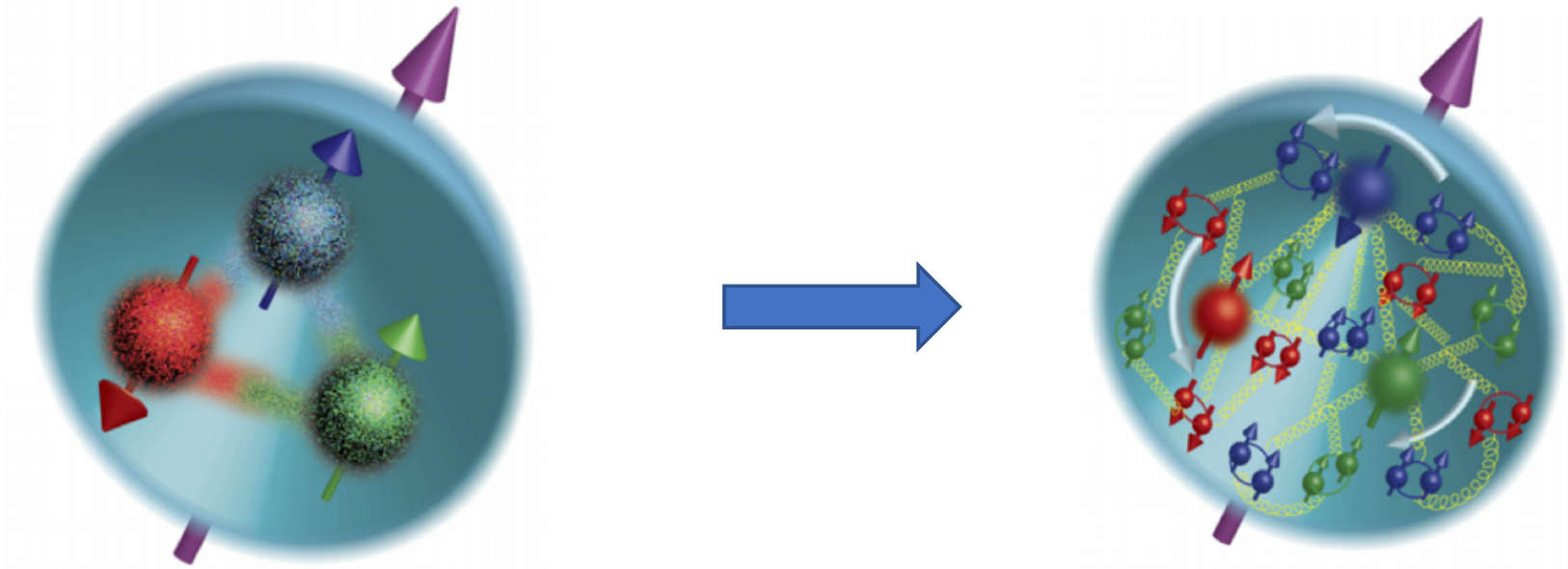
STAR W/Z Measurements

JinLong Zhang (Stony Brook University)
for the STAR Collaboration
June 4th, 2019

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

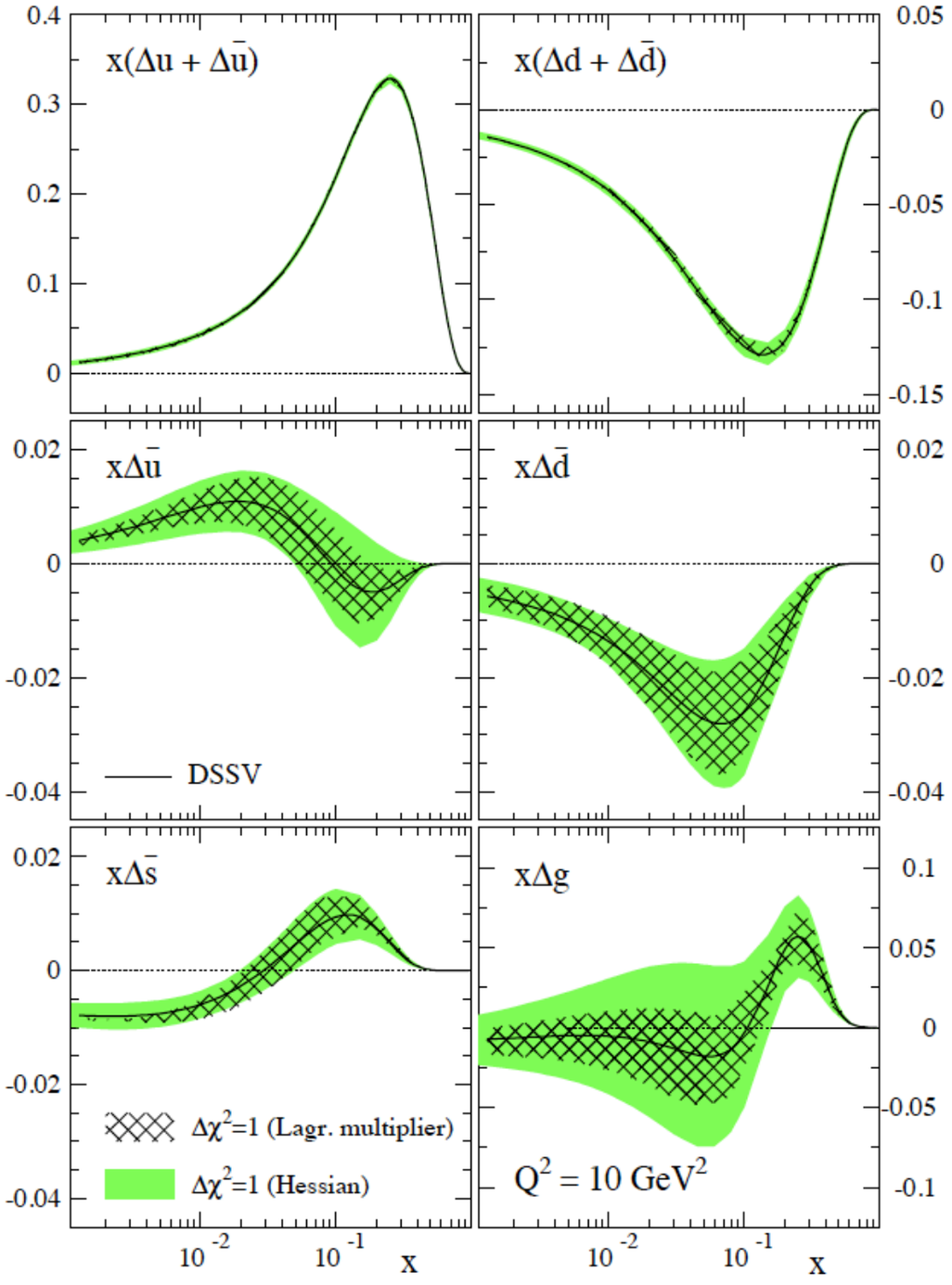
Before RHIC, mostly polarized DIS

- 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

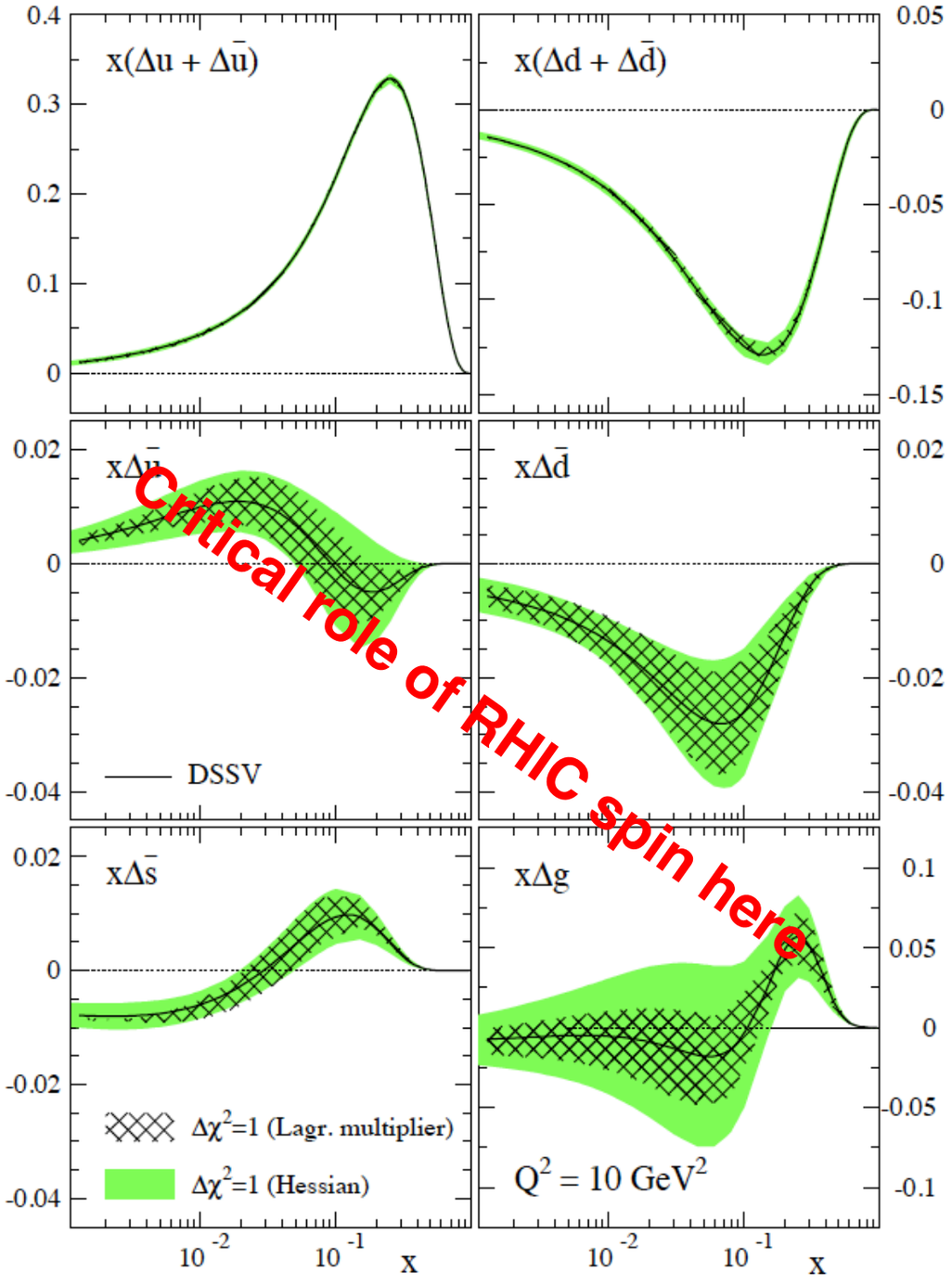
Before RHIC, mostly polarized DIS

- 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

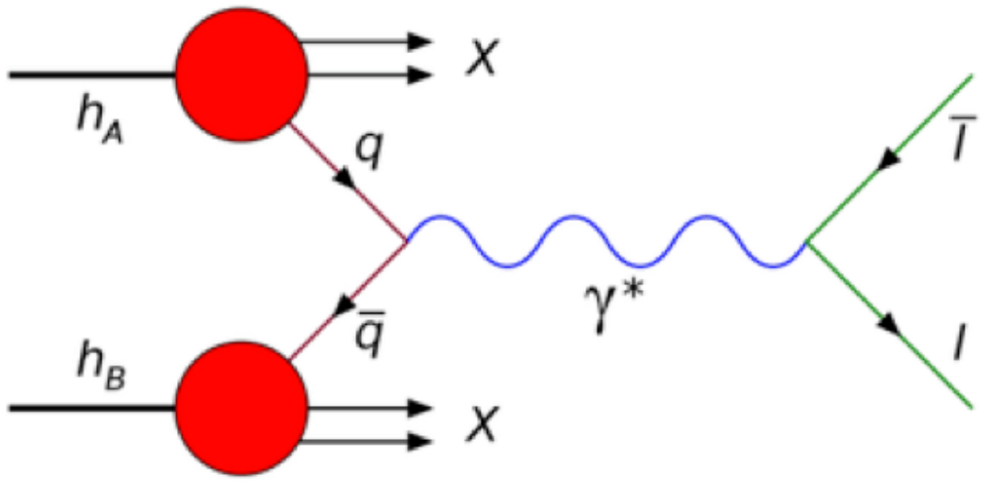
- Direct access to gluon spin
- ***Direct access to sea quarks***
- Transverse spin

DSSV2008
(Mostly pDIS + earlier RHIC results)

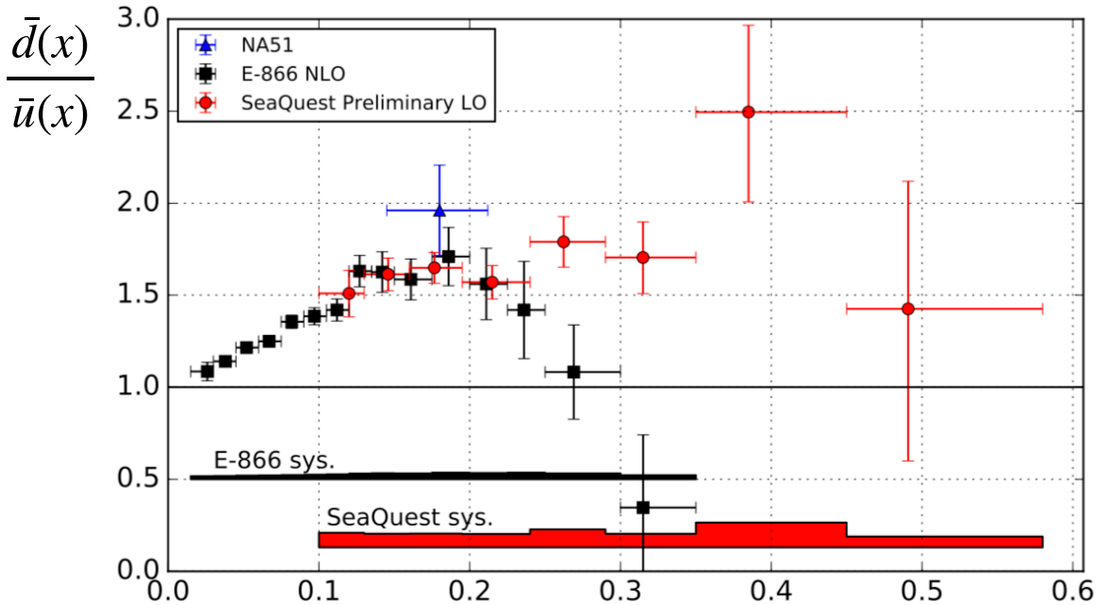


PRD 80, 034030 (2009)

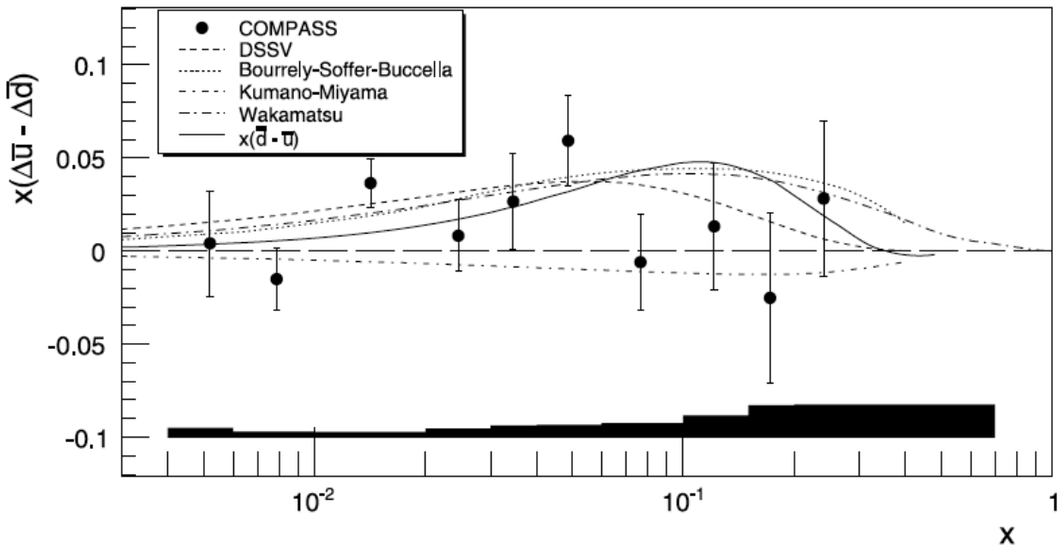
Sea quark flavor asymmetry



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.

