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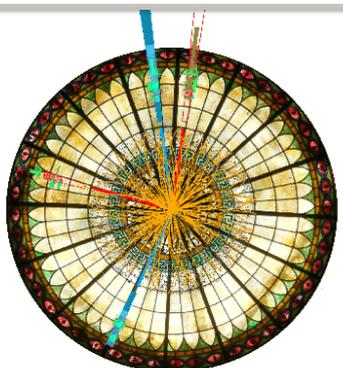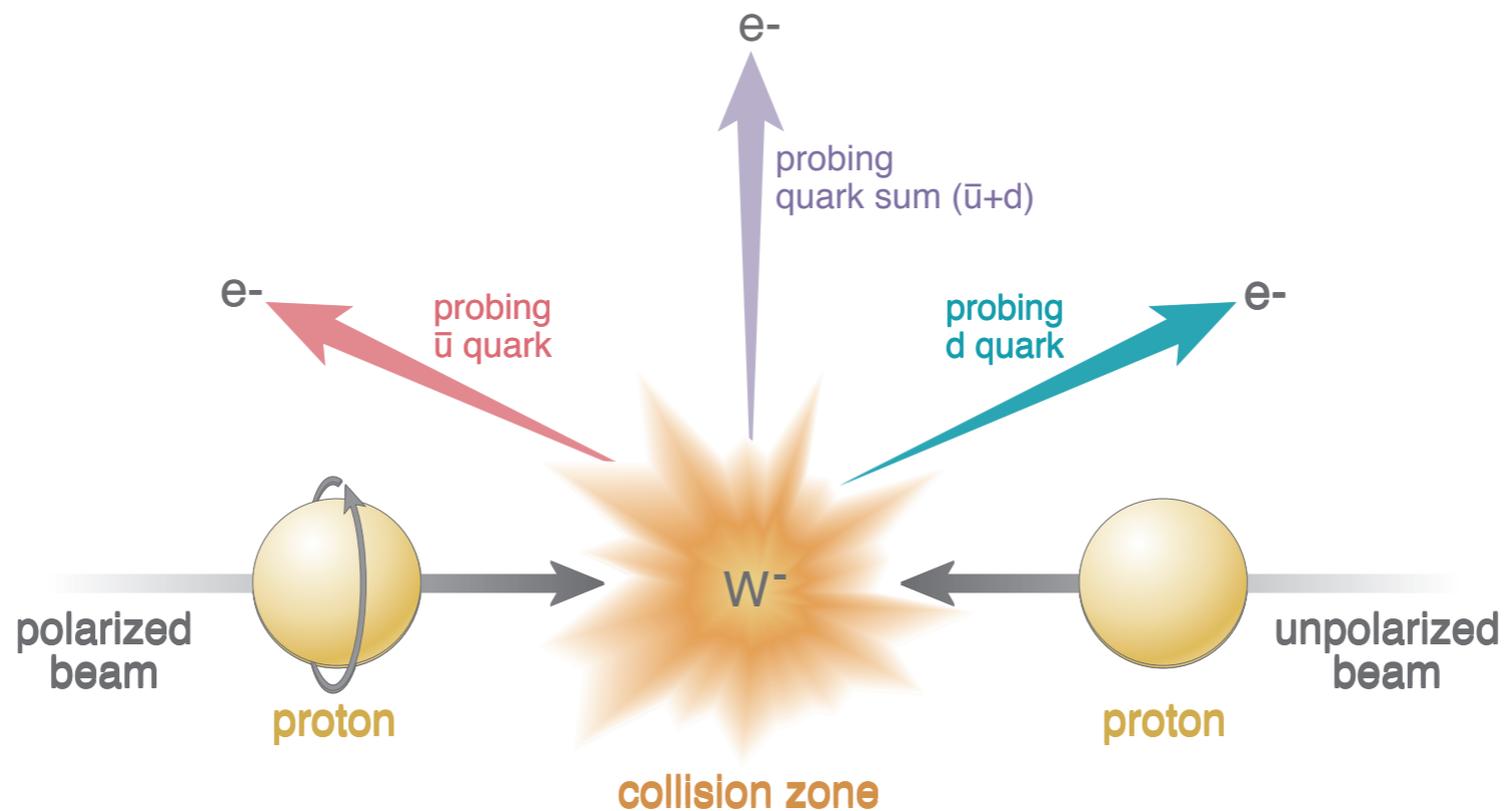

DIS 2015

XXIII International Workshop on
Deep-Inelastic Scattering and
Related Subjects

Dallas, Texas
April 27 – May 1, 2015

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(for the STAR collaboration)
Temple University

STAR
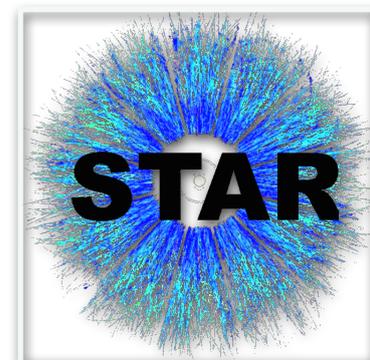
Evolving Picture of Proton's Spin Structure
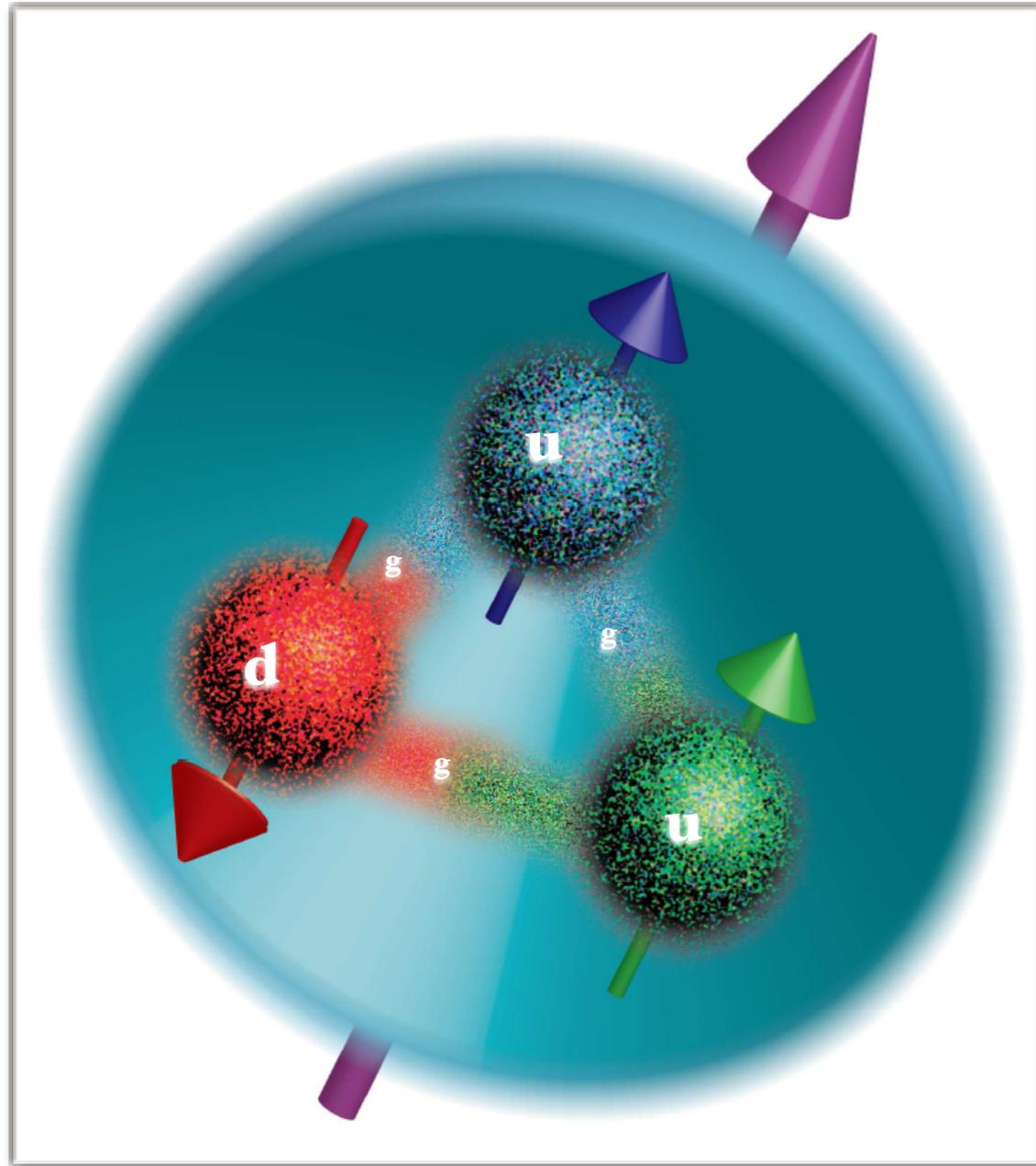
Valance Quarks

Sea Quarks

2
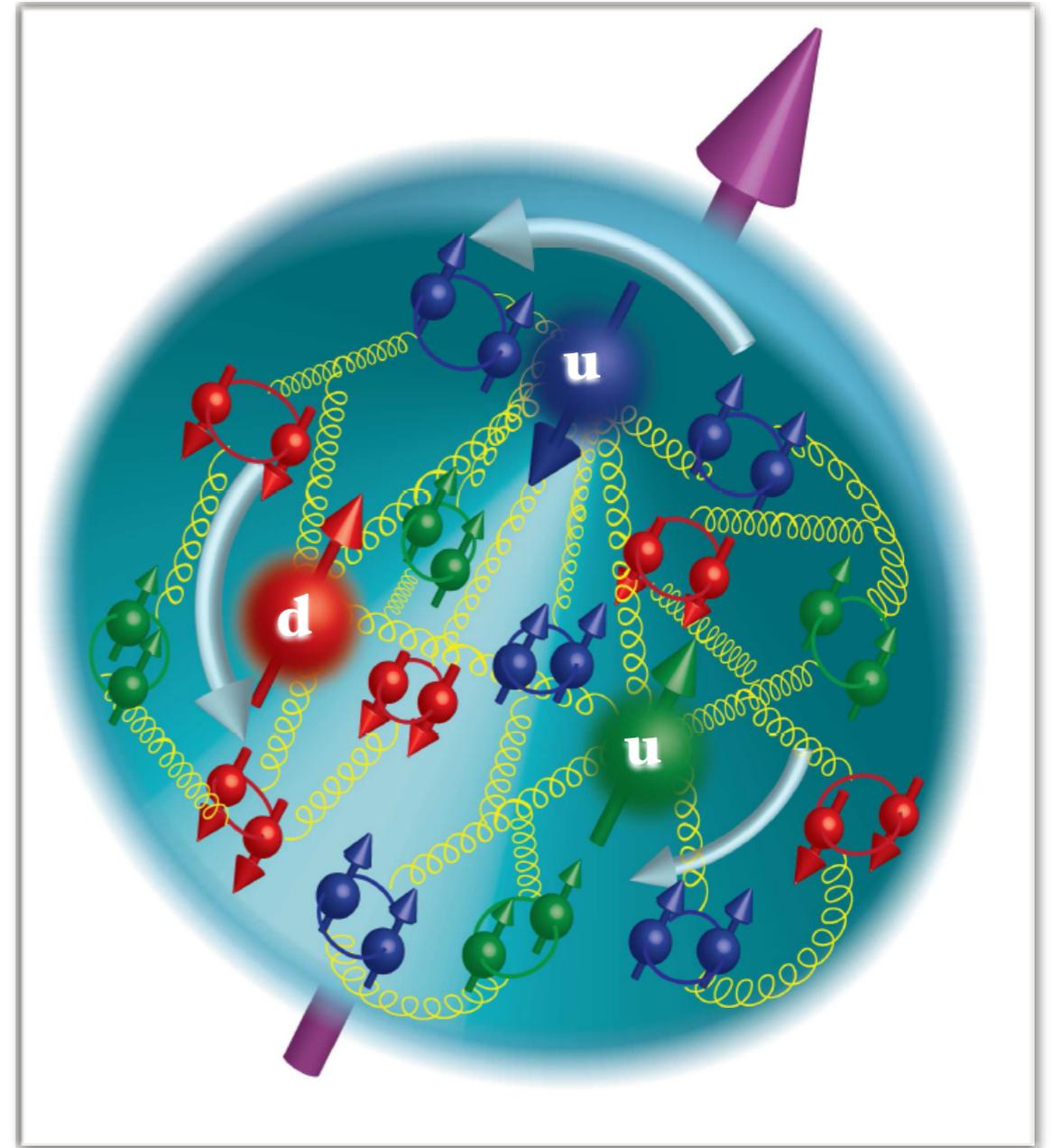
Anti Quark Polarization

Spin sum rule for **longitudinally** Polarized proton :

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

Jeffe and Monahar, 1990

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

~30 % from polarized inclusive DIS

Helicity PDF

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

**DSSV Global Analysis**

x(Δu+$\Delta\bar{u}$)

x(Δd+$\Delta\bar{d}$)

x $\Delta\bar{u}$

x $\Delta\bar{d}$

⬚⬚⬚ $\Delta\chi^2=1$ (Lagr. multiplier)

▬ $\Delta\chi^2=1$ (Hessian)

— DSSV

$Q^2 = 10$ GeV^2

PRD 80, 034030(2009)

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W Boson Production

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

probing quark sum ($\bar{u}+d$)

probing $\bar{u}$ quark

probing d quark

polarized beam — proton — collision zone — proton — unpolarized beam

W^-
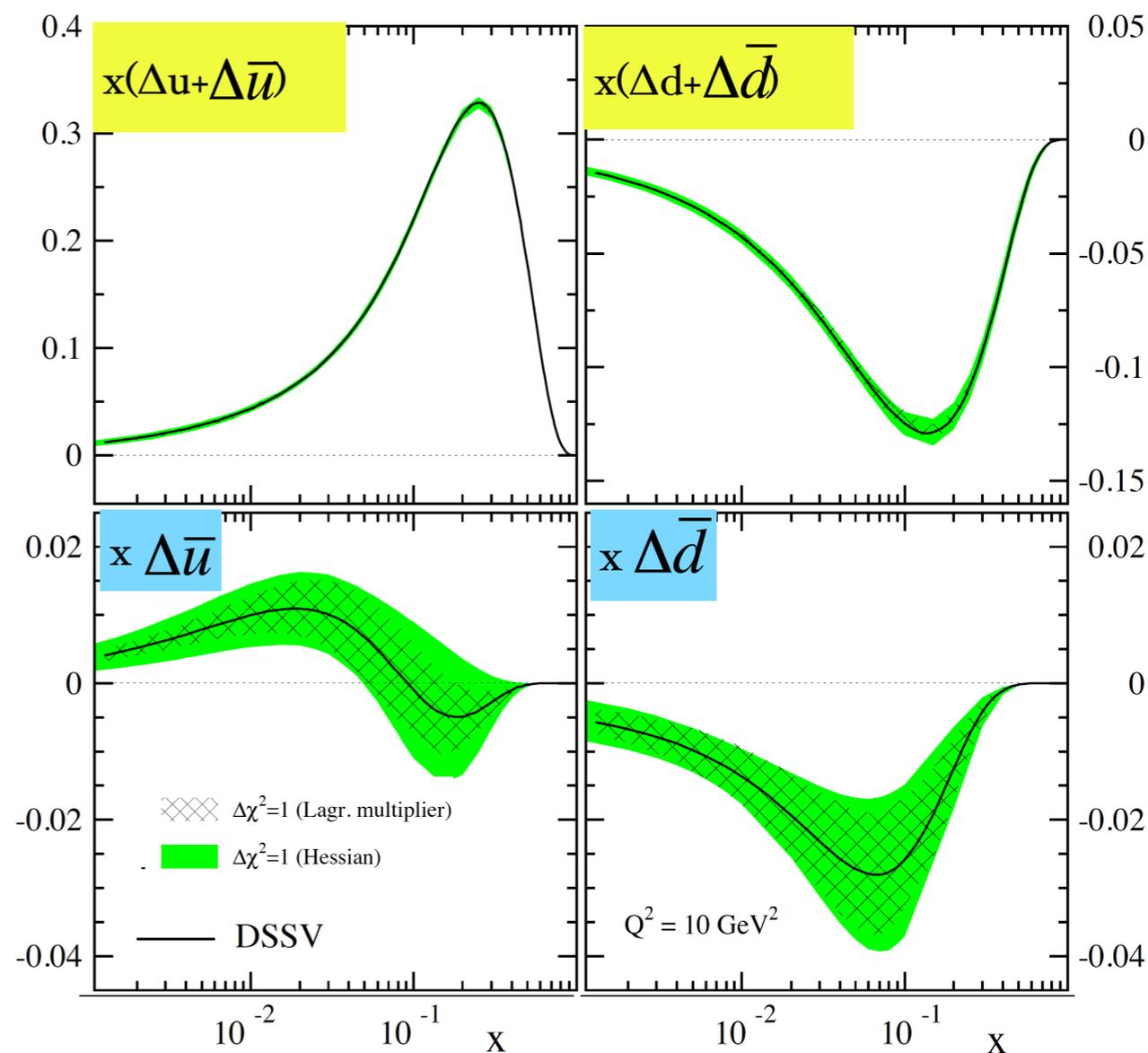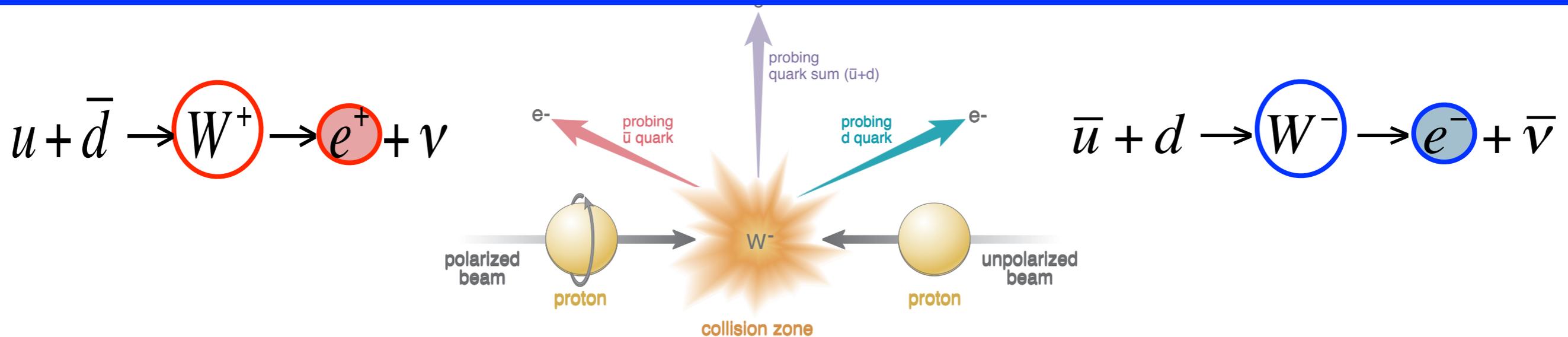
✤ **Direct Coupling** to the Quark and anti Quark of interest.

