Probing the nucleon spin structure at RHIC using the Electro-weak interaction

MENU, Pittsburgh
June 3, 2019

Ralf Seidl (RIKEN)
Outline

• EW heavy boson introduction
• Introduction to RHIC: PHENIX and STAR
• Longitudinal Spin physics using Ws
• Transverse spin and the Sivers Sign change via W/Zs
• Unpolarized W/Z measurements
• EW Future of RHIC and EIC
Discovery of W and Z bosons

- Parity violation of Weak interaction discovered in 1957 (Wu et al, Garwin et al)
- Electroweak unification by Glashow, Salam, Weinberg: heavy W and Z bosons, 79 Nobel
- “Discovery” at the SPS by UA1 and UA2
- 84: Carlo Rubbia, Simon van der Meer

W discovery:  

Z discovery:  
W and Z bosons

**W Bosons**
- Mass: 80.39 GeV
- Spin: 1
- Decay modes:
  - $l\nu$: 10.80% ($e, \mu, \tau$)
  - $q\bar{q}$: 10.80% ($ud, c\bar{s}$)*3

**Z Boson**
- Mass: 91.18 GeV
- Spin: 1
- Decay modes:
  - $\nu\bar{\nu}$: 6.8% ($e, \mu, \tau$)
  - $l^+l^-$: 3.4% ($e, \mu, \tau$)
  - $q\bar{q}$: 15.2% ($d, s, b$)*3
  - $q\bar{q}$: 11.8% ($u, c$)*3

Real W production in pp collisions: need to have enough energy to produce $W$: $x_1x_2\sqrt{s} > m_W$; general feature of DY like processes

With full W/Z kinematics known LO extraction of $x_1$ and $x_2$ possible
W production in pp collisions

• At reasonably high CMS energy real EW boson production possible
• Similar to DY, at LO $q+\bar{q}$ form $W/Z$
• Flavor composition is given by the charge of the $W$:
  • $W^+: u + \bar{d}$
  • $W^-: d + \bar{u}$
• For $Z$ larger $d + \bar{d}$ contribution than $u + \bar{u}$ (no u-quark dominance)
• Decay leptons with $(1 \pm \cos \theta)$ factors
  $$\sigma^{W^+} \approx u(x_1)d(x_2)(1 - \cos \theta)^2 + \bar{d}(x_1)u(x_2)(1 + \cos \theta)^2$$
  $$\sigma^{W^-} \approx d(x_1)\bar{u}(x_2)(1 + \cos \theta)^2 + \bar{u}(x_1)d(x_2)(1 - \cos \theta)^2$$

• Due to parity violation participating quark (left-handed) and antiquark (right-handed) helicities fixed

R.Seidl: EW spin structure at RHIC
W decay kinematics at RHIC (p+p at 510 GeV)
W decay kinematics at RHIC (p+p at 510 GeV)
W decay kinematics at RHIC (p+p at 510 GeV)
quark flavors and x ranges (@510GeV)

W⁻ → µ⁻ case: almost entirely forward d quarks and backwards ¯u

Proton 1   Proton 2

Central

Forward

R. Seidl: EW spin structure at RHIC
quark flavors and x ranges (@510GeV)

Central

Forward

W⁻ → μ⁻ x distribution 0.8 < η < 1.2

W⁻ → μ⁻ x distribution 1.2 < η < 2.4

W⁺ → μ⁺ x distribution 0.8 < η < 1.2

W⁺ → μ⁺ x distribution 1.2 < η < 2.4

W⁻ → μ⁻ case: almost entirely forward d quarks and backwards u̅ quarks

W⁺ → μ⁺ case: predominantly forward d̅ quarks and backwards u quarks

MENU 06/03/2019

R.Seidl: EW spin structure at RHIC
- Polarized proton beams from $\sqrt{s}$ of 62-510 GeV
- pA, AA collisions up to 200 GeV
- Spin rotators around PHENIX and STAR to select long. or transversely polarized beams
- Global and local polarimetry
• Polarized proton beams from $\sqrt{s}$ of 62-510 GeV
• pA, AA collisions up to 200 GeV
• Spin rotators around PHENIX and STAR to select long. or transversely polarized beams
• Global and local polarimetry
• Polarized proton beams from $\sqrt{s}$ of 62–510 GeV
• $pA$, $AA$ collisions up to 200 GeV
• Spin rotators around PHENIX and STAR to select long. or transversely polarized beams
• Global and local polarimetry
Main Spin Questions

• How is the spin of the proton distributed? What is the role of gluons and sea quarks?

