THE SPIN OF THE PROTON - WHY WE SHOULD CARE

E.C. Aschenauer
if you look through a higher and higher resolution microscope you discover a femto Universe size scale $10^{-15}$ m = 1 femto m (fm)

Big Question:
can we understand how the visible matter is formed from the smallest elementary building blocks
A major goal of physics is to understand the basic building blocks of all matter and the pieces that make up those building blocks and the pieces that make up those pieces... and those pieces... etc...

A Nucleus is made of nucleons: protons and neutrons

nucleons are very complex objects!!

quarks bound together by gluons form nucleons

All elementary building blocks can be characterized by their mass, spin and charge

[Diagram showing nucleons and quarks]
THE THEORY TO EXPLAIN THE “FEMTO-UNIVERSE”

Quantum Chromodynamics (QCD)

Its features:

- Developed in the 1970s, Nobel price in 2004
- New particle to mediate the force that is characteristic for the theory
  - Gluon discovered at the end of the 1970s at PETRA@DESY in Germany
- The "charge" of the strong force is called color, each quark comes in one of three colors: red, green or blue.
- The color force is transmitted by the gluon and is very strong
- Quantum Chromodynamics (QCD)

<table>
<thead>
<tr>
<th>Force Relative Strength</th>
<th>1 keeps you in your seat</th>
<th>10^43 holds nucleons together</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitation</td>
<td>Force in QCD</td>
<td></td>
</tr>
</tbody>
</table>

- The color force between quarks decreases with decreasing distance and grows larger at large distances
- Quarks and gluons cannot be found in isolation

we understand many things but cannot yet calculate/predict mass, charge and spin from first principles in QCD
Proton Mass: $1.8 \times 10^{-27}$ kg

The Sum of all Quark masses accounts for 1% of the proton mass

Where does the rest of the mass hide?

*Can Gluons be the answer?*

If yes need many to account for the missing mass

**The proton is dominated by gluons**
Proton spins are used to image the structure and function of the human body using the technique of magnetic resonance imaging.

What is Spin? Google....

- revolve quickly and repeatedly around one's own axis,
- twist and turn so as to give an intended interpretation,

"The President's spokesmen had to spin the story to make it less embarrassing"

Wikipedia: In quantum mechanics and particle physics, spin is an intrinsic form of angular momentum carried by elementary particles, composite particles (hadrons), and atomic nuclei
SPIN is one of the fundamental properties of matter, all elementary particles, but the Higgs carry spin. Studying Spin revealed many surprises in physics, proton anomalous magnetic moment → substructure cannot be explained by a static picture of the proton.

Proton Spin:

It is more than the number $\frac{1}{2}$ ! It is the interplay between the intrinsic properties and interactions of quarks and gluons.

If we do not understand the proton spin in QCD, we do not fully understand QCD!

need a polarized collider to have full access to the proton dynamics.
How are sea quarks and gluons and their spin distributed in space and momentum inside the nucleon?

How are these quark and gluon distributions correlated with the overall nucleon properties, such as spin direction?

What is the role of the motion of sea quarks and gluons in building the nucleon spin?

How do quarks and gluons hadronize into final-state particles?

To separate interaction dependent phenomena from intrinsic properties, different complementary probes are needed.

**EM interaction**
- Photon
  - Sensitive to electric charge
  - Insensitive to color charge

**Weak Interaction**
- Weak Boson
  - Sensitive to weak charge ~flavor
  - Insensitive to color
HOW AND WHAT DO WE MEASURE
**Beam:** 27.5 GeV e⁺; ±50% polarization
**Target:** polarized gas targets H, D, <85% He³, <50% polarization
unpolarised gas targets H₂ to Xenon
**Lumi:** polar: 5x10³¹ cm⁻²/s⁻¹; unpolar: 3x10³²-³³ cm⁻²/s⁻¹
Data taking finished June 2007