✤ Maximum **violation of parity** leads to perfect **spin separation.**
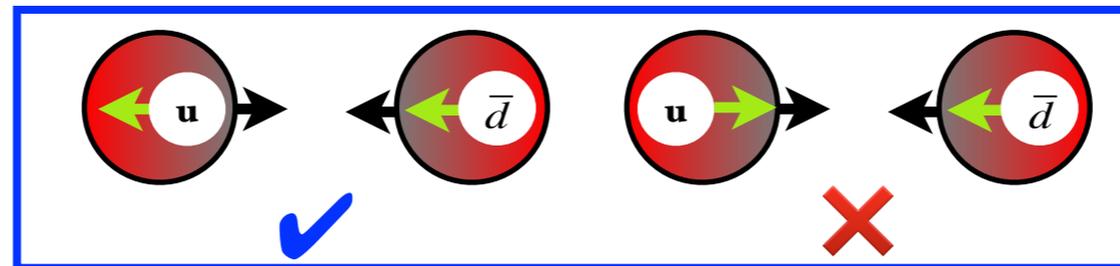
✤ **High** resolution scale **(Q²)** set by the **W mass.**

✤ **Easy detection** via the **leptonic decay channels**.

Parity violating longitudinal single spin asymmetry

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

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W A_L :Theoretical Aspects

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

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

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

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

e⁻ θ
$\bar{u}$ d

backward e⁻
parallel to W⁻
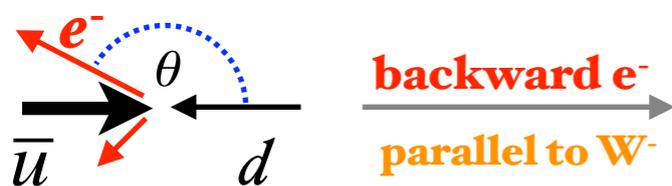
$$\frac{\Delta\bar{u}}{\bar{u}}$$

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

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

e⁺ θ
$\bar{d}$ u

forward e⁺
anti parallel to W⁺

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

A_L

$A_L^{W^-} = \frac{\Delta\bar{u}}{\bar{u}}$

W^-

$A_L^{W^-} = -\frac{\Delta d}{d}$

	W^-	W^+	
			RHICBOS
			DNS-K
			DNS-KKP
			DSSV08
			CHE
			DSSV08

W^+

$A_L^{W^+} = \frac{\Delta\bar{d}}{\bar{d}}$

$A_L^{W^+} = -\frac{\Delta u}{u}$

lepton pseudorapidity η_e
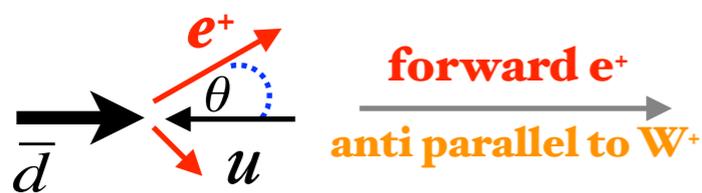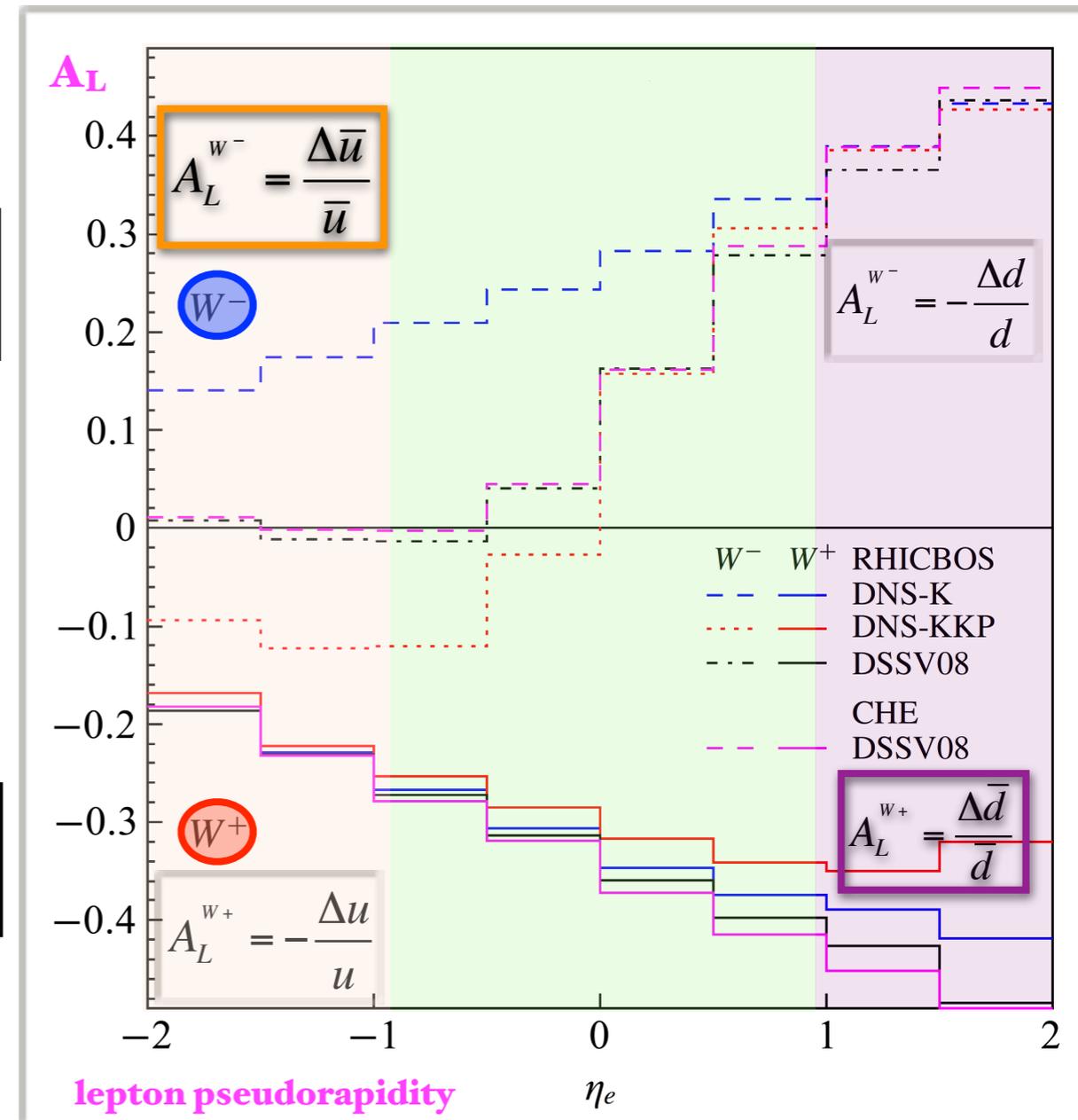
RHIC : Relativistic Heavy Ion Collider

STAR Detector Overview

η=-1.1

η=0

Endcap Electro-Magnetic Calorimeter (EEMC)

η=+1.1

Beam - Beam Counter (BBC)

Magnet

Forward GEM Tracker (FGT)

Time Projection Chamber (TPC)

Barrel Electro-Magnetic Calorimeter (BEMC)
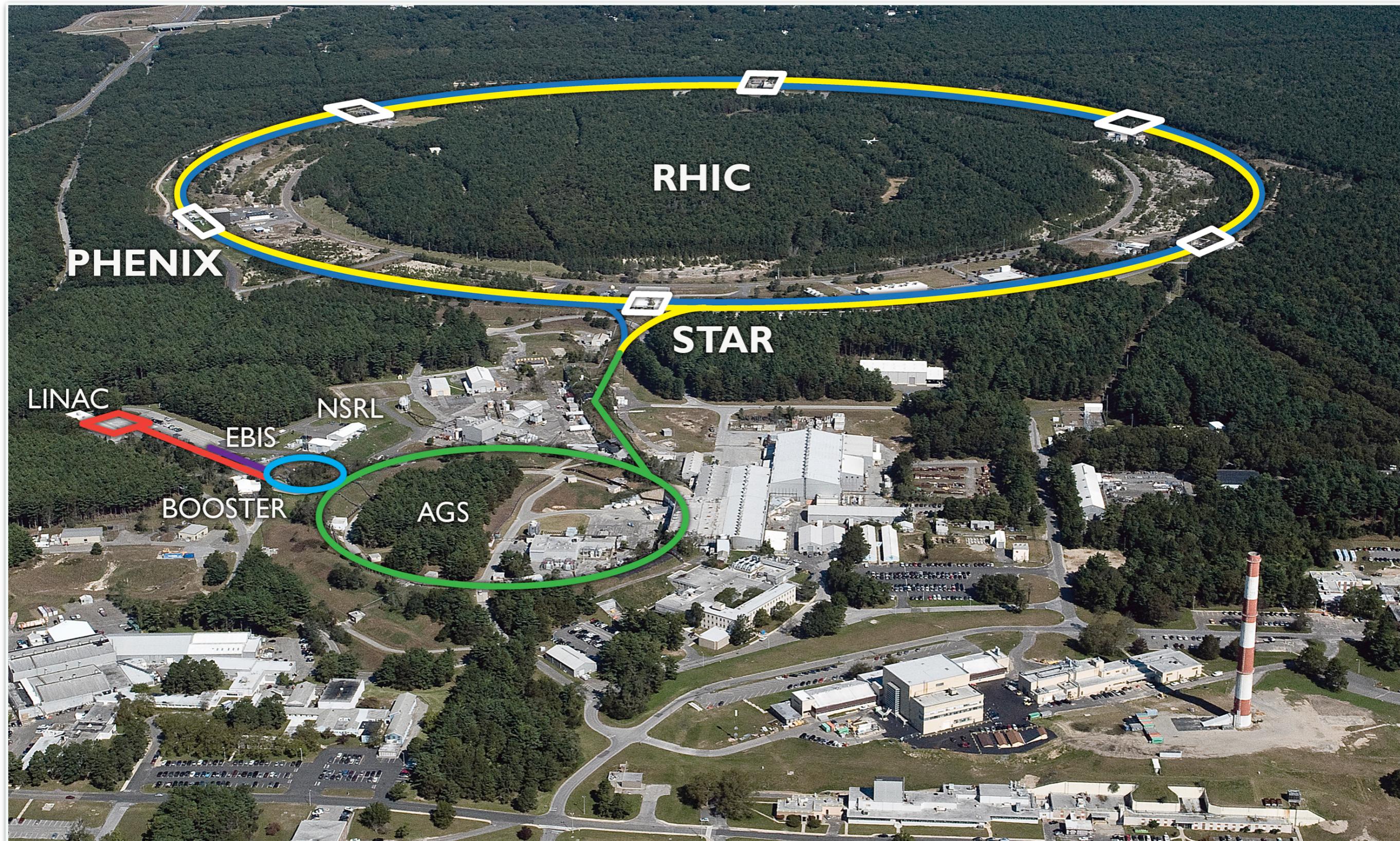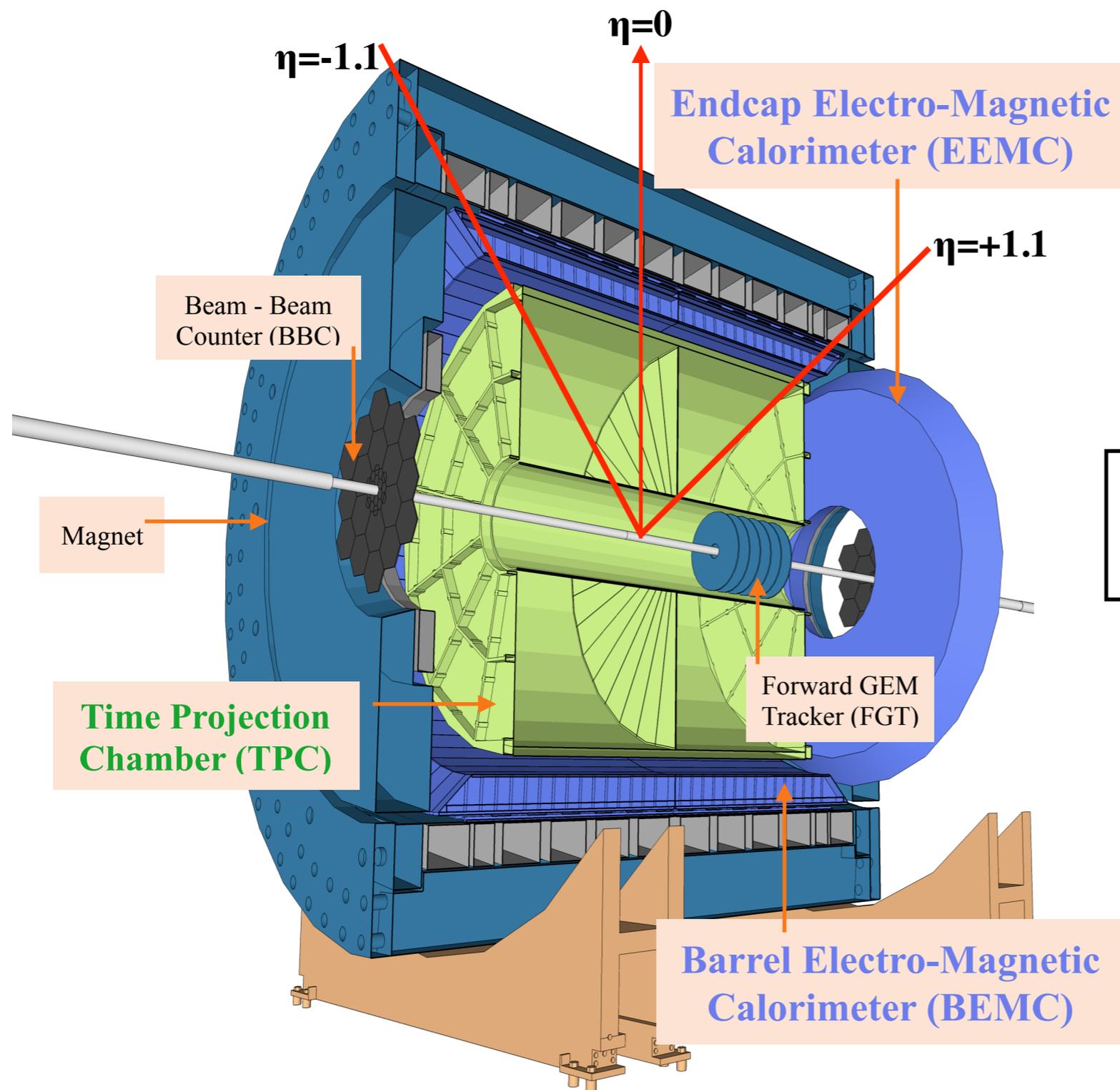
$$\eta = -\ln (\tan(\theta/2))$$

TPC: **Charge particle tracking**

BEMC, EEMC: EM Calorimetry

TPC	: -1.3 < η < +1.3
BEMC	: -1.0 < η < +1.0
EEMC	: +1.1 < η < +2.0
FGT	: +1.0 < η < +2.0

Year 2012

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

W-> e+ν candidate
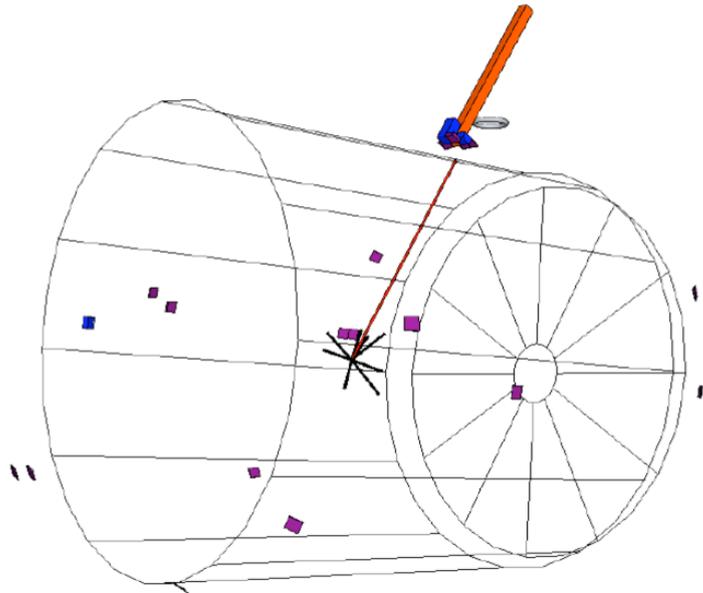
Isolated tracks -> isolated EMC cluster

Large opposite missing "energy"

$P_T > 10$ GeV
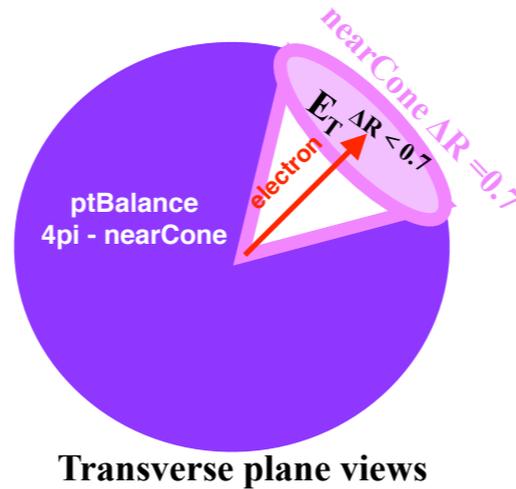
Transverse plane views

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

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

QCD background candidate
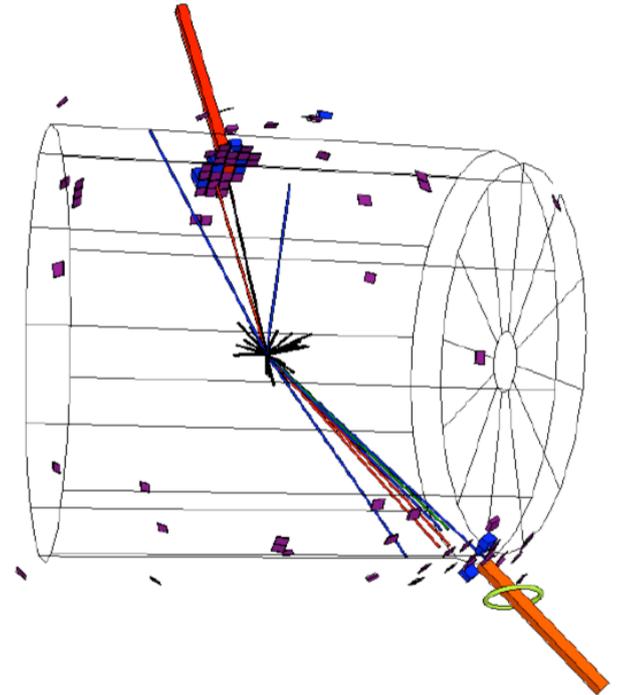
Several tracks -> several EMC towers

No large missing "energy"

E_T distribution

- Candidate track and BEMC cluster reconstructed
- $E_T^e > 14$ GeV and $E_T^e/E_T^{4\times4} > 0.95$
- $E_T^e/E_T^{\Delta R < 0.7} > 0.88$
- P_T- balance $\cos(\phi) > 14$ GeV/c

