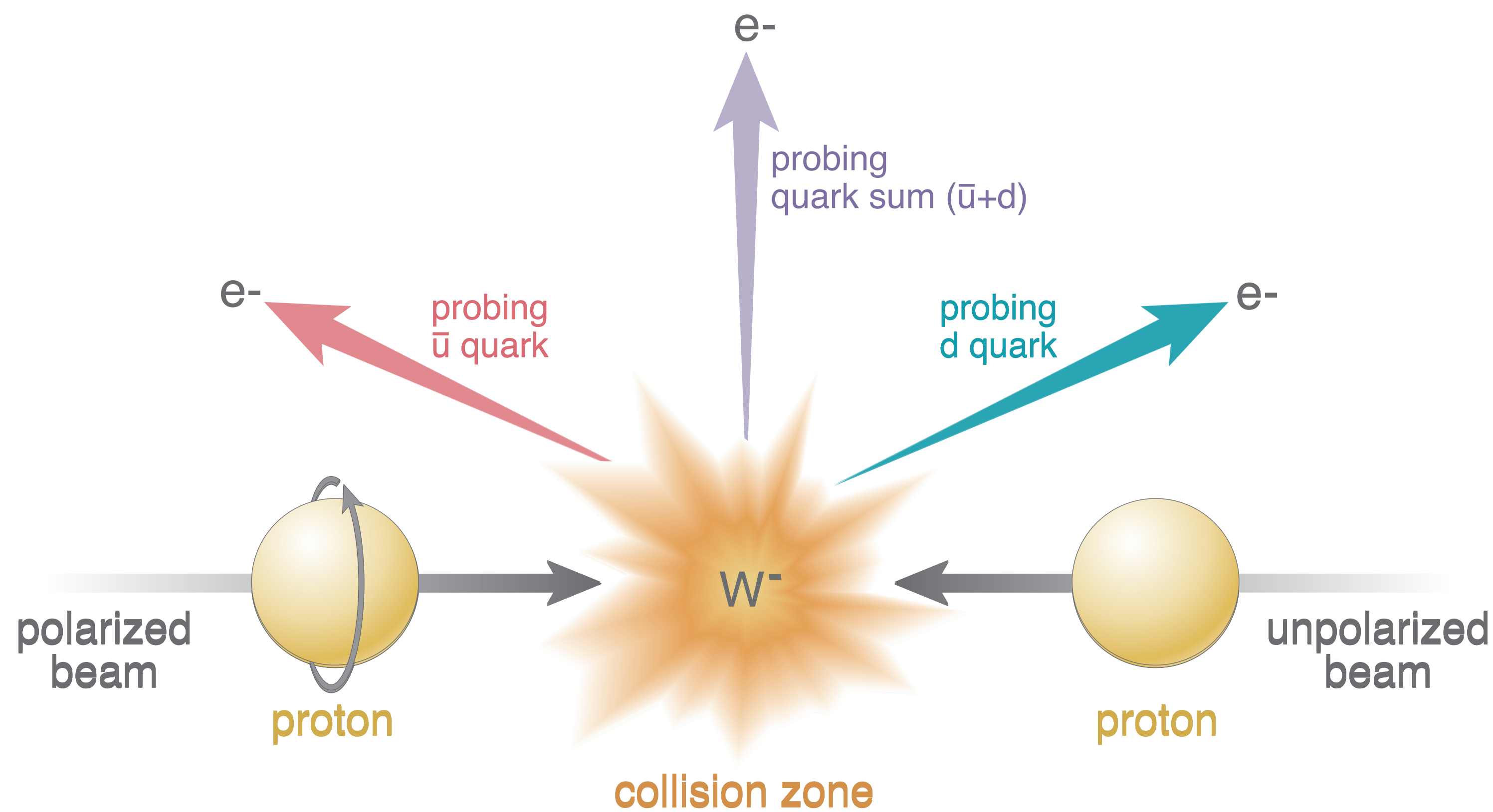
Measurement of longitudinal single-spin asymmetries for $W^{\pm}$ boson production in polarized p+p collision at $\sqrt{s}$=510 GeV at RHIC



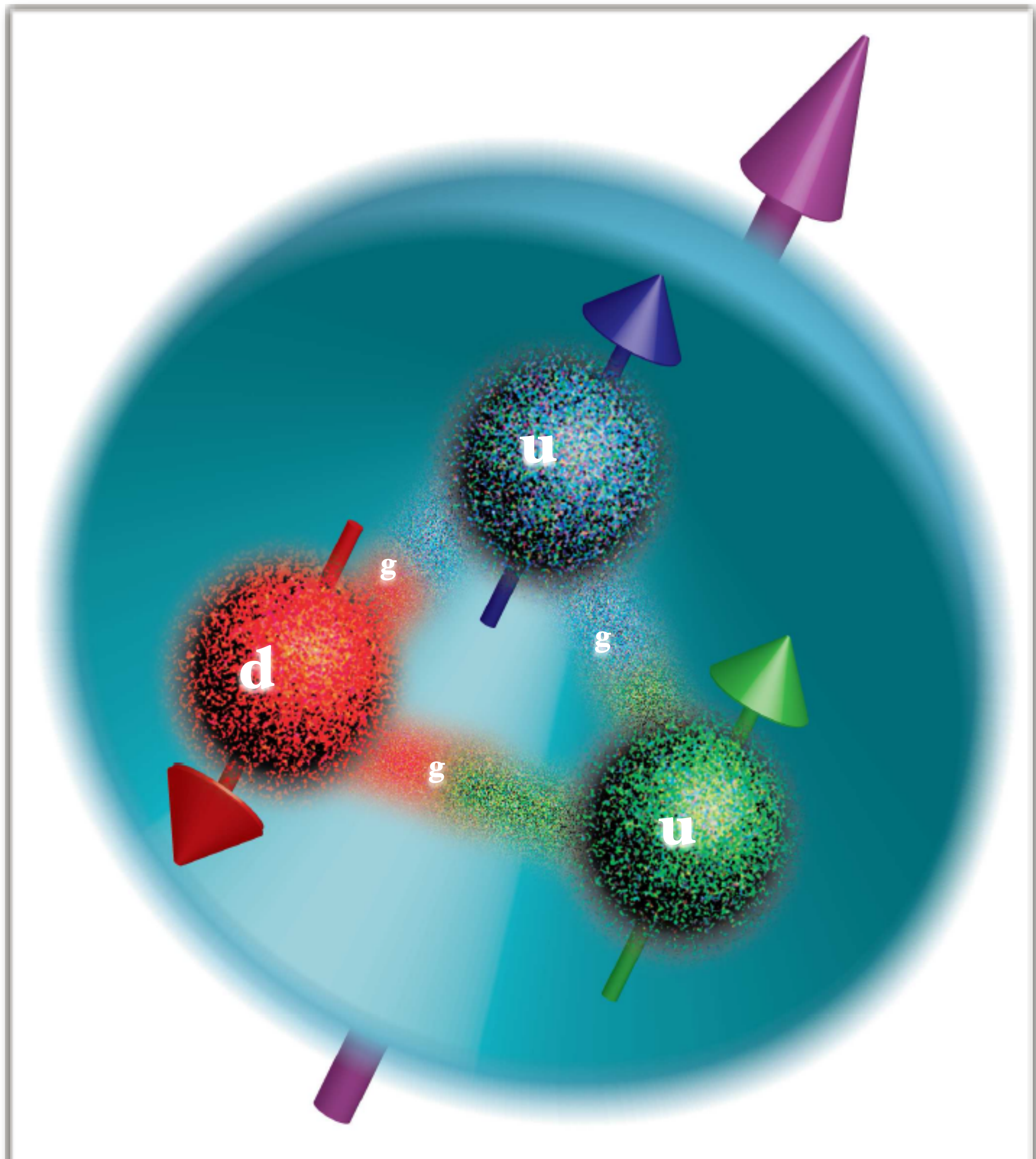
DIS 2015
XXIII International Workshop on Deep-Inelastic Scattering and Related Subjects

Dallas, Texas
April 27 – May 1, 2015

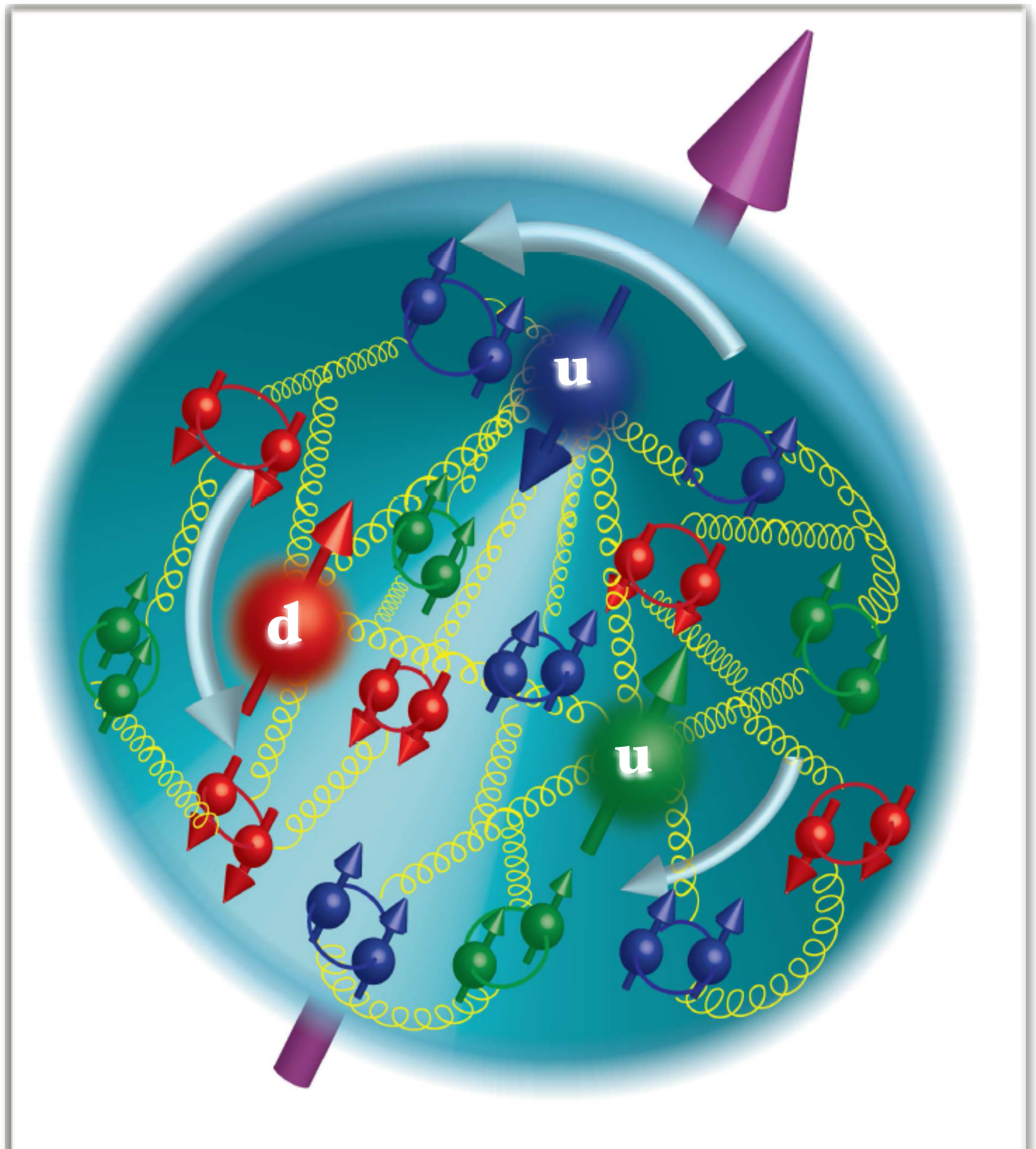
Devika Gunarathne
(for the STAR collaboration)
Temple University

STAR

Evolving Picture of Proton's Spin Structure



Valance Quarks



Sea Quarks

Anti Quark Polarization

Spin sum rule for longitudinally Polarized proton :

$$< S_p > = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

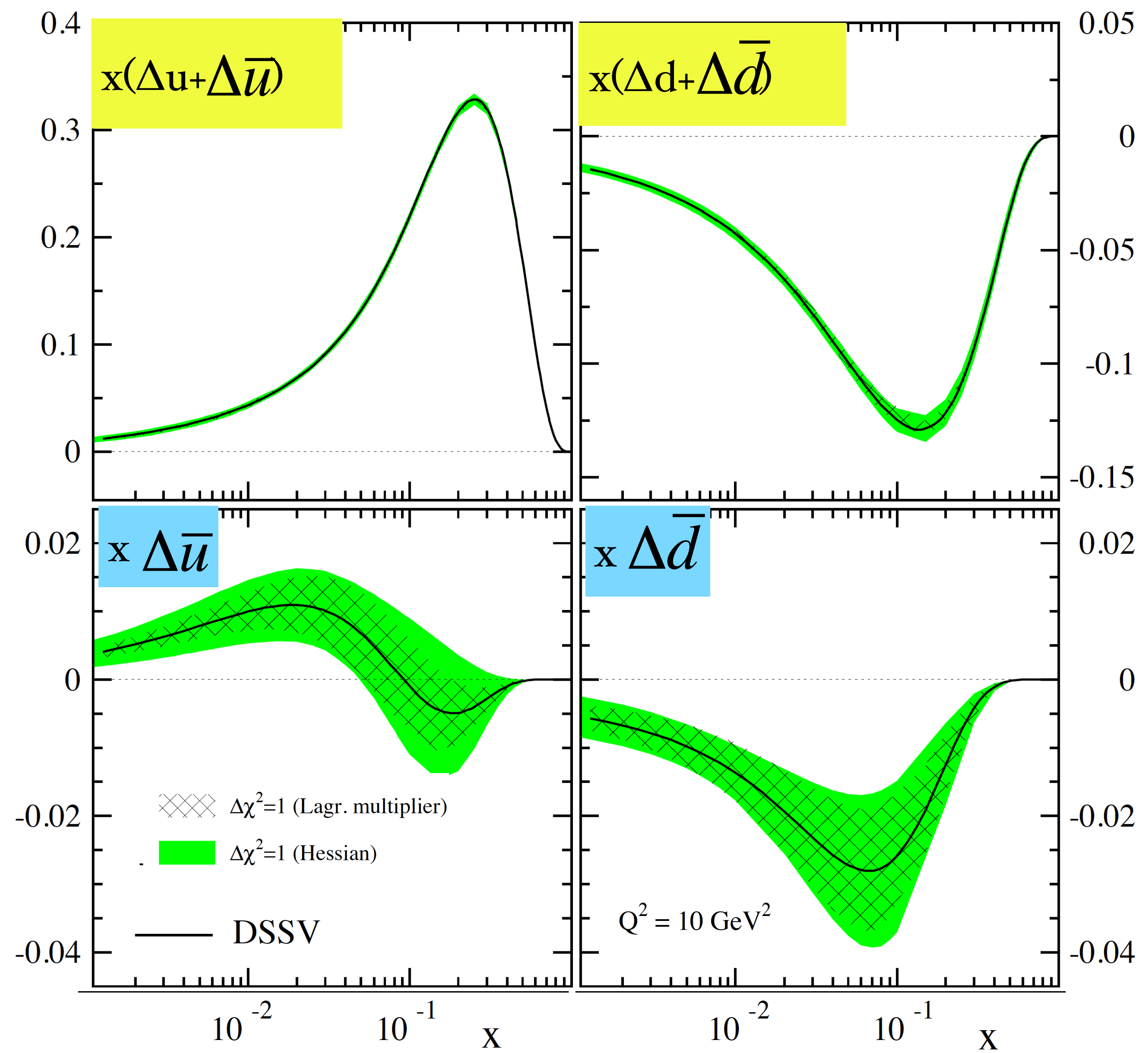
$$\Delta\Sigma = \int (\Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s})dx$$

~30 % from polarized inclusive DIS

Helicity PDF

$$\Delta f(x,Q^2) \equiv f^+(x,Q^2) - f^-(x,Q^2)$$

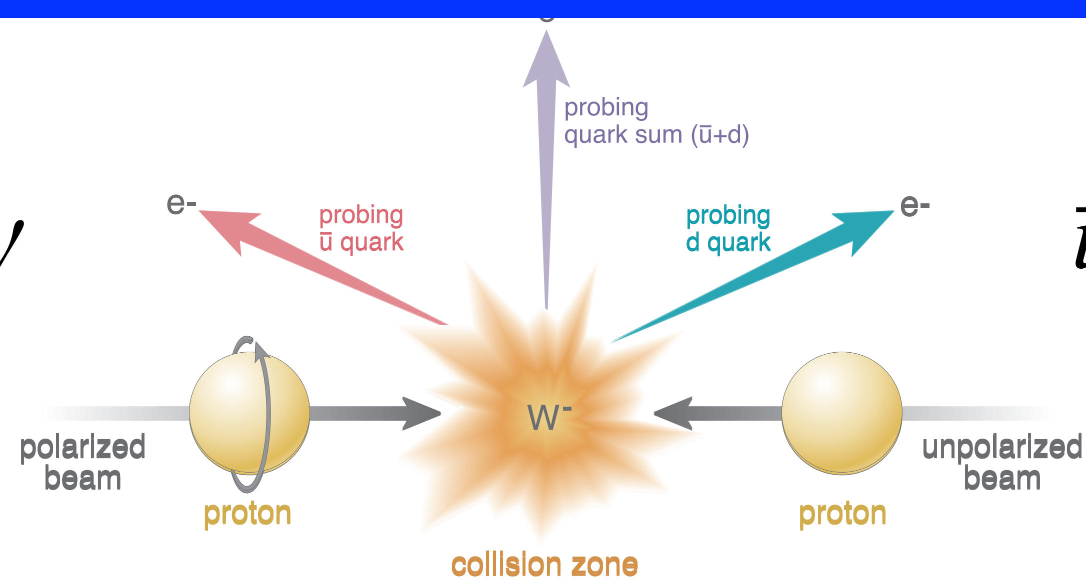
DSSV Global Analysis



PRD 80, 034030(2009)

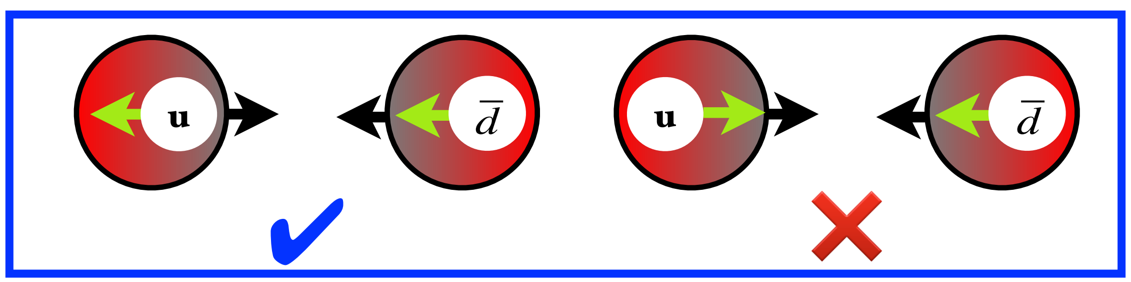
W Boson Production

$$u+\bar{d} \to W^{+} \to e^{+} + \nu$$



$$\bar{u}+d \to W^{-} \to e^{-} + \bar{\nu}$$

- **Direct Coupling to the Quark and anti Quark of interest.**
- **Maximum violation of parity leads to perfect spin separation.**



- **High resolution scale (Q^2) set by the W mass.**
- **Easy detection via the leptonic decay channels.**

Parity violating longitudinal single spin asymmetry

$$A_L = \frac{\sigma^{+} - \sigma^{-}}{\sigma^{+} + \sigma^{-}}$$

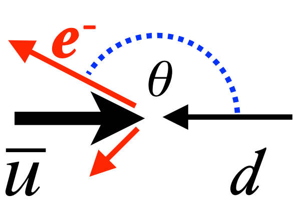
W A_L :Theoretical Aspects

W A_L, highly sensitive to individual polarizations at forward and backward decay lepton pseudo rapidity (η_e)

$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right) \qquad < x_{1,2} > \sim \frac{M_W}{\sqrt{s}} e^{\pm \eta_e/2}$$

$$\eta <<< 0 \rightarrow x_1 << x_2, \theta \rightarrow \pi$$

$$A_L^{e^-} \approx \frac{\int_{\otimes(x_1,x_2)} [\Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 - \Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2]}{\int_{\otimes(x_1,x_2)} [\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 + d(x_1)\bar{u}(x_2)(1+\cos\theta)^2]}$$



