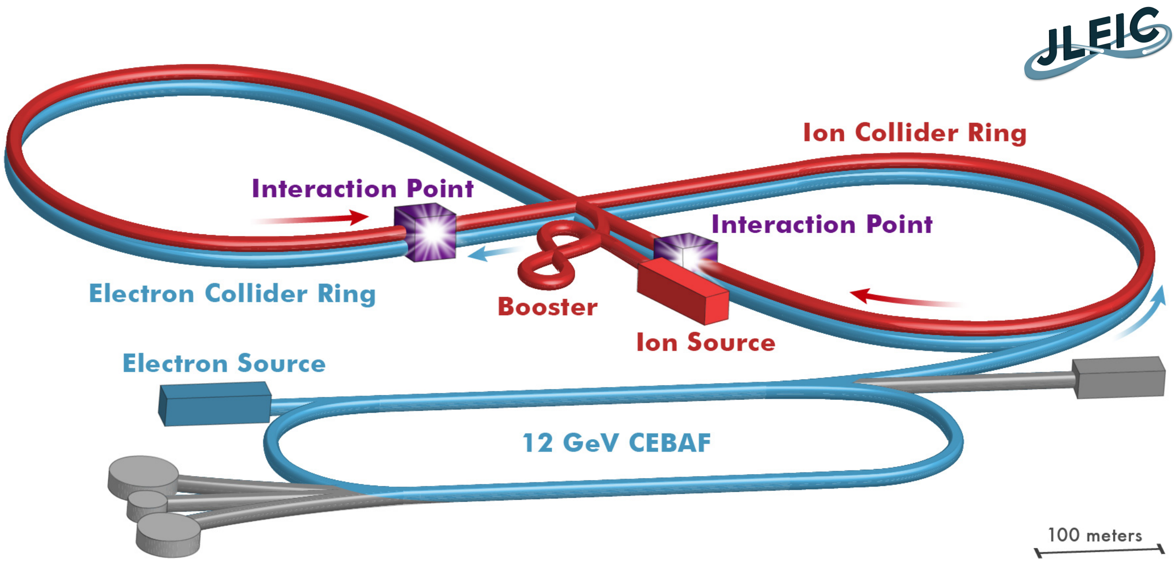
Jefferson Lab Electron-Ion Collider and Diffractive Physics



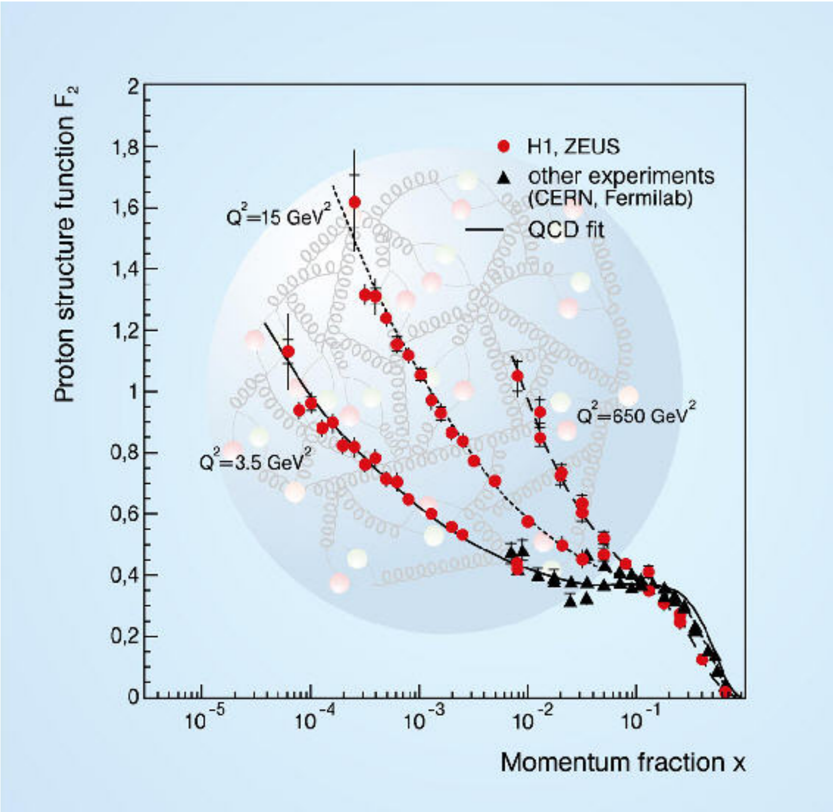
Rik Yoshida
Jefferson Lab

Diffraction 2016
Catania, Italy, September 3, 2016

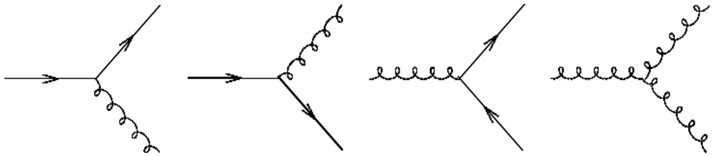
Jefferson Lab
Thomas Jefferson National Accelerator Facility

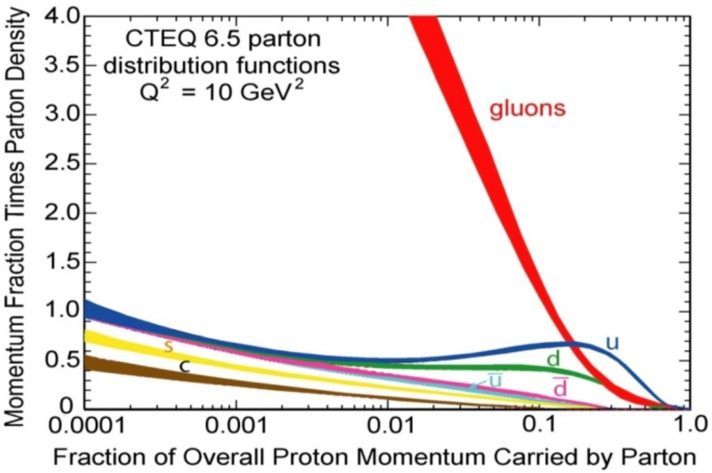
Introduction: DIS, Diffraction and the Electron-Proton Collider

Proton Structure measurements at HERA



QCD analysis

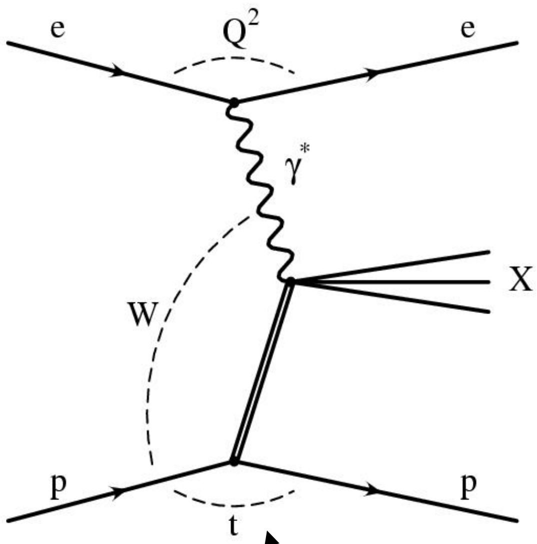


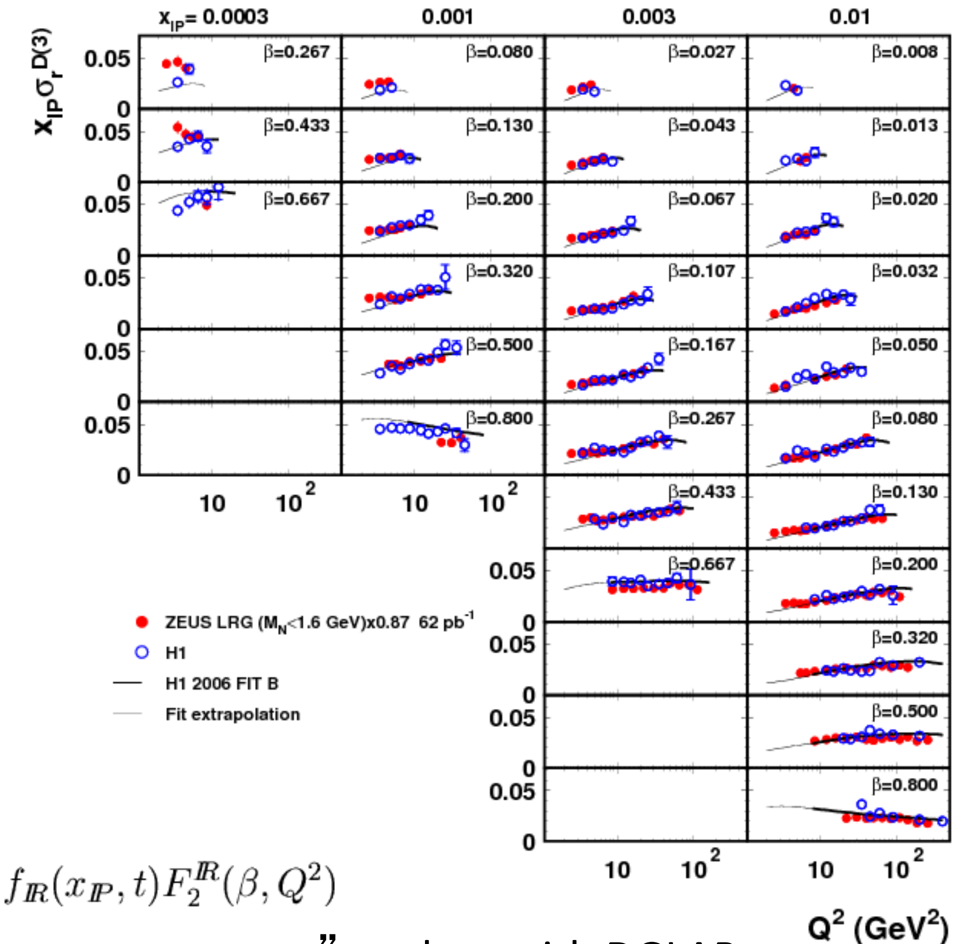


A part of Wilczek's comments upon the Nobel Prize announcement (2004)

proposed specific experimental tests of our ideas. In the fourth paper some technical objections to the theory were cleared up, and in the fifth and sixth papers further experimental consequences, regarding the pointwise evolution of structure functions, were derived. The most dramatic of these, that protons viewed at ever higher resolution would appear more and more as field energy (soft glue), was only clearly verified at HERA twenty years later.

Diffractive DIS at HERA





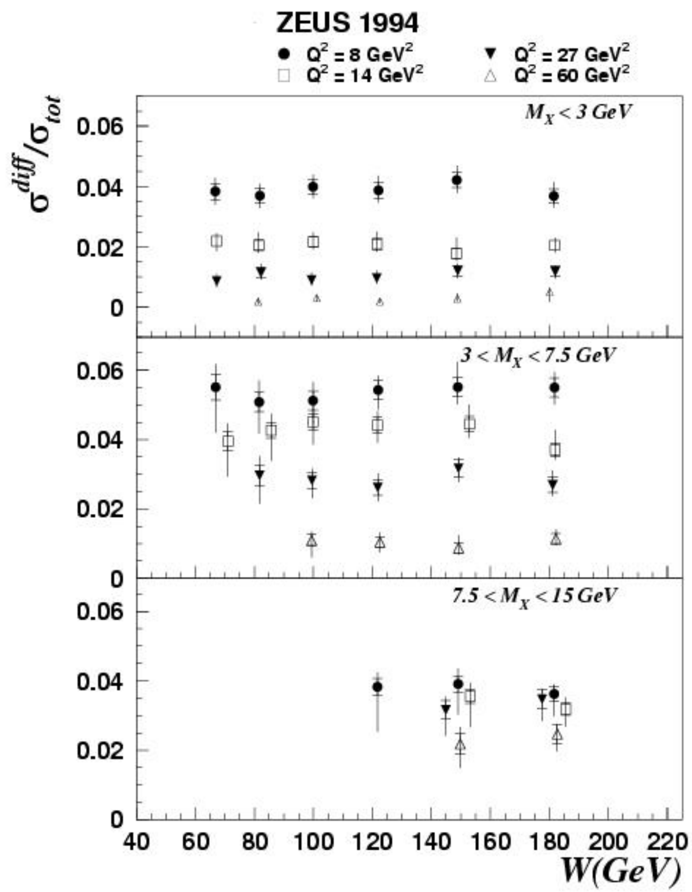
"Pomeron flux"

$$F_2^{D(4)}(x_{I\!P}, t, \beta, Q^2) = f_{I\!P}(x_{I\!P}, t) F_2^{I\!P}(\beta, Q^2) + f_{I\!R}(x_{I\!P}, t) F_2^{I\!R}(\beta, Q^2)$$

"Pomeron structure" evolves with DGLAP

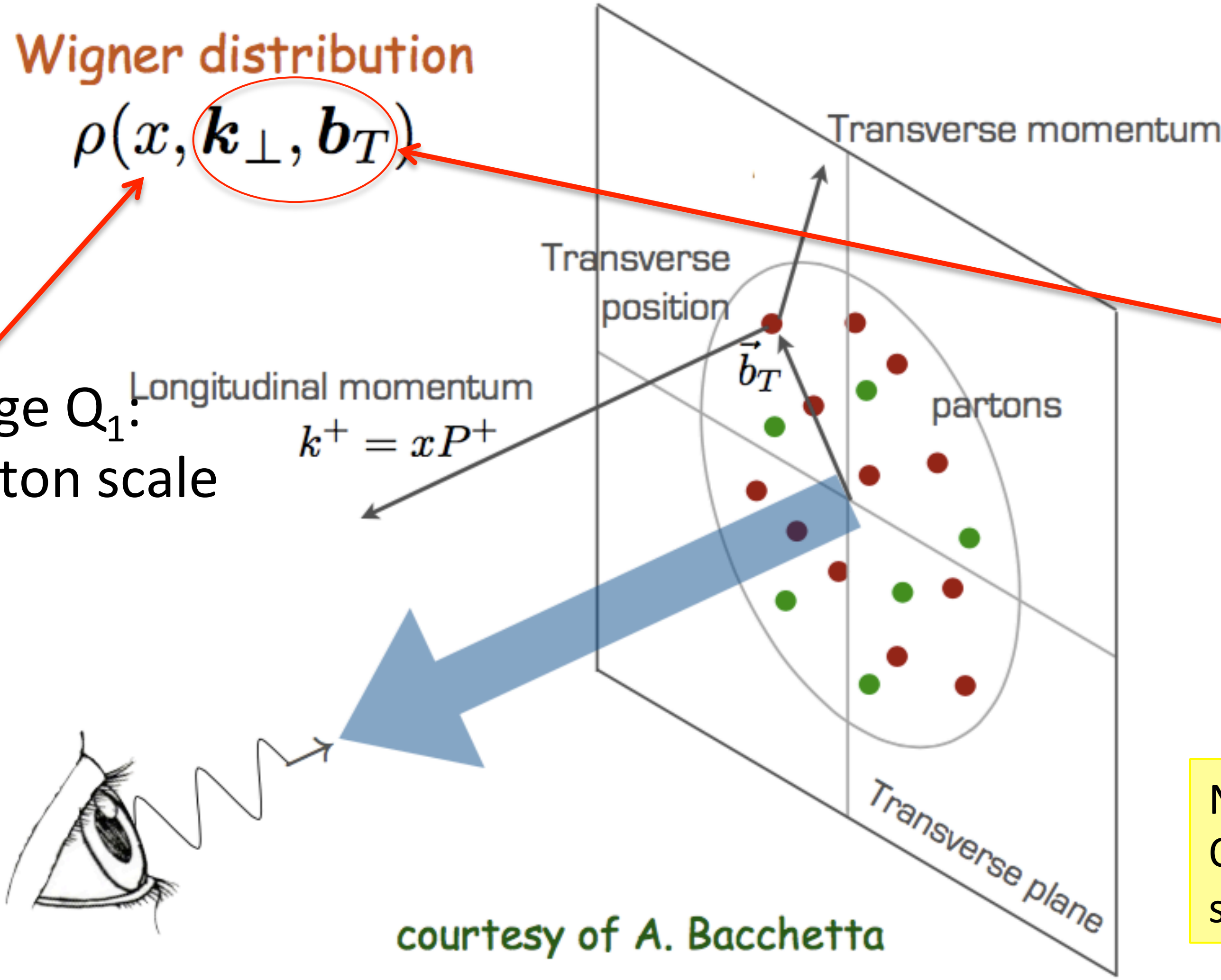
How Does DDIS fit with Proton Structure ?

Diffractive parton densities and its DGLAP analyses fails to give any explanation of the central mystery of DIS diffraction—the "pomeron flux factor"



- Why so much of it. ~10% at Q^2 as high as 30 GeV^2.
- Why is the ratio (diff)/(tot) flat in W (or 1/x)?
  - If (tot) is proportional to (gluon)
  - Isn't (diff) proportional to $(gluon)^2$??
- Doesn't the flatness point to some sort of non-linearity (saturation) after all?

Theoretical Framework



Large Q_1: parton scale

Theoretical progress in the past decades:

Need access to transverse quantities
Scale is "soft"

Small Q_2: proton scale

Need access to Q_1 and Q_2 (<<Q_1) simultaneously

Unanswered Questions

What is the internal structure of the proton beyond the longitudinal x?

How does the mass of the proton arise?

How does the spin of the proton arise?

How does confinement work?

What is the partonic nature of nucleon-nucleon interaction in nuclei?

The reasons we could not answer these questions at HERA:

There was no polarized proton beam

There were no polarized ion beams

Limited access to transverse structure: access to Q_2 (~ Λ_{QCD}= 0.2 GeV)

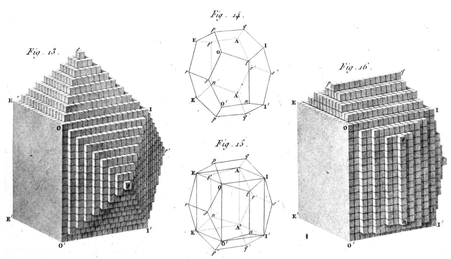
Multi-dimensional measurement, exclusive reactions: need high luminosity

Need ability to measure quantities of order Q_2: Lower proton energy, so reduce Λ_{QCD}/E_{proton} by factor 10 or so (but maintain high enough Q_1, however). Need better detector for measuring small transverse quantities.

