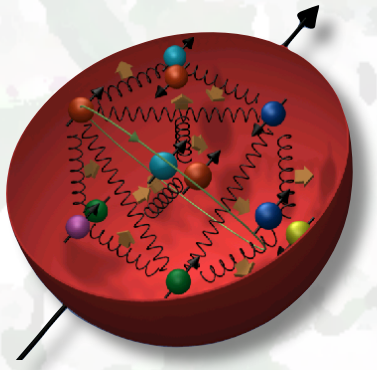
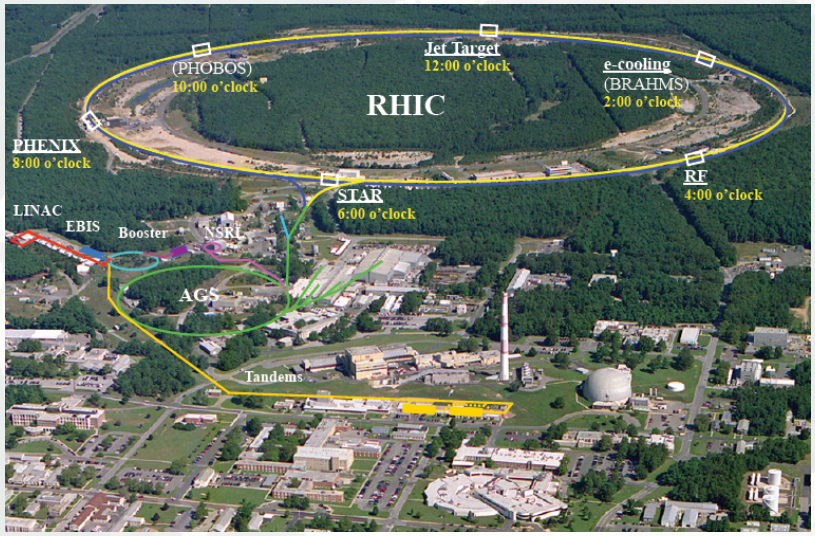
Constraining unpolarized and polarized quark / antiquark PDF's using $W^{\pm}$ boson production in high-energy polarized p+p collisions at RHIC

Bernd Surrow
TEMPLE UNIVERSITY



U.S. DEPARTMENT OF ENERGY | Office of Science
DOE NP contract: DE-SC0013405

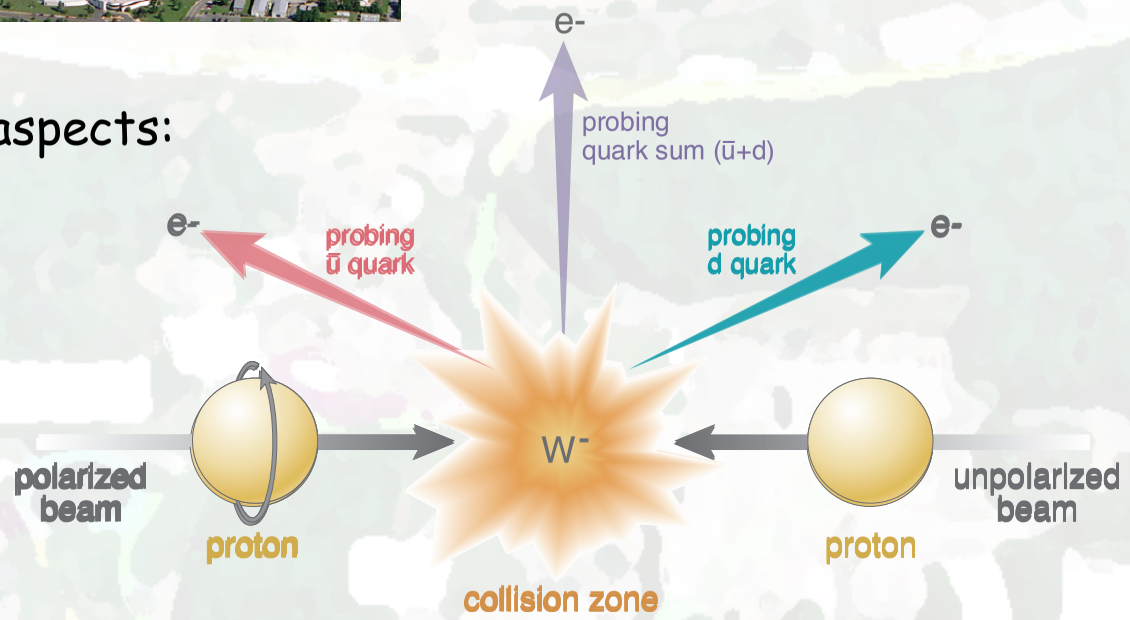
Outline



- Results / Status: $W^{\pm}$ production
  - Reconstruction
  - Cross-section measurement
  - Cross-section ratio measurement
  - Asymmetry A_L measurement

- Experimental aspects: RHIC / STAR

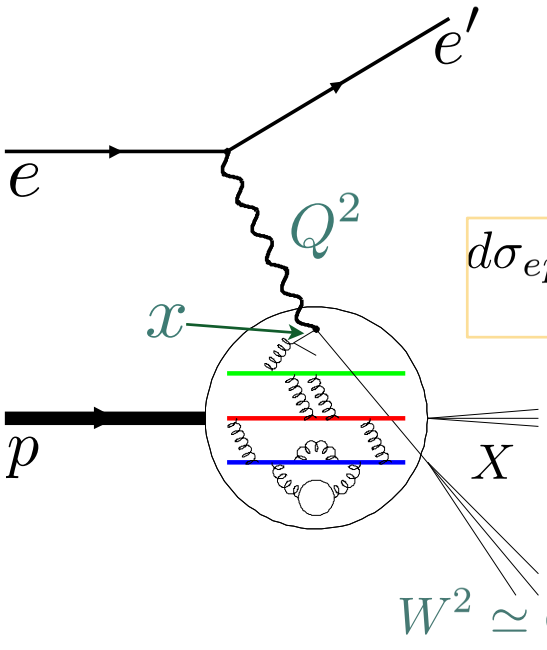
- Theoretical foundation



- Summary and Outlook

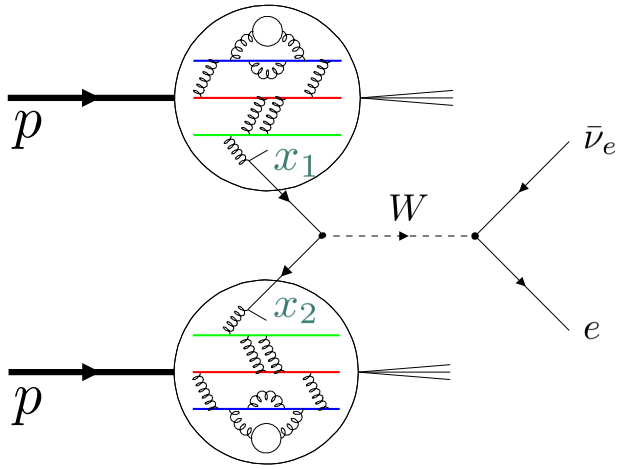
Theoretical foundation

- How do we probe the structure and dynamics of matter in ep vs. pp scattering?



$$d\sigma_{ep} \propto F_2 = \sum_q x e_q^2 f_q(x)$$

Universality



$$d\sigma_{pp} \propto f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h$$ Factorization

Momentum contribution

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

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

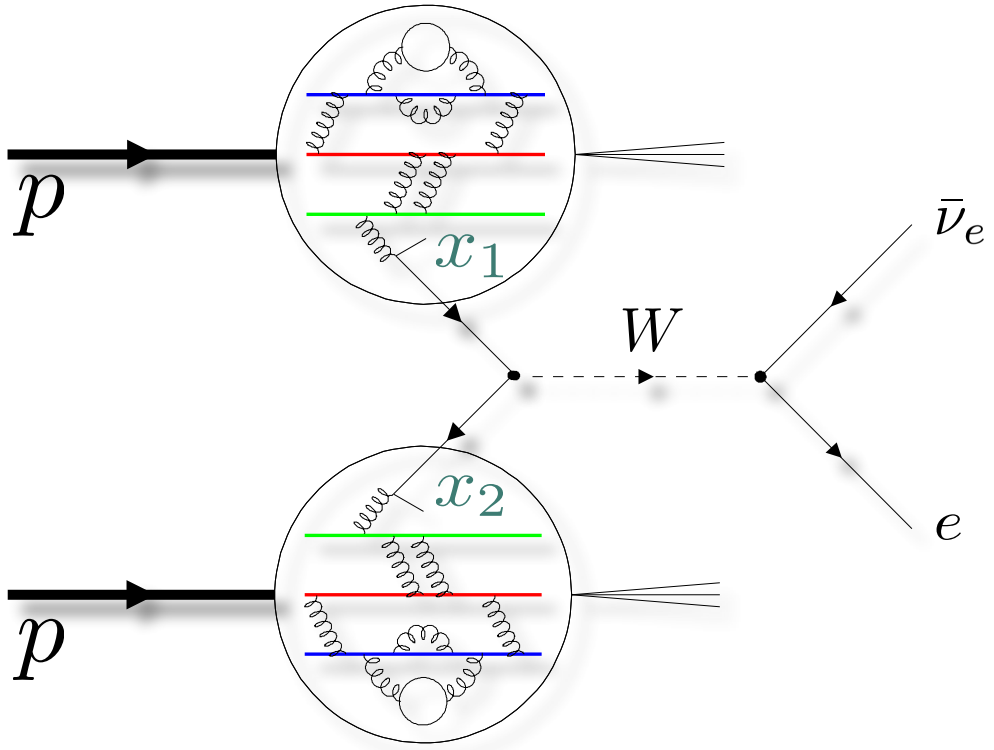
Spin contribution

Theoretical foundation

- Proton spin structure using high-energy polarized p+p collisions - W production
  - Observable: Quark/Anti-quark polarization (W production)
    - Longitudinal single-spin asymmetry A_L

$$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

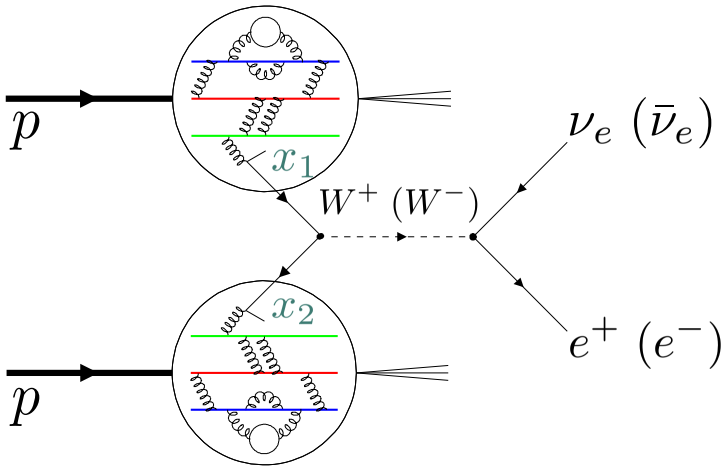
    - Parity violation for W production!



  - Features of W boson production probing parton distributions:
    - Direct sensitivity to quark (u/d) / anti-quark (ubar/dbar) distributions
    - Large scale defined by W mass (~80GeV)
    - Simple final state of charged leptons: No dependency on fragmentation functions
  - Polarized and unpolarized partonic cross-sections known at NLO / Resummation framework - W A_L asymmetry results powerful input for global analyses such as DSSV and NNPDF at NLO level!

Theoretical foundation

- Probing the quark flavor structure: W boson production (1)



$$y_l = y_W + \underbrace{\frac{1}{2}\ln\frac{1+\cos\theta^*}{1-\cos\theta^*}}_{y_l^*}$$

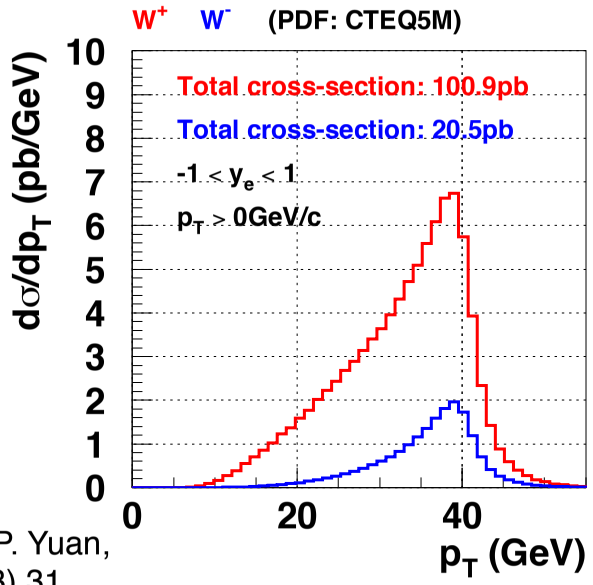
$$p_T = p_T^* = \frac{M_W}{2}\sin\theta^*$$

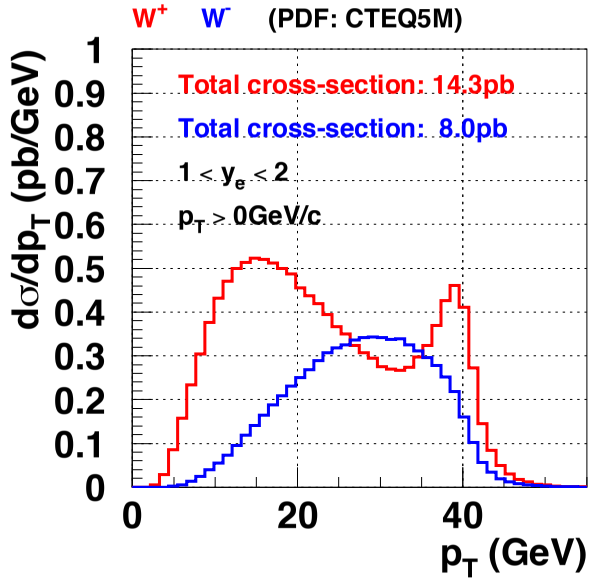
$$x_1 = \frac{M_W}{\sqrt{s}}e^{y_W}$$

$$x_2 = \frac{M_W}{\sqrt{s}}e^{-y_W}$$

$$\frac{M_W}{\sqrt{s}} = 0.16$$

- Key signature: High p_T lepton (e^-/e^+)(Max. $M_W/2$) - Selection of W^+/W^- : Charge sign discrimination of high p_T lepton
- Required: Lepton/Hadron discrimination



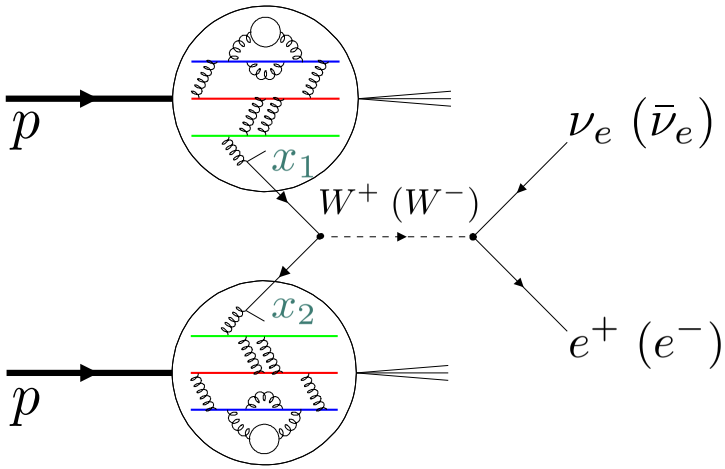


P. M. Nadolsky and C.P. Yuan, Nucl.Phys. B666 (2003) 31.

Total (√s=500GeV) σ(W⁺)=135pb and σ(W⁻)=42pb

Theoretical foundation

- Probing the quark flavor structure: W boson production (1)



