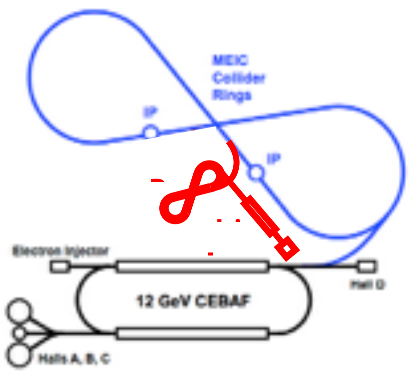
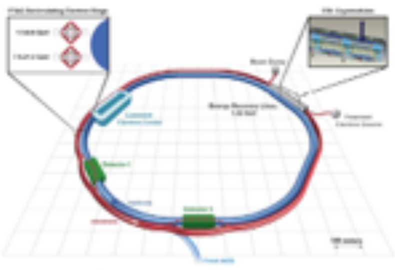
Jefferson Lab

BROOKHAVEN NATIONAL LABORATORY

Electron-Ion Collider at Jefferson / Brookhaven Lab: new opportunities for the UK





Daria Sokhan

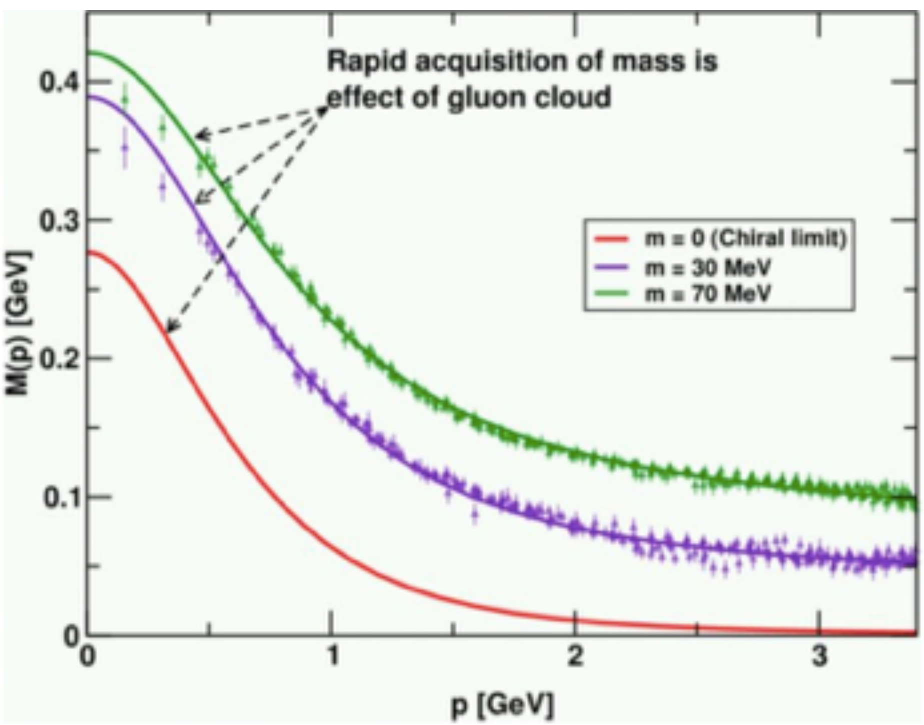
University of Glasgow

IoP Particle Accelerator and Beams Group Conference
8th April 2016 — Huddersfield, UK.

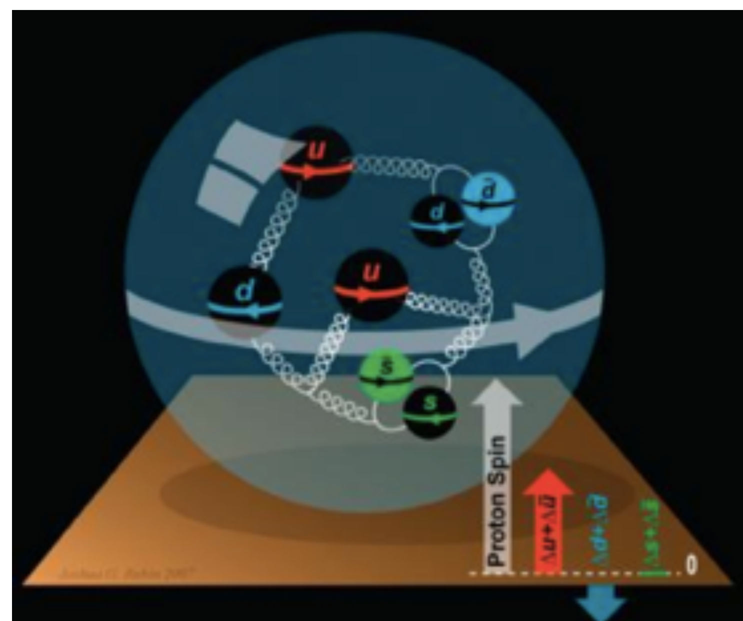
Main problems of hadron physics

- Can we understand the properties of nucleons, nuclei and the strong interaction from fundamental principles?

- How is the mass of the hadron generated from the bare masses of quarks?



- What is the composition of nucleon spin?



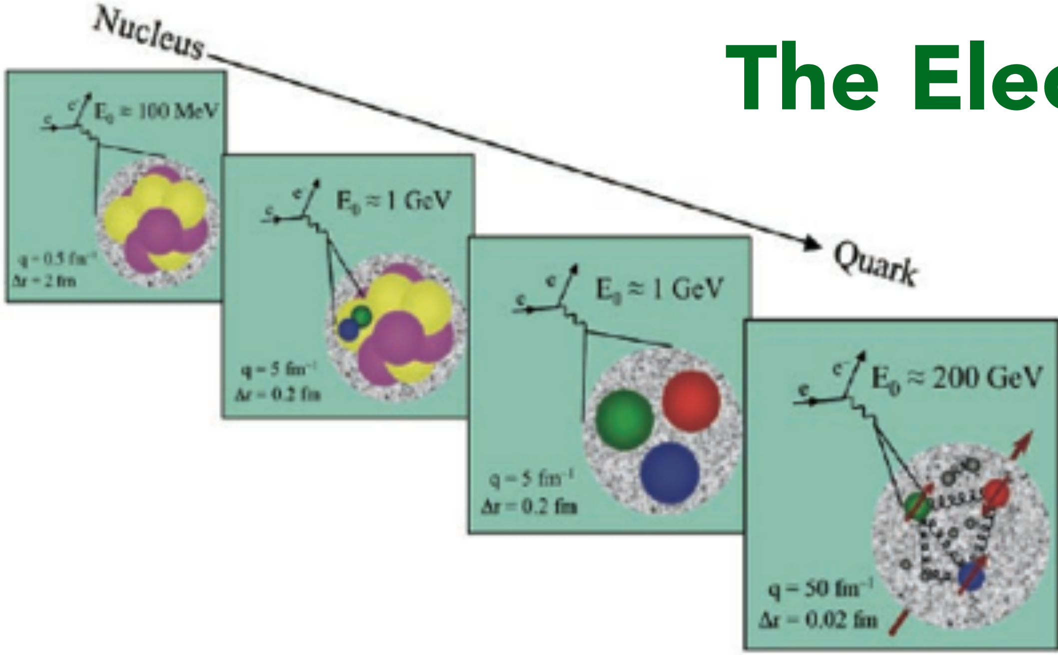
The burning questions of tomorrow

(if you're a hadron physicist, that is...)

- How are the **sea quarks and gluons**, and their spins, distributed in space and momentum inside the **nucleon**?
- How does the **nuclear environment** affect the distributions of quarks and gluons and their interactions? QCD molecules.
- Where does the **saturation of gluon densities** set in? Boundary between dilute quark-gluon matter and dense soft glue.
- How does **colour charge propagate** in nuclear matter? What are the differences for light and heavy quarks?

Electron-Ion Collider

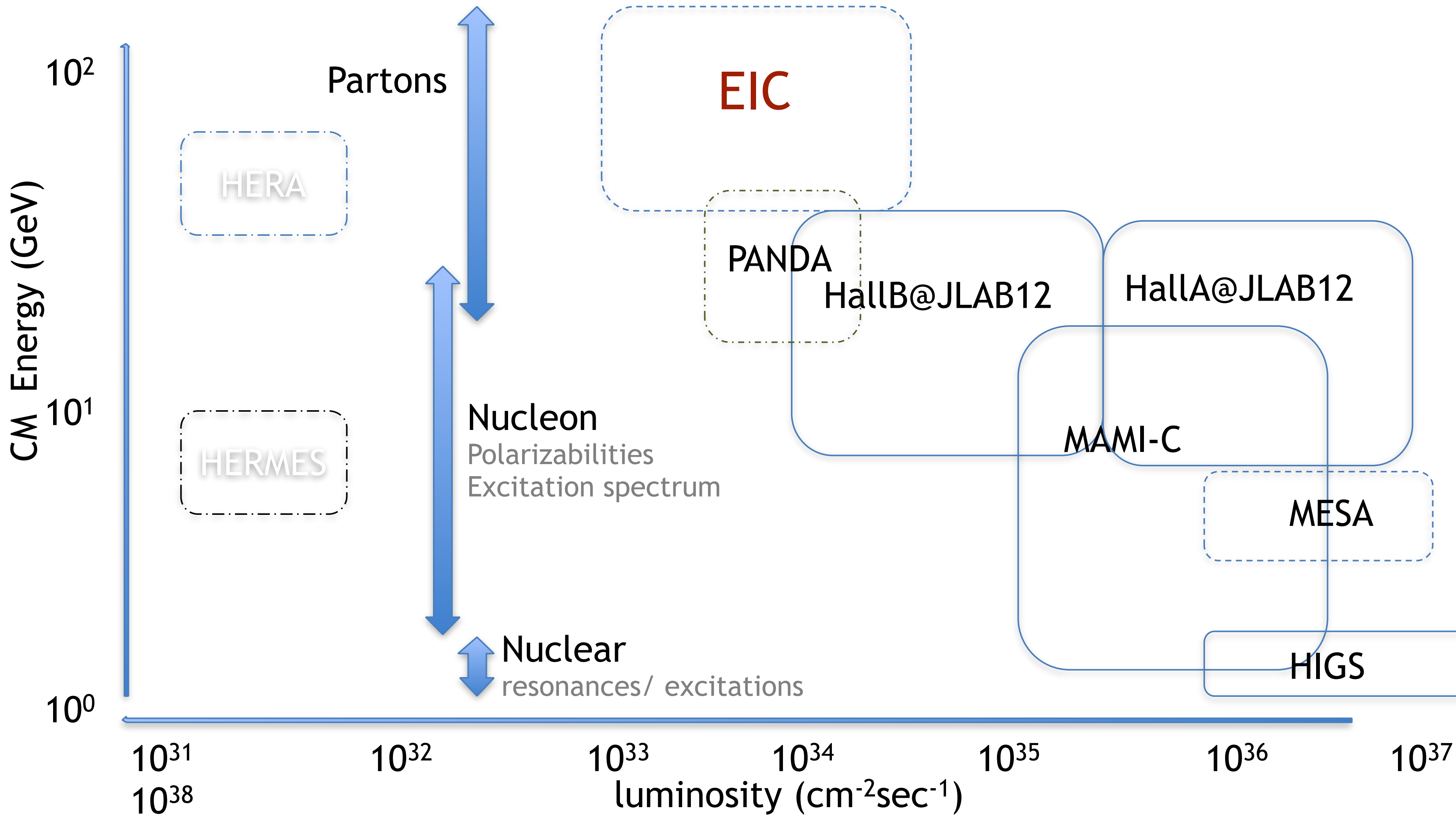
The Electron-Ion Collider



- ***2007 Nuclear Physics Long Range Plan**: "The EIC is embodying the vision of reaching the next QCD frontier"*
- ***2015 Nuclear Physics Long Range Plan**:"high-energy, high-luminosity polarised EIC as the highest priority for new facility construction following completion of FRIB"*

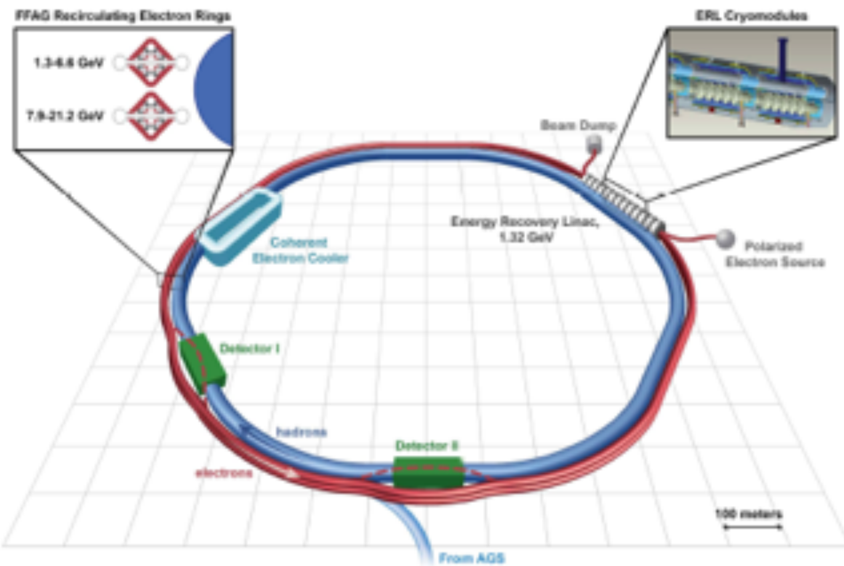
- Well-understood EM probe: polarised ep and eA collider.
- Polarised hadron beams for spin correlations.
- Full range of (stable) ion species (nuclear matter scaling), coherent contributions from many nucleons amplify gluon density.
- Wide range of centre of mass energy: 20 GeV - 140 GeV
- High luminosity (10^{33} - 10^{34} cm^{-2} s^{-1}): intensity frontier.
- High resolution, high acceptance, hermetic detector systems.