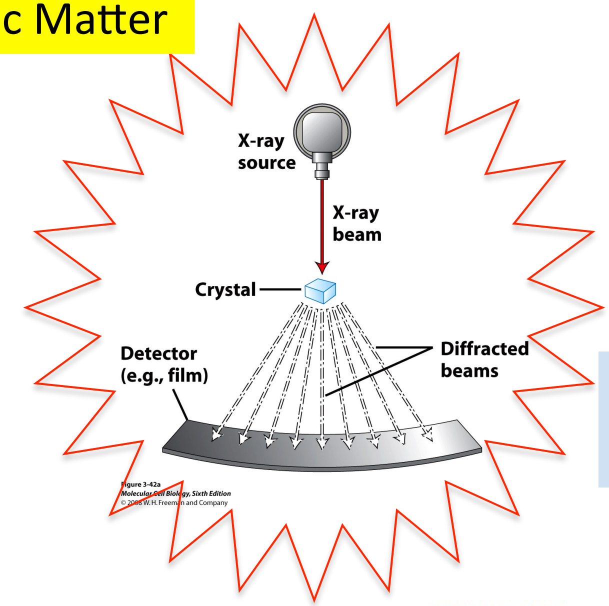
Physics of the Electron-Ion Collider

New Probes and New Science

Example: Structure of Atomic Matter

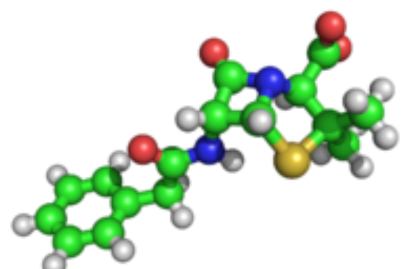


Crystal Structure: 1801

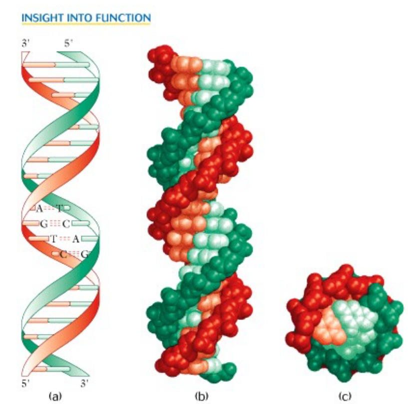


Advent of X-ray Diff. 1912

Probe with the right scale!



3D structure of penicillin: 1945

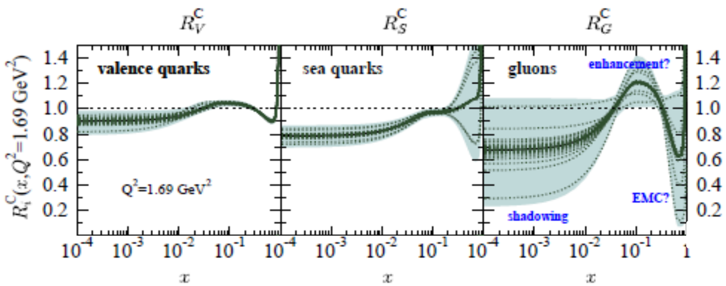


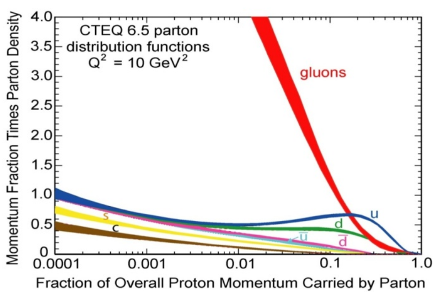
Precise understanding of structure leads to rich new sciences

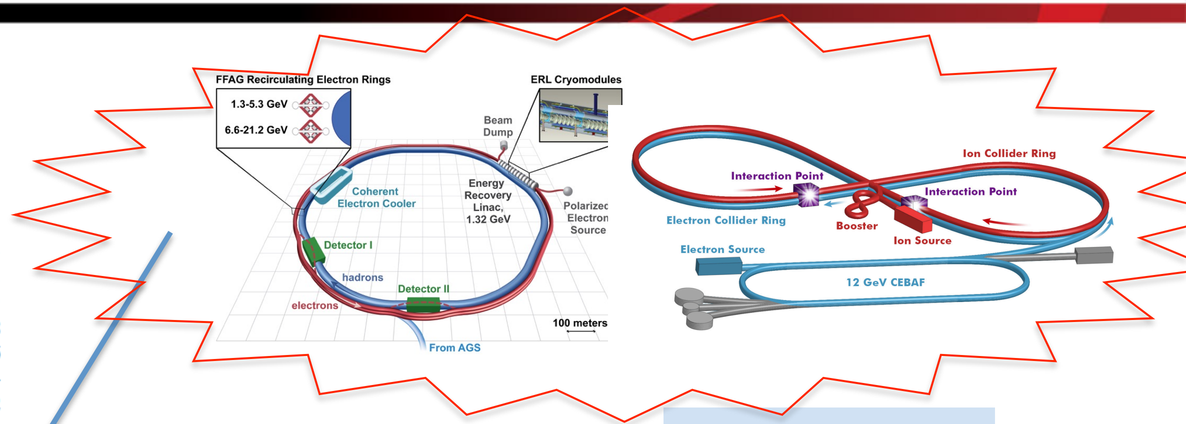
Double Helix: 1953

New Probe for Nuclear Science

2016

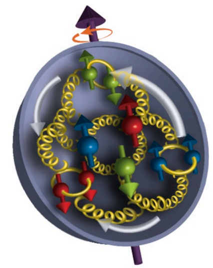


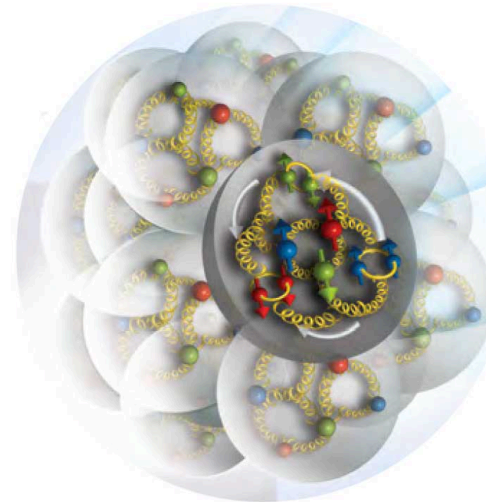




Advent of EIC: ~2027

Probe with the right scale!



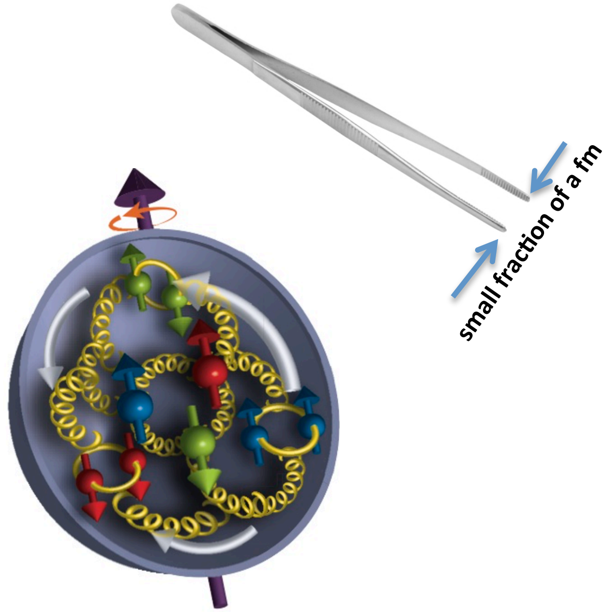


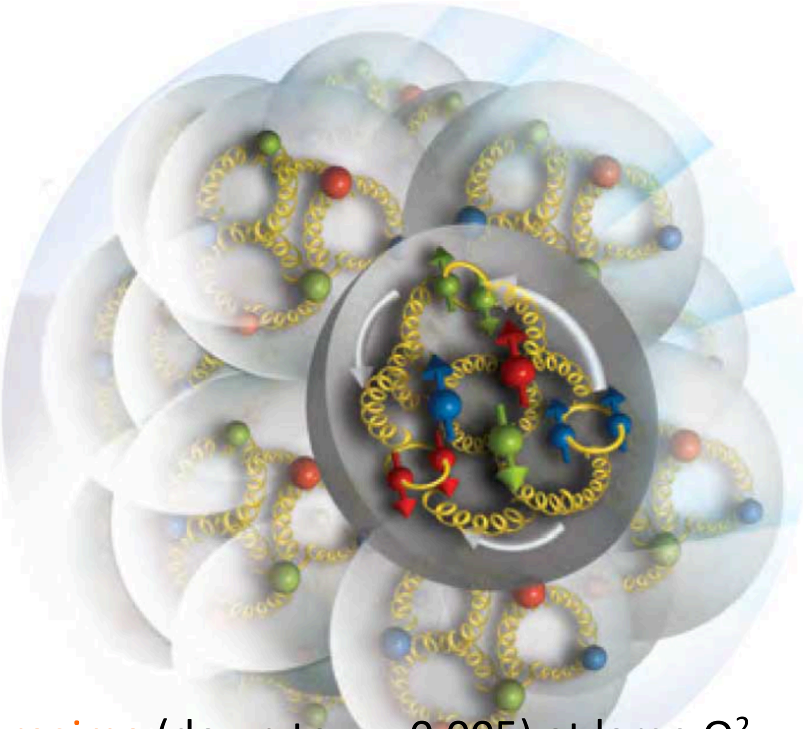
Precise understanding of structure and dynamics: dawn of new science

Jefferson Lab

EIC Physics Program

Program aim: Revolutionize the understanding of nucleon and nuclear structure and associated dynamics. Explore new states of QCD.



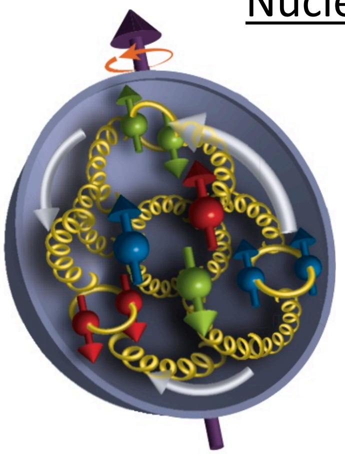


Program

- Probe the nucleon in the many-body regime (down to $x \approx 0.005$) at large Q^2
- Probe the nuclei in the N-N and multi-N interaction regime at large Q^2
- Extend our understanding of QCD (saturation, jets in cold nuclear matter)

Boring? Sounds like you've heard this for 30 years? No! Not Really!

Understanding the Nucleon at the Next Level



Nucleon: A many-body system with challenging characteristics

Relativistic (M_{proton} >> M_{quark})

Strongly Coupled (QCD)

Quantum Mechanical (Superposition of configurations)

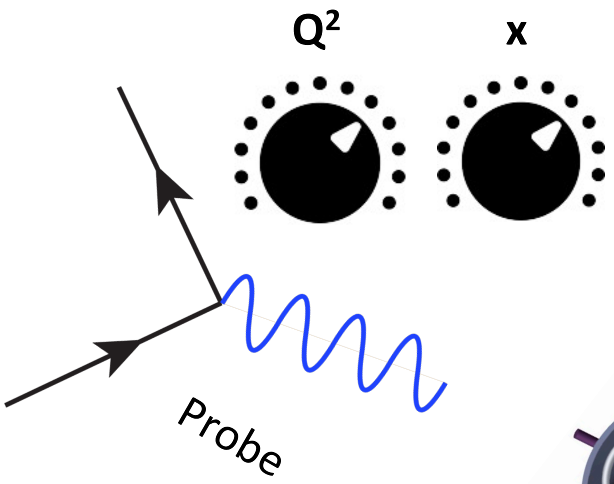
Measure in the Multi-Body regime:
- Region of quantum fluctuation + non-perturbative effects → dynamical origin of mass, spin.

For the first time, get (almost?) all relevant information about quark-gluon structure of the nucleon

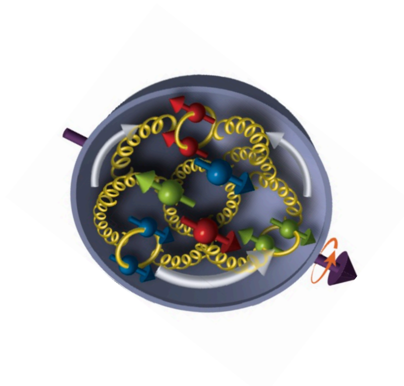
Designing EIC → Designing the right probe

- Resolution appropriate for quarks and gluons
- Ability to project out relevant Q.M. configurations

Parameters of the Probe

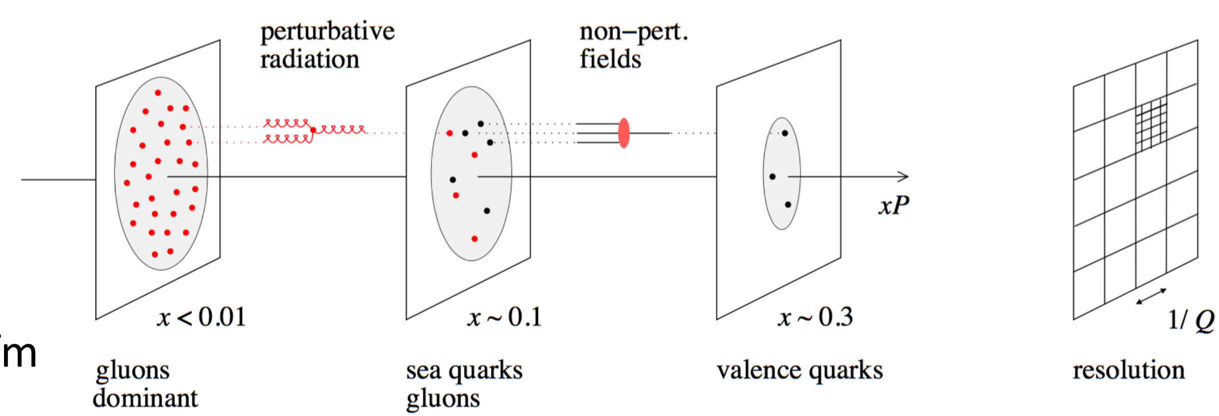


Ability to change **x** projects out different configurations where different dynamics dominate



Ability to change **Q^2** changes the resolution scale

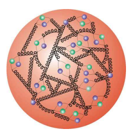
Q^2= 400 GeV^2 => 1/Q = .01 fm



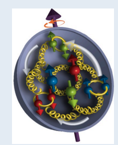
Where EIC Needs to be in x (nucleon)

Saturation Regime: Needs to be Accessed via Ions (see later)

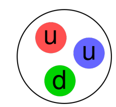
Collective Regime



Many-body Regime



Few-body Regime



10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 X (for proton)

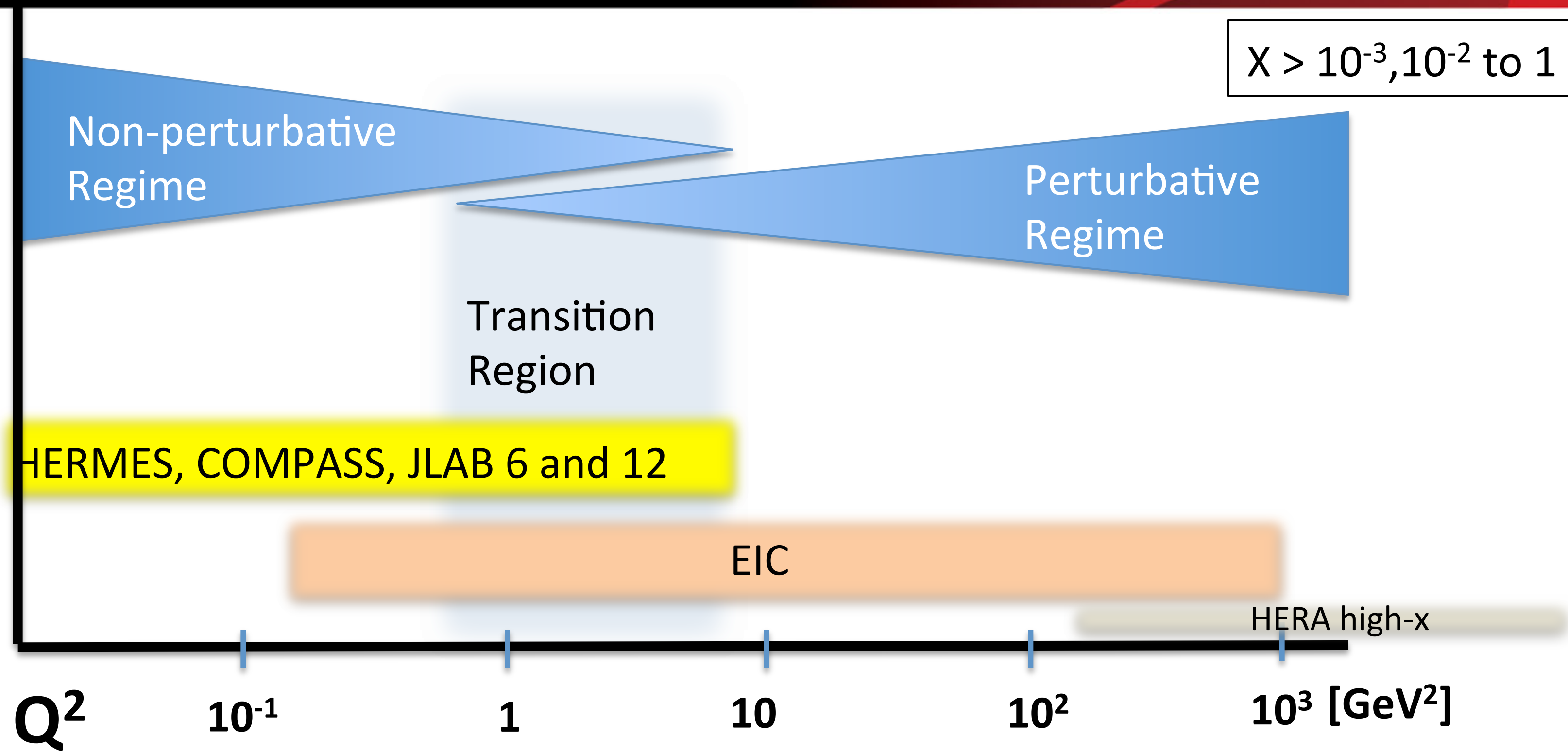
QCD Radiation Dominated (Studied at HERA)

