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 does the nuclear environment affect the distribution of quarks and gluons and their interaction in nuclei?

How does the transverse spatial distribution of gluons compare to that in the nucleon?

How does matter respond to fast moving color charge passing through it? Is this response different for light and heavy quarks?

Where does the saturation of gluon densities set in?

Is there a simple boundary that separates the region from more dilute quark gluon matter? If so how do the distributions of quarks and gluons change as one crosses the boundary?

Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?
Our understanding of some fundamental properties of the Glasma, sQGP and Hadron Gas depend strongly on our knowledge of the initial state!

3 conundrums of the initial state:

1. What is the spatial transverse distributions of nucleons and gluons?
2. How much does the spatial distribution fluctuate? Lumpiness, hot-spots etc.
3. How saturated is the initial state of the nucleus?

→ unambiguously see saturation

Advantage over p(d)A:

- eA experimentally much cleaner
  - no “spectator” background to subtract
- Access to the parton kinematics through scattered lepton (x, Q^2)
- initial and final state effects can be disentangled cleanly
- Saturation:
  - no alternative explanations, i.e. no hydro in eA
**HERA (ep):**

Despite high energy range:
- $F_2, G_p(x, Q^2)$ outside the saturation regime
- Need also $Q^2$ lever arm!
- Only way in $ep$ is to increase $\sqrt{s}$
- Would require an $ep$ collider at $4\sqrt{s} \sim 1-2$ TeV → LHeC

**eRHIC (eA):**

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

L ~ $(2m_N x)^{-1} > 2 R_A \sim A^{1/3}$

Probe interacts coherently with all nucleons

**Gold:** 197 times smaller effective $x$!
Hard diffraction in DIS at small $x$

Diffraction in $e+A$:
- coherent diffraction (nuclei intact)
- breakup into nucleons (nucleons intact)
- incoherent diffraction

Predictions: $\sigma_{\text{diff}}/\sigma_{\text{tot}}$ in $e+A \approx 25-40\%$
HERA: 15% of all events are hard diffractive

Why is diffraction so important?
- Sensitive to spatial gluon distribution

$\frac{d\sigma}{dt} \equiv \text{Fourier Transformation of Source Density } \rho_g(b)$

Hot topic:
- Lumpiness?
- Just Wood-Saxon+nucleon $g(b)$

Incoherent case:
measure fluctuations/lumpiness in $g_A(b)$

VM: Sensitive to gluon momentum distributions
- $\sigma \sim g(x, Q^2)^2$
Black disc limit characterized by $\sigma_{\text{diff}}/\sigma_{\text{tot}} = 1/2$ (Hera sees 1/7)

Large fraction of diffractive event is unambiguous signature for reaching the saturated limit

Fraction of low-mass coherent diffraction in ep and eA at eRHIC:

Find:
- w/o non-linear effects, eA/ep ratio stays roughly one
- non-linear effects enhance $\sigma_{\text{diff}}$ in eA scattering

Day-1 signature for Saturation


- Unique probe - allows to measure momentum transfer $t$ in $eA$ diffraction

- In general, one cannot detect the outgoing nucleus and its momentum.

**Dipole Cross-Section:**

$$t = (p_A - p'_A)^2 = (p_{VM} + p'_e - p_e)^2$$

- Small size ($J/\psi$): cuts off saturation region
- Large size ($\phi, \rho, \ldots$): “sees more of dipole amplitude” → more sensitive to saturation

**Experimental Cuts:**
- $p(V_{decay\ products}) > 1$ GeV/c

**Dipole Radius:**

$$Q_s^2 \sim \frac{1}{r^2}$$
Idea: momentum transfer $t$ conjugate to transverse position ($b_T$)
- coherent part probes “shape of black disc”
- incoherent part (dominant at large $t$) sensitive to “lumpiness” of the source (fluctuations, hot spots, ...)

Spatial source distribution:

$$F(b) \sim \frac{1}{2\pi} \int_0^\infty d\Delta \Delta J_0(\Delta b) \sqrt{\frac{d\sigma}{dt}}$$

$$t = \frac{\Delta^2}{(1-x)} \approx \Delta^2 \quad \text{(for small } x \text{)}$$
**“Helicity sum rule”**

\[
\frac{1}{2} h = \langle p, \frac{1}{2} | J_{QCD}^z | p, \frac{1}{2} \rangle = \sum_q \frac{1}{2} S_q^z + S_g^z + \sum_q I_q^z + I_g^z
\]

- **Gluon spin**
- **Quark spin**
- **Angular momentum**
- **Total u+d+s quark spin**

**Contribution to proton spin to date:**
- **Gluon:** 20% (RHIC)
- **Quarks:** 30% (DIS)
- **MISS 50% → low x**

**Can an eRHIC give the final answer?**

**The Holy Grail**
- The Spin Sum Rule

**What Composes the Spin of the Proton**

- **\( \Sigma_q \Delta q \)**
- **\( L_g \)**
- **\( \delta q \)**
- **\( f_{1T} \)**

*Brookhaven National Laboratory*
Present vs eRHIC Kinematic Coverage

Current polarized DIS data:
○ CERN △ DESY ◇ JLab □ SLAC

Current polarized BNL-RHIC pp data:
● PHENIX π⁰ △ STAR 1-jet

eRHIC extends x coverage by up to 2 decades (at Q²=1 GeV²)

RHIC pp data constraining Δg(x) in approx. 0.05 < x < 0.2
likewise for Q² data plotted at xT=2pT/√S

