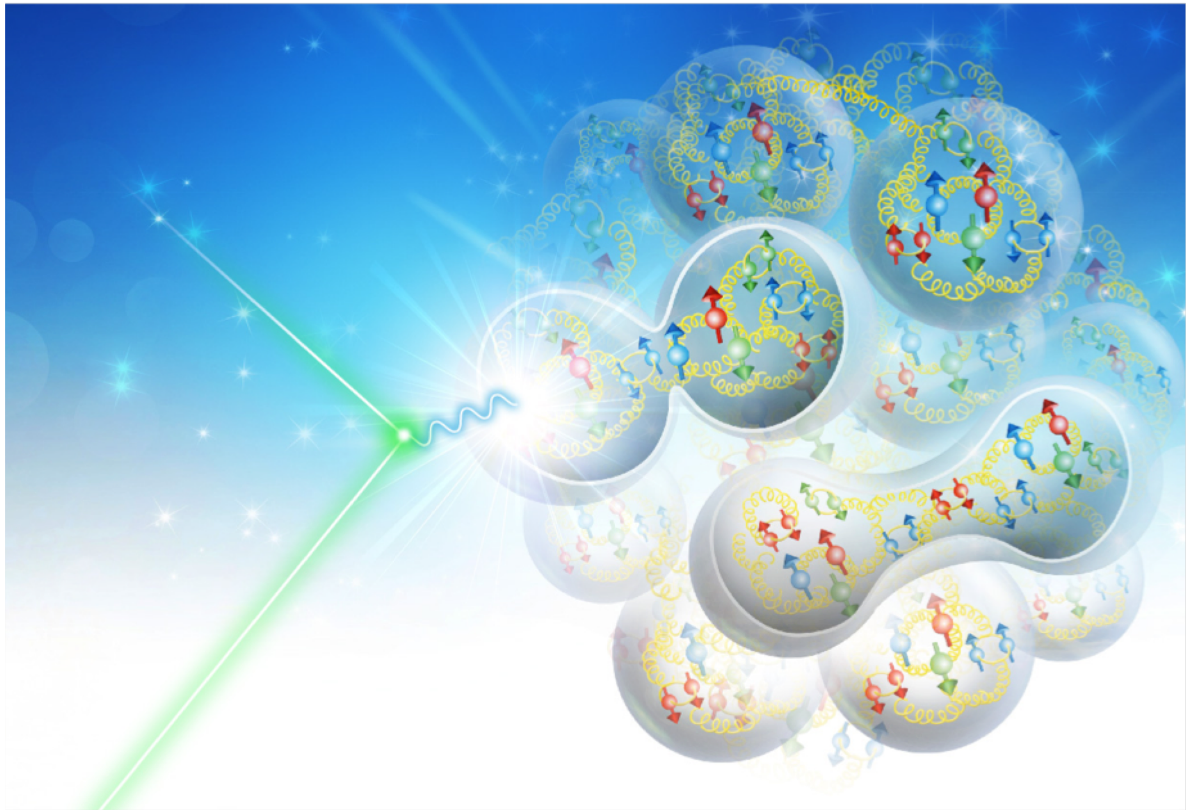
The way to the Electron-Ion Collider in the U.S.

Machine-Detector interface

JLEIC Detector concept

Thanks to the JLEIC IR and Detector Study group for discussion and material, in particular Yulia Furletova and Rik Yoshida.



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Jefferson Lab Exploring the Nature of Matter

U.S. DEPARTMENT OF ENERGY Office of Science

JSA

Future nuclear physics facility

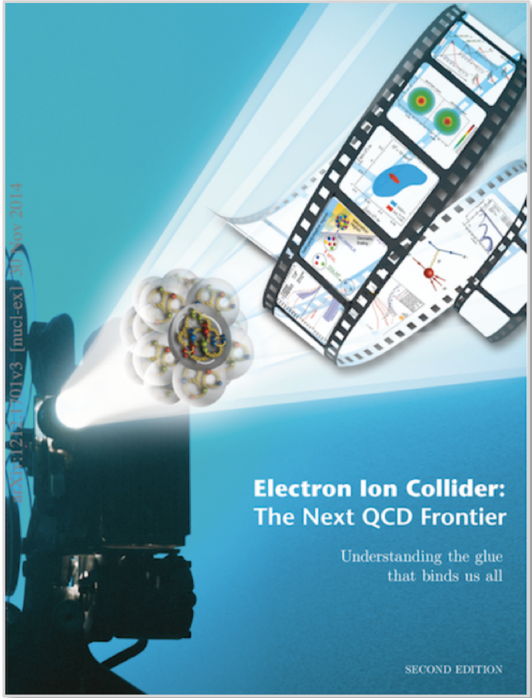
The Electron-Ion Collider Project

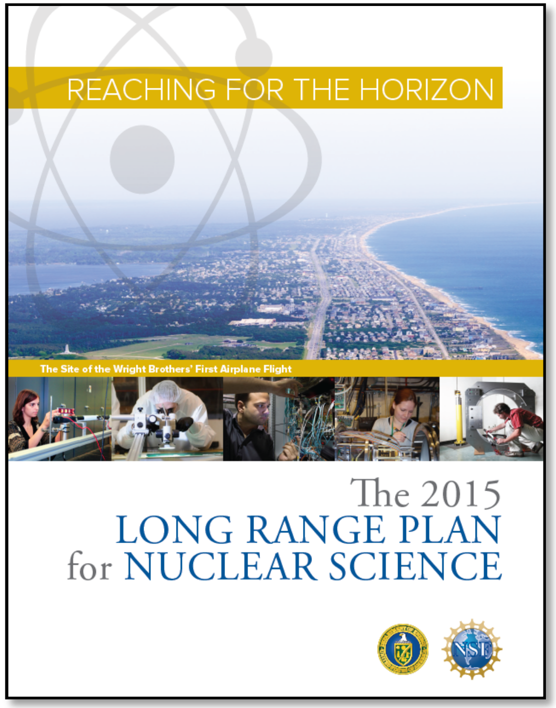
Why an Electron-Ion Collider?

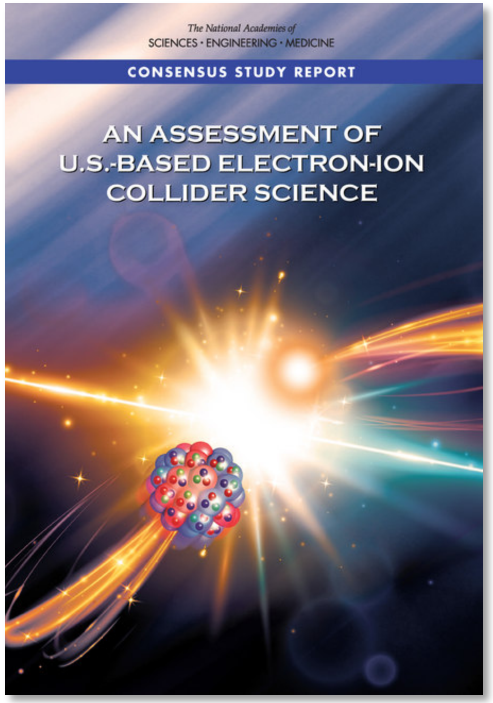
Right tool:

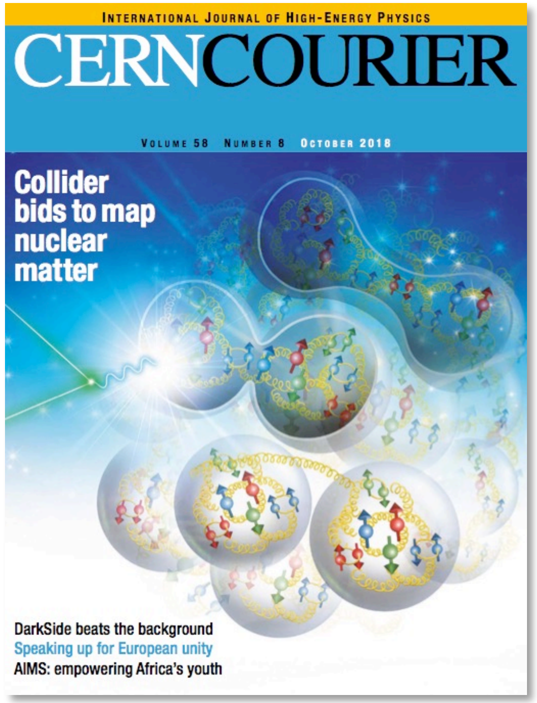
- to precisely **image quarks and gluons** and their interactions
- to explore the new **QCD frontier of strong color fields in nuclei**
- to understand **how matter at its most fundamental level is made**.

Understanding of nuclear matter is **transformational**, perhaps in an even more dramatic way than how the understanding of the atomic and molecular structure of matter led to new frontiers, new sciences and new technologies.

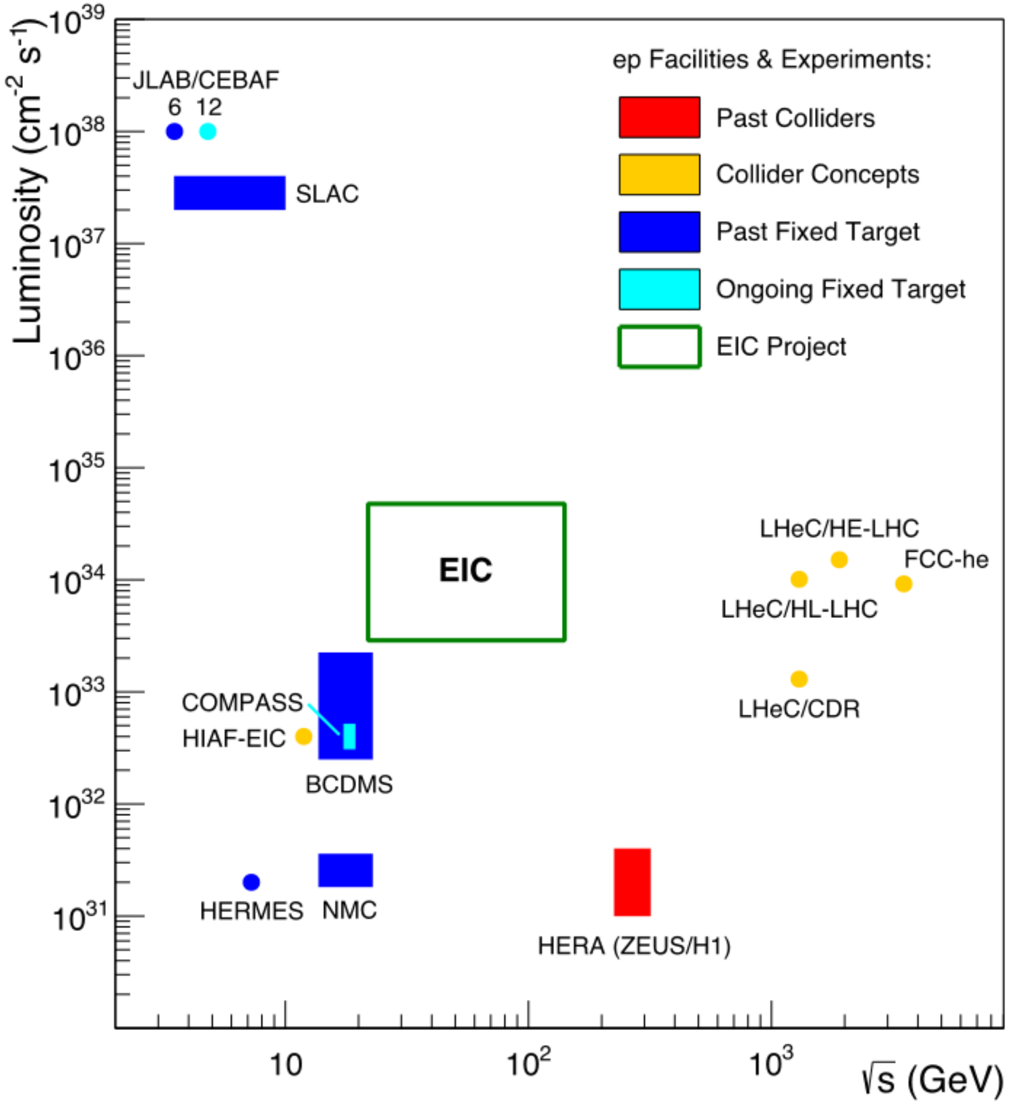








The Electron-Ion Collider (EIC)



Frontier accelerator facility in the U.S.

World's first collider of

- polarized electrons and polarized protons/light ions (d, ^{3}He)
- electrons and nuclei

Versatile range of

- beam energies: $\sqrt{s_{ep}}$ range ~20 to ~100 GeV upgradable to ~140 GeV
- beam polarizations for electrons, protons and light ions (longitudinal, transverse, tensor), at least ~70% polarization
- ion beam species: D to heaviest stable nuclei

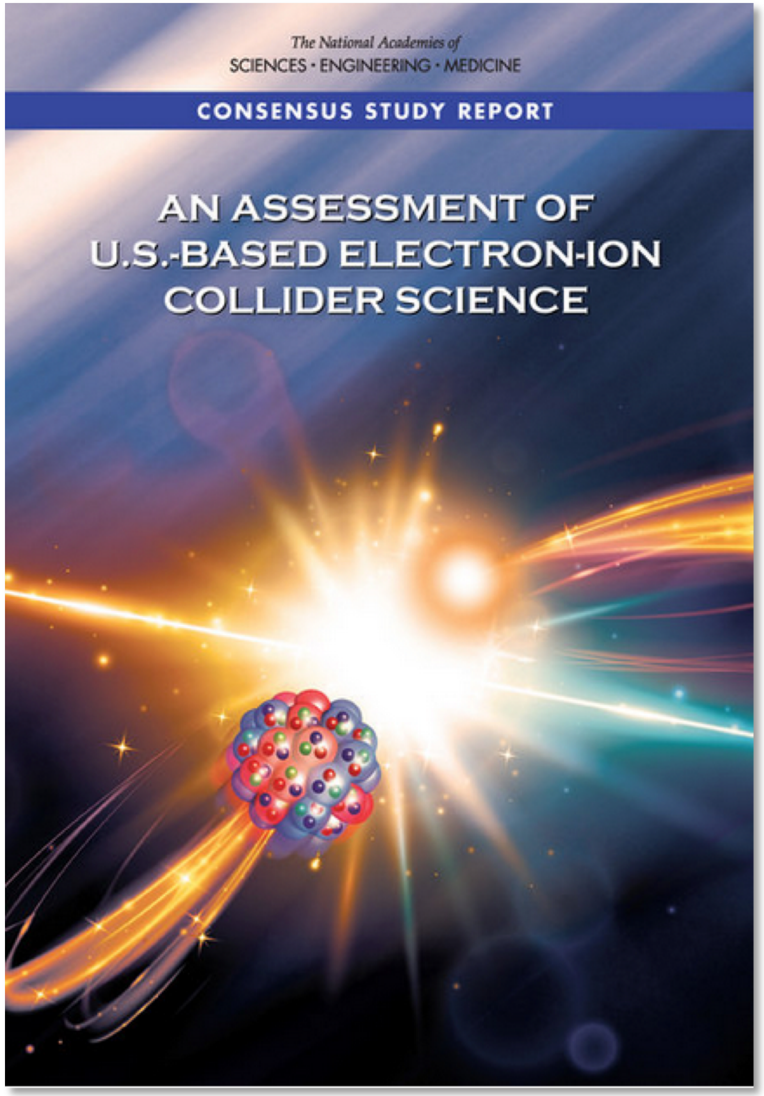
High luminosity

- 100 to 1000 times HERA luminosity

Frontier accelerator facility in the U.S.

Performance requirements for the EIC

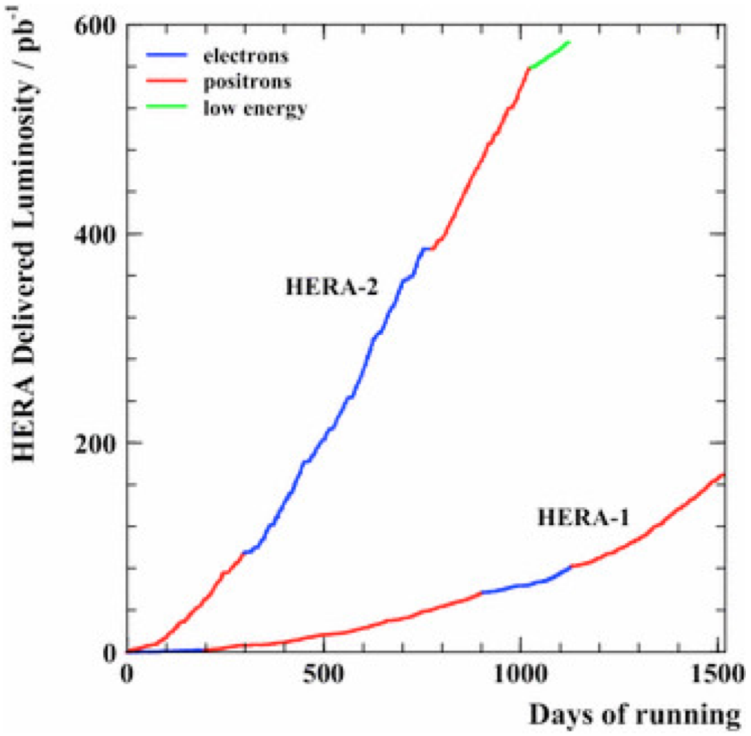
NAS report: Performance requirements



- Extensive center-of-mass energy range, from ~20-100 GeV, upgradable to ~140 GeV, to map the transition in nuclear properties from a dilute gas of quarks and gluons to saturated gluonic matter.
- Ion beams from deuterons to the heaviest stable nuclei.
- Luminosity on the order of 100 to 1,000 times higher than the earlier electron-proton collider Hadron-Electron Ring Accelerator (HERA) at Deutsches Elektronen-Synchrotron (DESY), to allow unprecedented three-dimensional (3D) imaging of the gluon and sea quark distributions in nucleons and nuclei.
- Spin-polarized (~70 percent at a minimum) electron and proton/light-ion beams to explore the correlations of gluon and sea quark distributions with the overall nucleon spin. Polarized colliding beams have been achieved before only at HERA (with electrons and positrons only) and Relativistic Heavy Ion Collider (RHIC; with protons only).
- One or more interaction regions, which integrate the detectors into the collider and preserve the extensive kinematic coverage for measurements.

- $\sqrt{s_{ep}}$ range ~20 to ~100 GeV upgradable to ~140 GeV
- Ion beams from D to heaviest stable nuclei
- 100 to 1000 times HERA luminosity
- At least ~70% polarization for electrons, protons and light ions
- One or more IR with integrated detector with high acceptance

Luminosity requirements for the EIC



In HERA-2, ~600 pb^{-1} of integrated luminosity was delivered (to ZEUS) over ~1000 days of running.

The means that HERA-2 delivered ~0.6 pb^{-1}/day or ~4 pb^{-1}/week of integrated luminosity during "running". There were two collider experiments, so inflate this a little to **6 pb^{-1}/week** .