Sign-P_T balance

data

MC

STAR 2012 Data

$W \rightarrow e\nu$ MC
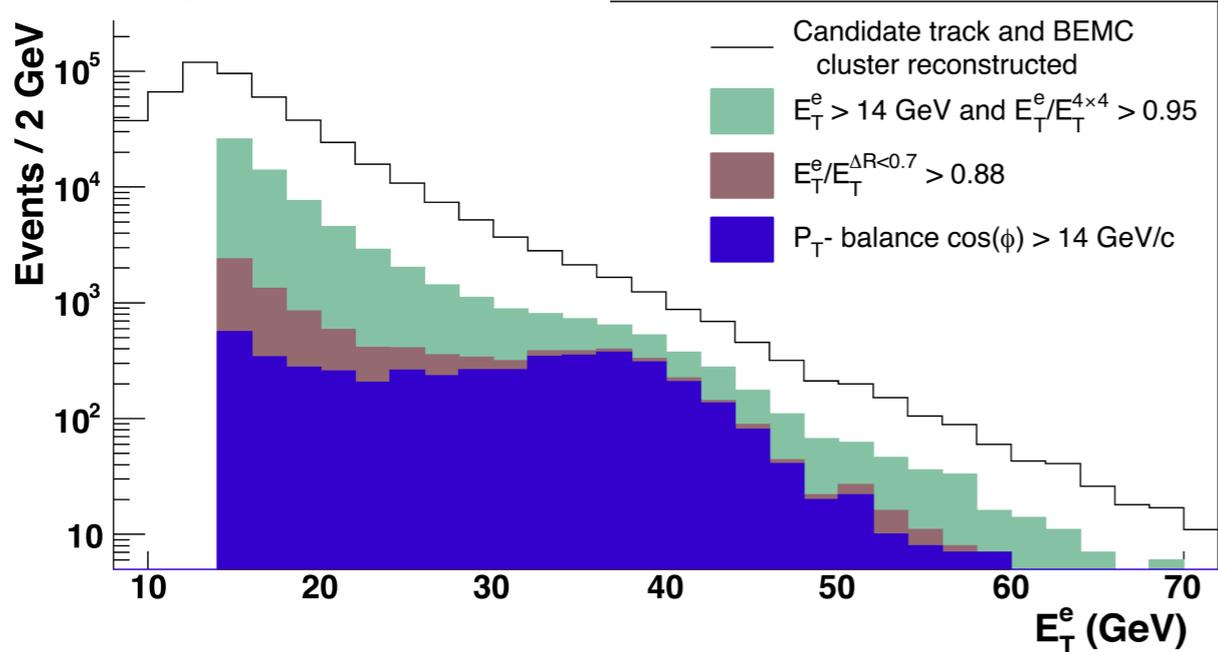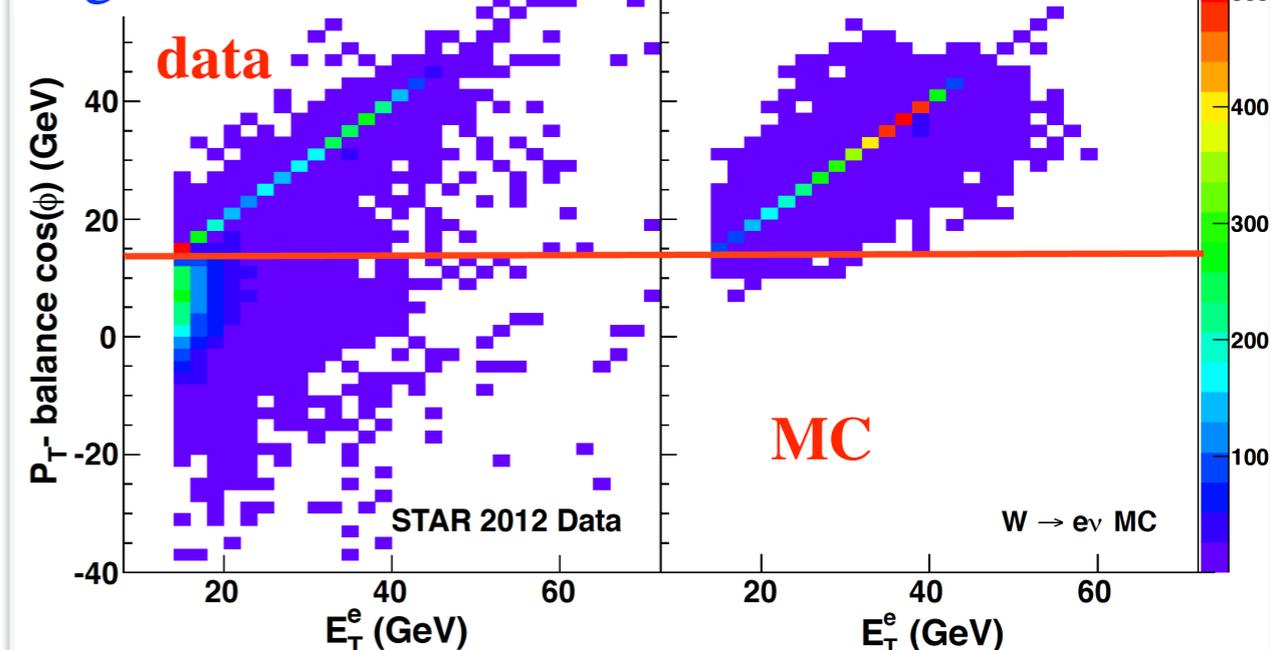
Mid-rapidity Background Estimation

Electron |η_e|<0.5
- STAR Data
- W → e ν MC
- Data-driven QCD

Electron 0.5<|η_e|<1.1
- Second EEMC
- W → τ ν MC
- Z → ee MC

W+

Positron |η_e|<0.5

W-

Positron 0.5<|η_e|<1.1

Events / 2 GeV

E_T^e (GeV)
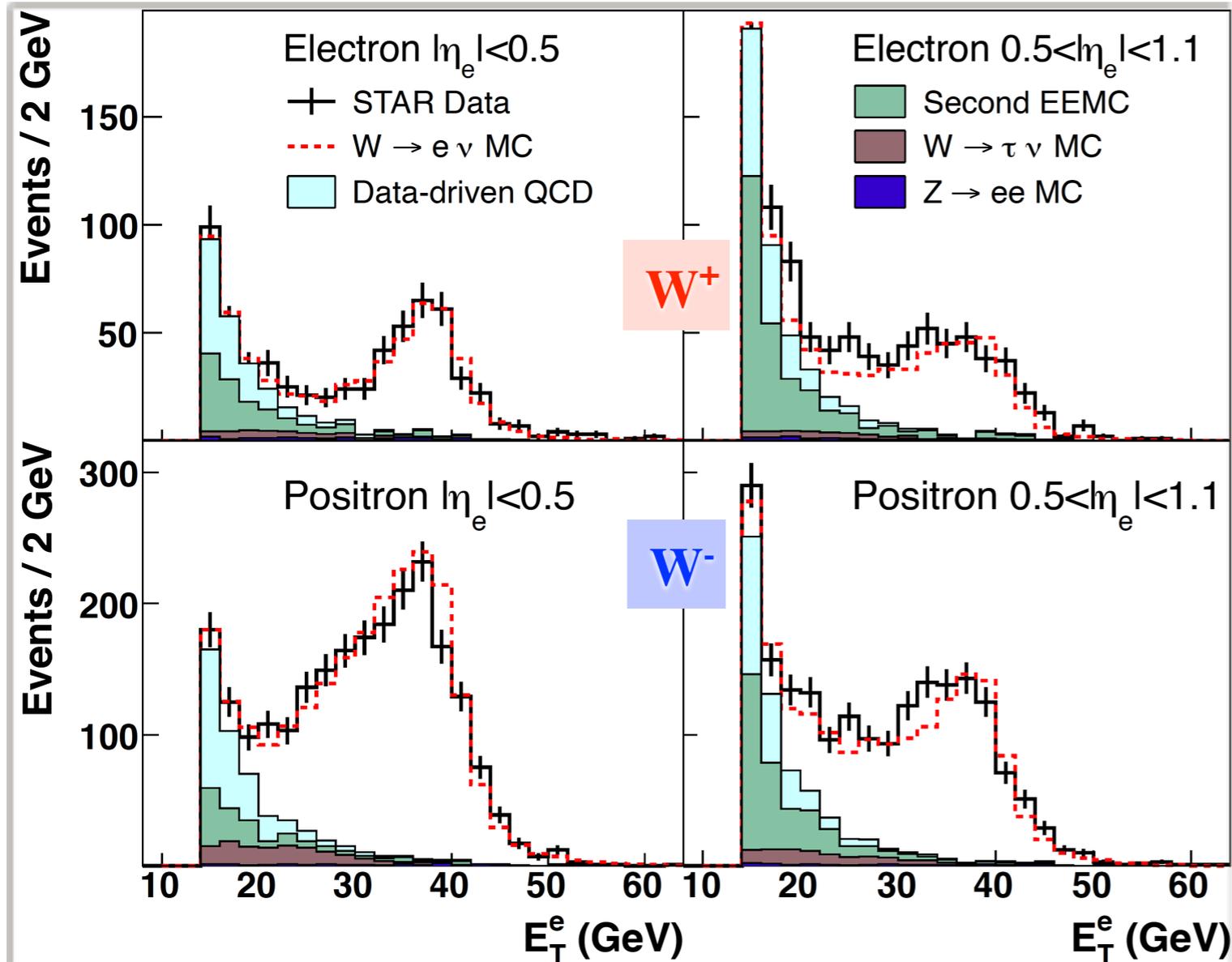
PRL 113,72301 (2014)

Primary Background

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

❖ **Second Endcap** $-2 < \eta < -1.09$

❖ **Data driven QCD** |η| >2

Electroweak BG

❖ $W \dashrightarrow \tau\nu$

❖ $Z \dashrightarrow e^+ + e^-$

MC Embedded in Zero-bias events

Forward rapidity (1<η_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

$$\vec{p}+p \rightarrow W^{\pm} \rightarrow e^{\pm} + \nu$$

$\sqrt{s}=510$ GeV $25 < E_T^e < 50$ GeV

W⁻

W⁺

W⁺ W⁻

Rel lumi syst

- STAR Data CL=68%
- DSSV08 RHICBOS
- DSSV08 CHE NLO
- LSS10 CHE NLO
- DSSV08 L0 $\Delta\chi^2/\chi^2 = 2\%$ error

3.4% beam pol scale uncertainty not shown
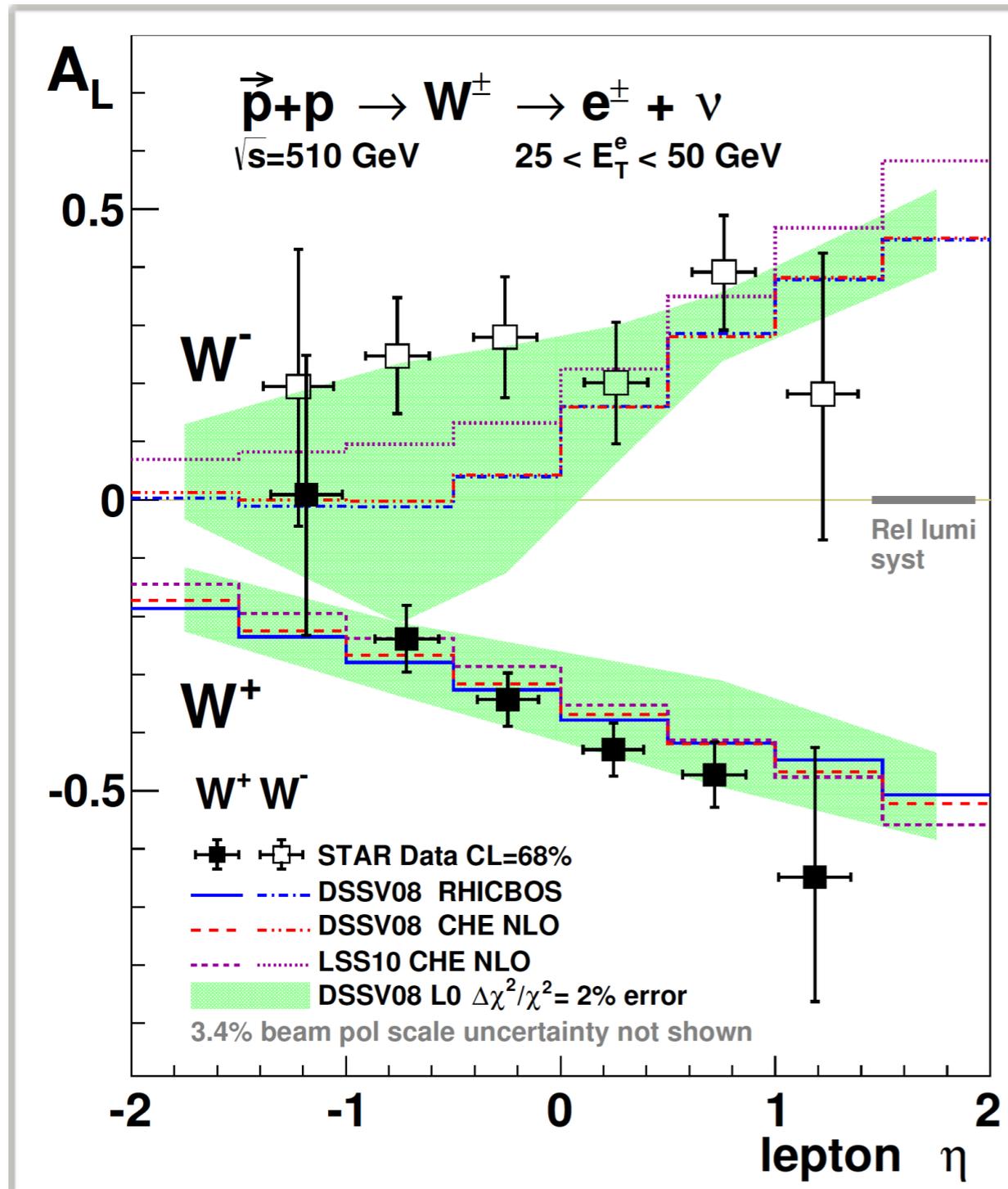
PRL 113,72301 (2014)

❧ **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 $\boxed{\Delta\bar{u}}$, 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 |η_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 $\boxed{\Delta\overline{u}}$ (negative -> positive) and $\boxed{\Delta\overline{d}}$ due to A$_L$ W from STAR .**

✤ **STAR 2012 W results provide significant constraints on anti u and anti d quark polarization.**
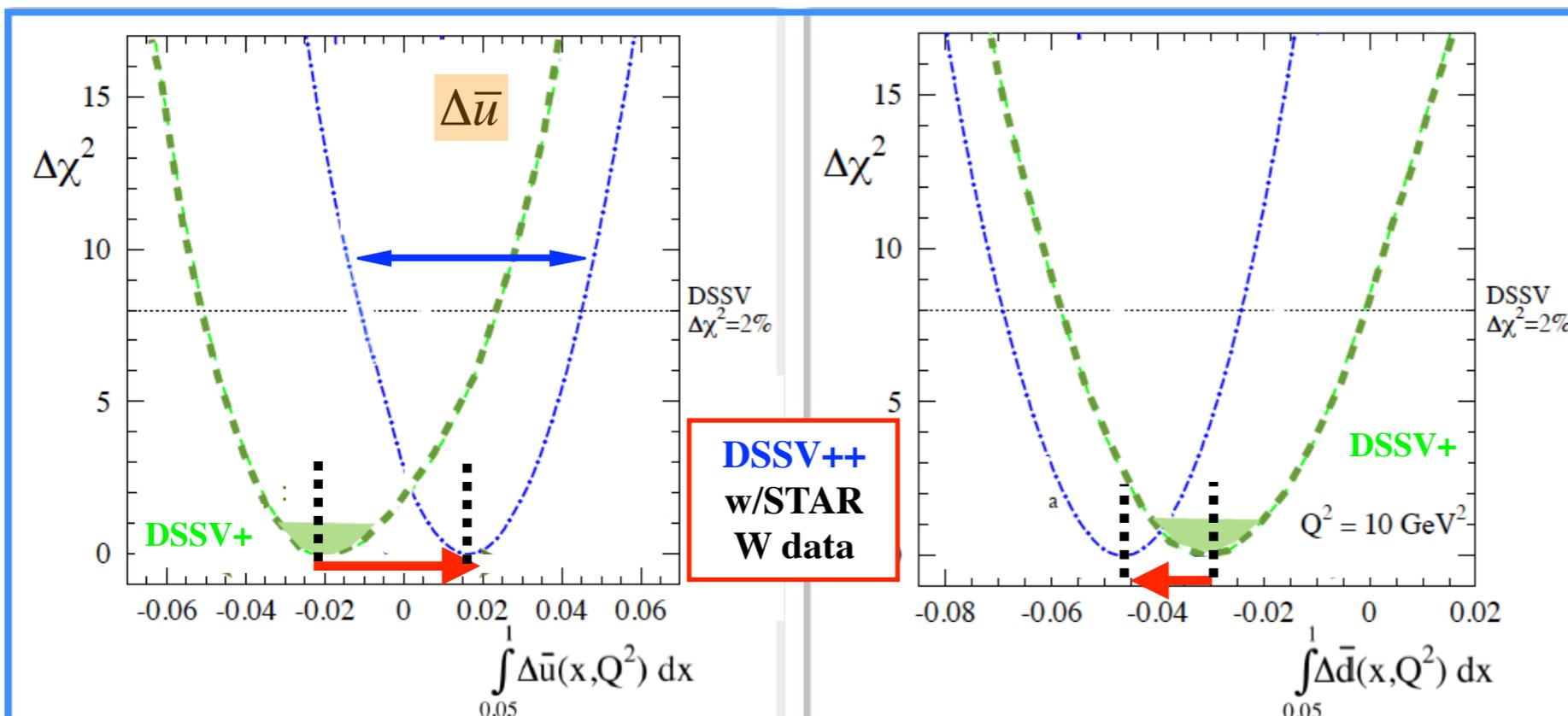
arXiv: 1304.0079