EIC √s=45 GeV, 0.01 ≤ y ≤ 0.95
EIC √s=45 GeV, 0.01 ≤ y ≤ 0.95

5 × 100 GeV eRHIC stage-1

4.6 x 10⁻³ COMPASS

E.C. Aschenauer

Brookhaven National Laboratory
THE WAY TO FIND THE SPIN

cross section:
\[ \frac{d^2 \sigma}{d\Omega dE'} \sim L_{\mu\nu} W^{\mu\nu} \]

\[ W^{\mu\nu} = -g^{\mu\nu} F_1 - \frac{p^\mu p^\nu}{v} F_2 + \frac{i}{v} \varepsilon^{\mu\nu\lambda\sigma} q^\lambda s^\sigma g_1 + \frac{i}{v^2} \varepsilon^{\mu\nu\lambda\sigma} q^\lambda \left( p \cdot q s^\sigma - s \cdot q p^\sigma \right) g_2 \]

pQCD scaling violations

\[ \frac{d g_1}{d \log(Q^2)} \sim -\Delta g(x, Q^2) \]

\[ \Delta \Sigma(Q^2) = \int g_1(x, Q^2) dx = \int \Delta q_f(x, Q^2) dx \]

dramatic reduction of uncertainties:

now eRHIC 5x100/250 GeV

world data
\[ \frac{1}{2} \hbar = \left\langle P, \frac{1}{2} \left| J_{QCD}^z \right| P, \frac{1}{2} \right\rangle = \sum \frac{1}{2} S_q^z + S_g^z + \sum L_q^z + L_g^z \]

* CAN WE SOLVE THE SPIN SUM RULE? *

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

- can expect approx. 5-10% uncertainties on $\Delta \Sigma$ and $\Delta g$
- need to control systematics

- current data
- w/ eRHIC data

what about the orbital angular momentum?
the way to 3d imaging of the proton and the orbital angular momentum $L_q$ & $L_g$

Measure them through exclusive reactions golden channel: DVCS

**Spin-Sum-Rule in PRF:**

from $g_1$

$$\frac{1}{2} = J^z_q + J^z_g = \frac{1}{2} \Delta \Sigma + \sum_q \mathcal{L}^z_q + J^z_g$$

$$J^z_{q,g} = \frac{1}{2} \left( \int_{-1}^{1} x \, dx \left( H^{q,g} + E^{q,g} \right) \right)_{t \to 0}$$

**GPDs:**
Correlated quark momentum and helicity distributions in transverse space

responsible for orbital angular momentum
imaging in valence region but limited t-range

HERA results on GPDs very much limited by lack of statistics

quantum numbers of final state $\rightarrow$ selects different GPD

**DVCS:** wide range of observables ($\sigma$, $A_{UT}$, $A_{LU}$, $A_{UL}$, $A_{C}$) to disentangle GPDs
DVCS data at end of HERA

D. Mueller, K. Kumericki, S. Fazio, and ECA

\[ e^+ e^- \rightarrow H, H, E, \bar{E} (x, \xi, t) \]

\[ x^+ \xi \]

\[ p, p' \]

\[ \gamma \]

Fourier Transfo

\[ x_B F(x_B b) \text{ (fm}^{-2}) \]

\[ 0.004 < x < 0.0063 \]

\[ 10 \text{ GeV}^2 < Q^2 < 17.8 \text{ GeV}^2 \]

E.C. Aschenauer

Brookhaven National Laboratory
M. Diehl & ECA

To improve imaging on gluons add J/ψ observables

- cross section
- $A_{UT}$
- ....

GPD H+ J/ψ

Fourier will constrain GPDs

eRHIC will tell us the orbital angular momenta of quarks and gluons

$e + p \rightarrow e + p + J/ψ$

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

Brookhaven Science Associates
Where do we stand to realize EIC@RHIC
eRHIC

Latest Review:
NSAC 2013 Subcommittee Report on Scientific Facilities:

“The Subcommittee ranks an EIC as Absolutely Central in its ability to contribute to world-leading science in the next decade.”

“There are outstanding R&D issues that remain to be addressed in order to achieve performance metrics. Staging approaches to the EIC are also being explored by [BNL and JLab]. Both laboratories are actively addressing R&D issues and are making good progress.”
Staging: All lepton beam energies scale proportionally by adding SRF cavities to the injector $E_0=5, 10, 20, 30$ GeV.

All magnets would be installed from the day one and we would be cranking power supplies up as energy is increasing.

Animation is by N. Tsoupas.

ERL: energy recovery linac
19 mrad crossing angle and crab-crossing

High gradient (200 T/m) large aperture Nb$_3$Sn focusing magnets

Arranged free-field electron pass through the hadron triplet magnets

Integration with the detector: efficient separation and registration of low angle collision products

Gentle bending of the electrons to avoid SR impact in the detector
**Challenge**

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Increase/reduction beyond the state of the art</th>
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<tbody>
<tr>
<td>Polarized electron gun</td>
<td>10 x increase</td>
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<tr>
<td>Coherent Electron Cooling</td>
<td>New concept</td>
</tr>
<tr>
<td>Multi-pass SRF ERL</td>
<td>5 x increase, 30 x increase</td>
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<tr>
<td>Crab crossing</td>
<td>New for hadron colliders</td>
</tr>
<tr>
<td>Understanding beam-beam effects</td>
<td>New type of collider</td>
</tr>
<tr>
<td>$\beta^*=5$ cm</td>
<td>5x reduction</td>
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<tr>
<td>Multi-pass SRF ERL</td>
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<tr>
<td>Feedback for kink instability suppression</td>
<td>Novel</td>
</tr>
<tr>
<td>Space charge effect compensation</td>
<td>Novel</td>
</tr>
</tbody>
</table>

- **Hourglass the pinch effects are included. Space charge effects are compensated.**
- **Energy of electrons can be selected at any desirable value at or below 30 GeV**
- **The luminosity does not depend on the electron beam energy below or at 20 GeV**
- **The luminosity falls as $E_e^{-4}$ at energies above 20 GeV**
- **The luminosity is proportional to the hadron beam energy: $L \sim E_h/E_{top}$**
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<td></td>
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</table>

Currently investigate machine and IR design with a less ambiguous R&D to reach $10^{33}$ cm$^{-2}$s$^{-1}$ with 10 GeV initial beam energy.

Can we do with less?

- no cooling not possible lose all exclusive physics
  - more conventional cooling
  - reduced lumi $10^{33}$

- need to remove crossing angle and go to head on collisions
  - beams get separated by dipoles close to IR
  - impact on synchrotron rad.

