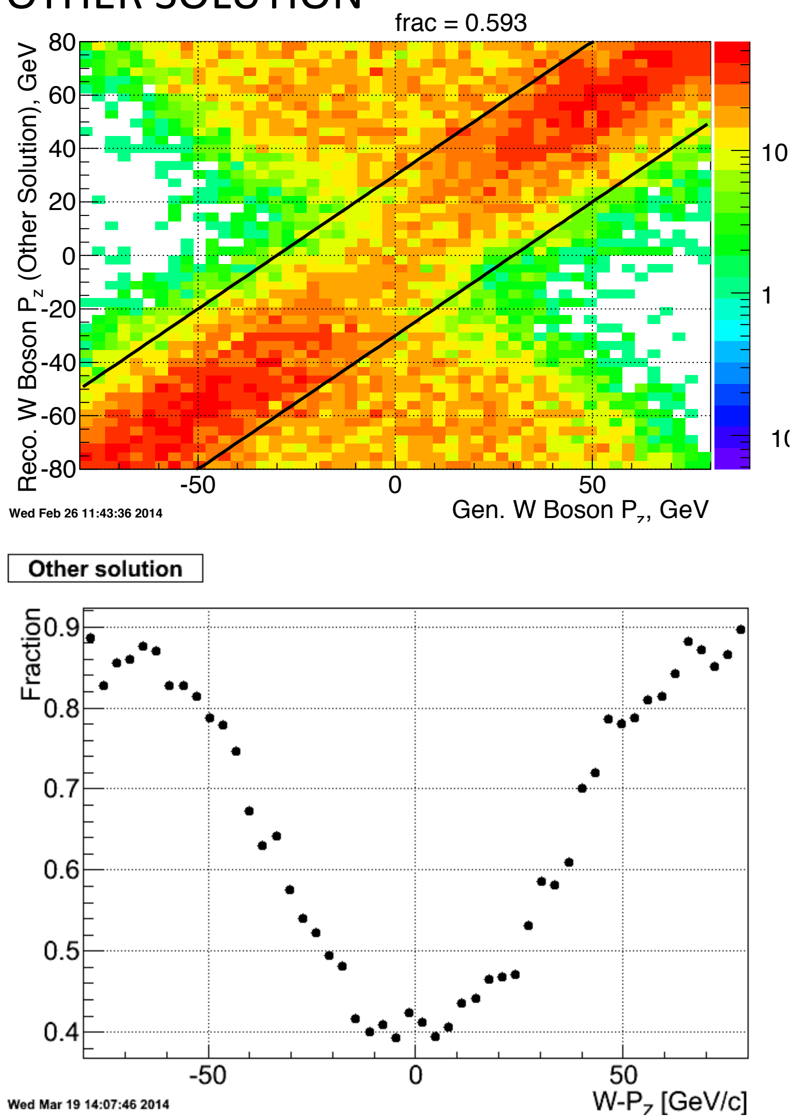
W P_Z reconstruction

Determine the fraction for correctly reconstructed events (for both solutions)

