e+A(p) physics with an electron-ion collider at RHIC

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Brookhaven National Lab

on behalf of the BNL EIC Science Task Force and friends
What is eRHIC?

**Electron accelerator**

to be built

Unpolarized and polarized leptons
5-20 (30) GeV

70% e⁻ beam polarization goal
polarized positrons?

Centre-of-mass energy range: $\sqrt{s}=30-200$ GeV; $L \sim 100-1000 \times$ Hera
longitudinal and transverse polarization for p/He³ possible

**RHIC**

Existing = $2B

Polarized protons
50-250 GeV

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

Polarized light ions He³
166 GeV/u
From RHIC to eRHIC

- RHIC
- PHENIX 8:00 o'clock
- LINAC
- EBIS
- Booster
- NSRL
- AGS
- eLenses 10:00 o'clock
- STAR 6:00 o'clock
- Jet/C-Polarimeters 12:00 o'clock
- ANDY 2:00 o'clock
- RF 4:00 o'clock
- Tandems
- ERL Test Facility

Plot showing the transition from RHIC to eRHIC with various facilities and time markers.
From RHIC to eRHIC

eRHIC staging:
All energies scale proportionally by adding SRF cavities to the injector and two linacs and cranking power supplies up.

Vertically separated recirculating passes. # of passes will be chosen to optimize eRHIC cost.

Gap 5 mm total
0.3 T for 30 GeV

3rd detector

Coherent e-cooler

Beam dump
Polarized e-gun

100m

 Vertically separated recirculating passes. # of passes will be chosen to optimize eRHIC cost.
Detector requirements

**Inclusive Reactions:**
- Momentum/energy and angular resolution of $e'$ critical
- Very good electron pid
- Moderate luminosity $>10^{32} \text{ cm}^{-1} \text{ s}^{-1}$
- Need low $x \sim 10^{-4} \rightarrow$ high $\sqrt{s}$ (Saturation and spin physics)
Detector requirements

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**Semi-inclusive Reactions:**
- Excellent particle ID: $\pi,K,p$ separation over a wide range in $\eta$
- full $\Phi$-coverage around $\gamma^*$
- Excellent vertex resolution $\rightarrow$ Charm, bottom identification
- high luminosity $>10^{33}$ cm$^{-1}$ s$^{-1}$ (5d binning ($x,Q^2,z,p_t,\phi$))
- Need low $x \sim 10^{-4}$ $\rightarrow$ high $\sqrt{s}$
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Exclusive Reactions:
- Exclusivity → high rapidity coverage → rapidity gap events
- high resolution in t → Roman pots
- high luminosity >10^{33} cm⁻¹ s⁻¹ (4d binning (x,Q²,t,Φ))
The pillars of the eRHIC physics programme

- Wide physics programme with demanding requirements on detector and machine performance
The pillars of the eRHIC physics programme

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- Physics of strong colour fields

- Spin physics
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- 3D Imaging
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- 3D Imaging
- Hadronisation
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- Physics of strong colour fields
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Most compelling physics questions

Spin physics

๏ What is the polarisation of gluons at small $x$ where they dominate?
๏ What is the $x$-dependence and flavour decomposition of the polarised sea?

Determine quark and gluon contributions to the proton spin at last!!
Most compelling physics questions

Spin physics

- What is the polarisation of gluons at small \( x \) where they dominate?
- What is the \( x \)-dependence and flavour decomposition of the polarised sea?

Determine quark and gluon contributions to the proton spin at last!!

Imaging

- What is the spatial distribution of quarks/gluons in nucleons AND nuclei?
- Understand deep aspects of gauge theories revealed by \( k_T \) dependent distributions

Possible window to orbital angular momentum

Strong Colour Fields and Hadronisation

- Quantitatively probe the universality of strong colour fields in \( A+A \), \( p+A \) and \( e+A \)
- Understand in detail the transition to the non-linear regime of strong gluon fields and the physics of saturation
- How do hard probes in \( e+A \) interact with the medium?

