An Electron-Ion Collider is a machine of discovery:
to discover new phenomena in the structure of nucleon and nucleus.

\[ \Delta \bar{u} \neq 0, \; \Delta \bar{d} \neq 0, \; \Delta \bar{u} - \Delta \bar{d} \neq 0 \]

- SIDIS double-spin asymmetry \( A_{1N}^{h} \) provides access to \( \Delta q, \Delta \bar{q} \)
- Three independent methods of SIDIS spin-flavor decomposition
  - NLO global fit.
  - Leading-order “purity” method as in HERMES and COMPASS.
  - Leading-order and NLO Christova-Leader method: \( A_{1N}^{\pi^{+} - \pi^{-}} \)
- Example-I: JLab-12GeV, Hall A on polarized neutron \((^3\text{He})\) target.
- Example-II: EIC
Flavor Asymmetry in Unpolarized Nucleon Sea

Nucleon sea polarized? Flavor symmetric? \( \Delta \bar{u} \neq 0, \Delta \bar{d} \neq 0, \Delta \bar{u} - \Delta \bar{d} \neq 0 \)

Pauli-blocking model: \( \int_0^1 [\Delta \bar{u}(x) - \Delta \bar{d}(x)] dx = \frac{5}{3} \cdot \int_0^1 [\bar{d}(x) - \bar{u}(x)] dx \approx 0.2. \)
STAR Collaboration

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

\[ A_L \]

Deviation from DSSV08
(sea pol. ~ 0)

\[ \Delta \chi^2/\chi^2 = 2\% \text{ error} \]

3.4% beam pol scale uncertainty not shown
STRW data introduced shifts to sea polarization in NLO global fit (DSSV)
NNPDF arXiv:1406.5539

STRA W data introduced shifts to sea polarization in NLO global fit (NNPDF)
NNPDF arXiv:1406.5539

STRA W data introduced shifts to sea polarization in NLO global fit (NNPDF)
StaGsGcal Model prediction. Bourrely, Buccella, Soffer PLB 726, 296 (2013)

BBS2008: a rather large sea polarization 10\textasciitilde{}20\%, strong flavor dependency.
Flavor Tagging Through SIDIS and Leading-Order “Purity” Method

Detect the leading hadron from the current fragmentation and measure double-spin asymmetry: \( A_1^h = \Delta \sigma^h / \sigma^h \).

Leading order naive \( x-z \) separation:

\[
\Delta \sigma^h = \sum_{f=q,\bar{q}} e_f^2 \Delta q_f(x) D_f^h(z)
\]

Reaction on a “free quark”:
highest possible \( Q^2, W, p_\pi \) and \( W' \).

HERMES calculated “purity” from a LUND based Monte Carlo:

\[
A_1^h = \sum_a \frac{e_a^2 q_a(x) D_a^h(z)}{\sum_b e_b^2 q_b(x) D_b^h(z)} \frac{\Delta q_a(x)}{q_a(x)}
\]

Fragmentation “tags” flavor and charge of struck quark.

Effects of non-vanishing sea polarizations will show up in SIDIS asymmetries.
Polarized Sea Flavor Asymmetry

HERMES and COMPASS Leading-Order extractions

\[ x \Delta u(x) \]

\[ x \Delta d(x) \]

\[ x \Delta u(x) \]

\[ x \Delta d(x) \]

\[ x \Delta s(x) \]

\[ \mu^2 = 2.5 \text{ GeV}^2 \]
Flavour Asymmetry $\Delta \bar{u} - \Delta \bar{d}$

(leading-order “purity” method)

Caveat: assuming precision knowledge of quark to hadron fragmentation functions.
Strangeness polarization

Caveat: assuming precision knowledge of quark to hadron fragmentation functions.
At NLO, also requires knowledge of gluon density and gluon to hadron fragmentation functions.
SIDIS at NLO

\[ \Delta \sigma^h = \sum_i e_i^2 \Delta q_i \left[ 1 + \frac{\alpha_s}{2\pi} \Delta C_{qq} \otimes D_{qi}^h \right] + \left( \sum_i e_i^2 \Delta q_i \right) \otimes \frac{\alpha_s}{2\pi} \Delta C_{qg} \otimes D_G^h + \Delta G \otimes \frac{\alpha_s}{2\pi} \Delta C_{qq} \otimes \left( \sum_i e_i^2 D_{qi}^h \right) \]

- NLO global QCD-fit with inclusive and SIDIS data constrain \( \Delta q_i \) and \( \Delta G \).

