What is the spatial mapping of quark and gluon fields in the nucleon AND nucleus.

Is the missing spin to be found via quark orbital momentum?

Are new phases of matter (Color-Glass Condensate) accessible at low x in nuclei?
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 the 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?
Traditionally we treated proton as a 1D object → What are the quark, gluon intrinsic spin contributions to the nucleon’s spin?

Last 10+ years: Theoretical tools and experiments to view proton as a (2+1)D object became available.

$$\begin{bmatrix} \frac{1}{2} \end{bmatrix}_{\text{proton}} = \frac{1}{2} \Delta \Sigma + L_Q + \Delta G + L_G$$

What are the position & momentum correlations amongst partons? Do they contribute to nucleon’s spin?
Unified view of the Nucleon Structure

- Wigner distributions:
  - TMDs – confined motion in a nucleon (semi-inclusive DIS)
  - GPDs – Spatial imaging of quarks and gluons (exclusive DIS)

- EIC – 3D imaging of partons: Quarks (fixed target), Gluons (collider)
Physics at Low x?


Method of including non-linear effects (McLerran, Venugopalan)

- Small coupling, high gluon densities
- BK/JMWLK equations lead to a Saturation Scale $Q_s(Y)$

At $Q_s$ gluon emission balances the recombination

Strongly correlated gluonic system at high energy (low-x)

Universal? Color Glass Condensate??

Linear QCD
BFKL: gluon emission

Nonlinear QCD
BK/JMWLK gluon recombination

Need a higher energy e-p collider than HERA?

→ Large Hadron electron Collider (LHeC)

→ Nuclei: naturally enhance the densities of partonic matter

Why not use Nuclear DIS at high energy?
Gluon and the consequences of its properties:

Gluons carry color charge → Can interact with other gluons!

Apparent “indefinite rise” in gluon distribution in proton!

What could limit this indefinite rise? → saturation of soft gluon densities via $gg \rightarrow g$ recombination must be responsible.

No unambiguously observation
Fundamental limiting state of matter
“Color Glass Condensate”

McLerran & Venugopalan et al

“...The result is a self catalyzing enhancement that leads to a runaway growth. A small color charge in isolation builds up a big color thundercloud....”

F. Wilczek, in “Origin of Mass”
Nobel Prize, 2004
How to reach the high gluon density?

Alternatively,
Probe the nucleons in **NUCLEI**
US Electron Ion Collider (EIC)

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

*Enhancement of $Q_S$ with $A$, not energy*
EIC Basics and Timeline

- **Center of Mass Energies:** 20 GeV - 141 GeV
- **Maximum Luminosity:** $10^{34}$ cm$^{-2}$s$^{-1}$
- **Hadron Beam Polarization:** 80%
- **Electron Beam Polarization:** 80%
- **Ion Species Range:** p to Uranium
- **Interaction regions:** up to two
Interaction Region

RHIC yellow ring: EIC hadron ring

Add electron storage ring in existing tunnel

Possible IR location: IP6

+/- 4.5 meters for detectors

Limited outside radius
The purpose of the Yellow Report Initiative is to advance the state and detail of the documented physics studies (White Paper, INT program proceedings) and detector concepts (Detector and R&D Handbook) in preparation for the realization of the EIC. The effort aims to provide the basis for further development of concepts for experimental equipment best suited for science needs, including complementarity of two detectors towards future Technical Design Reports (TDRs).