Brookhaven Science Associates
**What Needs to be Covered by the Detector**

### Inclusive Reactions in ep/eA:
- **Physics:** Structure Fcts.: $g_1$, $F_2$, $F_L$
- Very good electron id $\rightarrow$ find scattered lepton
- Momentum/energy and angular resolution of $e'$ critical
- Scattered lepton $\rightarrow$ kinematics

### Semi-inclusive Reactions in ep/eA:
- **Physics:** TMDs, Helicity PDFs $\rightarrow$ flavor separation, dihadron-corr., ...
  $\rightarrow$ Kaon asymmetries, cross sections
- Excellent particle ID: $\pi^\pm, K^\pm, p^\pm$ separation over a wide range in $\eta$
- Full $\Phi$-coverage around $\gamma^*$
- Excellent vertex resolution $\rightarrow$ Charm, Bottom identification

### Exclusive Reactions in ep/eA:
- **Physics:** GPDs, proton/nucleus imaging, **DVCS**, excl. VM/PS prod.
- Exclusivity $\rightarrow$ large rapidity coverage $\rightarrow$ rapidity gap events
  $\rightarrow$ reconstruction of all particles in event
- High resolution in $t$ $\rightarrow$ Roman pots
Extremely wide physics program puts stringent requirements on detector performance:

- High acceptance $-5 < \eta < 5$
- Good PID ($\pi, K, p$ and lepton) and vertex resolution
- Same rapidity coverage for tracking and calorimeter → good momentum resolution, lepton PID
- Low material density because of low scattered lepton $p$ → minimal multiple scattering and bremsstrahlung
- Very forward electron and proton/neutron detection
- Fully integrated in machine IR design

Summary:
Full Geant Model based on Generic EIC R&D detector concepts

https://wiki.bnl.gov/eic/index.php/DIS:_What_is_important
barrel silicon tracker:
- MAPS technology: ~20x20mm² chips, ~20 µm 2D pixels
- 6 layers at [30..160] mm radius
- 0.37% $X_0$ in acceptance per layer simulated precisely;
- digitization: single discrete pixels, one-to-one from MC points

forward/backward silicon trackers:
- 2x7 disks with up to 280 mm radius
- N sectors per disk: 200 µm silicon-equivalent thickness
- digitization: discrete ~20x20 µm² pixels

TPC:
- ~2m long; gas volume radius [300..800] mm
- 1.2% $X_0$ IFC, 4.0% $X_0$ OFC; 15.0% $X_0$ aluminum endcaps
- digitization: idealized, assume 1x5 mm GEM pads

GEM trackers:
- 3 disks behind the TPC endcap
- STAR FGT design
- digitization: 100 mm resolution in X&Y; gaussian smearing
\[ \pi^+ \text{ track momentum resolution vs. pseudo-rapidity} \]

\[ \sigma_p / P \%\]

- \[ 32 \text{ GeV/c} \]
- \[ 16 \text{ GeV/c} \]
- \[ 1 \text{ GeV/c} \]

\[ \text{Pseudo-rapidity} \]

\[ \rightarrow \text{expect 2\% or better momentum resolution in the whole kinematic range} \]
π⁺ track momentum resolution at \( \eta = 3.0 \) vs. Silicon thickness

-> ~flat over inspected momentum range because of very small Si pixel size

\[ \sigma_p/P \] vs. \( \pi^+ \) momentum [GeV/c]

- 800 microns
- 400 microns
- 200 microns
- 100 microns
- 10 microns

π⁺ track momentum resolution at \( \eta = 3.0 \) vs. Silicon pixel size

-> 20 micron pixel size is essential to maintain good momentum resolution

\[ \sigma_p/P \] vs. \( \pi^+ \) momentum [GeV/c]

- 100 microns
- 50 microns
- 20 microns
main requirements:

- Yield large enough bending for charged tracks at large $\eta$
- Keep field inside TPC volume as homogeneous as possible
- Keep magnetic field inside RICH volume(s) small

$\rightarrow$ use OPERA-3D/2D software

Presently used design: MRS-B1

Total Length : 2.4 m
Inner Radius : 1.0 m
Outer Radius : 1.1 m
Central B field: 3.0 T
10 GeV/c electron hitting one of the four BEMC quadrants

- PWO-II, layout a la CMS & PANDA
- -2500mm from the IP
- both projective and non-projective geometry implemented
- digitization based on PANDA R&D

Same event (details of shower development)
- tungsten powder scintillating fiber sampling calorimeter technology
- +2500mm from the IP; non-projective geometry
- sampling fraction for e/m showers ~2.6%
- "medium speed" simulation (up to energy deposit in fiber cores)
- reasonably detailed digitization; “ideal” clustering code

- “Realistic” digitization: 40MHz SiPM noise in 50ns gate;
- 4m attenuation length; 5 pixel single tower threshold;
- 70% light reflection on upstream fiber end;

--> good agreement with original MC studies and measured data
- same tungsten powder + fibers technology as FEMC,
- ... but towers are tapered
- non-projective

⇒ barrel calorimeter collects less light, but response (at a fixed 3° angle) is perfectly linear

⇒ simulation does not show any noticeable difference in energy resolution between straight and tapered tower calorimeters
LEPTON-HADRON SEPARATION VIA E/p

all plots: 10GeV x 100GeV beams

HADRON IDENTIFICATION WITH RICH

consider hadrons in pseudo-rapidity range ~[1.0 .. 3.0]

-> pion/kaon/proton identification should be possible up to momenta ~40 GeV/c
MIGRATION IN ($x, Q^2$) BINS

10 GeV x 100 GeV beams

→ “survival probability” is above ~80% in the region, where tracking has superior resolution

detector designed based on already achieved performance

dedicated detector fully tuned to do EIC physics program as in WP

HERA: $y > 0.005$

high $y$ limited by radiative corrections

→ can be suppressed by requiring hadronic activity

low $y$-coverage: limited by $E_e$ resolution

→ hadron method

→ or change beam energy
2013/14: Develop physics case and preliminary design for eRHIC.

Run RHIC annually until 2016; thereafter every other year.

Use reduced RHIC running to complete accelerator and detector R&D, detailed design and prototyping for eRHIC.

Construct sPHENIX.

2017: Install electron cooling

2018/19: Perform beam energy scan II.

