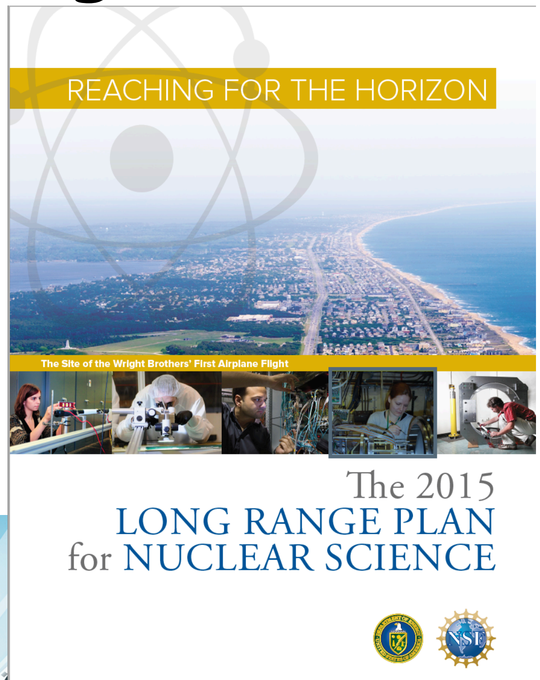
Electron Ion Collider

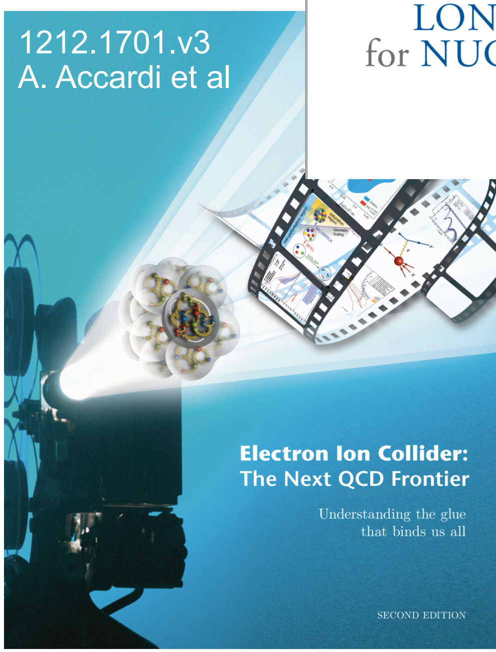
Yulia Furletova, on behalf of JLAB EIC working group

3D Nucleon Tomography, Jefferson Lab, Mar 15-17, 2017

U.S. DEPARTMENT OF ENERGY JSA Jefferson Lab

Long Range Plan



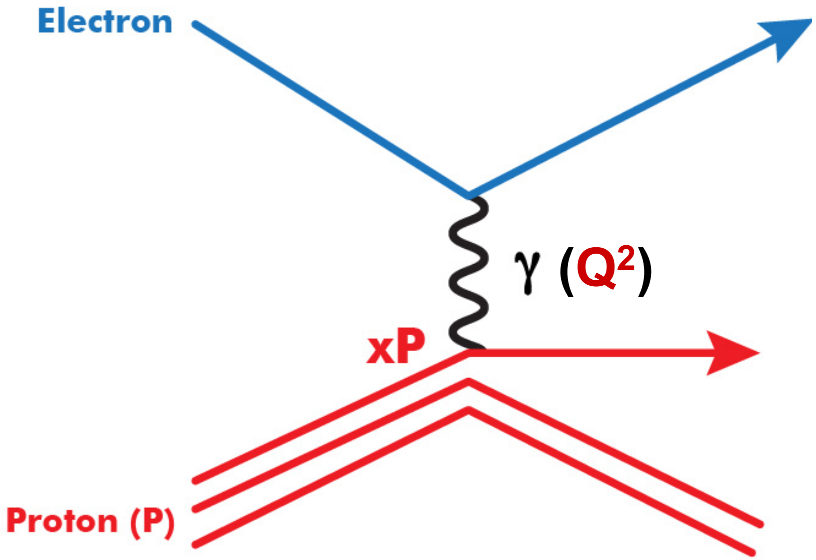


The NSAC recommend "a high-energy high-luminosity polarized Electron-Ion Collider (EIC) as the highest priority for new facility construction.."

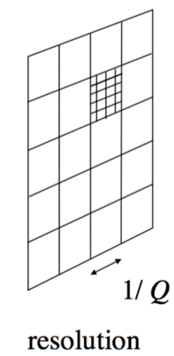
The Next QCD Frontier

- Understanding of nucleon and nuclear structure and associated dynamics (3D structure)
- Probe the nucleon and nuclei in different interaction regimes.
- Extend our understanding of QCD (saturation, propagation of quarks/jets in cold nuclear matter)

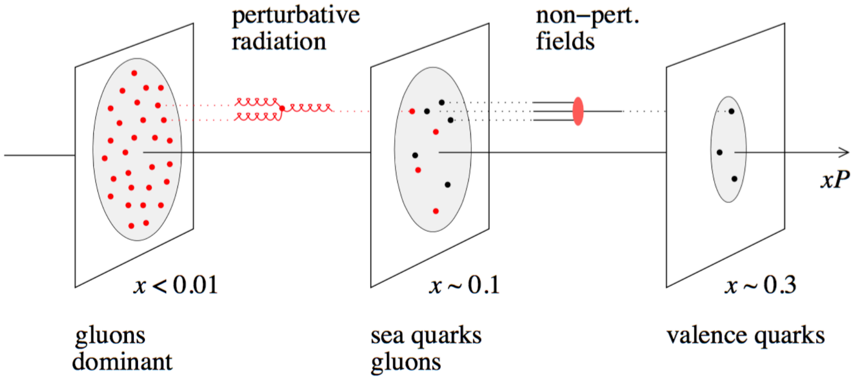
Electron proton scattering



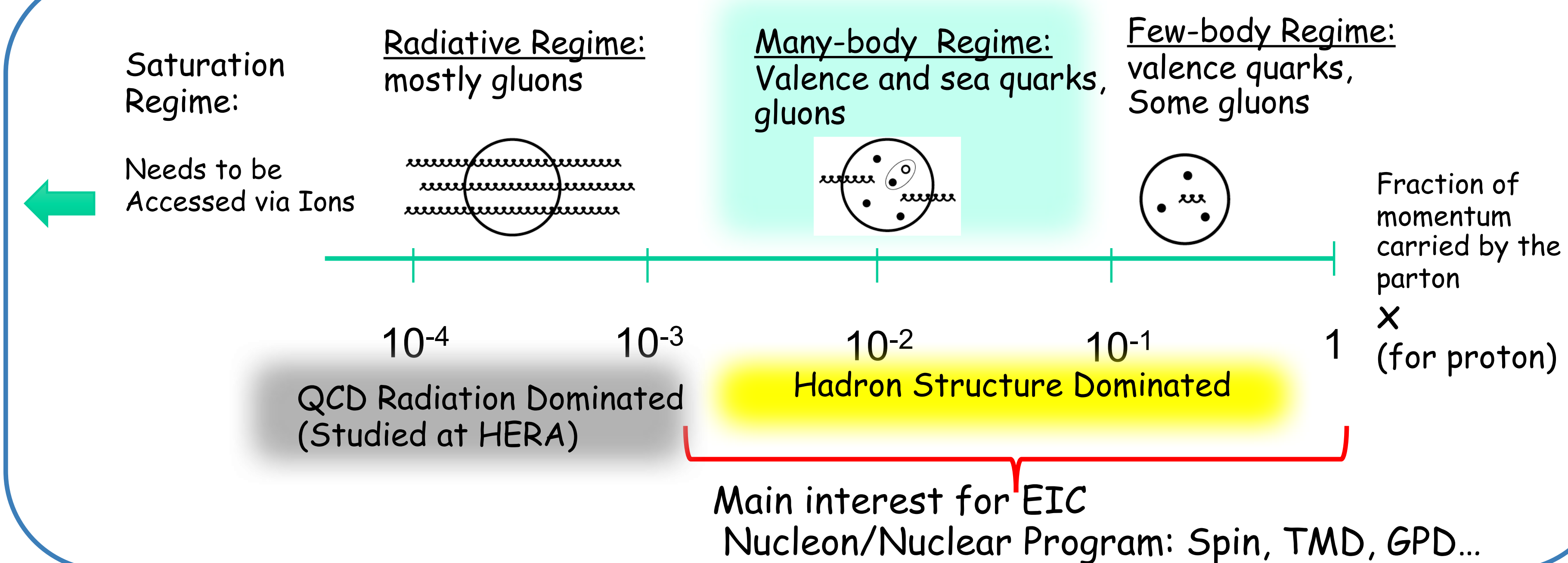
Ability to change Q^2 changes the resolution scale



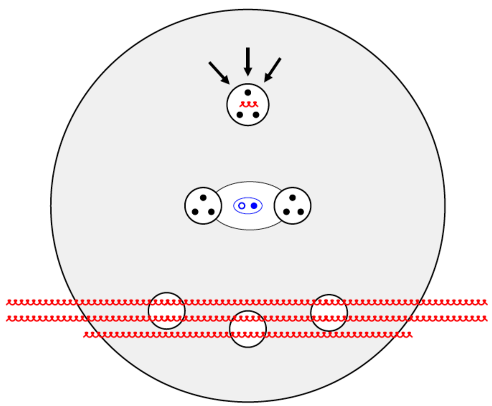
Ability to change **x** projects out different configurations where different dynamics dominate



Electron-Ion Collider range (x)



Nucleon interactions

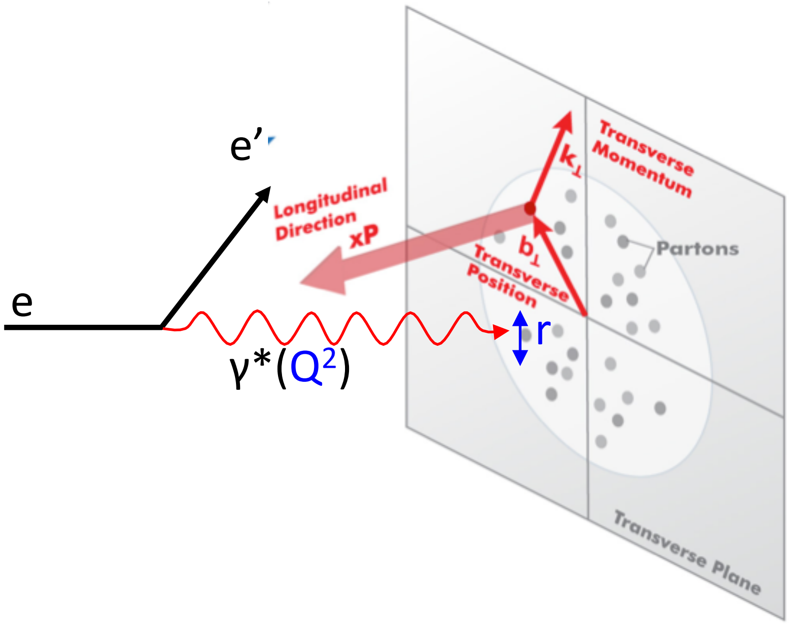


- x > 0.3 "EMC effect"
  Modified single-nucleon structure? Non-nucleonic degrees of freedom?
- x ~ 0.1 "Antishadowing"
  QCD structure of pairwise NN interaction, exchange mechanisms
- x < 0.01 "Shadowing"
  QM interference, collective gluon fields

3D Structure of Nucleons and Nuclei

3D Structure of Nucleons and Nuclei:

- Need to measure positions and momenta of the partons transverse to its direction of motion.
- These quantities (k_T, b_T) are of the order of a few hundred MeV.

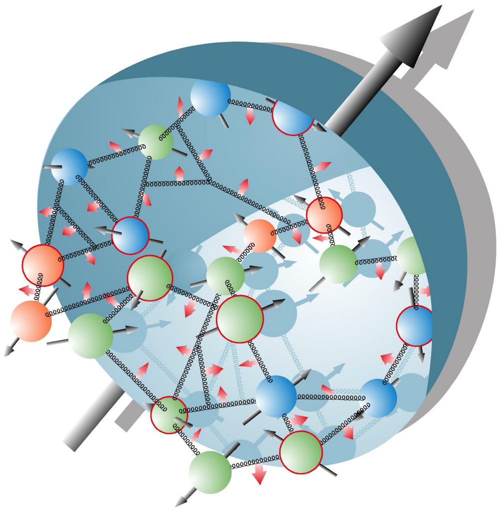


Transverse Momentum Dependent Distributions (TMD): k_t
Generalized Parton Distributions (GPD): b_t