### Table

<table>
<thead>
<tr>
<th>$\eta$</th>
<th>$\theta$</th>
<th>Nomenclature</th>
<th>Electrons and Photons</th>
<th>$\pi/K/\rho$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(mrad)</td>
<td></td>
<td>Resolution $\sigma/E$</td>
<td>PID</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\pi$ suppress up to</td>
<td>$\text{min } E$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$1\text{E}-4$</td>
<td>$\text{photon}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$1\text{E}-2$</td>
<td>Separation</td>
</tr>
<tr>
<td>-4.0 to -3.0</td>
<td></td>
<td></td>
<td>not accessible</td>
<td>$\leq 10 \text{ GeV/c}$</td>
</tr>
<tr>
<td>-3.5 to -3.0</td>
<td></td>
<td></td>
<td>$1%/E\oplus2.5%/E\oplus1%$ (for 40 cm space)</td>
<td>$20 \text{ MeV}$</td>
</tr>
<tr>
<td>-3.0 to -2.5</td>
<td></td>
<td></td>
<td>$2%/E\oplus(4.8%)%/E\oplus2%$ (Upper limit achievable with 50 cm space)</td>
<td>$\leq 6 \text{ MeV}$</td>
</tr>
<tr>
<td>-2.5 to -2.0</td>
<td></td>
<td>Central Detector</td>
<td>$2%/E\oplus(12.1%)%/E\oplus(2.3%)$ (for 30 cm space)</td>
<td>$100 \text{ MeV}$</td>
</tr>
<tr>
<td>-2.0 to -1.5</td>
<td></td>
<td></td>
<td>A better stochastic term can be achieved with more space: 2.5% with crystals, 35 cm, 10% sampling, 45 cm, 4% SoftGlass, 65 cm</td>
<td>$\geq 3 \sigma$</td>
</tr>
<tr>
<td>-1.5 to -1.0</td>
<td></td>
<td>Barrel</td>
<td>$2%/E\oplus(4.7%)%/E\oplus2%$ (Upper limit achievable with 40 cm space)</td>
<td>$\leq 6 \text{ GeV/c}$</td>
</tr>
<tr>
<td>-1.0 to -0.5</td>
<td></td>
<td></td>
<td>$3\sigma \text{ e/m up to } 15 \text{ GeV/c}$</td>
<td>$60 \text{ MeV}$</td>
</tr>
<tr>
<td>-0.5 to 0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0 to 0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5 to 1.0</td>
<td></td>
<td>Forward Detector</td>
<td>$2%/E\oplus(4.7%)%/E\oplus2%$ (Upper limit achievable with 40 cm space)</td>
<td>$\leq 50 \text{ GeV/c}$ (worse approaching 3.5)</td>
</tr>
<tr>
<td>1.0 to 1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5 to 2.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0 to 2.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5 to 3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.0 to 3.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
$p = m\gamma\beta \quad E = m\gamma$ velocity(\(\beta\)) measurement yields mass.

- **Direct measurement:**
  - Record signal time at multiple locations, calculate \(v\).
  - “Fast” detector = low transit time spread (most easily achieved at small transit time)

- **Velocity-dependent interaction(s) with detector:**
  - Specific Ionization (aka \(\frac{dE}{dx}\))
  - Cherenkov Radiation: \(\cos \theta_C = \frac{1}{n\beta}\)
    - \(\theta_C\) measured wrt track direction.
    - Thus dependent upon deliverables from tracking
  - Bremsstrahlung: \(P = \frac{q^2\gamma^4}{6\pi\varepsilon_0c}\left(\beta^2 + \left(\frac{\beta\cdot\vec{v}}{1-\beta^2}\right)^2\right)\)
  - Transition Radiation: \(I = \frac{Z^2e^2\gamma\omega_p}{3c}\)

TOF covered well in prior presentations, not repeated here.
Available Space Depends Upon Tracking Options

- Cylindrical defining volume
- +/- ~ 1.2 meters
- Outer radius:
  - ~20 cm for hybrid
  - ~50 cm for All-silicon
- Hybrid Option allows for dE/dx
- MUCH smaller than STAR or ALICE

YR baseline detector configurations

- New baseline based on the ITS3 sensor, services and support design
- Two configurations are simulated within the YR effort
  - Hybrid with gas outer tracker and end-caps
    - TPC barrel and large area MPGDs for end cap tracking
    - MPGD barrel and large area MPGDs for end cap tracking
  - All-Si compact tracker

LAURA GONELLA

10 μm pixel pitch
0.05% X/X₀ vtx layers
0.55% X/X₀ tracking layers
0.24% X/X₀ disks
Specific ionization is a function of $\beta$. PID bands vs momentum.
Crossing $\sim \beta = 0.7$ (TOF can help)

Limitations from Landau tails:
- Primary ionization Statistics = Poisson
- Total ionization = Landau
- Traditional Approach:
  - Lots of gas & lots of samples
- Forward thinking approaches:
  - Gas choice to minimize Landau
  - “Cluster Counting”