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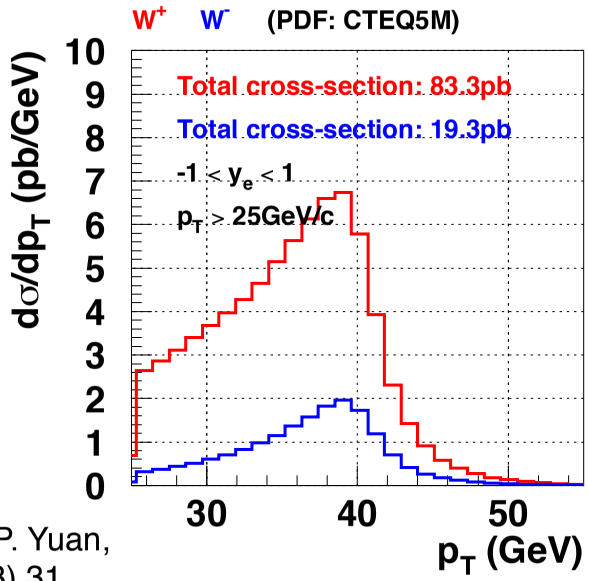
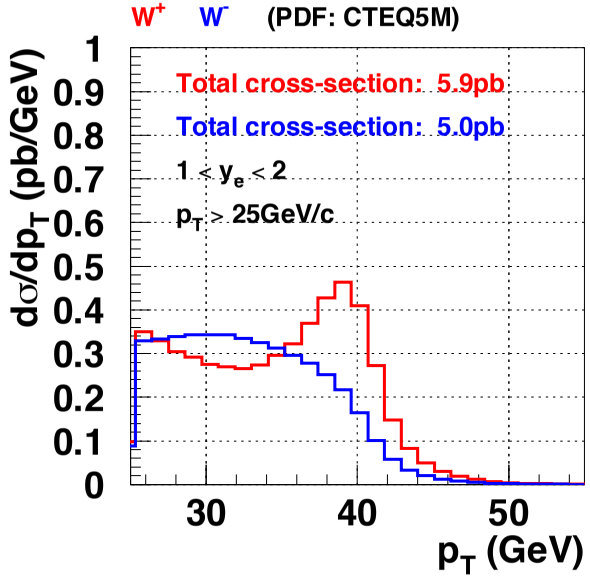
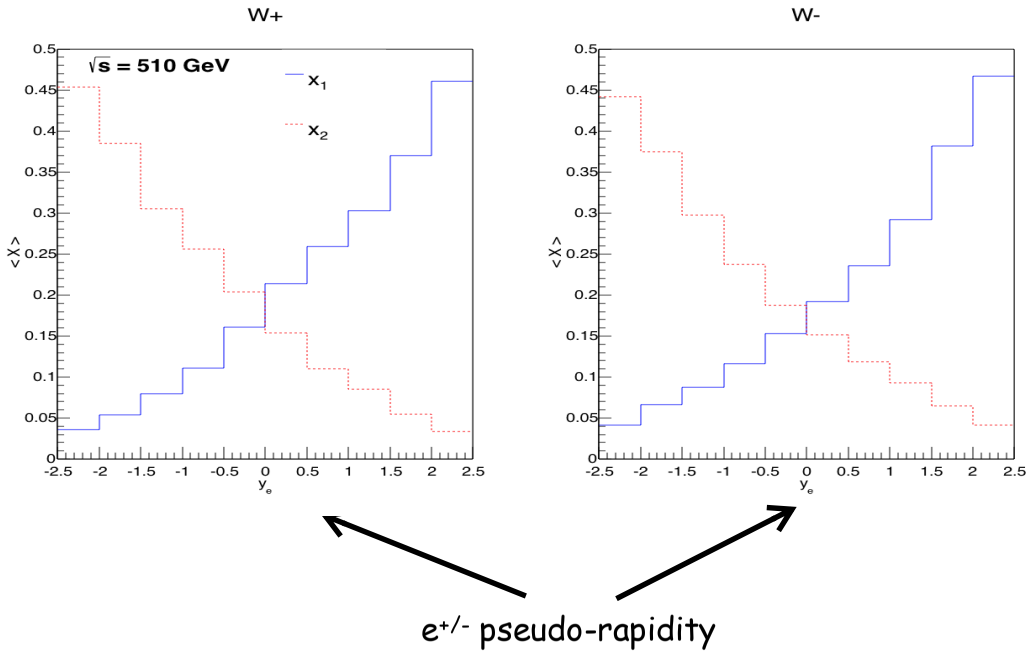


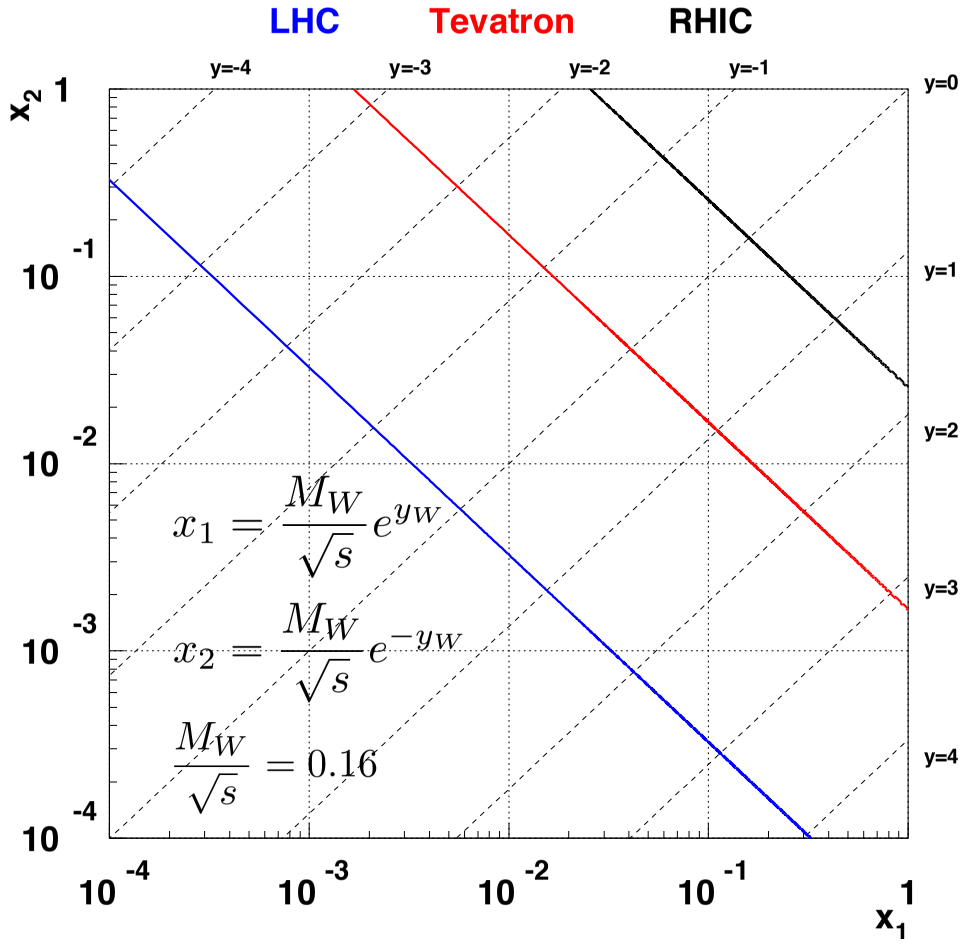


Total (√s=500GeV) σ(W⁺)=135pb and σ(W⁻)=42pb

Theoretical foundation

- Probing the quark flavor structure: W boson production (2)





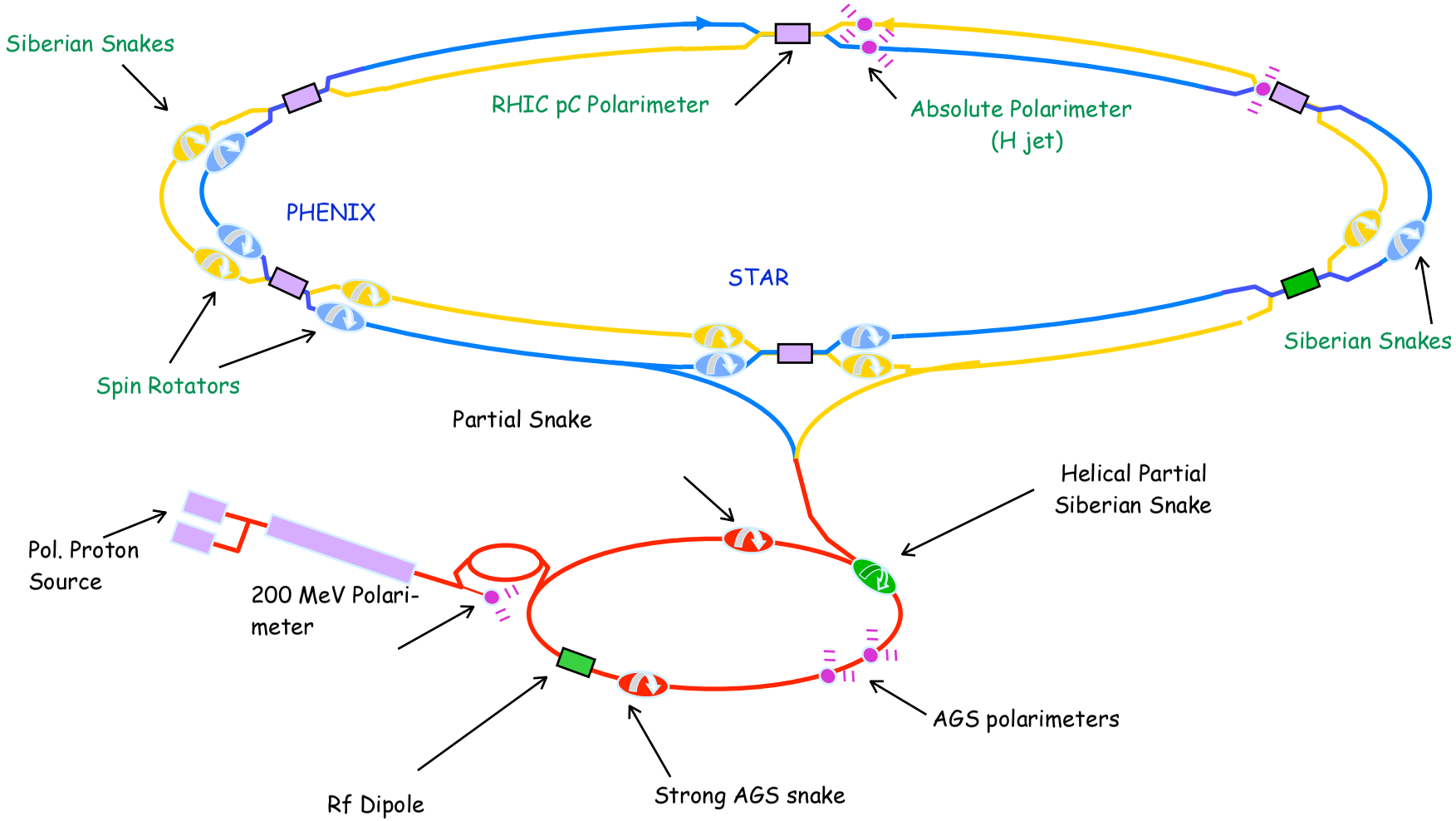
- Approximate kinematic range at RHIC:

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

- Measurement at LHC in high-x range would require very forward measurements

Experimental aspects - RHIC

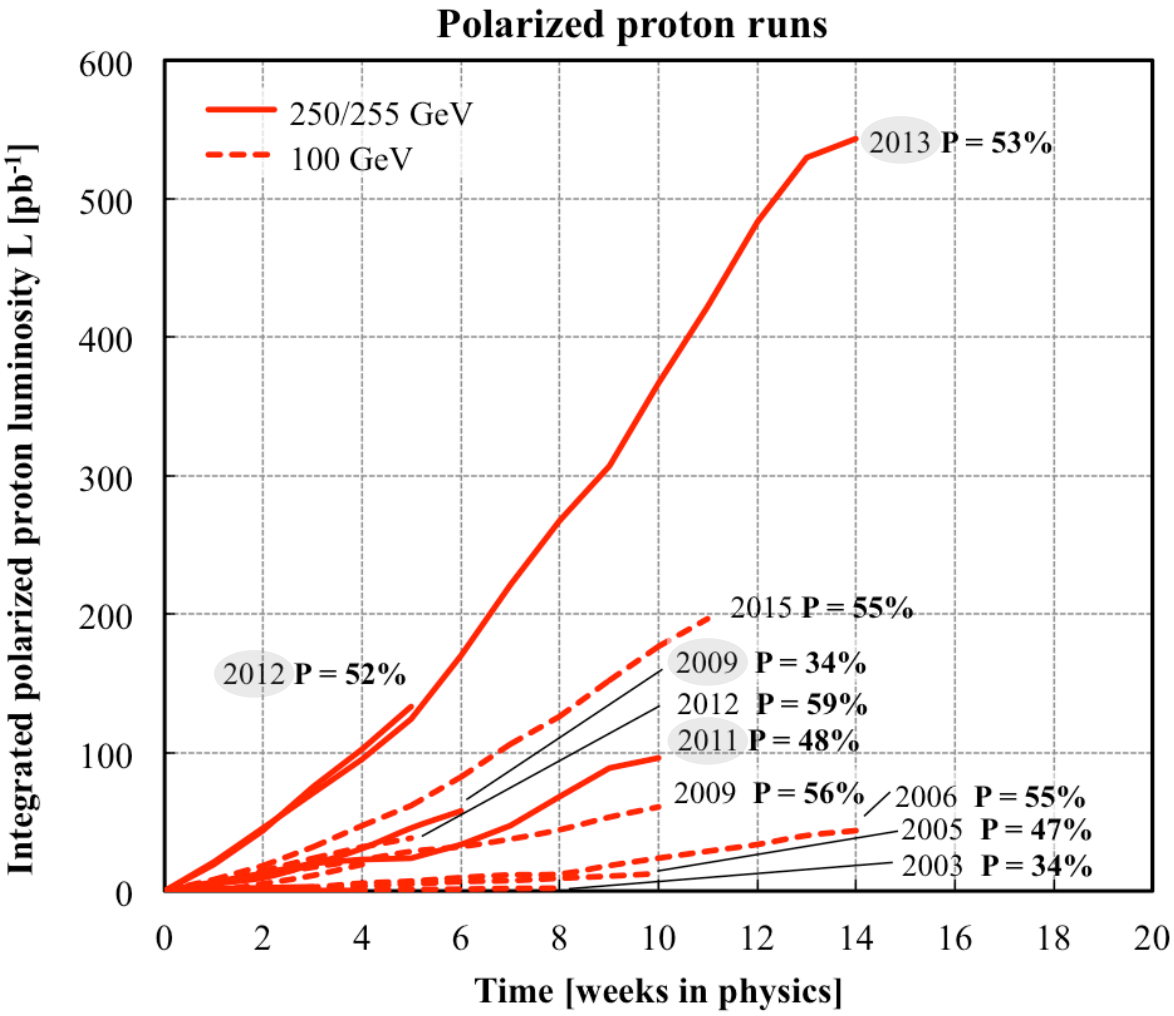
- The world's first polarized proton+proton collider



Experimental aspects - RHIC

- Polarized p-p collisions
  - Production runs at $\sqrt{s}$=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})
Run 9	12	0.38	1.7
Run 11	9.4	0.49	2.3
Run 12	72	0.56	24
Run 13	250	0.54	73