Hadron Structure Dominated

Main interest for EIC Nucleon/Nuclear Program

Spin,TMD, GPD…

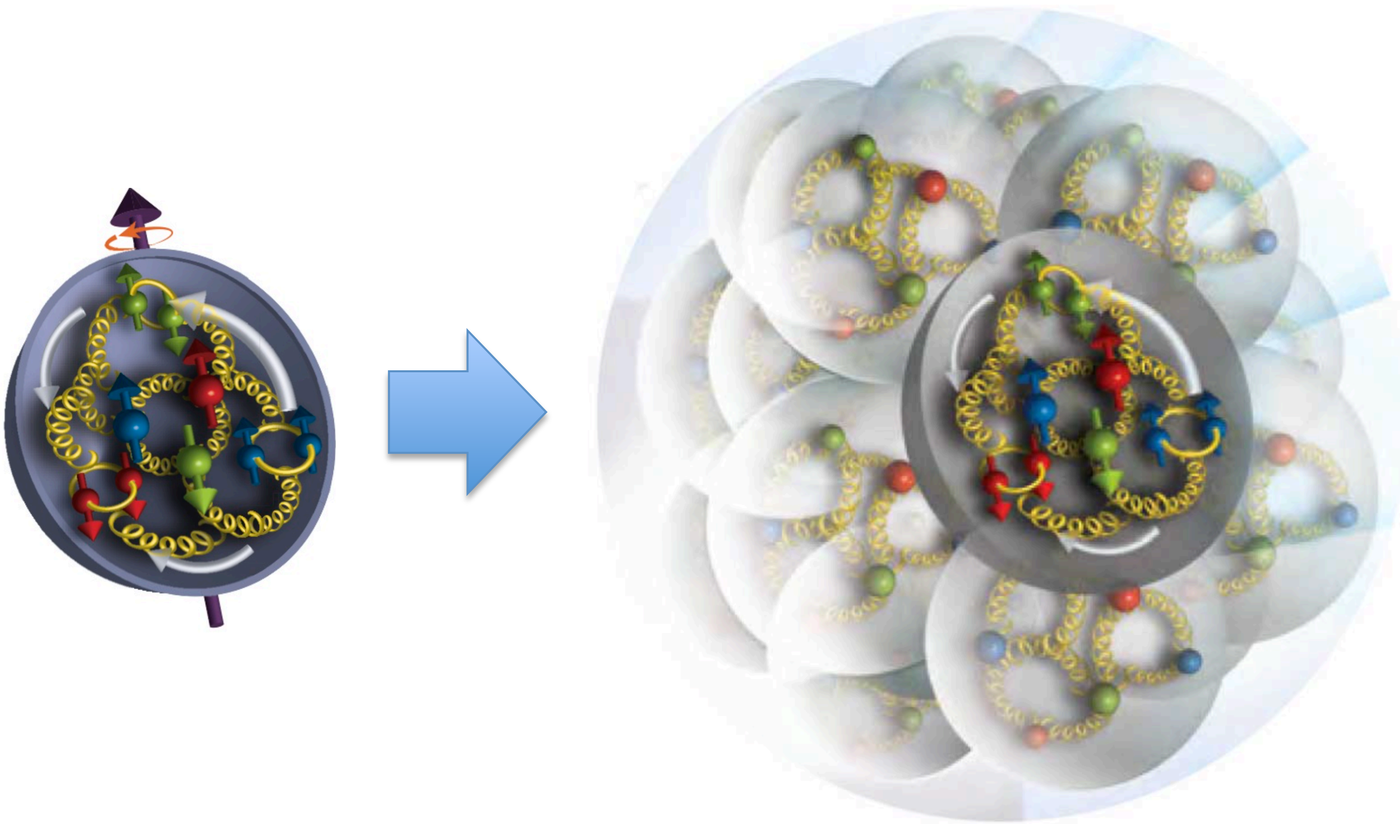
Where EIC needs to be in Q^2 (Q_1^2)



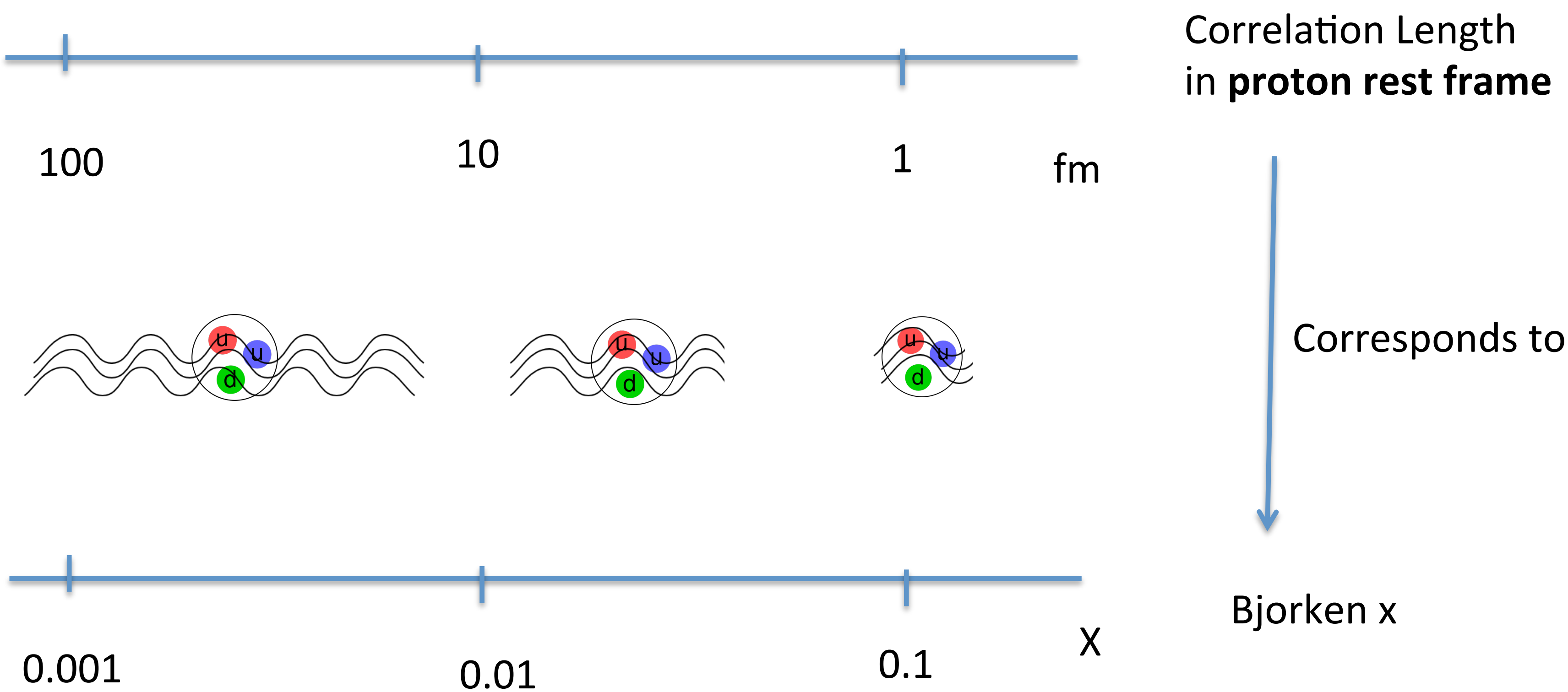
- Include non-perturbative, perturbative and transition regimes
- Provide long evolution length and up to Q^2 of ~1000 GeV^2 (~.005 fm)
- Overlap with existing measurements

Disentangle Pert./Non-pert., Leading Twist/Higher Twist

Understanding the Nuclei at the Next Level

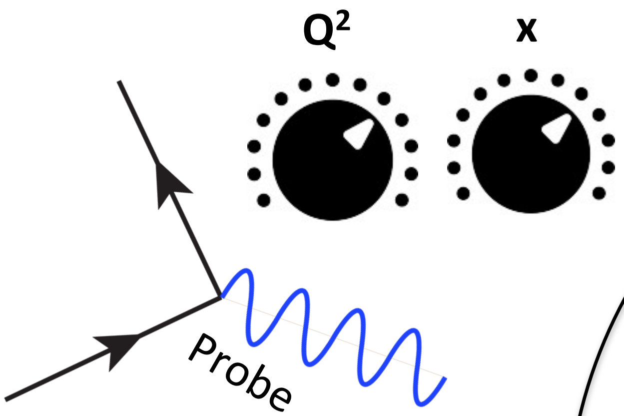


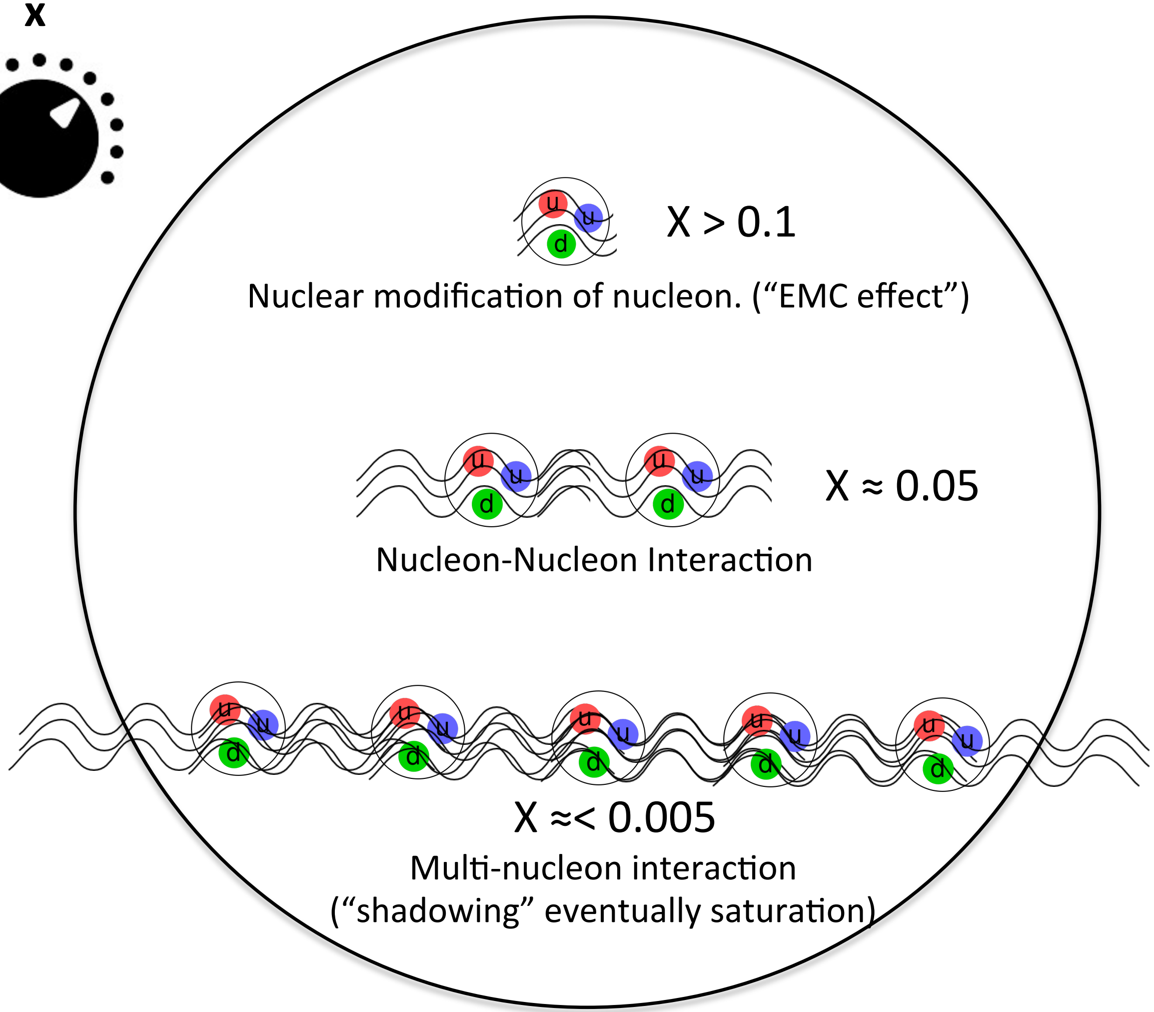
Bjorken x and length scale



In the proton rest frame, QCD field ($x < 0.1$) extends far beyond the proton charge radius

Parameters of the Probe (Nuclei)



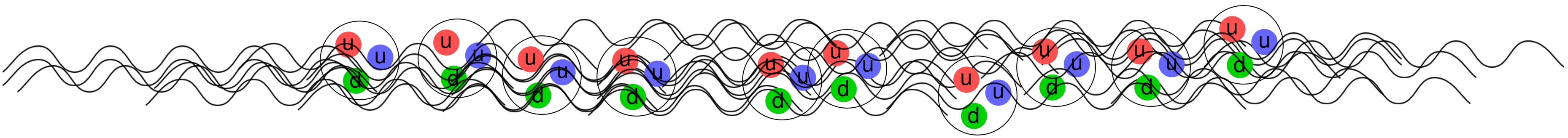


Probing the nucleon interaction in the nuclei (note this is different from correlation measurements)

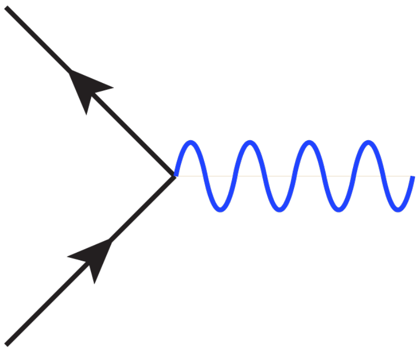
Note: the x range for nuclear exploration is similar to the nucleon exploration

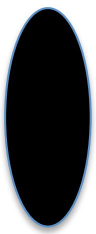
Beyond Nuclear Structure

Saturation



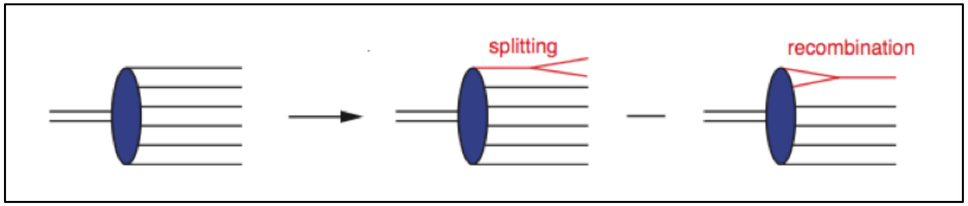
Eventually at low enough x





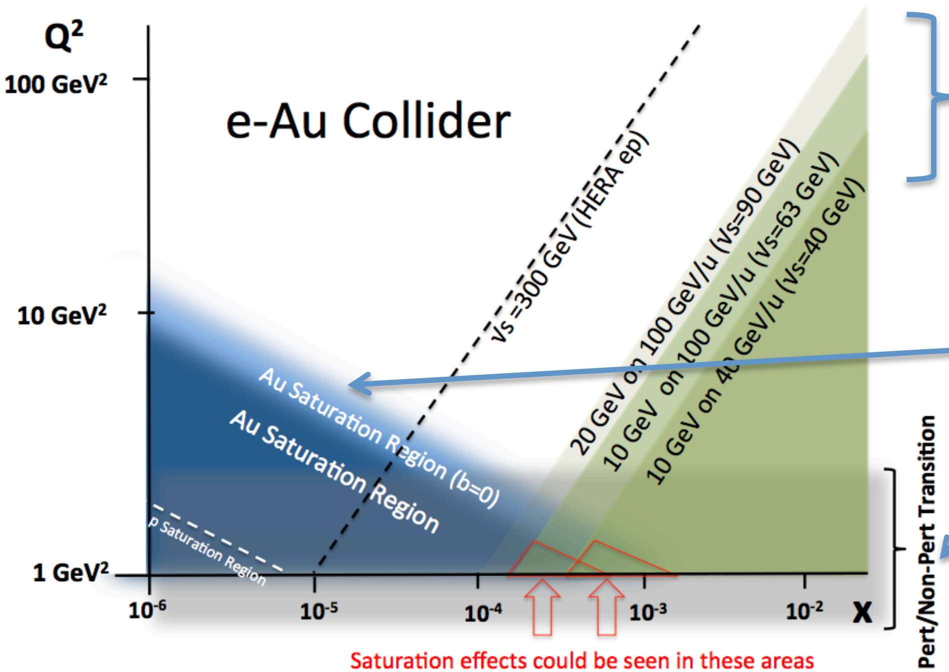
Cross-section will saturate

Equivalent to →



EIC will approach saturation in electron-Ion collisions

Saturation Regime and EIC



EIC kinematic reach for various scenarios

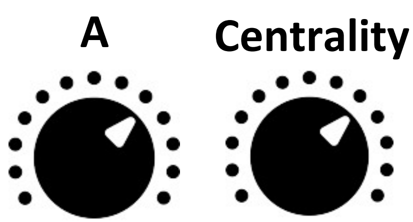
Two competing scales

$Q_s(x)$: Saturation Scale

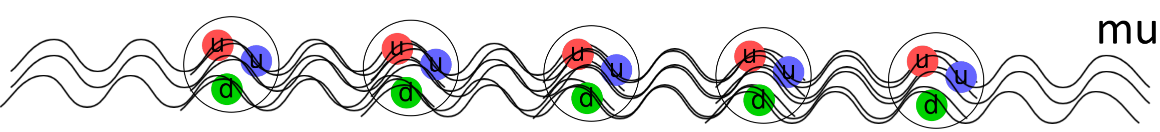
Q_0 : Perturtative when $Q > Q_0$

Ideally, x such that $Q_s >> Q_0$

EIC has two knobs to turn



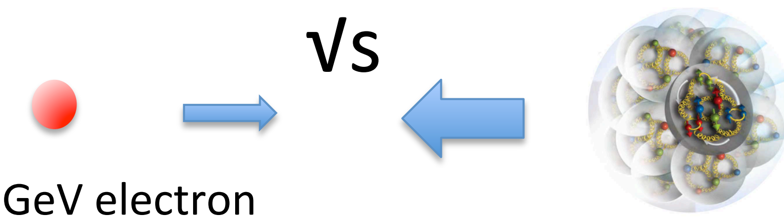
Investigate the on-set of saturation



multi-nucleon coherence → saturation

Designing The Right Probe: √s

What are the right parameters for the collider for the EIC science program?

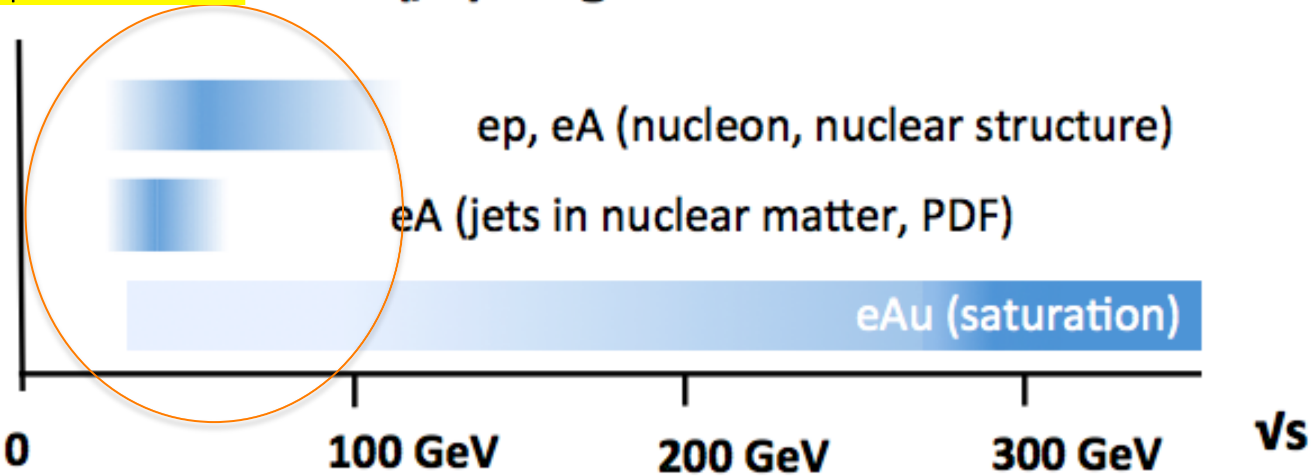


~10 GeV electron realizable

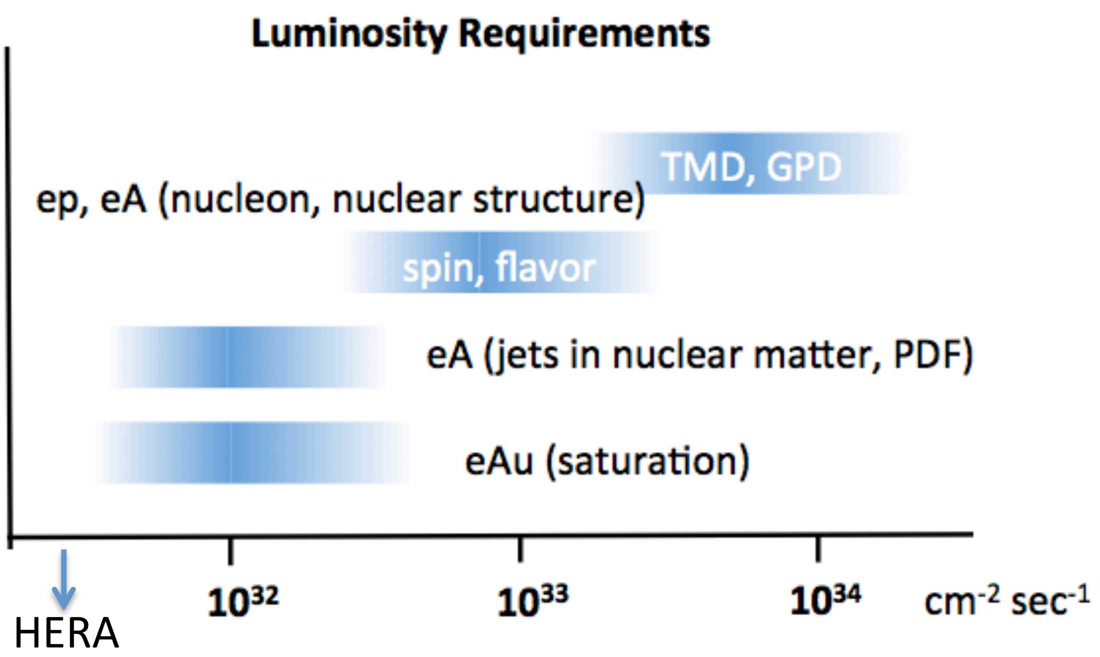
~100 GeV/u ion

Leaving $Q_2/E_{proton} > 10^{-3}$

√s(/u) range of interest

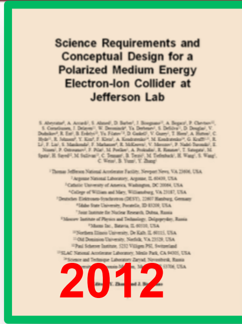


Luminosity Needed for Topics

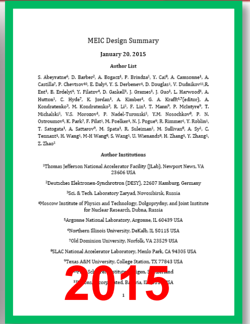


Central mission of EIC (nuclear and nucleon structure) requires high luminosity.

