EIC Science Program
eRHIC

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DIS2017
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Birmingham, UK

Electron Ion Collider – eRHIC

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

2015 NSAC Long Rang Plan

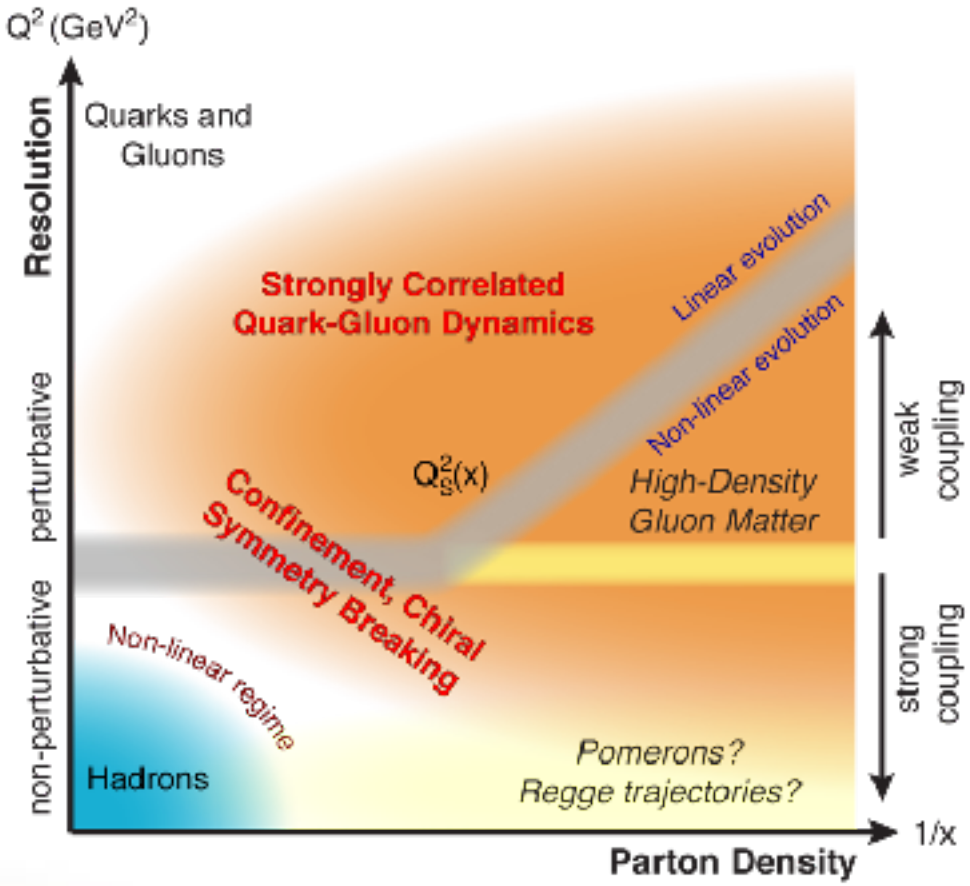
NSAC Long Range Plan (2015)
Recommendation III

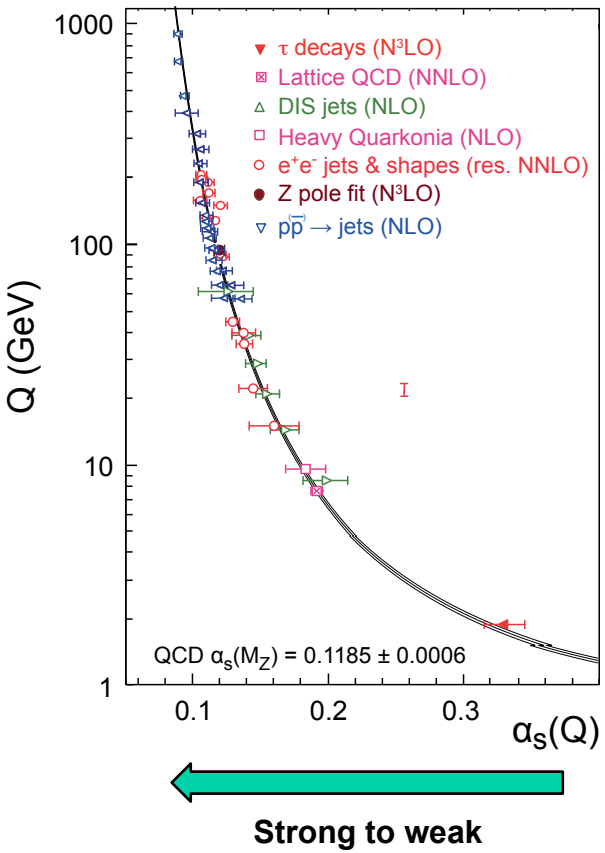
We recommend a high-energy, high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.

National Academy of Sciences Study (2017-18)

The committee will assess the scientific justification for a U.S. domestic electron ion collider facility, taking into account current international plans and existing domestic facility infrastructure. In preparing its report, the committee will address the role that such a facility could play in the future of nuclear physics, considering the field broadly, but placing emphasis on its potential scientific impact on quantum chromodynamics.

The cold QCD matter landscape



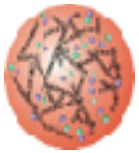


The EIC, with its wide kinematic range, access to polarization and nuclei, will enable the exploration of the full cold QCD matter landscape.

EIC science: energy, polarization, luminosity

Saturation regime

QCD radiation (DGLAP) dominated regime



Few-body/ valence quark regime

x

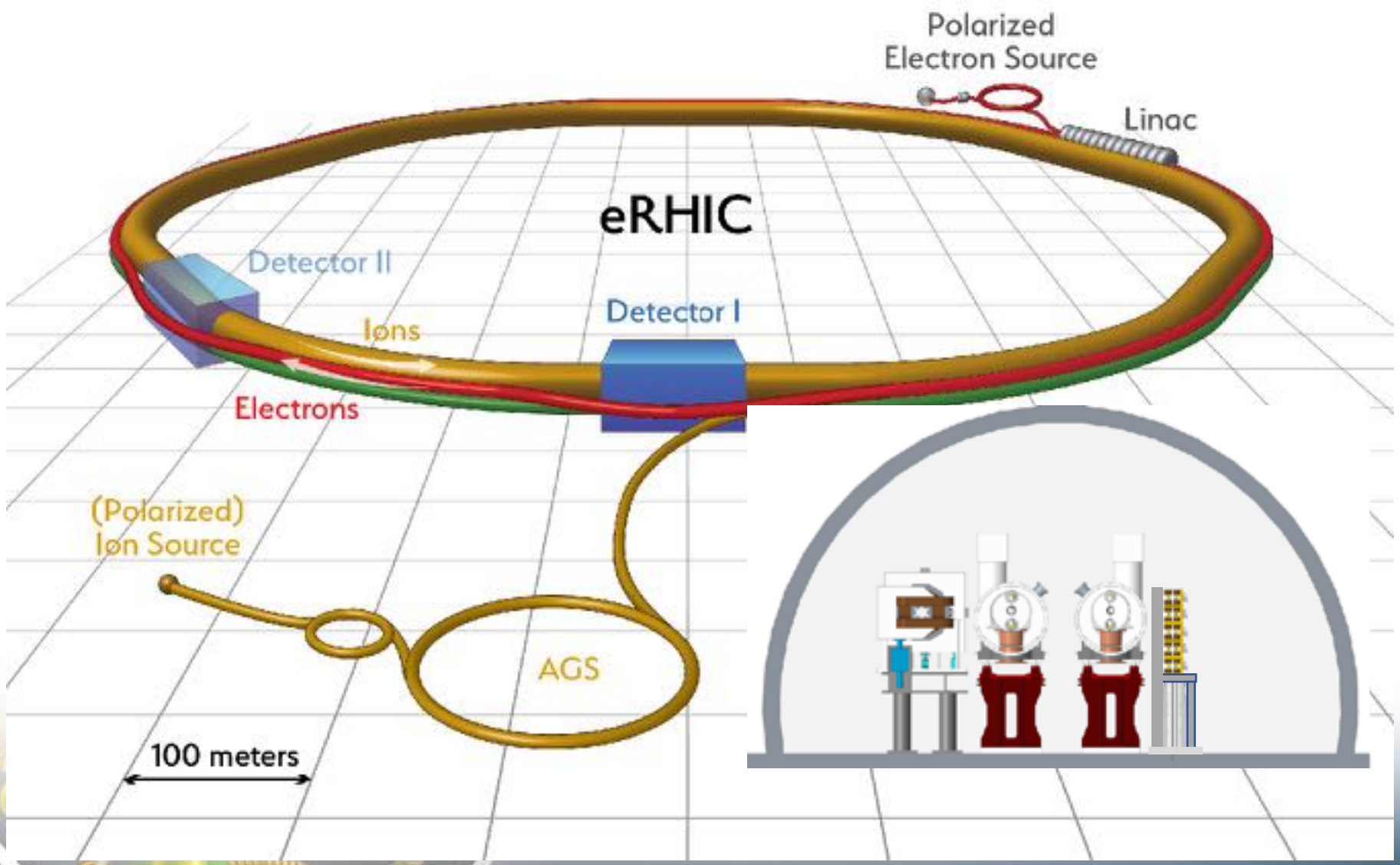
Large center-of-mass coverage:
Access to wide kinematic range in x and Q^2

