22nd International Spin Symposium [SPIN 2016]
September 25-30, 2016 at UIUC

U.S. DEPARTMENT OF ENERGY
DOE NP contract: DE-SC0013405

Measurements of W single spin asymmetries and W cross section ratios at STAR

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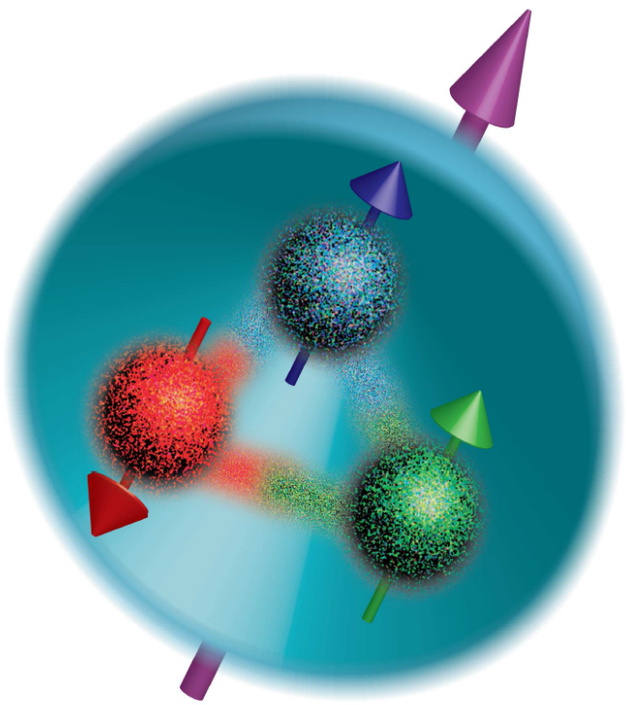
OUTLINE

- Introduction
  - Anti-quark polarization
  - Flavor asymmetry of the sea
- Theoretical Foundation [W A_L / W R_W]
- Experimental Aspects [RHIC / STAR]
- Results
  - W A_L
  - W R_W
- Summary

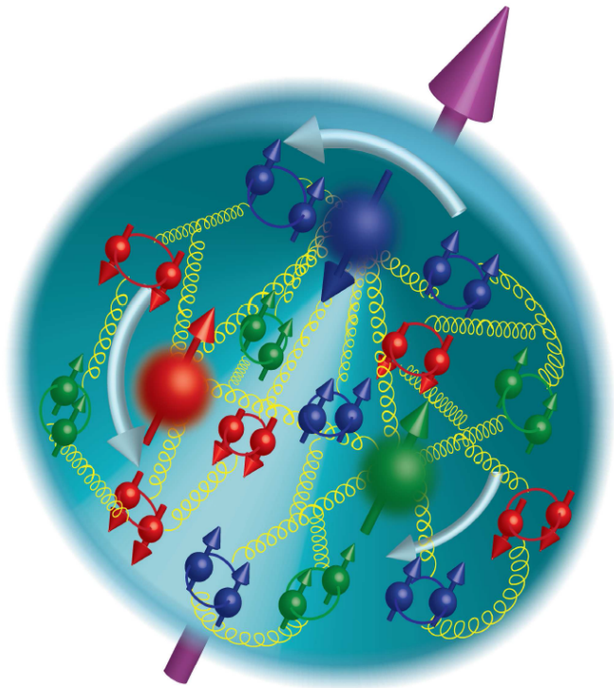
INTRODUCTION : Proton Helicity Structure



1989 : EMC : DIS

$$\Delta\Sigma = 0.12 \pm 0.09 \pm 0.14$$

"Spin Crisis"



Naive Parton Model

$$\frac{1}{2} = \frac{1}{2}(\Delta u_v + \Delta d_v)$$

Gluons , Sea quarks are polarized.

→

Parton orbital angular momentum.

Current Understanding

$$< S_z >= \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

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

DIS

- Well measured!
- Not sensitive to flavor separation!

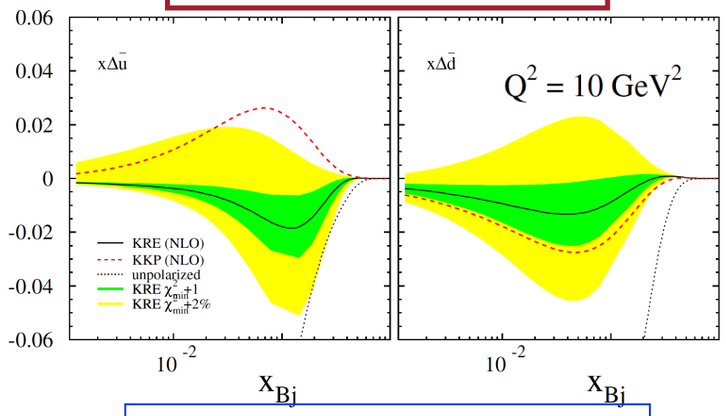
SIDIS

- FF's use to tag flavor!
- Flavor separation / quark, anti-quark separation!
- But large uncertainties in FFs.

Light anti-Quark Polarization: Current Knowledge

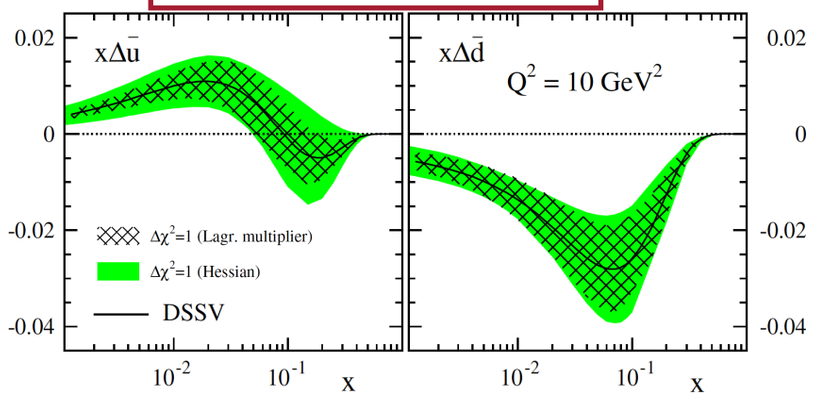
- NLO calculations
- Mainly SIDIS

DNS : data < y2000



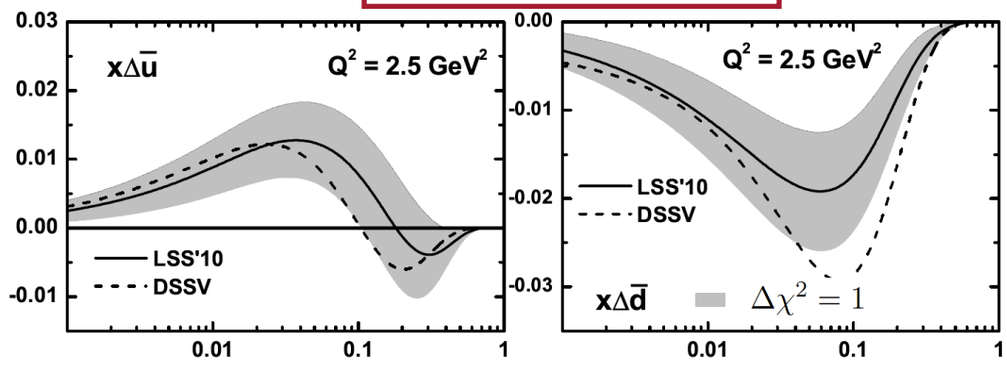
Phys. Rev. D 71, 094018 (2005)

DSSV : data < y2004



Phys. Rev. D 80, 034030 (2009)

LSS : data < y2006



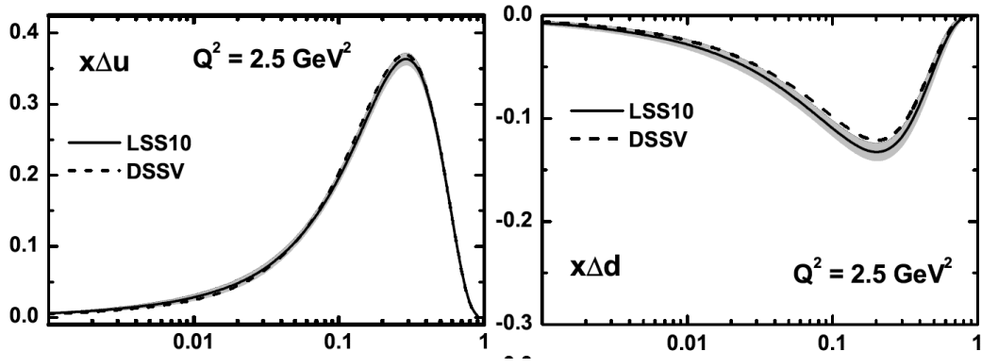
Phys. Rev. D 82, 114018 (2010)

More Precise / large / increased kinematic range - DATA sets

More Precise FFs

Improved global fitting tools

But still less precise, in comparison to valance sector



W A_L measurements at RHIC provide a unique (direct sensitivity to $\bar{u}$,$\bar{d}$) and clean approach (free of FFs) to constrain anti-quark helicity PDFs at much larger Q^2 scale set by W mass (~6400 GeV^2).

Flavor Asymmetry of the Unpolarized Sea

Simple Perturbative picture of the sea created by gluon splitting

- Equal amount of $\bar{u}$,$\bar{d}$ [$\bar{u}$,$\bar{d}$ roughly equal mass / gluon is flavor blind]
- SU(3) flavor symmetry

Breaking of the sea symmetry ~ 1970s

- Violation of Gottfried Sum Rule [GSR] - First indication of a asymmetric sea

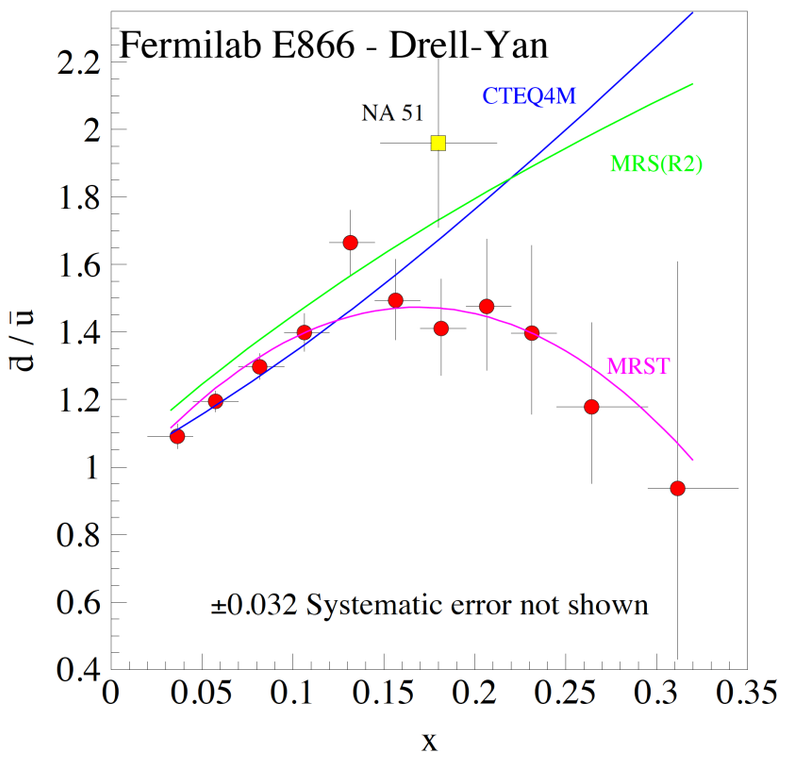
NMC **Phys. Rev. Lett 66, (1991) 2712**

0.235 ± 0.026 at $Q^2 = 4\ \mathrm{GeV}^2$

- significantly below 1 /3

- Drell-Yan [E866] - more concrete evidence

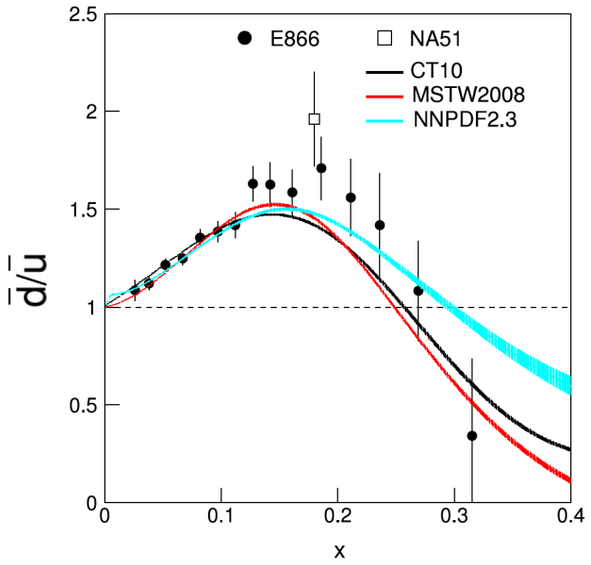
Phys. Rev. Lett 80, (1998) 3715



- Increases linearly up to x ~ 0.15.
- Drops off at higher x.
- Qualitative explanation at low x of $\bar{d} > \bar{u}$.
- Failed to explain higher x of $\bar{u} > \bar{d}$.