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \mathcal{L}_G + \mathcal{L}_q \]
Main Spin Questions

• How is the spin of the proton distributed? What is the role of gluons and sea quarks?

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \mathcal{L}_G + \mathcal{L}_q \]
Main Spin Questions

• How is the spin of the proton distributed? What is the role of gluons and sea quarks?

• What is the origin of transverse spin effects and how does it relate to the 3D momentum and position structure of the Nucleon?

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \mathcal{L}_G + \mathcal{L}_q \]

⇒ Sivers, Collins effects, TMDs GPDs, orbital angular momentum
Main Spin Questions

• How is the spin of the proton distributed? What is the role of gluons and sea quarks?

• What is the origin of transverse spin effects and how does it relate to the 3D momentum and position structure of the Nucleon?

• What is the role of sea quarks in an unpolarized nucleon?

$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \mathcal{L}_G + \mathcal{L}_q$$

- Sivers, Collins effects, TMDs, GPDs, orbital angular momentum
- W and DY measurements
\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \mathcal{L}_G + \mathcal{L}_q \]

Longitudinal Spin
Real W production as access to (anti)quark helicities

- Maximally parity violating V-A interaction selects only lefthanded quarks and righthanded antiquarks:
  - Having different helicities for the incoming proton then selects spin parallel or antiparallel of the quarks.
  - Difference of the cross sections gives quark helicities Δq(x).

- No Fragmentation function required.
- Very high scale defined by W mass.

Bourrely, Soffer
Real W production as access to (anti)quark helicities

- Maximally parity violating V-A interaction selects only lefthanded quarks and righthanded antiquarks:
  - Having different helicities for the incoming proton then selects spin parallel or antiparallel of the quarks
  - Difference of the cross sections gives quark helicities $\Delta q(x)$

- No Fragmentation function required
- Very high scale defined by W mass

Real $W$ production as access to (anti)quark helicities

- Maximally parity violating $V$-$A$ interaction selects only **lefthanded** quarks and **righthanded** antiquarks:

  - Having different helicities for the incoming proton then selects spin parallel or antiparallel of the quarks

  - Difference of the cross sections gives quark helicities $\Delta q(x)$

- No Fragmentation function required

- Very high scale defined by $W$ mass

Bourrely, Soffer
Real W production as access to (anti)quark helicities

- Maximally parity violating V-A interaction selects only lefthanded quarks and righthanded antiquarks:
- Having different helicities for the incoming proton then selects spin parallel or antiparallel of the quarks
- Difference of the cross sections gives quark helicities $\Delta q(x)$
- No Fragmentation function required
- Very high scale defined by W mass

$\Delta q(x)$ $\Delta \bar{q}(x)$

Bourrely, Soffer
Sea quark polarization via W production

- Single spin asymmetry proportional to quark polarizations
- Large asymmetries
- Forward/backward separation smeared by W decay kinematics
Sea quark polarization via W production

- Single spin asymmetry proportional to quark polarizations
  - Large asymmetries
  - Forward/backward separation smeared by W decay kinematics

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

\[
A_L^{W^-} \approx \frac{-\Delta d(x_1)\bar{u}(x_2)(1 + \cos \theta)^2 + \Delta\bar{u}(x_1)d(x_2)(1 - \cos \theta)^2}{d(x_1)\bar{u}(x_2)(1 + \cos \theta)^2 + \bar{u}(x_1)d(x_2)(1 - \cos \theta)^2}
\]
Central $W+Z \rightarrow e$ asymmetries

- Leptonic $W$ decays very clearly visible via Jacobian peak
- Large asymmetries found, consistent between experiments
- $e^-$ significantly above latest global fit

PHENIX: Phys.Rev. D93 (2016), 051103
Forward $W+Z \rightarrow \mu$ asymmetries

- At forward rapidities no Gaussian peak to identify $W$ decay muons
- Lower $P_T$ hadrons as fake high $P_T$ “muons”
- Successfully performed unbinned max likelihood analysis to identify signal

- Asymmetries as expected
- Some indication of reduced $W$ asymmetries in high-$x$ d-quark dominated region
W measurements

STAR2013:
PRD99 (2019) 051102

- Clearly asymmetric polarized sea seen with all of longitudinal 510 GeV running analyzed
- Sea quark helicities well constrained at $x > 0.1$
- Asymmetric sea rules out simple pion-cloud models!