2020/21: Perform high luminosity jet measurements.

2022-24: RHIC shutdown and conversion into eRHIC (10 GeV e-beam); upgrade of STAR/sPHENIX to eRHIC detectors.

2024: Commission eRHIC.

Of course all subject to funding by DOE.
The eRHIC will profoundly impact our understanding of QCD with its high energy, high luminosity $eA$ and polarized $eA$ collisions. A dedicated eRHIC detector is essential to do the physics program as envisioned by the community and it will be critical to form a eRHIC community beyond RHIC. eRHIC machine design ambitious, but will push collider technologies in several regions.
BACKUP
**Electron-“Ion” colliders in the past and future:**

<table>
<thead>
<tr>
<th></th>
<th>HERA@DESY</th>
<th>LHeC@CERN</th>
<th>eRHIC@BNL</th>
<th>MEIC@JLab</th>
<th>HIAF@CAS</th>
<th>ENC@GSI</th>
</tr>
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<tbody>
<tr>
<td>$E_{CM}$ (GeV)</td>
<td>320</td>
<td>800-1300</td>
<td>45-175</td>
<td>12-140</td>
<td>12 → 65</td>
<td>14</td>
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<tr>
<td>proton $x_{\text{min}}$</td>
<td>$1 \times 10^{-5}$</td>
<td>$5 \times 10^{-7}$</td>
<td>$3 \times 10^{-5}$</td>
<td>$5 \times 10^{-5}$</td>
<td>$7 \times 10^{-3}$ → $3 \times 10^{-4}$</td>
<td>$5 \times 10^{-3}$</td>
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<td>ion</td>
<td>p</td>
<td>p to Pb</td>
<td>p to U</td>
<td>p to Pb</td>
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<td>p to $^{40}\text{Ca}$</td>
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<tr>
<td>polarization</td>
<td>-</td>
<td>-</td>
<td>p, $^3\text{He}$</td>
<td>p, d, $^3\text{He}$ ($^6\text{Li}$)</td>
<td>p, d, $^3\text{He}$</td>
<td>p, d</td>
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<tr>
<td>$L$ [cm$^{-2}$ s$^{-1}$]</td>
<td>$2 \times 10^{31}$</td>
<td>$10^{33}$</td>
<td>$10^{33-34}$</td>
<td>$10^{33-34}$</td>
<td>$10^{32-33}$ → $10^{35}$</td>
<td>$10^{32}$</td>
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<td>IP</td>
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<td>2+</td>
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<tr>
<td>Year</td>
<td>1992-2007</td>
<td>2022 (?)</td>
<td>2022</td>
<td>Post-12 GeV</td>
<td>2019 → 2030</td>
<td>upgrade to FAIR</td>
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POSSIBLE SCHEDULE TO REALIZE eRHIC

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<td>RHIC II upgrades</td>
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<td>sPHENIX/STAR upgrades</td>
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<td>eRHIC</td>
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<td>eRHIC detector</td>
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<td>eRHIC physics</td>
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Projects/Construction

Operations
Increasing Lepton Beam Energy:
5 GeV: $Q^2 \sim 1$ GeV $\Rightarrow \eta \sim -2$
10 GeV: $Q^2 \sim 1$ GeV $\Rightarrow \eta \sim -4$

highest $E'_e$ at most negative rapidities independent of $E_h$
CUTS: $Q^2 > 0.1 \text{GeV}^2$ & $0.01 < y < 0.95$

-5 < rapidity < -4

-4 < rapidity < -3

-3 < rapidity < -2

-2 < rapidity < -1

20 GeV on 250 GeV
10 GeV on 100 GeV
5 GeV on 50 GeV

higher $\sqrt{s}$: scattered lepton has small scattering angle $\rightarrow$ negative rapidities
Cuts: $Q^2 > 1 \text{ GeV}$, $0.01 < y < 0.95$, $z > 0.1$

Increasing Hadron Beam Energy: influences max. hadron energy at fixed $\eta$

Increasing $30 \text{ GeV} < \sqrt{s} < 170 \text{ GeV}$

$\Rightarrow$ hadrons are boosted from forward rapidities to negative rapidities

$\Rightarrow$ no difference between $\pi^\pm$, $K^\pm$, $p^\pm$
hadron/photon suppression factor needed for $p_e > 1$ GeV:
-5 < η < -1: < 10 GeV
-3 < η < -2: ~10
-2 < η < -1: > 100
-1 < η < 0: ~1000

hadron suppression factor

p_{max} hadron for PID:
-5 < η < -1: < 10 GeV
-1 < η < 1: < 5 GeV
1 < η < 5: < 50 GeV

no cuts applied

5 GeV x 50 GeV

hadron
photon
electron
**LEPTON IDENTIFICATION**

**hadron/photon suppression factor**

needed for $p_e > 1$ GeV:

- $-5 < \eta < -1$: $> 100$
- $-4 < \eta < -3$: $> 10$
- $-3 < \eta < -2$: $> 10^4$
- $-2 < \eta < -1$: $> 10^4$

**20 GeV x 250 GeV**

**hadron**

**photon**

**electron**

no cuts applied

$p_{\text{max hadron for PID}}$:

- $-5 < \eta < -1$: $< 30$ GeV
- $-1 < \eta < 1$: $< 10$ GeV
- $1 < \eta < 5$: $< 100$ GeV
Gluon density dominates at $x < 0.1$

- Rapid rise in gluons described naturally by linear pQCD evolution equations
- This rise cannot increase forever - limits on the cross-section
  $\Rightarrow$ non-linear pQCD evolution equations provide a natural way to tame this growth and lead to a saturation of gluons, characterised by the saturation scale $Q^2_s(x)$. 

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Other than in $p$: $G(x,Q^2)$ for nuclei is little known.