Polarized electron and hadron beams:
Access to spin structure of nucleons and nuclei
Spin is vehicle to access 3D spatial and momentum structure of the nucleon

Nuclear beams:
Accessing the highest gluon densities

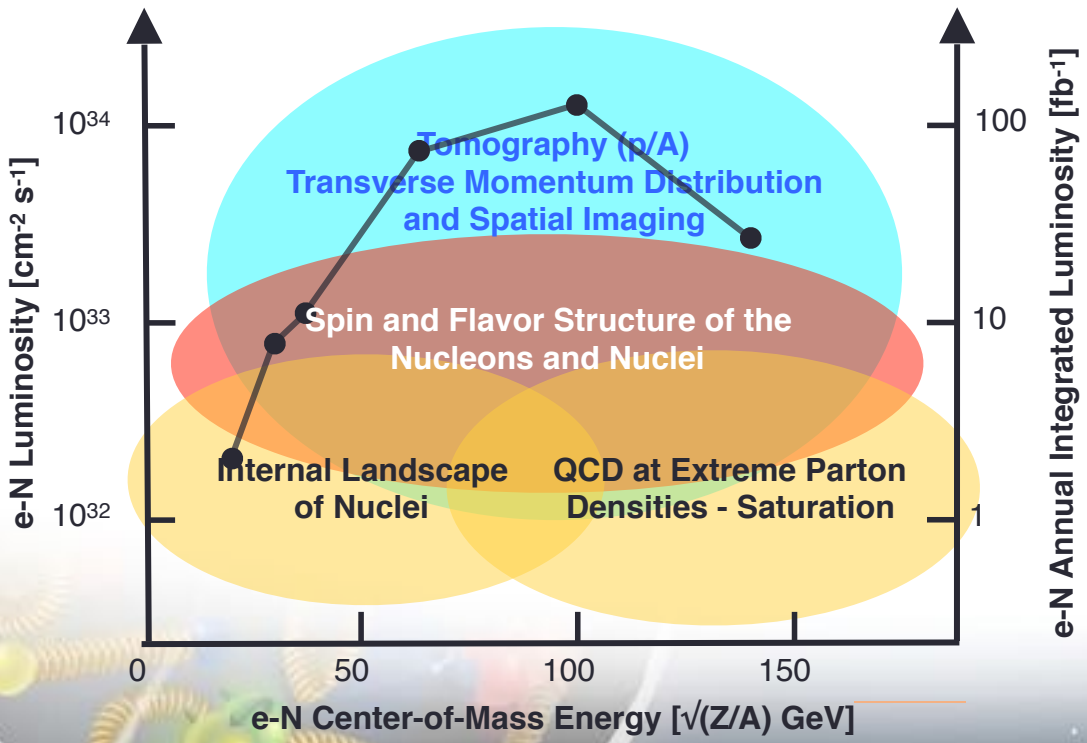
High luminosity:
Essential for mapping 3D structure of nucleons and nuclei and access to rare probes

eRHIC RR Concept



eRHIC Requirements

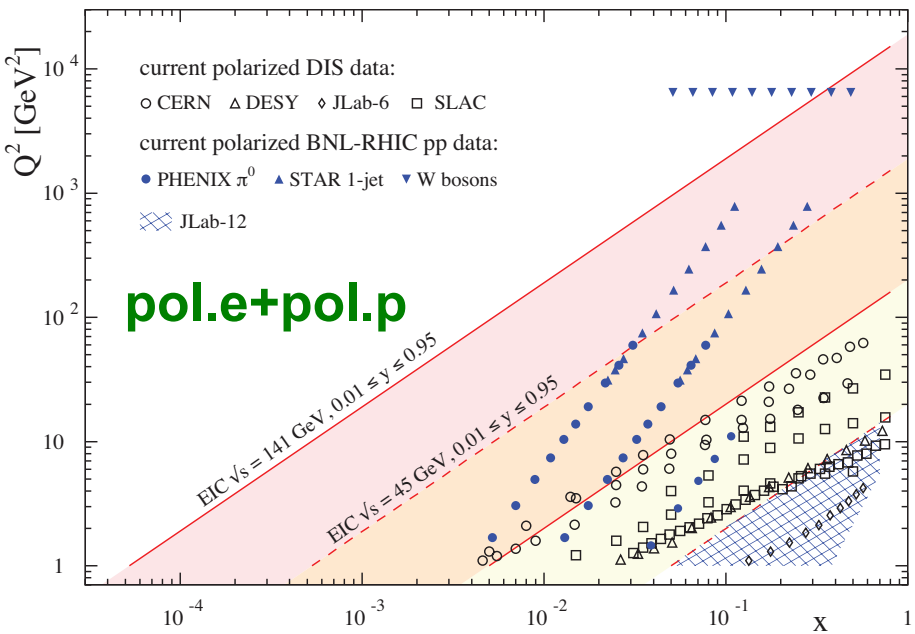
- Large luminosity (< 10^{34} $cm^{-2}s^{-1}$)
- Center of mass energy range (30−140) GeV
- Both hadron and electron beams are highly longitudinally spin polarized
- Large detector acceptance, in particular for small-angle scattered hadrons (optimized *high luminosity* & *high acceptance* running modes)

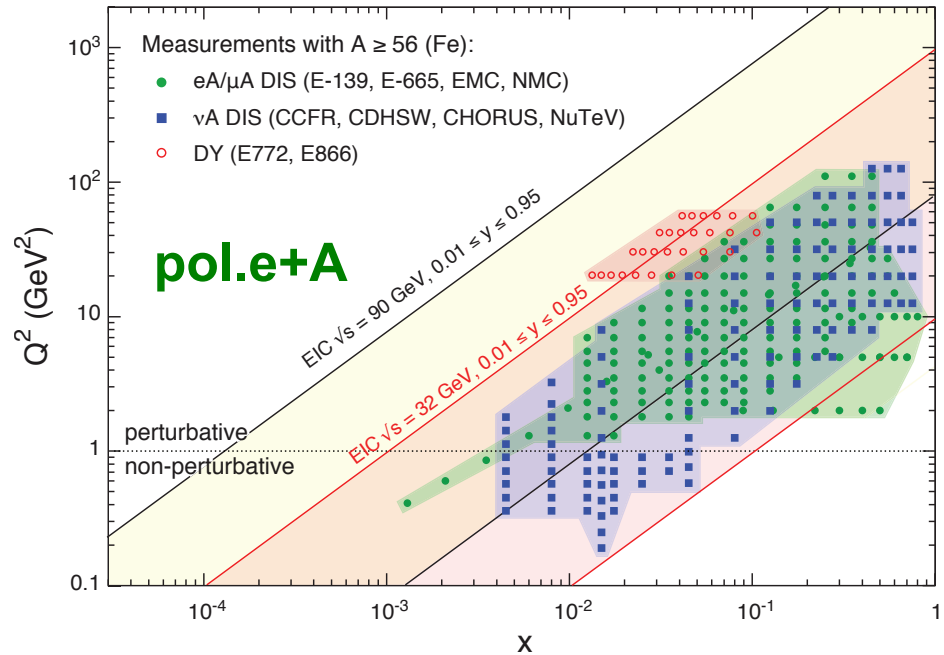


Species for eRHIC Design

		Hadrons (GeV/u)		
		50	100	275
Electrons, GeV	5	p, Au	p, Au	
	7.5	Au		
	10		p	p
	15		Au	
	18	Au	Au	p