Hadron Physics facilities



Plus others without much UK involvement to date e.g. J-PARC

EIC: a tale of two labs

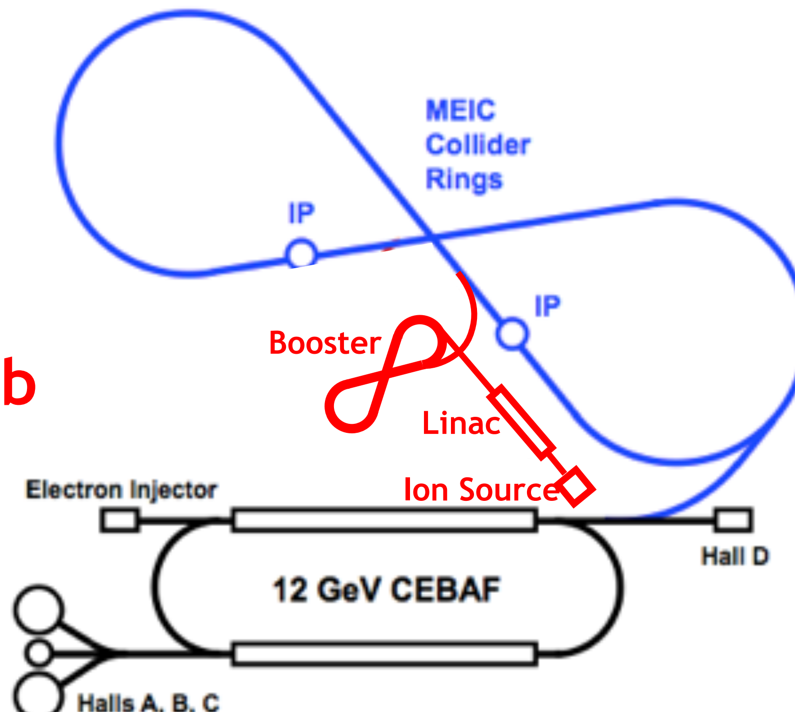


eRHIC at Brookhaven National Lab

arXiv:1409.1633

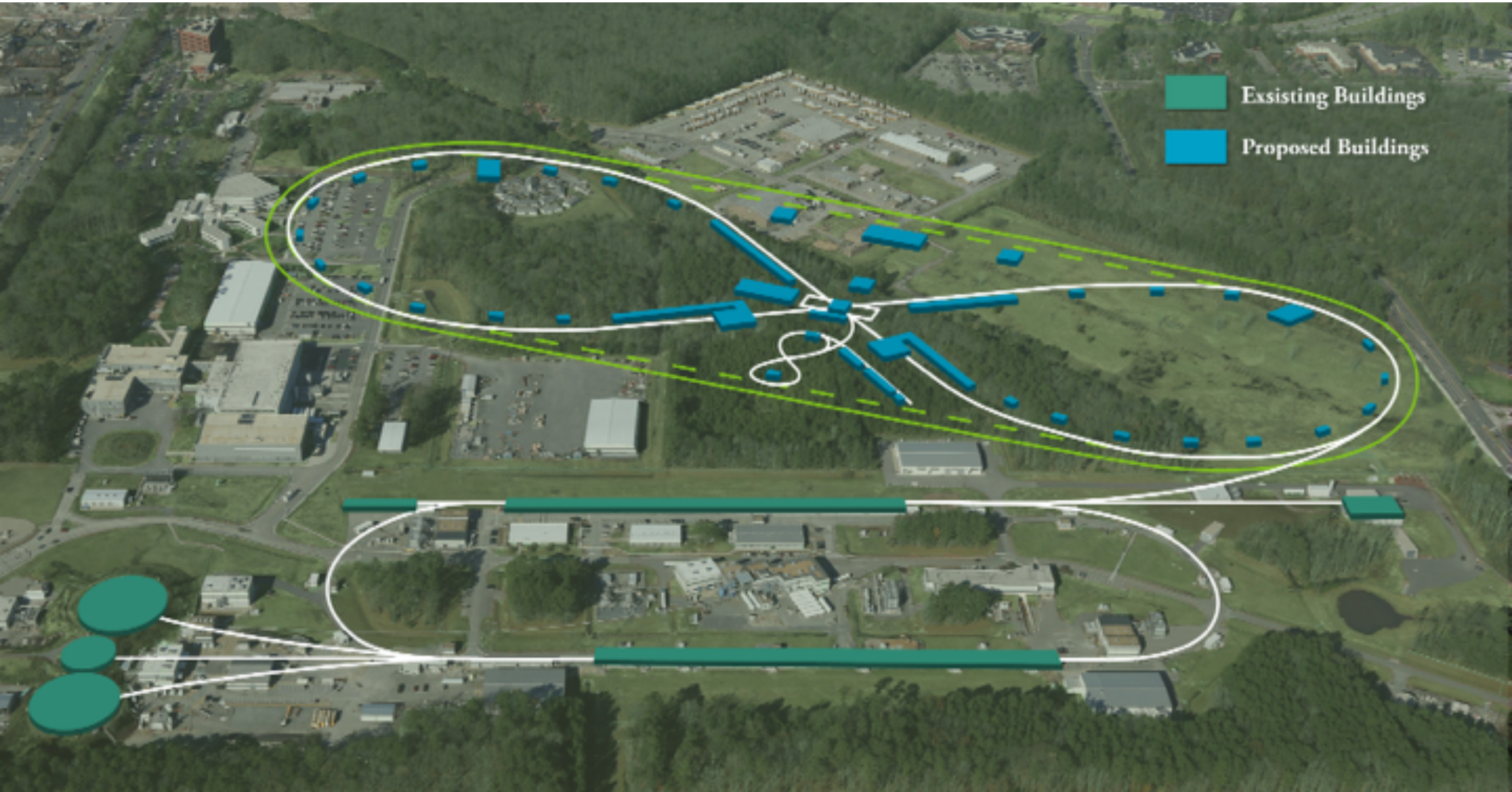
JLEIC at Jefferson Lab

arXiv:1504.07961



JLEIC: the Jefferson Lab EIC

- Use the existing accelerator (Continuous wave Electron Beam Accelerator Facility, CEBAF) as a source of high energy, highly-polarised electron beam.
- Add figure-of-8 collider rings for the electron and ion beams:



JLEIC Design Goals

Energy

Full coverage of CM energy from **15** to **65** GeV

Electrons **3-10** GeV, protons **20-100** GeV, ions **12-40** GeV/u

Ion species

Polarized light ions: **p**, **d**, **^{3}He**, and possibly **Li**

Un-polarized light to heavy ions up to A above 200 (Au, Pb)

Support 2 detectors

Full acceptance capability is critical for the primary detector

Luminosity

10^{33} to 10^{34} $cm^{-2}s^{-1}$ per IP in a *broad* CM energy range

Polarization

At IP: longitudinal for both beams, transverse for ions only

All polarizations >70%

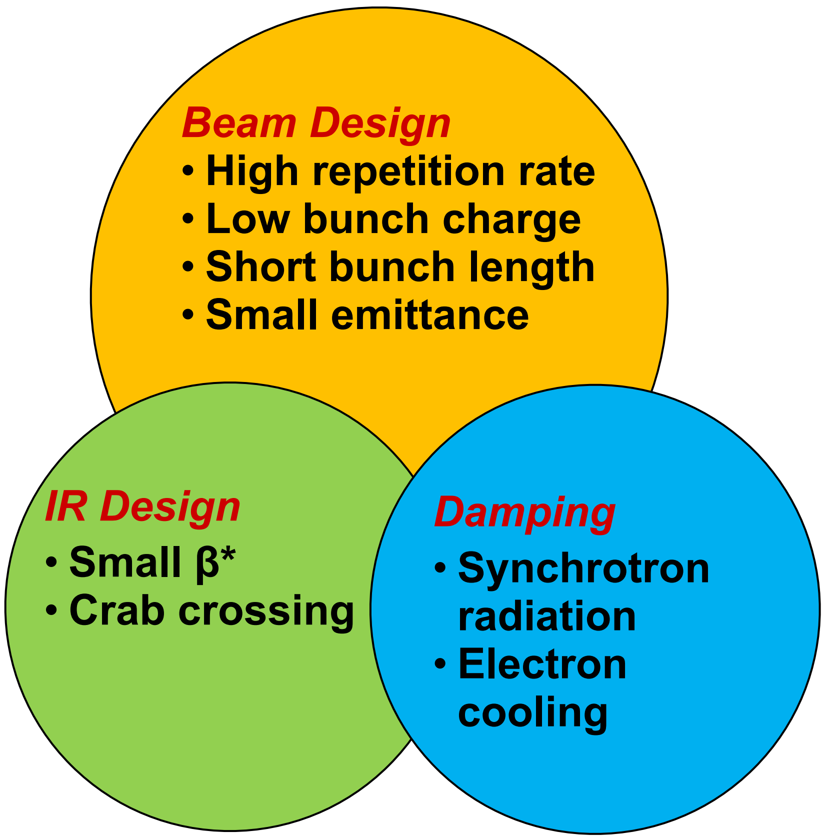
Upgrade to higher energies and luminosity possible

20 GeV electron, **250 GeV** proton, and **100 GeV/u** ion

High luminosity, high polarisation

- High luminosity through high bunch repetition rate CW colliding beams

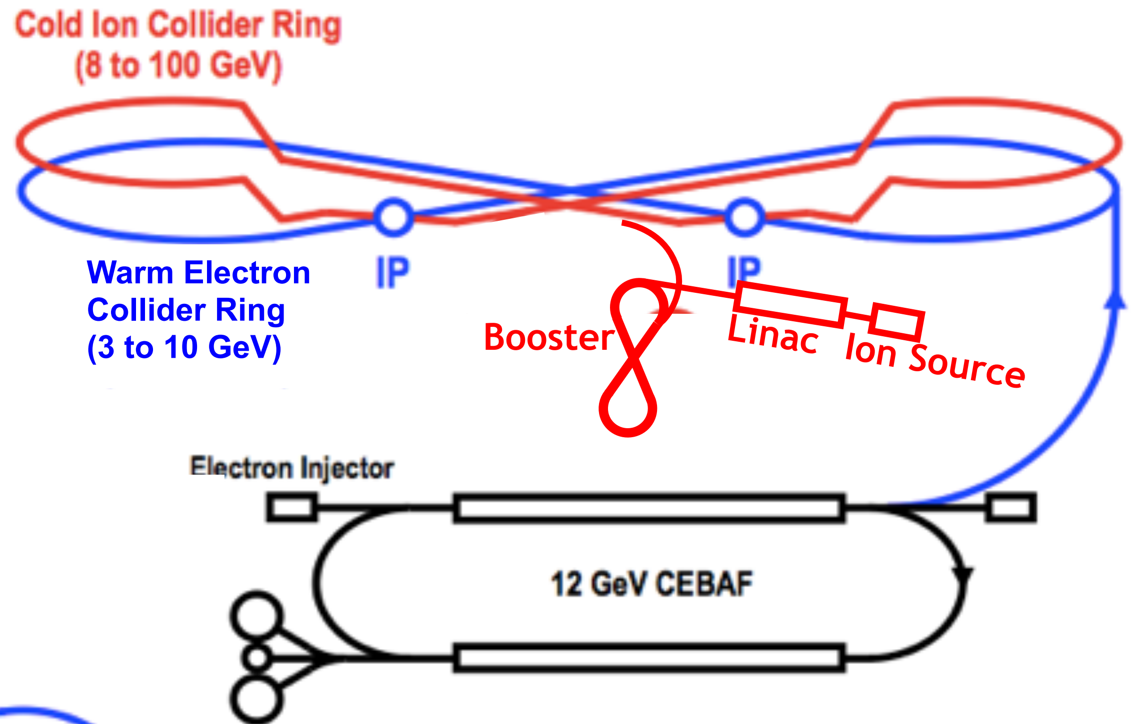
$$L = f\frac{n_1 n_2}{4\pi\sigma^*_x\sigma^*_y} \sim f\frac{n_1 n_2}{\varepsilon\beta^*_y}$$

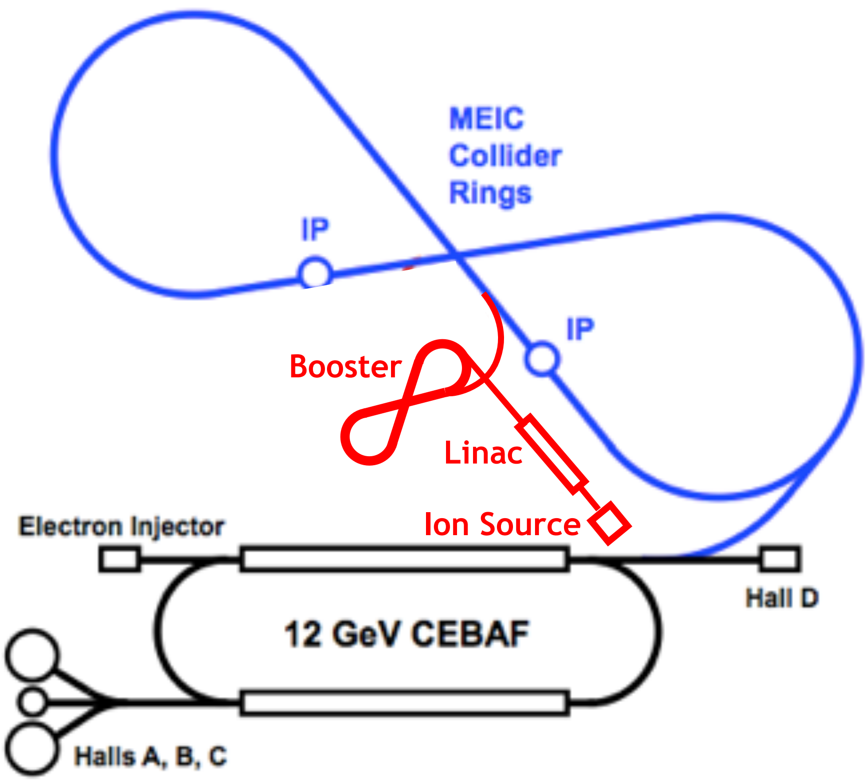


All rings are figure-8: critical advantages for both ion and electron beam polarization:

- **Spin precessions** in the left & right parts of the ring are exactly cancelled
- Net spin precession (***spin tune***) is **zero**, thus energy independent
- Spin is easily controlled and stabilized by small solenoids or other compact spin rotators

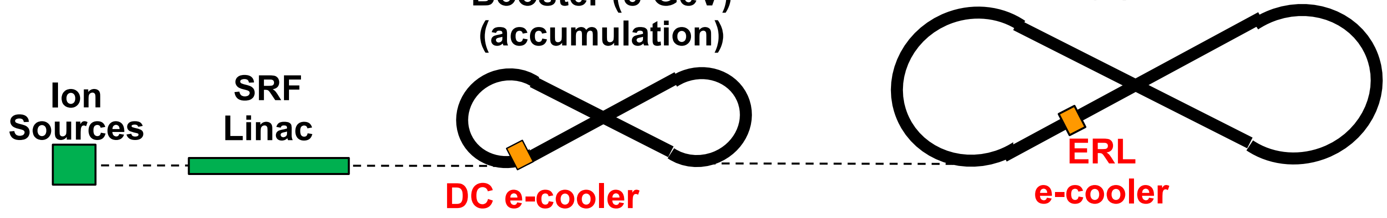
JLEIC Baseline: a ring-ring collider





- CEBAF acting as a full energy injector, up to 10 GeV, 1mA, > 80% polarisation.
- Initial filling and top-off/continuous injection.
- Matching bunch repetition frequency: 1497 MHz linac beam into a collider ring with 476 MHz (trick: since 1497/476 ~ 22/7, injecting every 22nd linac bunch into one of 7 bucket periods)