Key: $FL(x,Q^2) \sim xG(x,Q^2)$

99% of all $h^+\mu^- \pm$ have $p_T < 2$ GeV/c

"Bulk Matter" $\Rightarrow x < 0.01$

E.C. Aschenauer

Measurements with $A \geq 56$ (Fe):
- $eA/\mu A$ DIS (E-139, E-665, EMC, NMC)
- $\nu A$ DIS (CCFR, CDHSW, CHORUS, NuTeV)
- $DY$ (E772, E866)
\[ \frac{d^2 \sigma^{eA \rightarrow eX}}{dxdQ^2} = \frac{4 \pi \alpha^2}{xQ^4} \left[ \left( 1 - y - \frac{y^2}{2} \right) F_2(x,Q^2) - \frac{y^2}{2} F_L(x,Q^2) \right] \]

- Expect strong non-linear effects in $F_L$

- Relative contributions of higher twist effects to $F_L$ amplified in $eA$

**Dipole model (J. Bartels et al.)**

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- Measurement of $F_L$ requires running at different $s$.
- $F_2$, $F_L$: negligible stat. error, systematics dominated.
- A dependence helps to discriminate between linear and non-linear (saturation) models.
- Precision nPDF: Huge impact on pA, AA programs.
Goal: going after the source distribution of gluons through Fourier transform of $d\sigma/dt$

Find: Typical diffractive pattern for coherent (non-breakup) part

As expected: $J/\Psi$ less sensitive to saturation effects than larger $\Phi$-meson
At $y=0$, suppression of away-side jet is observed in $A+A$ collisions. No suppression in $p+p$ or $d+A$ $\rightarrow x \sim 10^{-2}$

$$x_A = \frac{k_1 e^{-y_1} + k_2 e^{-y_2}}{\sqrt{s}} \ll 1$$

However, at forward rapidities ($y \sim 3.1$), an away-side suppression is observed in $dAu$

Away-side peak also much wider in $d+Au$ compared to $pp$ $\rightarrow x \sim 10^{-3}$
**Theory: Saturation**

Dominguez, Xiao, Yuan, Lee, Zheng '11/12

- **Exp:** Saturation versus “conventional” scenario

- eA-MC: Pythia6.4 + nPDF (EPS09) + nuclear geometry from DPMJetIII without PS
- Here for 10 fb\(^{-1}\)/A (~ 20 weeks), std. experimental cuts
- Clear signal, pronounced differences between sat and no-sat
What happens if we add a nuclear medium

**Observables:**
- **Broadening:** $\Delta p_t^2$ linked directly with saturation scale
- **Attenuation:** ratio of hadron production in $A$ to $d$
  - modifications of nPDF cancel out

$$\Delta p_t^2 = \left( p_t^2_A \right)_A - \left( p_t^2_p \right)_p$$
$$R^h_A(Q^2, x, z, p_t, \Theta)$$
**Hermes:**

$E_e = 27 \text{ GeV} \rightarrow \sqrt{s} = 7.2 \text{ GeV}$

$E_h = 2-15 \text{ GeV}$

Unprecedented precision to distinguish between different models

Unprecedented large $v$ range

Hadronization in and out of charm for the first time

**EIC:**

$E_e = 35 \text{ GeV}$

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

$8 < Q^2 < 12 \text{ GeV}^2$

$32.5 < v < 37.5 \text{ GeV}$

$0.01 < y < 0.85$

$x > 0.1$

$J/Ldt = 10 \text{ fb}^{-1}$

$E_e = 145 \text{ GeV}$

$Q^2 = 35 \text{ GeV}^2$

$30 < Q^2 < 40 \text{ GeV}^2$

$140 < v < 150 \text{ GeV}$

$0.01 < y < 0.85$

$x > 0.1$

$J/Ldt = 10 \text{ fb}^{-1}$
Scaling violations of $g_1$ (Q$^2$-dependence) give indirect access to the gluon distribution via DGLAP evolution at midrapidity.

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

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

Integral in RHIC x-range:

Contribution to proton spin to date:
- Gluon: 20%
- Quarks: 30%

Jet $A_{LL}$
**g_1**  THE WAY TO FIND THE SPIN

**cross section:** \( \frac{d^2 \sigma}{d\Omega dE'} \sim L_{\mu\nu} W^{\mu\nu} \)

\[
W^{\mu\nu} = -g^{\mu\nu} F_1 - \frac{p_\mu p_\nu}{v} F_2 + \frac{i}{v} \epsilon^{\mu\nu\lambda\sigma} q_\lambda s_\sigma (g_1) + \frac{i}{v^2} \epsilon^{\mu\nu\lambda\sigma} q_\lambda (p \cdot q s_\sigma - s \cdot q p s_\sigma) g_2
\]

**pQCD scaling violations**

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

\[
\Delta \Sigma(Q^2) = \int_0^1 g_1(x, Q^2) \, dx = \int_0^1 \Delta q_f(x, Q^2) \, dx
\]
DIS scaling violations mainly determine $\Delta g$ at small $x$

In addition, SIDIS data provide detailed flavor separation of quark sea

Yet, small $x$ behavior completely unconstrained

$\Rightarrow$ determines $x$-integral, which enters proton spin sum

- includes only "stage-1 data"
- can be pushed to $x=10^{-4}$ with 20 x 250 GeV data

"Issues":
- (SI)DIS @ eRHIC limited by systematic uncertainties
  need to control rel. lumi, polarimetry, detector performance, ...
  very well
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)
- Excellent reconstruction of \( H_{sea} \) and good reconstruction of \( H_g \) (from \( d\sigma/dt \) )
Requirements:

- High Luminosity \( > 10^{33} \text{ cm}^{-2}\text{s}^{-1} \)
- Flexible center of mass energies
- Electrons and protons/light nuclei polarised
- Wide range of nuclear beams
- A wide acceptance detector with good PID (e/h and \( \pi, K, p \))
- Wide acceptance for protons from elastic reactions and neutrons from nuclear breakup
Unpolarized and polarized leptons 5-20 (30) GeV

70% $e^-$ beam polarization goal
polarized positrons?