Currently have no experimental knowledge of gluons in nuclei at small \( x \)!!
spin physics
10 week INT programme - Fall 2010

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Talks online
Application form
Exit report
Friends of the INT
Obtain an INT preprint number
INT homepage

http://www.int.washington.edu/PROGRAMS/10-3/

Gluons and the quark sea at high energies: distributions, polarization, tomography

September 13 to November 19, 2010

This INT program will address open questions about the dynamics of gluons and sea quarks in the nucleon and in nuclei. Answers to these questions are crucial for a deeper understanding of hadron and nuclear structure in QCD at high energies. Many of them are relevant for understanding QCD final states at the LHC, which often provide a background for physics beyond the standard model. The topics addressed in this program have important ramifications for understanding the matter produced in heavy-ion collisions at RHIC and the LHC.
10 week INT programme - Fall 2010

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## Golden measurements in spin

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<td>polarised gluon distribution $\Delta g$</td>
<td>scaling violations in inclusive DIS</td>
<td>gluon contribution to the proton spin</td>
<td>coverage down to $x \sim 10^{-4}$; $\mathcal{L}$ of about 10 fb⁻¹</td>
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<td>polarised quark and antiquark densities</td>
<td>semi-incl. DIS for pions and kaons</td>
<td>quark contr. to proton spin; asym. like $\Delta\bar{u}-\Delta\bar{d}$; $\Delta s$</td>
<td>similar to DIS; good particle ID</td>
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<td>novel electroweak spin structure functions</td>
<td>inclusive DIS at high $Q^2$</td>
<td>flavour separation at medium-x and large $Q^2$</td>
<td>$\sqrt{s} \geq 100$ GeV; $\mathcal{L} \geq 10$ fb⁻¹; positrons; polarised $^{3}$He beam</td>
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The quest for $\Delta g$ - where do we stand?

- inclusive pions and jets remain the main probes
- jet/hadron correlations are essential to cover smaller $x$

- low-x behaviour is unconstrained
  - significant polarisation still possible
  - no reliable error estimate for 1st moment

- By 2015 - expect to have:
  - DSSV 2.0 global analysis on new world data
  - reduced uncertainties in $\Delta g$ in current $x$ range
  - evidence of a node further scrutinised
  - extend $x$-range towards lower $x$
    - 500 GeV running and particle correlations

DSSV includes "only" RHIC run6 data
The quest for $\Delta g$ - what can we do at eRHIC?

**strategy to quantify impact:** global QCD fits with realistic pseudo-data

- $A_1^P$ - EIC 5×250 GeV - 20 fb$^{-1}$

  Measurements limited by systematics – need to control them very well

**issues:** bunch-by-bunch polarimetry, relative luminosity, detector performance, …
The quest for $\Delta g$ - what can we do at eRHIC?

how effective are scaling violations?

quantitative studies based on simulated data for eRHIC stage-1: $5 \times (50, 100, 250, 325)$ GeV

$\chi^2$ profile for $\int_{0.0001}^{1} \Delta g(x, Q^2) \, dx$

expect to determine $\int_{0}^{1} dx \Delta g(x, Q^2)$ at about 10% level (more studies needed)

kinematic reach down to $x = 10^{-4}$ essential to determine integral
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New pseudo-data

data for DIS and SIDIS ($\pi^\pm$, $K^\pm$)

10 fb\(^{-1}\) each, 70% beam pol.

Cuts:

- $W^2 > 10 \text{ GeV}^2$
- depol. factor > 0.1
- $0.001 < y < 0.95$
- $1^\circ < \theta < 179^\circ$
- $p_e > 0.5 \text{ GeV}$
- $p_{\text{hadr}} > 1 \text{ GeV}$

Global analysis:

- use relative uncertainty of each point to produce mock data (based on DSSV)
- randomise data within 1\(\sigma\)
- for SIDIS: incl. 5%(10%) uncertainty from pion (kaon) frag. functions
- map out $\chi^2$ profiles with Lagrange multiplier method (Hessian is work in progress)
Update on $\Delta g$

- Very similar results to before
- Slightly larger uncertainties
- Need to study $10^{-4}\rightarrow 1$ range
- Need to translate into error on x-shape of $\Delta g$
What about $\Delta q$?

