“I think that I shall never see
A collision as lovely as ě on ë"
The *pp* Spin Program at RHIC

- Status of $\Delta G$ measurements
- $W/Z^*$ production and $A_L$
- Transversity at mid-rapidity
The RHIC rings: A Decade of Developing a Resource

Pol. Proton Source
500 µA, 400 µs

RHIC

Absolute Polarimeter (H jet)

RHIC pC Polarimeters

Siberian Snakes

Spin Rotators

Solenoid Snake

Linac Booster

Cold Snake

Warm Snake

AC Dipole

AGS pC CNI Polarimeter

AGS

200 MeV Polarimeter

PHENIX (∼p)

STAR (∼p)

A_{NDY} (∼p)
✓ ~5 weeks each of pp200 and pp500
✓ 2 new heavy-ion species (U+U and Cu+Au)
Bottom line: For all four species / beam energies, all established run goals were exceeded, often by factors greater than two. Stochastic cooling works!
The Spin Puzzle: Understanding nucleon substructure

The RHIC spin program:
Study hard partonic scattering processes in polarized $pp$ collisions, using polarization of one parton to probe helicity preferences of the other

→ Provides a “snapshot” of spin distributions:

$$\langle S_z^p \rangle = \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \langle L_z^{\text{quarks}} \rangle + \langle L_z^{\text{gluons}} \rangle$$

→ $p$DIS studies consistently show quark helicity contributions ~30%!

1. Can gluonic spin and partonic orbital angular momentum account for the remaining 70%?

2. Can we unravel the individual terms that contribute to $\Delta \Sigma$?

Hirai, Kumano, Saito
Results from 2009: gluon polarization may be non-zero

For inclusive $\pi^0$ (PHENIX) and jet (STAR) asymmetries

- Statistical errors ~ 2-3 times smaller than in 2006
- Data significantly higher than DSSV global fits

\[ \text{STAR Jet } A_{LL} : \int dx \Delta g \sim 0.1 \]
Correlation studies: more evidence from di-jets

From crude interpolation: 2009 pp200 jet data suggest that perhaps \( \sim 25\% \) of the proton’s spin may be carried by gluons!
Much more precise data – most at 500 GeV – to come

From runs 12, 13, 14 \rightarrow \text{substantial gains at all kinematics, especially to lower regions of } x \text{ (down to } \sim 0.01)\text{.}
Flavor Asymmetry of the Sea: the RHIC W program

Unpolarized Flavor asymmetry

- Naïve expectation: a “free” gluon splits to $u$ and $d$ pairs equally often
- Quantitative calculation of Pauli blocking does not explain $\bar{d}/\bar{u}$ ratio
- E866 results are qualitatively consistent with pion cloud models, chiral quark soliton models, instanton models, etc.

Polarized flavor asymmetry

- “Hints” from recent COMPASS data
- Extracting polarized flavor asymmetry could help differentiate among models

$Q^2 = 54\text{GeV}$

$\pm 0.032$ Systematic error not shown

$\bar{d}/\bar{u}$

$\frac{\Delta \bar{u} - \Delta \bar{d}}{\bar{u}}$

$\frac{\Delta u - \Delta d}{u}$

arxiv1007.4061
Probing the Sea Through W Production at RHIC

Measure parity-violating single-spin asymmetry:
(Helicity flip in one beam while averaging over the other)

\[ A_L^W = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \]

- V-A coupling \rightarrow left-handed W’s couple
  l.h. \( q \) with r.h. \( q \rightarrow \) perfect spin separation
- Detect W’s through \( e^+e^- \) decay channels
- Typically find \( x_q > x_q \rightarrow \) W highly boosted
- In \( W^+(-) \) rest frame, lepton is preferentially emitted along (against) W spin direction

\[ l^+(-) \]

\[ u + \bar{d} \rightarrow W^+ \rightarrow e^+ + \nu \]
\[ \bar{u} + d \rightarrow W^- \rightarrow e^- + \bar{\nu} \]

\[ \sqrt{x_1 x_2} = 0.16 \]
Finding W’s at RHIC: a very clean signature!

Pythia+Geant
p+p→W→e+ν event
@ 500 GeV

Dictates key experimental requirements:
• Good e.m. calorimetry → measure $E_e$
• Good tracking → lepton charge sign
• Large angular coverage → isolation cuts on lepton and away-side energy
Finding W’s at RHIC: Detectors are up to the task!

A (possible) real W!
Finding W’s at RHIC: Detectors are up to the task!