eRHIC kinematic reach





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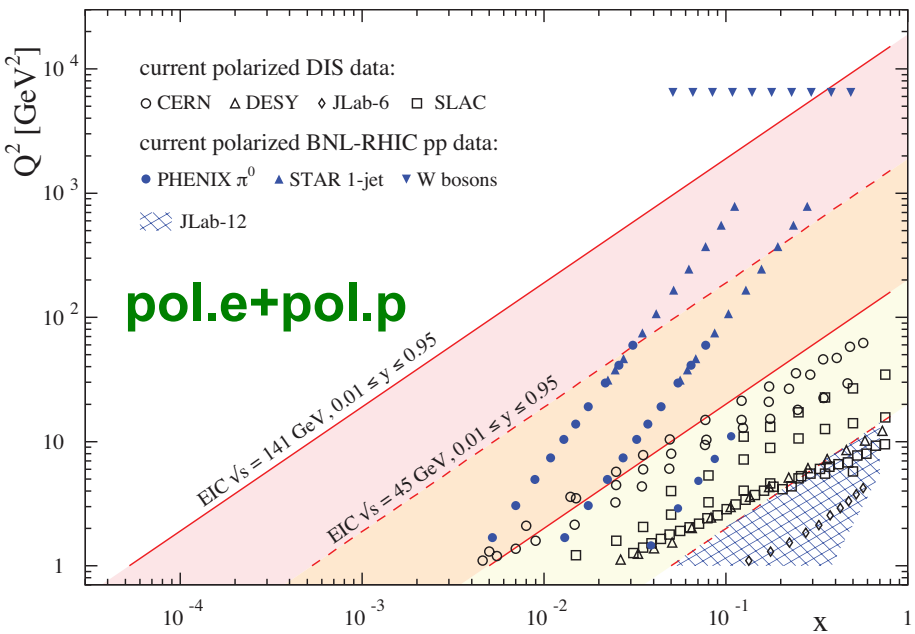
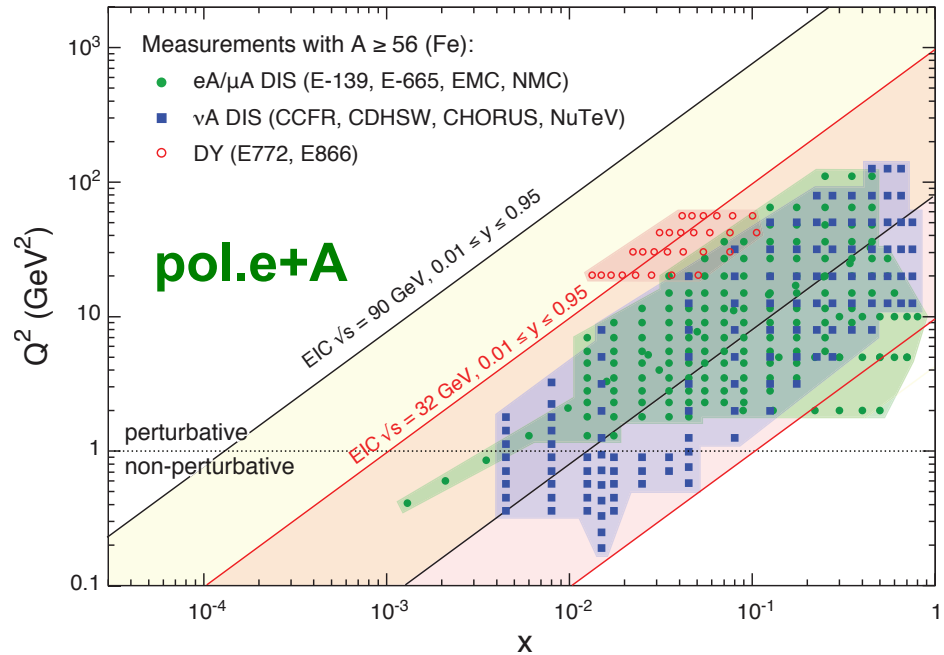
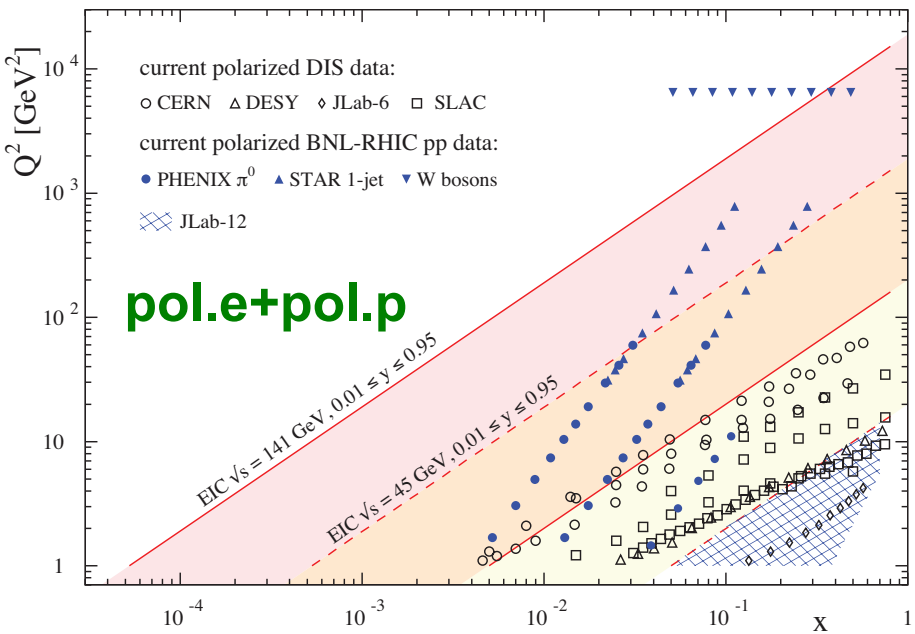


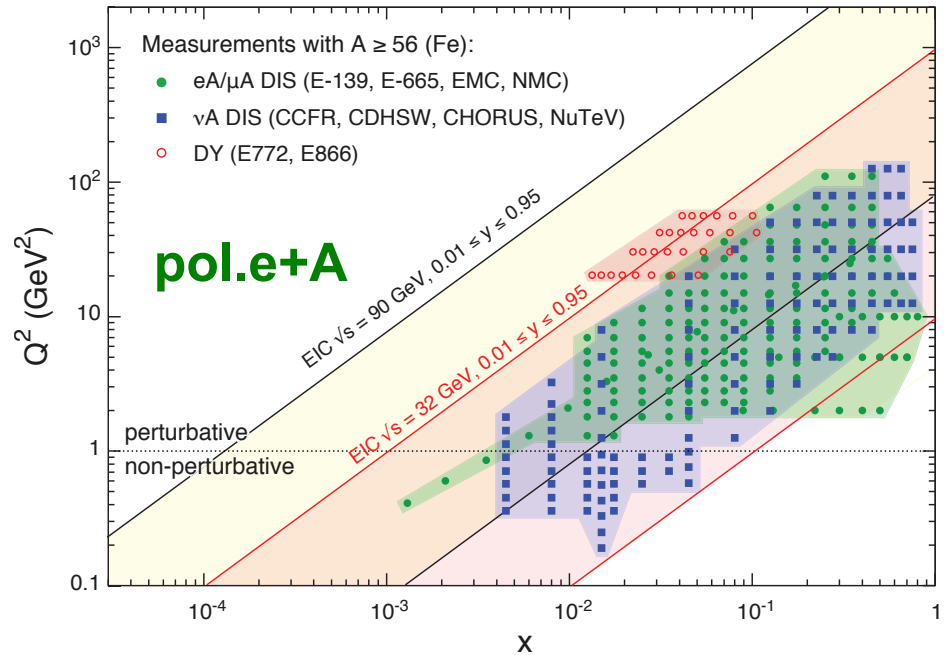


Fundamental questions in ep collisions:

- What is the spin structure of the proton?
- What is the transverse spatial and momentum structure of the proton?
- How does the nonlinear dynamics of QCD manifest itself in proton structure beyond the collinear limit?

eRHIC kinematic reach



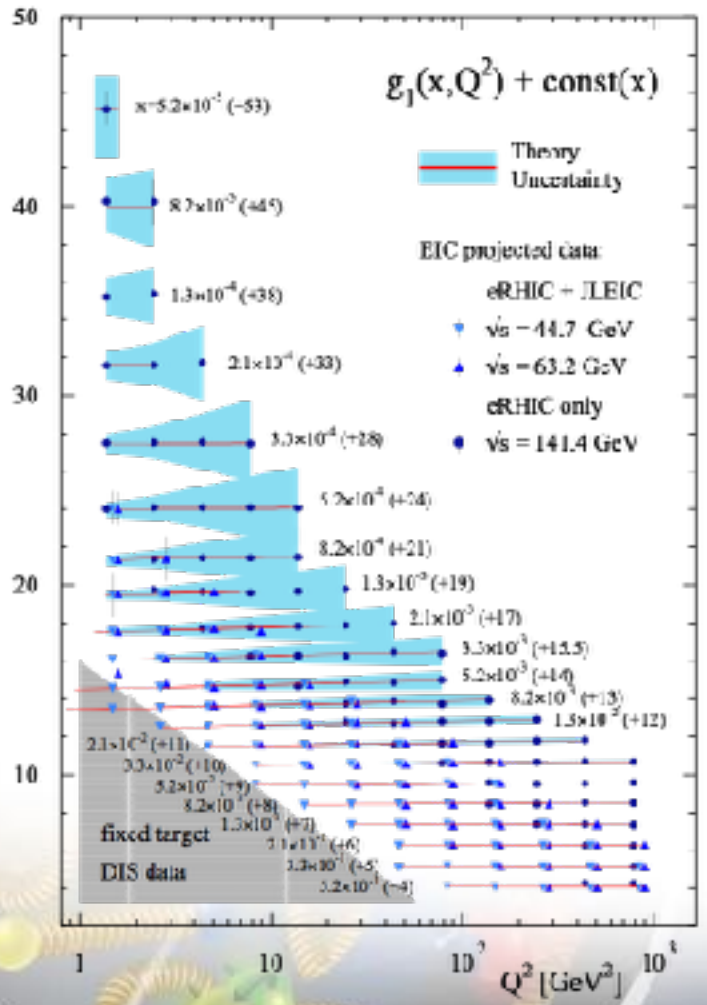


Fundamental questions in e+A collisions:

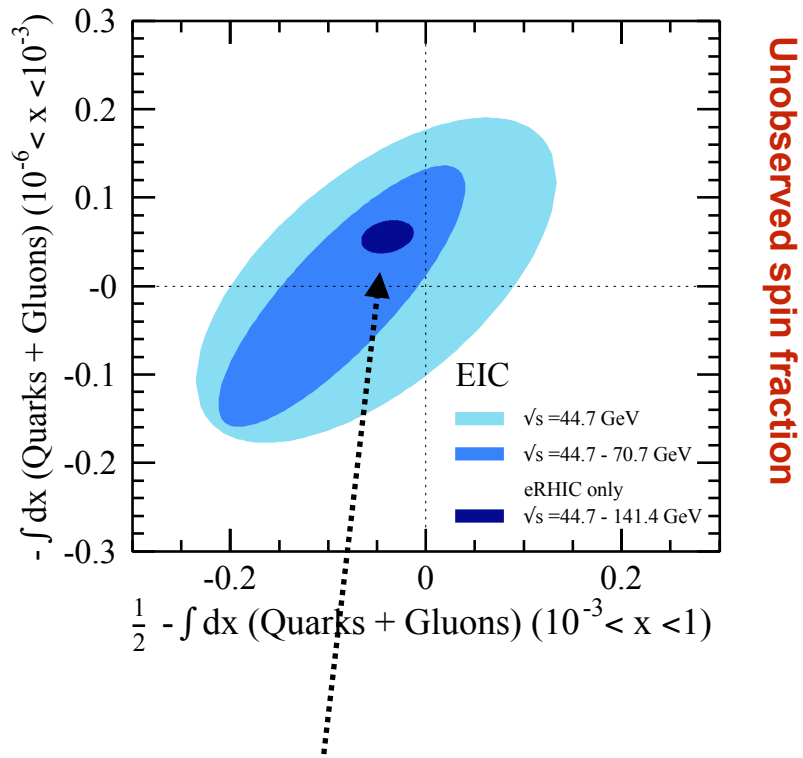
- What is the quark-gluon structure of light and heavy nuclei?
- Can we find and explore a novel universal regime of strongly correlated QCD dynamics? What are the degrees of freedom in this new regime?
- Can the nuclear "color filter" provide novel insight into the propagation, attenuation and hadronization of colored probes?

Spin of the Proton

The polarized PDF $g_1(x,Q^2)$

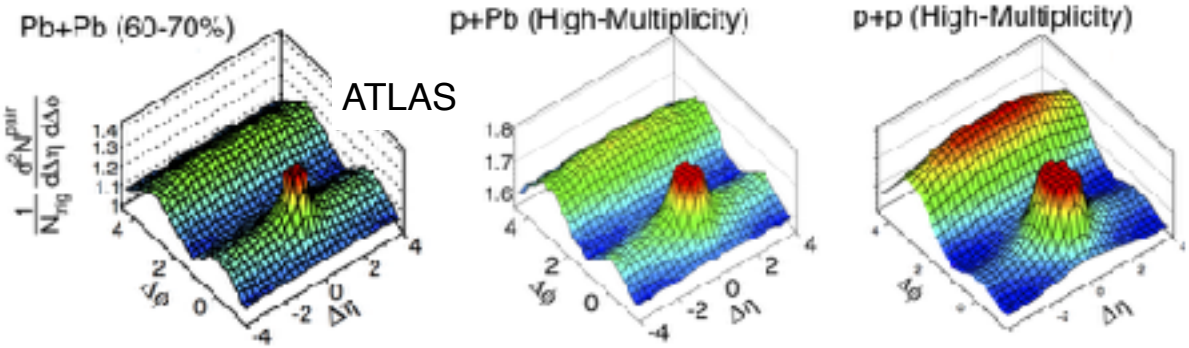


Orbital angular momentum



Full eRHIC CM energy needed to disentangle the different contributions to the proton spin with less than 10% uncertainty ($\Delta J < 0.05\hbar$)

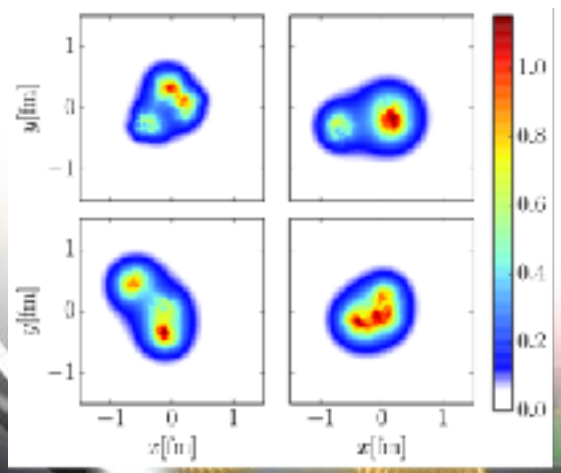
Proton structure in pA and pp



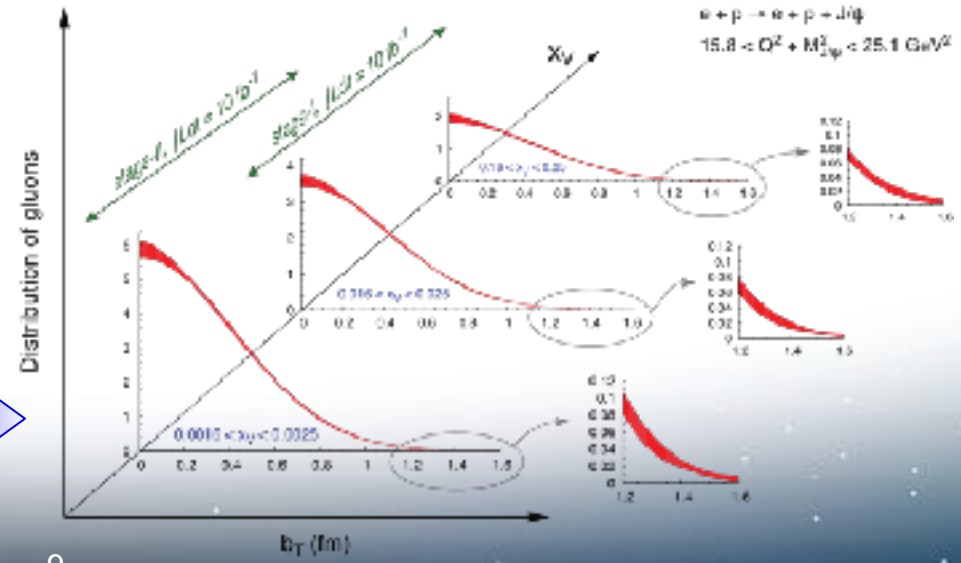
eRHIC will map out the spatial quad and gluon structure of the proton

Shape fluctuations of the proton at x = 10^{-2} – 10^{-3} are essential to explaining the observed collective behavior of pA and pp