HERA average luminosity (while running)
- 6 pb^{-1}/(one week in seconds) = 10^{31} $cm^{-2}s^{-1}$

EIC luminosity 100 – 1000 times HERA luminosity:
- **0.6 fb^{-1} to 6 fb^{-1}/week** of running or
- **average luminosity** (while running) **of 10^{33} to 10^{34} cm^{-2} s^{-1}**

6 fb^{-1}/week ➔ 100 fb^{-1}/year assuming 10^7 s in year (running ~1/3 of the year or a *snowmass* year)

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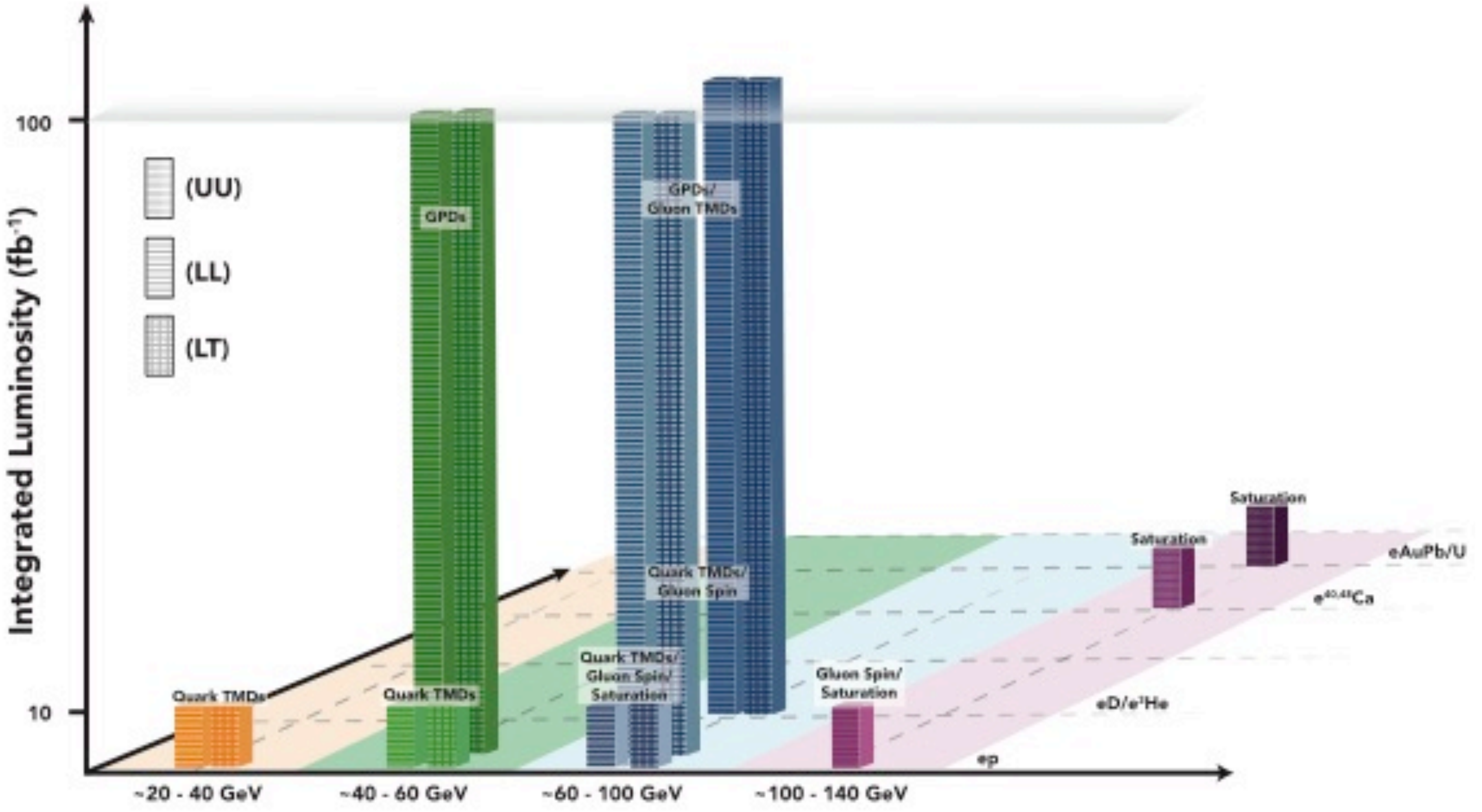
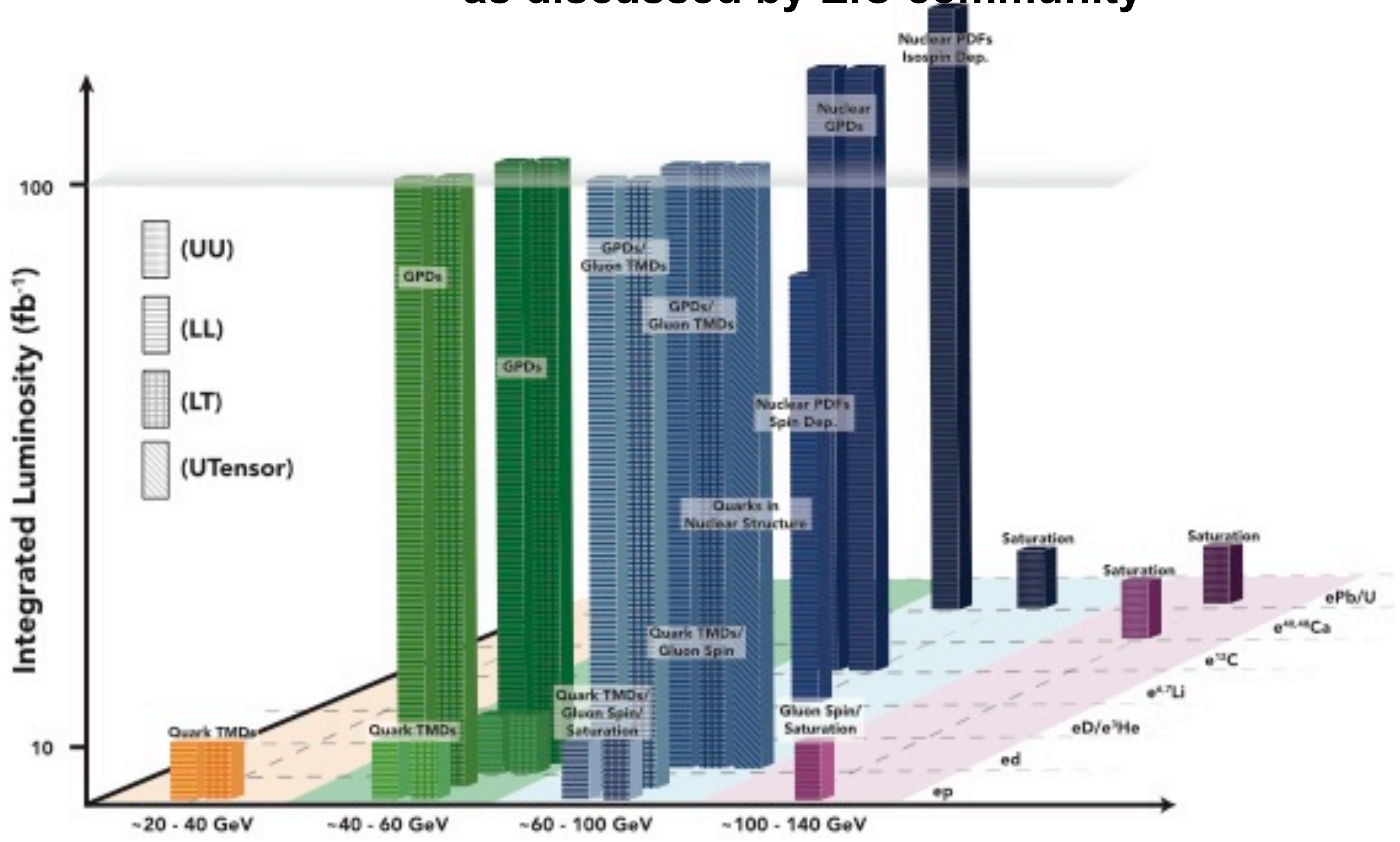
Projected luminosity needs (EIC Whitepaper)

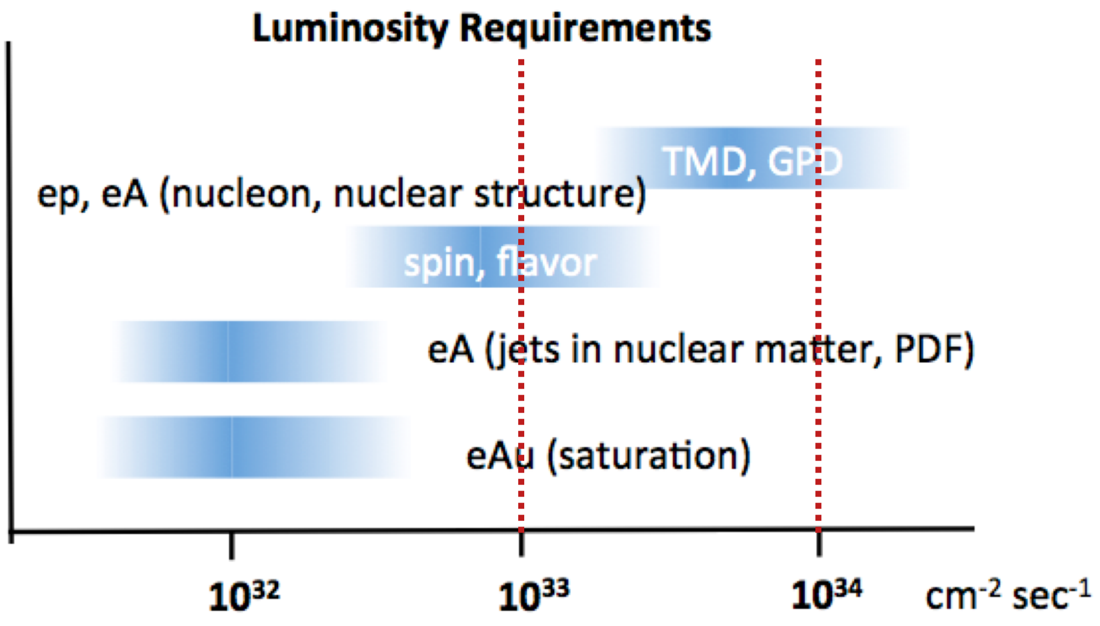


Projected luminosity needs (beyond EIC Whitepaper)

as discussed by EIC community



Luminosity requirements

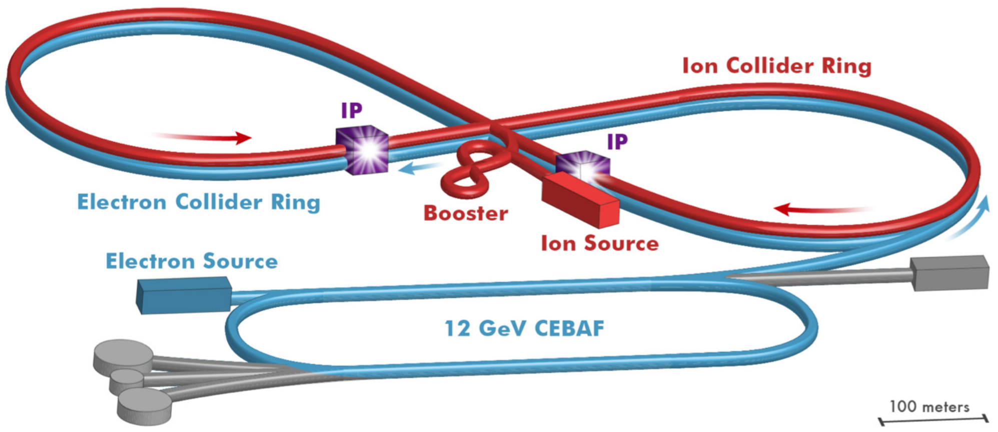


Central mission of EIC (nuclear and nucleon structure) requires **high luminosity** (10^{34}).

We cannot start the nucleon structure program without high luminosity
We need high-luminosity at the start of physics running at the EIC.

JLEIC design strategy: High luminosity and polarization

>80% polarization for both **electrons** and **light ions**



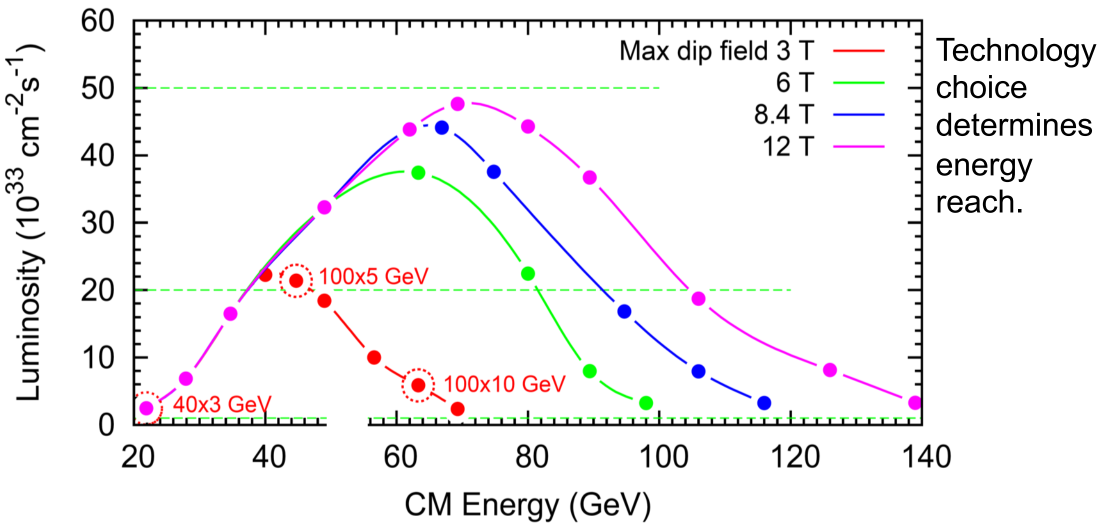


Figure-8 shaped ring-ring collider

- zero **spin tune** (net spin precession)
- energy-independent **spin tune**
- **polarization** easily preserved and manipulated:
  - by small solenoids
  - by other compact spin rotators

High luminosity

- high-rate collision of short bunches
  - with small emittance
  - with low charge
- **ion beam:** high-energy electron cooling (R&D)
- **electron beam:** synchrotron radiation damping

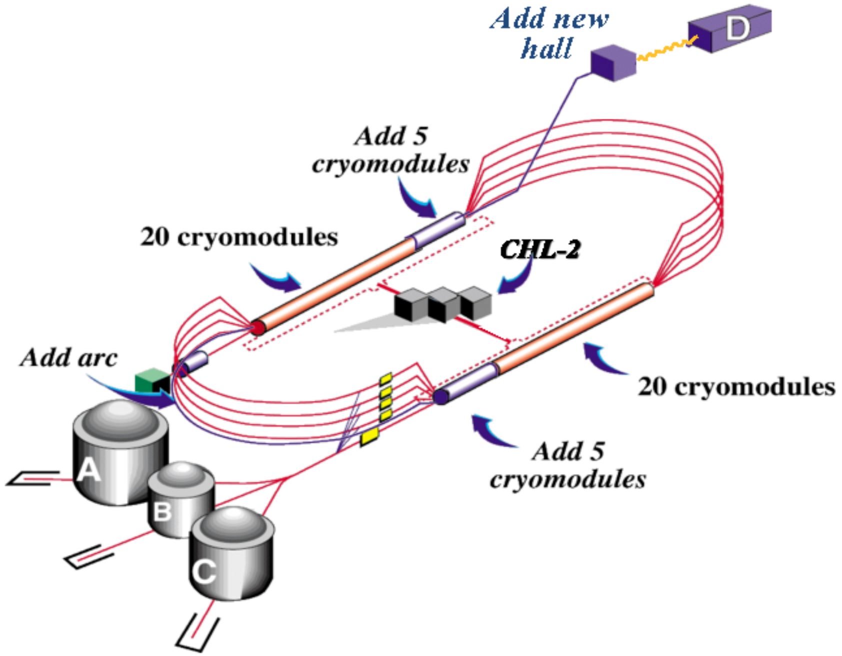
JLEIC energy reach √s =**20 –100 GeV**, upgradable to **140 GeV** using 12 T magnets (HE-LHC, FCC)

Detector design

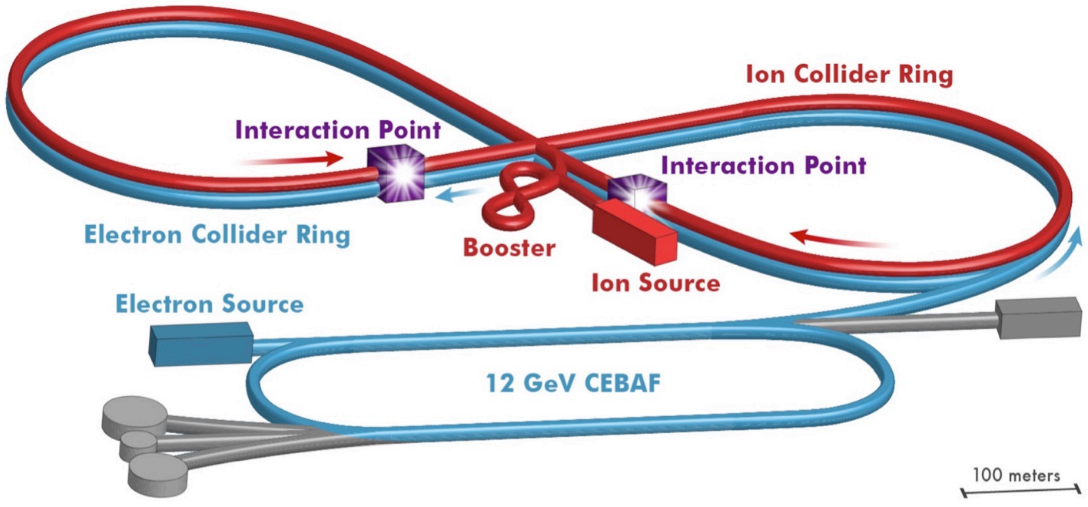
General design considerations

From 12 GeV Science Program to EIC

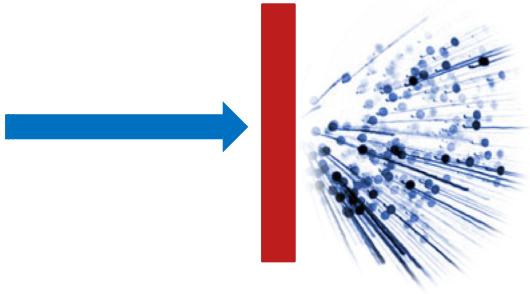
CEBAF for 12 GeV Science Program



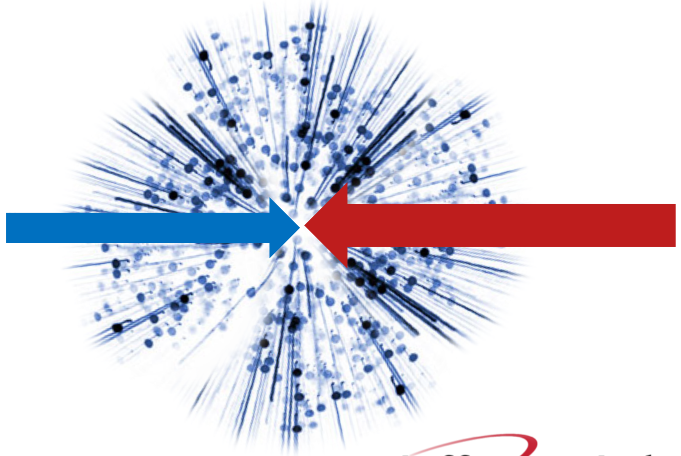
Electron-Ion Collider



Fixed-target experiments

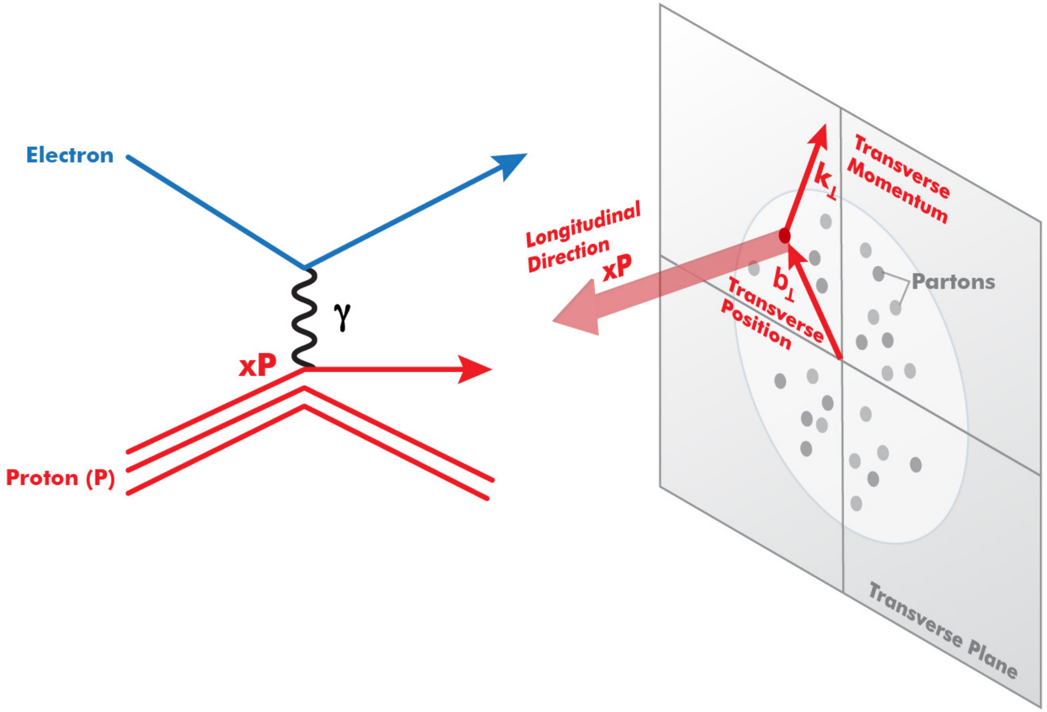


Collider experiments



Mapping position and motion of quarks and gluons

Study nuclear matter **beyond longitudinal description** makes the **requirements for IR and detector design different** from all previous colliders including HERA.