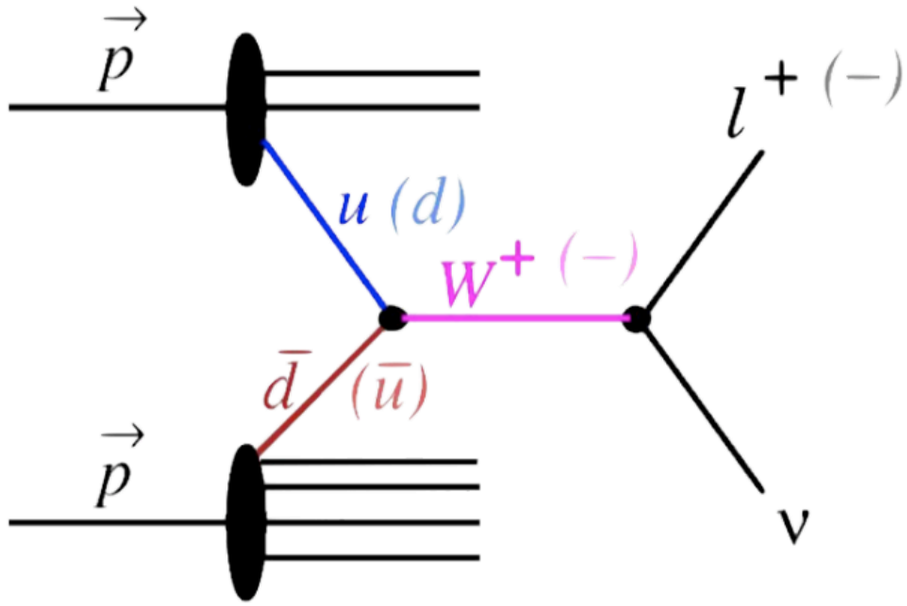


COMPASS, PLB 693, 227 (2010)

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 measures W boson via its leptonic decay.



Parity-violating longitudinal single-spin asymmetry:

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

From W A_L to quark/anti-quark spin

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

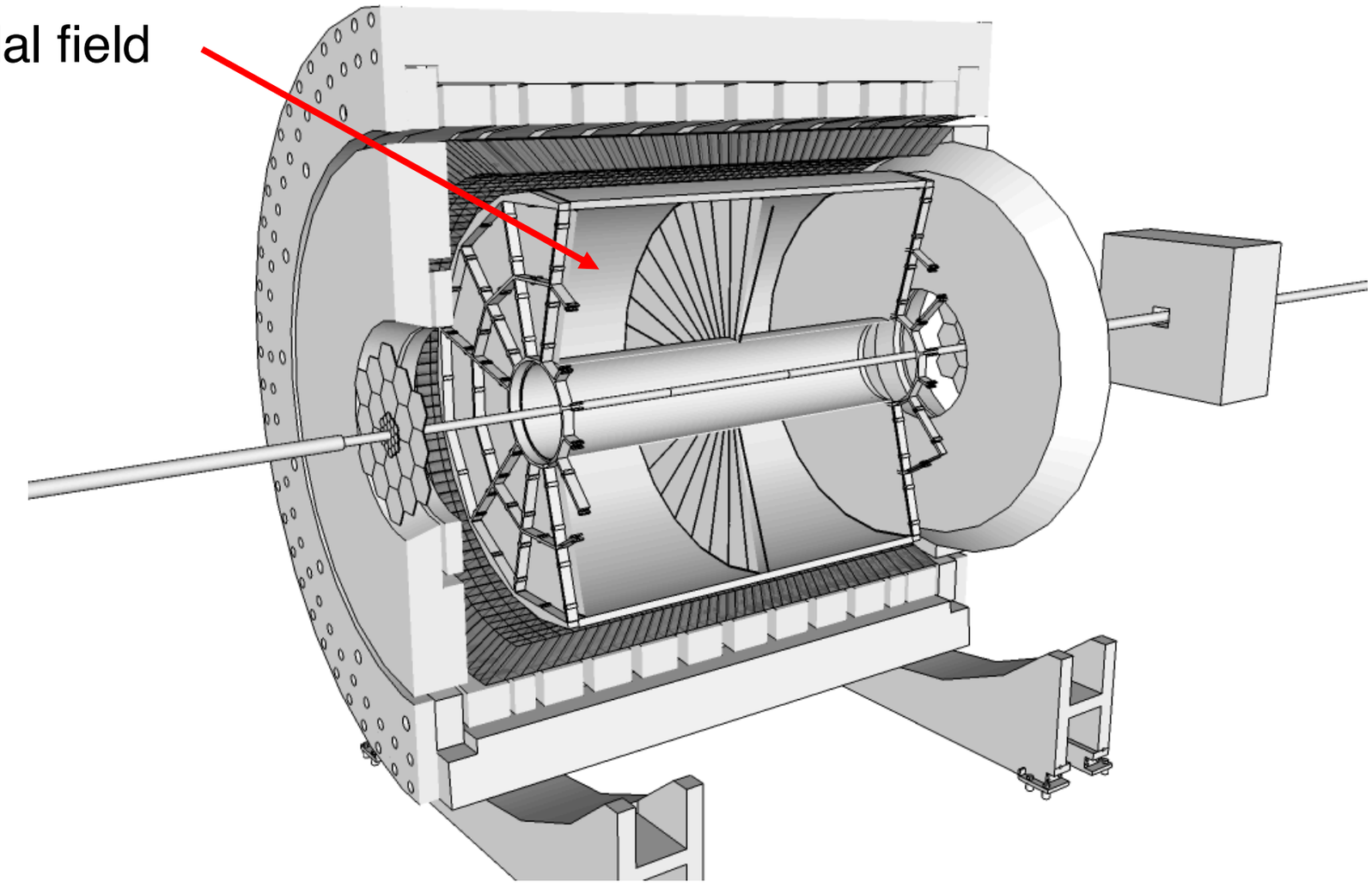
$$A_L^{W^-} \propto \frac{-\Delta d(x_1)\bar{u}(x_2) + \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)} \simeq \begin{cases} -\frac{\Delta d(x_1)}{d(x_1)}, y_W \gg 0 \ (x_1 \gg x_2) \\ \frac{\Delta\bar{u}(x_1)}{\bar{u}(x_1)}, y_W \ll 0 \ (x_1 \ll x_2) \end{cases}$$