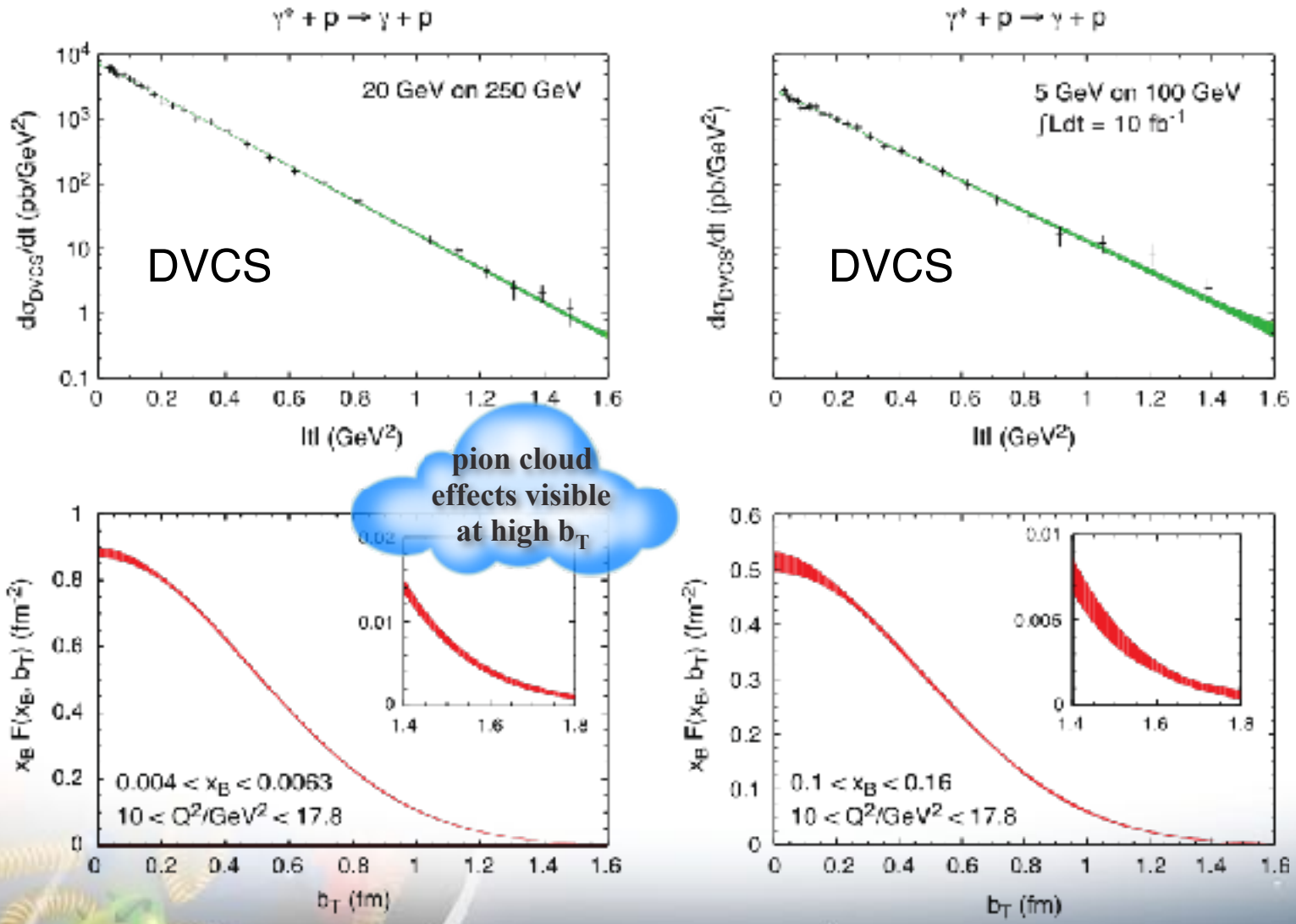
Proton density profiles at x ~ 10^{-3}



Coherent and incoherent J/Ψ production



2+1d-Imaging in coordinate space



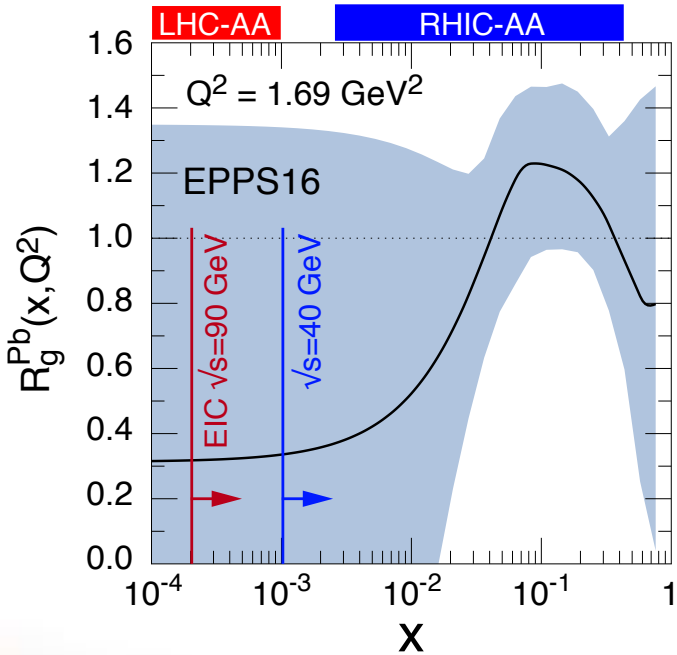
High precision imaging of proton at eRHIC at low and high x

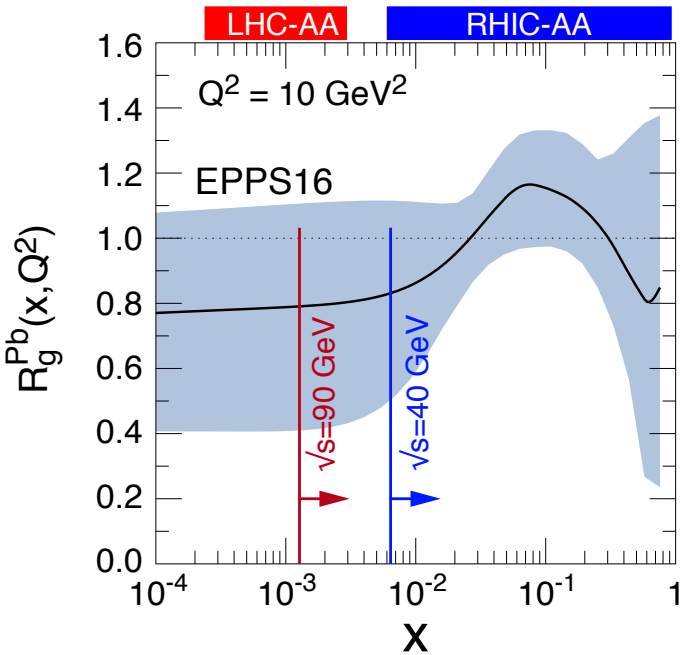
Nuclear Structure Functions

Inclusive DIS on eA: $$\frac{d^2\sigma^{eA\to eX}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

quark+anti-quark

gluon

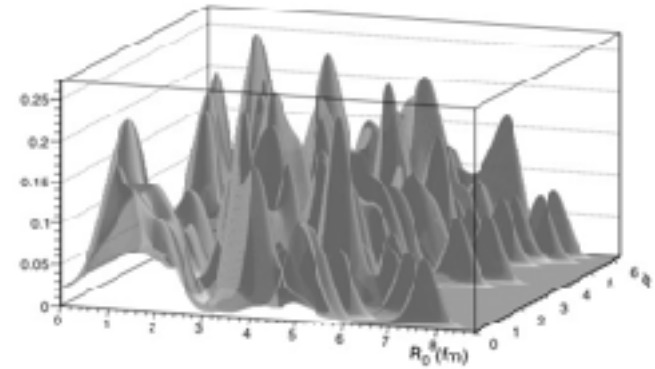




Full eRHIC energy required to constrain nPDFs for the A+A and p+A programs at LHC

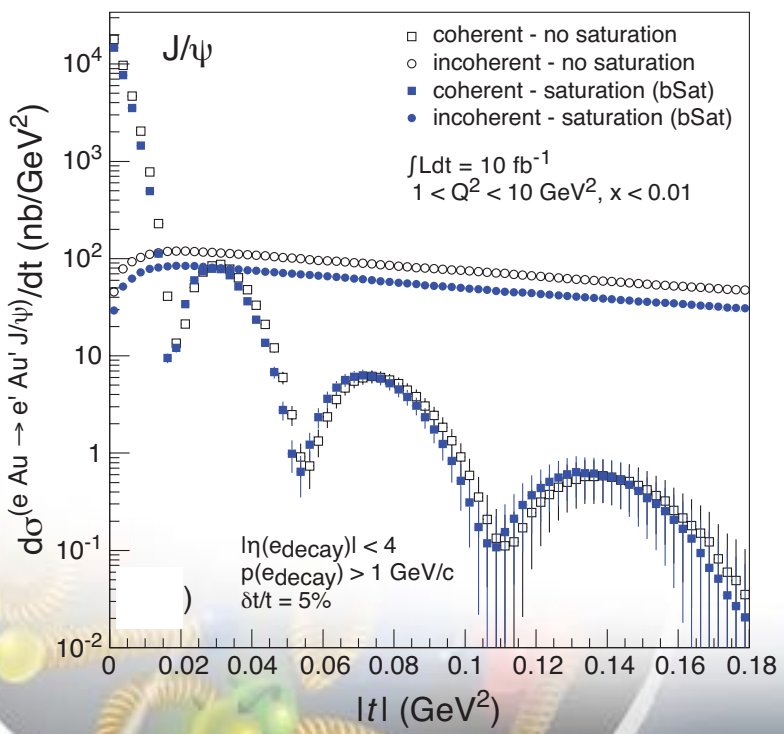
Imaging of Nuclei

Possible Source distribution



Diffractive vector meson production

- coherent part ⇒ average shape
- incoherent part ⇒ variance/lumpiness
  - probes fluctuations at scale ~1/t



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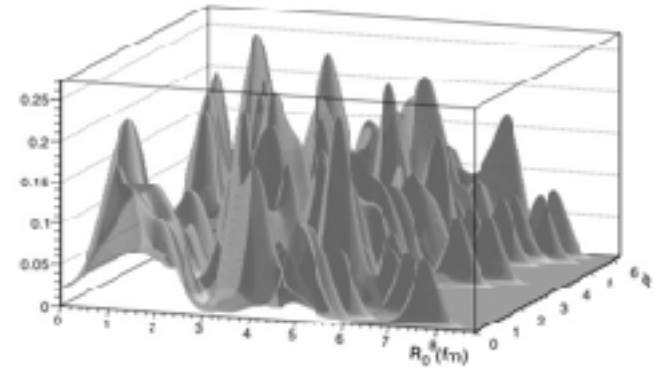