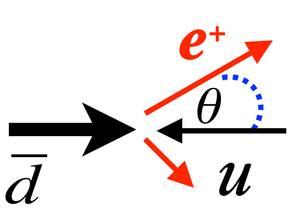
backward e^-

parallel to W^-

$$\frac{\Delta\bar{u}}{\bar{u}}$$

$$\eta >>> 0 \rightarrow x_1 >> x_2, \theta \rightarrow 0$$

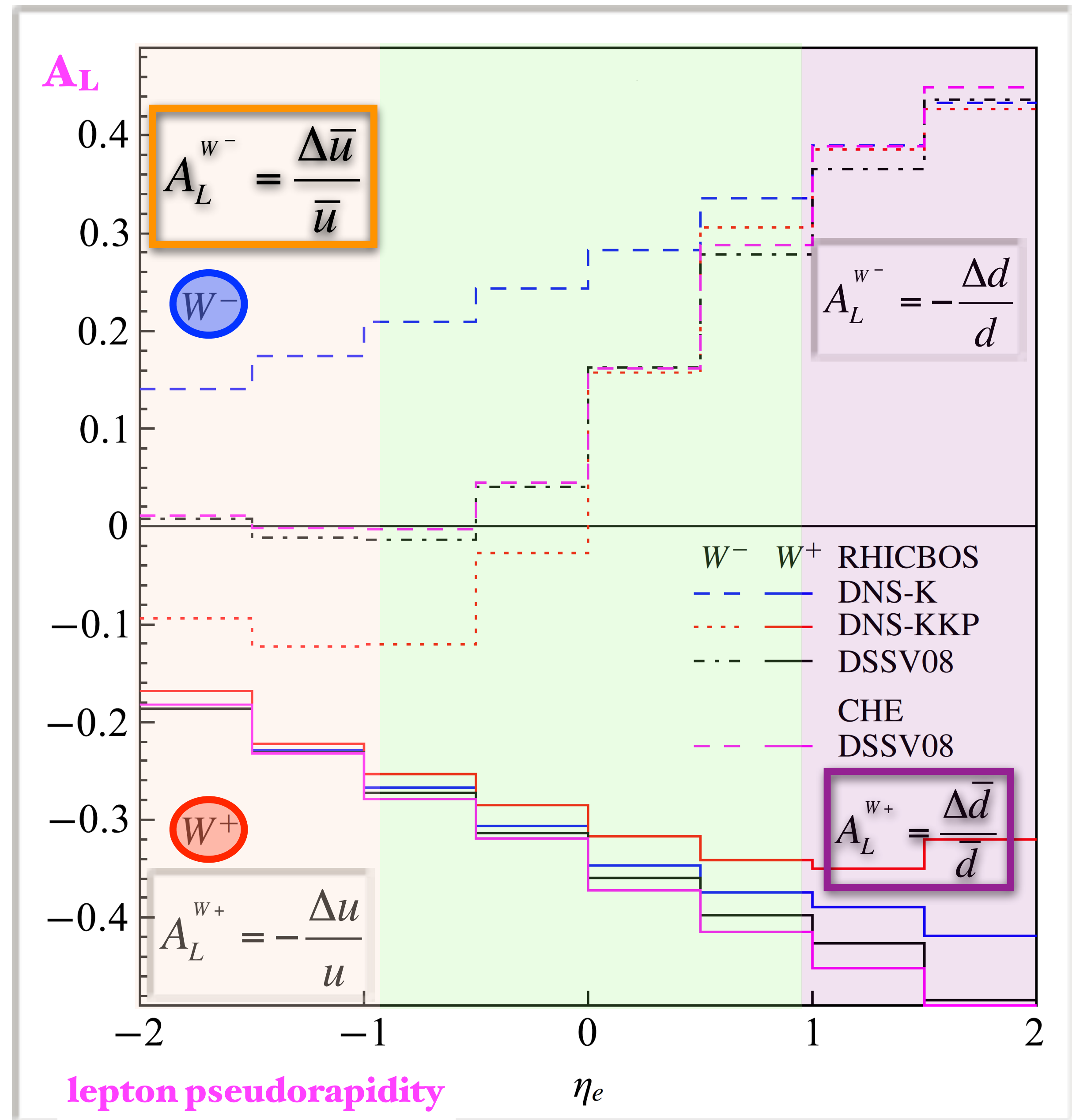
$$A_L^{e^+} \approx \frac{\int_{\otimes(x_1,x_2)} [\Delta\bar{d}(x_1)u(x_2)(1+\cos\theta)^2 - \Delta u(x_1)\bar{d}(x_2)(1-\cos\theta)^2]}{\int_{\otimes(x_1,x_2)} [\bar{d}(x_1)u(x_2)(1+\cos\theta)^2 + u(x_1)\bar{d}(x_2)(1-\cos\theta)^2]}$$



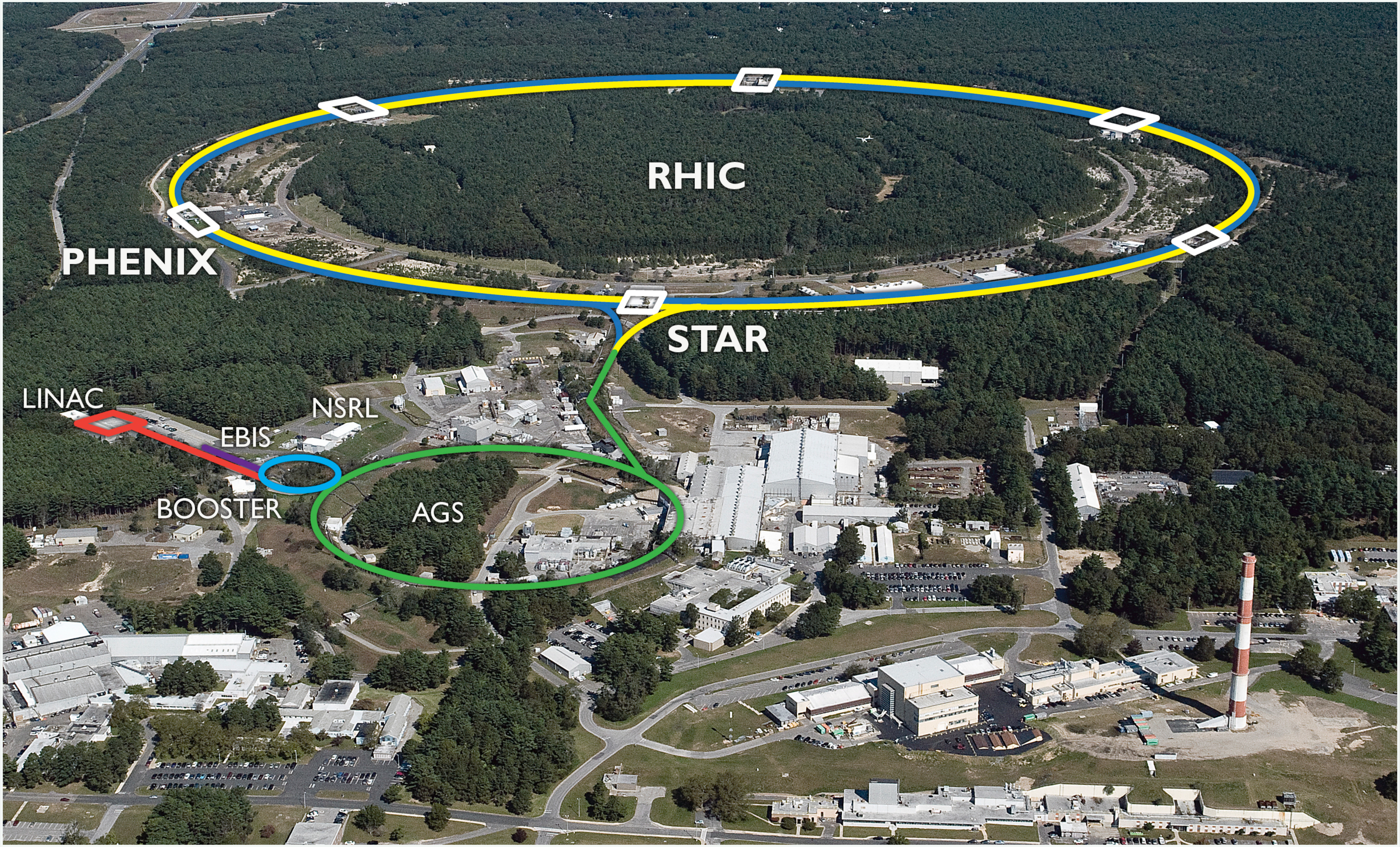
forward e^+

anti parallel to W^+

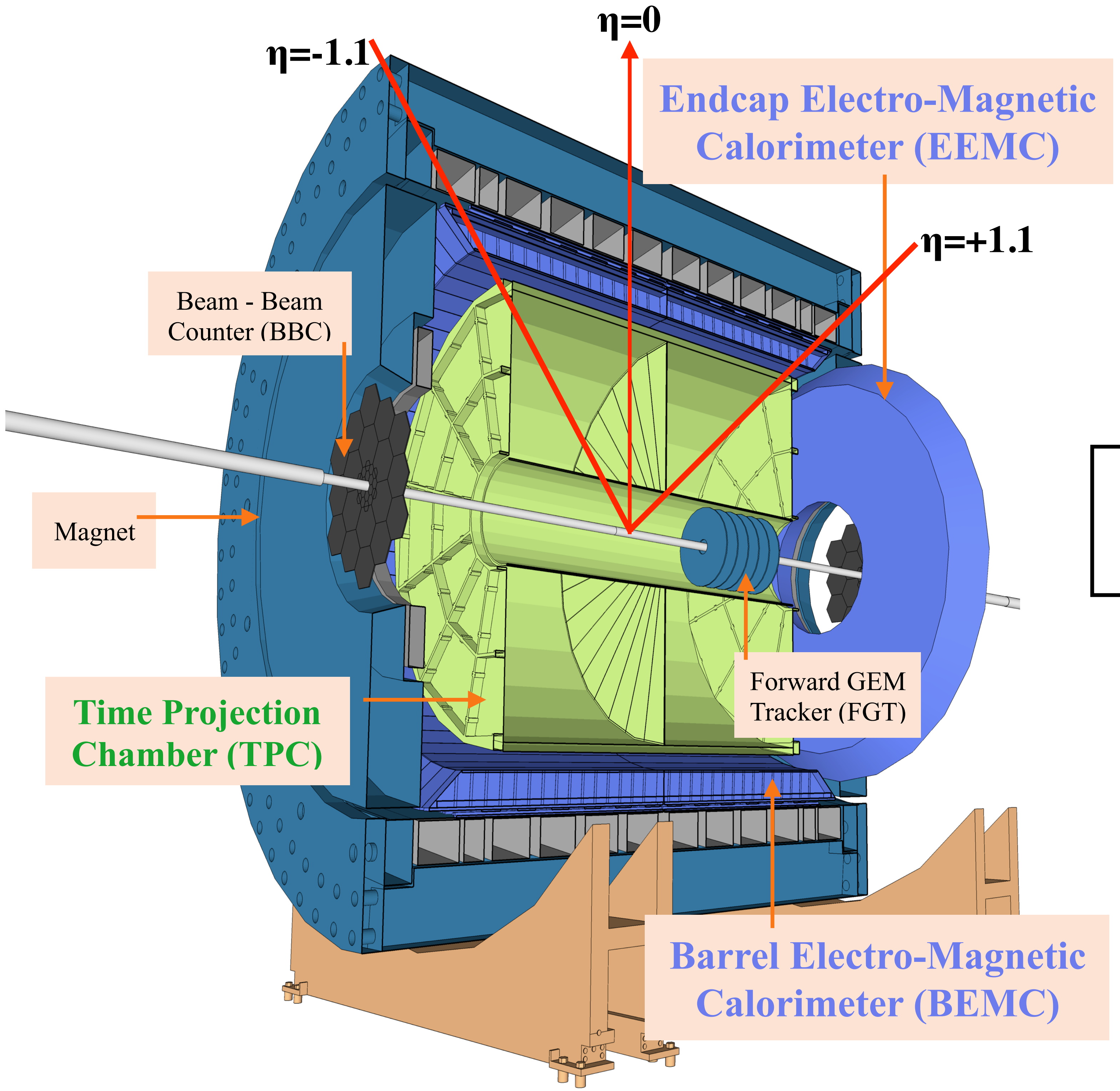
$$\frac{\Delta\bar{d}}{\bar{d}}$$



RHIC : Relativistic Heavy Ion Collider



STAR Detector Overview



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

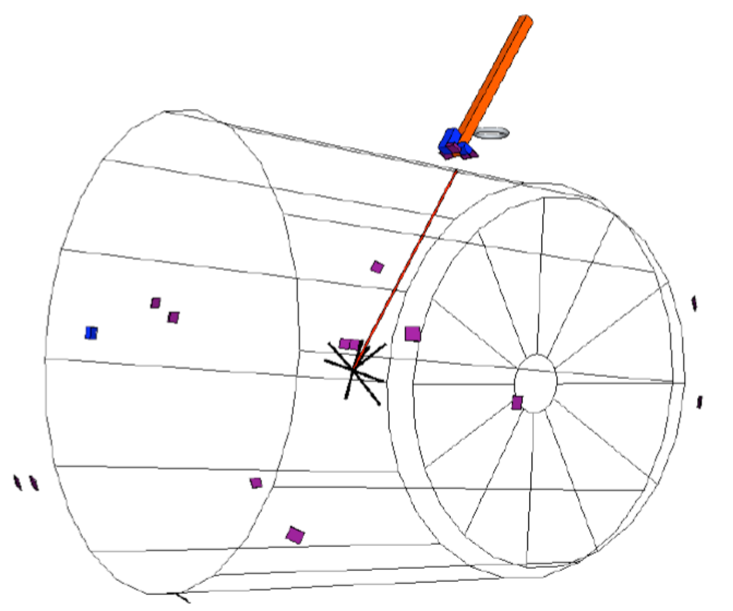
TPC: Charge particle tracking

BEMC, EEMC: EM Calorimetry

TPC	**: $-1.3 < \eta < +1.3$**
BEMC	**: $-1.0 < \eta < +1.0$**
EEMC	**: $+1.1 < \eta < +2.0$**
FGT	**: $+1.0 < \eta < +2.0$**

Mid-rapidity ($|\eta_e| < 1$) W Selection

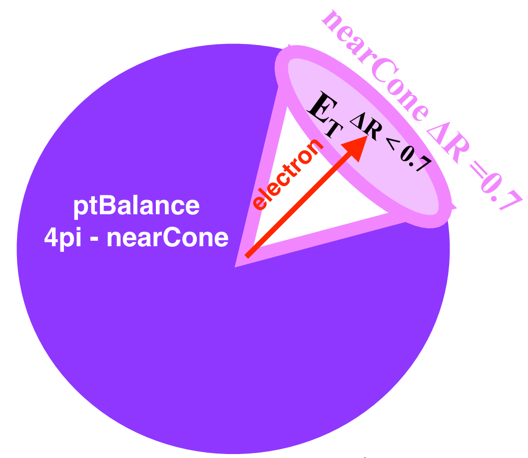
W-> e+ν candidate



Isolated tracks -> isolated EMC cluster

Large opposite missing "energy"

$P_T > 10$ GeV

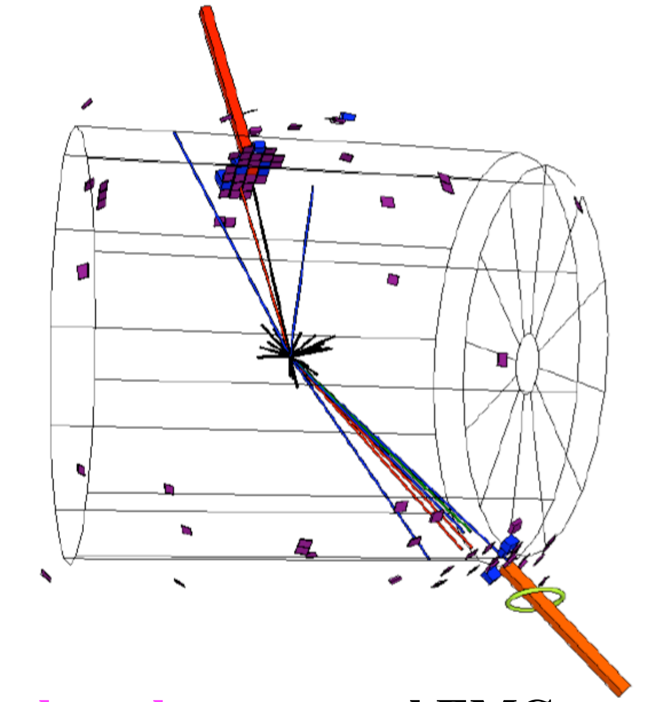


Transverse plane views

$$\vec{p}_T^{\,balance} = \vec{p}_T^{\,e} + \sum_{\Delta R > 0.7} \vec{p}_T^{\,jets}$$

$$signed\ P_T - balance = \frac{(\vec{p}_T^{\,e} \cdot \vec{p}_T^{\,balance})}{|\vec{p}^{\,e}|}$$

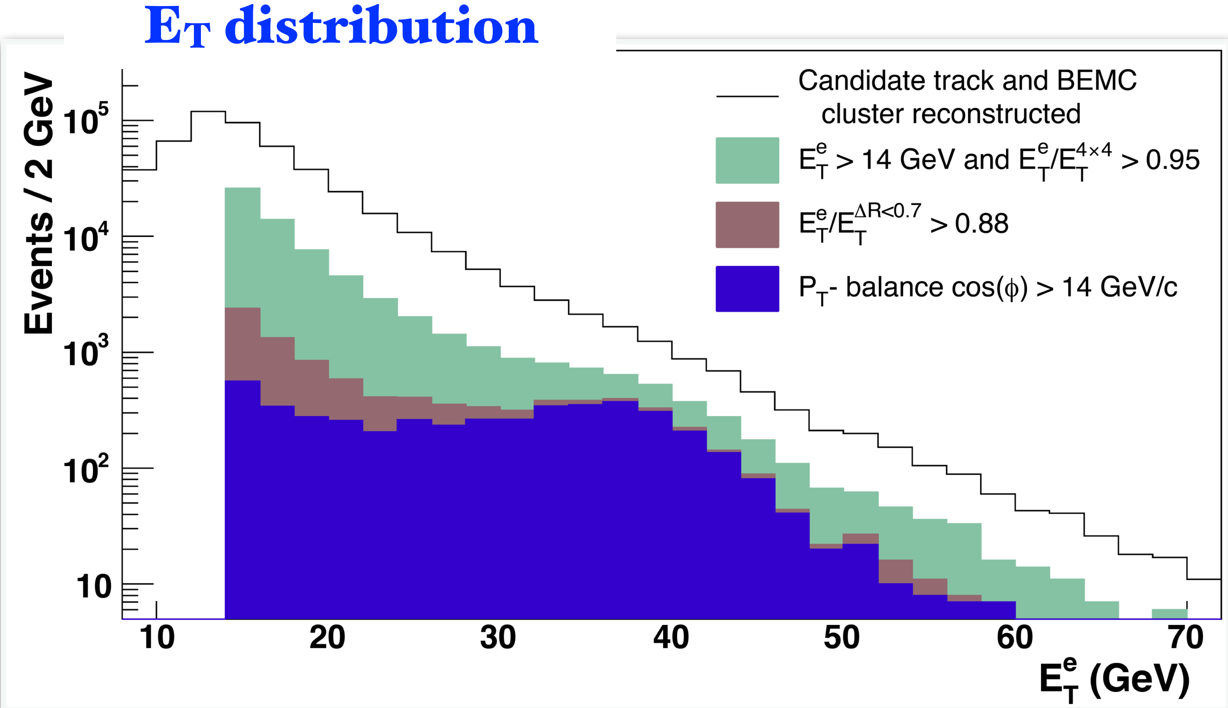
QCD background candidate



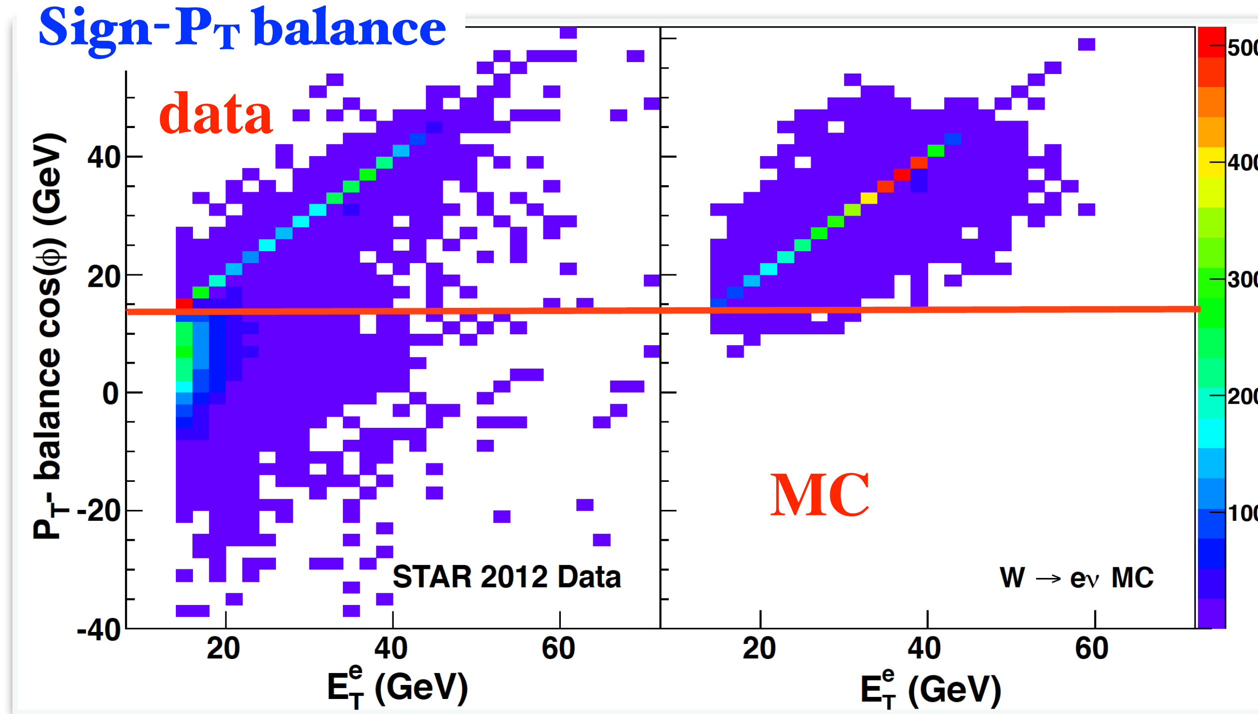
Several tracks -> several EMC towers

No large missing "energy"