Jefferson Lab EIC(JLEIC) Baseline Design



arXiv:1209.0757



arXiv:1504.0796

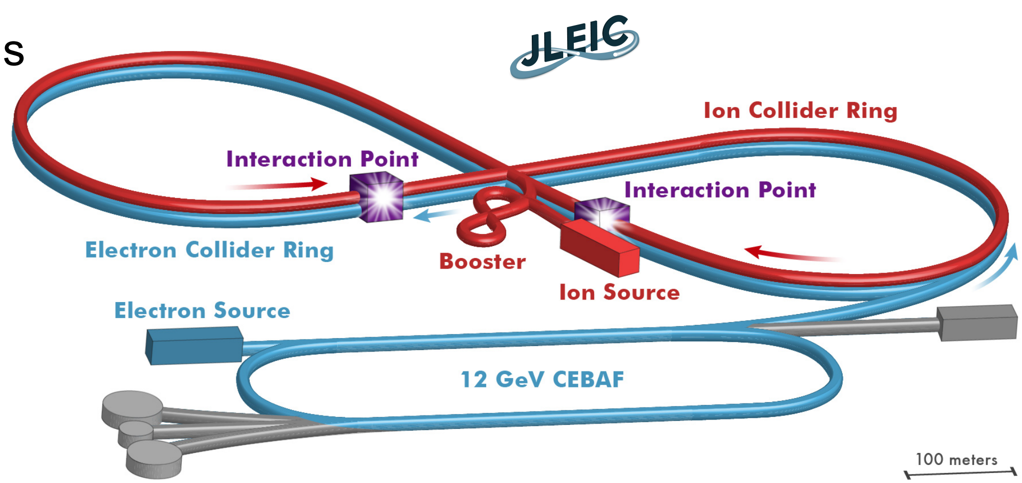
Features:

- E_e: 4-10 GeV, $E_{p(ion)}$:30-100 GeV (×Z/A)
- $\sqrt{s}$: ~ 20 – 65 GeV with high luminosity throughout this range.
- Collider ring circumference: ~2100 m
- Electron collider ring and transfer lines : PEP-II magnets, RF (476 MHz) and vacuum chambers
- Ion collider ring: super-ferric magnets (3T)
- Booster ring: super-ferric magnets
- SRF ion linac

- Low-risk luminosity ~ 5-10 × 10^{33} cm^{-2} s^{-1}

Goals:

- Balance of civil construction versus magnet costs and risks
- Aim overall for low technical risks



Collaborators:

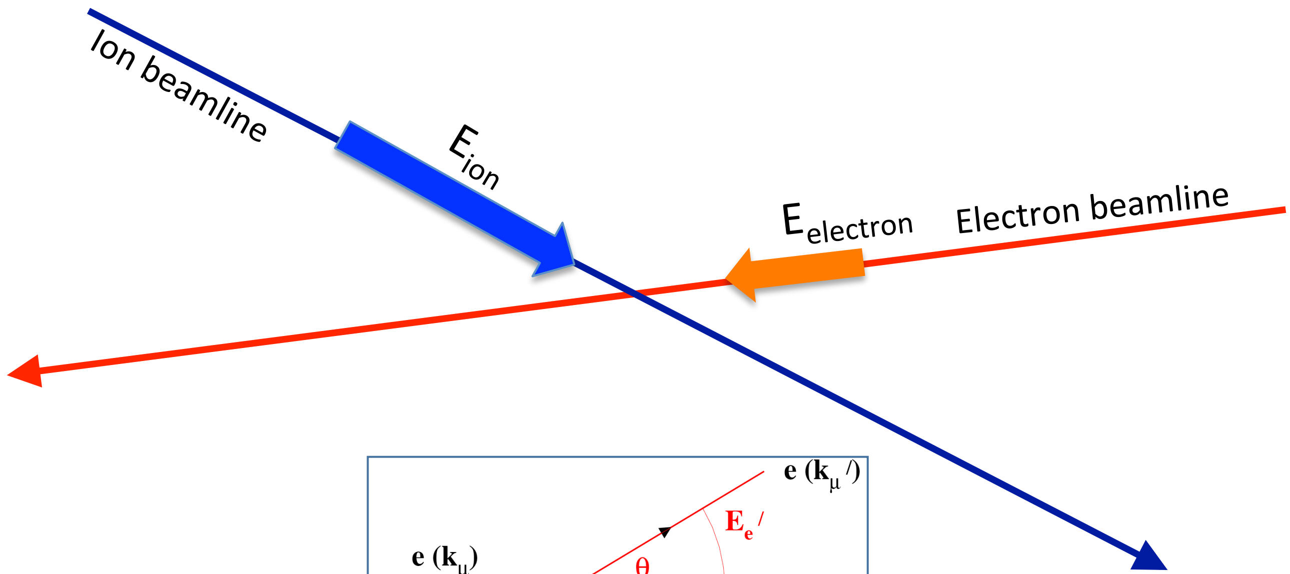
ANL, LBNL, Fermilab, SLAC,
Texas A&M
Also DESY, Dubna

Competing proposal from BNL in previous talk

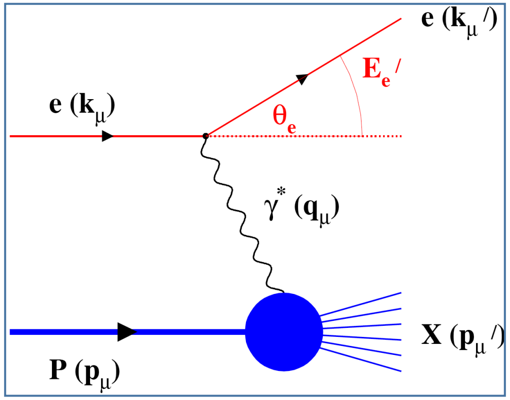
EIC Detector and Accessing Q_2

DIS and Final State Particles

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**.



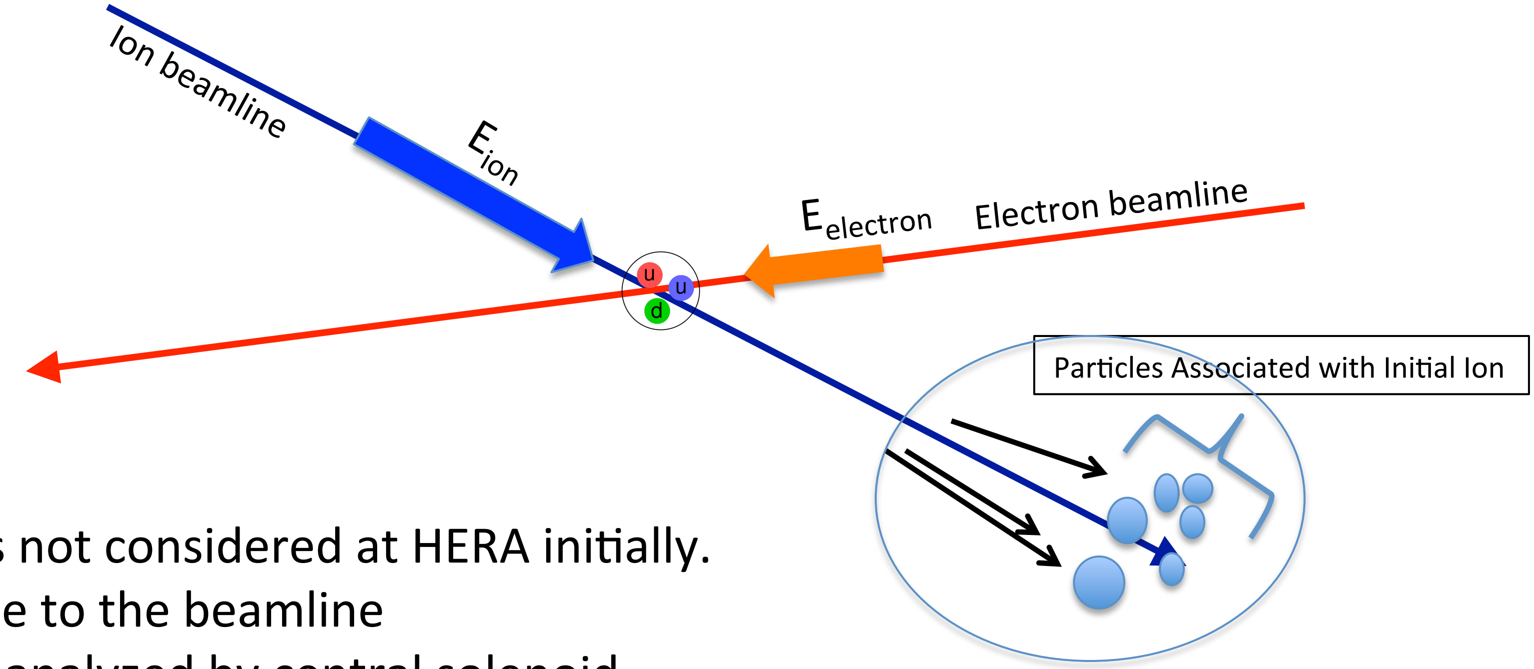
Need more than this



Need to access $Q_2 << Q_1$

Particles Associated with the Initial Ion

For EIC, particles of the "target remnant" is as important as the struck parton. e.g. Measure $t \sim Q_2 \sim \Lambda_{QCD}$



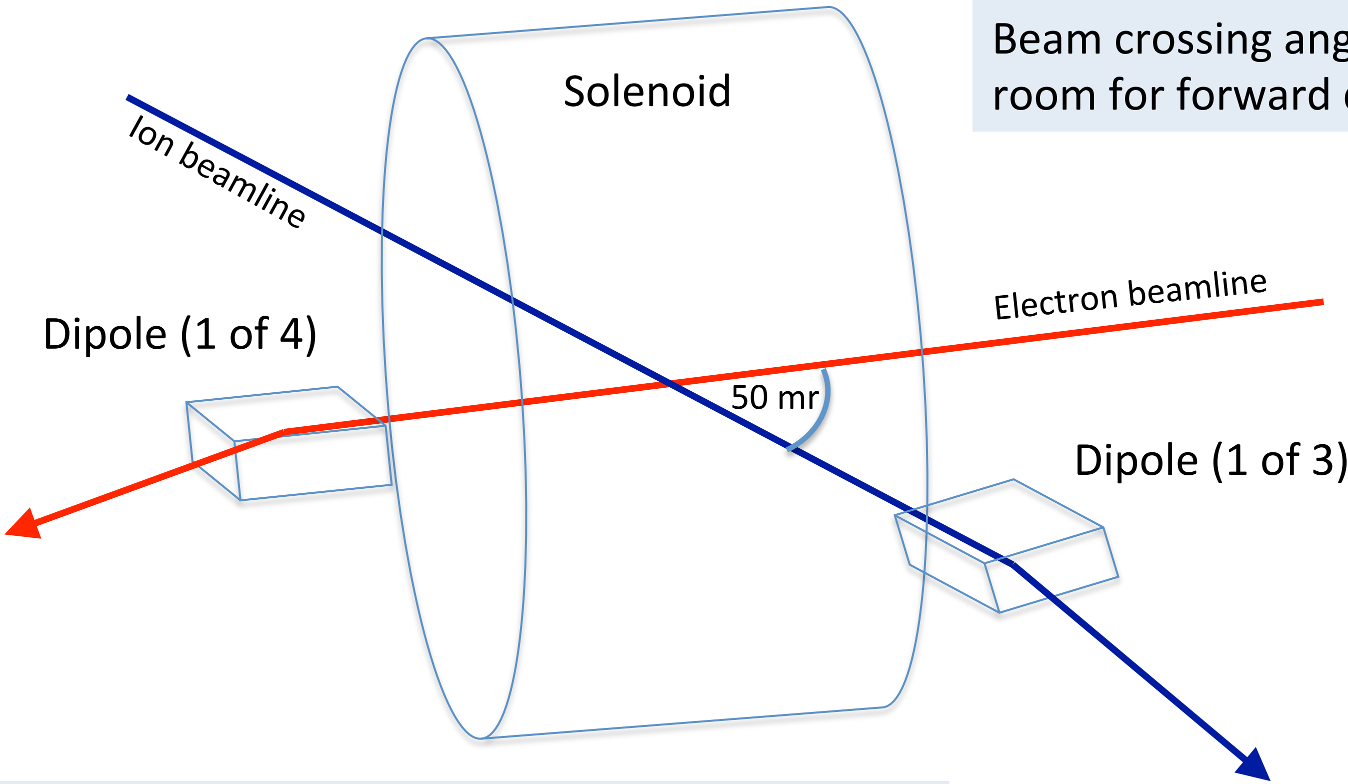
- Was not considered at HERA initially.
- Close to the beamline
- Not analyzed by central solenoid.
- **Aim for ~100% acceptance and good resolution at EIC.**

Remember acceptance is equally important as luminosity!

Interaction Region Concept

NOT TO SCALE!

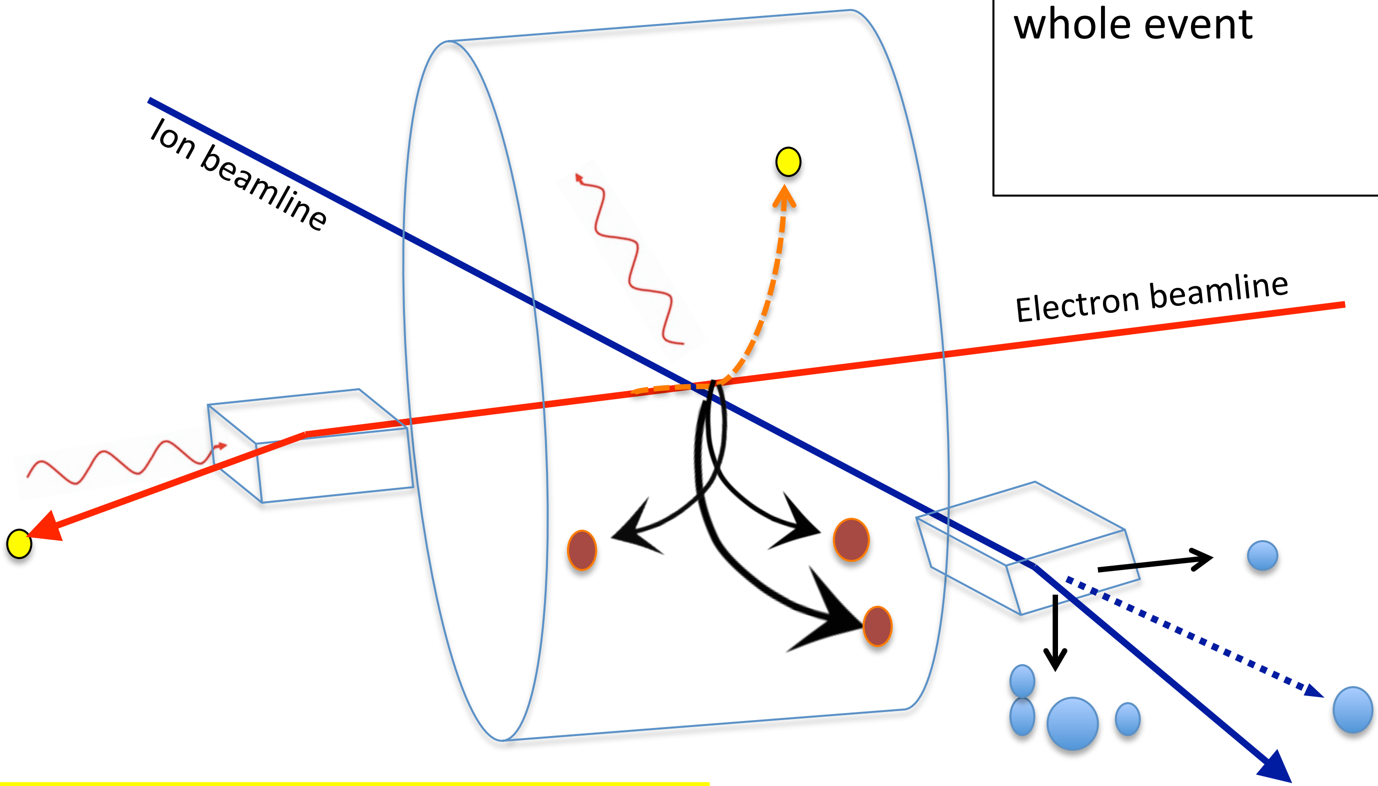
Beam crossing angle creates room for forward dipoles



