Stony Brook University

W/Z Measurements at RHIC

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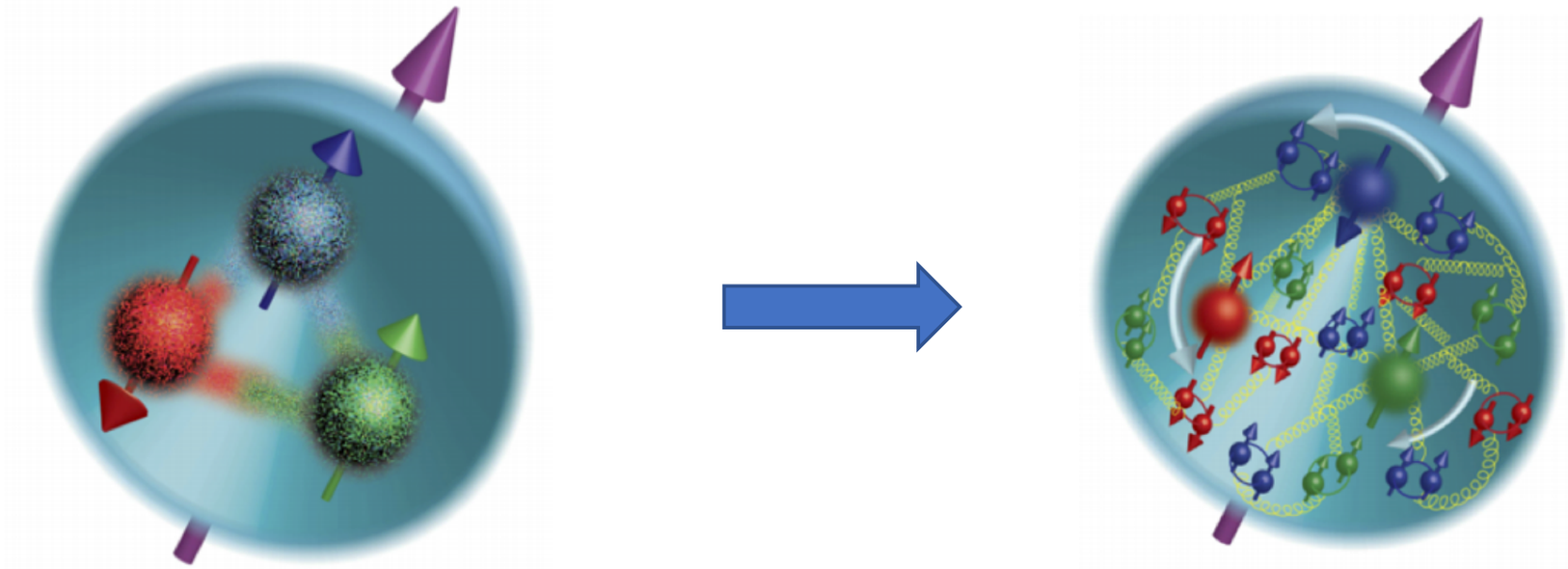
Thanks to **Sanghwa Park** (SBU)
for the materials of PHENIX W/Z measurements

Proton Spin Structure



- Proton spin puzzle: integral of quark polarization measured in DIS to be only ~30% of the proton spin

- Contributions from quark/antiquarks spin ($\Delta\Sigma$), gluon spin (ΔG) and possibly from the orbital angular momentum (L)

$$< S_p > = \frac{1}{2} = \frac{1}{2}\,\Delta\Sigma + \Delta G + L_q + L_g$$

Jaffe-Manohar 1990

Proton Spin Structure

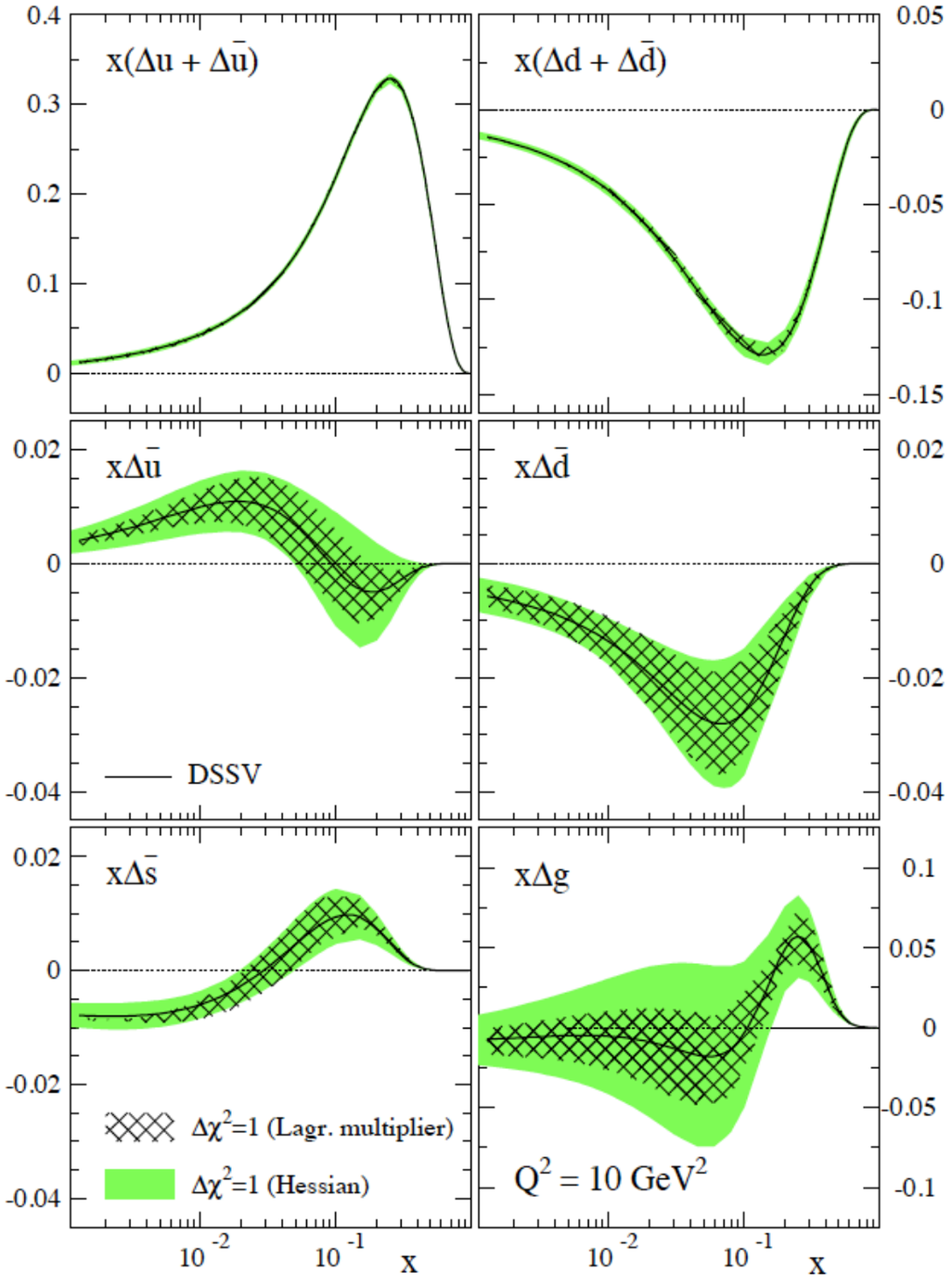
Before RHIC, mostly polarized DIS

- Total quark spin contributions pinned down pretty well
- Flavor separation was accessible via semi-inclusive DIS but has to reply on Fragmentation Functions; additional uncertainty introduced
- No direct access to gluon spin

RHIC spin program

- Direct access to gluon spin
- Direct access to sea quarks
- Transverse spin

DSSV2008
(Mostly pDIS + earlier RHIC results)



PRD 80, 034030 (2009)

Proton Spin Structure

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RHIC spin program

- Direct access to gluon spin
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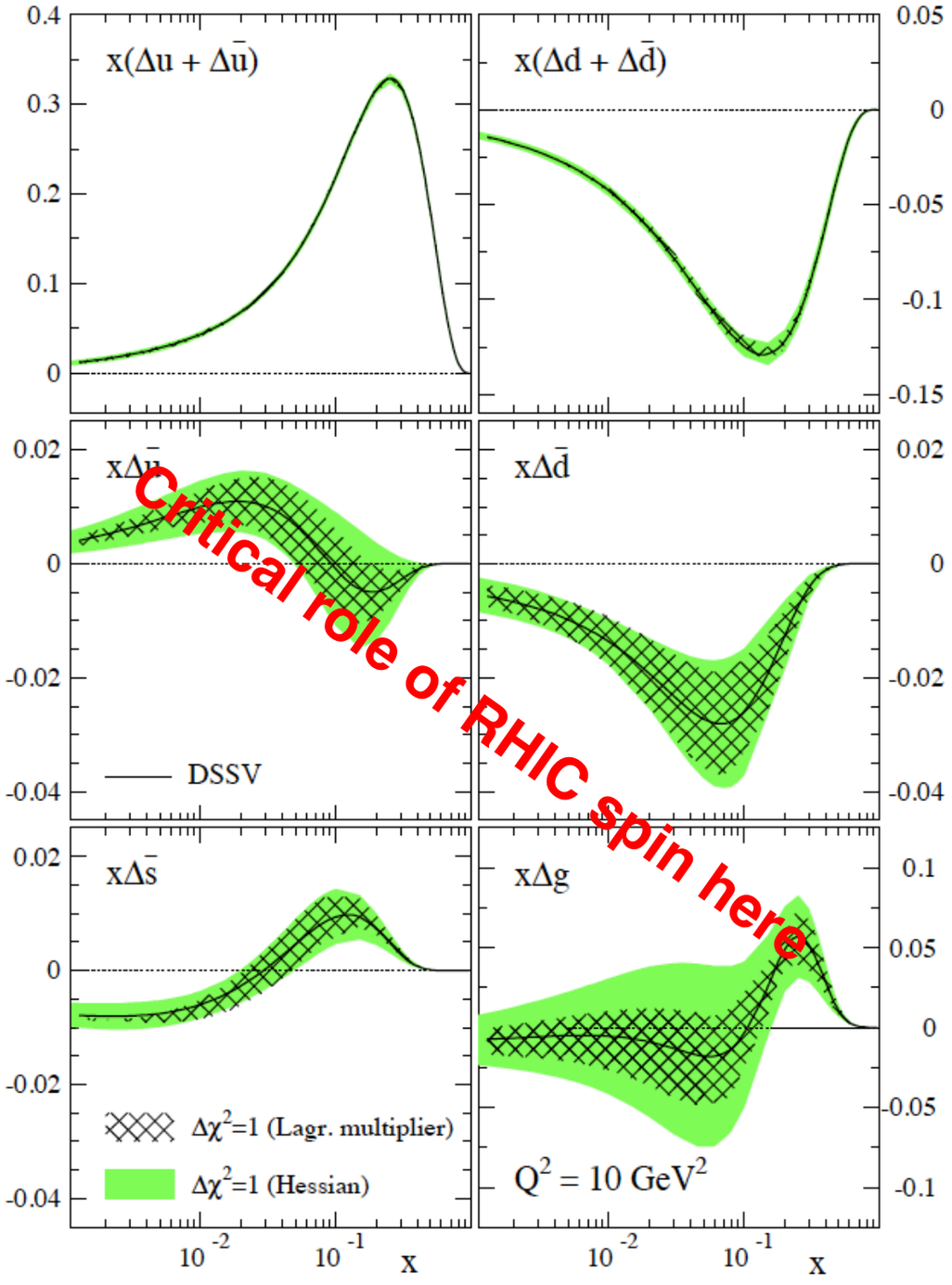
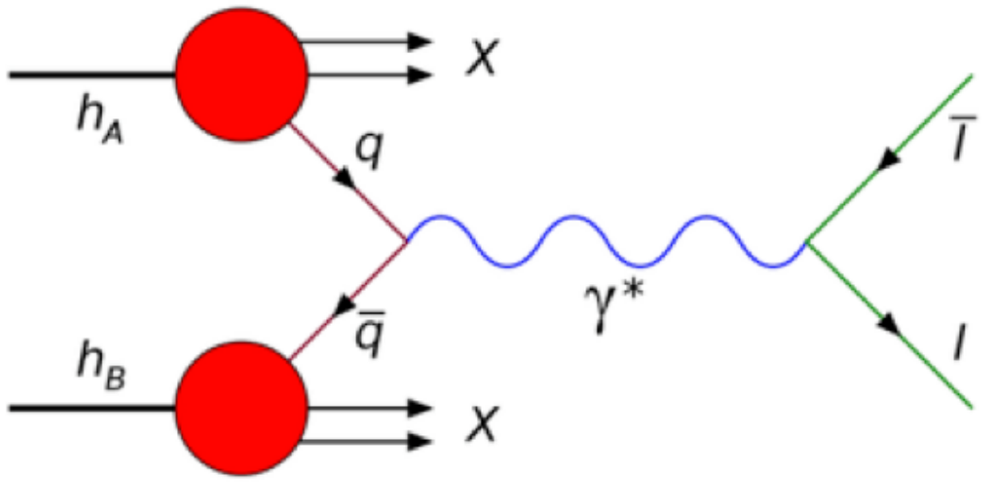
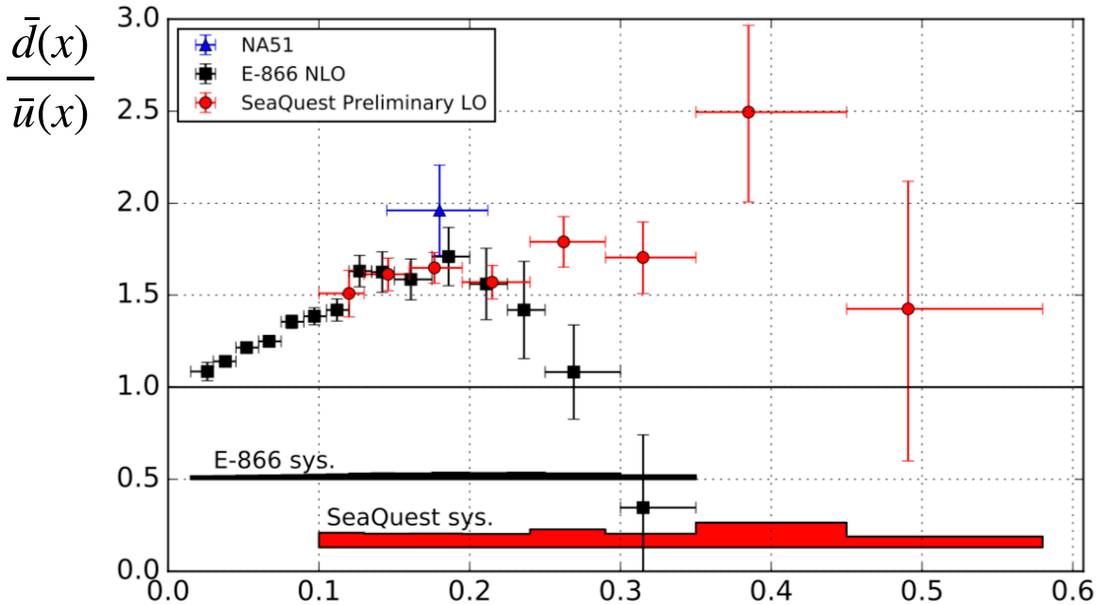


PRD 80, 034030 (2009)

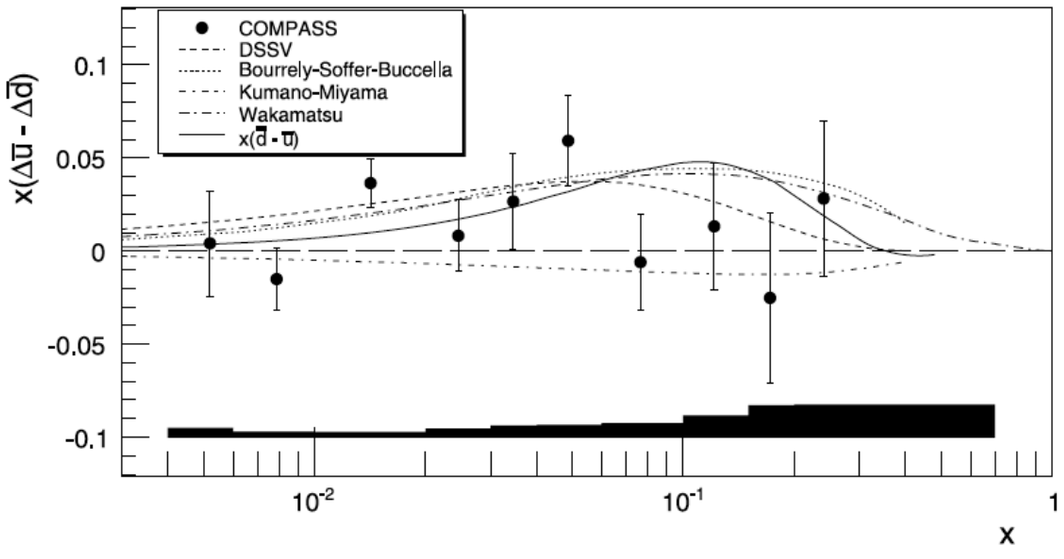
Sea quark flavor asymmetry



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



- Surprisingly, flavor asymmetry was observed in *unpolarized* sea with $\bar{d}(x) > \bar{u}(x)$
- Different models explaining the flavor asymmetry give different predictions for *polarized* asymmetry.
- Critical Role of RHIC spin program is also here.

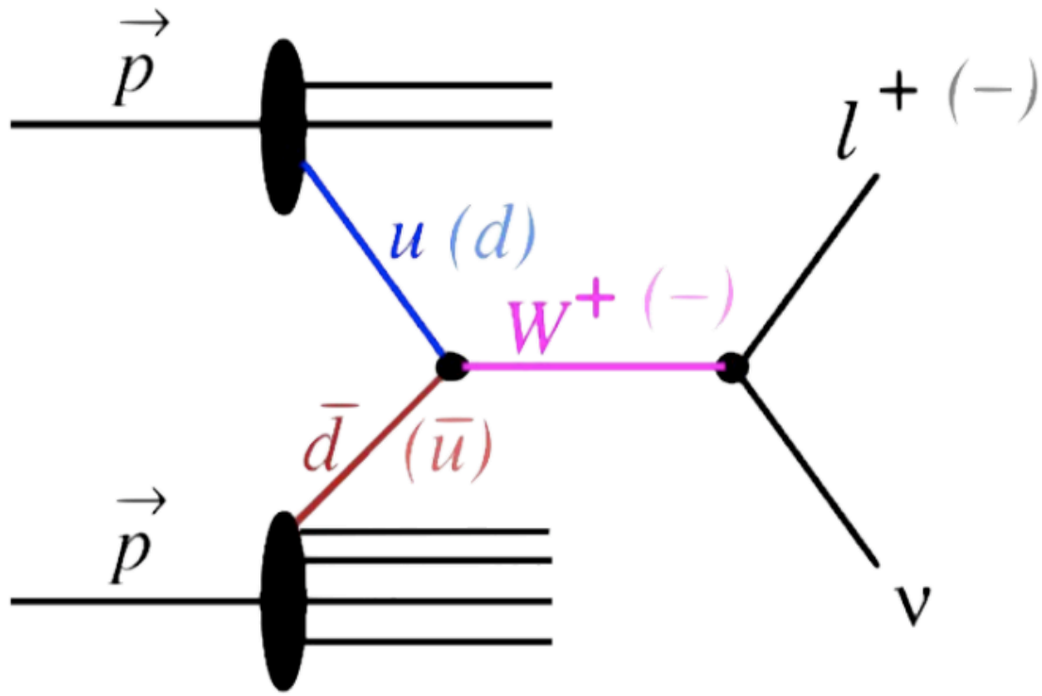


COMPASS, PLB 693, 227 (2010)

Probing sea quarks via W production

Unique way to study proton spin flavor structure:

- RHIC provides polarized proton beams
- W boson selects quarks/antiquarks with specific helicity
- STAR and PHENIX measure W boson via the leptonic decays

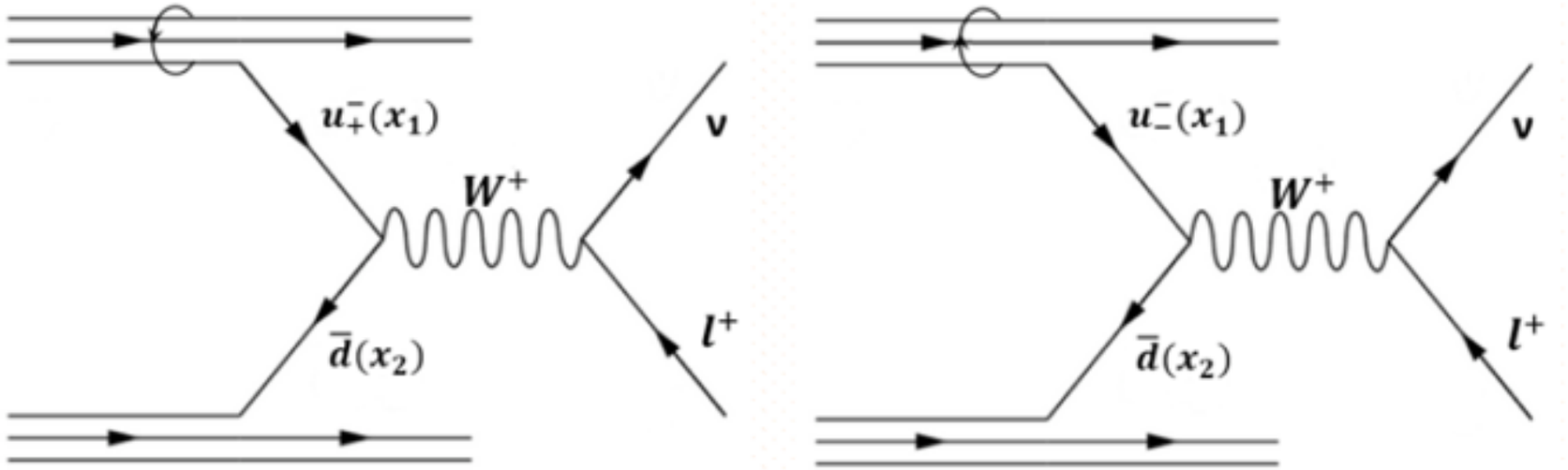


Parity-violating longitudinal single-spin asymmetry:

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

From W A_L to quark/anti-quark spin

- Example: W+ production, u quark from polarized proton beam;



$$A_L^{W^+} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \propto \frac{u_+^-(x_1)\bar{d}(x_2) - u_-^-(x_1)\bar{d}(x_2)}{u_+^-(x_1)\bar{d}(x_2) + u_-^-(x_1)\bar{d}(x_2)} = -\frac{\Delta u(x_1)}{u(x_1)}$$

- Analogous for the other cases.