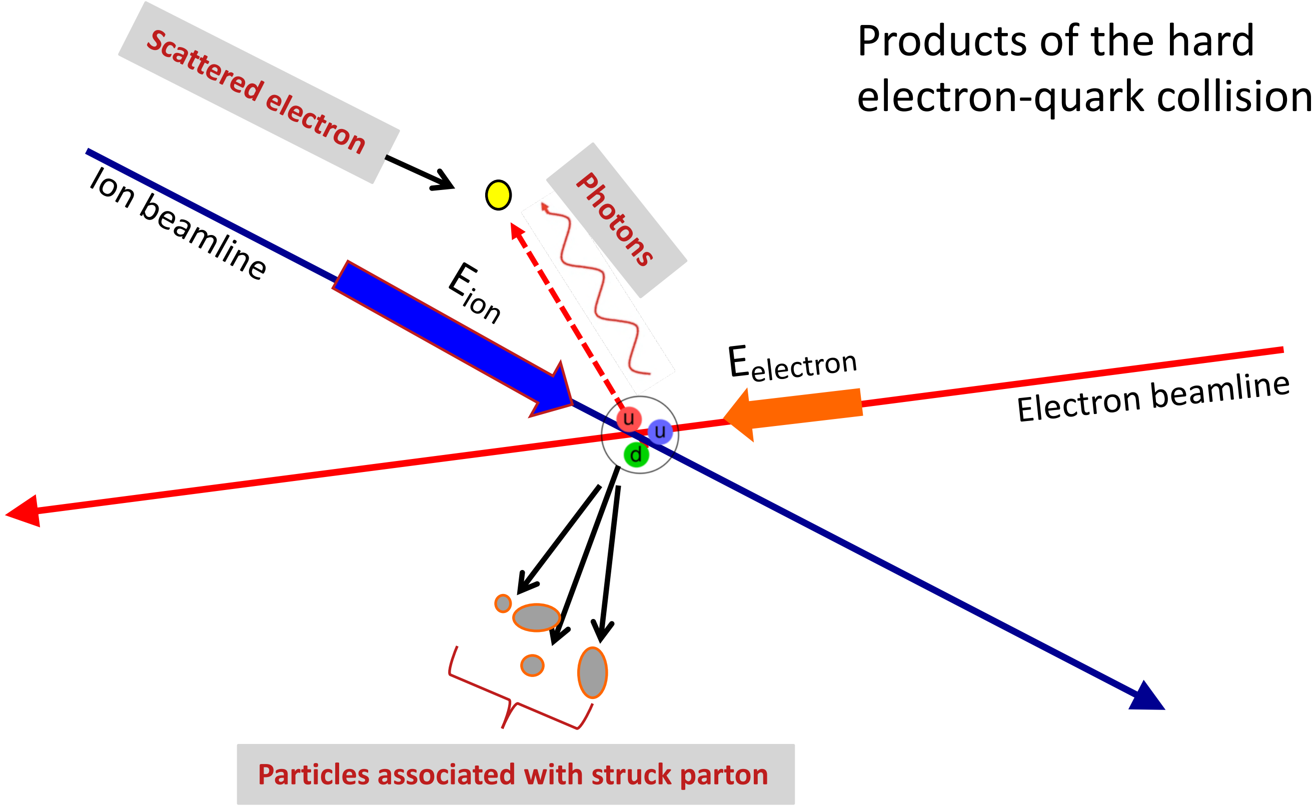


3D imaging in space and momentum

longitudinal structure (PDF)
+ transverse position Information (GPDs)
+ transverse momentum information (TMDs)

order of a few hundred MeV **measurement**

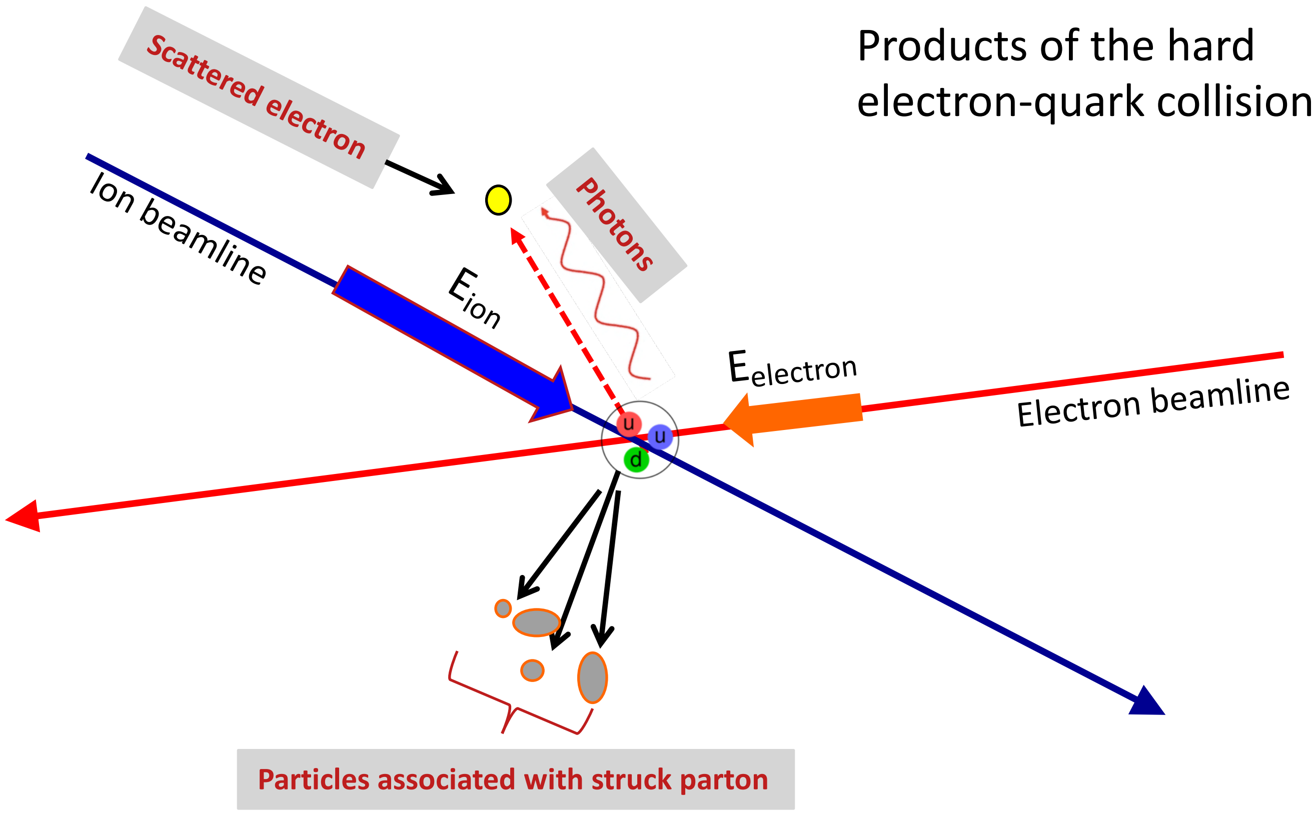
Particle Identification



Products of the hard electron-quark collision

Transverse and flavor structure measurement of the nucleon and nuclei: The particles associated with struck parton must have its species identified and measured. **Particle ID much more important than at HERA** colliders.

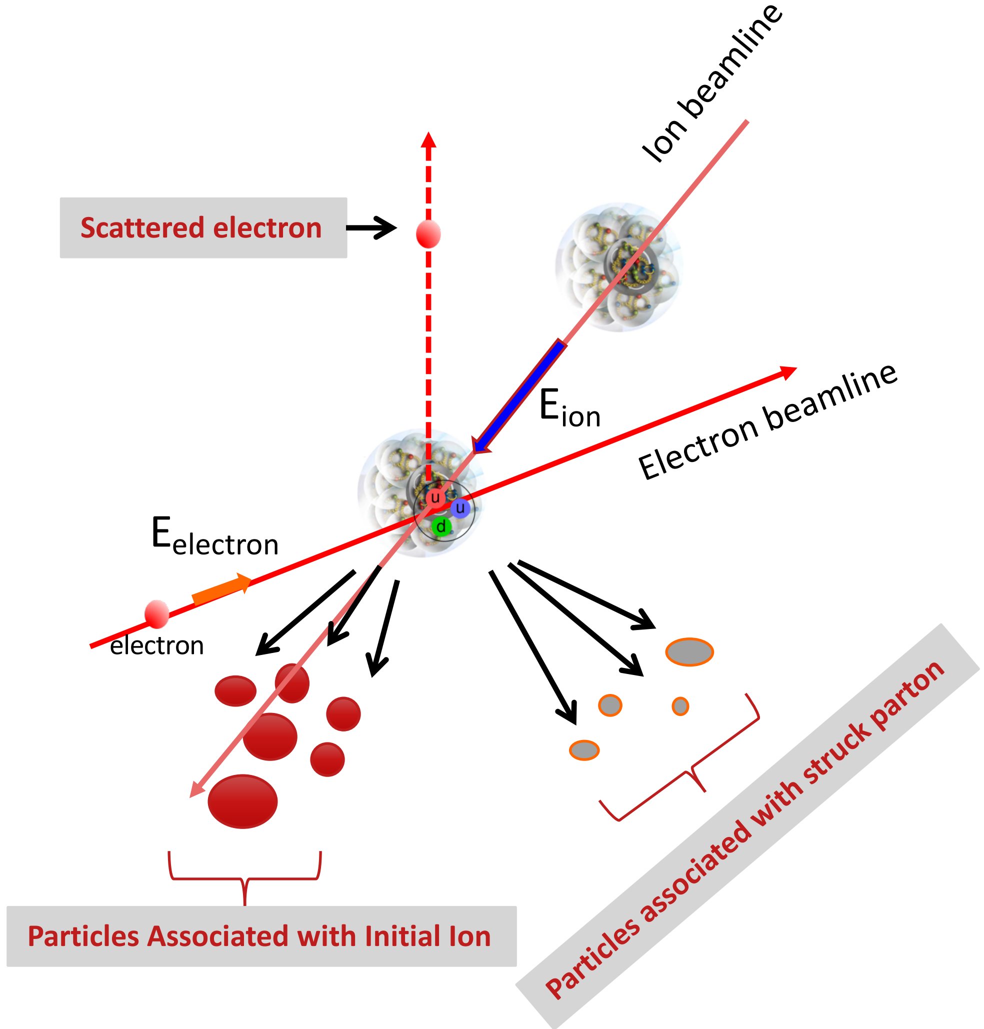
Final-state particles in the central rapidity



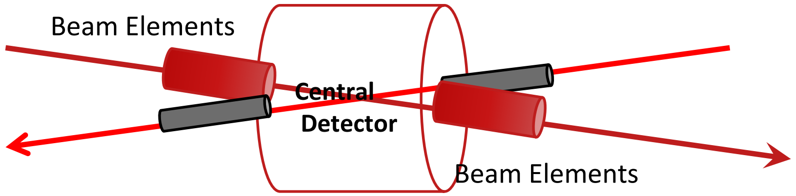
Products of the hard electron-quark collision

Asymmetric collision energies will boost the final state particles in the ion beam direction: **Detector requirements change as a function of rapidity.**

Final-state particles



The aim is to get **~100% acceptance** for all final state particles, and measure them with good resolution.



Experimental challenges:

- beam elements limit forward acceptance
- central Solenoid not effective for forward

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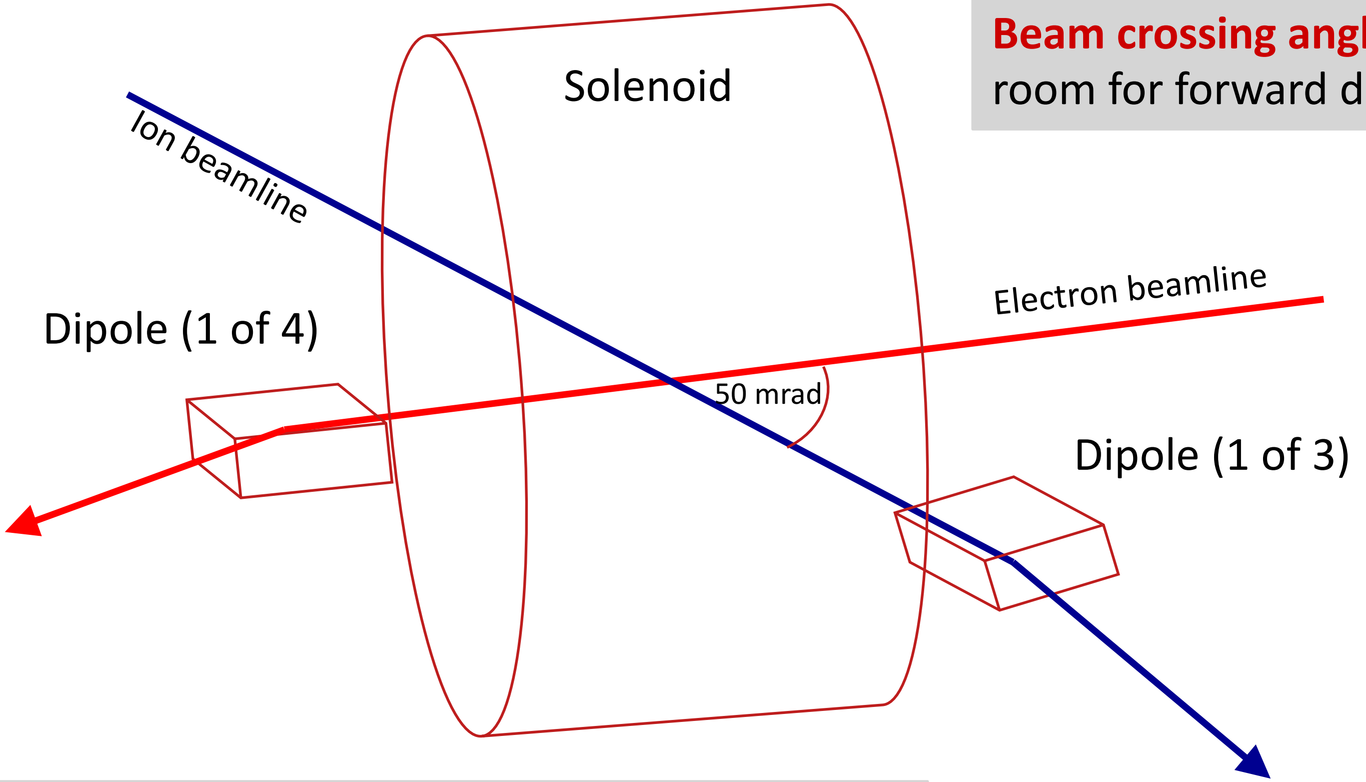
Interaction region concept

NOT TO SCALE!

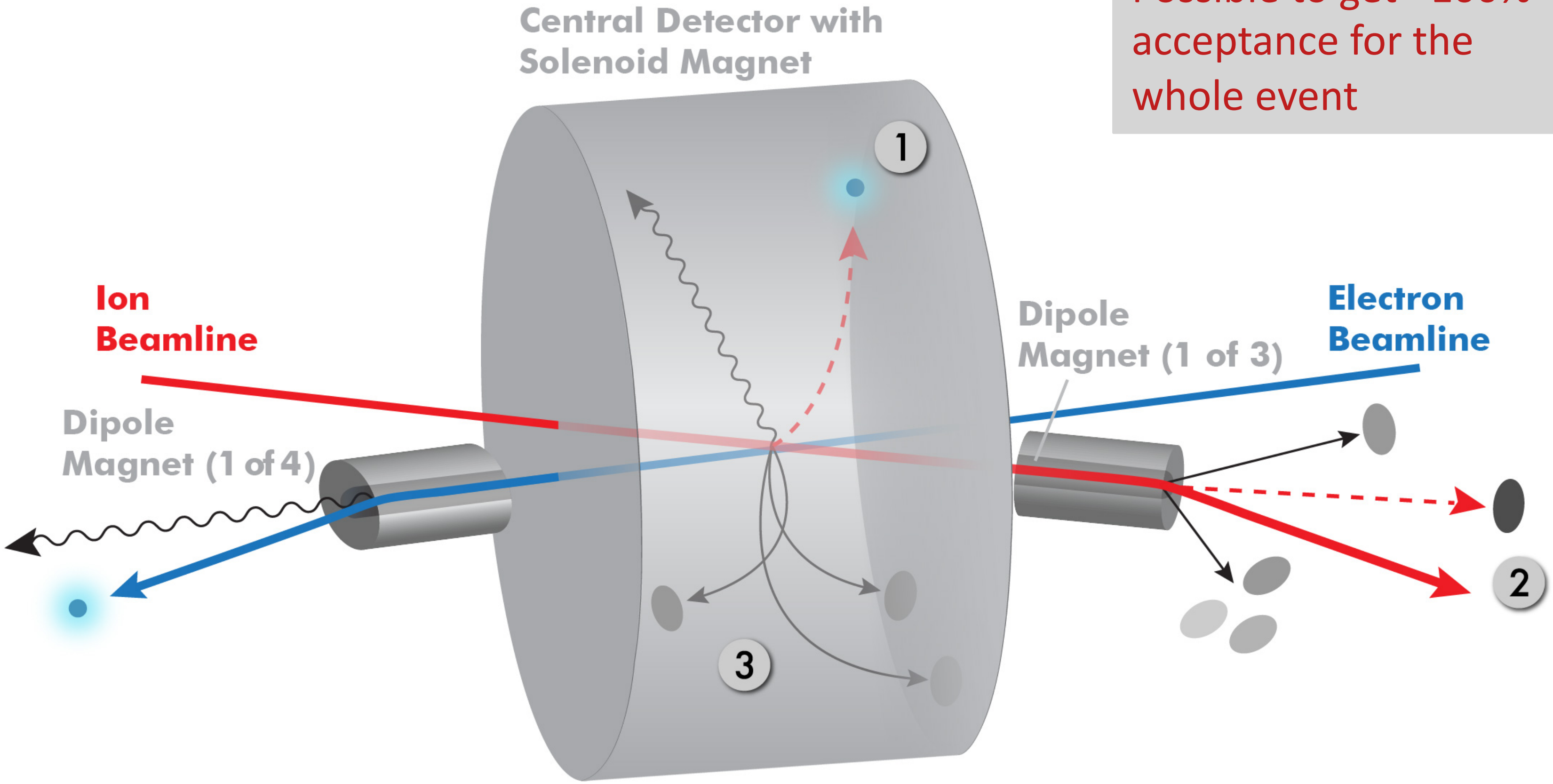
Beam crossing angle creates room for forward dipoles



Dipoles analyze the forward particles
and create space for detectors in the forward direction

Interaction region concept

Possible to get ~100% acceptance for the whole event

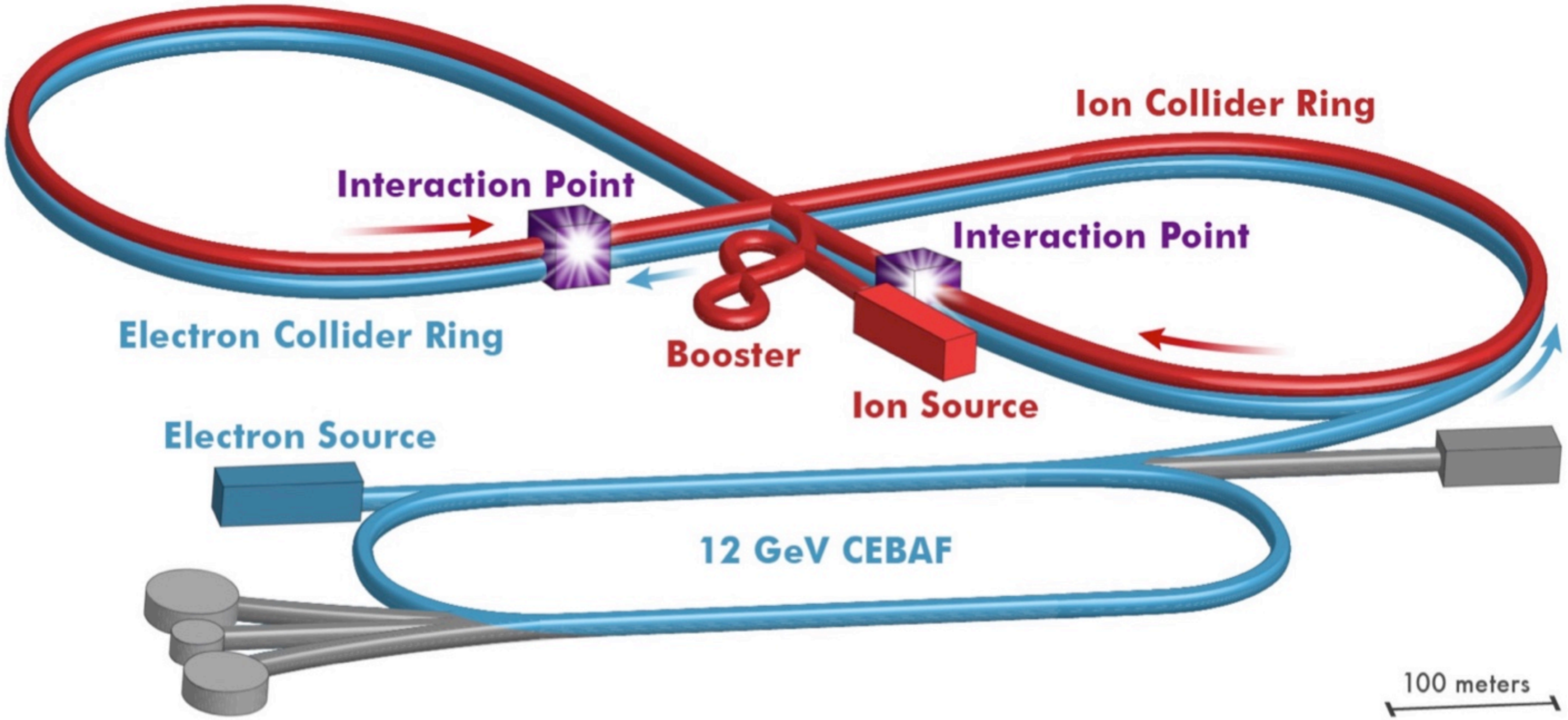


Total acceptance detector (and IR)