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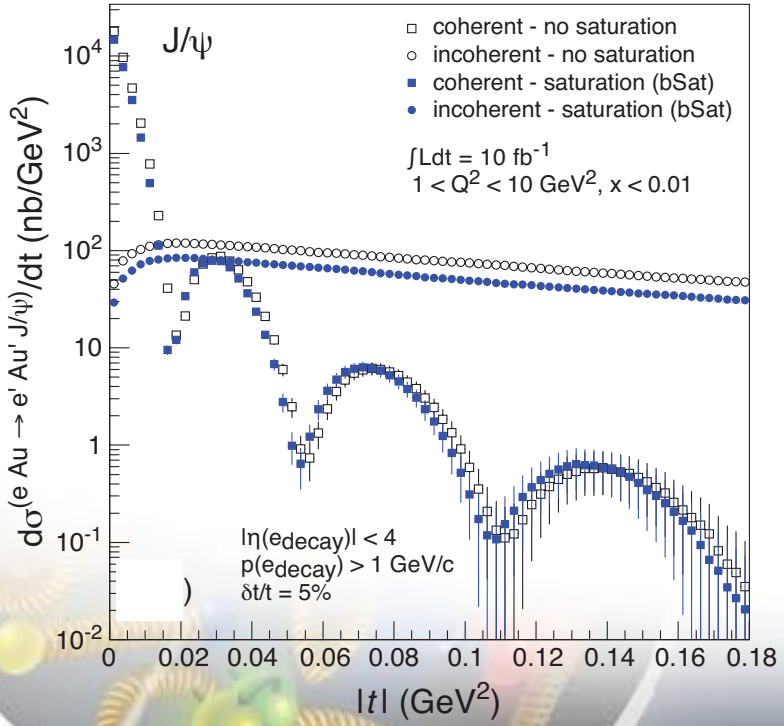
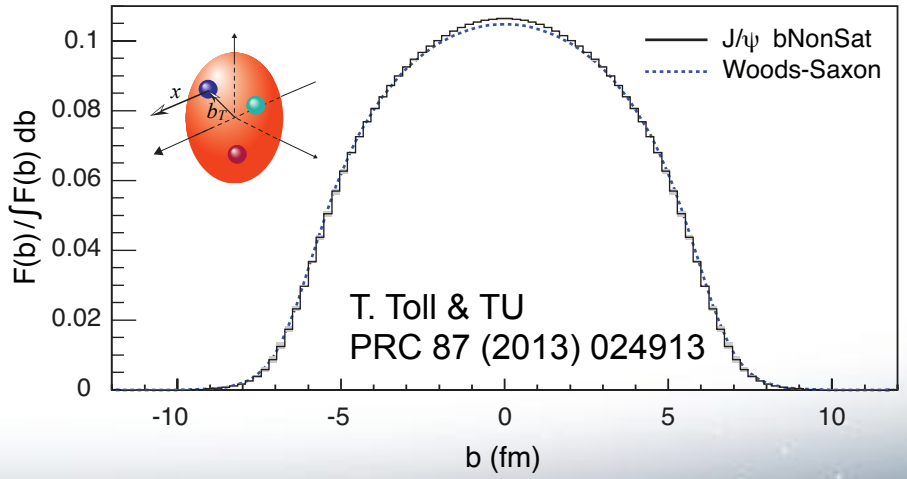


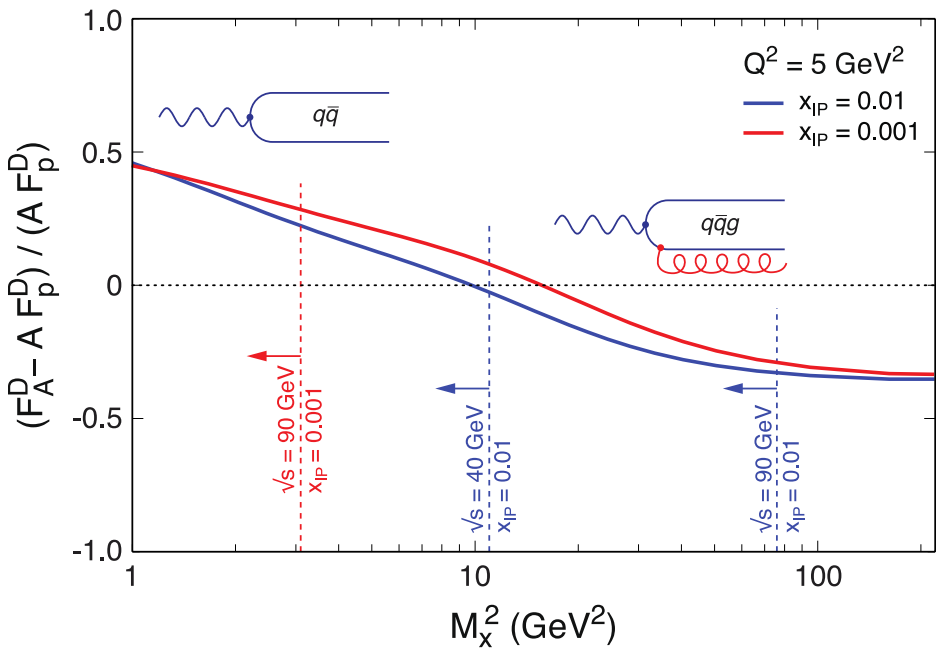
Fourier Transform



Recover chosen input distribution

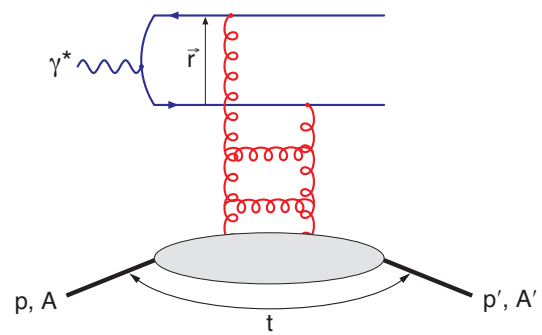
Saturation and nuclear opacity

Sign Change in $\sigma_{diff}/\sigma_{total}$:

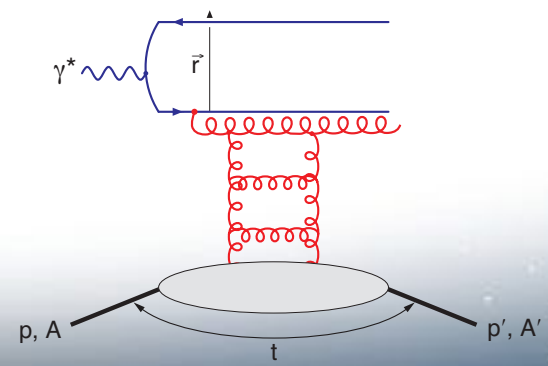


Observing the dependence on M_x over a wide range in x and Q^2 is crucial: Sufficient $\sqrt{s}$ range is key.

Nucleus is "blacker" than proton. Elastic scattering probability of a $q\bar{q}$ dipole is maximal in the "black" limit



$q\bar{q}g$ component vanishes in black disk limit



Jets

Jets have been shown to be a “golden tool” for the study of quarks and gluons in pp, pA and AA. This extends to ep and eA.

Jet Physics in ep:

- **Diffractive di-jets offer opportunity to access Wigner functions in QCD**
- **Precise measurement of high x unpolarized gluon distribution functions can have impact on high Mass BSM searches at the LHC**
- **Alternative measurement of polarized gluon distribution function**
- **Precision measurement of polarized and unpolarized hadronic photon structure**

Jet Physics in eA:

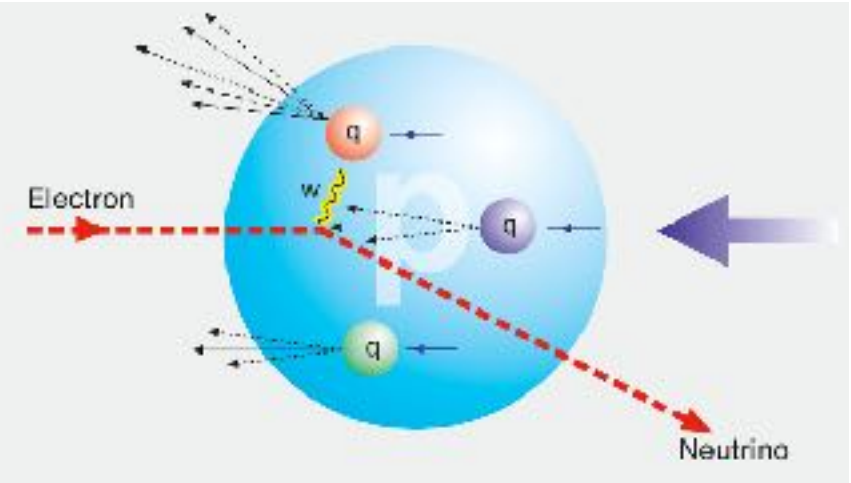
- **Unique opportunity to study jet propagation in cold dense QCD matter**
  - **Jet/Hadron production and attenuation in semi−inclusive DIS will shed light on the process of hadronization**
- **Event shape observables for precise extraction of α_s**
- **Jet substructure observables will provide a detailed picture of in-medium parton shower (longitudinal and transverse) evolution**