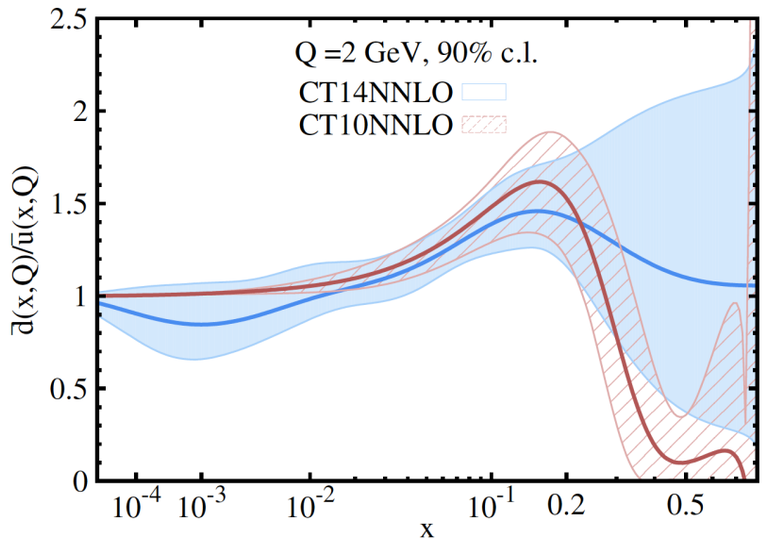
Flavor Asymmetry of the Unpolarized Sea : Current knowledge

- E866 in comparison to recent NNLO



- Recent (CT10,etc) NNLO Fits seems to follow the shape but still relatively large uncertainties at large x.
- The most recent (CT14) suggest a constant approach towards 1 at large x, with large uncertainties.

arXiv:1506.07443v3

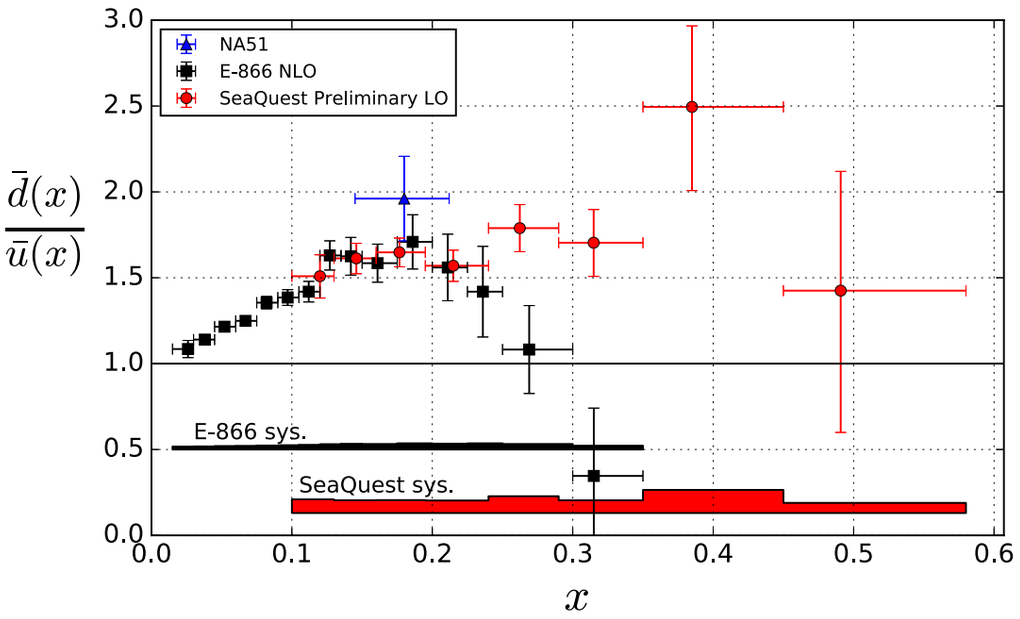


Progress in Particle and Nuclear Physics 79(2014)95-135

Need more data / experiment to understand $\bar{d}/\bar{u}$ behavior!

- SeaQuest E906 - Preliminary

B. Kerns et al. (SeaQuest Collaboration), APS April Meeting, 2016



- Lower Q^2 than Drell-Yan E866.
- Measurement extended to large x.
- Will help to minimize any process dependent assumptions.

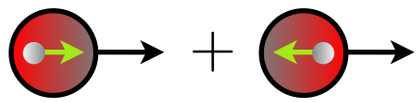
W production at RHIC at much larger Q^2 than Drell-Yan

Provides an important, completely independent cross check of flavor asymmetry of the sea through measurements of W cross section ratio!

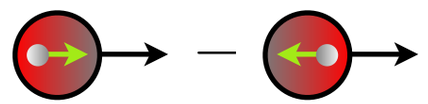
Theoretical Foundation - W A_L

- Spin asymmetry measures ratio of polarized to unpolarized structure functions → polarized PDFs

Momentum distribution

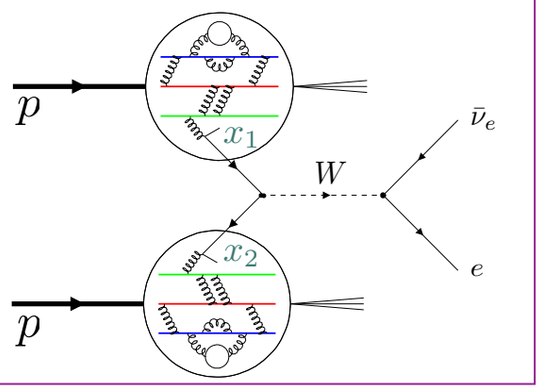
$f(x) =$  $f^+(x) + f^-(x)$

$$\frac{g_1(x)}{F_1(x)} = \frac{\sum_q e_q^2(\Delta f_q(x) + \Delta \bar{f}_q(x))}{\sum_q e_q^2(f_q(x) + \bar{f}_q(x))} = A_1 \equiv \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

$\Delta f(x) =$  $f^+(x) - f^-(x)$

Helicity distribution

- Probing quark / anti-quark (sea) flavor structure using W boson production at RHIC

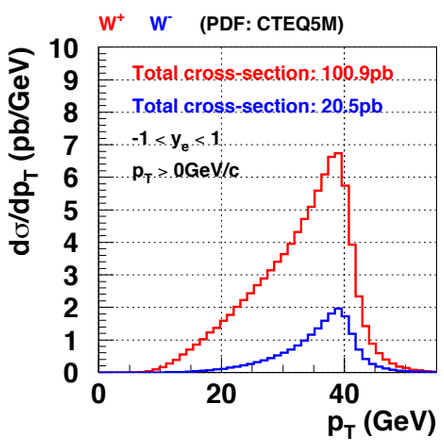


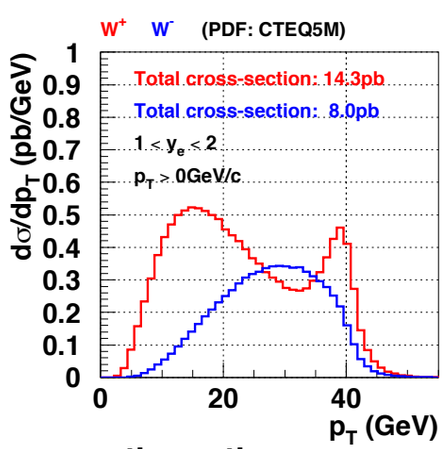
In comparison to SIDIS,

- Direct sensitive to ū,d̄
- Large Q^2 defined by W mass (more reliable perturbative calculation / hight twist effects unimportant!)
- Large parity violating coupling give rise to singe-spin asymmetry which directly related to anti-quark helicity PDFs.
- Free of FFs.
- Easy detection via decay leptons.

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

At RHIC environment





- Reconstruct W decay lepton kinematics ($P_T \sim M_W/2$, η_e)

$$y_l = y_W + \frac{1}{2}\ln\frac{1+\cos\theta^*}{1-\cos\theta^*} \qquad p_T = p_T^* = \frac{M_W}{2}\sin\theta^*$$

$$x_{1,2} = \frac{M_W}{\sqrt{s}} e^{\pm y_w} \qquad \frac{M_W}{\sqrt{s}} = 0.16$$

Theoretical Foundation W A_L - η dependance

Rapidity dependance of W AL provides sensitivity to parroting kinematics.

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

$$< x_{1,2} > \sim \frac{M_W}{\sqrt{s}} e^{\pm\eta_e/2}$$

$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

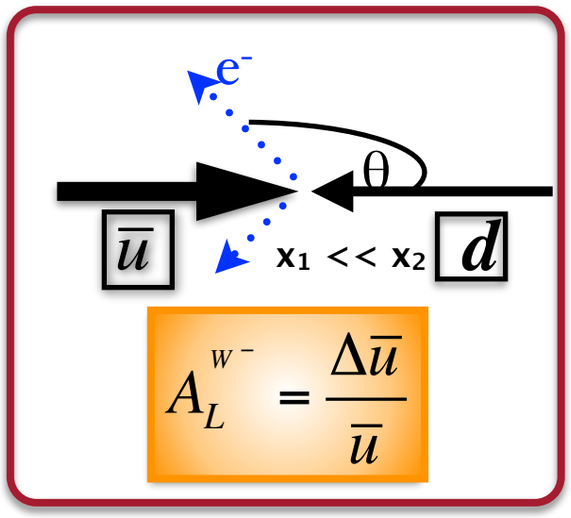
η <<< 0 —> x_1 <<< x_2

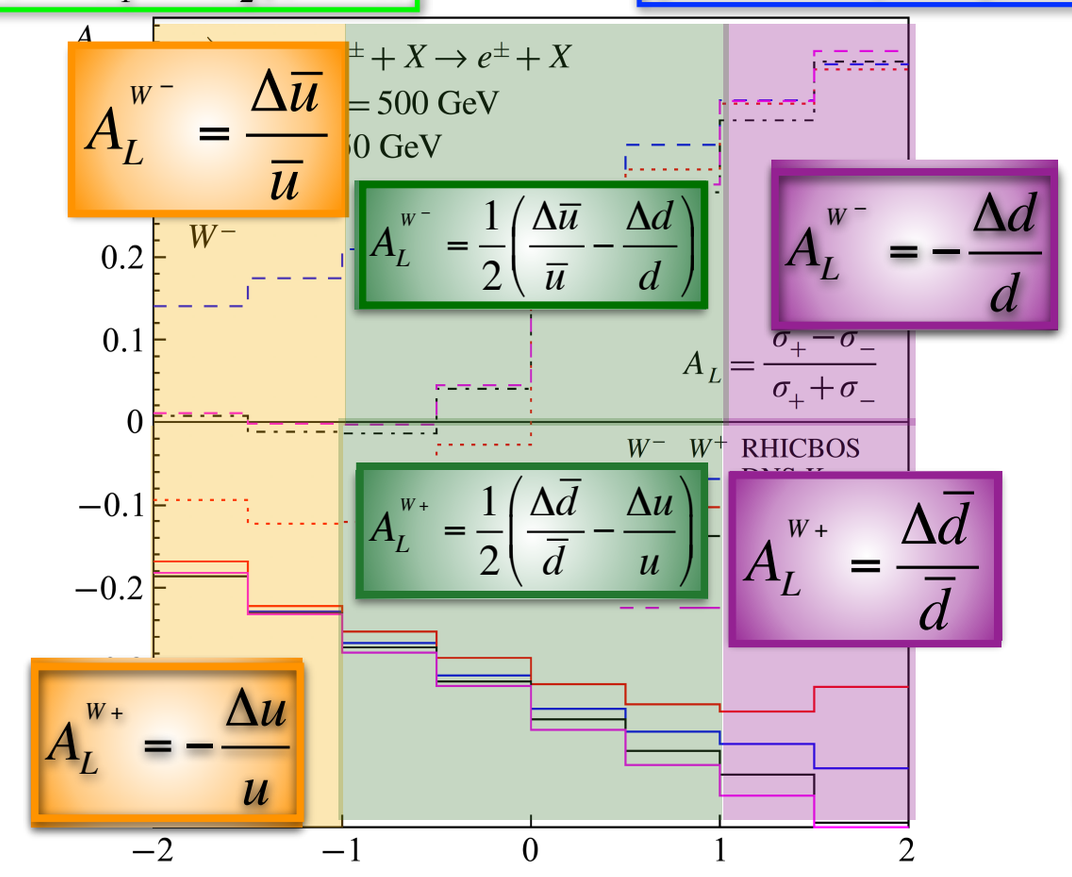
η >>> 0 —> x_1 >>> x_2

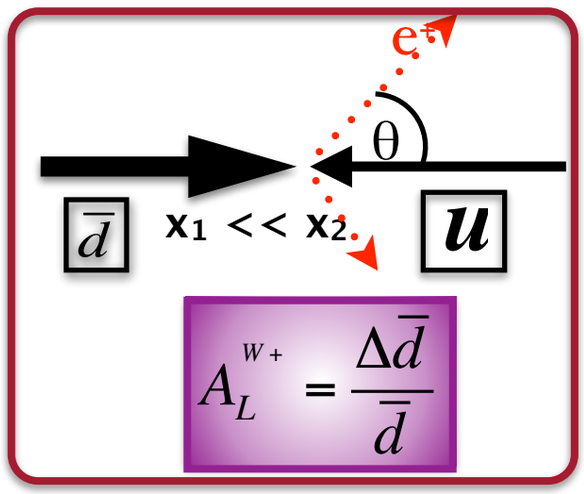
η = 0 —> x_1 ~ x_2

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

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







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

Theoretical Foundation: W unpolarized cross-section ratio

W unpolarized cross section ratio

$$R(x_F) \equiv \frac{\sigma_W^+}{\sigma_W^-} = \frac{u(x_1)\,\bar{d}(x_2) + \bar{d}(x_1)\,u(x_2)}{\bar{u}(x_1)\,d(x_2) + d(x_1)\,\bar{u}(x_2)} + NLO + NNLO + \ldots$$