**surprise:** $\Delta s$ small & positive from SIDIS data

- but 1st moment is negative and sizable due to “constraint” from hyperon decays (F,D) (assumed SU(3) symmetry - debatable M. Savage)
- drives uncertainties on $\Delta \Sigma$ (spin sum)
What about $\Delta q$?

- Current uncertainties DSSV

DSSV (incl. latest COMPASS data)

- Simulated impact of RHIC
  - W boson data on global fit
  - Reduction of uncertainties for $0.07 < x < 0.4$ can test consistency of low $Q^2$ SIDIS data in that $x$ regime
First results on the quark sea

- very encouraging results
- as expected, DIS has no impact
- need to study 0.0001-1 range
- need to translate into error on x-shape
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- note the change of scale on x-axis
- perhaps “neutron beam” would lead to further improvements
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- should be able to test “constraint” from SU(3) symmetry (F,D values from hyperon decays)
e+A physics
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<td>parton energy loss, shower evolution; energy loss mechanisms</td>
<td>light flavours and charm; jets</td>
<td>rare probes and bottom; large-x gluons</td>
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<td>flavour separated nuclear PDFs</td>
<td>charged current and $\gamma Z$ structure functions</td>
<td>EMC effect origin</td>
<td>full flavour separation for $10^{-2} &lt; x &lt; 1$</td>
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<td>DVCS; diffractive vector mesons</td>
<td>interplay between small-$x$ evolution and confinement</td>
<td>moderate $x$ with light, heavy nuclei</td>
<td>smaller $x$, saturation</td>
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Integrated gluon distributions from inclusive structure functions
# Integrated gluon distributions from inclusive structure functions

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- **Deliverables:**
  - integrated gluon distributions

- **Observables:**
  - $F_{2,L}$

- **What we learn:**
  - nuclear wave function; saturation, $Q_s$
  - gluons at $10^{-3} < x < 1$

- **Stage-I:**
  - saturation regime

- **Stage-II:**
  - saturation regime

- **Charm:**
  - $F_{c2,L}$
  - $F_{D2,L}$

- **Diffractive:**
  - difficult measurement / interpretation

- **Saturation regime**
Measuring the glue via Structure Functions

\[ \sigma_r(x, Q^2) = F_2^A(x, Q^2) - \frac{y^2}{Y} + F_L^A(x, Q^2) \]
Measuring the gluons: extracting $F_L$

$$\sigma_r(x, Q^2) = F_2^A(x, Q^2) - \frac{y^2}{Y^+} F_L^A(x, Q^2)$$

- $F_L \sim \alpha_s x G(x, Q^2)$
  - $y = Q^2/xs$
  - require an energy scan to extract $F_L$

- 3 different proton energies run at HERA
  - 2 low-statistics runs
  - bad for $F_L$ extraction
Measuring the gluons: extracting $F_L$

$$\sigma_r(x, Q^2) = F_2^A(x, Q^2) - \frac{y^2}{Y + F_L^A(x, Q^2)}$$

- $F_L \sim \alpha_s x G(x, Q^2)$
  - $y = Q^2/\xi s$
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920 GeV protons
Measuring the gluons: extracting $F_L$

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H1 and ZEUS

575 GeV protons
Measuring the gluons: extracting $F_L$

$$\sigma_r(x, Q^2) = F_2^A(x, Q^2) - \frac{y^2}{Y + F_L(x, Q^2)}$$

- $F_L \sim \alpha_s x G(x, Q^2)$
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○ $F_L \sim \alpha_s x G(x, Q^2)$

→ $y = Q^2/xs$

→ require an energy scan to extract $F_L$

○ 3 different proton energies run at HERA

→ 2 low-statistics runs

→ bad for $F_L$ extraction

![Graph showing $F_L$ vs. $Q^2$]
Are $F_2/F_L$ good differentiators of models?

In order to see if measuring $F_2/F_L$ at an EIC is “worthwhile”, we need to see if a measurement could differentiate between models.