FIRST SOLUTION



OTHER SOLUTION

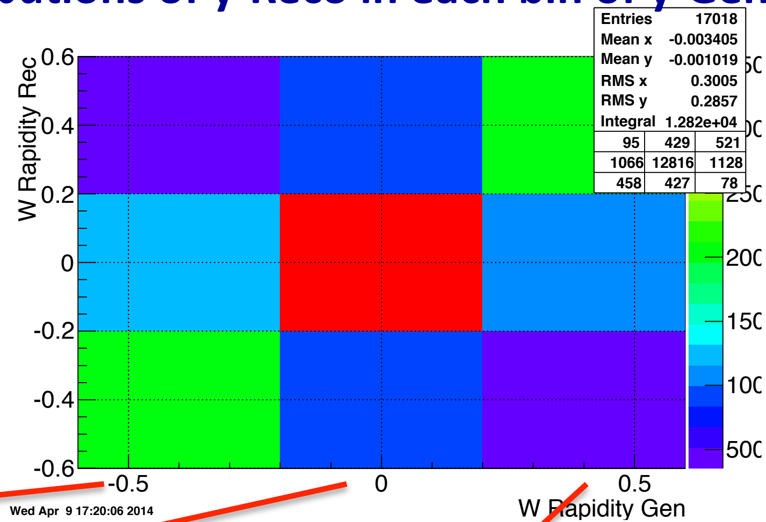


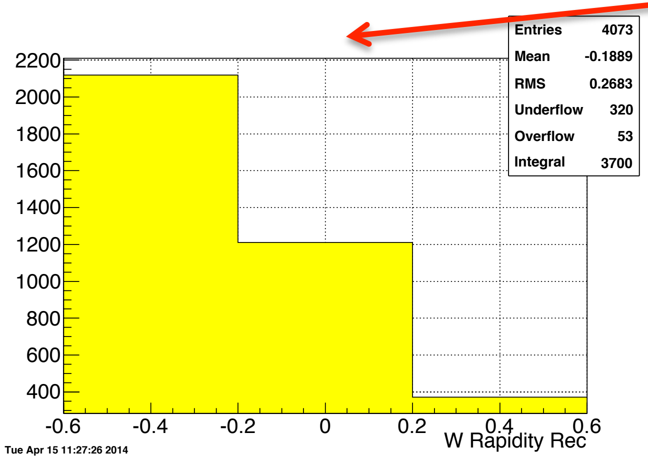
Rapidity binning

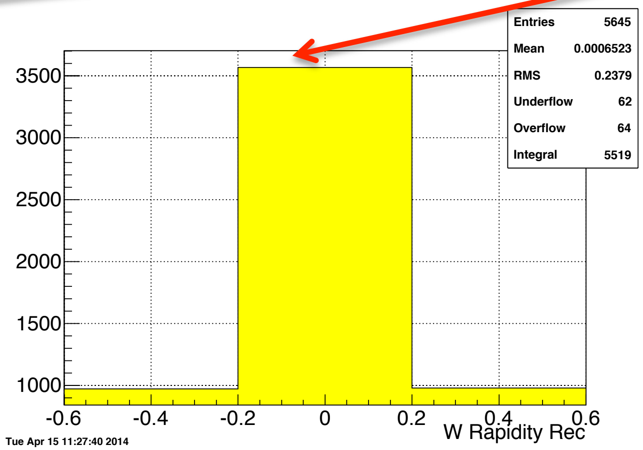
Three W-y bins = {-0.6; -0.3; 0.3; 0.6}

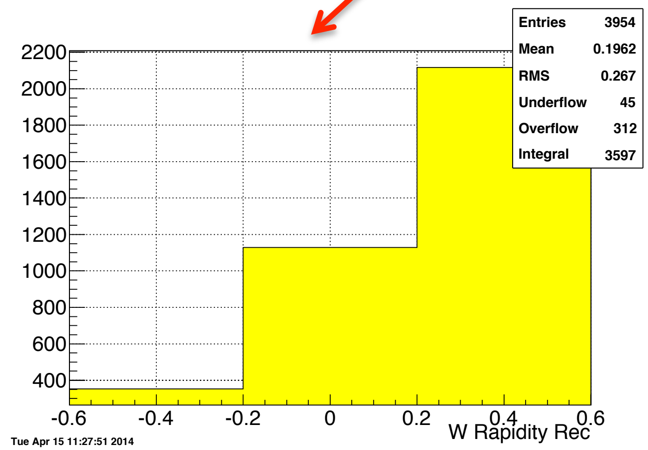
bin1 survival probability = 52%
bin2 survival probability = 63%
bin3 survival probability = 54%