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

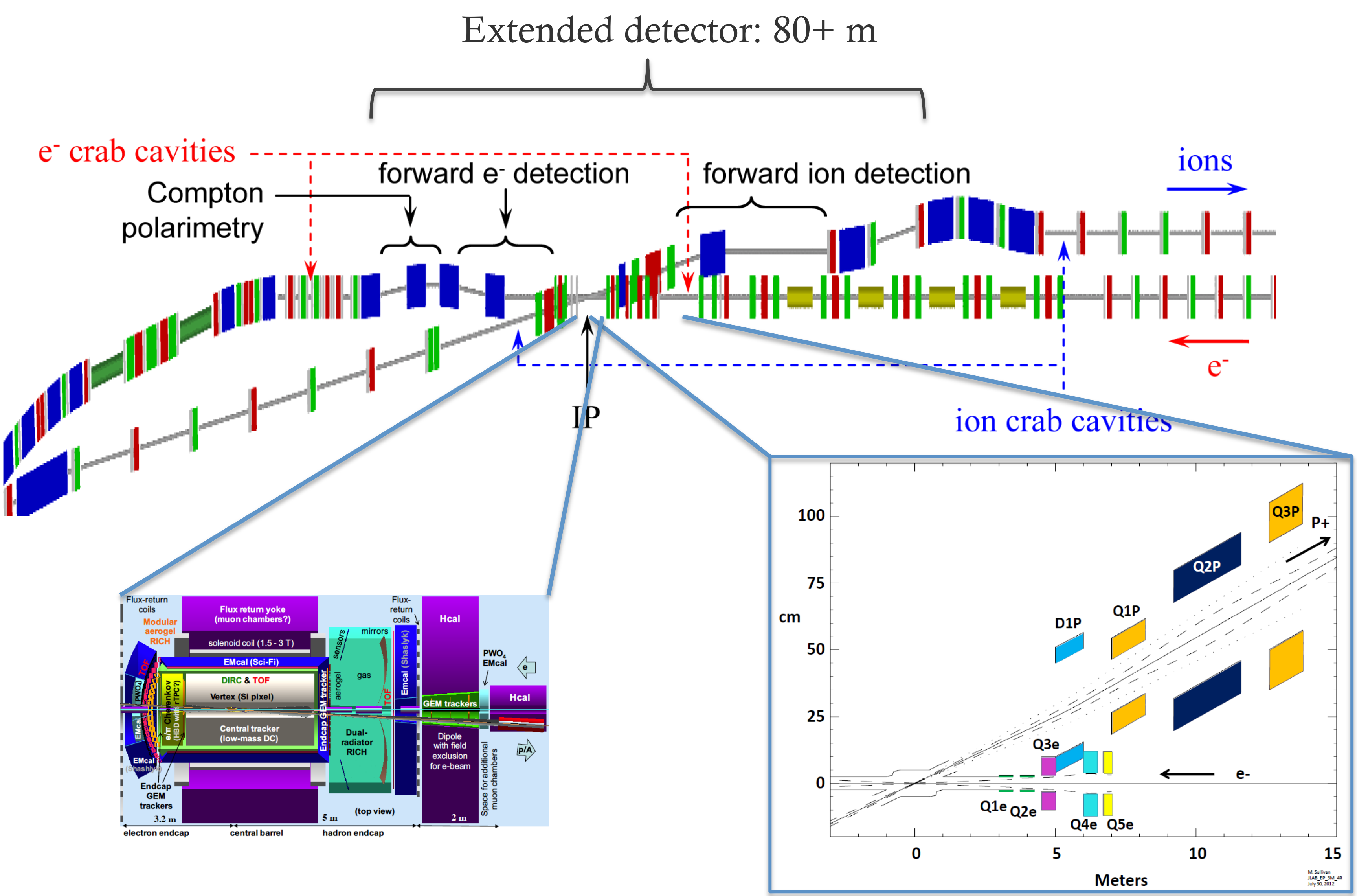
Interaction Region Concept

Possible to get ~100% acceptance for the whole event



Aim for total acceptance detector (and IR)

JLEIC IR and Detector Layout



FORWARD ION-BEAM DIRECTION

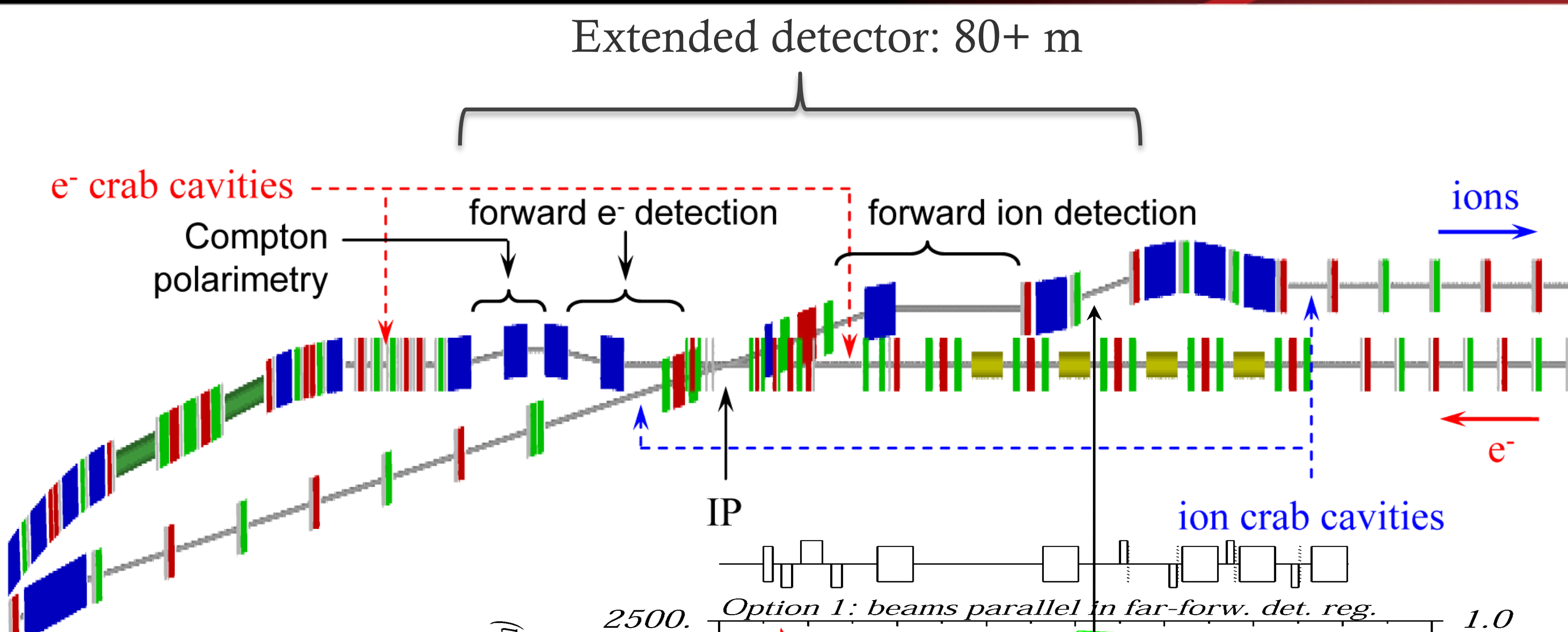
EIC forward detection requirements

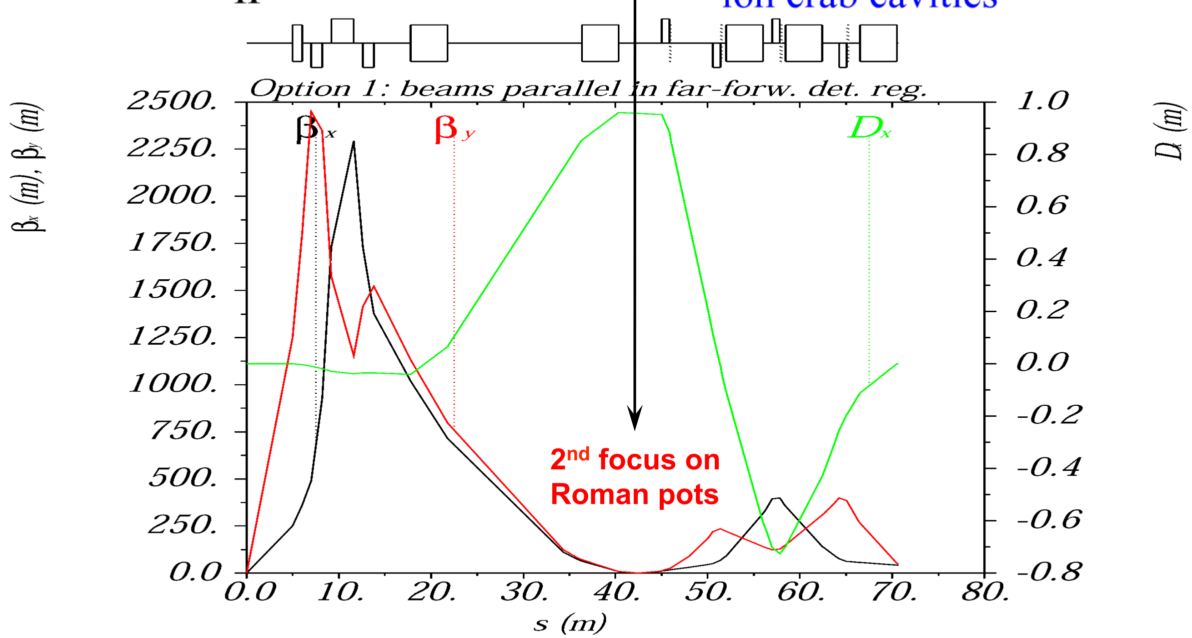
- Good acceptance for recoil nucleons (rigidity close to beam)
  - **Diffractive processes on nucleon, coherent nuclear reactions**
  - Small beam size at detection point (to get close to the beam)
    Secondary focus on roman pots, small beam emittance (cooling)
  - Large dispersion (to separate scattered particles from the beam)

- Good acceptance for fragments (rigidity different than beam)
  - **Tagging in light and heavy nuclei, nuclear diffraction**
  - Large magnet apertures (low gradients)
  - Detection at several points along a long, aperture-free drift region

- Good momentum- and angular resolution
  - **Free neutron structure through spectator tagging, imaging**
  - Both in roman pots and fixed detectors

Ion optics for near-beam detection

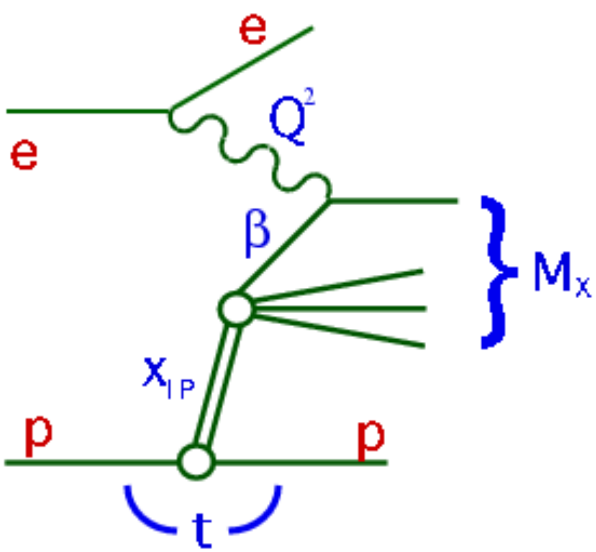


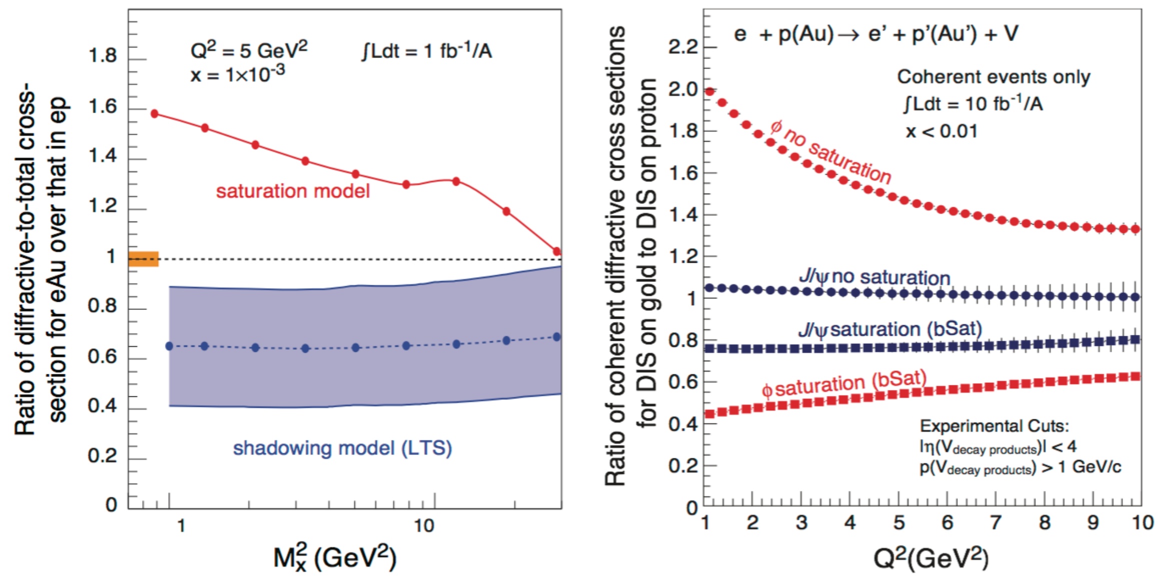


- A large ***dispersion*** at the detection point separates scattered (off-momentum) particles from the beam.
- A ***second focus*** and small emittance (cooling) allows moving detectors closer to the beam

An Example: Diffractive DIS

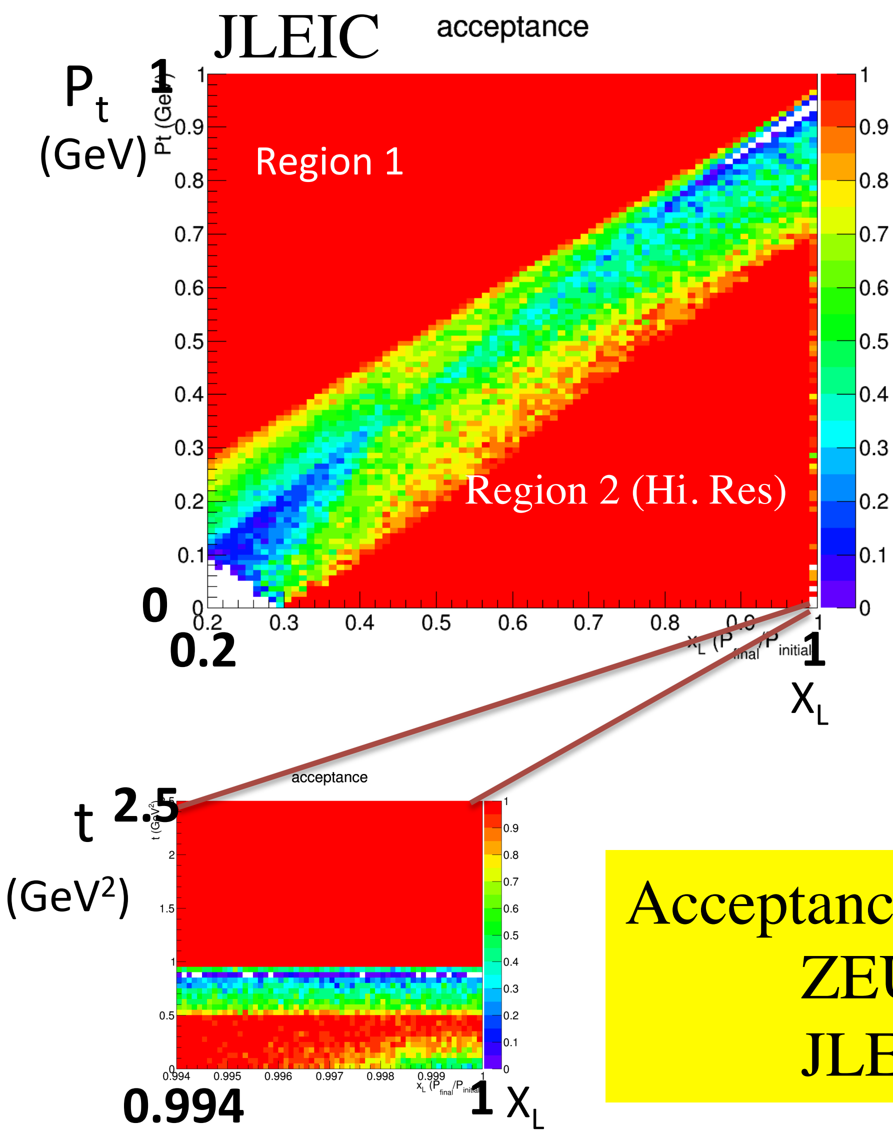
Signature for Saturation (among other things)

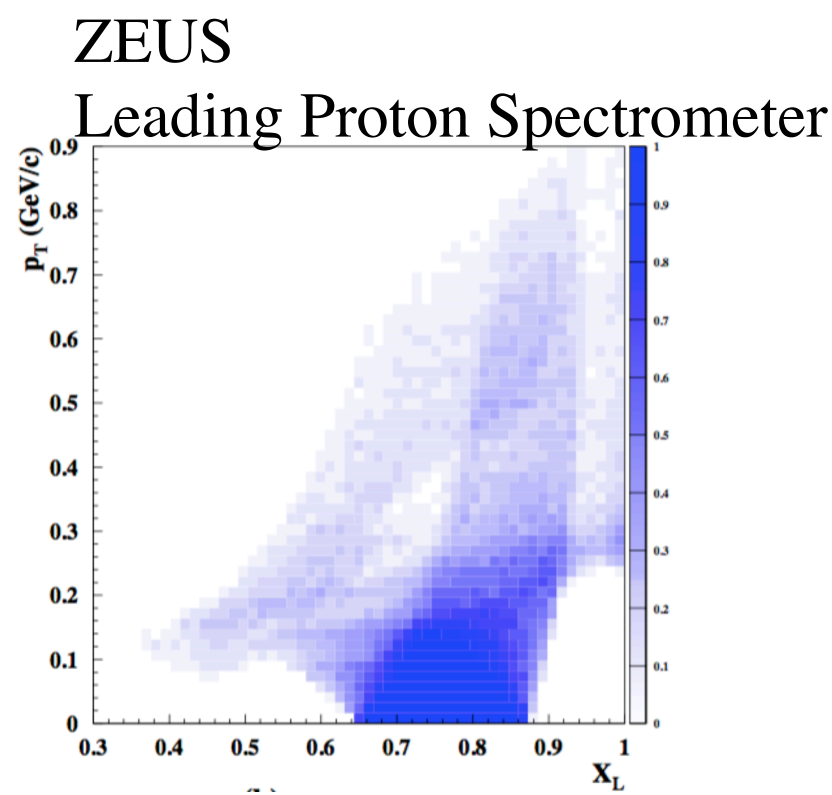




Identify the scattered proton: distinguish from proton dissociation
Measure $\mathbf{X_L = E_p'/E_p}$, and $\mathbf{P_t}$ (or **t**) (equiv. to measuring M_x)