$$R = \frac{N_O^+ - N_B^+}{N_O^- - N_B^-} \cdot \frac{\epsilon^-}{\epsilon^+}$$

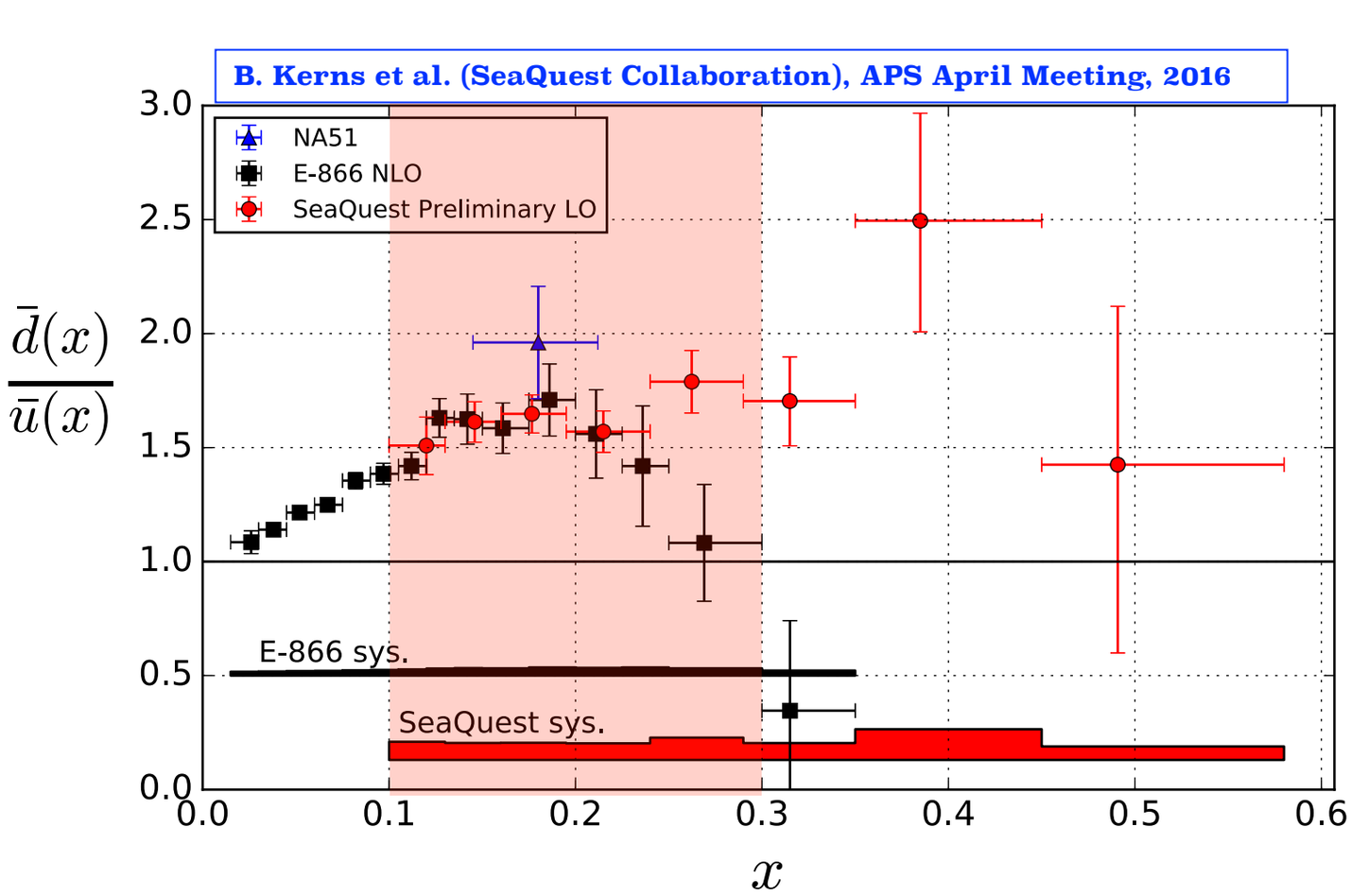
$N_O^{+(-)}$ = measured positron (electron) decay events

$N_B^{+(-)}$ = Positive (negative) background events

ε = lepton detection efficiency

RHIC kinematic coverage (mid-rapidity) is sensitive in particular to "turn over" region of x in $\bar{d}/\bar{u}$.

mid-rapidity => $|\eta| < 1$, $0.1 < x < 0.3$



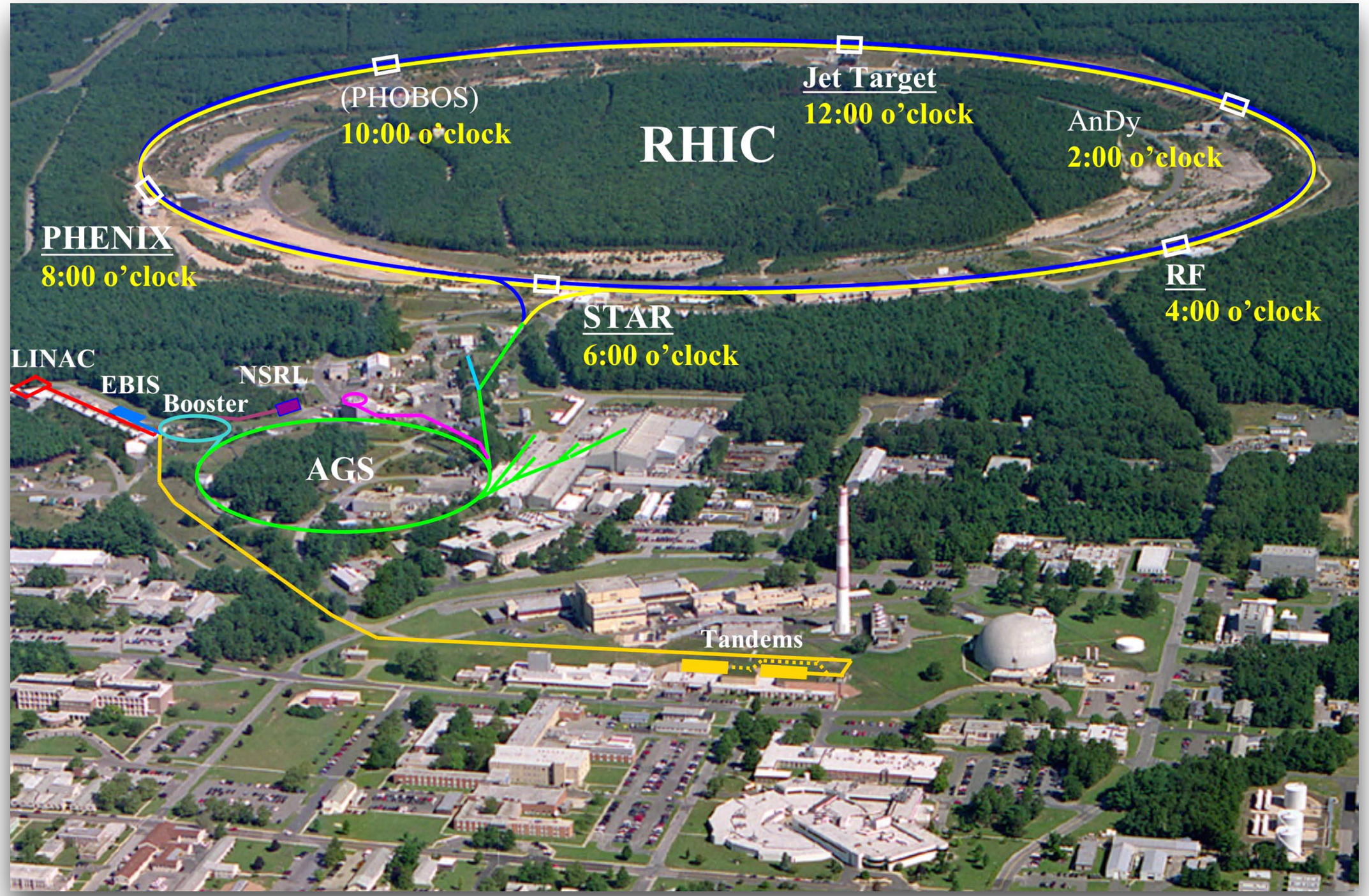
- Approximate kinematic range at RHIC:

$0.06 < x < 0.4$ for $-2 < \eta < 2$

EXPERIMENTAL ASPECT - RHIC-I

- **RHIC : Relativistic Heavy Ion Collider**

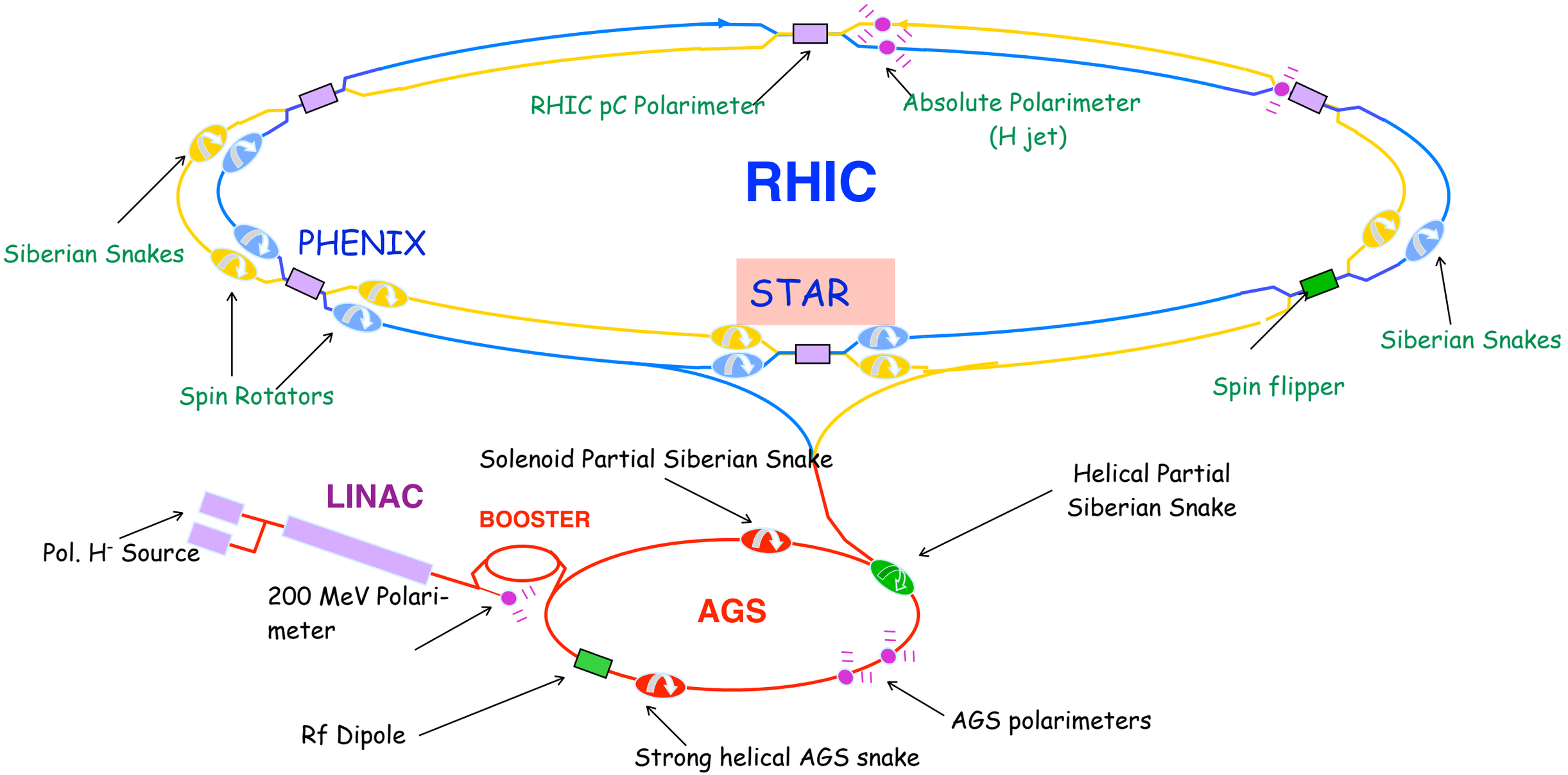
The World's first polarized hadron collider!



EXPERIMENTAL ASPECT -RHIC-II

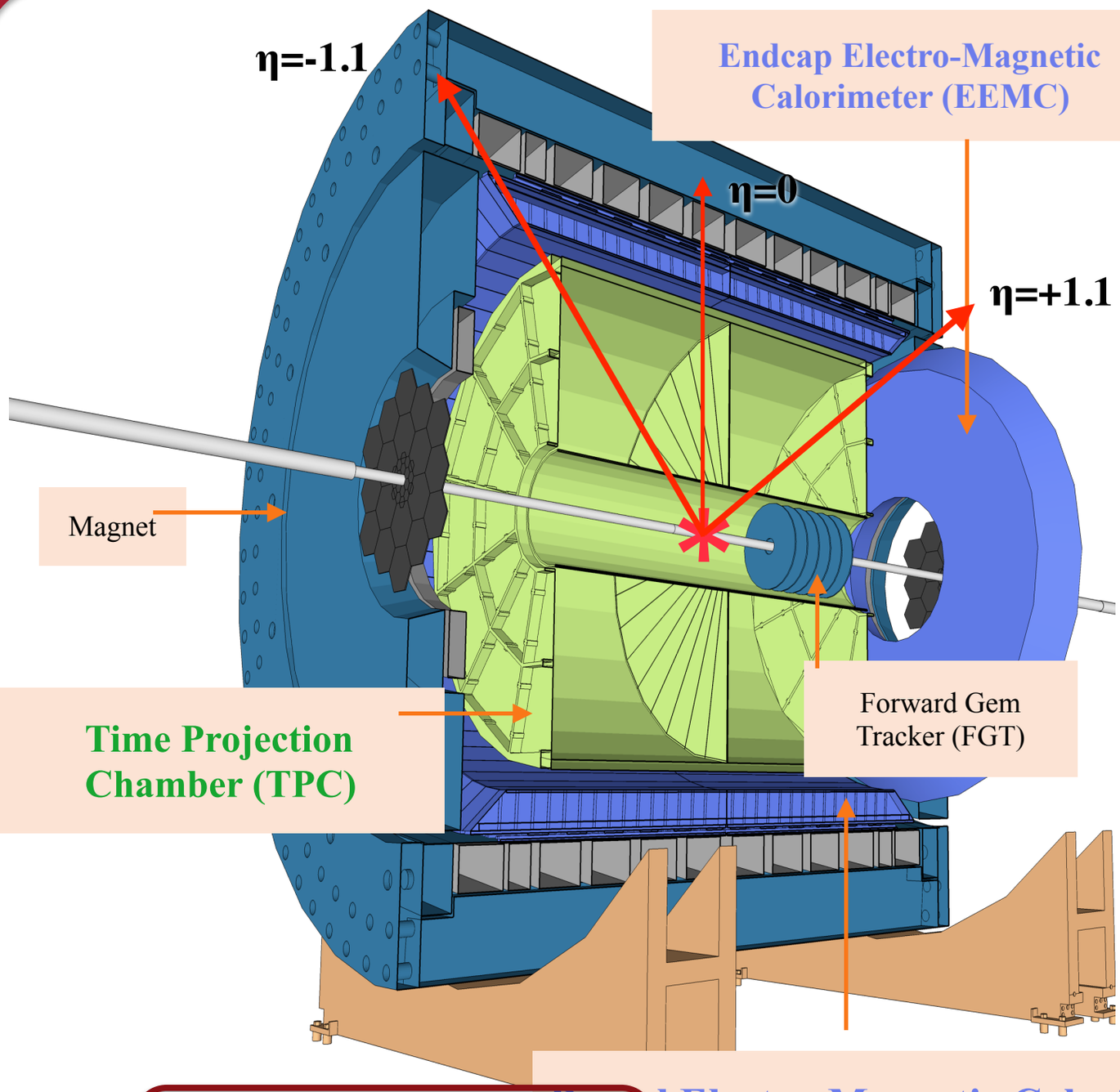
- **RHIC : Relativistic Heavy Ion Collider**

Spin varies from bunch to bunch. Spin pattern changes from fill to fill.
Spin rotators provide choice of spin orientation.