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

STAR Detector

Nucl. Instrum. Meth. A499, 624, 2003

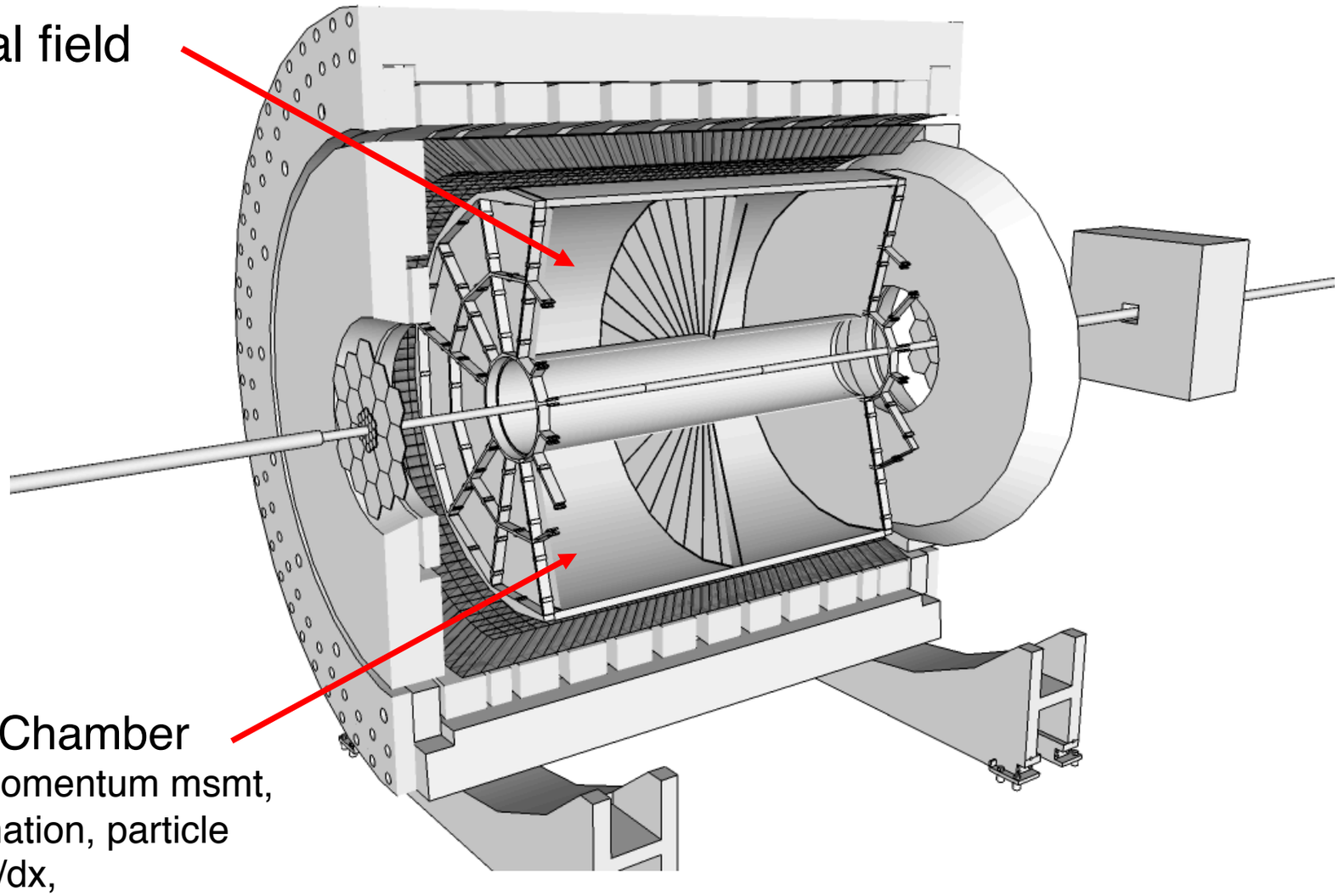
0.5 T solenoidal field



STAR Detector

Nucl. Instrum. Meth. A499, 624, 2003

0.5 T solenoidal field



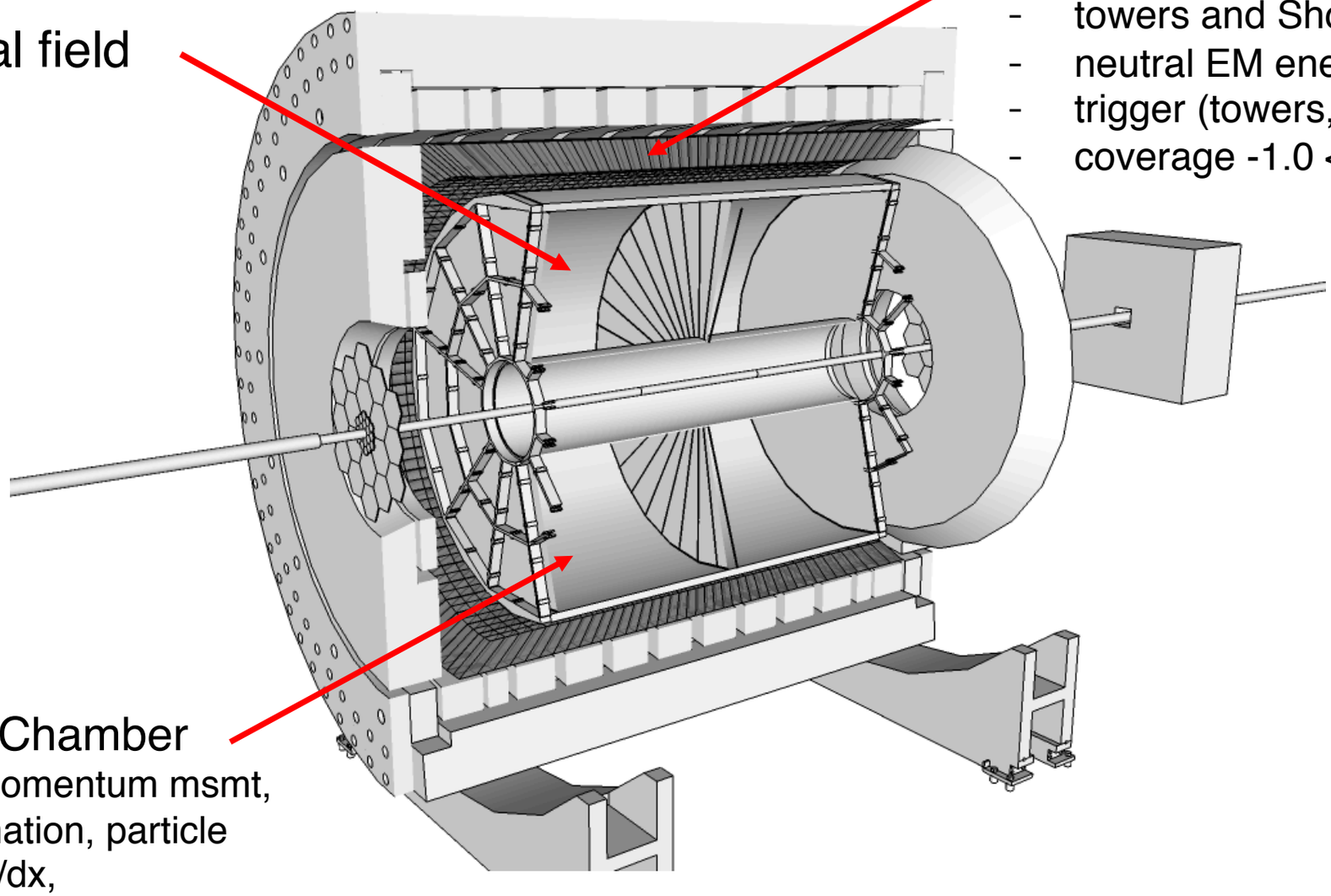
Time Projection Chamber

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

STAR Detector

0.5 T solenoidal field

Nucl. Instrum. Meth. A499, 624, 2003



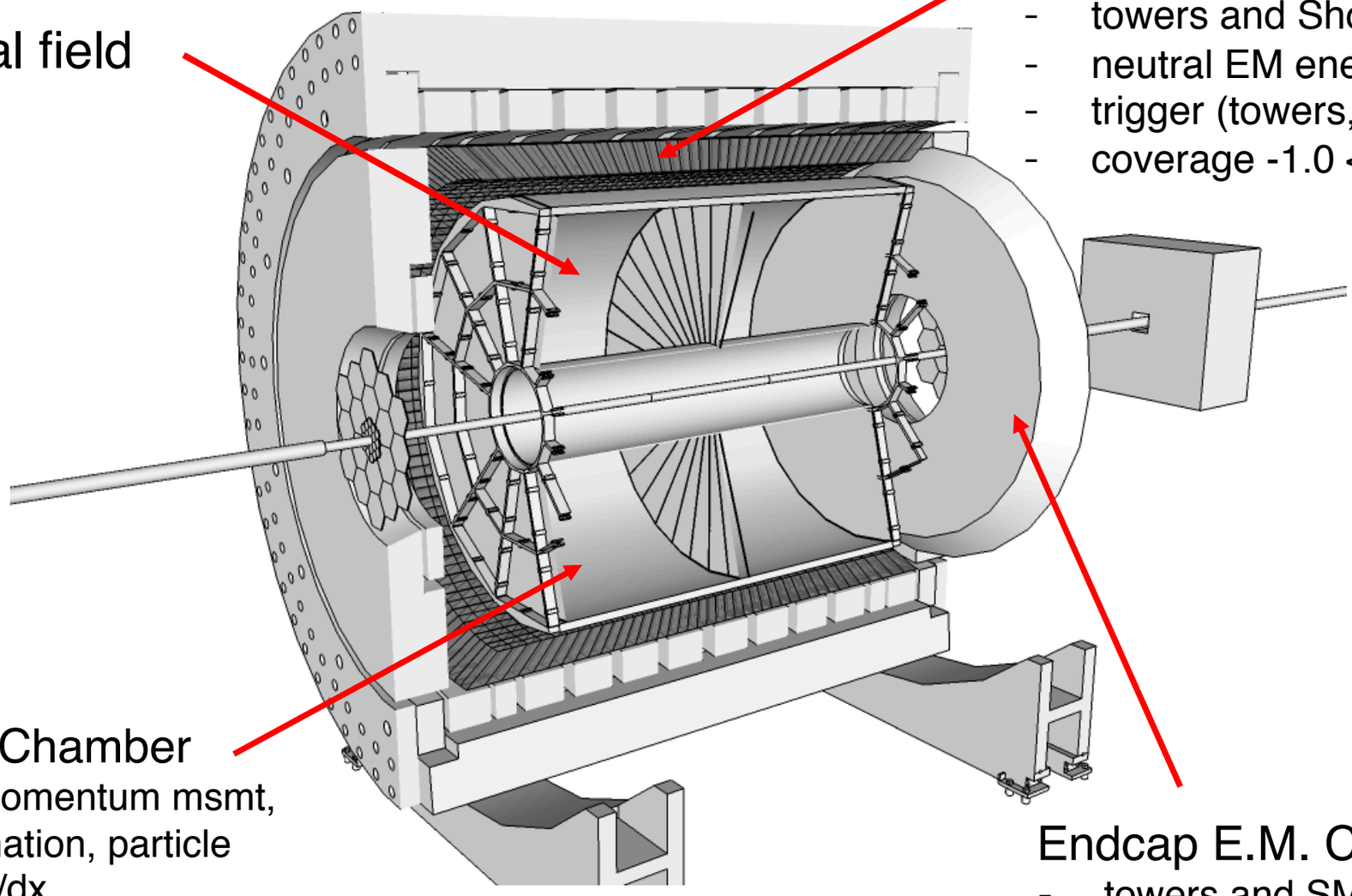
Barrel E.M. Calorimeter
- towers and Shower Maximum Det.
- neutral EM energy measurement,
- trigger (towers, patches of towers)
- coverage $-1.0 < \eta < 1.0$

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

STAR Detector

0.5 T solenoidal field

Nucl. Instrum. Meth. A499, 624, 2003

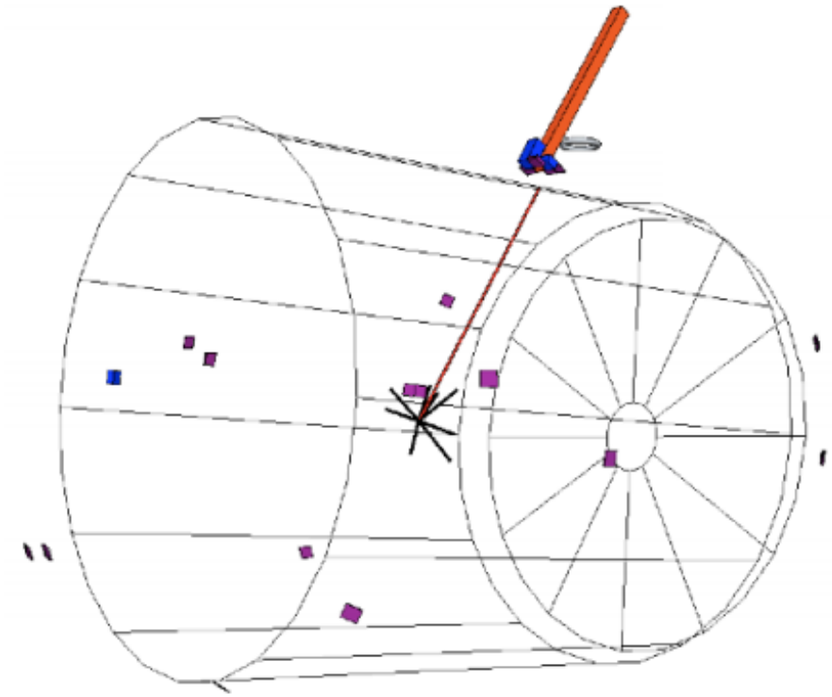


Barrel E.M. Calorimeter
- towers and Shower Maximum Det.
- neutral EM energy measurement,
- trigger (towers, patches of towers)
- coverage $-1.0 < \eta < 1.0$

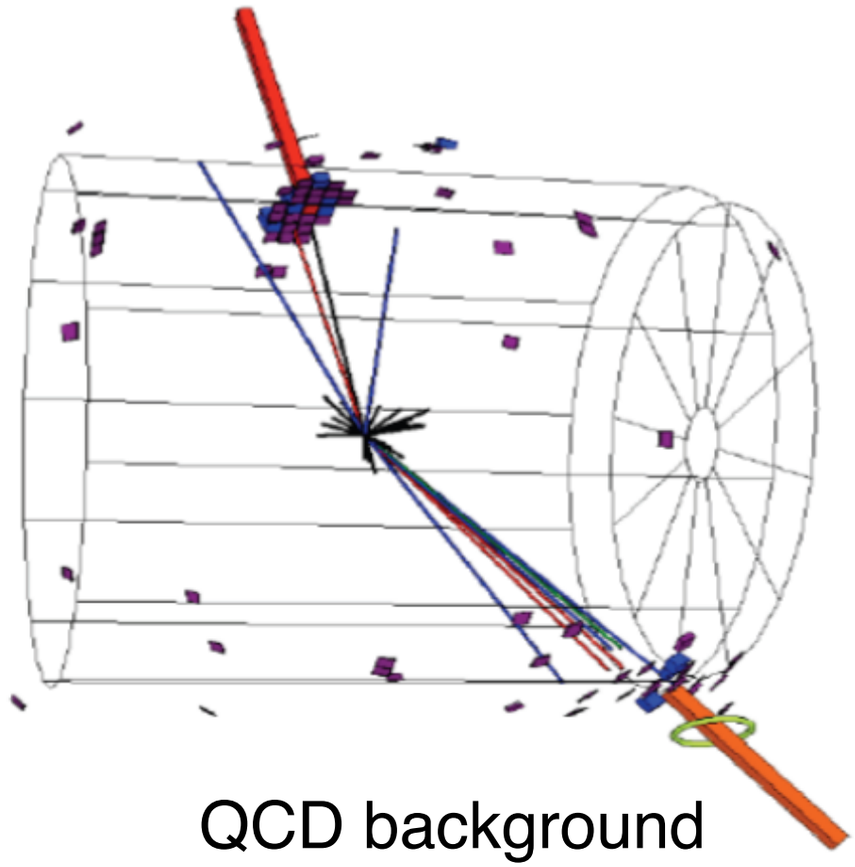
Time Projection Chamber
- charged track momentum msmt,
- charge determination, particle identification dE/dx,
- collision vertex reconstruction
- coverage $-1.3 < \eta < 1.3$

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

Measuring W at STAR



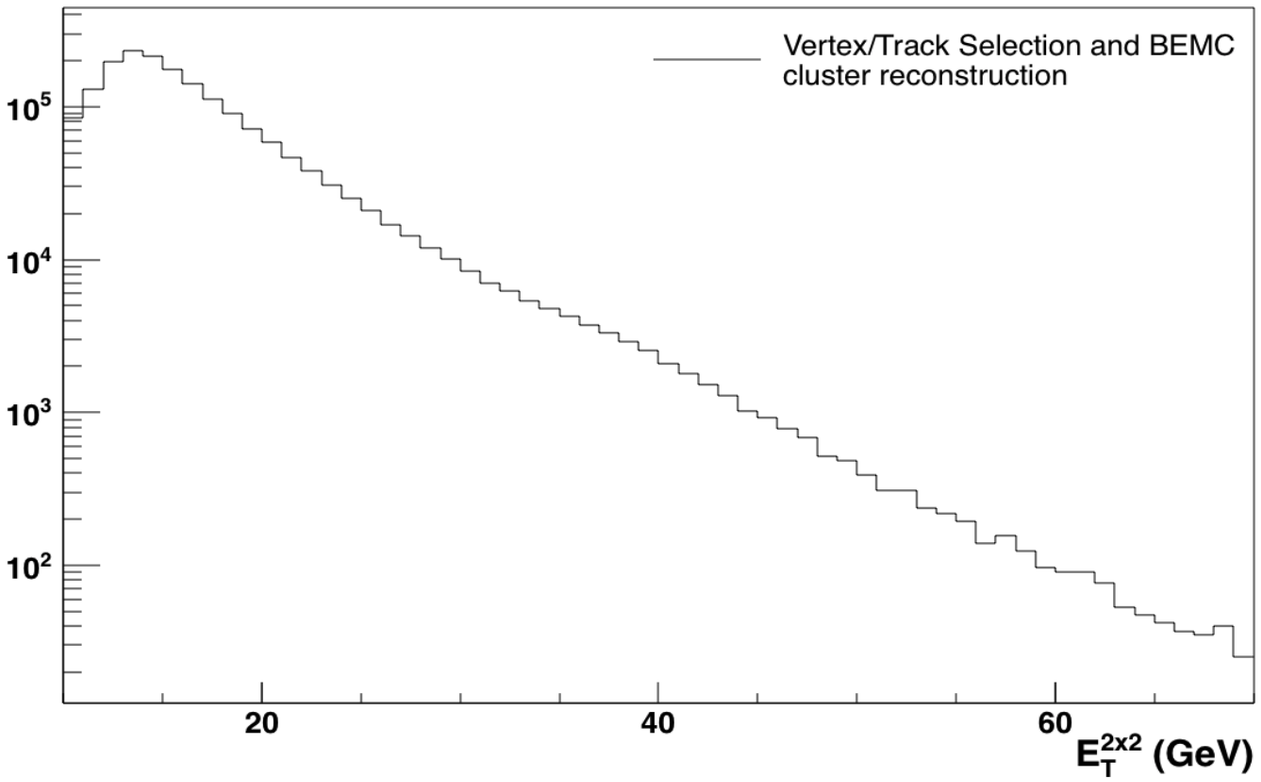
$W \rightarrow e + \nu_e$

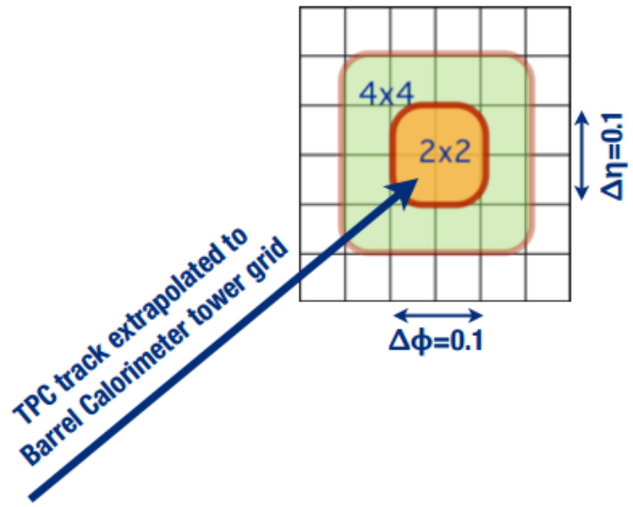


QCD background

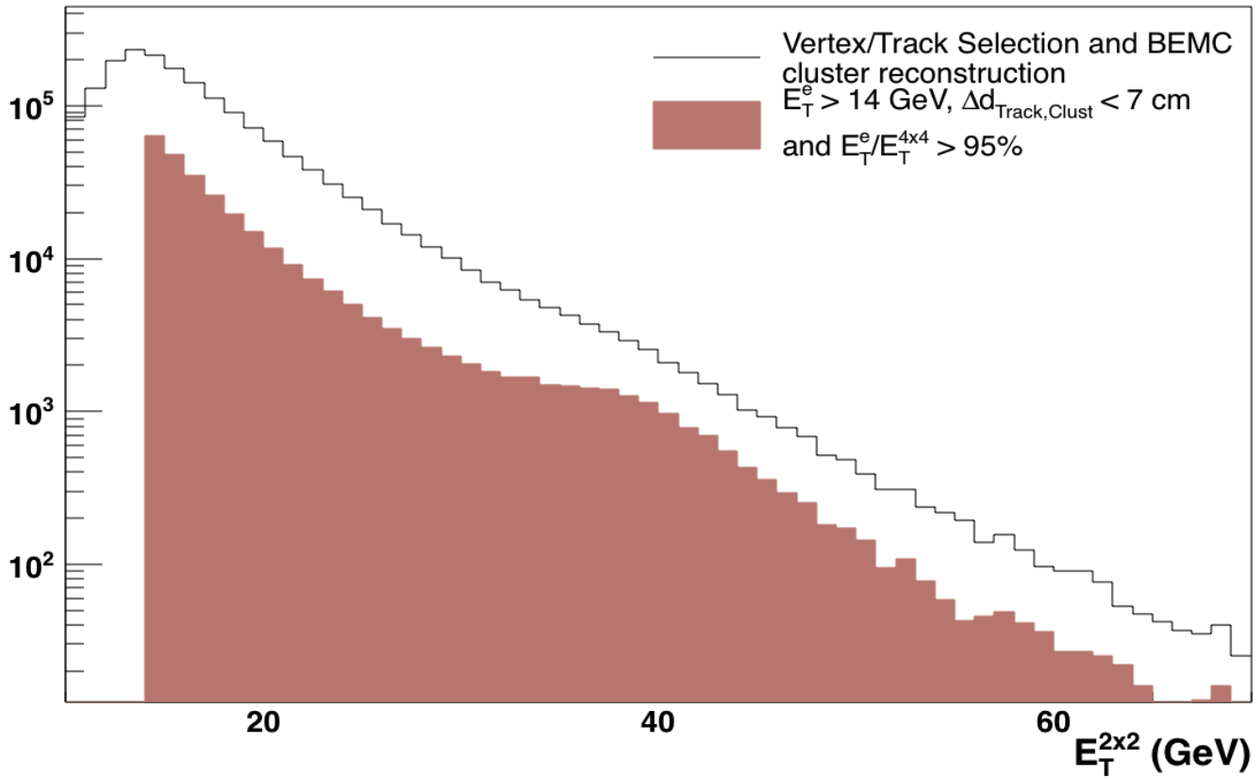
- Isolated $e^+(e^-)$: isolated high momentum track + isolated EM cluster
- Undetected $\nu_e(\bar{\nu}_e)$: large missing energy opposite to $e^+(e^-)$
- Jacobian peak: $e^+(e^-)\ p_T$ peak around $M_W/2$ (~40 GeV)