**SM1**
- **RICH**
- **ECal & HCal**
- **μ Filter**
- **Trigger-hodoscopes**

**SM2**
- **6LiD Target**

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**Beam:** 160 GeV µ⁺: 80% polarization
**Target:** polarized targets ³He, ⁶LiD, NH₃, several unpolarised targets
**Hall-D:** for spectroscopy 9 GeV tagged polarised photons & a 4π detector

**Beam:** ≤12 GeV e⁻; 85% polarization
**Target:** polarized targets ³He, ⁶LiD, NH₃, several unpolarised targets

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**Hall A**
- Two high-resolution spectrometers & large installations

**Hall B**
- Large acceptance spect. electron/photon beams

**Hall C**
- Super high momentum spectrometer, high luminosity and forward angles

**Hall D**
- Two high-resolution spectrometers & large installations

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What do we collide?

- Light ions (d, Si, Cu)
- Heavy ions (Au, U)
- Polarized protons

Beams: $\sqrt{s} = 500$ GeV pp; 50-60% polarization
Lumi: ~60 pb$^{-1}$/week

Run parameters:
- 2013 $P = 53\%$

PHENIX Detector

STAR Detector
**hadron-hadron:**

- **Hard Scattering Process**
- \( D_{q}^{\pi^{0}}(z) \)
- **Pro's:**
  - direct access to gluons
  - RHIC collider \( \rightarrow \) wider kinematics reach
- **Con's:**
  - no direct access to parton kinematics

**lepton-hadron:**

- **Incoming lepton**
- **Virtual photon**
- **Scattered lepton**
- **Target nucleon**
- **Pro's:**
  - direct access to parton kinematics
- **Con's:**
  - no direct access to gluons
  - all polarised DIS experiments are fixed target \( \rightarrow \) limited kinematics reach

\( q(x_{1}), g(x_{2}) \): Parton distribution functions (PDF) (no polarisation effects)

\( \Delta q(x_{1}), \Delta g(x_{2}) \): polarised parton distribution functions

\( x_{1}, x_{2} \): fraction of the proton momentum carried by a parton

\( Q^{2} \): the energy transfer in the hard scattering of the partons

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**GLOSSARY OF p+p & e+p COLLISIONS**

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"Helicity sum rule"

\[
\frac{1}{2} \hat{h} = \left\langle P, \frac{1}{2} \mid J_{QCD}^{z} \mid P, \frac{1}{2} \right\rangle = \sum_{q} \frac{1}{2} S_{q}^{z} + \sum_{q} \frac{1}{2} S_{g}^{z} + \sum_{q} L_{q}^{z} + L_{g}^{z}
\]

Can quarks and gluons explain all the spin?

→ what is the role of gluons?
→ what is the role of sea quarks?
→ How much orbital angular momentum is needed?
THE GLUON CONTRIBUTION
What is measured?

Double Spin Asymmetry:

\[ A_{LL} \sim \frac{1}{P_{\text{Yellow}} P_{\text{Blue}}} \frac{N^{++} - N^{+-}}{N^{++} + N^{+-}} \]

Stat. Uncertainty:

\[ \delta A_{LL} \sim P_{\text{Yellow}}^2 P_{\text{Blue}}^2 \sqrt{L_{\text{int}}} \]

**N:** number of a specific final state product

**STAR:** counts Jets

Jet direction

**PHENIX:** counts \( \pi^0 \)s

\[ gq \rightarrow gq \]

\[ \pi^0 \]

\[ \gamma \]

\[ \gamma \]

**ECAL**

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E.C. Aschenauer
Scaling violations of $g_1$ ($Q^2$-dependence) give indirect access to the gluon distribution via DGLAP evolution.

RHIC polarized pp collisions at midrapidity provide direct access to gluons ($gg, qg$).