arXiv: 1304.0079
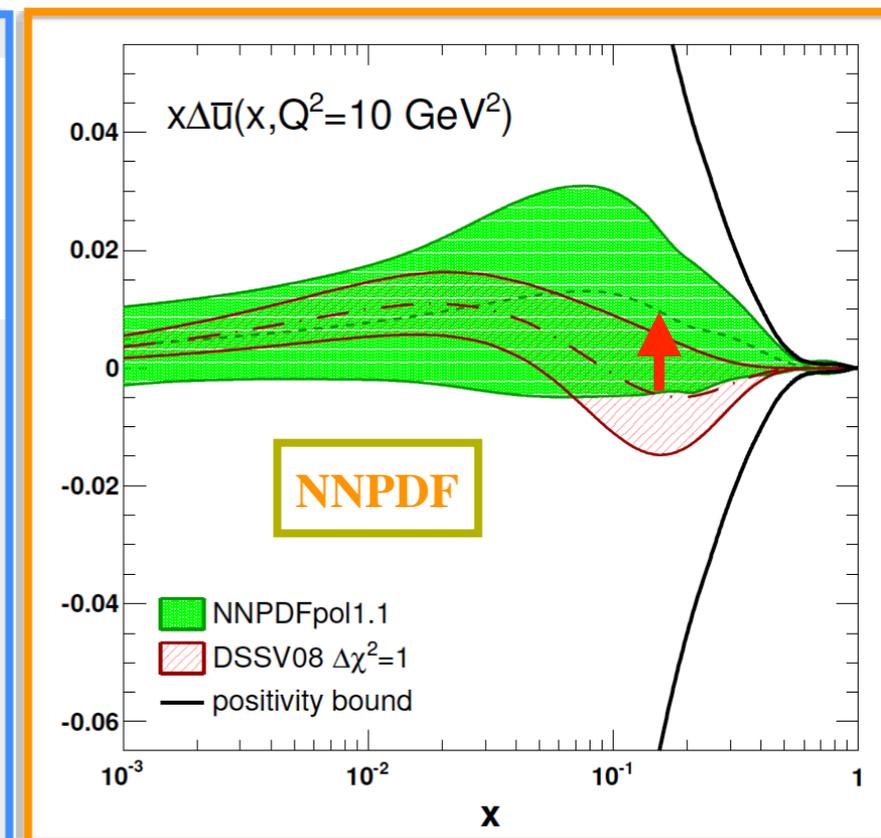
arXiv: 1403.0440

2013 Data Sample

Barrel EMC triggered Integrated Luminosity

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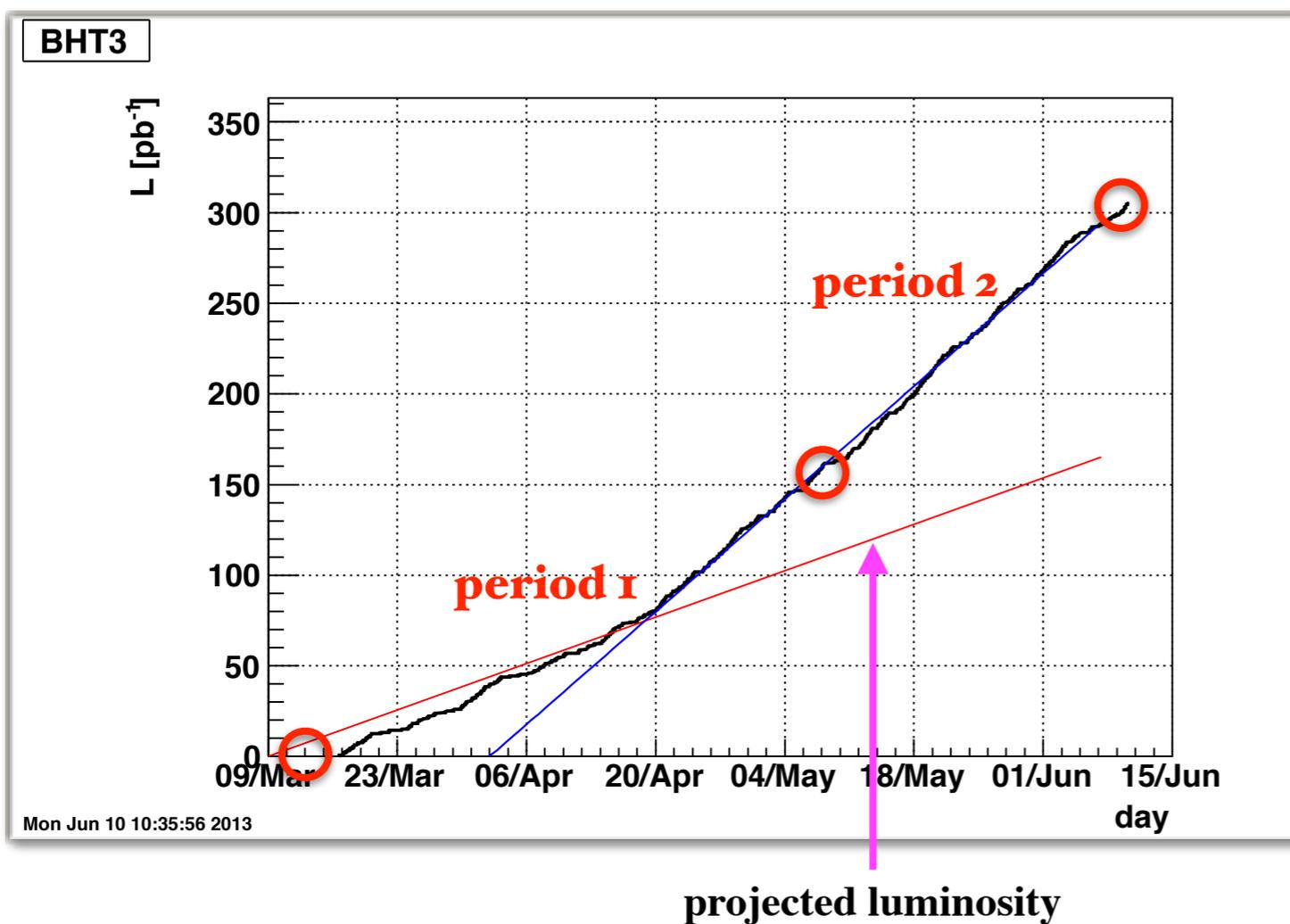
	L (pb^{-1})	P	FOM (P^{2}L (pb^{-1}))
Run 9	12	0.38	1.7
Run 11	9.4	0.49	2.3
Run 12	72	0.56	24
Run 13	**~ 300**	**0.54**	**~ 87**

In 2013 STAR collected total integrated luminosity of ~300 pb^{-1} at √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!!!!**


TPC
vertex
Q^+ = 5 GeV
Q^- = 5 GeV
~15 cm
200 cm of tracking
BEMC
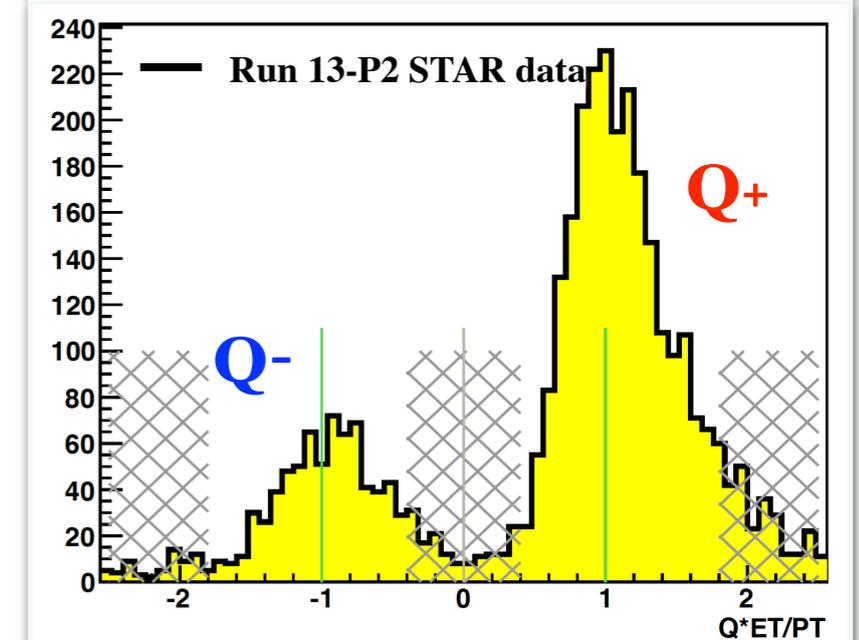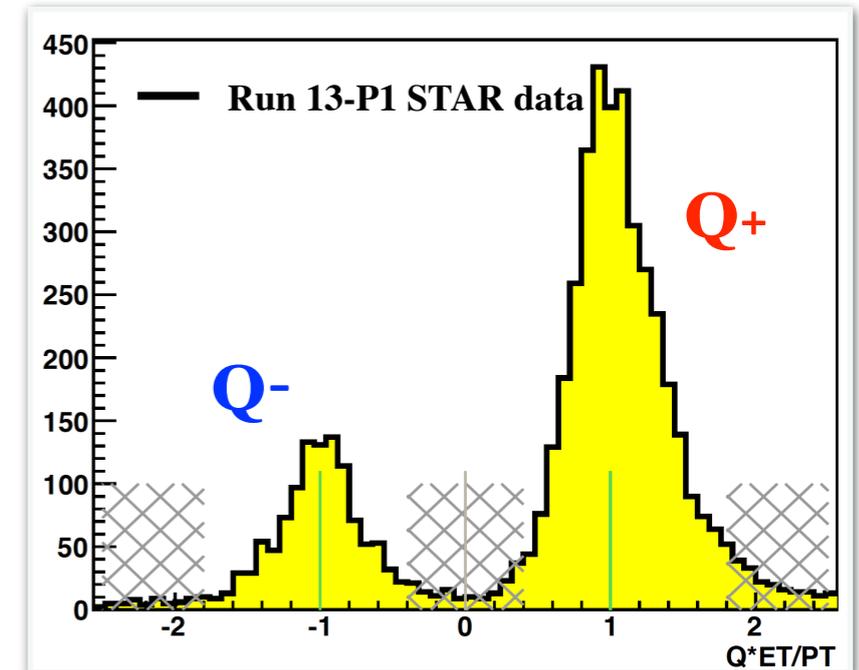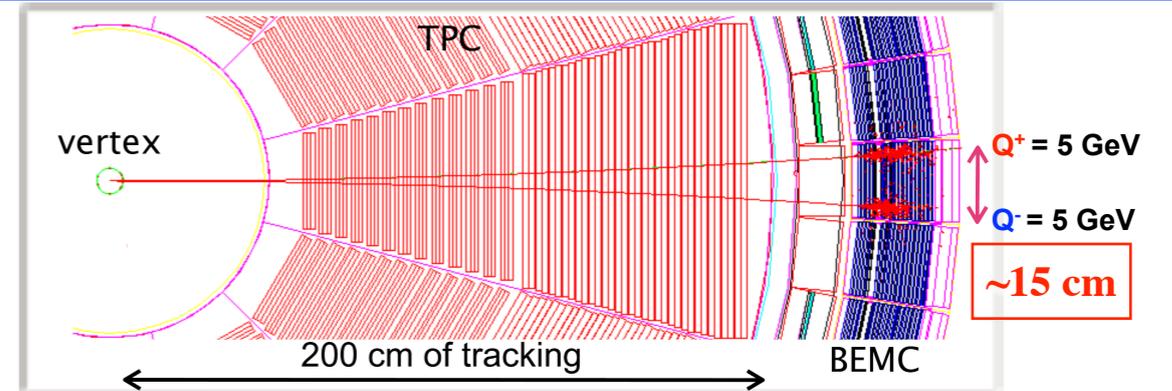
global TPC tracks

W candidate tracks

Run 13-P1 STAR data
Q+
Q-

Run 13-P2 STAR data
Q+
Q-

13
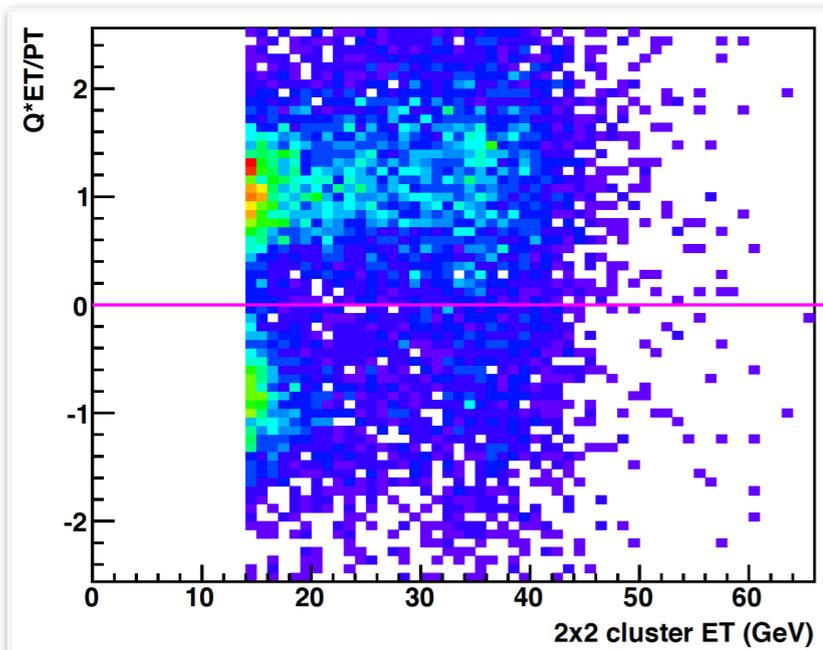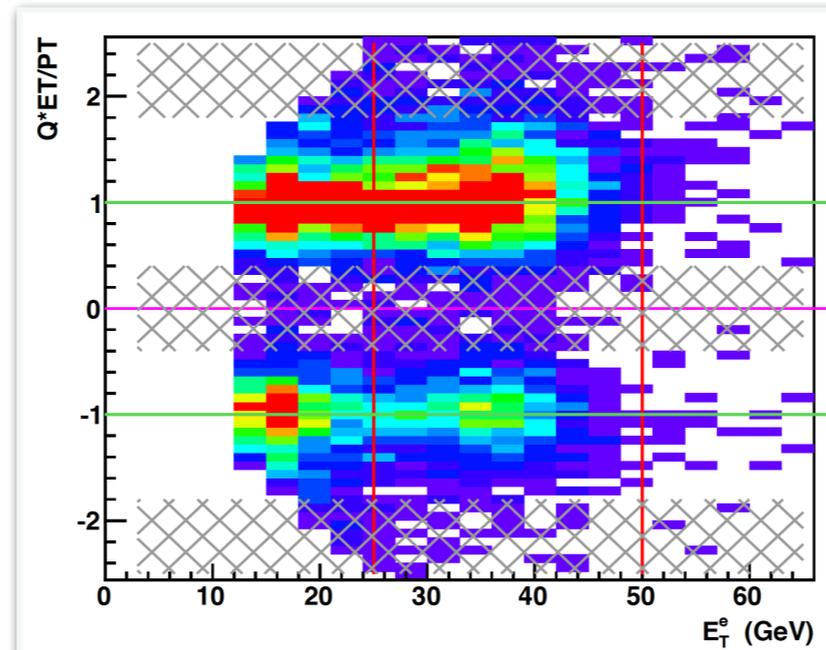
Detector Calibration
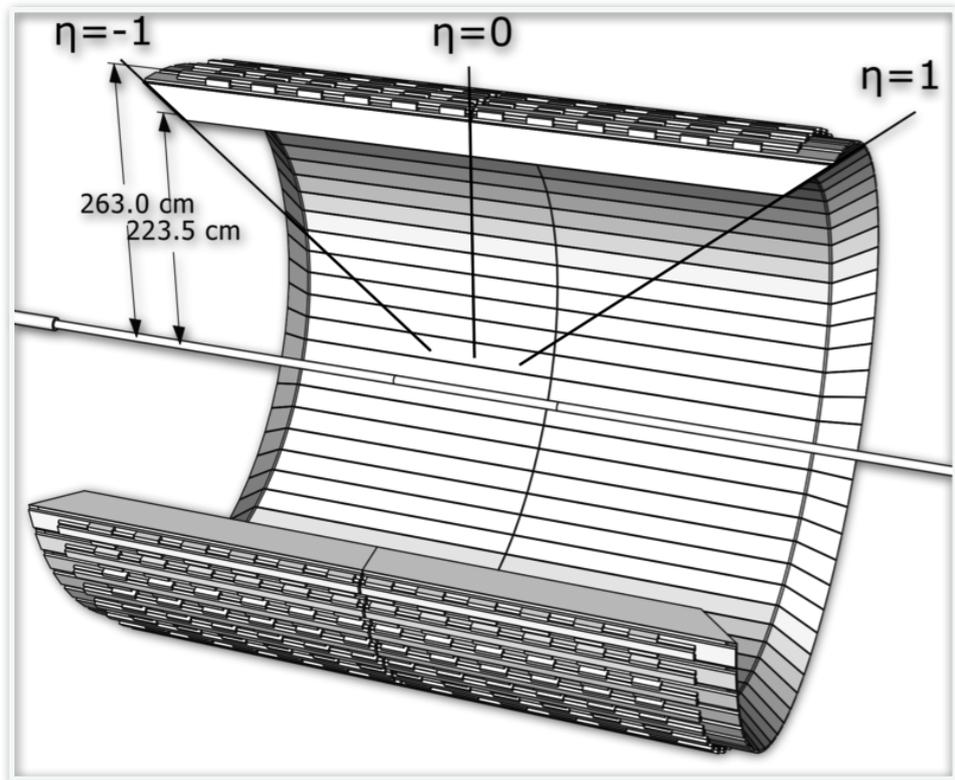
♣ BEMC

✦BEMC is a sampling calorimeter and it is segmented into 4800 towers, each with $\Delta\eta \times \Delta\phi = 0.05 \times 0.05$
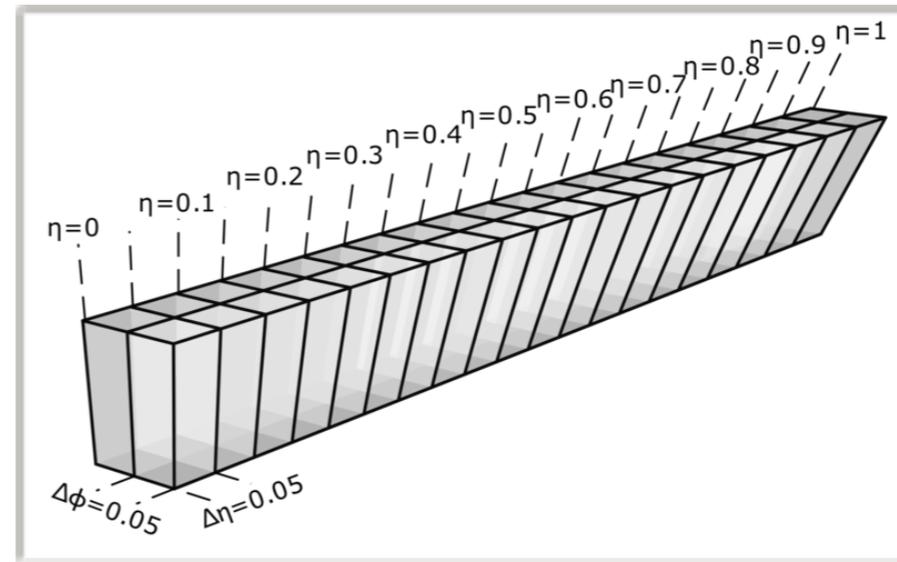
The geometry of the calorimeter towers in a BEMC module

**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.

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STAR 2013 W A_L Projections

STAR W A_L Projections

STAR Run 2013 Projection

$\vec{p}+p \rightarrow W^{\pm} \rightarrow e^{\pm} + \nu$

$\sqrt{s}$=510 GeV $25 < E_T^e < 50$ GeV

$L_{delivered}$=460pb^{-1}

<P> = 53%

W^-

W^+ W^-
- DSSV08 RHICBOS
- DSSV08 CHE NLO
- LSS10 CHE NLO
- DSSV08 L0 $\Delta\chi^2/\chi^2$= 2% error