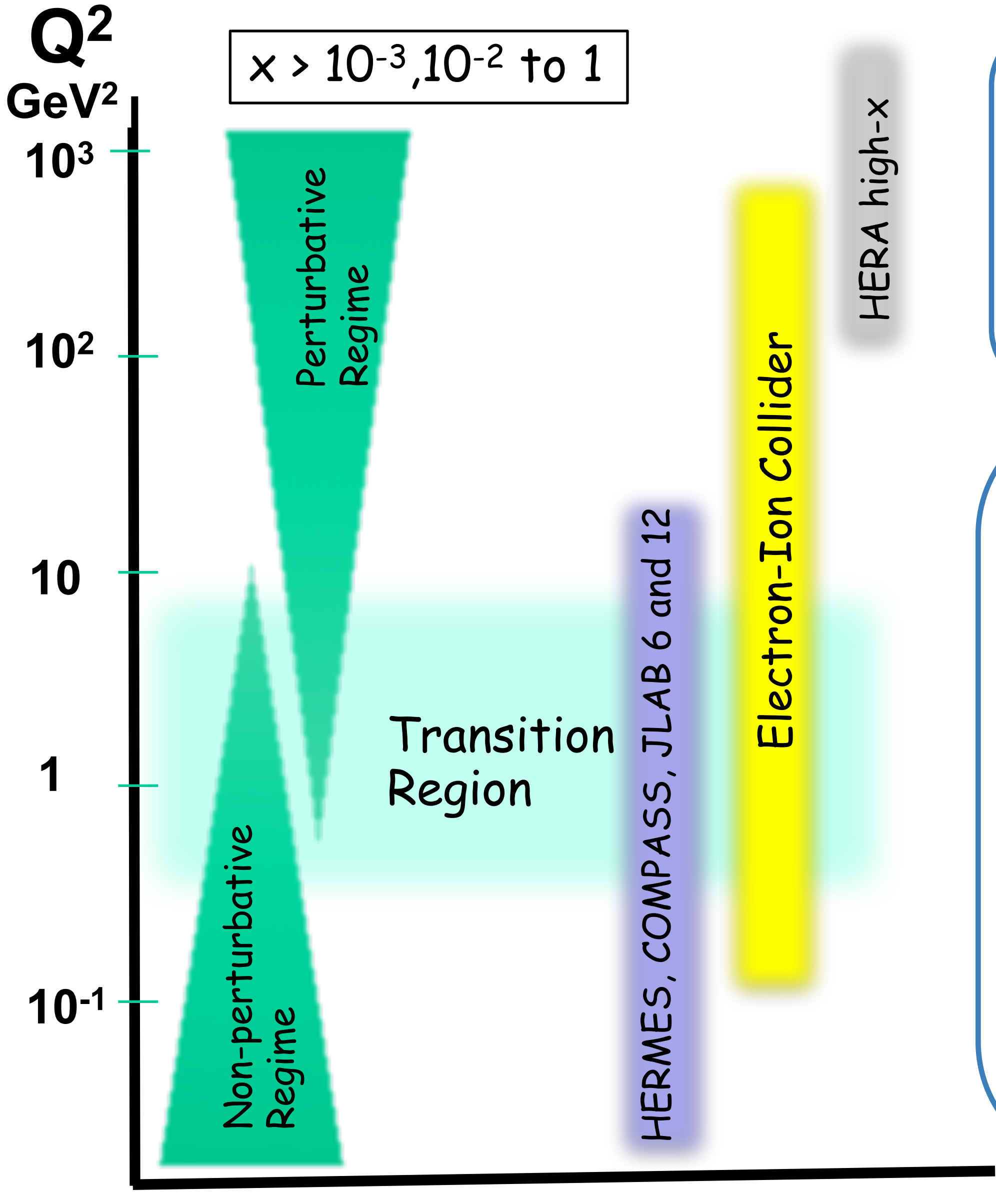
Polarizaton

Understanding hadron structure cannot be done without understanding spin:

- polarized electrons and
- polarized protons/light ions



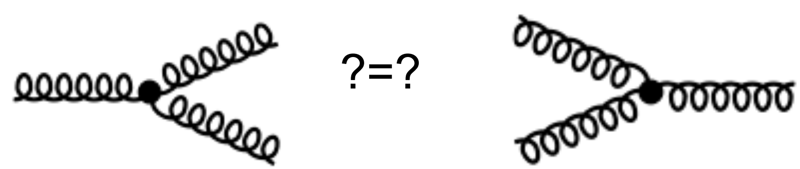
Electron-Ion Collider range (Q2)

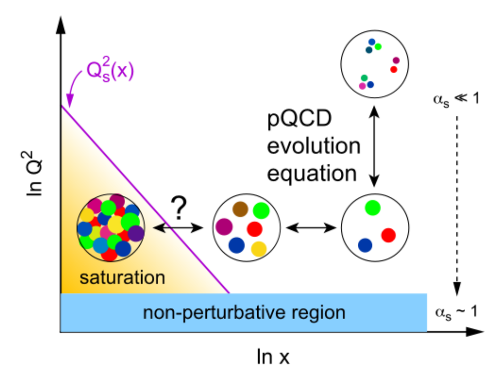


- Include non-perturbative, perturbative and transition regimes
- Provide long evolution length and up to Q^2 of ~1000 GeV^2 (~.005 fm)
- Overlap with existing measurements

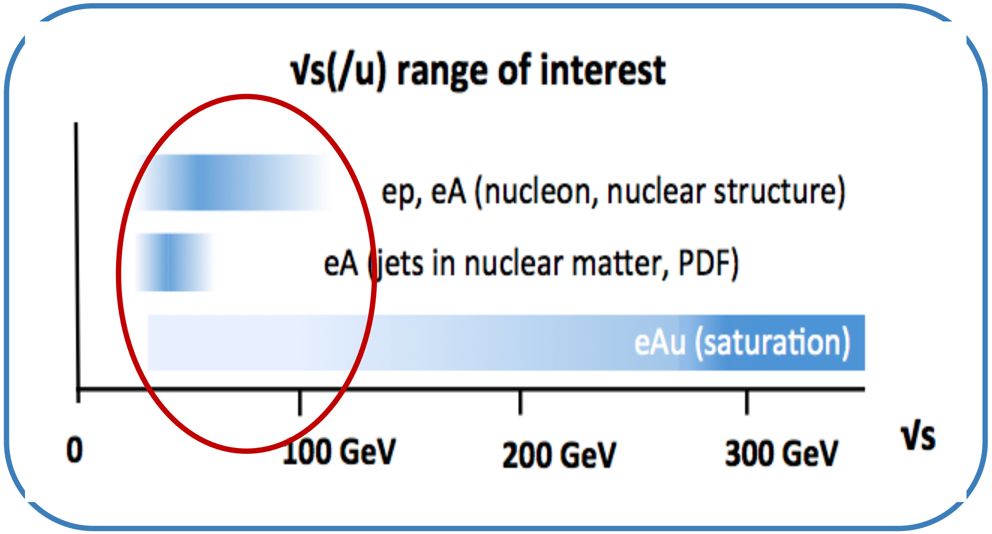
Saturation regime at EIC

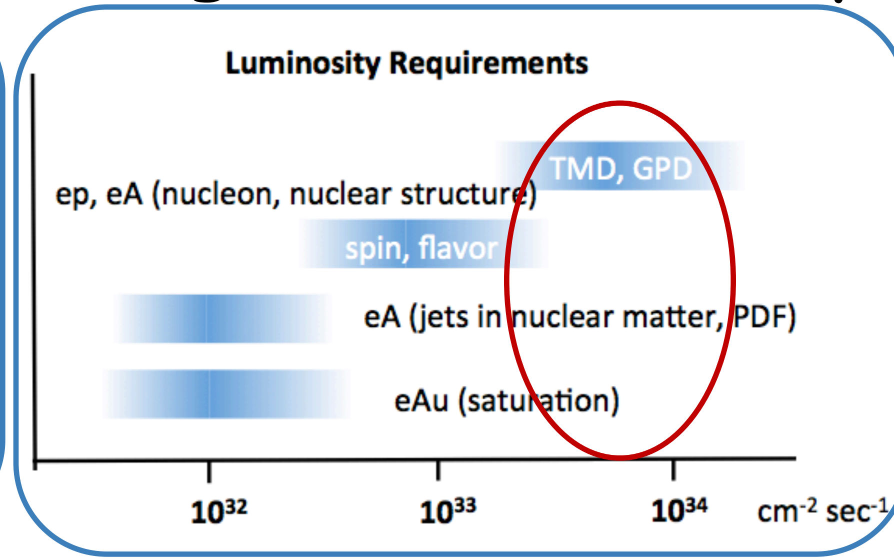
At very low x, cross-section will saturate.
could be investigated in transition region





Electron-Ion Collider: √s range and luminosity

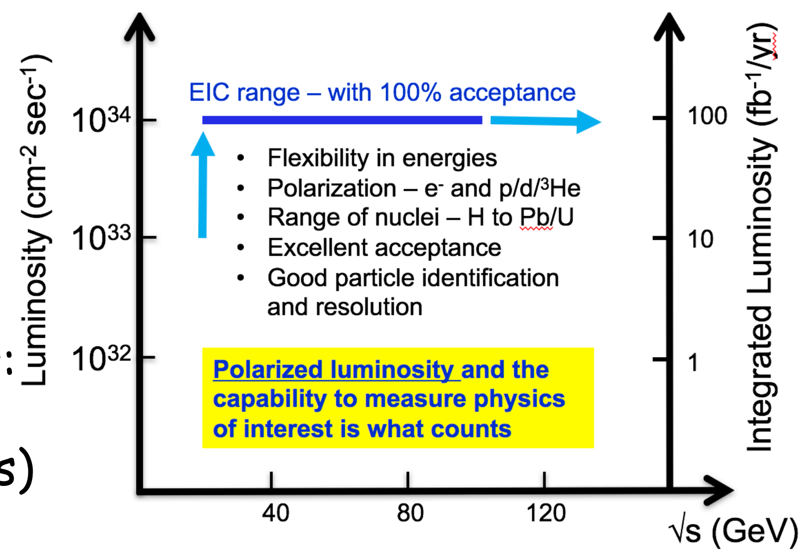




Beam energy:
Various center of mass energy (low, medium, high)

High luminosity :

- high precision physics
- rear physics
- various measurements/configurations: (different ions, different center of mass energies, different polarizations)



A high luminosity is needed to carry out the EIC physic program

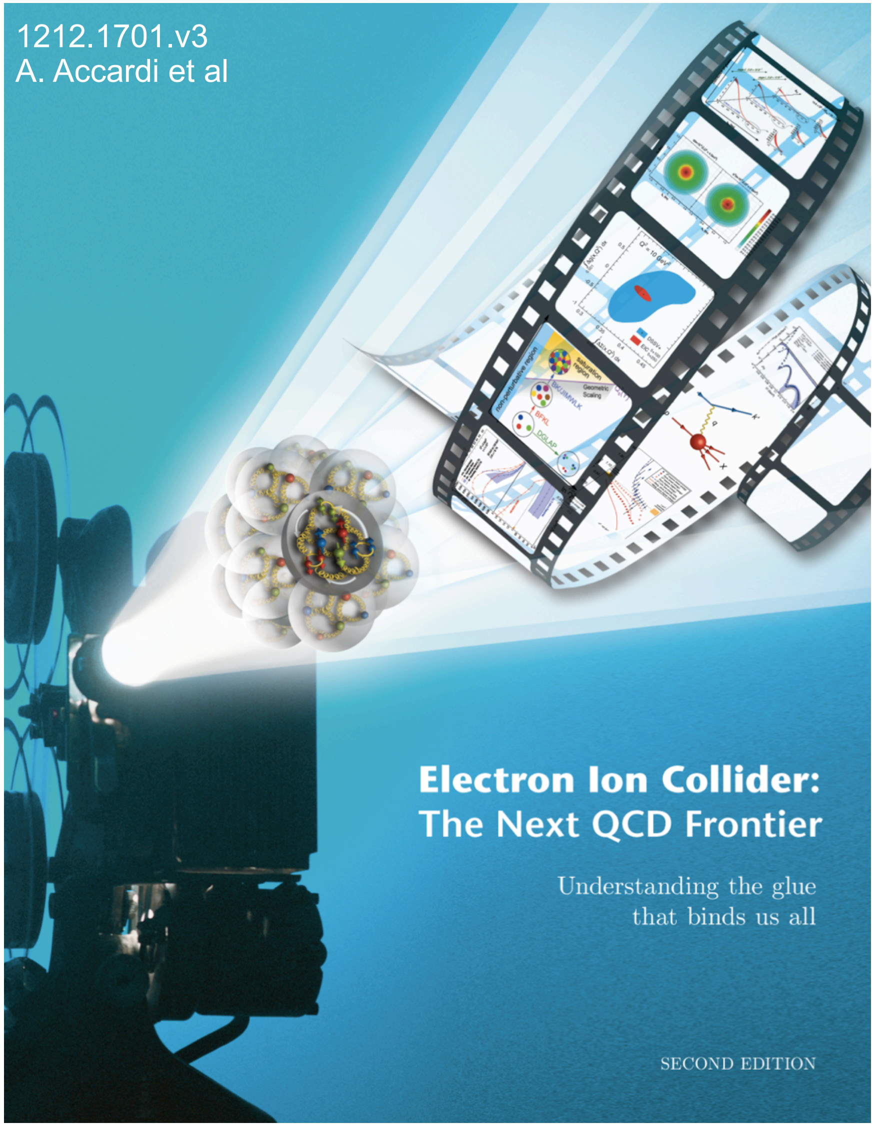
The Electron Ion Collider

For e-N collisions at the EIC:
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 3-10(20) GeV
- ✓ Luminosity L_{ep} ~ 10^{33-34} cm^{-2}sec^{-1}
- ✓ 100-1000 times HERA
- ✓ 20-~100 (~140) GeV Variable CoM

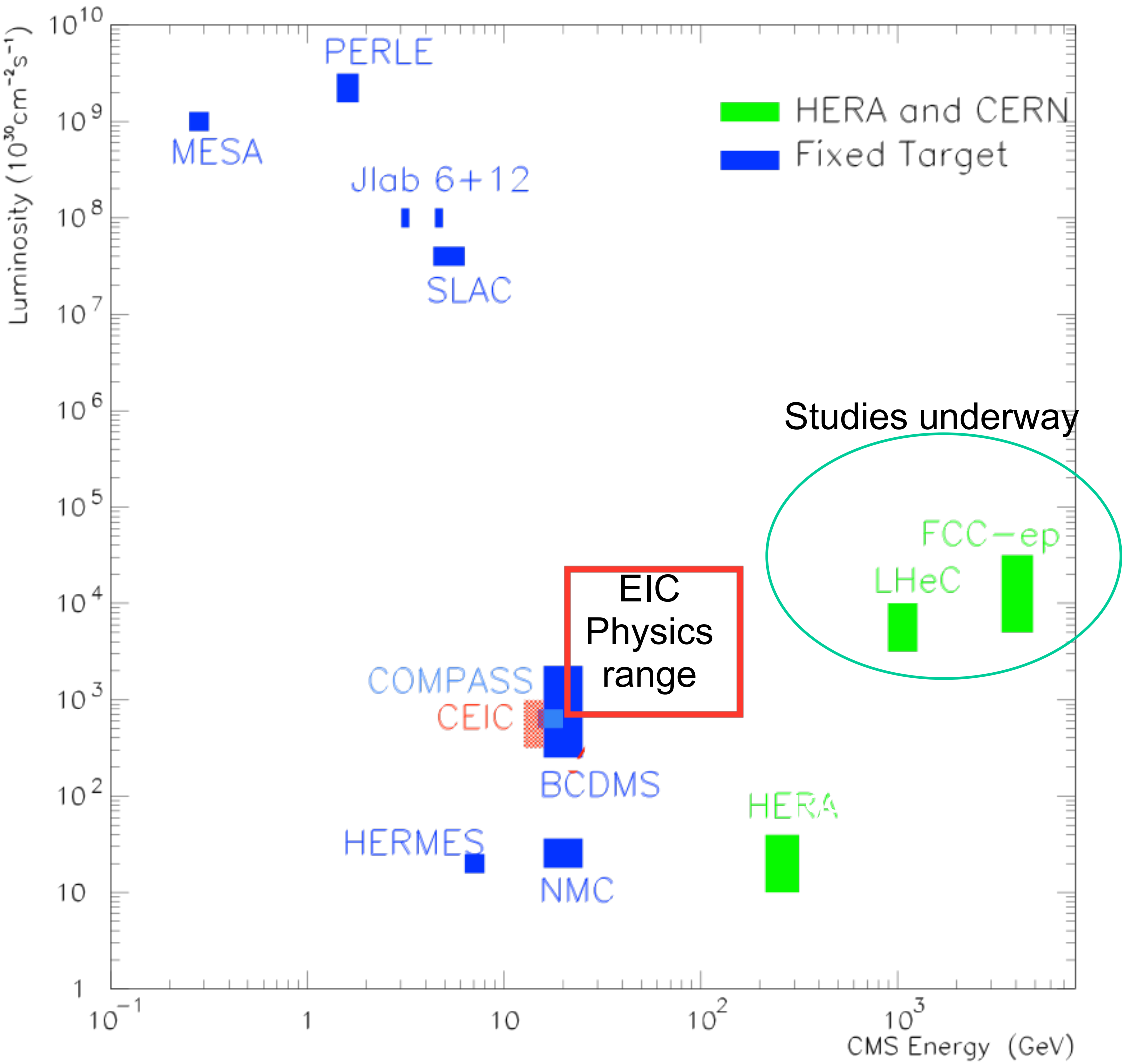
For e-A collisions at the EIC:
- ✓ Wide range in nuclei
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