EXPERIMENTAL ASPECT - STAR

- **STAR : Solenoidal Tracker At RHIC**



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

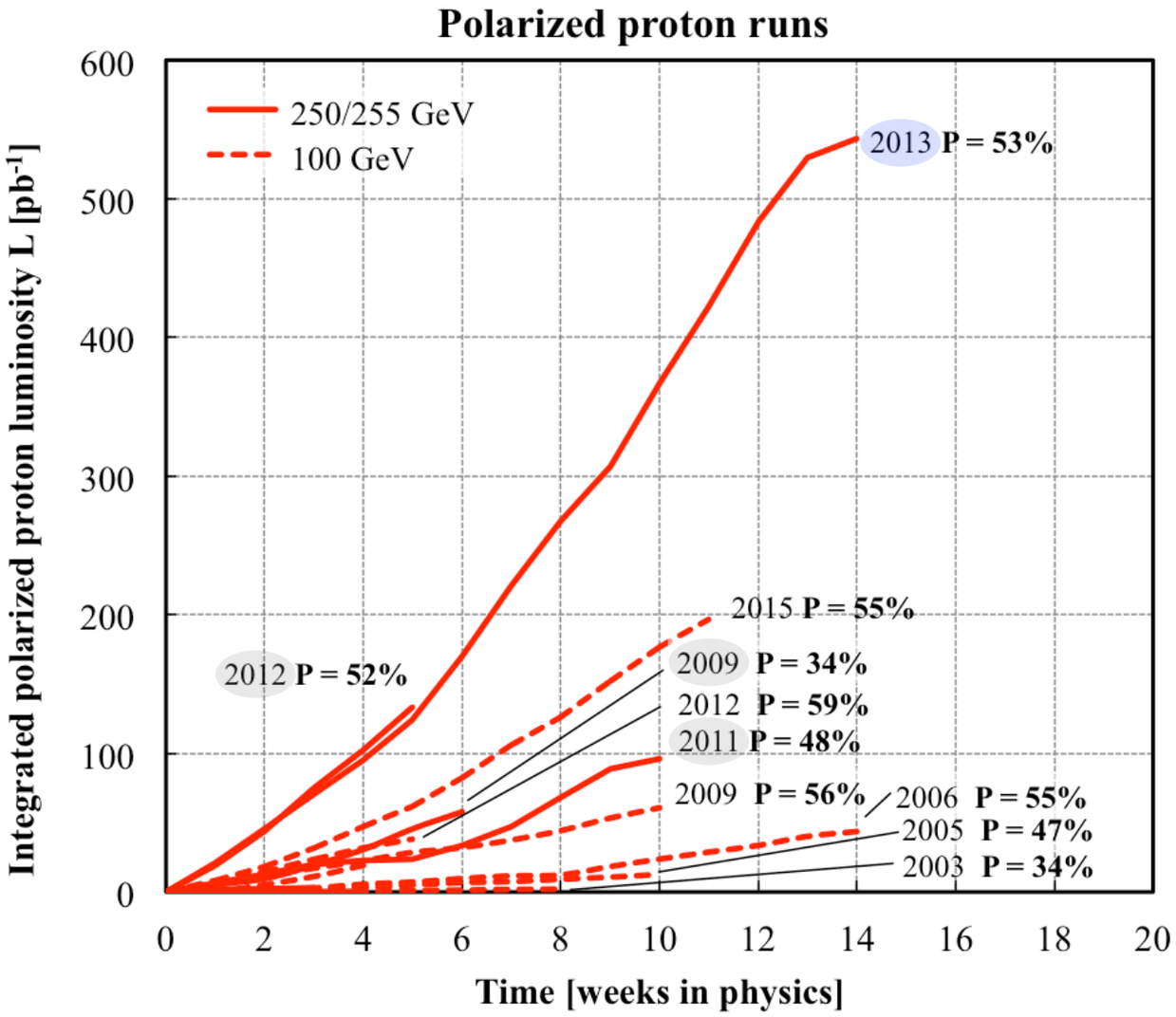
TPC: Charged particle tracking

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**

ANALYSIS - RHIC PP running STAR W data collection

- Production runs at √s=500/510GeV (long. polarization) in 2009, 2011, 2012 and 2013:
  W production (Quark polarization) / Jet and Hadron production (Gluon polarization)

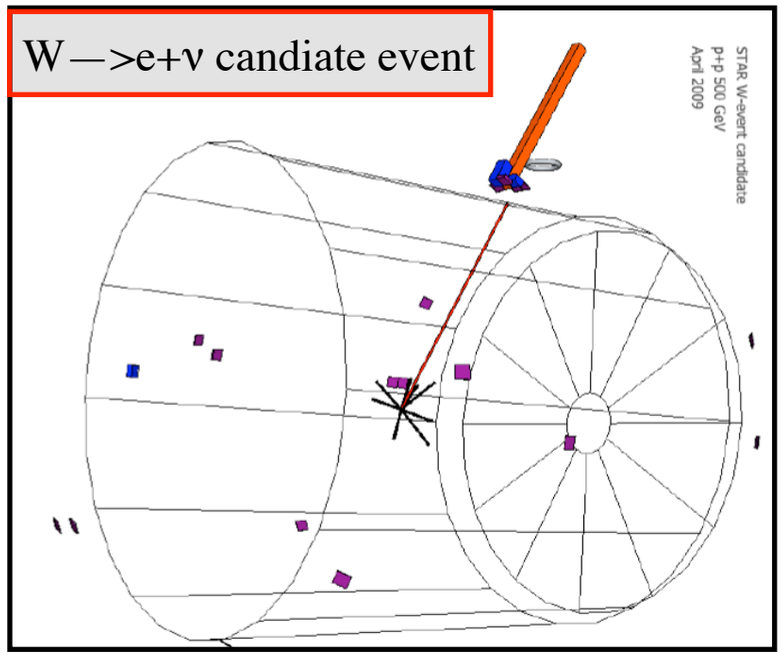


Run	L (pb^{-1})	P (%)	FOM (P^2L) (pb^{-1})
2009	12	0.38	1.7
2011	9.4	0.49	2.3
2012	77	0.56	24
2013	246.2	0.56	77.2

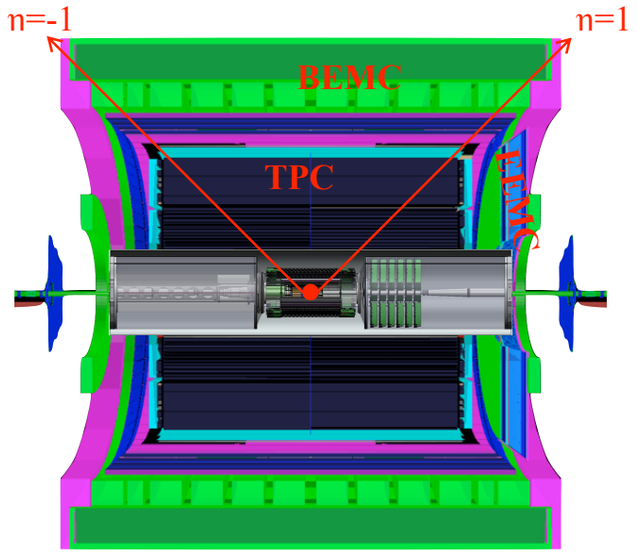
- W A_L recent result present today is from data collected during year 2013, the largest data set STAR ever collected!
- Prior W A_L analysis from data collected during 2009 and 2011+2012 are published!

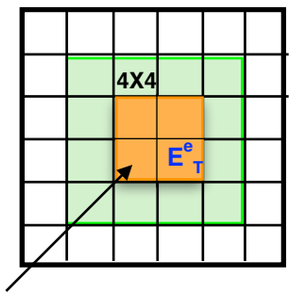
STAR: PRL 106, 062002(2011) STAR: PRL 113, 072301(2014)

ANALYSIS -Mid rapidity STAR W selection criteria

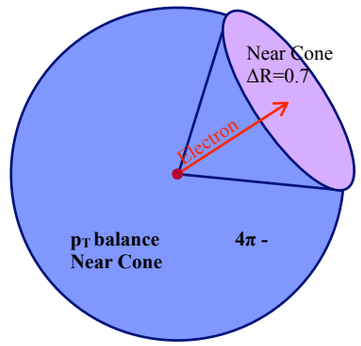


- Isolated high PT track pointing to isolated EMC cluster
- Large Imbalance in the reconstruct vector PT sum in 4π due to undetected neutron

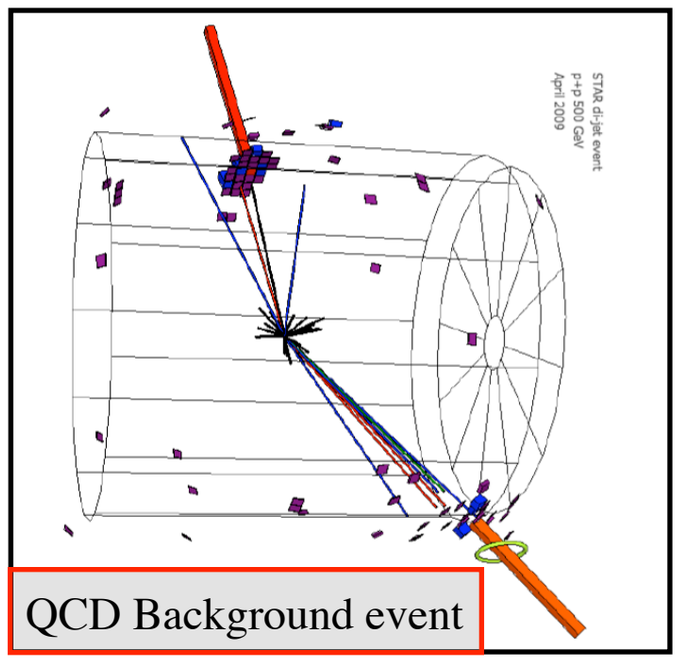




TPC track extrapolated
to Barrel colorimeter tower grid



Transverse plane view



- Several tracks pointing to several EMC clusters.
- PT sum is balanced by the Jet opposite in π.

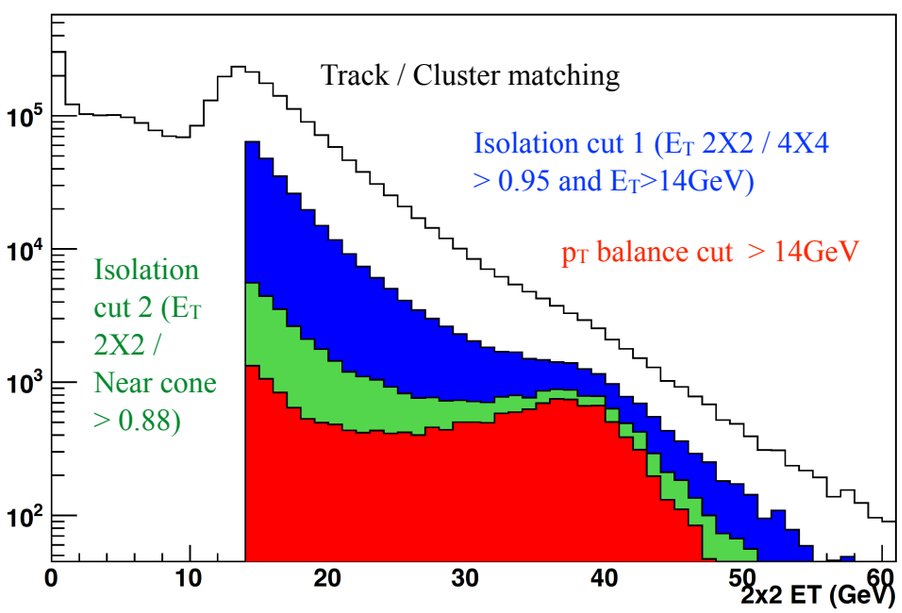
- Mid-rapidity STAR W selection criteria
  - Match p_T > 10 GeV track to BEMC cluster
  - Isolation ratio 1 / Isolation ratio 2
  - p_T-balance cut

