collinear (un)-polarized PDFs and fragmentation functions


Electron Ion Collider
The inner life of hadrons
Parton distribution functions
$r_s(x, Q^2) = \frac{s(x, Q^2) + \bar{s}(x, Q^2)}{d(x, Q^2) + \bar{u}(x, Q^2)}.$
Proton PDFs at high x

Baseline: CJ-15

Relative error improvement:

- pseudo-data for $0.01 < x < 0.9$
- NC Cross sections on proton target
- $F_2^n$ from deuterium with tagged proton spectator
- $10 \times 100 \text{ GeV}^2$ at $100 \text{ fb}^{-1}$
- energy scan $\sqrt{s}=57, 49, 28 \text{ GeV}$ at $10 \text{ fb}^{-1}$

→ more studies in progress
**SIDIS:**

Detect identified hadrons in coincidence to scattered lepton
→ needs fragmentation functions to correlate hadron type with parton
→ Detector: PID over a wide range of $\eta$

**Charge Current:**

$W$-exchange: direct access to the quark flavor
no FF - complementary to SIDIS
→ Detector: large rapidity coverage and large $\sqrt{s}$

**Jets:**

tag sea-quarks through the sub-processes and jet substructure
→ Detector: large rapidity coverage and PID
Observables: Charge Current in ep and eA

W-exchange:
direct access to the quark flavor

Ws are maximally parity violating
→ Ws couple only to one parton helicity

\[ W^- + p \rightarrow u\bar{d} \]
\[ W^- + n \rightarrow d\bar{u} \]

Complementary to SIDIS:
- high Q^2-scale: > 100 GeV^2
- best way to measure at very high x
- extremely clean theoretically
- No Fragmentation function
→ stringent test on theory
approach for SIDIS
UNIVERSALITY of PDFs

EIC:
first time charge current physics
in polarized ep and eA collisions

effective neutron target:
(un)polarized Deuterium or /and He-3
through tagging the spectator proton(s)

Deuterium spectator protons: 10 GeV x 100 GeV
He-3 spectator protons: 10 GeV x 166 GeV
EIC has a large kinematic coverage for charge current events (○)
Observables: Charge Current in ep and eA

Just some of the physics opportunities:

polarized ep/en:
- test models based on helicity retention $\Delta d/d \rightarrow 1$
- precision test models assuming charge symmetry violation
- precision test handiness of $W$s
- tag charm in coincidence with $CC$ event $\rightarrow \Delta s$

unpolarized ep/en:
- impact on PDFs $\rightarrow$ high $x$ quark PDFs
  - tag charm in coincidence of $CC$ event $\rightarrow s$
- precision constrain on light quark weak neutral current couplings $a_u, v_u, a_d v_d$

unpolarized eA:
- Test Models for the EMC-effect
  - charge symmetry violation
  - Isovector EMC effect
  (Cloet, Bentz, Thomas et. al., PRL 102 252301)
Generated 10 fb\(^{-1}\) worth of ep CC events with DJANGOH for 20 GeV x 250 GeV is used to get the impact on PDFs. Good agreement between pseudo-data and prediction.
Impact of CC@EIC to PDFs

\[ xU = xu + xc \]
\[ xD = xd + xs \]
\[ x\bar{U} = x\bar{u} + x\bar{c} \]
\[ x\bar{D} = x\bar{d} + x\bar{s} \]
\[ xu_{\nu} = xU - x\bar{U} \]
\[ xd_{\nu} = xD - x\bar{D} \]

Very strong impact on \( x\bar{D} \)
Significant impact on \( xu_{\nu} \)
Need to still understand in detail why there is impact on \( x\bar{U} \)

→ very promising first results
What can an EIC Do?

Should study what NC and CC cross sections at EIC can tell us on the vector and axial-vector weak neutral current couplings.
What can SIDIS@EIC Teach us

Cuts:
$Q^2 > 1 \, \text{GeV}^2$, $0.1 < y < 0.95$, $W^2 > 10 \, \text{GeV}^2$, $p_T > 0.2 \, \text{GeV}$

PID:
- $-3.5 < \text{rapidity} < -1$ RICH: $0.5 < p < 5 \, \text{GeV}$
- $-1.5 < \text{rapidity} < -1$ dE/dx: $0.2 < p < 0.6 \, \text{GeV}$
- $-1 < \text{rapidity} < 1$: dE/dx & DIRC: $0.2 < p < 4 \, \text{GeV}$
- $1 < \text{rapidity} < 3.5$ RICH: $0.5 < p < 50 \, \text{GeV}$
- $1 < \text{rapidity} < 1.5$ dE/dx: $0.2 < p < 0.6 \, \text{GeV}$