Integral in RHIC $x$-range:

$$\int_{0.05}^{0.2} dx \Delta g \approx 0.005 \pm 0.129 \pm 0.164 \quad @ \ 10 \text{ GeV}^2$$
STAR 2009
\( p+p \rightarrow \text{Jet}+X \)
\( \sqrt{s} = 200 \text{ GeV} \)

1. \( |\eta| < 0.5 \)

2. \( 0.5 < |\eta| < 1 \)

\[ A_{LL} \]

\[ p_{T} \text{ (GeV/c)} \]

\( \pm 6.5\% \) scale uncertainty from polarization not shown

PHENIX

\[ A_{LL} \]

Run-5 (0.4\% scaling uncert.)
Run-6 (0.3\% scaling uncert.)
Run-9 (\( \pm 7.0\% \) scaling uncert.)

\[ p_{T} \text{ (GeV/c)} \]

\[ A_{LL} \]

\[ A_{LL} \]

\[ p_{T} \text{ (GeV/c)} \]

\[ A_{LL} \]

\[ p_{T} \text{ (GeV/c)} \]

\[ A_{LL} \]

\[ p_{T} \text{ (GeV/c)} \]
QCD analysis of world data; especially new 2009 RHIC data

**DSSV:** arXiv: 1404.4293, PRL 113, 012001

- **Before Run-09**
- **After Run-09**

Gluon contribution (down to $x \sim 10^{-3}$) looks positive and smaller than 1

$\int dx \Delta g \sim 0.2 \pm 0.06 \pm 0.07 \text{ @ } 10 \text{ GeV}^2$

*First time a significant non-zero $\Delta g(x)$*

What about very small $x$ ($x < 10^{-3}$)? How can we reduce the uncertainty?
Reduce uncertainties:
at low $x$ → higher beam energy → new 500 GeV data at mid-rapidity
→ go to forward rapidities $|\eta| > 1$
overall: more statistics
several other channels, i.e. di-jets, charged pions, $J/\Psi$, ….
sometimes lower statistics, but very different systematics

New data sets will have a high impact
FURTHER IMPROVED KNOWLEDGE ON $\Delta g(x, Q^2)$

- Factor 2 reduced uncertainties at $x \sim 10^{-3}$

$$\int_{x_{\text{min}}}^{1} dx \Delta g \sim 0.36 \text{ at } 10 \text{ GeV}^2$$

- Gluons: $\sim 72\%$ of proton spin

- DSSV 2014 with 90\% C.L. band
- projection with RHIC data $\leq 2015$:
- STAR: 1-jet 200 & 510 GeV
- PHENIX: incl. $\pi^0$ 510 GeV at mid & fwd rapidity

$\int Q^2 = 10 \text{ GeV}^2$

$\int x_{\text{min}} \Delta g(x, Q^2)$

- Let's see what RHIC can teach us about $\Delta q_f$
THE QUARK CONTRIBUTION
Why is Separating Quark Flavors Important?

- Nuclear structure is encoded in parton distribution functions
- Understand dynamics of the quark-antiquark fluctuations
- Flavor asymmetry in the light quark sea in the proton
  - Unpolarized: $\bar{u} \neq \bar{d} \Rightarrow$ caused by non-perturbative effects
  - Polarized case?
- Shape of polarized sea-quark PDFs critical for quark contribution to spin

Region constrained by data:

$$\int_{0.001}^{1} dx \Delta \Sigma \sim 0.366 \pm 0.042 @10\text{GeV}^2$$

$$\int_{0}^{1} dx \Delta \Sigma \sim 0.242 @10\text{GeV}^2$$

Graphical representation:

- $\Delta \Sigma(Q^2) = \int dx \Delta q_f(x, Q^2)$
- $Q^2 = 10\text{GeV}^2$
- DSSV 2014 with 90% C.L. band
- All bands 90% C.L.
Correlation between detected hadron and struck $q_f$

"Flavor - Separation"

Inclusive DIS: $\Delta \Sigma = (\Delta u + \Delta d + \Delta u + \Delta d + \Delta s + \Delta s)$

Semi-inclusive DIS: $(\Delta u, \Delta d, \Delta u, \Delta d, \Delta s, \Delta s)$

Polarised Quark Densities:
- u-quarks polarised in the spin direction of the proton
- d-quarks polarised opposite to the spin direction of the proton
- sea-quarks still pretty unknown

