DRELL YAN IN POLARIZED PP COLLISIONS
Is the proton looking like this?

"Helicity sum rule"

\[ \frac{1}{2} h = \langle P, \frac{1}{2} | J_{QCD}^z | P, \frac{1}{2} \rangle = \sum_q \frac{1}{2} S_q^z + \sum_q L_g^z + \sum_q L_g^z \]

Test unique QCD predictions for relations between single-transverse spin phenomena in p-p scattering and those observed in deep-inelastic lepton scattering.

Where do we stand solving the "spin puzzle"?
What do we know: NLO Fit to World Data

D. De Florian et al. arXiv:0804.0422

<table>
<thead>
<tr>
<th></th>
<th>$\chi^2_{\text{DIS}}$</th>
<th>$\chi^2_{\text{SIDIS}}$</th>
<th>$\Delta u_v$</th>
<th>$\Delta d_v$</th>
<th>$\Delta \bar{u}$</th>
<th>$\Delta \bar{d}$</th>
<th>$\Delta s$</th>
<th>$\Delta g$</th>
<th>$\Delta \Sigma$</th>
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<tbody>
<tr>
<td>DSSV</td>
<td>0.813</td>
<td>-0.458</td>
<td>0.036</td>
<td>-0.115</td>
<td>-0.057</td>
<td>-0.084</td>
<td>0.242</td>
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But how do we access $L_q$ and $L_g$??

- Includes all world data from DIS, SIDIS and pp
- Kretzer FF favor SU(3) symmetric sea, not so for KKP, DSS
- $\Delta \Sigma \sim 25-30\%$ in all cases
More insights to the proton - TMDs

- Unpolarized distribution function $q(x), G(x)$
- Helicity distribution function $\Delta q(x), \Delta G(x)$
- Transversity distribution function $\delta q(x)$
- Boer-Mulders distribution function $h_1^T$
- Sivers distribution function $f_{1T}^q$

Correlation between $\overline{S}_q^T$ and $\overline{S}_q^N$
Correlation between $\overline{S}_q^T$ and $k_q$
Correlation between $\overline{S}_N^T$ and $k_q$
Processes to study Single Spin Asymmetries

- Polarized pp scattering
- $\delta q_f, f_{1T}^\perp$

- Polarized SIDIS
- $\pi, K, \gamma$ jet
- $u, d, s, g$

- Polarized DY
- $f_{1T}^\perp$
- $e^+/\mu^+$
- $e^-/\mu^-$

- $u, d, s, g$
- $u, d, s, g$
- $u, d, s$
- $u, d, s, g$
- $u, d, s$
Sivers fct., what do we know?

Quasireal Photoproduction similar to pp

Results follow DIS-Sivers

$\rightarrow$ asymmetries fall at high $p_T$

$\rightarrow$ as predicted for pp
What else do we know

Lattice:
P. Haegler et al.
lowest moment of distribution of unpol. q in transverse pol. proton
ANL ZGS \(\sqrt{s}=4.9\) GeV
BNL AGS \(\sqrt{s}=6.6\) GeV
FNAL \(\sqrt{s}=19.4\) GeV

Big single spin asymmetries in \(p^+p\) !!

Naive pQCD (in a collinear picture) predicts \(A_N \sim \alpha_s m_q / \sqrt{s} \sim 0\)

What is the underlying process? Do they survive at high \(\sqrt{s}\)?
Large $A_N$ observed in forward hadron production from $\sqrt{s}=5$ GeV to $\sqrt{s}=200$ GeV

Proposed mechanisms
- Sivers
- Collins
- twist-3 effect (collinear)
- ...

need other observables to disentangle underlying processes

? Universality?

E. C. Aschenauer
BNL PAC, June 2010
First ideas by theorists to separate underlying processes:
\( A_N \) for \( \gamma\text{-jet} \to \text{sivers} \)
\( A_N \) for \( \pi^0\text{-jet} \to \text{Collins} \)

Universality breaking
Roger, Mulders hep-ph:1001.2977

QCD:

DIS: attractive FSI

Drell-Yan: repulsive ISI

\[ \text{Sivers}_{\text{DIS}} = - \text{Sivers}_{\text{DY}} \]

Transverse momentum dependent

Collinear/ twist-3

Both models expect sign change
DY Feasibility @ IP-2

- **Idea:** have DY feasibility test at IP-2
  - staged measurements over 3 years
  - re-use as much detector equipment as possible
    - keep cost low
  - Phenix and Star need upgrades to measure DY $|\eta|>2$
    - next decadal plans

- **Measurement:**
  - why IP-2
    - always transverse polarization
    - measure parallel to $\sqrt{s} = 500$ GeV W-program
      - more physics output for RHIC
      - time scale to accomplish HP13 in time and beat COMPASS and lessons learned benefit STAR and Phenix upgrades
  - Kinematic requirements
    - $\eta > 3$, $M>4$ GeV, $\sqrt{s} = 500$ GeV
      - optimizes Signal $A_N$
      - optimizes Signal / Background
      - optimizes DY rate
      - same kinematic as measured $A_N$
Collision Energy Dependence of Drell Yan Production

Comments...