Distributions of y-Reco in each bin of y-Gen







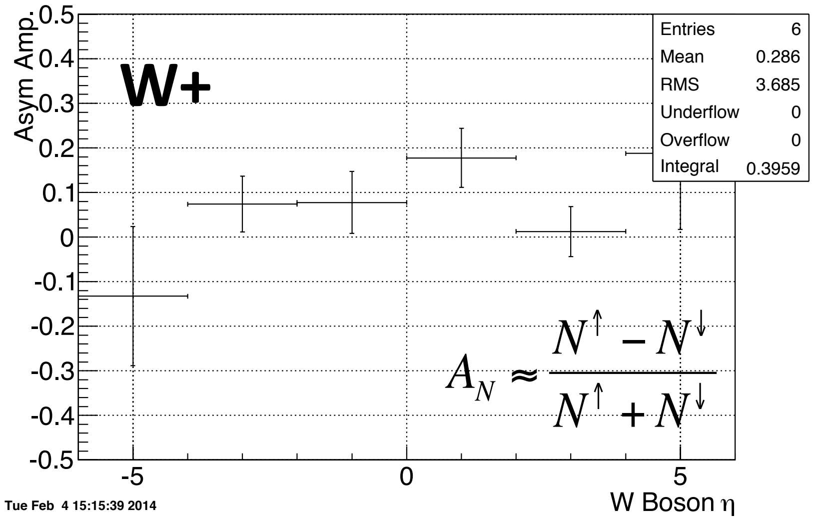


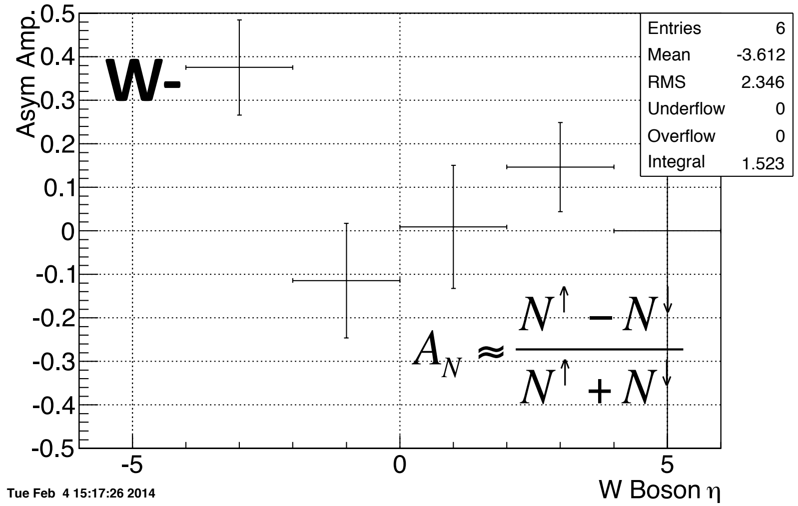
~11% of reco. events migrate more than one y-bin

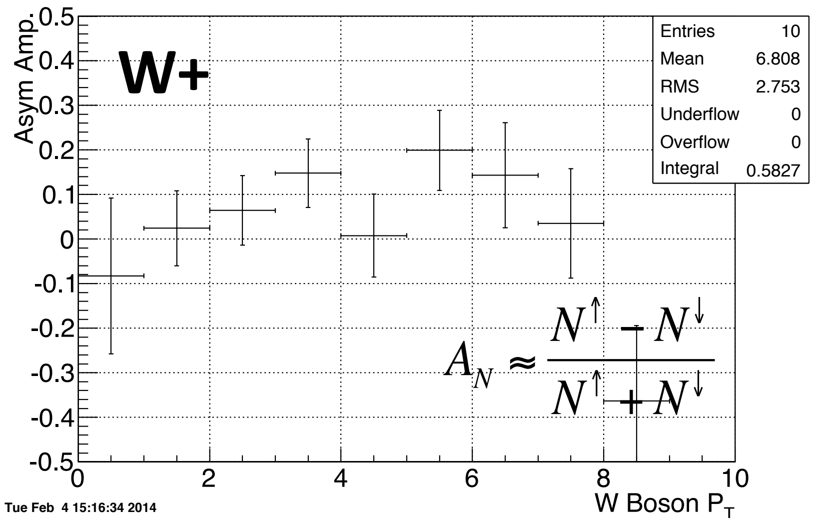
~2% of reco. events migrate more than one y-bin