Models:

- **MSTW08**: code downloadable from HEPFORGE. Code to extract $F_2/F_L$ obtained privately from Graeme Watt
  - Global fit, using total cross-section from HERA
  - DGLAP evolution

- **IPSat**: data kindly provided by T. Lappi
  - Fit to ZEUS’96 data - $\chi^2/d.o.f. \sim 1.2$

- **bCGC**: data kindly provided by T. Lappi
  - Fit to Zeus’96 data - $\chi^2/d.o.f. \sim 1.62$

- **rcBK**: AAQMS data kindly provided by J. Albacete
  - Evolution along $x$ with BK equation
  - Fit to H1+ZEUS combined 2006 data

- **Leading-Twist Shadowing**: FGS10 data kindly provided by V. Guzey
  - Evolved with DGLAP

Data:

The current implementation of FGS10 uses CTEQ5m as its PDF.

This overestimates the gluon contribution quite drastically compared to more modern calculations.

- New curves are on their way from FGS10 with CTEQ6.
- Not ready for this meeting.
- Following $F_L$ data therefore still uses CTEQ5m for FGS10.
$F_2(p)$ - low $Q^2$
$F_2(p)$ - higher $Q^2$
$F_2(A)/A$ - low $Q^2$
$F_2(A)/A$ - $p$ vs $A$
F_2 ratios: F_2(A)/AF_2(p)
$F_L(p) - \text{low } Q^2$
$F_L(p) - \text{higher } Q^2$
$F_L(A)/A$ - low $Q^2$
$F_L(A)/A$ - higher $Q^2$

Graphs showing $F_L/A$ vs $x$ for different $Q^2$ values, with data and theory curves for various collaborations and nuclear targets.
$F_L(A)/A - p \text{ vs } A$
\( F_L \) ratios: \( F_L(A)/AF_L(p) \)
Double ratios - $F_L(A)/AF_L(p)$: $F_2(A)/AF_2(p)$
Double ratios - $\frac{F_L(A)}{AF_L(p)}: \frac{F_2(A)}{AF_2(p)}$
Feasibility study: \( \sigma_r(x, Q^2) = F_2^A(x, Q^2) - \frac{y^2}{Y+} F_L^A(x, Q^2) \)

- Simulated data for e+A coverage in x-Q^2 space
  - 3 energies is the minimum requirement in the F_L capability study
  - 1^{st} stage only gets to medium x
  - Need high electron energy to get to "small" x
Feasibility study:

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

Strategies:

- slope of \( y^2/Y_+ \) for different \( s \) at fixed \( x \) & \( Q^2 \)

**e+p:** 1st stage

- 5x50 - 5x325 running combined
- 4 weeks/each

(50% eff)

- stat. error shown and negligible

To Do:

- refine method & test how well we can extract \( F_L \) in e+A collisions
Extracting $F_2$ and $F_L$ at the EIC

- $F_{2,L}$ extracted from pseudo-data generated for 1 month running at 3 eRHIC energies
  - $5+100$ GeV
  - $5+250$ GeV
  - $5+325$ GeV
- Data, with errors, added to theoretical expectations from ABKM09 PDF set
  - valid for $Q^2 > 2.5$ GeV$^2$
Evolution of $F_L(p)$ with $Q^2$ - fixed $x$
Evolution of $F_L(p)$ with $Q^2$ - fixed $x$
Evolution of $F_L(p)$ with $Q^2$ - fixed $x$
Charm and diffractive structure functions, $F^{D}_{2,L}, F^{c}_{2,L}$

- $F^{c}_{2,L}$ give more direct access to the gluon distribution than the inclusive $F_2$ structure function
  - QCD calculations with non-zero $m_c$ are scheme dependent and can absorb saturation signals if not handled correctly
- $F^{D}_{2,L}$ is also sensitive to the gluon distribution
  - Differences between linear and non-linear models appear at higher $Q^2$ than for $F_2$ (8 GeV$^2$ vs 2 GeV$^2$)
    - More experimentally challenging measurement than $F_2$