Goal: Achieve $dE/dx$ performance with least gas volume

<table>
<thead>
<tr>
<th>TPC</th>
<th>Pad rows</th>
<th>Gas</th>
<th>Radial Drift Vol. [cm]</th>
<th>$dE/dx$ [keV/cm]</th>
<th>Primary Ionization [cm]</th>
<th>Total Ionization [cm]</th>
<th>Total Ionization/Initial Ionization</th>
<th>Integrated Primary Ionization</th>
<th>$dE/dx$ resolution $\eta_{=0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>STAR w/ iTPC</td>
<td>72</td>
<td>P10 - 10% methane, 90% argon</td>
<td>150</td>
<td>2.344</td>
<td>23.2</td>
<td>89.9</td>
<td>3.9</td>
<td>3,480</td>
<td>6.5%</td>
</tr>
<tr>
<td>ALICE 2010</td>
<td>160</td>
<td>(Ne/CO2 90/10)/N2 5% (N2 not in calculation)</td>
<td>161.8</td>
<td>1.705</td>
<td>14.35</td>
<td>47.8</td>
<td>3.3</td>
<td>2,322</td>
<td>5% (cosmic)</td>
</tr>
</tbody>
</table>

sPHENX 2019 w/ iTC R1 | 48       | Ne/C4 50/50 | 60 | 4.28 | 31.5 | 71.5 | 2.3 | 1,890 | This study |

Compact size
High primary ionization
Low secondary ionization

Dots = STAR
Boxes = sPHENIX Test Beam

Speculative Cluster Counting Concept

Scaling to our available length:

- $N_{\text{cluster}} \propto \text{Length}$
- $\sigma_N = \sqrt{N_{\text{cluster}}} \propto \sqrt{L}$

Using a 3σ reference @ 40 cm gas:

- $3\sqrt{\frac{120}{40}} = 5.2$

Existing Concept (“Timepix”)

- Avalanche onto Silicon Pixels
- Tiny Pixels (smaller than cluster spacing)
- Sufficient gain for single electron
- In principle can work
- Expensive for large area.
- Can we accomplish with conventional tech?
Drift leverages huge Lorentz angle as “magnifier”

Clusters spread across space and time.

Higher B = Lower Transverse diffusion

- Example: T2K(130 V/cm) has only $25 \frac{\mu m}{\sqrt{cm}}$ at 3 Tesla

Detect (count) clusters with conventional means.

Early Conceptual Stage: Requires R&D
Leading Barrel PID Technology: DIRC

- At normal incidence, Cerenkov light is internally reflected for $n > \sqrt{2}$
- Cerenkov angle preserved if bars meticulously flat with 90 degree corners.
- Spectacularly compact PID device with photon detection at end.

Generic reference design: 1m barrel radius, 16 sectors
176 bars: synthetic fused silica, 17mm (T) · 32mm (W) · 4200mm (L)
Photo sensors: MCP-PMTs - 3x3mm² pixels
Original BaBar DIRC was effectively “proximity focused”

hpDIRC section creates focused ring improving resolution.

Excellent match to EIC needs.

Strict requirements on “correlated terms”, (e.g. angular resolution of tracking)

Works with either standard tracking solution.
Hadron End: Dual RICH

- **Cherenkov radiator**
  - Refractive Index
    - $n = 1.02$ (aerogel) 1.0008 ($C_2F_6$)
  - Length of the radiator
    - $L = 4$ cm (aerogel), 160 cm ($C_2F_6$)
- **Mirrors**
- **Photon Detector**
  - 3 mm pixel size; 200-500 nm MAPMT
- **Particle Generation**
  - Originate from the vertex

- External Assumption

- Exquisite detail in simulation.
- AI-based optimization.
- Uses constant external angular resolution assumption.
- Similar external constraint assumed as deduced for separate gas & aerogel RICHes

**Tracking**

<table>
<thead>
<tr>
<th>Tracking</th>
<th>Angular resolution</th>
<th>Impact point resolution</th>
<th>Momentum resolution</th>
<th>Magnetic Field</th>
<th>Space Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Angular resolution</strong></td>
<td>$\sigma = 0.5$ mrad (1 mm over 2 m) - whole momentum range</td>
<td>$\sigma = 0.3$ mm</td>
<td>+/- few percent</td>
<td>3 Tesla Central Field in JL-MEIC spectrometer</td>
<td>(based on original spectrometer constraints)</td>
</tr>
<tr>
<td><strong>Impact point resolution</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Momentum resolution</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$dP/P$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Magnetic Field</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Space Requirement</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>longitudinal length</strong></td>
<td>JLEIC: $\approx 1.6$ m, ePHENIX: $\approx 1.0$ m</td>
<td></td>
<td></td>
<td></td>
<td>(based on original spectrometer constraints)</td>
</tr>
<tr>
<td><strong>transverse radius</strong></td>
<td>JLEIC: $\approx 2.5$ m, ePHENIX: $\approx 2$ m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>beam pipe radius</strong></td>
<td>$\approx 10$ cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td>no direct external background</td>
<td>only background produced by the simulated charged particle: Delta rays, Rayleigh scattering ...</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**NOTE:** PMTs to the side makes optical aberration (“Emission”) dominant
Electron Arm: Modular RICH