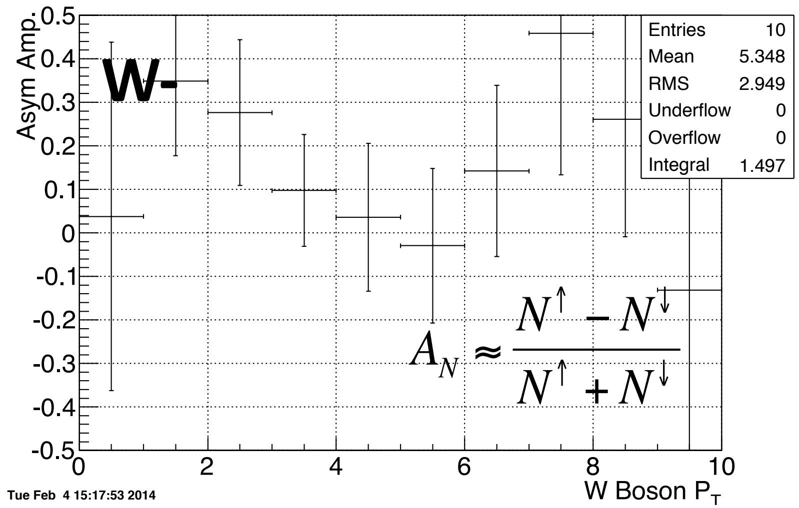
~11% of reco. events migrate more than one y-bin

