First results of $W^\pm$ boson production in high-energy polarized p+p collisions at RHIC at BNL

Bernd Surrow
Outline

- W production - Recent Results
  - First $W^+/W^-$ Cross-section and $A_L$ Measurement at STAR

- Experimental aspects:
  - RHIC / STAR

- Introduction

- Summary and Outlook
How do we probe the structure and dynamics of matter in ep / pp scattering?

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

\[ W^2 \approx Q^2/x \]

\[ d\sigma_{pp} \propto f_1 \otimes f_2 \otimes \sigma_h \otimes D_f^h \]

Introduction

Momentum contribution

\[ f(x) = f^+(x) + f^-(x) \]

Spin contribution

\[ \Delta f(x) = f^+(x) - f^-(x) \]
What do we know about the polarized quark and gluon distributions?

- Spin carried by quarks is very small ($\Delta \Sigma \sim 0.3$)!

$$\frac{1}{2} \Delta \Sigma = \langle S_q \rangle + \langle S_g \rangle + \langle L_q \rangle + \langle L_g \rangle$$

$$\Delta \Sigma = \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}$$

$$\Delta q_i(Q^2) = \int_0^1 \Delta q_i(x, Q^2) \, dx$$

$$\Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2) \, dx$$

Introduction
Polarized semi-inclusive DIS results: HERMES / COMPASS

- Semi-inclusive DIS: Correlation of flavor content of hadron with flavor of quark / antiquark probed
- Good agreement of COMPASS and HERMES LO analysis
- Good agreement with global fit analysis / Sea quark distributions compatible with zero
- Great value of independent probe at large momentum scales (sub-leading twist effects unimportant) without hadronic fragmentation
- STAR W program in e-decay mode at mid-rapidity and forward/backward rapidity

\[ \frac{u / \Delta u}{d / \Delta d} \]

\[ W^+ (W^-) \]

\[ A_L^W = \frac{1}{P} \frac{N^+ (W) - N^- (W)}{N^+ (W) + N^- (W)} \]

\[ \nu_e (\bar{\nu}_e) \]

\[ e^+ (e^-) \]

\[ \Delta \bar{d} / \bar{d} (\Delta \bar{u} / \bar{u}) \]

- Key signature: High \( p_T \) lepton
  \((-e^-/e^+)(\text{Max. } M_W/2)\) - Selection
  of \( W^+ / W^- \): Charge sign
discrimination of high \( p_T \) lepton

- Required: Lepton/Hadron
discrimination

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

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

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

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

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

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Total (\( \sqrt{s}=500\text{GeV} \)) \( \sigma(W^+) = 135 \text{pb} \) and \( \sigma(W^-) = 42 \text{pb} \)
Introduction

- Leptonic rapidity inherits relation to mean $x$
  - Forward rapidity: $\eta > 0$
    - $<x_1>$ larger than $<x_2>$
  - Backward rapidity: $\eta < 0$
    - $<x_1>$ less than $<x_2>$
- Mid-rapidity: $\eta \sim 0$
  - $<x_1>$ similar to $<x_2>$

\[
< X_{1,2} > \approx \frac{M_W}{\sqrt{S}} e^{\pm \eta/2}
\]

D. deFlorian and W. Vogelsang, hep-ph/1003.4533
**Introduction**

- **$A_L$** behavior for STAR mid-rapidity and forward/backward rapidity region

### Calculations:
2. deFlorian / Vogelsang: D. deFlorian, private communications.
Collider: The First polarized p+p collider at BNL

- RHIC Performance - Overview

- First collisions of polarized proton beams at √s=500GeV (long. polarization): Run 9
## Collider: The First polarized p+p collider at BNL

### RHIC polarized p+p running

<table>
<thead>
<tr>
<th>RHIC RUN</th>
<th>$s$ [GeV]</th>
<th>$L_{\text{recorded}}$ [pb$^{-1}$] (trans.)</th>
<th>$L_{\text{recorded}}$ [pb$^{-1}$] (long.)</th>
<th>Polarization [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RUN 2</td>
<td>200</td>
<td>0.15</td>
<td>0.3</td>
<td>15</td>
</tr>
<tr>
<td>RUN 3</td>
<td>200</td>
<td>0.25</td>
<td>0.3</td>
<td>30</td>
</tr>
<tr>
<td>RUN 4</td>
<td>200</td>
<td>0</td>
<td>0.4</td>
<td>40-45</td>
</tr>
<tr>
<td>RUN 5</td>
<td>200</td>
<td>0.4</td>
<td>3.1</td>
<td>45-50</td>
</tr>
<tr>
<td>RUN 6</td>
<td>200</td>
<td>3.4/6.8</td>
<td>8.5</td>
<td>60</td>
</tr>
<tr>
<td>RUN 8</td>
<td>200</td>
<td>7.8</td>
<td>-</td>
<td>45</td>
</tr>
<tr>
<td>RUN 9</td>
<td>200 / 500</td>
<td>-</td>
<td>25 / 14</td>
<td>55 / 40</td>
</tr>
</tbody>
</table>