Ion Beam Formation

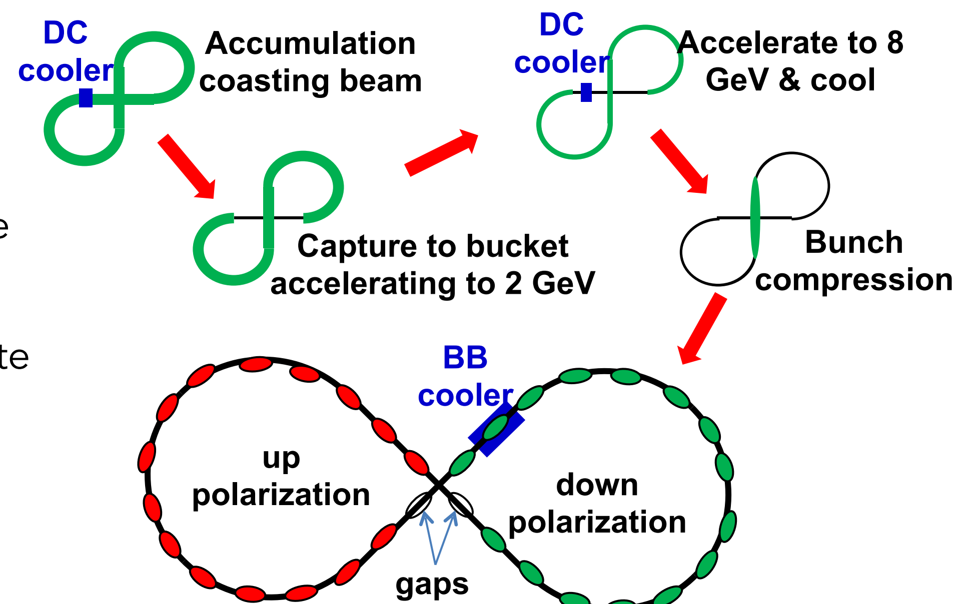


Key design features

- Demonstrated technologies for ion beams / Linacs
- Warm RF & SRF in Linac for efficient acceleration of wide range of ion species
- Booster and collider; of super-ferric magnets (up to 3 T)
- Stored ion beam current is up to 0.5A.
- High (8 GeV for p, 3.2 GeV/u for Pb ions) extraction energy from booster to mitigate space charge effect in the collider ring
- Bunch repetition 476 MHz, all cavities can operate at double that for future upgrades.
- Figure-8 shape for superior beam polarization
- DC e-cooling in the booster
- Bunched beam e-cooling in the collider ring

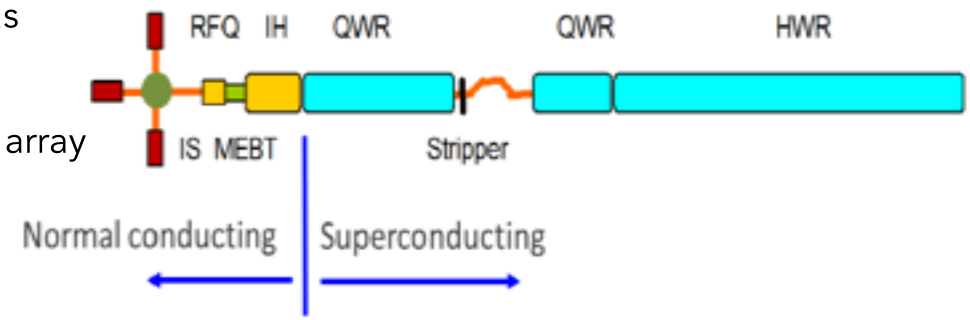
Beam formation scheme

- Ratio of circumferences of two rings: 9
- Repeat the circle up to 9 times



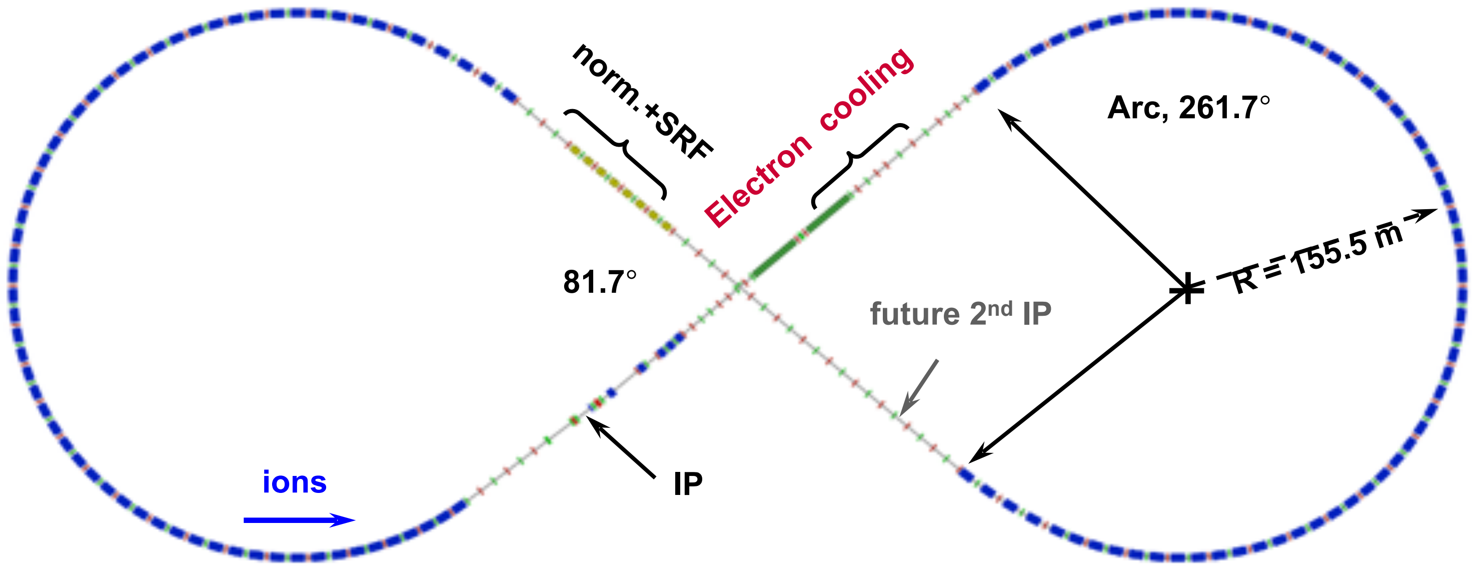
The Ion Linac

- Developed by ANL collaborators, based on ANL Atlas Upgrade cavities
- Using SRF cavities for efficient acceleration of a wide array of ion species
- Warm front-end up to ~ 5 MeV/u for all ions
- SC QWR section up to 13 MeV/u for Pb ions
- A stripper for heavy ions for more effective acceleration: $Pb^{28+} \rightarrow Pb^{67+}$
- SC high energy section (QWR+HWR) up to 280 MeV for protons and 100 MeV/u for Pb ions

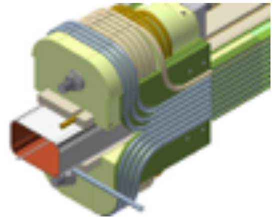


	Baseline
Species (for reference design)	*p,*
Kinetic energy (p, Pb) (MeV/u)	*285, 100*
Maximum pulse current (mA) *Light ions (A/Q<3)* *Heavy ions (A/Q>3)*	 *2* *0.5*
Pulse repetition rate (Hz)	*up to 10*
Pulse length: (ms) *Light ions (A/Q<3)* *Heavy ions (A/Q>3)*	 *0.50* *0.25*
Maximum pulse power (kW)	*560*
Fundamental frequency (MHz)	*115*
Total length (m)	*130*

Collider Ring



Super-ferric magnets

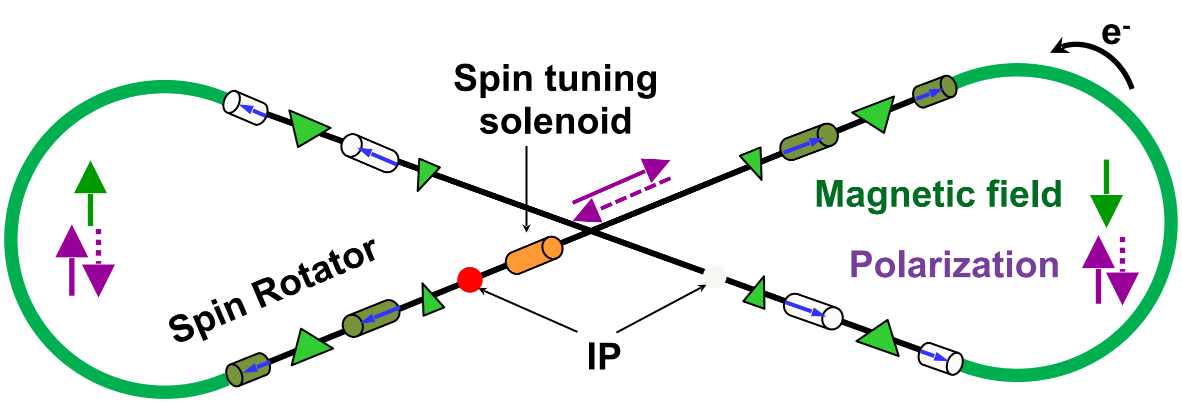


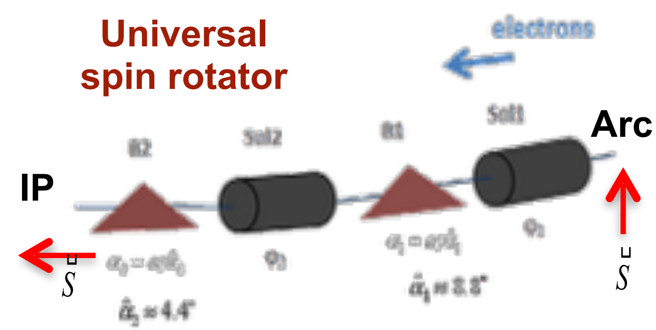
- Using super-ferric magnets (up to 3T)
- A figure-8 shape for high ion polarization
- Stacked above the electron ring; ions travel to the plane of electron ring in vertical chicanes for collisions
- Supports two detectors and all insertions (low-beta, spin elements, RF, e-cooling, injection, chromatic compensation)

Circumference	m	2154
Crossing angle	*deg*	*81.7*
Lattice type		*FODO*
Dipole & quad length	*m*	*8 & 0.8*
Cell length	*m*	*22.8*
Maximum field	*T*	*3*
Transition gamma		*12.46*
Natural chromaticity		*-101 / -112*

Electron Polarisation

- **Vertical polarization** in arcs to avoid spin diffusion
- **Longitudinal polarization** at collision points using universal spin rotators
- **Universal spin rotator** (fixed orbit) rotates spin orientation from 3 to 12 GeV
- Desired **spin flipping** is implemented by changing polarization of the injected beam
- **Figure-8** geometry removes electron spin tune energy dependence
  (Significantly suppresses the synchrotron sideband resonance)
- **Continuous injection** of bunch trains from the CEBAF is considered
  (preserve and/or replenish the polarization, especially at higher energies)
- **Spin matching** in key areas considered to further improve polarization lifetime



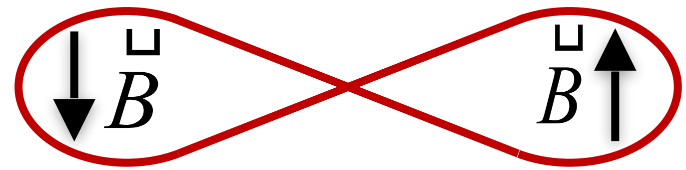


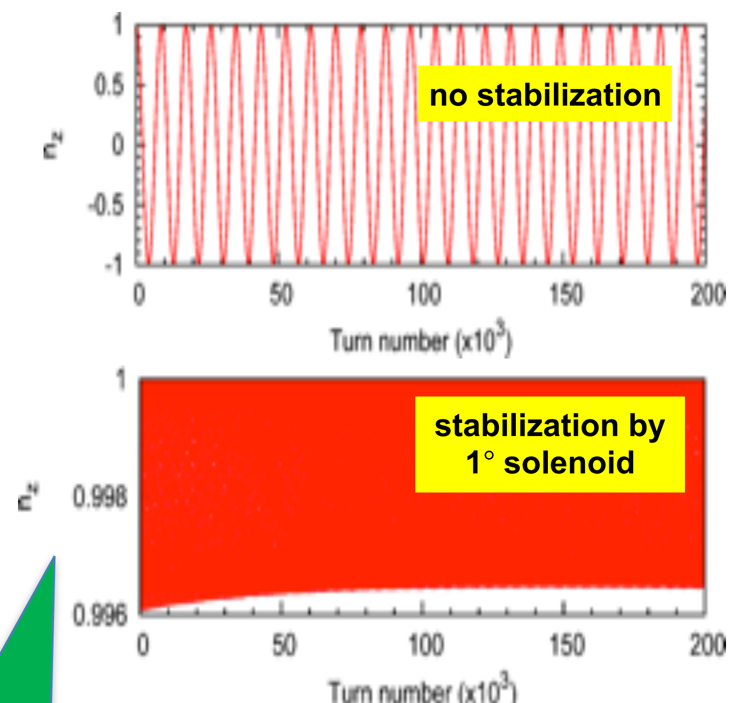
Ion Polarisation

Figure-8 design feature

- Spin precessions in the two arcs are exactly cancelled,
  - ➔ The spin tune is zero, independent of energy
  - ➔ Avoid spin resonance crossing
  - ➔ Eliminates depolarization during acceleration
- In an ideal structure (without perturbations) all solutions are periodic
- It allows for stabilization and control of the polarization by small field integrals
  - ➔ 2 Tm control solenoids can stabilize proton & deuteron spins up to 100 GeV
- Spin rotators are compact, easily rampable and give no orbit distortion
- It is currently the only practical way to accommodate polarized deuterons in medium energy
- It allows for a spin flipping system with a spin reversal time of ~1 s