3.4% beam pol scale uncertainty not shown

W^+

lepton η
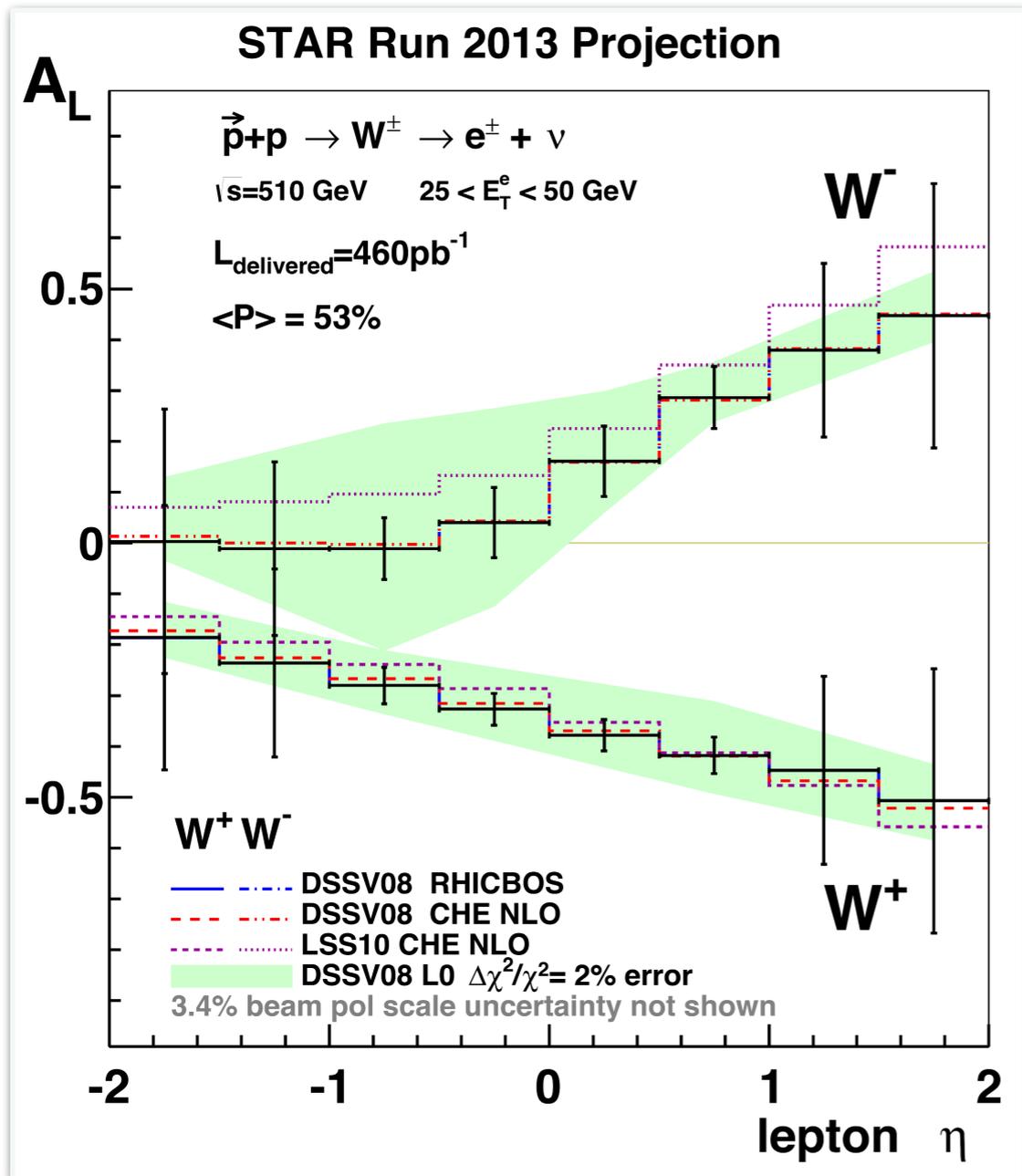
Higher precision results are expected from much larger statistics

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

Impact on antiquark polarization

$\overline{u}$ **polarization**

$x\Delta\overline{u}$

$Q^2 = 10$ GeV^2

- DSSV
- DSSV+
- DSSV++ with proj. W data

$\overline{d}$ **polarization**

$x\Delta\overline{d}$

$Q^2 = 10$ GeV^2
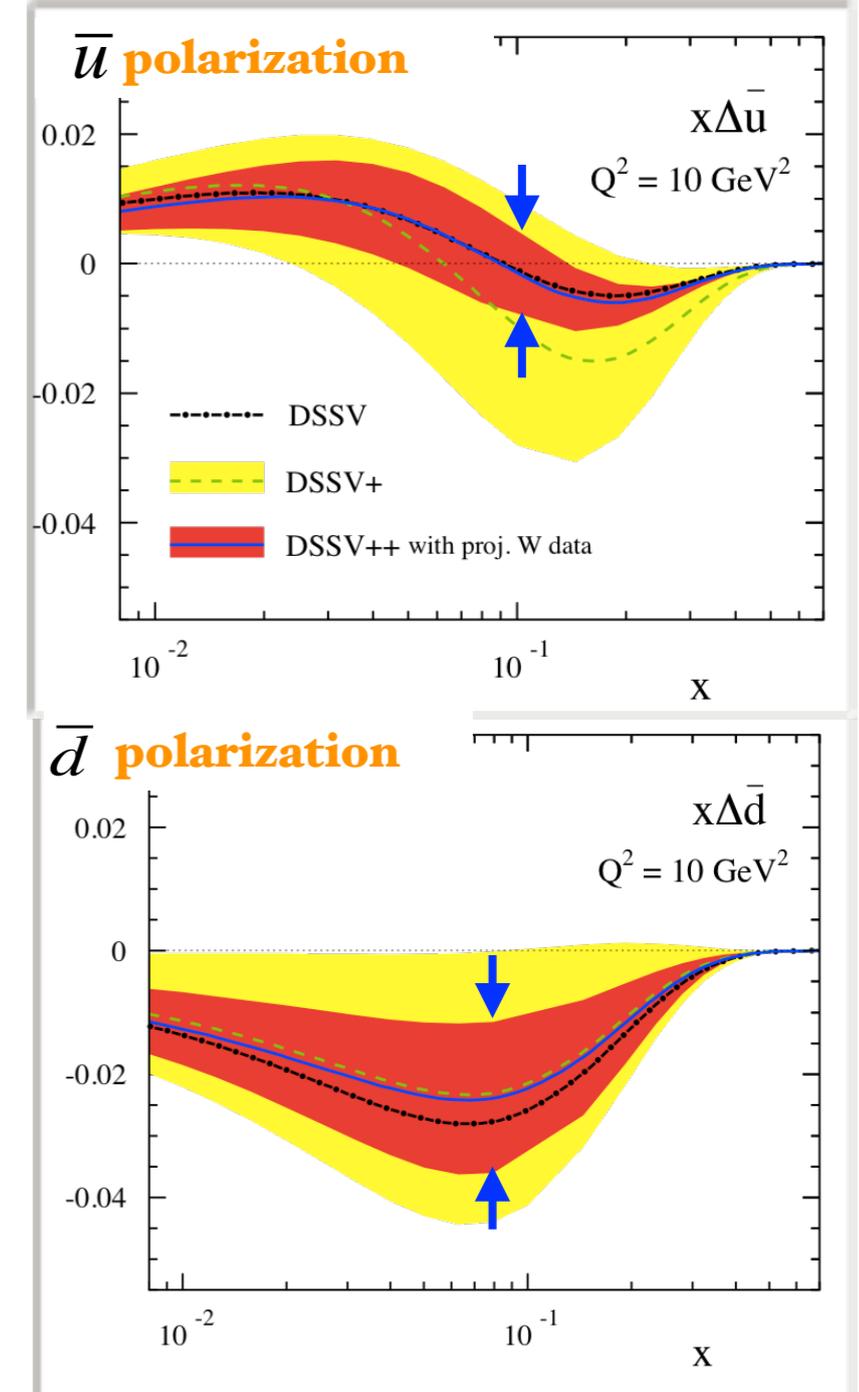
arXiv: 1304.0079

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
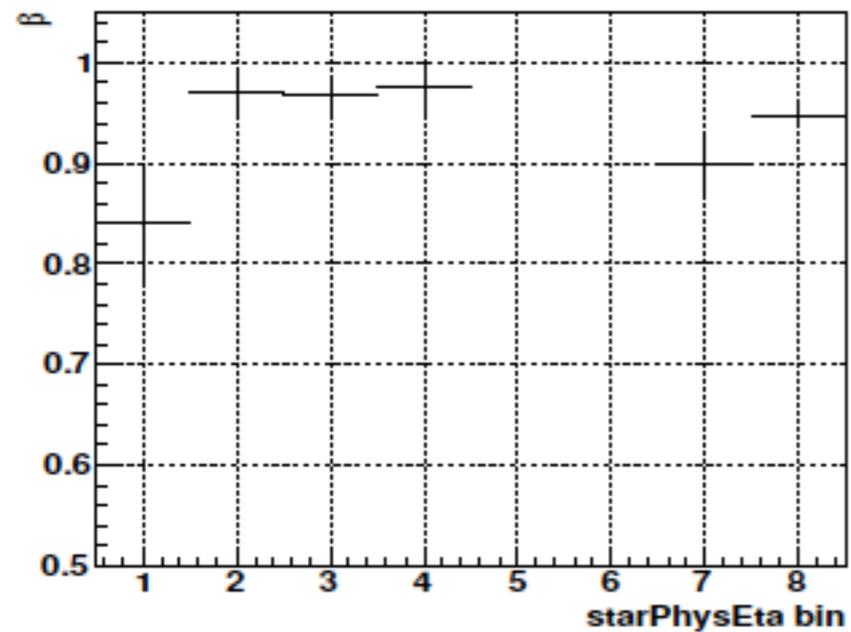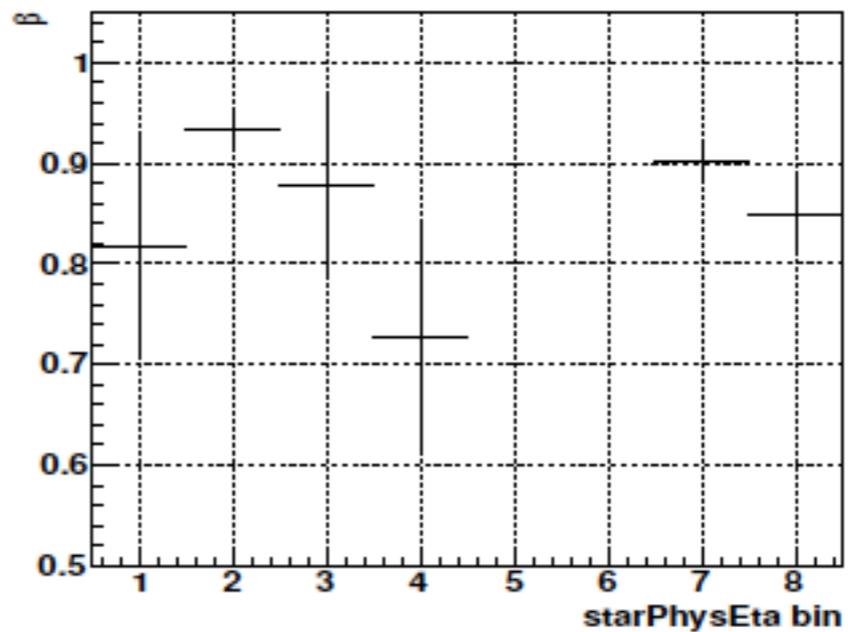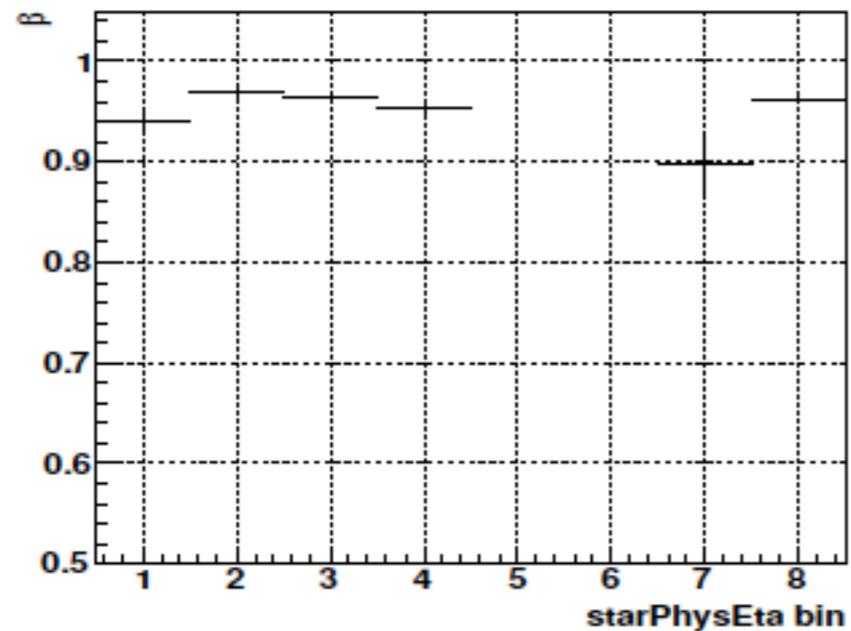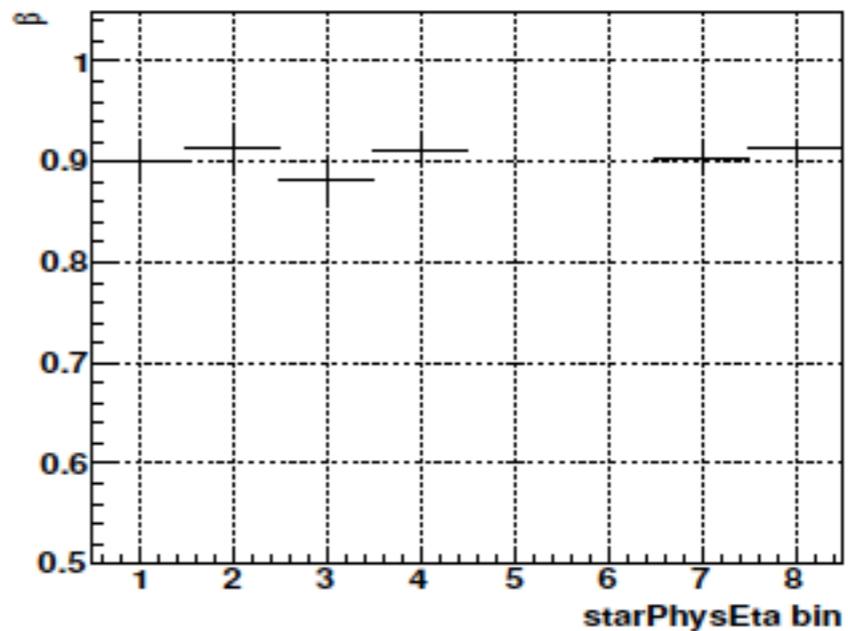
W^+ β: ~ 0.95, W^- β: ~ 0.9

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

The figure shows A_L versus η_e for the process $\vec{p} + p \rightarrow W^{\pm} + X \rightarrow e^{\pm} + X$, STAR $\sqrt{s} = 500$ GeV, $25 < E_T^e < 50$ GeV, with W^- and W^+ data. Definition: $A_L = \dfrac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$.

Legend: W^- / W^+ RHICBOS; DNS-K; DNS-KKP; DSSV08; CHE DSSV08. Syst. uncertainty due to background, w/o pol. norm. uncertainty of 9.2%.
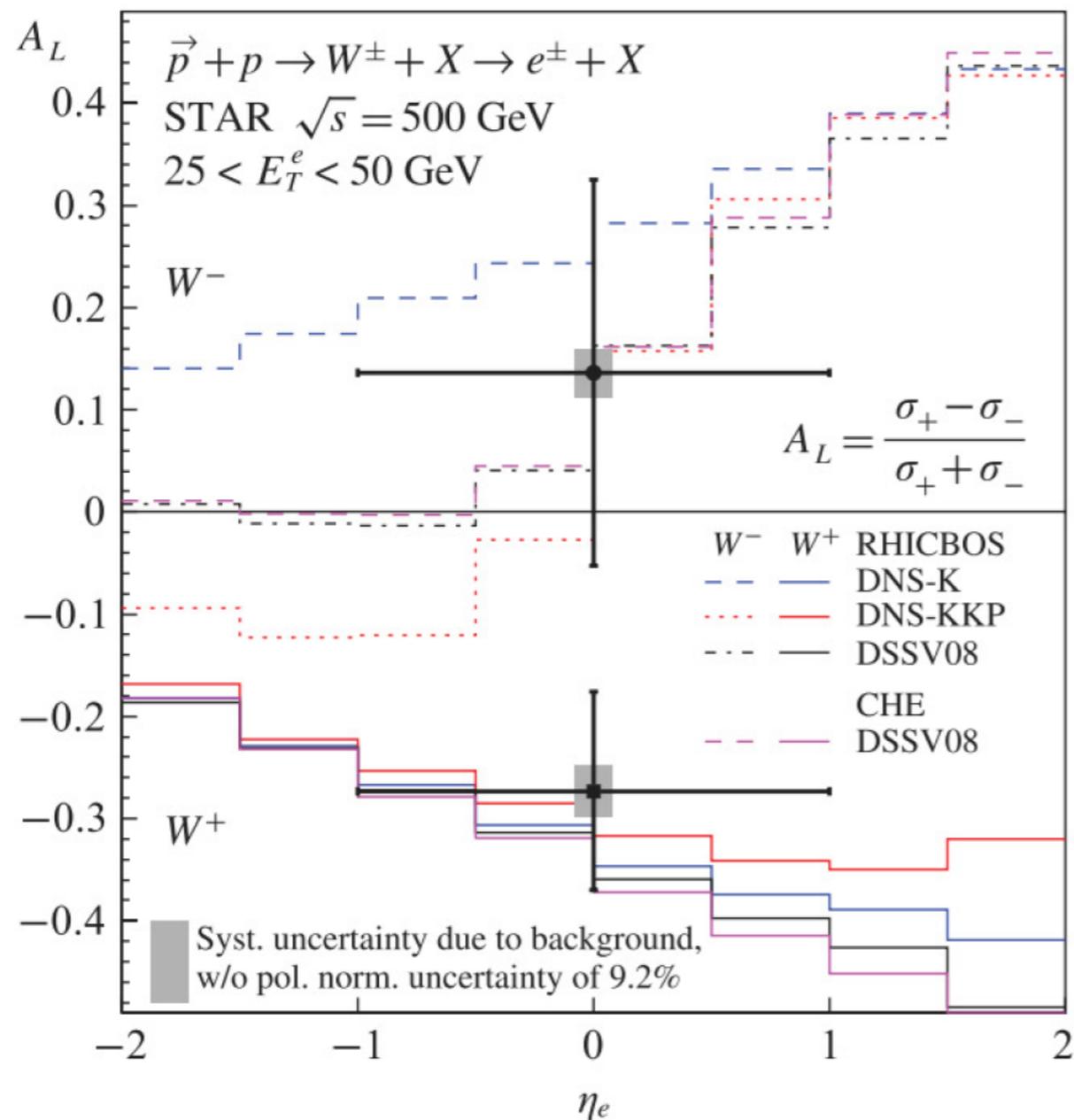
STAR pp500 Longitudinal		
Run	L (pb^{-1})	$W^+(W^-)$ raw yield
2009	12	462 (192)
2011	9	342 (103)
2012	77	2417 (734)

PRL 106, 062002 (2011)