- **Transverse program**: $A_N$ measurement of forward $\pi^0$ and $\eta$ production (Run 2 / Run 6 / Run 8)
- **Gluon polarization program**: Inclusive jet and hadron production (Run 3/4, Run 5, Run 6 and Run 9)
- **W program**: First $A_L$ measurement $W^+$ and $W^-$ boson production from Run 9
The STAR Experiment at RHIC

- **Overview**
  - Calorimetry system with $2\pi$ coverage: BEMC (-1<\(\eta<1\)) and EEMC (1<\(\eta<2\))
  - TPC: Tracking and particle ID
  - ZDC: Relative luminosity and local polarimetry
  - BBC: Relative luminosity and Minimum bias trigger

First collisions of polarized proton beams at STAR at $\sqrt{s} = 500\text{GeV}$: Run 9 (P~40% / L~14pb$^{-1}$)

- **STAR Mid-rapidity W program** (-1<\(\eta<1\)): BEMC and TPC
- **STAR Forward/Backward W program** (1<\(\eta<2\)): EEMC and TPC / FGT (Installation in summer 2011)
W production results: Algorithm

- W reconstruction - Algorithm: Idea

Transverse plane view

- ptBalance `egg` 4pi - nearCone
- awayCone delPhi=0.7 sum all
- sum only jets
- electron nearCone delR=0.7

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We found \(\sim 600\) of those kinds of events!
We recorded and rejected ~1.5M of those kinds of events!
W production results: $Z^0$ event

- Event display ($Z$ event candidate) and detector signature

We found a handful of those kinds of events!
Lego plots - STAR BEMC/TPC

W production results: Lego plots

Run 9 STAR Data (√s=500GeV)

BEMC $E_T$ Distribution (GeV)

TPC $p_T$ Distribution (GeV/c)

W event

Di-Jet event
**W production results: Algorithm Details**

**W reconstruction - Algorithm: Details (1)**

**General:**
- Select L2W-E_T triggered events
- Select vertices with |Z|<100 cm

**Electron isolation cuts:**
- Electron candidate is any primary TPC track with global \( P_T > 10 \text{ GeV}/c \)
- Extrapolate TPC track to BTOW tower
- Compute 2x2 tower cluster \( E_T \), require \( E_T \) sum > 15 GeV
- Require the excess \( E_T \) in 4x4 tower patch over 2x2 patch to be below 5%
- Require distance of 2x2 cluster vs. TPC track below 7 cm

**Near-cone veto:**
- Compute near-cone \( E_T \) sum of BEMC+TPC over \( \Delta R=0.7 \) in eta-phi space
- Require near-cone excess \( E_T \) below 12%

**Away-'cone' cuts: \( p_T \) balance requirement**
- Vector sum > 15GeV/c of: 2X2 tower cluster \( p_T \) and \( p_T \) of any number of jets outside near-cone
- \( E_T \) of jet > 3.5GeV
W production results: Algorithm Details

- **W reconstruction - Algorithm : Details (2)**
  - Lepton meas. in TPC (direction) and in BEMC (energy)
    - TPC & BEMC matching
  - Suppress background
    - BEMC cluster isolation
    - Near-side veto
    - Away-side veto

Transverse plane view

Select 2x2 cluster with highest $E_T$ sum

TPC track extrapolated to BTOW tower grid

Counts

<table>
<thead>
<tr>
<th>$E_T^e / E_T^{4\times4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Counts</td>
</tr>
<tr>
<td>0.5</td>
</tr>
<tr>
<td>1.0</td>
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Signed $p_T$ balance (GeV)

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</tbody>
</table>

W events

Di-Jet events

M-C: W's

M-C: QCD

STAR data

M-C arb. norm.
W production results: Algorithm Details

- Evolution of $E_T$ distribution vs. cut ID

Using the algorithm a clear Jacobian peak can be seen characteristic for $W$ production in contrast to QCD background!
Mid-rapidity high $p_T$ $e^\pm$ charge separation

**Q**: Charge-sign of reconstructed track

- Positron $p_T = 5$ GeV/c
- Electron $p_T = 5$ GeV/c

$+/-$ distance $D$: $\sim 1/p_T$

- $p_T = 5$ GeV/c : $D \sim 15$ cm
- $p_T = 40$ GeV/c : $D \sim 2$ cm

Assign:
- $Q/p_T > 0$ positrons
- $Q/p_T < 0$ to be electrons

Successful separation of different charge states!