$$E^e_T / E_T^{4X4} > 95\%$$

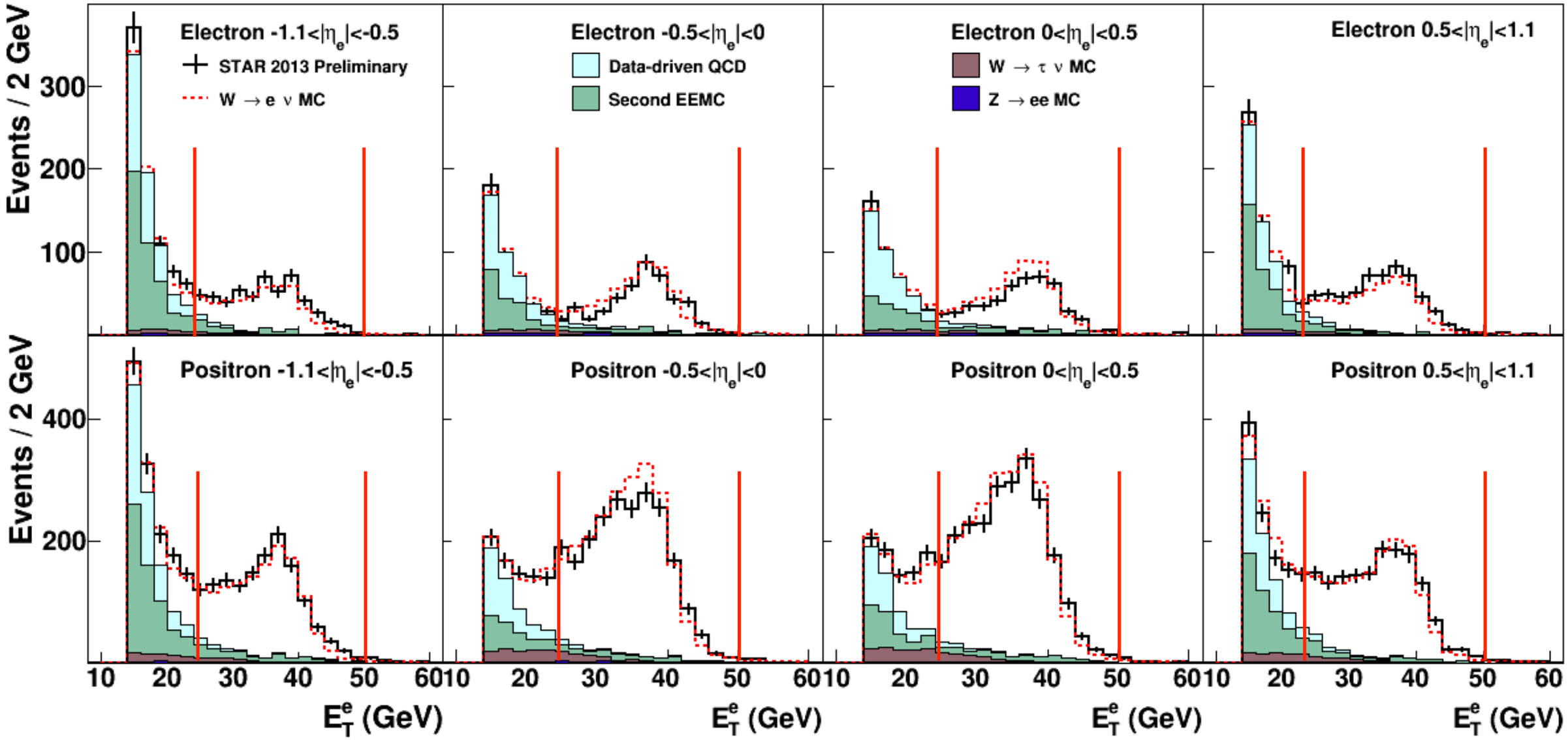
$$E^e_T / E_T^{\Delta R < 0.7} > 88\%$$

$$\vec{p_T}^{bal} = \vec{p_T}^{e} + \sum_{\Delta R > 0.7} \vec{p_T}^{jets}$$

$$P_T\text{-balance}\cos(\phi) = \frac{\vec{p_T}^{e} \cdot \vec{p_T}^{bal}}{|\vec{p_T}^{e}|}$$



ANALYSIS -Mid rapidity STAR W BG Estimation



Primary Background

ElectroWeak Background

- Data-driven QCD : BG Events which satisfy $e^{+/-}$ candidate isolation cuts due to "jet" escape detection outside STAR acceptance , $|\eta|>2$.
- Second EEMC : due to "jet" escape detection at "non-existent" East EEMC, estimate based on "real" West EEMC

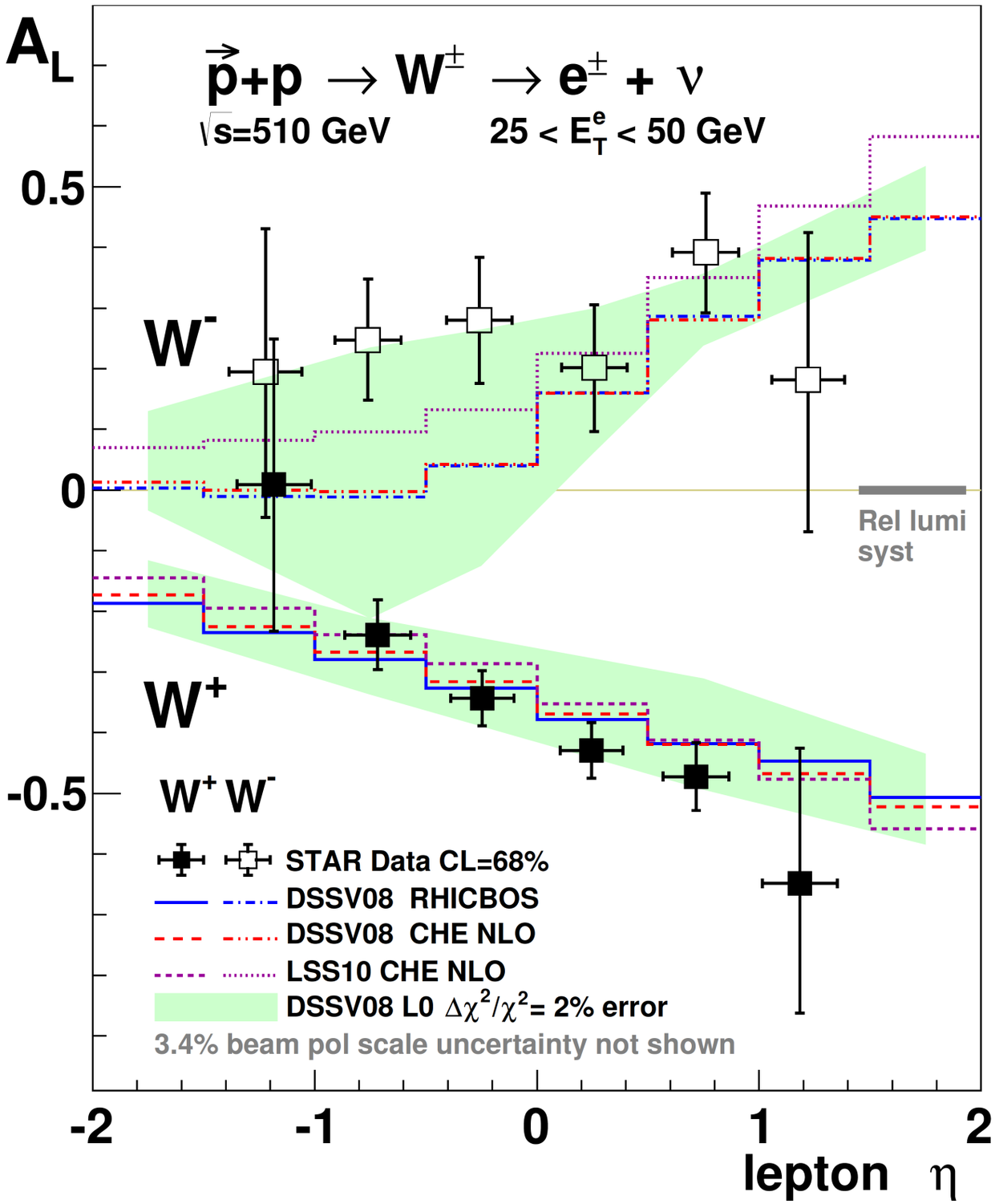
- Determine from MC simulation

$Z \longrightarrow e^+ + e^-$

$W \longrightarrow \tau + \nu$

RESULTS - W A_L - STAR 2012 -

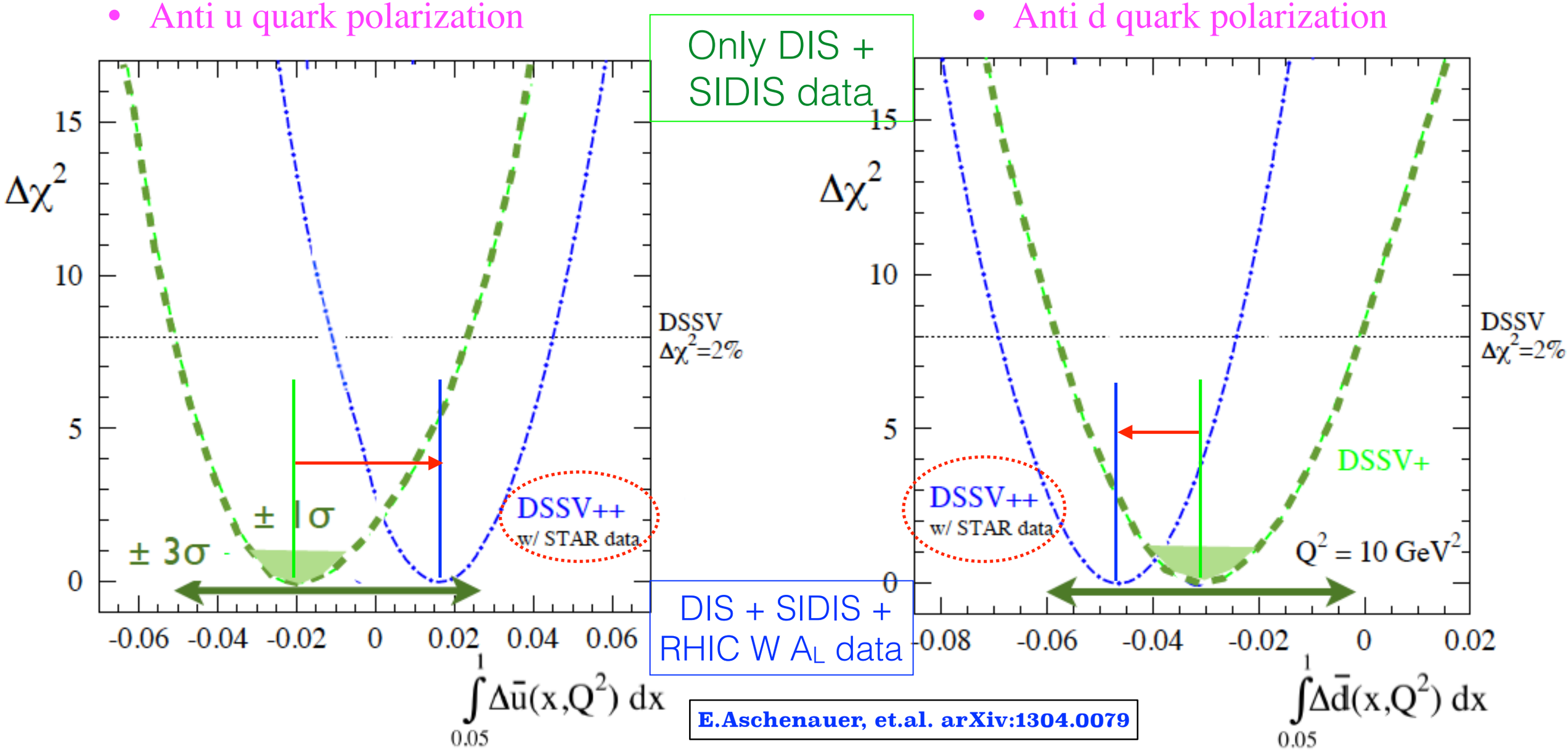
- STAR 2011 + 2012 W AL Published Results **STAR, PRL113,072301(2014)**



- A_L for W^+ is consistent with theoretical predictions constrained by polarized SIDIS data
- A_L for W^- is larger than the prediction for $\eta_e < 0$,which suggest large $\Delta\bar{u}$.
- Indication of positive $\Delta\bar{u}$ at $0.05<\eta<0.2$.

RESULTS - W A_L - STAR 2012 Impact - I

- Impact on helicity PDF from DSSV [STAR 2012 W AL Preliminary]



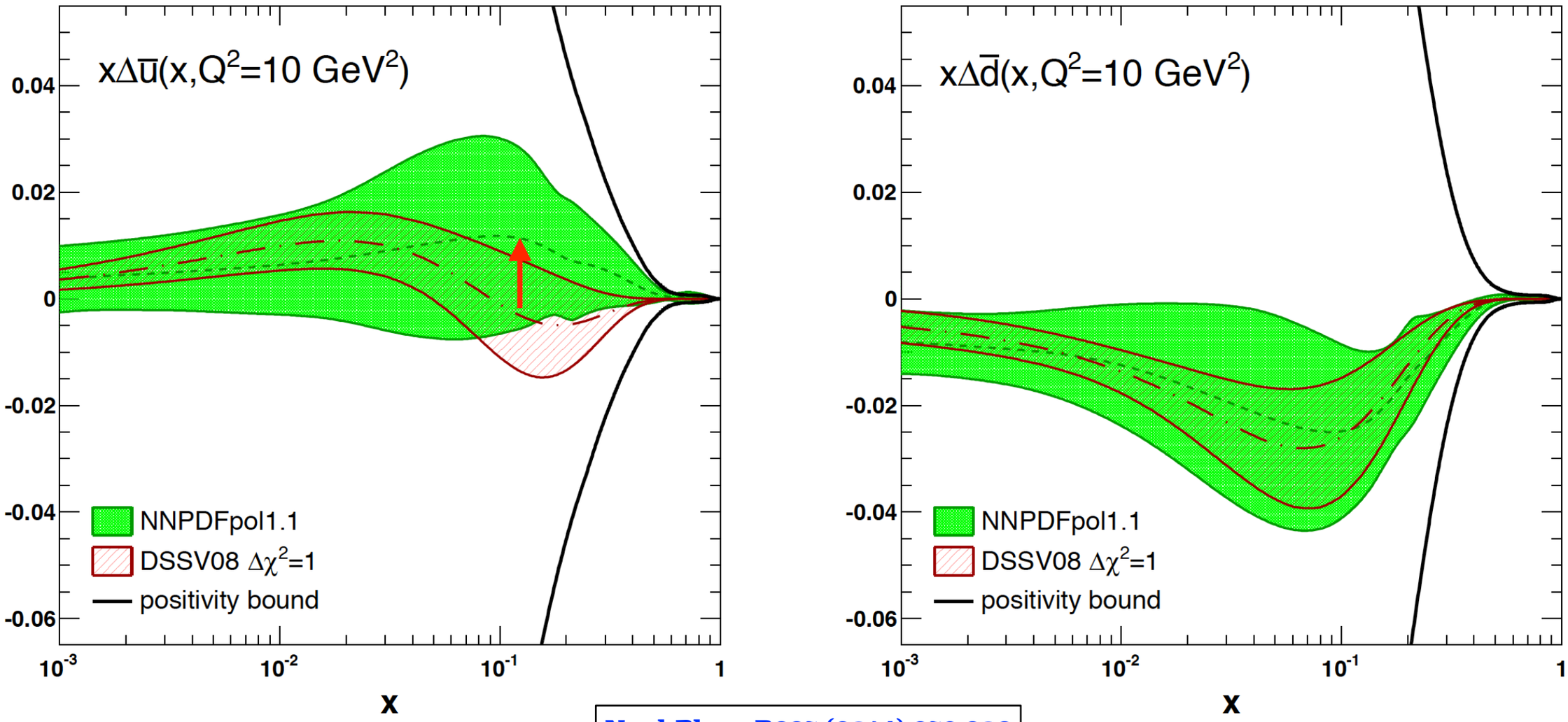
- Significant constraints on both $\Delta\bar{u}$ and $\Delta\bar{d}$.
- Significant shift of $\Delta\bar{u}$ central value from STAR 2012 W A_L data.