From W A_L to quark/anti-quark spin

$$A_L^{W^+} \propto \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} \simeq \begin{cases} -\frac{\Delta u(x_1)}{u(x_1)}, y_W \gg 0 \ (x_1 \gg x_2) \\ \frac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}, y_W \ll 0 \ (x_1 \ll x_2) \end{cases}$$

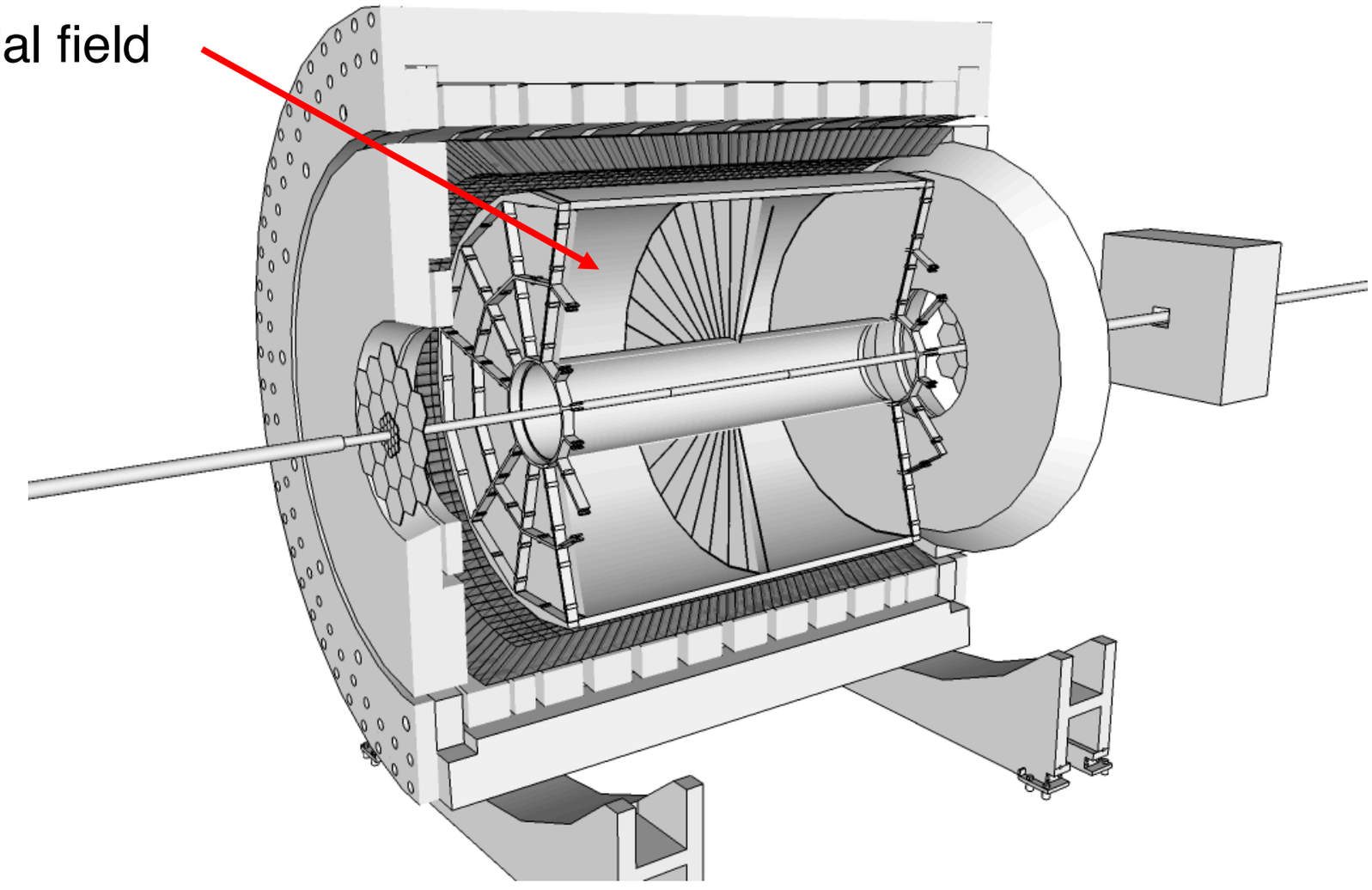
$$A_L^{W^-} \propto \frac{-\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)} \simeq \begin{cases} -\frac{\Delta d(x_1)}{d(x_1)}, y_W \gg 0 \ (x_1 \gg x_2) \\ \frac{\Delta\bar{u}(x_1)}{\bar{u}(x_1)}, y_W \ll 0 \ (x_1 \ll x_2) \end{cases}$$

- Flavor separation at forward/backward rapidity; demand of rapidity coverage.

STAR Detector

Nucl. Instrum. Meth. A499, 624, 2003

0.5 T solenoidal field



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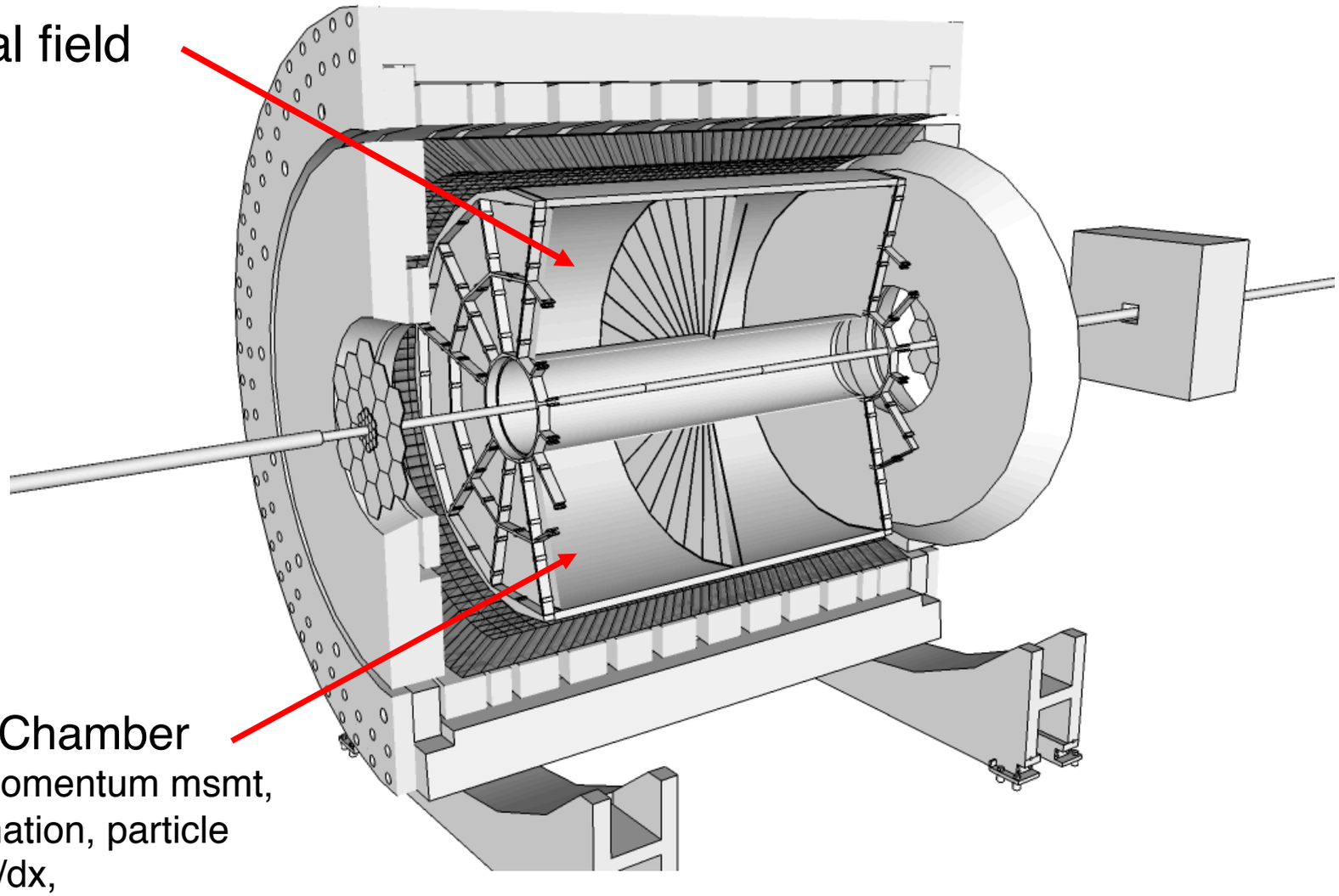

Time Projection Chamber

- charged track momentum msmt,
- charge determination, particle identification dE/dx,
- collision vertex reconstruction
- coverage $-1.3 < \eta < 1.3$

STAR Detector

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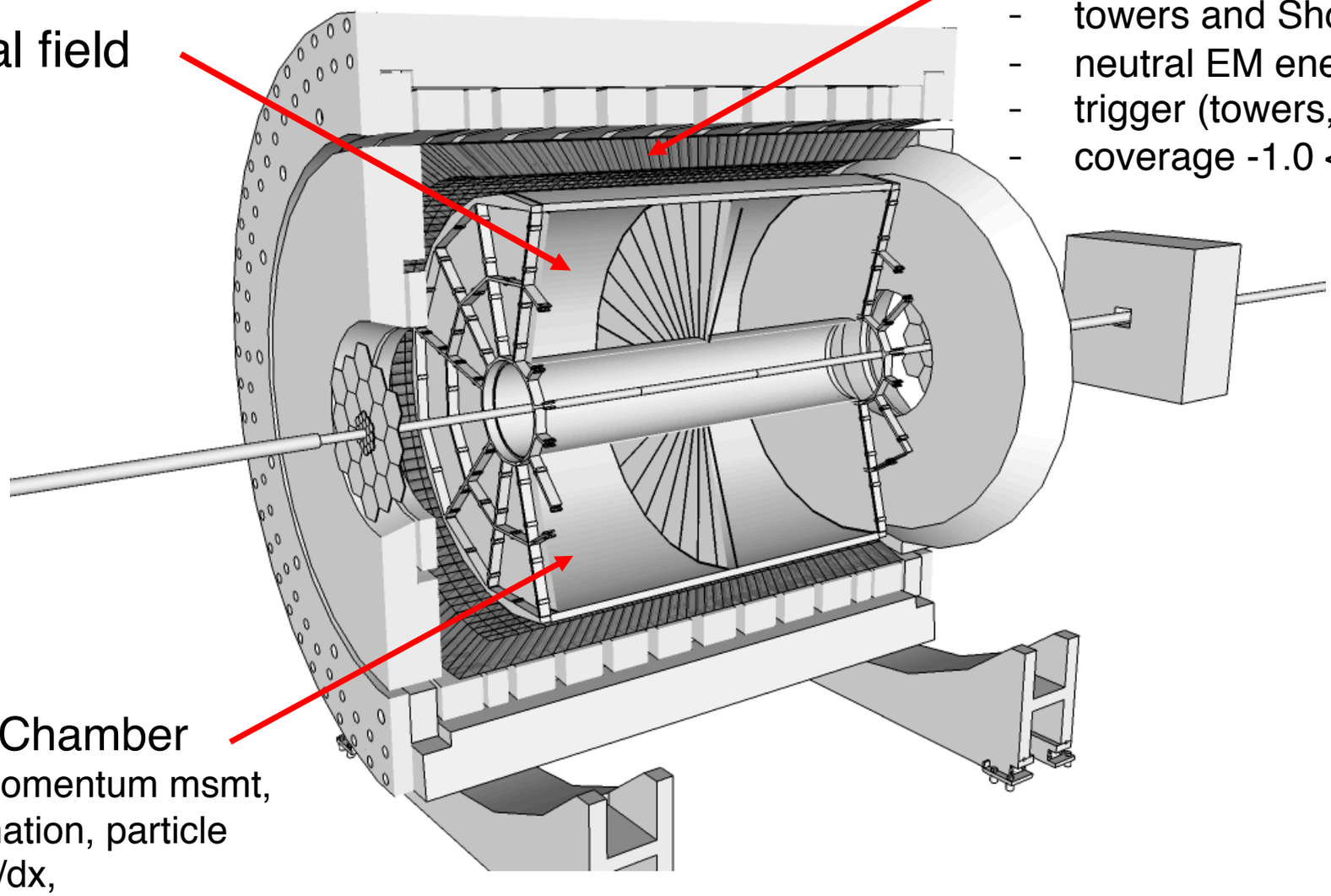

Barrel E.M. Calorimeter
- towers and Shower Maximum Det.
- neutral EM energy measurement,
- trigger (towers, patches of towers)
- coverage $-1.0 < \eta < 1.0$

Time Projection Chamber
- charged track momentum msmt,
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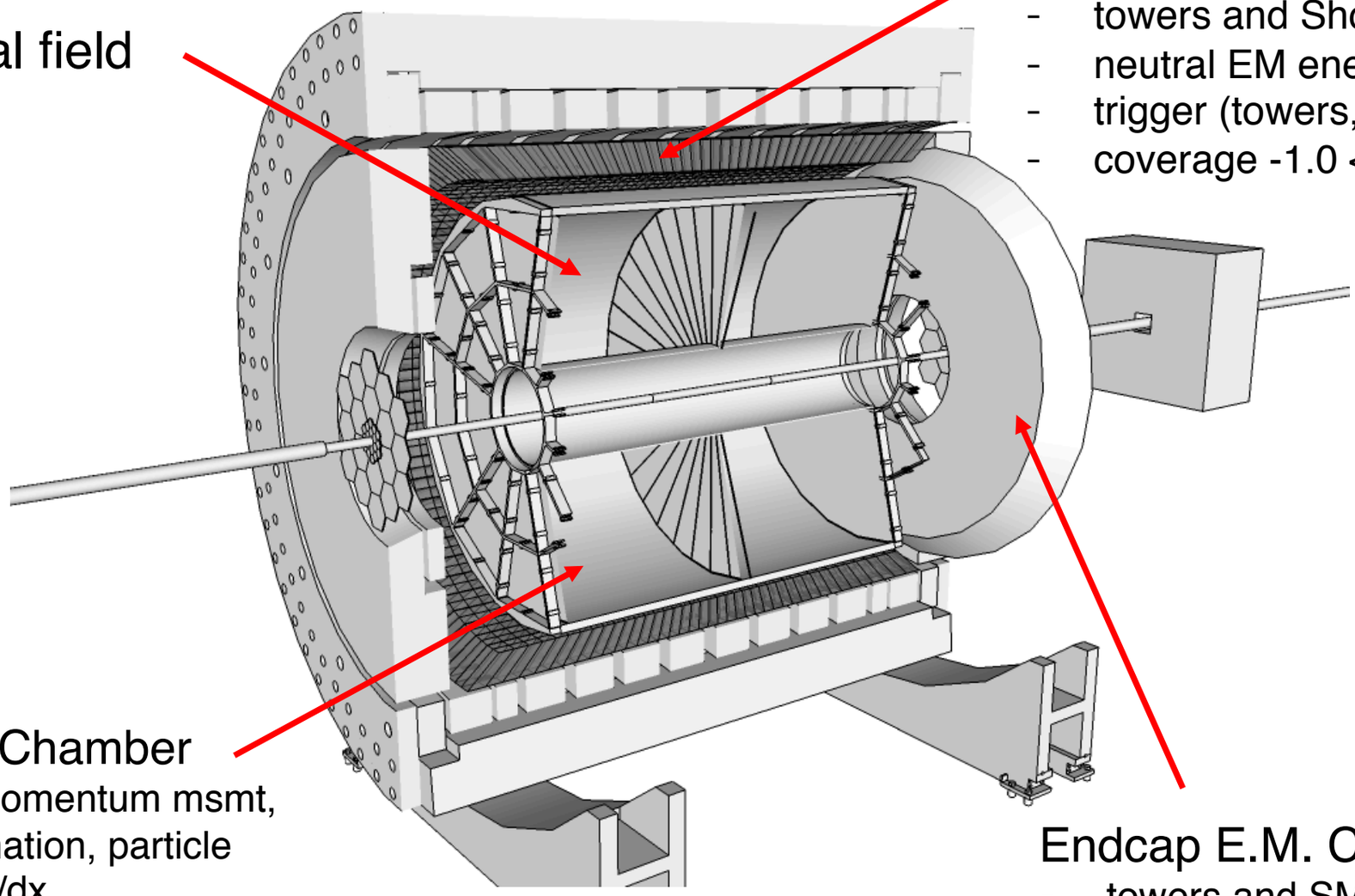
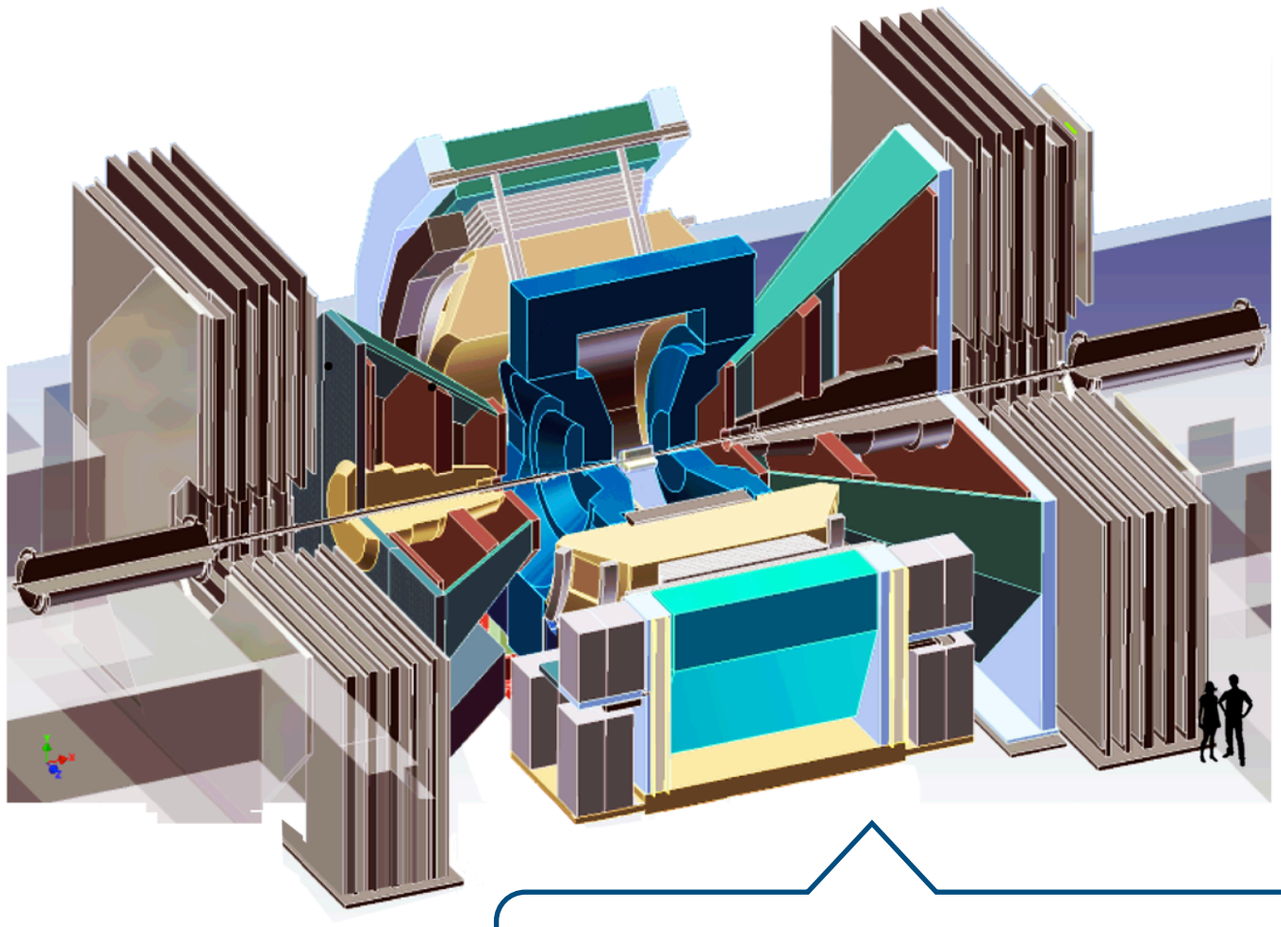