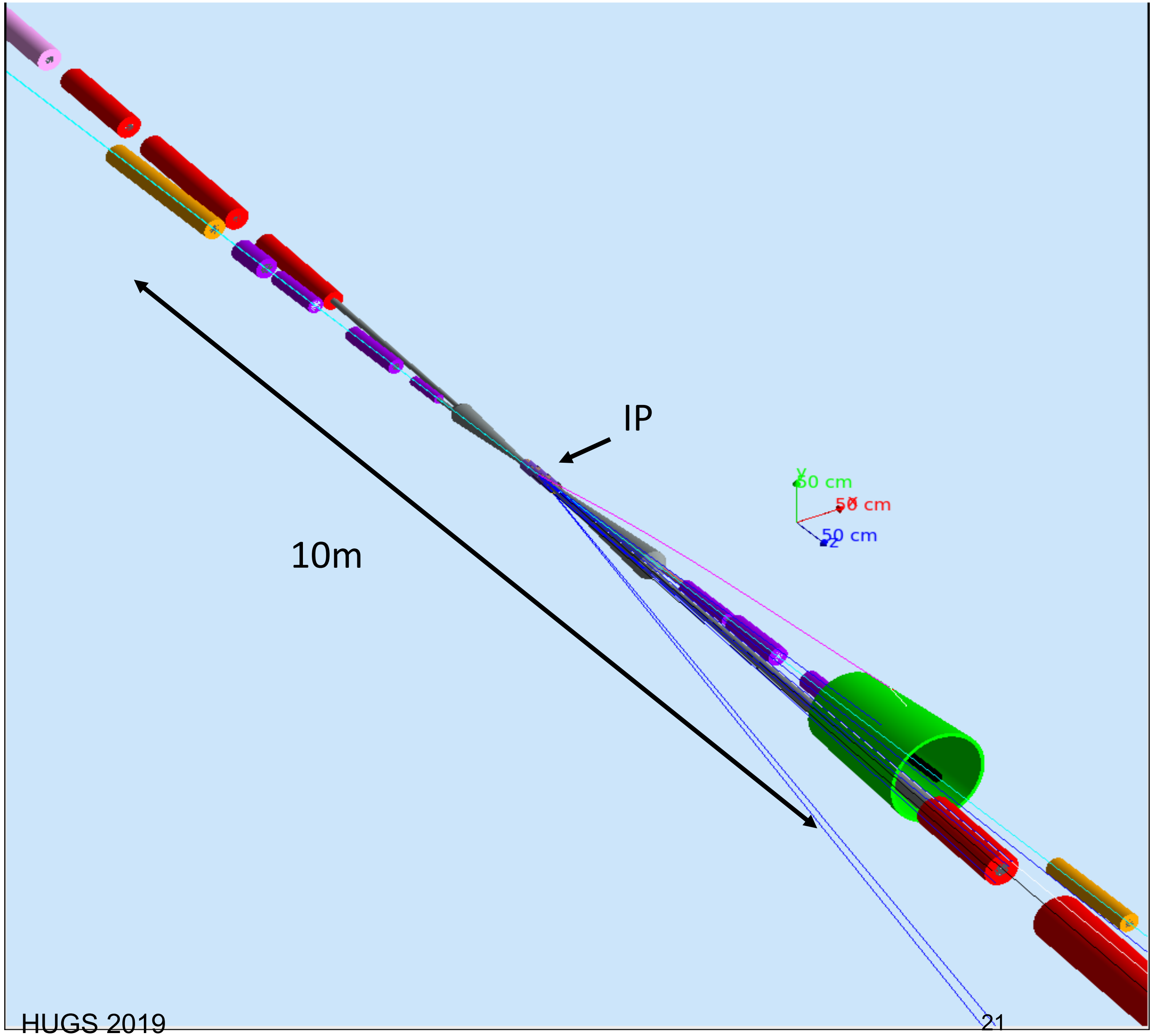
Interaction region (IR) design: Placement of interaction points (IP)

Background reduction

- far from electron bending magnets (**synchrotron radiation**)
- close to proton/ion bending (**hadron background**)



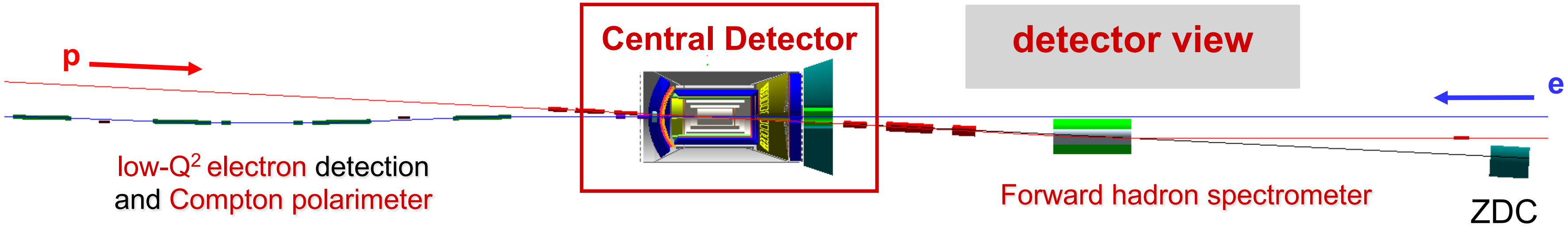
IR design: Detector size



Final Focus Quadrupole (FFQ) magnets to deliver beam to IP

- the closer to IP, the larger luminosity
- limit acceptance

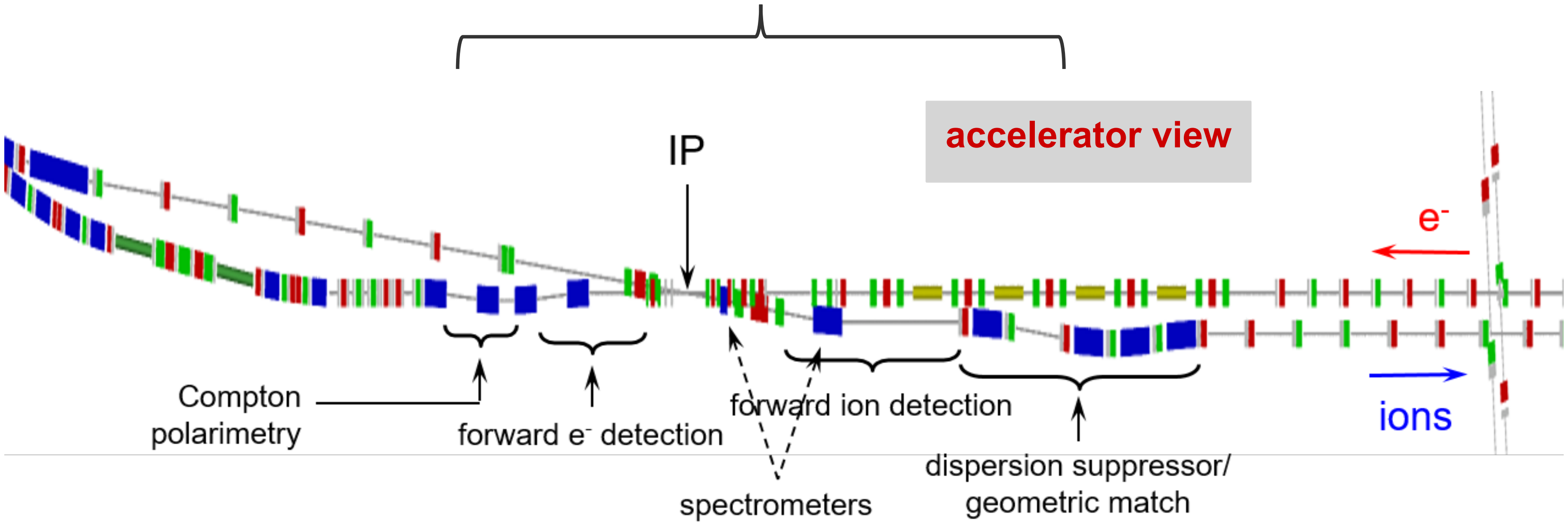
Detector and interaction region



Extended detector: 80m

30m for multi-purpose chicane, 10m for central detector, 40m for the forward hadron spectrometer

fully integrated with accelerator lattice



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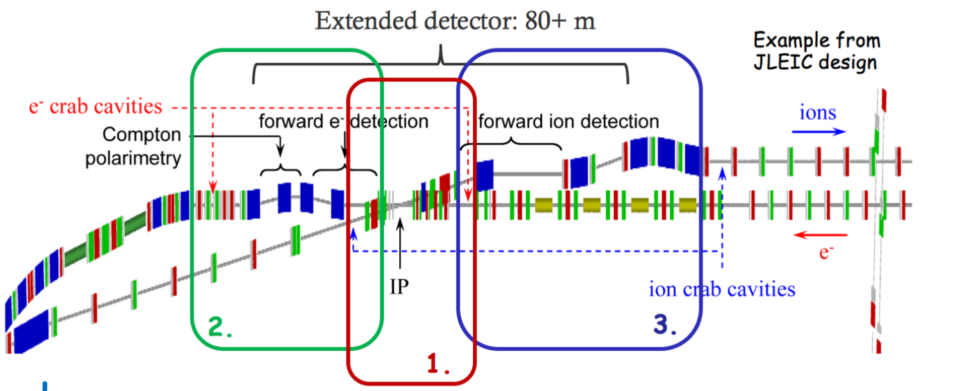
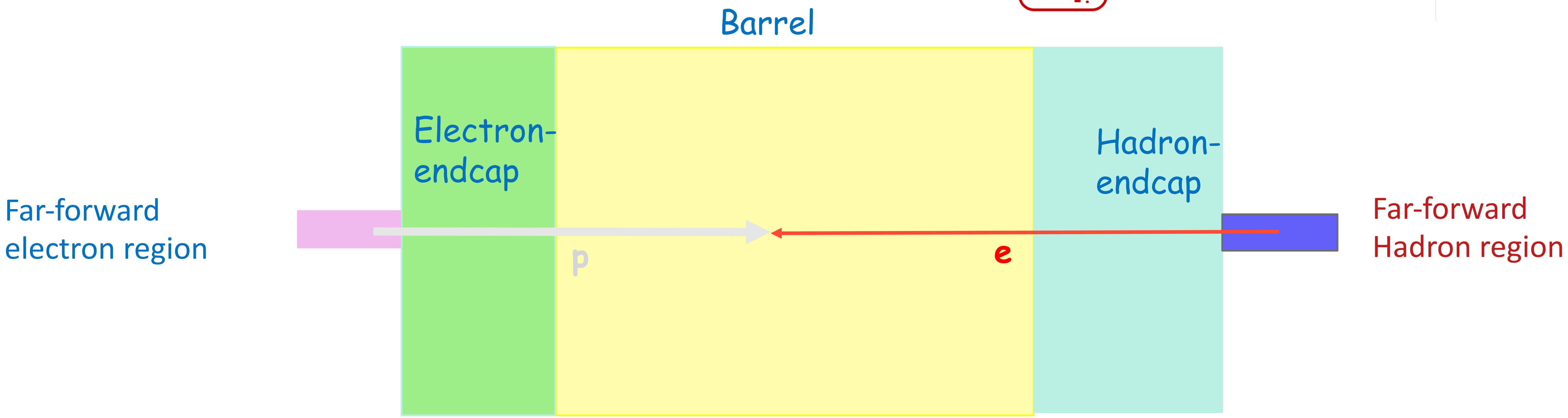
Detector design

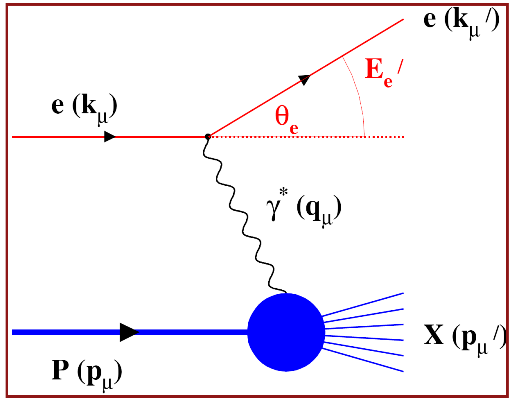
Central Detector

Detector coverage



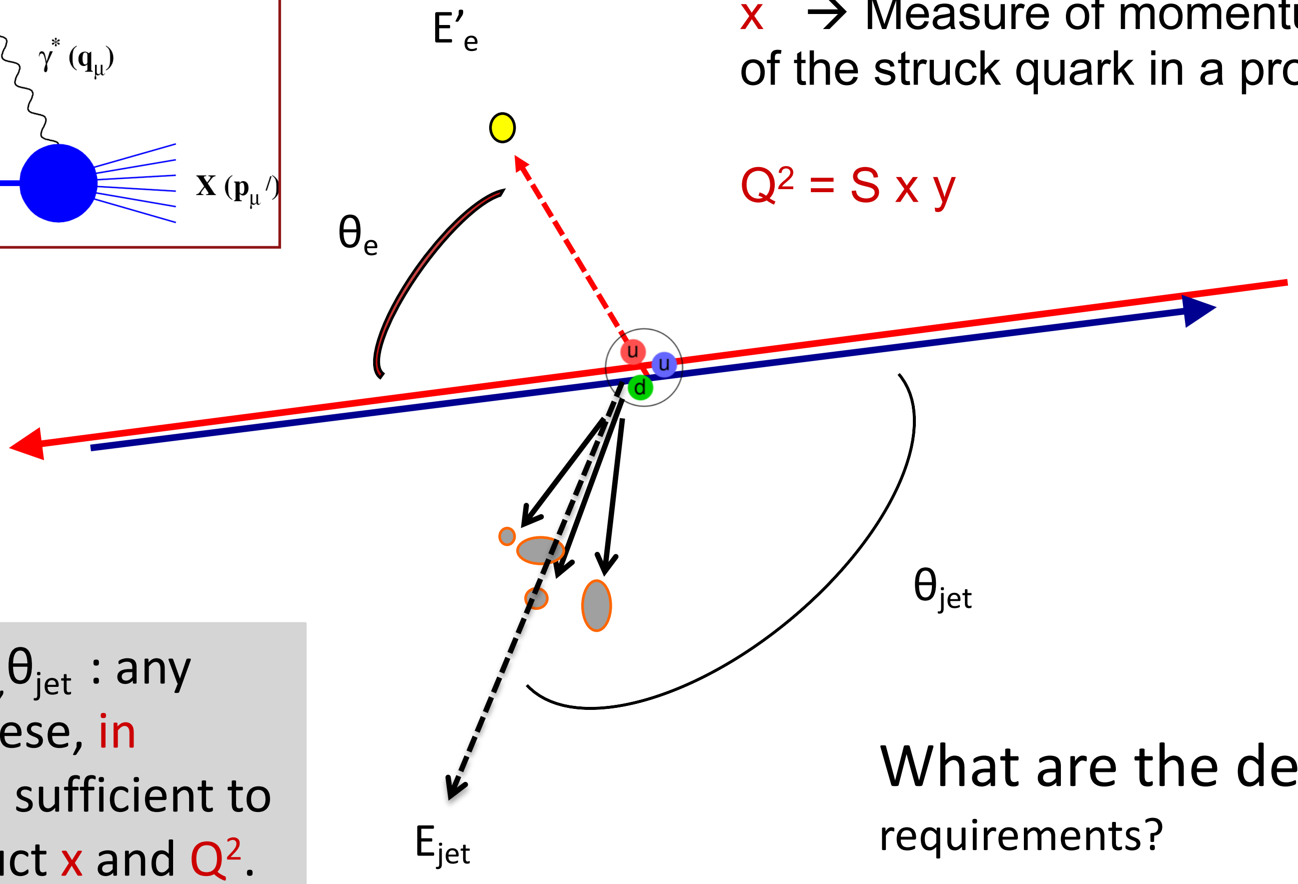


Basic kinematic reconstruction



Q^2 → Measure of resolution
y → Measure of inelasticity
x → Measure of momentum fraction of the struck quark in a proton

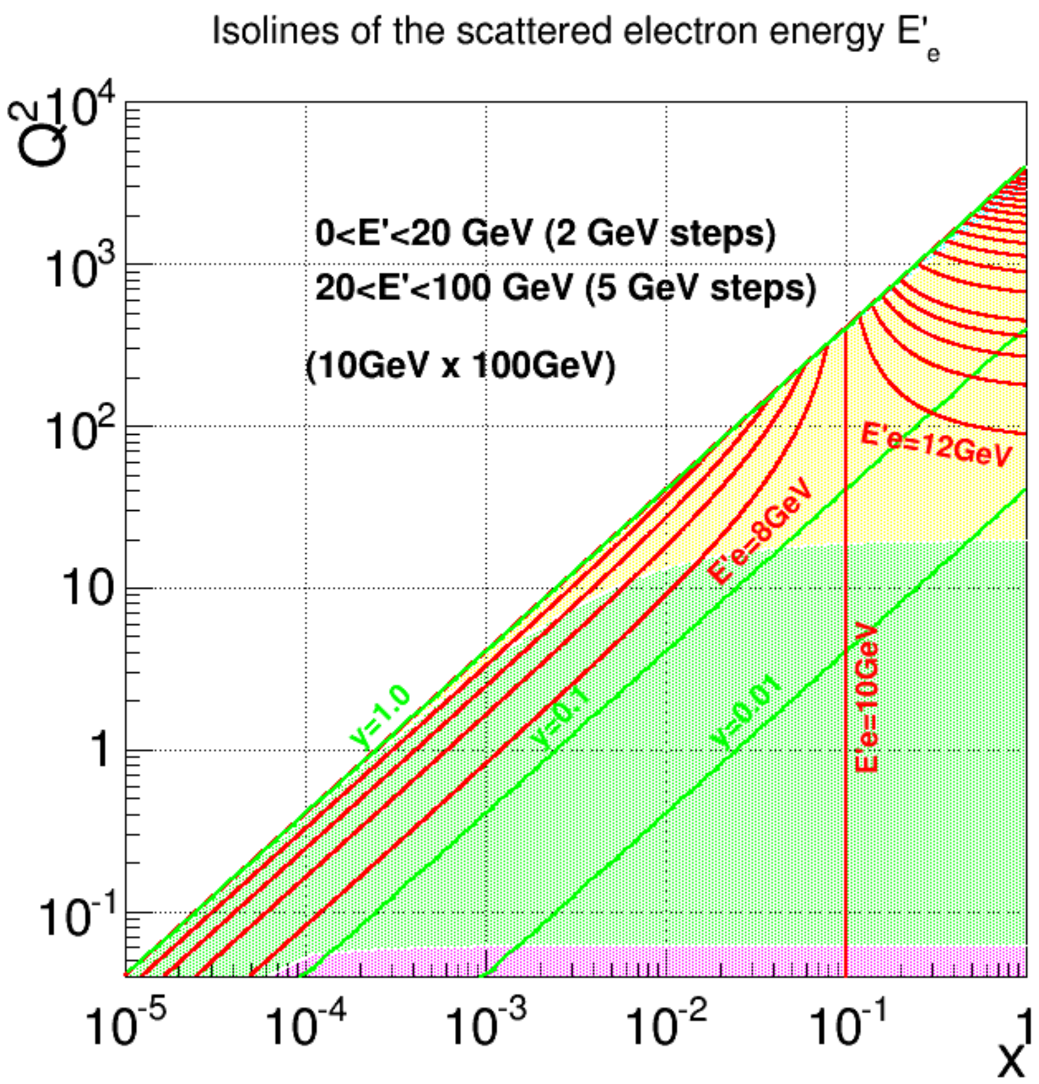
$Q^2 = S\ x\ y$

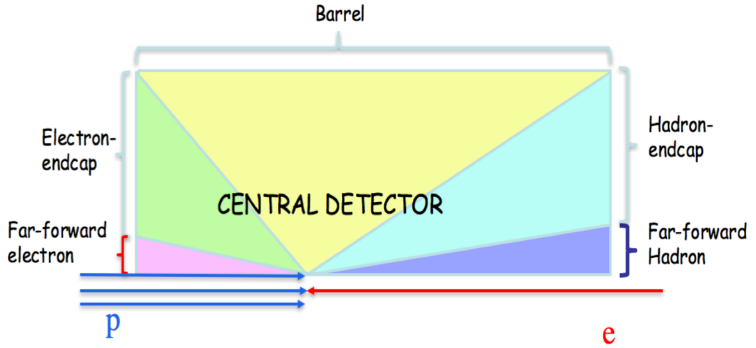


E'_{e}, θ_e, E_{jet}, θ_{jet} : any two of these, in principle, sufficient to reconstruct x and Q^2.