NLO QCD global fit needs inputs of:
- quark and gluon densities
- quark to hadron fragmentation functions
- gluon to hadron fragmentation functions

There’s an alternative method to avoid these complications...
An alternative way to obtain flavor non-singlet $\Delta \bar{u} - \Delta \bar{d}$

Flavor non-singlet:

$$\Delta q_3(x) = [\Delta u(x) + \Delta \bar{u}(x)] - [\Delta d(x) + \Delta \bar{d}(x)].$$

$$\Delta \bar{u}(x) - \Delta \bar{d}(x) = \frac{1}{2} \Delta q_3(x) - \frac{1}{2} [\Delta u_v(x) - \Delta d_v(x)].$$

At the leading order:

$$\Delta q_3(x)|_{LO} = 6 [g_1^p(x) - g_1^n(x)].$$

$$[\Delta \bar{u}(x) - \Delta \bar{d}(x)]|_{LO} = 3 [g_1^p(x) - g_1^n(x))] - \frac{1}{2}(\Delta u_v - \Delta d_v)|_{LO}.$$ 

- Obtain non-singlet $\Delta q_3(x)$ through inclusive measurements of $g_1^p(x) - g_1^n(x)$.
- Obtain $\Delta u_v(x) - \Delta d_v(x)$ through SIDIS on $\vec{p} - \vec{n}$.
Flavor Non-Singlet $\Delta u_v(x) - \Delta d_v(x)$ at LO


$$A_{1p}^{\pi^+ - \pi^-}(\vec{p}) = \frac{\Delta \sigma_p^{\pi^+} - \Delta \sigma_p^{\pi^-}}{\sigma_p^{\pi^+} - \sigma_p^{\pi^-}} = \frac{4\Delta u_v - \Delta d_v}{4u_v - d_v}$$

$$A_{1d}^{\pi^+ - \pi^-}(\vec{p} + \vec{n}) = \frac{\Delta \sigma_d^{\pi^+} - \Delta \sigma_d^{\pi^-}}{\sigma_d^{\pi^+} - \sigma_d^{\pi^-}} = \frac{\Delta u_v + \Delta d_v}{u_v + d_v}$$

$$A_{1He}^{\pi^+ - \pi^-}(\vec{n} + 2\vec{p}) = \frac{\Delta \sigma_{He}^{\pi^+} - \Delta \sigma_{He}^{\pi^-}}{\sigma_{He}^{\pi^+} - \sigma_{He}^{\pi^-}} = \frac{4\Delta d_v - \Delta u_v}{7u_v + 2d_v}$$

Ideally: measurements on three targets to over-constrain $\Delta u_v - \Delta d_v$:

$$(\Delta u_v - \Delta d_v)_{LO} = \frac{1}{5} \left[ \left(4u_v - d_v\right)A_{1p}^{\pi^+ - \pi^-} - \left(7u_v + 2d_v\right)A_{1He}^{\pi^+ - \pi^-}\right]$$

Without the complication of Fragmentation Functions.
SIDIS at NLO

\[
\Delta \sigma^h = \sum_i e_i^2 \Delta q_i \left[ 1 + \frac{\alpha_s}{2\pi} \Delta C_{qq} \otimes \right] D_{q_i}^h \\
+ \left( \sum_i e_i^2 \Delta q_i \right) \otimes \frac{\alpha_s}{2\pi} \Delta C_{qq} \otimes D_G^h + \Delta G \otimes \frac{\alpha_s}{2\pi} \Delta C_{qq} \otimes \left( \sum_i e_i^2 D_{q_i}^h \right)
\]

- NLO global QCD-fit with inclusive and SIDIS data constrain \( \Delta q_i \) and \( \Delta G \).
- Gluon density vanishes in \( \pi^+ - \pi^- \) (gluons carry no flavor).
  