Barrel E.M. Calorimeter
- towers and Shower Maximum Det.
- neutral EM energy measurement,
- trigger (towers, patches of towers)
- coverage $-1.0 < \eta < 1.0$

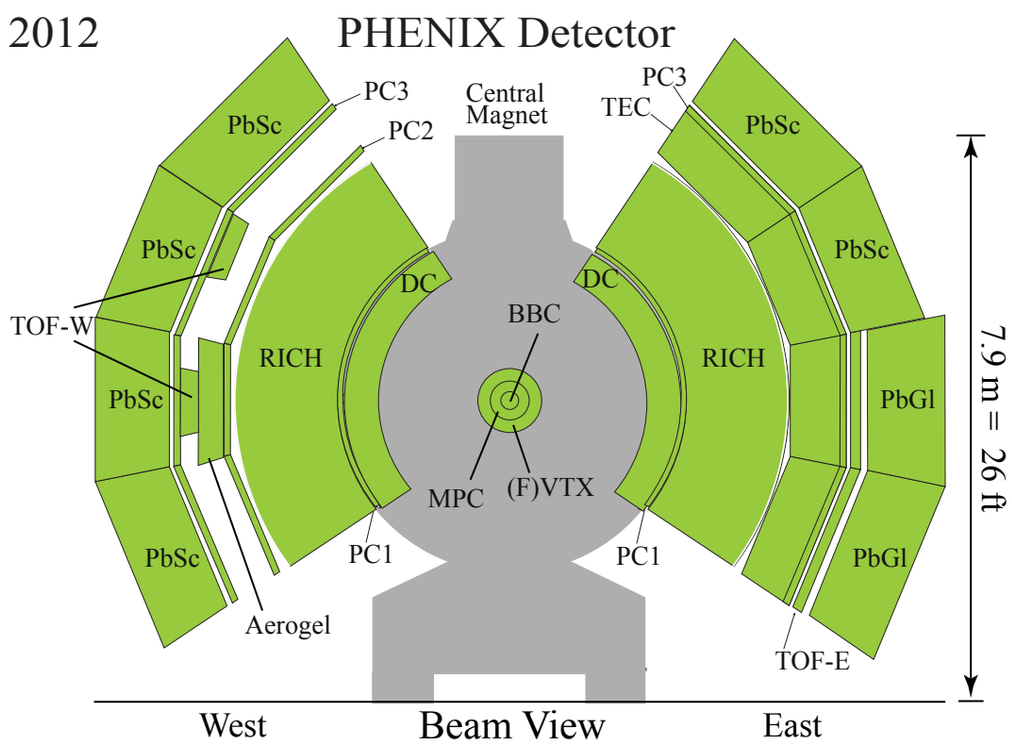
Time Projection Chamber
- charged track momentum msmt,
- charge determination, particle identification dE/dx,
- collision vertex reconstruction
- coverage $-1.3 < \eta < 1.3$

Endcap E.M. Calorimeter
- towers and SMD.
- neutral EM energy measurement,
- trigger (towers, patches of towers)
- coverage $1.1 < \eta < 2.0$

PHENIX Detector

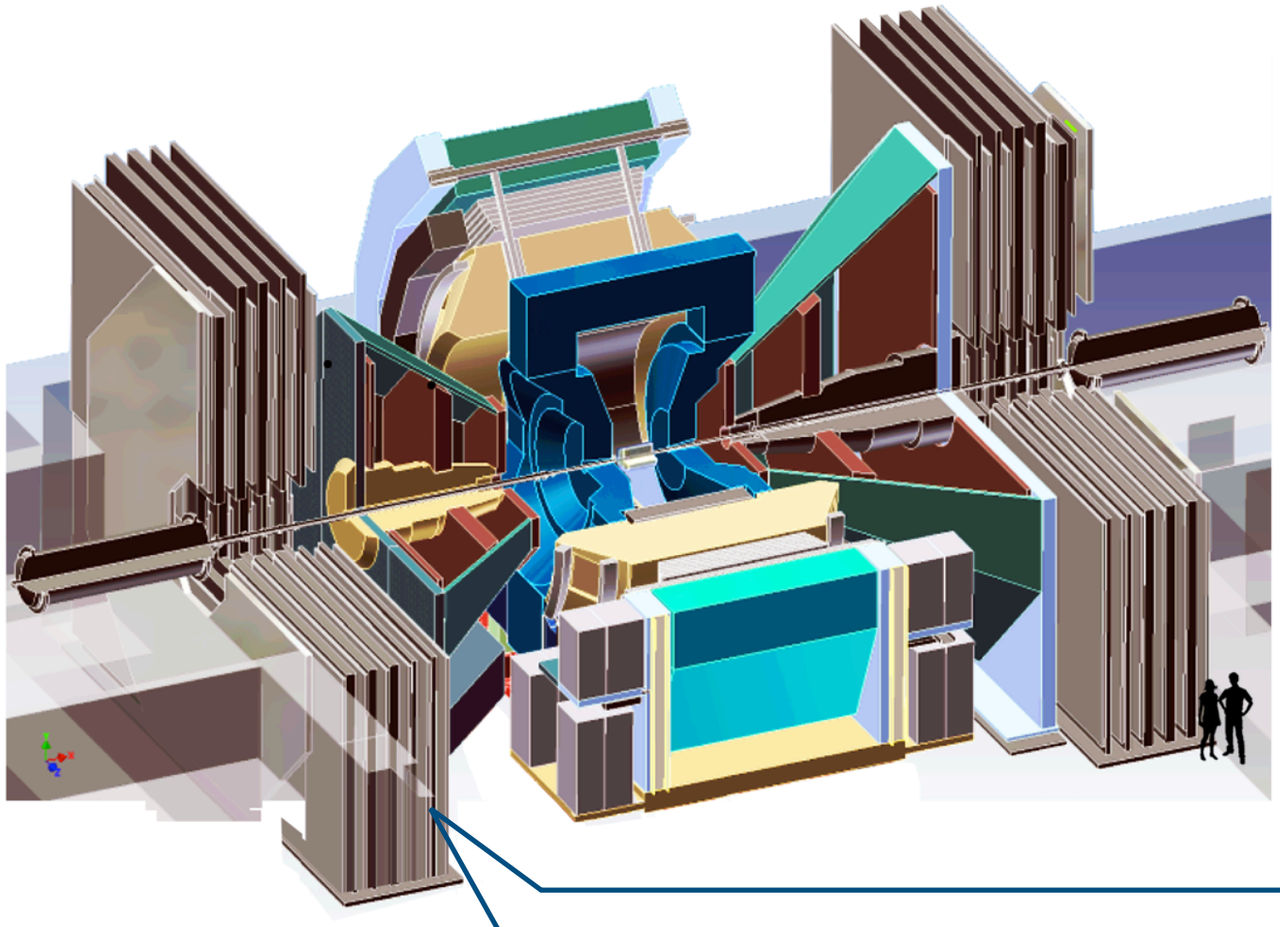


PHENIX mid-rapidity

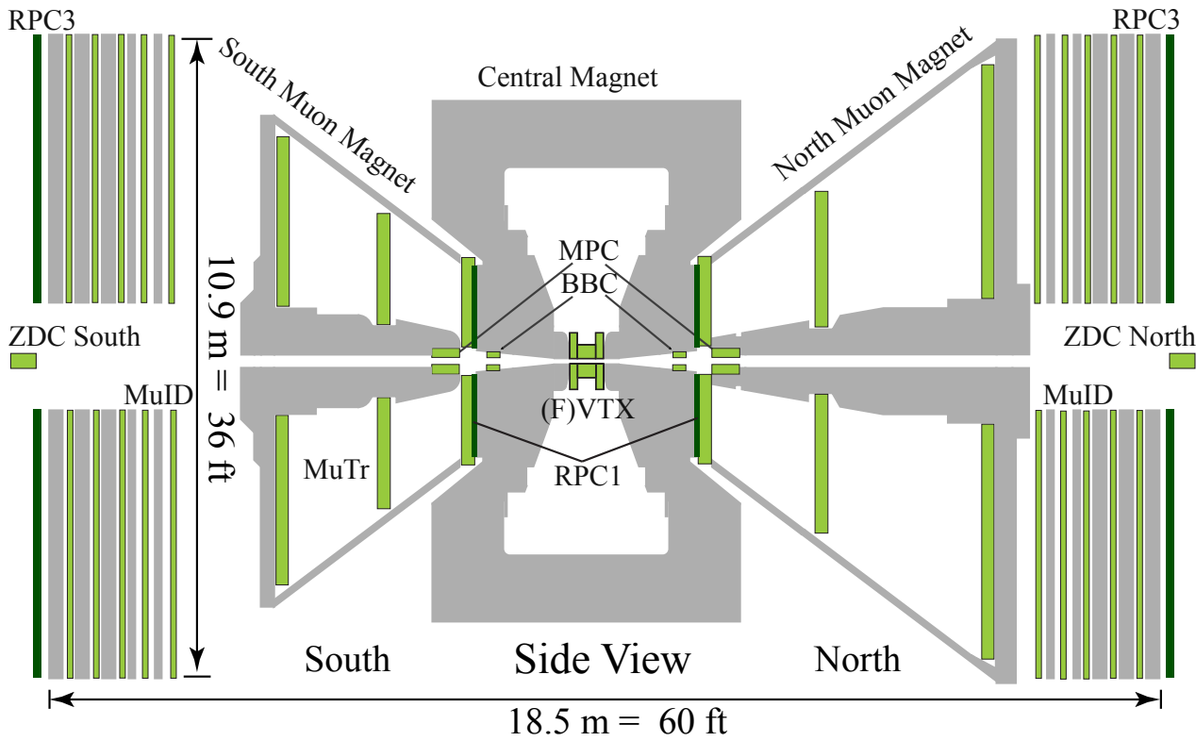


- $W^{\pm} \rightarrow e^{\pm} + \nu_e$ channel
- Two arm detector: $\Delta\phi = (\pi/2)\times 2$, $|\eta| < 0.35$
- High energy electron trigger by Electromagnetic Calorimeter
- Drift chamber (DC) and Pad chamber (PC) for tracking and charge separation

PHENIX Detector

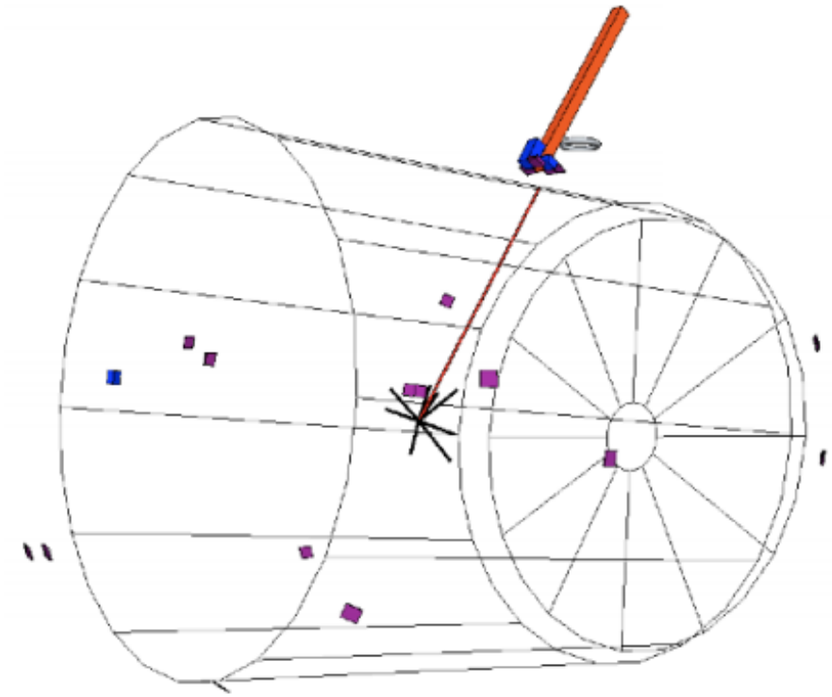


PHENIX forward rapidity

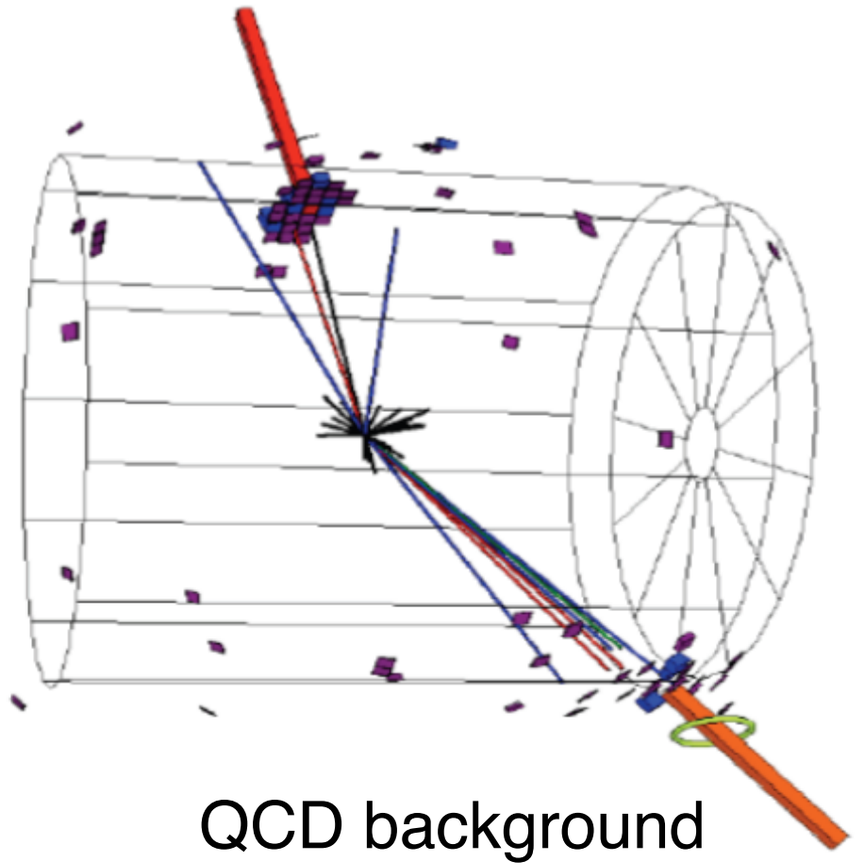


- $W^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$ channel
- Two arm detector: $1.2 < |\eta| < 2.4$, Full azimuthal coverage
- Muon tracking chamber (MuTr)
- Muon Identifier (MuID) for PID
- Upgrade in 2012: high pT trigger, Resistive Plate Chambers (RPC), Forward Silicon Trackers (FVTX)