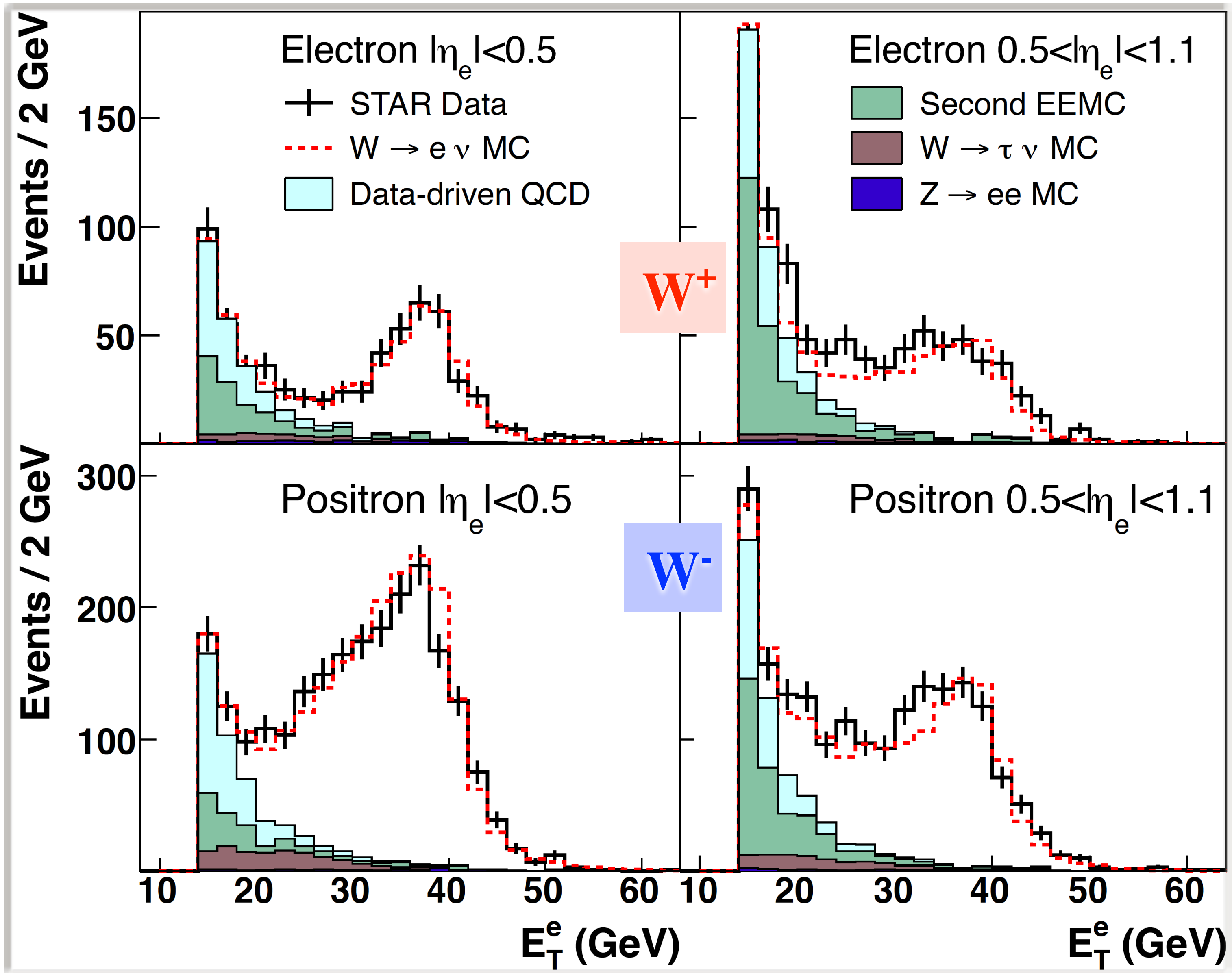
E_T distribution



Sign-P_T balance



Mid-rapidity Background Estimation



PRL 113,72301 (2014)

Primary Background

QCD processes where a jet fragments satisfy candidate $e^{+/-}$ isolation cuts while all other jets escape detection outside the acceptance.

- ✤ Second Endcap $-2 < \eta < -1.09$
- ✤ Data driven QCD $|\eta| < 2$

Electroweak BG

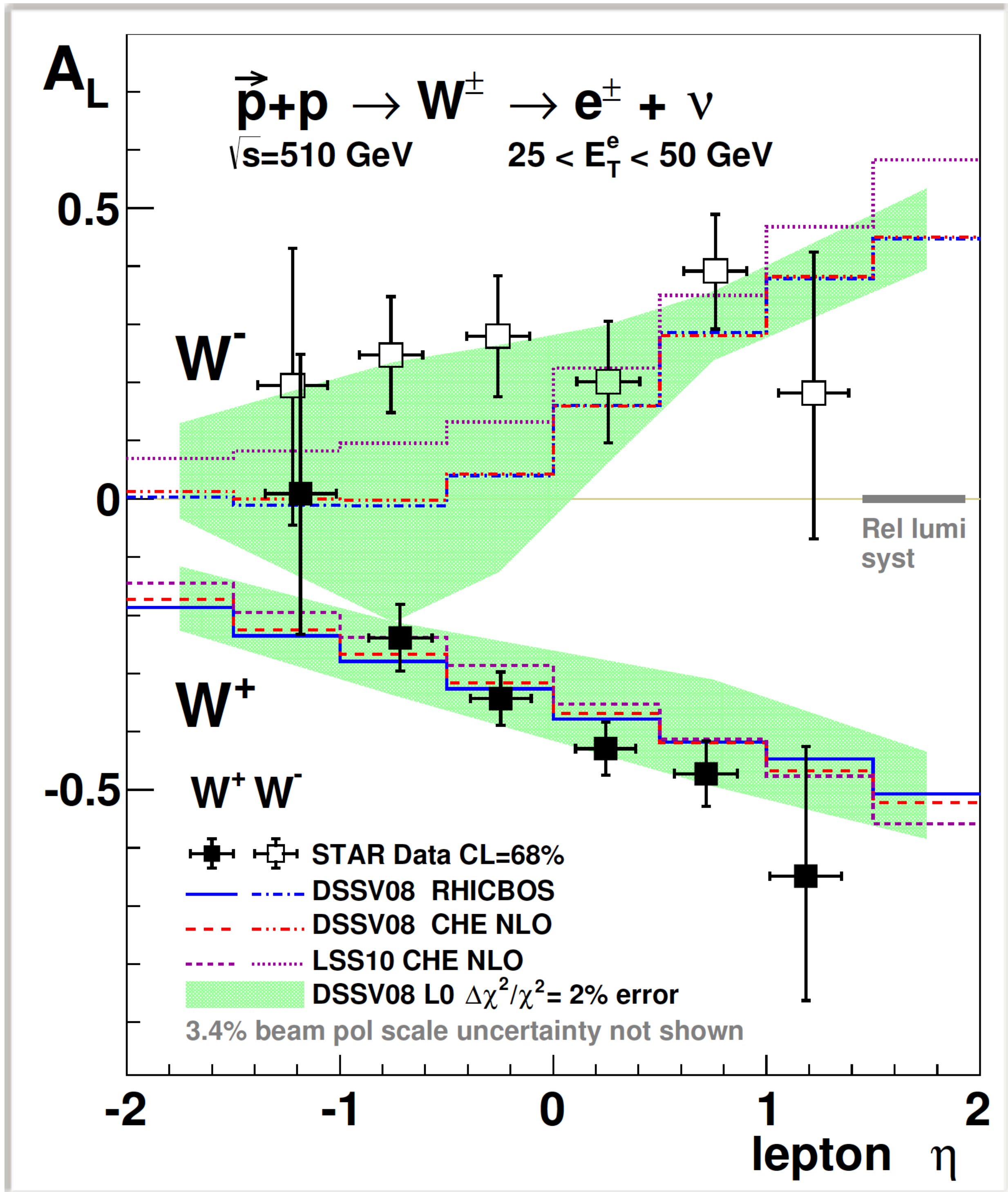
- ✤ $W \rightarrow \tau\nu$
- ✤ $Z \rightarrow e^+ + e^-$

MC Embedded in Zero-bias events

Forward rapidity ($1<\eta_e<1.4$) W selection uses similar technique as mid rapidity and Background Estimation improve using additional Endcap Shower Maximum Detector (ESMD)

Results

W A_L (η_e) 2012+2011



PRL 113,72301 (2014)

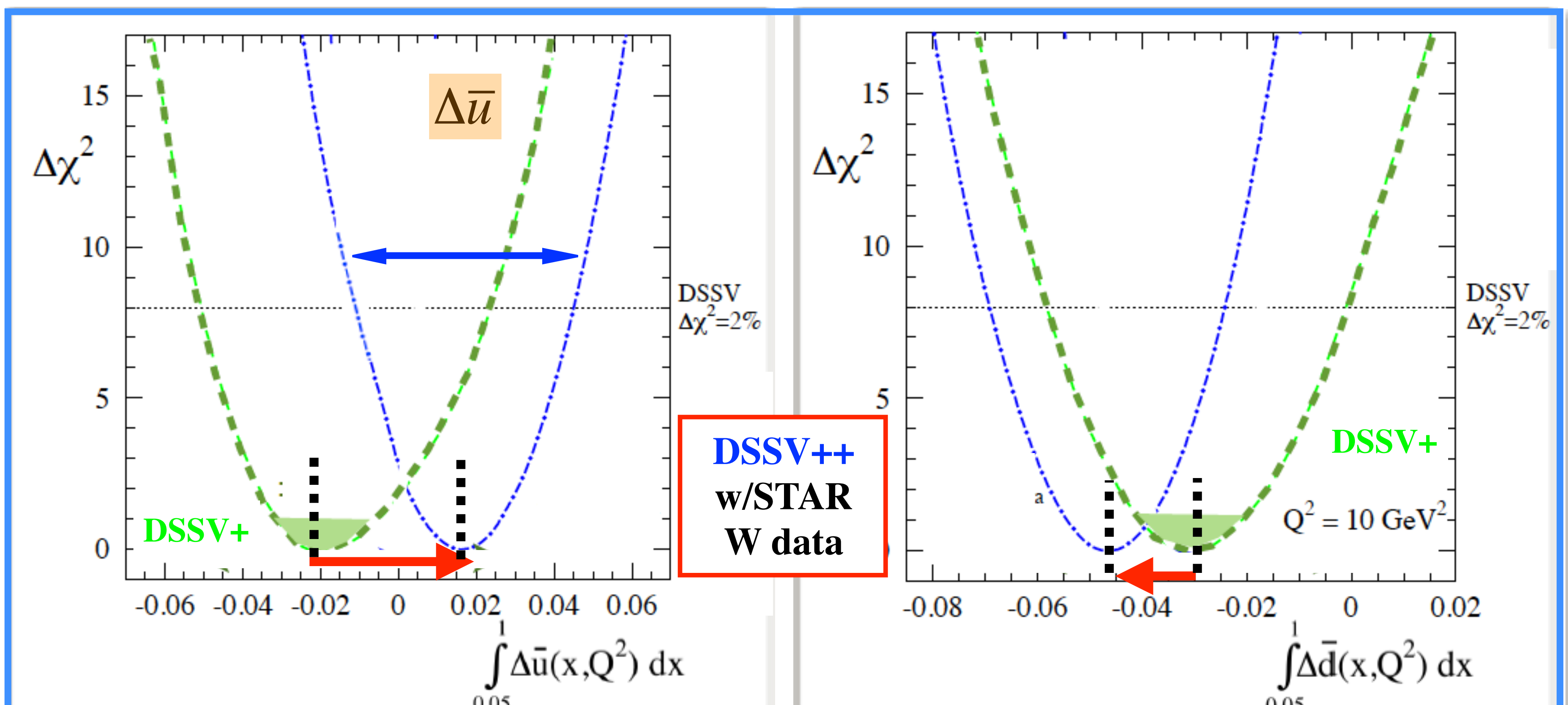
- ✤Profile Likelihood method used to extract Asymmetries from combination of 2012 and 2011 data.
- ✤$A_L(W^-)$ is larger than the DSSV Predictions.
  - ✦The enhancement at $\eta_e < 0$, in particular is sensitive to the $\Delta\bar{u}$, polarized antiquark distribution.
- ✤A_L (W^+) is consistent with theoretical predictions using the DSSV polarized PDFs.
- ✤The Systematic uncertainties for A_L are well under control for $|\eta_e| < 1.4$.

Impact on Recent Global Analysis

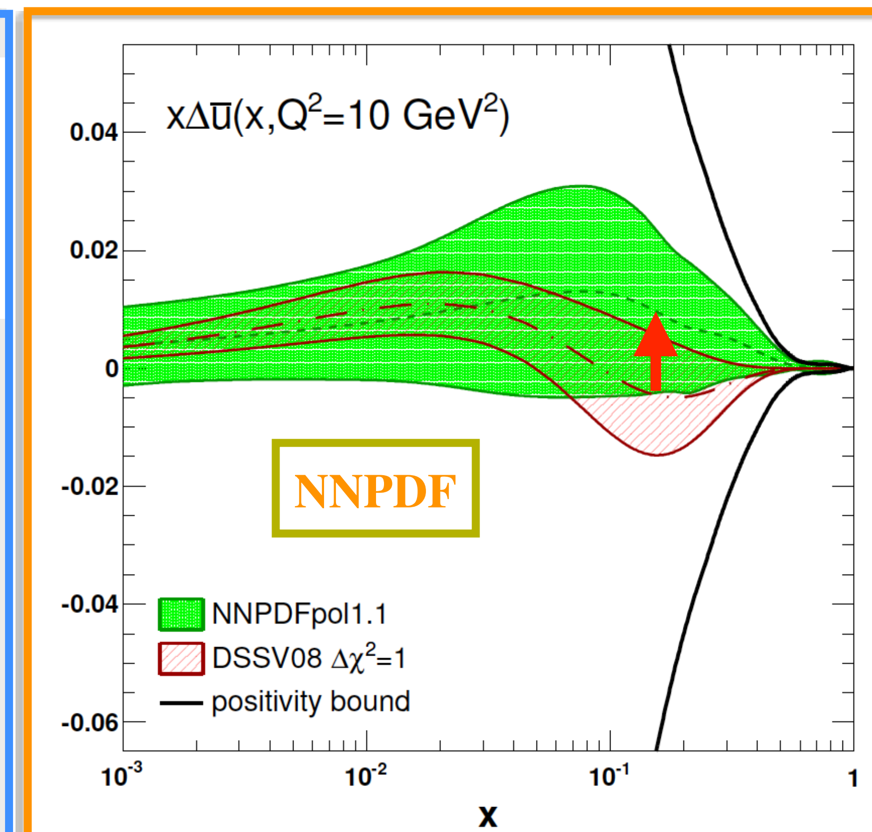
- ✤Preliminary Global analysis (DSSV++) from DSSV group and recent NNPDF includes preliminary STAR 2012 W A_L data.

- ✤Shift in central value for $\Delta\bar{u}$ (negative -> positive) and $\Delta\bar{d}$ due to A_L W from STAR .

- ✤STAR 2012 W results provide significant constraints on anti u and anti d quark polarization.



arXiv: 1304.0079 arXiv: 1304.0079

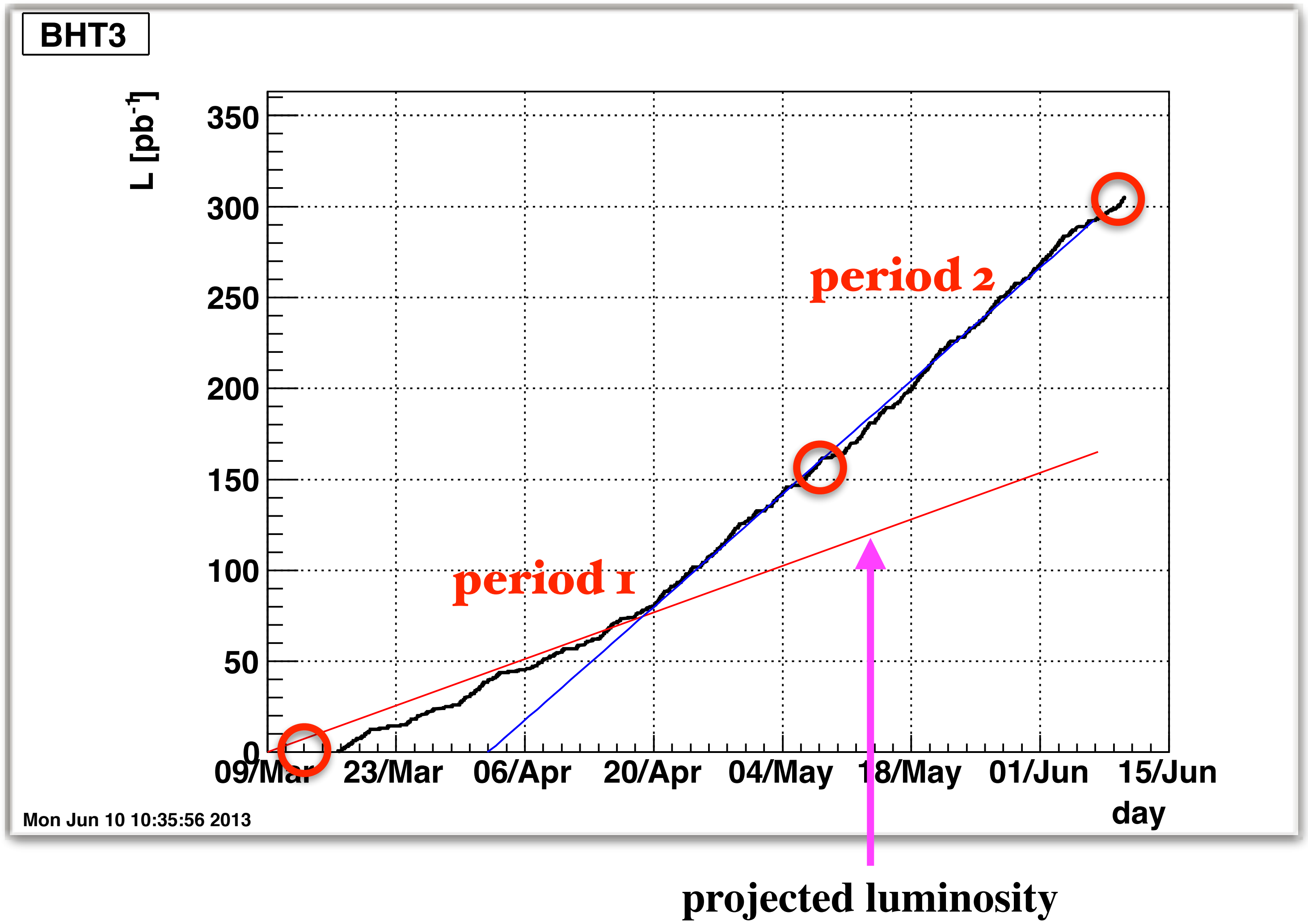


arXiv: 1403.0440

STAR 2013 W Analysis Status

2013 Data Sample

Barrel EMC triggered Integrated Luminosity

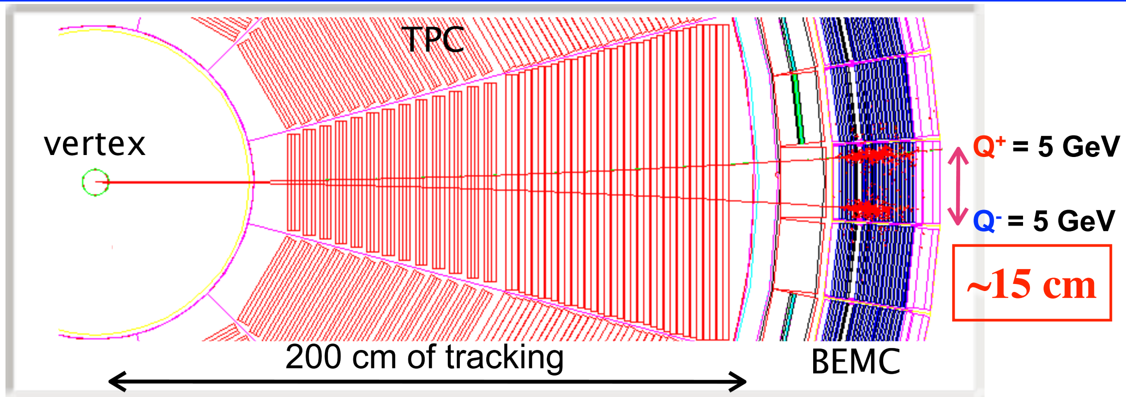


	L (pb^{-1})	P	FOM (P^2L (pb^{-1}))
Run 9	12	0.38	1.7
Run 11	9.4	0.49	2.3
Run 12	72	0.56	24
Run 13	~ 300	0.54	~ 87

In 2013 STAR collected an average luminosity of ~300 pb^{-1} at $\sqrt{s}$ =500 GeV with an average beam polarization of ~54% .

