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

Devika Gunarathne
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CURRENT KNOWLEDGE

- Anti-quark polarization
- Flavor asymmetry of the sea

THEORETICAL FOUNDATION [W Asymmetry ($A_L$) / W cross section ratio (RW)]

EXPERIMENTAL ASPECTS [RHIC / STAR]

RESULTS

- $W A_L$
- $W RW$

SUMMARY
Light anti-Quark Polarization: Current Knowledge

- NLO calculations
- Mainly pSIDIS

DNS: data < y2000
DSSV: data < y2004
LSS: data < y2006

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More Precise / large / increased kinematic range - DATA sets

More Precise FFs
Improved global fitting tools

- Phys. Rev. D 80, 034030 (2009)
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More Precise / large / increased kinematic range - DATA sets

More Precise FFs

Improved global fitting tools

But still less precise, in comparison to valence sector

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DNS: data < y2000
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\( W \bar{A}_L \) measurements at RHIC provide a unique (direct sensitivity to \( \bar{u}_L, \bar{d}_L \)) 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: Current knowledge

- Drell-Yan E866 - First concrete evidence

\[ \frac{\bar{d}}{\bar{u}} \text{ theoretical predictions and model calculations} \]

- Recent fit results for CT14 and MMHT14 $\frac{\bar{d}}{\bar{u}}$ ratio shows slight decrease at large $x$

- Model expectation for BS15 $\frac{\bar{d}}{\bar{u}}$ ratio increases at large $x$

\[ \frac{\bar{d}}{\bar{u}} \text{ at large } x \]

\[ \pm 0.032 \text{ Systematic error not shown} \]


\[ \text{Nucl. Phys. A948 (2016) 63-77} \]
Flavor Asymmetry of the Unpolarized Sea: Current knowledge

- Drell-Yan E866 - First concrete evidence

- SeaQuest E906 - Preliminary [also shown E866 results]

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

- Lower $Q^2$ [$\sim$29 GeV$^2$] than Drell-Yan E866 [54 GeV$^2$] (not so significant impact though).

- Measurement extended to large $x$.

- Disagreement with E866 at high $x$. 

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

Devika Gunarathne — W $\Lambda$ and W cross-section ratio measurements at STAR — SPIN 2016 — Sep 25-30 2016 at UIUC
Flavor Asymmetry of the Unpolarized Sea: Current knowledge

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

- SeaQuest E906 - Preliminary [also shown E866 results]

- W production at RHIC at much larger $Q^2$ [6400 GeV$^2$] 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 - $W A_L$

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

- Direct sensitivity to $\bar{u}, \bar{d}$.
- Large $Q^2$ defined by $W$ mass (more reliable perturbative calculation / higher twist effects unimportant!).
- Parity violating coupling gives rise to single-spin asymmetry which is directly related to anti-quark helicity PDFs.
- Free of FFs.
- Easy detection via decay leptons.

In comparison to SIDIS, $A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$

At RHIC kinematics

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

  \[
y_l = y_W + \frac{1}{2} \ln \frac{1 + \cos \theta^*}{1 - \cos \theta^*}\
  \]

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

  \[
x_{1,2} = \frac{M_W}{\sqrt{s}} e^{\pm y_w}\
  \]

  \[
  \frac{M_W}{\sqrt{s}} = 0.16
  \]

- STAR now can also reconstruct full $W$ kinematics via its recoil => used for cross section analysis

Devika Gunarathne — $W A_L$ and $W$ cross-section ratio measurements at STAR — SPIN 2016 — Sep 25-30 2016 at UIUC
Theoretical Foundation $W_A^L - \eta$ dependence

Rapidity dependance of $W_A^L$ provides sensitivity to partonic kinematics.

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

$\eta \ll 0 \rightarrow \theta \rightarrow \pi$

$\eta \gg 0 \rightarrow \theta \rightarrow 0$

$\eta = 0 \rightarrow \theta = \pi/2$

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

$\eta \ll 0 \rightarrow x_1 \ll x_2$

$\eta \gg 0 \rightarrow x_1 \gg x_2$

$\eta = 0 \rightarrow x_1 \sim x_2$
Rapidity dependence of $W A_L$ provides sensitivity to partonic kinematics.