  Flavor non-singlet observable \( A_{\pi^+}^{\pi^-} \) is theoretically clean.
From $A_{1N}^{\pi^+ - \pi^-}$ to $\Delta u_v$, $\Delta d_v$ and $\Delta \bar u - \Delta \bar d$

Christova and Leader, NPB607,369 (2001), flavor non-singlet combination:

$$\frac{\Delta \sigma_{\pi^+}^p - \Delta \sigma_{\pi^-}^p}{\sigma_{\pi^+}^p - \sigma_{\pi^-}^p} = \frac{(4\Delta u_v - \Delta d_v) [1 + \otimes (\alpha_s/2\pi) \Delta C_{qq} \otimes]}{(4u_v - d_v) [1 + \otimes (\alpha_s/2\pi) C_{qq} \otimes]} D_u^{\pi^+ - \pi^-}$$

$$\frac{\Delta \sigma_{He}^{\pi^+} - \Delta \sigma_{He}^{\pi^-}}{\sigma_{He}^{\pi^+} - \sigma_{He}^{\pi^-}} = \frac{(4\Delta d_v - \Delta u_v) [1 + \otimes (\alpha_s/2\pi) \Delta C_{qq} \otimes]}{(7u_v + 2d_v) [1 + \otimes (\alpha_s/2\pi) C_{qq} \otimes]} D_u^{\pi^+ - \pi^-}$$

$\Delta u_v$ and $\Delta d_v$ are non-singlets do not mix with the other quark and gluon densities.

$$(\Delta \bar u - \Delta \bar d)|_{LO} = \frac{1}{2} (\Delta q_3 + \Delta d_v - \Delta u_v)|_{LO}$$

where $\Delta q_3 = 6(g_1^p - g_1^n)$ from inclusive data.

“Bjorken Sum Rule” links the moments at all orders of QCD (Sissakian et al. PRD68, 031502 (2003)).

$$2 \int_0^1 (\Delta \bar u - \Delta \bar d) dx + \int_0^1 (\Delta u_v - \Delta d_v) dx = |\frac{g_A}{g_V}| = 1.2670 \pm 0.0035$$
An JLab-12GeV Example: PR12-14-008

- Spectrometer layout of SIDIS
- **Independent electron and hadron arms:**
  - Large momentum bite
  - Moderate solid angle
  - High-rate capability
  - Excellent PID
- $h^+/h^-$ symmetric acceptance

BigBite (SBS) as electron (hadron) arm

- SIDIS w/BB 30 deg, SBS 14 deg.
  - 60 cm polarized $^3$He
  - 10.5 atm
  - $I_{\text{beam}} \geq 40 \mu A$

- SIDIS w/BB 30 deg, SBS 10 deg.

Polarized Sea Flavor Asymmetry
$\langle Q^2 \rangle$ of SBS+BB SIDIS: > HERMES, < COMPASS

![Graph showing $\langle Q^2 \rangle$ as a function of $x_{bj}$, with data points for different energy proposals and HERMES He-3.]
Projected Neutron Asymmetry Precision—1D for all hadrons

- Projected asymmetry precisions (stat. only) in $A_{1n}^h$ vs $x$, integrated over $z$, $p_T$, compared to prediction of “DSSV+” NLO global fit, arXiv: 1108.3955
Projected Asymmetry Precision, 2D (x,z), E = 11 GeV

- High precision measurements on a dense grid of (x, z).
- Consistent deviations from NLO QCD prediction?