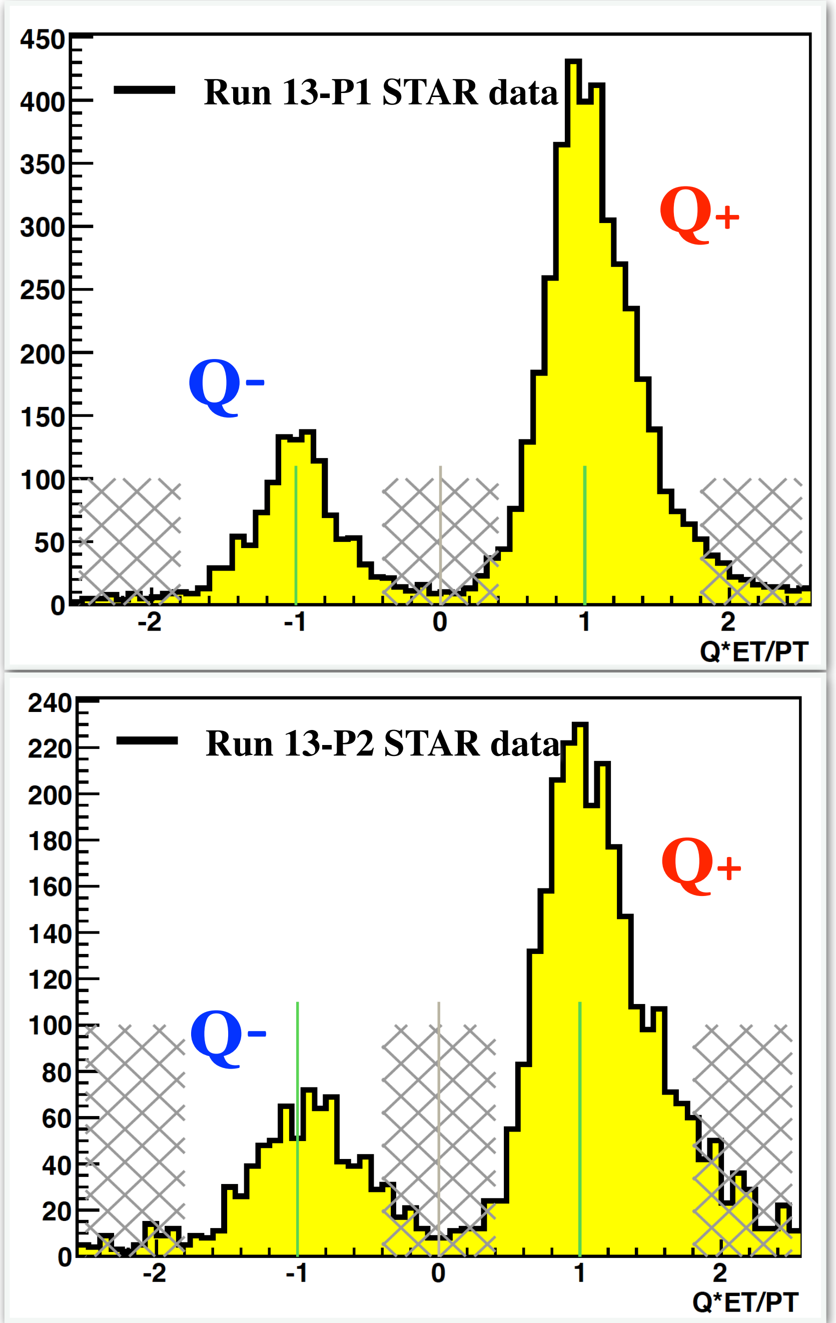
Detector Calibration

✤ TPC

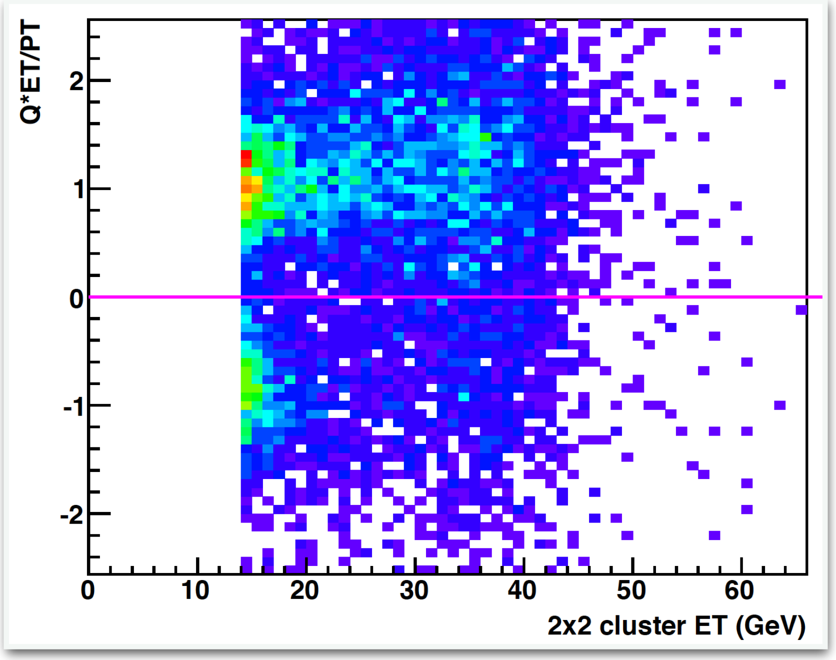


✤ **Charge Sign reconstruction is based on bending of TPC tracks in the presence of magnetic field.**

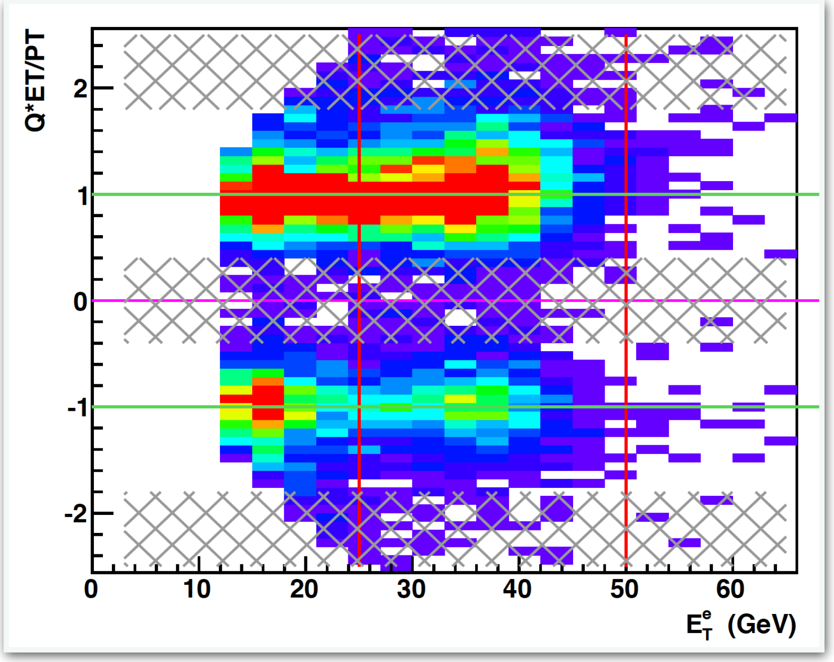
✤ **Challenging environment of charge-sign discrimination at high-pT using TPC in high luminosity / pile-up operation - Very careful TPC calibration required!!!!**



global TPC tracks

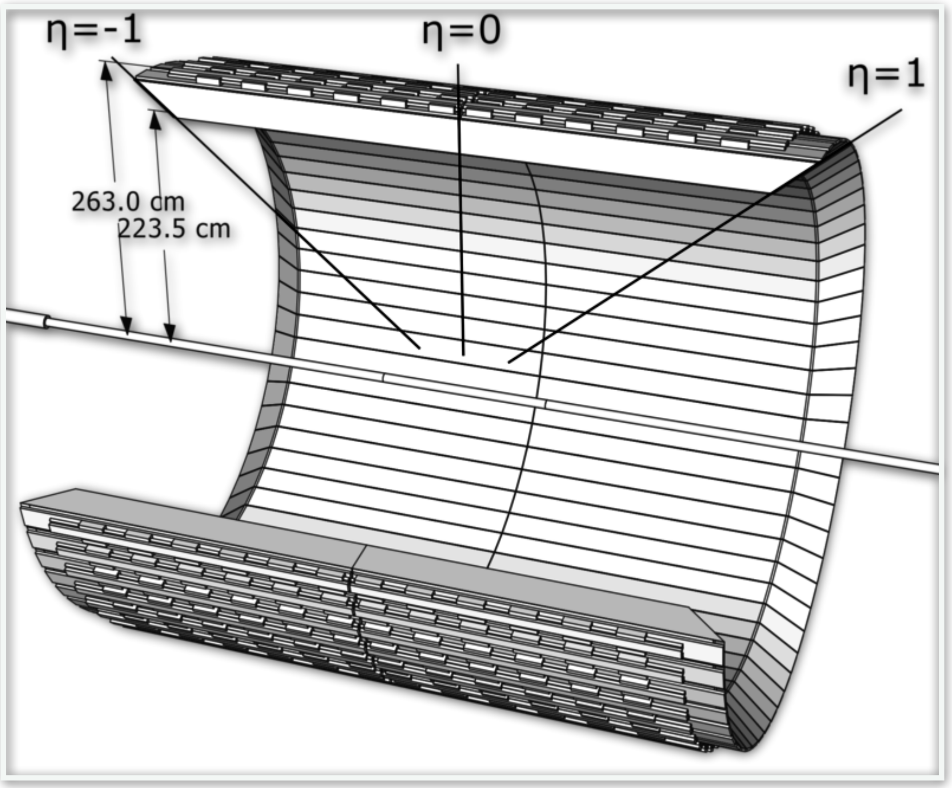


W candidate tracks

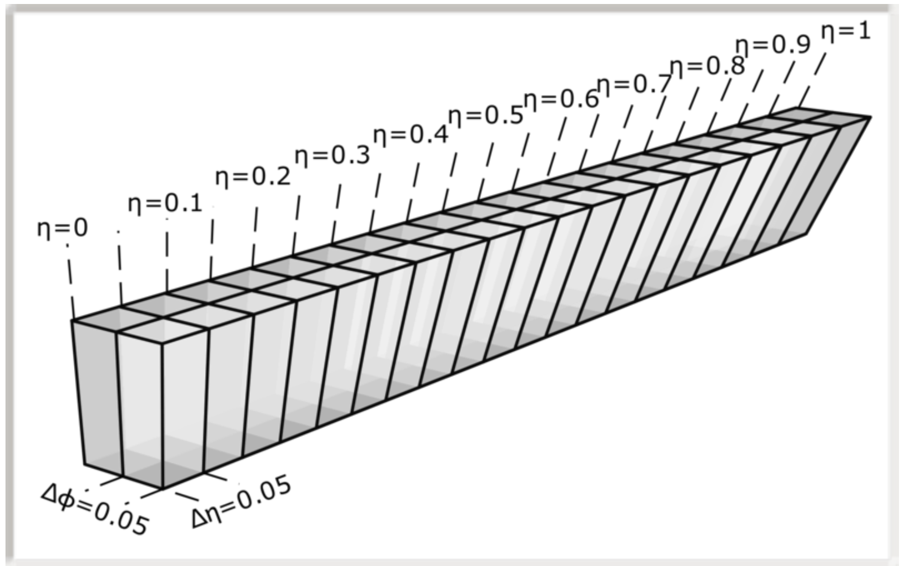


Detector Calibration

✤ BEMC



✦BEMC is a sampling calorimeter and it is segmented into 4800 towers, each with $\Delta\eta X \Delta\phi = 0.05x0.05$



The geometry of the calorimeter towers in a BEMC module

Calibration need to be done considering all possible Energy ranges !!!

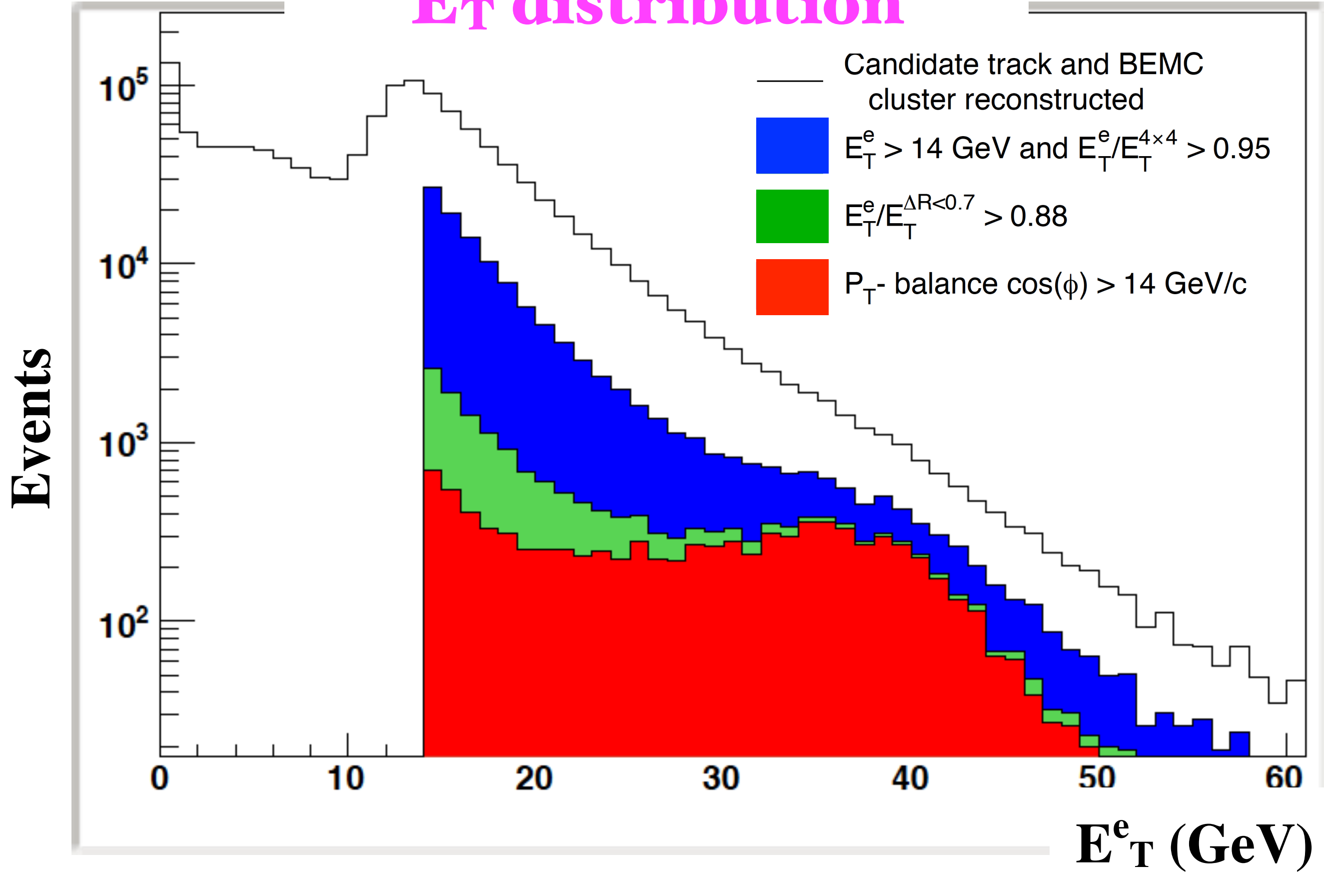
✦ In the low energy range **relative Calibration of towers** is done using abundant **MIPs (high P hadrons)**

✦ **E/P from electrons** is used to obtain **absolute calibration.**

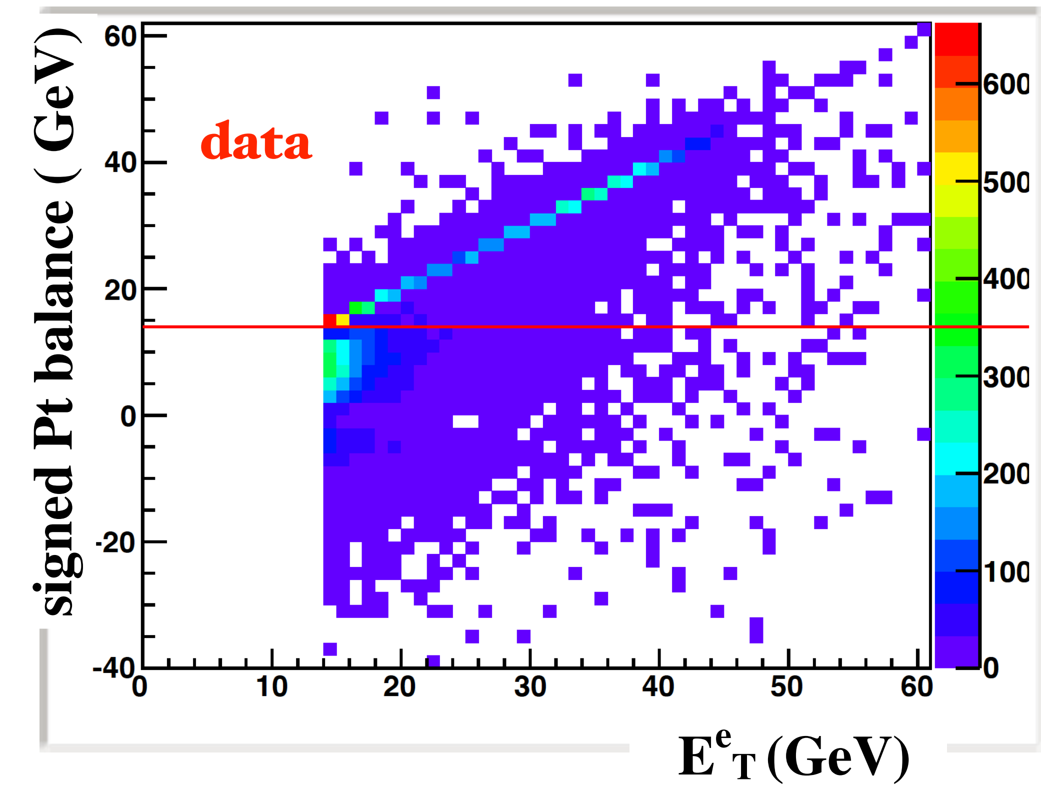
✦ Other **High Energy probes** (from rare processes) such as **Z invariant mass peak position** , **slope of the sharp drop of W jacobian peak** will be used to calibrate in the high energy range.