$K^-$
- $0.1 < z < 0.20$ $dN/dy$ at $5 \, \text{GeV} \times 100 \, \text{GeV}$
- $0.20 < z < 0.30$ $dN/dy$ at $20 \, \text{GeV} \times 250 \, \text{GeV}$
Use reweighting method to define EIC SIDIS data impact on collinear unpolarized PDFs and Fragmentation functions

Correlation factor of observable $\mathcal{O}$ to a flavor $i$

$$\rho[f_i, \mathcal{O}] = \frac{\langle \mathcal{O} \cdot f_i \rangle - \langle \mathcal{O} \rangle \langle f_i \rangle}{\Delta \mathcal{O} \Delta f_i},$$

account for uncertainties

$$S[f_i, \mathcal{O}] = \frac{\langle \mathcal{O} \cdot f_i \rangle - \langle \mathcal{O} \rangle \langle f_i \rangle}{\xi \Delta \mathcal{O} \Delta f_i},$$

$\xi = \frac{\delta \mathcal{O}}{\Delta \mathcal{O}}$

$\delta \mathcal{O}$: exp. uncertainty

Observable

$\Delta$ PDF in Observable

$\sqrt{s}=45$ GeV

$\sqrt{s}=140$ GeV
Use reweighting method to define EIC SIDIS data impact on collinear unpolarized PDFs and Fragmentation functions.

Correlation factor of observable $O$ to a flavor $i$:

$$
\rho [f_i, O] = \frac{\langle O \cdot f_i \rangle - \langle O \rangle \langle f_i \rangle}{\Delta O \Delta f_i},
$$

account for uncertainties

$$
S[f_i, O] = \frac{\langle O \cdot f_i \rangle - \langle O \rangle \langle f_i \rangle}{\xi \Delta O \Delta f_i},
$$

$\xi = \frac{\delta O}{\Delta O}$

$\delta O$ : exp. uncertainty

Observable

$\Delta$ PDF in Observable
PDF Constrain from SIDIS\@EIC

$\sqrt{s}=45$ GeV

$\sqrt{s}=145$ GeV

Impressive constrain of light quarks for $x<0.1$
need to investigate $x>0.1$ more
$\rightarrow$ impact grows with $\sqrt{s}$
If you want to know s-PDF ask the EIC
→ impact grows with $\sqrt{s}$
Utilize the same method as for PDFs

**singlet FF** $D_{q+\bar{q}}^{h\pm}$

**non-singlet FF** $D_{q-\bar{q}}^{h\pm}$
Example for Jet Physics at an EIC: Unpolarized and polarized photon structure

Details: X. Chu, ECA arXiv:1705.08831
In high energy ep collision, two types of processes lead to the production of di-jets:

- **Direct** contributions: point-like photon
- **Resolved** contributions: hadronic photon

**Di-jets@EIC ideal probe to constrain (un)polarised Photon-PDFs**

- Direct/resolved contributions can be separated reconstructing $x_\gamma$

\[
x_\gamma^{\text{rec}} = \frac{1}{2E_e y} (p_{T1} e^{-\eta_1} + p_{T2} e^{-\eta_2})
\]
Photon Parton Structure

unpolarized cross section:

\[ \frac{d^2}{dx d\log((p_T^{di-jet})^2)} \]

\[ 10^2 (p_T^{di-jet})^2 \text{ [GeV}^2\text{]} \]

Input: proton-CTEQ-5 & g: SAS

polarized cross section:

\[ \frac{d^2}{dx d\log((p_T^{di-jet})^2)} \]

\[ 10^2 (p_T^{di-jet})^2 \text{ [GeV}^2\text{]} \]

Input: proton-DSSV & \( \gamma \): PLB 337 373 (1994)
Photon Parton Structure

Jets from photon and proton side are well separated in $\eta$ for quark initiated processes.

It would be wonderful to have unpolarised photon PDFs with all data (LEP & HERA and before) fitted with uncertainties.

Identified hadron tagging in jet enhances flavor sensitivity.
What else can be done

The Holy Grail

The Spin Sum Rules

Jaffe & Manohar

Xiangdong Ji
Why should we care?