Only reweighting exercise for STAR data so far, no global fit with all W data, yet
Transverse Spin

- Transversity: $h_{1,q}(x)$
- Sivers Function: $f_{1T,q}(x, k_T)$
- Boer Mulders function
The Sivers sign change prediction

• Sivers effect: Initially expected to be zero due to naïve Time-reversal-odd nature
• Brodsky-Hwang-Schmidt + Belistky-Yuan: interference of handbag diagram and handbag+soft gluon can create it, but dependence of direction of gauge link
• Collins: modified universality of Sivers function: opposite sign in DY vs SIDIS

\[ f_{1T,q}^{\perp DY}(x, k_T) = -f_{1T,q}^{\perp DIS}(x, k_T) \]
Drell-Yan type measurements at RHIC

- Traditional DY measurements (4-8, 11-17 GeV) established but charm, bottom and onia backgrounds make it difficult for spin asymmetries → planned in future upgrades and 2017 data set
- Use real W/Z production in the same way

- Advantage: high scale probes also TMD evolution
- Difficulty: need to fully reconstruct the W/Z boson for the azimuthal asymmetries
  → Use recoil method (to reconstruct W transverse momentum and rapidity
General Strategy for $W A_N$

- Find $W \rightarrow e$ candidate (~40 GeV electron, missing $E_T$ from neutrino)

- Obtain momentum sum of hadronic final state for recoil
  - Correct for missing particles at high rapidities via MC
  - Momentum balance gives $P_T^W$ and $\phi_W$. 

- Solve $W$ mass equation for longitudinal $W$ momentum $\rightarrow$ $W$ rapidity

- Calculate $W A_N$ as a function of rapidity or $P_T^W$
Towards the Sivers sign change

- Using recoil method reconstruct $W$ transverse momentum and azimuthal asymmetry
- First indication of expected sign change!
- Evolution effects could reduce size of asymmetries
- 2017 data taking (analysis ongoing) will substantially improve statistics; also DY and Z asymmetries
Towards the Sivers sign change

- Using recoil method reconstruct W transverse momentum and azimuthal asymmetry
- First indication of expected sign change!
- Evolution effects could reduce size of asymmetries
- 2017 data taking (analysis ongoing) will substantially improve statistics; also DY and Z asymmetries

STAR: PRL 116 (2016) 132301
Towards the Sivers sign change

- Using recoil method reconstruct $W$ transverse momentum and azimuthal asymmetry
- First indication of expected sign change!
- Evolution effects could reduce size of asymmetries
- 2017 data taking (analysis ongoing) will substantially improve statistics; also DY and $Z$ asymmetries

STAR: PRL 116 (2016) 132301
Unpolarized EW measurements
$W$ production asymmetries $\rightarrow$ light sea

- At central rapiditides $0.1 < x < 0.3$ probed with peak $\sim 0.16$
- No nuclear effects (no deuterons were harmed for these measurements)
- Very high scale

$$\frac{\sigma_{W^+}}{\sigma_{W^-}} \approx \frac{u(x_1)\overline{d}(x_2) + \overline{d}(x_1)u(x_2)}{d(x_1)\overline{u}(x_2) + \overline{u}(x_1)d(x_2)}$$
Total W and Z cross sections

- Total cross sections consistent with world data/expectations

- Z/W ratios further constrain sea quark PDFs

Graphs showing data points and curves for total cross sections and Z/W ratios.
EW spin physics at the EIC
EIC

• 2015 NSAC long range plan highest priority new facility: electron Ion Collider (EIC)
• Very positive National Academy of Science review
• DOE CD process starting soon
• 2 potential realizations:
  • JLEIC (CEBAF+new pol. ion accelerator – concentration on first high intensity, lower CMS energy)
  • eRHIC (RHIC + new pol electron beam – concentration on first high CMS energy, initially lower intensity)
• ePHENIX (fsPHENIX + electron side+PID)
CC at the EIC