Two proposals for realization of the science case -
both designs use DOE's significant investments in infrastructure



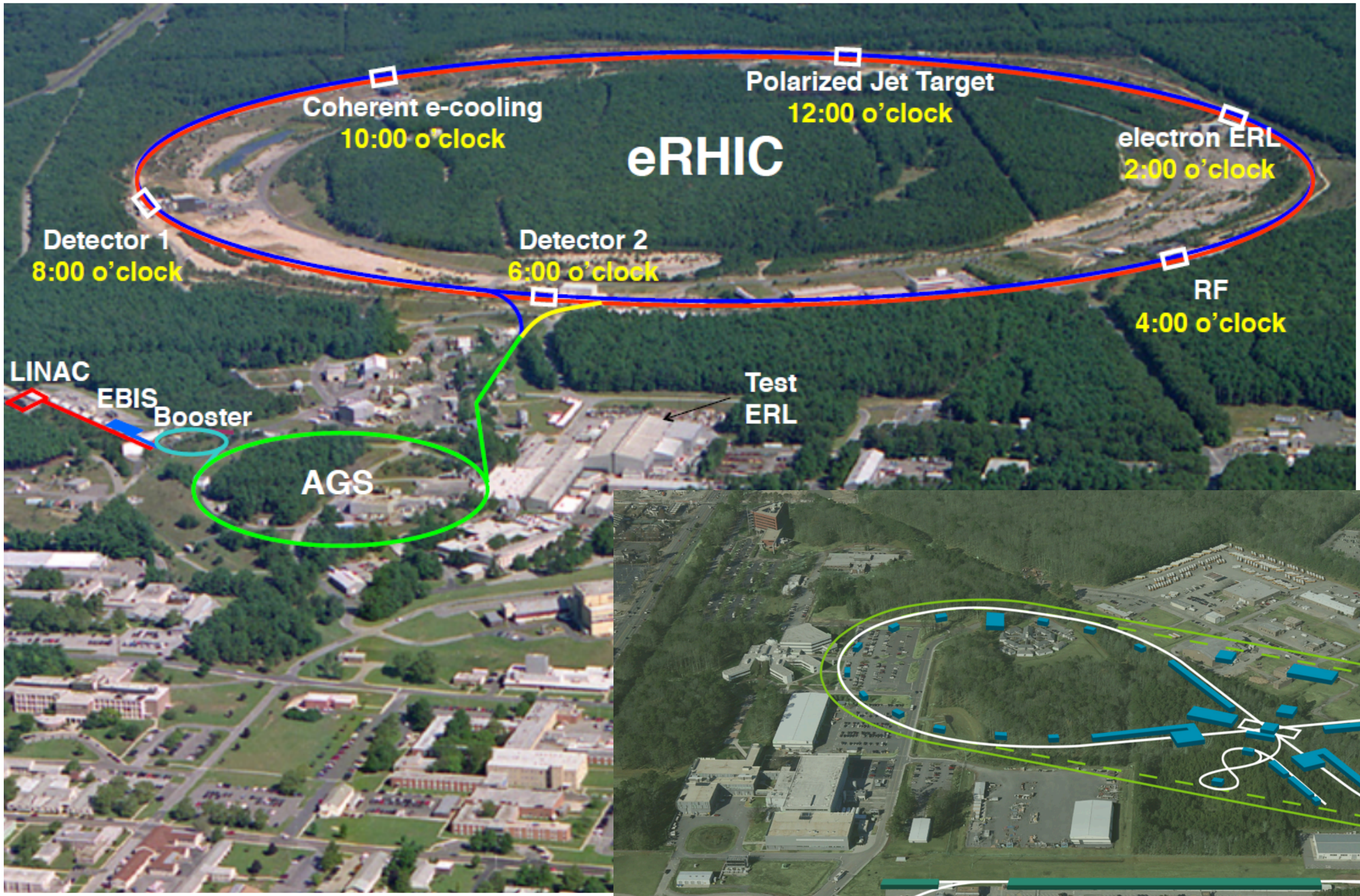
Past, existing and proposed DIS facilities



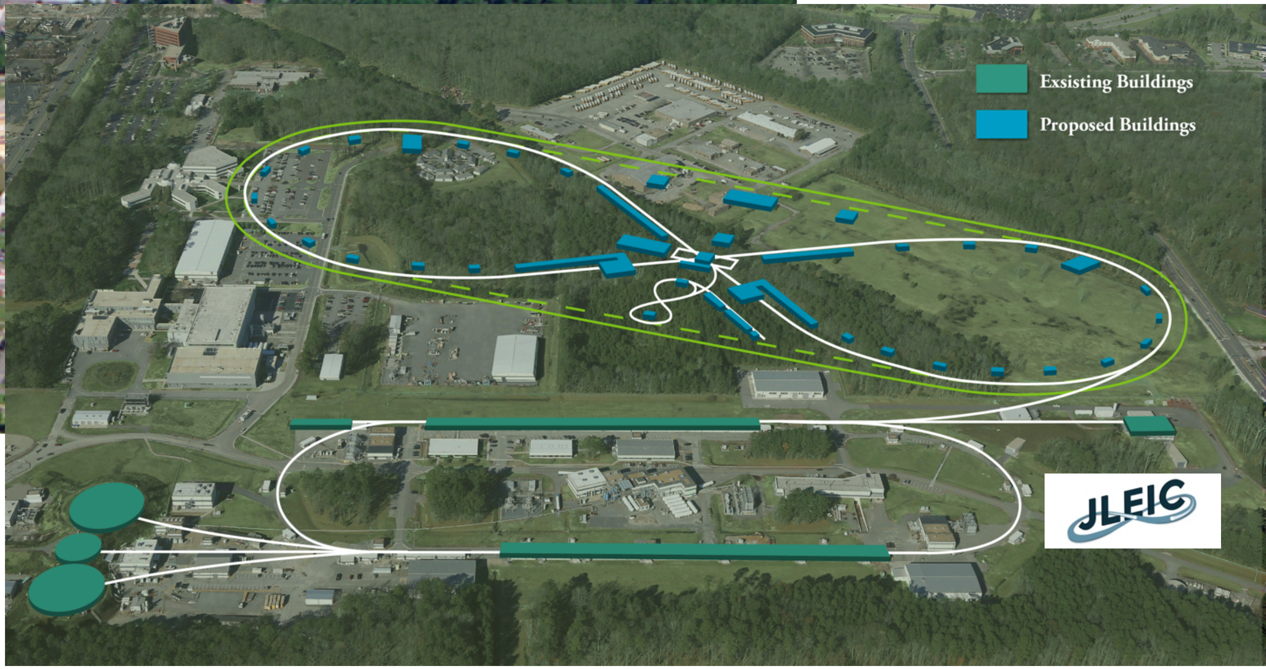
EIC will be a unique facility.

No other machine, existing or planned can address the physics of interest satisfactorily.

US-Based EIC Proposals



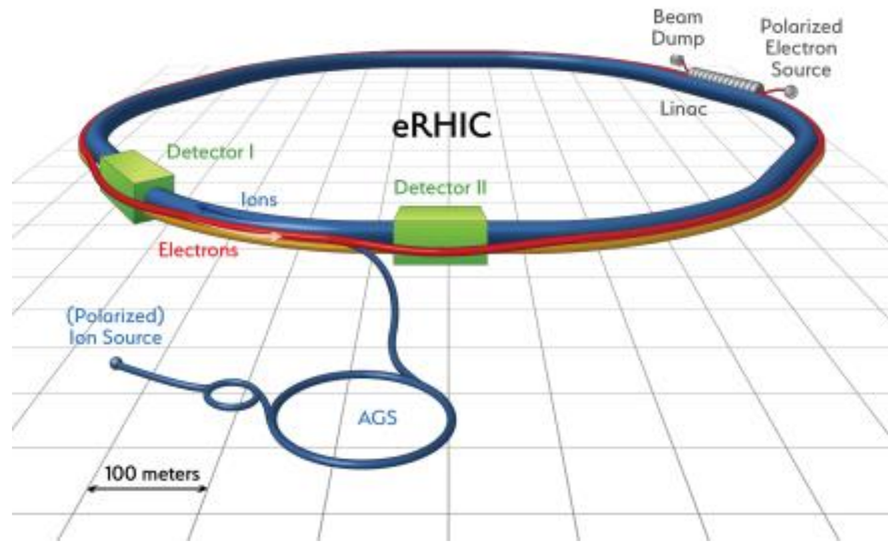
Brookhaven Lab
Long Island, NY



Jefferson Lab
Newport News, VA

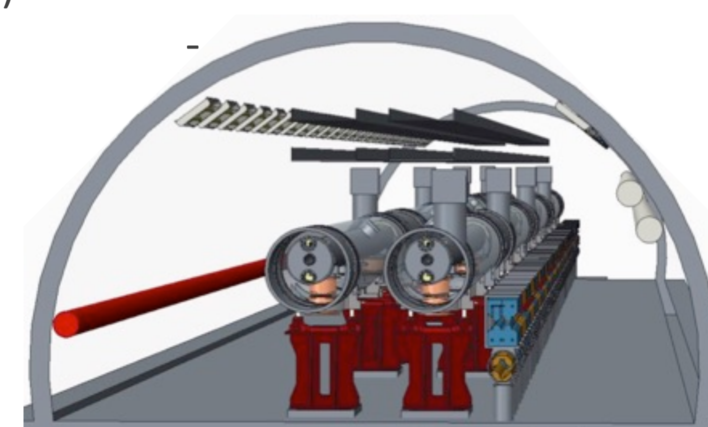
From F. Willecke, BNL

eRHIC design strategy



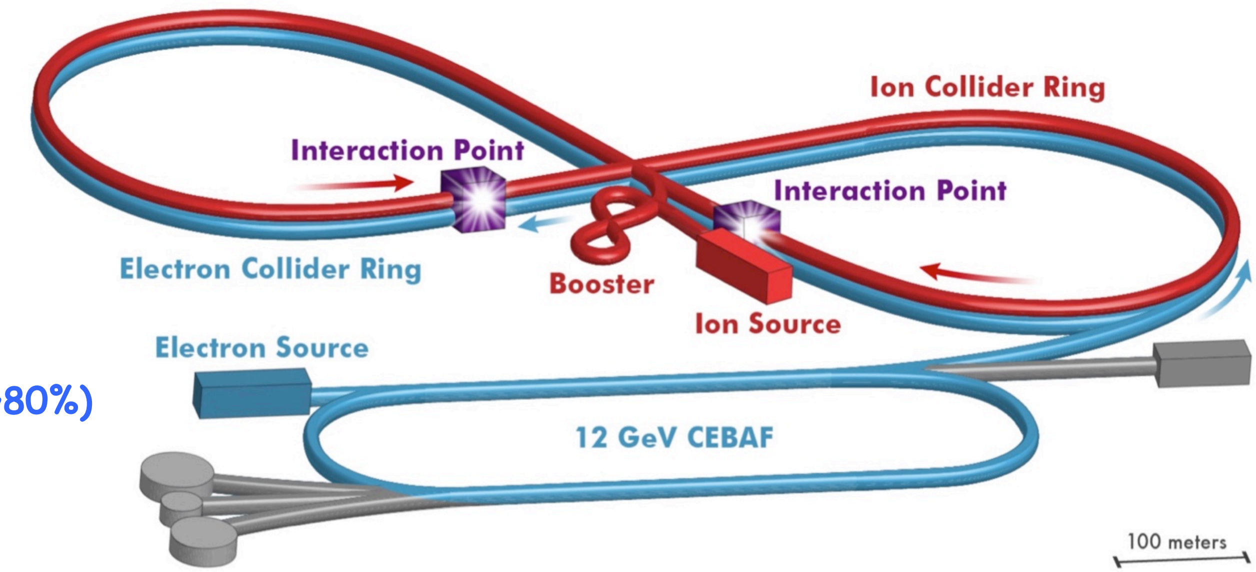
Exploiting RHIC with its
- superconducting magnets, 275 GeV protons
- its large accelerator tunnel and
- its long straight sections
- its existing Hadron injector complex

by
adding an electron accelerator
of 18 GeV in the same tunnel
- high energy reach in e-Ion collisions
- with modest synchrotron radiation, (low operating cost)
- making use of - superconducting LINAC technology -
and multi-turn recirculation
- using either the energy recovery (ERL) concept
or a high intensity electron storage ring
- achieve high luminosity electron-Hadron collisions
over a large range of CM Energies