W plain asymmetry

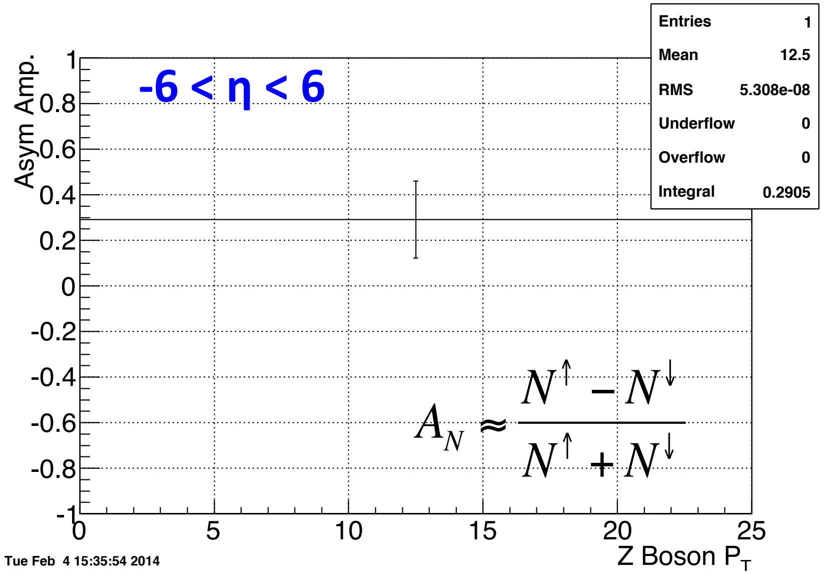






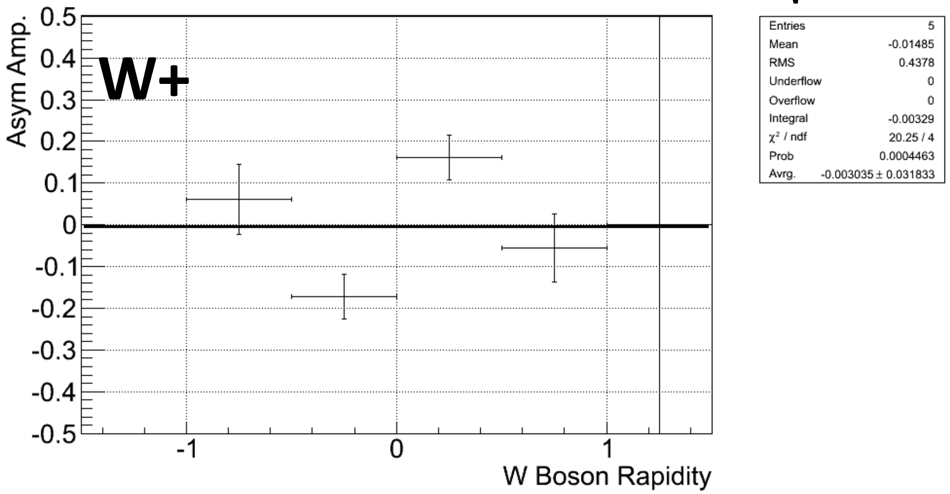


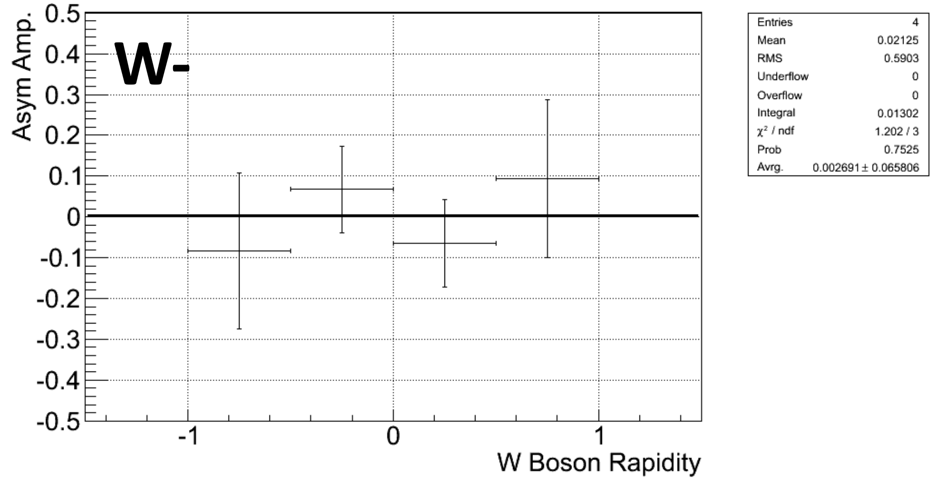
Z^0 plain asymmetry

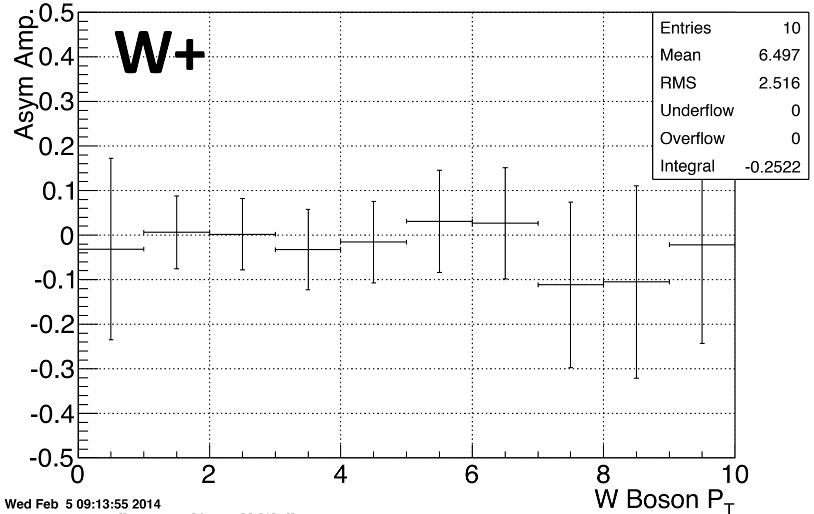