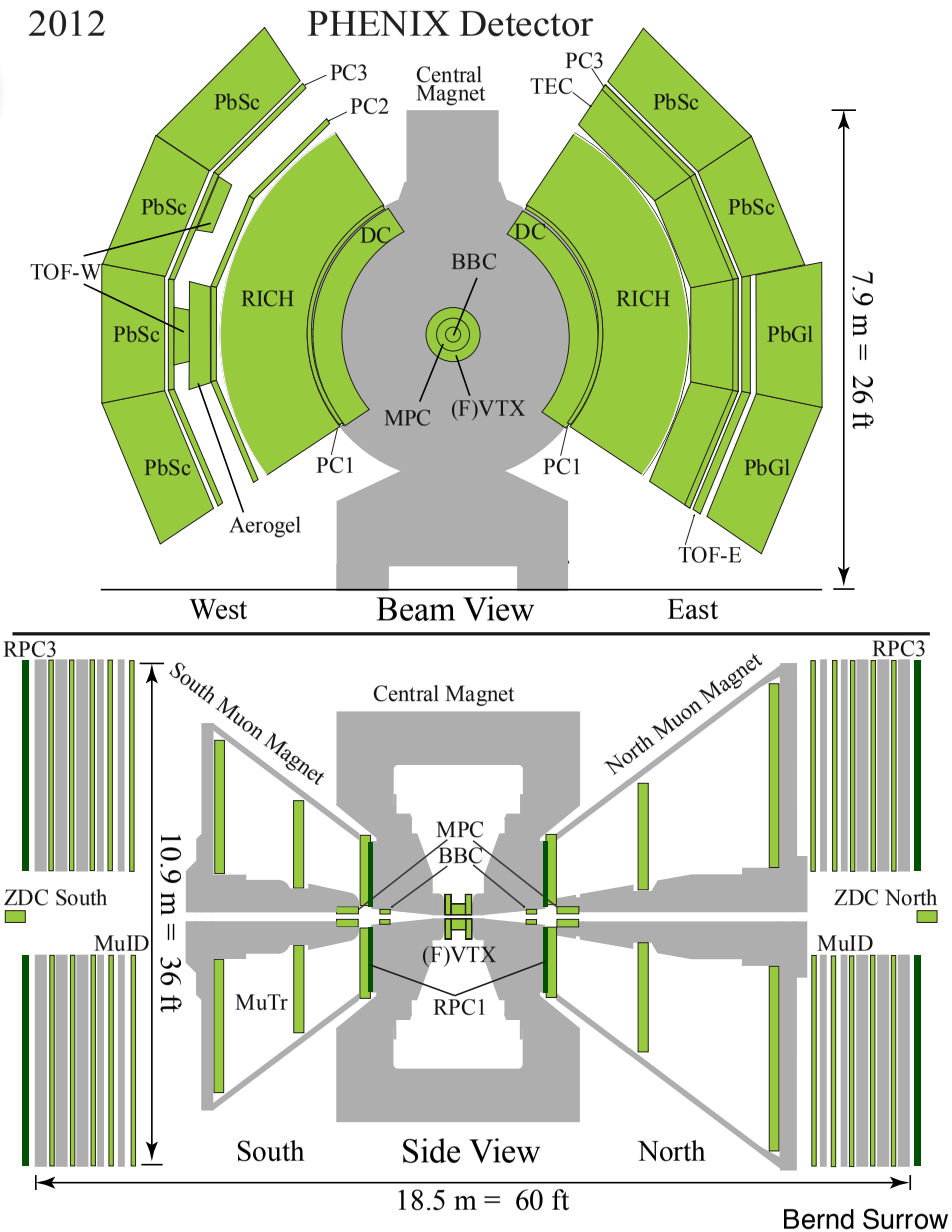


Experimental aspects - PHENIX

- Overview

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

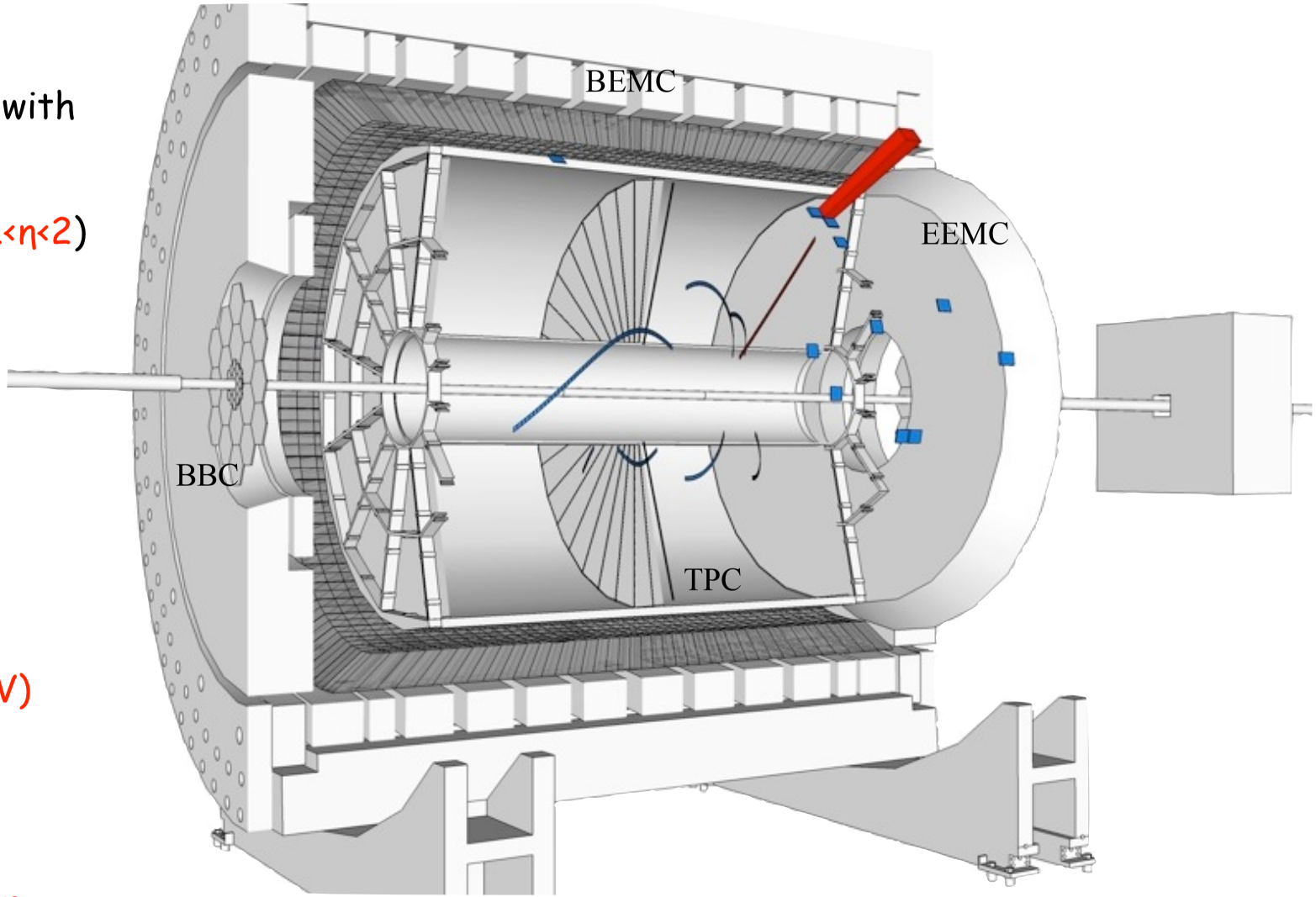
  - π^0, η, γ
    - Electromagnetic Calorimeter (PbSc/PbGl)
      ($|\eta| < 0.35$, $\varphi = 2 \times \pi/2$)
  - $\pi^{\pm}$, e, $J/\psi \rightarrow e^+e^-$
    - Drift Chamber (DC)
    - Ring Imaging Cherenkov Detector (RICH)
    - Electromagnetic Calorimeter (PbSc/PbGl)
  - μ, $J/\psi \rightarrow \mu^+\mu^-$
    - Muon Id/Muon Tracker ($1.2 < |\eta| < 2.4 + 2\pi$)
  - π^0, η
    - MPC ($3.1 < |\eta| < 3.9 + 2\pi$)
  - Relative Luminosity
    - Beam Beam Counter (BBC) ($3.0 < \eta < 3.9$)
    - Zero Degree Calorimeter (ZDC)



Experimental aspects - STAR

- Overview

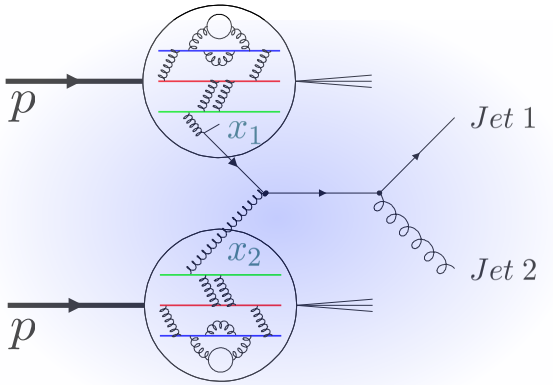
  - Calorimetry system with 2π coverage: BEMC (-1<η<1) and EEMC (1<η<2)
  - TPC: Tracking and particle ID
  - ZDC: Relative luminosity and local polarimetry (500GeV)
  - BBC: Relative luminosity and Minimum bias trigger

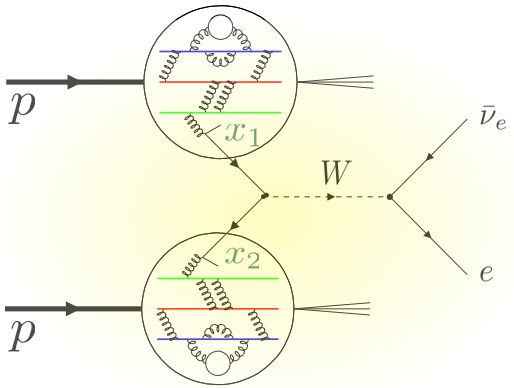


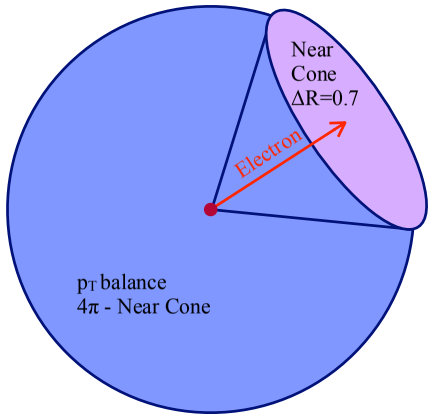
$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

Results / Status - W reconstruction

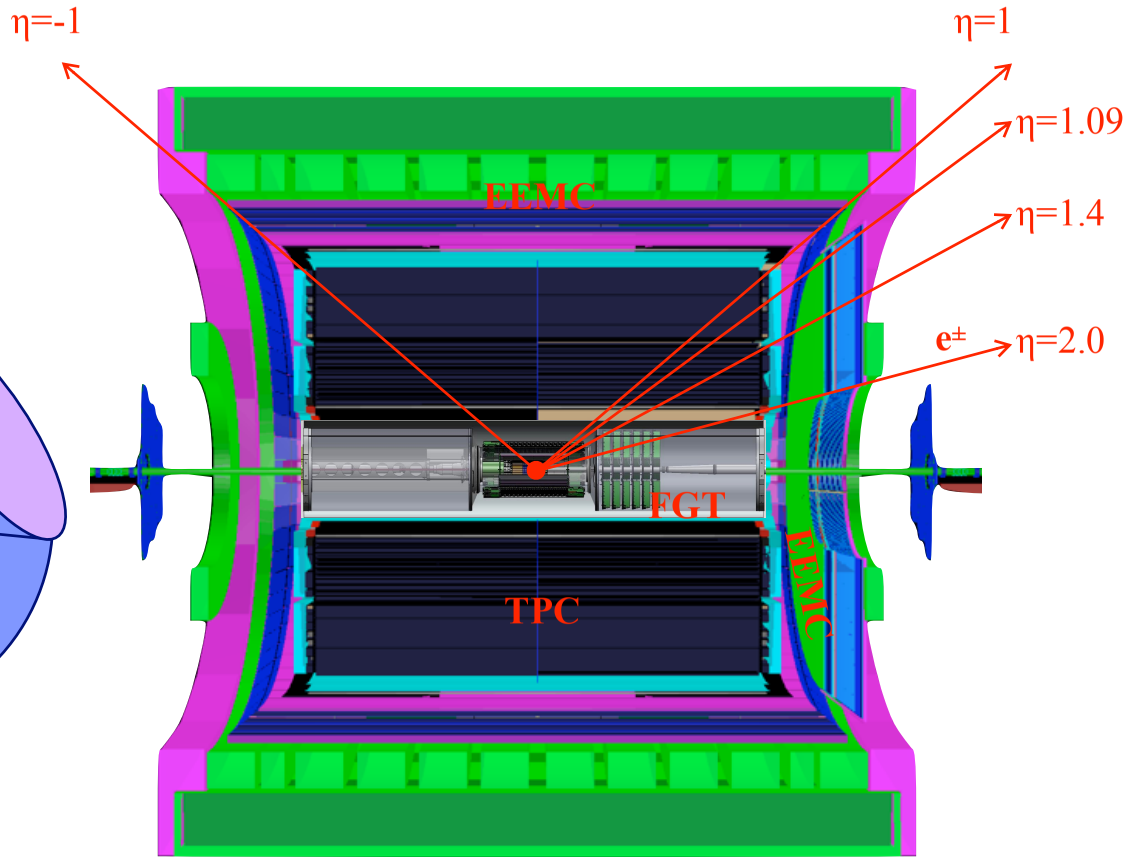
- W boson reconstruction at STAR vs. pseudo-rapidity η







Transverse plane view



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

Results / Status - W reconstruction

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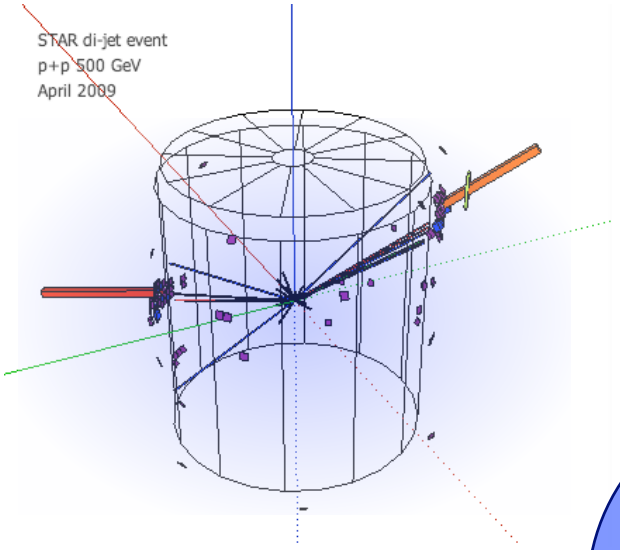