Mid-rapidity Analysis Status : W selection

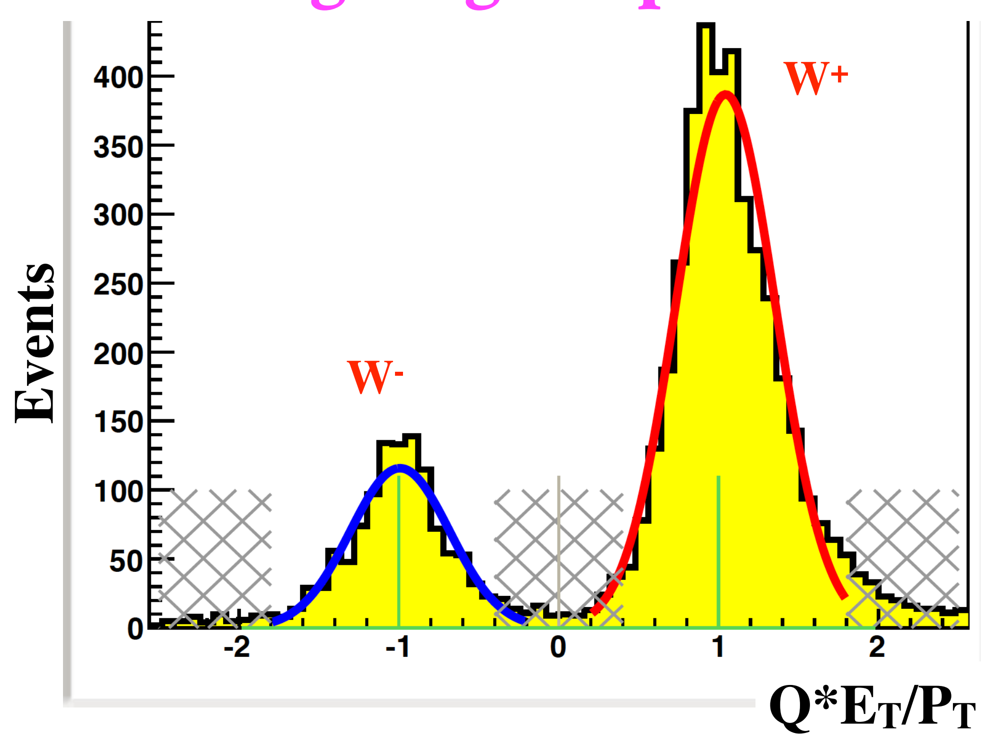
E_T distribution

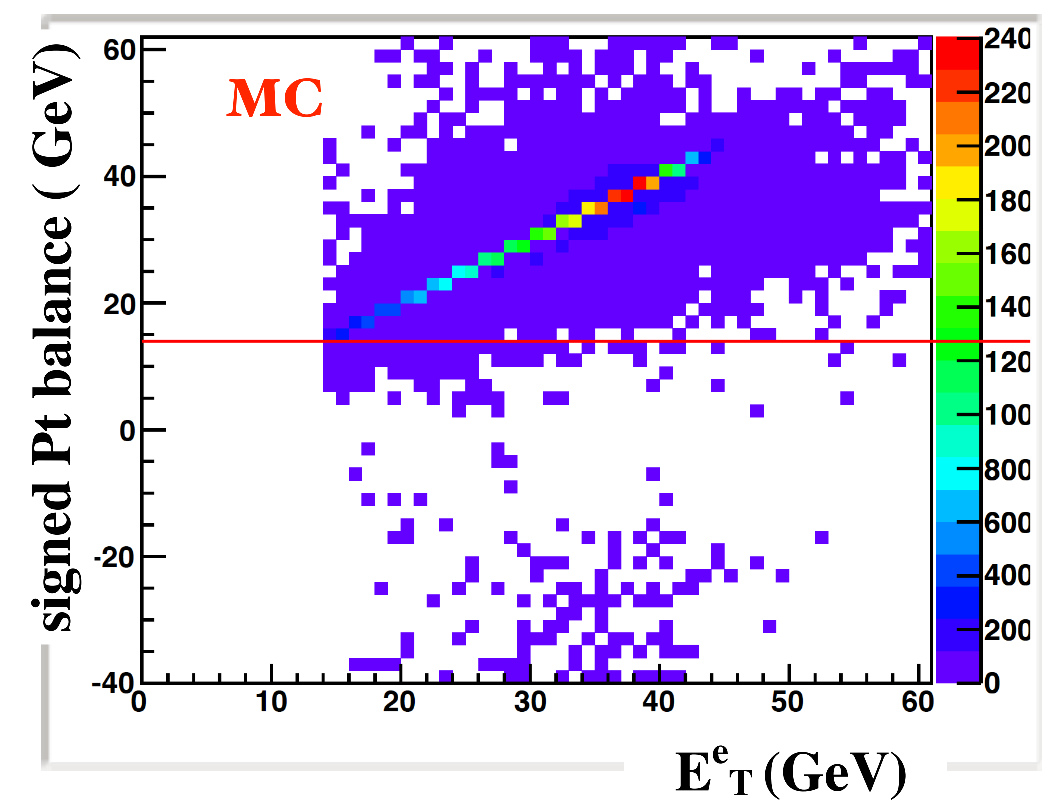


Sign-P_T balance



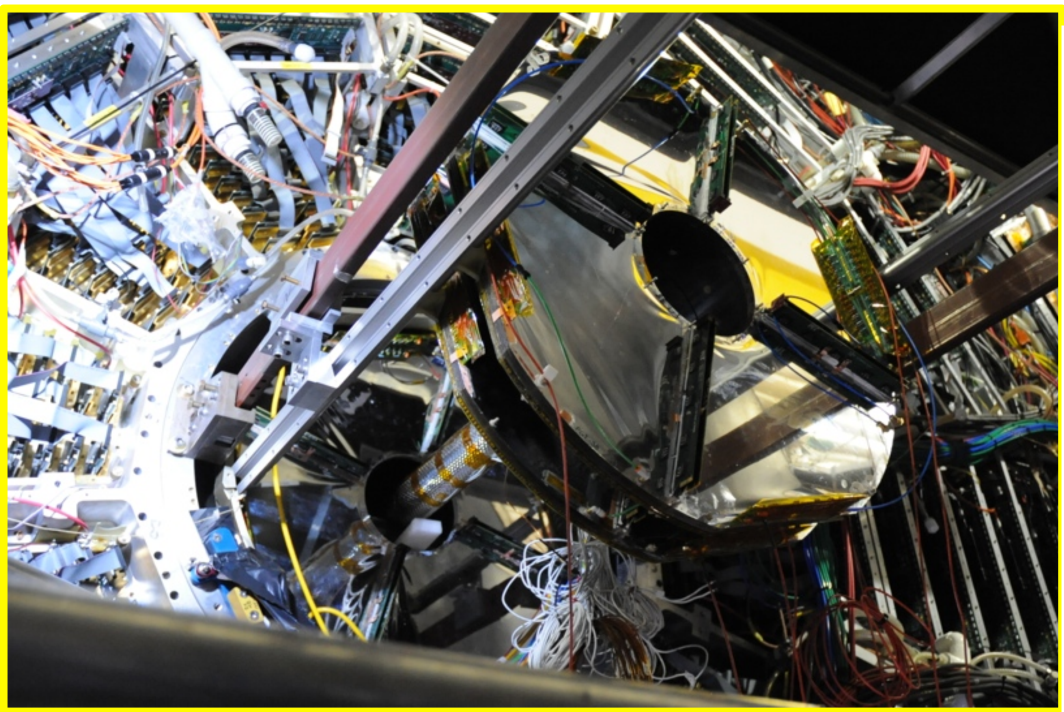
Charge-sign Separation

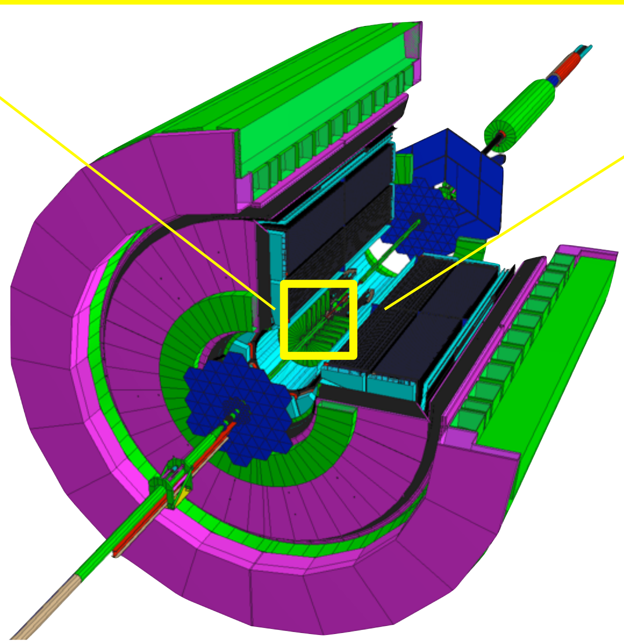




Forward-rapidity Analysis Status :

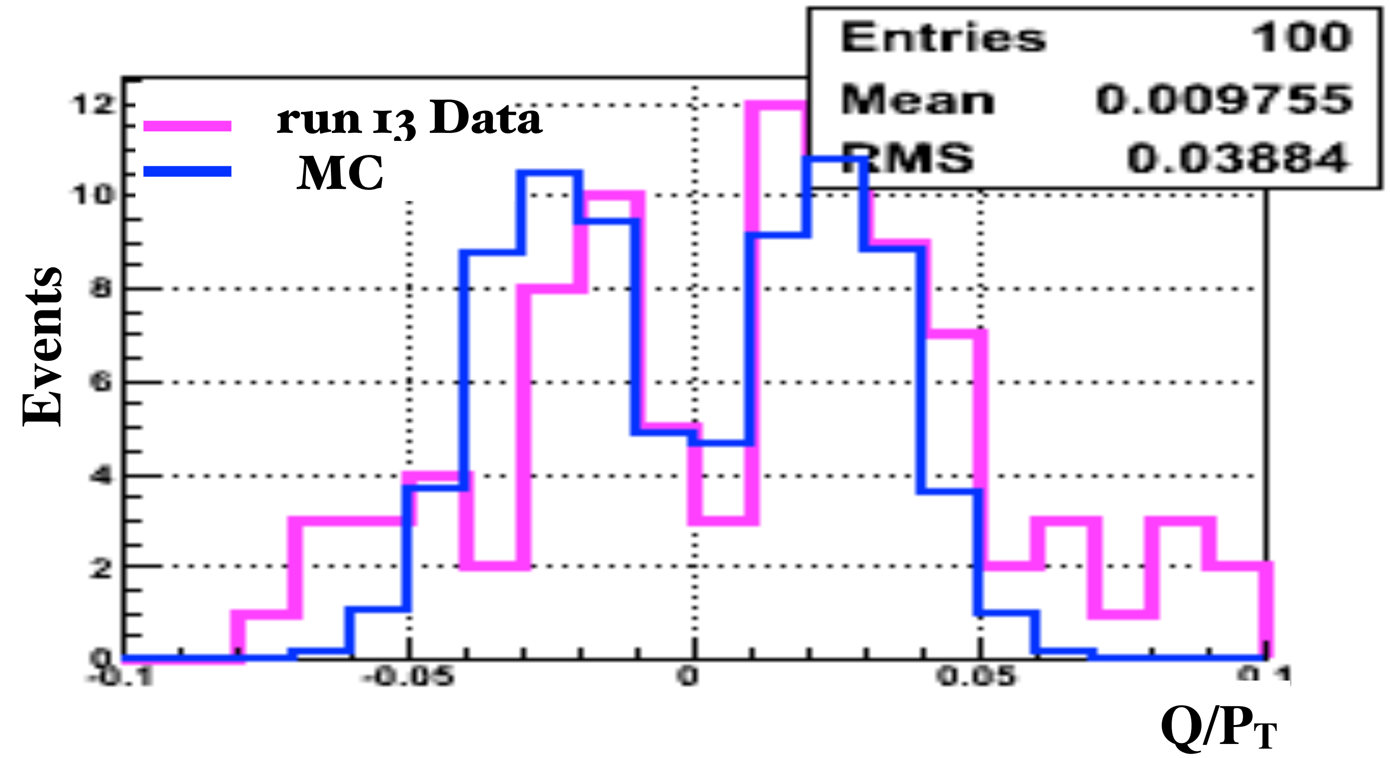
FGT (Forward Gem Tracker)





W Charge-sign Separation using FGT

FGT(2≥hits)+Vertex+EEMC+Prompt



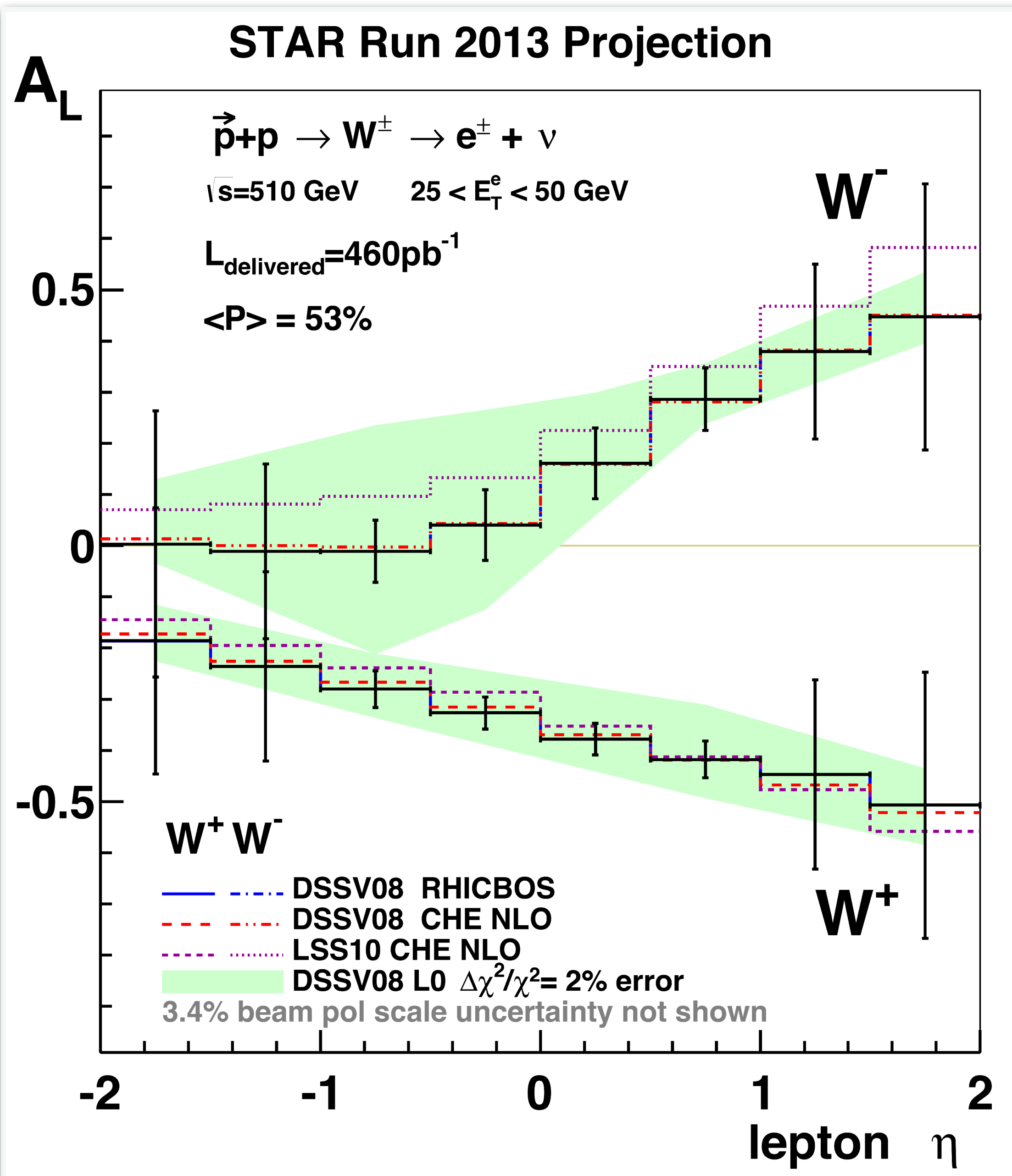
Prompt = actual measurement using TPC internal Multi-Wire proportional chamber

FGT res=0.02cm , VTX-XY res=0.02cm, VTX-Z res=1cm, TPC prompt res=0.1cm, EEMC res=0.3cm

~2.5 sigma separation with FGT+VTX+EEMC +PROMPT (~1/3 events)

STAR 2013 W A_L Projections

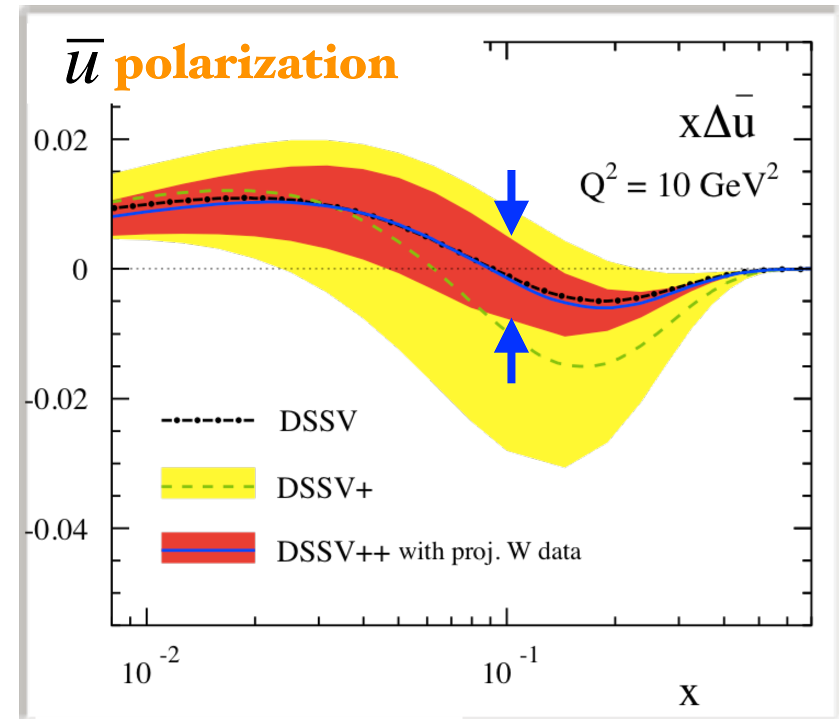
STAR W A_L Projections

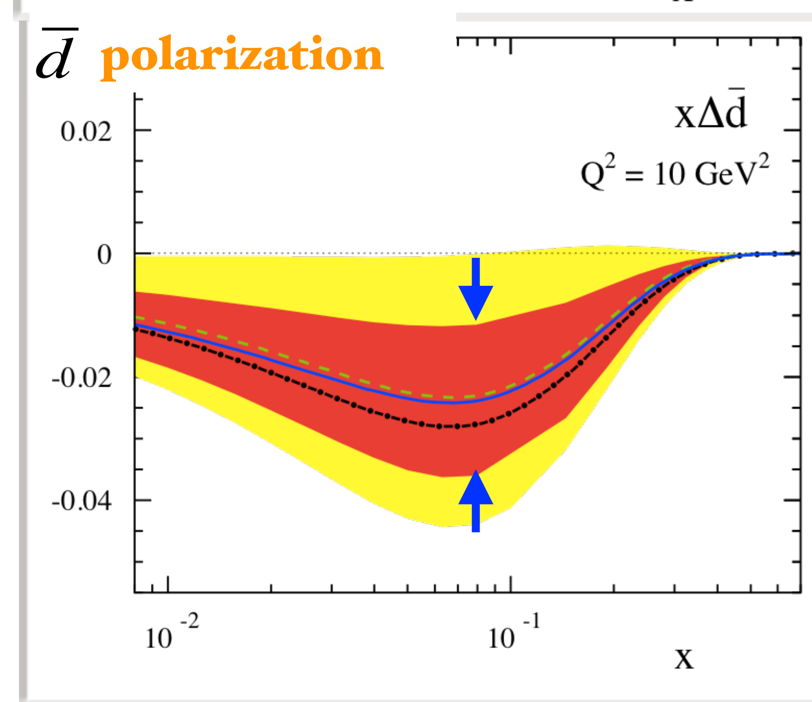


Higher precision results are expected from much larger statistics

Extension of forward and backward acceptance enhances sensitivity to $\bar{u}$ and $\bar{d}$ quark polarization

Impact on antiquark polarization





arXiv: 1304.0079

Summary / Outlook

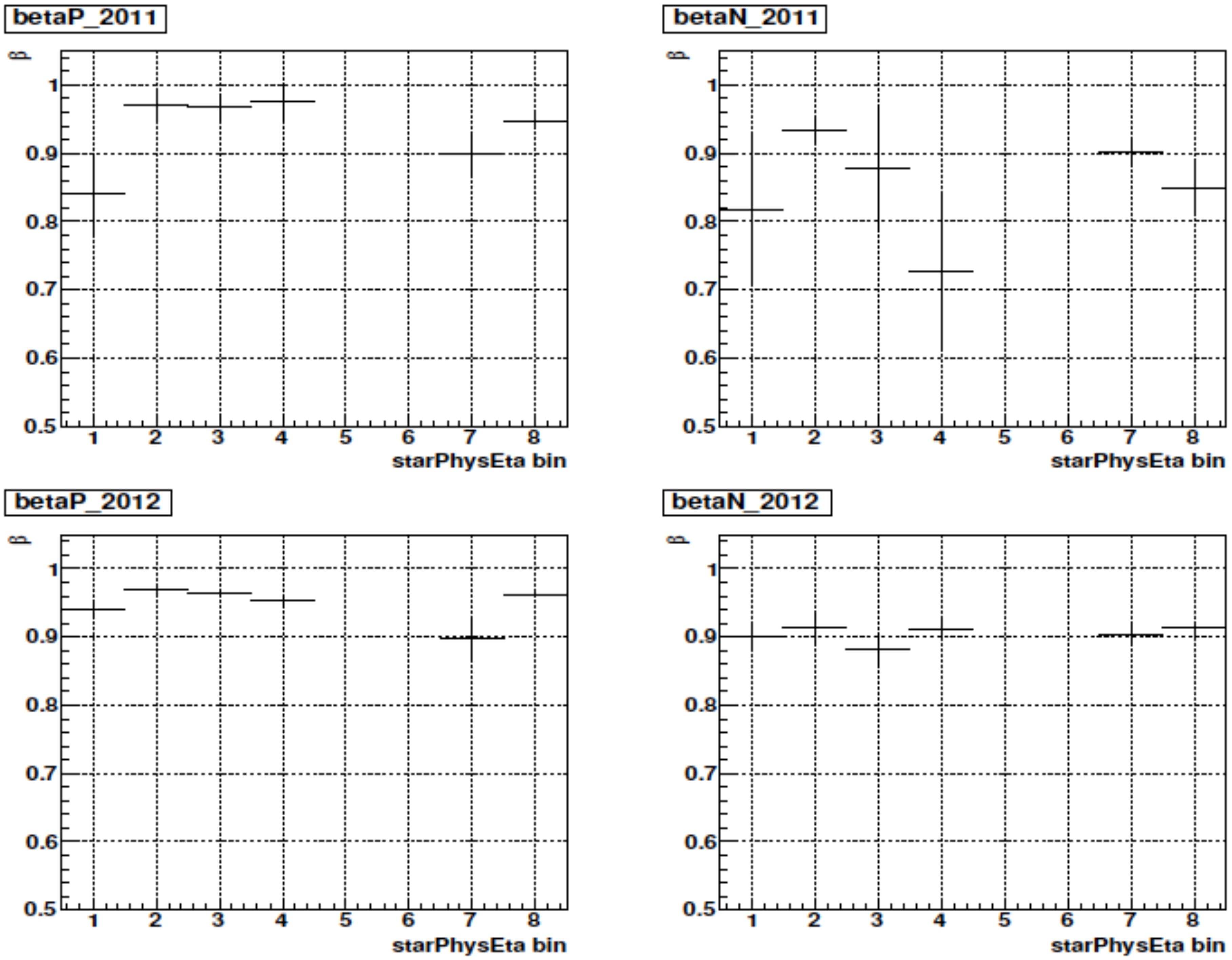
- **The Production of W boson in polarized P+P collisions provides a new means to study the spin and flavor asymmetries of the proton sea quark distribution.**
- **STAR has measured the parity violating single spin asymmetry A_L for $|\eta_e| < 1.4$ from 2012 and 2011 data, providing the first detailed look at the asymmetries η_e dependence.**
- **STAR 2012 W A_L results provide significant constraints on anti u and anti d quark polarization.**
- **Large statistics of STAR Run 2013 is being analyzed now in mid-rapidity region ($|\eta| < 1$) and will use the 510 GeV Barrel EM calorimeter calibration which is in progress.**
- **Run 2013 analysis will be extended up to $\eta = 1.4$ utilizing the EEMC in the forward region and then very forward region using the FGT as the tracking device requiring completion of carful calibration of EEMC and FGT.**
- **High precision results from 2013 will improve the constraints on the sea quark polarization.**