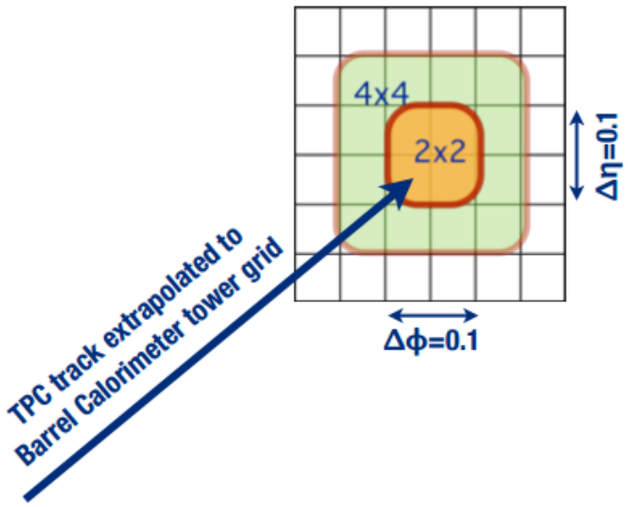
W selection

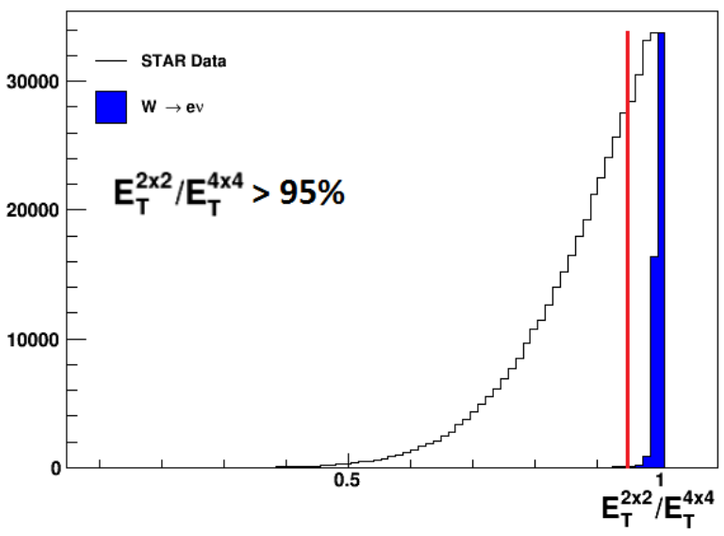

Vertex/Track Selection and BEMC cluster reconstruction
10^5
10^4
10^3
10^2
20
40
60
E_T^{2x2} (GeV)


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

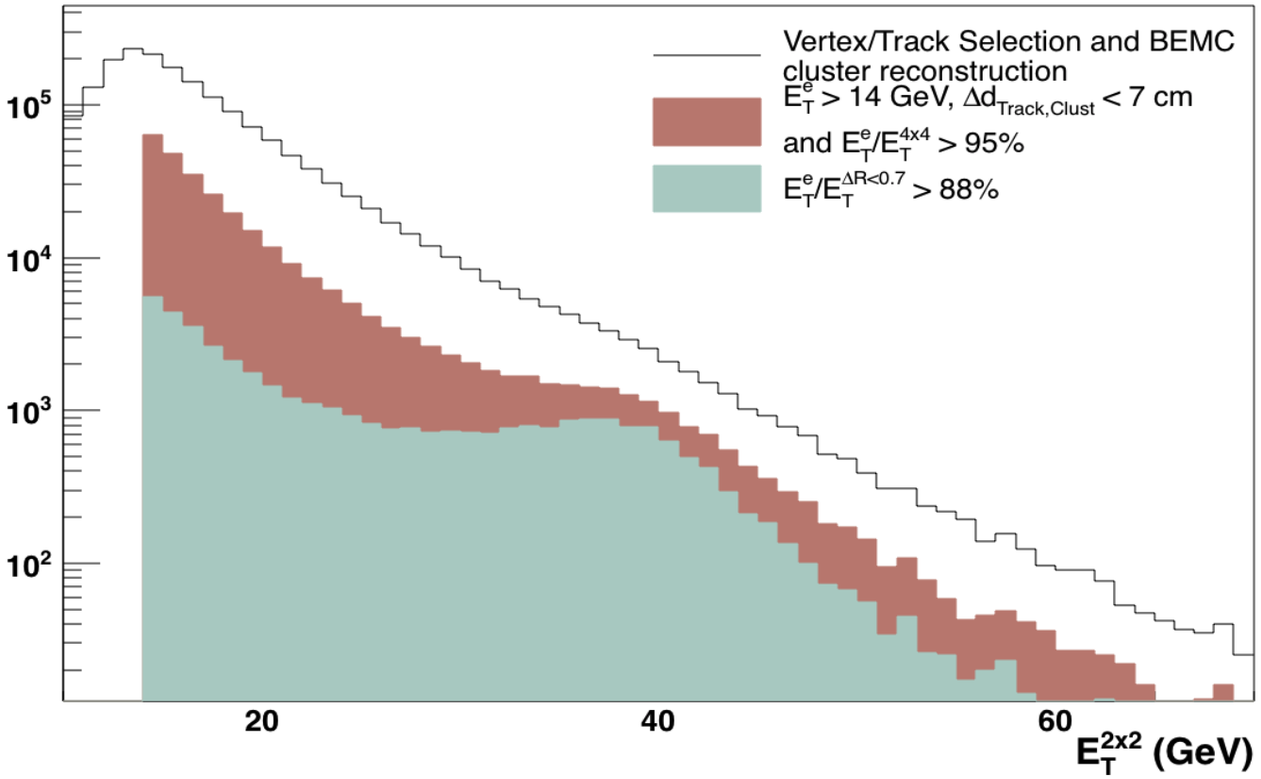
W selection

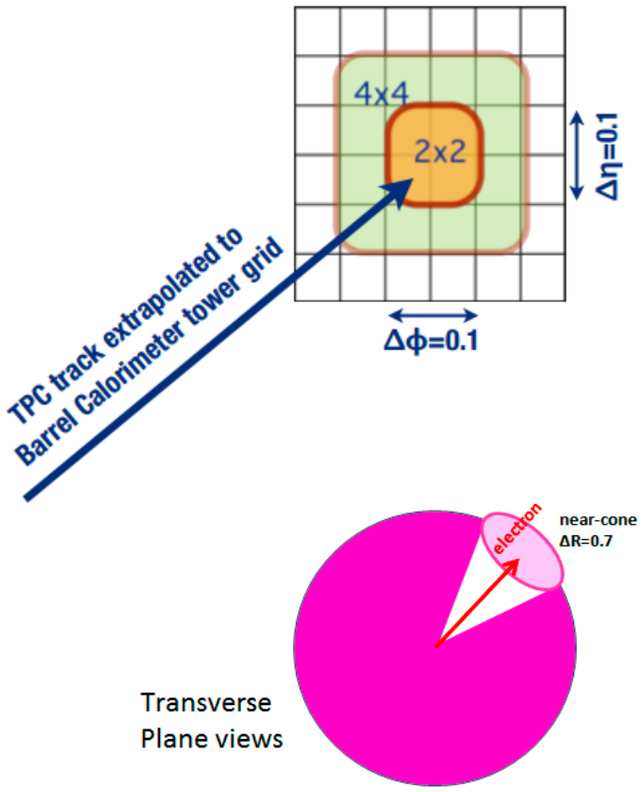

Vertex/Track Selection and BEMC cluster reconstruction
$E_T^e > 14$ GeV, $\Delta d_{Track,Clust} < 7$ cm
and $E_T^e/E_T^{4x4} > 95\%$
10^5
10^4
10^3
10^2
20
40
60
E_T^{2x2} (GeV)

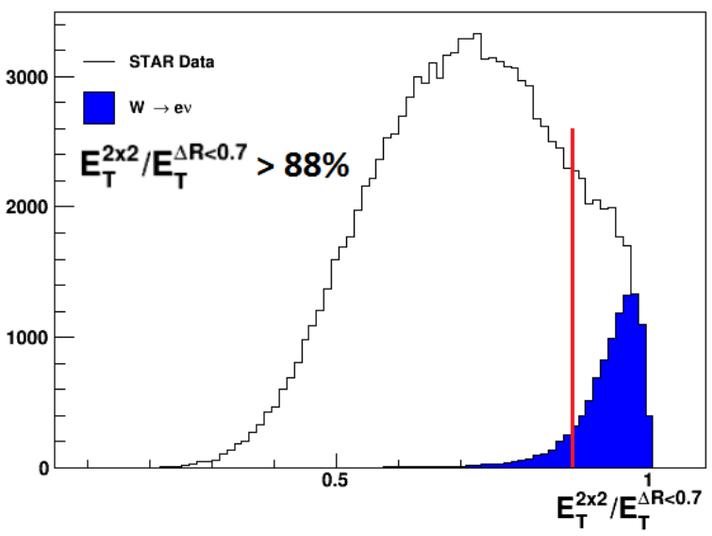

4x4
2x2
Δη=0.1
Δϕ=0.1
TPC track extrapolated to
Barrel Calorimeter tower grid


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

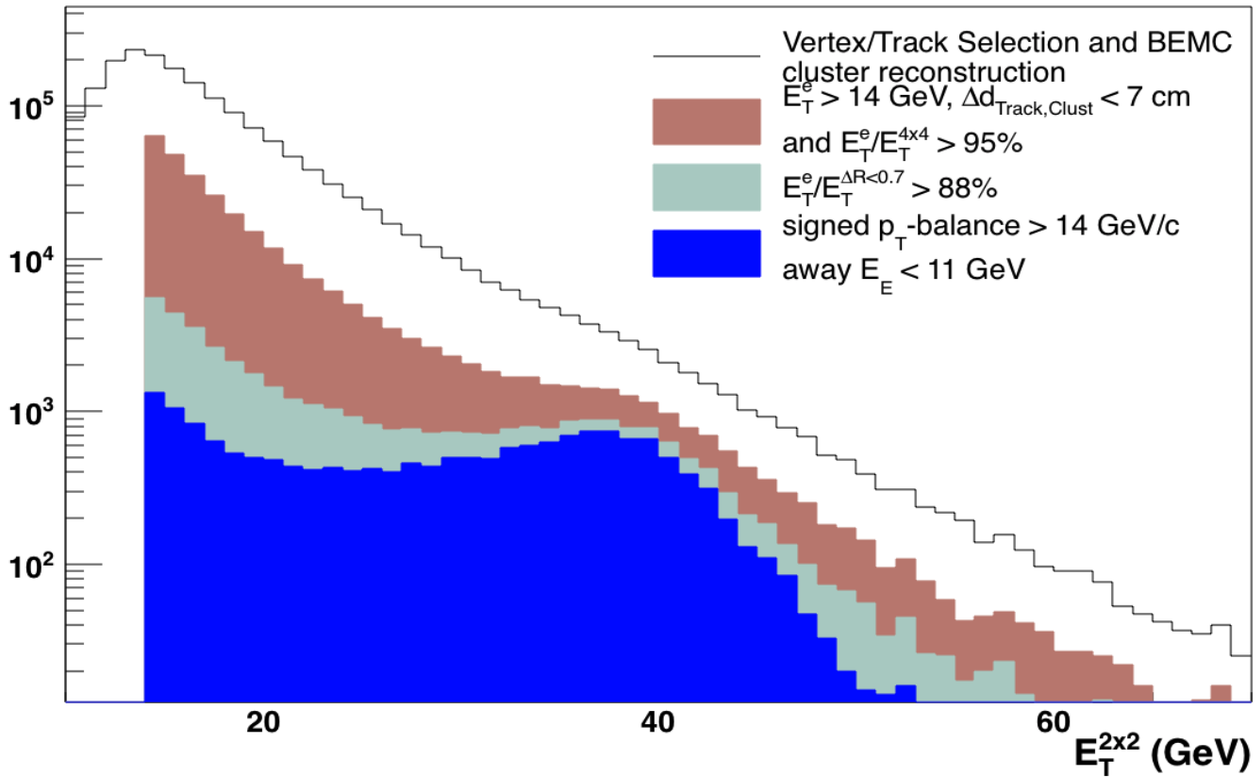
W selection

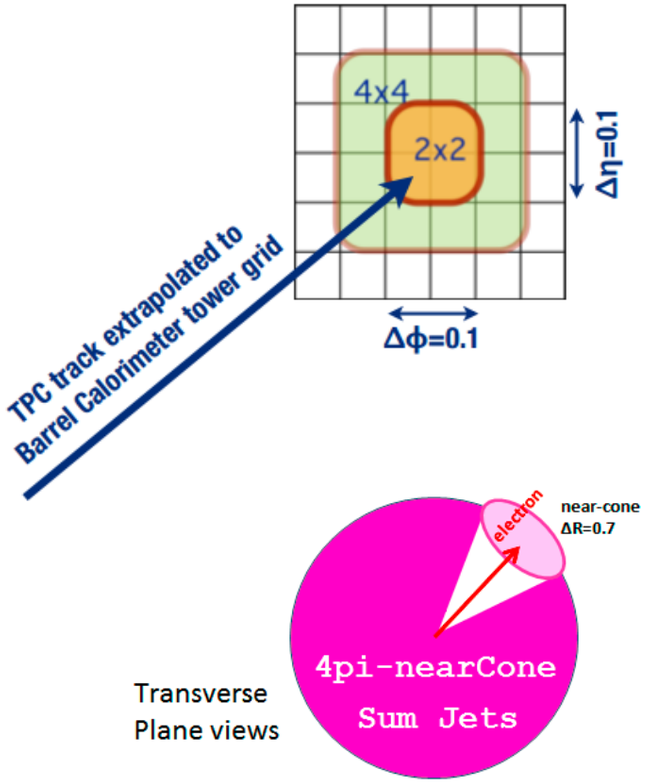

Vertex/Track Selection and BEMC cluster reconstruction
E_T^e > 14 GeV, $\Delta d_{Track,Clust}$ < 7 cm
and E_T^e/E_T^{4x4} > 95%
$E_T^e/E_T^{\Delta R<0.7}$ > 88%
10^5
10^4
10^3
10^2
20
40
60
E_T^{2x2} (GeV)

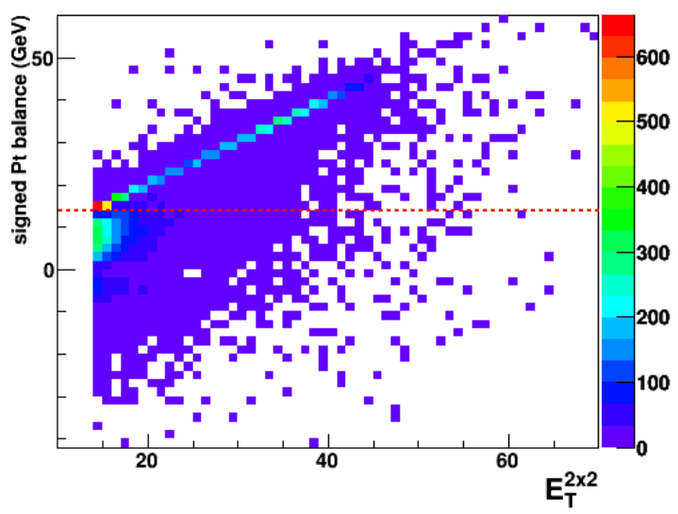

4x4
2x2
Δη=0.1
Δϕ=0.1
TPC track extrapolated to Barrel Calorimeter tower grid
near-cone ΔR=0.7
election
Transverse Plane views

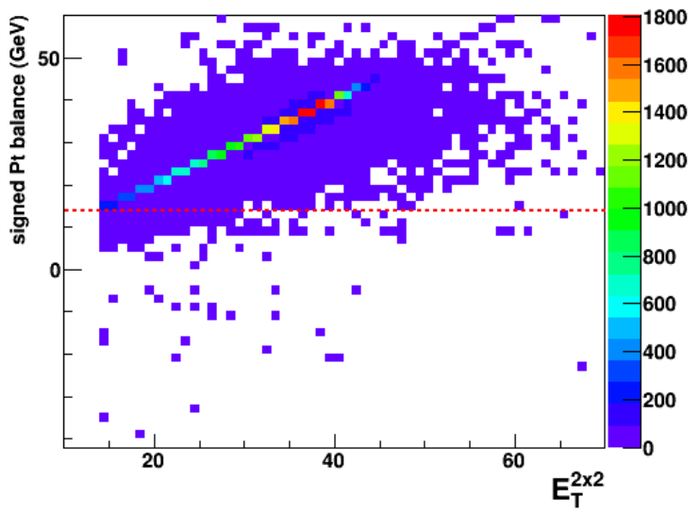

STAR Data
W → eν
$E_T^{2x2}/E_T^{\Delta R<0.7}$ > 88%
3000
2000
1000
0
0.5
1
$E_T^{2x2}/E_T^{\Delta R<0.7}$