TPC

vertex

Q^+ = 5 GeV

Q^- = 5 GeV

200 cm of tracking

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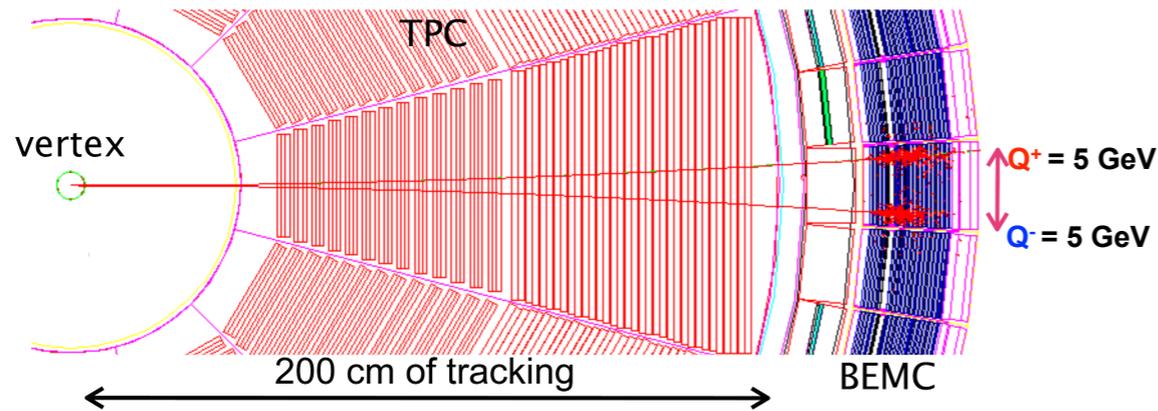
- Charge sign reconstruction based on TPC track bending
- Estimate wrong sign contamination by fitting $Q * E_T/pT$ with Gaussian.

gauss fit: x0, σ
- -1.04 , 0.32
- 0.99 , 0.30
- sum of both

Entries   2826

Q-

Q+

$Q*E_T/P_T$
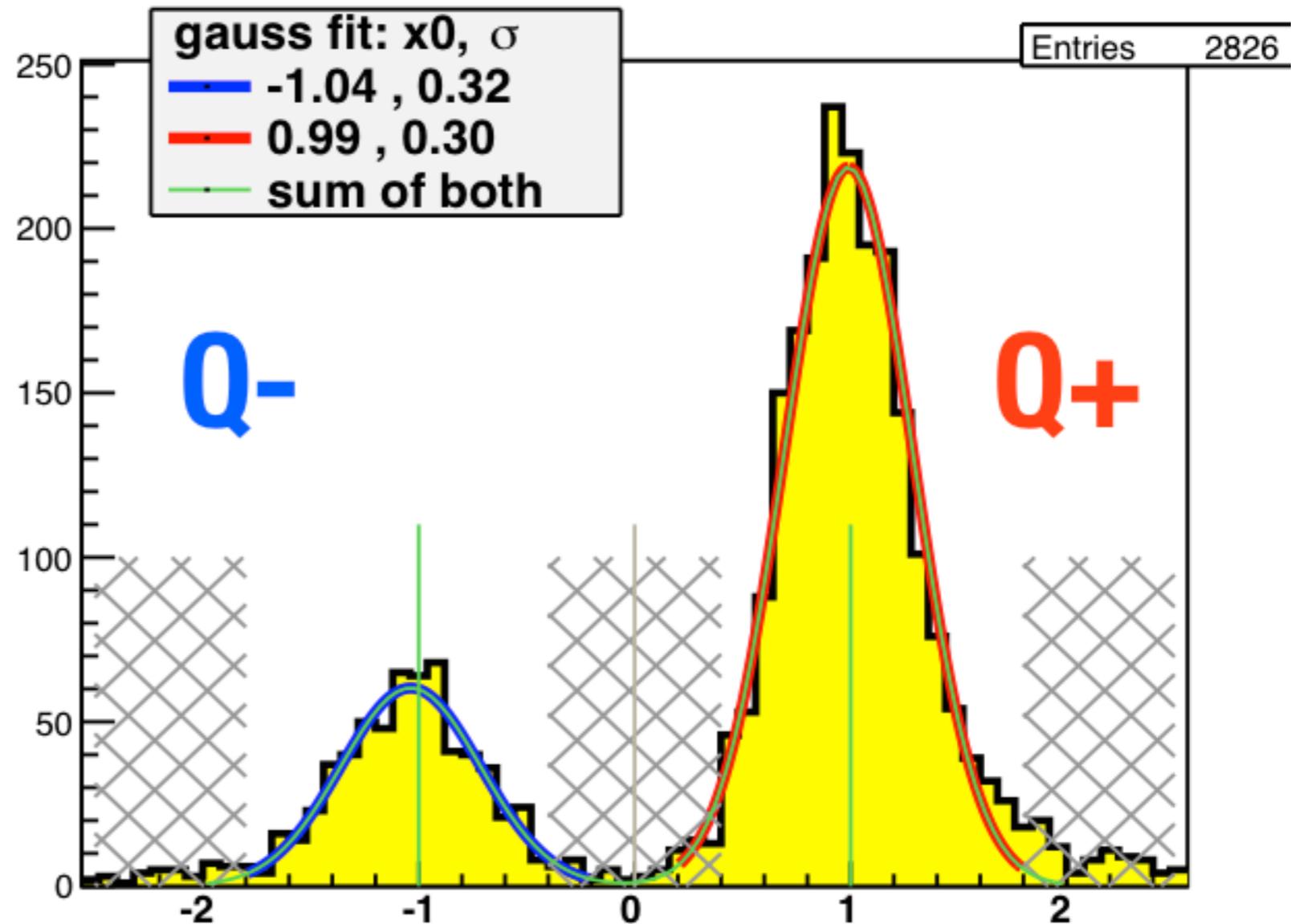
⬤ **Profile Likelihood** method used in **extracting Asymmetries** from **combination of run 2012 and run 2011 data** [simple gaussian uncertainties breakdown particularly for small 2011 data sample]

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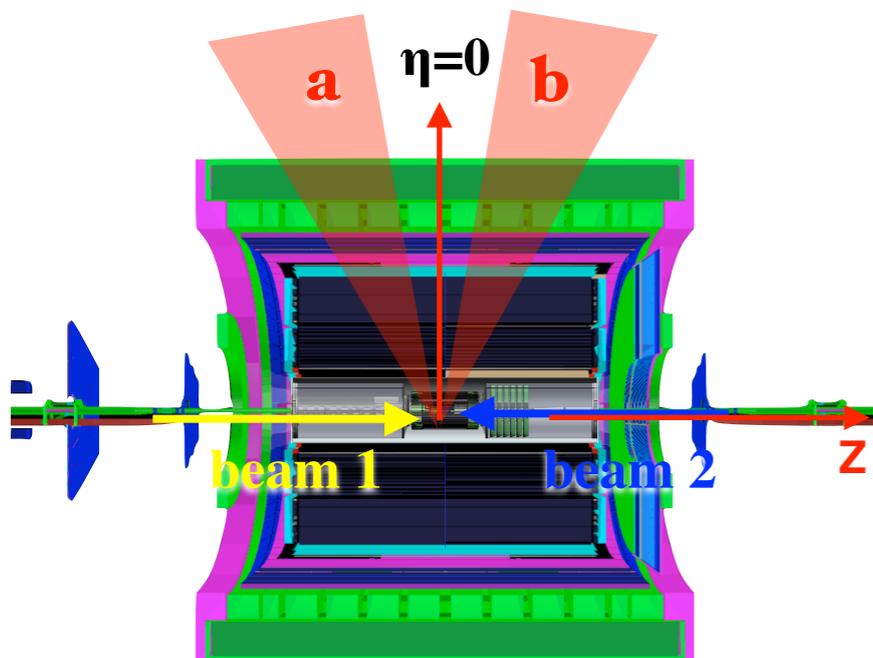
g(β) - **Gaussian probability for estimated dilution background β**

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

Run 12 Preliminary results compare to Final

STAR FINAL Run 2012+2011
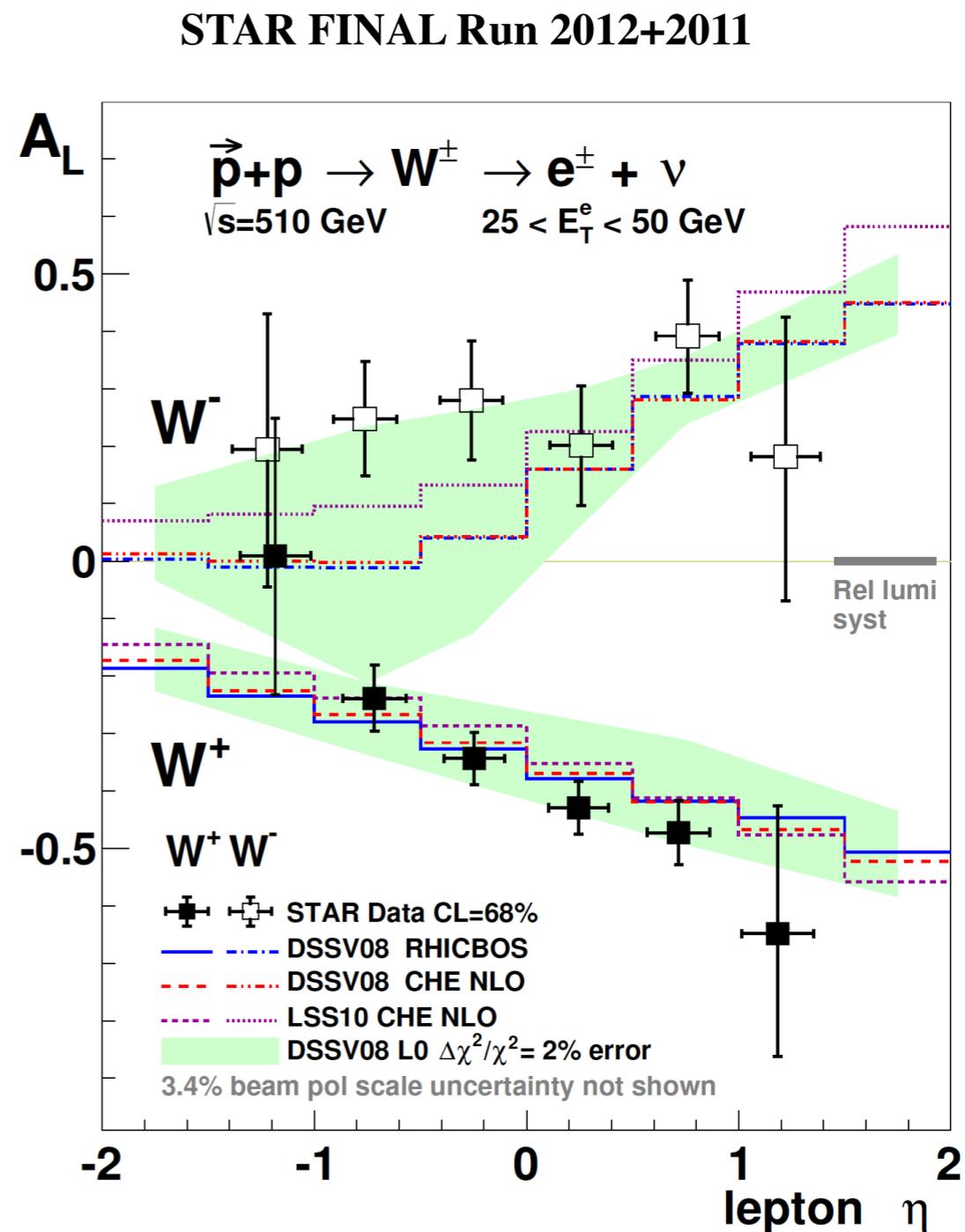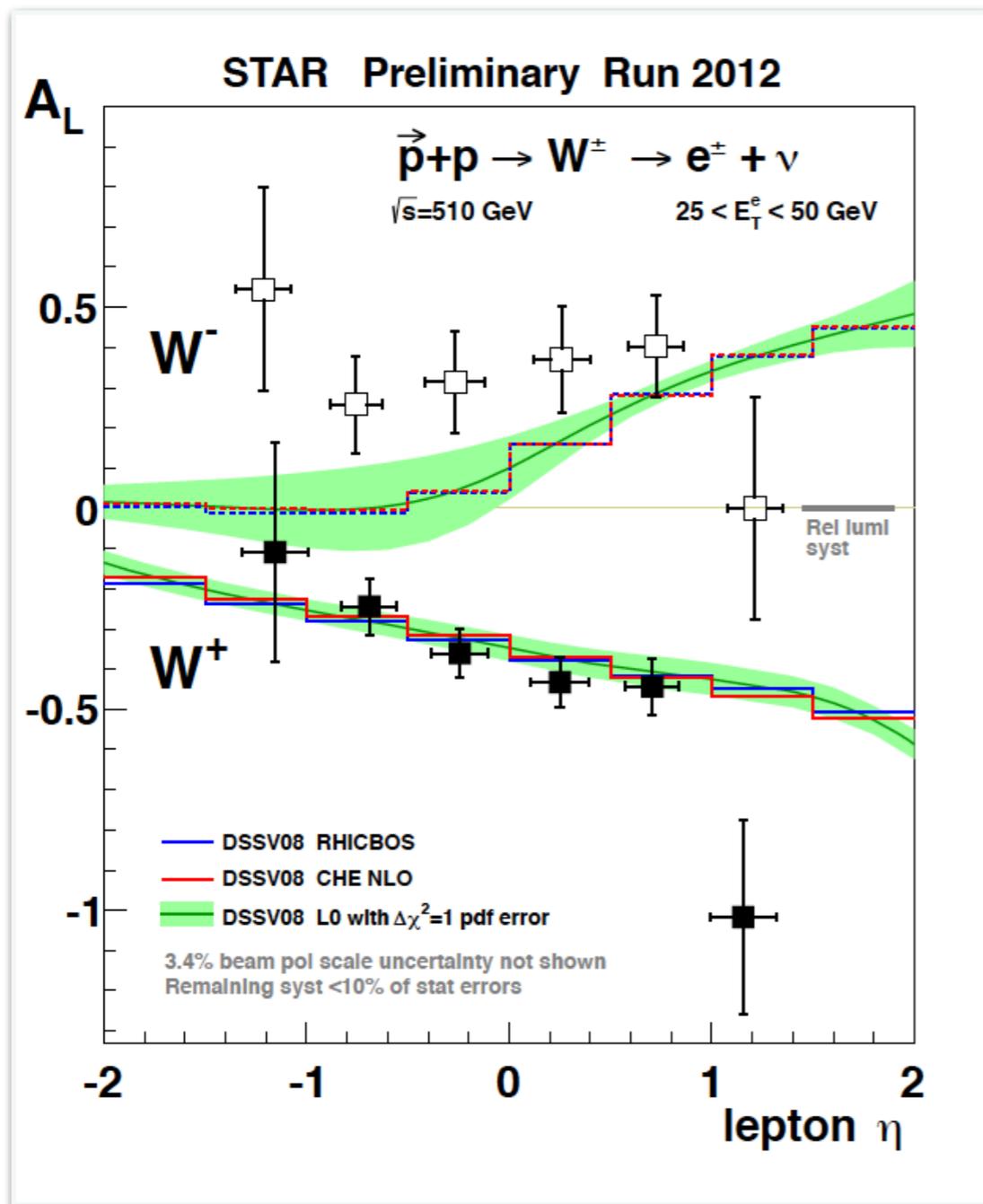
PRL 113,72301 (2014)