Polarized Sea Flavor Asymmetry
\[ \frac{\sigma_q}{\sigma_{all}} = e_f^2 q_f \cdot D^h_f / \sum_i e_i^2 q_i \cdot D^h_i \quad (@z_h = 0.5) \]

Measurements on neutron \( A_{1n}^h \) is most sensitive to \( \Delta d \).
Physics Impacts

- Impacts through NLO Global fit, DSSV2008.
- Impacts through leading-order purity method.
- Impacts through leading-order Christova-Leader method.
Impacts to sea quark polarization: through NLO Global fit DSSV2008

Results of a DSSV study, impacts on error bands of sea quark polarization:

- **Slight reduction on** $u$**bar**
- **Very significant reduction on** $d$**bar**
- **Noticeable reduction on** $s$=$s$**bar**

Black: width of parabolas at a 2% increase of the DSSV $\chi^2$ ($\sim 1\sigma$).
Red: when including new data of this experiment.
Leading-Order “Purity” Method as in HERMES and COMPASS
Leading-Order “Purity” Method

Sensitivity to Strangeness Polarization

This experiment

$E_0=11$ GeV
$E_0=8.8$ GeV

COMPASS
HERMES

Statistical Model
Leading-Order Christova-Leader Method: I

\[(\Delta d_v - \frac{1}{4}\Delta u_v)_{LO} = \frac{1}{4}(7u_v + 2d_v)A^{\pi^+ - \pi^-}_{1He}\]

\[
A^{\pi^+ - \pi^-}_{1He} = \frac{\Delta\sigma^+_{He} - \Delta\sigma^-_{He}}{\sigma^+_{He} - \sigma^-_{He}} = \frac{A^{+}_{1He} - A^-_{1He}}{1 - r}.
\]

\[
r = \frac{\sigma^-_{He}}{\sigma^+_{He}}
\]

\[
[\Delta\bar{u}(x) - \Delta\bar{d}(x)]_{LO} = 3[g_1^p(x) - g_1^n(x)] - \frac{1}{2}(\Delta u_v - \Delta d_v)_{LO}
\]
Polarized sea flavor asymmetry: non-perturbative in nature, intrinsic property of nucleon.
Example-II: “Chinese EIC” e+p Case

A very preliminary study

Pe=3 GeV, pol.=0.85
Pp=12 GeV, pol.=0.60
“A dilution free COMPASS experiment”.

Integrated Luminosity=3.5 fb^{-1} (200 days, @50% machine_up*exp_up )
Inclusive DIS A_{1p}
SIDIS A_{1p}^{h} h=\pi^{+}, \pi^{-}, K^{+}, K^{-}, charged-particle only. 50% PID*reconstruction_eff.

SIDIS kinematics cut:
y cut: 0.05<y<0.9
Q2 cut: 1.0<Q2
W cut: 2.0<W
in SIDIS 0.3<z<0.7
A very preliminary study

Leading-Order “Purity” Method
Only shown ~1/5 of \((x, Q^2)\) bins.
Integrated over \(z\) at each \((x, Q^2)\)

Very sensitive to \(u\)-quark, ~ubar quark
Less sensitive to \(d\)-quark, ~dbar quark
Need both proton and \(^3\)He beam

Need to feed the dense grid of
“projected precision” to DSSV for an impact study.
Summary

\[ \Delta \bar{u} \not= 0, \Delta \bar{d} \not= 0, \Delta \bar{u} - \Delta \bar{d} \not= 0 \]

We will make SIDIS measurements at JLab-12GeV Hall A for spin-flavor decomposition:

- High precision over a dense kinematic grid, constrain \( \Delta u, \Delta d \)
- Consistent deviation from DSSV2008 prediction -> sea polarization.
- Check consistency between different extraction methods.
- Set limits on the size of higher-twist/higher-order terms.

A testing ground for EIC experiments.

An Electron-Ion Collider is a machine of discovery: to discover new phenomena in the structure of nucleon and nucleus.
Gluon densities and gluon fragmentation functions vanish in $\pi^+ - \pi^-$