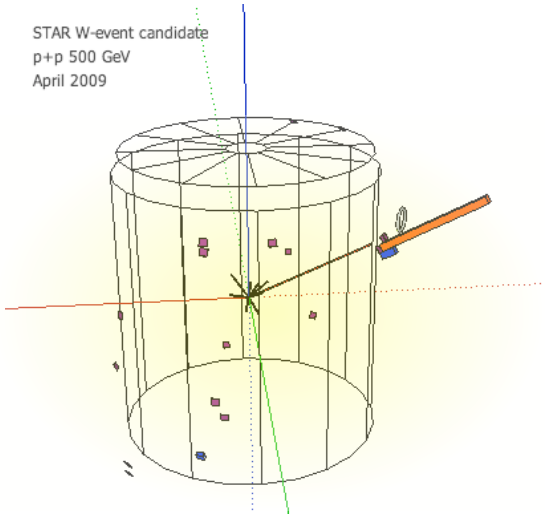

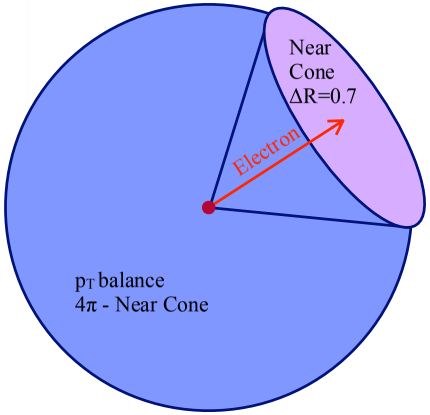

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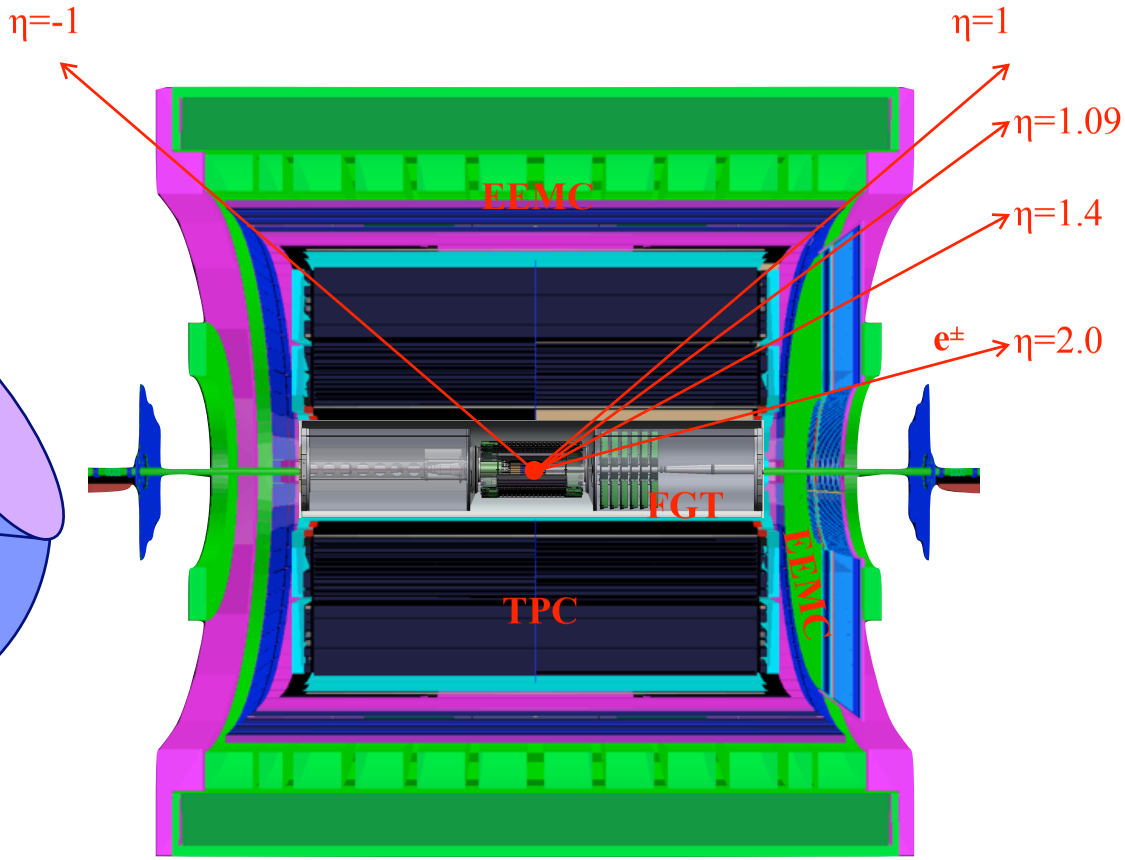


$$\eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

Results / Status - W reconstruction

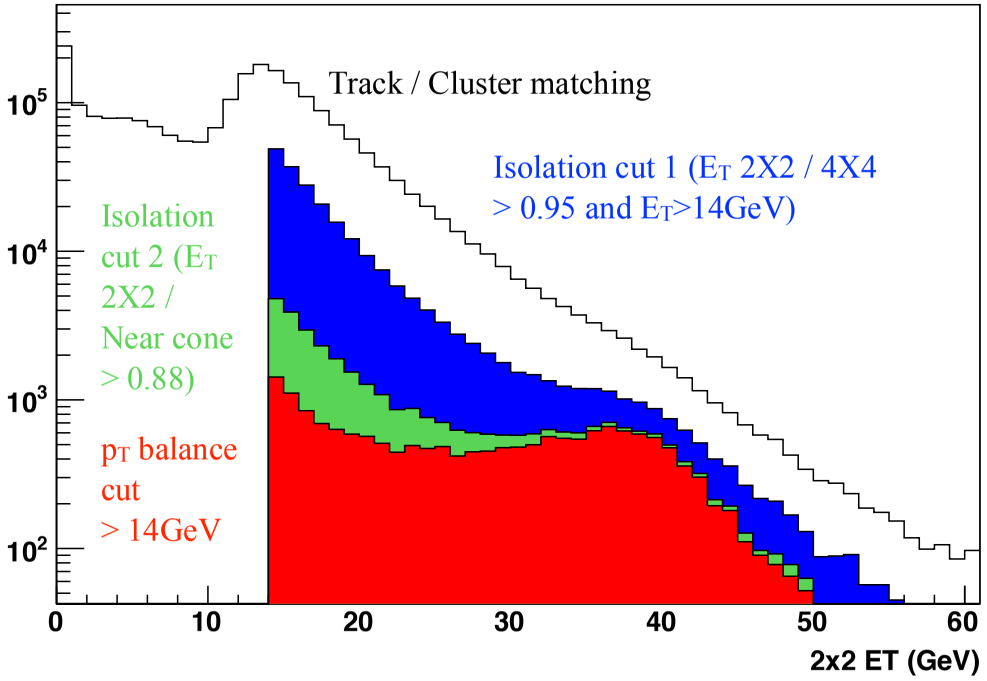
- Mid-rapidity STAR selection criteria
  - Match p_T > 10 GeV track to BEMC cluster
  - Isolation ratio 1 / Isolation ratio 2
  - p_T-balance cut

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

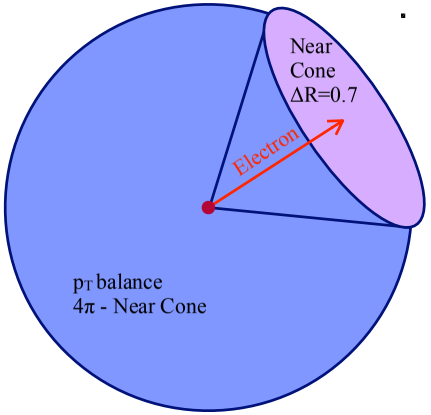
$$P_T\text{-balance}\cos(\phi) = \frac{\vec{p_T}^{\,e} \cdot \vec{p_T}^{\,bal}}{|\vec{p_T}^{\,e}|}$$

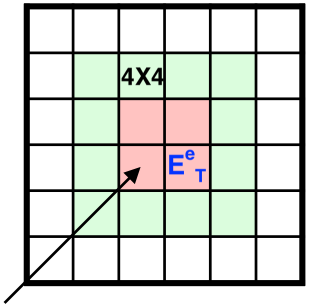
Barrel electron candidate, cut=max 2x2

Run 13



Transverse plane view



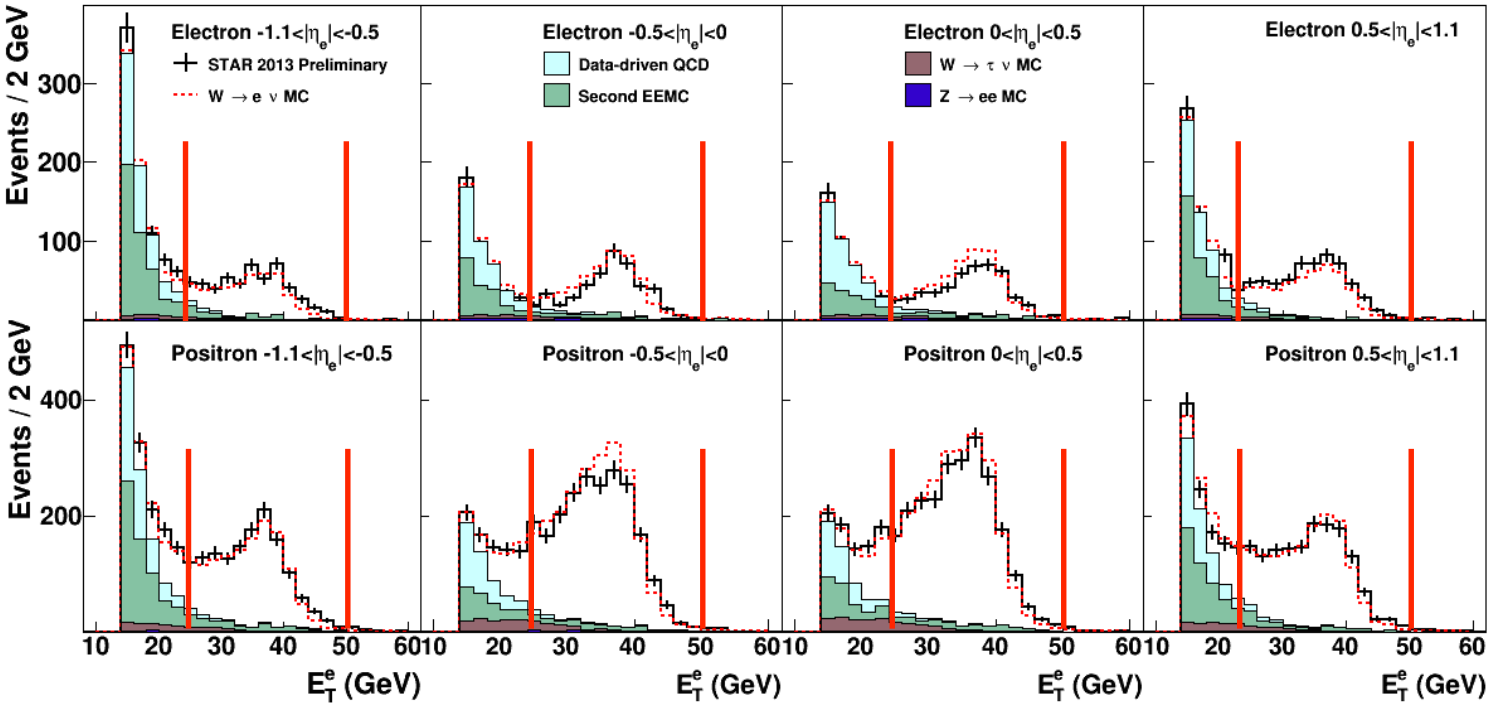


TPC track extrapolated to Barrel calorimeter tower grid

Results / Status - W reconstruction

- Mid-rapidity W^+ / W^- signal distributions / Background determination

Run 13

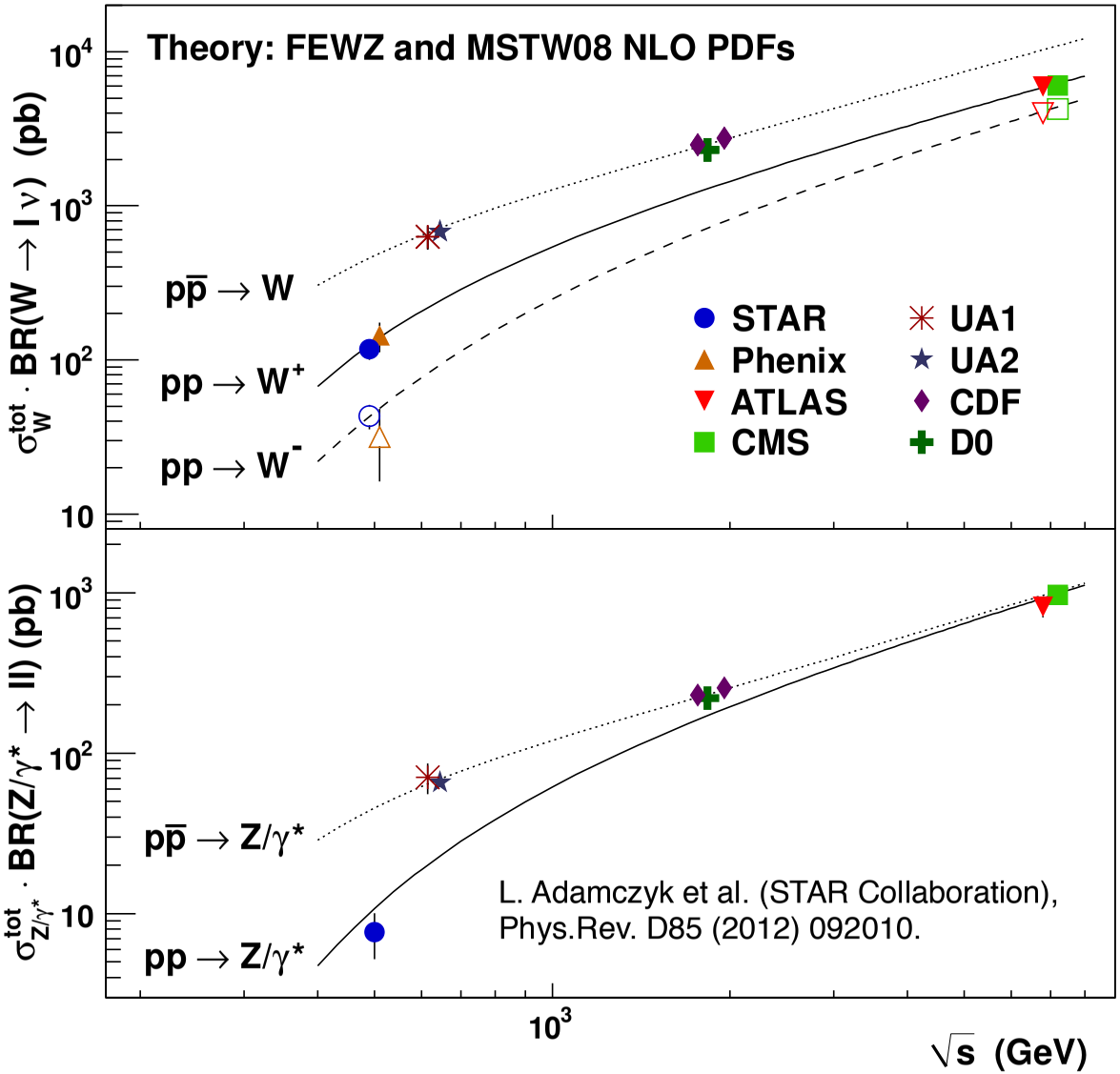


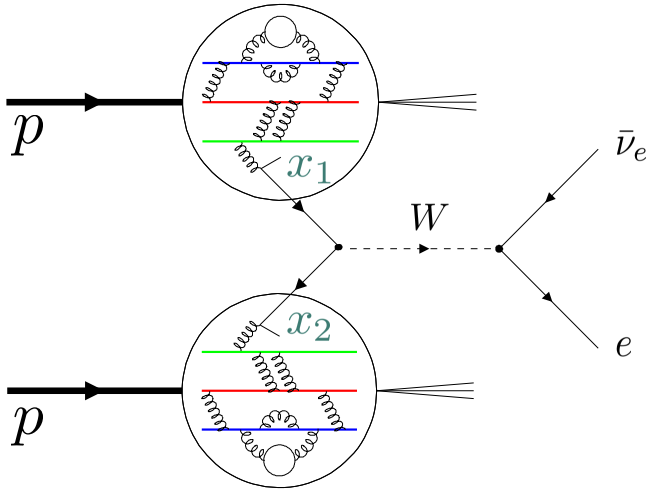
STAR E_T distributions for W^-/W^+ candidate events well described by $W \rightarrow e + \nu$ (W-e decay) signal events and data-driven QCD background estimation plus electro-weak background events in four mid-rapidity η bins

- QCD background:
  - Data-driven QCD background estimate: Background which satisfy $e^\pm$ candidate isolation cuts
  - Second EEMC QCD background estimate: Background ("Jet") at non-existing calorimetric coverage for $-2 < \eta < 1.1$ based on instrumented calorimetric coverage with STAR EEMC for $1.1 < \eta < 2$
- Electro-Weak background: $Z \rightarrow e^+ + e^-$ (Z decay) and $W \rightarrow \tau + \nu$ (W-Tau decay) / PYTHIA-MC estimation!