Endcap W Selection
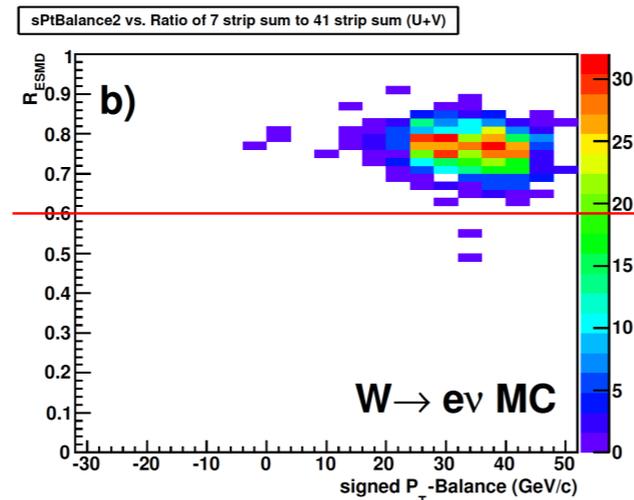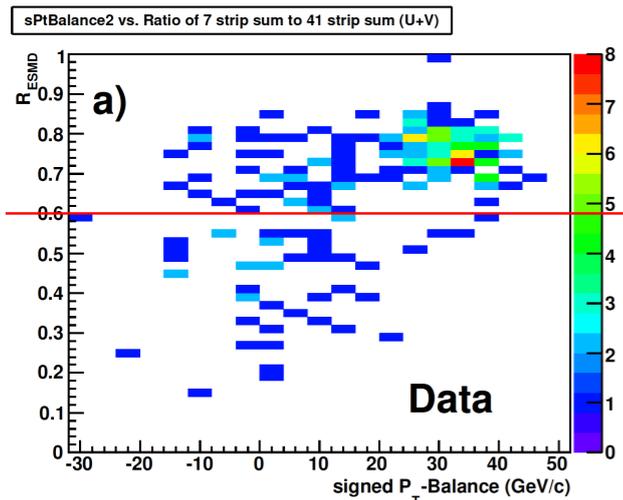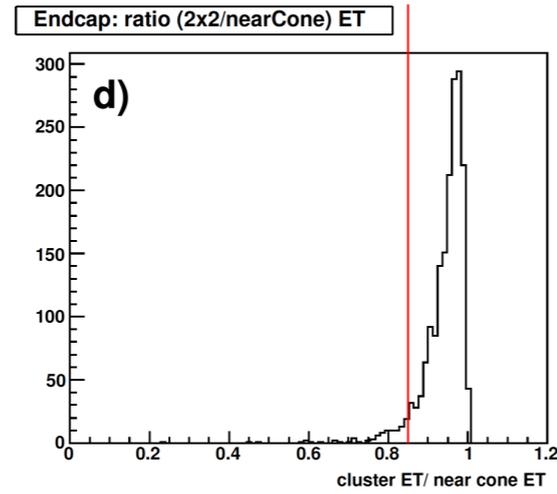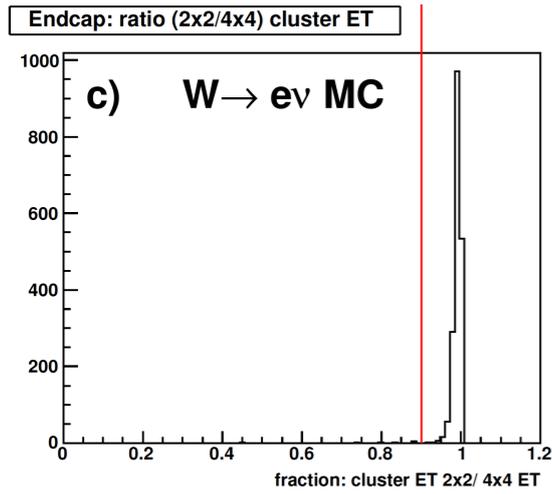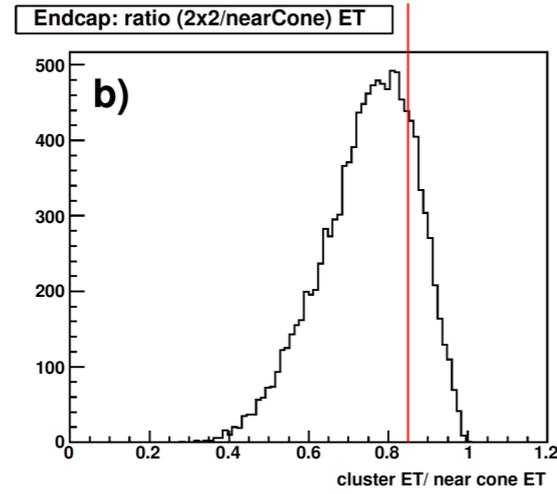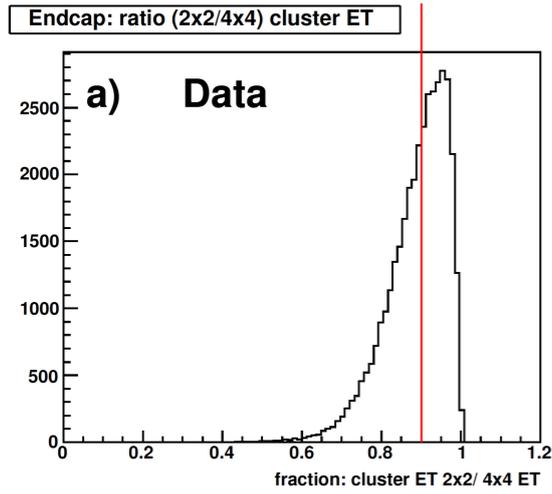
ESMD CUTS
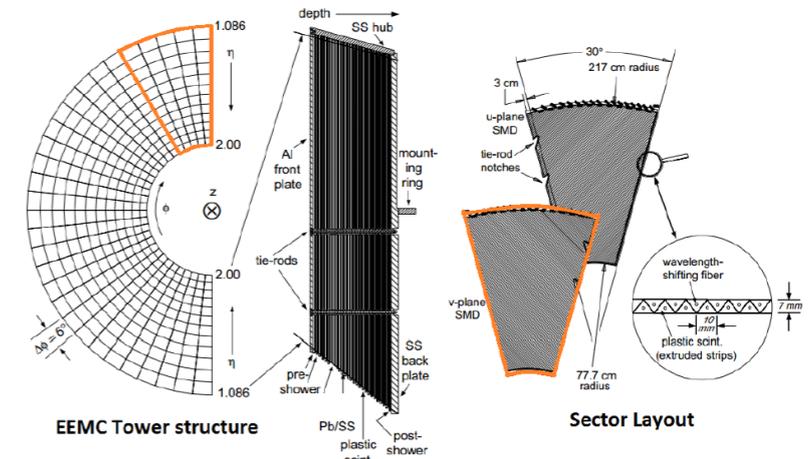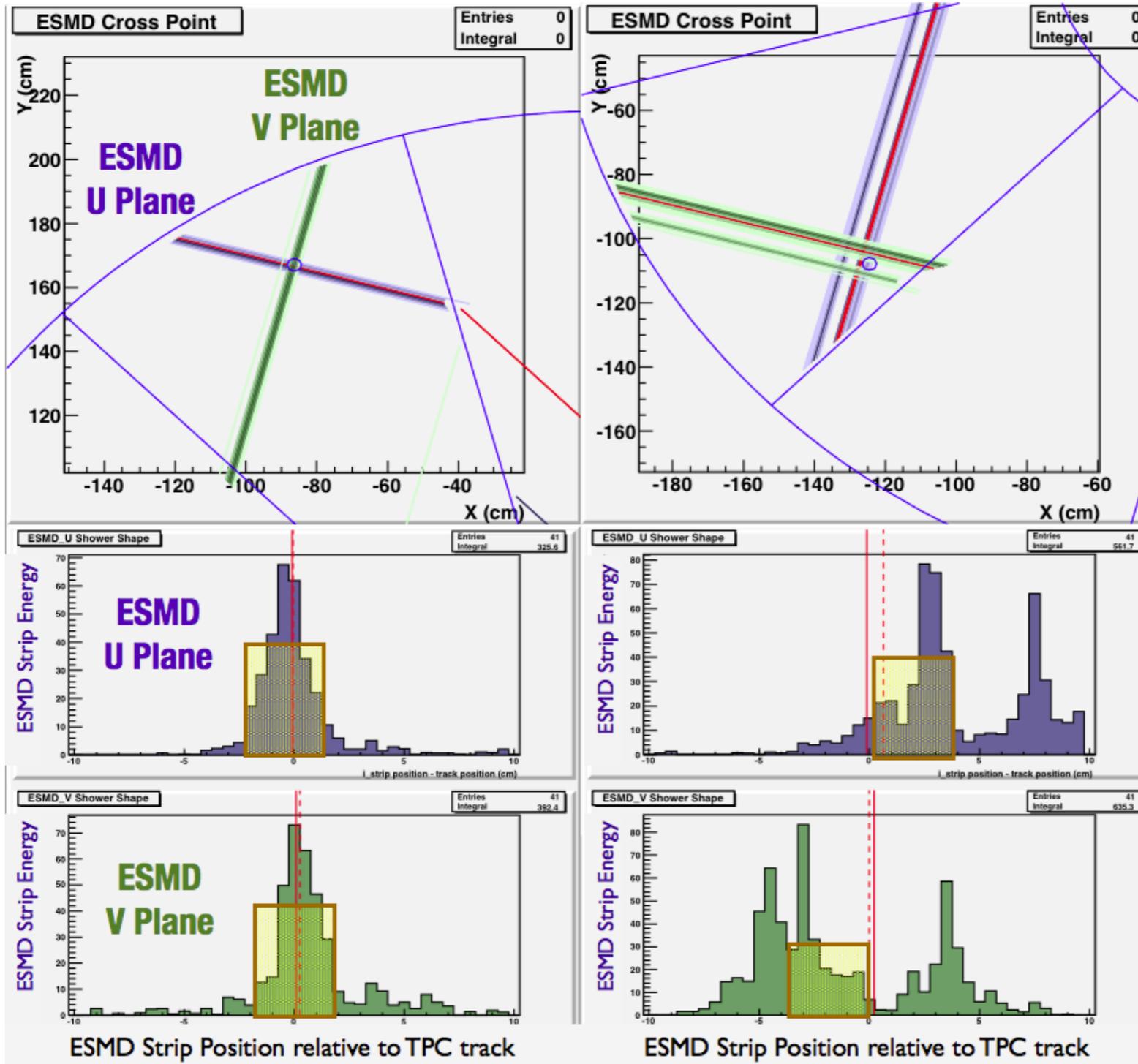
$$R_{ESMD} = \frac{\sum_{i=-3}^{+3} E_i^U + E_i^V}{\sum_{i=-20}^{+20} E_i^U + E_i^V}$$
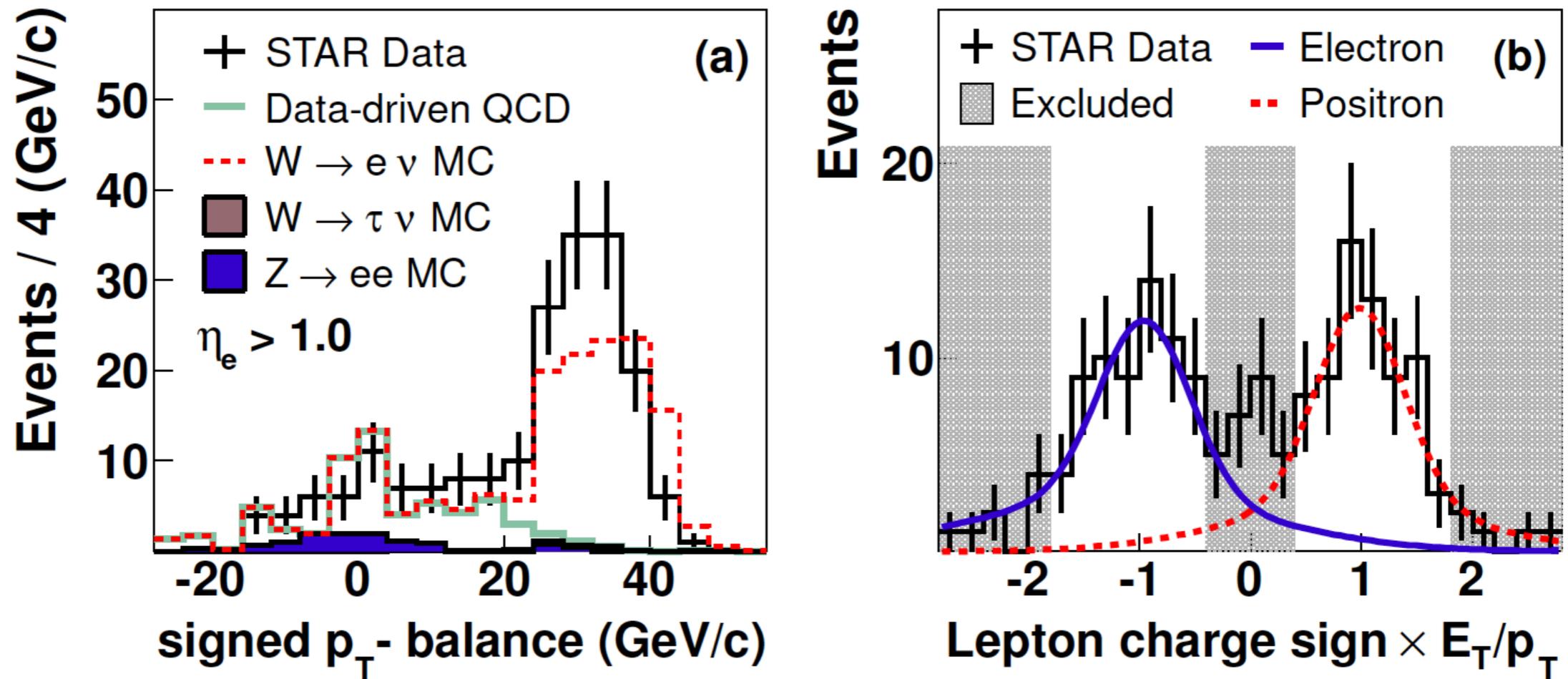
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$$A_{LL} = \frac{(\sigma^{++}+\sigma^{--})-(\sigma^{+-}+\sigma^{-+})}{(\sigma^{++}+\sigma^{--})+(\sigma^{+-}+\sigma^{-+})}$$
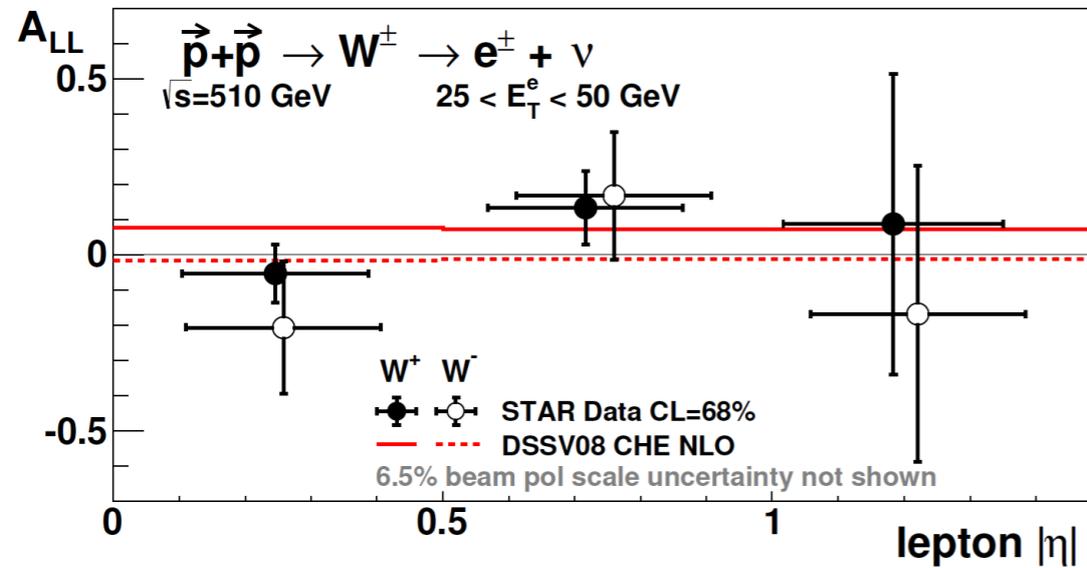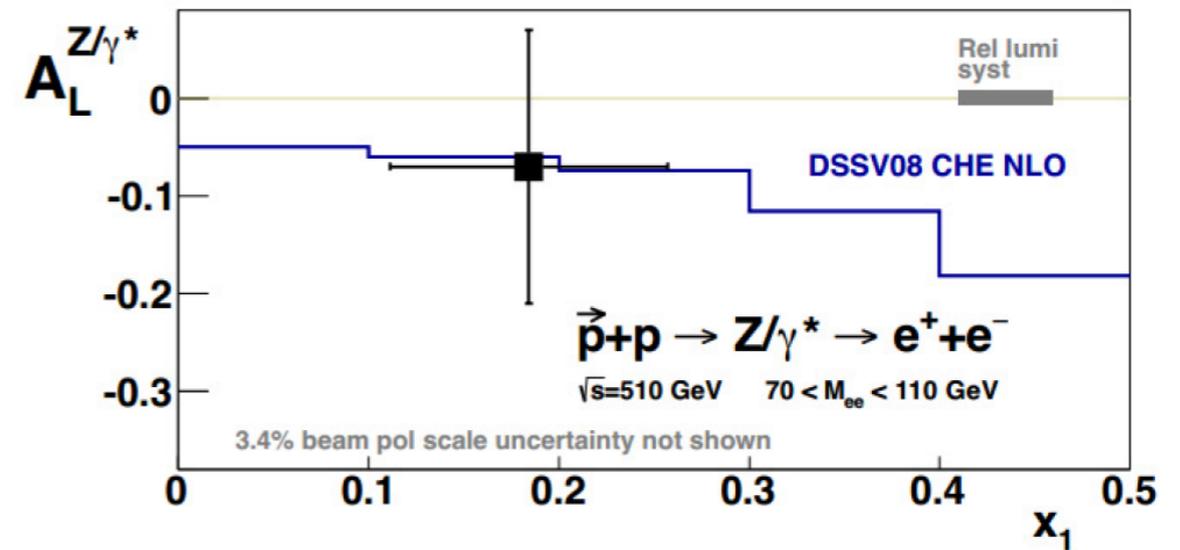
PRL 113,72301 (2014)

Z invariant mass
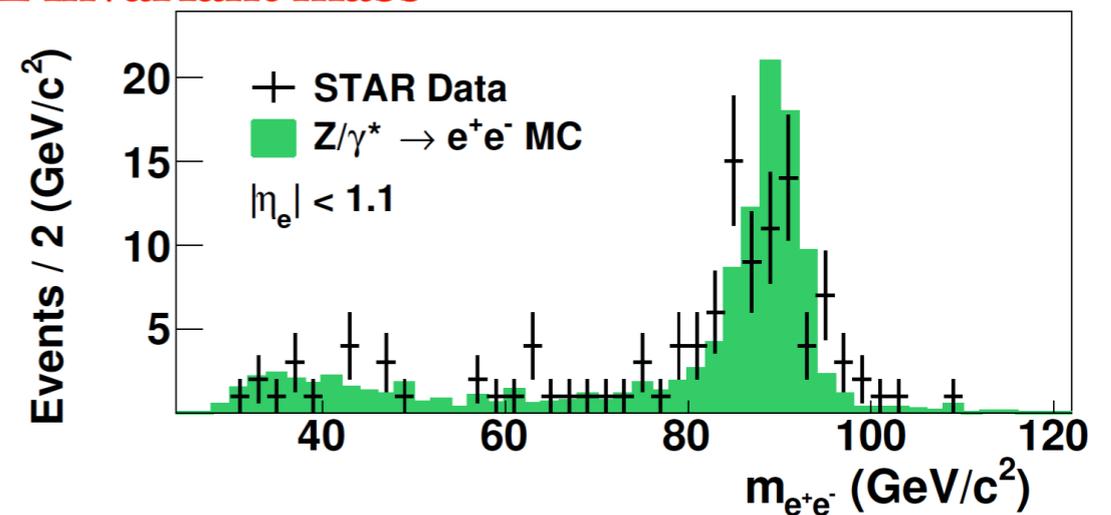
PRL 113,72301 (2014)

* 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

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 kinametics 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


p

x_1

W

$\bar{\nu}_e$

e

x_2

p

p

x_1

$Jet\ 1$

x_2

$Jet\ 2$

p

STAR W-event candidate
p+p 500 GeV
April 2009

STAR di-jet event
p+p 500 GeV
April 2009
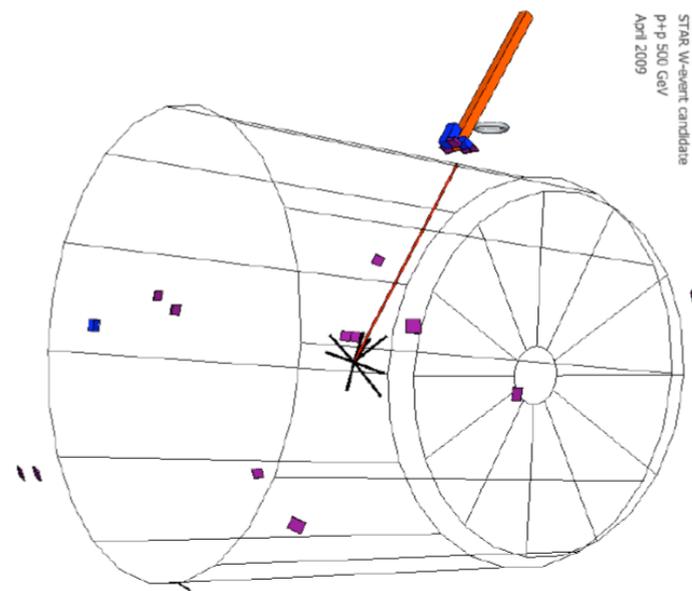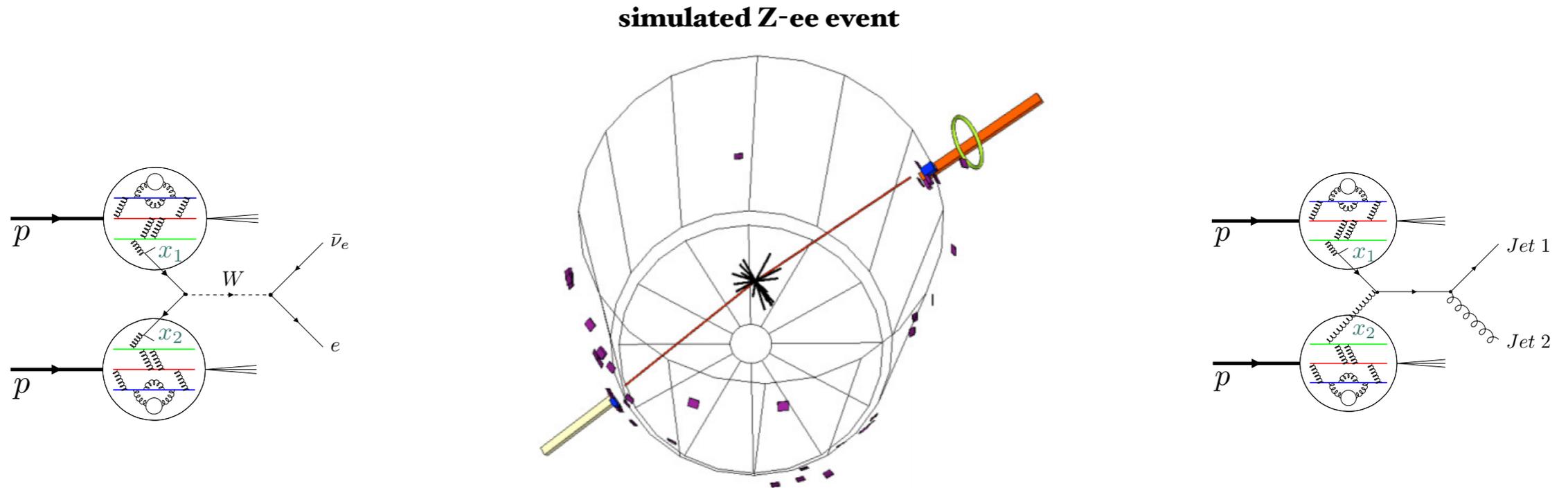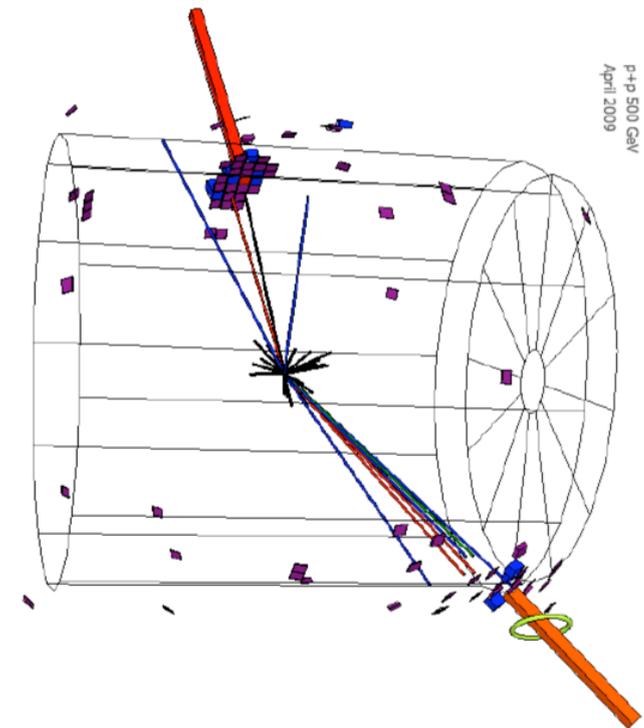
simulated W->e event