$A_{1p}$ incl.
$ud \rightarrow W^+$

$\bar{d}\bar{u} \rightarrow W^-$

Complementary to SIDIS:
very high $Q^2$-scale 6400 GeV$^2$
extremely clean theoretically
No Fragmentation function
$\rightarrow$ stringent test on theory approach for SIDIS

UNIVERSALITY of PDFs

Ws naturally separate quark flavors
$\rightarrow$ rapidity: sea vs. valence quarks

Ws are maximally parity violating
$\rightarrow$ Ws couple only to one parton helicity
RHIC data indicate a “surprise”
unpolarised: \( \bar{u} - \bar{d} < 0 \)
polarised: \( \Delta \bar{u} - \Delta \bar{d} > 0 \)
some non-perturbative models will be challenged to explain this

\[ A_L = \frac{\Delta u}{u} - \frac{1}{2} \left( \frac{\Delta u}{u} - \frac{\Delta d}{d} \right) - \Delta d \]

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

\[ x \Delta \bar{d}(x, Q^2) \]
\[ x \Delta d(x, Q^2) \]

\[ \int_{\tau_{\text{deliv}}}^{\tau_{2011\pm2012}} = 140 \text{ pb}^{-1} \]

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IF THE RUN-13 DATA ARE FULLY ANALYZED

Run-13 reduced uncertainties by factor 2

$\vec{p} + p \rightarrow W^\pm \rightarrow e^\pm + \nu$

$s = 510 \text{ GeV}$

$25 < E_T < 50 \text{ GeV}$

$\Delta u$ and $\Delta d$

RHIC/STAR $W^\pm$-data will be a strong constraint for $\Delta u$ and $\Delta d$

$3.3\%$ beam pol scale uncertainty not shown

$Q^2 = 10 \text{ GeV}^2$

$\int \Delta u(x, Q^2) \, dx$

$x \Delta u$

$\Delta^2 = 2\%$ in DSSV analysis

$\Delta^2 = 2\%$ in DSSV analysis

$Q^2 = 10 \text{ GeV}^2$

$x \Delta d$

$\int \Delta d(x, Q^2) \, dx$

$\Delta^2 = 2\%$ in DSSV analysis

$Q^2 = 10 \text{ GeV}^2$

$\Delta^2 = 2\%$ in DSSV analysis
**Quantum Tomography of the Nucleons & Nuclei**

Join the real 3D experience!!

Spin as vehicle to do tomography of the nucleon

What is the dynamic structure of the proton and nuclei

2D+1 picture in momentum and coordinate space

Visualize color interactions in QCD

Collective phenomena and correlations in fragmentation

New physics aspects due to confined motion

E.C. Aschenauer
Transverse momentum dependent distributions (TMD)
**Why Should We Care About TMDs**

- Provide a way to image the nucleus / nuclei in transverse and longitudinal momentum space (2+1d)
- Provide access to spin-orbit correlations
- Provide constrains to quark-gluon-quark correlations in the proton and in fragmentation

**1st Mellin Moment of transversity → tensor “charge”** \[ \delta q = g_T^{q} = \int_0^1 dx \left[ h_1^q(x,Q^2) - h_1^q(x,Q^2) \right] \]

- Tensor charge not directly accessible in low-energy footprint of new physics at higher scales?
- Neutron \( \beta \) decay → high precision \( \delta q \) → 3-5 TeV bound for BSM scale

- Un-integrated gluon density \( g(x,Q^2,k_T) \) important for physics at small \( x \)
- → CGC
- → many applications at LHC, i.e. Higgs production

**Specific References**

  - WW Linearly polarized gluon distribution contributes with \( \cos(2\phi) \) azimuthal angular dependence

**Graphical Elements**

- Diagram showing the emergence of a scale \( Q_s \)
- Graph of \( k_T \) vs. \( Q_T \)
- Graph of \( v_2(P_T,q_T) \) vs. \( q_T \) for different phases and nuclear effects