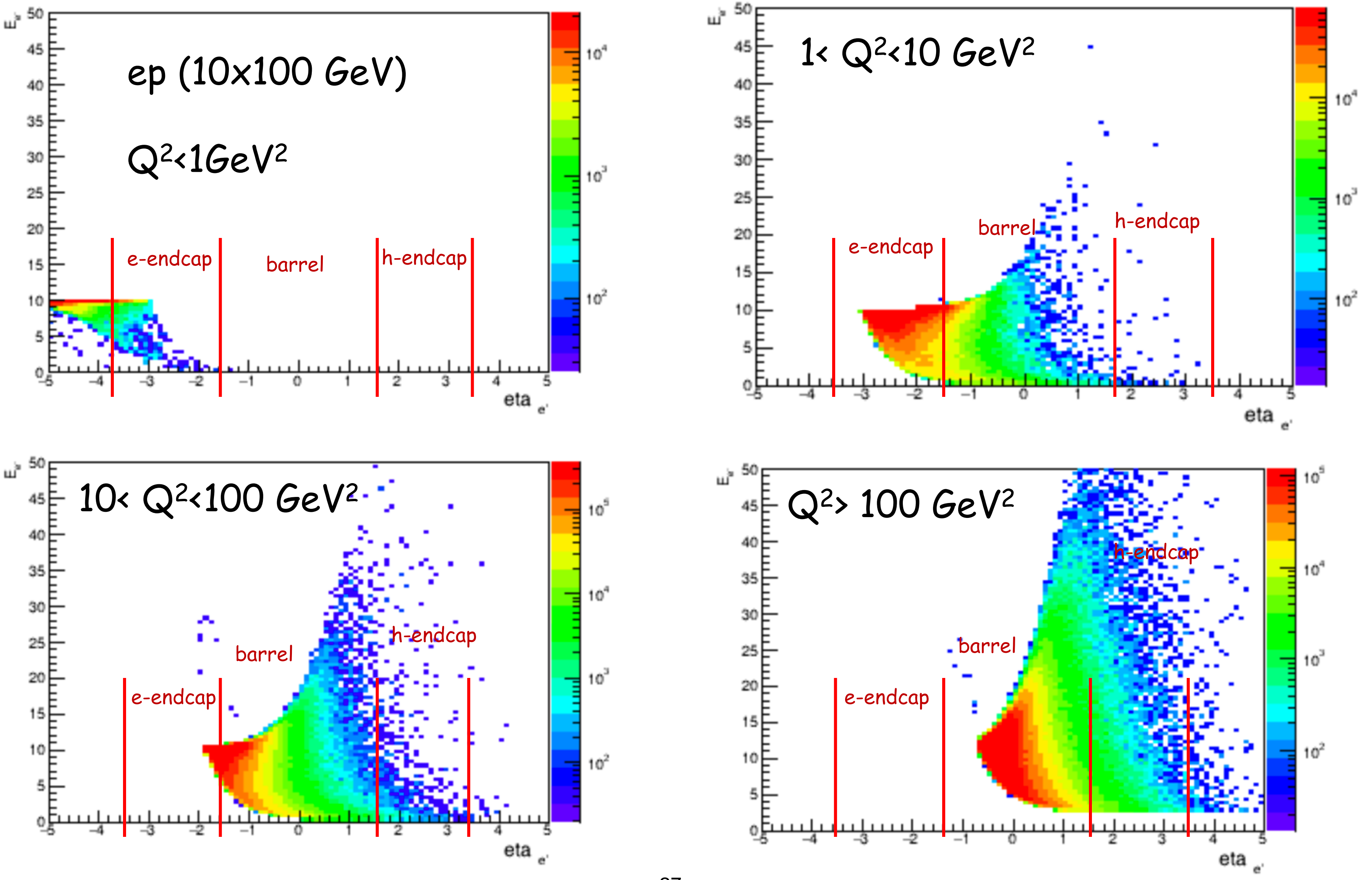
What are the detector requirements?

Electron isoline plot

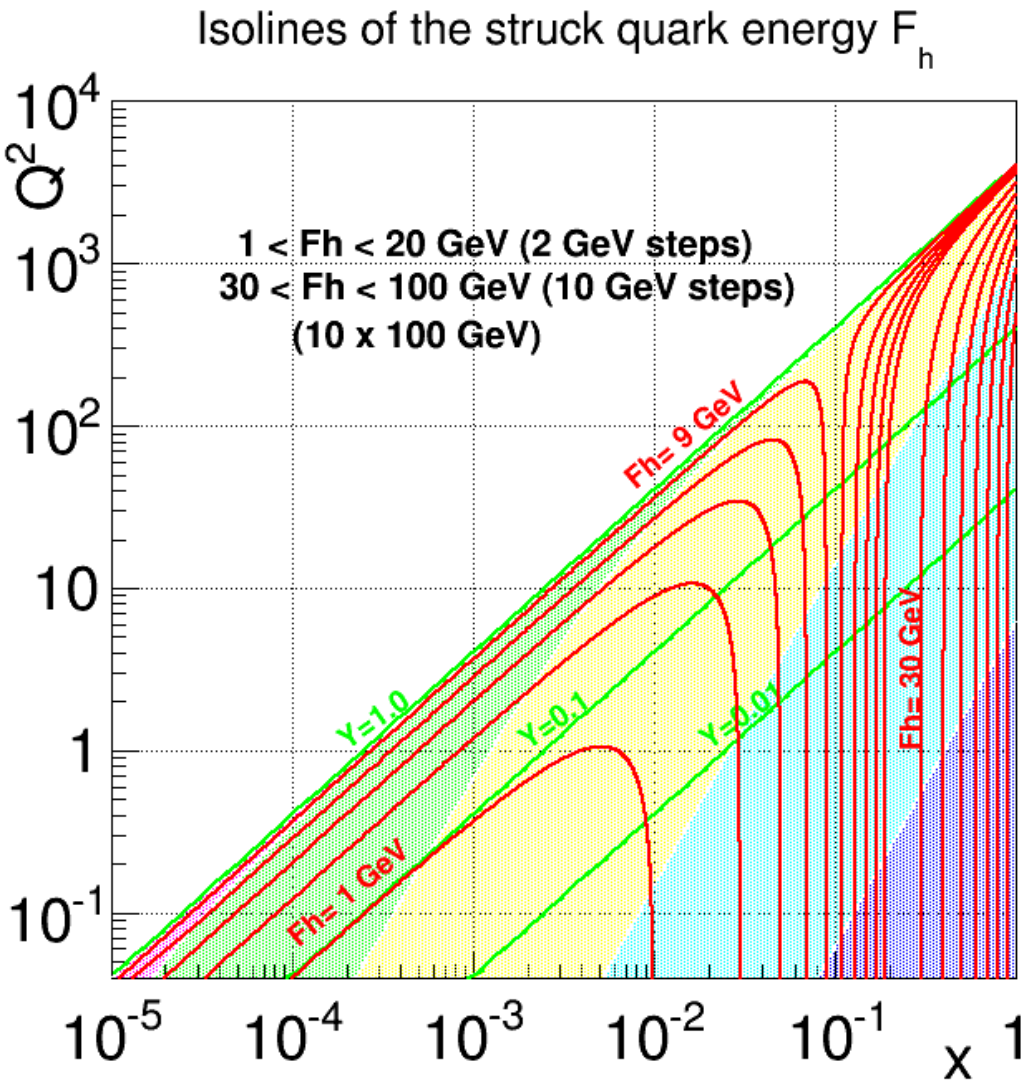


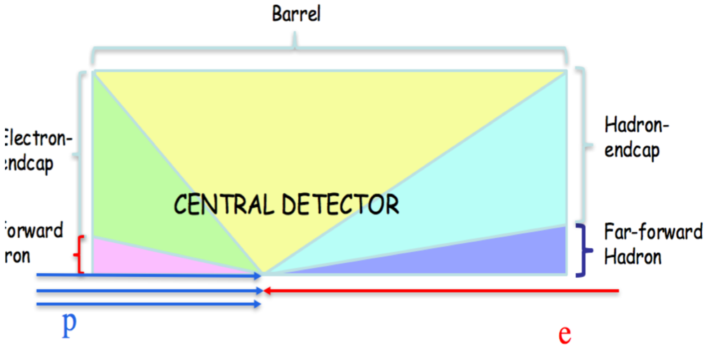


Detection of scattered electron



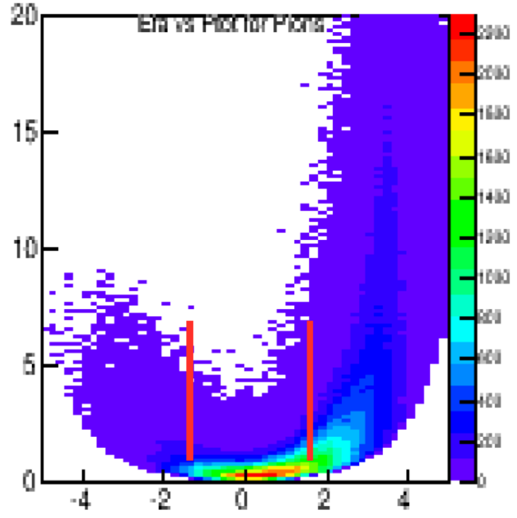
Quark (jet) isoline plot

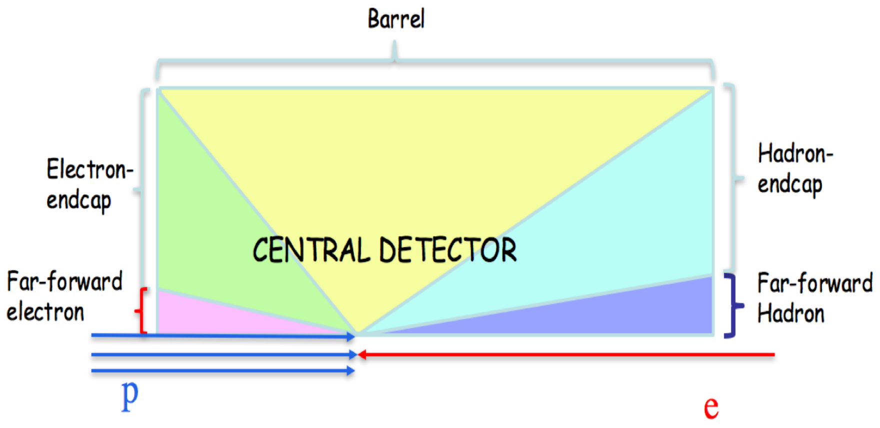




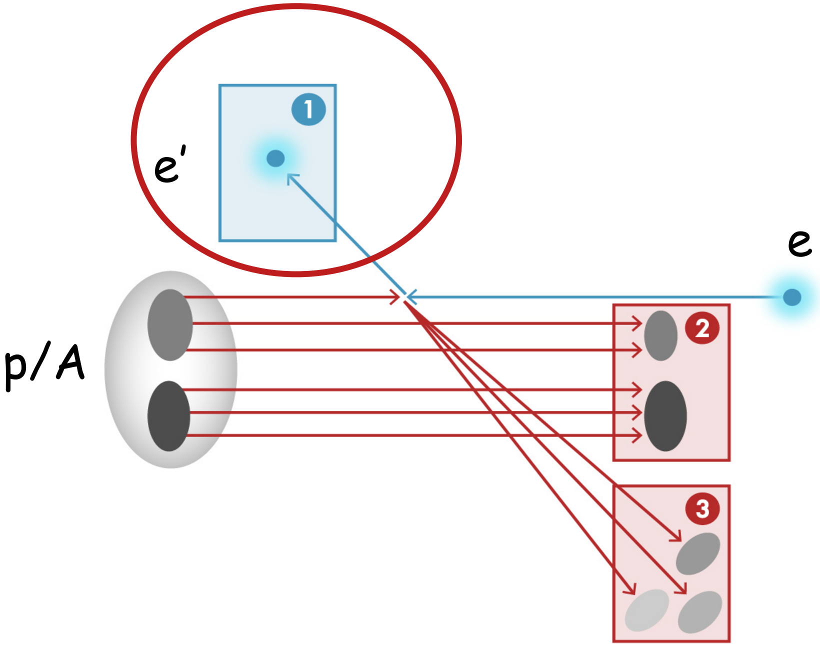
Particle distribution

	E-endcap	Barrel	H-endcap
E'e	<8GeV	8-50GeV	>50 GeV
Ejet	<10GeV	~10-50GeV	20-100GeV
E,hadrons	<10GeV	<15GeV	~15-50GeV
occupancy	low	medium	high





DIS kinematics: Electron method



Kinematic reconstruction

a) *Electron method* uses **information from scattered electron ONLY:**

$$Q^2_{\rm EM} = 2E_e E_{e'} \left(1 + \cos\theta_{e'}\right),$$

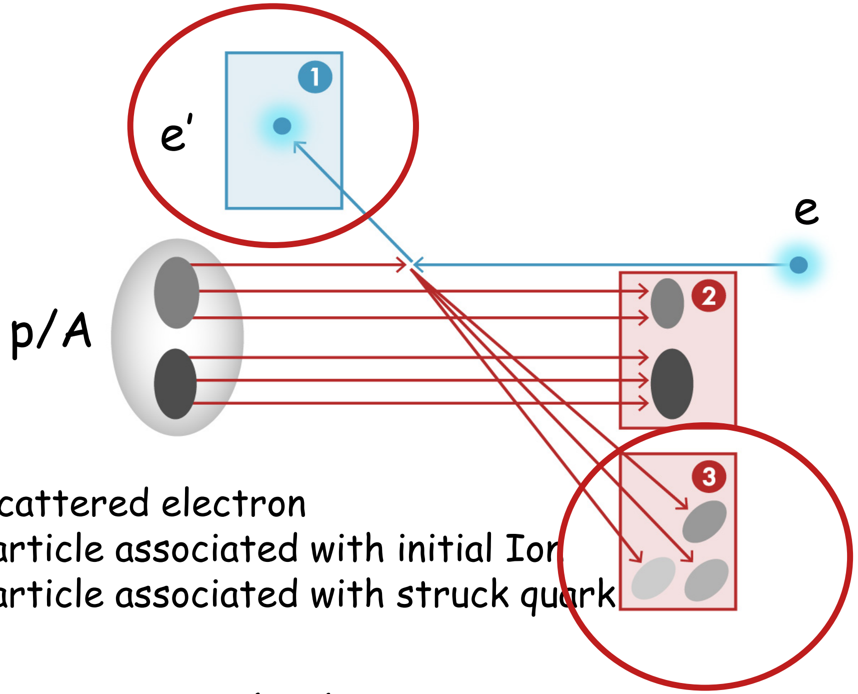
$$y_{\rm EM} = 1 - \frac{E_{e'}}{2E_e}\left(1 - \cos\theta_{e'}\right),$$

$$x = \frac{Q^2}{4E_e E_{\rm ion}} \frac{1}{y}$$

Notes:

- Linear dependence on $E_{e'}$ of the Q^2
- This method could NOT be used for $y < 0.1$

DIS kinematics: Double angle and sigma methods



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

All other methods require measurements of hadronic final states (particle associated with struck quark), here are just two examples

b) *Double angle method*

$$Q^2_{\mathrm{DA}} = \frac{4E_e^2 \sin\gamma_h\,(1+\cos\theta_{e'})}{\sin\gamma_h + \sin\theta_{e'} - \sin(\theta_{e'}+\gamma_h)},$$

$$y_{\mathrm{DA}} = \frac{\sin\theta_{e'}\,(1-\cos\gamma_h)}{\sin\gamma_h + \sin\theta_{e'} - \sin(\theta_{e'}+\gamma_h)},$$

Note: Does not require measurements of scattered electron energy, but require a good knowledge of hadronic final state :

$$\cos\gamma_h = \frac{P^2_{T,h} - \left(\sum_h (E_h - p_{z,h})\right)^2}{P^2_{T,h} + \left(\sum_h (E_h - p_{z,h})\right)^2}$$

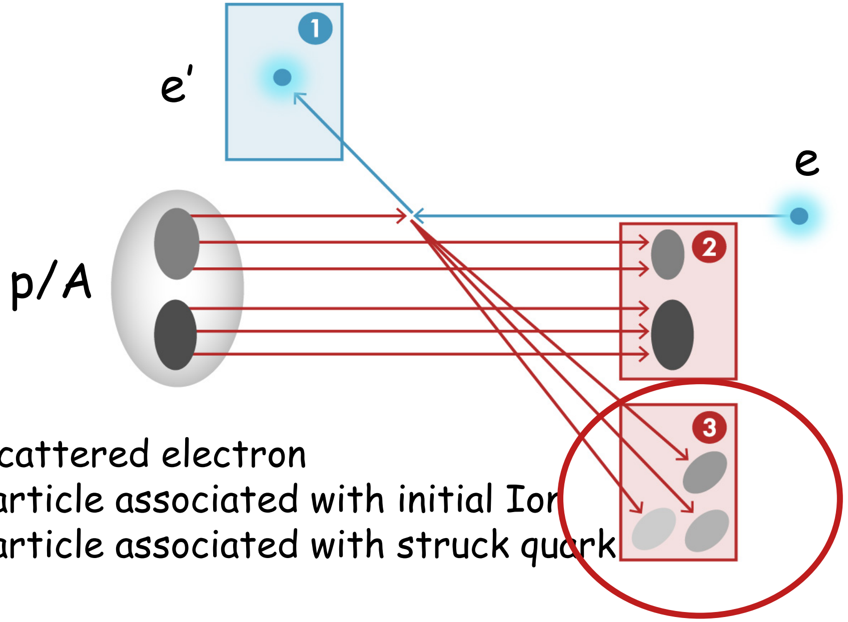
c) *Sigma method*

$$y_{e\Sigma} = \frac{\Sigma_h\,(E_h - p_{z,h})}{E - P_z},$$

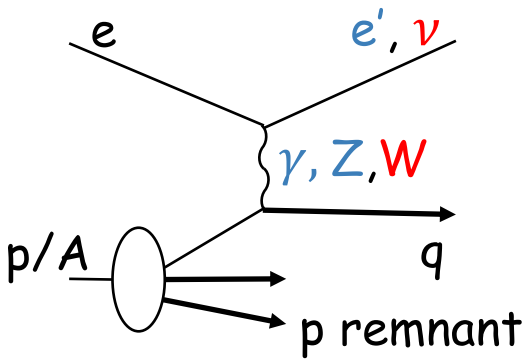
$$Q^2_{e\Sigma} = \frac{(E_{e'}\sin\theta_{e'})^2}{1-y}.$$

Note: Does not depend on initial electron beam energy, less influenced by a initial state radiation

DIS kinematics: Jacquet –Blondel method



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



DIS kinematic could be reconstructed from hadronic final state only

d) Jacquet –Blondel method

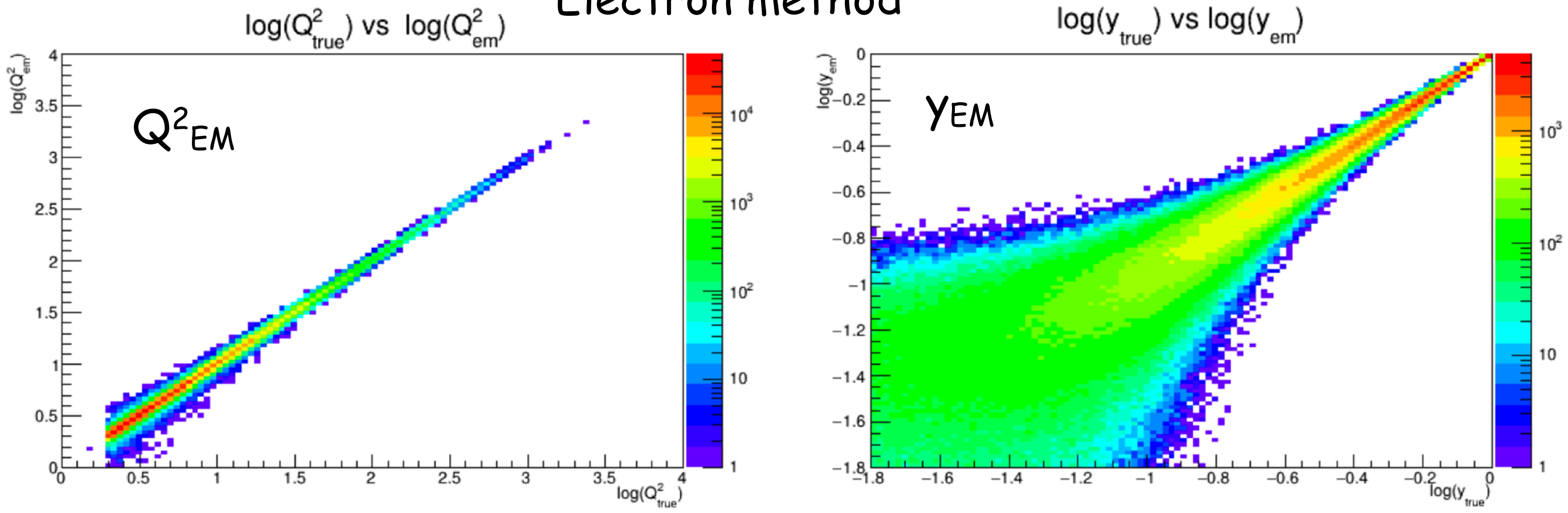
$$y_{JB} = \frac{1}{2E_e} \sum_h (E_h - p_{z,h}),$$

$$Q^2_{JB} = \frac{1}{1 - y_{JB}} \left[\left(\sum_h p_{x,h} \right)^2 + \left(\sum_h p_{y,h} \right)^2 \right].$$

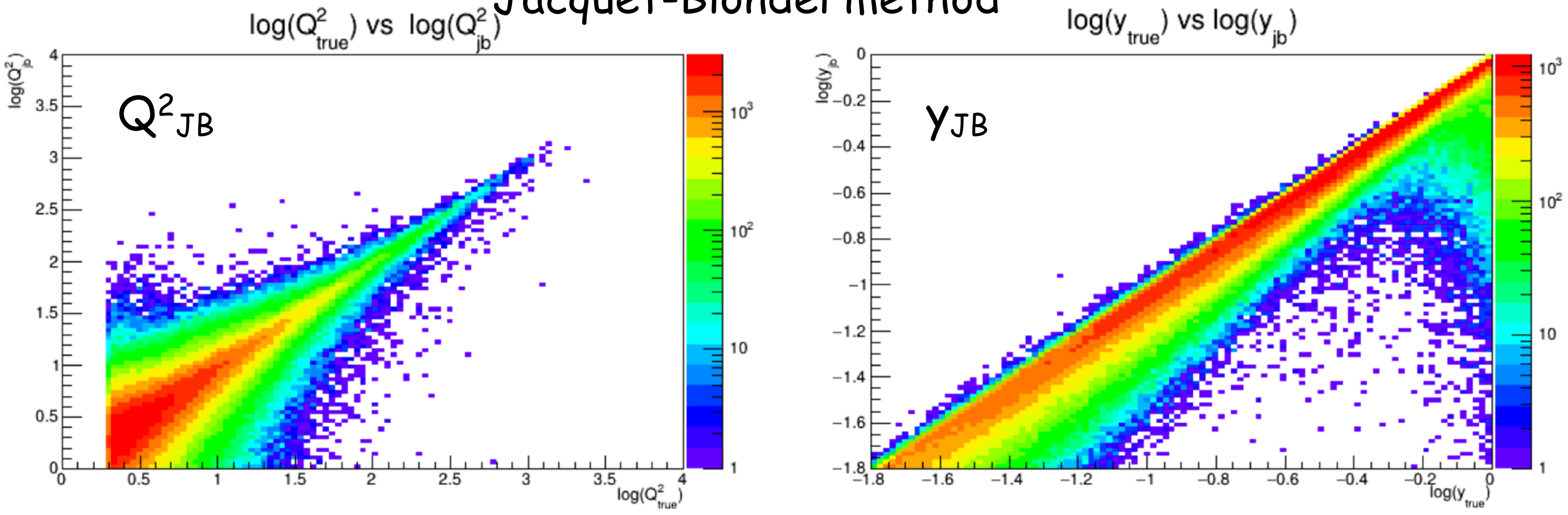
Note: poor resolution compare to other methods, but
this is the only method for Charged Current DIS events!!!