Spin ideal tool to understand the dynamics of sea quarks and gluons inside the hadron

Despite decades of QCD - **Spin** one of the least understood quantities

- Consequence very few models, but several physics pictures, which can be tested with high precision data

- **the pion/kaon cloud model**
  - rooted in deeper concepts → chiral symmetry
  - generated q-qbar pairs (sea quarks) at small(ish)-x are predicted to be unpolarized
  - gluons if generated from sea quarks unpolarised → spatial imaging
  - a high precision measurement of the flavor separated polarized quark and gluon distributions as fct. of x is a stringent way to test.

- **the chiral quark-soliton model**
  - sea quarks are generated from a "Dirac sea" with a rich dynamical structure but excludes gluons at its starting scale
  - sea quarks are polarized → asymmetry $\Delta\bar{u}\neq\Delta\bar{d}$
  - a high precision measurement of the flavor separated polarized quark as fct. of x is a stringent way to test

- **stringent test of lattice calculations**
  - the relative importance of lattice graphs
  - probe quark is connected to the proton wave function or is created from the 'gluon soup' inside the proton
What we have now: $\int \Delta g(x)$

DSSV: arXiv:0904.3821
DSSV*: DSSV + all new (SI)DIS
DSSV: DSSV* & RHIC 2009

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

First time a significant non-zero $Dg(x)$
- strong constrain on $\int \Delta g(x)$
- first $\int \Delta g(x) > 0$
- completely consistent with DSSV* in 90% C.L.

Impact in NNPDF
only STAR jets included
very fast evolution in RHIC kinematics

\[ \Delta g^{1,[0.05-0.2]}(Q^2) \equiv \int_{0.05}^{0.2} \Delta g(x, Q^2) \, dx \]
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: $\text{ubar} < \text{dbar}$

Helicity: $\Delta\text{ubar} > \Delta\text{dbar}$

TMDs: ????

- shape of polarized sea-quark PDFs critical for quark contribution to spin

$\Delta \Sigma$ does not converge at low $x$

- due to current constrains put in the fits
- strangeness was identified to be one of the least known quantities

- both unpolarized and polarized

\[
\int dx \Sigma\sim 0.366 \pm 0.042 \text{ @10 GeV}^2
\]

\[
\int dx \Delta \Sigma\sim 0.242 \text{ @10 GeV}^2
\]
current polarized DIS data:
- CERN
- DESY
- JLab-6
- SLAC

current polarized BNL-RHIC pp data:
- PHENIX
- STAR 1-jet
- W bosons
- JLab-12

EIC Ös = 141 GeV, 0.01 ≤ y ≤ 0.95
EIC Ös = 45 GeV, 0.01 ≤ y ≤ 0.95

eic extends x coverage by ~2 decades

likewise for Q²

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

What do we know:

\[
\frac{1}{2} \hat{h} = \left\langle P, \frac{1}{2} | J_{QCD}^z | P, \frac{1}{2} \right\rangle = \frac{1}{2} \int dx \Delta \Sigma(x,Q^2) + \int_{0}^{1} dx \Delta G(x,Q^2) + \int_{0}^{1} dx \left( \sum_{q} L_{q}^z + L_{g}^z \right)
\]

\[\frac{1}{2} - \frac{1}{2} \int dx \left[ \frac{1}{2} DS + Dg \right] (x,Q^2)\]

\[Q^2 = 10 \text{ GeV}^2\]

**Orbital Angular Momentum**

**Gluon** 40%  
**Quarks** 30%  
**=** Orbital Angular Momentum
To determine the contribution of quarks and gluons to the spin of the proton, one needs to measure the cross section difference $g_1$ as function of $x$ and $Q^2$.