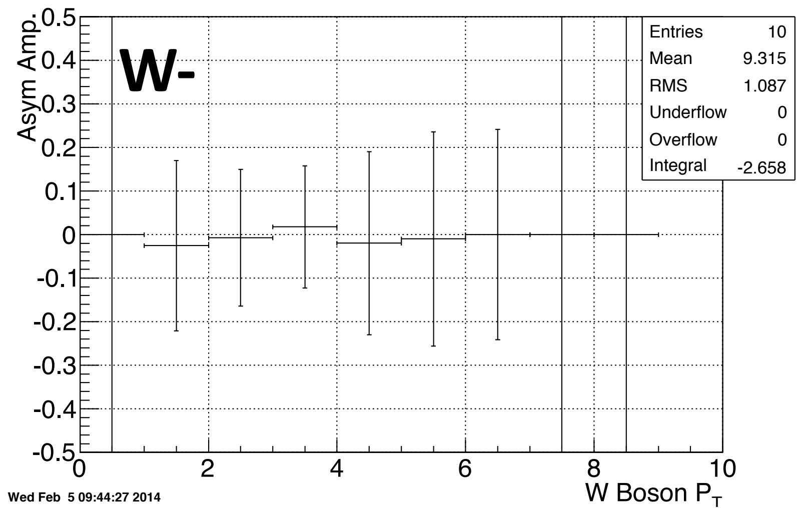
Geometrical Asymmetry

$$A_N \approx \frac{\sqrt{N_R^{\uparrow} N_R^{\downarrow}} - \sqrt{N_L^{\uparrow} N_L^{\downarrow}}}{\sqrt{N_R^{\uparrow} N_R^{\downarrow}} + \sqrt{N_L^{\uparrow} N_L^{\downarrow}}}$$