Measurement of DIS kinematics

Electron method



Jacquet-Blondel method



Particle detection and identification

via interaction with detector material

Stable particles only 27 (13) particles in PDG have cτ > 1µm (500µm)

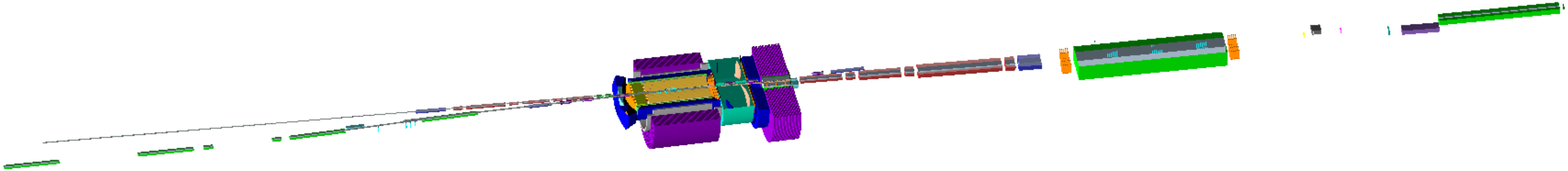
- Electrons/positrons ($e^{\pm}$)
- Gammas (γ)
- Individual hadrons ($\pi^{\pm}$, $K^{\pm}$,p)
- Neutral hadrons (n,K^0_L)
- Muons ($\mu^{\pm}$)
- Neutrinos (ν)

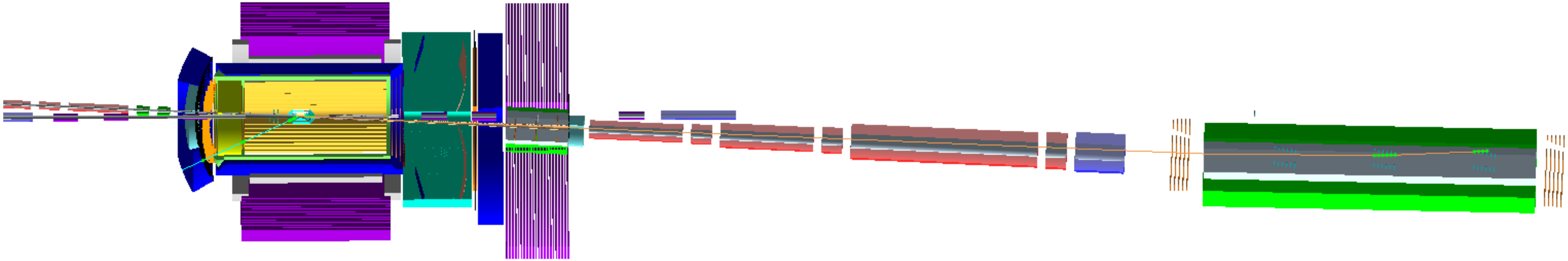
Measurements

- Charge and Momentum measurements
- Energy measurements
- Vertex origination
- Particle ID

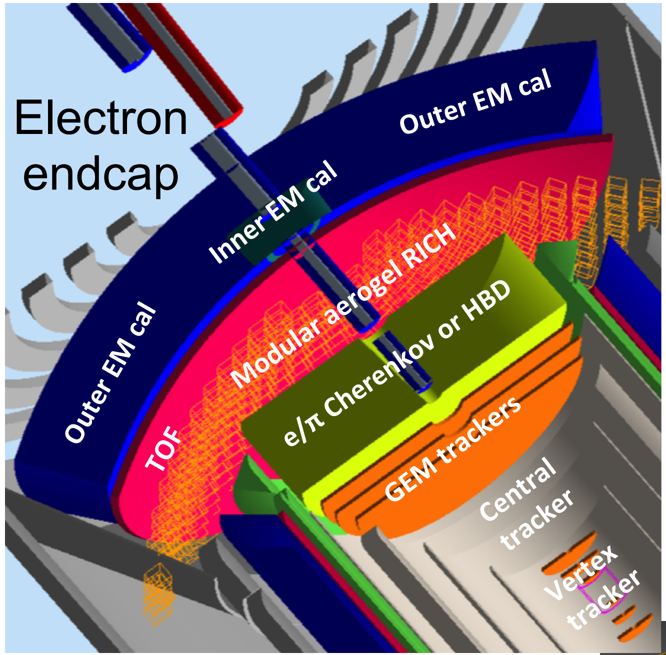
Position, origination and direction (x,y,z) →	Tracking detectors
Momentum (p) →	Tracking detectors in magnetic field
Energy (E) →	Calorimeter
Mass (m) Velocity (β) →	Time of flight Cherenkov radiation Transition radiation

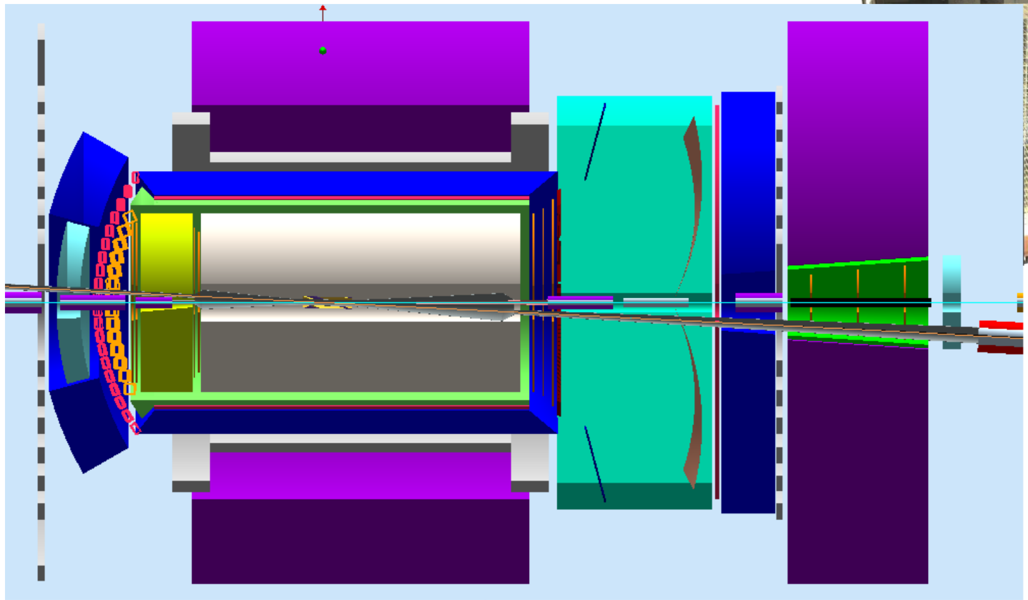
Simulation of the JLEIC Detector

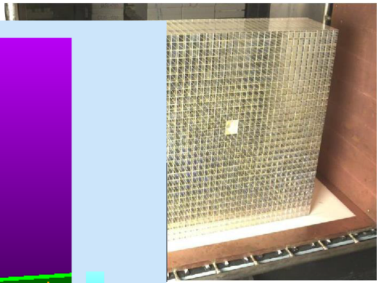




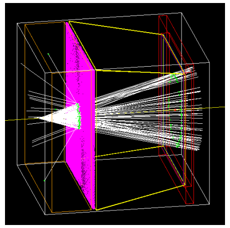
Generic EIC detector R&D program



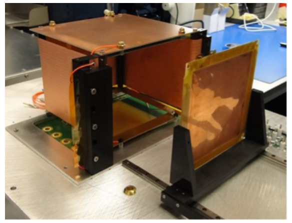




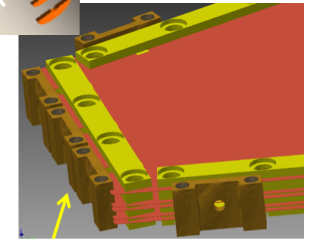
eRD1 – PWO_4 small-angle EMcal



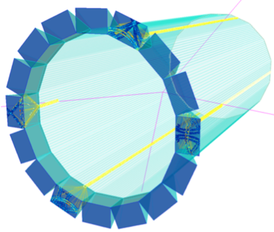
eRD14 – modular aerogel RICH



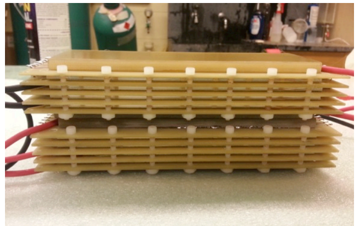
eRD6 – HBD/TPC?



eRD3 & eRD6 – GEM trackers



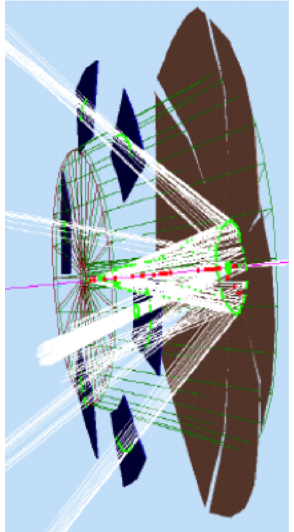
eRD14 – DIRC



eRD14 – MRPC TOF

eRD14 – photosensors

eRD14 – dual-radiator RICH



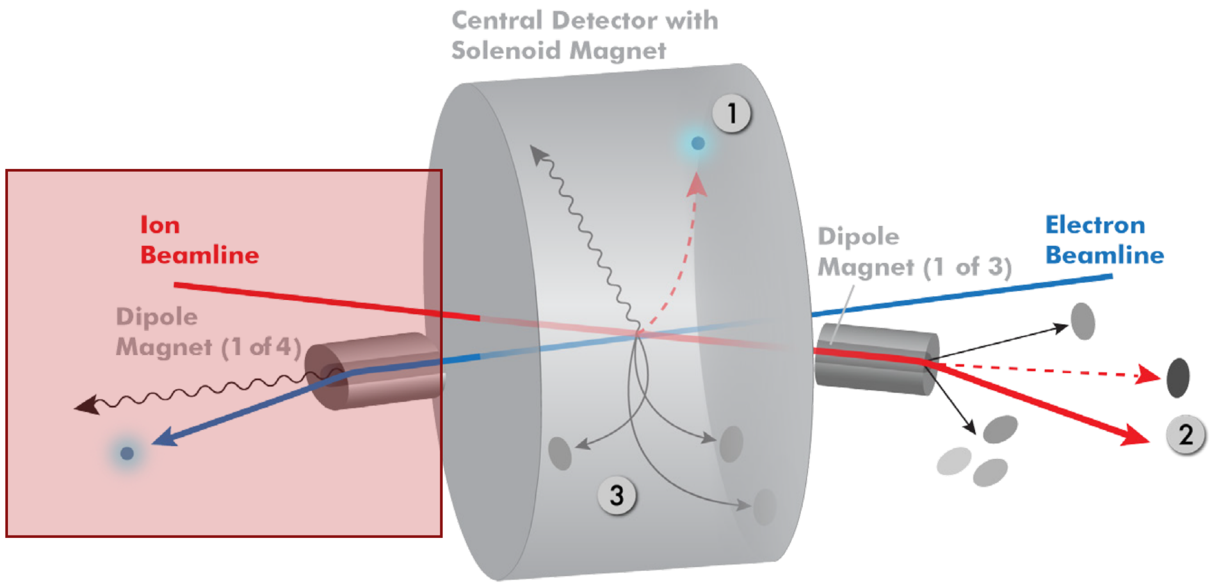
R&D program by BNL and JLab

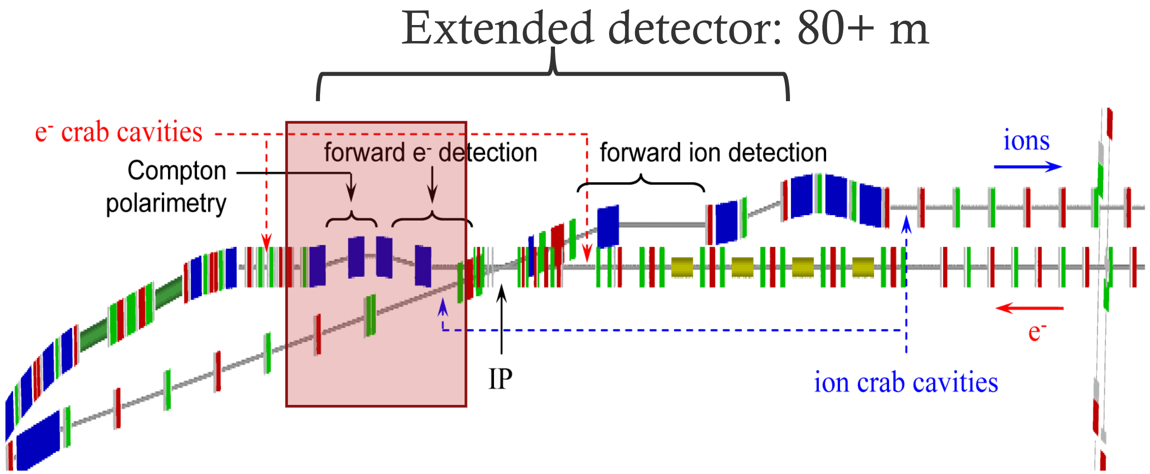
JLab detector implements many of the projects

Detector design

Far-forward electron detection

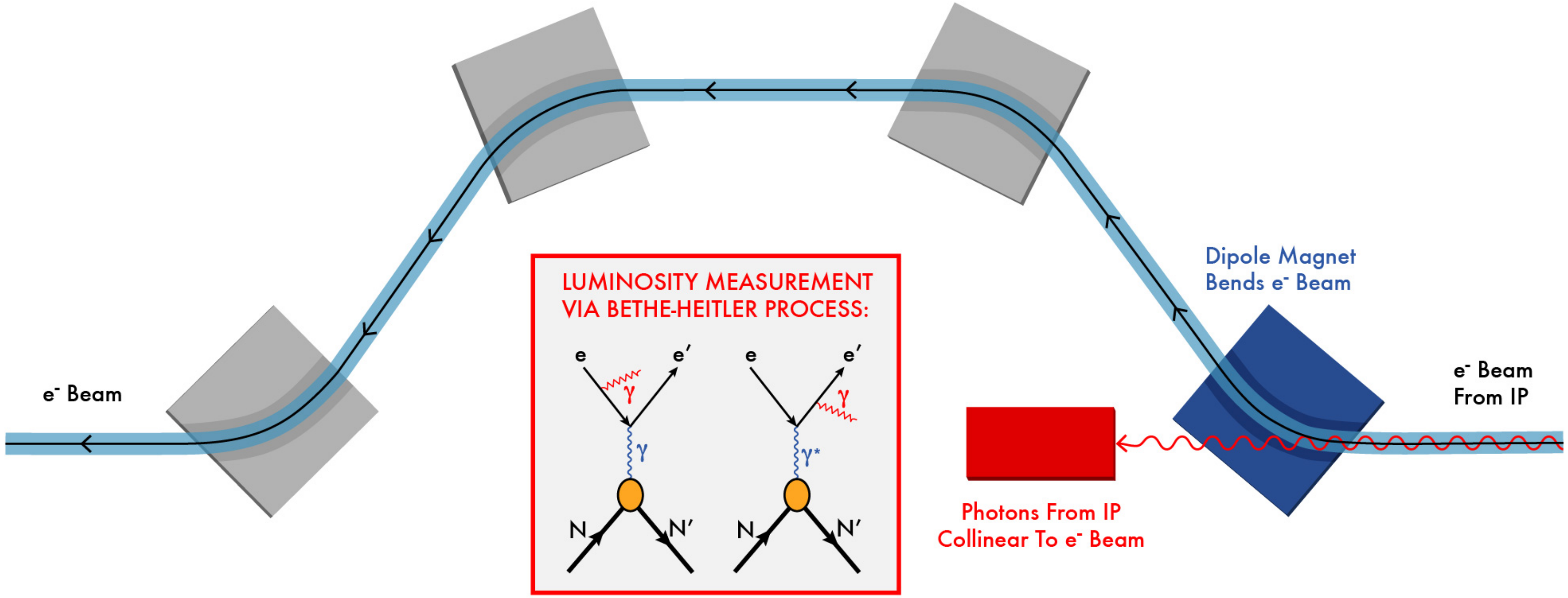
Far-forward electron detection



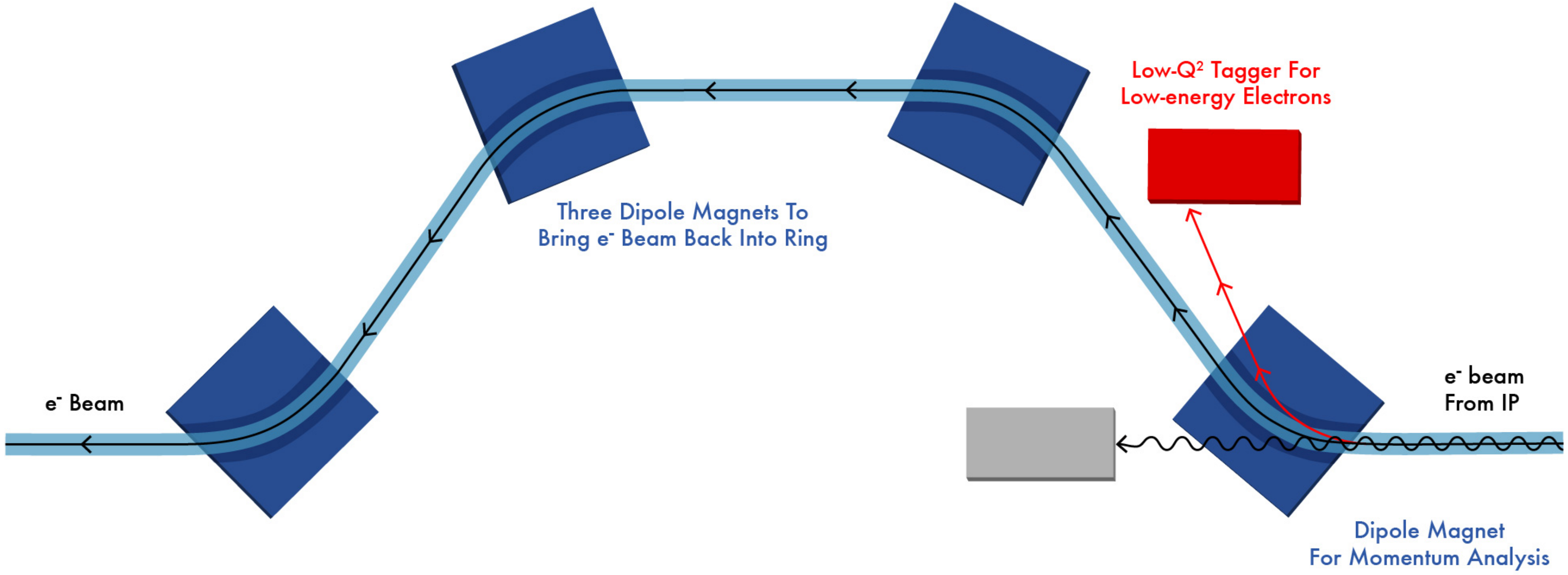


Luminosity measurement

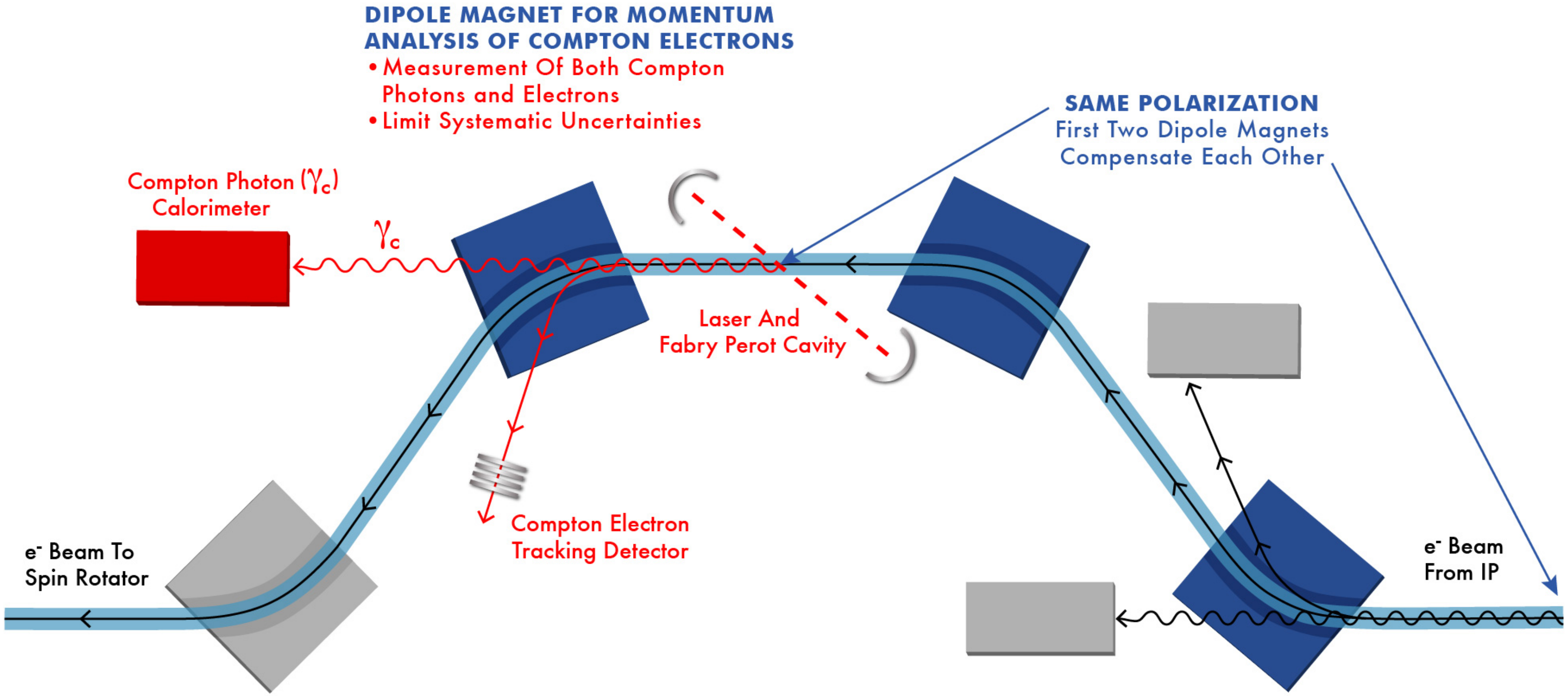
Use Bethe-Heitler process to monitor luminosity (same as HERA)