**Quark contribution:**
The integral of $\Delta q$ over $x$ from 0 to 1

**Gluon contribution:**
$dg_1(x,Q^2)/d\ln Q^2 \rightarrow \Delta g(x,Q^2)$
$g_1$ the way to find the Spin

**Cross section:**
$$\frac{d^2\sigma}{d\Omega dE'} \sim L_{\mu\nu} W^{\mu\nu}$$

$$W^{\mu\nu} = -g^{\mu\nu} F_1 - \frac{p^\mu p^\nu}{v} F_2 + \frac{i}{v} \epsilon^{\mu\nu\lambda\sigma} q^\lambda s^\sigma g_1$$

$$+ \frac{i}{v^2} \epsilon^{\mu\nu\lambda\sigma} q^\lambda \left( p \cdot q s^\sigma - s \cdot q p^\sigma \right) g_2$$


**Unseen precision and x-Q^2 coverage**

- Present uncertainties
- EIC projected data:
  - $\sqrt{s} = 44.7$ GeV
  - $\sqrt{s} = 63.2$ GeV
  - $\sqrt{s} = 141.4$ GeV

**Fixed target DIS data**

- $g_1(x, Q^2) + \text{const}(x)$
- $Q^2$ (GeV$^2$)

**pQCD scaling violations**

$$\frac{dg_1}{d\log(Q^2)} \sim -\Delta g(x, Q^2)$$

$$\Delta \Sigma(Q^2) = \int_0^1 g_1(x, Q^2) dx = \int_0^1 \Delta q_f(x, Q^2) dx$$
rough small-$x$ approximation to $Q^2$-evolution:

\[
\frac{dg_1}{d\log(Q^2)} \propto -\Delta g(x, Q^2)
\]

spread in $\Delta g(x, Q^2)$ translates into spread of scaling violations for $g_1(x, Q^2)$

- need $x$-bins with at least two $Q^2$ values to compute derivative (limits $x$ reach somewhat)

- error bars for moderate 10fb$^{-1}$ per c.m.s. energy; bands parameterize current DSSV+ uncertainties
What forms the Spin of the Proton

The polarized SF $g_1(x, Q^2)$ as measured at EIC for low to high $\sqrt{s}$

$g_1(x, Q^2) + \text{const}(x)$

| $x=5.2$ | $10^3 (+53)$ |
| $8.2$ | $10^3 (+45)$ |
| $1.3$ | $10^4 (+38)$ |
| $2.1$ | $10^4 (+33)$ |
| $3.3$ | $10^4 (+28)$ |
| $5.2$ | $10^4 (+24)$ |
| $8.2$ | $10^4 (+21)$ |
| $1.3$ | $10^3 (+17)$ |
| $2.1$ | $10^3 (+15.5)$ |
| $3.3$ | $10^3 (+15.5)$ |
| $5.2$ | $10^3 (+14)$ |
| $8.2$ | $10^3 (+13)$ |
| $1.3$ | $10^3 (+12)$ |

EIC projected data:
- eRHIC + JLEIC
- $\sqrt{s} = 44.7 \text{GeV}$
- $\sqrt{s} = 63.2 \text{GeV}$
- $\sqrt{s} = 141.4 \text{GeV}$

Theory Uncertainty

Only with the center-of-mass energies available at EIC the different contributions to the spin of the proton can be disentangled.
Where does the Spin of the proton hide

“Helicity sum rule:”

\[ \frac{1}{2} \hat{\hbar} = \left\langle P, \frac{1}{2} | J_{QCD}^z | P, \frac{1}{2} \right\rangle = \sum_q \frac{1}{2} S_q^z + \sum_g (S_g^z + L_g^z) \]

1/2 - Gluon - Quarks = orbital angular momentum
Can cover the same kinematics for $g_1^{\pi, K}$ as for $g_1$ → will constrain $\Delta q$

yet, small $x$ behavior completely unconstrained → determines $x$-integral, which enters proton spin sum

- includes data for $\sqrt{s}=45$ GeV & 70 GeV
- can be pushed to $x=10^{-4}$ with $\sqrt{s}=140$ GeV data
- Lox $x$-behavior for $\Delta s$ is artificial due to constraints put in the fits 3F-D → EIC can remove all constrains

"issues":
- (SI)DIS @ EIC limited by systematic uncertainties need to control rel. lumi, polarimetry, PID performance, ... very well
probing a possible asymmetry in the polarized sea

- current SIDIS data not sensitive to $\Delta \bar{u}(x) - \Delta \bar{d}(x)$ (known to be sizable for unpol. PDFs)
- many models predict sizable asymmetry [large $N_c$, chiral quark soliton, meson cloud, Pauli blocking]

Thomas, Signal, Cao; Holtmann, Speth, Fassler; Diakonov, Polyakov, Weiss; Schafer, Fries; Kumano; Wakamatsu; Gluck, Reya; Bourrely, Soffer, ...