Polarized protons 50-250 GeV

Light ions (d, Si, Cu) Heavy ions (Au, U) 50-100 GeV/u

Polarized light ions He$^3$ 166 GeV/u

Center mass energy range: $\sqrt{s}=30-200$ GeV; $L\sim 100-1000 \times $Hera
longitudinal and transverse polarization for $p$/He$^3$ possible
**eRHIC: design luminosity**

<table>
<thead>
<tr>
<th></th>
<th>e</th>
<th>p</th>
<th>$^2$He$^3$</th>
<th>$^{79}$Au$^{197}$</th>
<th>$^{92}$U$^{238}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy, GeV</strong></td>
<td>20</td>
<td>250</td>
<td>167</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td><strong>CM energy, GeV</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>100</td>
<td>82</td>
<td>63</td>
<td>63</td>
<td></td>
</tr>
<tr>
<td><strong>Number of bunches/distance between bunches</strong></td>
<td>107 nsec</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
</tr>
<tr>
<td><strong>Bunch intensity (nucleons) $\times 10^{11}$</strong></td>
<td>0.36</td>
<td>4</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td><strong>Bunch charge, nC</strong></td>
<td>5.8</td>
<td>64</td>
<td>60</td>
<td>39</td>
<td>40</td>
</tr>
<tr>
<td><strong>Beam current, mA</strong></td>
<td>50</td>
<td>556</td>
<td>556</td>
<td>335</td>
<td>338</td>
</tr>
<tr>
<td><strong>Normalized emittance of hadrons, 95%, mm mrad</strong></td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Normalized emittance of electrons, rms, mm mrad</strong></td>
<td>16</td>
<td>24</td>
<td>40</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td><strong>Polarization, %</strong></td>
<td>80</td>
<td>70</td>
<td>70</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td><strong>rms bunch length, cm</strong></td>
<td>0.2</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td><strong>$\beta^*$, cm</strong></td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td><strong>Luminosity per nucleon, $\times 10^{34}$ cm$^{-2}$s$^{-1}$</strong></td>
<td>2.7</td>
<td>2.7</td>
<td>1.6</td>
<td>1.7</td>
<td></td>
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</tbody>
</table>

Hourglass the pinch effects are included. Space charge effects are compensated.
Energy of electrons can be selected at any desirable value at or below 30 GeV
The luminosity does not depend on the electron beam energy below or at 20 GeV
The luminosity falls as $E_e^{-4}$ at energies above 20 GeV
The luminosity is proportional to the hadron beam energy: $L \sim E_h/E_{top}$

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E. C. Aschenauer
**PID:**

-1<η<1: DIRC or proximity focusing Aerogel-RICH

1<|η|<3: RICH

**Lepton-ID:**

-3 < η < 3: e/p

1<|η|<3: in addition Hcal response & γ suppression via tracking

|η|>3: ECAL+Hcal response & γ suppression via tracking

-5<η<5: Tracking (TPC+GEM+MAPS)
Calorimetry
- W-Scintillator & W-Si
  - compact and high resolution
- Crystal calorimeters PbW & BGO
  - BNL, Indiana University, Penn State Univ., UCLA, USTC, TAMU
Pre-Shower
- W-Si
- LYSO pixel array with readout via X-Y WLS fibers
  - Univ. Tecnica Valparaiso
PID via Cerenkov
- DIRC and timing info
  - Catholic Univ. of America, Old Dominion, South Carolina, JLab, GSI
  - RICH based on GEM readout
    - e-PID: GEM based TRD \( \rightarrow \) eSTAR
    - BNL, Indiana Univ., USTC, VECC, ANL
Tracking
- \( \mu \)-Vertex: central and forward based on MAPS
- Central: TPC/HBD provides low mass, good momentum, \( dE/dx \), eID
  - Fast Layer: \( \mu \)-Megas or PImMS
  - Forward: Planar GEM detectors

More Info on EIC-Detector R&D:
https://wiki.bnl.gov/conferences/index.php/EIC_R%252D
**μ-vertex detector:**
- 6 layers with [30..160] mm radius
- 0.37% $X_0$ in acceptance per layer simulated precisely;
- digitization: single discrete pixels, one-to-one from MC points

**Forward/backward μ-vertex detector:**
- 3+5+3 silicon disks with up to 280 mm radius
- N sectors per disk; 200 $\mu$m silicon-equivalent thickness
- digitization: discrete ~20x20 $\mu$m$^2$ pixels

**TPC**
- ~2m long; gas volume radius [300..800] mm
- 1.2% $X_0$ IFC, 4.0% $X_0$ OFC; 15.0% $X_0$ aluminum endcap
- digitization: assume known (gaussian) resolutions in "r" and "Z" and 1x5 mm GEM pads (up to 100 points per track)

**Forward tracking:**
- 3 disks behind the TPC endcap
- rather precise START FGT design implemented
- digitization: 100 $\mu$m resolution in X&Y; gaussian...
Results from GEMINI++ for 50 GeV Au

Results:
With an aperture of ±3 mrad we are in relative good shape
• enough “detection” power for $t > 0.025$ GeV$^2$
• below $t \sim 0.02$ GeV$^2$ we have to look into photon detection
  ‣ Is it needed?

Question:
• For some physics rejection power for incoherent is needed $\sim 10^4$
  ➔ How efficient can the ZDCs be made?

by Thomas Ullrich

+/−5 mrad acceptance seems sufficient
$$t = (p_4 - p_2)^2 = 2[(m_{p_{in}} m_{p_{out}}) - (E_{in} E_{out} - p_{z_{in}} p_{z_{out}})]$$

→ "Roman Pots" acceptance studies see later

Simulations by J.H Lee
PROTON DISTRIBUTION IN Y VS X AT S=20 M

without quadrupole aperture limit

20x250

with quadrupole aperture limit

20x250

5x50
Accepted in Roman Pot (Example) at S=20M

25x250
Entries 67542

5x50
Entries 36266

Generated Quad aperture limited RP (at 20m) accepted

$p_T [\text{GeV/c}]$
Wide physics program with high requirements on detector and machine performance
PDFs do not resolve transverse momenta or positions in the nucleon. Fast moving nucleon turns into a 'pizza' but transverse size remains about 1 fm.

Compelling Questions:
1. How are quarks and gluons spatially distributed?
2. How do they move in the transverse plane?
3. Do they orbit and do we have access to spin-orbit correlations?