- \( \bar{q}q \rightarrow \gamma^* \) has \( \hat{\sigma} \sim 1/\hat{s} \)
- partonic luminosities increase with \( \sqrt{s} \)
- net result is that DY grows with \( \sqrt{s} \)
- largest \( \sqrt{s} \) probes lowest \( x \)

⇒ Consider large-\( x_F \) DY at \( \sqrt{s}=500 \) GeV

\[
x \sim \frac{2p_T}{\sqrt{s}} e^{-y}
\]
\[
x_f = x_1 - x_2
\]
\[
M^2 = x_1 x_2 s
\]
\[
x_2 \sim M^2 / (x_F s)
\]
Equipment in place:

- Hcal is existing 2x9x12 modules from E864 (NIM406,227)
- BBC and ZDC

Goal:

- establish impact of 3 IR operation on PheniX and Star luminosity
- calibrate HCAL
  - absolute Energy scale with $\rho$, $\Phi$, $K_s$
  - gains with cosmics
- measure the hadronic background to benchmark MCs further
What do we know about the Backgrounds

Can we trust PYTHIA at forward rapidities

- PYTHIA 5.7 compared well to $\sqrt{s}=200$ GeV data [PRL 97 (2006) 152302]
- Little change until “underlying event” tunings for LHC created forward havoc
- PYTHIA 6.4 needs a bit more tuning
  ⇒ but reproduces NLO-pQCD calculations and data
  ⇒ used PYTHIA 6.222 for simulations
Electron pairs in different rapidity ranges:

**all, central** ($|y|<1$), **forward** ($|y|>2$), **very forward** ($|y|>3$)

- **minimum bias**: QCD $2 \rightarrow 2$ processes & diffractive processes
  - wide rapidity ($\pm 4$)
  - very basic cuts

- **Drell Yan**: qualitative needs to be scaled $\sim x10^{-6}$

**Background decreases faster than signal at forward $\eta$**
e^+e^- DY expectations at large x_F @ \(\sqrt{s}=500\) GeV

Model 1 = EMcal \((2m)^2 / (0.2m)^2\) beam hole at 10m / no magnetic field
Model 2 = L/R modular EMcal \((0.9m \times 1.2m)\) at 5m / no magnetic field

Setup planned for Run 12/13

Remarks:

- reasonable efficiency can be obtained for large-x_F DY with existing equipment
- final estimates of DY yield must follow estimates of background rejection
- critical question for decadal planning: is charge sign discrimination required?
What are the biggest background contributions

Background to e+e- DY pairs:

- hadronic background from QCD 2→2
  - h±/e± discrimination – requires estimates of p+p collisions and EMcal response
  - charged/neutral discrimination
- photon conversion in beam-pipe and other material
- Open Beauty
- Open Charm

Charm even further reduced going to \( \eta > 3 \)
Dileptons from open beauty at large $x_F$

Remarks:
- Direct production of open beauty results in ~15% background at large $x_F$.
- Large forward acceptance $1 < \eta < 4$ for the future would require discrimination (isolation).

E.C. Aschenauer                  BNL PAC, June 2010
Background: Di-hadrons and $\gamma$

Remarks:

- No cluster simulation and charge sign determination included
- $h^\pm h^\mp$ suppression probability consistent with full GEANT treatment for $E=10$ GeV
- dN/df modeled by uniform distribution to $f_{\text{max}}$ needs some more sophistication

ISR low-mass $e^+e^-$ DY reports limiting background as conversion photons (PLB91,475)

$N(\gamma_c-\gamma_c)=0.25\times N_{\text{back}}$  $N(\gamma_c-h^\pm)=0.47\times N_{\text{back}}$  $N(h^\pm-h^\pm)=0.28\times N_{\text{back}}$

Require $\pi^0 \rightarrow \gamma\gamma$ suppression

Remarks:

- Require $\pi^0 \rightarrow \gamma\gamma$ suppression

E.C. Aschenauer  BNL PAC, June 2010
Background: Di-hadrons and $\gamma$

**Remarks:**

- Conversion photons significantly reduced by $\pi^0 \rightarrow \gamma \gamma$ veto
- Preshower thickness tuned, although perhaps is not to critical given photon veto
- Linearly decreasing dN/df estimates smaller hadronic background
  - increased sophistication needed for reliable estimates,
  - although hadron interaction model uncertainties in MC could easily dominate
- measure hadron background @ Run-11
Additional Equipment to Run 11:

- EMcal is modeled as only (3.8cm)$^2 \times$ (45cm) lead glass
- Preshower (1cm Pb sandwiched by 0.5cm Scintillator) requires construction
- PHOBOS split-dipole expected to be in place, but not used

Goal:

- establish DY $A_N$ can be measured without charge identification
- 9400 DY-events
  \[ |A_N| \sim 0.13 \delta A_N \sim 0.02 \]
  with $M_{\gamma^*} > 4 \text{ GeV}$,
  $p_{z,\gamma^*} > 25\text{ GeV}$, $p_{t,\gamma^*} < 2\text{ GeV}$
  @ 150pb$^{-1}$
Additional Equipment to Run 11/12:

- PHOBOS split-dipole magnetic field in GEANT model used for charge sign determination
- Fiber tracker and MWPC stations require specifications and construction

Goal:

- establish what charge identification adds to DY measurements

Summary

- **DY feasibility test @ IP-2 will provide**
  - test of fundamental QCD prediction: \( \text{Sivers}_{\text{SIDIS}} = - \text{Sivers}_{\text{DY}} \)
    - resolve HP-13
    - impact on transverse physics program of EIC
  - timely and cost effective measurement
  - will benchmark requirements for DY upgrades for PHENIX and STAR
    - i.e., charge sign measurement needed or not
  - **DY @ RHIC will allow further important measurements:**
    - complementary to ep, dA
    - nPDFs
    - parton propagation in nuclear medium
    - more speculative: q-Saturation → EIC → Universality

- **Big unknown what is the luminosity impact of 3-IR operation**
  - lets measure it in Run-11
What else can DY @ RHIC teach us

Parton Propagation in Nuclear Medium:

**eAu:**
- hadron formation in-/outside nucl. medium
- gluon radiation
- $p_T$ broadening due to both effects
- **EIC:**
  - wide $\nu$ coverage

**dAu / pAu:**
- no hadron formation
- only due to gluon radiation
- $e^+e^-$ DY better resolution than $\mu^+\mu^-$
Saturation:
- dAu: Strong hints from RHIC at $x \sim 10^{-3}$
- ep: No (?) hints at Hera up to $x=6.32\cdot10^{-5}$, $Q^2 = 1-5$ GeV$^2$

Nuclear Enhancement:

$$Q_s^2(x,A) \sim cQ_0^2\left(\frac{A}{X}\right)^{1/3}$$

EIC Coverage:
- Need lever arm in $Q^2$ at fixed $x$ to constrain models
- Need $Q > Q_s$ to study onset of saturation
- $eA$: $\sqrt{s} = 50$ GeV is marginal, around $\sqrt{s} = 100$ GeV desirable
- low mass DY
  - access to quark saturation?
  - universality of saturation
BACKUP
**Compass:**
- $\pi p \oplus s = 200\text{GeV}^2$, $300\text{GeV}^2$, $360\text{GeV}^2$, $400\text{GeV}^2$
- $2\text{GeV} < M_{\mu^+\mu^-} < 2.5\text{GeV}$ and $4\text{GeV} < M_{\mu^+\mu^-} < 9\text{GeV}$
- Target: $\text{NH}_3 \rightarrow$ dilution factor $f=0.22$

**PHENIX:**
- $pp \at \sqrt{s} = 200\text{GeV}$
- $4\text{GeV} < M_{\mu^+\mu^-} < 9\text{GeV}$ with existing $\mu$-arms $1.2 < |\eta| < 2.4$
- not possible in parallel to W-program

**STAR:**
- $pp \at \sqrt{s} = 200\text{GeV}$
- $4\text{GeV} < M_{e^+e^-} < 9\text{GeV}$ assumed significant hardware upgrade

Details: http://spin.riken.bnl.gov/rsc/write-up/dy_final.pdf
Earlier $e^+e^-$ DY experiments