Cherenkov radiator
- (Aerogel) refractive index, \( n = 1.03 \)
- Length of the radiator, \( L = 3\text{cm} \)
- Lens with focal length, \( f = 6'' \)

Photon Detector
- 3 mm pixel size

Hadron ID requirements relaxed...aerogel only
- Additionally require eID ~ 4GeV/c
- Modular RICH focused by Fresnel Lens
  - Sharp image improves resolution.
  - Transmission of lens combats dispersion
- Provides TOF with suitable readout device (LAPPD)

NOTE: Similar performance to aerogel in dRICH
eID by Transition Radiation (TRD)

1: Make TR photons:
- Index, n, change
- X-ray regime

2: Layered to get more photons

3: ID TR photons by energy/pos

4: Reject Pions

“Threshold detector” (TR X-rays produced or not)

$P_{\text{min}} \sim 1$ GeV (rejection \(-\text{constant at higher momentum}\))

Balance between $X_0$ and rejection
PHENIX HBD optimized for 1e-vs-2e separation.
- 20 photoelectrons vs 40 photoelectrons
- Non-zero hadron response.
- Re-optimize for EIC??

Unfocused Threshold Cherenkov

Limiting by 1st Gap

Garfield + Fast Monte Carlo

Pion Signals Simulated

1st Gap Dominates!
Speculative HBD++ ??

Conceptual Idea

- microMEGAS provide the smallest gas length.
- Gain from any or all of three layers:
  - Gain from GEM
  - Gain from $\mu_1$
  - Gain from $\mu_2$

Speculative! Requires R&D

HBD: Phenix
HBD+: Gem + 1-stage $\mu$M gain
HBD++: GEM _ 2-stage $\mu$M gain
Direct measurements of velocity require a fast charge collection device.

The time resolution is automatically helped by small devices:

- LGAD: Low Gain Avalanche Device. Instantly small.
- MCP: Micro Channel Plate → LAPPD (Large Area Picosecond Photon Detector)
PID from TOF requires:
- Time resolution.
- Maximum path length.
- Known ring makes size restrictions!
  - Civil construction already there.
  - One ring outsize the detector.

Practical Implementation:
- Tempting to assume time resolution scales as $\sqrt{N}$
- Extreme care required to minimize or eliminate correlated errors (e.g. “start clock jitter”)
Electron Ion Collider has passed “CD0” and will be built at BNL.

Detector challenges in PID are exacerbated by limited available space.

Asymmetric collisions lead to asymmetric requirements

Options exist to leverage

- TOF.
- Cherenkov
- \( \text{dE/dx} \)

Solutions seem to be in hand.

More R&D possible on alternative speculative avenues.
BACKUP SLIDES
Cherenkov Pointing:

- Parameterizations of gas Cherenkov indicate pointing required at 0.5-1.0 mrad level while inside the radiator.
- Calculations of aerogel devices indicate 0.5-1.0 mrad level.
- Calculations of DIRC indicate 0.5 mrad level or better.

TOF:

- Path length can influence PID resolution at the best δt.
- Non-trivial influence of “material budget distribution”.
- Need deeper understanding of this issue.

PID requirements toughening with time:

- SIDIS group shown on right. Jets want even more.
- PID requirements are not symmetric in eta, driven by 0.8 → 1.0
- Is a symmetric barrel optimal at our asymmetric collider?

Meta-materials: Game changer, but we can’t assume these will work:
What is the meaning of “Long Shadow”?
Additional Integration Points

- Gas RICH at highest momentum (hadron arm) does not enjoy an over-abundance of Cherenkov photons (love to have lots of Zed).
- Angular resolutions required for Cherenkov-based PID detectors must be evaluated WITHIN the radiator:
  - Services at Zed > 1.2 may scatter particle before hadron arm Cherenkov.
  - DIRC bars scatter particles on their own (17 mm quartz)
  - Must evaluate needs of a tracking layer behind Cherenkov devices.
- Cherenkov detectors require photo-sensors
  - Many technologies are sensitive to field strength and orientation.
  - 1 Tesla at the sensor is fine.
  - Easy to achieve with central field = 1.5 Tesla.
  - Very challenging but seems doable if central field = 3 Tesla...trade off with optical aberration as you move sensors back.
  - SiPM sensors operate fine in the field, but radiation damage can lead to high rate of “false photons”
- Need to minimize bending of tracks within the RICH.