Charged Current in ep and eA

eRHIC will provide access to charged current physics in polarized ep and eA

W-exchange uniquely discriminates quark flavors (u/d)

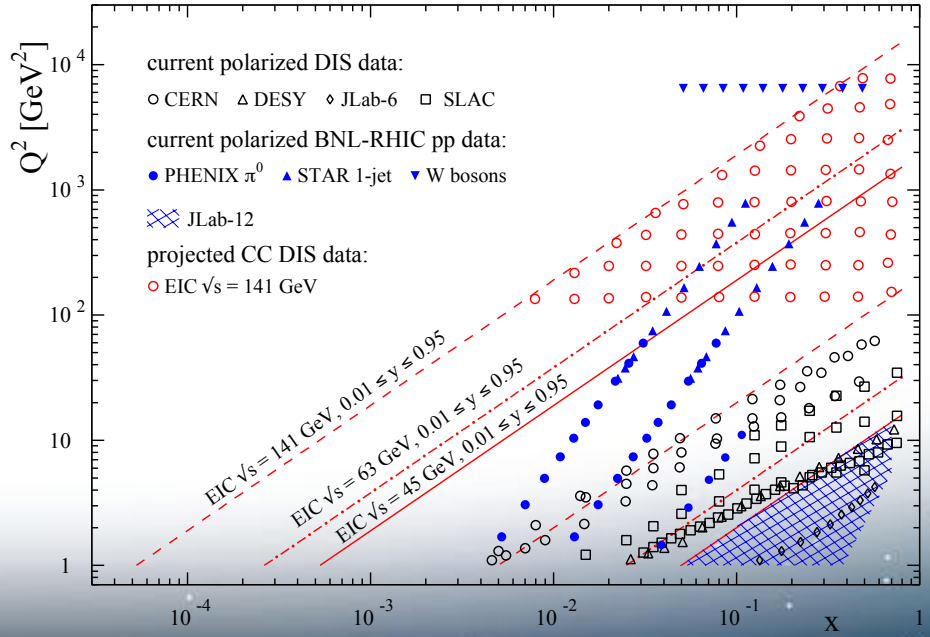
W-exchange is maximally parity violating and couples only to one parton helicity



Complementary to SIDIS:

- High Q^2-scale: > 100 GeV^2
- Extremely clean theoretically
- No Fragmentation function

→ stringent test on theory approach



Physics opportunities:

Polarized ep / en:

- Test helicity retention models

Unpolarized eA:

- Test models of the EMC effect

eRHIC Deliverables: The first 4 years

….making “reasonable” luminosity growth assumptions

Year 1 and 2: eAu at full energy

$\int L$ ~1.2 fb^{-1} will give the first results in completely unknown territory

- Nuclear PDFs
- First look to saturation through di-hadrons and diffraction

Year 3: Longitudinal polarized ep beams at full energy

$\int L$ ~2.6 fb^{-1} will give very important results on

- Definitive spin structure of the proton
- Unpolarized PDFs at large Q^2 and x
- (Un-)polarized fragmentation functions

Year 4: Split the run between transverse polarized ep running at full energy and eA running for different nuclear beams and energies

$\int L$ ~5 fb^{-1} transverse polarized ep data will give very important

- First results on the momentum and spatial 3d structure of the proton

$\int L$ ~5 fb^{-1} eA data with different nuclei and energies will

- Measure nuclear PDFs
- Study the evolution of Q_s with x and A

Summary & Outlook

eRHIC energy and luminosity range would enable a robust physics program that promises to

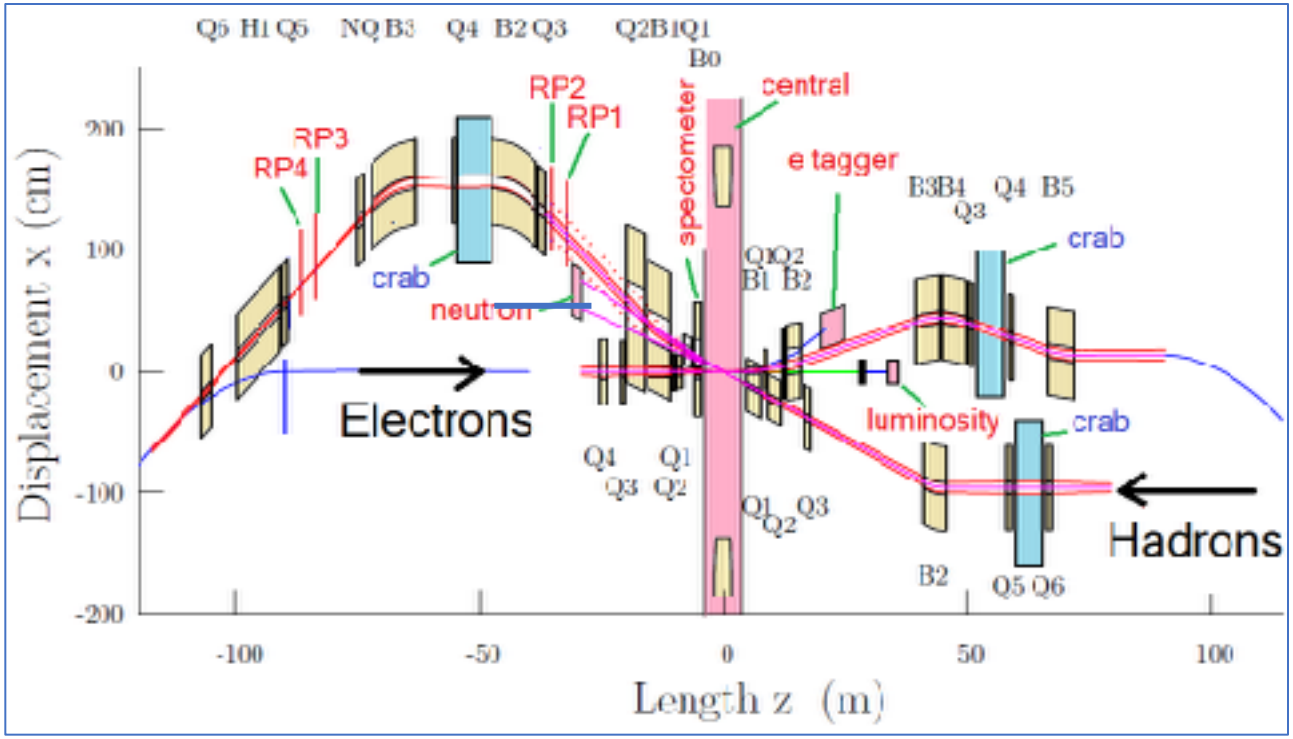
- **fully access the sea-quark and gluon dominated regime**
- **reveal the dynamics of sea quarks and gluons in hadrons**
- **open up the phase space for new probes of nucleon / nuclear structure (jets, charge current, etc.)**

Several additional observables that benefit from the full eRHIC energy range are currently under study. Examples are:

- **Polarized and unpolarized hadronic photon structure & photon PDFs**
- **High precision PDFs at high x and high Q^2 will reduce the uncertainties from QCD background in high mass searches at the LHC**
- **Diffractive di-jets to directly constrain Wigner functions**
- **Possible symmetry violations in deep inelastic scattering**
- **…….**


return
backup

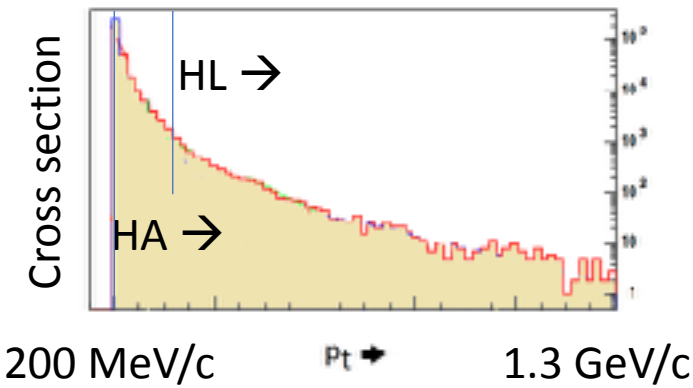
Interaction Region Layout



- Interleaved arrangement of electron and hadron quadrupoles
- 22 mrad total crossing angle, using crab cavities
- Beam size in crab cavity region independent of energy – crab cavity apertures can be rather small, thus allowing for higher frequency
- Forward spectrometer (B0) and Roman Pots (R1-R4) for full acceptance