W selection







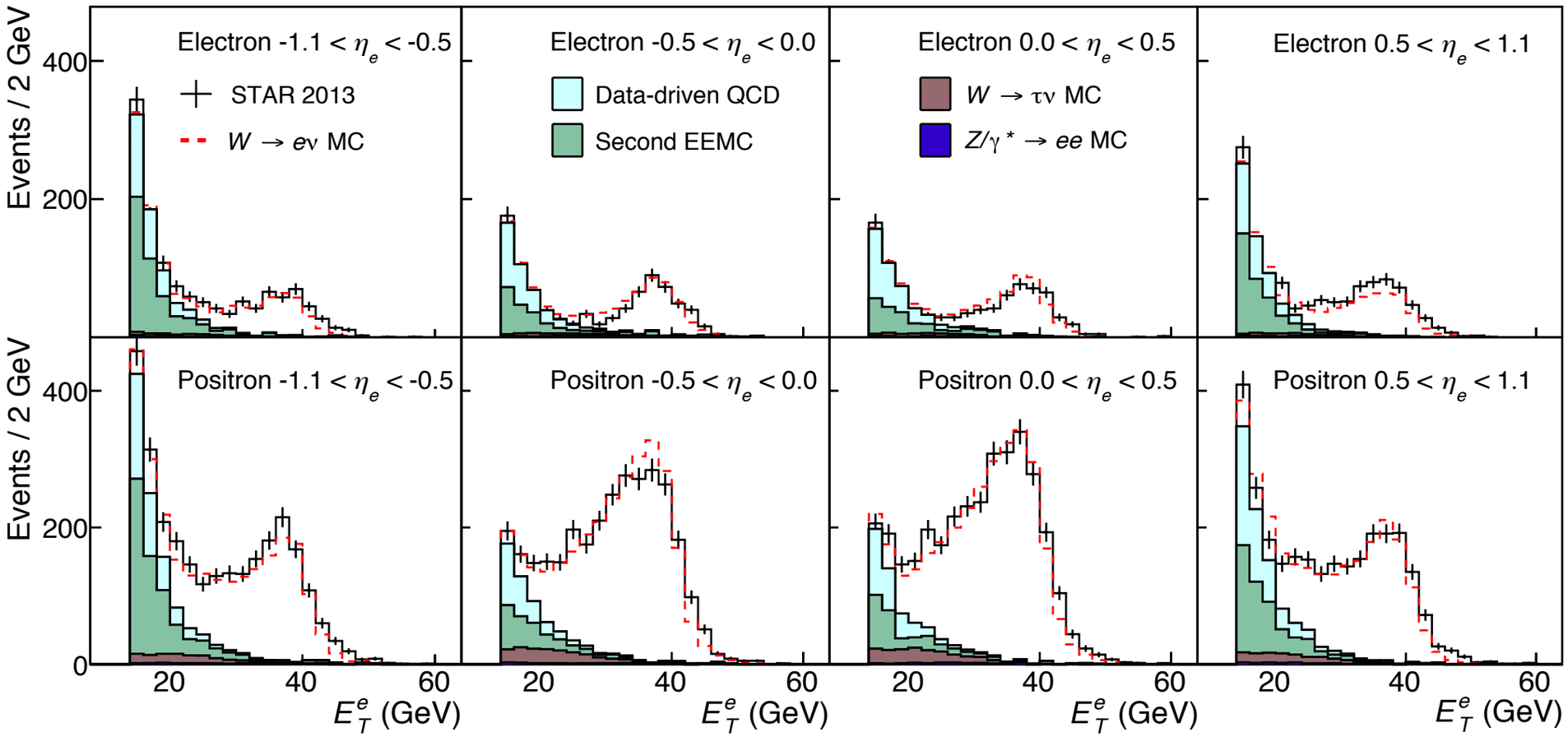


$$\vec{p}_T^{\,bal} = \vec{p}_T^{\,e} + \Sigma_{\Delta R<0.7}\, \vec{p}_T^{\,jets}$$

Signed-p_T balance $=$

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

Background Analysis

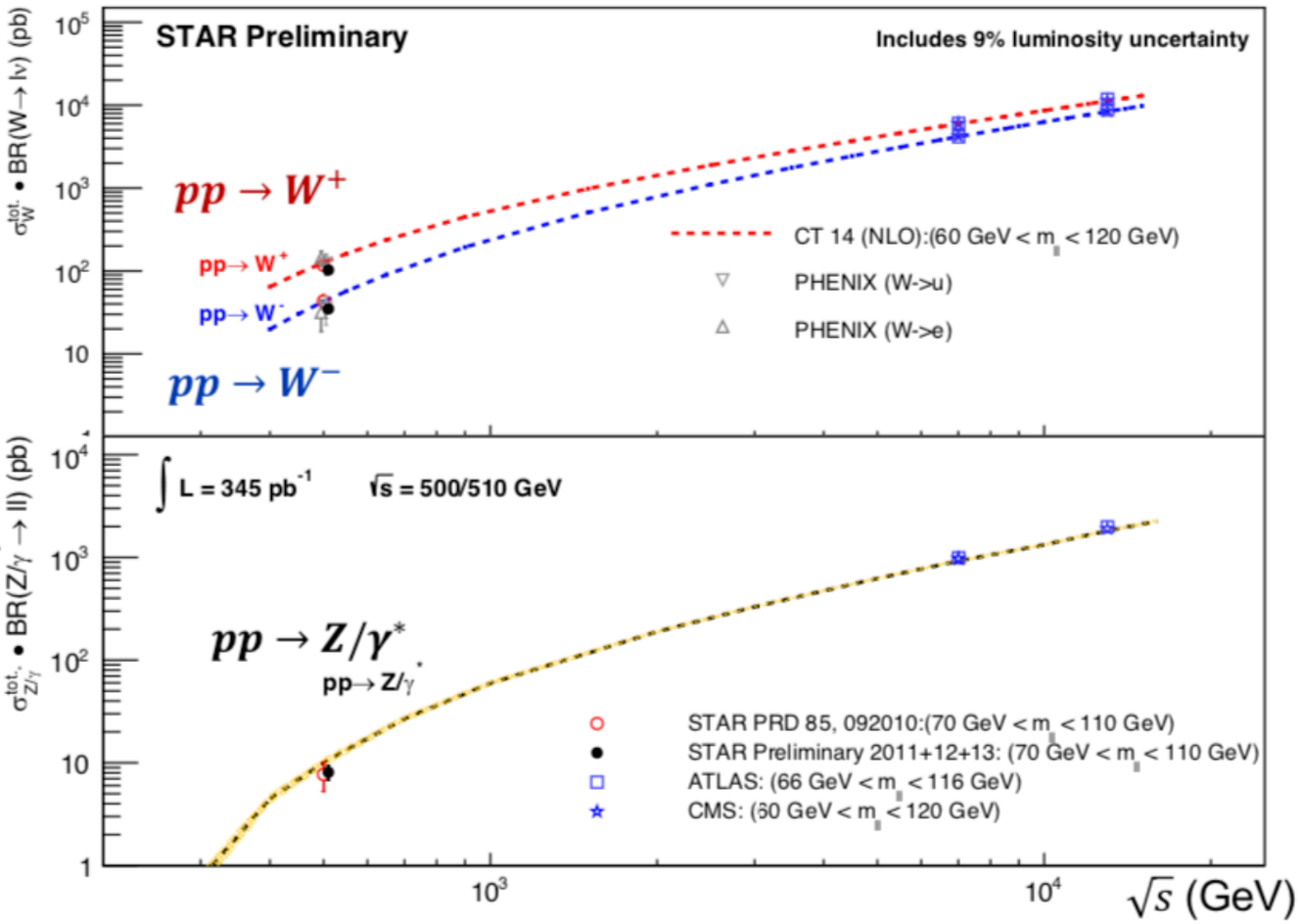


Residual backgrounds:

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

W/Z Total Cross Section

See Matt Posik's Poster

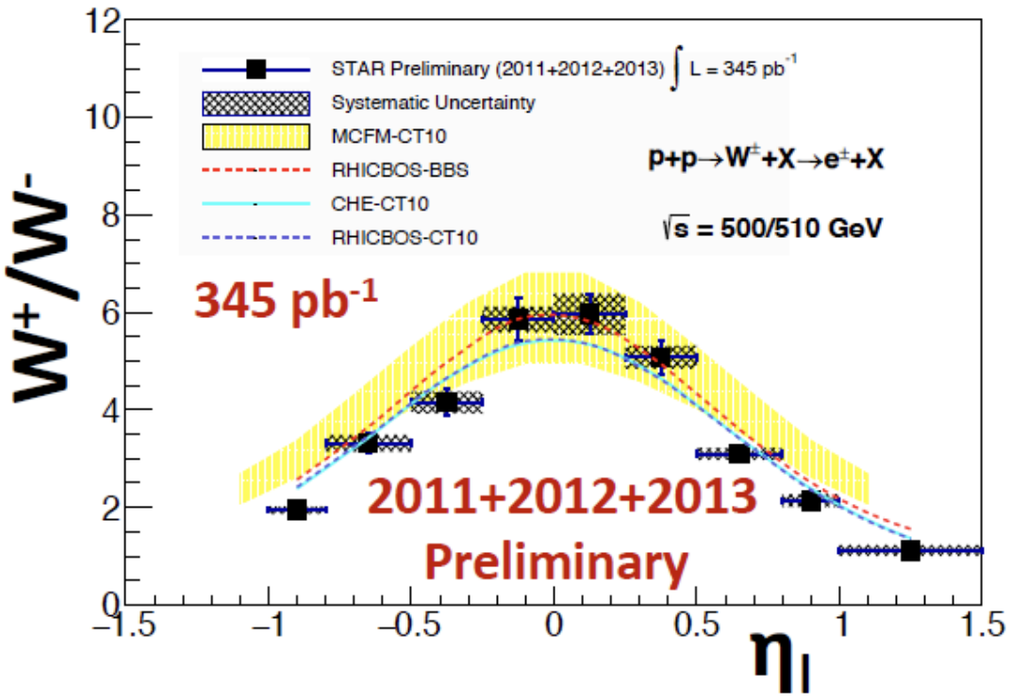


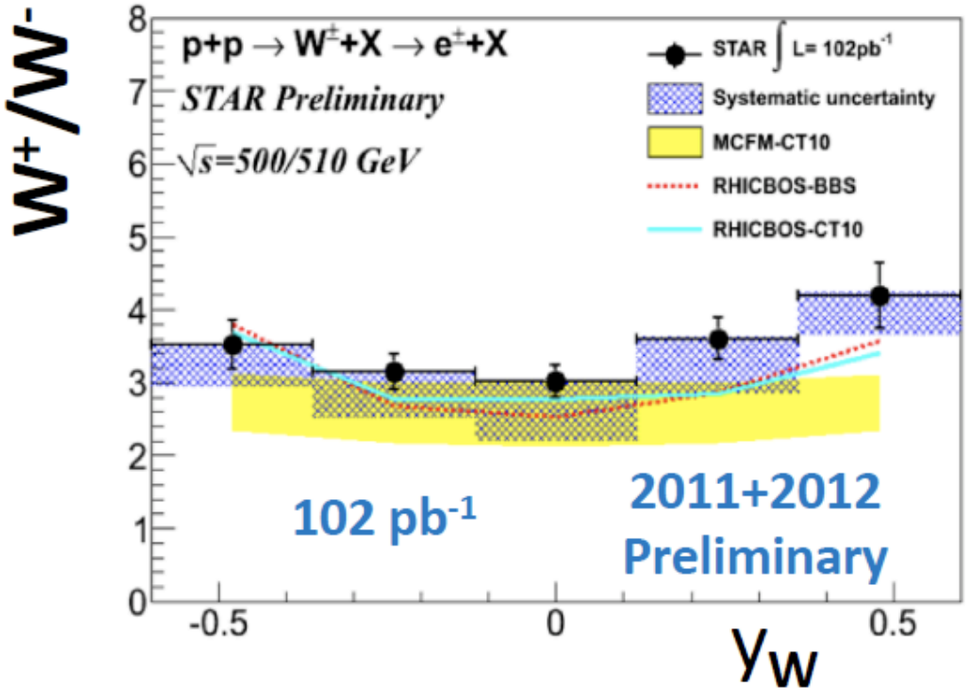
- Both NC and CC cross section measurements consistent with theoretical predication (CT14 NLO) and world data.

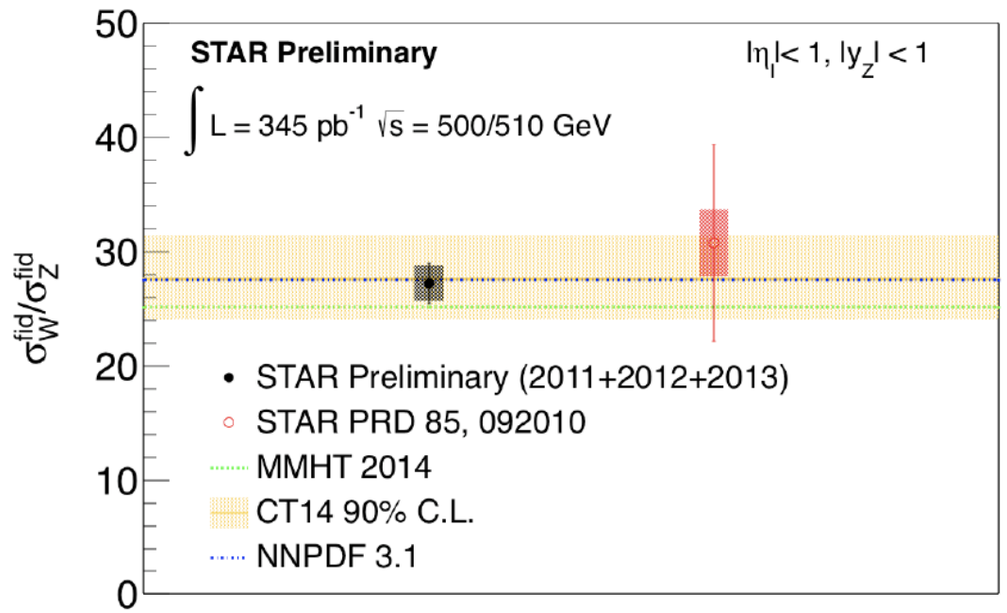
- Support the pQCD interpretations for asymmetry measurements.