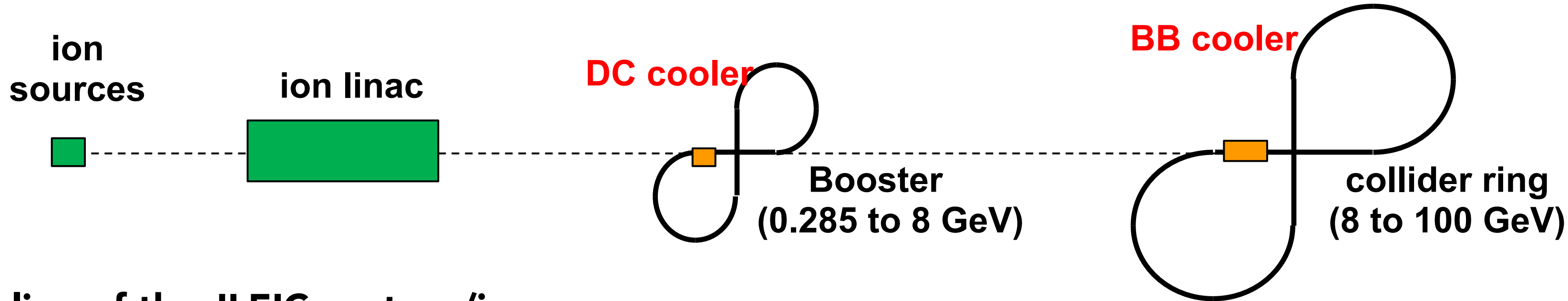
Spin tracking in progress
(figure-8 with an error)





Different scale

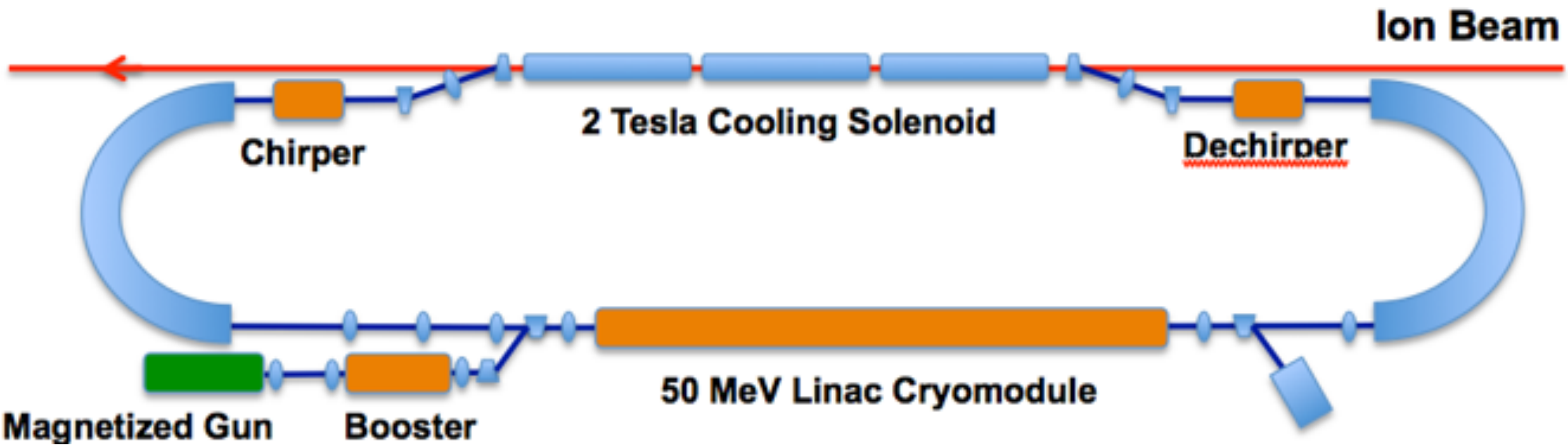
Multi-step cooling



- **Cooling of the JLEIC protons/ions**
  - Achieve a small emittance and a short bunch length of 1 to 2 cm (with strong SRF)
  - Enable ultra strong final focusing and crab crossing
  - Suppress intra-beam scatterings (IBS), maintaining beam emittance & luminosity lifetime
- **Needs two coolers for multi-step cooling**
  - **Low-energy DC cooler**: ***within state-of-the-art***, similar to the 2 MeV COSY cooler
  - **High-energy BB cooler**: using SRF linac & ERL technology, currently under development

Ring	Cooler	Function	Ion energy	Electron energy
			GeV/u	*MeV*
Booster ring	*DC*	*Injection/accumulation of positive ions*	*0.11 ~ 0.19 (injection)*	*0.062 ~ 0.1*
		Emittance reduction	*2*	*1.1*
Collider ring	*Bunched Beam Cooling (BBC)*	*Maintain emittance during stacking*	*7.9 (injection)*	*4.3*
		Maintain emittance	*Up to 100*	*Up to 55*

ERL Cooler

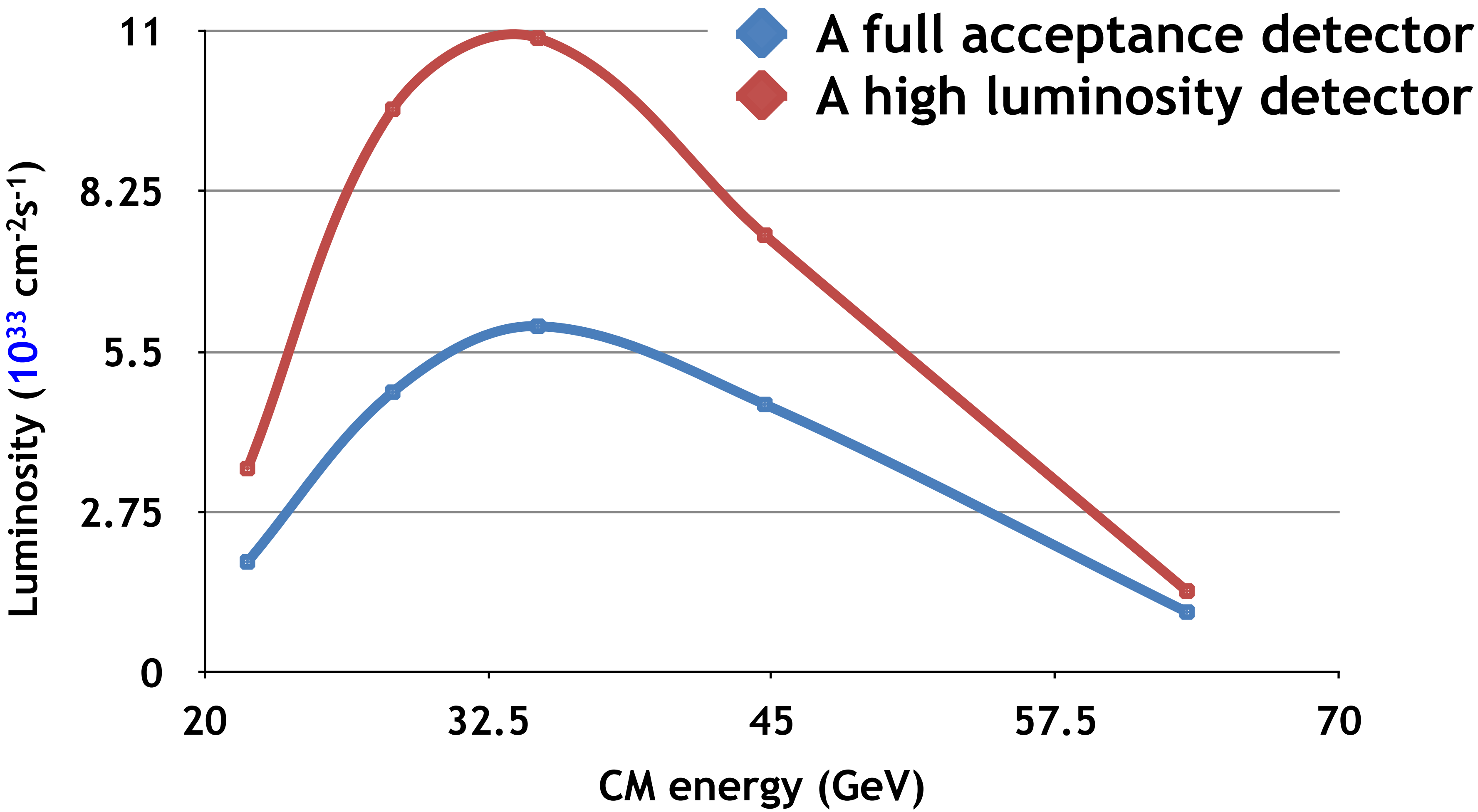


Beam energy	MeV	20–55
Bunch charge	*nC*	*0.42*
Repetition rate	*MHz*	*476*
Bunch length, full	*ps*	*20*
Emittance (rms)	*µm rad*	*30*
Energy spread (rms)	*10*	*3*
Solenoid field	*T*	*2*
Solenoid length	*m*	*30*

Challenges:

- Has to run at high current (200mA)
  - **Energy recovery** required and therefore SRF cavities.
- Charge density varies along the micro-bunch so space charge vary and cannot be perfectly compensated.
- No micro-pulsed high current magnetized source has been demonstrated
- Efficacy of bunch-beam cooling to be tested numerically and experimentally (IMP)

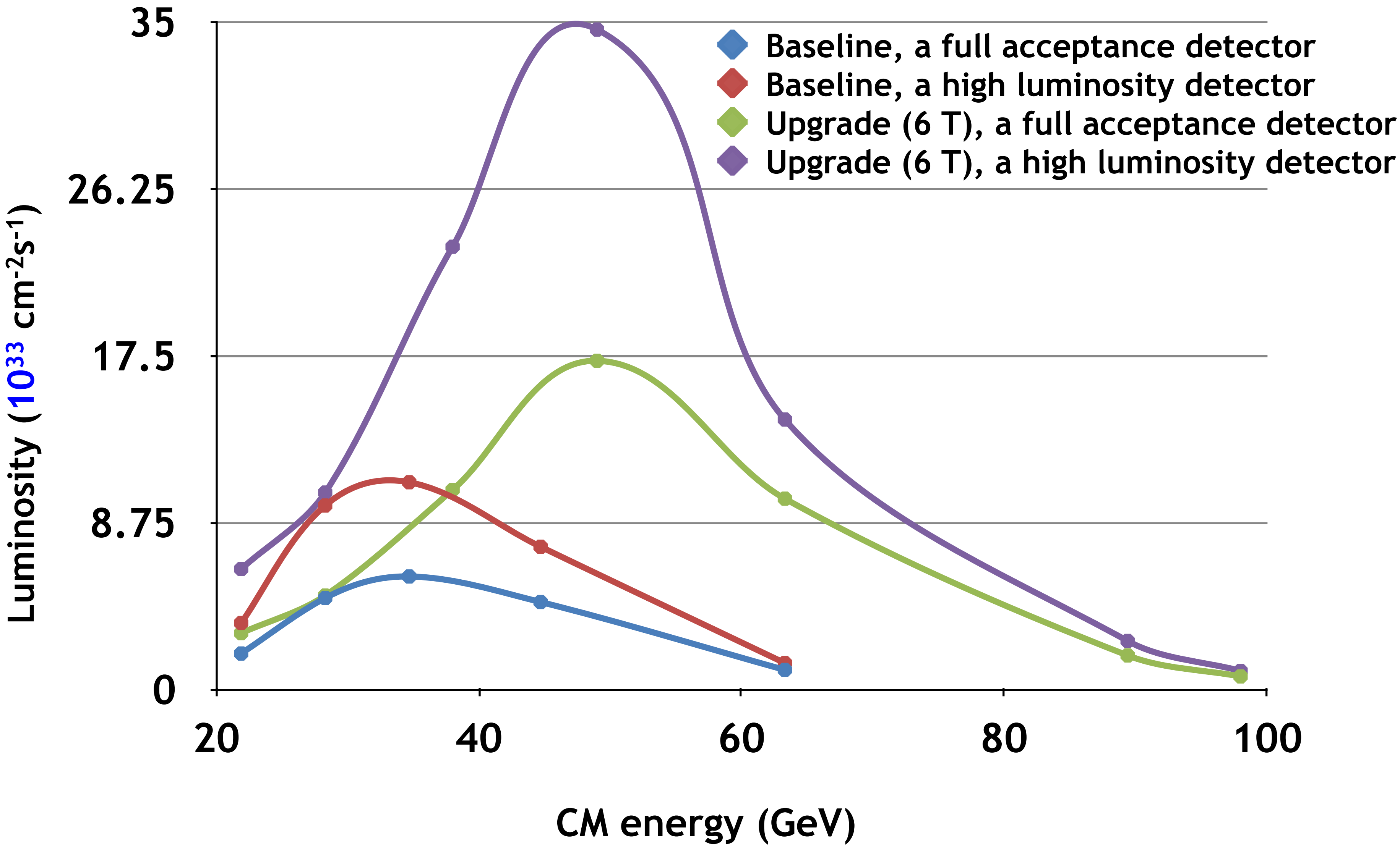
e-p Luminosity



The baseline performance requires a **single pass ERL bunched beam cooler**

Without bunched beam cooling luminosity down by a factor 2-3

Luminosity for the energy upgrade (12 GeV e - 200 GeV p)



Status of JLEIC

- Baseline underwent recent revision for a cost optimisation while preserving/improving the performance. This includes reuse of PEP-II equipment for the electron ring, selecting super-ferric magnets for the ion booster and collider ring, elimination of the earlier-proposed large ion booster

- Passed NSAC review in 2015.

- A number of major design works required within the next couple of years: opportunities to join the team!