Results / Status: Cross-section W^+/W^-

- W/Z cross-section measurements at collider experiments

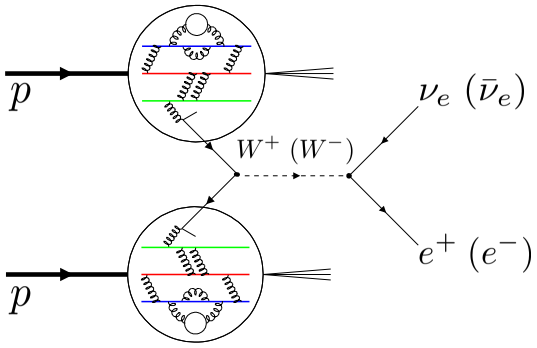




- Measured and theory evaluated cross-sections agree within uncertainties
- Theory calculations: Full NNLO framework

Results / Status: Cross-section ratio W^+/W^-

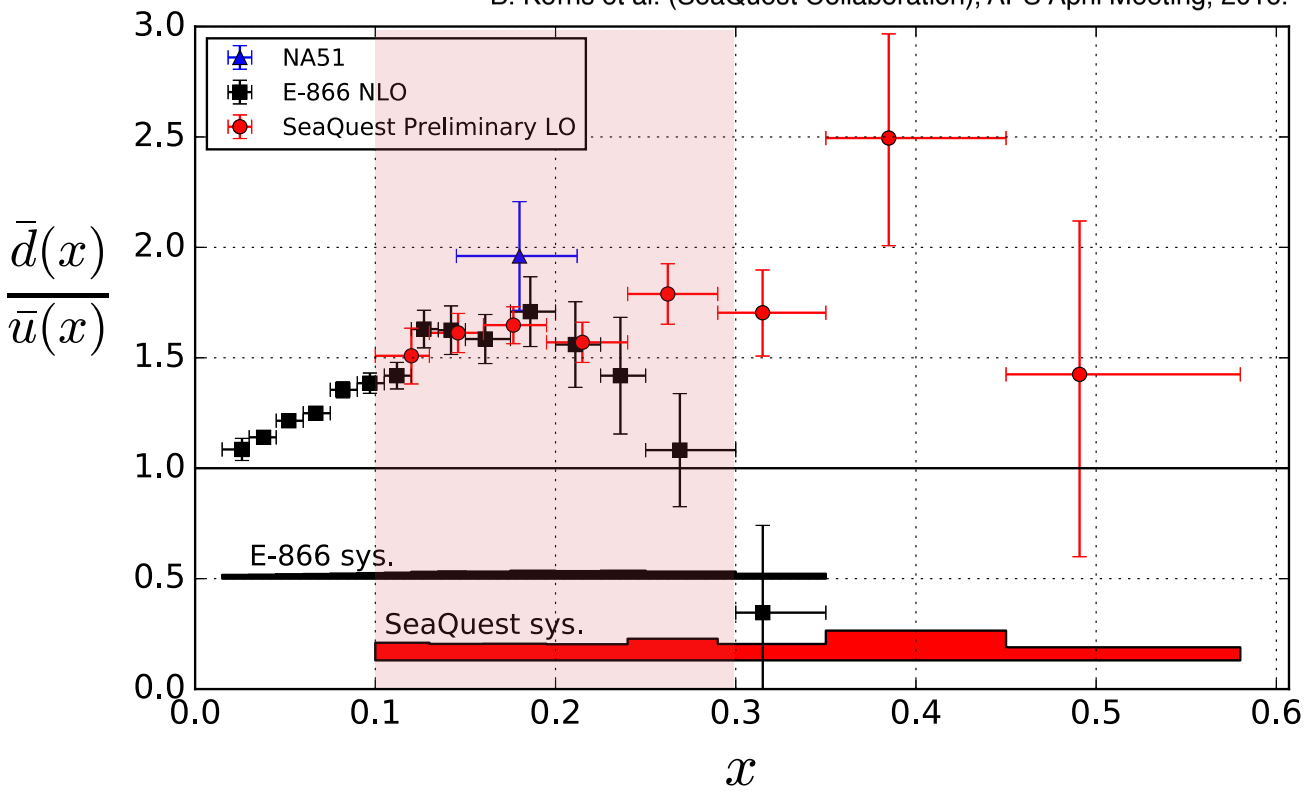
- STAR: Probing dbar / ubar ratio: QCD sea



$$R(x_F) \equiv \frac{\sigma_{W^+}}{\sigma_{W^-}} =$$

$$\frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

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



- STAR coverage at mid-rapidity: 0.1 < x < 0.3 for -1 < η < 1
- Constraints on global fitting for dbar/ubar through W production at higher Q^2 compared E906
- Independent cross-check of Drell-Yan data

Results / Status: Cross-section ratio W^+/W^-

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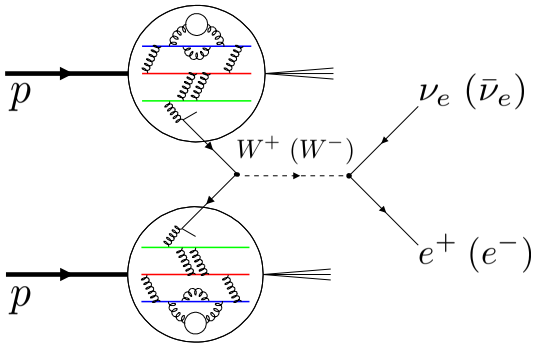
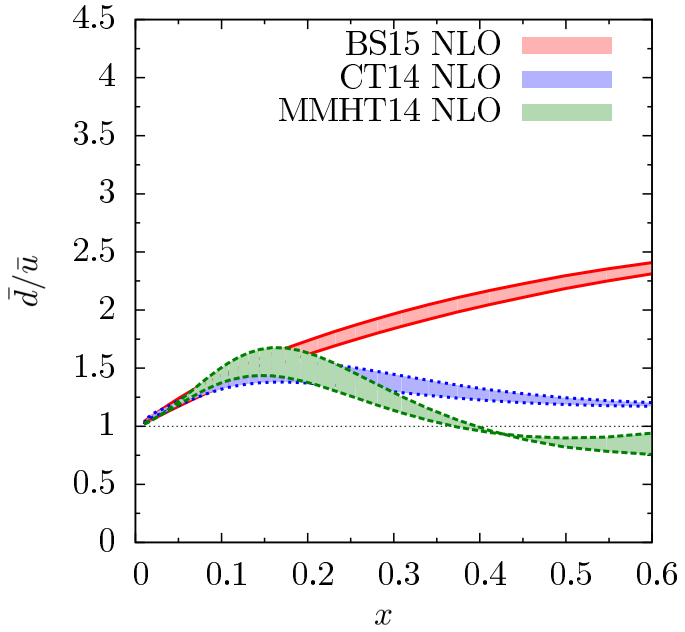
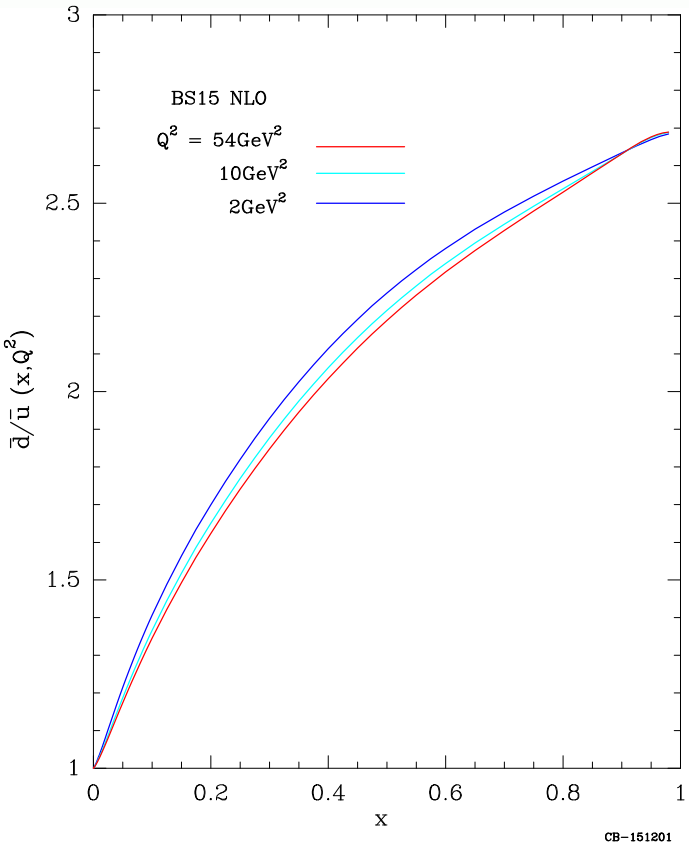


$$R(x_F) \equiv \frac{\sigma_{W^+}}{\sigma_{W^-}} = \frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{\bar{u}(x_1)d(x_2) + d(x_1)\bar{u}(x_2)}$$

C. Bourrely and J. Soffer (2013)





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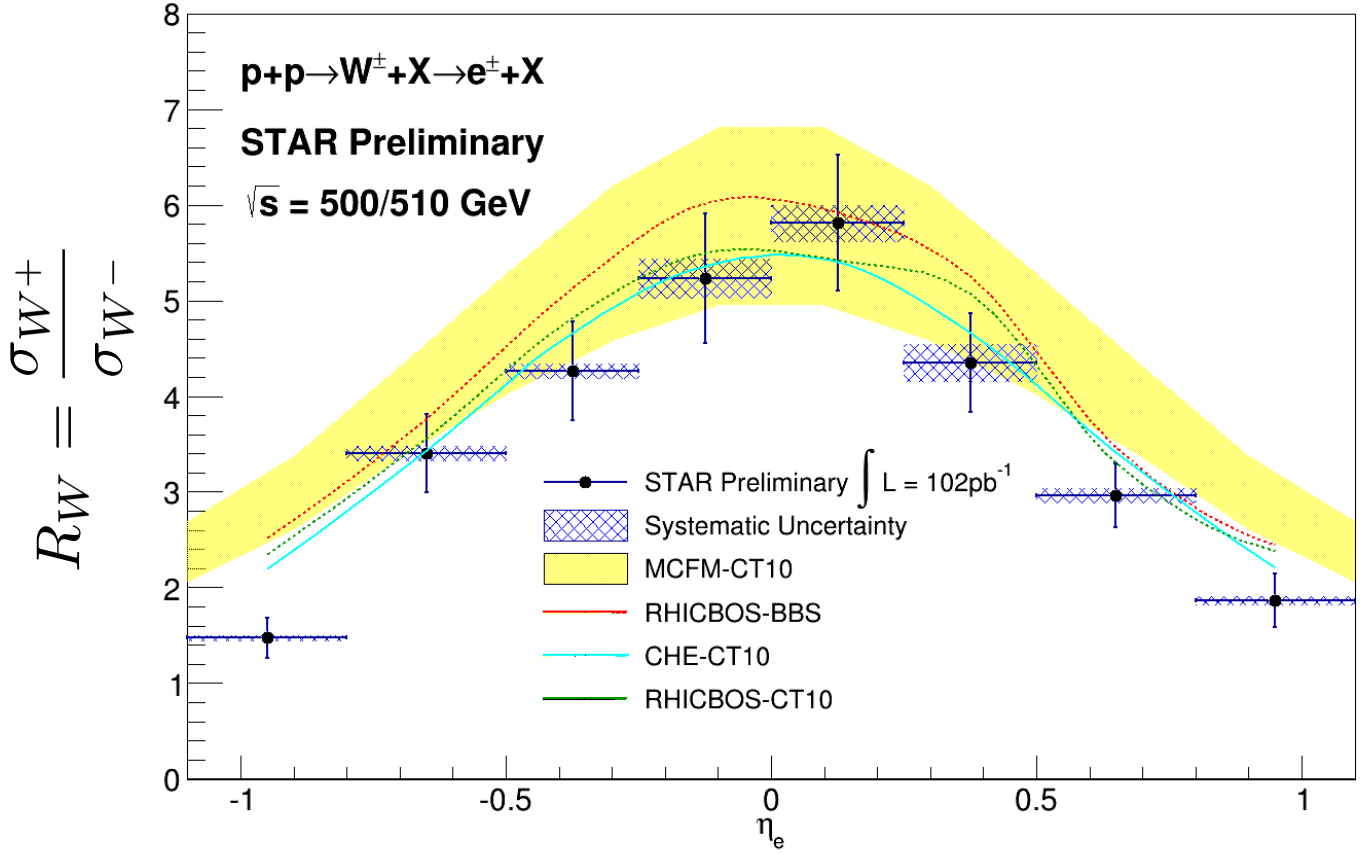
Results / Status: Cross-section ratio W^+/W^-

- STAR: W cross-section ratio measurements (Run 11 / 500GeV) (Run 12 / 510GeV)

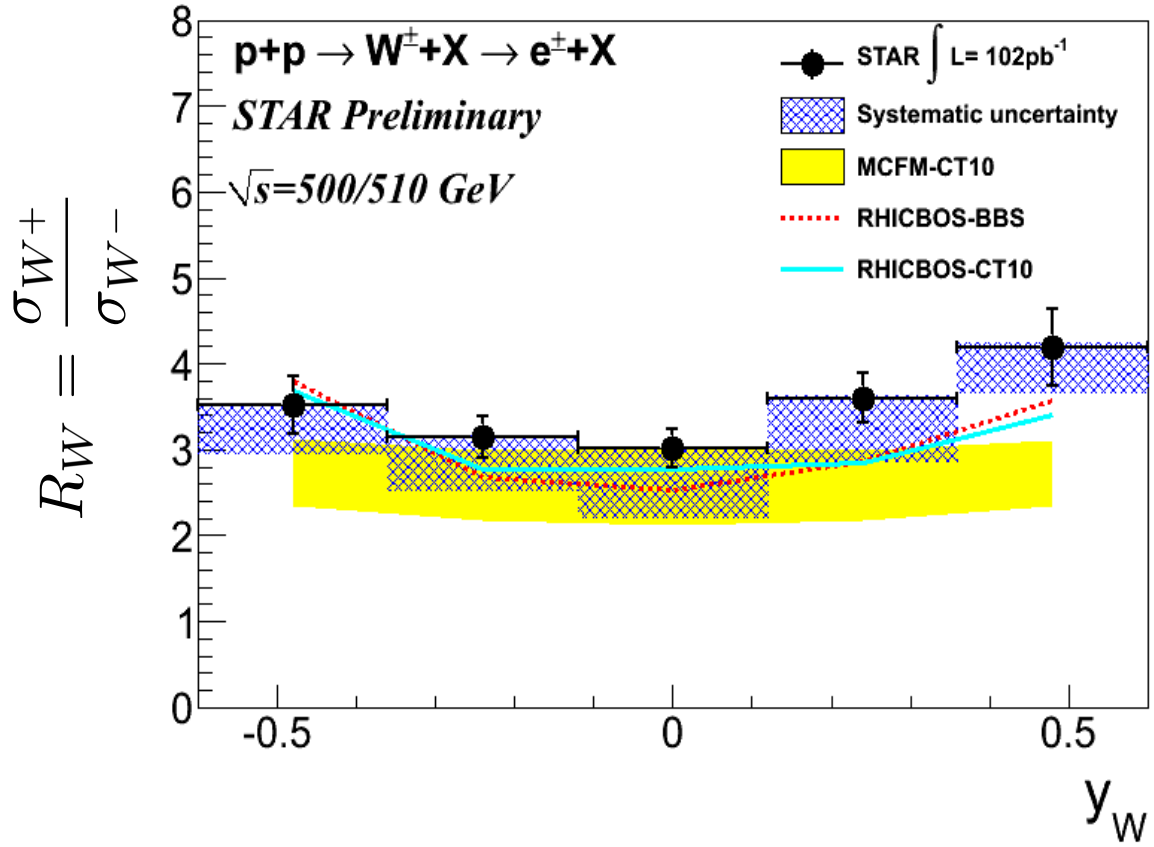


- Run 11 + Run 12 preliminary result: ~100pb^{-1}
- Run 13 data sample with ~250pb^{-1} will provide important improvement on precision
- Large Run 17 data sample of ~350pb^{-1}