Measuring W at STAR



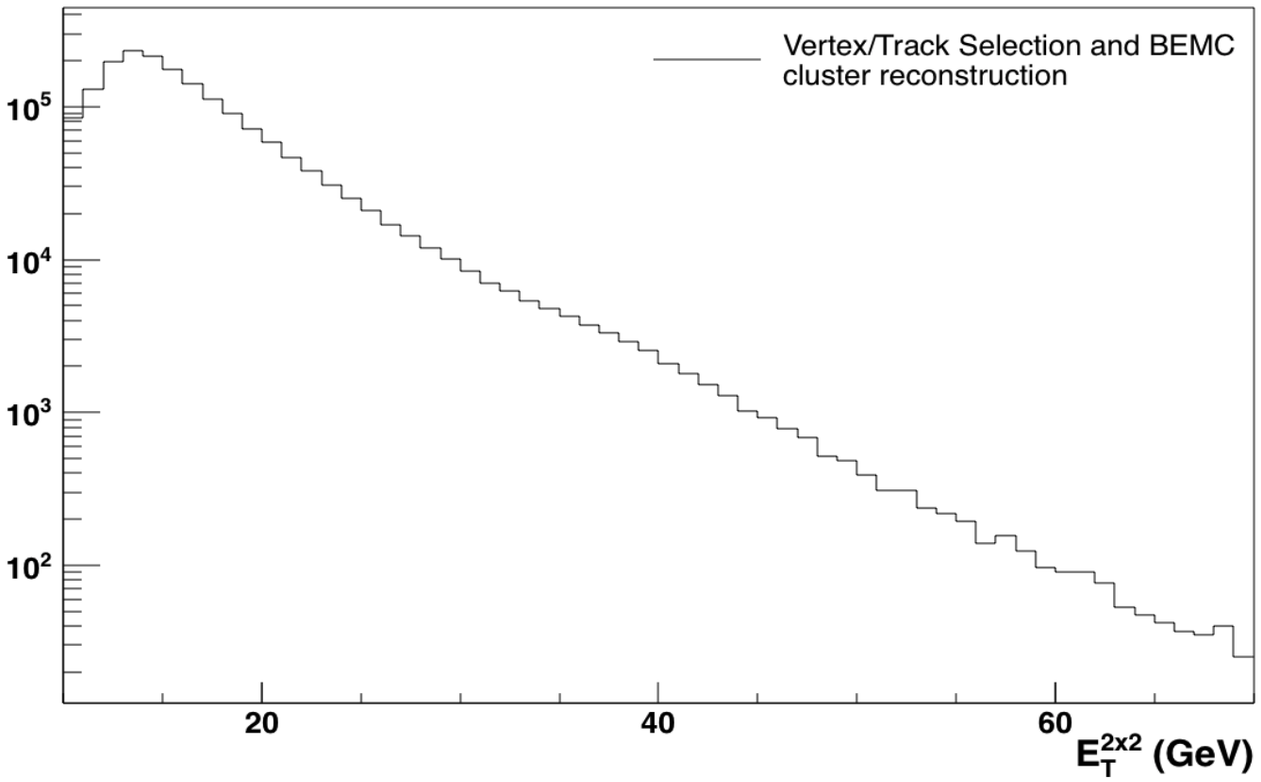
$W \rightarrow e + \nu_e$

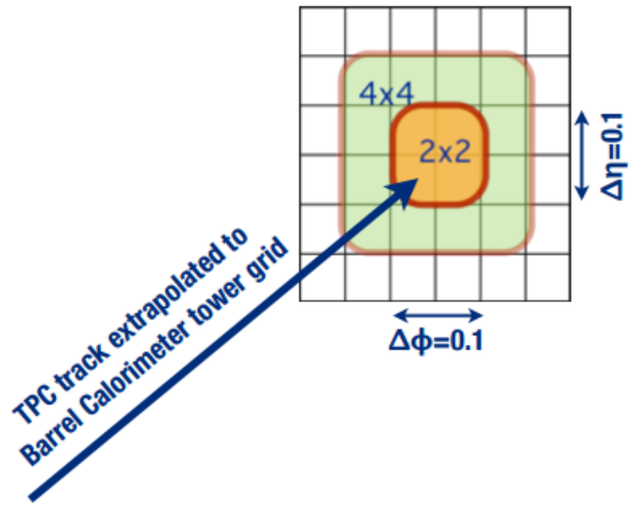


QCD background

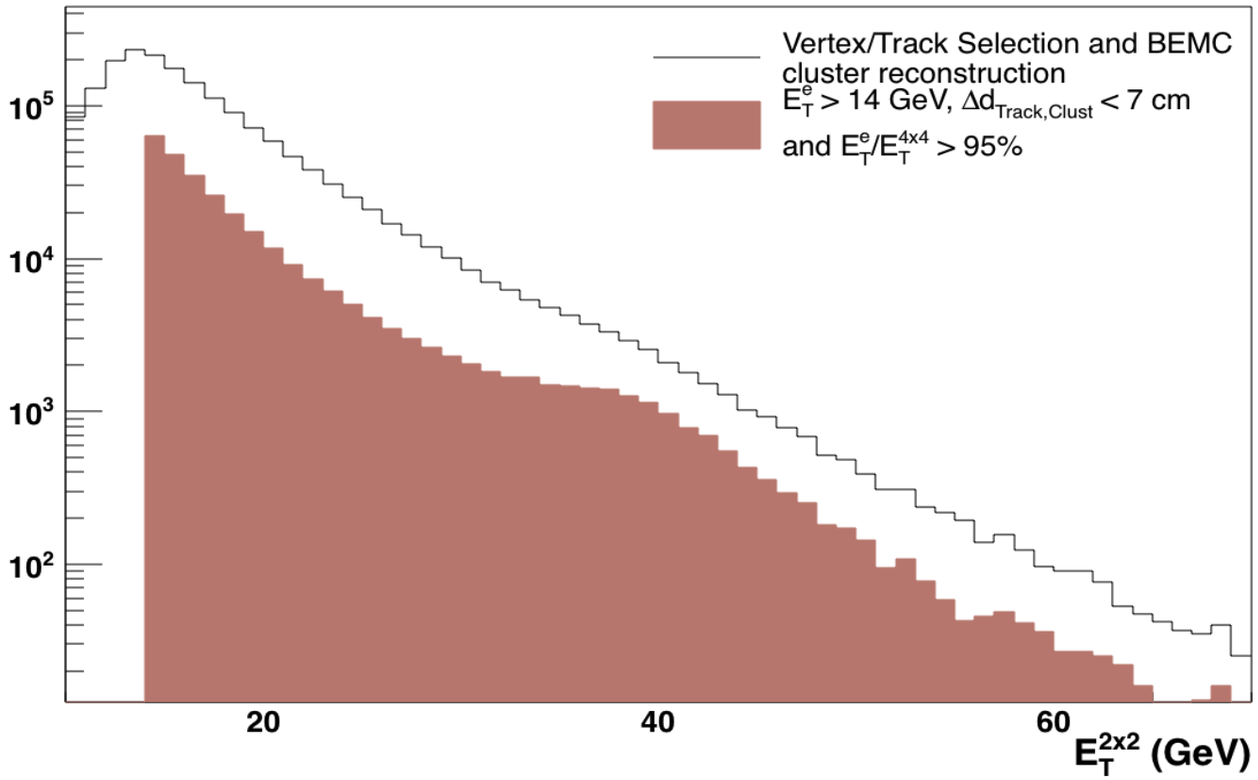
- Isolated $e^+(e^-)$: isolated high momentum track + isolated EM cluster
- Undetected $\nu_e(\bar{\nu}_e)$: large missing energy opposite to $e^+(e^-)$
- Jacobian peak: $e^+(e^-)\ p_T$ peak around $M_W/2$ (~40 GeV)

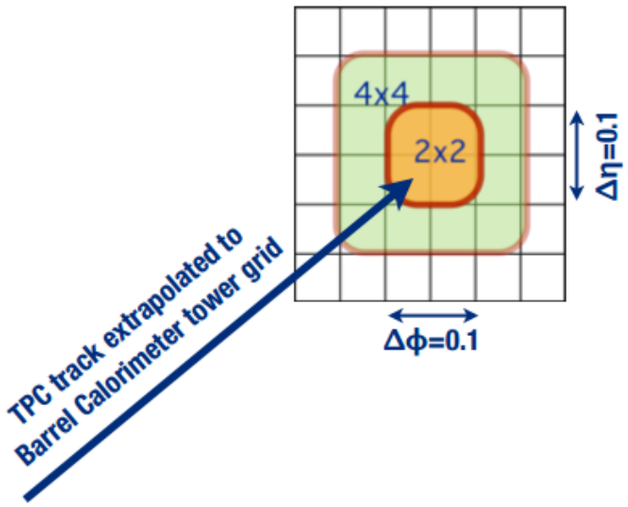
W selection

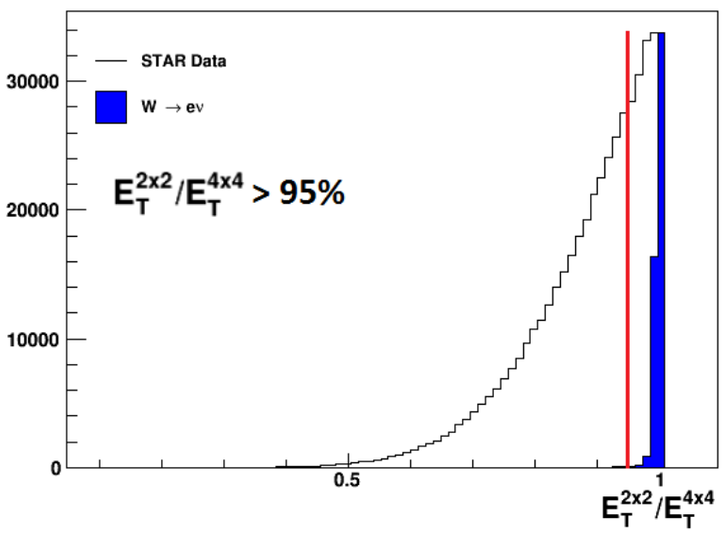

Vertex/Track Selection and BEMC cluster reconstruction
10^5
10^4
10^3
10^2
20
40
60
E_T^{2x2} (GeV)


4x4
2x2
Δη=0.1
Δφ=0.1
TPC track extrapolated to Barrel Calorimeter tower grid

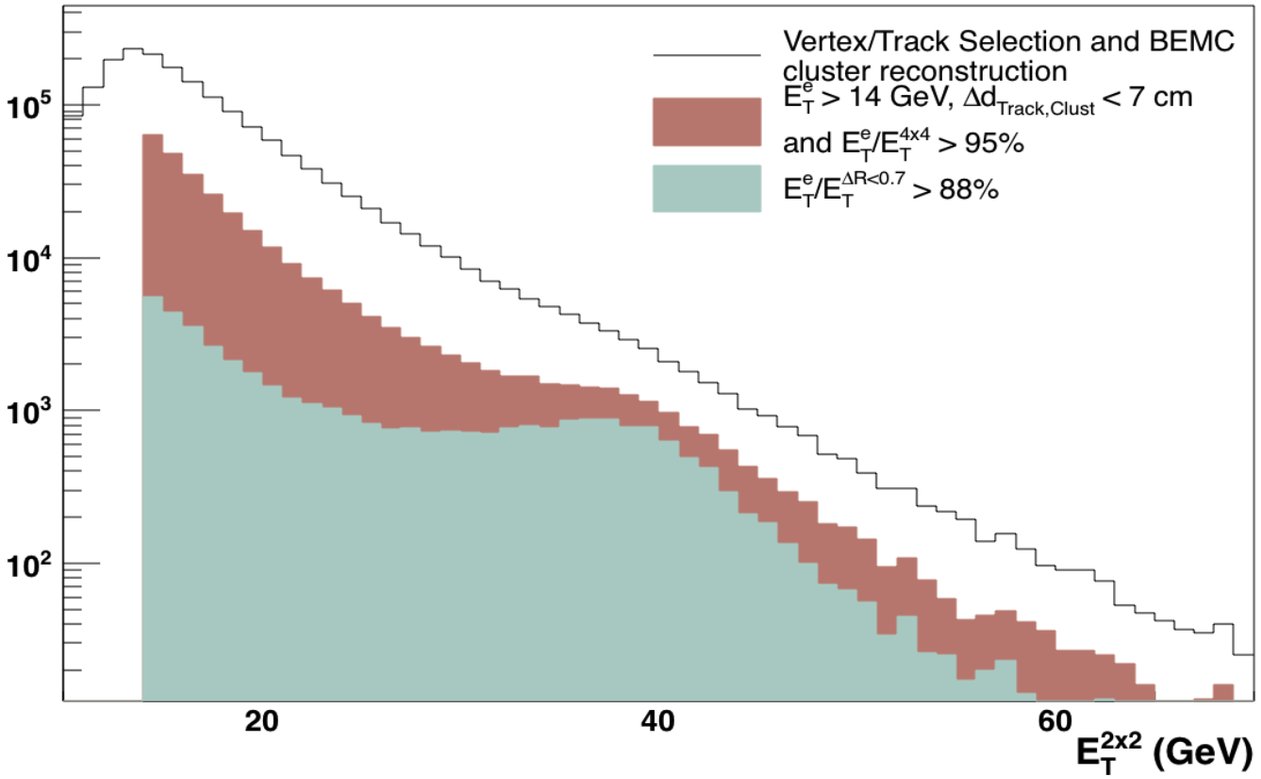
W selection

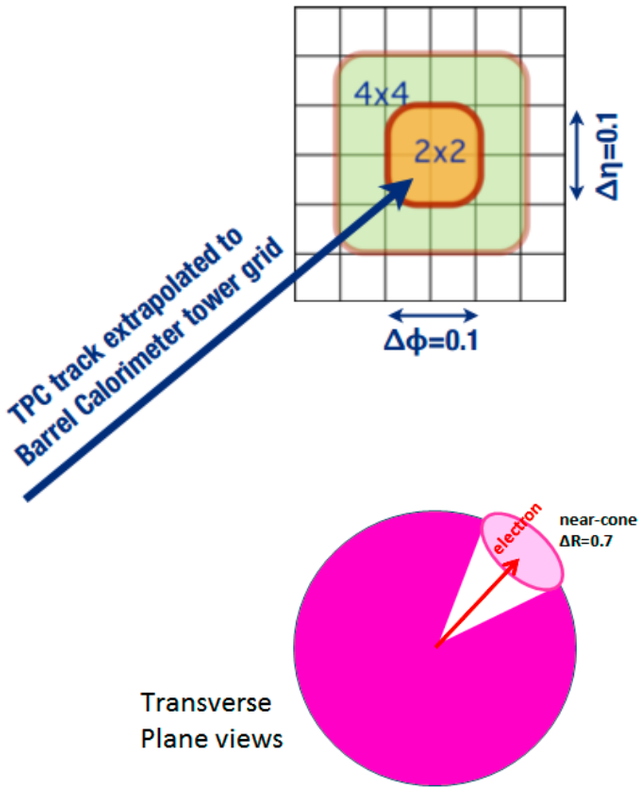

Vertex/Track Selection and BEMC cluster reconstruction
$E_T^e > 14$ GeV, $\Delta d_{Track,Clust} < 7$ cm
and $E_T^e/E_T^{4x4} > 95\%$
10^5
10^4
10^3
10^2
20
40
60
E_T^{2x2} (GeV)

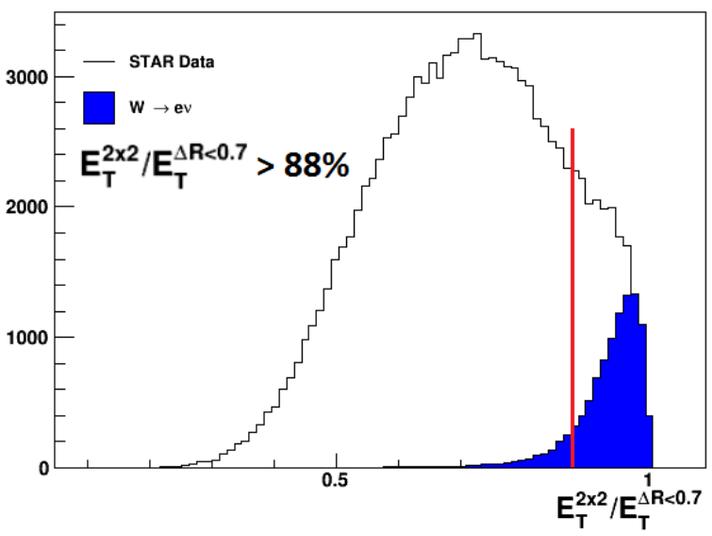

4x4
2x2
Δη=0.1
Δϕ=0.1
TPC track extrapolated to
Barrel Calorimeter tower grid


STAR Data
W → eν
$E_T^{2x2}/E_T^{4x4} > 95\%$
30000
20000
10000
0
0.5
1
E_T^{2x2}/E_T^{4x4}

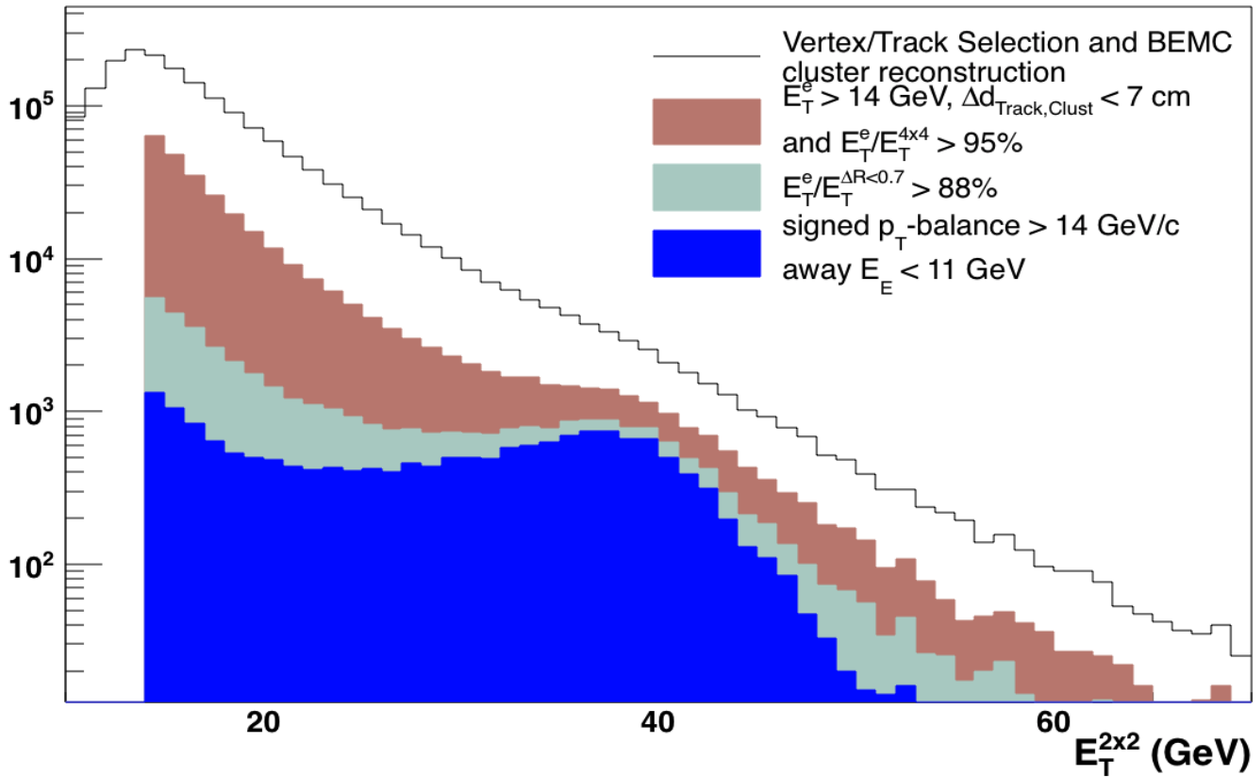
W selection

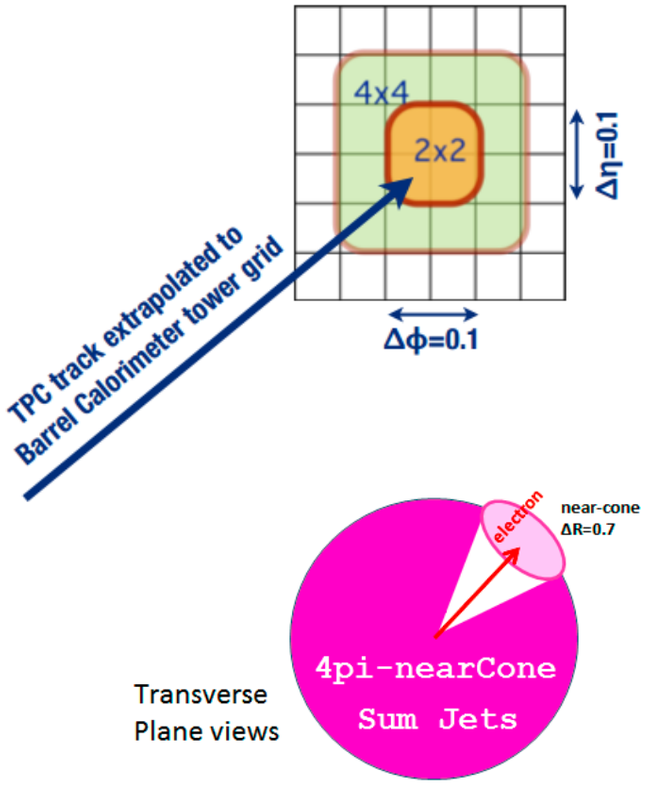

Vertex/Track Selection and BEMC cluster reconstruction
E_T^e > 14 GeV, $\Delta d_{Track,Clust}$ < 7 cm
and E_T^e/E_T^{4x4} > 95%
$E_T^e/E_T^{\Delta R<0.7}$ > 88%
10^5
10^4
10^3
10^2
20
40
60
E_T^{2x2} (GeV)

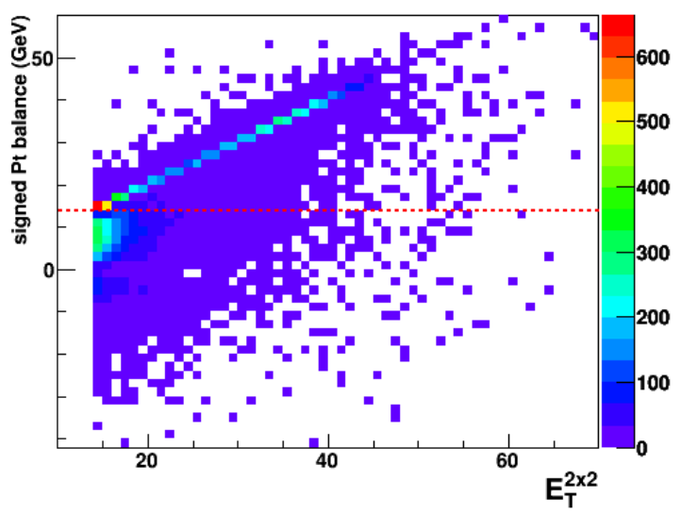

4x4
2x2
Δη=0.1
Δϕ=0.1
TPC track extrapolated to Barrel Calorimeter tower grid
near-cone ΔR=0.7
election
Transverse Plane views

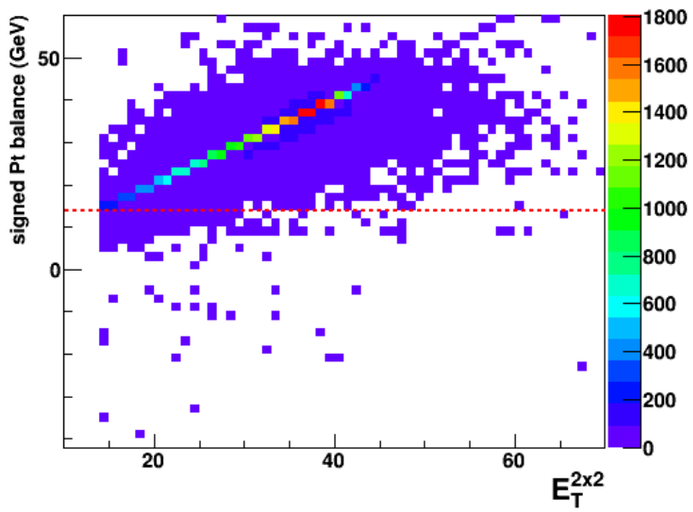

STAR Data
W → eν
$E_T^{2x2}/E_T^{\Delta R<0.7}$ > 88%
3000
2000
1000
0
0.5
1
$E_T^{2x2}/E_T^{\Delta R<0.7}$