W/Z Cross Section Ratio

See Matt Posik's Poster



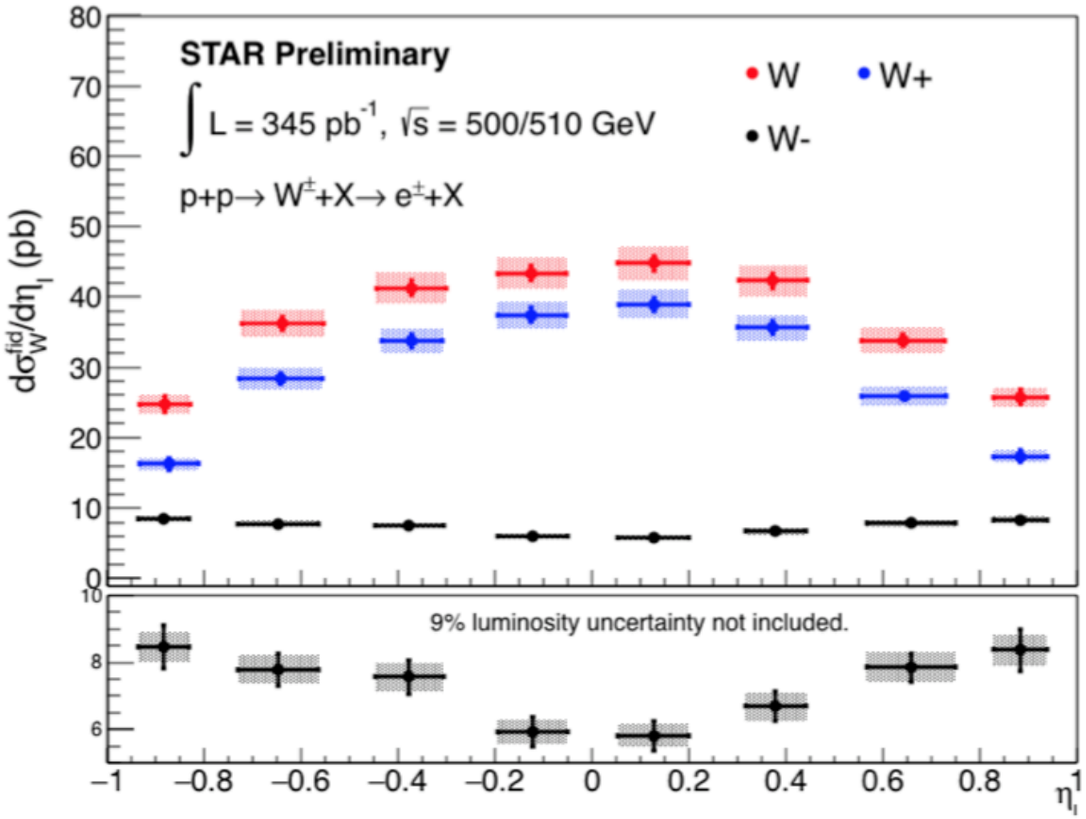


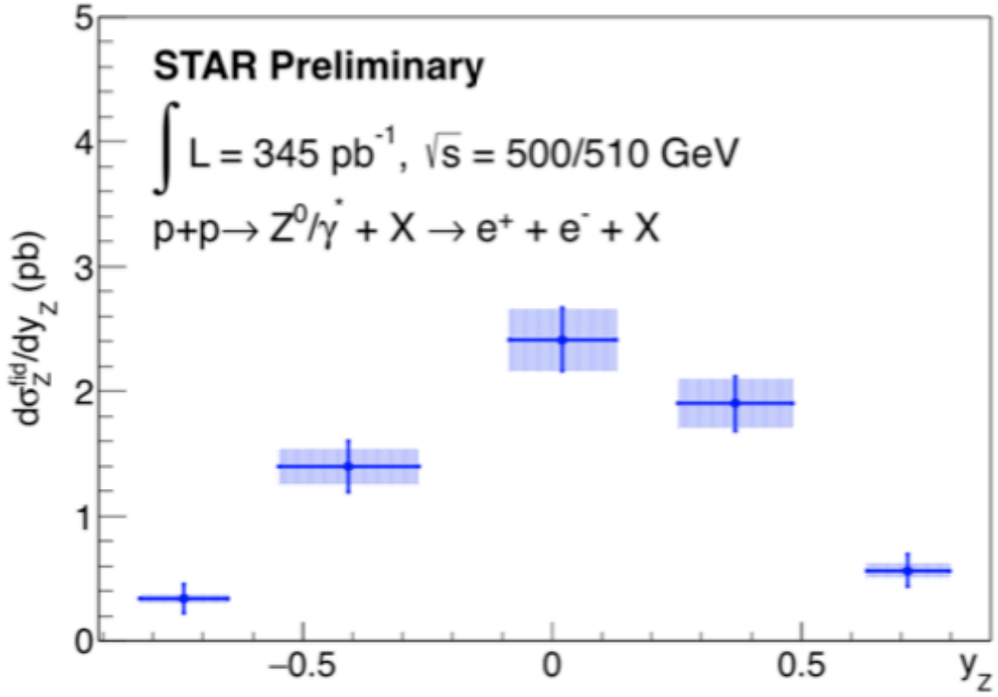


- Complementary measurement to SeaQuest and E-866, for ~0.06 < x < ~0.4 , constraining unpolarized sea quark distributions.
- W kinematics determined from data and simulation; Cornerstone for W A_N measurement

W/Z Differential Cross Section

See Matt Posik's Poster

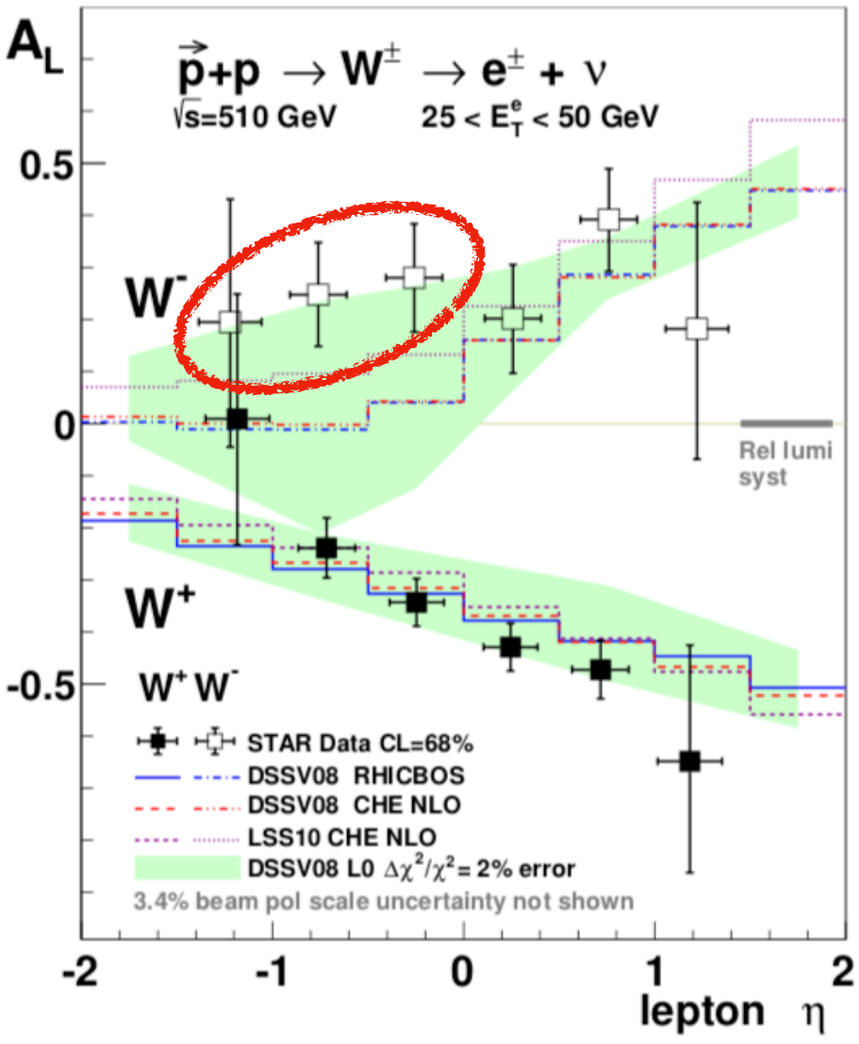




- Differential cross section can also provide constraints on the unpolarized quark/anti-quark distributions.
- Preliminary results from 2011+2012+2013 released on DIS2019 by Matt Posik.

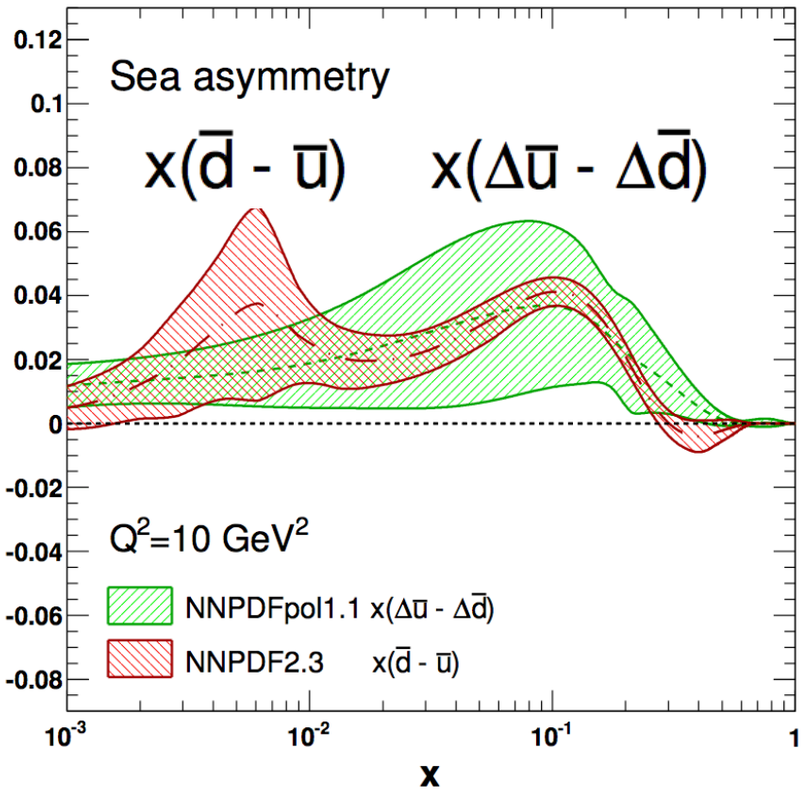
Earlier STAR W A_L results

- 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)

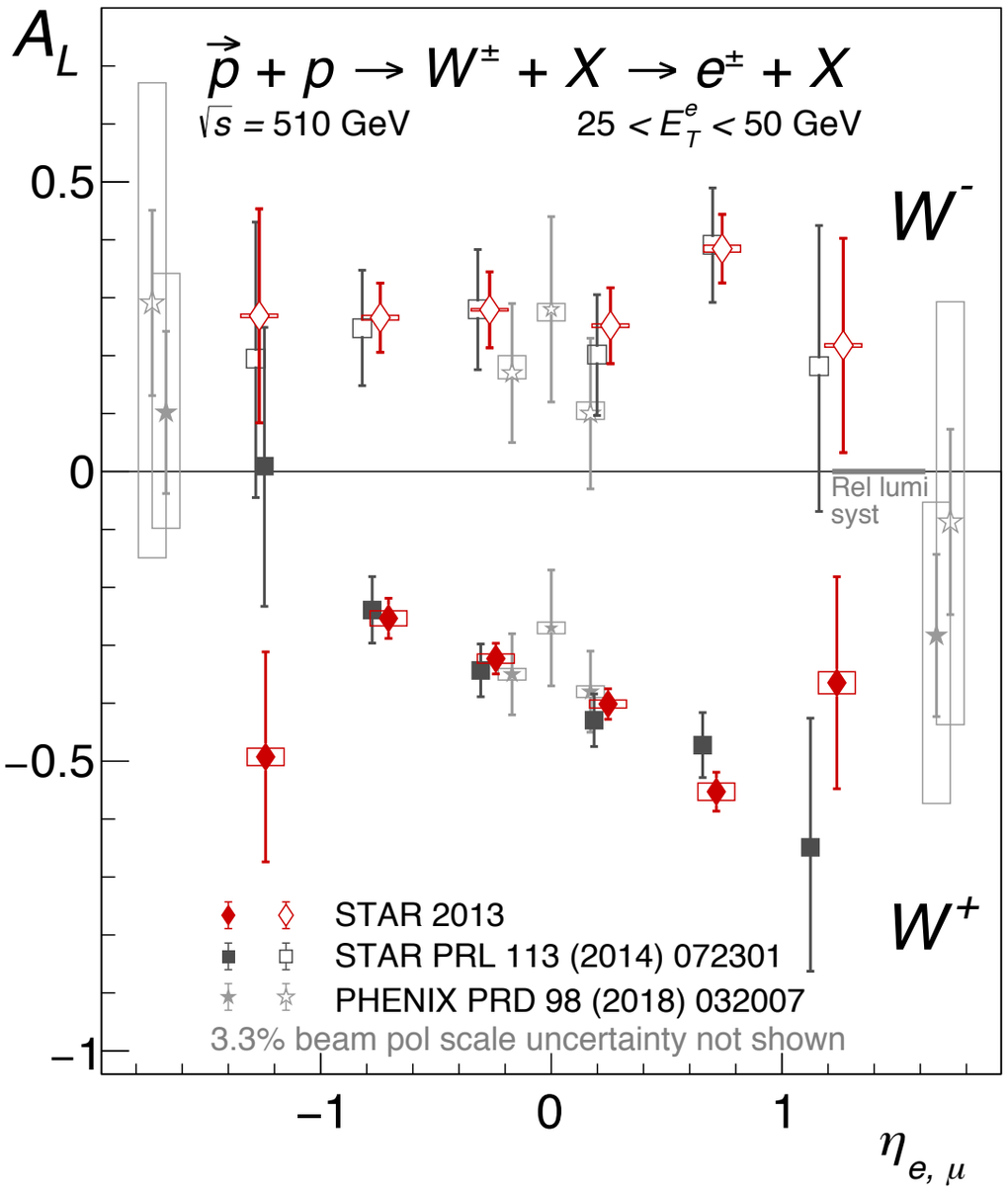
E. Nocera, PoS(DIS2014)204



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

Motivation for more precise data.

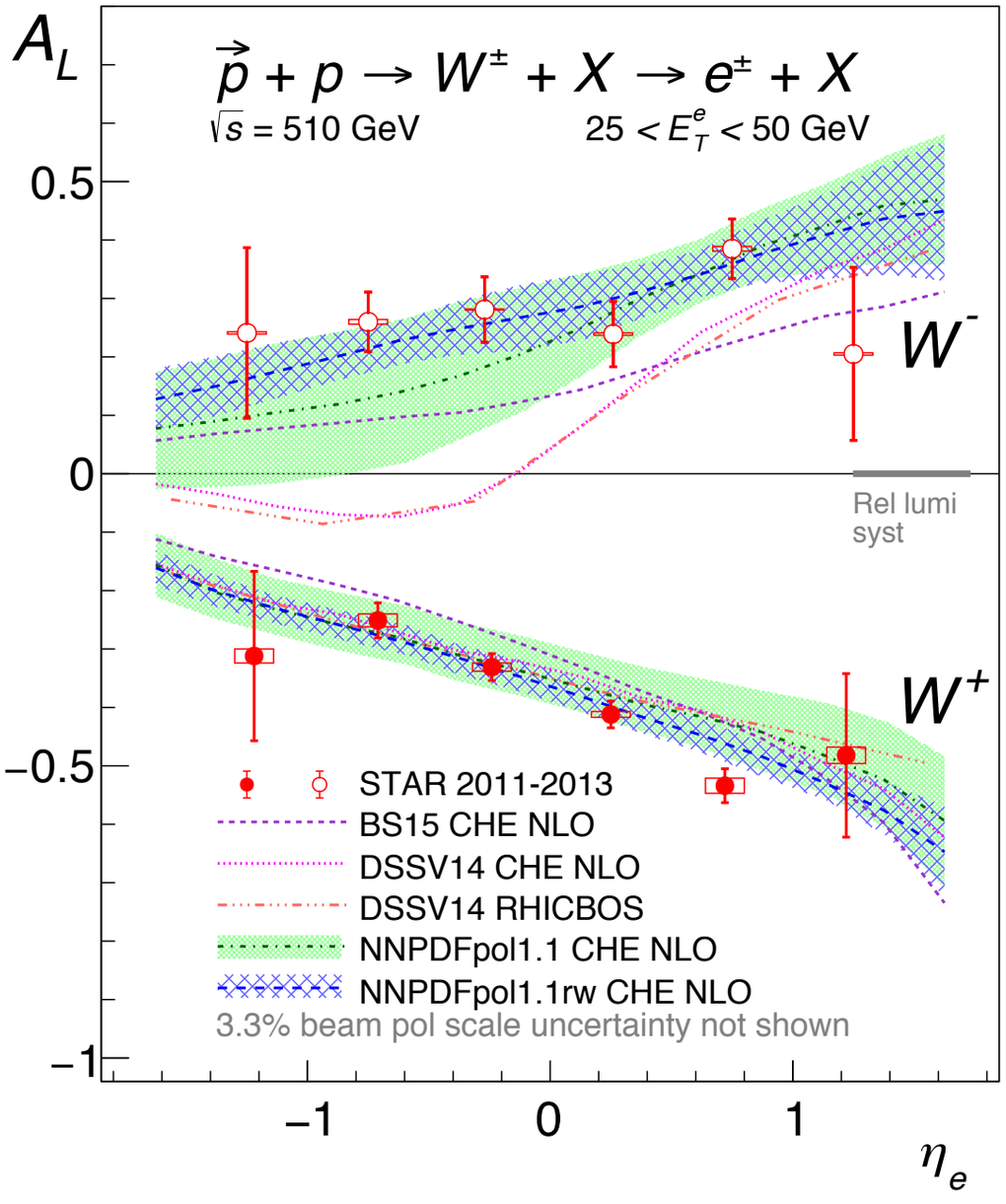
W A_L from Run 2013



PRD 99, 051102(R) (2019)