M. Posik et al. (STAR Collaboration), DIS 2015.

Results / Status: Cross-section ratio W^+/W^-

- STAR: W cross-section ratio measurements at (Run 11 / 500GeV) (Run 12 / 510GeV)

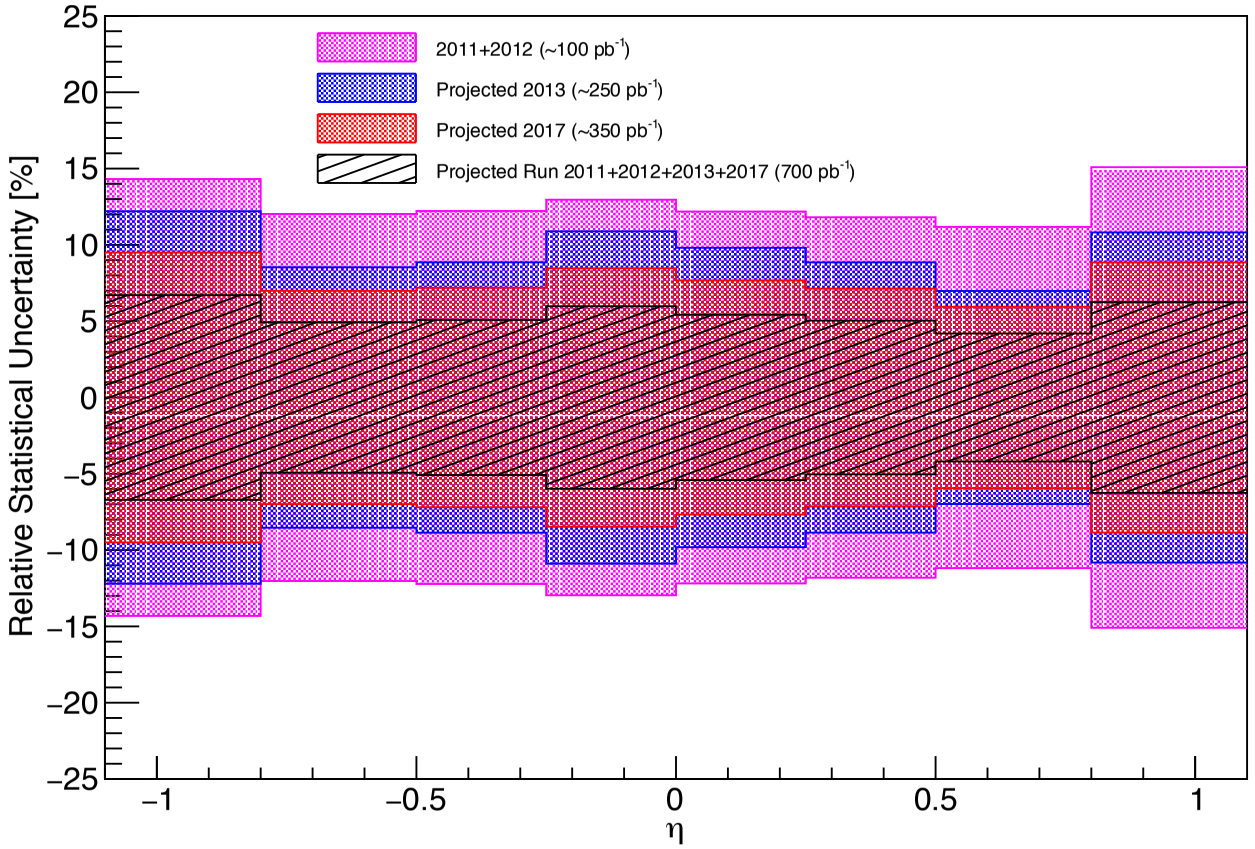


- W boson kinematics can be determined by reconstructing the W kinematics via its recoil
- Combination of data/MC simulations allows W boson rapidity reconstruction
- Critical for transverse single-spin asymmetry result of W production probing Sivers sign change

S. Fazio et al. (STAR Collaboration), DIS 2015.

Results / Status: Cross-section ratio W^+/W^-

- STAR: Run 11 / 12 uncertainties in comparison to projections for Run 13



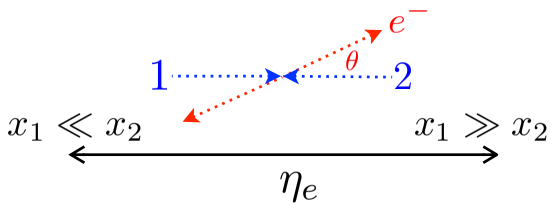
- Improved precision with Run 13 compared to Run 11+12 preliminary results

- Further improvement from Run 17 p+p data sample expected at 510GeV with 350pb^{-1}

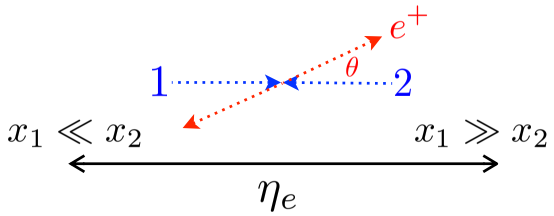
Results / Status: A_L asymmetry W^+/W^-

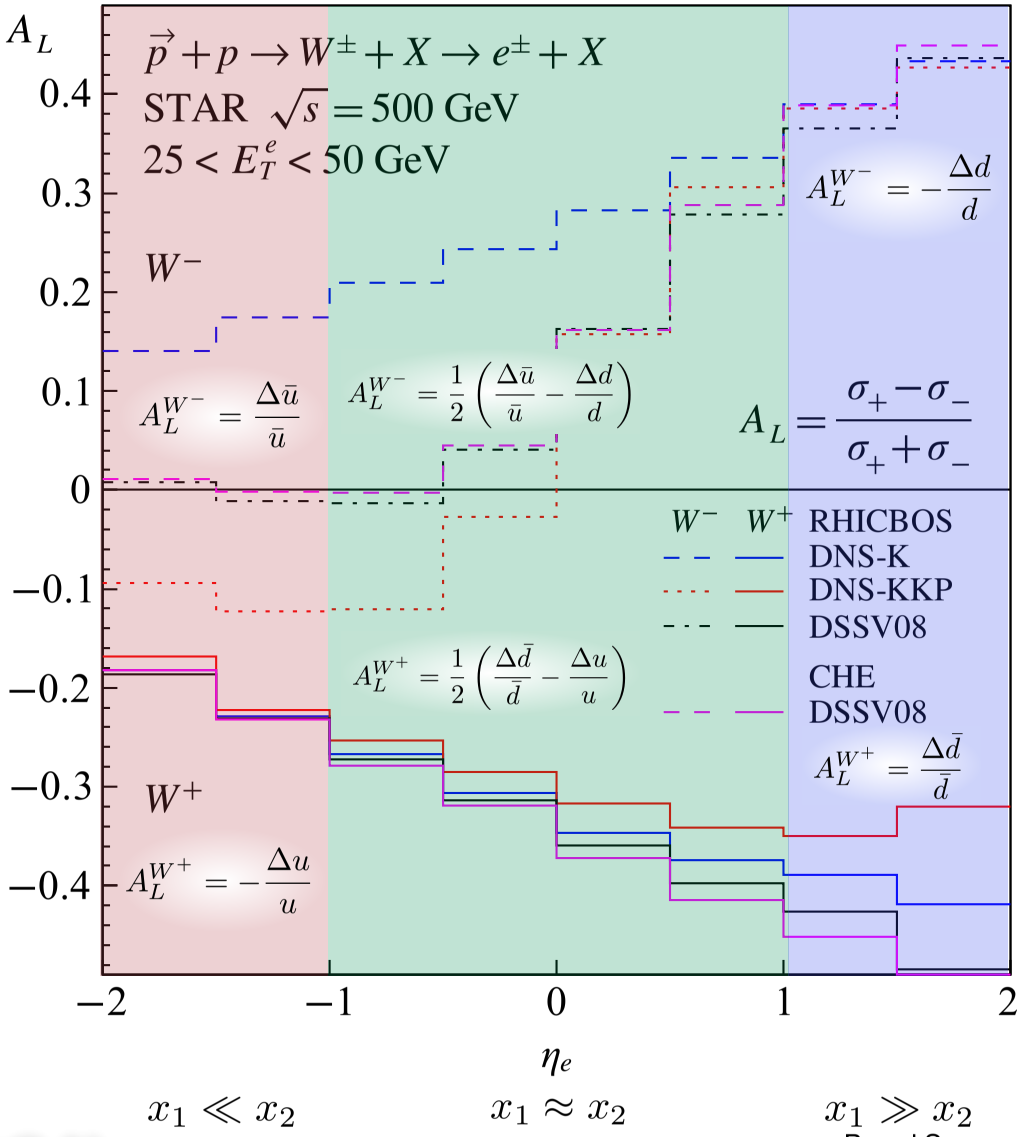
- RHIC Probing the quark flavor structure using W boson production

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



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





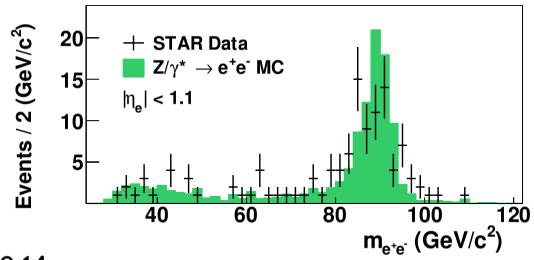
$\sqrt{s} = 500\,GeV$

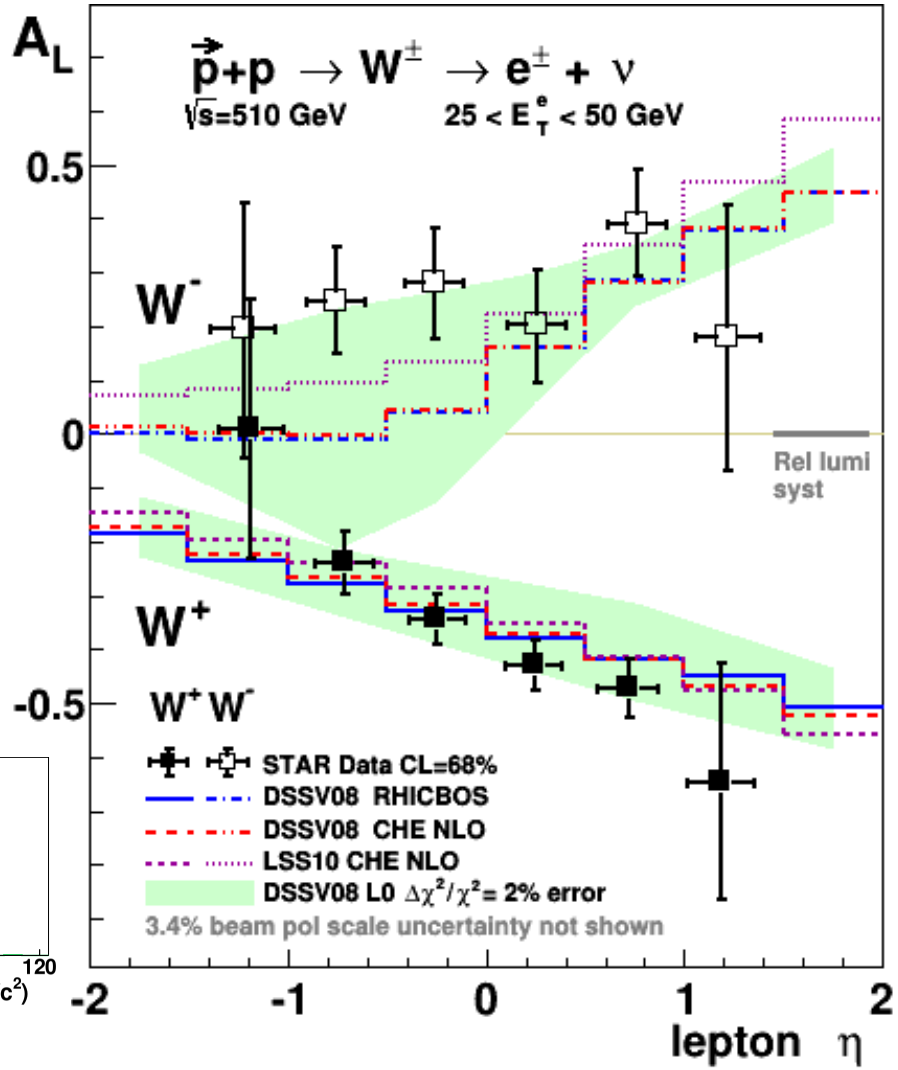
Results / Status: A_L asymmetry W^+/W^-

- STAR: Published W A_L measurements (Run 11 / 500GeV) (Run 12 / 510GeV)

L. Adamczyk et al. (STAR Collaboration), Phys. Rev. Lett. 113, (2014) 072301.

- Measured asymmetries constrain anti-quark polarizations: Larger asymmetry for W^- suggest large anti-u quark polarization!
- Critical: Measurement of W^+ and W^- asymmetries as a function η_e
- Extension of backward / forward η_e acceptance enhances sensitivity to anti-u / anti-d quark polarization