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**E.C. Aschenauer**
Till today TMDs come only from fixed target low scale, high x measurements need to establish concept at high $\sqrt{s}$ and different $x$ 

$\Rightarrow$ polarised pp at RHIC
**VISUALIZE COLOR INTERACTIONS IN QCD**

**Sivers function**

- Correlation of nucleon’s transverse spin with the $k_T$ of an unpolarized quark

- Measures spin-orbit correlations
- Link to parton orbital motion (through models)
- Reveals non-trivial aspects of QCD color gauge invariance

**QCD:**

**Critical test of factorization in QCD**

- No sign change
- Need to rethink QCD factorization

**Measure non-universality of sivers-function**

- Sivers function correlation of nucleon’s transverse spin with the $k_T$ of an unpolarized quark

**POSTER CHILD TMD:**

- Sivers function
- $\sin(\phi_h - \phi_s)$ modulation

**DIS:**

- $\gamma q$-scattering
- Attractive

**Sivers function**

- (Sivers$_{DY}$ or Sivers$_W$ or Sivers$_{Z0}$)
**Siver's Sign Change: $$A_{N}^{W}$$ First Results**

- Results based on 2011 25 pb$$^{-1}$$ transversely polarised 500 GeV data → published in PRL and PRL Editor pick
- $$y$$ and $$p_t$$ for fully reconstructed Ws → through recoil method used at Fermi-Lab and LHC

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**Asymmetry favors Sivers fct. sign change and small evolution**

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*STAR p-p 500 GeV (L = 25 pb$$^{-1}$$)*

- $$0.5 < P_T^W < 10$$ GeV/c

- **$$W^+ \rightarrow l^+\nu$$**
  - KQ (assuming "sign change")
  - Global $$\chi^2$$/d.o.f. = 7.4 /6
  - 3.4% beam pol. uncertainty not shown

- **$$W^- \rightarrow l^-\nu$$**
  - KQ (no "sign change")
  - Global $$\chi^2$$/d.o.f. = 19.6 /6
  - 3.4% beam pol. uncertainty not shown
Running conditions:
13 weeks transversely polarized p+p at 510 GeV $\int Ldt = 400$ pb$^{-1}$
$\rightarrow$ only STAR operational & dynamic $\beta^*$ throughout the fill
$\rightarrow$ smoothed lumi-decay during fills
$\rightarrow$ reduced pileup effects in TPC $\rightarrow$ high $W$ reconstruction efficiency

Will provide data to constrain TMD evolution
sea-quark Sivers fct $\rightarrow$ $y$-dependence
test sign-change if TMD evolution $\div \sim 5$ or less
**OUTLOOK**

What is the EIC:

A high luminosity ($10^{33} - 10^{34} \text{ cm}^{-2}\text{s}^{-1}$) polarized electron proton / ion collider with $\sqrt{s_{ep}} = 20 - 100 \text{ GeV}$ upgradable to 140 GeV

Why an EIC:

Revolutionize our view of nucleon structure and the glue!

→ a very diverse physics program impacting nuclear, heavy ion and high energy physics
EIC MACHINE DESIGNS

eRHIC

JLEIC

Lepton-Proton Scattering Facilities

CMS Energy (GeV)

Luminosity (10^{30} cm^{-2} s^{-1})
Both machine designs built on existing machines

**Linac - Ring**

- **Electron accelerator**
  - to be build
  - 80% polarized electrons, 2.6-21.2 GeV

- **RHIC**
  - Existing → reuse
  - 70% Polarized protons 25-250 GeV
  - Polarized light ions He$^+$ 17-166 GeV/u
  - Light ions (d, Si, Cu)
  - Heavy ions (Au, Pb, U) 10-100 GeV/u

- **full $\sqrt{s}$ range available from beginning → staging in luminosity**

- **Both machines utilize crossing angles**
  - 10 mrad
  - 50 mrad

- **Bunch frequency**
  - 9.4 MHz

- **Both designs take great care to have maximal to full acceptance for scattered protons from diffractive reactions, breakup neutrons and spectator tagging**