Is this less than 1 mrad scattering
High Momentum GEM RICH

- 1m of CF\textsubscript{4} radiator at 1.003 bar (slightly overpressure)
- CsI Photocathode on top GEM
- Mirror in deep UV -> MgF\textsubscript{2} coating
- Single Photon Capability -> quintuple GEM stack with APV25-SRS
- Particles ~perpendicularly incident on spherical mirror, focused onto a GEM stack directly

Performance from Parameterized Test Beam Data

- According to the parameterization, tracking is leading error contribution is worse than \~7 mrad, becomes negligible resolution factor around 2 mrad. Between 2 and 7 mrad, more detailed investigation is required.
- Plot shows viscerally the effect.
- More detailed simulation required.

NOTE: High chromaticity = loose requirement on tracking
Trivial (just math) Calculation:
• Assume photon measured perfectly.
• Tracker makes fixed error \( \alpha \).
• \( \delta \theta_C \) depends on both \( \frac{\langle N_{pe} \rangle}{ring} \) and \( \alpha \)!

Requirements depend upon performance
• Parameterizations:
  • Wide range of assumptions possible.
• Full Monte Carlo
  • Robust and Reliable results.

We present both parameterizations and full Monte Carlo calculations.
Basic Coupling of Tracking to PID

**Cherenkov Angle ($\theta_C$):**
- Centroid from $n$
- $\delta \theta_C$ from:
  - $N_{\text{photo-electrons}}$
  - chromaticity (aka dispersion; $n(\lambda)$)
  - pixel size
  - optical aberration (aka “emission”)
  - magnetic field
  - Track Pointing
- $\delta p$ from tracking

Strongly reliant upon tracking

**Time Of Flight (TOF):**
- Calculates $m^2$ using $p$, $\beta$.
- $\delta m$ from:
  - $\delta_t$
  - $\delta_p$
  - $\delta_L$
- $c \cdot 5 \text{ps} = 1.5 \text{ mm}$

Weakly reliant upon tracking...discussed in backup slides

**Dominant Term**

NOTE: Where PID is excellent, it can contribute to momentum resolution.

$$\Delta t = L \left( \frac{1}{v_1} - \frac{1}{v_2} \right)$$

$$\Delta t \approx \frac{L}{pc^2} \left[ (pc + \frac{m_1^2c^4}{2pc}) - (pc + \frac{m_2^2c^4}{2pc}) \right]$$

$$\Delta t = \frac{Lc}{2p^2} (m_1^2 - m_2^2)$$

$$\left( \frac{dm}{m} \right)^2 = \left( \frac{dp}{p} \right)^2 + \gamma^4 \left[ \left( \frac{dt}{t} \right)^2 + \left( \frac{dL}{L} \right)^2 \right]$$

**NOTE:**
- $N$ independent TOF measurements,
  - $\delta_t \rightarrow \frac{\delta_{t1}}{\sqrt{N}}$
- Challenges exist to make independent
  - Common clock
  - Etc...

NOTE:
- $\delta_1$ is tiny, $\delta_L$ is significant

$$\Delta t = \frac{Lc}{2p^2} (m_1^2 - m_2^2)$$
Many presentations.

Similar themes:
- Si as a vertex
- All-Silicon
Superb e/π Separation

- Focused Gas RICH
- Low index gas pushed the e/π out to 15 GeV or beyond.
- Compromise parameter is Zed length:
  - 1-1.5 meters in Zed
  - Under study:
    - Move $Z_{\text{vertex}}$ toward $-\eta$ exacerbating the space issue.

Notice:
- eID needs met w threshold device
- Optics maybe unnecessary
TOF needs a measurement of $p$ and $L$

- As $\delta t \rightarrow 5$ ps, requires precision path length $L$ ($c*\delta t \sim 1.5$ mm...tracking must exceed this.)
- Multiple scattering might be the biggest worry, need to ensure low material budget and/or enough tracking layers to catch scattering.
- Depends partly upon the material that does not provide position measurement:

- Several technologies reviewed, no one chosen yet
- AC-LGADs could provide a very good tracking layer (~100 um) + timing (20 ps)
- External start time provided by forward detectors could be helpful
- Study of Self-timing (Internal) using tracks
More Compact Cherenkov eID Detectors

Modular RICH: Fresnel-focused compact RICH

- Close to 4 GeV.
- Effective enough alone?
- Complementary detector?
  - TRD?
  - dE/dx?

- Useful at the lowest momenta.
- Performance limited by Mult. Scattering.
- Detailed simulations req’d and underway
- Expectation:
  - 3-4σ @ 1 GeV