RESULTS - W A_L - STAR 2012 Impact - II

- Impact on helicity PDF from NNPDF [RHIC W A_L]

  - Anti u quark polarization

  - Anti d quark polarization

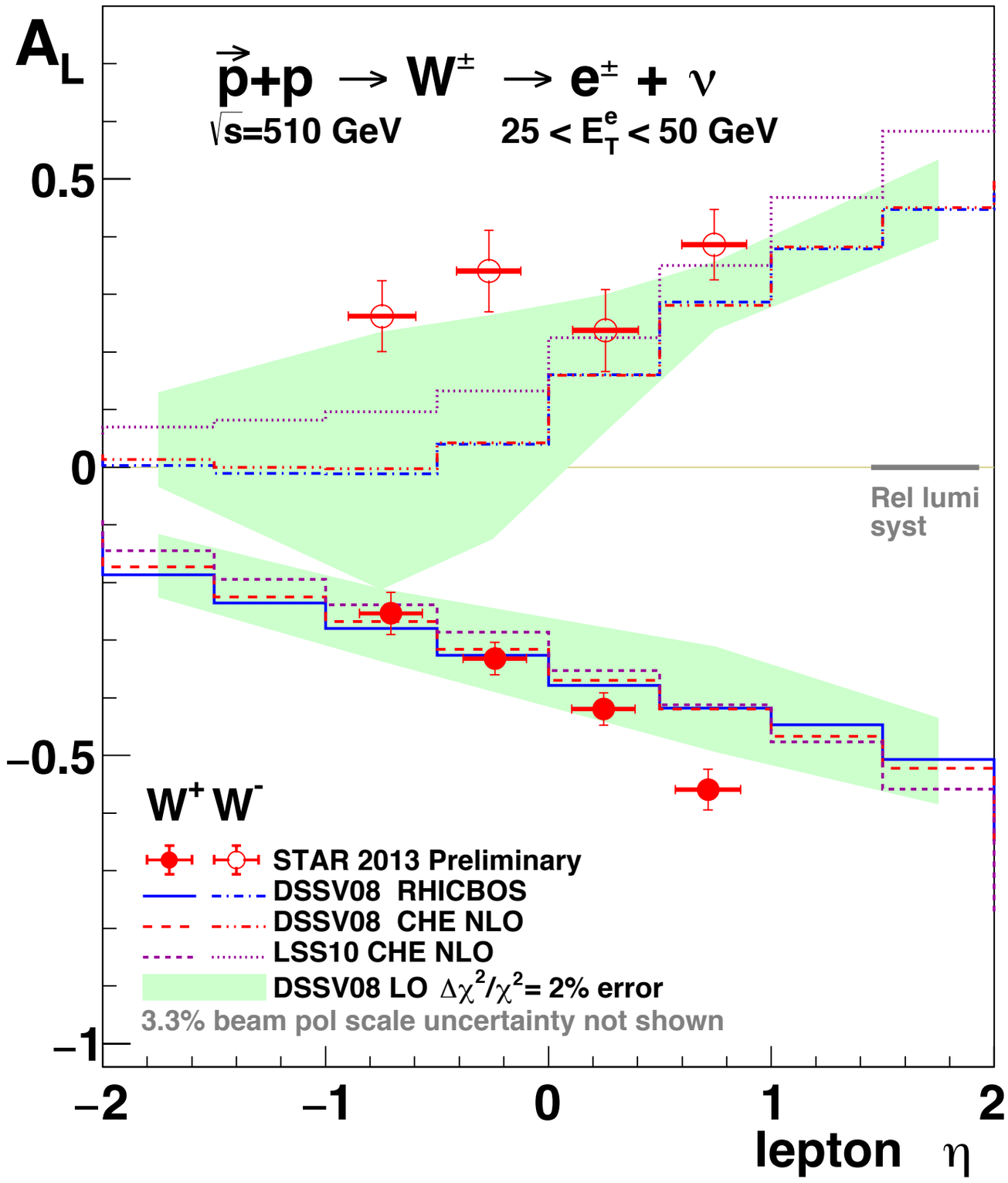


Nucl.Phys. B887 (2014) 276-308

- Significant shift of Δū central value from RHIC W A_L data

RESULTS - W A_L - STAR 2013

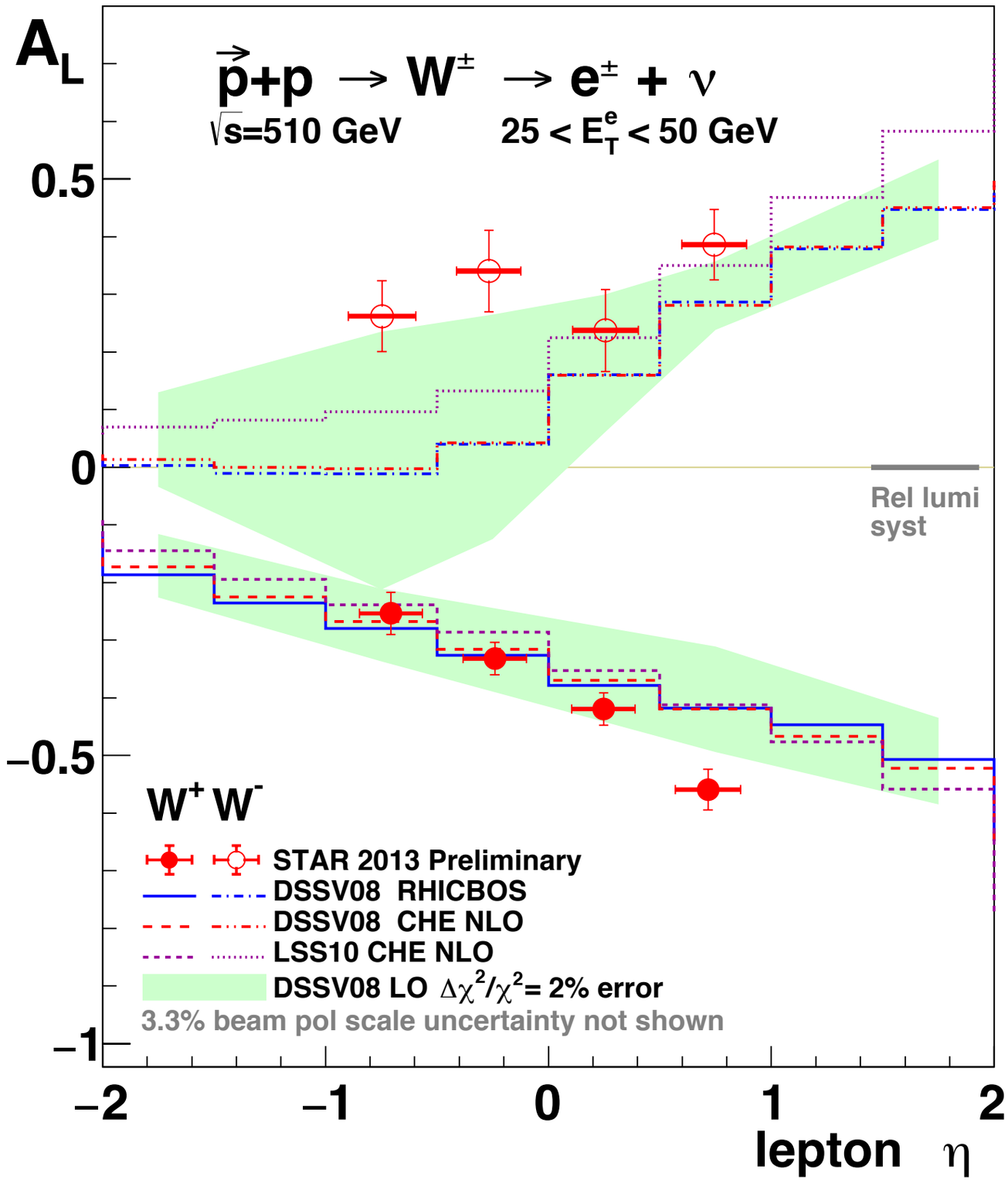
- STAR 2013 W A_L Preliminary Results => **Just Released @ INPC 2016!!!**



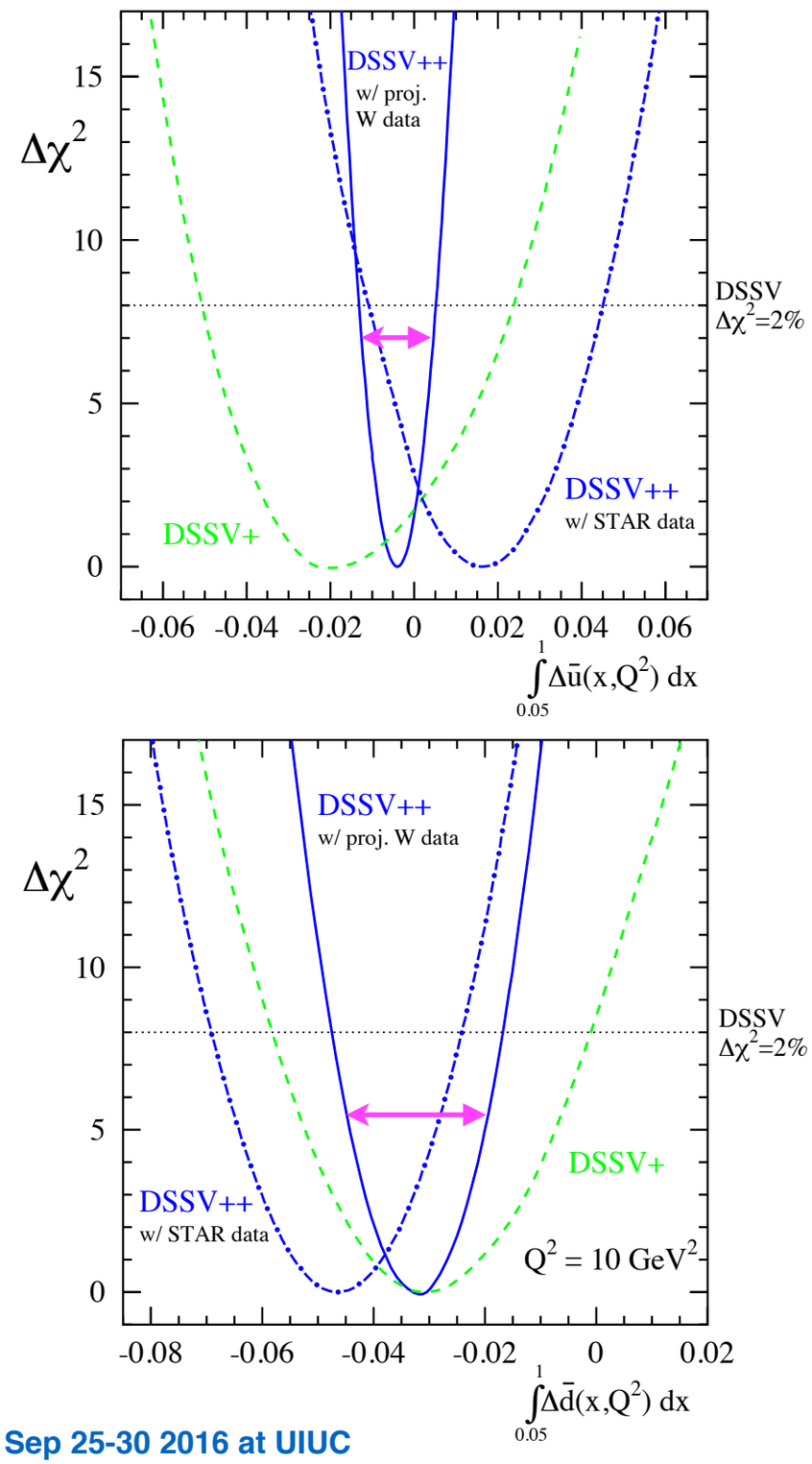
- The Most Precise measurements of W A_L up to date!
- Expect to further constrain $\Delta\bar{u}$ and $\Delta\bar{d}$.

RESULTS - W A_L - STAR 2013 - Projected Impact

- STAR 2013 Preliminary Results => Just Released !!!!

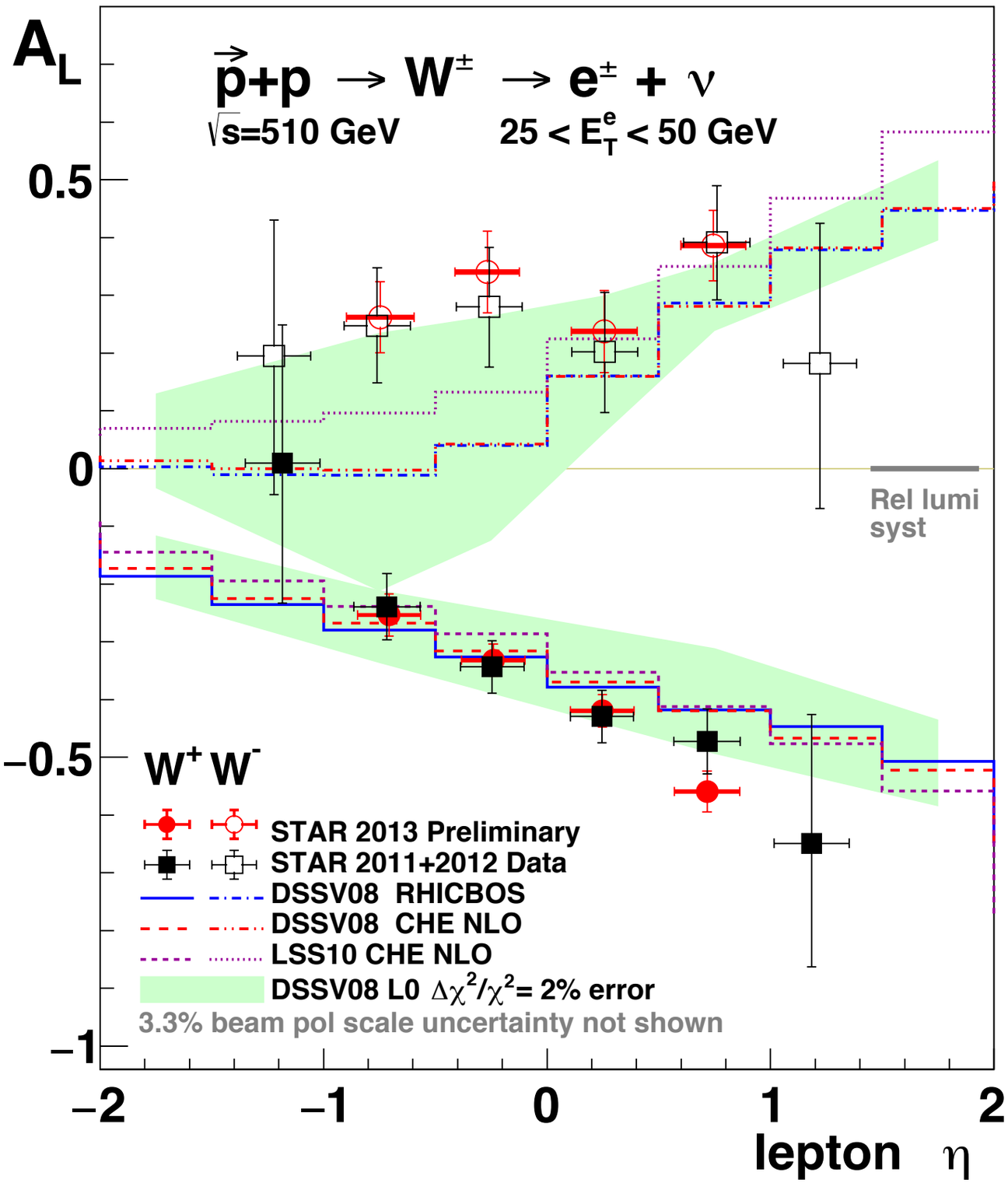


- Uncertainties projection from STAR 2013 W AL data !!!!