Backup

systematic uncertainties

- Beam polarization uncertainty: correlated scale 3.4%
- Relative luminosity uncertainty: correlated offset $\Delta A_L = 0.007$
- Background estimation: less than 10% of statistical error

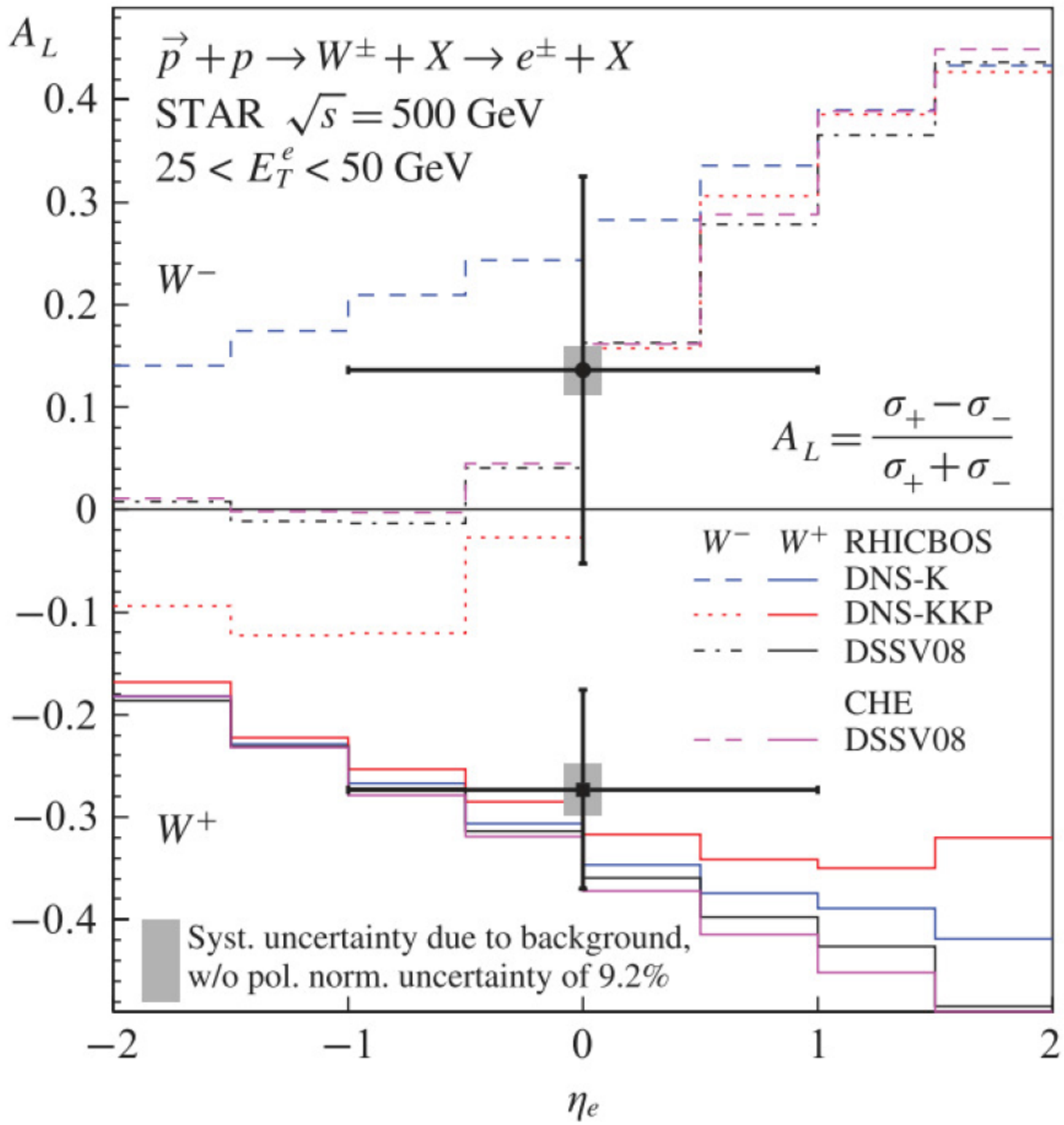
unpolarized BG β



W^+ β: ~ 0.95, W^- β: ~ 0.9

where $\beta = S/(S+B)$, S and B are the number of signal and background events in [25, 50] GeV

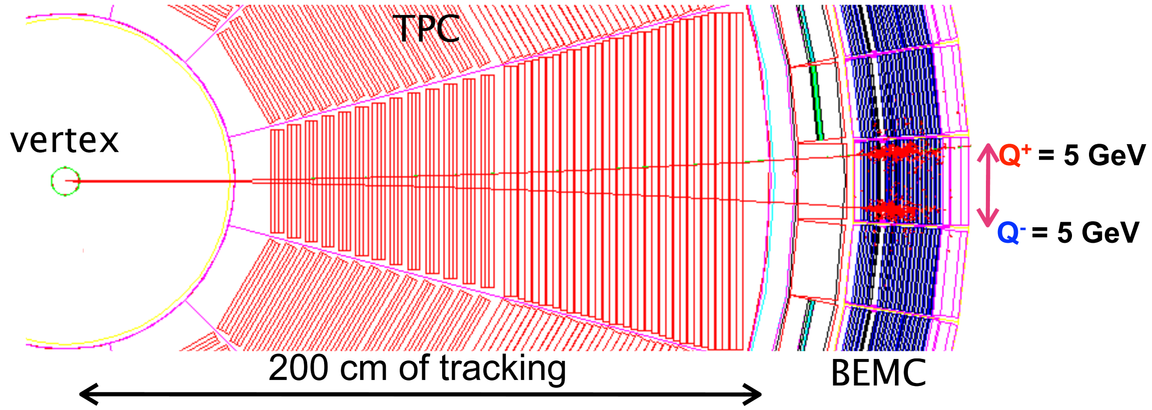
STAR 2009 W Results



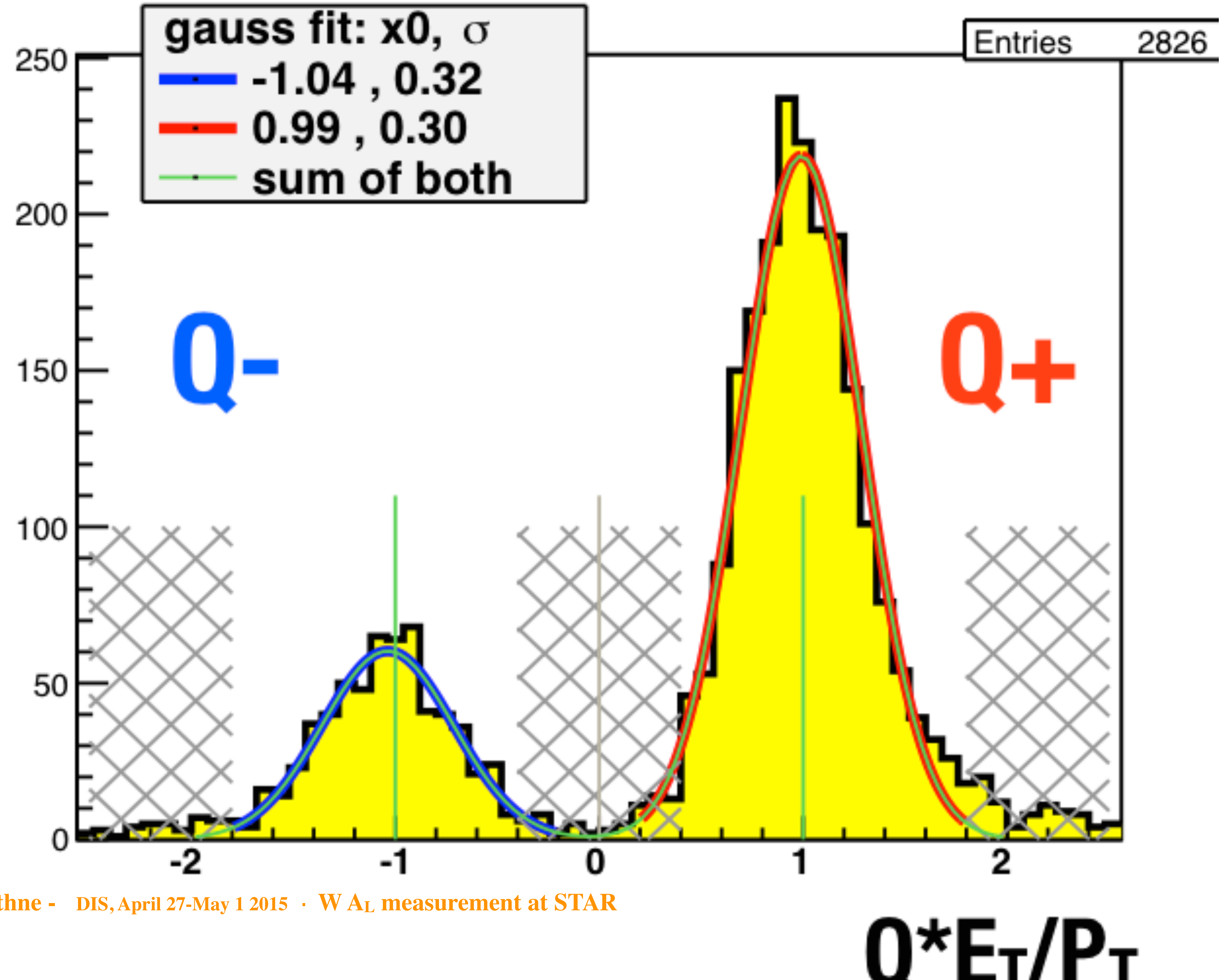
PRL 106, 062002 (2011)

STAR pp500 Longitudinal		
Run	L (pb^{-1})	$W^+(W^-)$ raw yield
2009	12	462 (192)
2011	9	342 (103)
2012	77	2417 (734)

Mid-Rapidity charge sign separation



- Charge sign reconstruction based on TPC track bending
- Estimate wrong sign contamination by fitting $Q * E_T / pT$ with Gaussian.

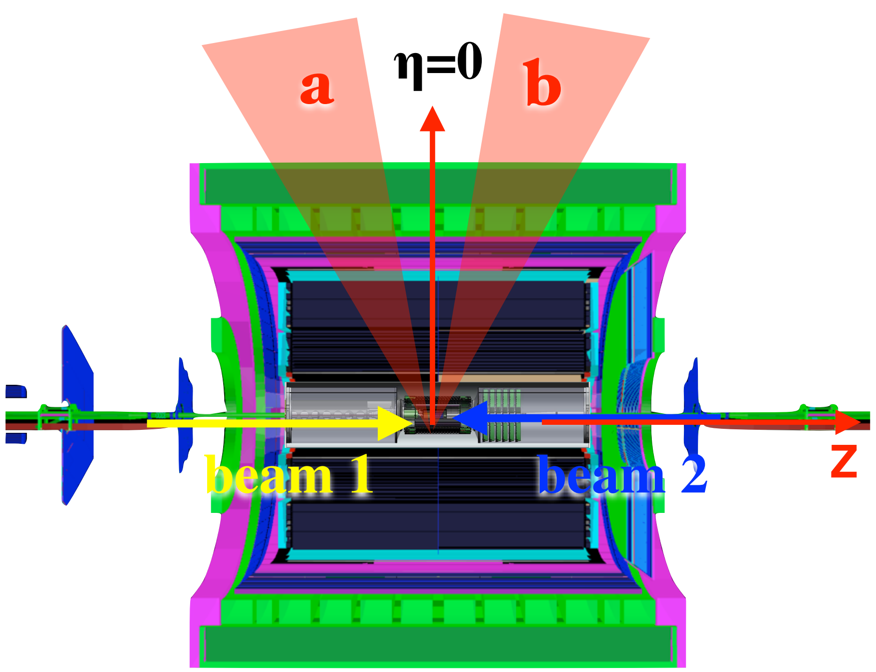


Extracting Asymmetries using Profile Likelihood Method

- Profile Likelihood method used in extracting Asymmetries from combination of run 2012 and run 2011 data [simple gaussian uncertainties breakdown particularly for small 2011 data sample]

- Define likelihood function for 8 spin-dependent yields from pair of symmetric η region of STAR

$$L = \Pi_i^4 p(M_i^a \mid \mu_i^a) p(M_i^b \mid \mu_i^b) g(\beta^a) g(\beta^b)$$



$p(M_i \mid \mu_i)$ - Poisson probability, for measured spin sorted yield M_i in the expected value μ_i given by:

$$\mu_{++}^a = I_{++} N(1 + P_1 \beta A_L^{+\eta_e} + P_2 \beta A_L^{-\eta_e} + P_1 P_2 \beta A_{LL}$$

$$\mu_{+-}^a = I_{+-} N(1 + P_1 \beta A_L^{+\eta_e} - P_2 \beta A_L^{-\eta_e} - P_1 P_2 \beta A_{LL}$$

$$\mu_{-+}^a = I_{-+} N(1 - P_1 \beta A_L^{+\eta_e} + P_2 \beta A_L^{-\eta_e} - P_1 P_2 \beta A_{LL}$$

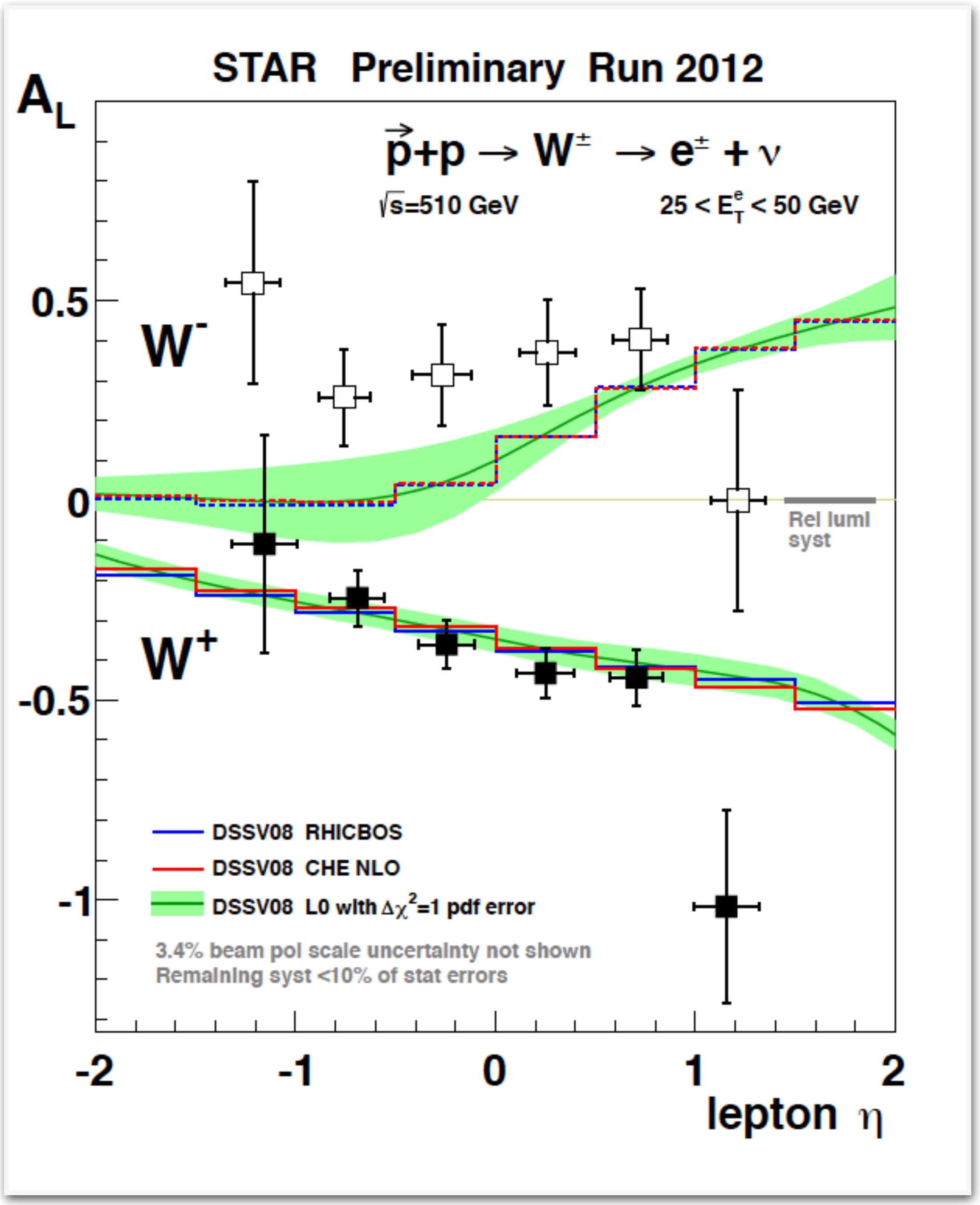
$$\mu_{--}^a = I_{--} N(1 - P_1 \beta A_L^{+\eta_e} - P_2 \beta A_L^{-\eta_e} + P_1 P_2 \beta A_{LL}$$

P_1, P_2 - beam polarization $A_L^{+\eta_e} (A_L^{-\eta_e})$ - single spin asymmetry
A_{LL} - double spin asymmetry N - spin averaged yield $I_{\pm\pm}$ - relative luminosity

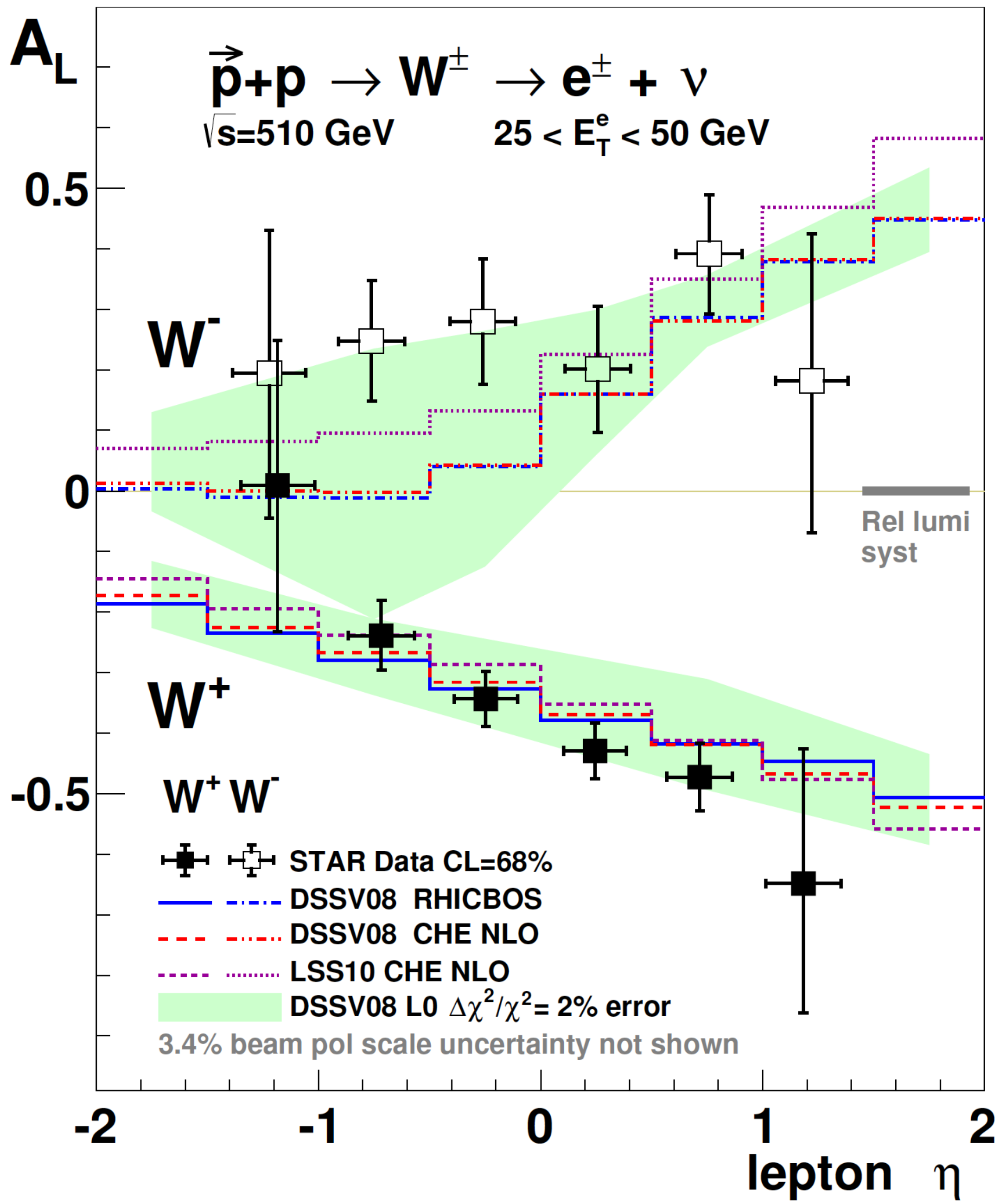
g(β) - Gaussian probability for estimated dilution background β