$x_P = 10^{-3}$

$Q^2 = 5 GeV^2$
$k_T$ dependent gluons, gluon correlations from di-hadron correlations, SIDIS (semi-inclusive DIS)
$k_T$ dependent gluons, gluon correlations from di-hadron correlations, SIDIS (semi-inclusive DIS)

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<td>onset of saturation</td>
<td>rare probes and bottom; large-x gluons</td>
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Direct link between $p_T$ of produced hadron and that of the small-x gluon

$$e+A \rightarrow e + h + X$$
**k_T dependent gluons, gluon correlations from di-hadron correlations, SIDIS (semi-inclusive DIS)**

\[ e+A \rightarrow e + h_1 + h_2 + X \]

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\[ e+A \rightarrow e + h + X \]

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di-hadron angular correlations in d+A

- At y=0, suppression of away-side jet is observed in A+A collisions
- No suppression in p+p or d+A

\[ x \sim 10^{-2} \]

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- However, at forward rapidities ($y \sim 3.1$), an away-side suppression is observed in d+Au
- Away-side peak also much wider in d+Au compared to p+p
  \[ x \sim 10^{-3} \]
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At forward rapidities (y ~ 3.1), an away-side suppression is observed in d+Au.
The away-side peak also much wider in d+Au compared to p+p collisions.

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di-hadron correlations in e+A

Never been measured - we expect to see the same effect in e+A as in d+A

At small-x, multi-gluon distributions are as important as single-gluon distributions and they contribute to di-hadron correlations

The non-linear evolution of multi-gluon distributions is different from that of single-gluon distributions and it is equally important that we understand it

The d+Au RHIC data is therefore subject to many uncertainties

- these correlations in e+A can help to constrain them better

Q^2 = 4GeV^2; z_{h1} = z_{h2} = 0.3

2 GeV < p_T^T < 3GeV

1GeV < p_T^A < 2GeV

Preliminary result from Bowen Xiao
di-hadron correlations in e+A

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- At small-x, multi-gluon distributions are as important as single-gluon distributions and they contribute to di-hadron correlations
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For a discussion of this work, see talk by Tobias Toll on Thursday

\[ Q^2 = 4\text{GeV}^2; z_{h1} = z_{h2} = 0.3 \]
\[ 2 \text{ GeV} < p_T^{T} < 3\text{GeV} \]
\[ 1\text{GeV} < p_T^{A} < 2\text{GeV} \]
transport coefficients in cold nuclear matter from large-x semi-inclusive DIS and jets
## Transport coefficients in cold nuclear matter

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<td>parton energy loss, shower evolution; energy loss mechanisms</td>
<td>light flavours and charm; jets</td>
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Jets and hadronization

- $t_p$ - production time of propagating quark
- $t_{hf}$ - hadron formation time
Jets and hadronization

What happens if we add a nuclear medium?

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A. Accardi
R. Dupre
Jets and hadronization

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Jets and hadronization

A. Accardi
R. Dupre

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Observables:

Broadening: $\Delta p_T^2 = \langle p_T^2 \rangle_A - \langle p_T^2 \rangle_p$: direct link to saturation scale
Jets and hadronization

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- **Attenuation:** $R^h_A(Q^2, \nu, z_h, p_T^2)$ : ratio of hadron production in A to D, modifications of nPDFs cancel out
Jets and hadronization

- \( t_p \) - production time of propagating quark
- \( t_{hf} \) - hadron formation time

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$p_T$ broadening - how can the EIC contribute?

HERMES:

Increase of $p_T$ broadening seen with increasing nuclear size - integrated over all variables
p_T broadening - how can the EIC contribute?

HERMES:

\[
\langle p_t^2 \rangle \left[ \text{GeV}^2 \right]
\]

\[
\Delta \langle p_t^2 \rangle \left[ \text{GeV}^2 \right]
\]

\[
\langle \mathcal{R}^2 \rangle \left[ \text{GeV}^2 \right]
\]

\[
\Delta \langle \mathcal{R}^2 \rangle \left[ \text{GeV}^2 \right]
\]

\[
Q^2 \left[ \text{GeV}^2 \right]
\]

\[
x
\]

\[
z
\]
$p_T$ broadening - how can the EIC contribute?