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

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Devika Gunarathe — $W A_L$ and $W$ cross-section ratio measurements at STAR — SPIN 2016 — Sep 25-30 2016 at UIUC
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$$\eta = -\ln \left( \tan \left( \frac{\theta}{2} \right) \right)$$

$$\eta \ll 0 \rightarrow x_1 \ll x_2, \theta \rightarrow \pi$$
one can expect sensitivity to the polarized quark and anti-quark distribution of the polarized parton. Note that the polar angle of the electron in the partonic c.m.s., with dominantly probed parton rapidities is less clear-cut than in the case of interactions entering. For lepton's rapidity. At large negative rapidities dominance of parton distributions, terms in the numerator and denominator of Eq. (5) strongly dominate, but at the same time their counterpart in the second term. Therefore, the asymmetry is found to be given by

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

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

\[
\eta \ll 0 \rightarrow x_1 \ll x_2, \theta \rightarrow \pi
\]

\[
\eta \gg 0 \rightarrow x_1 \gg x_2, \theta \rightarrow 0
\]

\[
\langle x_{1,2} \rangle \sim \frac{M_w}{\sqrt{s}} e^{\pm \eta_e/2}
\]
Rapidity dependance of $W A_L$ provides sensitivity to partonic kinematics.

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

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

\[
\eta \ll 0 \rightarrow x_1 \ll x_2, \theta \rightarrow \pi \\
\eta = 0 \rightarrow x_1 \sim x_2 \\
\eta \gg 0 \rightarrow x_1 \gg x_2, \theta \rightarrow 0
\]
Theoretical Foundation $W A_L - \eta$ dependence

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

Devika Gunarathne — $W A_L$ and $W$ cross-section ratio measurements at STAR — SPIN 2016 — Sep 25-30 2016 at UIUC
Theoretical Foundation: W unpolarized cross-section ratio

**W unpolarized cross section ratio**

\[ R(x_F) \equiv \frac{\sigma^+_W}{\sigma^-_W} = \frac{u(x_1) \bar{d}(x_2) + \bar{d}(x_1) u(x_2)}{\bar{u}(x_1) d(x_2) + d(x_1) \bar{u}(x_2)} + NLO + NNLO + \ldots \]

- Approximate kinematic range at RHIC:
  
  \[ 0.06 < x < 0.4 \quad \text{for} \quad -2 < \eta < 2 \]

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

RHIC kinematic coverage (mid-rapidity) is sensitive in particular to “turn over” region of x in \( \bar{d}/\bar{u} \) of E866.

\[ R = \frac{N^+_O - N^+_B}{N^-_O - N^-_B} \cdot \frac{\epsilon^-}{\epsilon^+} \]

- \( N^+_O(-) \) = measured positron (electron) decay events
- \( N^+_B(-) \) = Positive (negative) background events
- \( \epsilon \) = lepton detection efficiency

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**EXPERIMENTAL ASPECT - RHIC**

- **RHIC**: Relativistic Heavy Ion Collider

  The World’s first polarized hadron collider!

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

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![Diagram of RHIC](image-url)
EXPERIMENTAL ASPECT - STAR

• **STAR**: Solenoidal Tracker At RHIC

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

**TPC**: Charged particle tracking
**BEMC, EEMC**: EM Calorimetry

- TPC: \(-1.3 < \eta < +1.3\)
- BEMC: \(-1.0 < \eta < +1.0\)
- EEMC: \(+1.1 < \eta < +2.0\)
- FGT: \(+1.0 < \eta < +2.0\)
**ANALYSIS - RHIC PP running STAR W data collection**

- Production runs at $\sqrt{s}=500/510\text{GeV}$ (long. polarization) in 2009, 2011, 2012 and 2013:

  - **W production (Quark polarization)** / **Jet and Hadron production (Gluon polarization)**

<table>
<thead>
<tr>
<th>Run</th>
<th>L (pb$^{-1}$)</th>
<th>P (%)</th>
<th>FOM ($P^2L$) (pb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>12</td>
<td>0.38</td>
<td>1.7</td>
</tr>
<tr>
<td>2011</td>
<td>9.4</td>
<td>0.49</td>
<td>2.3</td>
</tr>
<tr>
<td>2012</td>
<td>77</td>
<td>0.56</td>
<td>24</td>
</tr>
<tr>
<td>2013</td>
<td>246.2</td>
<td>0.56</td>
<td>77.2</td>
</tr>
</tbody>
</table>

- $W_A$ recent result present today is from data collected during year 2013, the largest data set STAR ever collected!