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W production results: Charged-separated Yields

- Charge separated raw Signal / Jacobian Peak Distributions

- Charged separated $W^+/W^-$ candidate distributions of the BEMC cluster transverse energy $E_T$ (GeV)

- Cuts: All previously discussed cuts!
W production results: Background

- **Background treatment**
  
  - **PYTHIA+GEANT MC**
  
  
  - $W \rightarrow \tau + \nu_\tau$
  
  - $\tau \rightarrow e + \nu_e + \nu_\tau$

  1. Run analysis with EEMC in veto cuts
  2. Run analysis without EEMC in veto cuts
  3. Subtract two raw signals

- **Background systematics:**
  
  - Calculate different data driven QCD background shapes by varying $p_T$ balance and away-side $p_T$ cuts
  - Vary normalization region ($E_T < 17 - 21 \text{ GeV}$)
  - The largest deviation in each bin used for sys. error estimate

- **Data**
  
  - **Run 9 Data Missing Endcap Vetoed QCD Background**

  - **EMC Cluster $E_T$ (GeV)**

  - **Total Background**

  - **MC Normalized to $L=13.7 \text{ pb}^{-1}$**
Background subtraction

- Background distribution and background-subtracted signal distribution
- B/(S+B) ($E_T > 25\text{GeV}$) $W^-$: 16%
- B/(S+B) ($E_T > 25\text{GeV}$) $W^+$: 8%

<table>
<thead>
<tr>
<th>Background Events ($E_T &gt; 25\text{ GeV}$)</th>
<th>$W^- \rightarrow e^- + \bar{\nu}_e$</th>
<th>$W^+ \rightarrow e^+ + \nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W \rightarrow \tau + \nu_\tau$</td>
<td>$2.7 \pm 0.7$</td>
<td>$8.4 \pm 2.2$</td>
</tr>
<tr>
<td>Missing Endcap</td>
<td>$14 \pm 4$</td>
<td>$13 \pm 4$</td>
</tr>
<tr>
<td>Normalized QCD</td>
<td>$8.0^{+20}_{-4}$</td>
<td>$25^{+36}_{-9}$</td>
</tr>
<tr>
<td>Total</td>
<td>$25^{+21}_{-7}$</td>
<td>$46^{+36}_{-11}$</td>
</tr>
</tbody>
</table>
Data/MC Comparison of charge-separated Jacobian peak distributions

Comparison of data and PYTHIA+GEANT simulations for W signal events at $\sqrt{s}=500\text{GeV}$

Systematic uncertainties were estimated by varying cuts and normalization regions for QCD background and by varying BEMC energy scale uncertainty (±7.5%)
W production results: Cross-Section

Total $W^+ / W^-$ Cross-section results

<table>
<thead>
<tr>
<th></th>
<th>$W^+ \rightarrow e^+ + \nu_e$</th>
<th>$W^- \rightarrow e^- + \bar{\nu}_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{W}^{obs}$</td>
<td>156</td>
<td>513</td>
</tr>
<tr>
<td>$N_{back}$</td>
<td>$25 \pm 21$</td>
<td>$46 \pm 36$</td>
</tr>
<tr>
<td>$\epsilon_{total}$</td>
<td>$0.56 \pm 0.11$</td>
<td>$0.56 \pm 0.12$</td>
</tr>
<tr>
<td>$\int L dt \ (pb^{-1})$</td>
<td>$13.7 \pm 3.2$</td>
<td>$13.7 \pm 3.2$</td>
</tr>
</tbody>
</table>

Reasonable agreement between measured and theory evaluated cross-sections within uncertainties!
**W production results: Asymmetry measurement**

- **$A_L$ determination**

  \[ \frac{u}{\Delta u} \left( \frac{d}{\Delta d} \right) \]

  \[ \frac{\Delta \bar{d}}{\bar{d}} \left( \Delta \bar{u} / \bar{u} \right) \]

  \[ A_L^W = \frac{1}{P} \frac{N^+(W) - N^-(W)}{N^+(W) + N^-(W)} \]

- **First measurement of parity-violation in polarized proton-proton collisions at RHIC**

- **W*: Observe directly u quark polarization!

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W production results: Asymmetry result

Parity-violating single-spin asymmetry $W^+/W^-$ $A_L$ results

STAR Preliminary Run 9 ($\sqrt{s}=500$ GeV)

$p+p \rightarrow W^\pm \rightarrow e^\pm + \nu$

$E_T > 25$ GeV

$A_L(W^+)= -0.33 \pm 0.10$ (stat.) $\pm 0.04$ (syst.)