**HERMES:**

Measurements from HERMES can be repeated, with the addition of heavy quarks.
Attenuation - how can the EIC contribute?

**HERMES:**

\[ E_e = 27 \text{ GeV} \rightarrow \sqrt{s} = 7.2 \text{ GeV} \]
\[ E_h = 2-15 \text{ GeV} \]

\[ \nu = \text{virtual photon energy} \]
\[ Z_h = E_h/\nu \]
Attenuation - how can the EIC contribute?

**HERMES:**

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

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**EIC:**

light hadrons:

\[ \nu = \text{virtual photon energy} \]

\[ Z_h = E_h/\nu \]

\[ R_A^h \]

\[ R_M^h \]

\[ Q^2 \]

\[ z \]

hadronization in and out of nucleus
Attenuation - how can the EIC contribute?

**HERMES:**
\[ E_e = 27 \text{ GeV} \rightarrow \sqrt{s} = 7.2 \text{ GeV} \]
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**EIC:**

*charm hadrons:*

\[ \rho = \text{virtual photon energy} \quad \text{large } \rho \text{ range } \rightarrow \text{boost} \]

hadronization in and out of nucleus

\[ Z_h = E_h/\rho \]
Attenuation - how can the EIC contribute?

RHIC:

\( \frac{(e^+ + e^-)}{2} \)

Au+Au (central) \( \sqrt{s_{NN}} = 200 \) GeV

- STAR Au+Au 0-5% (PRL98, 192301)
- PHENIX Au+Au 0-10% (PRL96,032301)

EIC:

charm hadrons:

\[ \nu = \text{virtual photon energy} \]

\[ Z_h = E_h/\nu \]

\( \nu \) range \( \rightarrow \) boost

hadronization in and out of nucleus
Jets at an EIC

- E665 at FNAL have measured jets in μ+A at $\sqrt{s} \sim 30$ GeV
  - Feasible to start a jet programme in phase 1
  - caveat that collider kinematics are different to fixed target
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1+1 jets, dominated by q processes → allow study of parton propagation through cold nuclear matter
**Jets at an EIC**

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1+1 jets, dominated by $q$ processes $\rightarrow$ allow study of parton propagation through cold nuclear matter

$$\frac{d^2 \sigma_{2+1}}{dx dQ^2} = A_q(x, Q^2)q^A(x, Q^2) + A_g(x, Q^2)g_A(x, Q^2)$$

2+1 jets $\rightarrow$ sensitive to nuclear gluons

By measuring 1+1 jets, can extract information on gluons
Jets at an EIC

1+1 jets, dominated by q processes → allow study of parton propagation through cold nuclear matter

\[ \frac{d^2\sigma_{2+1}}{dx dQ^2} = A_q(x, Q^2)q^A(x, Q^2) + A_g(x, Q^2)g_A(x, Q^2) \]

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By measuring 1+1 jets, can extract information on gluons
b dependent gluons, gluon correlations from DVCS and diffractive vector meson production
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<td>moderate x with light, heavy nuclei</td>
<td>smaller x, saturation</td>
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See talk by Tobias Toll on Thursday afternoon
Summary and Conclusions

- The **e+p physics programme** at an EIC will allow us to study in detail the spin structure of the proton
  - Unprecedented coverage down to small-x, provide constraints on $\Delta g$ and $\Delta q$

- The **e+A physics programme** at an EIC will give us an unprecedented opportunity to study gluons in nuclei
  - Low-x: Measure the properties of gluons where saturation is the dominant governing phenomena
  - Higher-x: Understand how fast partons interact as they traverse nuclear matter and provide new insight into hadronization

- Understanding the role of gluons in nuclei is crucial to understanding RHIC (and LHC) heavy-ion results

**Good headway can be made on these measurements already with a stage-I eRHIC ($E_e = 5$ GeV)**

- The INT programme in the Fall of 2010 allowed us to formulate the observables in terms of golden and silver measurements
  - A detailed write-up of the whole programme (encompassing both e+A and e+p) is now published!!