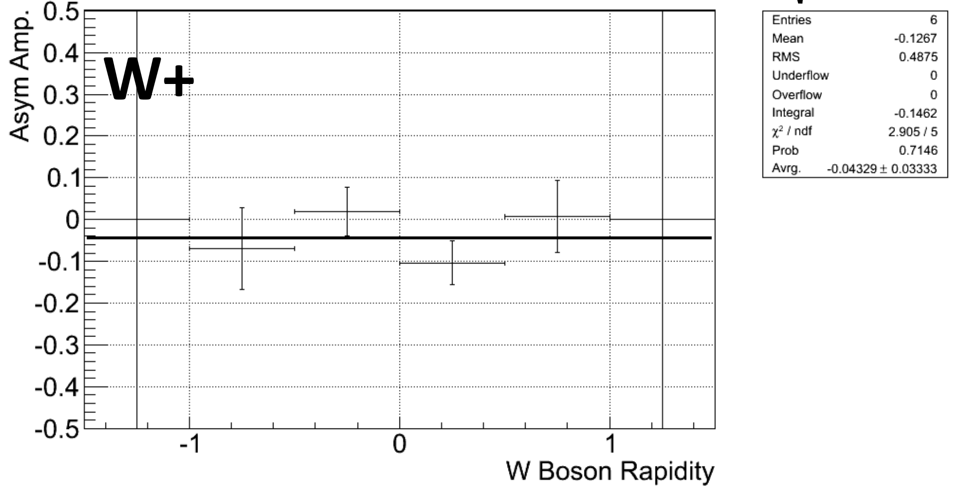


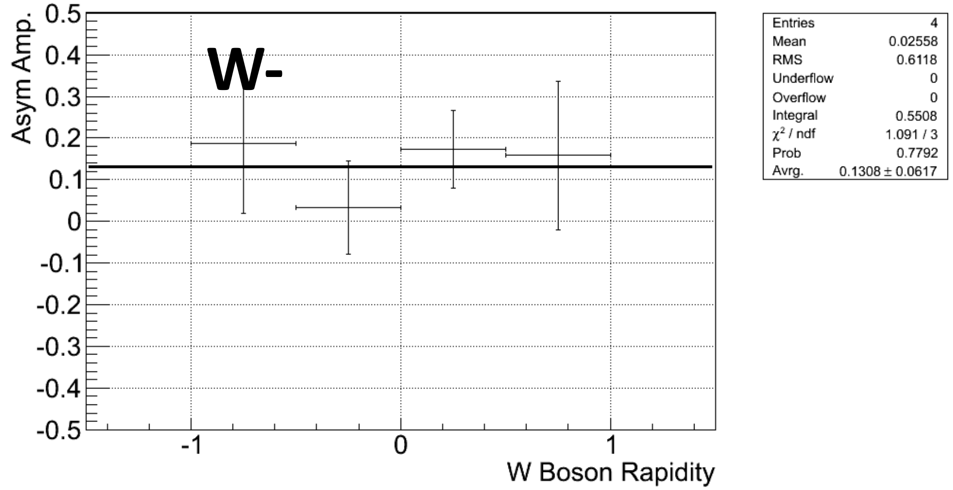


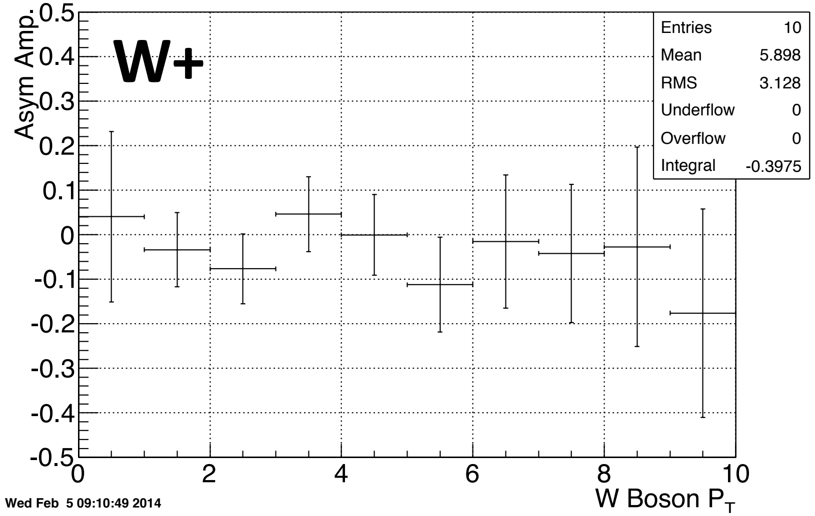


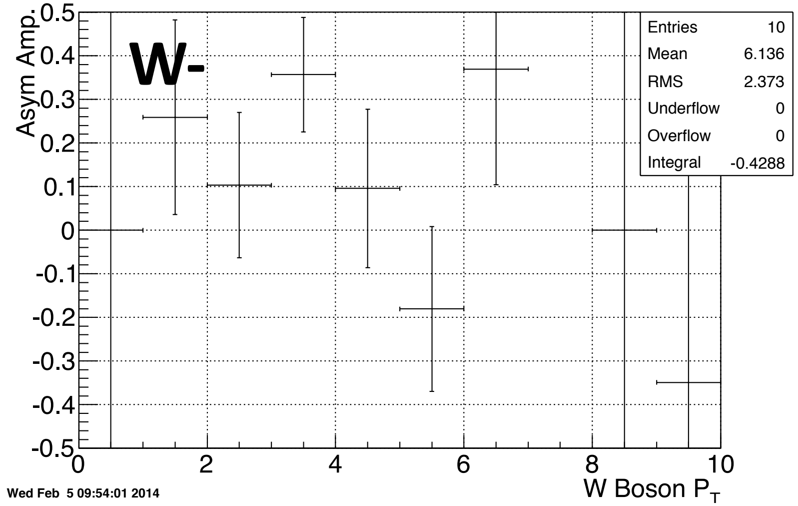
Luminosity Asymmetry

$$A_N \approx \frac{\sqrt{N_R^{\uparrow} N_L^{\uparrow}} - \sqrt{N_L^{\downarrow} N_R^{\downarrow}}}{\sqrt{N_R^{\uparrow} N_L^{\uparrow}} + \sqrt{N_L^{\downarrow} N_R^{\downarrow}}}$$