- **2 interaction regions**

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**JLEIC**

- **Ring - Ring**

- **reuse Cebaf as full energy lepton injector**
  - electron: 3–10 GeV
  - protons: 20–100 GeV
  - ions: 8–40 GeV/u for Pb
  - polarised ions: p, d, 3He, possibly Li

- **Polarisation for both beams: > 70%**

- **Luminosity $10^{33}$ to $10^{34}$ cm$^{-2}$s$^{-1}$ → staging center-of-mass energy**

- **Both machines utilize crossing angles**
  - 15 mrad

- **Bunch frequency**
  - 476 MHz
  - 159 MHz@$\sqrt{s}=63$ GeV

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*Yale University, October 2016*

*E.C. Aschenauer*
Much wider kinematic coverage

After EIC: spin puzzle will be solved

Gluon - Quarks = orbital angular momentum

current polarized DIS data:
- CERN - DESY - JLab - SLAC

current polarized BNL-RHIC pp data:
- PHENIX + STAR 1-jet + W bosons
- JLab-2

projected CC DIS data:
- EIC $\sqrt{s} = 141 GeV$

EIC projections:
- $\sqrt{s} = 77.5 GeV$
- $\sqrt{s} = 122.7 GeV$
- $\sqrt{s} = 141.4 GeV$

Gluon Quarks orbital angular momentum

DSSV 2014
DSSV 2008
90% C.L. band
2+1 DIMENSIONAL IMAGING: QUARKS & GLUONS

Wigner function

\[ W(x, b_T, k_T) \]

\[ \int d^2 b_T \]

\[ \int d^2 k_T \]

\[ f(x, k_T) \]

\[ f(x, b_T) \]

Momentum space

Coordinate space

Quarks

Gluons

Momentum space

Coordinate space

Spin-dependent 3D momentum space images from semi-inclusive scattering

Spin-dependent 2+1D coordinate space images from exclusive scattering

E.C. Aschenauer

Yale University, October 2016
**DVCS: Golden channel ➔ theoretically clean wide range of observables ($\sigma$, $A_{UT}$, $A_{LU}$, $A_{UL}$, $A_{C}$) to disentangle different GPDs**
The spin of the proton arises from the vacuum structure of QCD. Many new results pave the way to resolve the mystery about the origin of the spin of the proton. Start to get first data to get tomographic pictures of the proton.
Kinematics:

Quark splits into gluons splits into quarks ...

Gluon splits into quarks

Higher $\sqrt{s}$ increases resolution.

$Q^2 = -q^2 = -(k_{\mu} - k'_{\mu})^2$

Measure of resolution power

$Q^2 = 2E_eE'_e(1 - \cos \Theta_e)$

Measure of inelasticity

\[
y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e} \cos^2 \left( \frac{\Theta'_e}{2} \right)
\]

Measure of momentum fraction of struck quark

$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$
q(x₁), g(x₂): Parton distribution functions (PDF) (no polarisation effects)
→ a measure of the number of partons of different type in a proton
Δq(x₁), Δg(x₂): polarised parton distribution functions
describe the difference of how many partons have their spin aligned with the proton or anti-aligned

x₁, x₂: fraction of the proton momentum carried by a parton
Q²: the energy transfer in the hard scattering of the partons
Data compared to NLO pQCD calculations:

- Inclusive jet and di-jet cross section results in p+p collisions are consistent with NLO pQCD calculations after Had+UE corrections.
Data compared to NLO pQCD calculations:

- $\sqrt{s}=62$ GeV calculations may need inclusion of NLL (effects of threshold logarithms)
- $\sqrt{s}=200$ and 500 GeV: NLO agrees with data within ~30%
- good agreement also for $\eta>1$
- Input to QCD fits of gluon fragmentation functions $\rightarrow$ DSS

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HIGH PRECISION 2009 RHIC DATA \( \int dx \Delta g(x) \)

\[
\int dx \Delta g \sim 0.2 \pm 0.06 @ 10 \text{ GeV}^2
\]

First time a significant non-zero \( \Delta g(x) \)

- strong constrain on \( \int \Delta g(x) \)
- first \( \int \Delta g(x) > 0 \)
- completely consistent with \( \text{DSSV}^* \) in 90% C.L.