- Prior $W_A$ analysis from data collected during 2009 and 2011+2012 are published!

- **Phys. Rev. D85, 092010 (2012)**
- **STAR: PRL 106, 062002(2011)**
- **STAR: PRL 113, 072301(2014)**

Devika Gunarathne — $W_A$ and $W$ cross-section ratio measurements at STAR — **SPIN 2016** — Sep 25-30 2016 at UIUC
ANALYSIS - Mid rapidity STAR W selection criteria

TPC track extrapolated to Barrel colorimeter tower grid

Transverse plane view

Devika Gunarathne — W Al and W cross-section ratio measurements at STAR — SPIN 2016 — Sep 25-30 2016 at UIUC
W → e+ν candidate event

- Isolated high $P_T$ track pointing to isolated EMC cluster.
- Large Imbalance in the reconstructed vector $P_T$ sum in $4\pi$ due to undetected neutron.

QCD Background event

- Several tracks pointing to several EMC clusters.
- Vector $P_T$ sum is balanced by the Jet opposite in $\pi$.
• 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

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

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

\[ P_T^{\text{bal}} = P_T^e + \sum_{\Delta R > 0.7} P_T^{\text{jet}s} \]

\[ P_T^{\text{balance cos(}\phi)} = \frac{P_T^e \cdot P_T^{\text{bal}}}{|P_T^e|} \]
ANALYSIS - Mid rapidity STAR W BG Estimation

- 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.

Primary Background

ElectroWeak Background

- Determine from MC simulation
  
  $Z \rightarrow e^+ e^-$
  
  $W \rightarrow \tau + \nu$
**RESULTS - W A_L - STAR 2011+2012**

- STAR 2011 + 2012 W AL Published Results

\[ \vec{p} + p \rightarrow W^\pm \rightarrow e^\pm + \nu \]
\( \sqrt{s} = 510 \text{ GeV} \quad 25 < E_T^e < 50 \text{ GeV} \)

- 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 \( 0.05 < x < 0.2 \).
• Impact on helicity PDF from DSSV [STAR 2012 W A_L Preliminary]

• Anti u quark polarization

• Anti d quark polarization

• 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.
• Impact on helicity PDF from NNPDF pol 1.1 [RHIC W $A_L$]

• Anti $u$ quark polarization

• Anti $d$ quark polarization

• Significant shift of $\Delta \bar{u}$ central value from RHIC $W$ $A_L$ data.
• 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**

- $p+p \rightarrow W^\pm \rightarrow e^\pm + \gamma$

- $\sqrt{s}=510$ GeV

- $25 < E_T < 50$ GeV

$\chi^2/\chi^2_{\text{LO}}=2\%$ error

3.3% beam pol scale uncertainty not shown
• STAR 2013 W A_L Preliminary Results in comparison to STAR 2011+2012 published results

• STAR 2013 W A_L 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%.

\[ (p + p \rightarrow W^\pm \rightarrow e^\pm + \nu) \quad (s=510 \text{ GeV} \quad 25 < E_T^e < 50 \text{ GeV}) \]
STAR 2013 Preliminary Results in comparison to STAR 2011+2012 published results, PHENIX 2011+2012, PHENIX 2013 W AL results

- STAR 2013 Preliminary W AL results is the Most Precise measurements of W AL up to date!
- STAR 2013 preliminary W AL results consistent with published 2011 + 2012 results.
- Uncertainties were reduced by 40%.
- Also consistent with PHENIX results.
• STAR 2011+2012 Preliminary Results [statistics - 102 pb$^{-1}$]
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.
• **$R_W$ 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 for preliminary $W$ cross section results shown below as well as recently published transverse single-spin asymmetry measurements at STAR.  

\[ p+p \rightarrow W^\pm + X \rightarrow e^\pm + X \]

\[ \sqrt{s}=500/510 \text{ GeV} \]

\[ R_W(y_W) \]

\[ \text{Phys. Rev. Lett. 116 (2016) 132301} \]
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 constrain 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⁻¹, analyzing) and Run 17 data (~400 pb⁻¹, next year) will further improve precision of W cross section ratio measurements at STAR allowing to constrain dbar/ubar ratio.
BACK UP
INTRODUCTION: Proton Helicity Structure