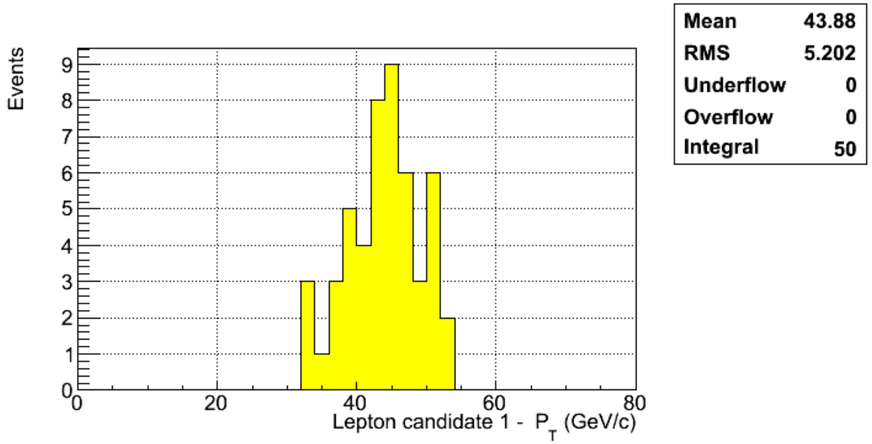


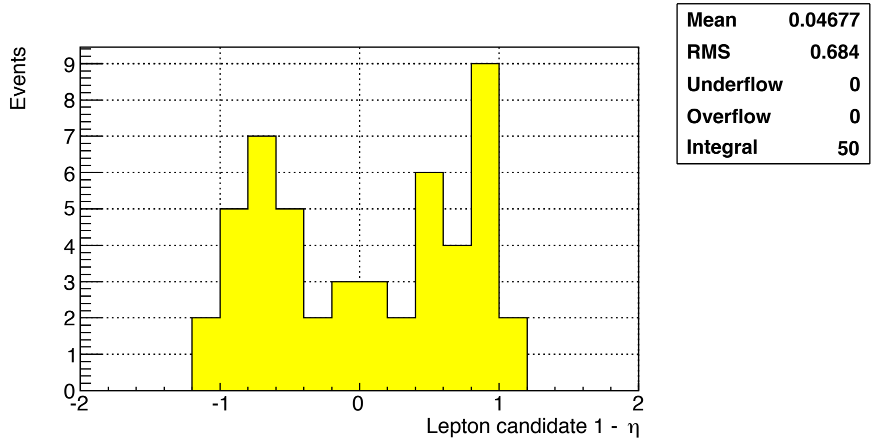


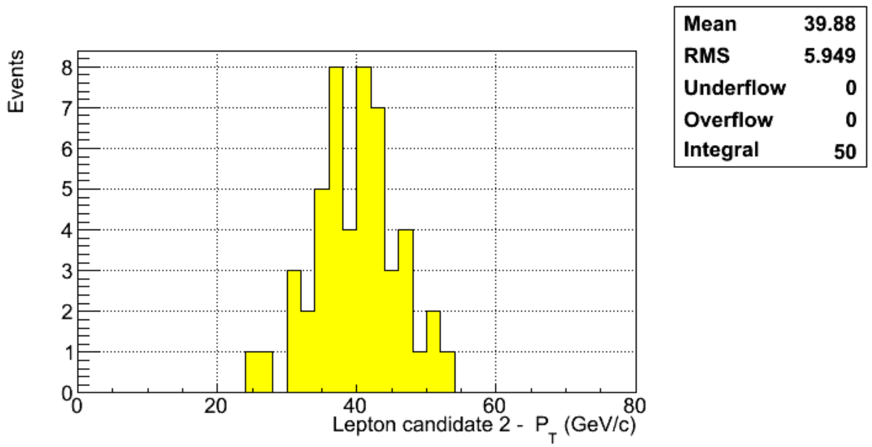


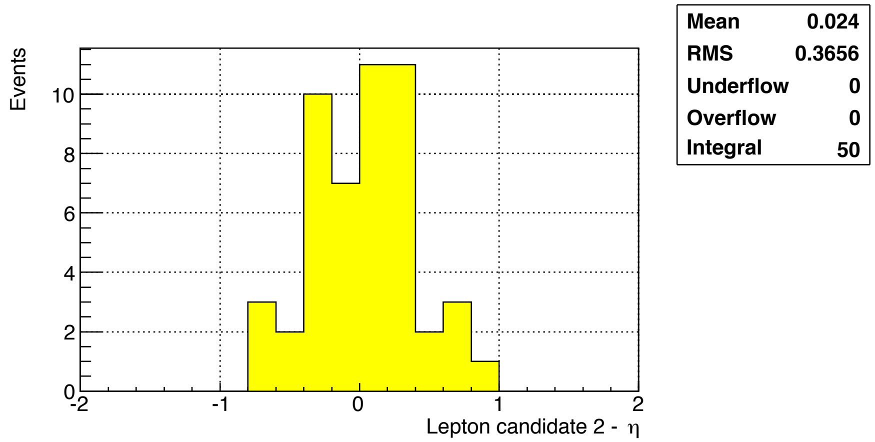


Z^0 lepton candidates









Lepton candidate go to central rapidity and have large P_T