Acceptance for p’ in DDIS





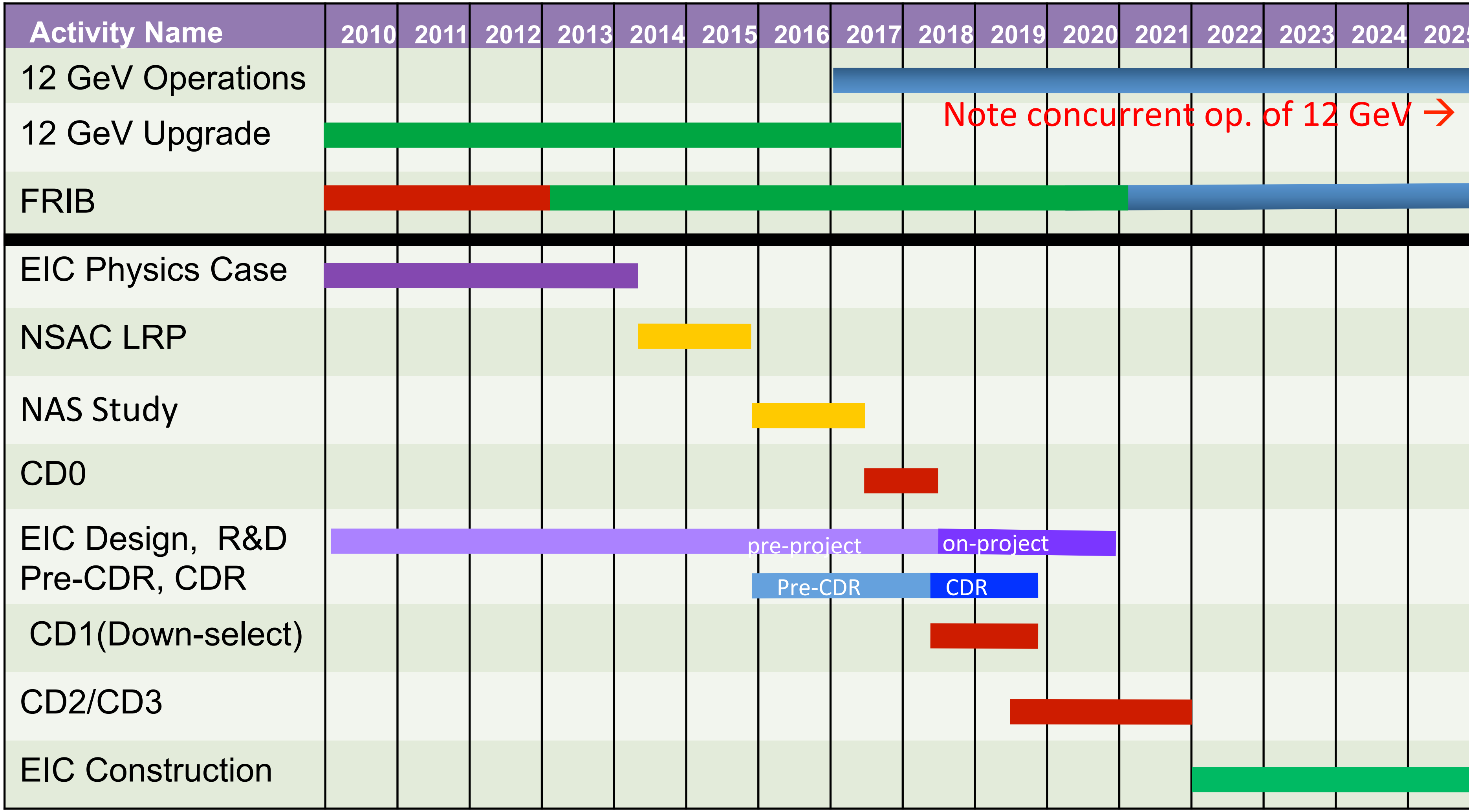
Acceptance in diffractive peak (X_L>~.98)

ZEUS: ~2%

JLEIC: ~100%

EIC Next Steps

EIC Timeline (for JLEIC planning)



CD0 = DOE "Mission Need" statement; **CD1** = design choice and site selection (VA/NY)

CD2/CD3 = establish project baseline cost and schedule

EIC Users Group

650 Members, 27 Countries, 142 Institutions

Just had 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 and now setting up Steering Committee.
- Much to prepare: case for the NAS committee, setting up working groups, plan the EIC physics program… (Come join us! eicug.org or come talk to me)
- Very first EIC User Group Satellite Meeting at INPC in Adelaide
  Monday September 12, from 5:45 to 7:00 pm
- (Virtual) Organizational EICUG meeting early 2017.
- EICUG meeting at Trieste, July 18-22, 2017, (INFN Trieste)

Conclusion

- EIC Program aim: Revolutionize the understanding of nucleon and nuclear structure and associated dynamics. Explore new states of QCD.

- For the first time, EIC will enable us to study the nucleon and the nucleus at the scale of quarks and gluons, over (arguably) all of the kinematic range that are relevant for exploring the nuclear and nucleon structure and the associated QCD dynamics.

- Outstanding questions raised both by the science at HERA, RHIC/LHC and at HERMES/COMPASS/Jefferson Lab, have **naturally led to the science and design parameters of the EIC.**

- There exists **world wide interest** in collaborating on the EIC. Now we must turn this into real participation!

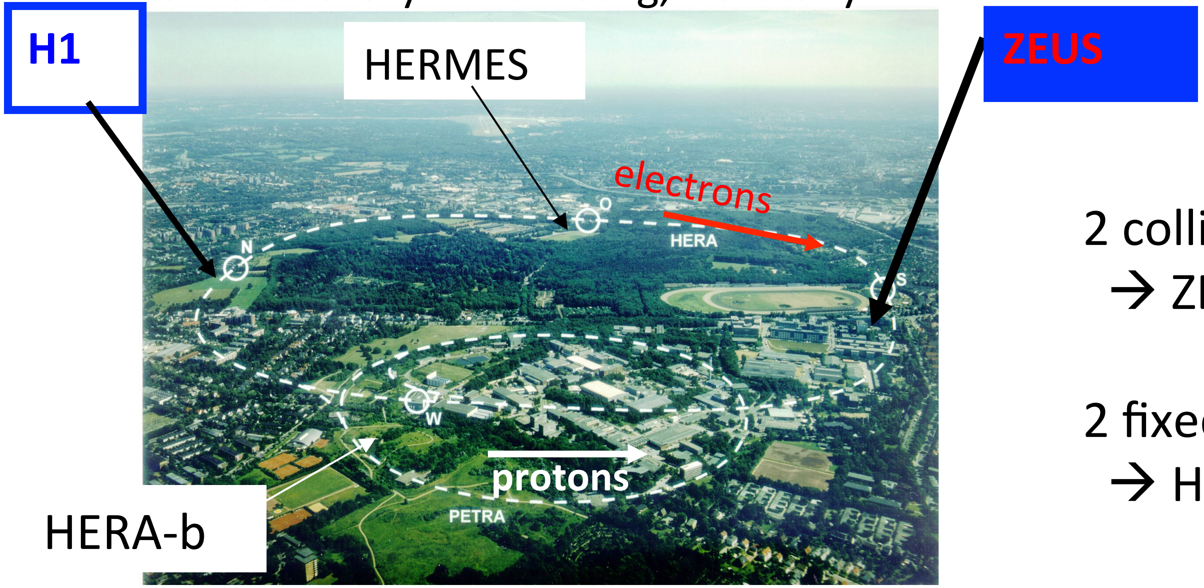
- In the next decades, with the advent of EIC, science of nucleon and nuclear structure will grow and become more central to the sciences. We're just getting started!

The future of science demands an Electron Ion Collider

BACKUP

HERA Electron-Proton Collider

DESY laboratory in Hamburg, Germany



2 collider experiments
→ ZEUS and H1

2 fixed target experiments
→ HERMES and HERA-b

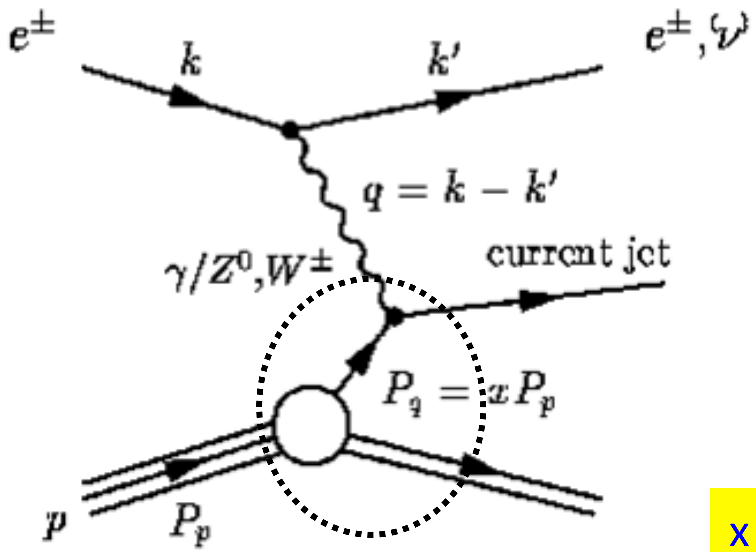
- 920 GeV protons (820 before1998)
- 27.5 GeV $e^{\pm}$
- 300/318 GeV c.o.m. energy
- 220 bunches, 96ns. crossing time
- 90 mA protons,40 mA positrons
- Instantaneous luminosity: $1.8x10^{31}cm^2s^{-1}$

HERA Data taking 1991-2007

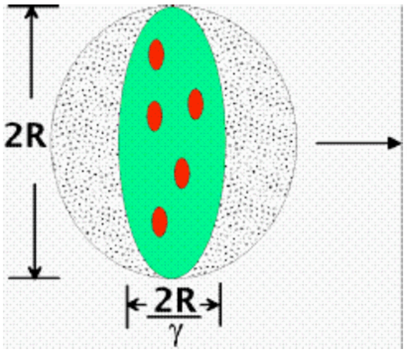
Mission: Explore QCD at highest scale (Q^2). Search for new phenomena.

Deep Inelastic Scattering I

ep collision



proton in "∞" momentum frame



"No" transverse momentum

$0 \leq x \leq 1$

x = fractional longitudinal momentum carried by the struck parton

$\sqrt{s}$ = ep cms energy

$Q^2 = -q^2$ = 4-momentum transfer squared (or virtuality of the "photon")

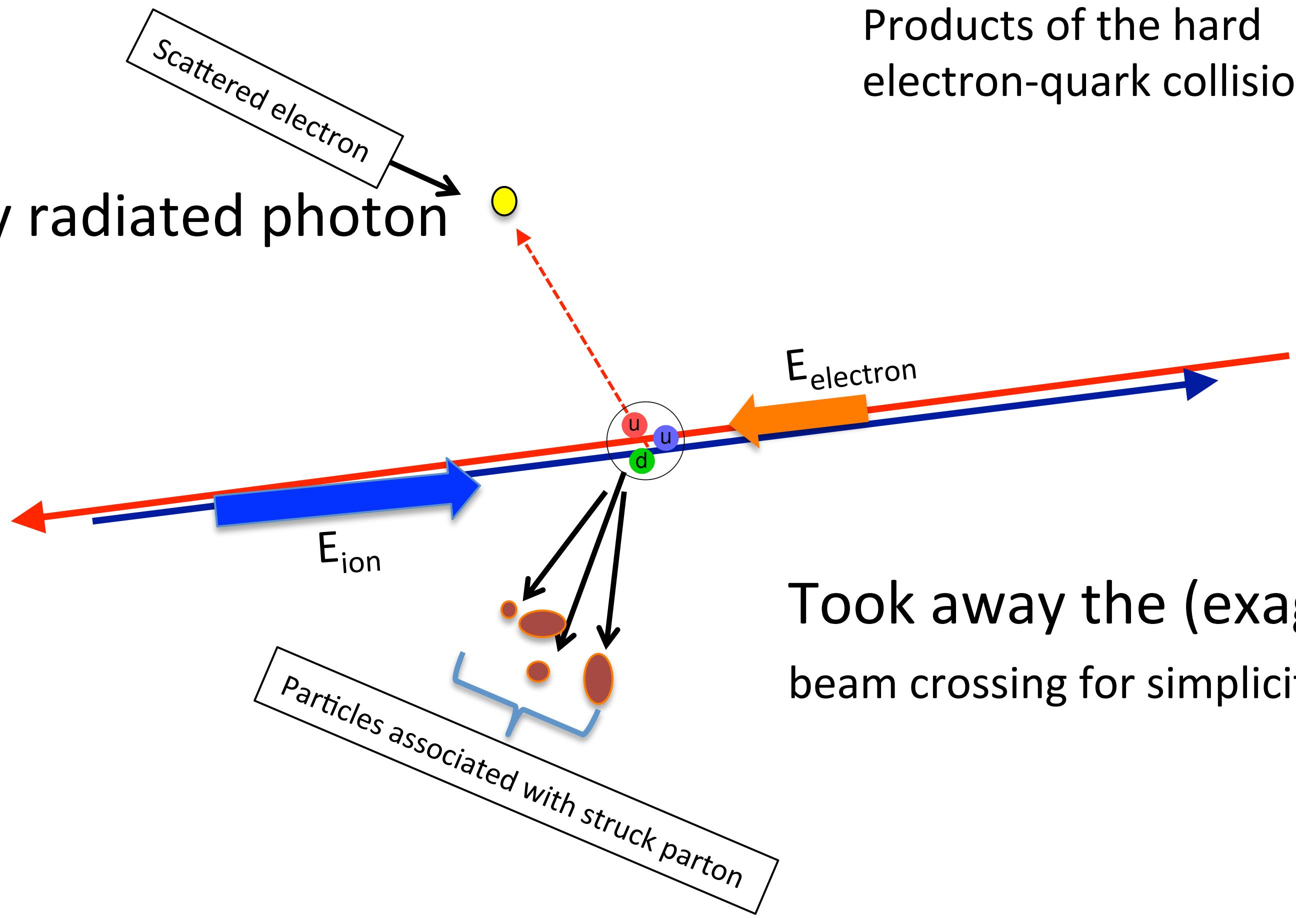
Limits understanding of nucleon structure.

CENTRAL DETECTOR

Final State Particles in the Central Detector

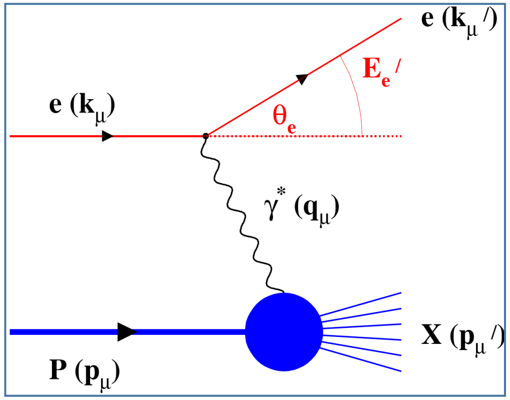
Products of the hard electron-quark collision

Took away radiated photon
for simplicity



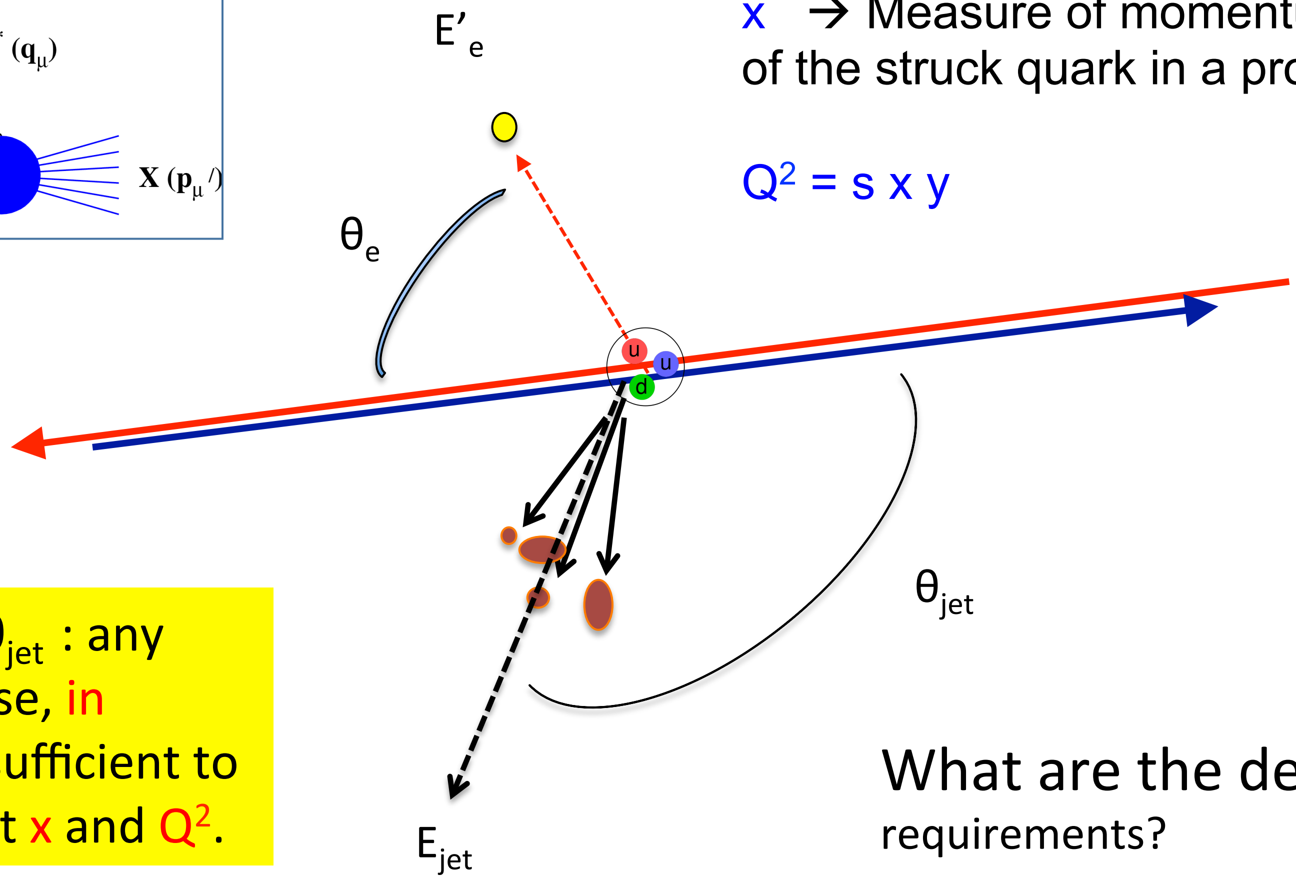
Took away the (exaggerated)
beam crossing for simplicity

Basic Kinematic Reconstruction



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

$Q^2 = s\ x\ y$

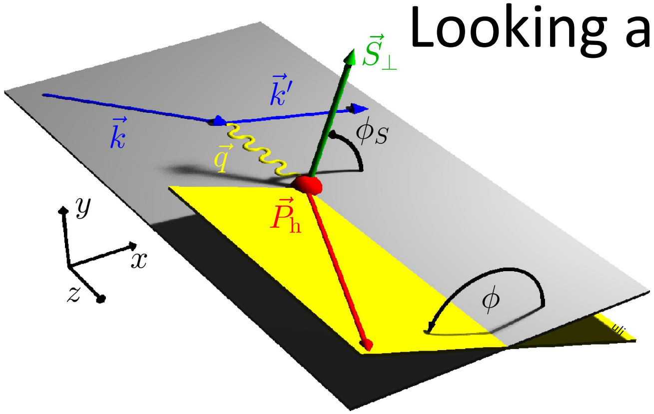


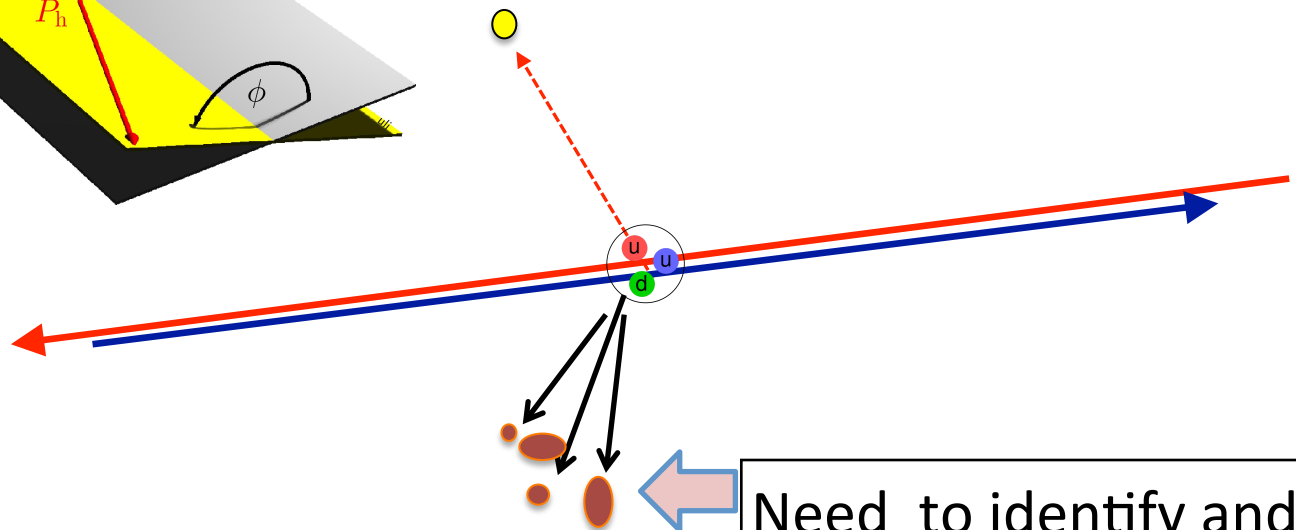
$E'_e, \theta_e, E_{jet}, \theta_{jet}$: any two of these, in principle, sufficient to reconstruct x and Q^2.