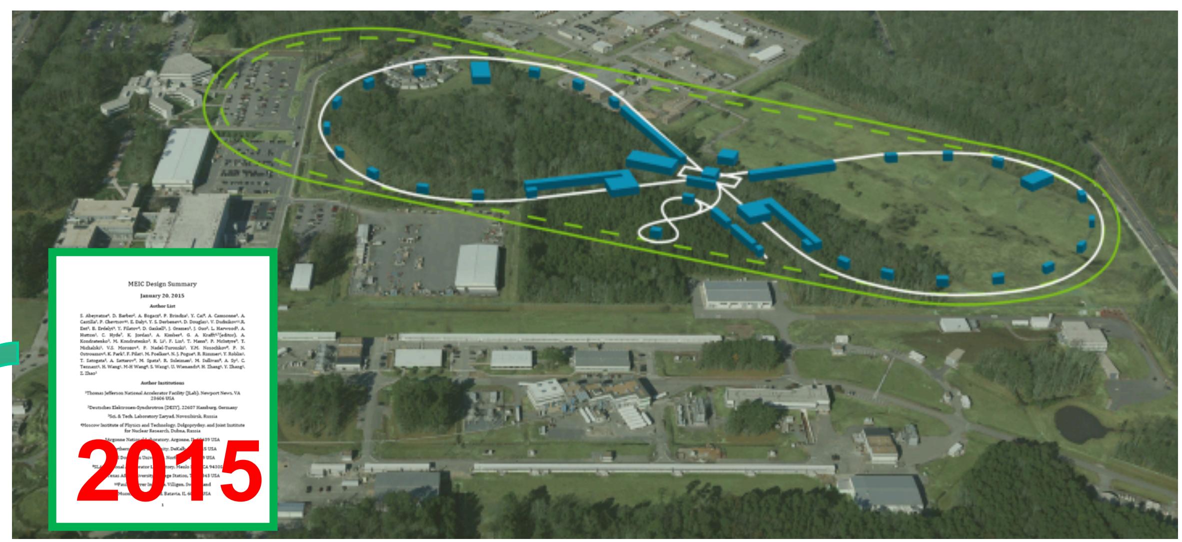


JLEIC design (Jan. **2017**)

energy range:
e-: 3 to 10 -12 GeV
p : 20 to 100-400 GeV
√s: 20 to **65-140 GeV**
(Magnet Technology Choice)

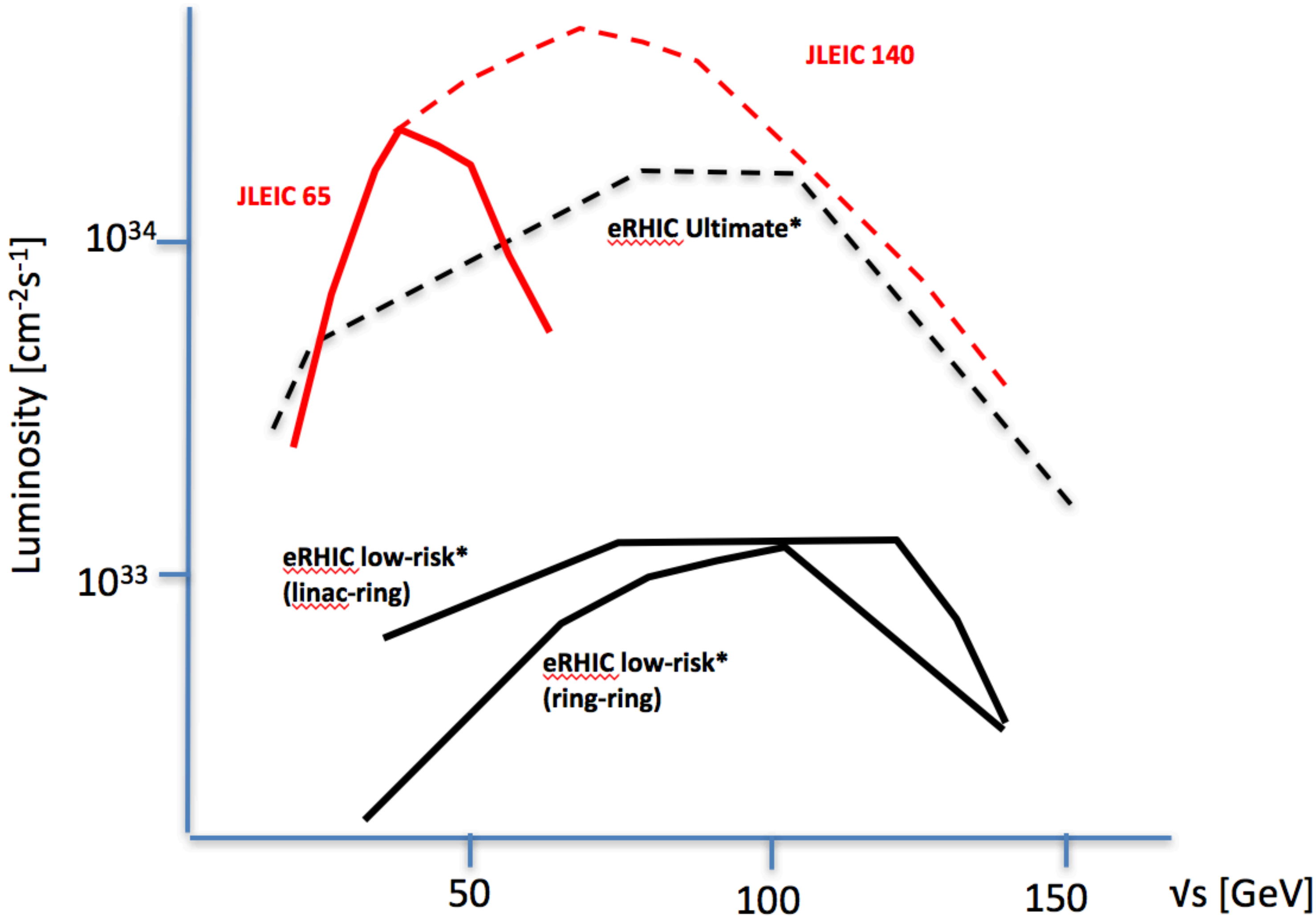


- Figure 8: High polarization (~80%)
- Electron complex
  - CEBAF
  - Electron collider ring
- Ion complex
  - Ion source
  - SRF linac
  - Booster
  - Ion collider ring
- Fully integrated IR and **detector**
- **2 Interaction Points possible**
- DC and bunched beam **coolers**



arXiv:1504.07961

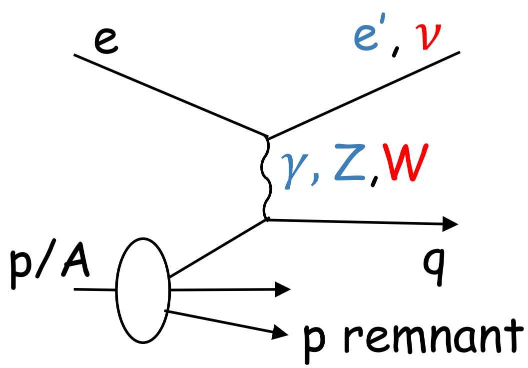
Comparison JLEIC and eRHIC (Jan. 2017)



*eRHIC parameters taken from F. Willike slides (F. Pilat talk) from EIC opportunities meeting for INFN, Genova (17 January, 2017)
JLEIC parameters can be found at eic.jlab.org/wiki (January, 2017 update)

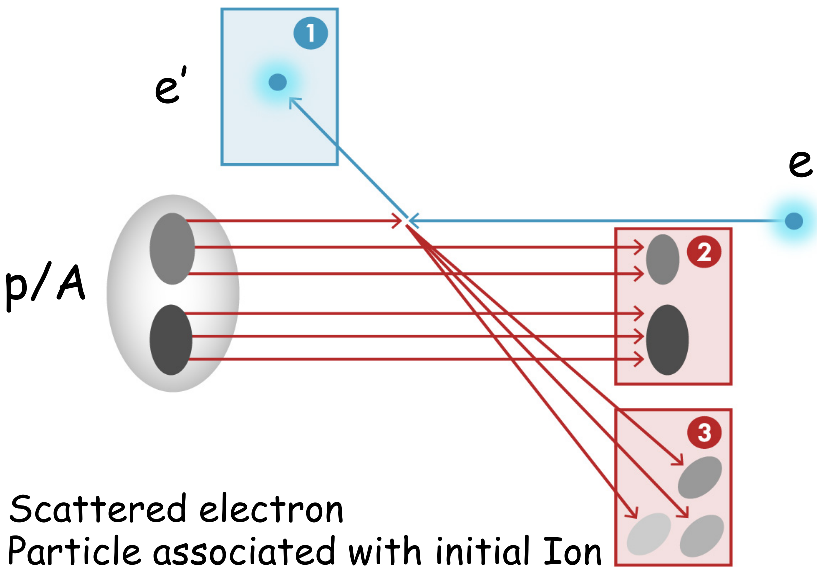
Deep inelastic scattering and General detector design considerations

Total acceptance detector



Aim of EIC is nucleon and nuclear structure beyond the longitudinal description.
This makes the requirements for the machine and detector different from all previous colliders including HERA.

"Statistics"=Luminosity × Acceptance



1. Scattered electron
2. Particle associated with initial Ion
3. Particle associated with struck quark

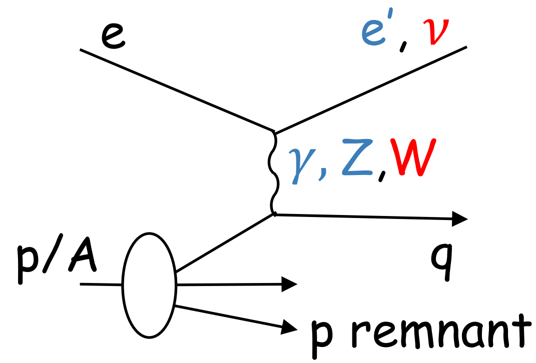
EIC Physics demands ~100% acceptance for all final state particles (including particles associated with initial ion)

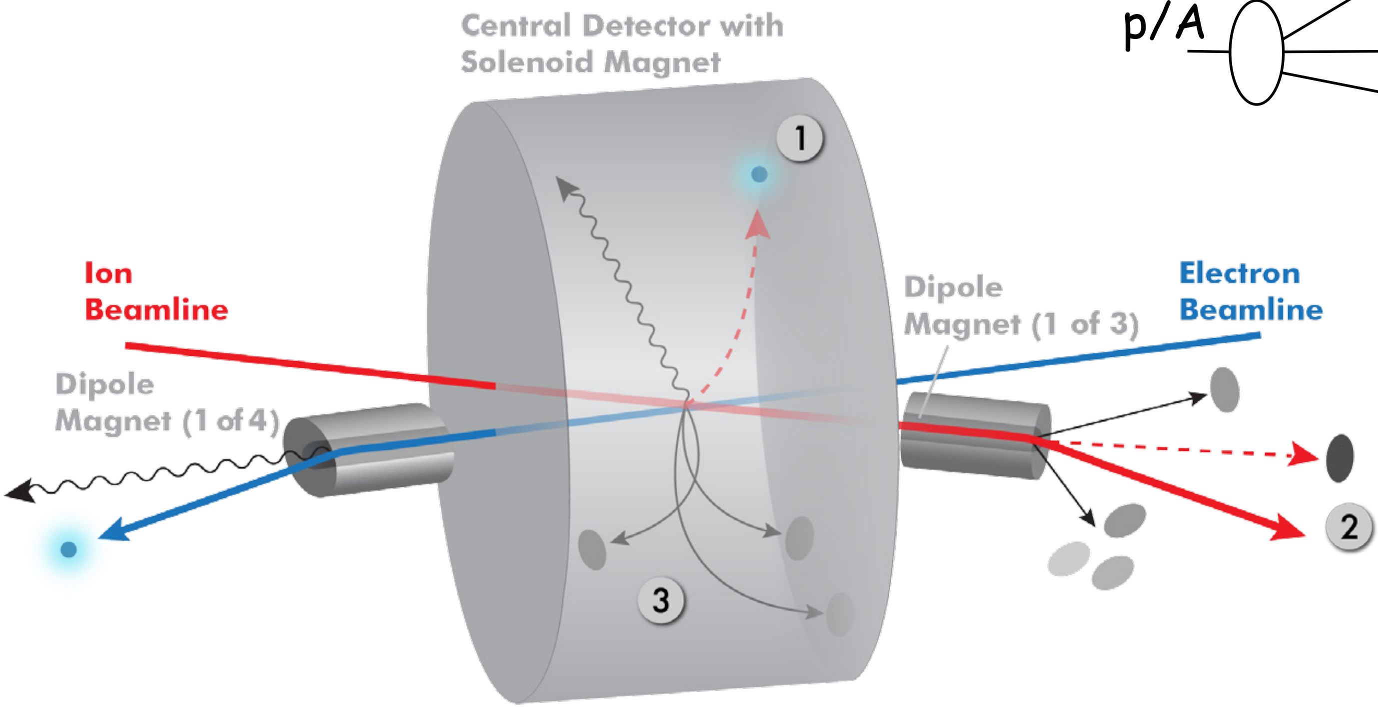
Ion remnant is particularly challenging

- not usual concern at colliders
- Higher the Ion Beam energy, more difficult to achieve.