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

W A_L from Run 2013

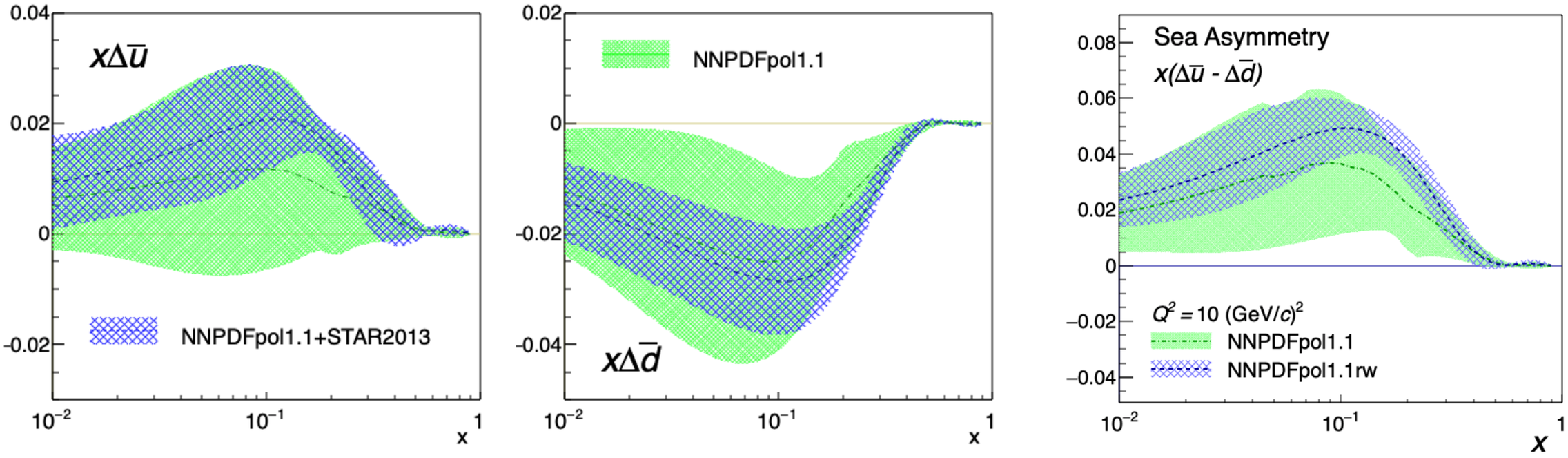


PRD 99, 051102(R) (2019)

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

Impacts of 2013 Results

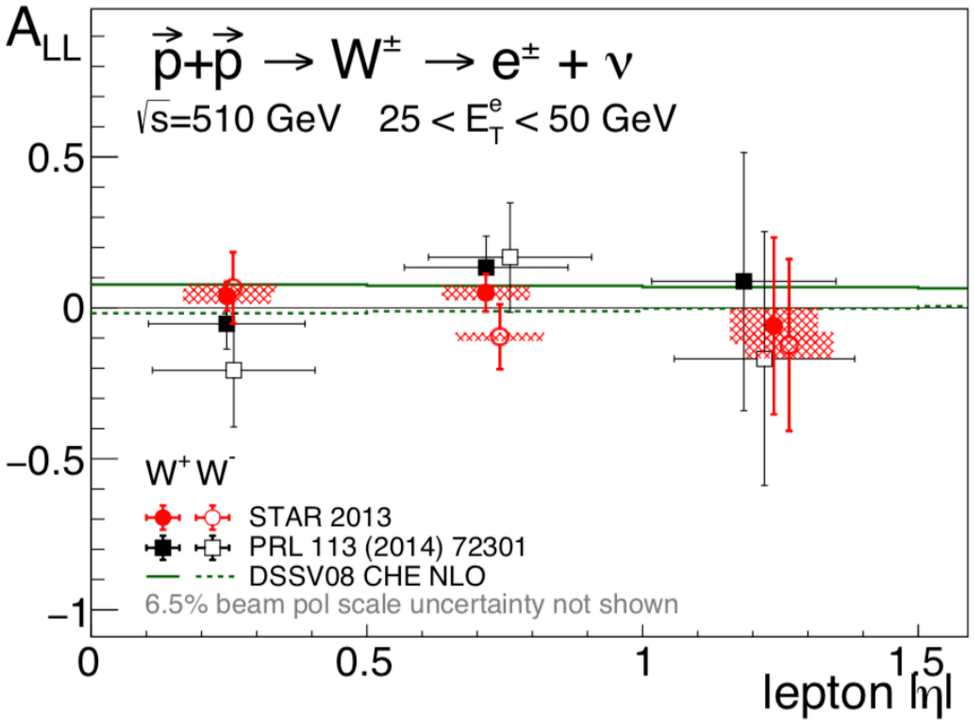
PRD 99, 051102(R) (2019)



- 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.

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

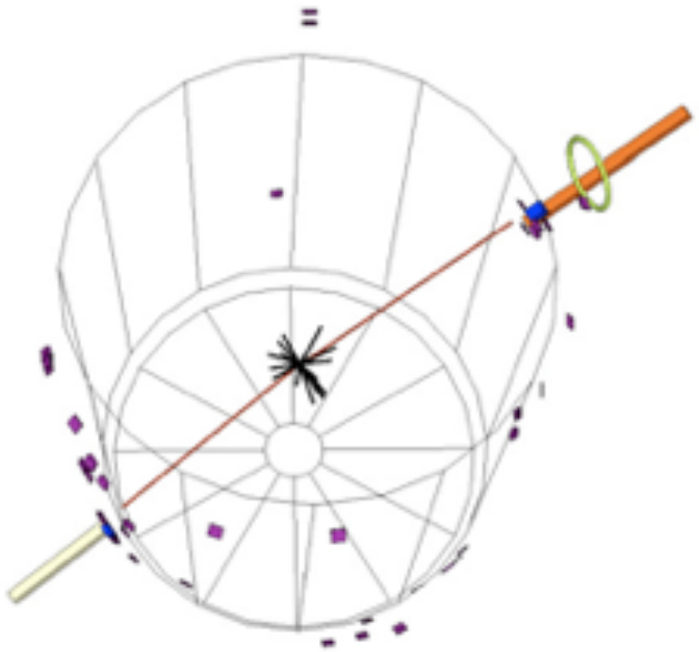
- Positivity constraints using combination of A_L and A_{LL}

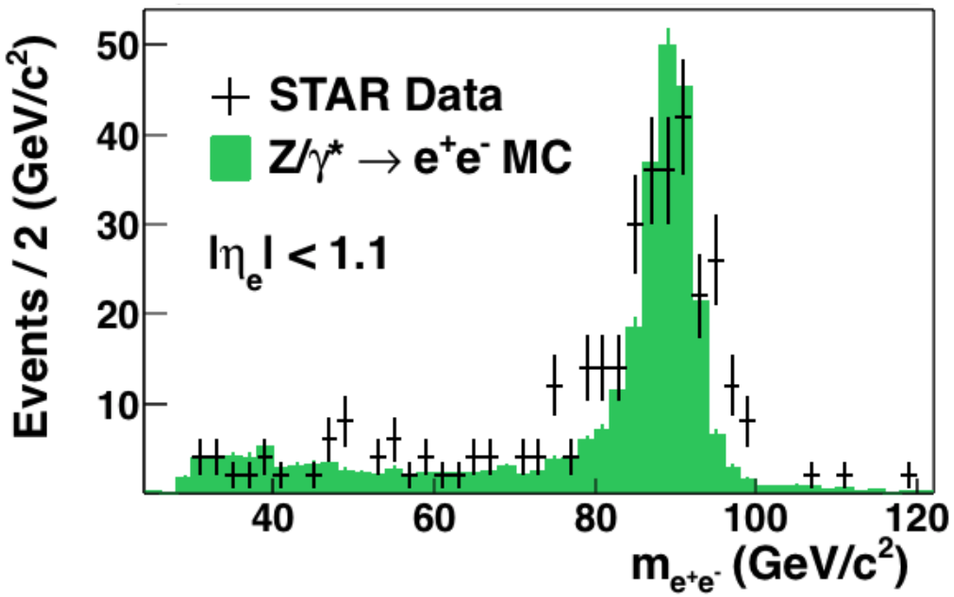
$$1 \pm A_{LL}^{W^\pm}(y_W) > |A_L^{W^\pm}(y_W) \pm A_{LL}^{W^\pm}(-y_W)|$$

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

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

Z/gamma* A_L

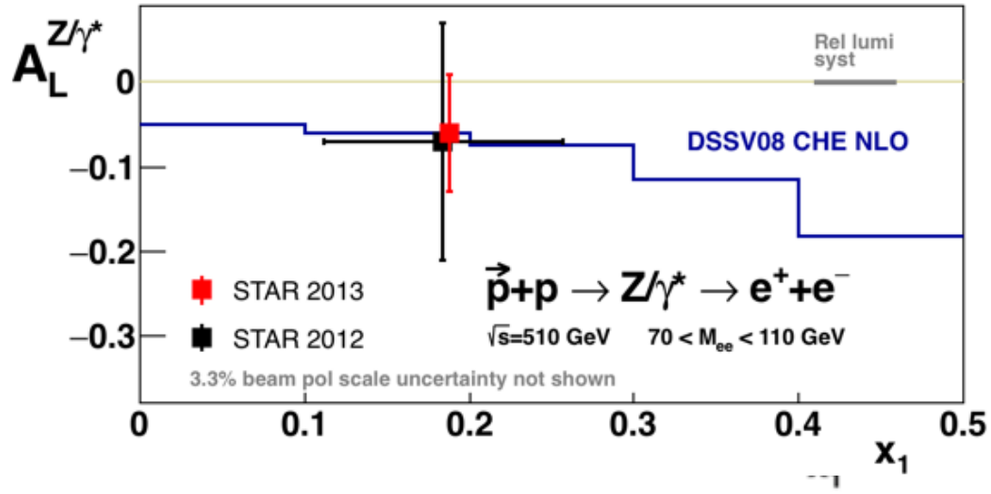




- Z bosons can be fully reconstructed

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

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

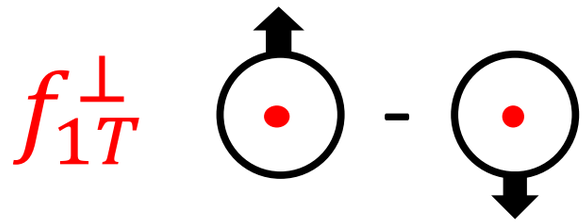


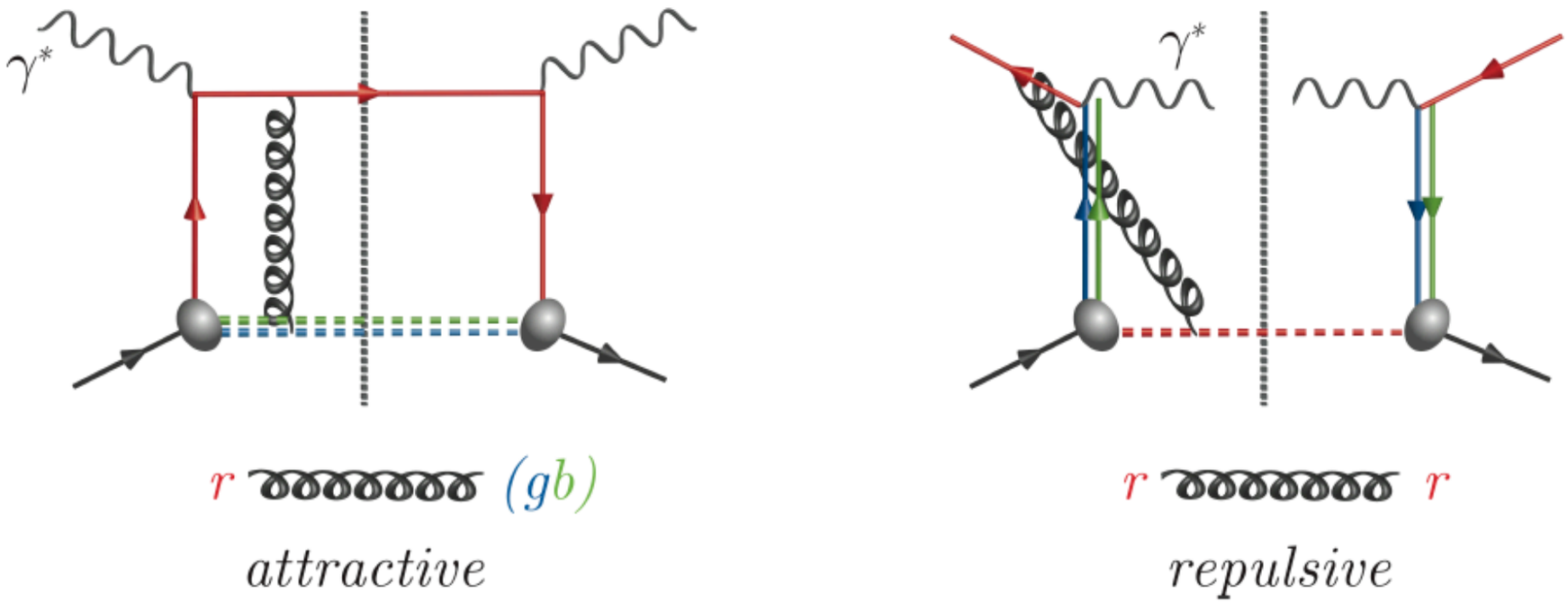
PRD 99, 051102(R) (2019)