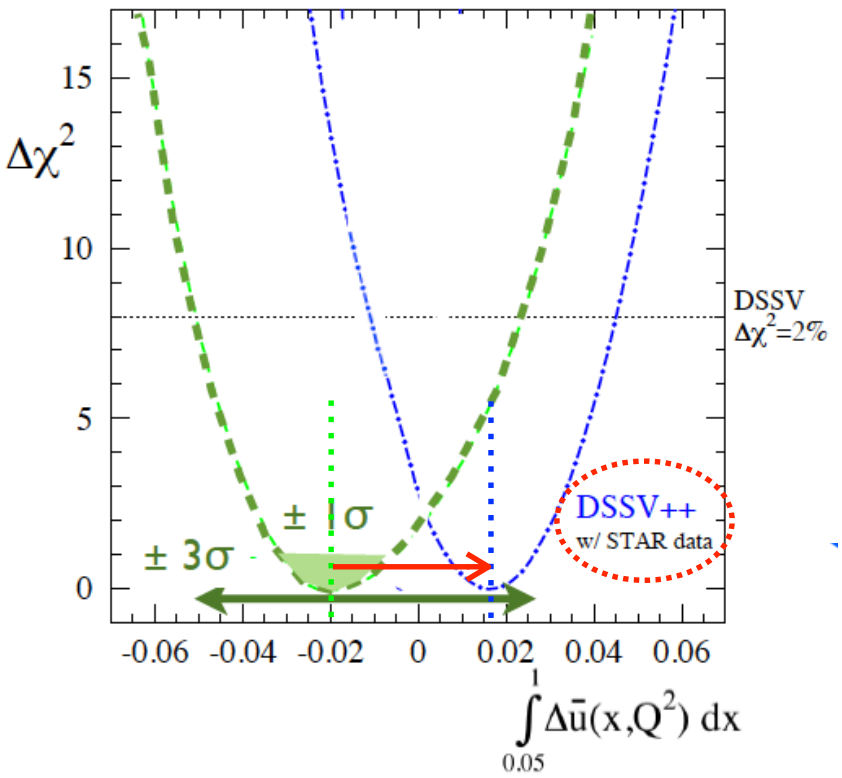


- A_L (Z/γ^*) result: $A_L = -0.07^{+0.14}_{-0.14}$

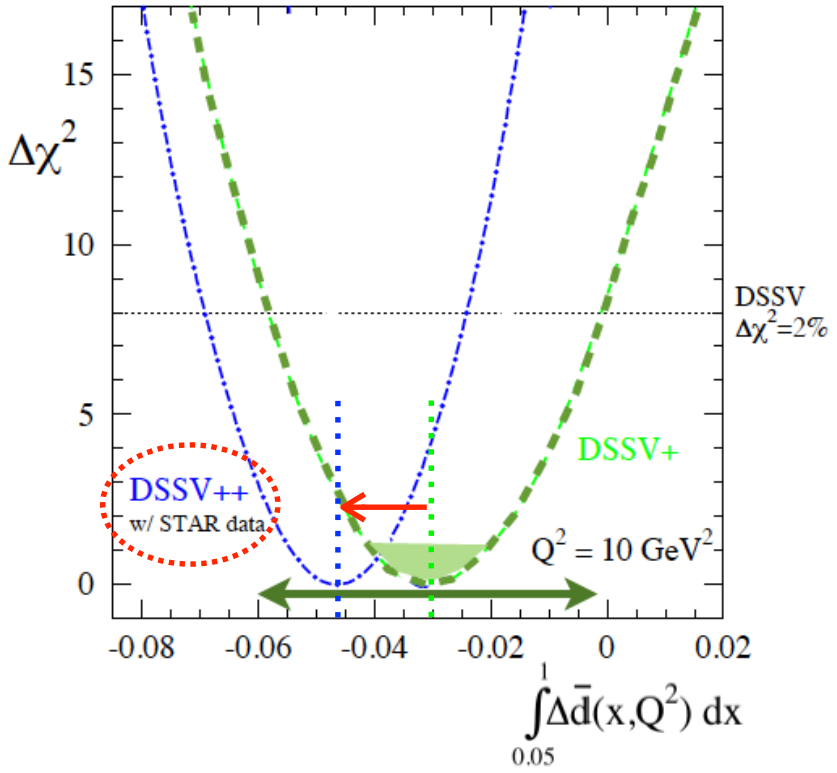
Results / Status: A_L asymmetry W^+/W^-

- Impact of STAR 2012 W A_L measurements (DSSV)

Anti-u quark polarization



Anti-d quark polarization



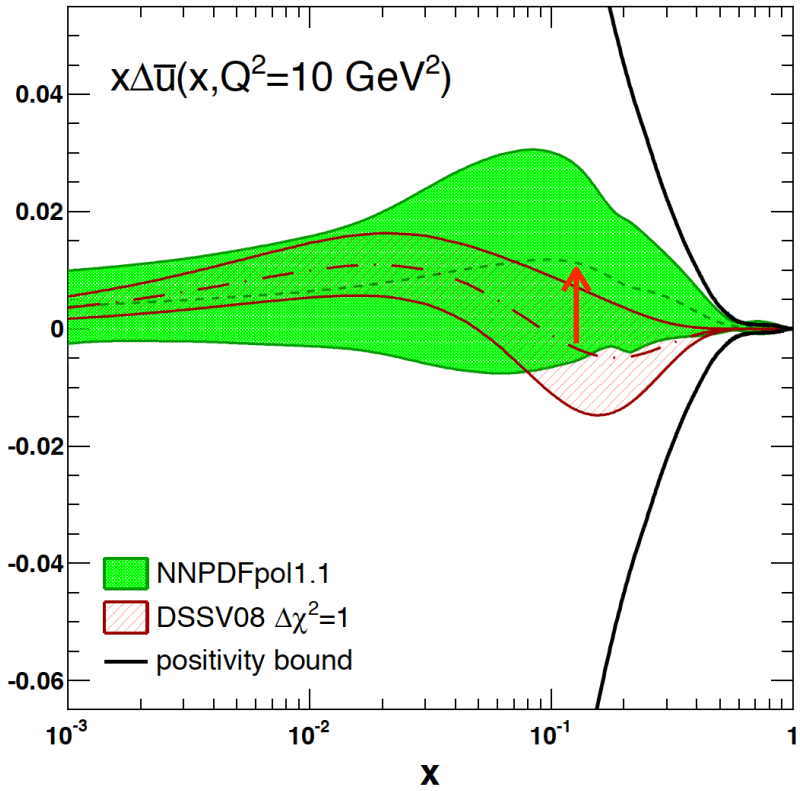
E. Aschenauer, arXiv: 1304.0079.

- Significant constraint for ubar and dbar.
- Significant shift of ubar central value from STAR 2012 W A_L prelim. data.

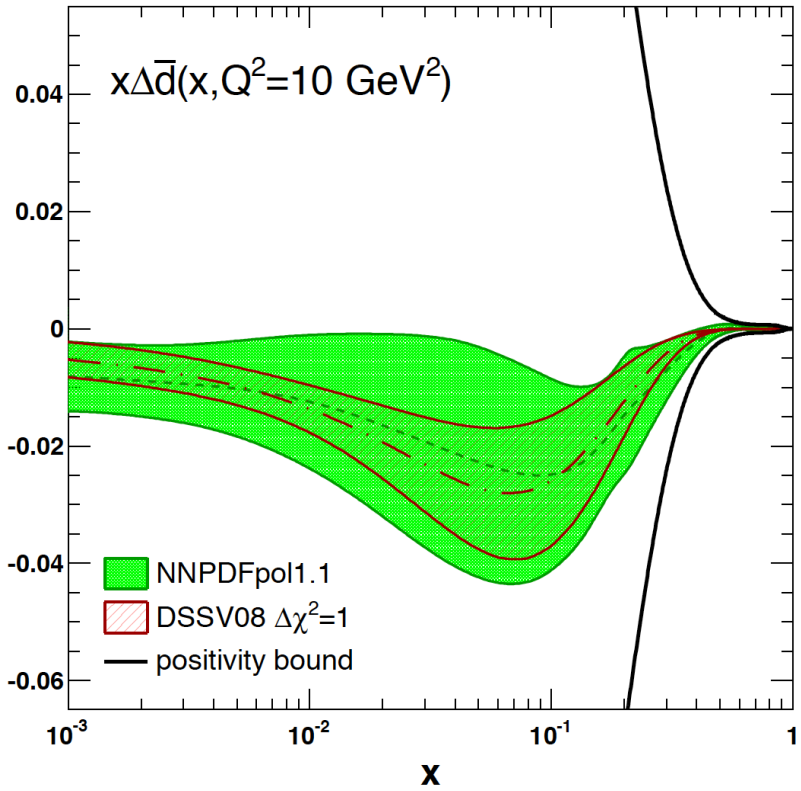
Results / Status: A_L asymmetry W^+/W^-

- Impact of STAR 2012 W A_L measurements (NNPDF) (1)

Anti-u quark polarization



Anti-d quark polarization



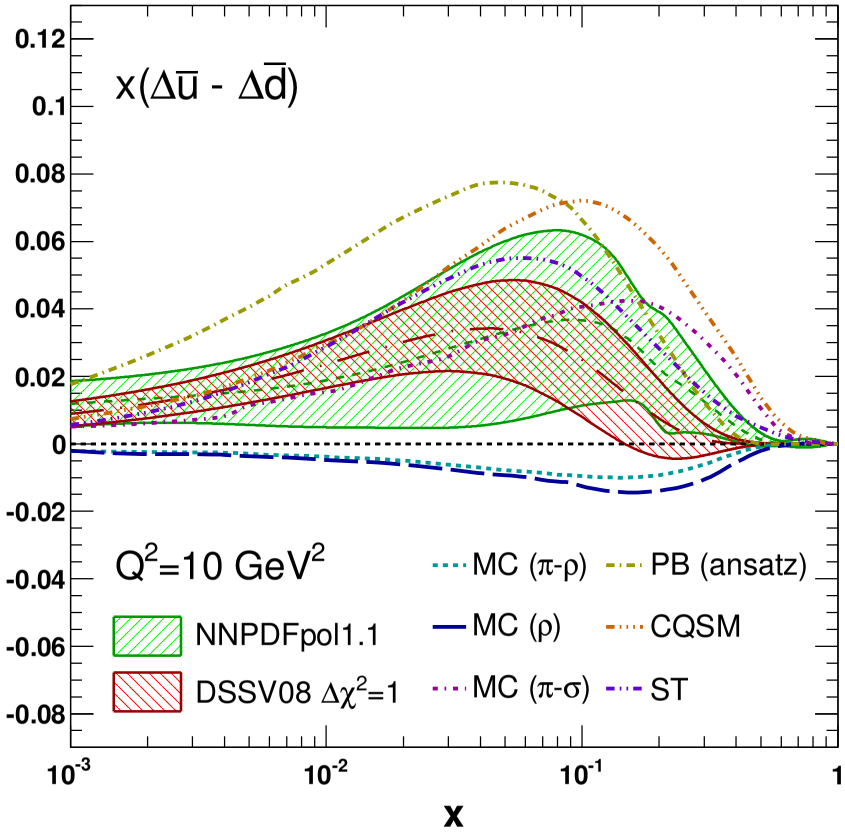
R. Ball et al. (NNPDF Collaboration), Nucl. Phys. B887, (2014) 276.

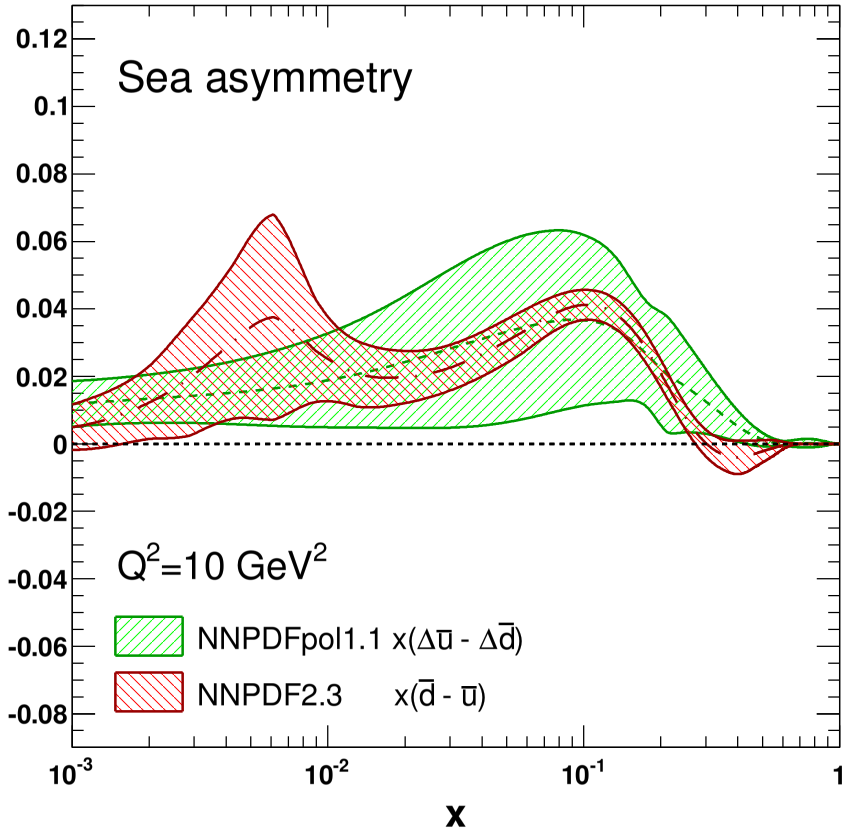
- Significant constraint for ubar and dbar.
- Significant shift of ubar central value from STAR 2012 W A_L prelim. data.

E. Nocera. PoS DIS2014 (2014) 204, arXiv: 1406:7122.

Results / Status: A_L asymmetry W^+/W^-

- Impact of STAR 2012 W A_L measurements (NNPDF) (2)





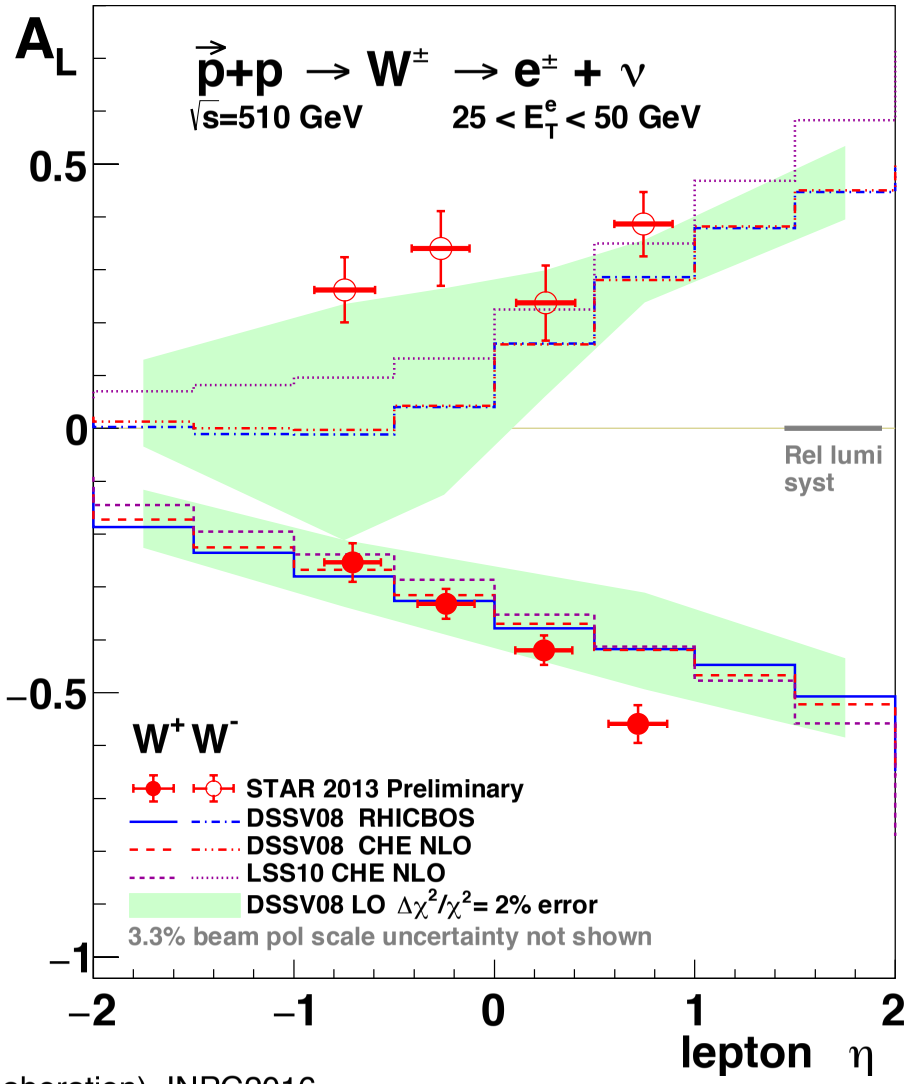
R. Ball et al. (NNPDF Collaboration), Nucl. Phys. B887, (2014) 276.

- Flavor asymmetry of ubar and dbar is positive
- Flavor asymmetry of ubar and dbar of similar magnitude as respective unpolarized difference!

E. Nocera. PoS DIS2014 (2014) 204, arXiv: 1406:7122.

Results / Status: A_L asymmetry W^+/W^-

- STAR: W A_L measurements (Run 13 / 510GeV)
  - The most precise measurement of W A_L up to date from Run 13 measured over 4 bins in mid-rapidity for W^+ and W^-
  - Expect to further constrain ubar / dbar.