Total acceptance detector

Beam elements limit forward acceptance
Beam crossing angle creates room for forward dipoles and gives a space for detectors in the forward regions





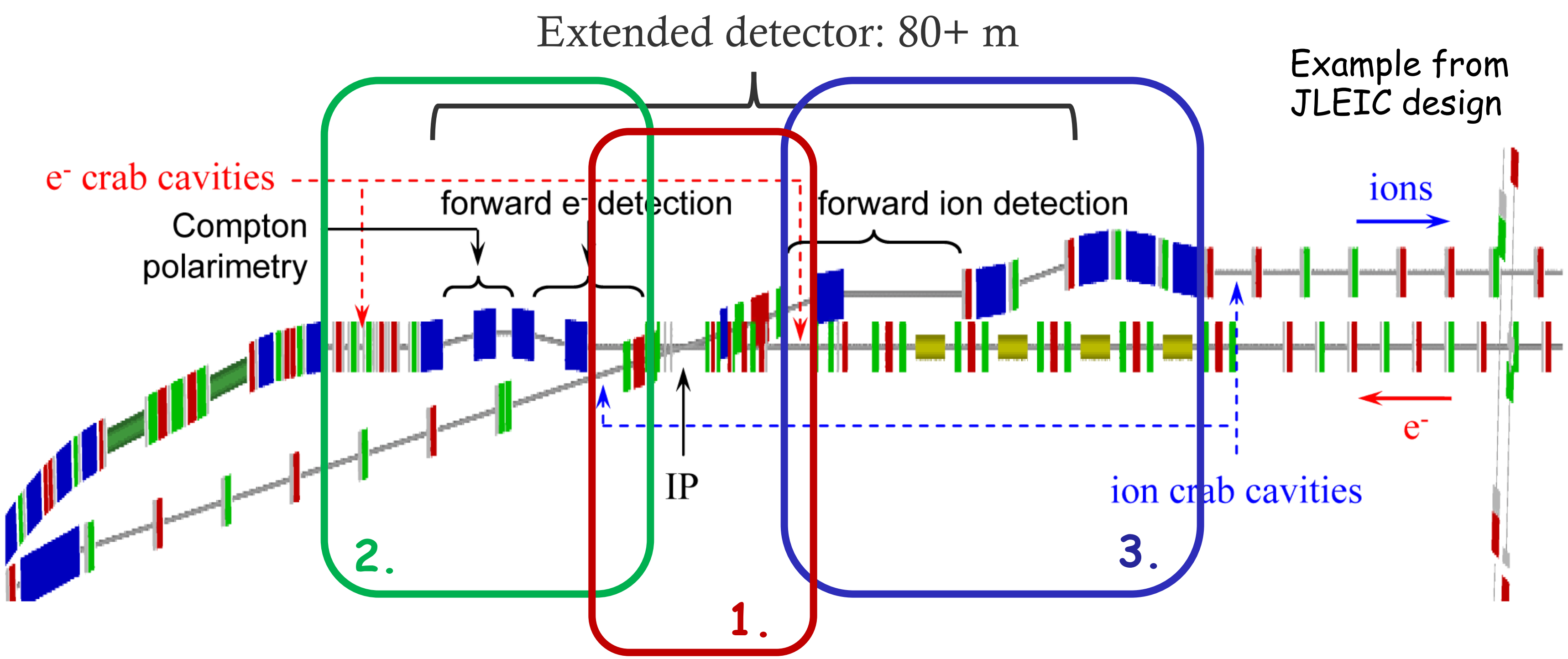
- Central detector - limitation in size:
  - -in R – size of solenoid magnet
  - -in L - a distance between ion quadrupoles which inverse proportional to luminosity

Need a Total acceptance detector (and IR) also for variable beam energies.

Integration with accelerator

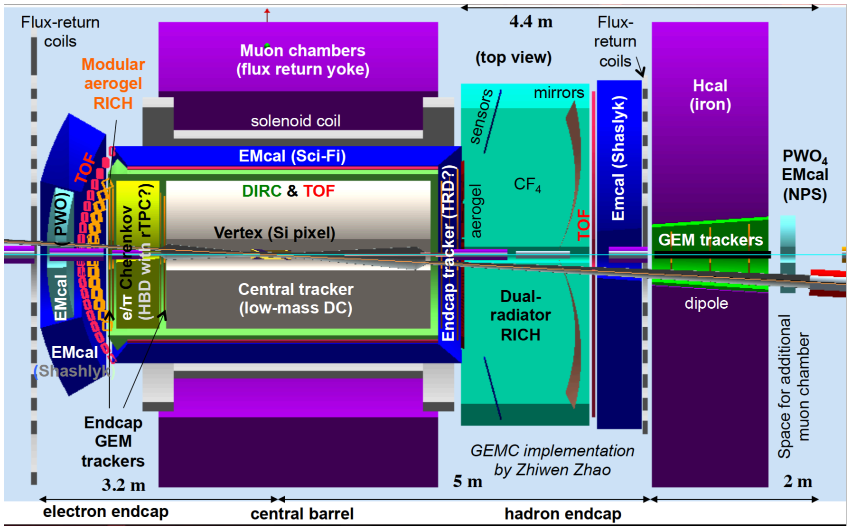
- IP placement (to reduce a background)
  -Far from electron bending magnets (synchrotron)
  -close to proton/ion bending (hadron background)

- Total size ~80m
1. Central detector ~10m
2. Far-forward electron detection ~30m
3. Forward hadron spectrometer ~40m

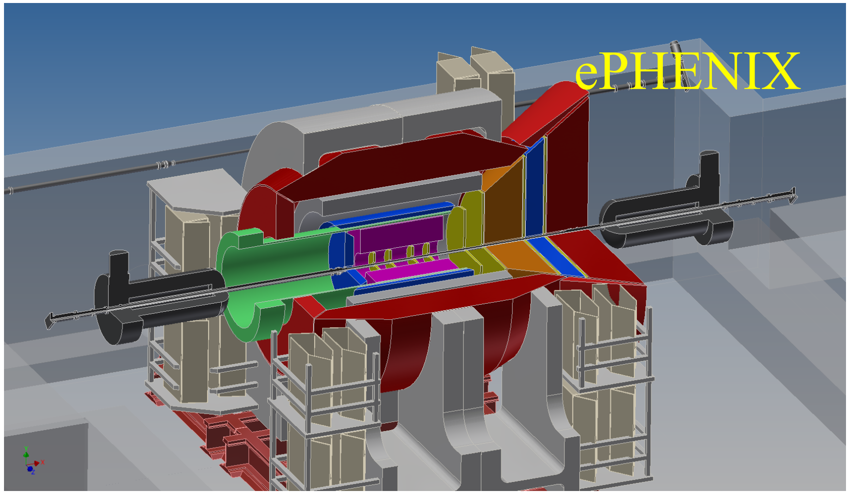


EIC Central detector overview

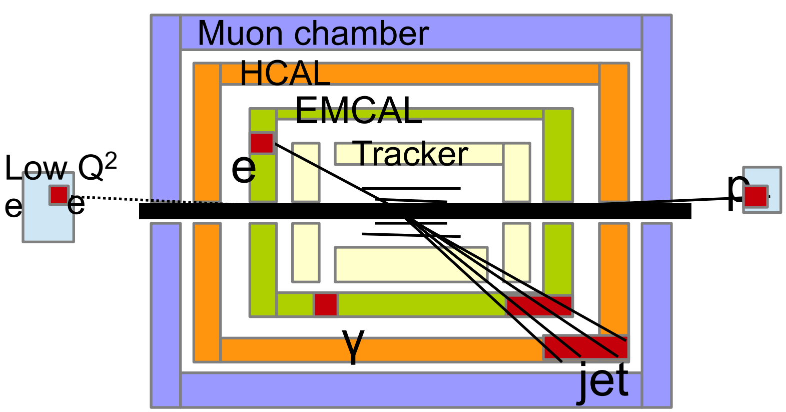
Jefferson Lab



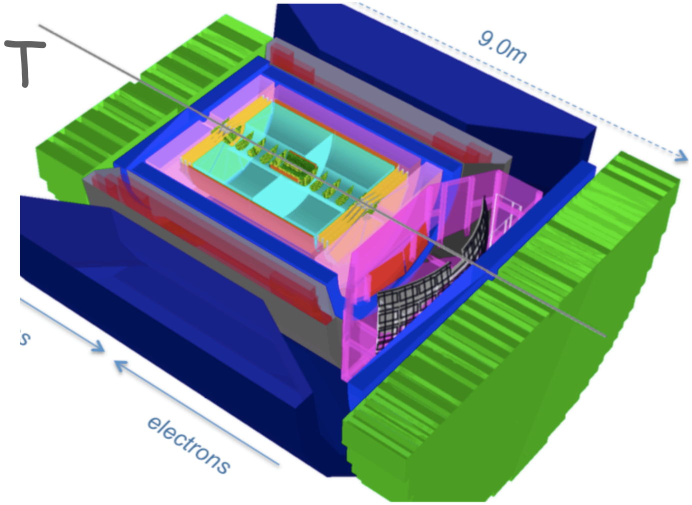
Brookhaven



2nd IP for jets



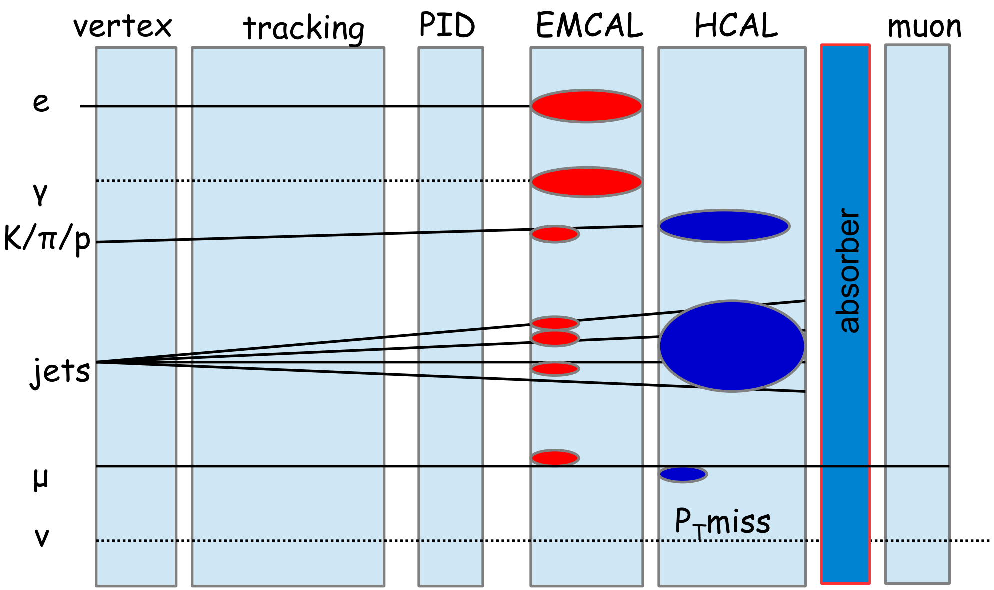
BeAST

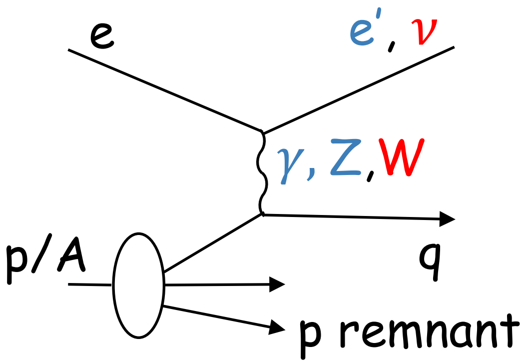


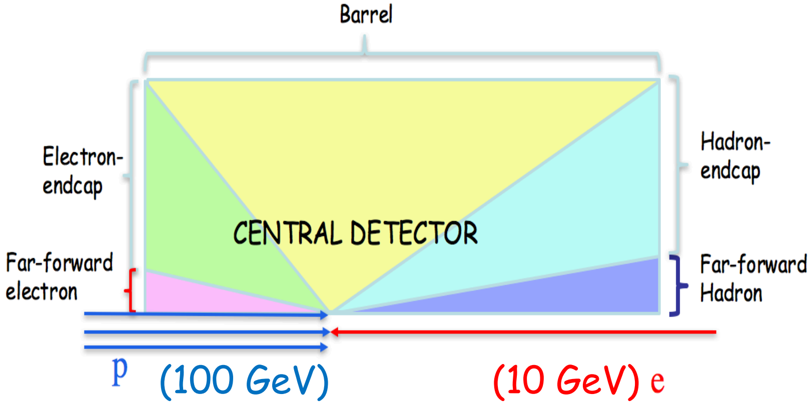
Modular design of the central detector

General structure of detectors

Stable particles (e,μ,π,K,p, jets(q,g), gamma, ν - P_T^{miss}):
Momentum/Energy, Type(ID), Direction, vertex







bunch crossing is every ~2ns

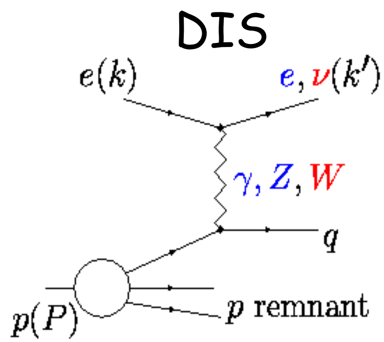
Pythia Minbias EIC (Q2> 10^{-6}) σ ~ 200 μb (HERA ~165 μb)
N events = σ•L ~ 2· 10^6 ev. per sec (2MHz) ~ 2 events / μs

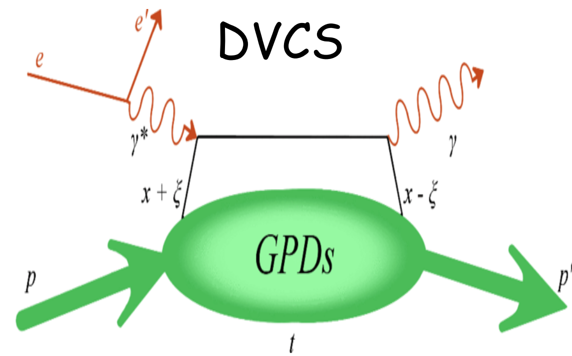
ZEUS/HERA(ep) ~3kHz

In order to reconstruct the kinematic x and Q^2 it is, in principle, sufficient to measure any two of these $E'_{e'}, \theta_{e'}, E_q, \theta_q$

EM Calorimeter

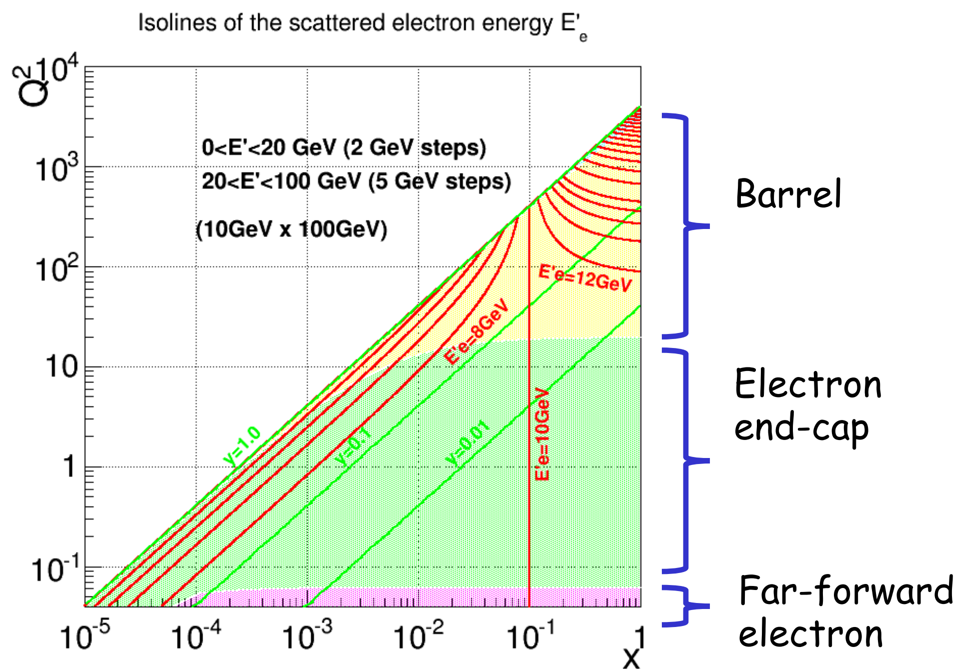
Electromagnetic Calorimeters measure EM showers and early hadron showers:
Energy, position, time





$PbWO_4$ Crystal EM Calorimeter

-Tungsten glass, similar to CMS or PANDA
- Time resolution: <2 ns
- Energy resolution: <2%/√E(GeV) + 1%
- Cluster threshold: 10 MeV
- Produced at two places (China, Russia)
- For CMS it took 10 years to grow all crystals !!!