Imminent plans for JLEIC

Design:

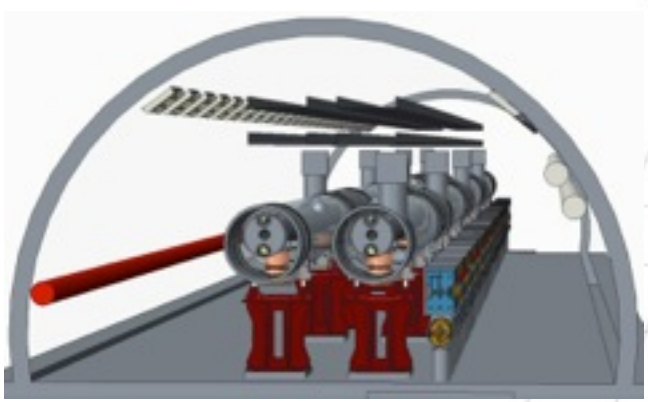
- ERL Cooler design
- Lower energy SRF linac, comparison with warm linac
- Electron ring emittance reduction
- Beam formation
- Synchronization
- Modeling (Electron cooling, Spin tracking, Space charge, Beam-beam, Non-linear dynamics, Collective effects)

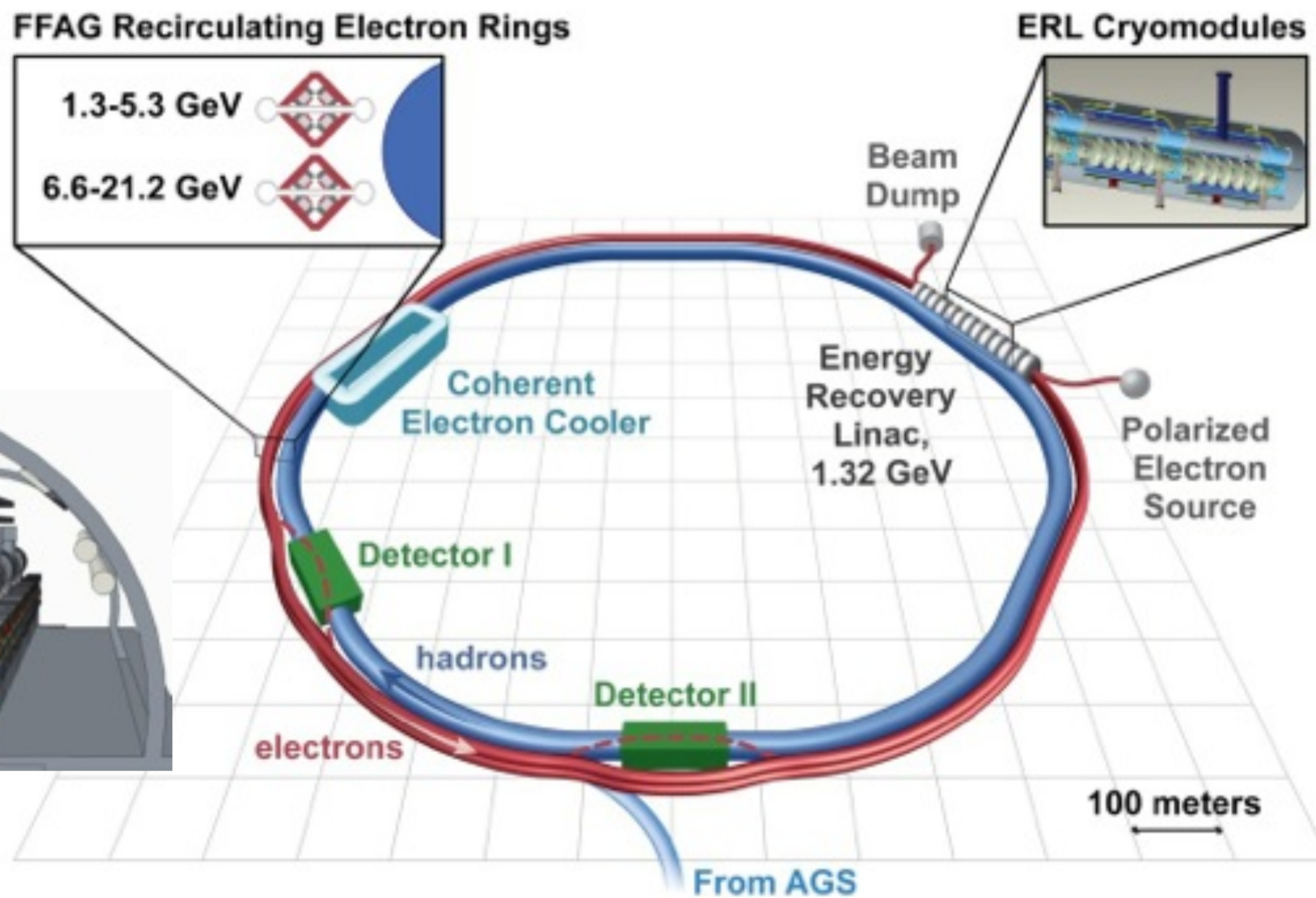
R&D and Engineering:

- Super-ferric magnet prototype
- Magnetized source for e- cooler
- Bunched beam cooling experiment
- 952 MHz SRF cavities for cooler and ion collider: design and prototype
- 952 MHz crab cavity design, integration, prototype
- FF quadrupoles
- Engineering study of PEP-II components: magnets, RF, vacuum chamber

eRHIC - EIC @ the Brookhaven National Lab

- Already have ion beam in RHIC
- Tunnel, supporting buildings and cryogenic facility in existence
- Addition of high-current, multi-pass Energy Recovery Linac (ERL) and electron recirculation rings using Fixed-Field Alternating Gradient (FFAG) magnets:

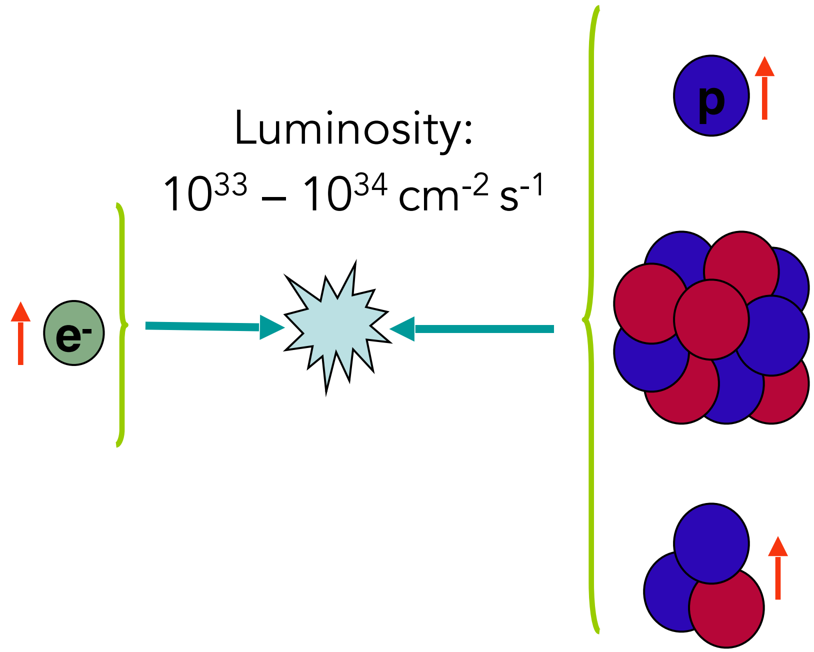




The electron and ion beams with eRHIC

80% polarized electrons: 1.3 – 21.2 GeV

Luminosity: $10^{33} – 10^{34}$ cm^{-2} s^{-1}



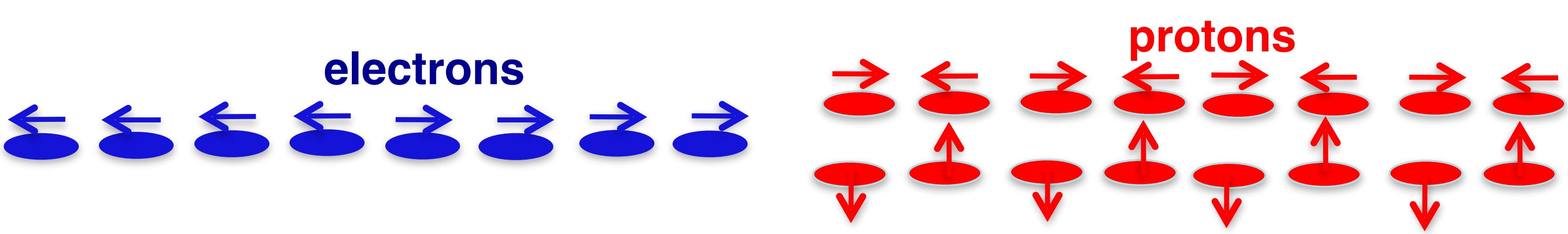
70% polarized protons
25 - 250 (275*) GeV

Light ions (d, Si, Cu)
Heavy ions (Au, U)
10 - 100 (110*) GeV/u

Pol. light ions (He-3)
17 - 167 (184*) GeV/u

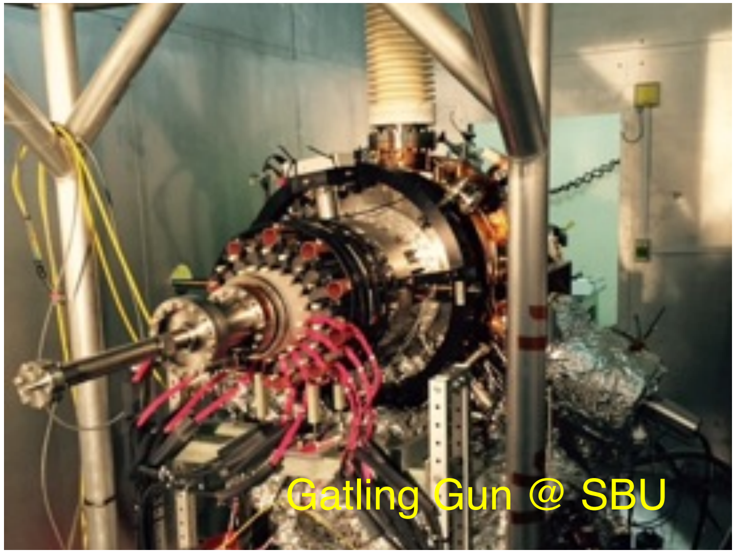
** Possibility of increasing RHIC energy by ~10%*

- Center-of-mass energy range: 20 – 145 GeV
- Full electron polarization at all energies
  Full proton and He-3 polarization with six Siberian snakes
- Any polarization direction in electron-hadron collisions:

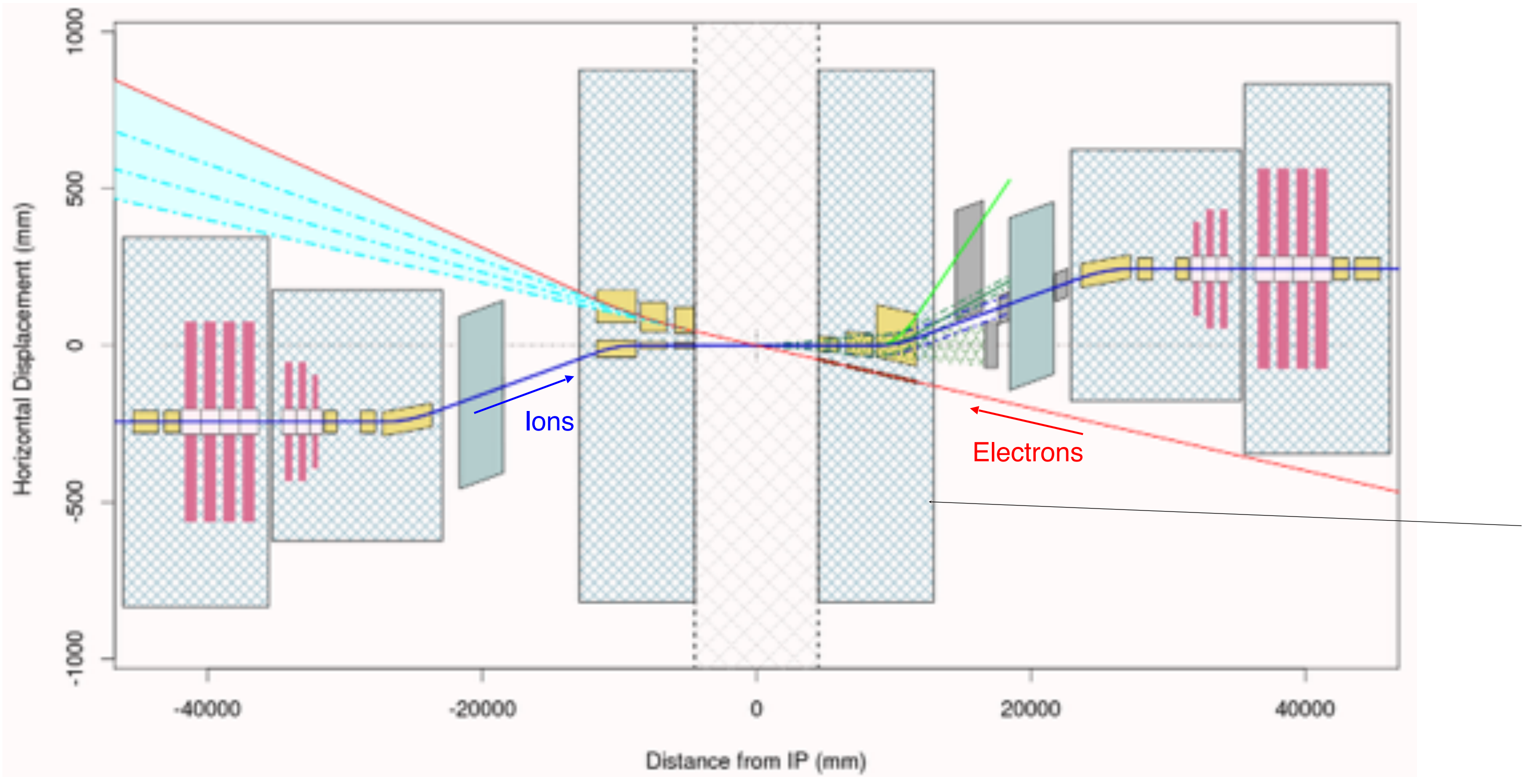


CW polarised electron gun

- 4 mA polarized e-beam with 20 minutes charge lifetime achieved
- More current with effectively larger cathode area and laser spot
- Tests started at MIT with very large cathode area
- Gatling gun: multiple cathodes to effectively increase cathode area
- Gatling Gun Test:
  - ✦ Photo current from two cathodes during first test at Stangenes Industries (CA)
  - ✦ Moved to Stony Brook; tests with beam started again
- Backup: Two high current guns can provide continuous beam by operating one while the cathode of the other gun is being replaced.