IR Design Related Issues under Development

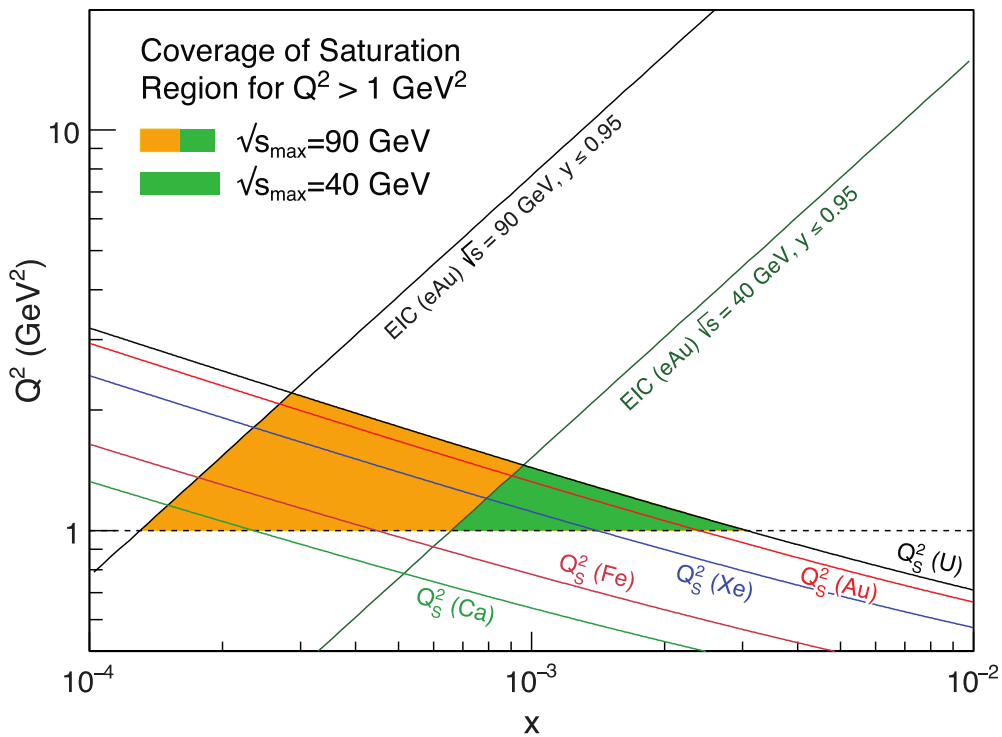
IR layout and achievable betas and corresponding p_t acceptance is work in progress



- *Extreme values of p_t of 0.2,1.3 GeV are inside of beam envelope for highest luminosity*
- *However, cross sections a low p_t are very large, so that a limited time (~20%) running at a high acceptance optics (larger beta) with reduced luminosity provides sufficient experimental data*

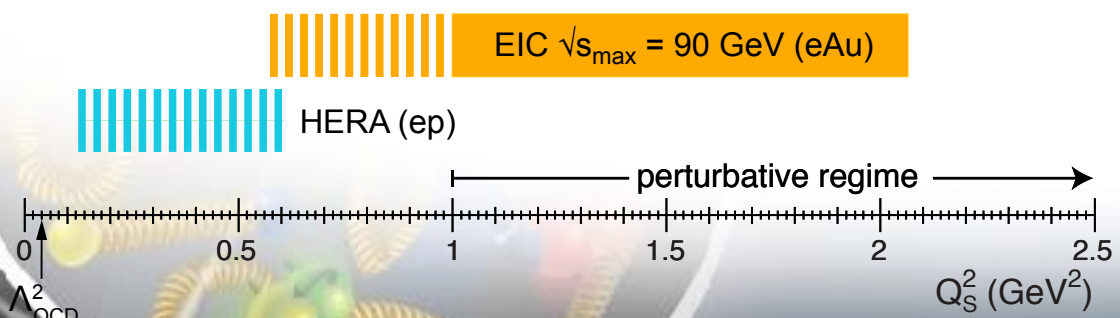
- Close to L = 10^{34} $cm^{-2}s^{-1}$ solution without active cooling
- Beam optics with lower luminosity and larger p_t acceptance to capture protons with p_t as small as 200 MeV (need to run only 10% of the time)
- Solution for chromatic corrections including 2nd order tune shifts and acceptable dynamic aperture is yet to be designed
- Need to develop a lattice adequate for electrons

Gluon Saturation: √s and A Matter

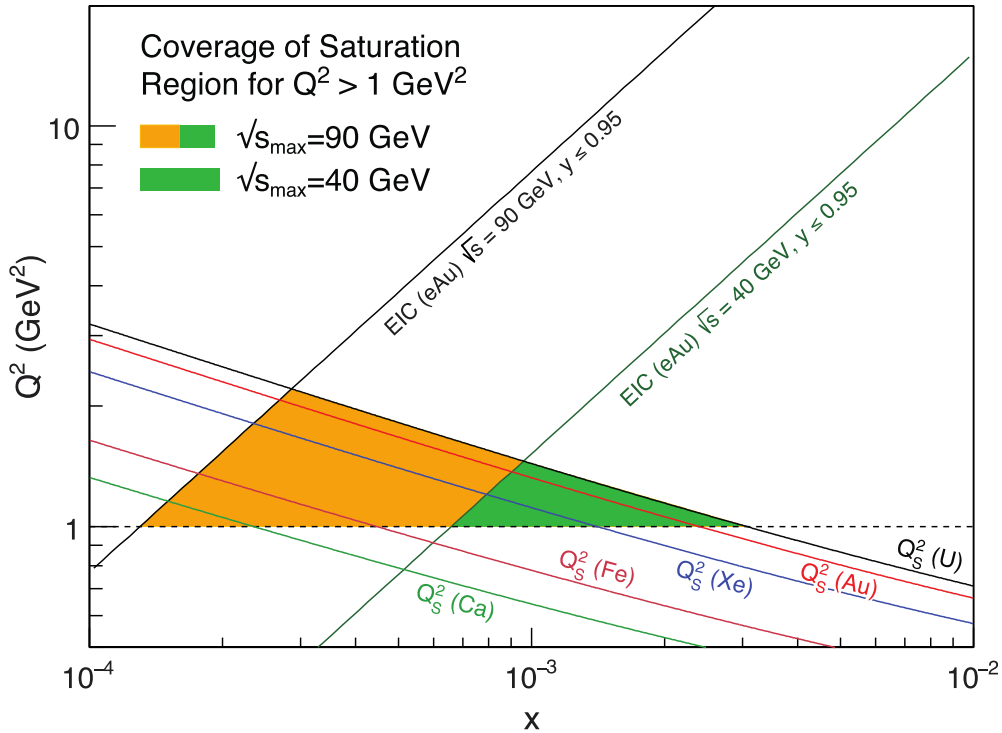


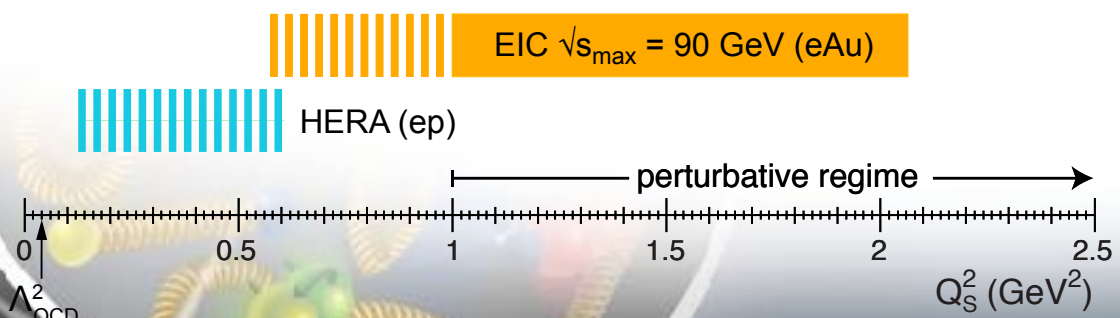
eA at EIC:

- Need to push into regime where comparison with our current understanding can be made ⇒ $Q^2 > 1$ GeV/c^2
- Require sufficient lever arm in *Q*, *x* to study evolution
- CGC predicts characteristic *A* dependence ⇒ requires large *A* lever arm



Gluon Saturation: √s and A Matter





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- Need to push for highest energy and heaviest ions

eRHIC luminosity evolution

We assume the following machine ramp-up in luminosity for the first 4 years of EIC, further both beams can be polarized from the start, and nuclear beams are available, as well as eRHIC can reach its highest √s

year	L_{Av} ($10^{33}cm^{-2}s^{-1}$)	∫L/year (fb^{-1})
1	0.1	0.2
2	0.3	1.1
3	0.6	2.6
4	1.8	11.3
5	6.5	46.3 (with cooling)

Need to correlate key EIC physics topics to machine luminosity growth