Sampling EM Calorimeter

- **Shashlyk** (scintillators +absorber)
-WLS fibers for readout
-**Sci-fiber EM(SPACAL):**

- Compact W-scifi calorimeter, developed at UCLA
- Spacing 1 mm center-to-center
- Resolution ~12%/√E
- On-going EIC R&D

- PWO for e-endcap - close to the beam – more precise and more radiation hard.
- Shashlyk for barrel– less expensive

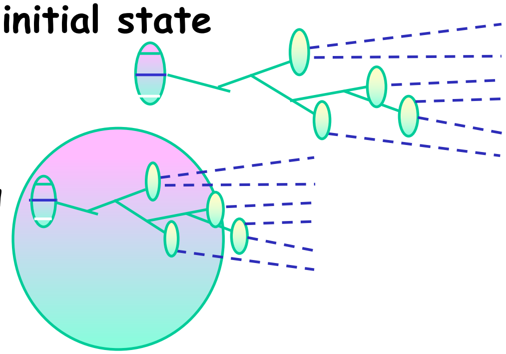
Jets at EIC and HCAL

Neutral current DIS

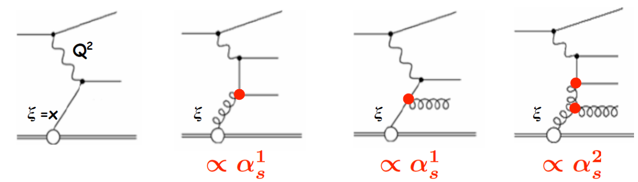
1) **Jets evolution and dynamics (jet == struck quark)**

2) **Jets as a probe of partonic initial state**

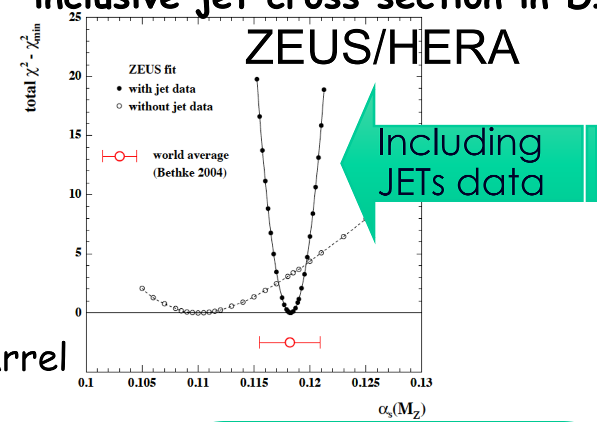
3) **Jets in medium (cold nuclear matter)**
   - ✓ energy loss, quenching
   - ✓ broadening
   - ✓ multiple-scattering.



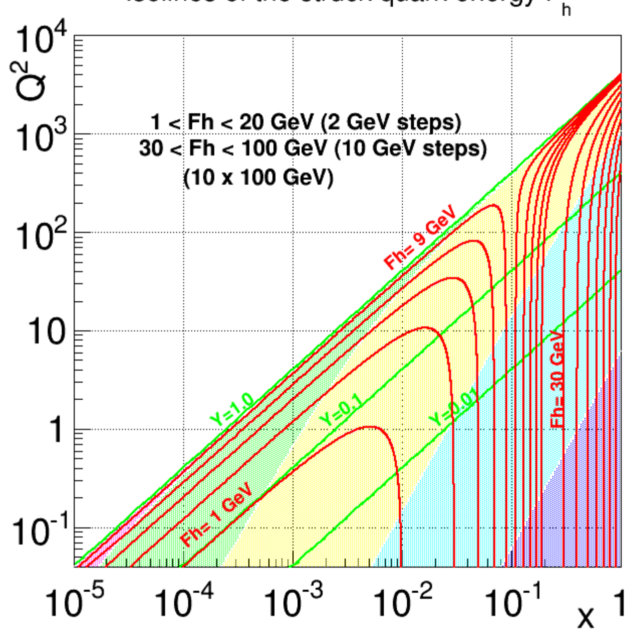
At EIC for the first time will be able to study in-medium propagation and hadronization of heavy quarks (charm and beauty)



Determination of α_s from the inclusive jet cross section in DIS



Isolines of the struck quark energy F_h



Barrel

Hadron end-cap

Far-forward hadrons

Charged current DIS

Neutrino in the final state =>
- Could use only jets to reconstruct a kinematics(x,Q2)
- Need 4π HCAL coverage for $P_T$miss

Could EIC data improve α_s measurements?
HCAL with poor resolution : $\sigma_E/E \sim 60\%/\sqrt{E}$
Uranium Calorimeter at ZEUS: $\sigma_E/E \sim 35\%/\sqrt{E}$
Need a new method for jet energy measurements!
⇒ Particle Flow Calorimeter ?

Tracking

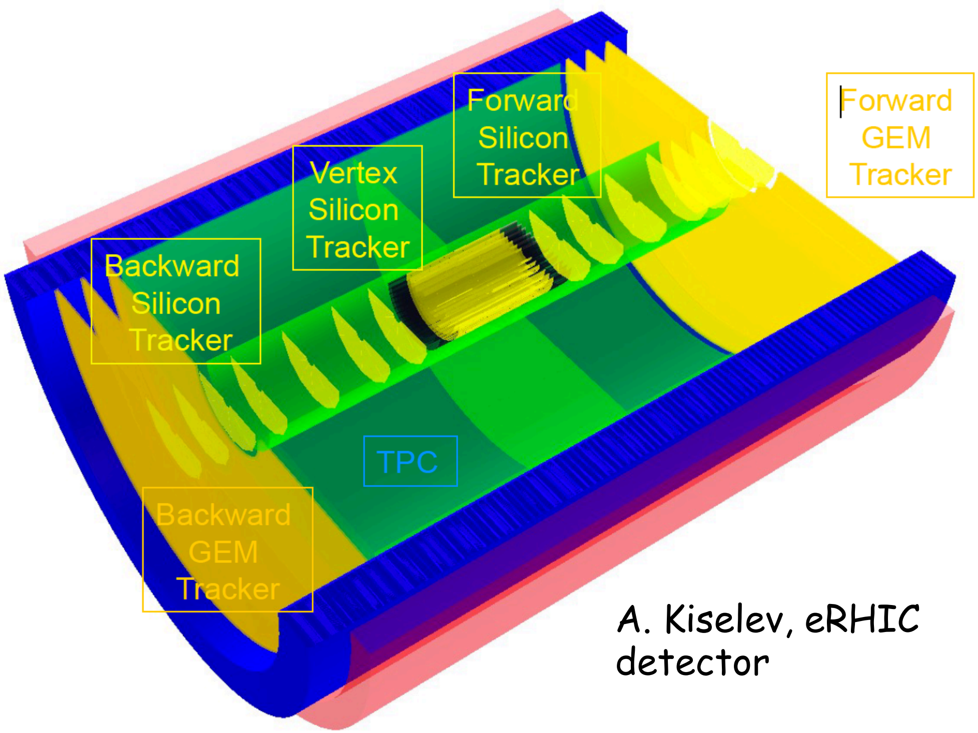
Main purpose of tracking:
-reconstruct charged tracks and measure their momenta precisely (~few %)
-dE/dx (PID) for low momentum tracks.

Barrel: TPC or drift chambers

- relatively fast detector,
- minimal multiple scattering
- limited PID

Endcaps: GEM

- High multiplicity in forward hadron region – we need a high granularity tracker
  resolution ~50 μm.
- Radiation hardness



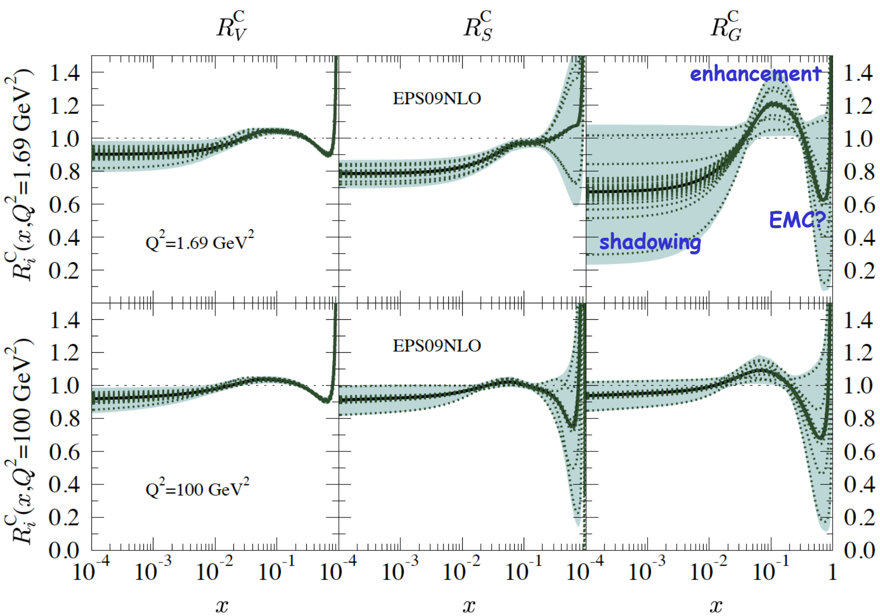
A. Kiselev, eRHIC detector

Vertex

Main purpose of vertex detector:

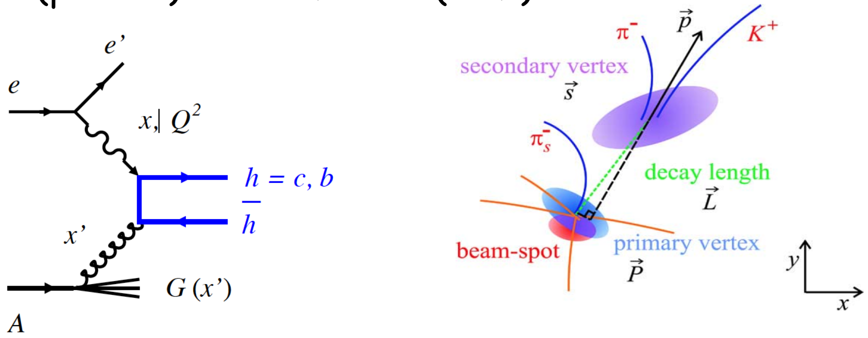
-Reconstruction of a primary vertex
-Reconstruct secondary vtx:
Tagging of c and b quarks (decay length ~100-500μm)
-improve momentum resolution of outer tracker
-provide stand-alone measurements of low-Pt particles
-dE/dx measurements for PID

Nuclear PDF parametrization EPS09 Eskola et al. 2009

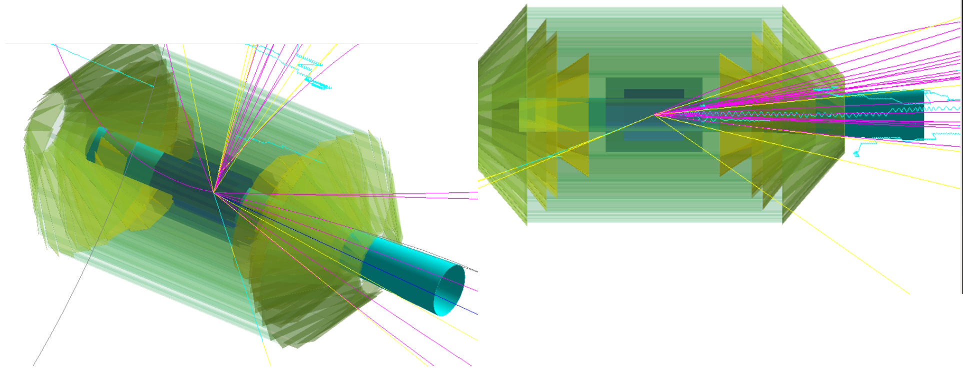


Heavy quarks

Boson (photon)- Gluon Fusion (BGF)



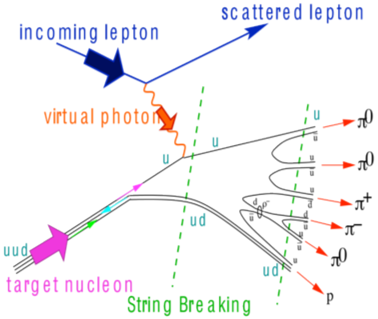
Charm high-Q2 event in the vertex detector

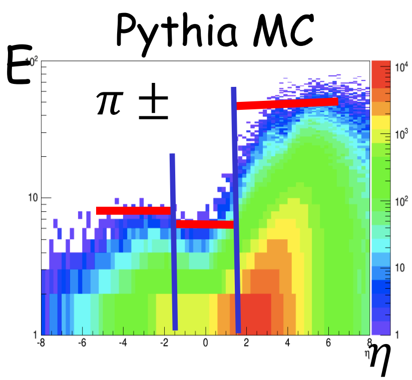


Vertex detector is a closest to IP detector.
Background increase an occupancy.
High granularity detector is needed (pixels)
Beam related background could cause a radiation damage.