Extract asymmetries from likelihood function $L_{2011} \times L_{2012}$

Run 12 Preliminary results compare to Final

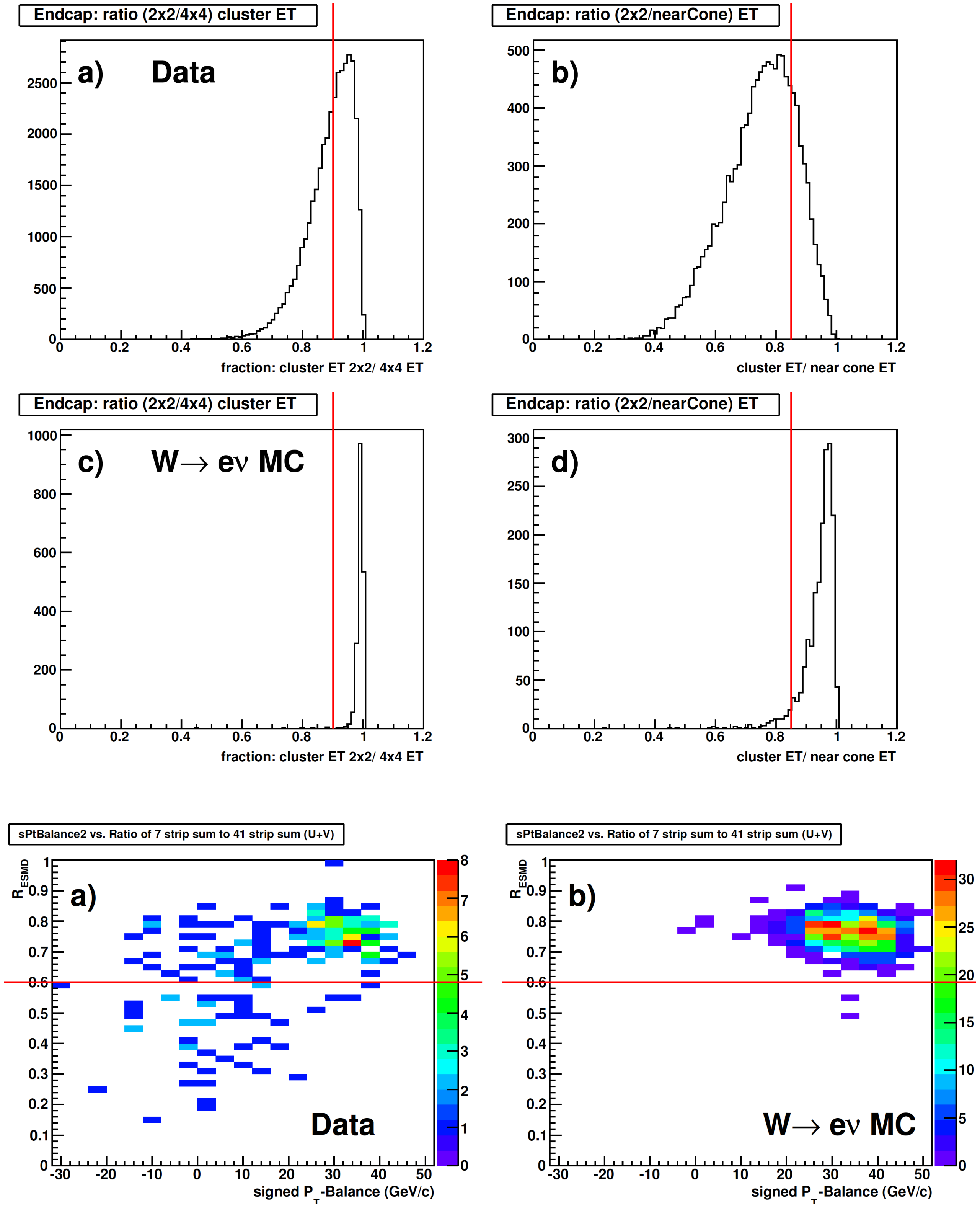


STAR FINAL Run 2012+2011

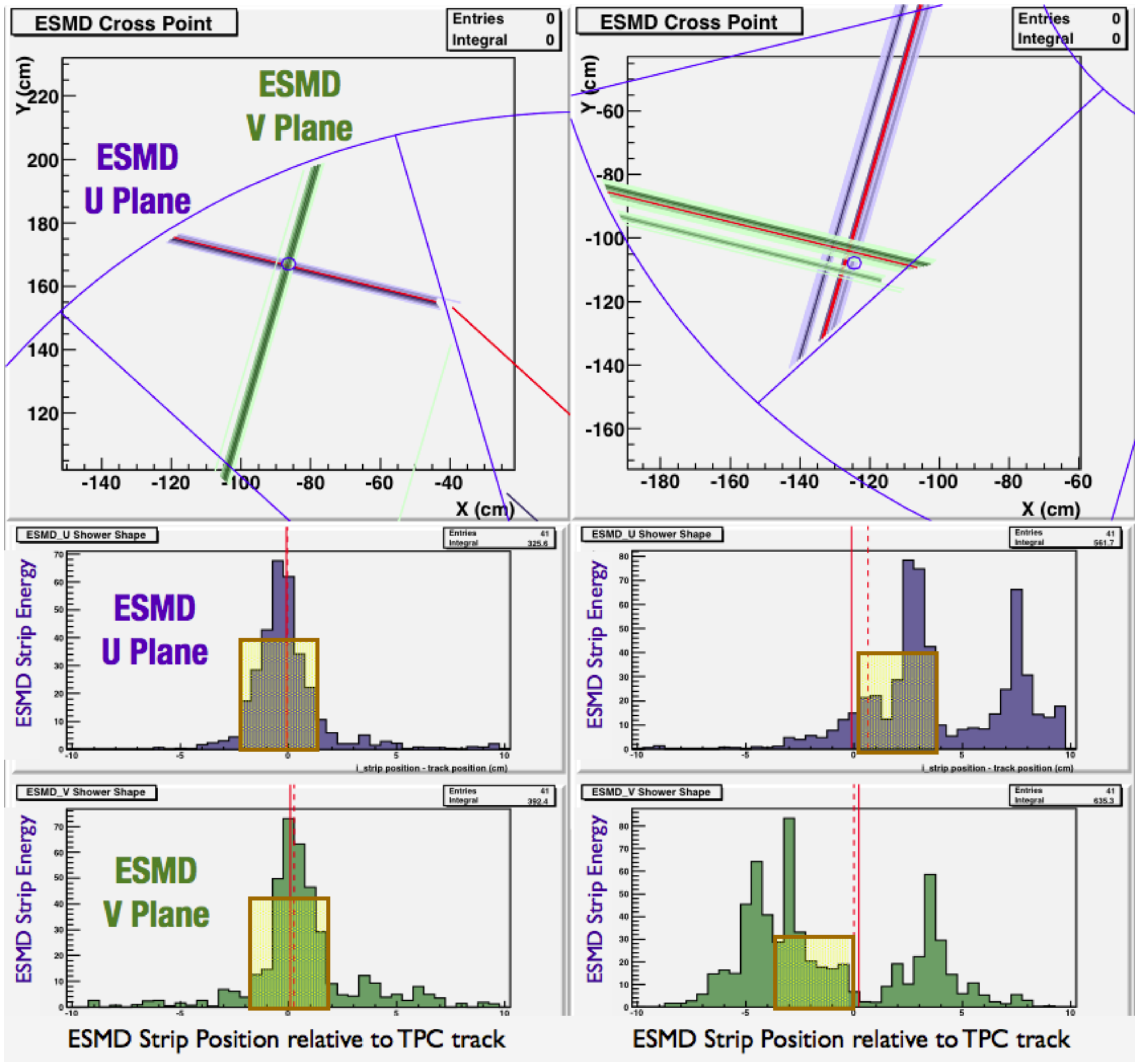


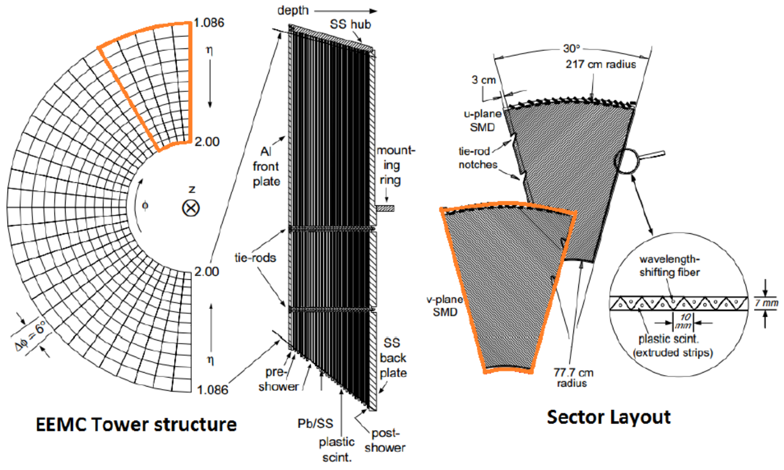
PRL 113,72301 (2014)

Endcap W Selection



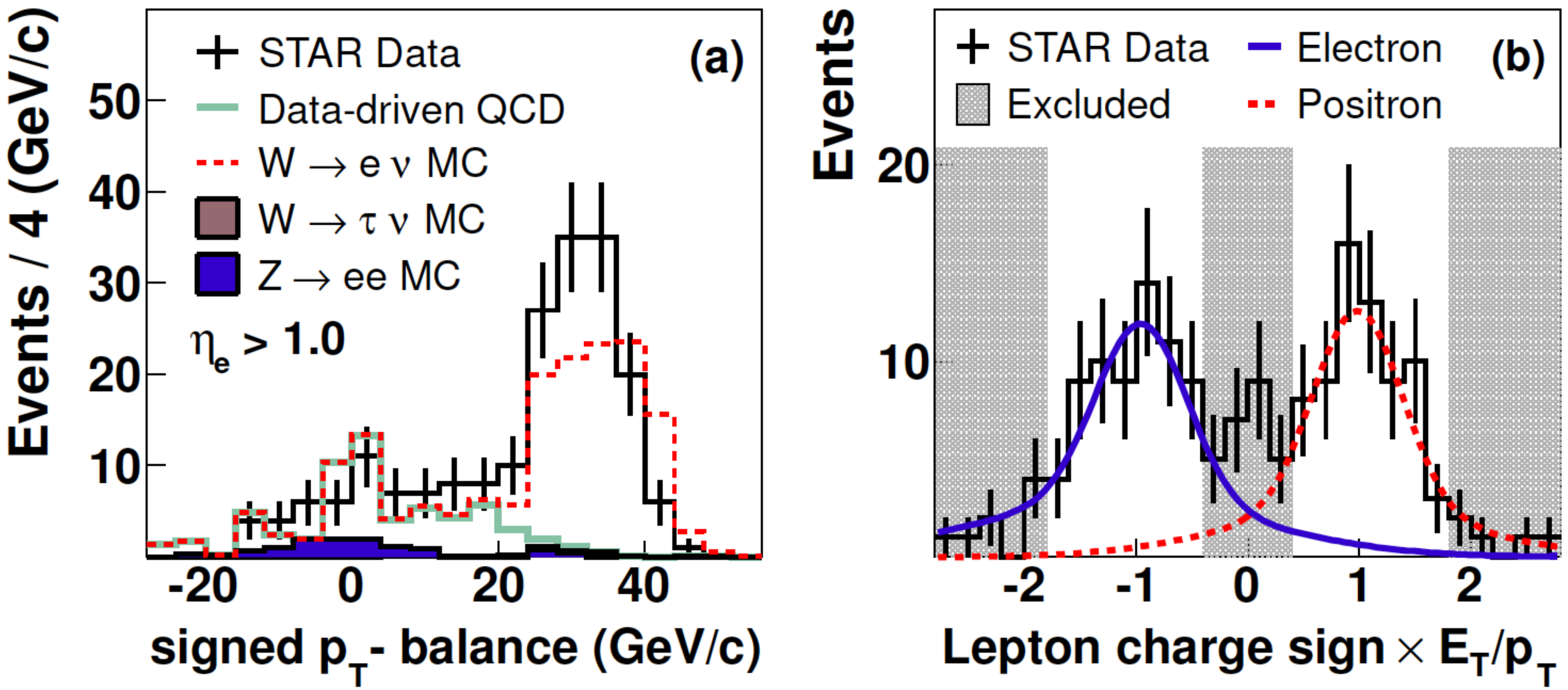
ESMD CUTS





$$R_{ESMD} = \frac{\sum_{i=-3}^{+3} E_i^U + E_i^V}{\sum_{i=-20}^{+20} E_i^U + E_i^V}$$

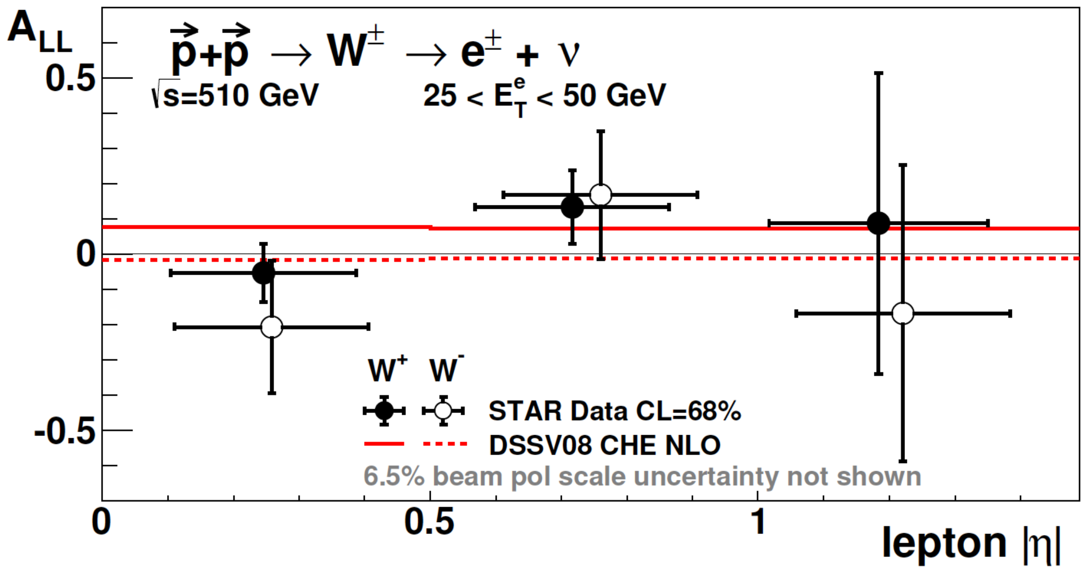
Forward Rapidity Background Estimation and charge sign separation



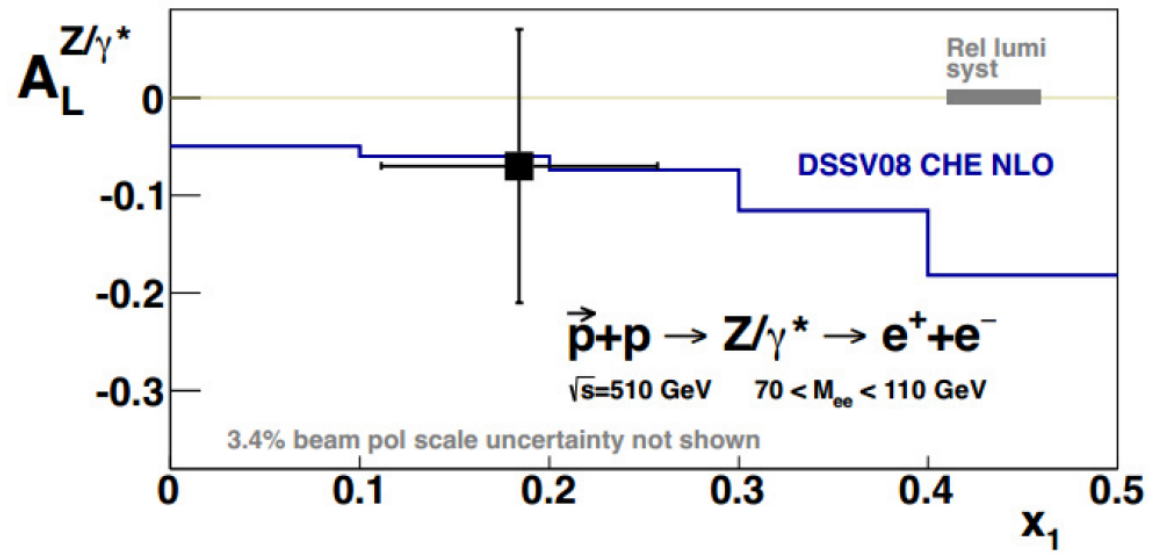
PRL 113,72301 (2014)

Run 12 ALL and Z AL results

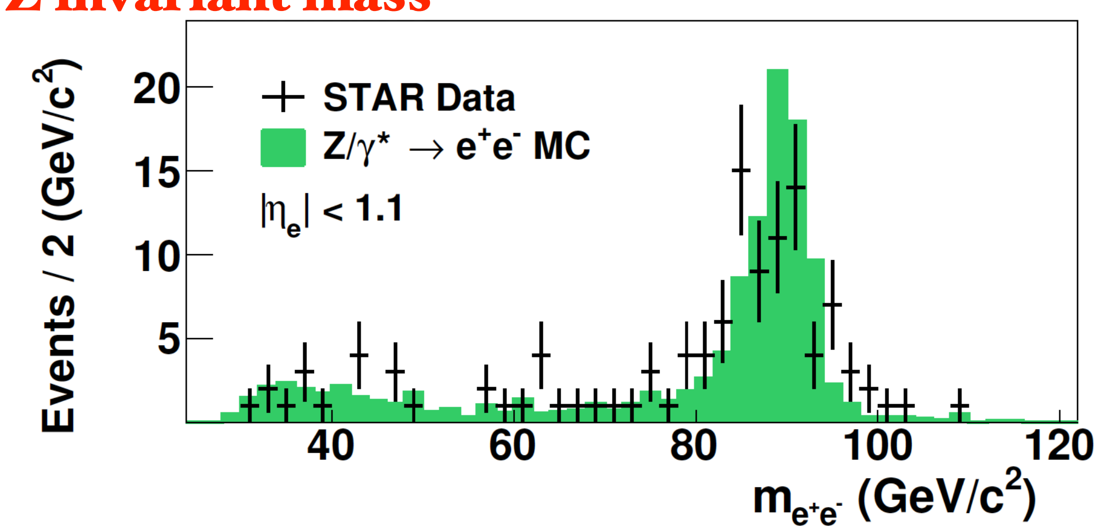
$$A_{LL} = \frac{(\sigma^{++}+\sigma^{--})-(\sigma^{+-}+\sigma^{-+})}{(\sigma^{++}+\sigma^{--})+(\sigma^{+-}+\sigma^{-+})}$$



PRL 113,72301 (2014)



Z invariant mass



PRL 113,72301 (2014)

- Probes different combination of quark polarizations

$$A_{LL} = \frac{\sigma^{++}-\sigma^{+-}}{\sigma^{++}+\sigma^{+-}} \qquad A_{LL}^{W+} \sim \frac{\Delta u}{u}\frac{\Delta \bar{d}}{\bar{d}} \qquad A_{LL}^{W-} \sim \frac{\Delta d}{d}\frac{\Delta \bar{u}}{\bar{u}}$$

- Asymmetries expected to be smaller, and first measurement consistent with predictions from DSSV

W production: more details

Helicity structure can see in the differential cross section of W

$$\frac{d\sigma_{W^+}}{d\cos\theta} \propto \bar{d}(x_1)u(x_2)(1+\cos\theta)^2 + u(x_1)\bar{d}(x_2)(1-\cos\theta)^2$$

$$\frac{d\sigma_{W^-}}{d\cos\theta} \propto \bar{u}(x_1)d(x_2)(1-\cos\theta)^2 + d(x_1)\bar{u}(x_2)(1+\cos\theta)^2,$$

W tends to boost direction of the valance quark traveling

Helicity structure of the interaction causes lepton to emit parallel (antiparallel) to W-(W+)

higher (lower) x parton in the collision is most likely quark (antiquark) . And quark is very likely to come from valance region

W longitudinal momentum

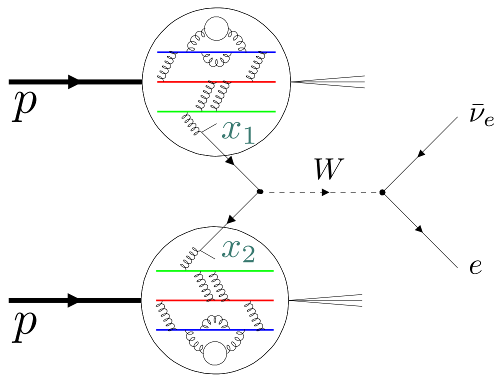
e decay kinematics in lab frame related to W boost direction