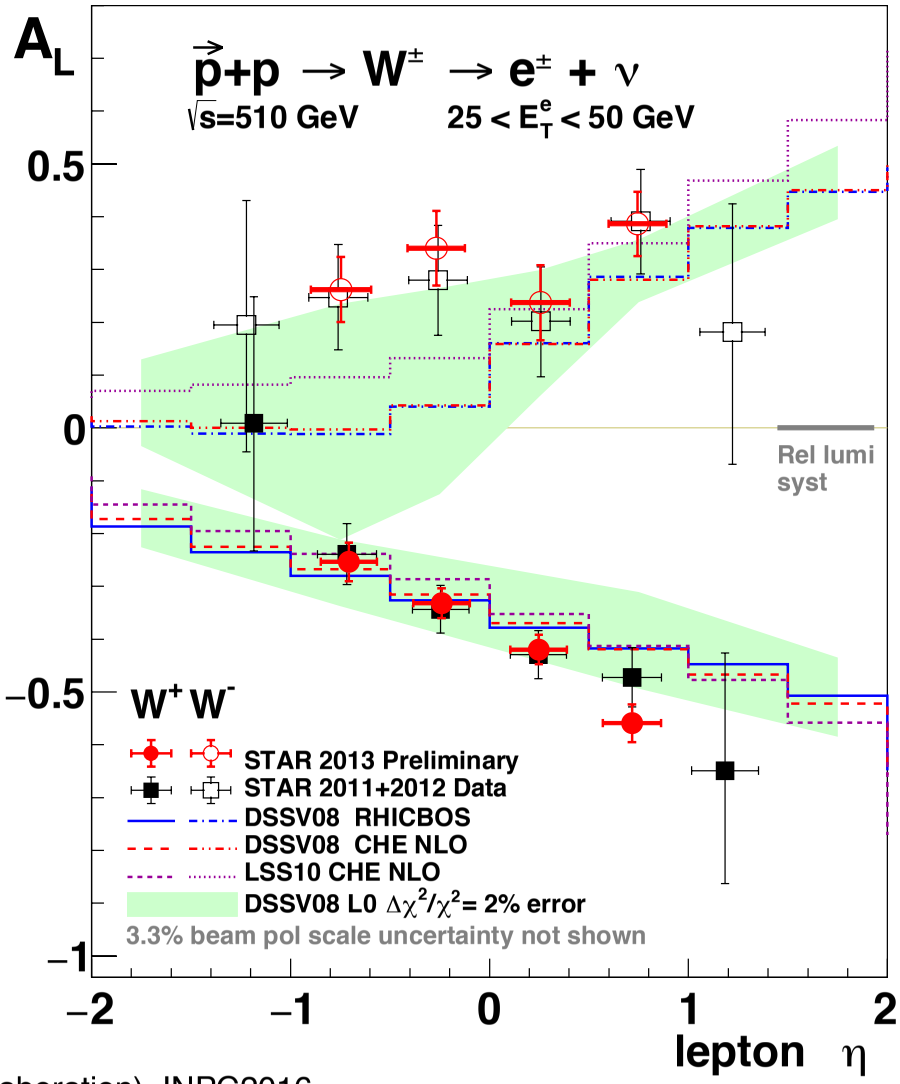


J. Zhang et al. (STAR Collaboration), INPC2016,
D. Gunarathne et al. (STAR Collaboration), SPIN2016.

Results / Status: A_L asymmetry W^+/W^-

- STAR: W A_L measurements (Run 11 / 500GeV) (Run 12 / 510GeV) and Run 13 (510GeV)

  - STAR 2013 W A_L preliminary results is the most precise measurement of W A_L up to date.
  - STAR 2013 preliminary W A_L results consistent with published 2011+2012 results.
  - Statistical uncertainties (Dominant uncertainties) were reduced by 40% / Similar systematic uncertainties.



J. Zhang et al. (STAR Collaboration), INPC2016,
D. Gunarathne et al. (STAR Collaboration), SPIN2016.

Results / Status: A_L asymmetry W^+/W^-

- World data: W A_L measurements STAR and PHENIX and mid-rapidity

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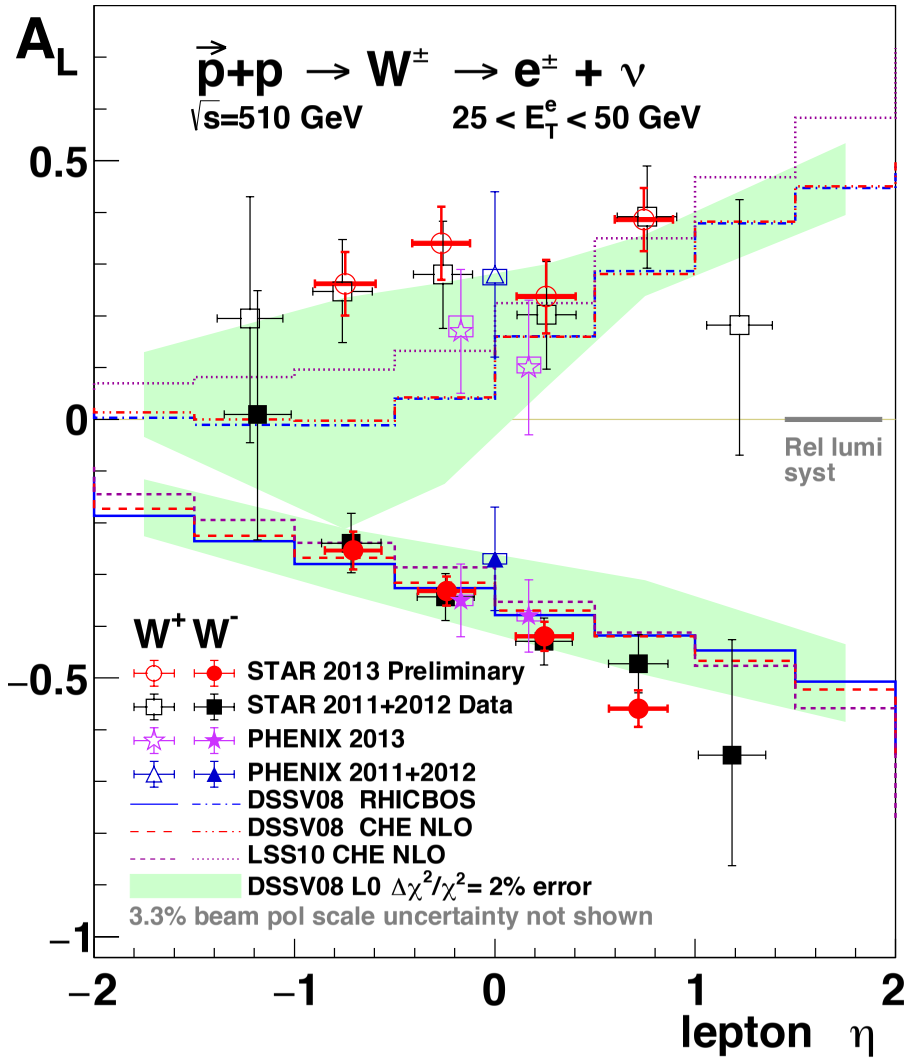

J. Zhang et al. (STAR Collaboration), INPC2016,
D. Gunarathne et al. (STAR Collaboration), SPIN2016.

Results / Status: A_L asymmetry W^+/W^-

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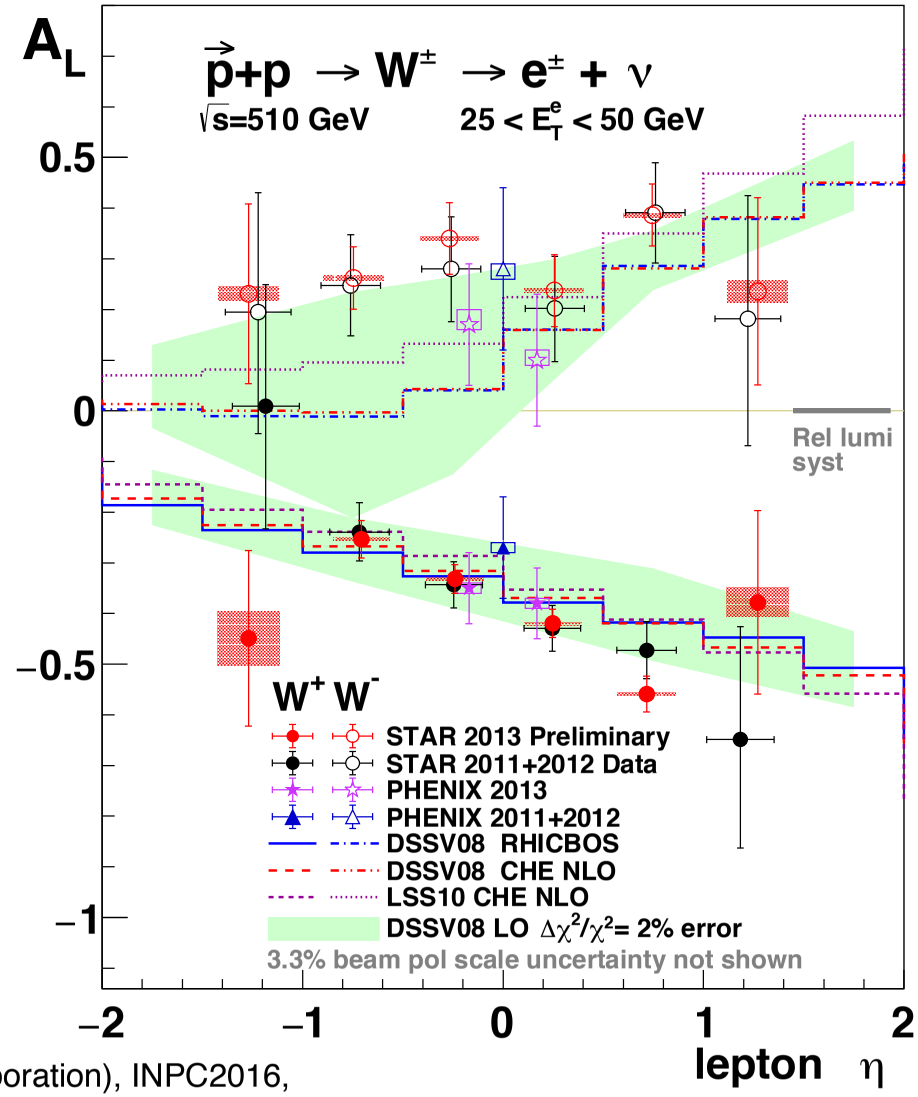
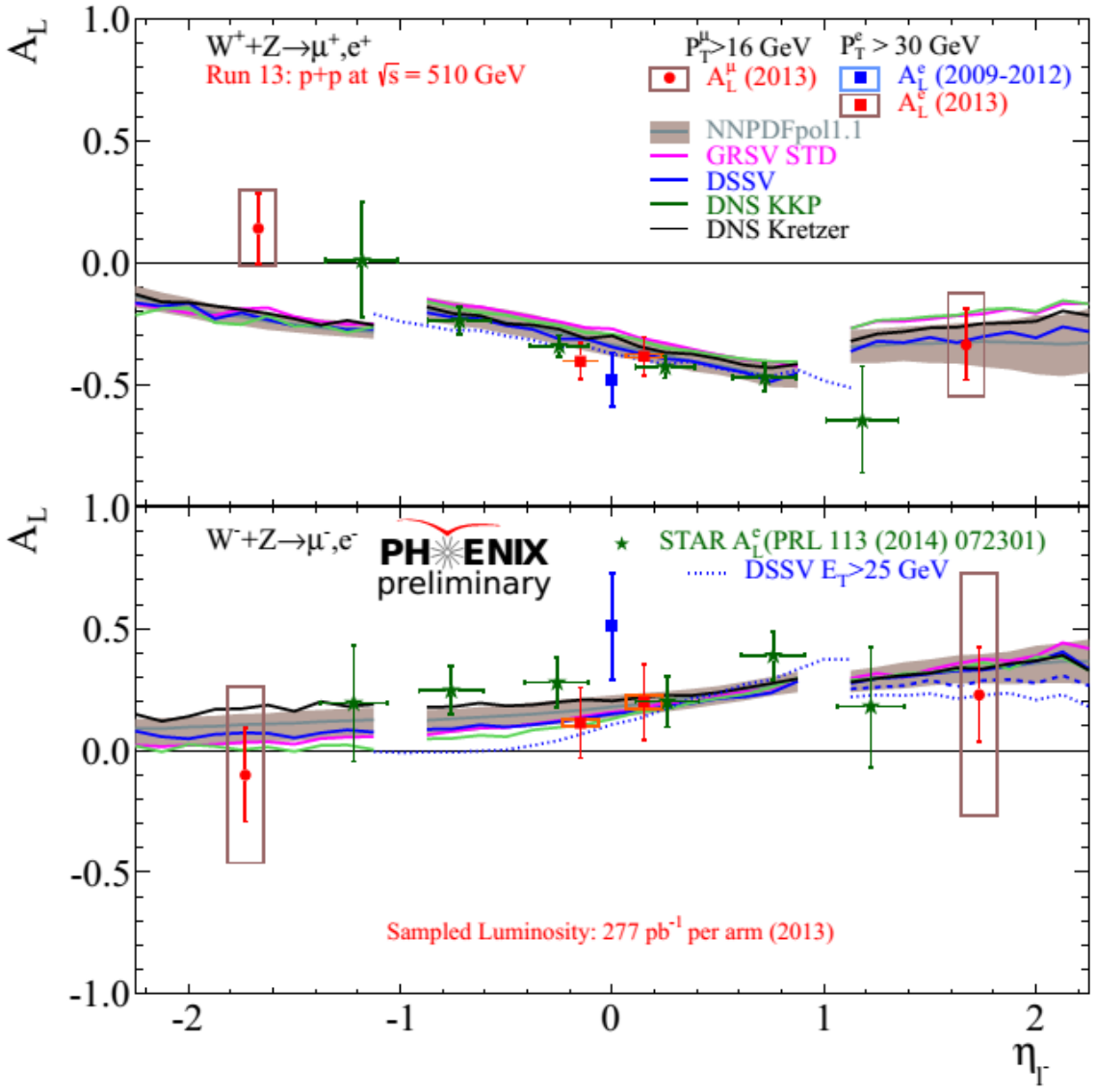


J. Zhang et al. (STAR Collaboration), INPC2016,
D. Gunarathne et al. (STAR Collaboration), SPIN2016,
A. Kraishan (STAR Collaboration), AGS/RHIC Users' Meeting 2016

Results / Status: A_L asymmetry W^+/W^-

- PHENIX: W A_L mid-rapidity and forward rapidity results



- Compilation of PHENIX Run 13 forward rapidity and mid-rapidity results together with STAR mid-rapidity results

PHENIX Mid-rapidity: A. Adare et al. (PHENIX Collaboration), Phys.Rev. D93 (2016) 051103.

Summary / Outlook

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 precise measurement to date. These results will help to further constrain anti-quark helicity distributions / Publication in preparation!
- New STAR 2013 W A_L prelim. results consistent with published STAR 2011+2012 results and published PHENIX mid-rapidity results.
- Preliminary cross-section ratio measurement (Run 11/12): Strong physics case of unpolarized dbar/ubar ratio using W production complementary to SeaQuest at FNAL / New Run 13 result in preparation!

Outlook

- Long 510GeV run in 2017 (Run 17) at transverse spin polarization of about 350pb^{-1}: W A_N / Unpol. QCD sea
- Unpolarized program for Run 17: Cross-section ratio measurements of W^+/W^- Unpolarized dbar / ubar probe
- Exciting long-term polarized pp/pA program beyond 2020 requiring forward detector upgrade (Cold QCD plan)

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DOE NP contract: DE-SC0013405

E. Aschenauer, Cold QCD plan, arXiv: 1602.03922.