W selection







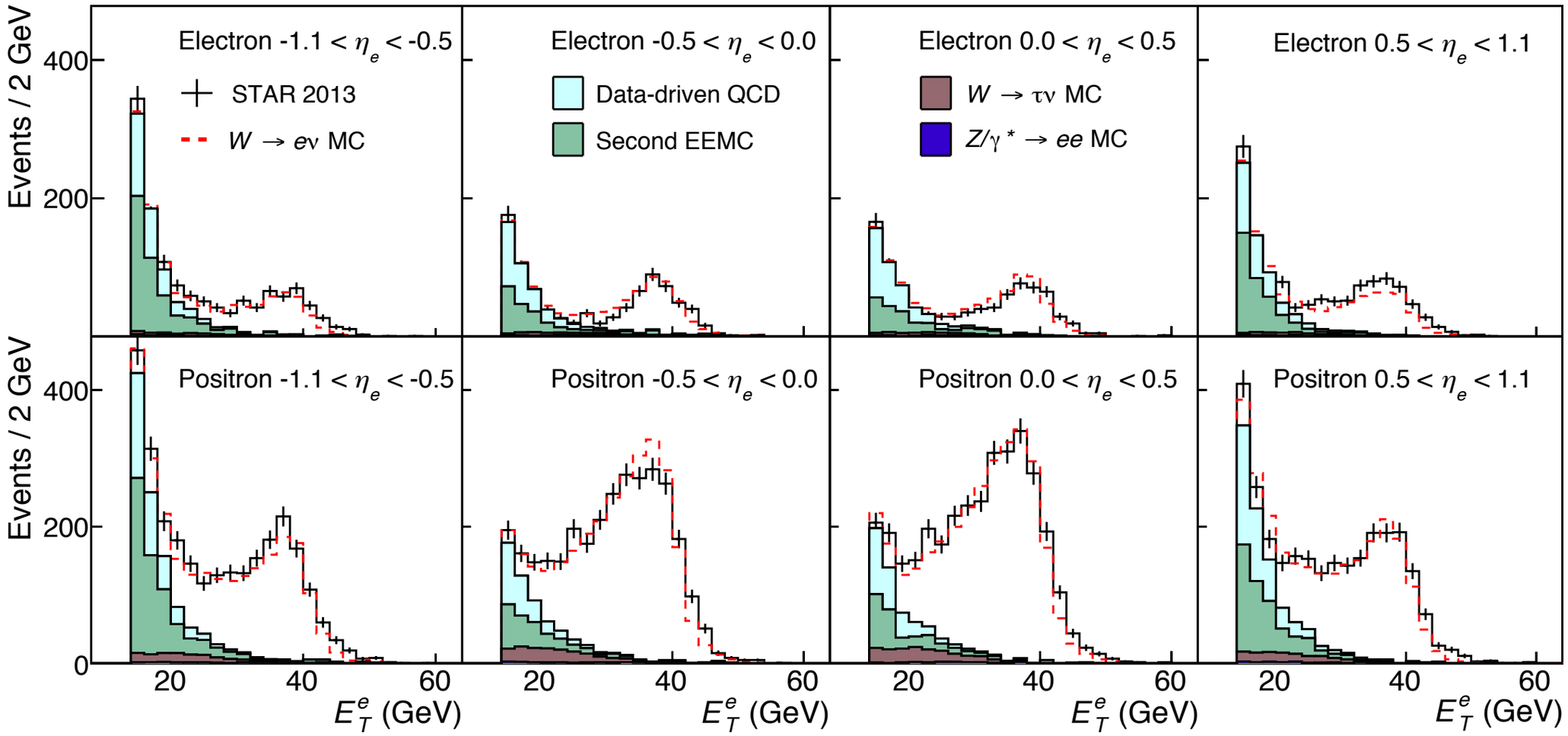


$$\vec{p}_T^{\,bal} = \vec{p}_T^{\,e} + \Sigma_{\Delta R<0.7}\, \vec{p}_T^{\,jets}$$

Signed-p_T balance $=$

$$\frac{\vec{p}_T^{\,e} \cdot \vec{p}_T^{\,jets}}{|\vec{p}_T^{\,e}|}$$

Background Analysis

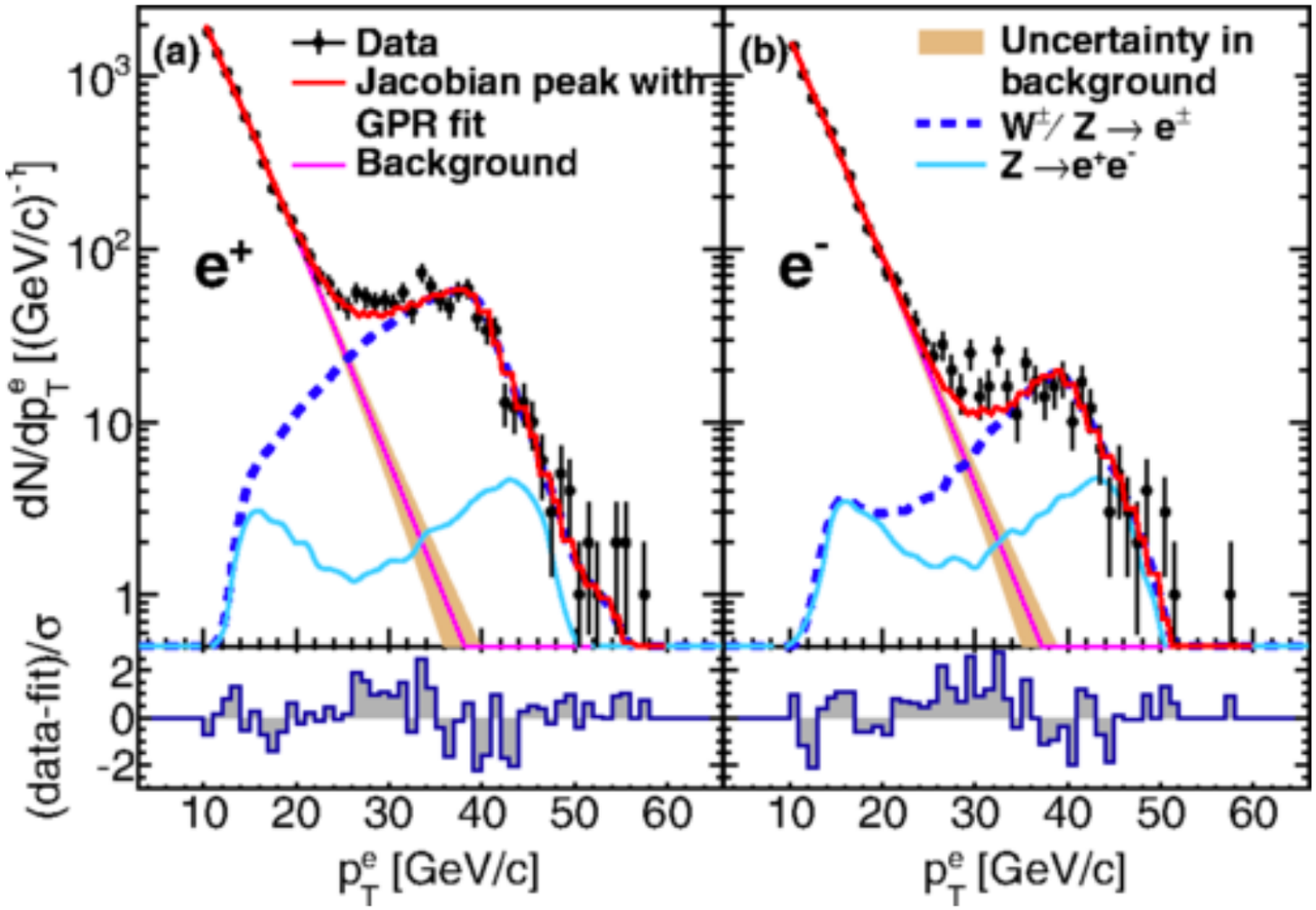


Residual background:

- W decay tau and then to electron/positron
- Z to electron-positron pair but one of them undetected
- QCD background

Mid-rapidity measurement at PHENIX

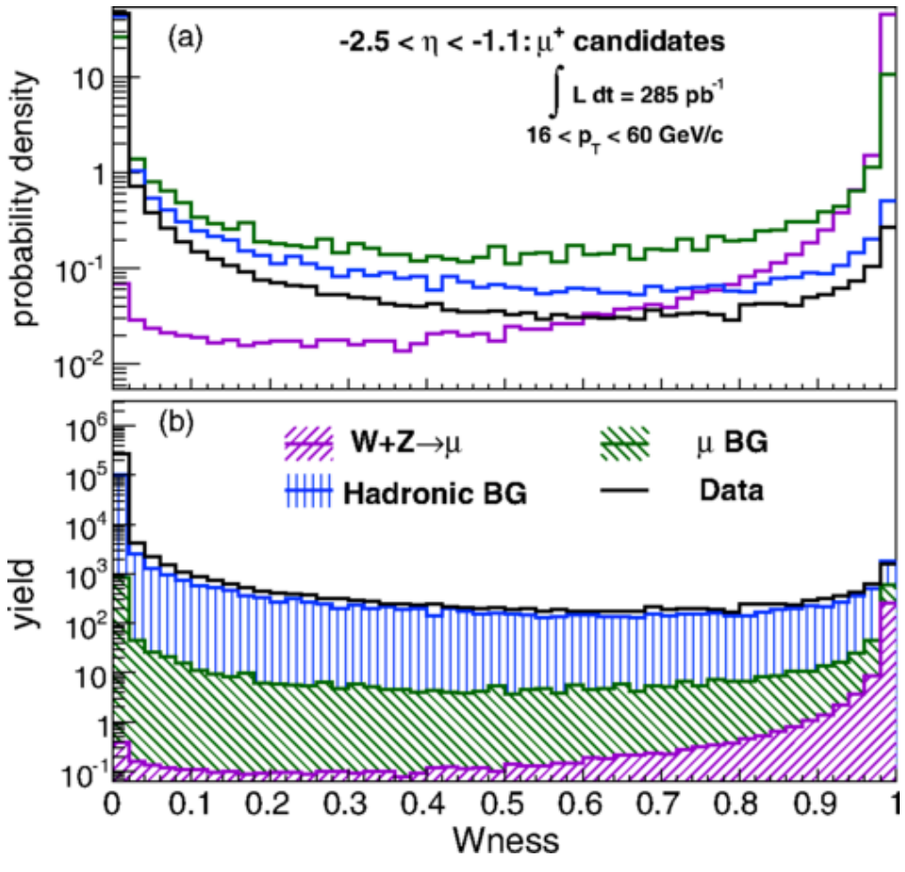
Phys. Rev. D 93, 051103(R) (2016)

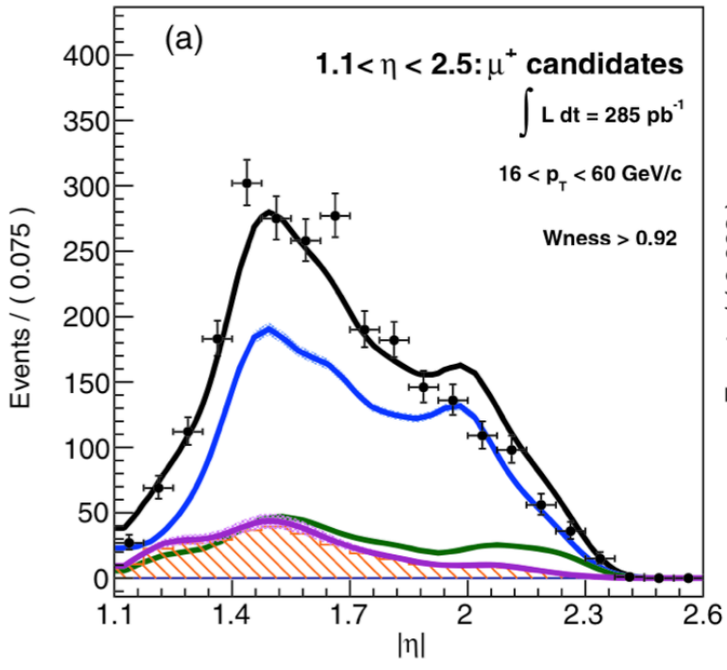


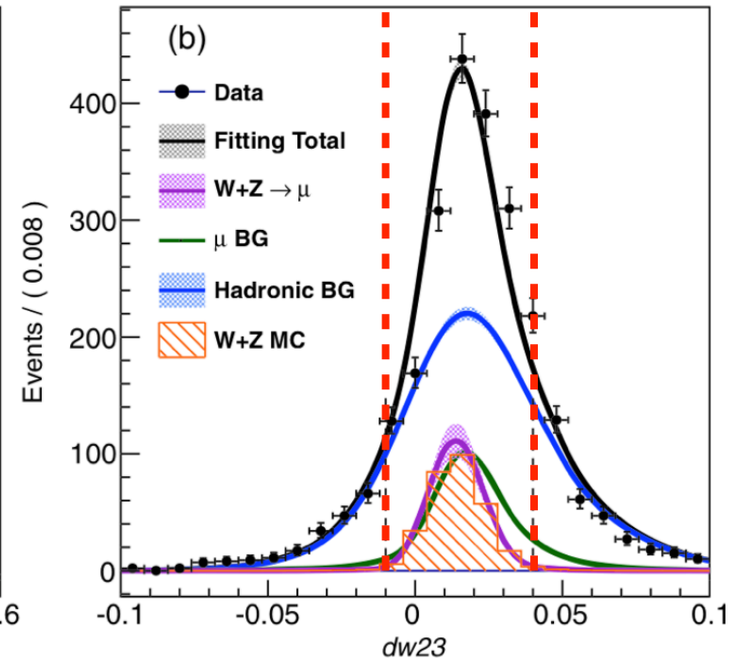
- Clear electron signal via Jacobian peak
- 97% (94%) of signal remains for e^+ (e^-) in the signal region (30-50 GeV/c)

Forward measurement at PHENIX

- Suppressed/no Jacobian peak
- Large hadron BG (low pT charged kaons, pions) -> fake high pT muons
- Multivariate analysis (5-9 signal/BG sensitive variables) to reduce BG





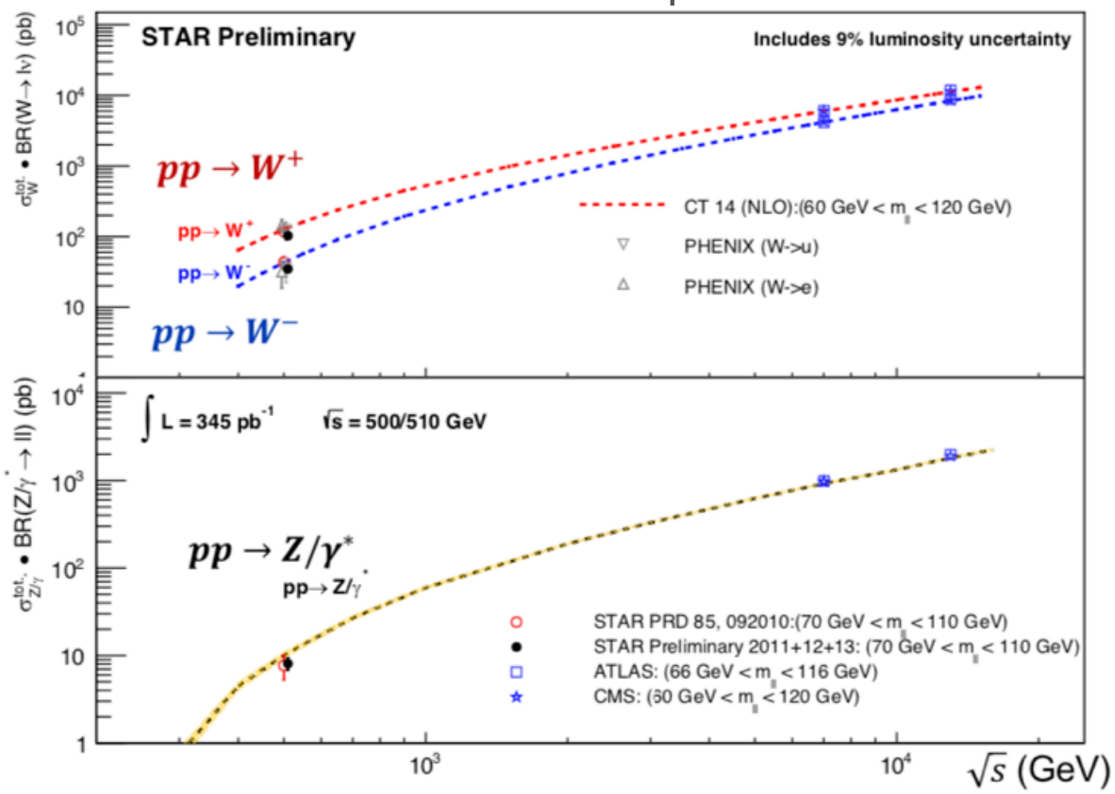


$$W_{ness} \equiv \frac{\lambda_{sig}(x)}{\lambda_{sig}(x) + \lambda_{BG}(x)} \begin{cases} W_{ness} \to 1 & \text{Signal-like event} \\ W_{ness} \to 0 & \text{BG-like event} \end{cases}$$

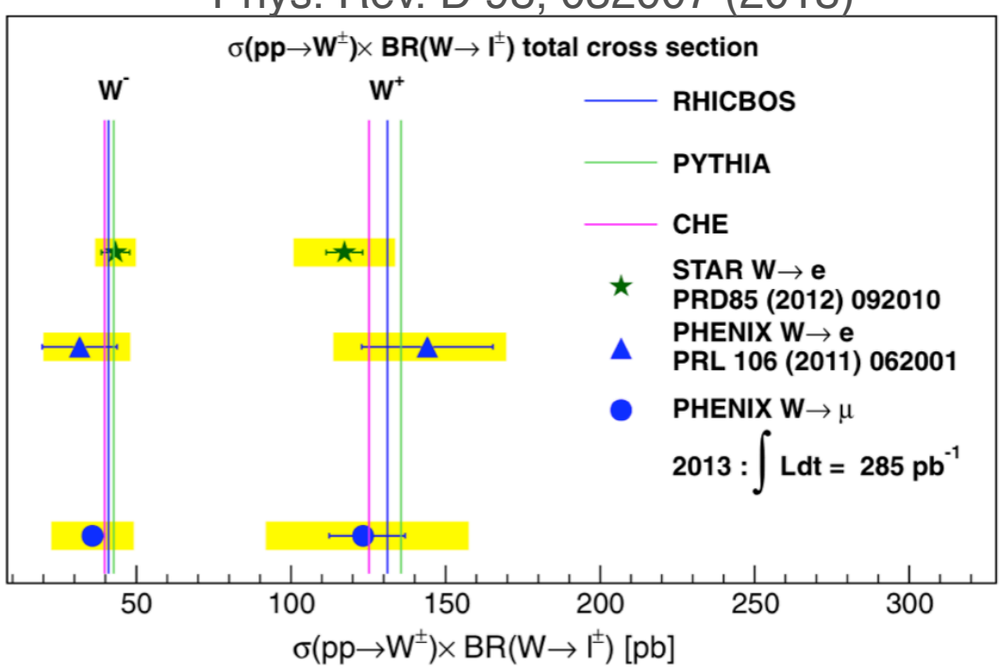
- 2D unbind maximum likelihood fit to estimate signal-to-background ratio
- Further restricting the azimuthal bend-plane variable (*dw23*) and pseudo-rapidity: 15-28% signal-to-background ratios

W/Z Total Cross Section

See Matt Posik's poster



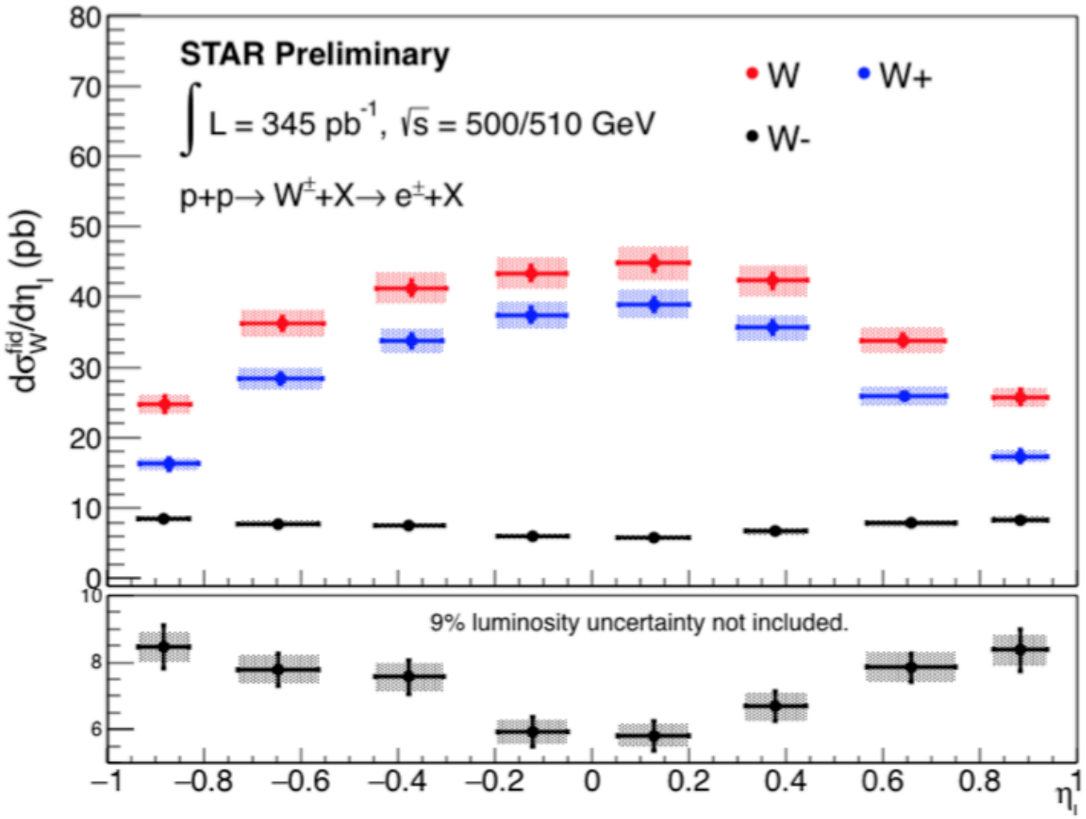
Phys. Rev. D 98, 032007 (2018)