What are the detector requirements?

Reconstruction for Transvers Structure

Looking at out-of –plane component in the final state





Need to identify and measure these particles

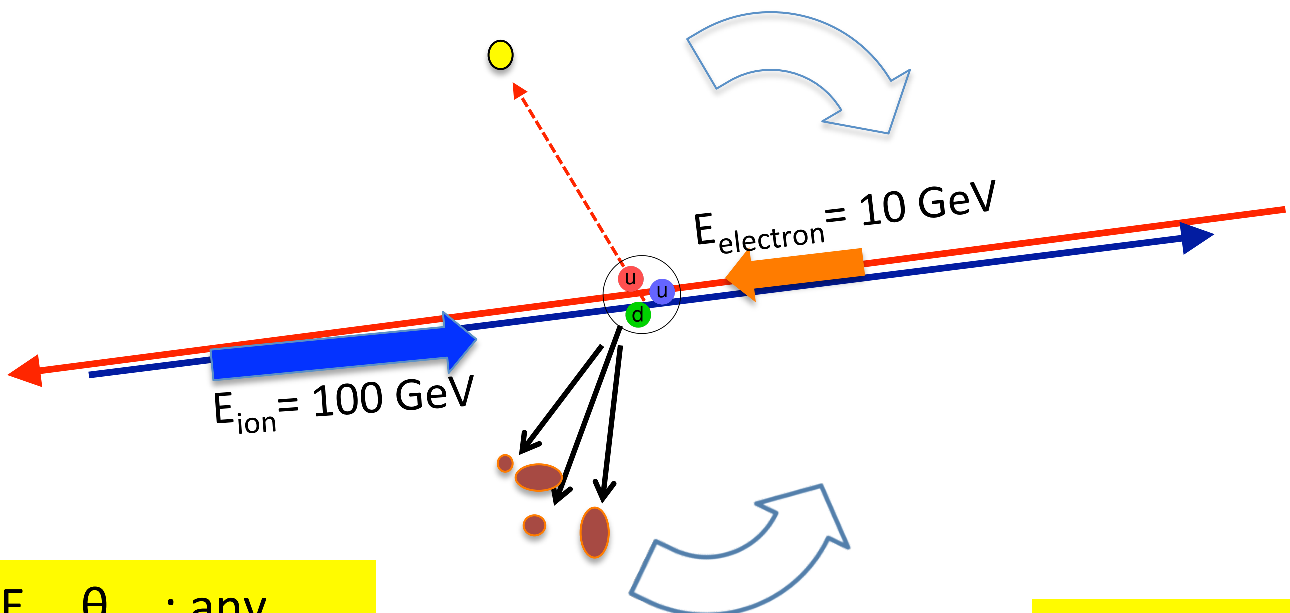
What are the detector requirements?

Note: multiplicities are low (~20 for ep)
Cross-sec x Lumi < 0.01 x HLLHC
< 0.1 interaction/crossing

How Boosted is the Final State?

No Monte Carlo needed to Determine

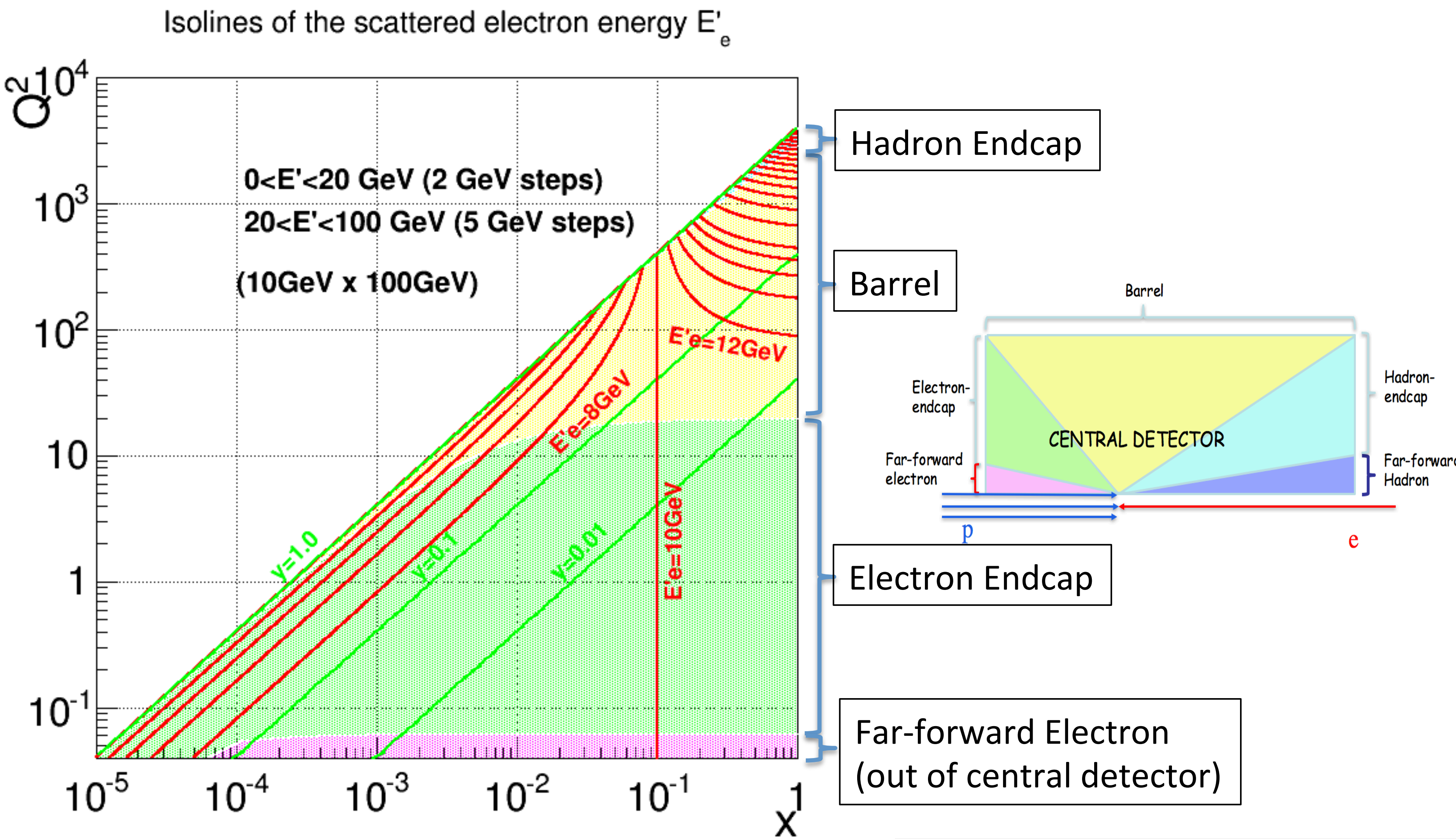
Boosted towards ion beam



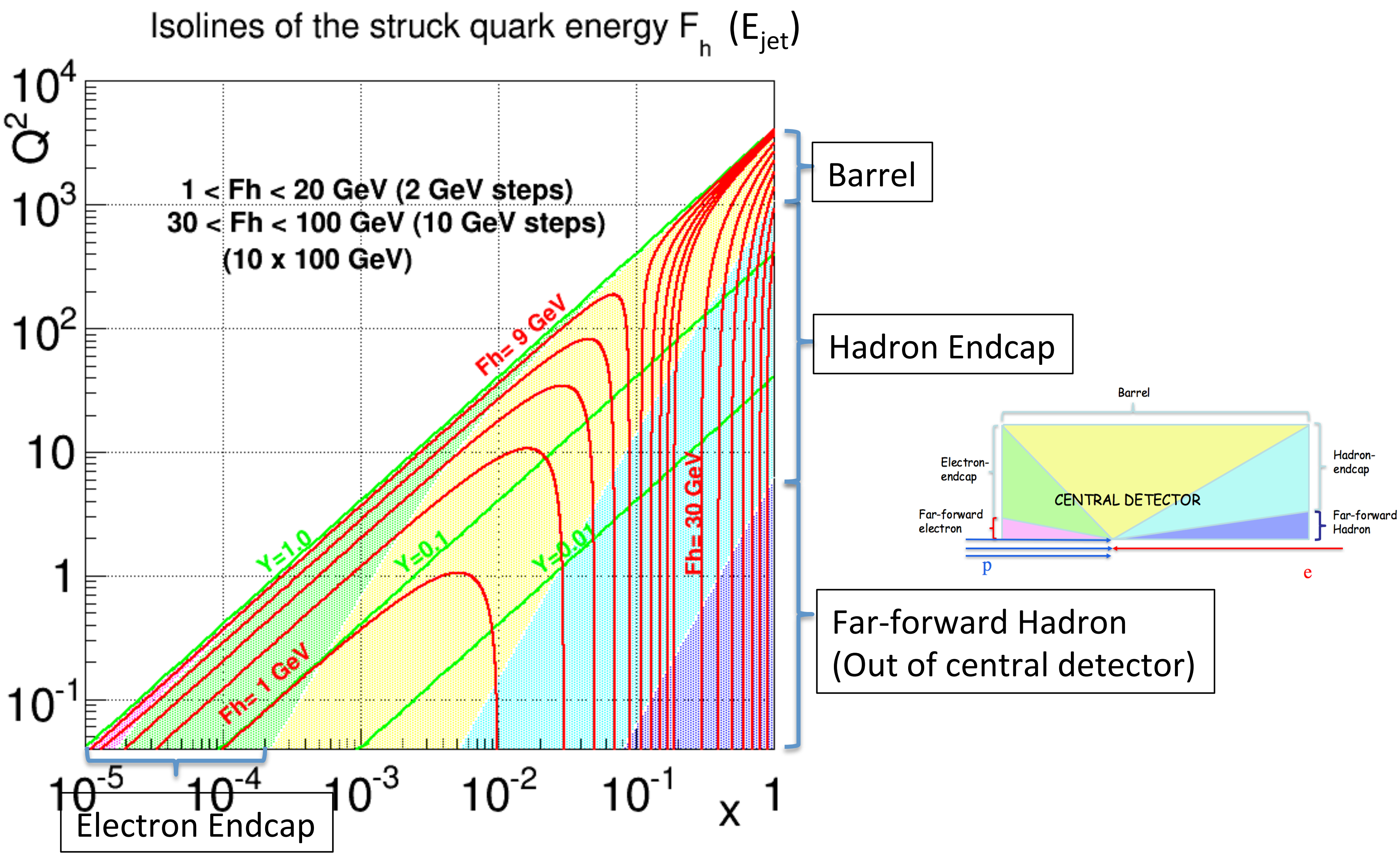
$E'_{e}, \theta_{e}, E_{jet}, \theta_{jet}$: any two of these, in principle, sufficient to reconstruct x and Q^2.