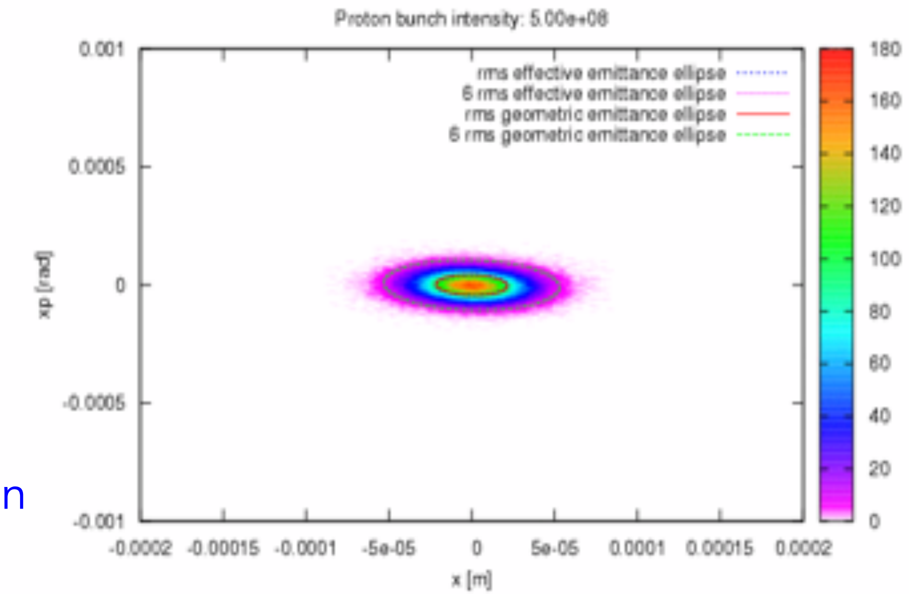
High luminosity, full acceptance Interaction Regions



- 10 mrad crossing angle and crab-crossing
- 90 degree lattice and beta-beat in adjacent arcs to reach beta* of 5 - 10 cm with good dynamic aperture
- Final focus doublet and dipole with large aperture for forward collision products and with field-free passage for electron beam
- Only soft bends of electron beam within 60 m upstream of IP

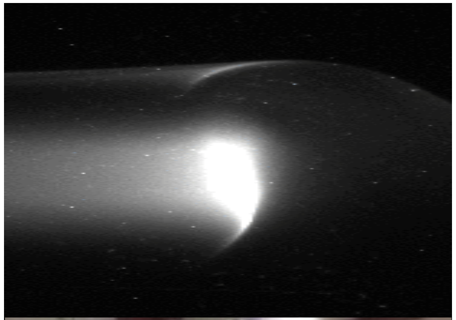
Linac - Ring collider: high luminosity

- For Linac-Ring collider the single collision of electron bunch removes the limitation of the beam-beam effect of the high energy hadron beam on the lower energy electron beam
- Can reach high luminosity with high intensity, low emittance hadron beam and lower intensity electron beam producing much less synchrotron radiation.
- Disruption of electron beam by hadron beam is large (similar to ILC) but emittance growth is limited due to the focusing by the hadron beam (pinch effect)
- Need strong hadron beam cooling (10 times in transverse and longitudinal direction) for highest luminosities, small vertex distribution, and small forward divergence
- Novel cooling method:
  - Coherent electron Cooling (CeC)
  - Required performance demonstrated in extensive simulations
  - Proof-of-Principle test underway at RHIC

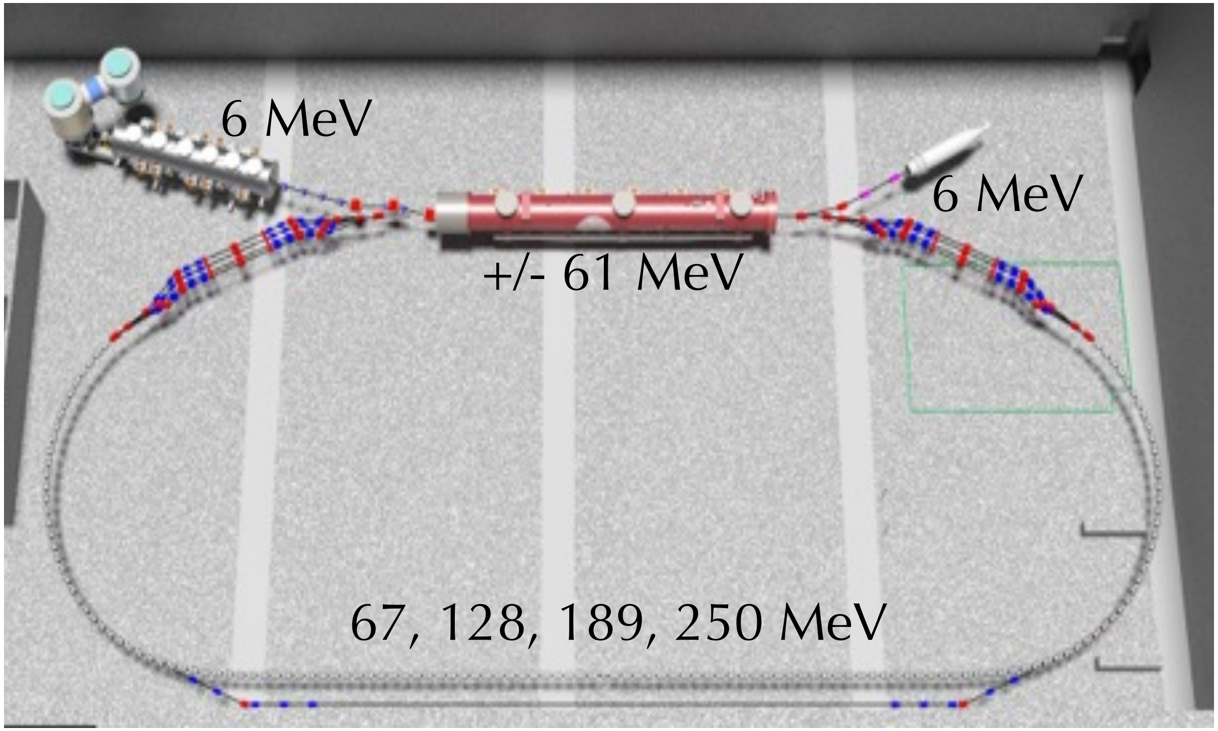


Tests of Coherent electron Cooling

- DOE NP R&D project aiming for demonstration of CeC technique is in progress since 2012
- Phase I of the equipment and most of infrastructure installed into RHIC's IP2
- First beam from SRF gun (3 nC/bunch, 1.7 MeV) on 6/24/2015; exceeds performance of all operating CW electron guns
- 20 MeV SRF linac and helical wigglers for FEL amplifier are installed
- Proof-of-principle demonstration with 40 GeV/n Au beam scheduled during RHIC Run 16 and 17
- Micro-bunching test also planned with same set-up



eRHIC prototype: test ERL @ Cornell



- Uses existing 6 MeV low-emittance and high-current injector and ~ 70 MeV CW SRF Linac
- ERL with single four-pass recirculation arc with x4 momentum range
- Permanent magnets used for recirculation arc
- Adiabatic transitions from curved to straight sections
- Test of spreader/combiner beam lines
- High current can be used to test HOM damping by replacing Linac with eRHIC Linac cryostat

Ring – Ring vs. ERL – Ring

$$L = f_b \left(\frac{4\pi\gamma_p\gamma_e}{r_p r_e} \right) (\xi_p \xi_e)(\sigma'_p \sigma'_e) \qquad \xi_p = \frac{r_p \beta^*_p}{4\pi\gamma_p} \frac{N_e}{\sigma_e^2} \qquad \xi_e = \frac{r_e \beta^*_e}{4\pi\gamma_e} \frac{N_p}{\sigma_p^2}$$

$$\frac{4\pi\gamma_p\gamma_e}{r_p r_e} = 2.7 \cdot 10^{36} \quad cm^{-2} \qquad \sigma'_p = \sigma'_e \le 0.15\,mrad \quad \xi_p \le 0.015 \qquad \xi_e \le 0.1$$

for E_p=250 GeV, E_e=20 GeV

for ring - ring

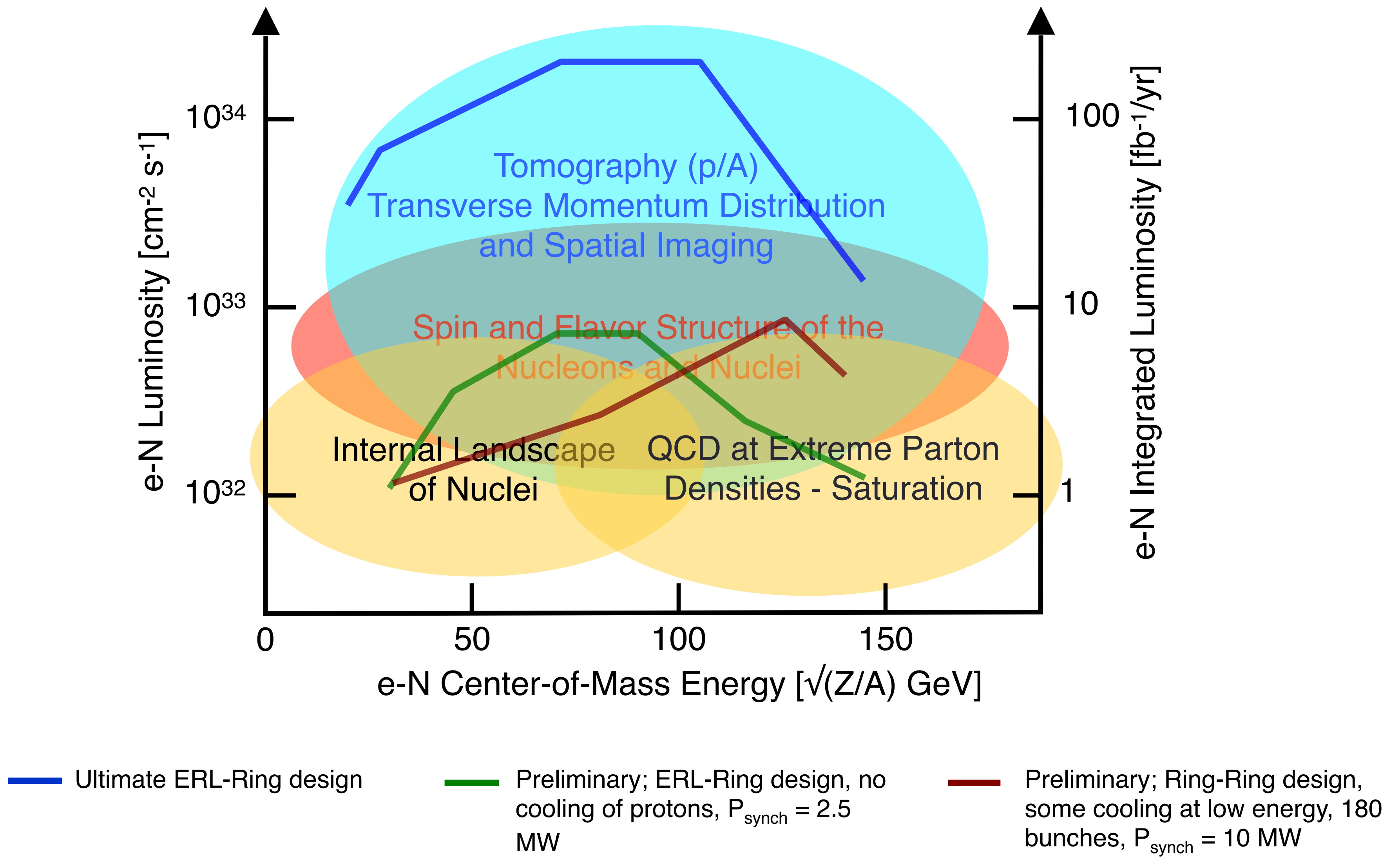
- Ring – Ring
  - For bunch rep. rate f_b = 10 MHz: $L \le 9 \times 10^{32}\ s^{-1}\ cm^{-2}$
  - Increase luminosity by increasing f_b (and electron current and synchrotron radiation power)
  - Decrease electron current (and synchrotron power) by **cooling proton beam** and use low emittance electron storage ring
  - High synchrotron radiation in detector and arcs is the main challenge
- ERL – Ring
  - For bunch rep. rate f_b = 10 MHz (or any rate) the luminosity is not limited; eRHIC design study had ξ_e=1.5: $L = 1.4 \times 10^{34}\ s^{-1}\ cm^{-2}$
  - Increase luminosity and/or decrease electron current by **cooling proton beam**
  - Source with high polarized electron current is the main challenge

Plan for eRHIC design

- Approach to the eRHIC design to minimize cost and risk:
  - The initial configuration of eRHIC should have enough center-of-mass reach (20 GeV pol. e x 250 GeV pol. p and 20 GeV e x 100 GeV/n Au) and detector acceptance to cover the whole EIC science case.
  - The initial luminosity could be lower and then increased through incremental upgrades, as was done for RHIC and other colliders.
- Present design is the linac-ring option with multi-pass ERL; minimises cost and risk, can cover the whole EIC physics case. R&D plan to retire the technical risks.
- Developing luminosity-staged versions of the eRHIC design to minimize initial cost and technical risk
- Two designs are being developed: Low risk ERL-Ring and Ring-Ring

Peak Luminosity and Centre of Mass Energy

- Science case areas indicate the range of peak luminosities with which a statistically significant result can be achieved in about one year (10^7 sec) of running.



Status of eRHIC

- eRHIC R&D plan that addresses critical technical risks of the eRHIC design over the next 2-3 years:
  - Development of ERL acceleration cavity with full HOM damping
  - Development of polarized electron source with high total current
  - Complete Coherent electron Cooling PoP test during RHIC runs 16 and 17
  - High intensity, multi-pass test-ERL with single recirculation arc to be built using Cornell high intensity electron injector and CW SRF Linac
- Develop cost effective, low risk ERL-Ring and Ring-Ring eRHIC design options with full energy coverage and 10^{32} - 10^{33} s^{-1} cm^{-2} luminosity. Basis for eRHIC project proposal.
- Cost effective upgrade to ~ 10^{34} s^{-1} cm^{-2} luminosity ERL-Ring design possible for both options.

eRHIC plans

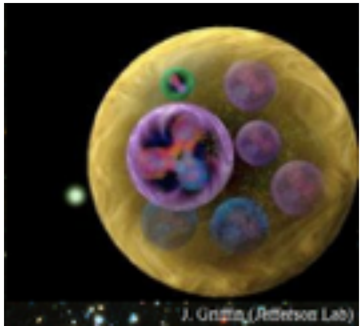
- There are four high priority eRHIC R&D items to be completed by ~ 2018.
    - ✦ Test of ERL acceleration cavity with full HOM damping
    - ✦ Test of polarized electron "Gatling Gun" with two to four cathodes and total current of about 10 mA; develop single high current polarized electron source
    - ✦ Complete Coherent electron Cooling PoP test during RHIC runs 16 and 17
    - ✦ High intensity, multi-pass test-ERL with single recirculation arc to be built using the Cornell high intensity electron injector and CW SRF Linac
- There is a plan to complete the BNL-Cornell FFAG-based test-ERL by ~ 2018 with non-DOE funding.

In summary

- ★ Two versions of EIC in parallel development: eRHIC at BNL and JLEIC at Jefferson Lab.
- ★ Design choice and site selection: ~ 2018/19
- ★ Construction start ~ 2021.
- ★ Opportunities for contribution and significant involvement on accelerator R & D (not to mention detectors and the physics programme…)

Workshop on EIC physics and engineering opportunities for the UK: ~ July. Watch this space!