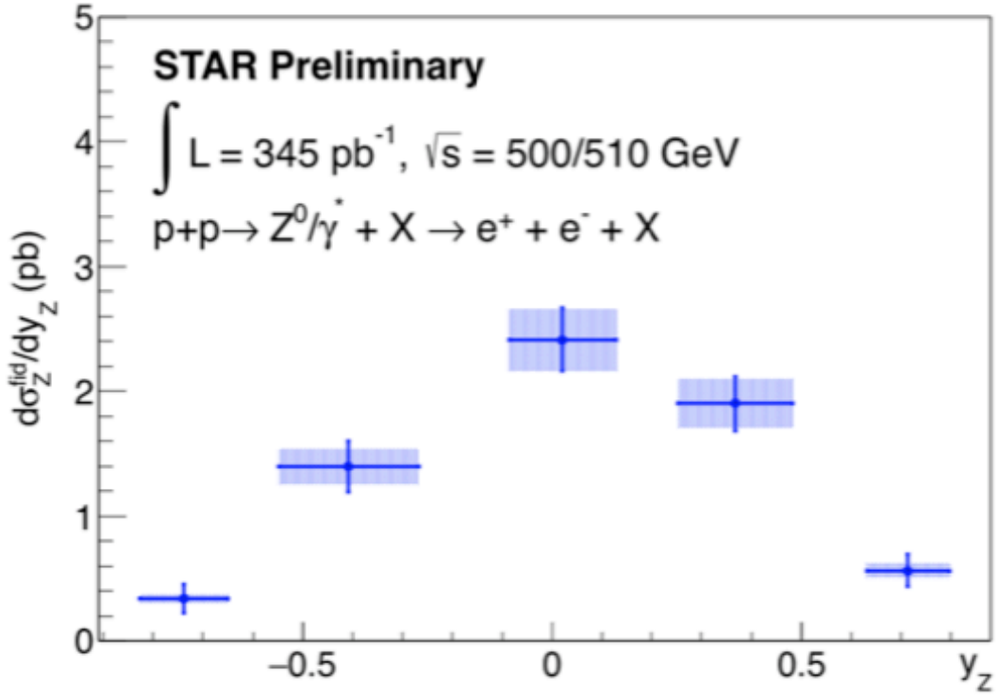


- STAR: electron channel for W and Z
- PHENIX: electron channel and **muon** channel for W
- Consistent with theoretical predictions and world data.
- Support the pQCD interpretations for asymmetry measurements.

W/Z Differential Cross Section

See Matt Posik's Poster

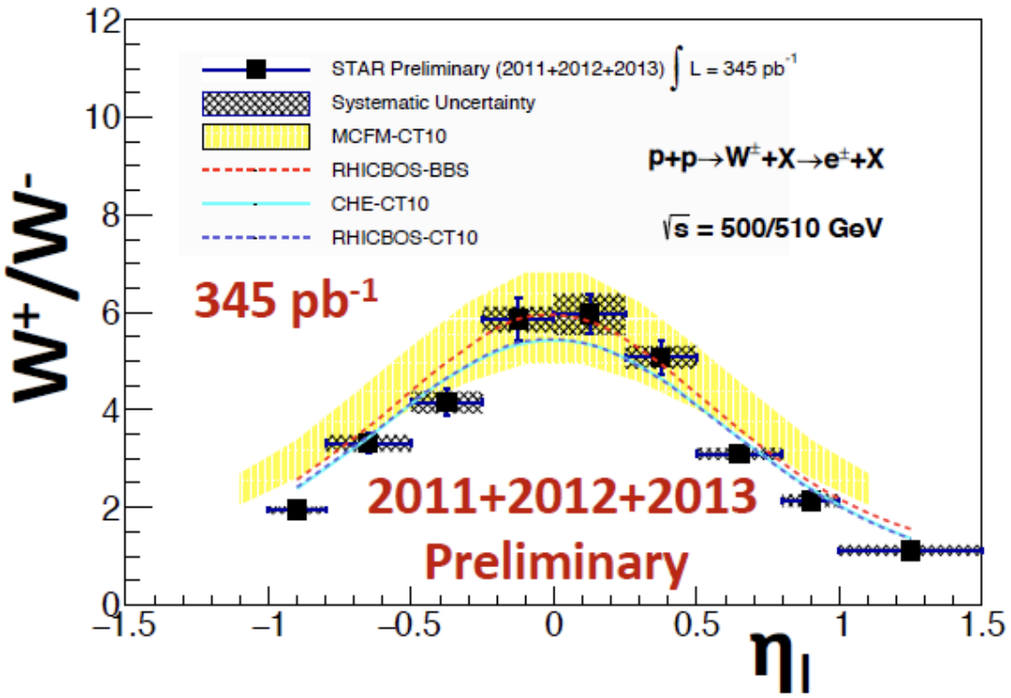


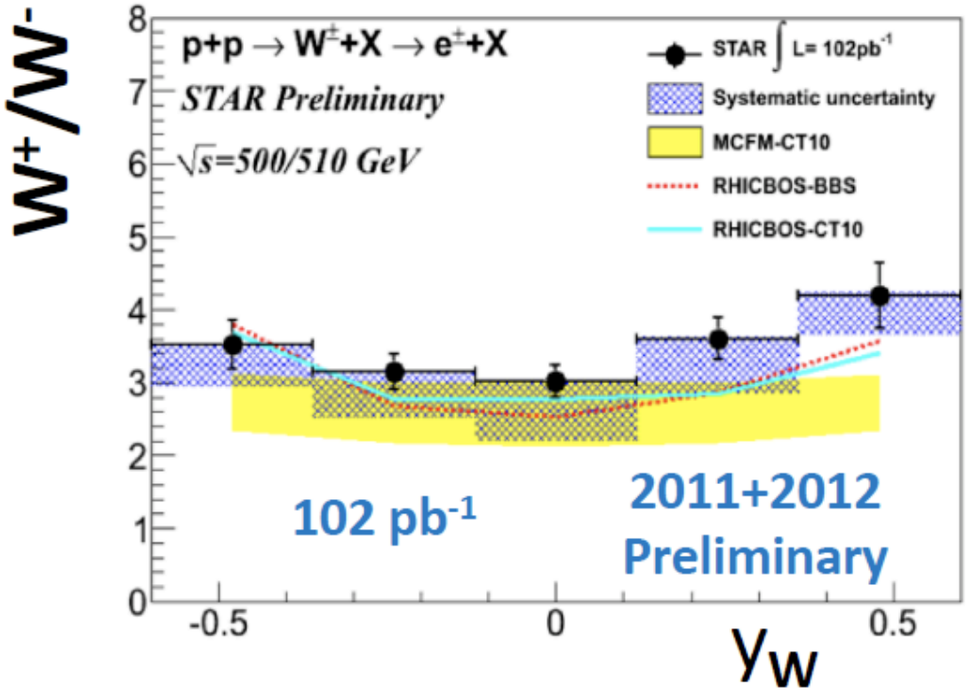


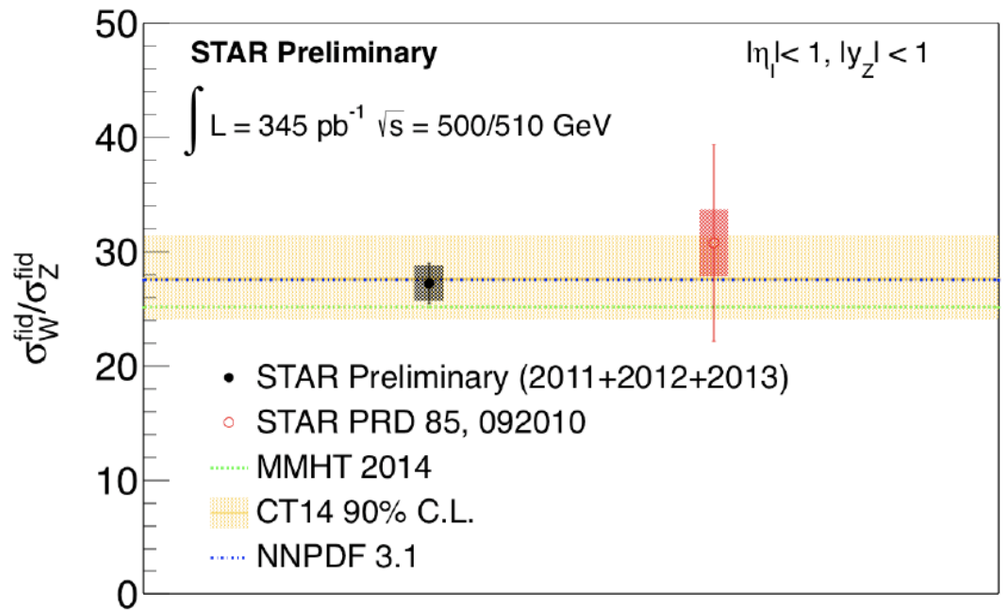
- Differential cross section can also provide constraints on the unpolarized quark/anti-quark distributions.
- Preliminary results from 2011+2012+2013 released on DIS2019 by Matt Posik.

W/Z Cross Section Ratio

See Matt Posik's Poster



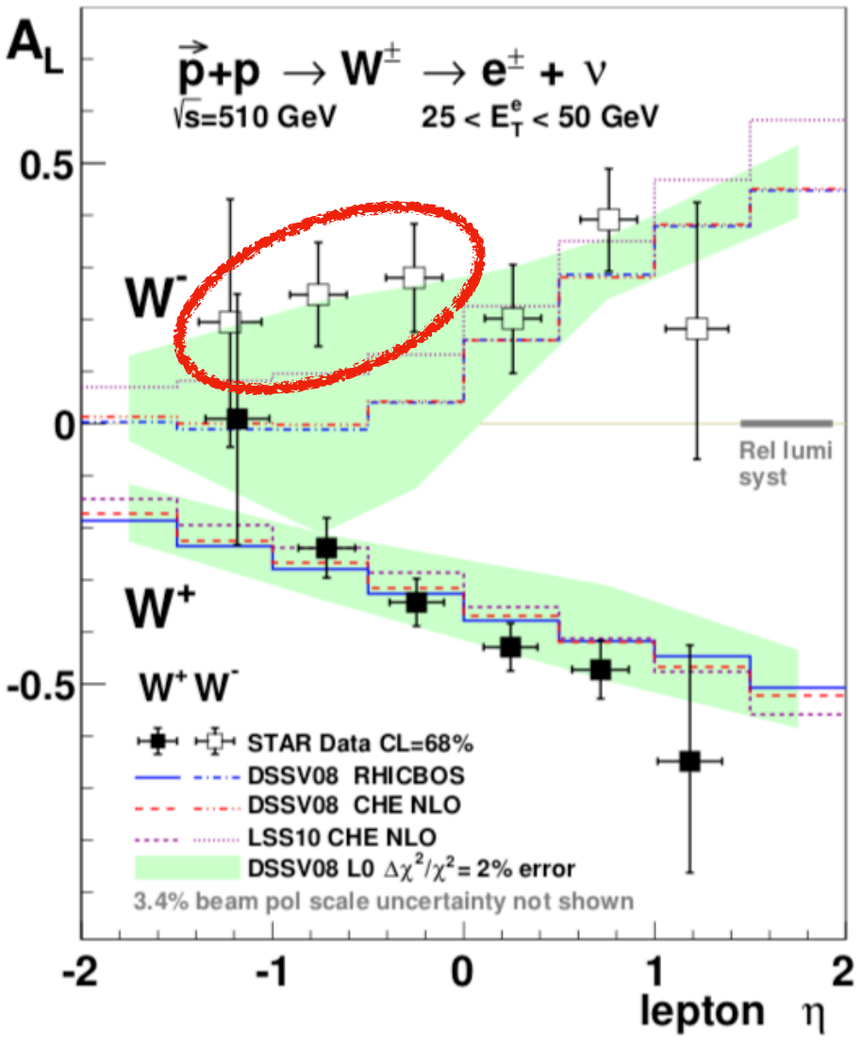




- Complementary measurement to SeaQuest and E-866, for ~0.06 < x < ~0.4 , constraining unpolarized sea quark distributions.
- W kinematics determined from data and simulation; Cornerstone for W A_N measurement

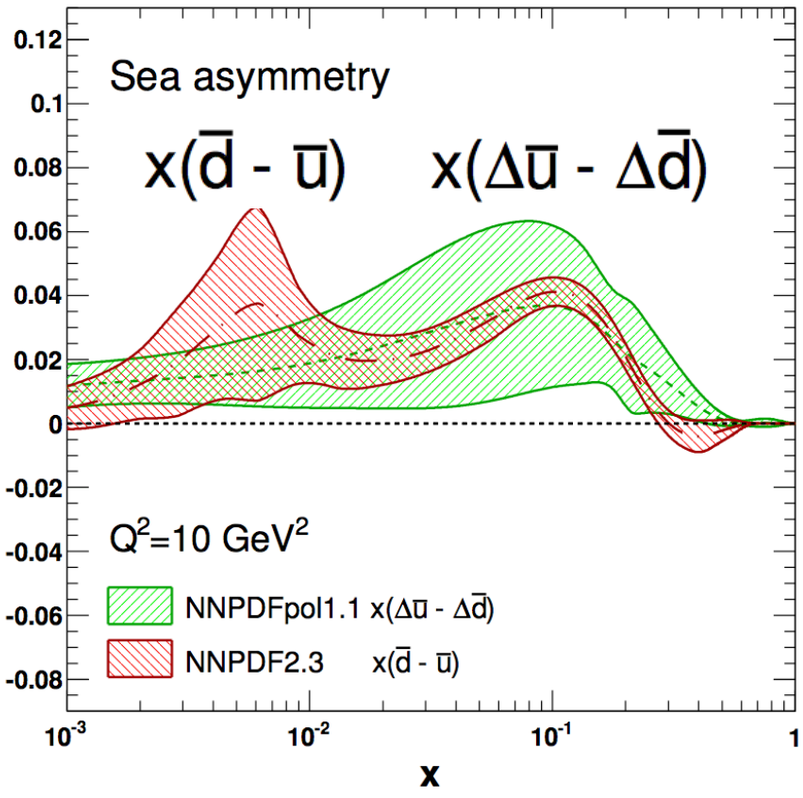
Earlier STAR W A_L results

- First W A_L from the initial 500 GeV run in 2009
- First eta-dependent results from 2011+2012 data



STAR, PRL 113, 072301 (2014)

E. Nocera, PoS(DIS2014)204

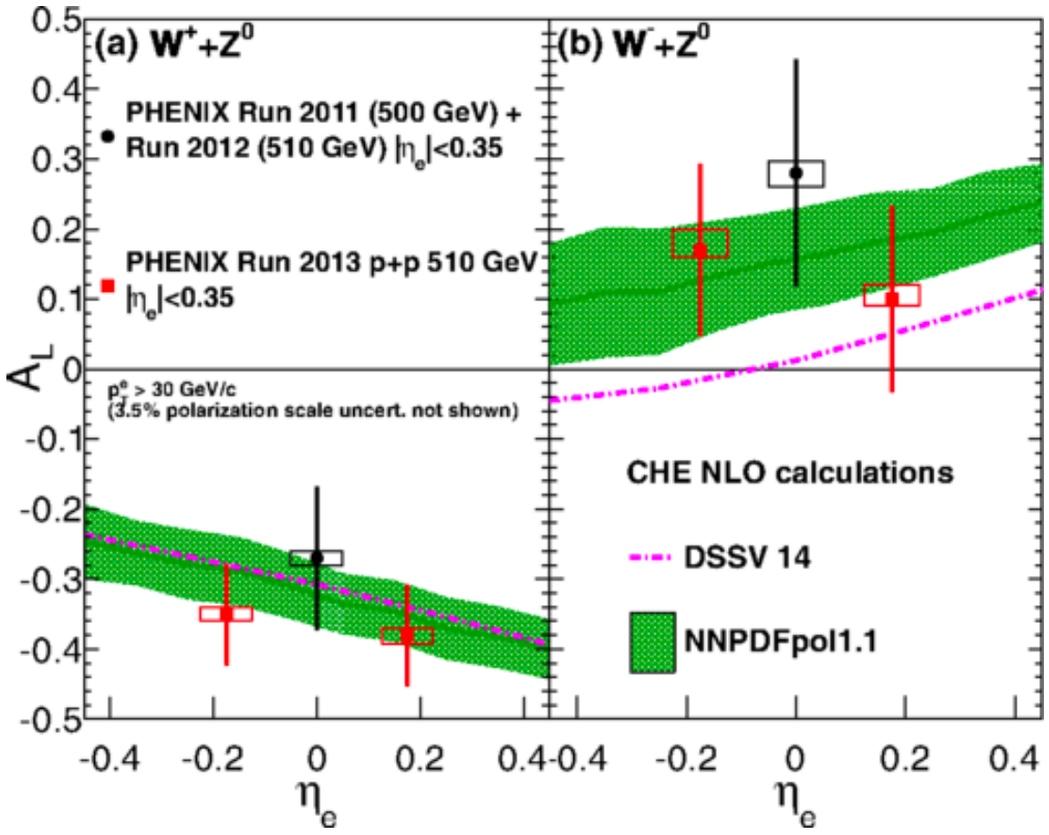


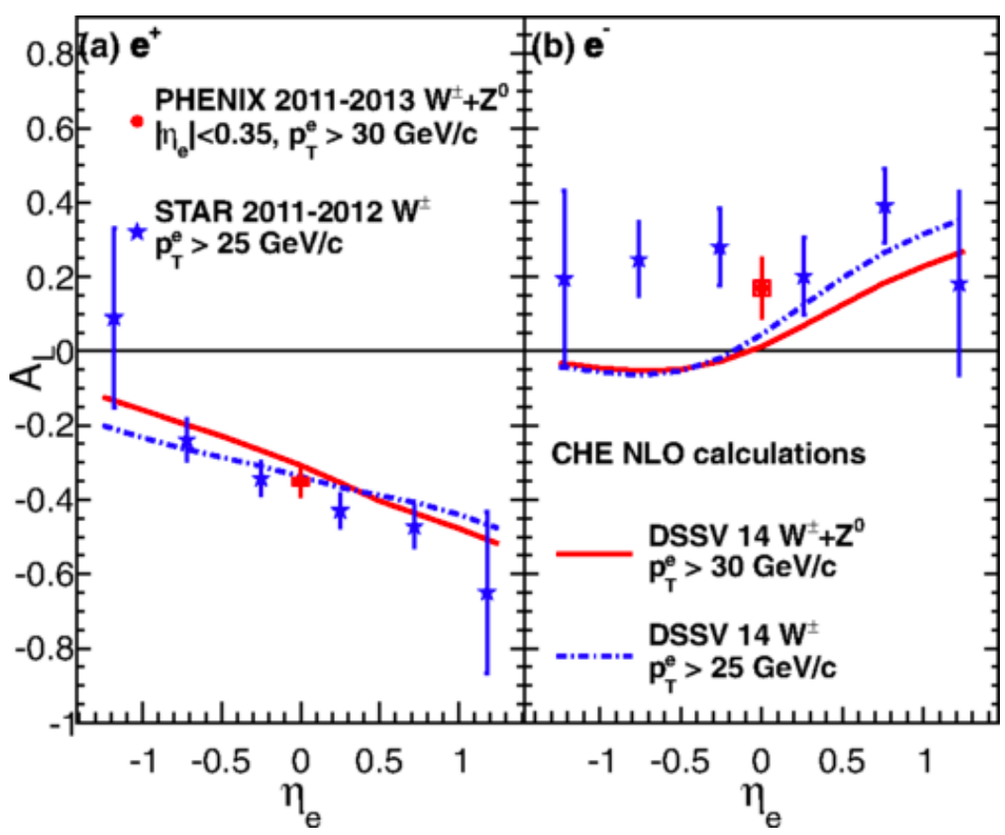
$\Delta\bar{u} > \Delta\bar{d}$? Opposite to unpolarized sea.