Hadrons Identification

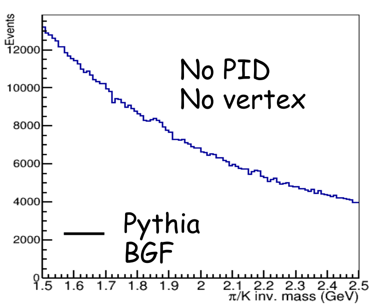
<u>Semi-inclusive DIS:</u> involves measurements of one or more final-state hadrons in addition to the detection of the scattered lepton.

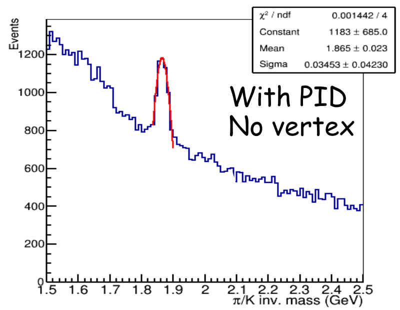




<u>Exclusive processes:</u>

D0 mass plots: $D^o \rightarrow K^- \pi^+$





Time of Flight: MRPC

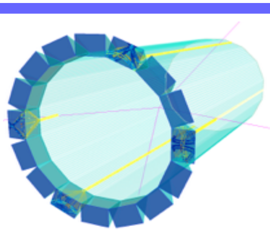
Multi-gap Resistive Plate Chamber (MRPC) R&D: achieved ~18 ps resolution with 36-105 μm gap glass MRPC π/K <3.5GeV

Electron end-cap: Modular RICH

- Modular aerogel RICH (eRD14 detector R&D)
- π/K separation up to ~10 GeV

Barrel: DIRC

- radially compact (2 cm)
- Particle identification (3σ) p/K < 10 GeV, π/K < 6 GeV, e/π < 1.8 GeV



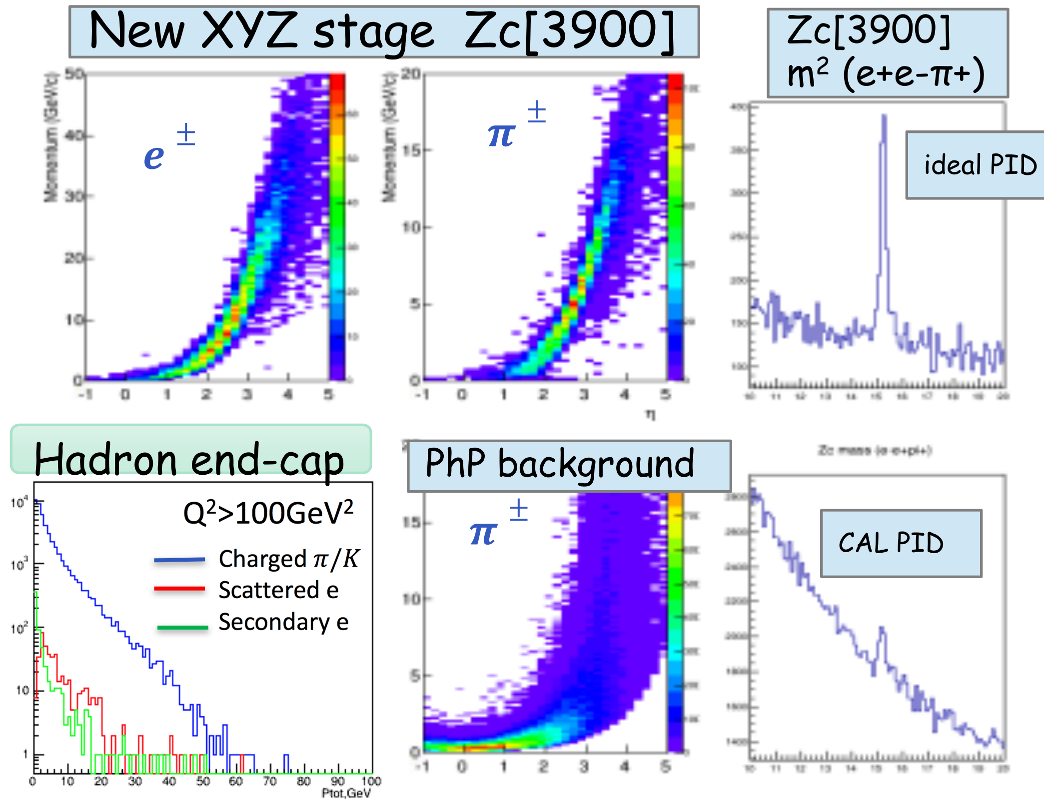
Hadron end-cap: dual-radiator RICH

- JLEIC design geometry constraint: ~160 cm length
- Aerogel in front, followed by CF4
- covers energy for π/K up to 50GeV
- Sensitive to magnetic field=> New 3T solenoid minimized a field in RICH region

σ(Zc[3900]) ~5 nb
σ(PhP, Q^2<1GeV) ~ 10^4nb

Electron Identification

Thanks to Justin Stevens



Physics:

- ✓ For rare physics, based on electron identification
- ✓ Charmonium, light vector mesons (ρ,ω,φ)
- ✓ Tetraquarks and Pentaquarks (and other XYZ states)
- ✓ Open Charm and Beauty physics
- ✓ Di-lepton production
- ✓ Scattered electron identification at Large-x, large-Q2

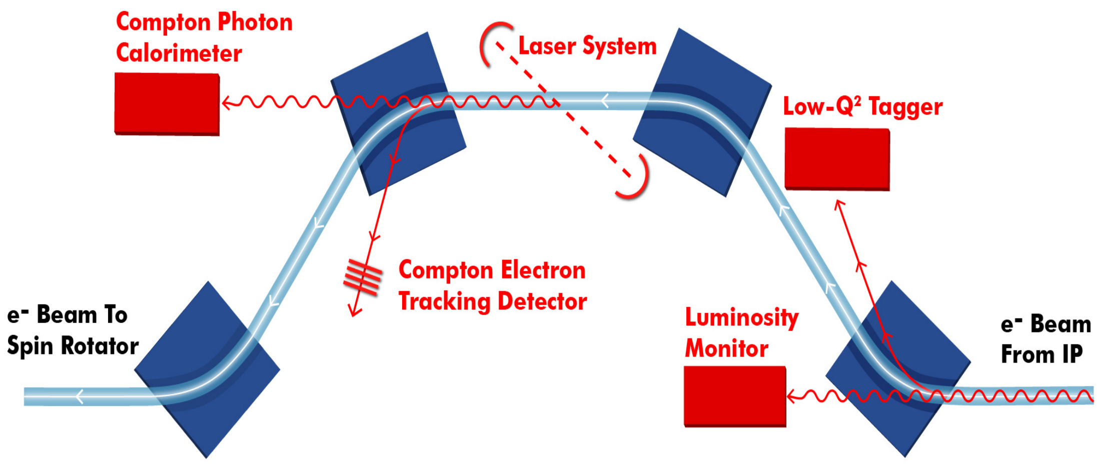
Transition radiation (TRD) for electron/hadron rejection: GEM/TRD

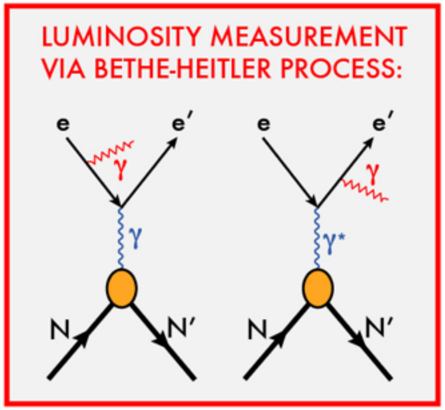
- combined high granularity tracker and PID.
- cover energy range 1-100GeV.
- provide additional e/hadron rejection factor 10-100.

Excellent e/π PID in the hadron endcap region is needed for electrons with energy 1-100GeV

Chicane for Electron Far-Forward Area

Example from
JLEIC design



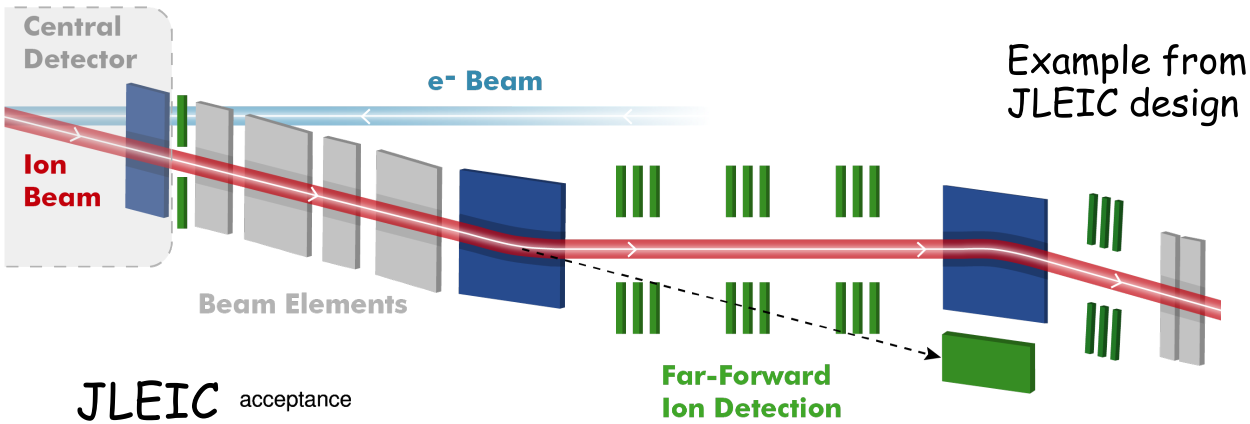


- **Low Q2 tagger**
- ✓ For low Q^2 electrons

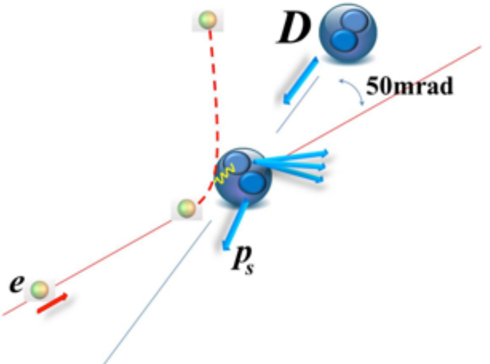
- **Luminosity monitor:**
- ✓ Luminosity measurements via Bethe-Heitler process
- ✓ First dipole bends electrons
- ✓ Photons from IP collinear to e-beam

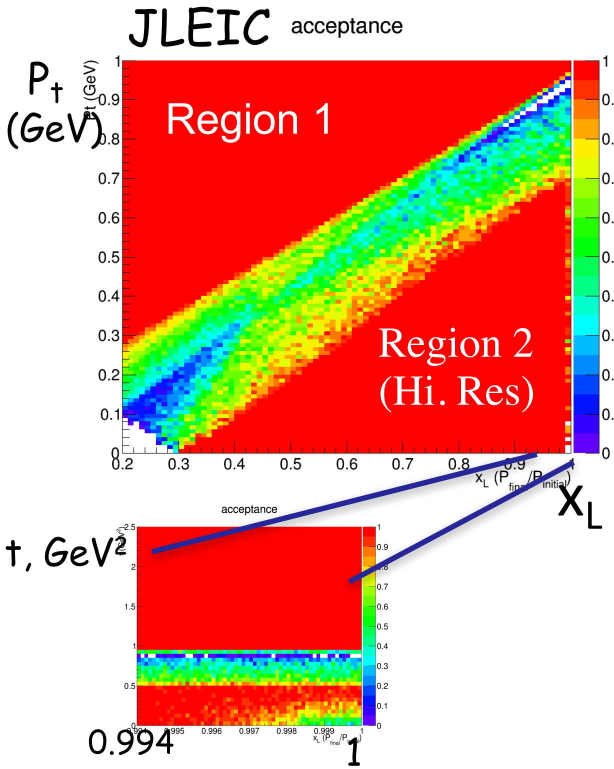
- **Polarization measurements**
- ✓ First two Dipoles compensate each other
- ✓ The same polarization as at IP
- ✓ Minimum background and a lot of space.
- ✓ Measurements of both Compton photons and electrons

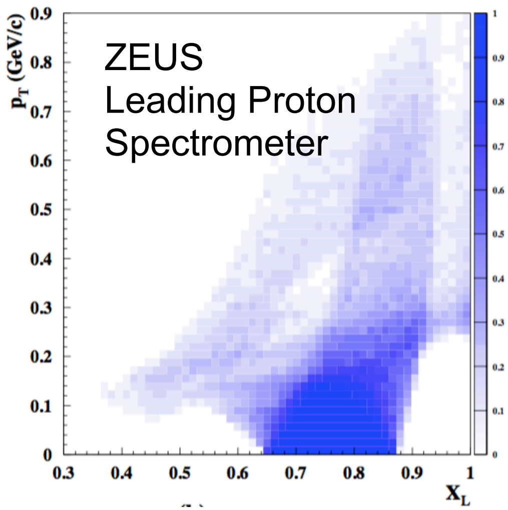
Far-forward ion direction area



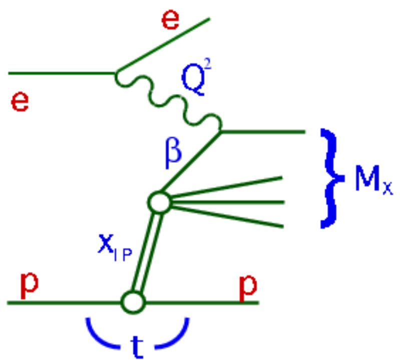
Example from JLEIC design







Diffraction



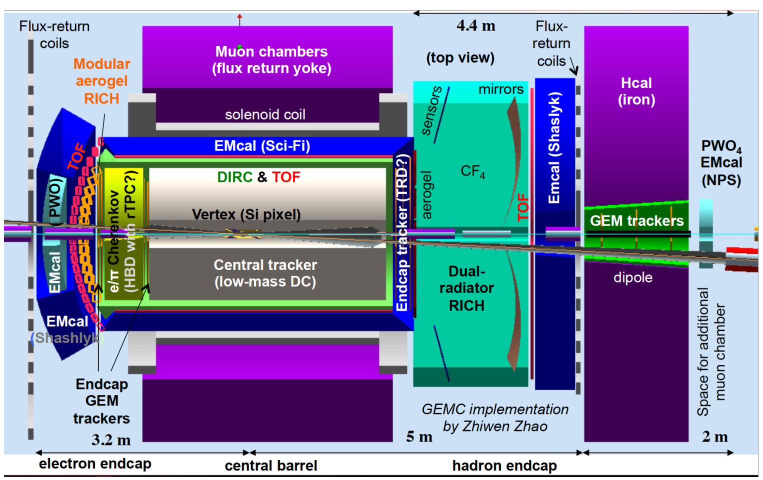
Acceptance in diffractive peak (x_L>0.98):
ZEUS ~2%
JLEIC ~100%

One detector or two?