RESULTS - W A_L - STAR 2012 vs 2013

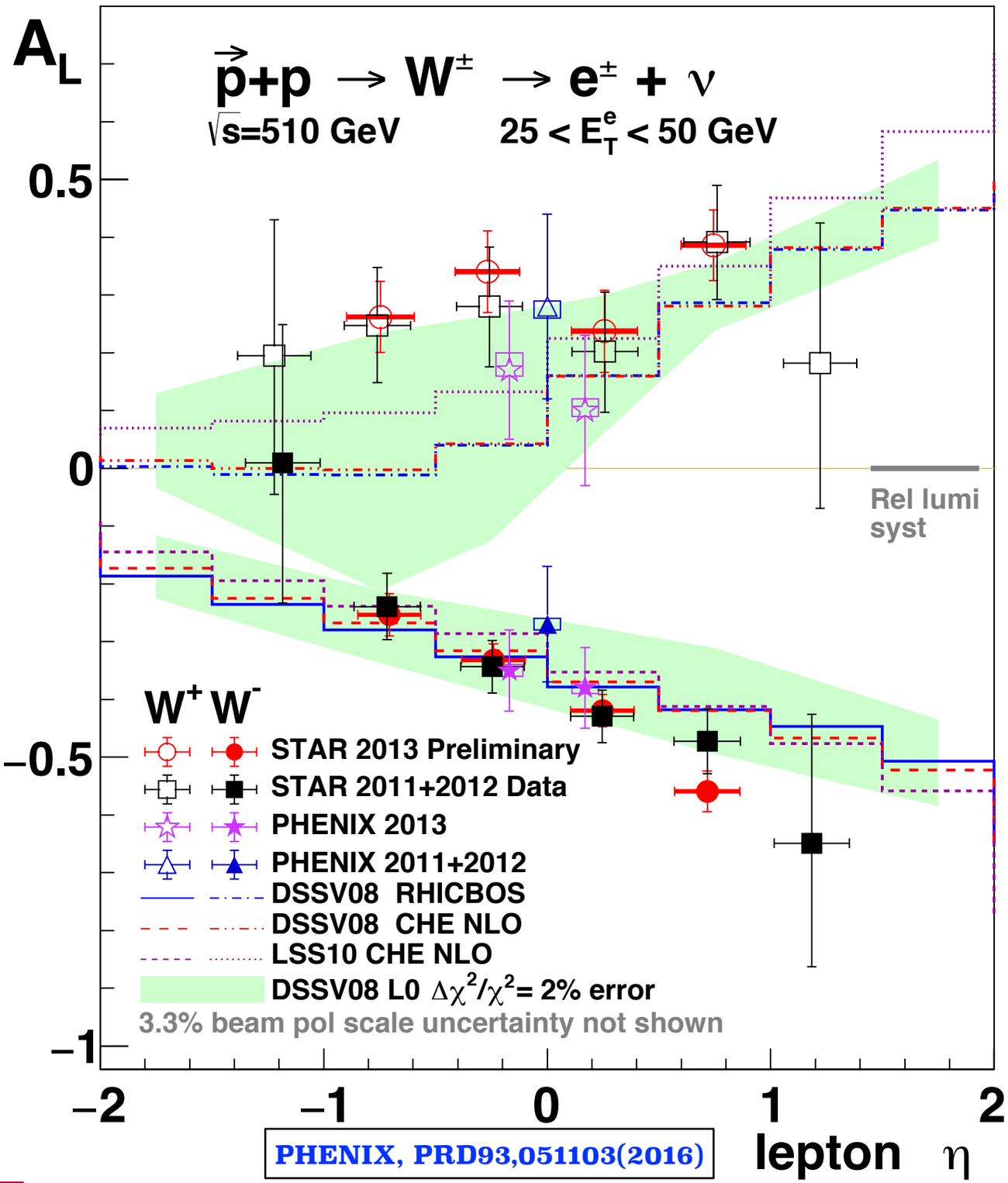
- STAR 2013 W A_L Preliminary Results in comparison to STAR 2011+2012 published results



- STAR 2013 W AL Preliminary results is the Most Precise measurements of W A_L up to date!
- STAR 2013 preliminary W AL results consist with published 2011 + 2012 results.
- Uncertainties were reduced by 40 %

RESULTS - W A_L - RHIC

- STAR 2013 Preliminary Results in comparison to STAR 2011+2012 published results , PHENIX 2011+2012, PHENIX 2013 W AL results



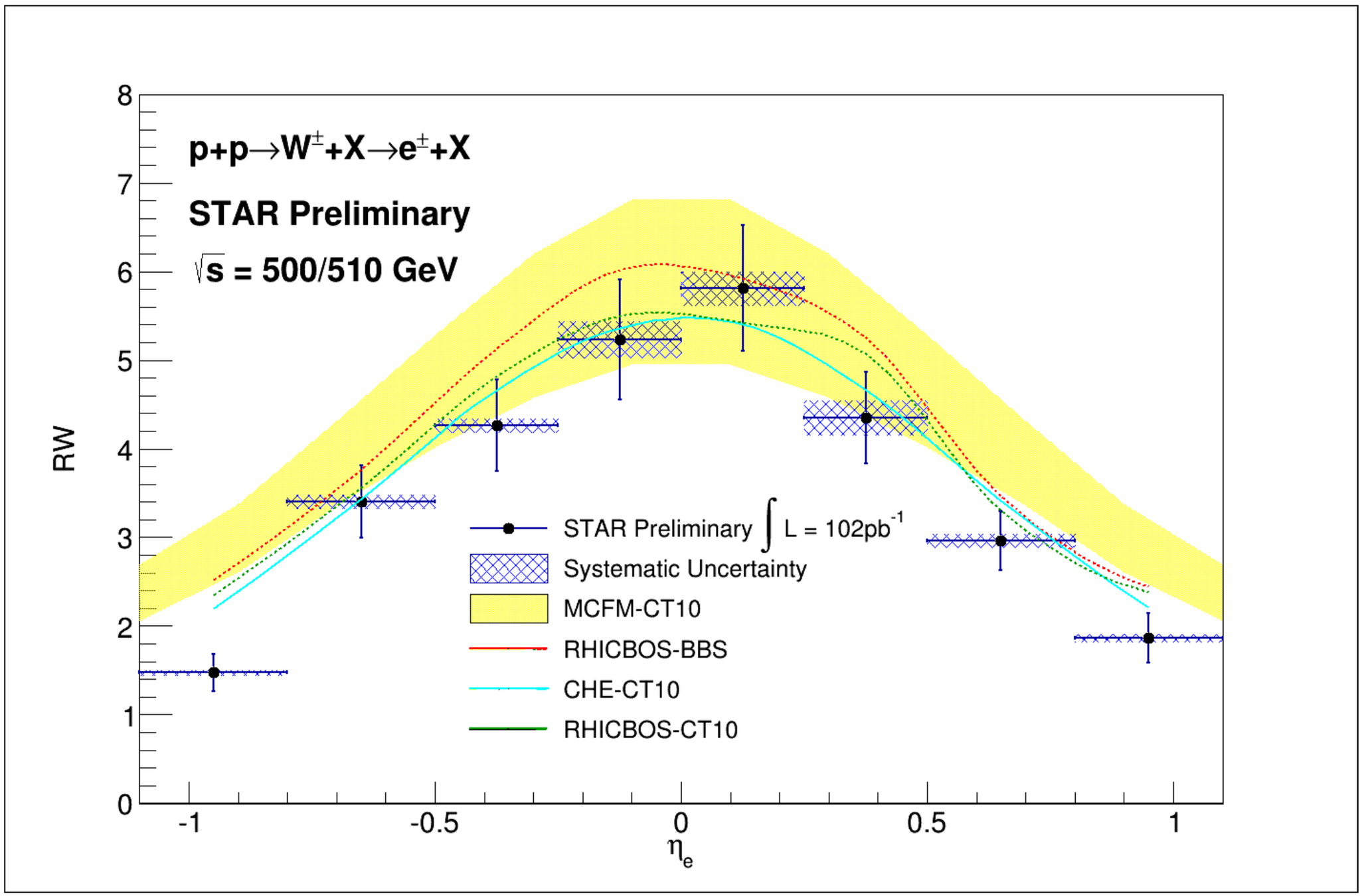
PHENIX, PRD93,051103(2016)

World data of W A_L

- STAR 2013 W AL Preliminary results is the Most Precise measurements of W A_L up to date!
- STAR 2013 preliminary W AL results consist with published 2011 + 2012 results.
- Uncertainties were reduced by 40 %
- Also consist with PHENIX results