$A_L(W^-)= 0.18 \pm 0.19$ (stat.) $+0.04 -0.03$ (syst.)

- $A_L(W^+)$ negative with a significance of 3.3 $\sigma$
- $A_L(W^-)$ central value positive
- Systematic errors of $A_L$ under control
- TPC charge separation works up to $p_T \sim 50$ GeV
- Measured asymmetries are in agreement with theory evaluations using polarized pdf's (DSSV) constrained by polarized DIS data

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

$A_L(W^+) = \frac{1}{2} \left( \frac{\Delta \bar{u} - \Delta d}{\bar{u} - d} \right)$

$A_L(W^-) = \frac{1}{2} \left( \frac{\Delta d - \Delta u}{d - u} \right)$

⇒ Universality of helicity distribution functions!
Future W program: Forward GEM Tracker

- FGT layout

- FGT: 6 light-weight triple-GEM disks using industrially produced GEM foils (Tech-Etch Inc.)
- New mechanical support structure
- Expected installation: Summer 2011
Future W program: Projections

- **A_L** projections

- **Assumptions:**
  - **Efficiency:**
    - Mid-rapidity: 0.65
    - Forward rapidity: 0.6
    - Assume availability of 9MHz RF
  - **Background:**
    - Mid-rapidity: Run 9
    - Forward rapidity: QCD MC simulations
  - **Full charge-sign discrimination at high-PT**

- **Conclusions:**
  - **W Program at RHIC** is a multi-year program - Initial sample of \( \sim 100 \text{ pb}^{-1} / \sim 50\% \) is only a step along the way!
  - **Critical:**
    - Design polarization performance of 70% to collect at least \( 300 \text{ pb}^{-1} \)
    - Polarization uncertainty \( \sim 5\% \)
Future W program: Projections

**STAR W Impact on polarized QCD sea**

- **DSSV08 Fit**
  - Include W results at RHIC (PHENIX and STAR)
    - assuming $-2 < \eta < 2$
    - with 200pb$^{-1}$
  - Strong constrain for $x>0.05$

D. deFlorian and W. Vogelsang, hep-ph/1003.4533
Summary

- **STAR High-energy polarized p-p program**
  - **pQCD**: Critical role to interpret measured asymmetries
  - First global analysis incl. RHIC SPIN data ⇒ Evidence for small gluon polarization for 0.05<x<0.2
  - Correlation measurements (Di-Jets / γ -Jets) will allow to provide needed constrain on the partonic kinematics ⇒ First Di-Jet cross-section measurement at RHIC at √s=200GeV
  - Run 9 analysis of 200GeV in full swing - Strong focus on di-jet measurements!
  - First Run 9 STAR W result (*Cross-section and A_L for W^+/W^- at mid-rapidity*) important milestone!
  - **Forward rapidity**: Complete FGT construction in ~fall 2010 followed by full system test and subsequent full installation in ~summer 2011
    ⇒ Ready for anticipated long 500GeV polarized pp run in FY12 (Run 12)
  - Future measurements of A_L at STAR at mid-rapidity and forward rapidity (*Wide rapidity coverage*) are expected to play an important role in our understanding of the polarized QCD sea!

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Outlook - RHIC SPIN

Three key elements:

- Gluon polarization
- Quark / Anti-Quark Polarization
- Transverse spin dynamics

Critical:

- Beam polarization: 70% / Narrow vertex region / Spin flipper
- Critical: Sufficient running time!

<table>
<thead>
<tr>
<th>Recorded Luminosity</th>
<th>Main physics Objective</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>~50pb⁻¹</td>
<td>Gluon polarization using di-jets and precision inclusive measurements</td>
<td>200 GeV</td>
</tr>
<tr>
<td>~100pb⁻¹</td>
<td>W production (Important consistency check to DIS results - Phase I) Gluon polarization (Di-Jets / Photon-Jets)</td>
<td>500 GeV</td>
</tr>
<tr>
<td>~300pb⁻¹</td>
<td>W production (Constrain antiquark polarization - Phase II) Gluon polarization (Di-Jets / Photon-Jets)</td>
<td>500 GeV</td>
</tr>
<tr>
<td>~30pb⁻¹</td>
<td>Transverse spin gamma-jet</td>
<td>200 GeV</td>
</tr>
<tr>
<td>~250pb⁻¹</td>
<td>Transverse spin Drell-Yan (Long term)</td>
<td>200 GeV</td>
</tr>
</tbody>
</table>