Required set of measurements & theoretical concepts:

1-D

Parton densities $f(x)$

2+1-D

Transverse momentum dependent PDFs $f(x, k_T)$

Semi-inclusive DIS

Impact parameter dependent PDFs $f(x, b_T)$

Wigner function $W(x, k_T, b_T)$

4+1-D

High-level connection measurable?

Important in other branches of Physics

Generalized PDF $H(x, 0, t)$

Exclusive processes $H(x, \xi, t)$
In QCD, all “constants” of quantum mechanics are actually strongly momentum dependent: couplings, number density, mass, etc.

So, a quark’s mass depends on its momentum.

Mass function can calculated and is depicted here.

In agreement: the vast bulk of the light-quark mass comes from a cloud of gluons, dragged along by the quark as it propagates.

Continuum- and Lattice-QCD

Running gluon mass

- Gluon is massless in UV, in agreement with pQCD
- Massive in infrared
  - \( m_G(0) = 0.67-0.81 \text{ GeV} \)
  - \( m_G(m_G^2) = 0.53-0.64 \text{ GeV} \)

DSE prediction confirmed by numerical simulations of lattice-regularised QCD

\[
m_G^2(k^2) \approx m_G^4/(k^2+m_G^2)
\]
- at small $x$ linear evolution gives strongly rising $g(x)$
  - cannot go on forever
- BK/JIMWLK non-linear evolution includes recombination effects $\Rightarrow$ saturation
  - Dynamically generated scale
    - Saturation Scale: $Q_s^2(x)$
      - Increases with energy or decreasing $x$
  - Scale with $Q^2/Q_s^2(x)$ instead of $x$ and $Q^2$

**Bremsstrahlung**

$\sim \alpha_s \ln(1/x)$

**Recombination**

$\sim \alpha_s \rho$

Saturation must set in at low $x$ $\Rightarrow$ high occupancy

\[ x = \frac{P_{\text{parton}}}{P_{\text{nucleon}}} \]
**EIC:**

- Extract the spatial multi-gluon correlations and study their non-linear evolution
  - essential for understanding the transition from a deconfined into a confined state.

**Advantage over p(d)A:**

- eA experimentally much cleaner
  - no “spectator” background to subtract
  - Access to the exact kinematics of the DIS process ($x, Q^2$)
**Kinematics:**

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

\[ Q^2 = 2E_e E_e' (1 - \cos \Theta_e') \]

\[ y = \frac{p q}{p k} = 1 - \frac{E_e'}{E_e} \cos^2 \left( \frac{\Theta_e'}{2} \right) \]

\[ x = \frac{Q^2}{2 pq} = \frac{Q^2}{sy} \]

- **Measure of resolution power**
- **Measure of inelasticity**
- **Measure of momentum fraction of struck quark**

**Quark splits into gluon splits into quarks...**

**Gluon splits into quarks...**

**10^{-16}m**

**10^{-19}m** → higher \( \sqrt{s} \) increases resolution
significant experimental and theoretical progress in past 25+ years, yet many unknocks ...

\[ \Delta g(x, Q^2) \]

• found to be small at \(0.05 < x < 0.2\) [RHIC, COMPASS, HERMES]

• RHIC can slightly extend \(x\) range & reduce uncertainties [500 GeV running & particle correlations]

yet, full 1st moment [proton spin sum] will remain to have significant uncertainties from unmeasured small \(x\) region

\[ \Delta q's (x, Q^2) \]

• known: quarks contribute much less to proton spin than expected from quark models
large uncertainties in \(\Delta \Sigma\) from unmeasured small \(x\)

• surprisingly small/positive \(\Delta s\) from SIDIS: large SU(3) breaking?

• flavor separation not well known, e.g., \(\Delta u - \Delta d\)
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)

smallest $x$ bins require $20 \times 250$ GeV 5 $\times$ 250 starts here

• error bars for moderate $10$ fb$^{-1}$ per c.m.s. energy; bands parameterize current DSSV+ uncertainties
observables sensitive to $E$:
($J_q$ input parameter in ansatz for $E$)

Hermes DVCS-TTSA [arXiv: 0802.2499]:

- DVCS $A_{UT}$ : HERMES
- nDVCS $A_{LU}$ : Hall A

$$A_{UT}^{\sin(\phi-\phi_T)\cos\phi} \sim \text{Im}(F_2 H - F_1 E)$$

E.C. Aschenauer

**eRHIC:**
HERMES like $A_{UT}$
20 GeV $\times$ 250 GeV
Lumi: 2x50fb$^{-1}$
BH fraction

5 GeV x 100 GeV
BH subtraction will be relevant in stage 1, at large y, depending on the x-Q^2 bin

BUT...

5 GeV x 100 GeV and
5 GeV x 250 GeV are overlapping:
x-sec. measurements at 5x250 at low-y can crosscheck the BH subtrac. made for 5x100

20 GeV x 250 GeV
BH subtraction will be not an issue for y<0.6
Diffraction Analogy: plane monochromatic wave incident on a circular screen of radius $R$

- coherent $\Rightarrow$ intact
- incoherent $\Leftrightarrow$ breakup of $p$
- HERA: 15% of all events are hard diffractive

- breakup into nucleons (nucleons intact)
- incoherent diffraction
- Predictions: $\sigma_{\text{diff}}/\sigma_{\text{tot}}$ in $e+A \sim 25-40\%$
**Diffraction in e+p:**
- coherent ⇔ p intact
- incoherent ⇔ breakup of p
- HERA: 15% of all events are hard diffractive

**Diffraction in e+A:**
- coherent diffraction (nuclei intact)
- breakup into nucleons (nucleons intact)
- incoherent diffraction
- Predictions: $\frac{\sigma_{\text{diff}}}{\sigma_{\text{tot}}}$ in e+A ~25-40%

$t = (p-p')^2$

$\beta$ is the momentum fraction of the struck parton w.r.t. the Pomeron

$x_{IP} = x/\beta$: momentum fraction of the exchanged object (Pomeron) w.r.t. the hadron