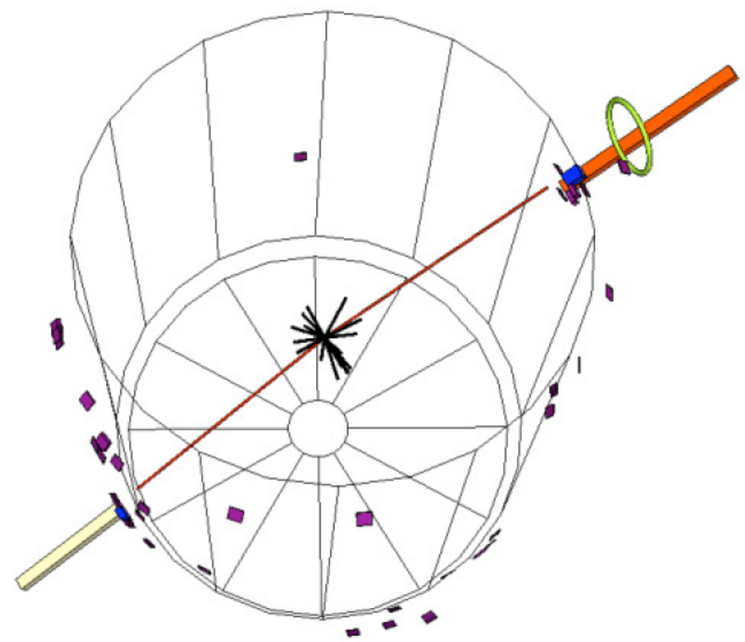
$$p_{L,W} = \frac{\sqrt{s}}{2}(x_1 - x_2)$$

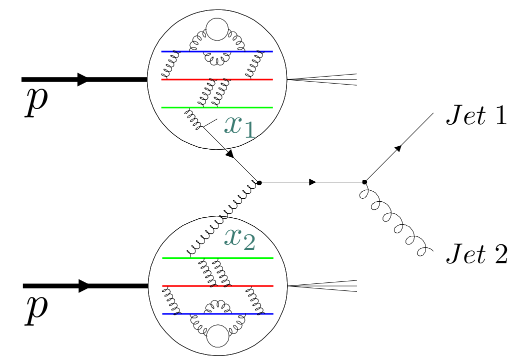
$$p_{L,e}^{lab} = \frac{1}{\gamma}p_{L,e}^{*} + \beta E_e^{lab}, \quad p_{L,e}^{*} = \cos\theta \cdot M_W/2 \quad (p_T^e = \sin\theta \cdot M_W/2).$$

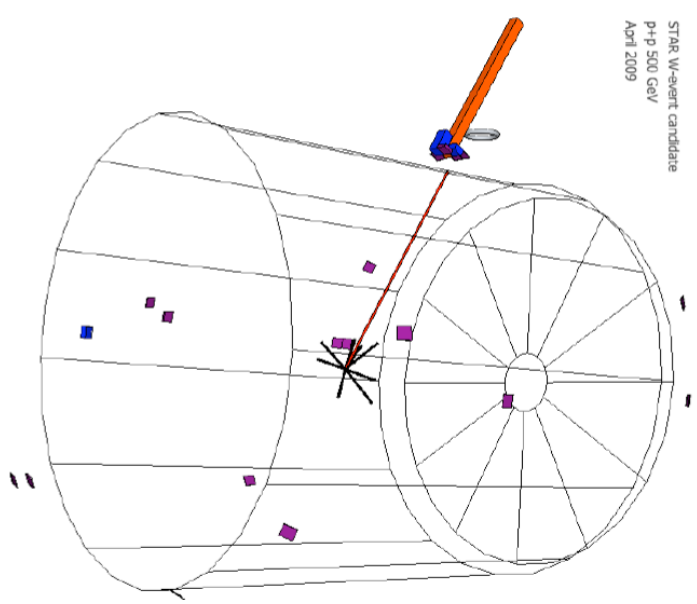
W , di-Jet and Z type events

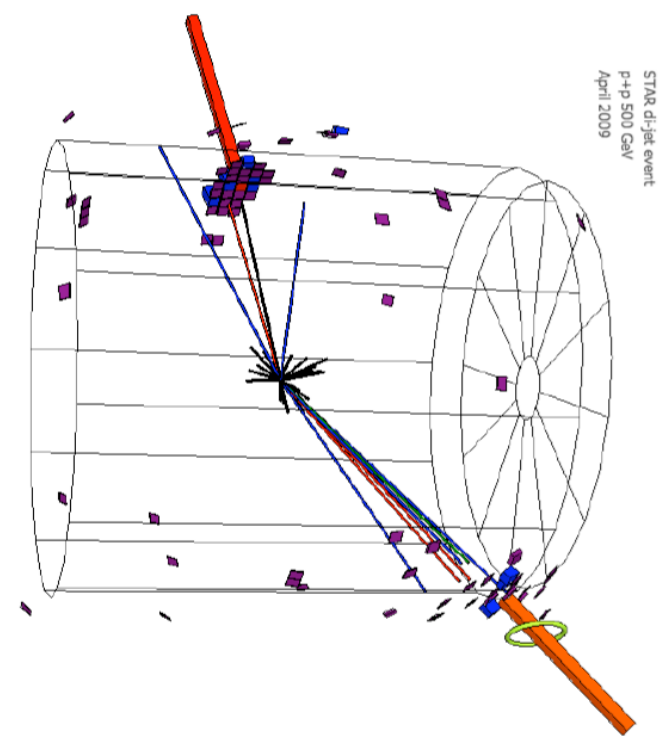
simulated Z-ee event











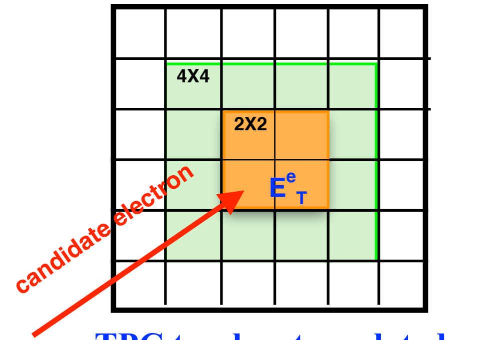
simulated W->e event

simulated di-jet event

Mid-rapidity ($|\eta_e| < 1$) W Selection

✤ Match P_T > 10 GeV TPC tracks to EMC cluster

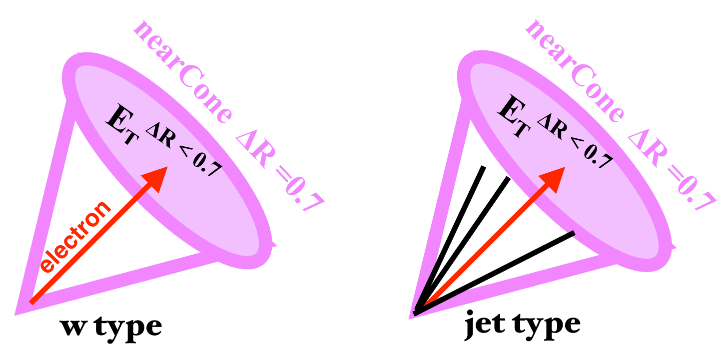
$E^e_T \;/\; E_T^{4X4} \quad > 0.95$



TPC track extrapolated
to Barrel colorimeter tower grid

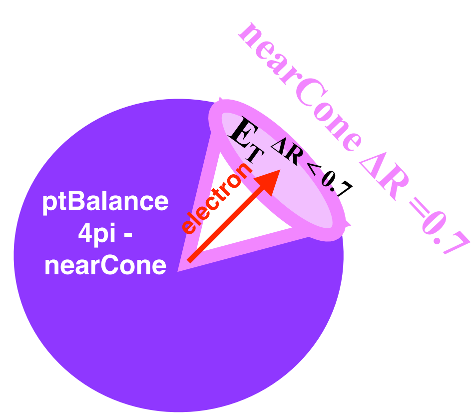
✤ Isolate from QCD di-jet type event

$E^e_T \;/\; E_T^{\Delta R < 0.7} \quad > 0.88$



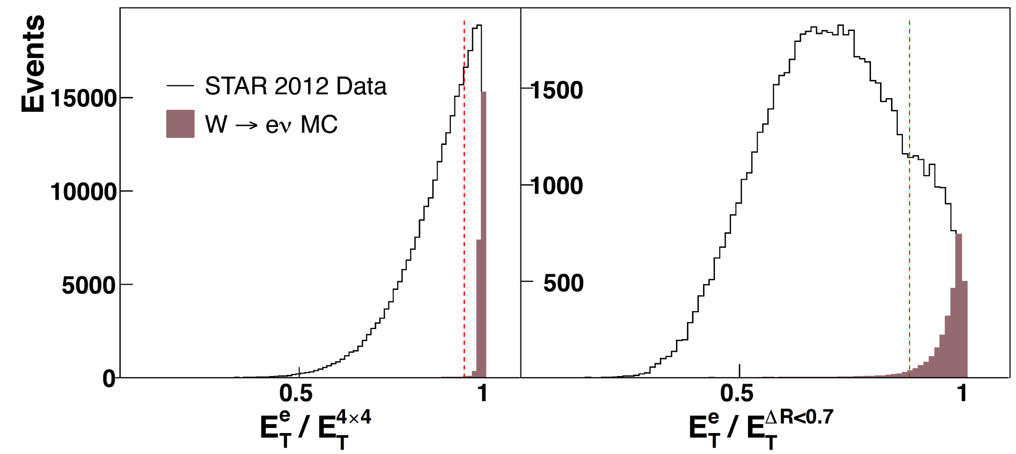
✤ Use Larger imbalance of transverse momentum

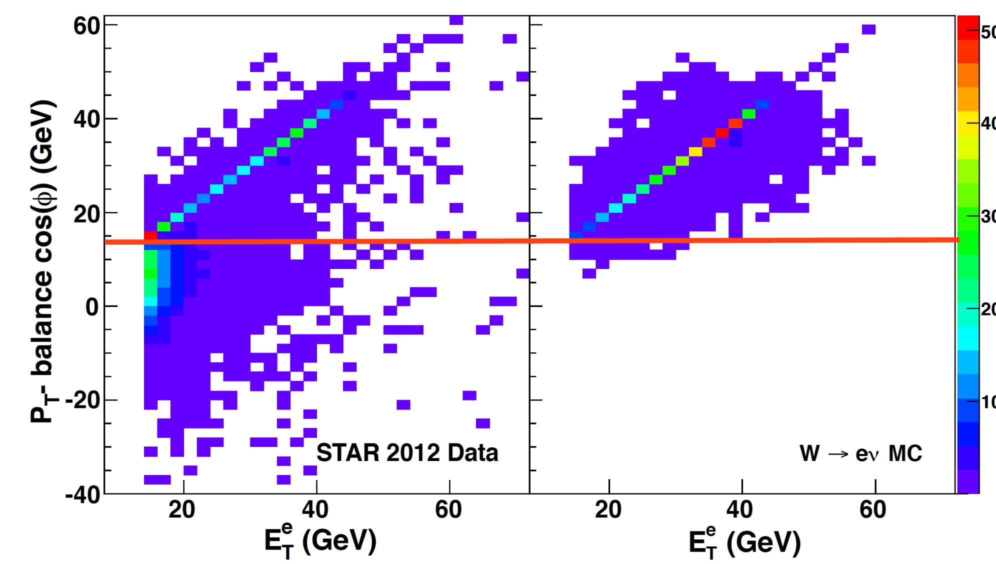
$$\vec{p}_T^{\,balance} = \vec{p}_T^{\,e} + \sum_{\Delta R > 0.7} \vec{p}_T^{\,jets}$$

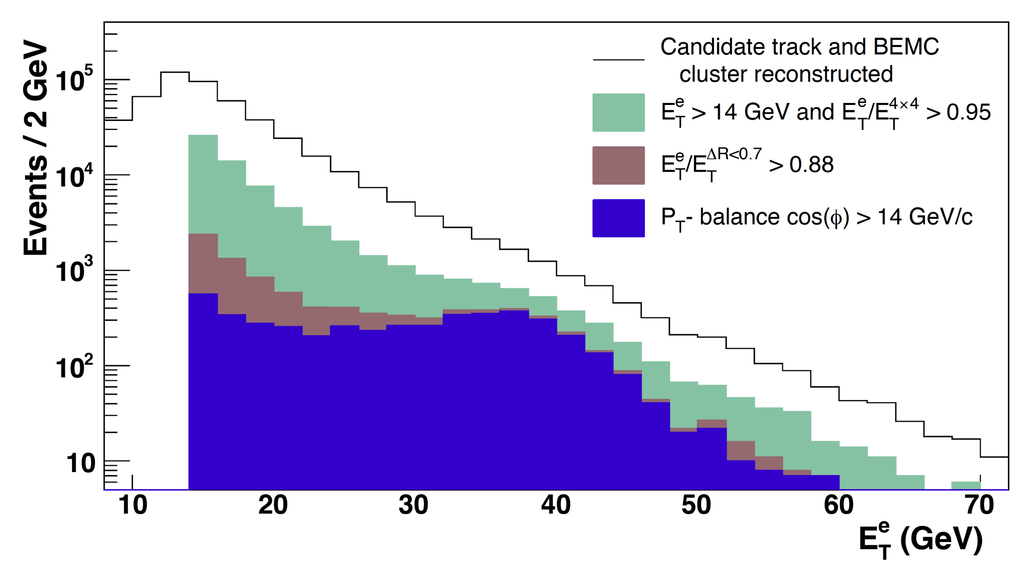


Transverse plane views

✤ e+ and e- Charge sign Separation

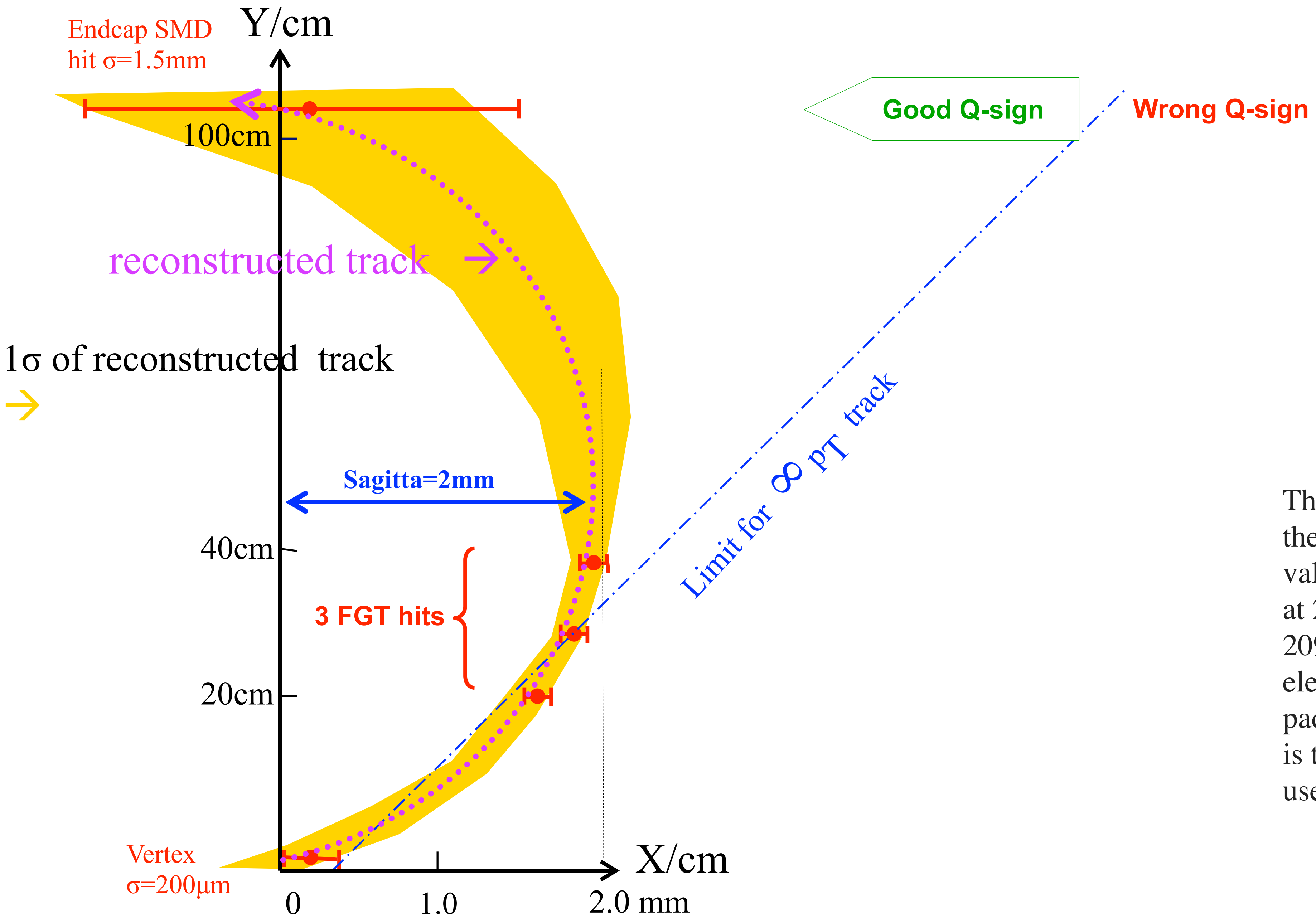






FGT

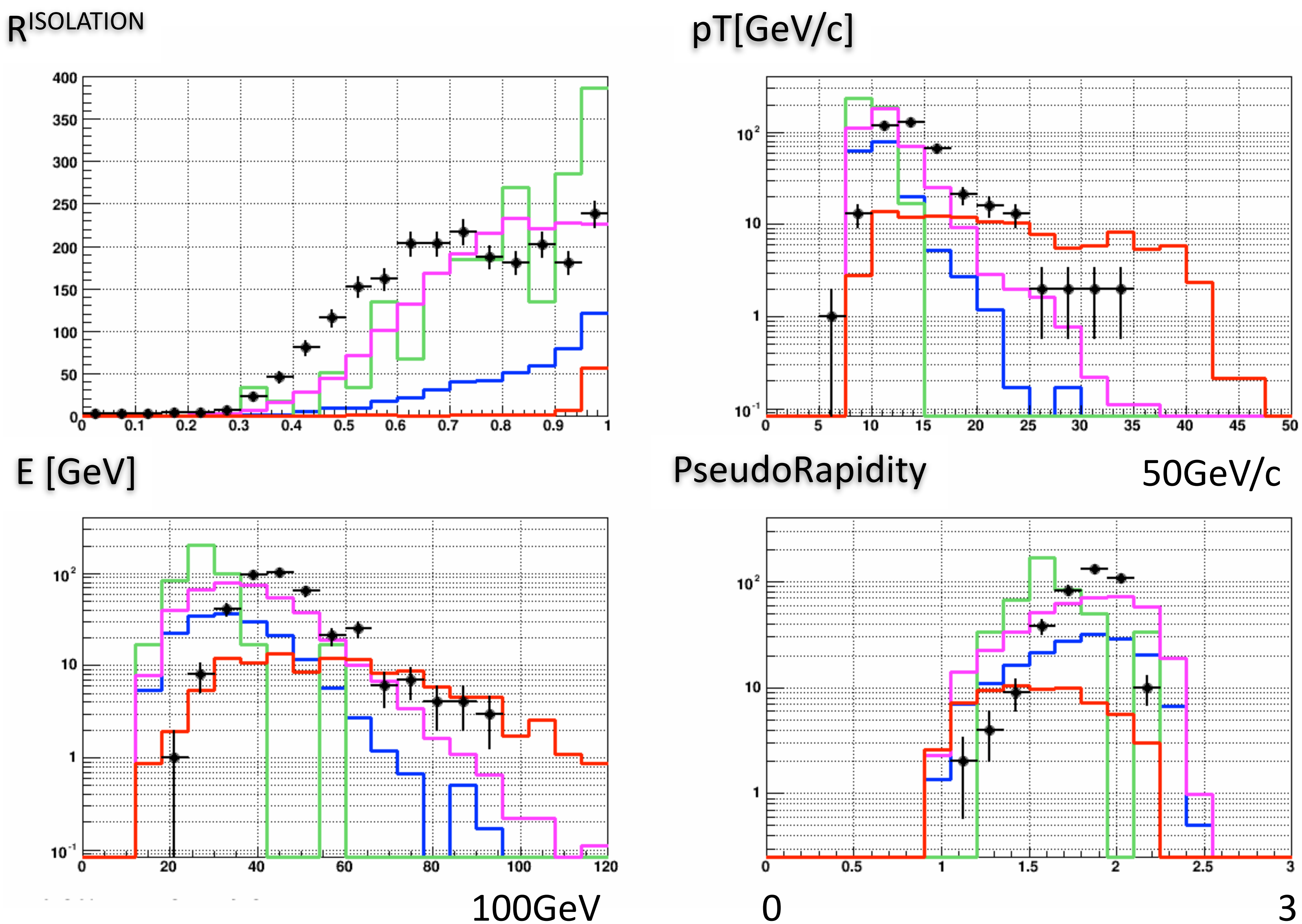
Illustration of charge-sign discrimination



The TPC prompt hits are 'hits' using the ANODE wires located at large Z values
at 209.5 cm for inner subsectors and 209.7 cm for outer subsectors. The electrons from a charge drift to the pad planes. The 'first signal in time' is then
used define a prompt hit.

FGT track reconstruction

- Comparison of data / fast MC: Track reconstruction



Run13 Data (FGT+VTX +EEMC, no prompt)

PYTHIA QCD charged hadrons

PYTHIA W

PYTHIA QCD electrons

PYTHIA QCD photons

The central values are both from the theoretical predictions. So the central values of the polarized anti-u and anti-d quarks should be same. The the uncertainties are estimated from the W yields. For the old version, it maybe estimated from the run9 W efficiency. But for the new version, the W yields are estimated from run13 W efficiency. Due to the higher <zdc> rate , the later one should be a little smaller. I roughly compared the error bars in these two projection plots, the differences is very slight, something like <10%. But, for the new version, we indeed don't have the corresponding polarized anti-u and anti-d distribution.

- **[simple gaussian uncertainties breakdown particularly for small 2011 data sample]**