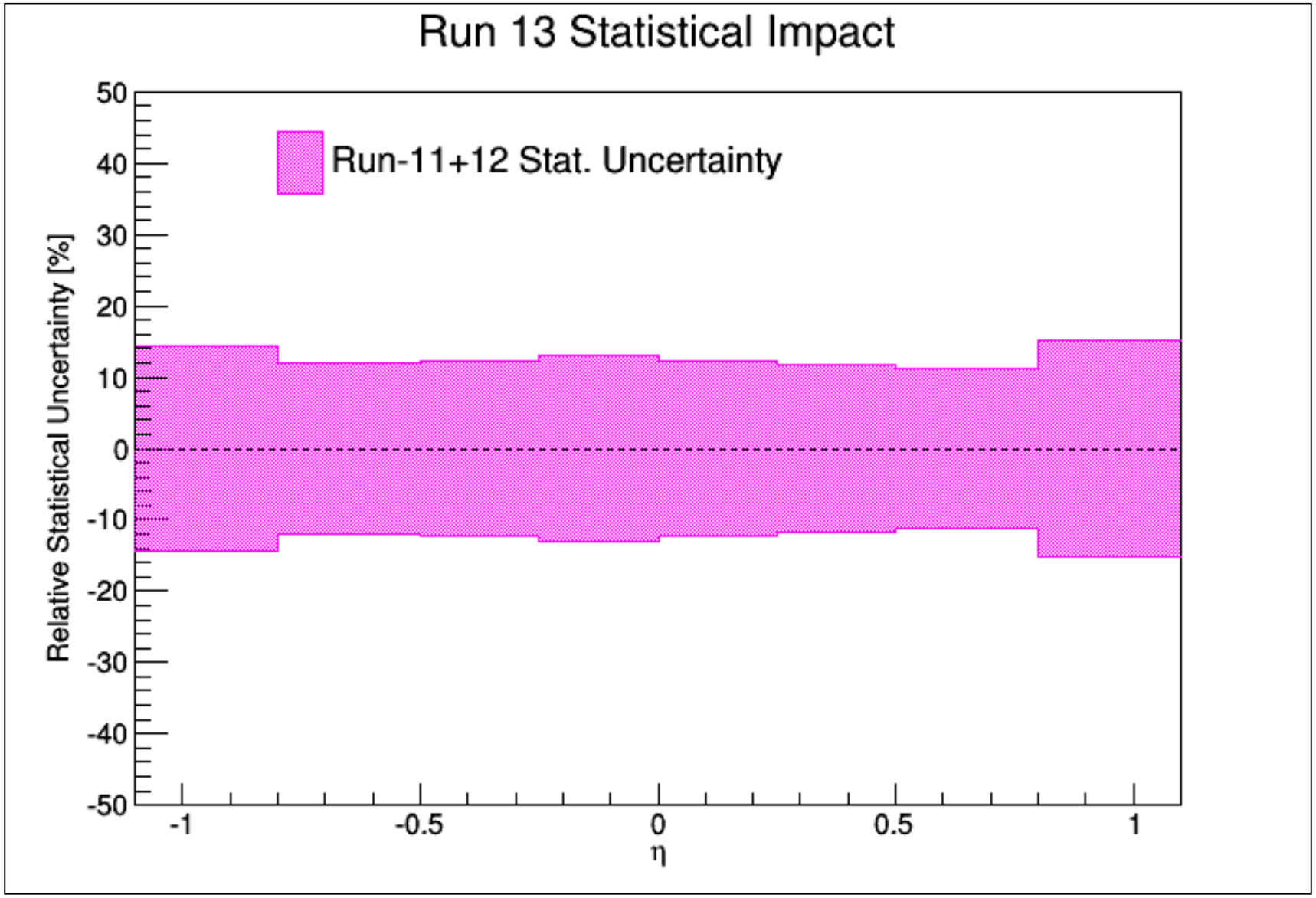
RESULTS - R_W - I

- STAR 2011+2012 Preliminary Results



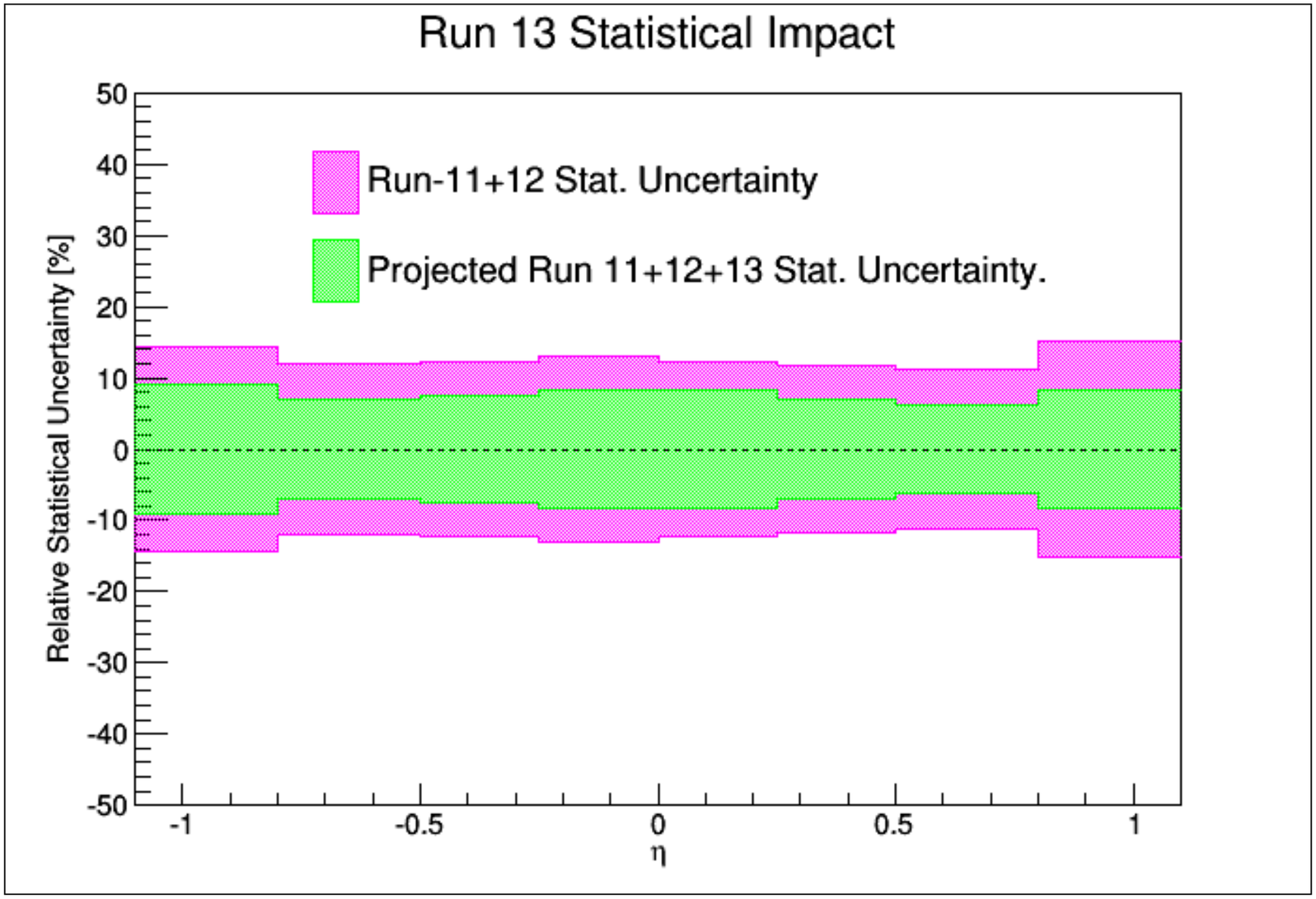
RESULTS - R_W - II

- Projected STAR Run 13 Statistical Impact



RESULTS - R_W - III

- Projected STAR Run 13 Statistical Impact

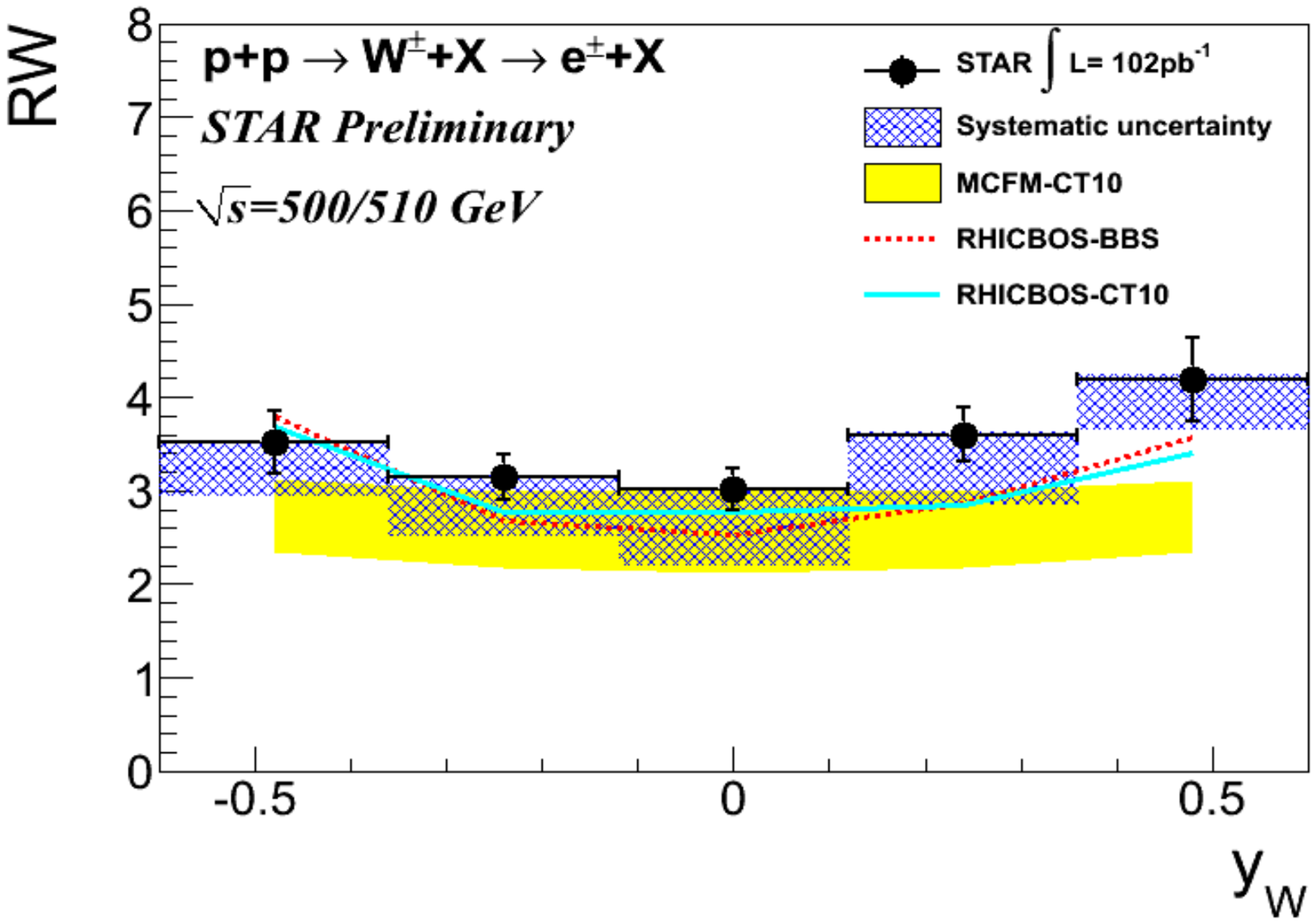


Inclusion of **Run-13** data will **improve** precision of the cross section ratios. Run-17 will add additional data of ~400 Pb^{-1} to improve further.

RESULTS - R_W - IV

- R_W vs W Rapidity

- W boson rapidity can be determined by reconstructing the W kinematics via its recoil
- Recently through the combination of data and MC simulations, a procedure for reconstructing the W boson rapidity has been established at STAR.
- This procedure has been applied to the 2011 + 2012 combined data set.



SUMMARY

- Mid-rapidity (Run 11/12): Published W asymmetry results suggest large anti-u quark polarization along with broken QCD sea

- New prelim. result of STAR 2013 W AL is the most precious measurement up to date. These results will help to further constraint antiquark helicity distributions.

- New STAR 2013 W AL prelim. results consistent with published STAR 2011+2012 results.

- Prelim. cross-section ratio measurement (Run 11/12): Strong physics case of unpolarized dbar/ubar probe using W production complementary to SeaQuest.

- Run 13 data (~300 pb , analyzing) and Run 17 data (~400 pb , next year) will further improve precision of W cross section ratio measurements at STAR.

BACK UP

STAR W AL 2011+2012, 2013 - Consistance checking

STAR 2013 W A_L Preliminary		
Lepton η Range	W^+ A_L	W^- A_L
-1.1<η<-0.5	-0.254 $\pm$ 0.037	0.262 $\pm$ 0.062
-0.5<η<0	-0.332 $\pm$ 0.028	0.340 $\pm$ 0.071
0<η<0.5	-0.420 $\pm$ 0.028	0.237 $\pm$ 0.071
0.5<η<1.1	-0.559 $\pm$ 0.036	0.386 $\pm$ 0.061

STAR 2011+2012 W A_L		
Lepton η Range	W^+ A_L	W^- A_L
-1.1<η<-0.5	-0.239 $\pm$ 0.057	0.247 $\pm$ 0.100
-0.5<η<0	-0.343 $\pm$ 0.045	0.280 $\pm$ 0.104
0<η<0.5	-0.429 $\pm$ 0.045	0.202 $\pm$ 0.104
0.5<η<1.1	-0.472 $\pm$ 0.056	0.391 $\pm$ 0.099

	W^+ A_L	W^- A_L
χ^2/n.d.f	1.83/4	0.32/4

STAR 2013 W AL - Systematic Uncertainties

- Background estimation:
  - From data-driven procedure, statistics of embedding sample
  - Less than 10% of statistical error
  - Negligible polarized background contribution

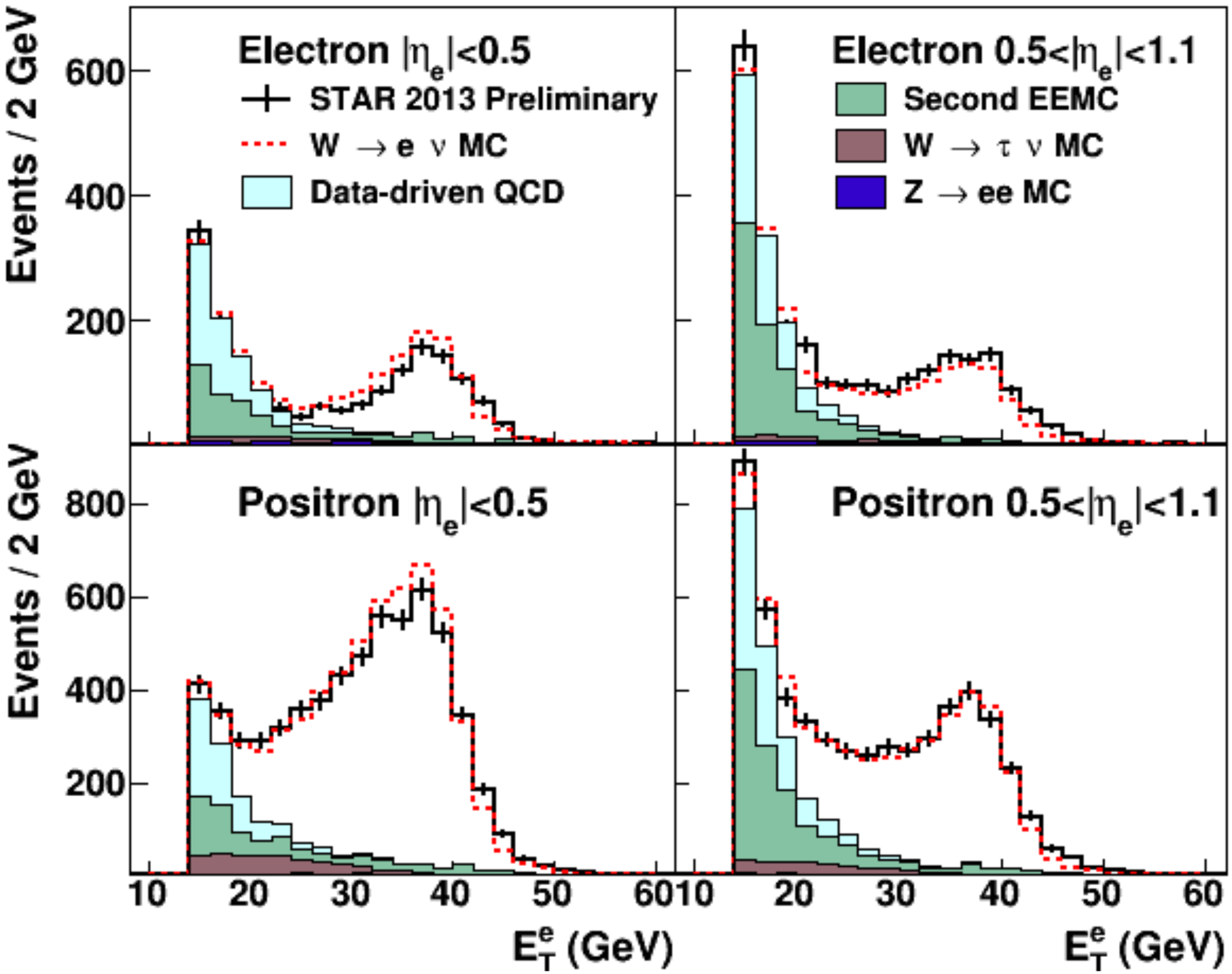
- BEMC gain calibration:
  - 4.5%

- Beam polarization uncertainty:
  - Correlated scale 3.3%

- Relative luminosity uncertainty:
  - Estimated from a high-p_T [25,50]GeV, QCD sample
  - Correlated offset 0.007 (2011+2012), 0.004 (2013)

BG - Foraward and central bins combined

- BG ESTIMATION



TPC Charge-sign Separation