Impact in NNPDF

only STAR jets included
very fast evolution in RHIC kinematics
Analysis Strategy to fully reconstruct Ws:
Follow the analysis steps of the $A_L$
$\rightarrow$ W candidate selection via high $p_T$ lepton
Data set 2011 transverse 500 GeV data set (25 pb$^{-1}$)

$\checkmark$ In transverse plane: $\vec{P}_T^W = \vec{P}_T^e + \vec{P}_T^\nu = \vec{P}_T^{\text{recoil}}$

$\checkmark$ Recoil reconstructed using tracks and towers: $\sum_i \vec{P}_T^i$ (tracks + trackless - clusters)

$\checkmark$ Part of the recoil not within STAR acceptance $\rightarrow$ correction through MC (Pythia)

W Rapidity reconstruction:
$\checkmark$ W longitudinal momentum (along z) can be calculated from the invariant mass: $M_z^2 = (E_e + E_\nu)^2 - (\vec{p}_e + \vec{p}_\nu)^2$

$\checkmark$ Neutrino longitudinal momentum component from quadratic equation $|\vec{p}_i|^2 (p_i^\nu)^2 - 2A\vec{p}_i p_i^\nu + |\vec{p}_i|^2 \vec{p}_i^\nu - A^2 = 0$ $A = \frac{M_z^4}{2} + \vec{p}_i^\nu \vec{p}_i^\nu$

GOOD data/MC agreement after $p_T$ correction
Kinematics:
DY e+e- in 2.5 < \eta < 4.0

Design follows successful
Preshower design
\rightarrow 3 layers of u, x, y with
SiPM readout

After analysis 2.5 < \eta < 4.0

With TMD Evolution
\rightarrow AN for DY to +/- 0.008

No TMD Evolution

Run-17 \int L_{\text{del}} = 400 \text{ pb}^{-1} \rightarrow AN for DY to +/- 0.008
<table>
<thead>
<tr>
<th>STAR FPS&amp;FMS: P=60%, Ldt=40 pb⁻¹</th>
<th>STAR FPS&amp;FMS: P=55%, Ldt=400 pb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>AN for direct photon production:</td>
<td>AN for direct photon production:</td>
</tr>
<tr>
<td>p⁺p→γ⁺dr +X @ s=200 GeV, y=3.5</td>
<td>p⁺p→γ⁺dr +X @ y=500 GeV, y=3.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>AN(W⁺⁻, Z⁰)</strong></th>
<th><strong>AN(DY)</strong></th>
<th><strong>AN(γ)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitive to Sivers effect non-universality through TMDs</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Sensitive to Sivers effect non-universality through Twist-3 T₉,₉₉(x,x)</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Sensitive to TMD or Twist-3 evolution</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Sensitive to sea quark Sivers or ETQS function</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Detector upgrade needed</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Biggest experimental challenge</td>
<td>Integrated luminosity</td>
<td>Background suppression integrated luminosity</td>
</tr>
</tbody>
</table>

Not a replacement for AN(W⁺⁻, Z⁰, DY) measurement but an important complementary piece in the puzzle.
at which $x$-range are sea quarks flavor symmetric?

High precision high-$x$ PDFs critical for searches at high masses at the LHC

$\Rightarrow$ RHIC

mid-rapidity jet cross sections
$\Rightarrow$ high $x$ gluons (200 GeV)

quark structure
$W^+/W^-$: $u$, $d$, $ubar$, $dbar$ PDFs
$\Rightarrow$ RHIC results complementary and earlier than E-906

$x$-range of $Ws$: 0.05 to 0.5
Systematics much smaller than statistical uncertainties.
Generalized Parton Distributions

Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

How are GPDs characterized?