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

\[ \langle S_z \rangle = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_z \]

**1989: EMC: DIS**

\[ \Delta \Sigma = 0.12 \pm 0.09 \pm 0.14 \]

“Spin Crisis”

**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.

Devika Gunarathne — W A and W cross-section ratio measurements at STAR — SPIN 2016 — Sep 25-30 2016 at UIUC
<table>
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<tbody>
<tr>
<td>$-1.1 &lt; \eta &lt; -0.5$</td>
<td>$-0.254 \pm 0.037$</td>
<td>$0.262 \pm 0.062$</td>
</tr>
<tr>
<td>$-0.5 &lt; \eta &lt; 0$</td>
<td>$-0.332 \pm 0.028$</td>
<td>$0.340 \pm 0.071$</td>
</tr>
<tr>
<td>$0 &lt; \eta &lt; 0.5$</td>
<td>$-0.420 \pm 0.028$</td>
<td>$0.237 \pm 0.071$</td>
</tr>
<tr>
<td>$0.5 &lt; \eta &lt; 1.1$</td>
<td>$-0.559 \pm 0.036$</td>
<td>$0.386 \pm 0.061$</td>
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</tbody>
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<tr>
<td>$-1.1 &lt; \eta &lt; -0.5$</td>
<td>$-0.239 \pm 0.057$</td>
<td>$0.247 \pm 0.100$</td>
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<tr>
<td>$-0.5 &lt; \eta &lt; 0$</td>
<td>$-0.343 \pm 0.045$</td>
<td>$0.280 \pm 0.104$</td>
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<tr>
<td>$0 &lt; \eta &lt; 0.5$</td>
<td>$-0.429 \pm 0.045$</td>
<td>$0.202 \pm 0.104$</td>
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<tr>
<td>$0.5 &lt; \eta &lt; 1.1$</td>
<td>$-0.472 \pm 0.056$</td>
<td>$0.391 \pm 0.099$</td>
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<table>
<thead>
<tr>
<th>$\chi^2$/n.d.f</th>
<th>$W^+ A_L$</th>
<th>$W^- A_L$</th>
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<tr>
<td>1.83/4</td>
<td></td>
<td>0.32/4</td>
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</table>

Devika Gunarathne — $W_A L$ and $W$ cross-section ratio measurements at STAR — SPIN 2016 — Sep 25-30 2016 at UIUC
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 - Forward and central bins combined

- **BG ESTIMATION**

![Graphs showing electron and positron distributions](image)
TPC Charge-sign Separation

vertex 200 cm of tracking BEMC

$Q^+ \text{ PT} = 5 \text{ GeV}$

$Q^- \text{ PT} = 5 \text{ GeV}$

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DSSV - Polarized flavor asymmetry

- DSSV global fit result

From recent DSSV++ result incl. STAR AL data:

\[ \int_{0.05}^{1} \Delta u(x, Q^2) dx \approx 0.02 \]

\[ \int_{0.05}^{1} \Delta \bar{d}(x, Q^2) dx \approx -0.05 \]
W reconstruction - Full kinematics

\[ \vec{P}_T^{W} = \vec{P}_T^{e} + \vec{P}_T^{\nu} = -\vec{P}_T^{\text{recoil}} \]

- Recoil Reconstruct using tracks and towers
- MC correction applied for part of the recoil not within STAR acceptance!

- Neutrino transverse momentum based on missing PT
  \[ \sum_{i \in \text{tracks}} \vec{P}_T^i \]

- Neutrino longitudinal momentum from decay kinematics
  \[ \vec{P}_T^{\nu} \approx - \sum_{i \in \text{tracks}} \vec{P}_T^i \]

- Neutrino longitudinal momentum from decay kinematics
  \[ M_W^2 = \left( E_e + E_\nu \right)^2 - \left( \vec{p}_e + \vec{p}_\nu \right)^2 \]
Efficiency studies

- depend very little on the charge
- Run 12 is less efficient in comparison to run 11, due to lower track reconstruction efficiency

lepton Rapidity

- Systematic are much less than statistical
- Syst. comes from Background subtraction

W rapidity

- Correction factors are approximately charge and interaction rate independent.
- No impact on cross-section ratios
- Syst. from Background subtraction and W reconstruction smearing