Motivation for more precise data.

PHENIX mid-rapidity A_L results

Phys. Rev. D 93, 051103(R) (2016)

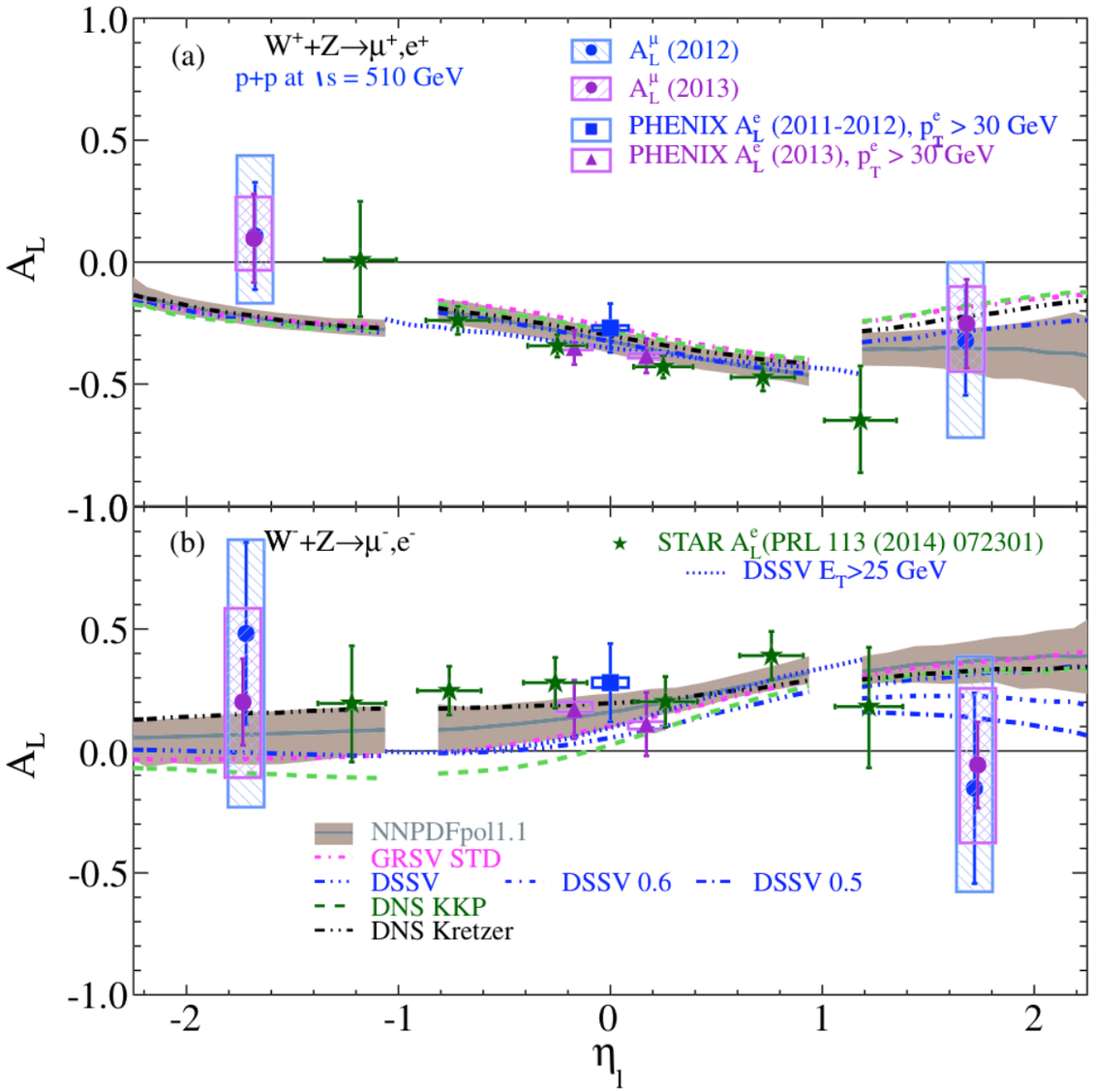




- A_L for W + Z
- Data above global fit (DSSV14) for e^-
- Consistent with the STAR 2011+2012 data

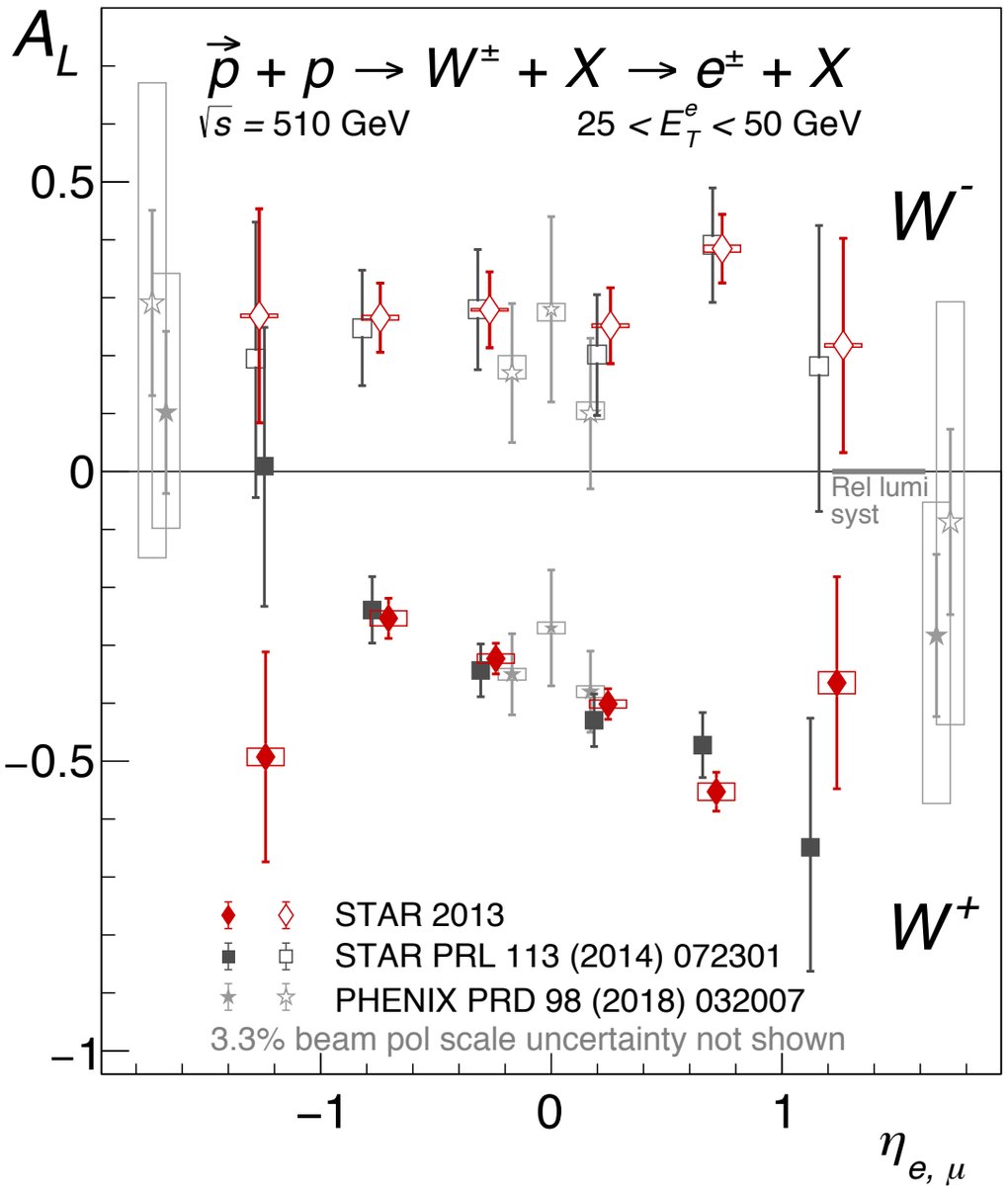
PHENIX forward AL results

Phys. Rev. D 98, 032007 (2018)



- First muon channel W/Z AL results.
- Consistent with theoretical predictions.

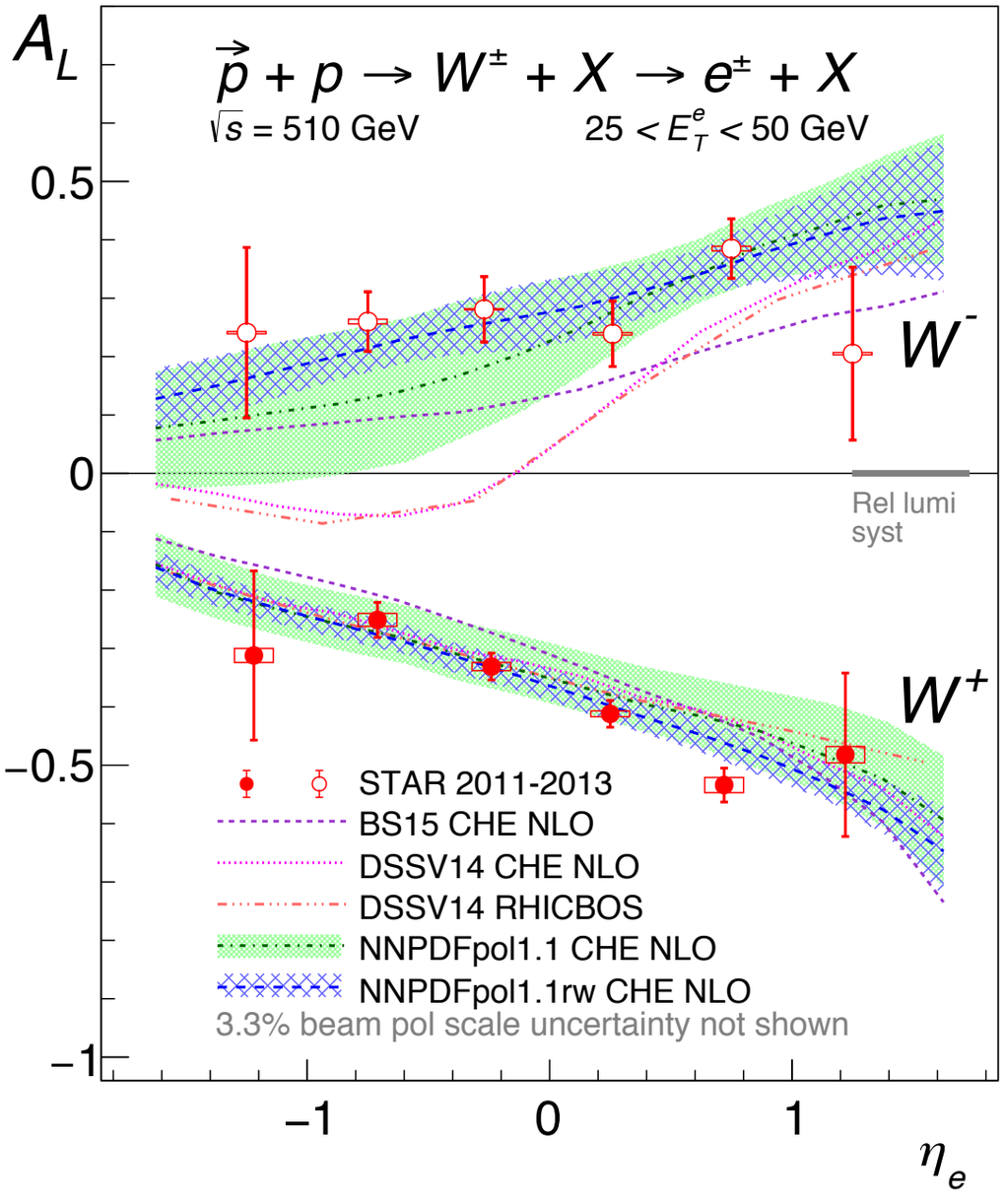
STAR 2013 results



PRD 99, 051102(R) (2019)

- Most precise W AL results from 2013 dataset
- Consistent with published RHIC results; with 40-50% smaller uncertainties than STAR 2011+2012
- Confirmed the larger than initially expected anti-up quark polarization first seen in the 2011+2012 data.

STAR 2013 results

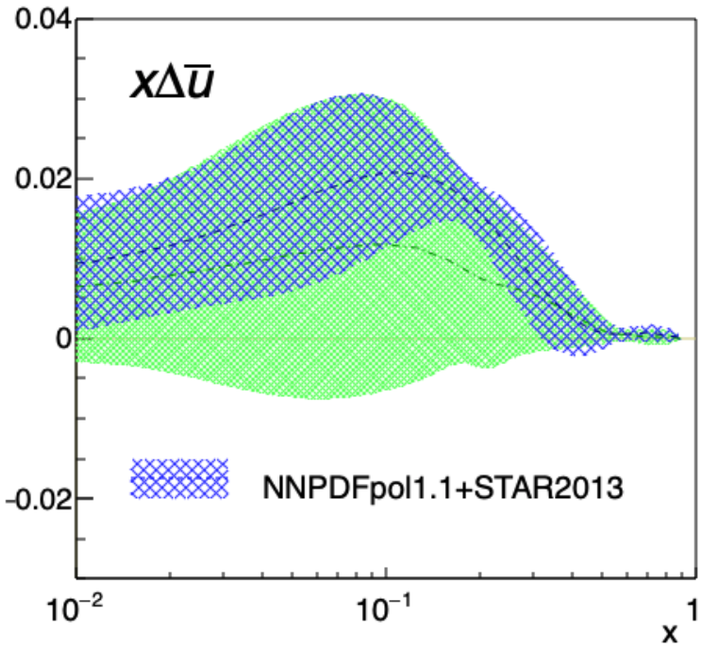


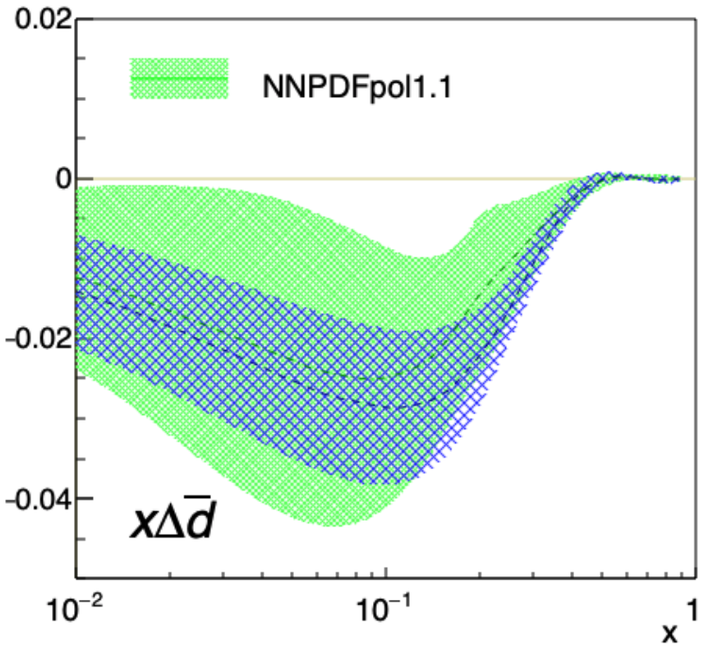
PRD 99, 051102(R) (2019)

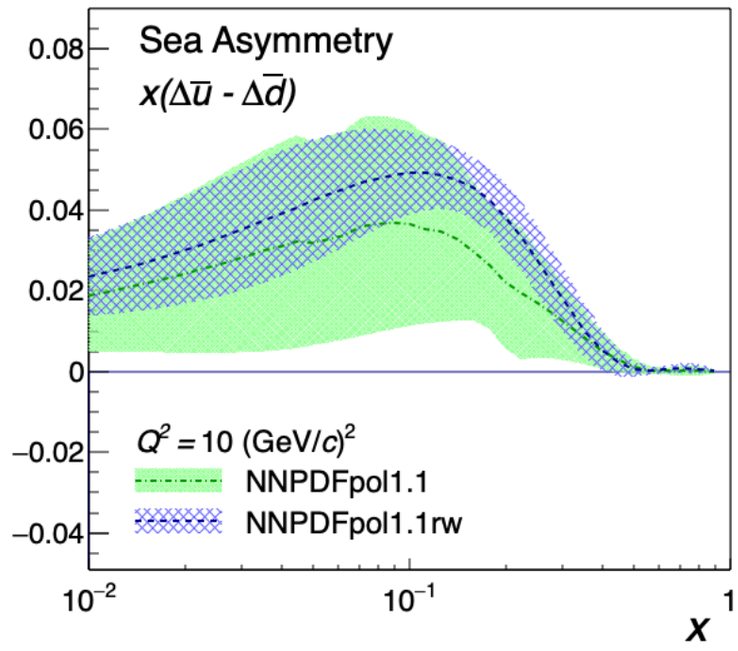
- Most precise W AL results from 2013 dataset
- Consistent with published RHIC results; with 40-50% smaller uncertainties than STAR 2011+2012
- Confirmed the larger than initially expected anti-up quark polarization first see in the 2011+2012 data.
- Combined results in comparison with theoretical predications

Impact of STAR 2013 results

PRD 99, 051102(R) (2019)



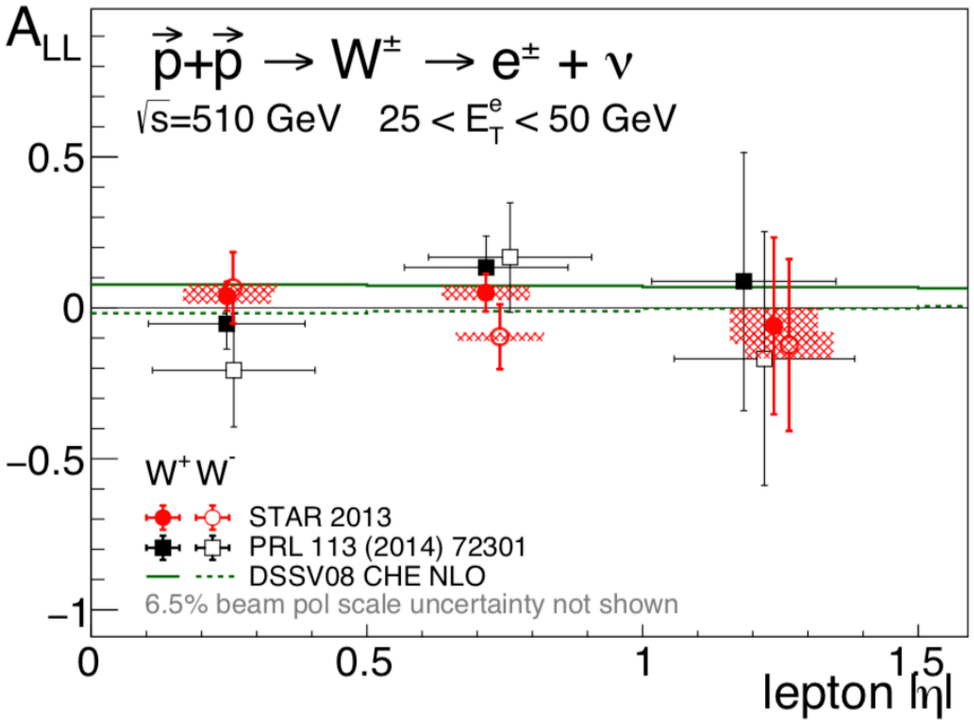




- Delta u-bar is now known to be positive
- Delta d-bar is now known to be negative
- The flavor asymmetry $\Delta\bar{u} - \Delta\bar{d}$ similar size but opposite sign to the unpolarized flavor asymmetry $\bar{u} - \bar{d}$

Double-spin Asymmetry

- Besides the single-spin asymmetries A_L, we have measured also the double-spin asymmetries A_{LL}.



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

PRD 99, 051102(R) (2019)

- Can also provide access to u-bar, d-bar polarization.