- **unpolarized**
  - $H^q(x, \xi, t)$
  - $E^q(x, \xi, t)$

- **polarized**
  - $\tilde{H}^q(x, \xi, t)$
  - $\tilde{E}^q(x, \xi, t)$

**Spin-Sum-Rule in PRF:**
\[
\frac{1}{2} = J^z_q + J^z_g = \frac{1}{2} \Delta \Sigma + \sum_q J^z_q + J^z_g
\]
\[
J^z_{q,g} = \frac{1}{2} \left( \int_{-1}^1 x \, dx \left( H^{q,g} + E^{q,g} \right) \right)_{t \to 0}
\]

- Conserve nucleon helicity
- Flip nucleon helicity
- Not accessible in DIS
- Responsible for orbital angular momentum

On the way to 3d imaging of the proton and access the orbital angular momentum $L_q$
Vary electron and proton beam spin directions:

- Electron beam longitudinal polarised
- Proton beam transverse polarised
- Proton beam longitudinal polarised

\[ Q^2 = 4.4 \text{ GeV}^2 \]
\[ x_B = \text{variable} \]
\[ -t = \text{variable} \]

**EIC pseudo data (KM10)**

- \( E_e \times E_p = 5 \times 100 \text{ GeV}^2 \)
- \( L = 2 \times 5 \text{ fb}^{-1} \)

**GPD models**

- KM10
- KM10a
- AFKM12

\( \Delta \sigma_{UT} \)

Brookhaven Science Associates

Yale University, October 2016

E.C. Aschenauer
Model of a quark GPD

\[ b_T \text{ (fm)} \]

\( b_T \) decreasing as a function of \( x \)

\[ \gamma^* + p \rightarrow \gamma + p \]

Valence (high \( x \)) quarks at the center \( \rightarrow \) small \( b_T \)

Sea (small \( x \)) quarks at the périphérie \( \rightarrow \) high \( b_T \) ?

GLUONS ???

EIC

20 GeV on 250 GeV

\[ Q^2 = 4.08 \text{ GeV}^2 \]
\[ = 7.28 \text{ GeV}^2 \]
\[ = 12.9 \text{ GeV}^2 \]

\( \langle b_T^2 \rangle \) (fm\(^2\))

\( X_B \) Yale University, October 2016
A global fit over all pseudo data was done, based on the GPDs-based model:

K. Kumerički, D. Müller, K. Passek-Kumerički 2007

Known values $q(x), g(x)$ are assumed for $H_q, H_g$ (at $\xi = 0, t=0$ forward limits $E_q, E_g$ are unknown)

Excellent reconstruction of $H_{\text{sea}}, H_{\text{sea}}$ and good reconstruction of $H_g$ (from $d\sigma/dt$)

Brookhaven Science Associates

Yale University, October 2016

E.C. Aschenauer
To improve imaging on gluons add $J/\psi$ observables

- cross section
- $A_{UT}$

$Q^2, \phi, J/\psi, DVCS$

$\rho, \phi, J/\psi, DVCS$

$\rho, \phi, J/\psi, DVCS$

F. C. Aschenauer

Yale University, October 2016

$GPD H^0: J/\psi$

$e + p \rightarrow e + p + J/\psi$

$15.8 < Q^2 + M^2_{J/\psi} < 25.1 \text{ GeV}^2$

$\int \mathcal{L} dt = 10 \text{ fb}^{-1}$

$\int \mathcal{L} dt = 10 \text{ fb}^{-1}$

at $20 + 250 \text{ GeV}$

at $5 + 100 \text{ GeV}$

BR($J/\psi \rightarrow e^+ e^-$) $d\sigma/dx_d/dt$ (pb/GeV$^2$)

$0.0016 < x_V < 0.0025$

$15.8 \text{ GeV}^2 < Q^2 + M^2_{J/\psi} < 25.1 \text{ GeV}^2$

$0.16 < x_V < 0.25$

$10 \text{ GeV}^2 < Q^2 + M^2_{J/\psi} < 15.8 \text{ GeV}^2$