$p+p$ DY at ISR, $\sqrt{s}=53$, 63 GeV


Comments (note: large $x_F$ at collider breaks new ground)
- most fixed target experiments do $\mu^+\mu^-$ DY

Fig. 1. The cross section $(d^2\sigma/dm dy)_{y=0}$ versus mass for the data at $\sqrt{s}=53$ and 63 GeV combined. The curve is a result of the fit to the continuum displayed in fig. 2. The inset shows the mass acceptance for “1977” and “1978” triggers and geometrical configurations calculated for isotropic decay distributions and production uniform in rapidity with $p_T$ dependence $d\sigma/dp_T^2 \sim \exp(-b p_T^2)$, where $b = 1.4$ GeV$^{-1}$. The mass acceptance changes by $\pm 15\%$ when the helicity decay distribution follows $dN/d\cos\theta \propto 1 + \alpha \cos^2\theta$ when $\alpha = \pm 1$, where $\theta$ is measured in the $s$-channel helicity frame.
Theoretical Predictions for DY in pp

Prediction of $A_N$ in collinear twist-3 approach

- Opposite sign of $A_N$ due to different conventions
- $\sqrt{s}=500$ GeV predictions very similar, since $x_F=x_1-x_2$ is the relevant parameter

To go very forward ensures to measure non-zero $A_N$

Big acceptance in $\eta$ will allow to measure shape of $A_N$ vs $\eta/x_F$

Kang & Qiu PRD 81 (2010) 054020

DY Feasibility Test

- Staged Experiment
- Assumptions:
  - run in parallel with W-program and keep impact on luminosity for Star and PheniX minimal
- Planned Staging:
  - Hcal + newly constructed BBC at IP2 for RHIC run 11 with goals of establishing impact of 3-IR operation and demonstrate calibration of Hcal to get first data constraints on charged hadron backgrounds
  - Hcal + EMcal + neutral/charged veto + BBC for RHIC run 12 with goals of zero-field data sample with $L_{\text{int}} \sim 150 \, \text{pb}$ and $P_{\text{beam}} = 50\%$ to observe dileptons from $J/\psi$, $\Upsilon$ and intervening continuum.
  - Hcal + EMcal + neutral/charged veto + BBC + split-dipole for RHIC run 13 with goals data sample with $L_{\text{int}} \sim 150 \, \text{pb}$ and $P_{\text{beam}} = 50\%$ to observe dileptons from $J/\psi$, $\Upsilon$ and intervening continuum to address whether charge sign discrimination is required
- Lessons learned will be integrated into STAR and PheniX next decadal plan upgrades for DY
Strategy for detector response estimates

- \( \sim 10^{12} \) p+p interactions in 50/pb at \( \sqrt{s}=500 \) GeV \Rightarrow \) full PYTHIA/GEANT not practical

- Parameterize GEANT response of EMcal and use parameterized response in fast simulator applied to full PYTHIA events

- Estimate rejection factors from GEANT for hadron calorimeter and preshower detector (both critical to \( h^\pm/e^\pm \) discrimination)

- Explicit treatment in fast simulator to estimate pathlength through key elements (beam pipe and preshower), to simulate photon conversion to e+e- pair

- Estimate effects from cluster merging in EMcal (d < \( \varepsilon d_{\text{cell}} \) / recommended is \( \varepsilon \approx 1 \))

- Estimate/simulate EMcal cluster energy and position resolutions.
  \( \sigma_E=15\%/\sqrt{E} \) and \( \sigma_{x(y)}=0.1d_{\text{cell}} \) used to date for \( \pi^0 \rightarrow \gamma\gamma \) rejection.

GEANT simulation of Emcal response to E>15 GeV \( \pi^\pm \) from PYTHIA 6.222 incident on \((3.8\text{cm})^2\times45\text{cm}\) lead glass calorimeter
EMcal response to hadrons

- Uniform dN/df too simplistic
- GEANT response not so different from 57 GeV pion test beam data from CDF [hep-ex/060808 and presentation file]
- Linear fit to dN/df gives $\chi^2$/DOF=1.3
- Increased sophistication in fast simulator for hadronic response of EMcal still needed

GEANT simulation of EMcal response to E>15 GeV $\pi^\pm$ from PYTHIA 6.222 incident on (3.8cm)$^2$ x 45cm lead glass calorimeter
Hadronic Background without and with PID

apply PID

E.C. Aschenauer
BNL PAC, June 2010
Di-hadron background estimate I

Remarks:

- No cluster simulation and charge sign determination included
- Suppression probability consistent with full GEANT treatment for E=10 GeV π
- dN/df modeled by uniform distribution to f_max is too simplistic
Phobos Split Dipole

Split dipole, $B_z(x,z)$ in kGauss at $y=0$, $z_{off}=110$ cm, rot=1

$p+p \rightarrow e^+e^-X$, $\sqrt{s}=500$ GeV, $z_{off}=110$ cm, rot=1, 1800 events
Cutting on individual detectors very inefficient

- convert responses into conditional prob.
- Bayes theorem $\rightarrow$ true probabilities
- Tracking $\rightarrow$ reduces conversion $e^+e^-$
- Clustering $\rightarrow$ reduces $\pi^0$
Lepton daughters from $\gamma^*$

Most important contributions for $\gamma^* x_F>0.1$ at $\sqrt{s}=500$ GeV

- high energy electrons and positrons ($E>10$ GeV)
- require detection at very forward angles
- $e^+e^-$ from $\gamma^*$ little affected by “modest” isolation (20mr half-angle cone)
- best solution for charge sign would be a dipole magnet (difficult for any collider)
Azimuthal angle for $\gamma^* \rightarrow e^+e^-$

- $e^+$ and $e^-$ in separate modules except when $\gamma^*$ has large $p_T$
- Azimuthal angle required for analyzing power measurement
- Resolution is primarily from measuring energies of $e^+$ and $e^-$
- Model 2 covers full azimuth despite modular coverage

$p+p \rightarrow e^+e^-+X, \sqrt{s}=500$ GeV, PYTHIA 6.222, $L_{int}=14$ pb$^{-1}$
Away-side peaks evident in peripheral dAu and pp.

Near side peaks unchanged in dAu for peripheral to central.

Azimuthal decorrelations show significant dependence on centrality.

RHIC: Signs of Saturation in dAu

E.C. Aschenauer

BNL PAC, June 2010
\[
\frac{d^2 \sigma^{NC}_{em}}{dx dQ^2} = \frac{2 \pi \alpha^2_{em} Y_+}{x Q^4} \left( F_2 - \frac{y^2}{y_+^2} F_L \pm \frac{Y}{Y_+} x F_3 \right)
\]

Assumptions:
- \(10 \text{GeV} \times 100 \text{GeV/n}\)
  - \(\sqrt{s} = 63 \text{GeV}\)
- \(L dt = 4/A \text{ fb}^{-1}\)
  - equiv to \(3.8 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}\)
  - \(T=2\) weeks; DC: 50%
- Detector: 100% efficient
  - \(Q^2\) up to kin. limit \(s_x\)
- Statistical errors only
  - Note: \(L \sim 1/A\)
Star: Forward Physics program

- add electromagnetic calorimetry at forward rapidity
- access low and high $x$

$\eta$: TPC: $-1.0 < \eta < 1.0$
BEC: $-1.0 < \eta < 1.0$

2003: FPD: $3.3 < \eta < 4.1$
2008: FMS: $2.5 < \eta < 4.1$

$x \sim \frac{2p_T}{\sqrt{s}} e^{-\eta}$
STAR forward detectors

FTP C (to be removed next year)

Proposed FHC (for jet & lambda)

≈ $6 L_{int}$ spaghetti calorimeter
10cm x 10cm x 120 cm “cells”

DX shell $R \sim 60$cm

FMS
In open position
x~50cm from beam

No space for FHC near beam
No space in front of FMS neither
Everything $\eta > 2$

14799 events

FMS closed
(FHC cannot be placed due to DX magnet)

6512 events

pythia6.222, $p+p \ @ \ \sqrt{s}=500$

DY process, 4M events/$6.7E^{-05}$mb $\sim 60/pb$

e+/e- energy $>10$GeV & $\eta > 2$

$x_F > 0.1 \ (25$GeV$)$

4GeV $< \text{invariant mass} < 10$GeV
Extremely Model dependent statement:

M. Burkardt et al.

$$(1 - x)f_{1T}^{\perp q}(x) = -\frac{3}{2}MC_F\alpha_s E^q(x, 0, 0)$$

$$\int_0^1 dx (1 - x)f_{1T}^{\perp q}(x) = -\frac{3}{2}MC_F\alpha \kappa^q$$

anomalous magnetic moment:

$$\kappa^u = +1.67$$

$$\kappa^d = -2.03$$

Lattice:
QCDSF collaboration
lowest moment of distribution of unpol. q in transverse pol. proton
and transverse pol. quarks in unpol. proton