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

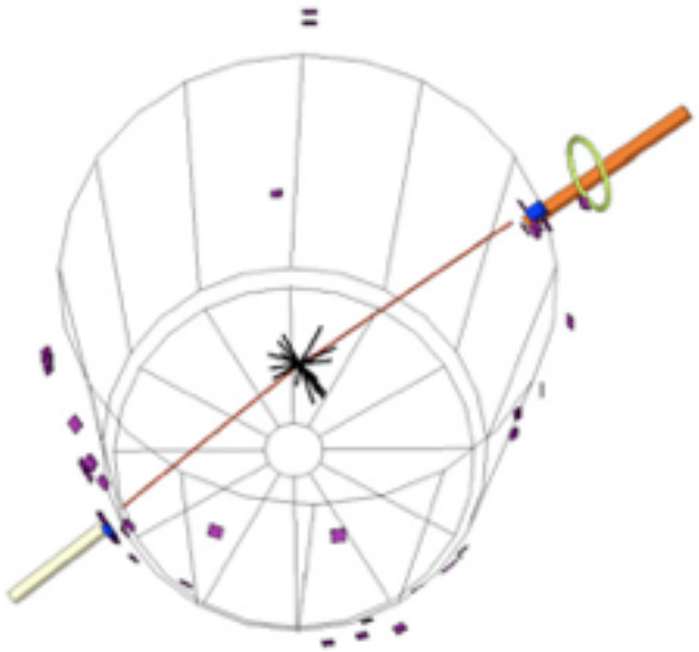
- Positivity constraints using combination of A_L and A_{LL}

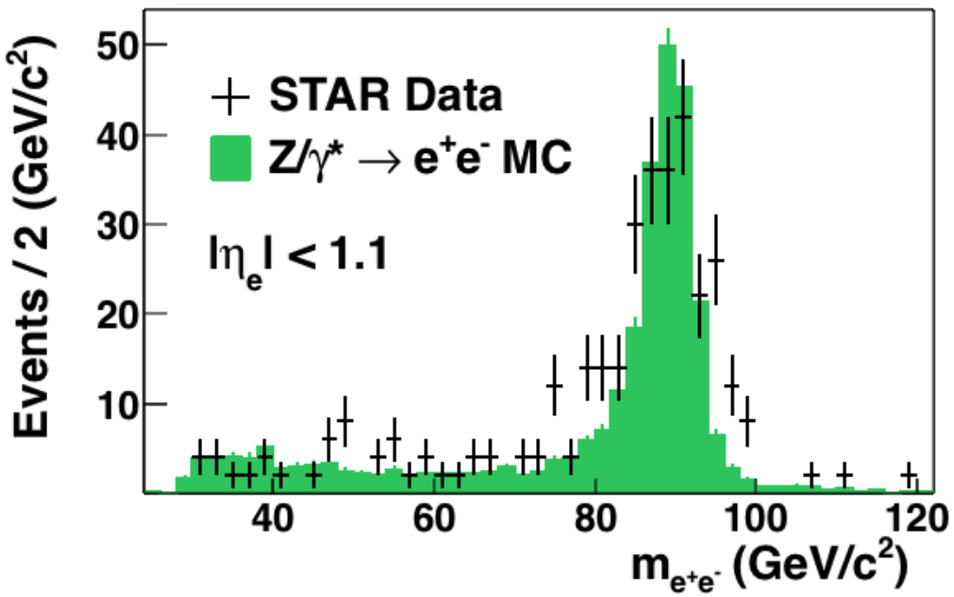
$$1 \pm A_{LL}^{W^\pm}(y_W) > |A_L^{W^\pm}(y_W) \pm A_{LL}^{W^\pm}(-y_W)|$$

Z.Kang, J.Soffer, Phys.Rev.D83,114020 (2011)

Clearly, they are less sensitive/constraining than the single-spin asymmetries.

Z/gamma* A_L

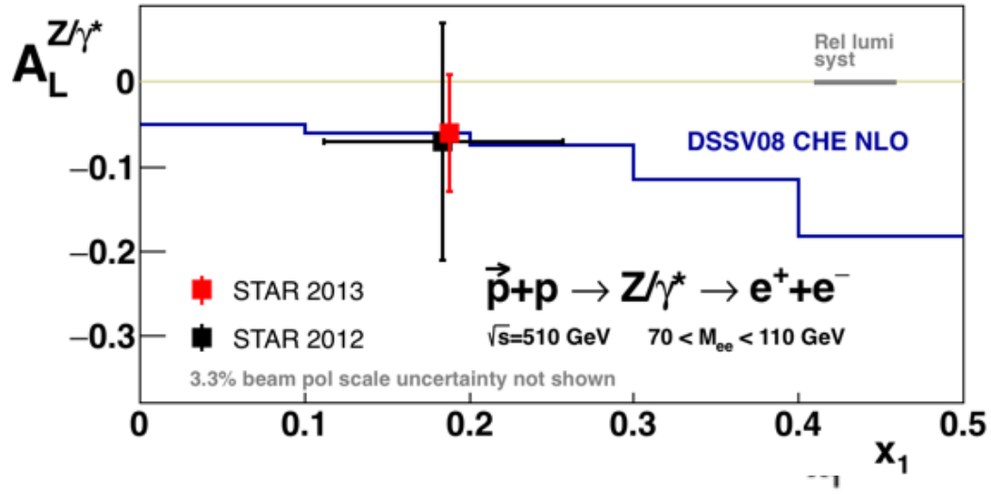




- Z bosons can be fully reconstructed

$$Z/\gamma^* \rightarrow e^+e^-$$

- Z A_L is sensitive to the combination of u, u-bar, d, and d-bar polarizations.

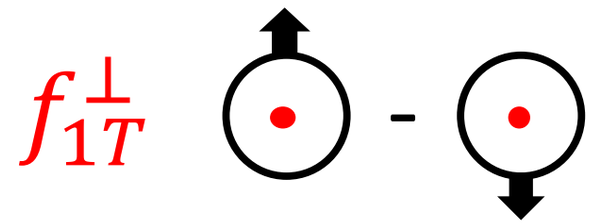


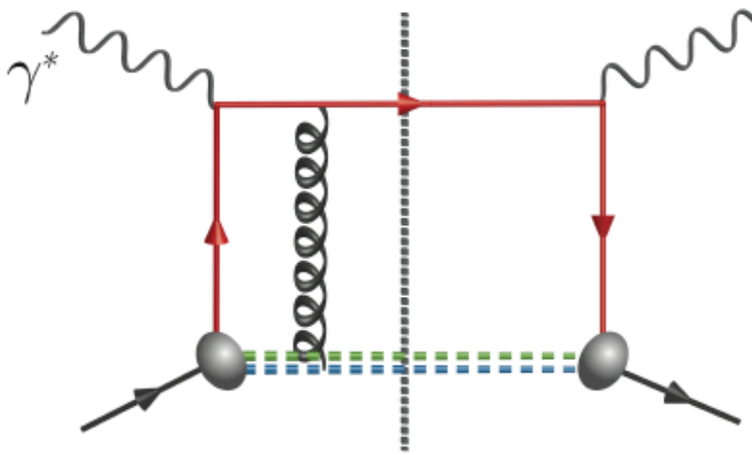
PRD 99, 051102(R) (2019)

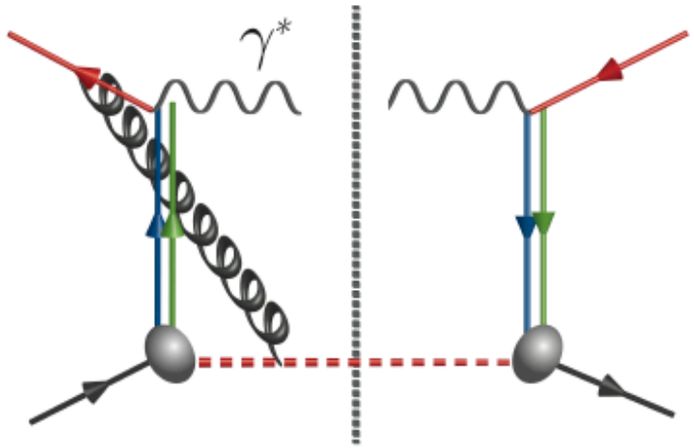
Experimentally very clean, but again by far less sensitive than W A_L.

Sivers' Sign Change

- Sivers function: one of 8 leading-twist TMDs; describing correlation between transverse spin of the nucleon and transverse momentum of the quark





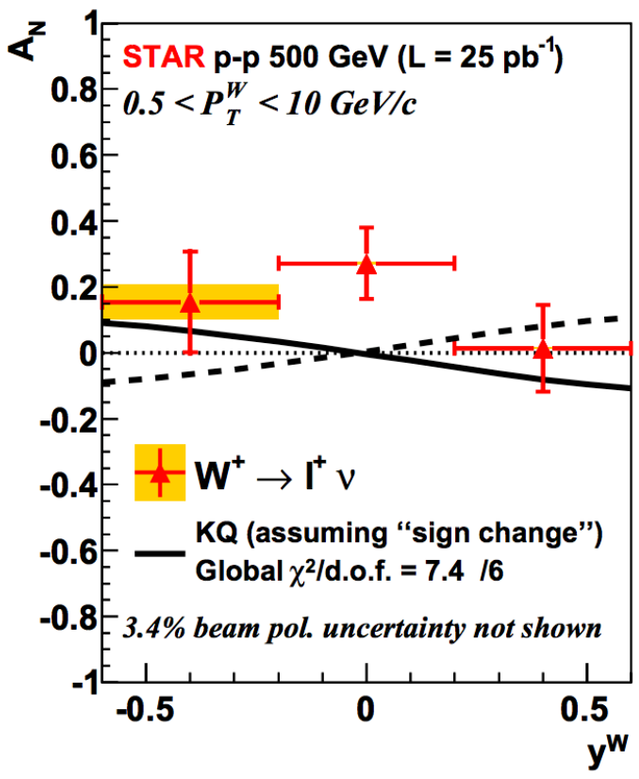


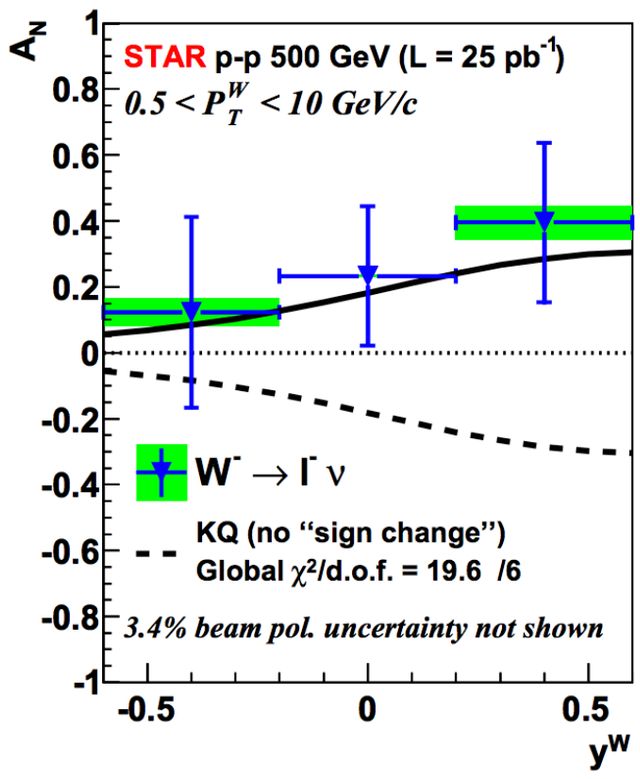
- Not universal: $f_{1T}^{\perp}$ (SIDIS) = $-f_{1T}^{\perp}$ (DY or W/Z)
- Experimental test is critical for our understanding of TMDs and TMD factorization

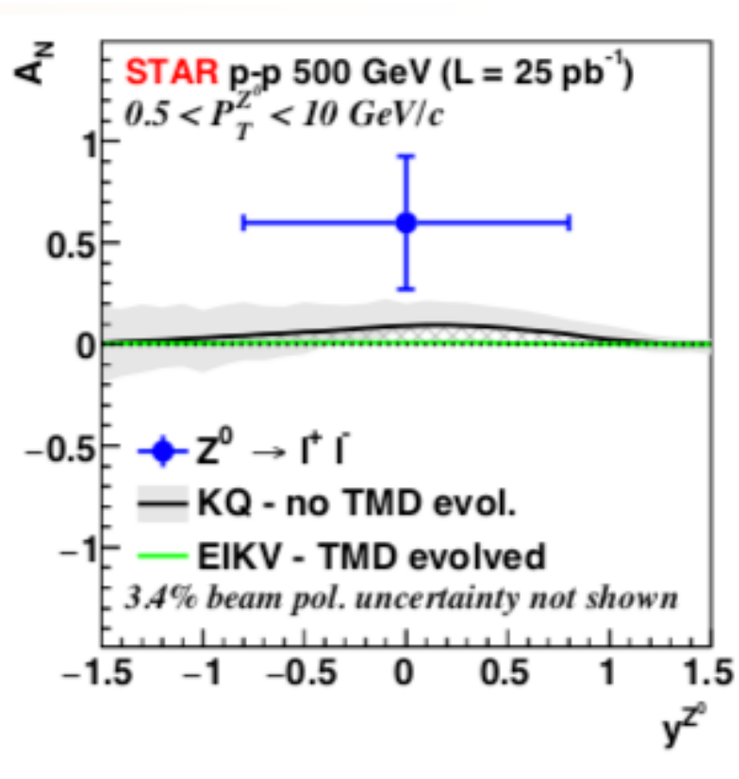
See Renee Fatemi's talk

First W/Z A_N results

STAR, PRL116(2016)132301

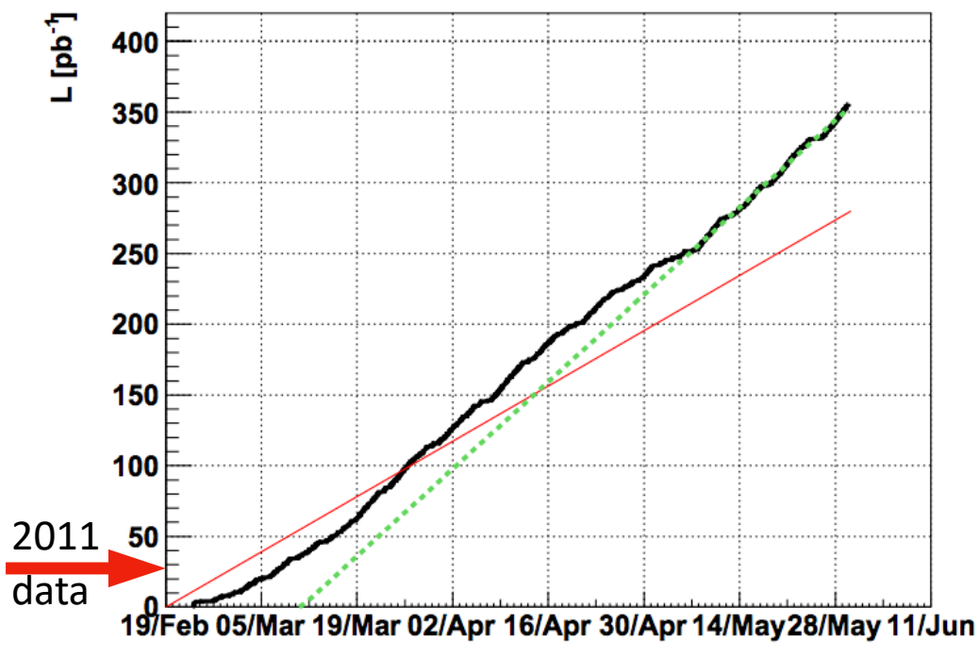






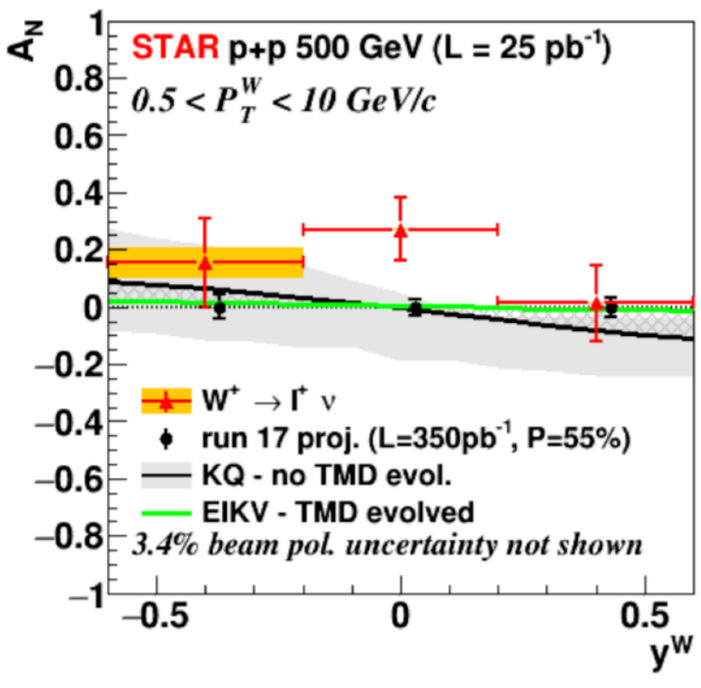
- First W/Z AN results favor the Sivers sign-change from data with an integral luminosity of 25 pb-1
- W kinematics fully reconstructed

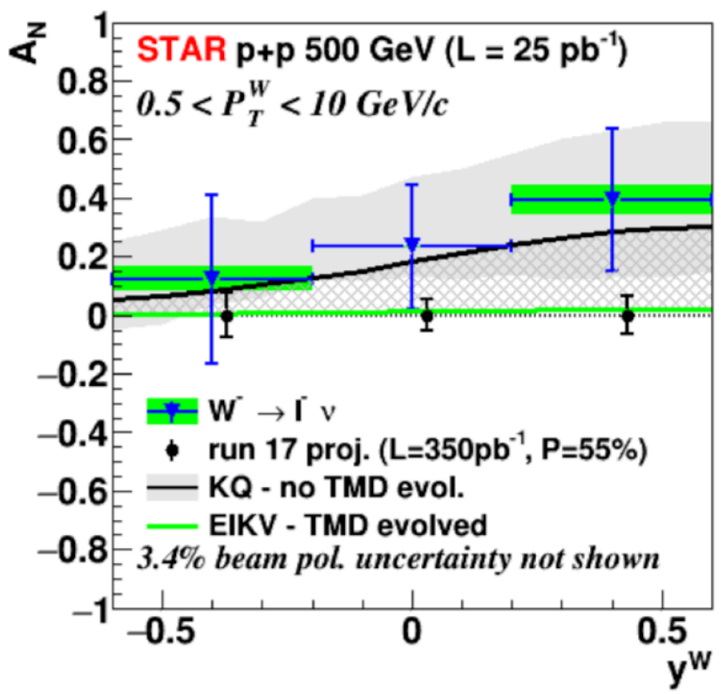
Projection of 2017

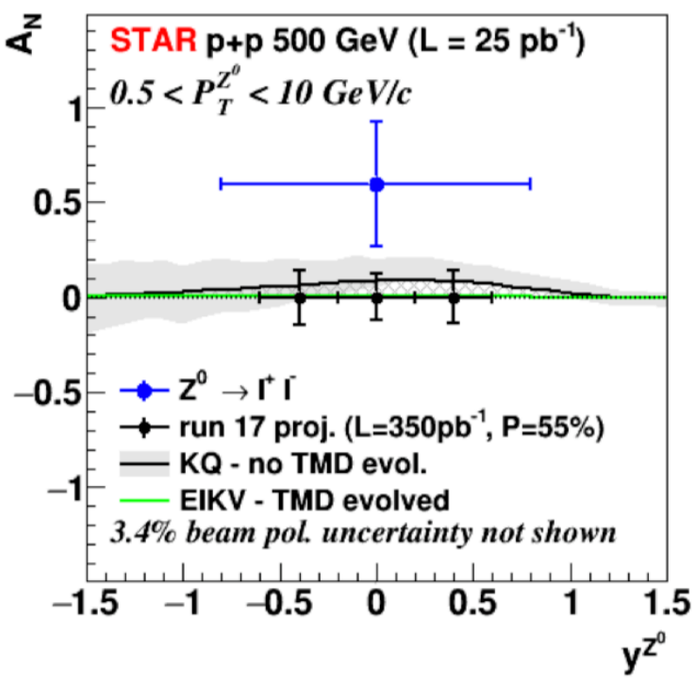


- 350 pb^{-1} recorded during 2017
- Analysis and detector calibration is ongoing

See Jae Nam's Poster







Summary

- RHIC W A_L measurement is concluded; final results:
  - PHENIX mid-rapidity: PRD 93, 051103(R) (2016)
  - PHENIX muon channel: PRD 98, 032007 (2018)
  - STAR: PRD 99, 051102(R) (2019)
- First experimental observation of a flavor-asymmetry between anti-up and anti-down polarizations, opposite to the unpolarized distributions.
- STAR W/Z cross section ratio measurement can provide constraints on unpolarized sea quark distributions
- STAR W/Z A_N first results favor Sivers sign change.
- More precise results from 2017 dataset on W/Z A_N and cross section ratio are coming.

Thank you for your attention!

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