can be easily studied at an EIC
main effect expected to be at not too small $x$ → can test $x$ dependence

can try to look into a possible $\Delta s(x) - \Delta \bar{s}(x)$ with $K^{+/-}$ SIDIS data

E.C. Aschenauer
INT-2018 Week-3
Observables: Charge Current in polarized ep

Polarized CC cross section

Approximate behavior of the LO single spin asymmetry

\[ A_{L}^{W,-,p} = \frac{\Delta u(x) - \Delta \bar{d}(x)}{u(x) + \bar{d}(x)} \]

\[ A_{L}^{W,-,n} = \frac{\Delta d(x) - \Delta \bar{u}(x)}{d(x) + \bar{u}(x)} \]

\[ y \to 0 \]

\[ y = \frac{1}{2} \]

\[ y \to 1 \]

similar to what is seen in W production in polarized pp

Polarized EW PHYSICS

\[ A_{L}^{W,-,N} = \frac{d^2 \Delta \sigma_{W,-,N}^{W} / dxdy}{d^2 \sigma_{W,-,N}^{W} / dxdy} \]

\[ g_1^{W,-,p}(x) = \Delta u(x) + \Delta \bar{d}(x) + \Delta c(x) + \Delta \bar{s}(x) \]
\[ g_1^{W,-,n}(x) = \Delta d(x) + \Delta \bar{u}(x) + \Delta c(x) + \Delta \bar{s}(x) \]

More Details: arXiv:1309.5327
More work to be done on unpolarized PDF and FF constrains
  - but EIC will be critical for PDF and FF constrains
  - did not discuss inclusive DIS and $F_2 \rightarrow$ but coverage better then for eA
    arXiv:1708.05654

EIC at high √s the only machine to unravel the different components to
the spin of the proton
  - critical for low-<i>x</i> behaviour

CC important observable for flavor separation and testing limitations of SIDIS

Questions to be answered before an EIC

- effective neutron target: √s Deuterium: 100 GeV Helium-3: 166 GeV
  - He-3 larger <i>x</i> coverage proton equivalent √s: 250 GeV
  - what is the better choice with respect to nuclear effects

- What are the limiting theoretical factors to determine high-<i>x</i> PDFs?
  - what is the golden observable to constrain $g(x,Q^2)$ at high <i>x</i>

- How can we measure $Lq$ and $Lg$ from Jaffe-Manohar

- What are the golden observables to learn about hadronization
  - Correlations between different rapidity ranges and distributions inside jets?
Inclusive Cross-Sections in eA

Direct Access to gluons at medium to high x by tagging photon-gluon fusion through charm events

Gluon distribution $\sim \frac{d\sigma(x,Q^2)}{d\ln Q^2}$
Direct Access to gluons in $e^+A$

For Details: arXiv:1708.05654

Direct Access to gluons at medium to high $x$ by tagging photon-gluon fusion through charm events.

High precision $F_L^{charm}$ will offer an opportunity to benchmark different GM-VFNS schemes with an unprecedented precision.
EIC: Impact on the Knowledge of 1D Nuclear PDFs

$\sqrt{s} < 45$ GeV

$\sqrt{s} < 90$ GeV

Ratio of PDF of Pb over Proton

- Without EIC, large uncertainties
  - With EIC significantly reduced uncertainties
- Complementary to RHIC and LHC pA data.
  Provides information on initial state for heavy ion collisions.
- Does the nucleus behave like a proton at low-$x$?
  - relevant to very high-energy cosmic ray studies
  - critical input to AA
- submitted to PRD arXiv:1708.05654
probes of nucleon helicity structure

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

\[ P\]

DIS

\[ \Delta q + \Delta \bar{q} \]

SIDIS

\[ \Delta q, \Delta \bar{q} \]

pions, kaons

charm, 2-hadrons

pp

\[ \Delta g \]

1-jet, 1-hadron

W^+/-' bosons

guiding principle: factorization

e.g. DIS

\[ d\Delta \sigma = \sum_{f=q,\bar{q},g} \int dx \Delta f(x, Q^2) d\Delta \hat{\sigma}_{\gamma*} f(xP, \alpha_s(Q^2)) \]

essential: QCD corrections

\[ d\Delta \hat{\sigma} = d\Delta \hat{\sigma}^{\text{LO}} + \alpha_s d\Delta \hat{\sigma}^{\text{NLO}} + \ldots \]

need DIS + SIDIS + pp to constrain all aspects of PDFs (a way to test factorization)