Low-Q^2 tagger

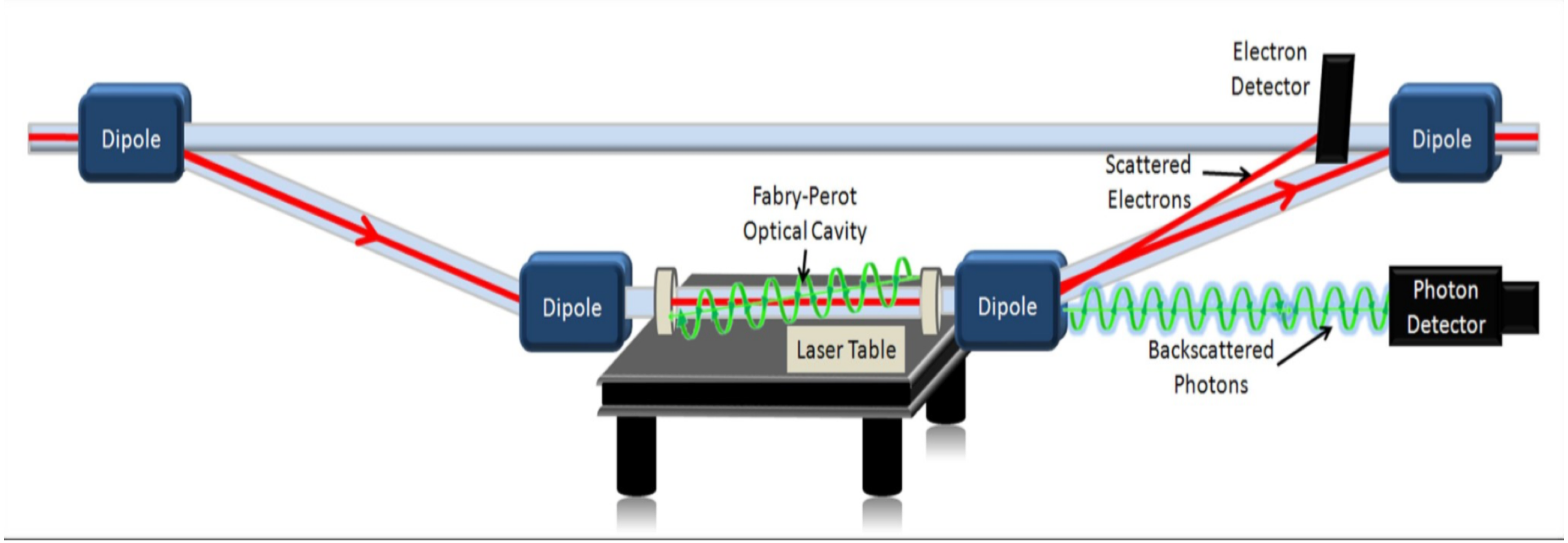


Polarization measurement



Note the off-momentum electrons from IP does not enter the luminosity Compton tracker.

Compton polarimetry

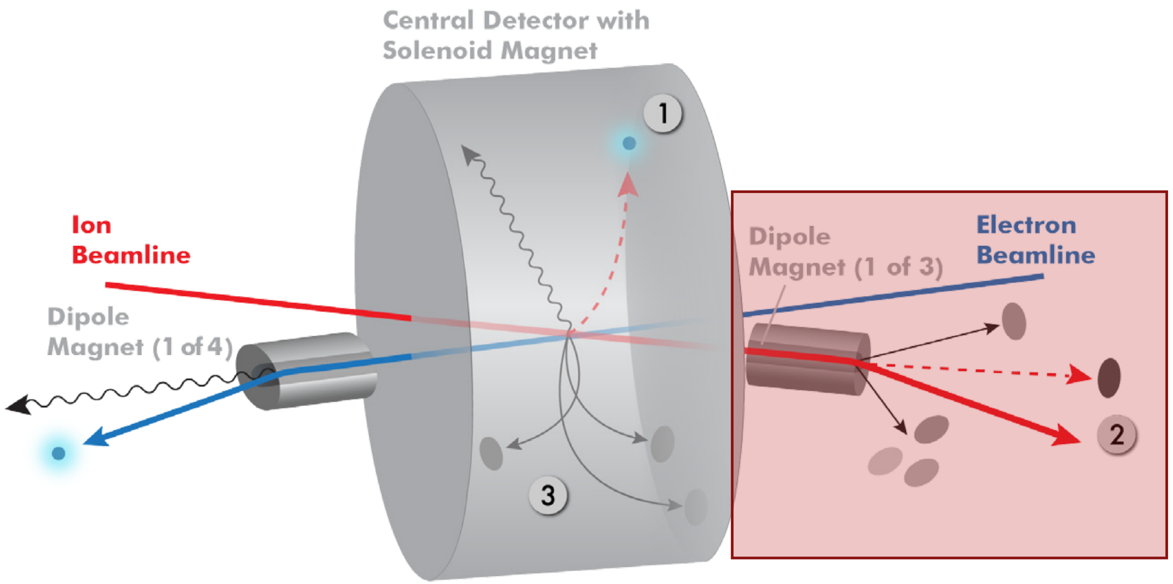


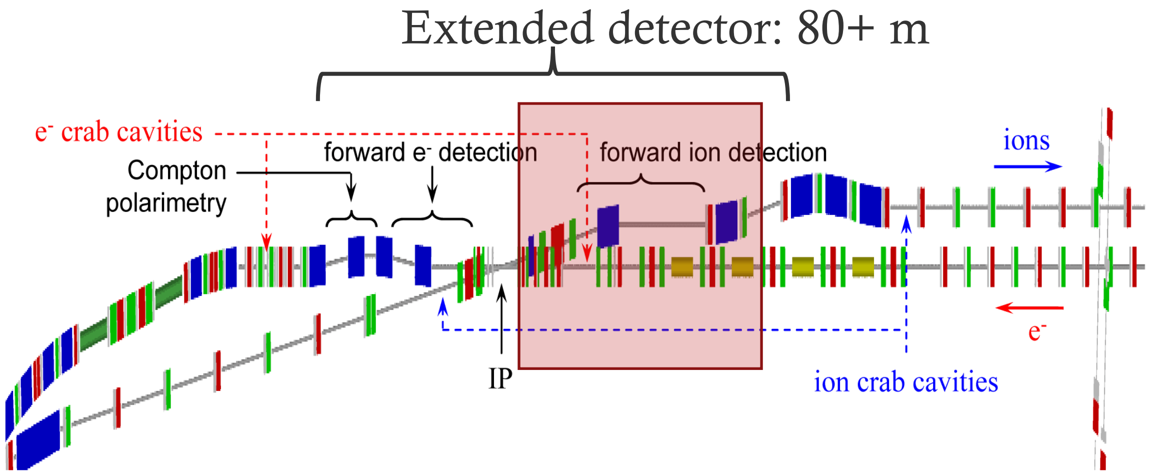
Existing Polarimeter in Hall C at JLab: Achieved 0.6% Precision

Detector design

Far-forward ion detection

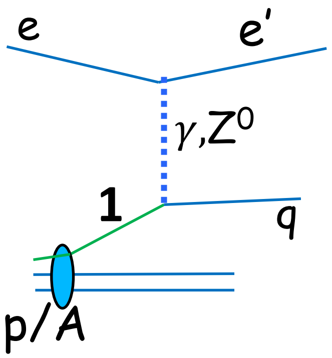
Far-forward ion detection



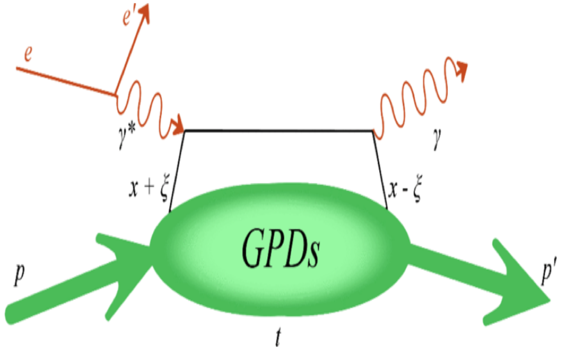


Far-forward ion detection requirements

Proton/Ion remnant



DVCS, VM production



Diffraction

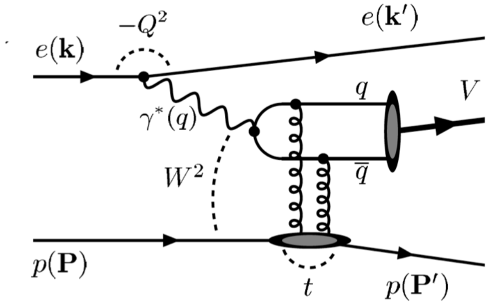
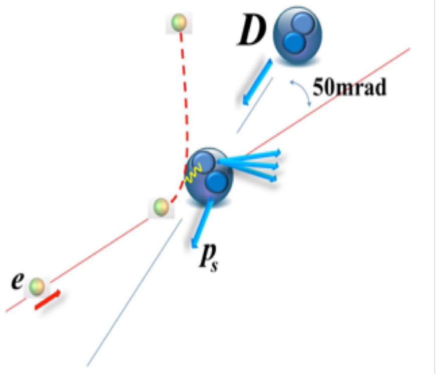
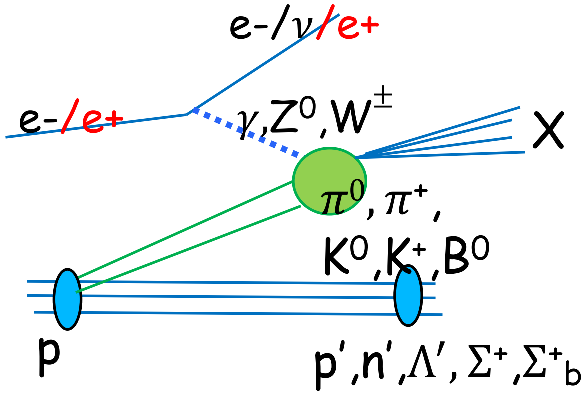


Figure 2. Exclusive vector meson production described by perturbative quantum chromodynamics.

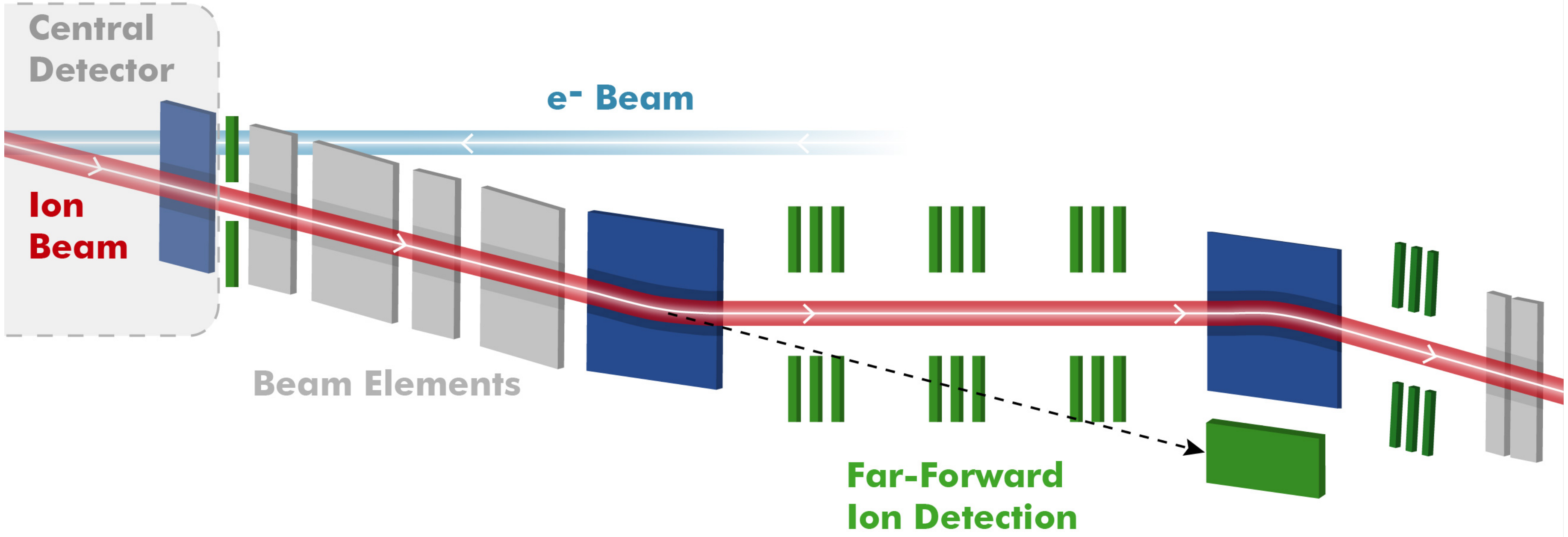
Scattering on deuteron
Double tagging



Pion/Kaon structure

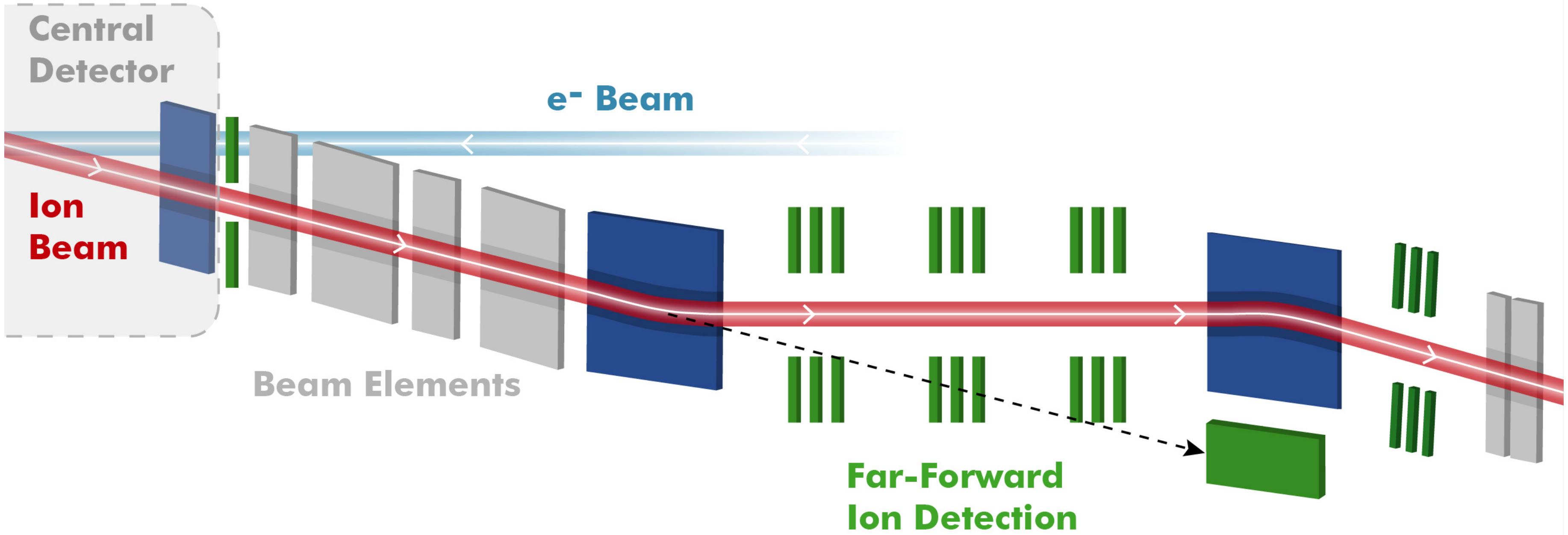


Far-forward ion detection



Forward detection requirements
- good acceptance for recoils nucleons (rigidity close to beam)
- good acceptance for fragments (rigidity different than beam)