Thank you!



Backup slides

What's in it for the UK?

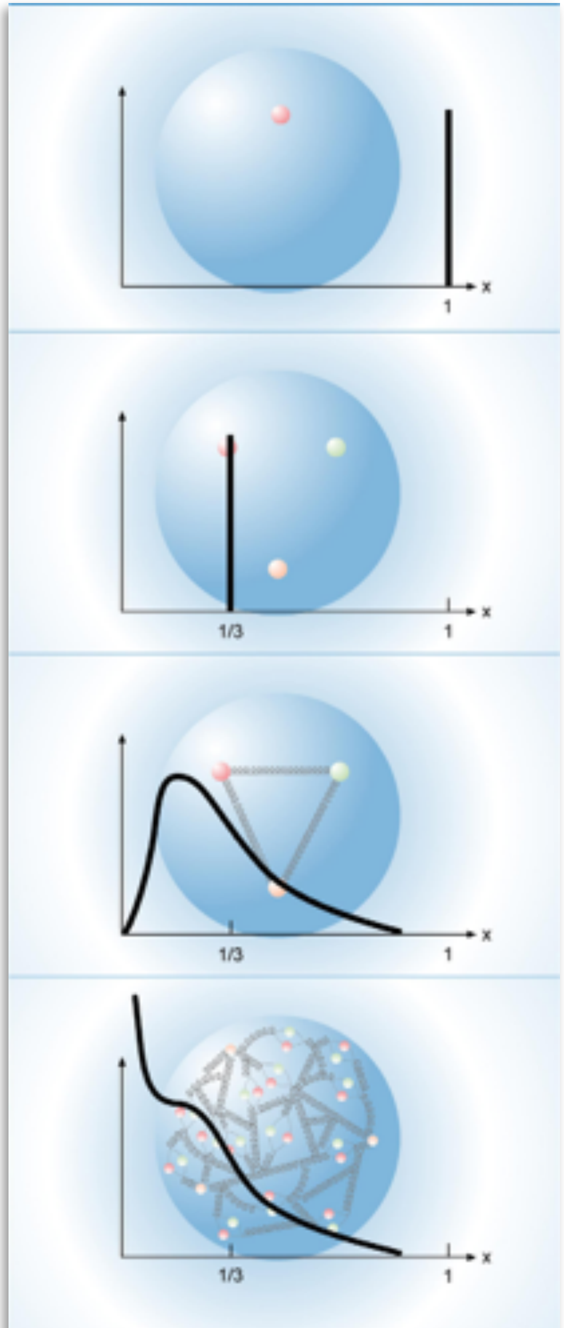
Alignment with physics interest in:

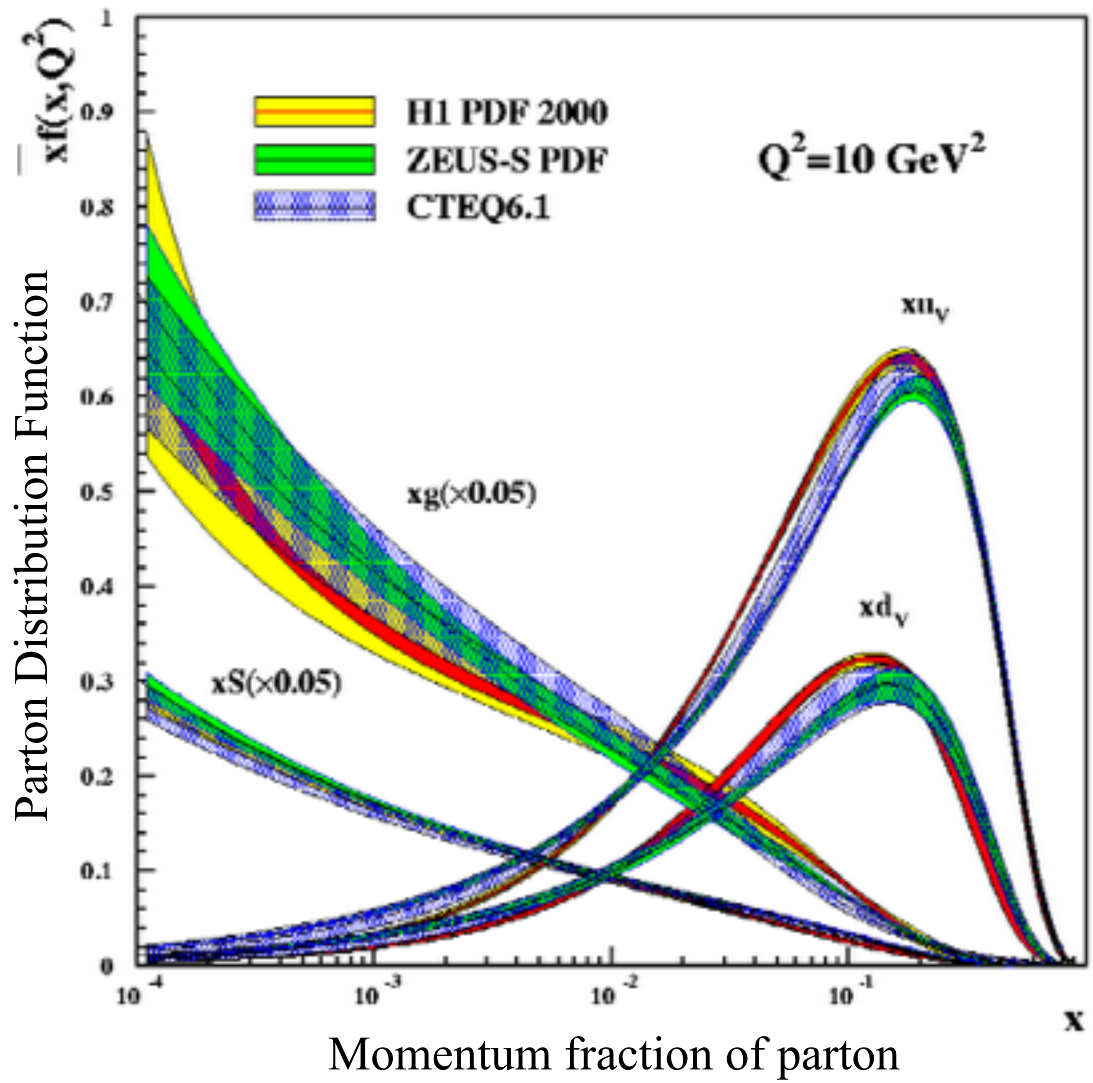
- QCD structure of nucleons and nuclei.
- Physics at high quark and gluon densities.
- Exploration of the QCD phase diagram.

After the end of the current JLab programme: natural next step to probe lower parton momenta and QCD at higher energies within the nuclear medium.

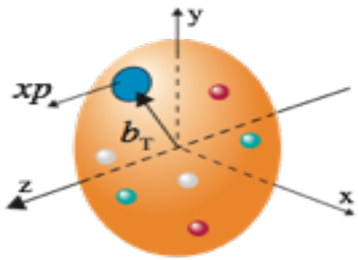
- Established track record at Jlab, CERN, RHIC, DESY.
- Significant contributions can be made by UK expertise to EIC's key physics areas.
- Large potential to contribute to hardware development (trigger, tracker, PID) and accelerator work!

The proton at different scales

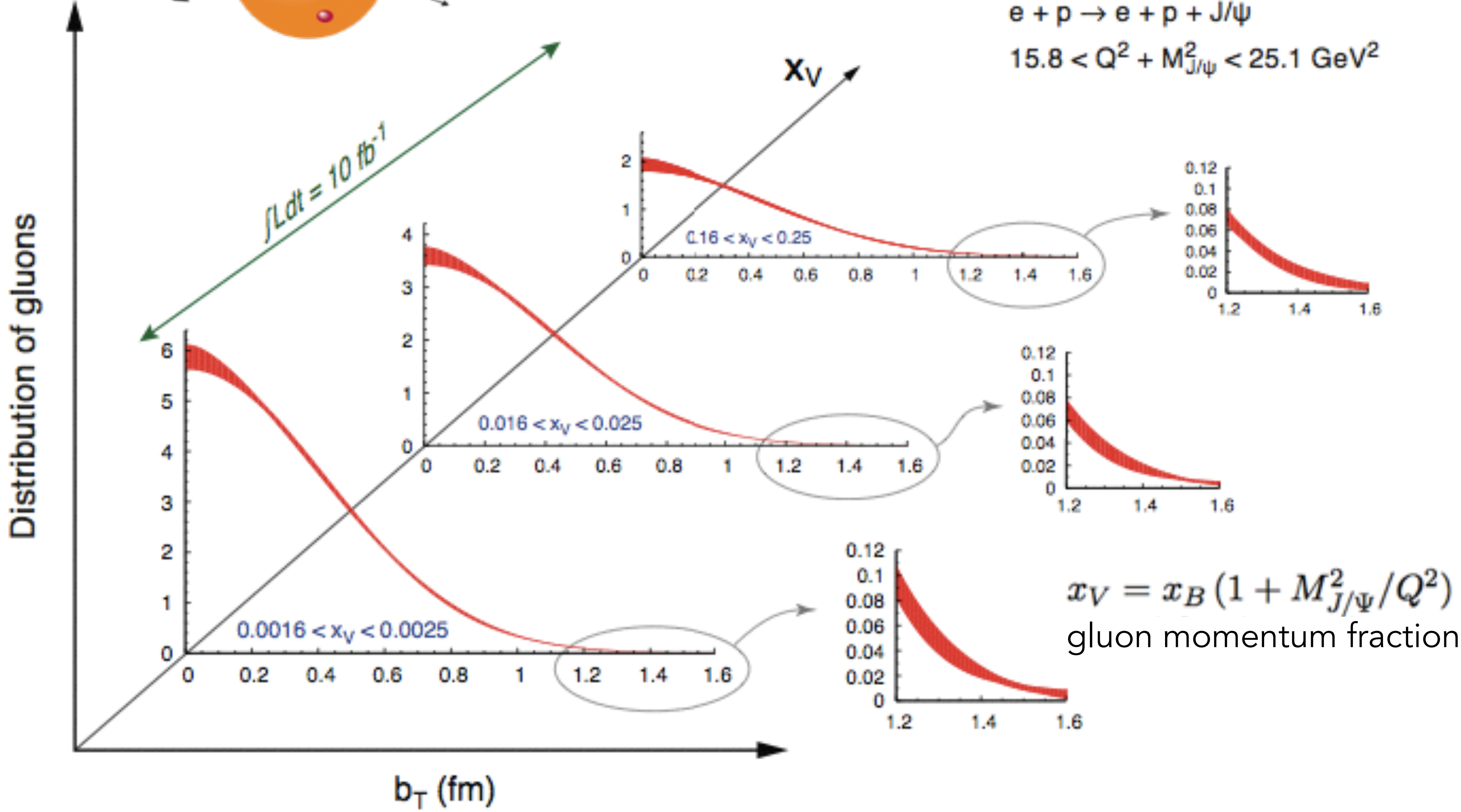




Nucleon and Nuclear Tomography @ EIC



- How are the sea quarks and gluons distributed in space and momentum inside the nucleon?



Nucleon Spin: what is its composition?

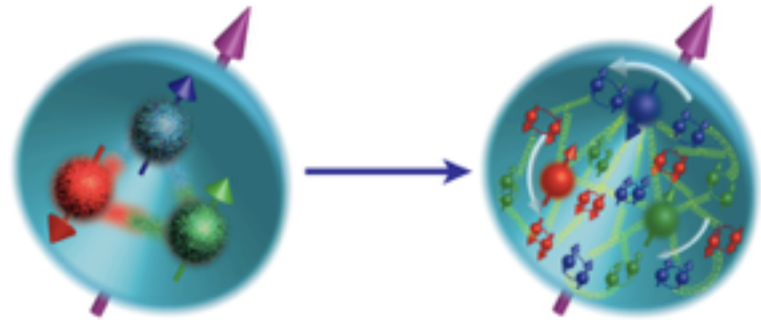
q orbital angular momentum

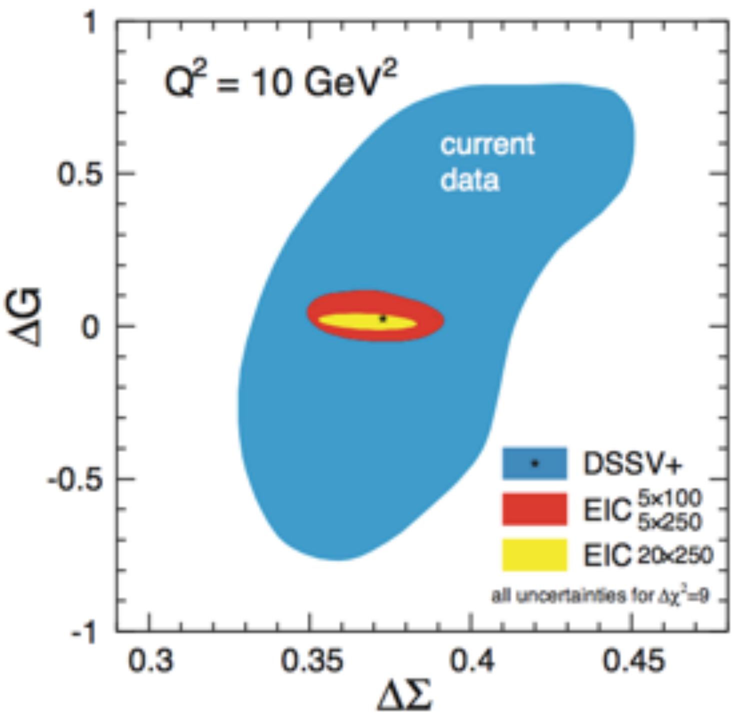
$$J_N = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