A (possible) real W!
Identify isolated electron candidates

- Require a track with $p_T > 10$ GeV/c to point to a $2 \times 2$ patch with $E_T > 15$ GeV
- Require $> 95\%$ of energy in $4 \times 4$ patch to lie inside the central $2 \times 2$ patch ($E_T^\circ$)
- Throw out event if the surrounding cone ($R = 0.7$) has $>10\%$ of candidate energy $E_T$
- Throw out event if too much energy is on opposite side ($180\degree$ away in $\phi$) \rightarrow reconstruct jets, check $p_T$ balance
Identify isolated electron candidates

- Require a track with $p_T > 10$ GeV/c to point to a 2 x 2 patch with $E_T > 15$ GeV
- Require > 95% of energy in 4 x 4 patch to lie inside the central 2 x 2 patch ($E_T^o$)
- Throw out event if the surrounding cone ($R = 0.7$) has >10% of candidate energy $E_T$
- Throw out event if too much energy is on opposite side (180° away in $\phi$) → reconstruct jets, check $p_T$ balance
Ensure that lepton charge separation is robust
STAR W’s from Run 9 – corrected yields

W signal displays features expected of characteristic “Jacobian Peak” (e.g., with peak at ~ ½ of W mass)

Background estimation: expect contributions from
- Electroweak:
  - $Z \rightarrow e^+e^-$
  - $W \rightarrow \tau \nu$
- QCD:
  - Data-driven

arXiv:1009.0326
Final W yields used for cross sections and $A_L$

STAR: $|\eta^e|<1$

$\rho + \rho \rightarrow W^- + X \rightarrow e^- + X$

- Electron $|\eta_e| < 1$
- Candidates
- Backg. est.
- $W$ signal

Positron $|\eta_e| < 1$

$\rho + \rho \rightarrow W^+ + X \rightarrow e^+ + X$

PHENIX: $|\eta^e|<0.35$

Counts per 2 GeV bin

- Positron candidates
  - All
  - After Isolation Cut

- Electron candidates
  - Estimated BG
  - Estimated BG after Isolation Cut
World data set for W production in pp and p\bar{p} colliders
Initial look at some $\eta$ dependencies

Lepton $\eta$ distributions in reasonable agreement with MC → weaker lepton “boost” for $W^+$ results in tightly clustering at $\eta = 0$

Ratio of $W^+ / W^-$ eliminates dominant systematic error of absolute luminosity → in excellent agreement with NLO calc’s w/ different PDF’s
Initial AL results: 2009 (first 500 GeV run!)

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

STAR $\sqrt{s} = 500$ GeV

$25 < E_T^e < 50$ GeV

At forward/backward rapidity, increased sensitivity to a single quark flavor

Need to push measurements (and detectors) towards the beam pipe!
First look at STAR results from Run 12: $P^2L \approx 25$ pb$^{-1}$

See W’s in EEMC! … and Z’s!
New forward detectors: PHENIX

Muon Piston Calorimeter (MPC):
\[ \text{PbWO}_4 \]
\[ 3.1 < |\eta| < 3.9 \quad 2\pi \text{ azimuth} \]
Gives access to lower \( x \rightarrow 10^{-3} \)
Fully available from 2008

VTX barrel \(|\eta|<1.2\)

FVTX endcaps
\[ 1.2<|\eta|<2.7 \]
mini strips

Fully available from 2008

FVTX: available from 2012
Forward Tracking into the Endcap: FGT Upgrade

FGT: 6 light-weight triple-GEM disks using industrially produced GEM foils (Tech-Etch Inc.)
14 (out of 24) quadrants installed for Run 12
Expected W asymmetries at PHENIX and STAR

- Confirm (or not) quark polarizations in valence region, $x = 0.1-0.3$
- Provide new constraints on antiquark helicities (no FF, high $Q^2$)
Moving towards transversity: Mid-rapidity Collins effect

\[ d\sigma \approx d\sigma^{UU} \left( 1 + A_N \sin(\phi_h - \phi_s) \right) \]

- Measure spin-dependent azimuthal distributions of charged pions in fully reconstructed jets
- **Sensitive to convolution of transversity and Collins fragmentation function**
- Expect improved uncertainties with new runs and larger simulations to reduce syst.
New tool: Interference Fragmentation Function

\[ \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} (\phi_s - \phi_R) = A_{UT} \sin(\phi_s - \phi_R) \quad A_{UT} \propto h_1 \cdot H_1^\perp \]

\( \phi_s \): Angle between polarization vector and event plane
Combining these data with the IFF measurements carried out at Belle, one can extract — for the first time — quark transversity, point by point.

**Greatly increased statistics already exists on tape!**
Outlook: the Spin Physics Program at RHIC

First tantalizing hints of non-zero gluonic contributions to the spin of the proton – perhaps as large as the contributions from quarks

Initial studies of W/Z* production very encouraging, limited statistics → quantities studied to date are consistent with NLO calculations

Over next 2-3 years: should achieve high precision on $\Delta G$, begin to map out $x$ dependence; study PV single-spin asymmetries $A_L$ over broad $\eta$

Very exciting glimpse of transversity!

→ *Must view these studies as key components of broader program to understand all aspects of parton spin behavior in the nucleon!*