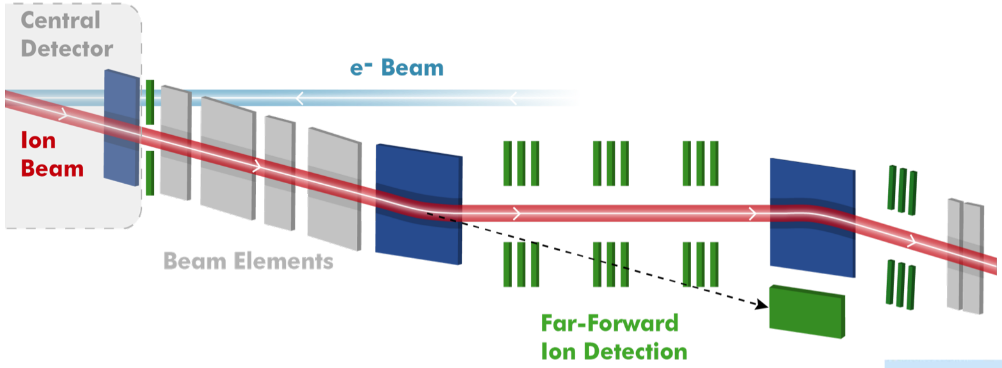
Far-forward ion detector design



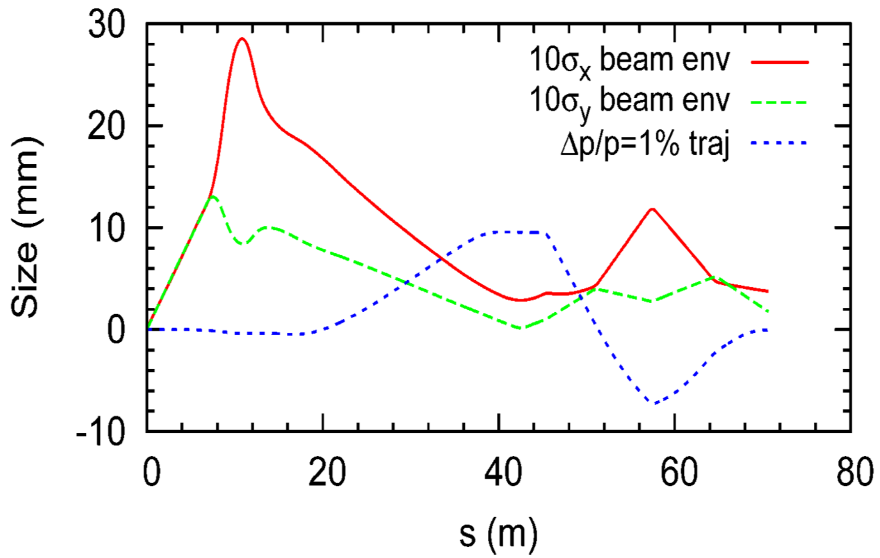
Detectors

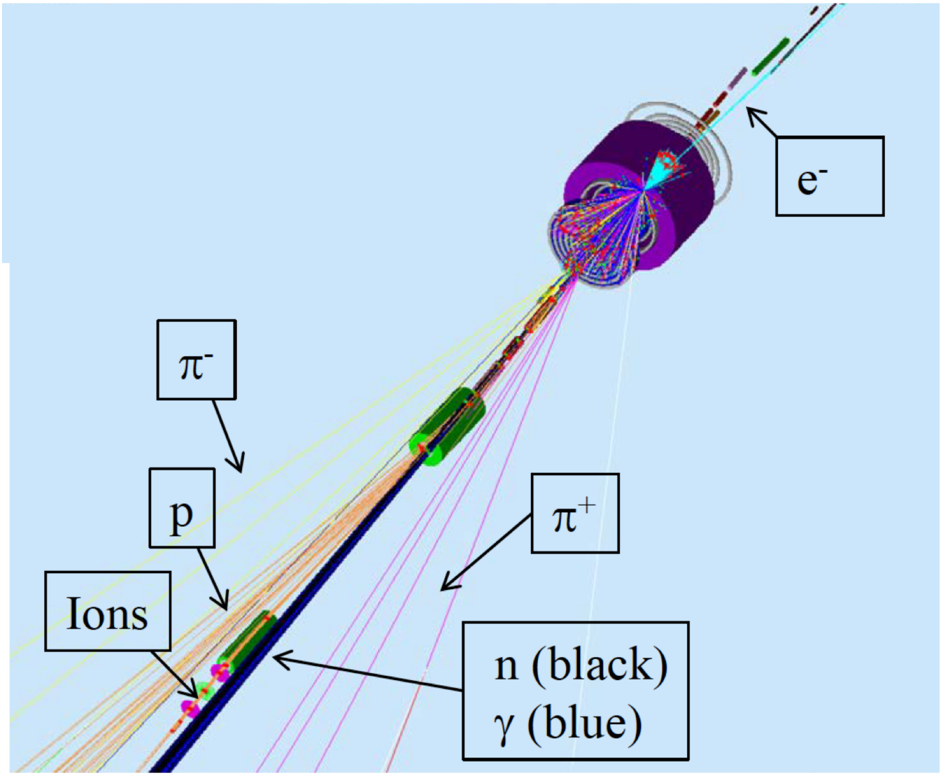
- **Tracking detectors** decay products of Λ', Σ $(\pi$,K)
- **Roman-pots** for (p)-tagging
- **Zero degree calorimeter** for (n)-tagging

Far-forward ion detector design considerations



- Main beam is focused
- High dispersion for off momentum particles

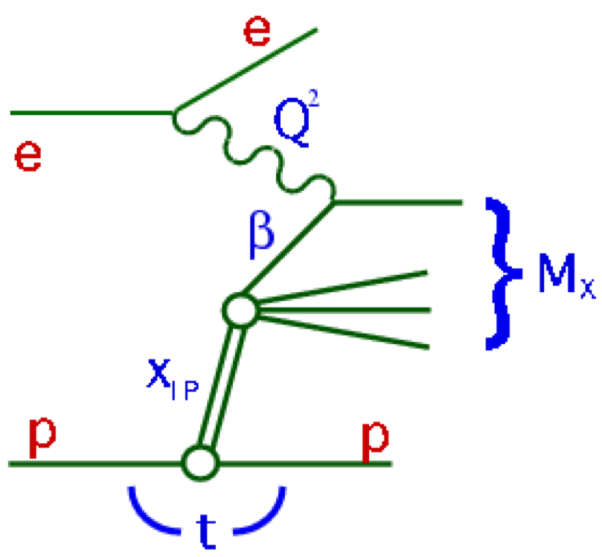




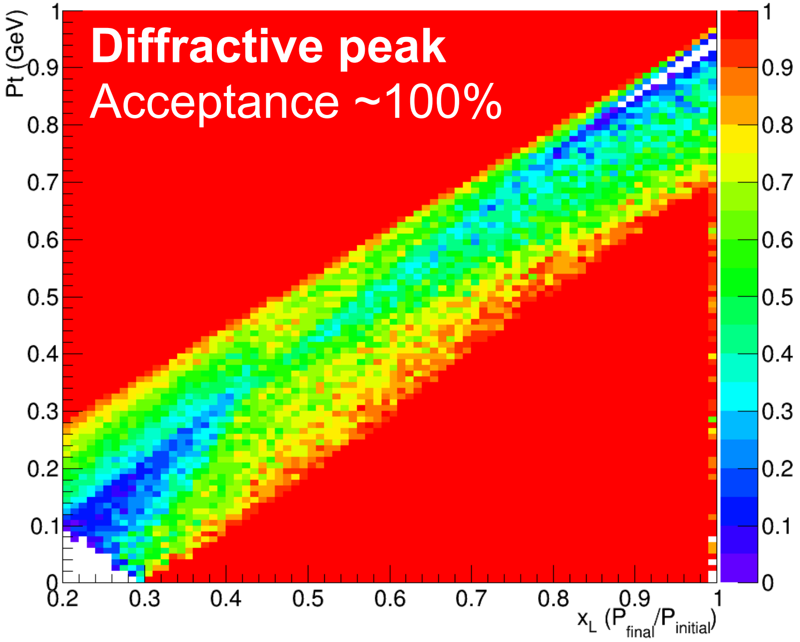
Example for far-forward detection: Diffractive DIS

Diffractive DIS

Signature for saturation

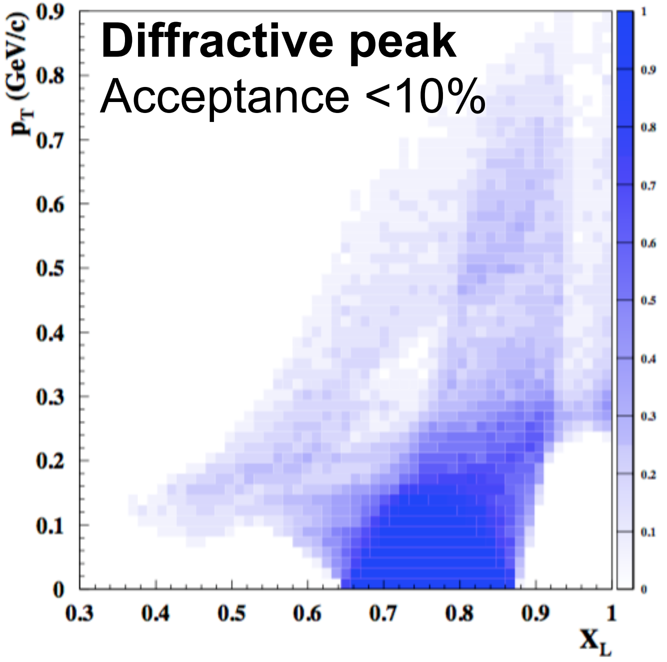


JLEIC



ZEUS

Leading Proton Spectrometer



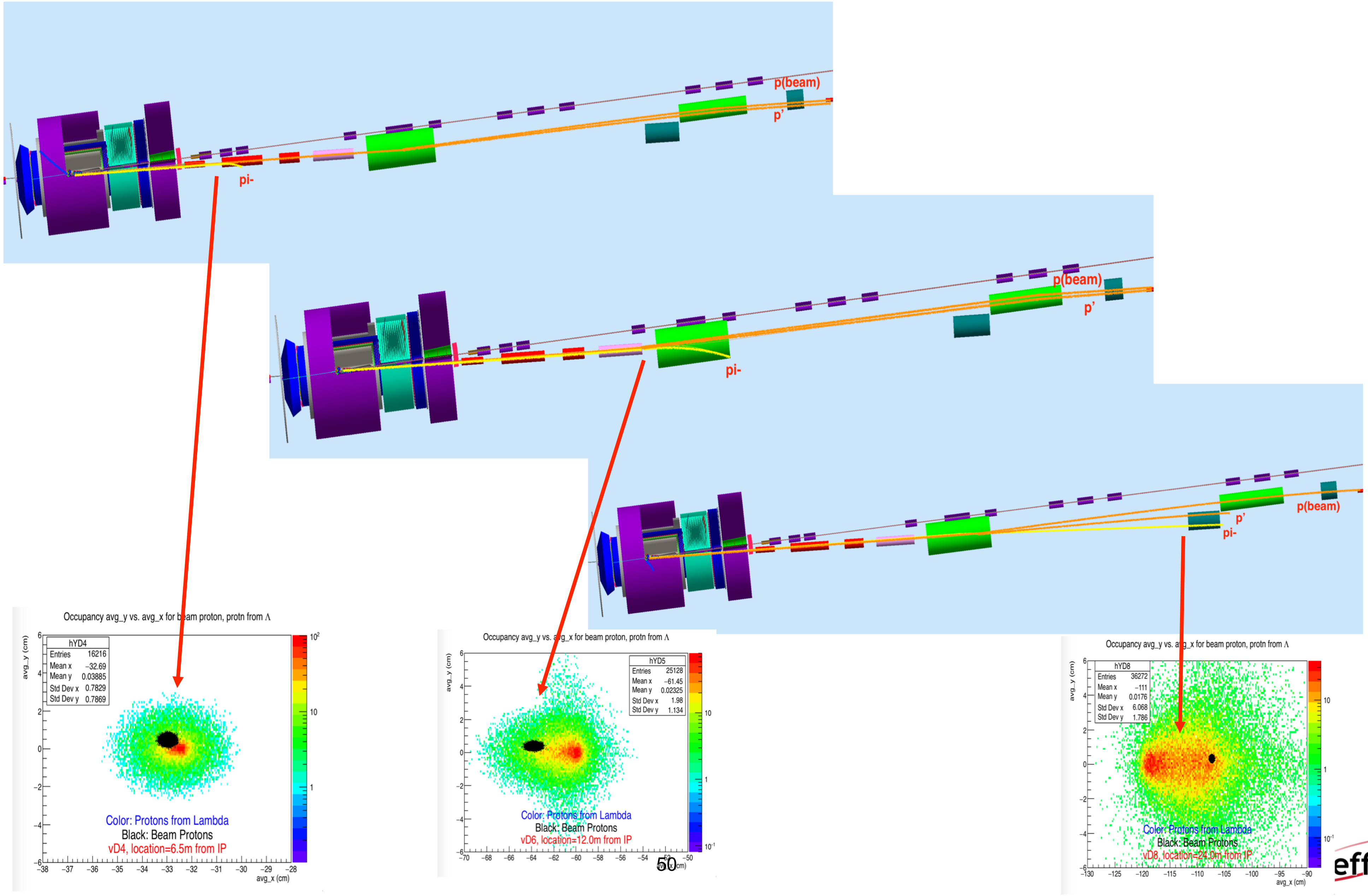
Identify the scattered proton p'

- distinguish from proton dissociation
- measure $X_L = E_p'/E_p$, and P_t (or t)

Measurement for p' in DDIS

diffractive peak X_L>~.98

Occupancy in far-forward ion direction

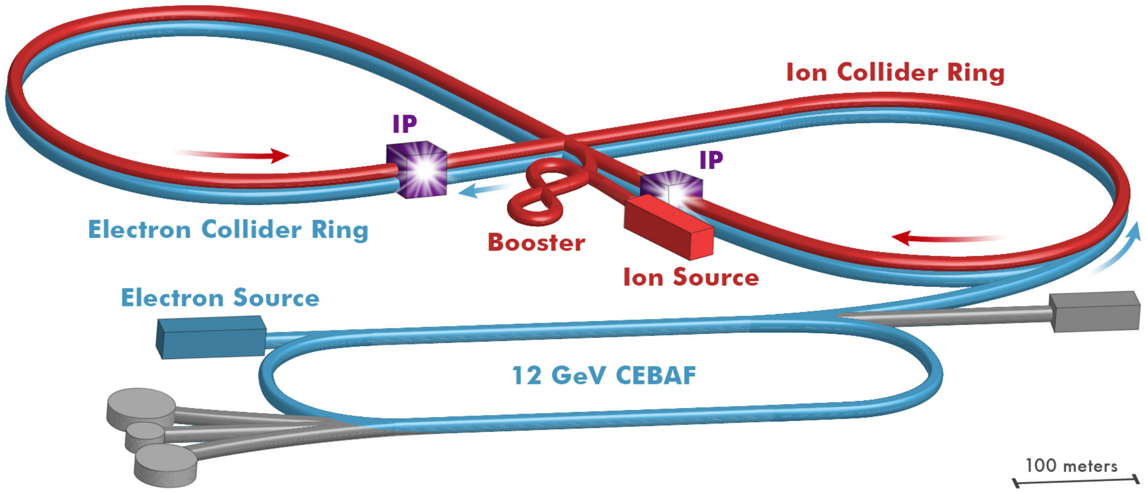


Detector design

Complementary detector concepts

Complementary detector scenarios at JLEIC

Two IPs / detectors optimized for **different capabilities** and using **complementary technologies** allow **better performance** and **improved cost-effectiveness**.



Advantages

- complementary sensitivity to physics, backgrounds and fake effects
- cross-checks on discoveries and important physics results
- combine results for precision measurements:
  - a combined reduction of systematics
  - in a ring-ring collider: detector luminosities can be added

Detector Options

Community effort
discuss detector ideas and concepts in EIC User Group

specialized detector

e.g., Caldwell, LHCb

general-purpose detector

hermetic detector

drivers: cost, luminosity

non-hermetic detector

e.g., PHENIX

small central detector

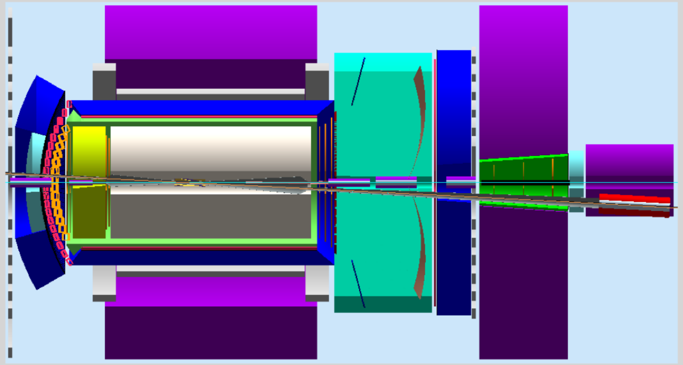
highest-luminosity
4π calorimetry

large central detector

PID
tracking

Complementary detector concepts at JLEIC

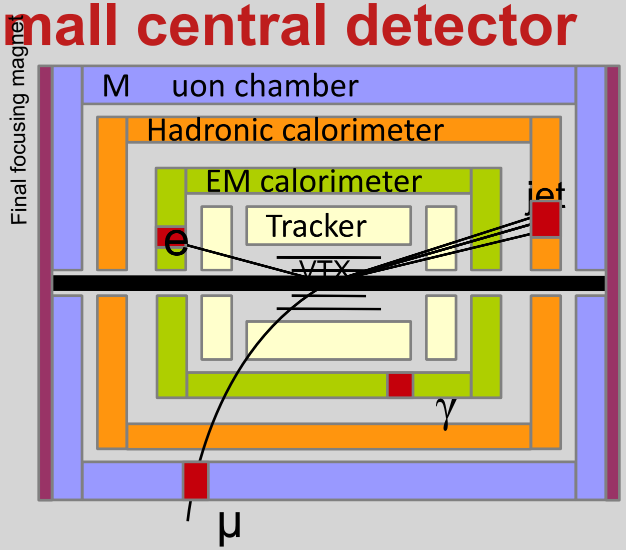
Large central detector



~10.5 m

- focus on single track reconstruction
- focus on (hadron) PID
- limited hadron calorimetry

Small central detector



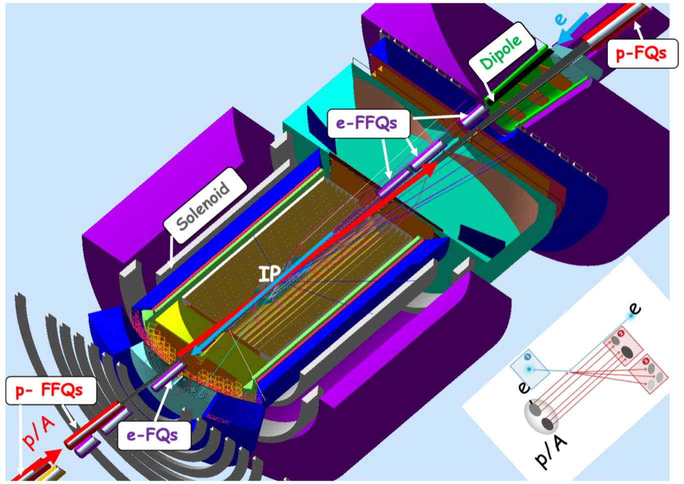
~8.0m (including muon chamber)

- focus on jet reconstruction
- focus on hadron calorimetry (4π)
- higher luminosity
- limited (hadron) PID

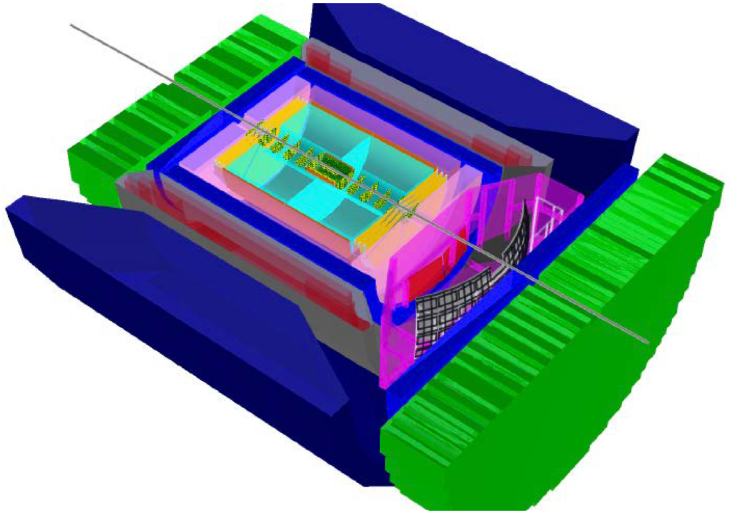
Jefferson Lab

Detector concepts for the EIC

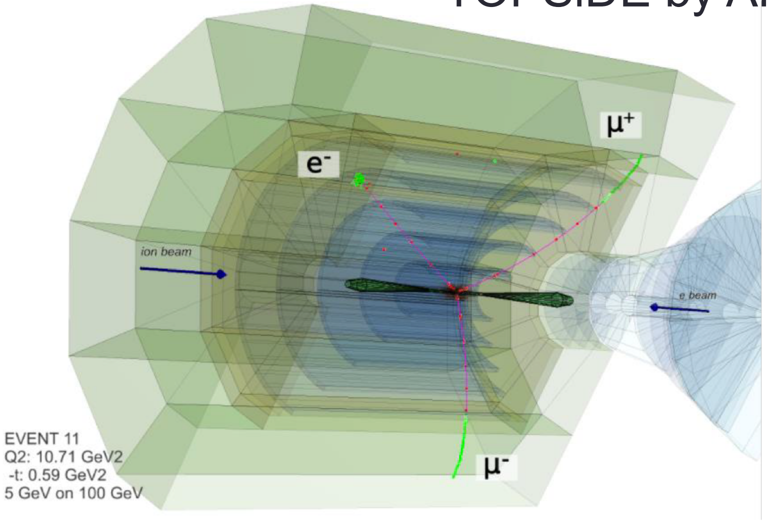
JLEIC Detector



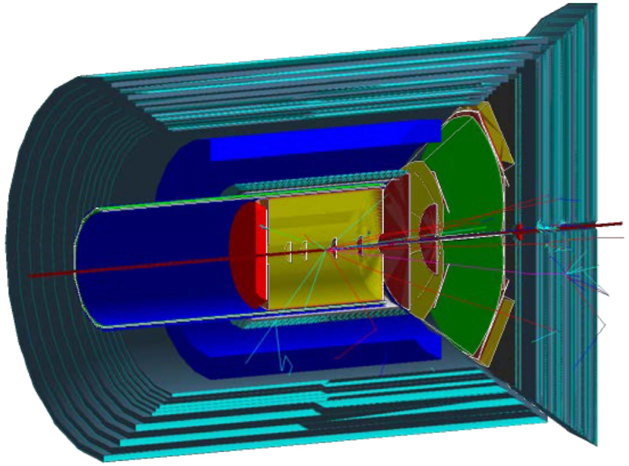
eRHIC Detector



TOPSiDE by ANL



eRHIC “Day 1” Detector



Markus Diefenthaler

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Summary

- Outstanding questions raised both by the science at HERMES/COMPASS/JLAB and RHIC/LHC, have naturally led to the science and design parameters of the EIC.
- EIC will enable us to embark on a **precision study of the nucleon and the nucleus at the scale of sea quarks and gluons**, over all of the kinematic range that are relevant.
- What we learn at JLAB 12 and later EIC, together with advances enabled by FRIB and LQCD studies, will open the door to **a transformation of Nuclear Physics**…
- … **but only if we build the right machine and detector**: Requirement for fully integrated IR and detector design and total acceptance detector