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

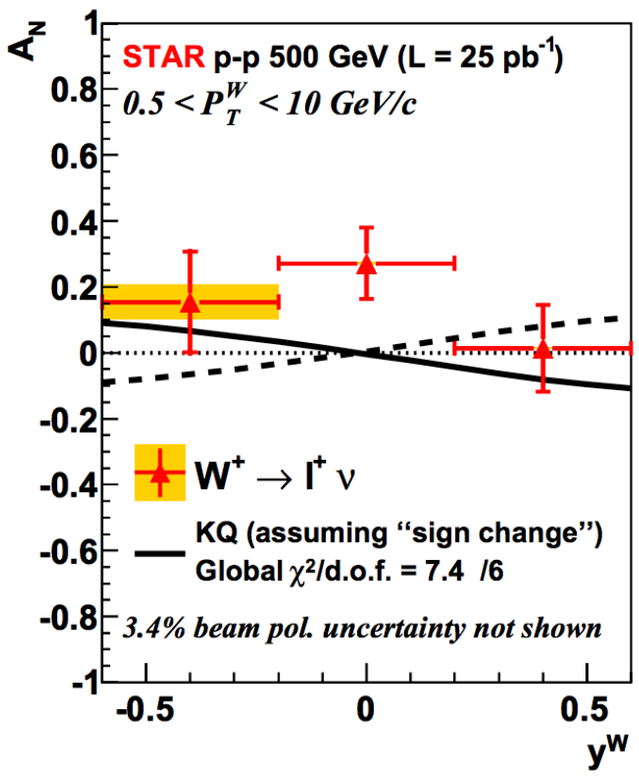


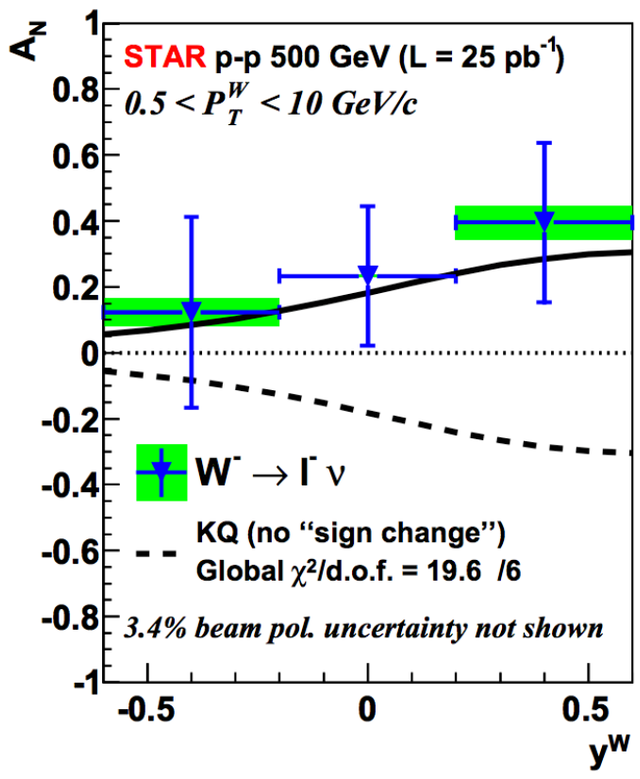


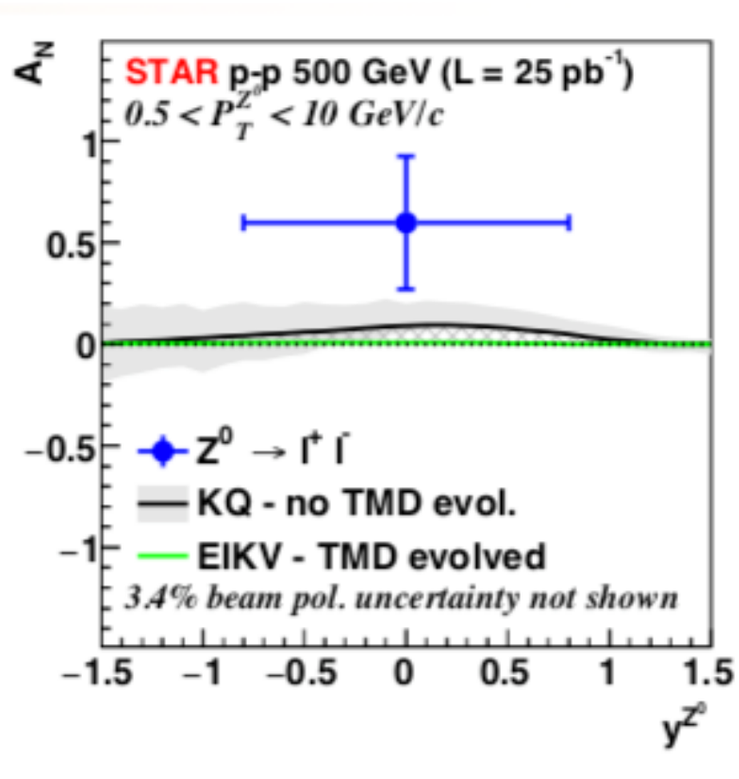
- Not universal: $f_{1T}^{\perp}$ (SIDIS) = $-f_{1T}^{\perp}$ (DY or W/Z)
- Experimental test is critical for our understanding of TMDs and TMD factorization

First W/Z A_N results

STAR, PRL116(2016)132301

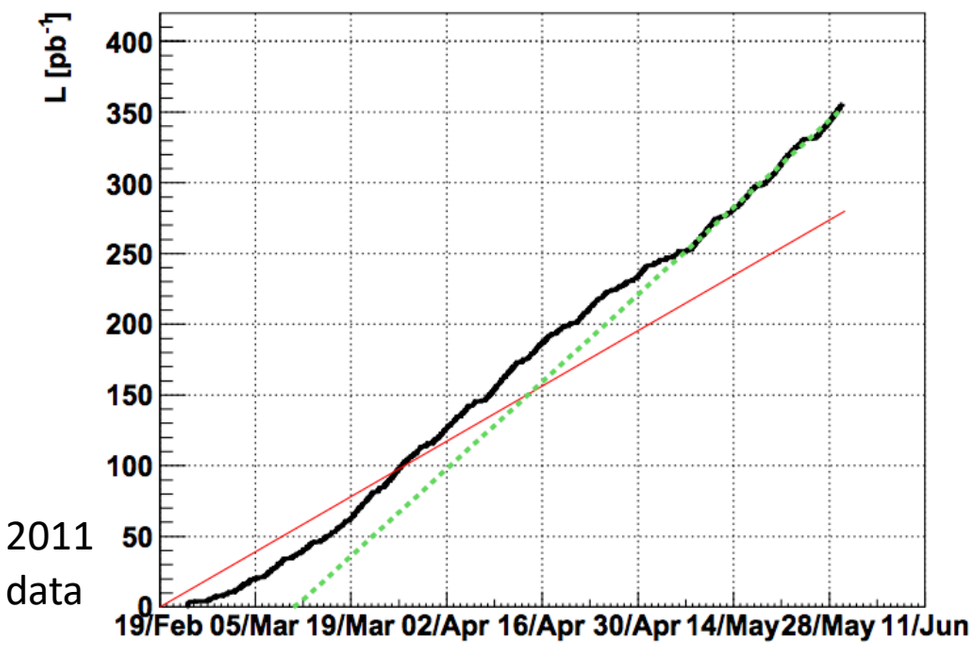






- First transverse W/Z A_N results favor the Sivers' sign-change from data with an integrated luminosity of ~25 pb^{-1}
- W kinematics fully reconstructed

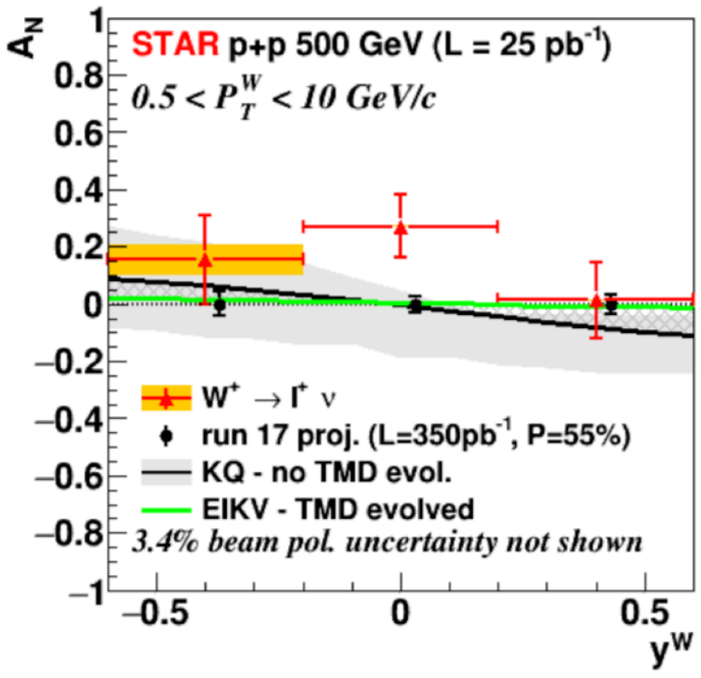
Projection of 2017

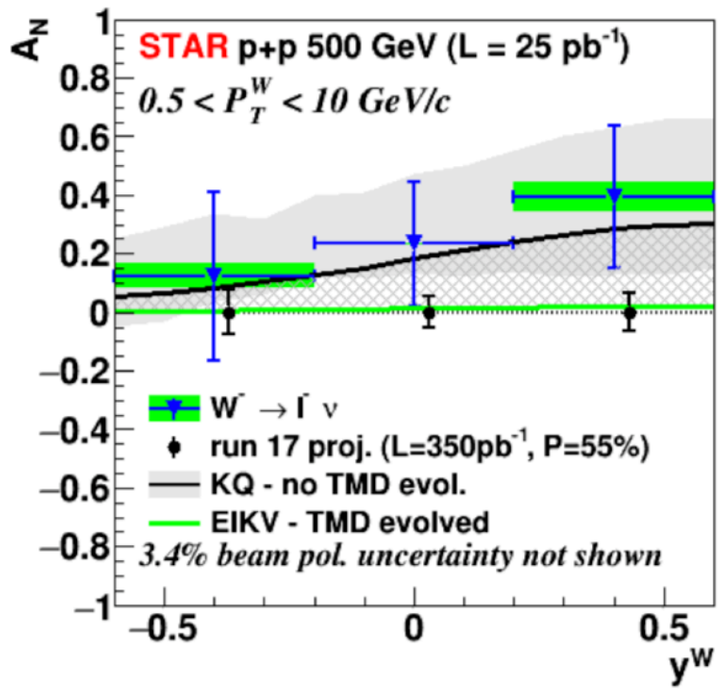


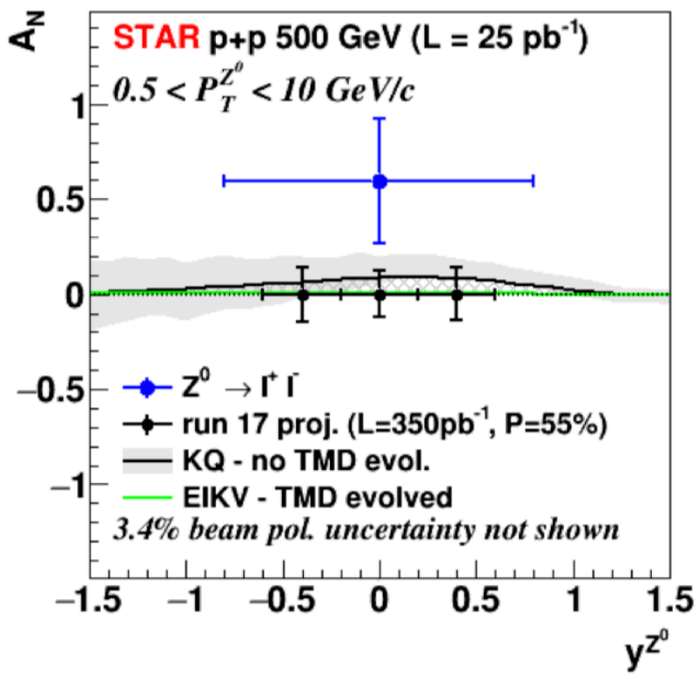
2011 data

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

See Jae Nam's Poster







Summary

- STAR W A_L measurement is concluded; final results:

  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

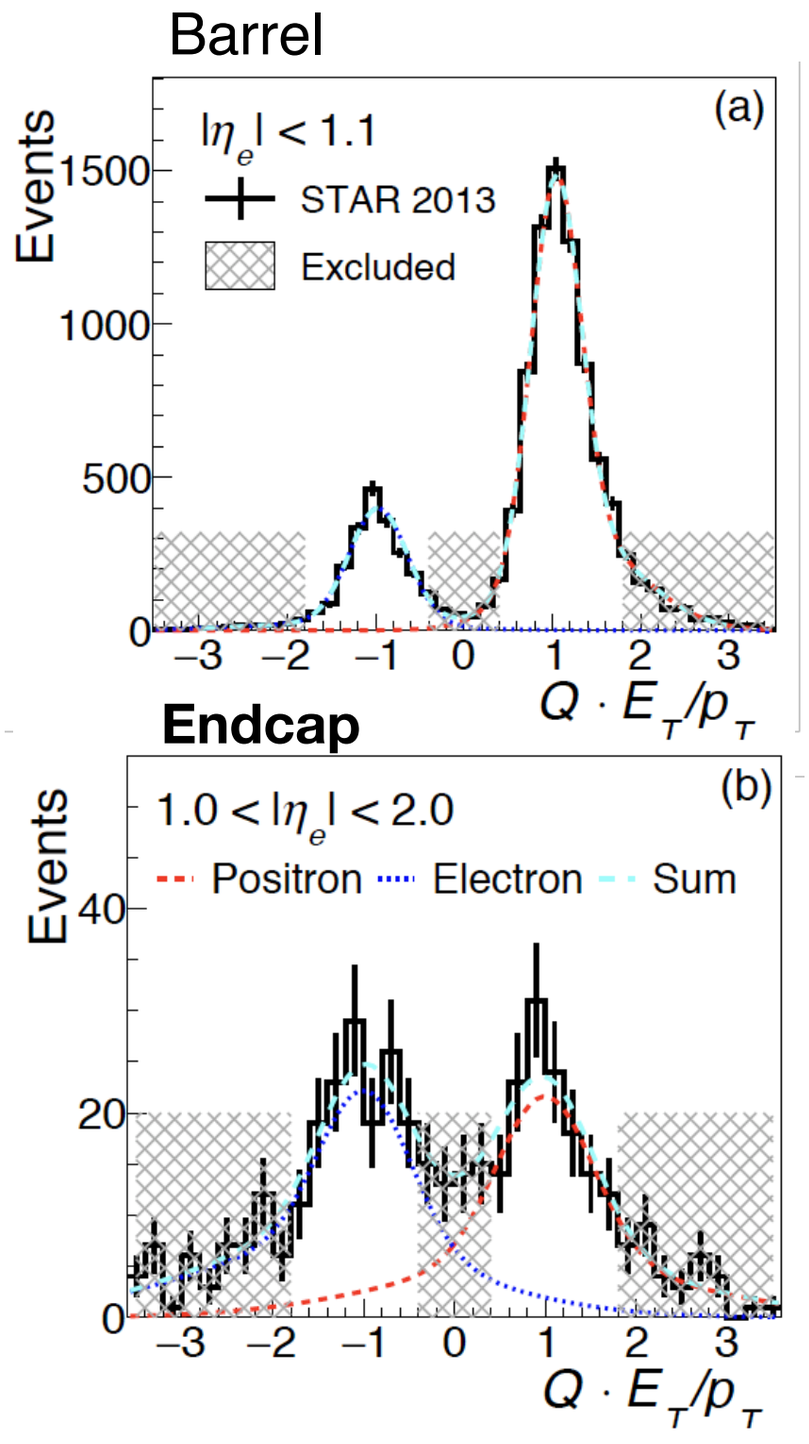
- STAR W/Z A_N first results favor Sivers sign change.

- More precise results from 2017 dataset on W/Z A_N and cross section ratio are coming.

Backup

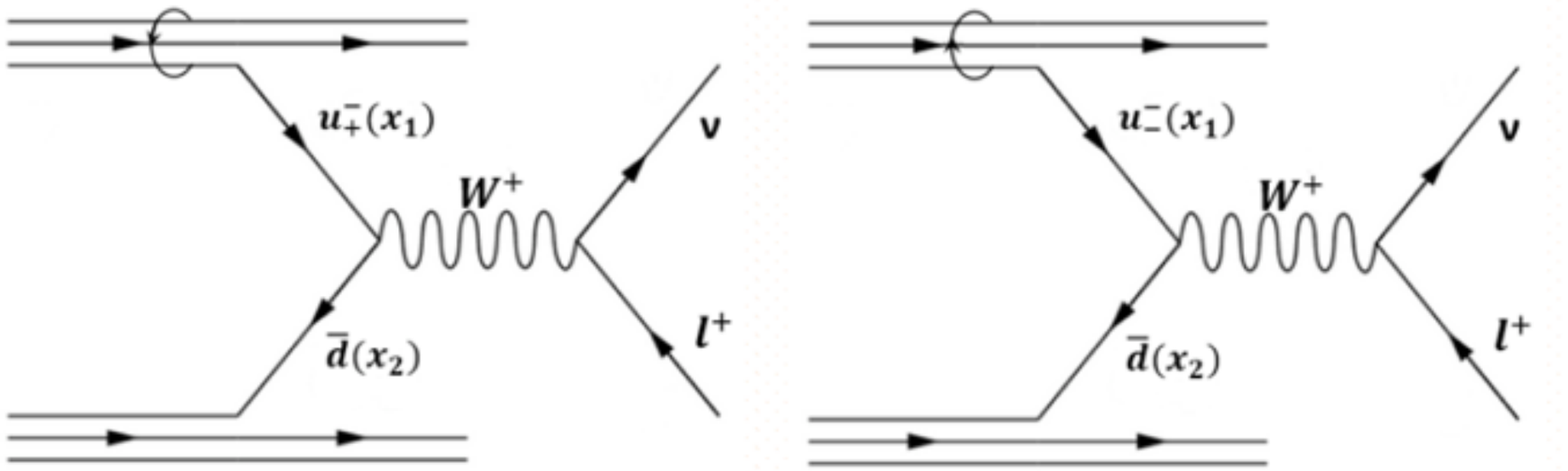
Charge Separation

- A_L has opposite sign for W^+ and W^-
- Wrong change-sign background, if any, thus causes bias and dilution of the signal
- Charge ID from TPC
- Negligibly small in the Barrel acceptance
- ~10% in the Endcap region; corrected for in the analysis



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.