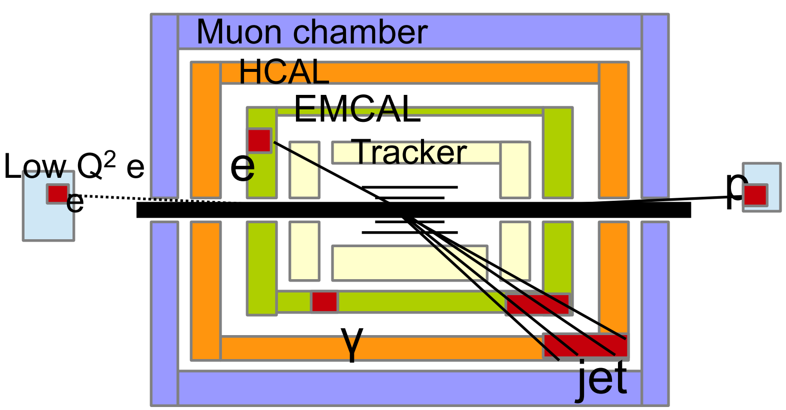
- Combine results for precision measurements
- Increase scientific productivity
- Cross-checks on discoveries and important physics results
- Provide complementary measurements

Example:

1st IP for single particle ID

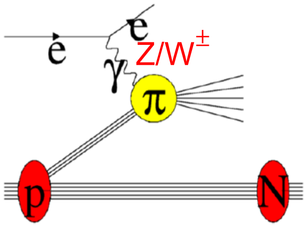


2nd IP for jets



Electron-Ion or Positron-Ion Collider ?

- Electroweak Pion and Kaon structure functions



$$A = \frac{\sigma_R^{CC,e^+} \pm \sigma_L^{CC,e^-}}{\sigma_R^{NC} + \sigma_L^{NC}}$$

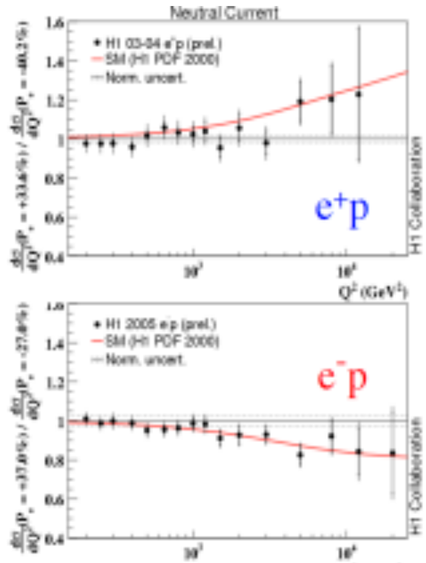
- Parity violation in weak neutral current at EW scale: observed for the first time in DIS

$$A^{\pm} = \frac{2}{P_R - P_L} \cdot \frac{\sigma_{NC}^{\pm}(P_R) - \sigma_{NC}^{\pm}(P_L)}{\sigma_{NC}^{\pm}(P_R) + \sigma_{NC}^{\pm}(P_L)} \qquad P_R > 0 \quad P_L < 0$$

- Charged Current DIS (W+ vs W-): up-type or down-type flavors

$$\frac{d^2\sigma(e^+p)}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2 + Q^2}\right)^2 \{(\bar{u} + \bar{c}) + (1-y)^2(d+s)\}$$

$$\frac{d^2\sigma(e^-p)}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2 + Q^2}\right)^2 \{(u + c) + (1-y)^2(\bar{d}+\bar{s})\}$$



- Neutral Current DIS

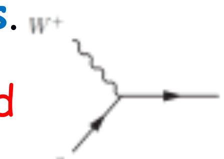
- Four lepton beams (+ and -, L and R) give vector- and axial-vector coupling of quarks (mainly u and d quarks)

- The difference between the e+p and e-p NC cross sections give direct access to the structure function xF3 .

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}[\tilde{\sigma}(e^-p) - \tilde{\sigma}(e^+p)]$$

- Charm production in Charged Current DIS:

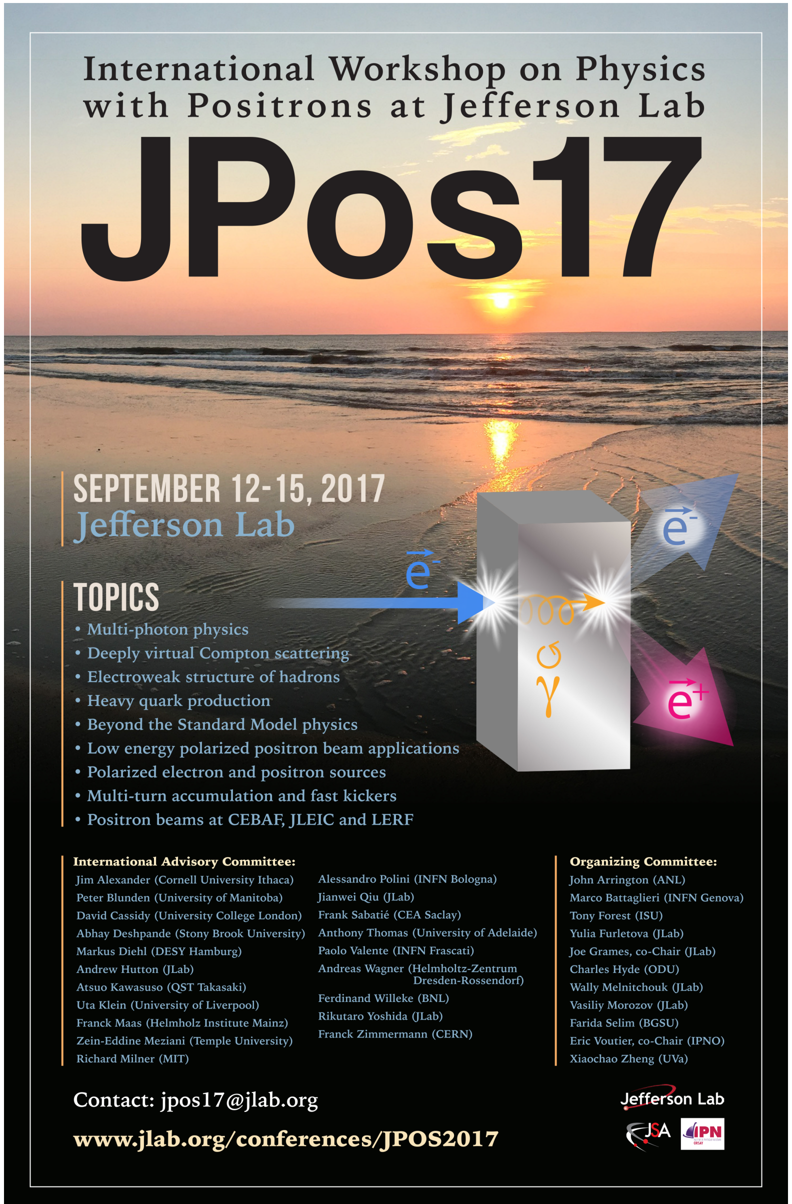
The charm and anticharm production in charged current DIS to **extract strange and anti-strange distributions.**



- Physics beyond the standard model

We need both: e+ and e- !

Electron-Ion or Positron-Ion Collider ?



September 12-15, 2017 at JLAB

- Multi-photon physics
- Deeply virtual Compton scattering
- Electroweak structure of hadrons
- Heavy quark production
- Beyond the Standard Model physics
- Low energy polarized positron beam applications
- Polarized electron and positron sources
- Multi-turn accumulation and fast kickers
- Positron beams at CEBAF, JLEIC and LERF

EIC User Group

Last summer: generic detector R&D with EIC UG meeting

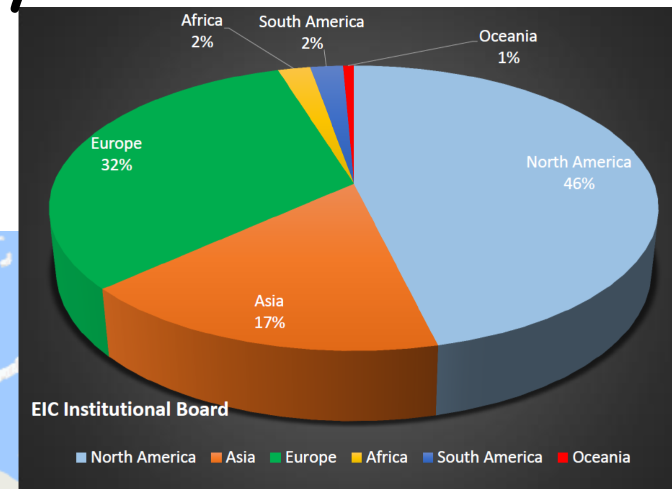
July 6-7, 2016 Generic EIC-related detector R&D meeting at Argonne.
July 7-9, 2016 EIC Users Group Meeting at Argonne.
http://eic2016.phy.anl.gov

- A Charter for EICUG Participation approved. Steering Committee largely in place.
- Much to prepare: case for the NAS committee, setting up working groups, plan the EIC physics program… (Come join us! eicug.org)
- UK EIC Opportunities Meeting October 13-14, 2016. Loch Lomond
- INFN (Italy) EIC Opportunities Meeting January 17, 2017. Genoa
- Organizational EICUG meeting (virtual) Feb/March 2017.
- EICUG meeting at Trieste, July 18-22, 2017, (INFN Trieste)

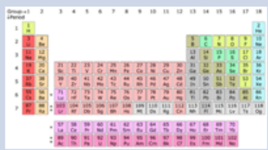
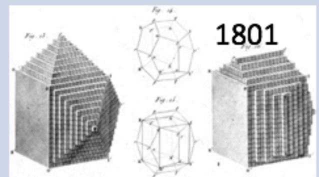
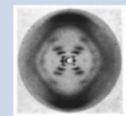
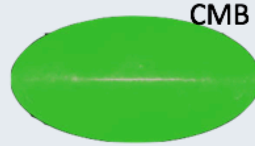
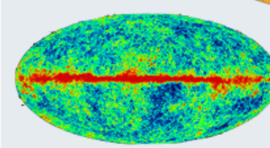
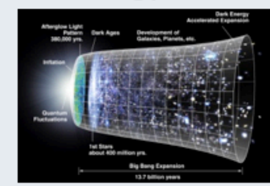
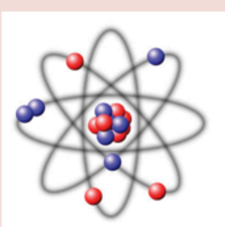
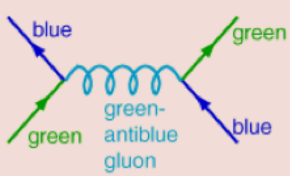
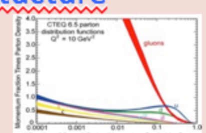
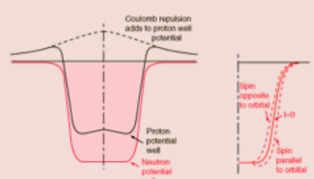
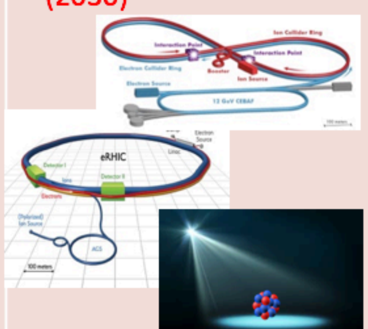
Worldwide Interest in EIC Physics

The EIC Users Group: EICUG.ORG

663 collaborators, 28 countries, 147 institutions... (October 09, 2016)



EIC: A Portal to a New Frontier

Dynamical System	Fundamental Knowns	Unknowns	Breakthrough Structure Probes (Date)	New Sciences, New Frontiers
Solids 	Electromagnetism Atoms 	Structure  1801	X-ray Diffraction (~1920)  	Solid state physics Molecular biology  DNA
Universe 	General Relativity Standard Model 	Quantum Gravity, Dark matter, Dark energy. Structure CMB 1965 	Large Scale Surveys CMB Probes (~2000)  	Precision Observational Cosmology 
Nuclei and Nucleons 	Perturbative QCD Quarks and Gluons $\mathcal{L}_{QCD} = \overline{\psi}(i\partial\!\!\!/ - gA\!\!\!/)\psi - \frac{1}{2}\mathrm{tr}\,F_{\mu\nu}F^{\mu\nu}$ 	Non-perturbative QCD Stucture  2017 	Electron-Ion Collider (2030) 	Structural QCD Nuclear Physics 

Summary

- Physics of nucleon and nuclear structure must drive the design.

High luminosity and polarization are essential for EIC physics program.

- EIC physics program demands a *total* acceptance detector. This means excellent forward/rear coverage in addition to the central coverage.
- R&D for accelerator, interaction region and detectors are progressing in a good collaboration among Accelerator Physicists, Experimentalists, and Theoreticians. Machine parameters, interaction region and detector design must go hand in hand, paying close attention to the emerging physics program of the EIC.
- It's important that many labs and universities - not only from within the Nuclear Physics community - get involved.

- Backup