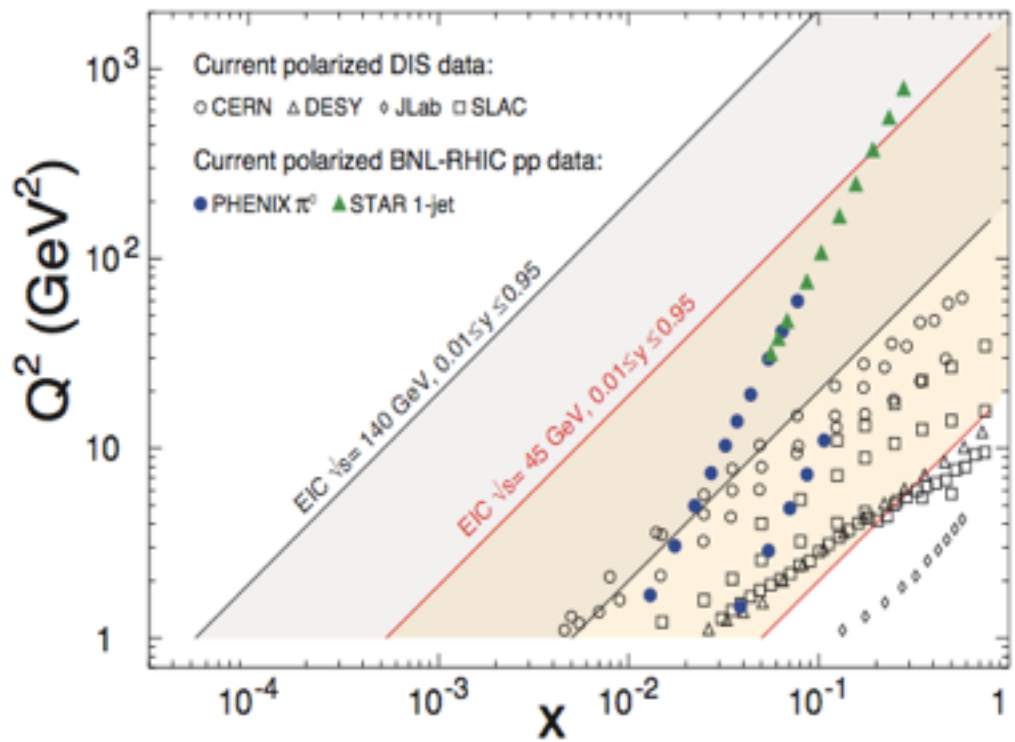
Quak spin

Gluon spin

g orbital angular momentum



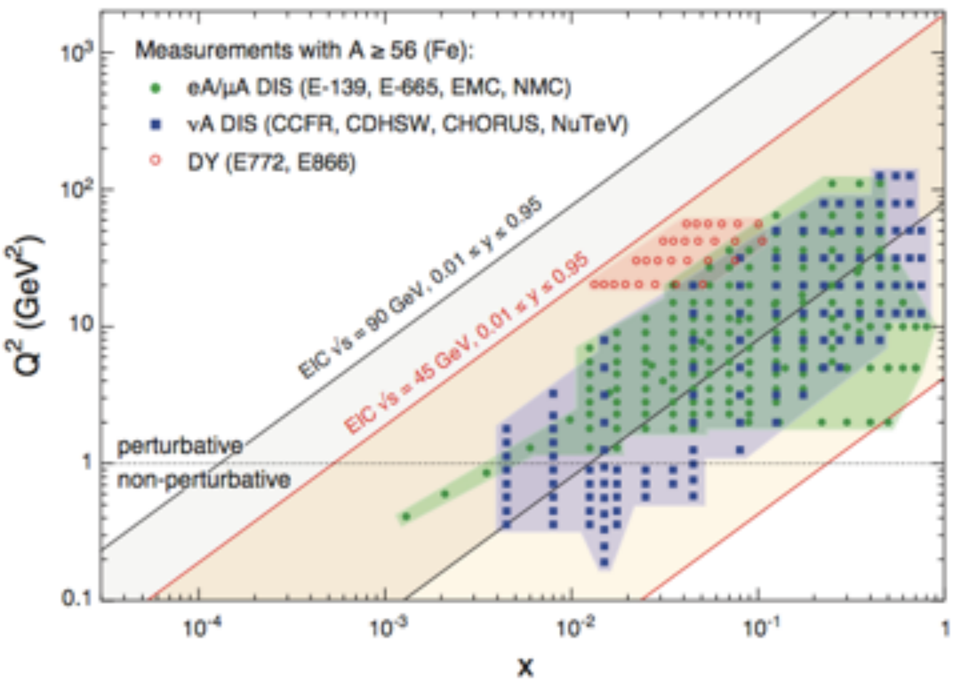


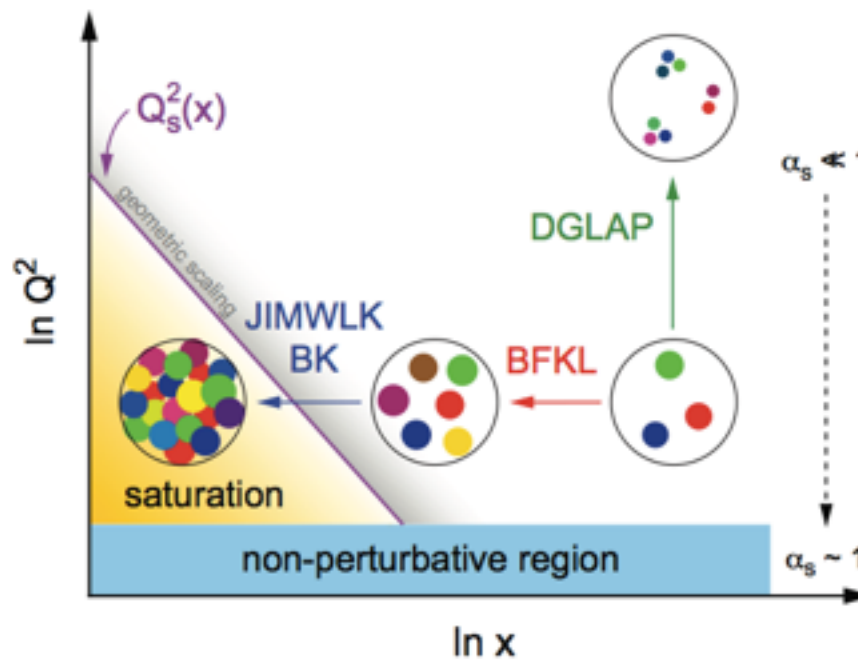


Gluon density saturation

- Saturation: at high gluon densities, gluon splitting & recombination reach an equilibrium: Colour Glass Condensate.

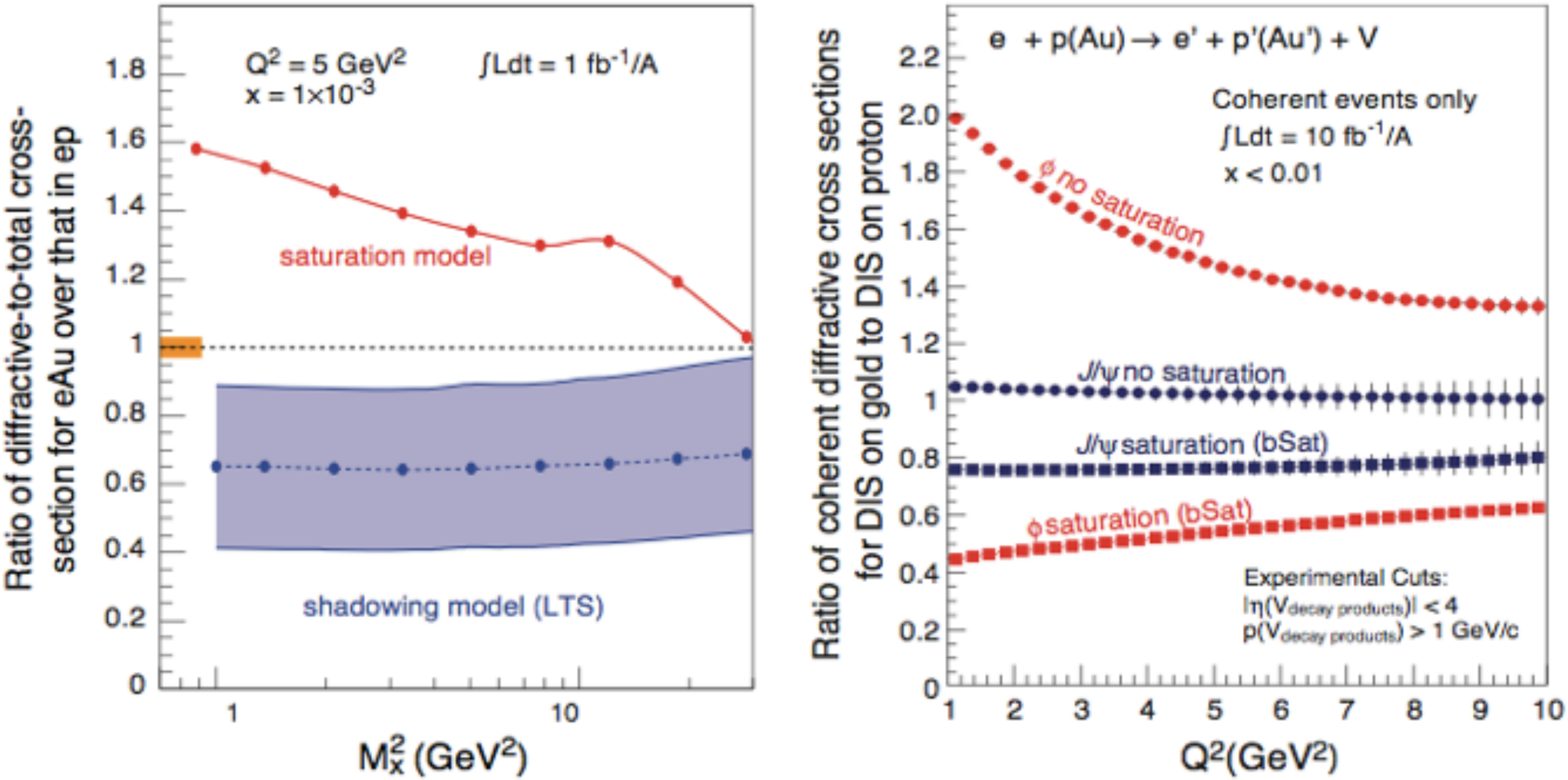
New, universal properties of hadronic matter.





- Where does the saturation of gluon densities set in?

Probing the saturation scale at the EIC

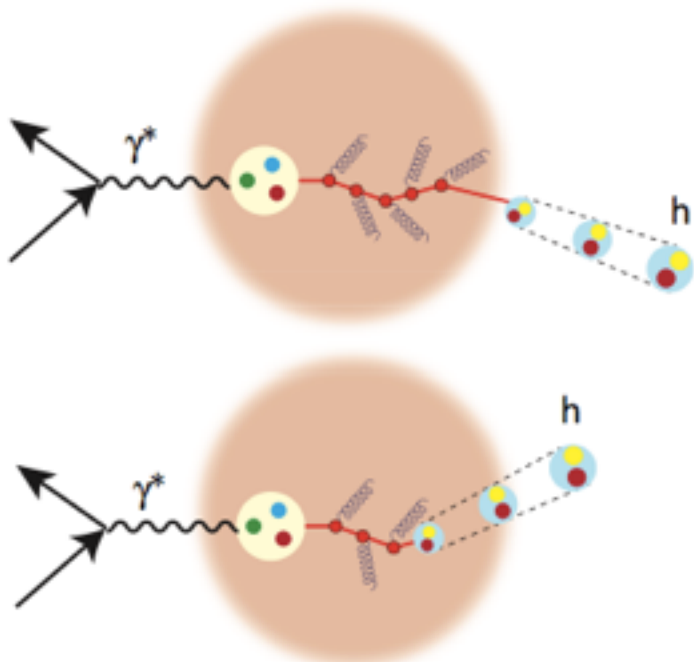


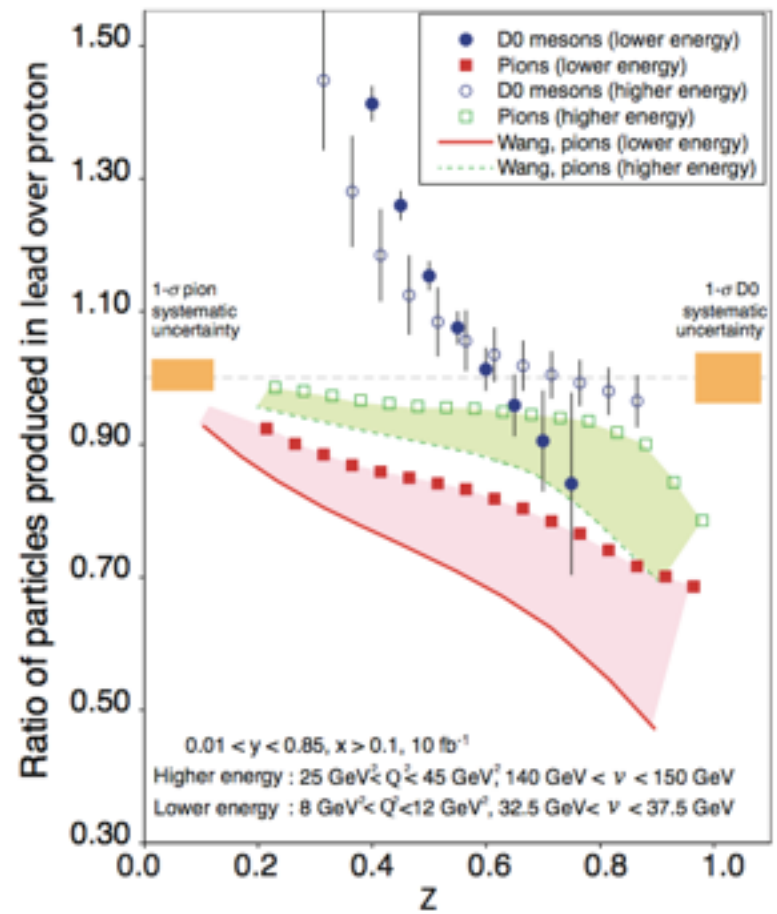
Propagation of Colour Charge in Nuclear Medium

How and where do quarks hadronise within nuclear matter?

How do they lose energy on passage through it?

What are the differences for heavy and light quarks?





Ratio of meson momentum to that of virtual photon

EIC: the deliverables

- **Nucleon spin composition:** contribution of quarks and gluons.
- **The motion of quarks and gluons in the nucleon:** correlation between nucleon spin and transverse motion of quarks and gluons (Semi-inclusive processes).
- **The tomographic images of the nucleon:** 3D distributions of sea quarks and gluons to complement valence distributions measured at CLAS and CLAS12 (exclusive reactions): QCD dynamics at large distances.
- **Tomography of nuclei**: structure functions for quarks different for nucleon and nuclei — extend to low x, and measure for totally unknown gluons.
- **QCD matter at an extreme gluon density:** determination of gluon saturation scale, exploration of this novel QCD matter (DIS and diffractive cross-sections on nuclei).
- **Quark hadronization:** Quark-mass dependence of the hadronisation process, response of nuclear matter to fast-moving colour charge (meson-production).