$\gamma^* A \rightarrow J/\psi A$

$Q^2 = 10$ GeV$^2$

$\Delta p \sim 10$ MeV/c

$Largest$ $rapidity$ $gap$ $in$ $event$

$Coherent$ $or$ $Breakup$ $of$ $A$

$y_{1,2}$

$F_2^{D,A}(x, Q^2, \beta, t) - \frac{y^2}{2} F_L^{D,A}(x, Q^2, \beta, t)$

$e+\text{Au}$

$\gamma^* A \rightarrow J/\psi A$

$Q^2 = 0$

$\Delta p \sim 10$ MeV/c
Identify Most Forward Going Particle (MFP)

- Works at HERA but at higher $\sqrt{s}$
- EIC smaller beam rapidities

Hermeticity requirement:
• needs just to detector presence
• does not need momentum or PID
• simulations: $\sqrt{s}$ not a show stopper for EIC
  (can achieve 1% contamination, 80% efficiency)
Enhancement of $Q_s$ with $A$ 
⇒ saturation regime reached at significantly lower energy in nuclei
**h-h FORWARD CORRELATION IN p(d)A AT RHIC**

- Small-$x$ evolution $\leftrightarrow$ multiple emissions
- Multiple emissions $\rightarrow$ broadening
- Back-to-back jets (here leading hadrons) may get broadening in $p_T$ with a spread of the order of $Q_S$

**Low gluon density (pp):**
- pQCD predicts $2 \rightarrow 2$ process
- $\Rightarrow$ back-to-back di-jet

**High gluon density (pA):**
- $2 \rightarrow$ many process
- $\Rightarrow$ expect broadening of away-side

First prediction by: C. Marquet ('07)
Latest review: Stasto, Xiao, Yuan arXiv:1109.1817 (Sep. '11)
How saturated is the initial state?

\[ \langle q_{\perp}^2 \rangle_{dAu} = \langle q_{\perp}^2 \rangle_{pp} + \Delta \langle q_{\perp}^2 \rangle \]
Sensitive to spatial gluon distribution

$$\frac{d\sigma}{dt} \equiv \text{Fourier Transformation of Source Density } \rho_g(b)$$

- Hot topic:
  - Lumpiness?
  - Just Wood-Saxon+nucleon $g(b)$
- Incoherent case: measure fluctuations/lumpiness in $g_A(b)$

Sensitive to gluon momentum distributions

$$\sigma \sim g(x, Q^2)^2$$

$$\frac{d\sigma_{\gamma^* p \rightarrow p \nu}}{dt} \sim |\Psi_V^* \frac{d\sigma_{qq}}{d^2 b} \Psi e^{-ib\Delta}|^2$$

$$\frac{d\sigma_{qq}}{d^2 b} \sim r^2 \alpha_s x g(x, \mu^2) T(b)$$

---

E.C. Aschenauer

Brookhaven Science Associates
In practice use reduced cross-section:

\[
\sigma_r = \left( \frac{d^2 \sigma}{dx dQ^2} \right) \frac{x Q^4}{2 \pi \alpha^2 [1 + (1 - y)^2]} = F_2(x, Q^2) - \frac{y^2}{1 + (1 - y)^2} F_L(x, Q^2)
\]

\[
= F_2(x, Q^2) - \frac{y^2}{Y^+} F_L(x, Q^2)
\]

How to extract \( F_L \)
- Need different values of \( y^2/Y^+ \)
- \( F_L \) slope of \( \sigma_r \) vs \( y^2/Y^+ \)
- \( F_2 \) intercept of \( \sigma_r \) vs \( y^2/Y^+ \) with \( y^- \) axis
In order to extract $F_L$ one needs at least two measurements of the inclusive cross section with “wide” span in inelasticity parameter $\gamma$ ($Q^2 = sxy$).

$F_L$ requires runs at various $\sqrt{s}$ ⇒ longer program

**EIC studies:**
- Statistical error is negligible in essentially whole range
- Systematical Error
  - Calibration
  - Normalization
  - Experiment
  - Radiative Corrections
**PREPARATION OF DIS AND SIDIS MOCK DATA**

- **PEPSI MC** to generate $\sigma^{++}$ and $\sigma^{+-}$ with LO GRSV PDFs

\[ \text{DIS} \quad \rightarrow \quad \text{SIDIS} \]

- Inclusive final-state
- Identified charged pions and kaons
- Assume modest 10 fb$^{-1}$ for each energy, 70% beam polarizations

\[ Q^2 > 1 \text{ GeV}^2, \quad 0.01 < y < 0.95, \quad \text{invariant mass } W^2 > 10 \text{ GeV}^2 \]

- Depolarization factor of virtual photon $D(y,Q^2) > 0.1$ (cuts on small $y$)

\[ \text{scattered lepton: } 1^\circ < \theta_{\text{elec}} < 179^\circ \quad \text{and} \quad p_{\text{elec}} > 0.5 \text{ GeV} \]

\[ \text{hadron: } p_{\text{hadr}} > 1 \text{ GeV}, \quad 0.2 < z < 0.9, \quad 1^\circ < \theta_{\text{hadr}} < 179^\circ \]

- Use rel. uncertainties of data to generate mock data by randomizing around DSSV+ by 1-$\sigma$
- **SIDIS**: incl. typical 5% (10%) uncertainty for pion (kaon) frag. fcts (from DSS analysis)

E.C. Aschenauer
\[ d\sigma \sim \left( \tau_{BH}^* \tau_{DVCS} + \tau_{DVCS}^* \tau_{BH} \right) + |\tau_{BH}|^2 + |\tau_{DVCS}|^2 \]

→ different charges: e⁺ e⁻:

\[ \Delta \sigma_C \sim \cos \phi \cdot \text{Re}\{H + \xi \tilde{H} + ...\} \]

→ polarization observables:

\[ \Delta \sigma_{LU} \sim \sin \phi \cdot \text{Im}\{H + \xi \tilde{H} + kE\} \]

\[ \Delta \sigma_{UL} \sim \sin \phi \cdot \text{Im}\{\tilde{H} + \xi H + ...\} \]

\[ \Delta \sigma_{UT} \sim \sin \phi \cdot \text{Im}\{k(H - E) + ...\} \]

\[ \xi = \frac{x_B}{2-x_B} \quad k = \frac{t}{4M^2} \quad \text{kinematically suppressed} \]

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