simulated di-jet event

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

❖ **Match $P_T > 10$ GeV TPC tracks to EMC cluster**

$$E_T^e \ / \ E_T^{4X4} \ > 0.95$$

TPC track extrapolated
to Barrel colorimeter tower grid
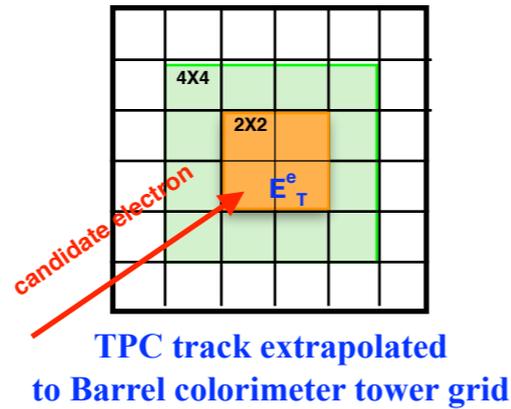
❖ **Isolate from QCD di-jet type event**

$$E_T^e \ / \ E_T^{\Delta R < 0.7} \ > 0.88$$

w type

jet type
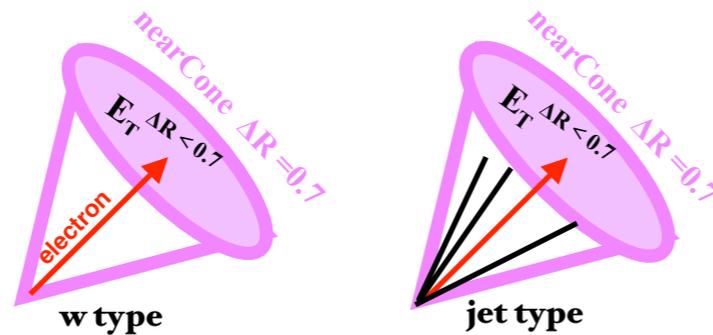
❖ **Use Larger imbalance of transverse momentum**

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

Transverse plane views
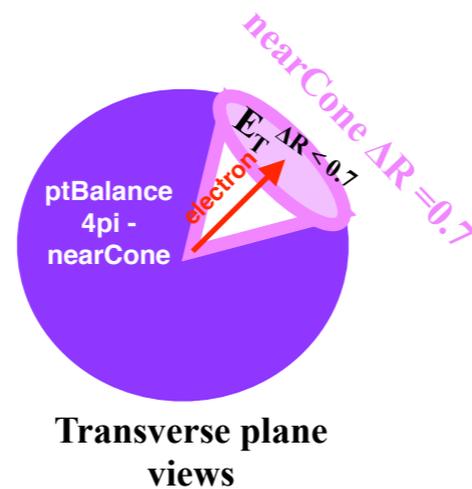
❖ **e+ and e- Charge sign Separation**
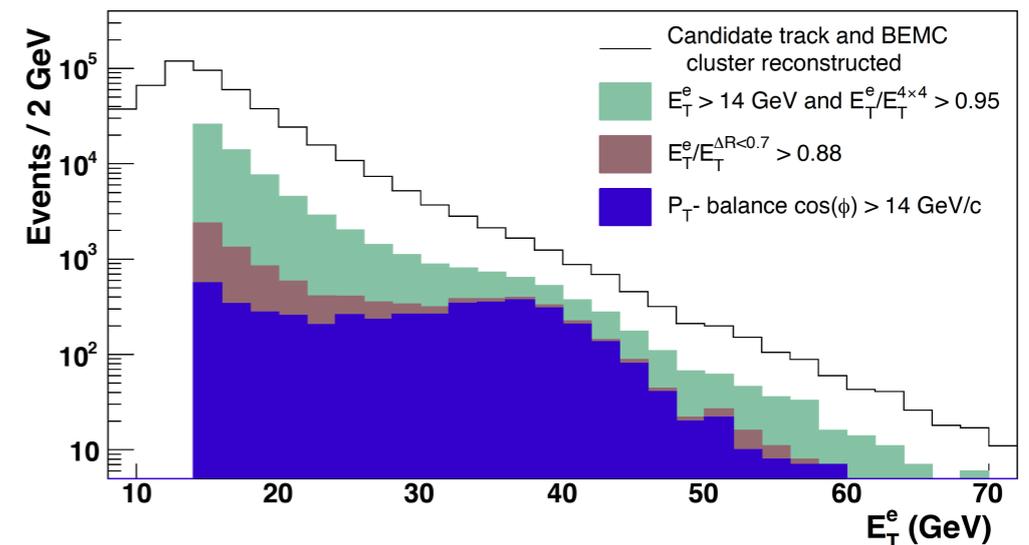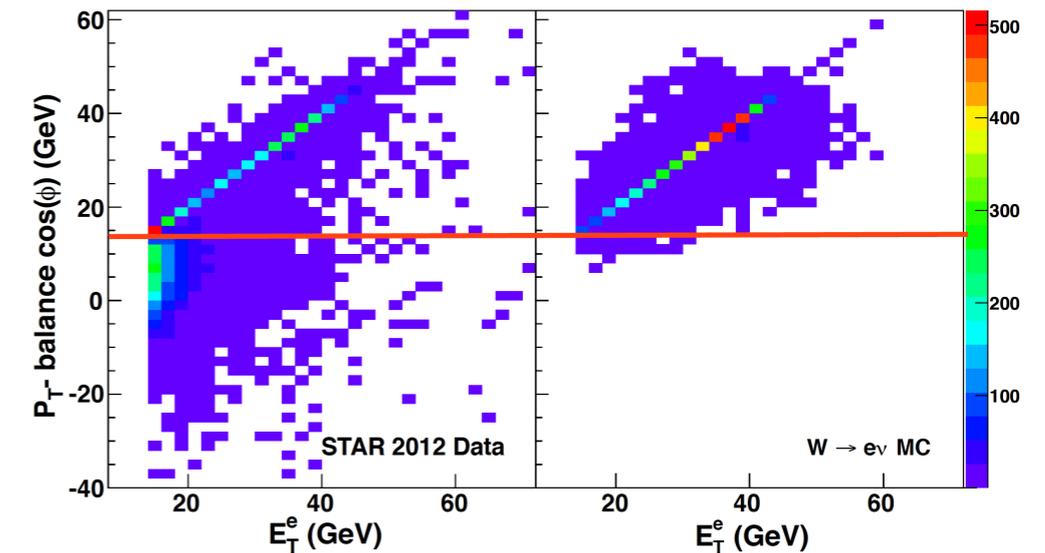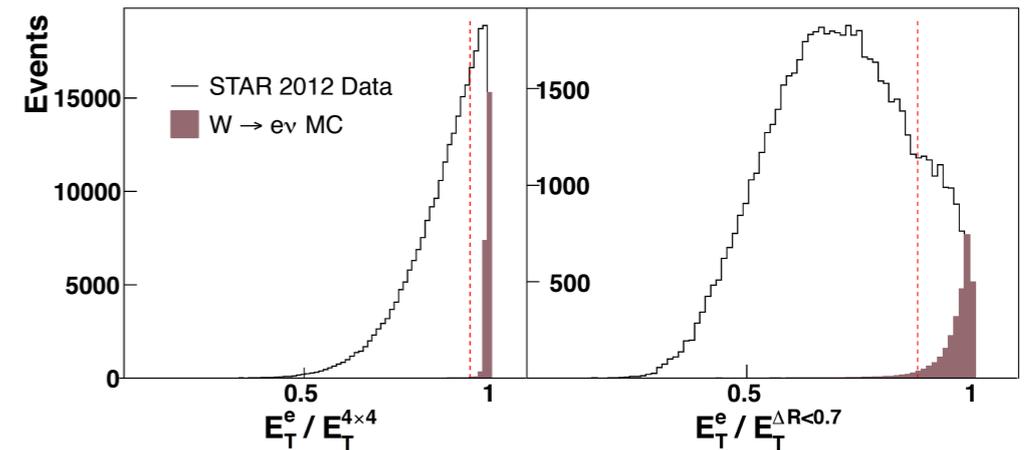
FGT

Illustration of charge-sign discrimination

Endcap SMD hit σ=1.5mm

Y/cm

100cm

Good Q-sign   Wrong Q-sign

reconstructed track →

1σ of reconstructed track
→

Sagitta=2mm

Limit for ∞ pT track

40cm

3 FGT hits

20cm

Vertex σ=200μm

X/cm

0   1.0   2.0 mm
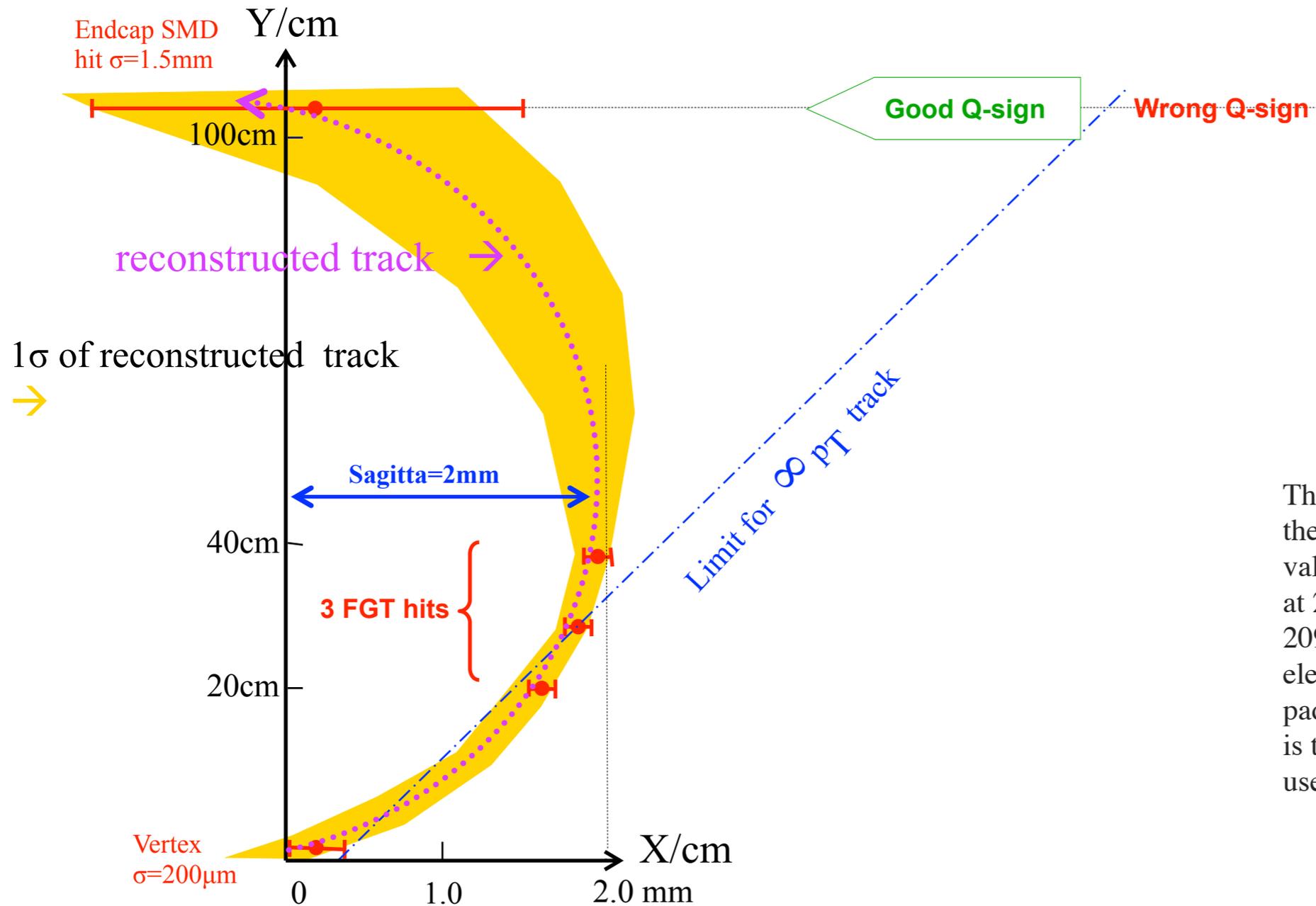
The TPC prompt hits are 'hits' using the ANODE wires located at large Z values at 209.5 cm for inner subsectors and 209.7 cm for outer subsectors. The electrons from a charge drift to the pad planes. The 'first signal in time' is then used define a prompt hit.

FGT track reconstruction

☐ Comparison of data / fast MC: Track reconstruction

R^ISOLATION
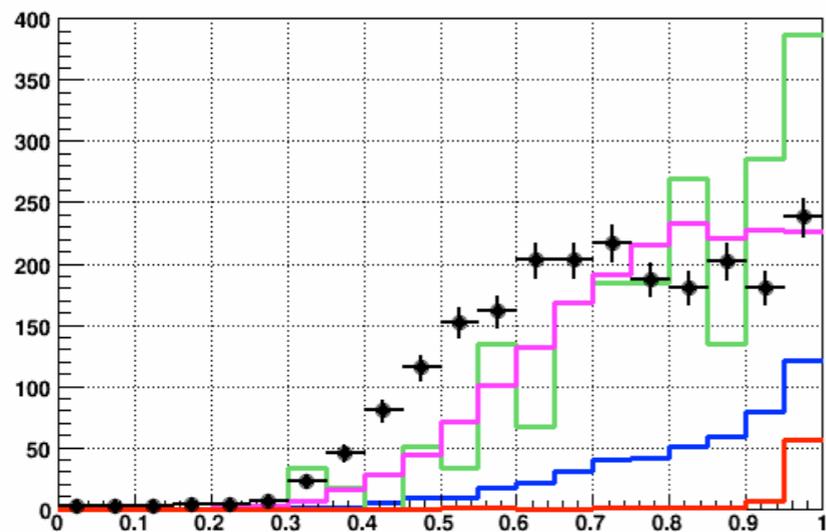
pT[GeV/c]
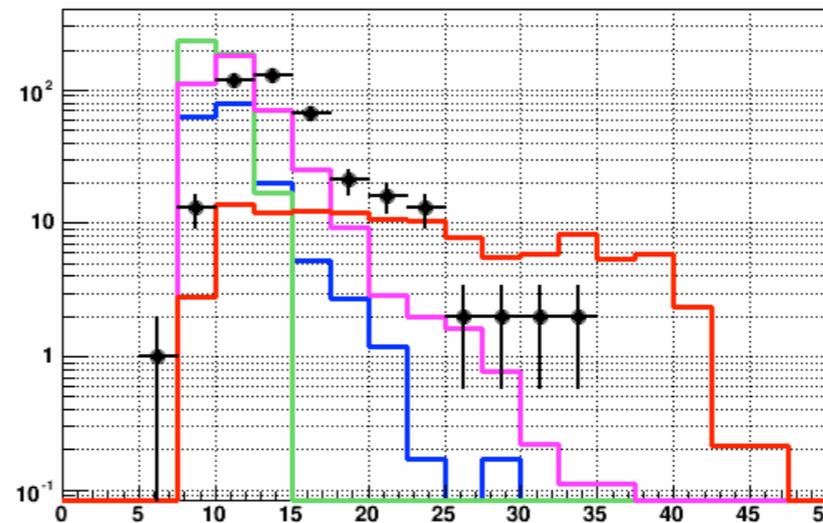
Run13 Data (FGT+VTX +EEMC, no prompt)

PYTHIA QCD charged hadrons

E [GeV]
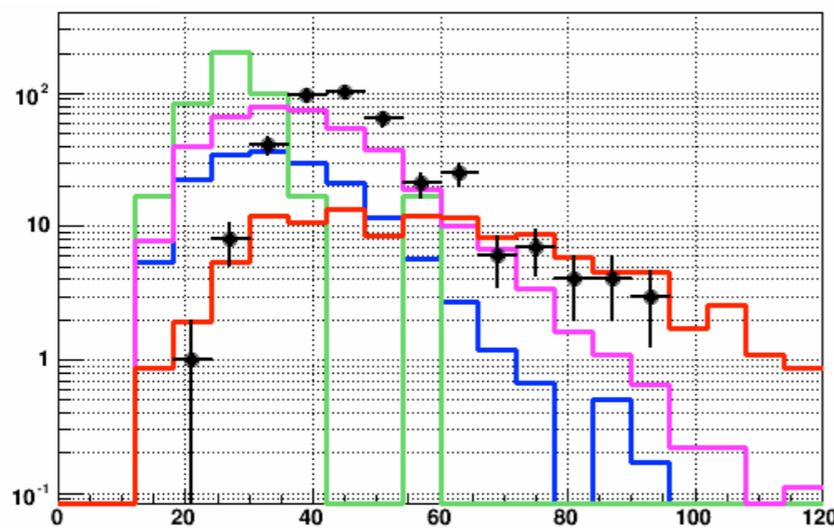
PseudoRapidity   50GeV/c

PYTHIA W

100GeV   0   3

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]