- charged current reactions and photon/Z interference can give additional insight into the nucleon structure
- Despite being virtual, energies need to be high to have a substantial cross section

\[
F_2^W = 2x(u + \overline{d} + \overline{s} + c\ldots) \\
F_3^W = 2x(u - \overline{d} - \overline{s} + c\ldots) \\
W^+ : u \rightarrow d\ldots
\]

Neutral current

Charged current
Charged Current DIS

\[ e^+ p \rightarrow \nu_e X \]

- Gain even more flavor sensitivity with the weak interaction:

\[
g_1^{W^-} = (\Delta u + \Delta \bar{d} + \Delta \bar{s} + \Delta c \ldots) \\
g_5^{W^-} = (\Delta u - \Delta \bar{d} - \Delta \bar{s} + \Delta c \ldots) \\
W^+ : u \rightarrow d \ldots
\]

- Requires hadronic method of DIS reconstruction, but good precision
- Charm jets to access \(\Delta s\)?
- Also of interest for TMDs? Transversity at high \(x\) and \(Q^2\)!

*Phys. Rev. D88 (2013) 114025*
• Access valence and sea quarks at high scale and higher $x$

• Substantial reduction in uncertainties
Summary

- W/Z production a tool to study the nucleon spin structure at RHIC
- Asymmetric polarized light quark sea (opposite sign to unpolarized light sea)
- First indications of a sign change of the Sivers function in W/Z production

- Clean access to unpolarized light quark sea from W/Z production
- More to come in the future at RHIC (CNM 2017-23 plan)
- Charged current DIS at the EIC
Quark and antiquark helicities probed in W production

- Building single spin asymmetries of decay lepton
  
  $$A_L = \frac{1}{P} \frac{\vec{N} - \vec{N}}{\vec{N} + \vec{N}}$$

- Positive lepton asymmetries sensitive to $\Delta u (x)$ and $\Delta d (x)$

  $$A_L^{W^+} \approx - \frac{\Delta u(x_1)d(x_2) - \Delta \bar{d}(x_1)u(x_2)}{u(x_1)d(x_2) + \bar{d}(x_1)u(x_2)}$$

- Negative lepton asymmetries sensitive to $\Delta d (x)$ and $\Delta u (x)$

  $$A_L^{W^-} \approx - \frac{\Delta d(x_1)\bar{u}(x_2) - \Delta \bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}$$
eRHIC Realization

• Use existing RHIC
  • Up to 275 GeV protons
  • Existing: tunnel, detector halls & hadron injector complex

• Add 18 GeV electron accelerator in the same tunnel
  • Use either high intensity Electron Storage Ring or Energy Recovery Linac

• Achieve high luminosity, high energy e-\(p/A\) collisions with full acceptance detector

• Luminosity and/or energy staging possible
Unpolarized proton structure polarized lepton beams included

\[
\frac{d^2 \sigma^i}{dx dy} = \frac{2\pi \alpha^2}{xyQ^2} \eta^i \left[ Y_+ F^i_2 \pm Y_- x F^i_3 - y^2 F^i_L \right]
\]

- \(F_L\) measures the violation of the Callen-Gross relation
- Flavor information from \(\gamma Z\) interference, \(Z\) exchange and in particular charged current (\(W\) exchange) interactions
- \(Z\) and \(W\) parts of \(F_3\) depend on lepton helicity

\[
F^\gamma_2 = x \sum_q e^2_q (q + \bar{q})
\]

\[
F^{\gamma Z}_2 = x \sum_q 2e_q g^q_V (q + \bar{q})
\]

\[
F^Z_2 = x \sum_q (g^q_V + g^q_A)(q + \bar{q})
\]

\[
F^{\gamma Z}_3 = \sum_q 2e^2_q g^q_A (q - \bar{q})
\]

\[
F^Z_3 = \sum_q 2g^q_V g^q_A (q - \bar{q})
\]

\(F^W_2^{-} = 2x(u + \bar{d} + \bar{s} + c\ldots)\)

\(F^W_3^{-} = 2x(u - \bar{d} - \bar{s} + c\ldots)\)

\(W^+ : u \rightarrow d\ldots\)
Electroweak information

Neutrino CC DIS

Hadron collider W production asymmetries

4/19/2017
Weak interaction and $F_3$