Given x and Q^2, **$E'_{e}, \theta_{e}, E_{jet}, \theta_{jet}$** are all fixed

Electron Isoline Plot

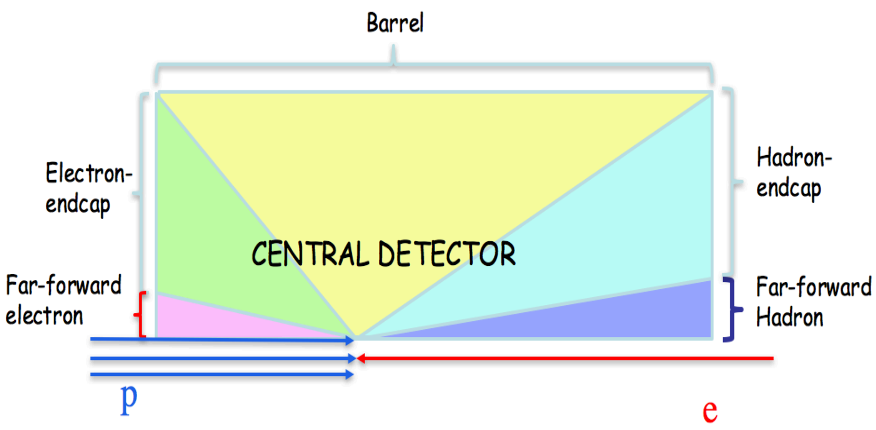


Quark(Jet) Isoline Plot



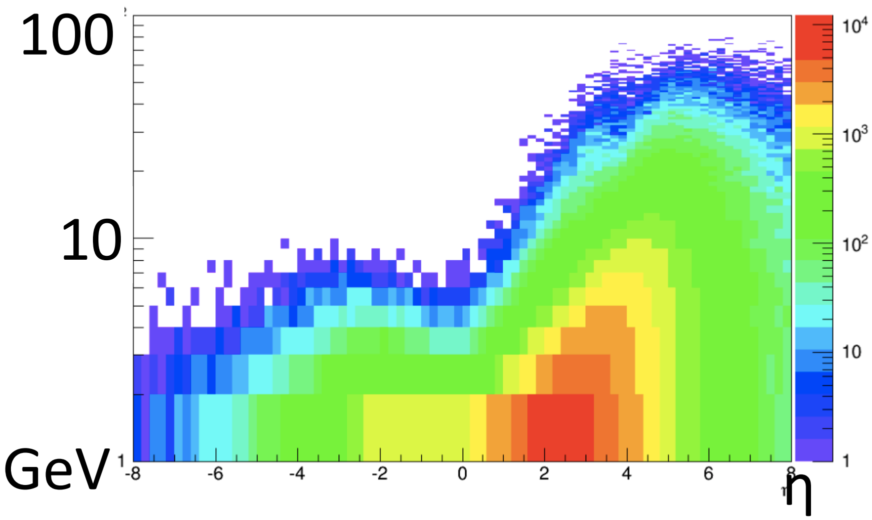
Particle Distribution

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

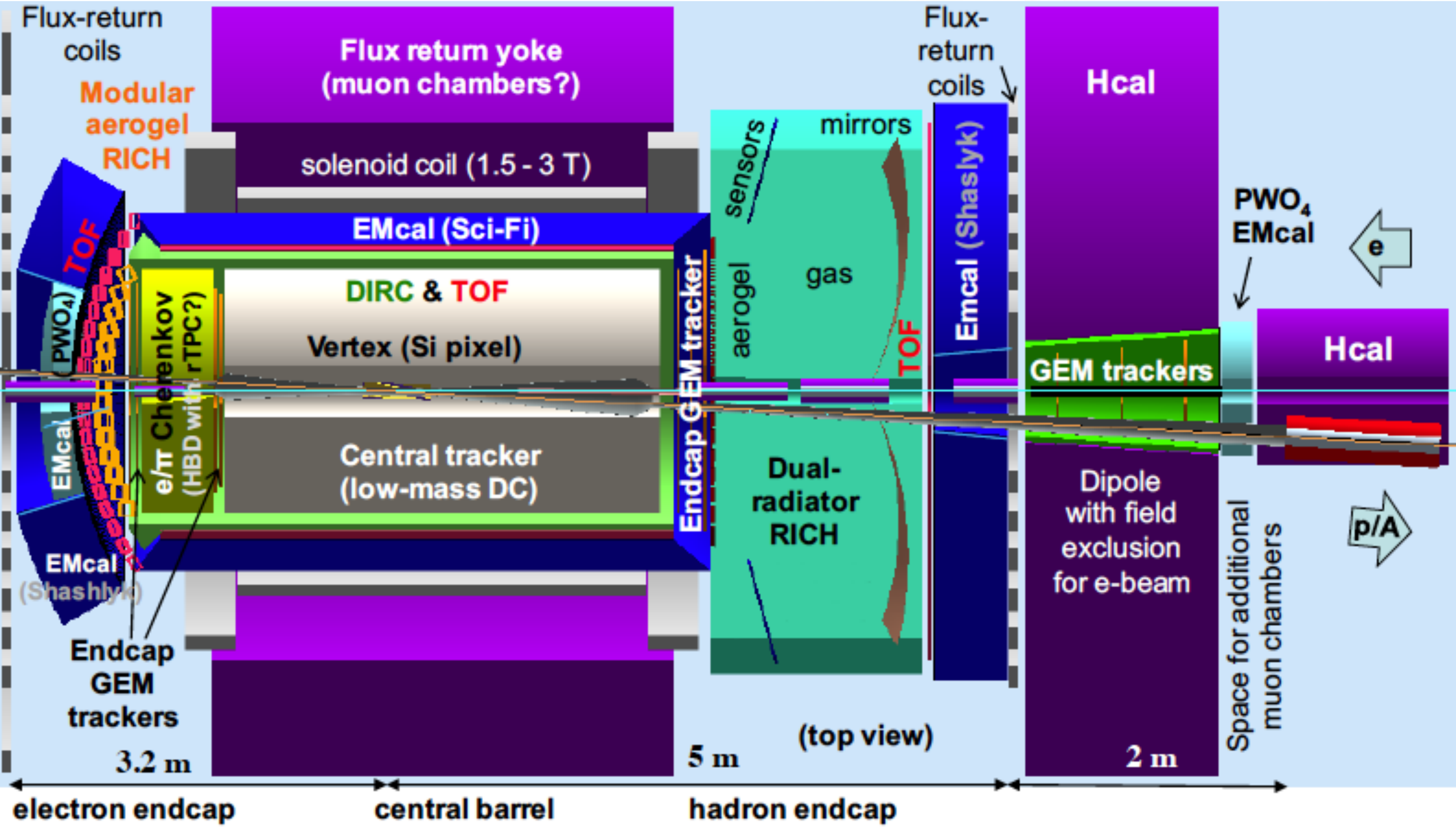


Pythia MC

$\pi^{\pm}$ Energy

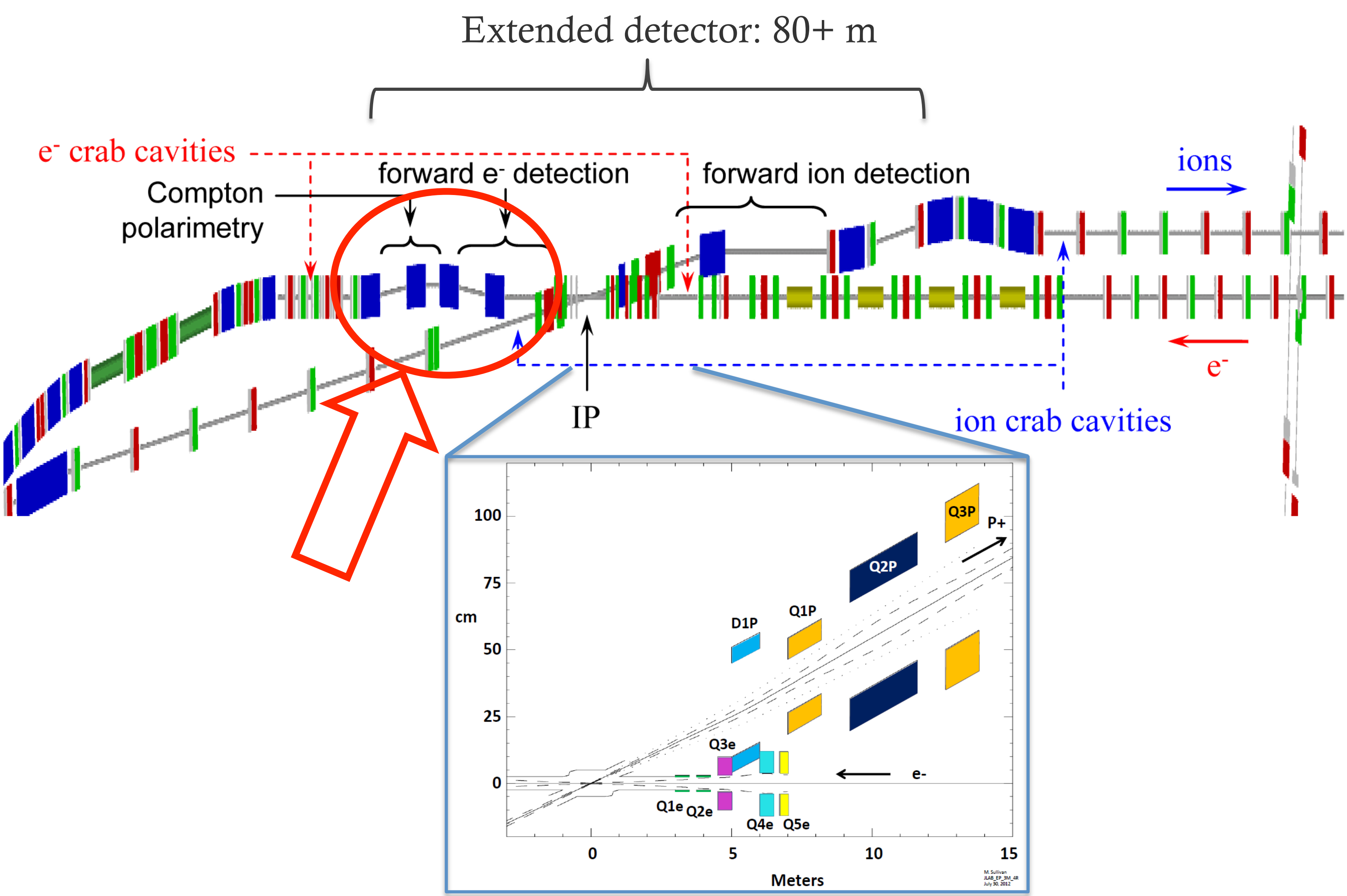


Current JLEIC Concept



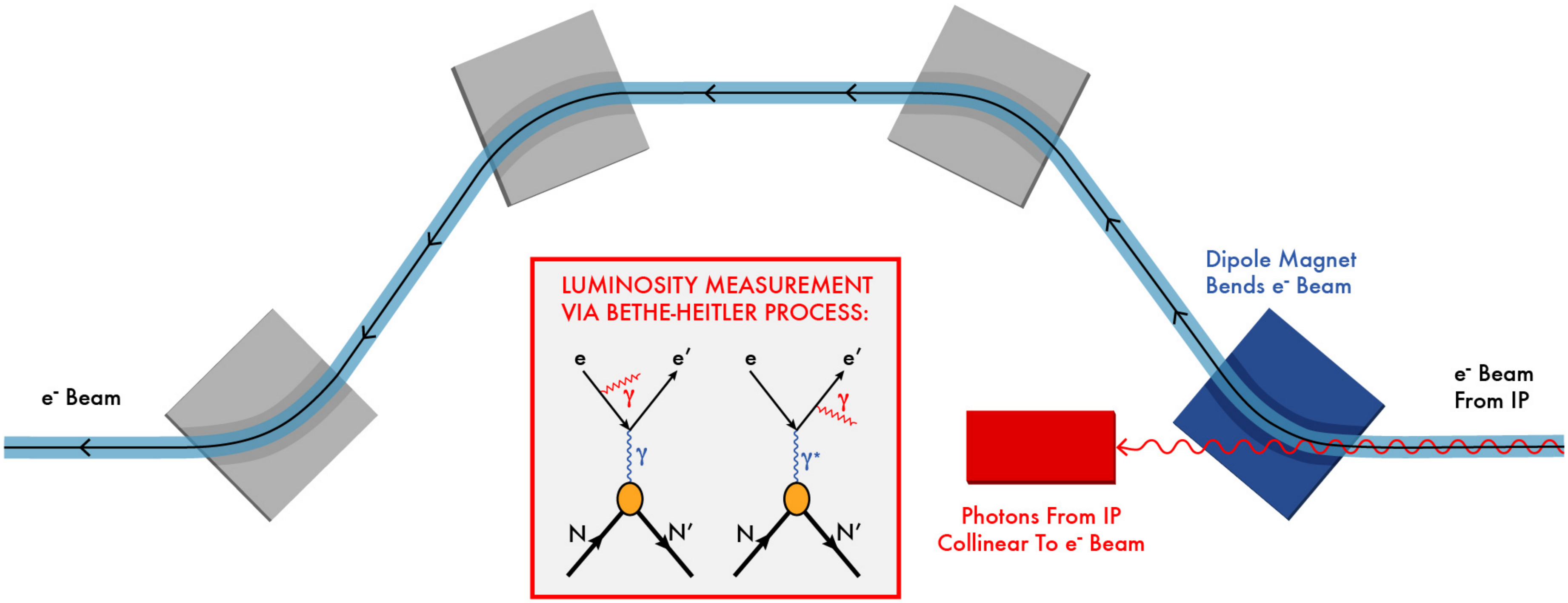
ELECTRON-BEAM DIRECTION

Chicane for Electron Forward Area

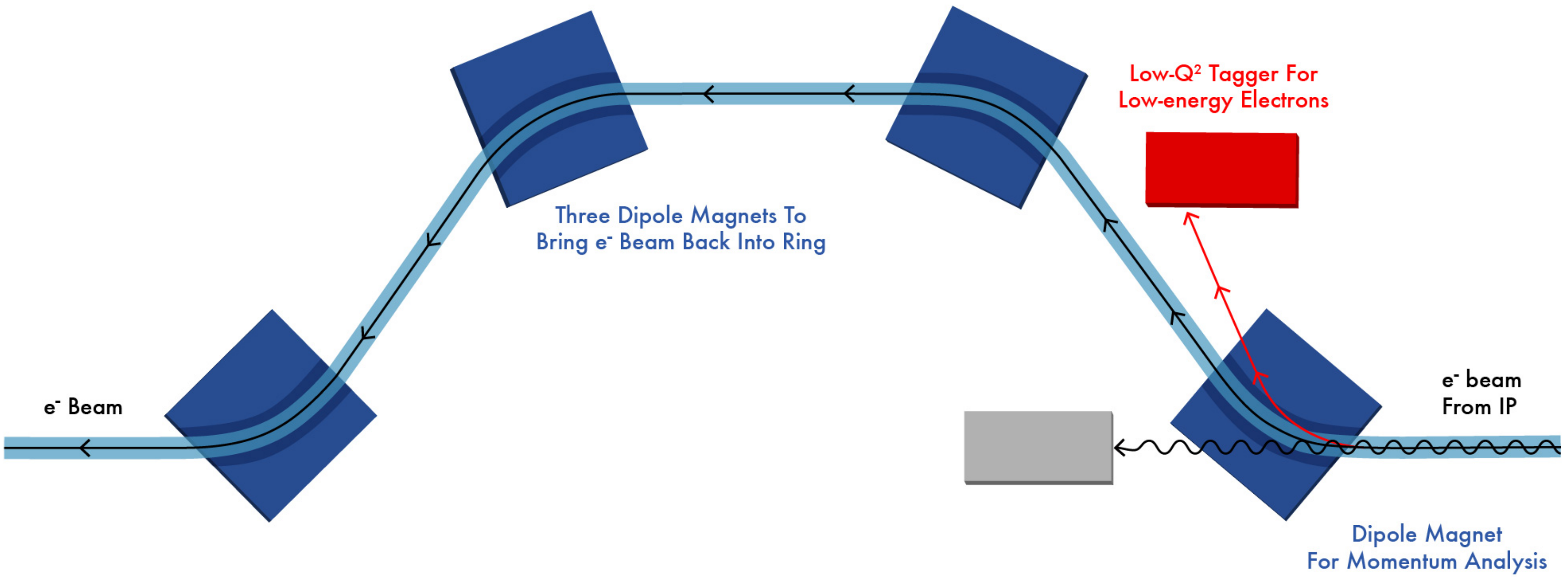


Luminosity Measurement

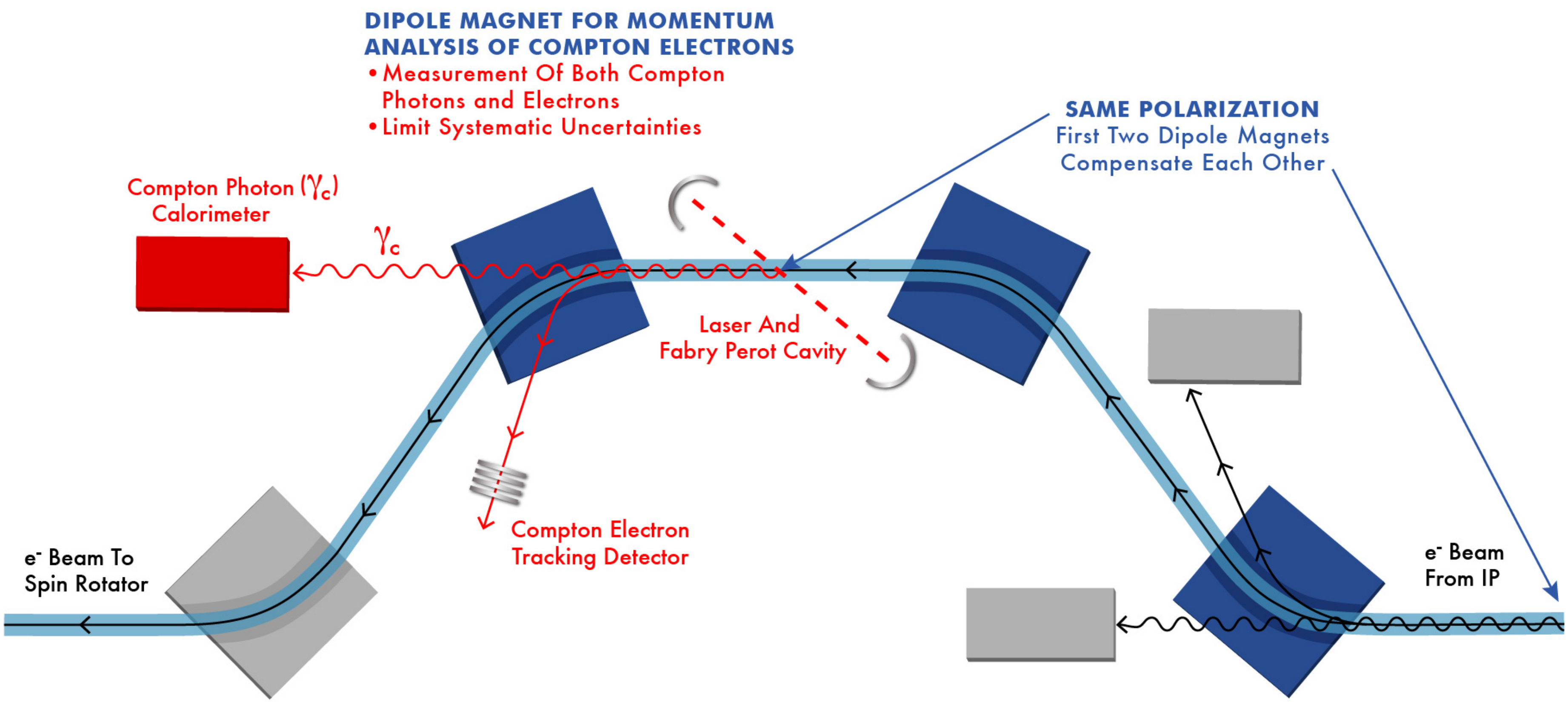
Use Bethe-Heitler process to monitor luminosity: same as HERA



Low Q^2 Tagger

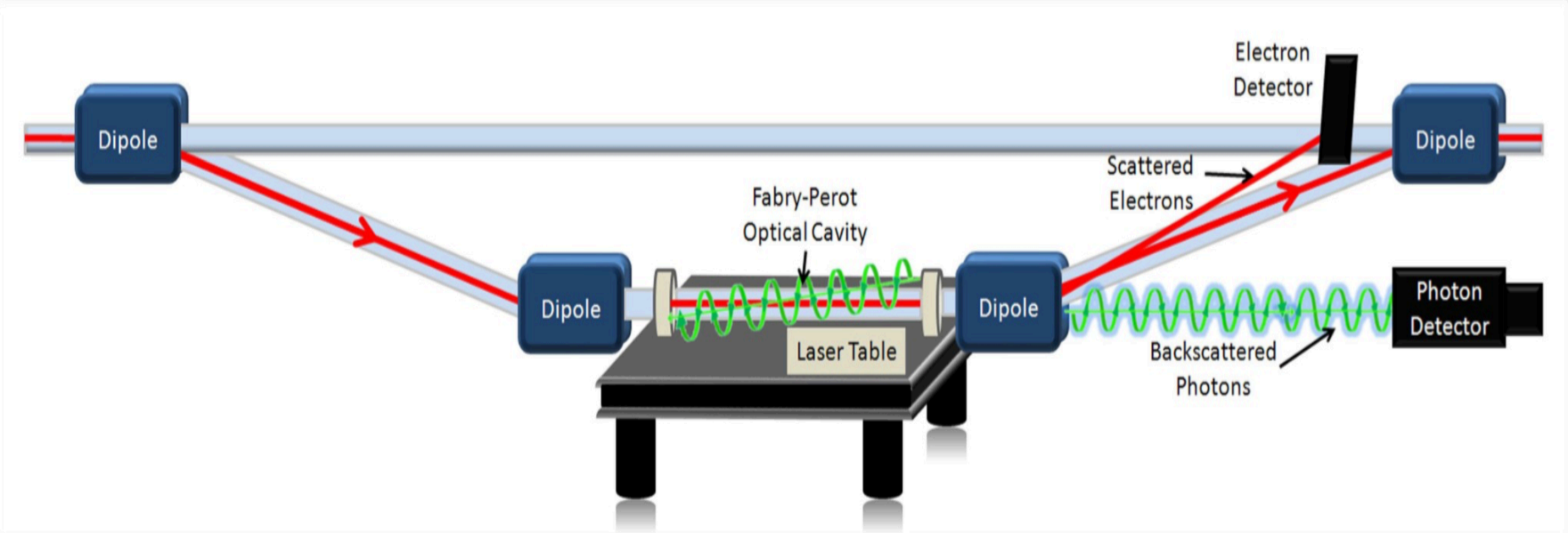


Polarization Measurement



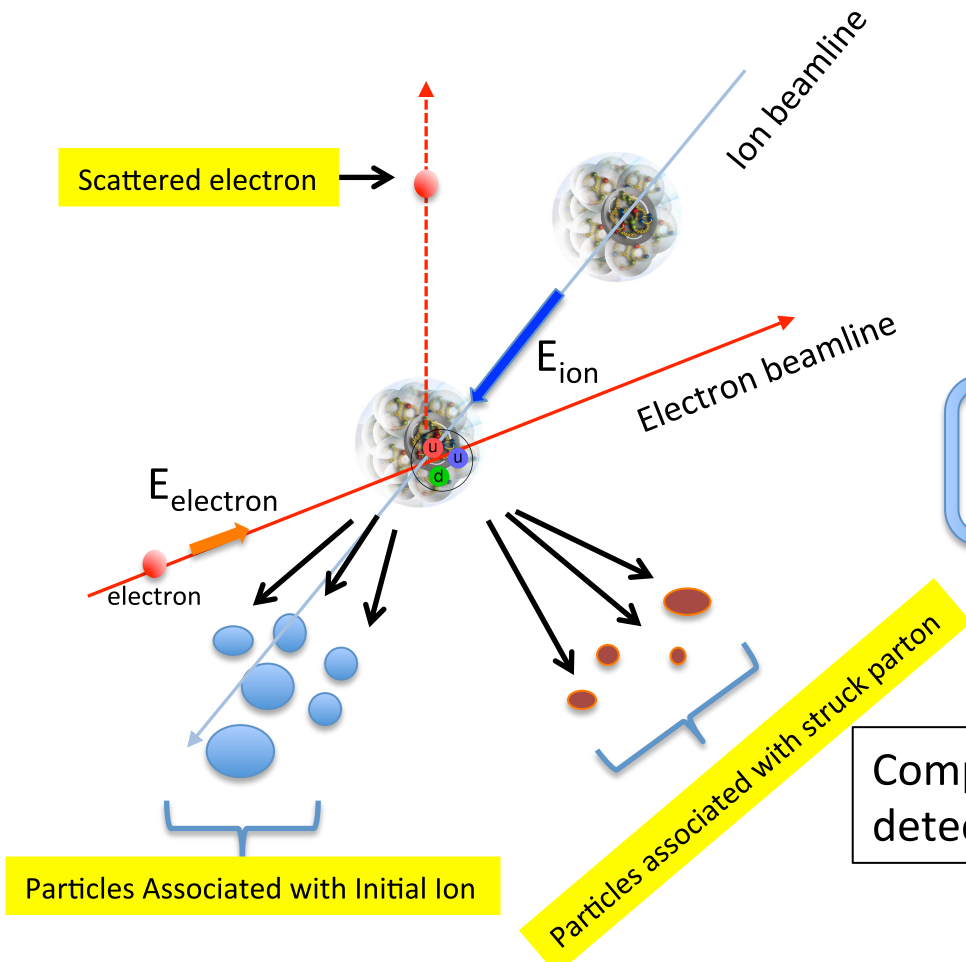
Note the off-momentum electrons from IP does not enter the
Compton tracker for polarimetry.

Compton Polarimetry



Existing Polarimeter in Hall C at JLab: Achieved 1% Precision

E_{ion} and $E_{ion}/E_{electron}$



EIC needs to detect all three types of particles

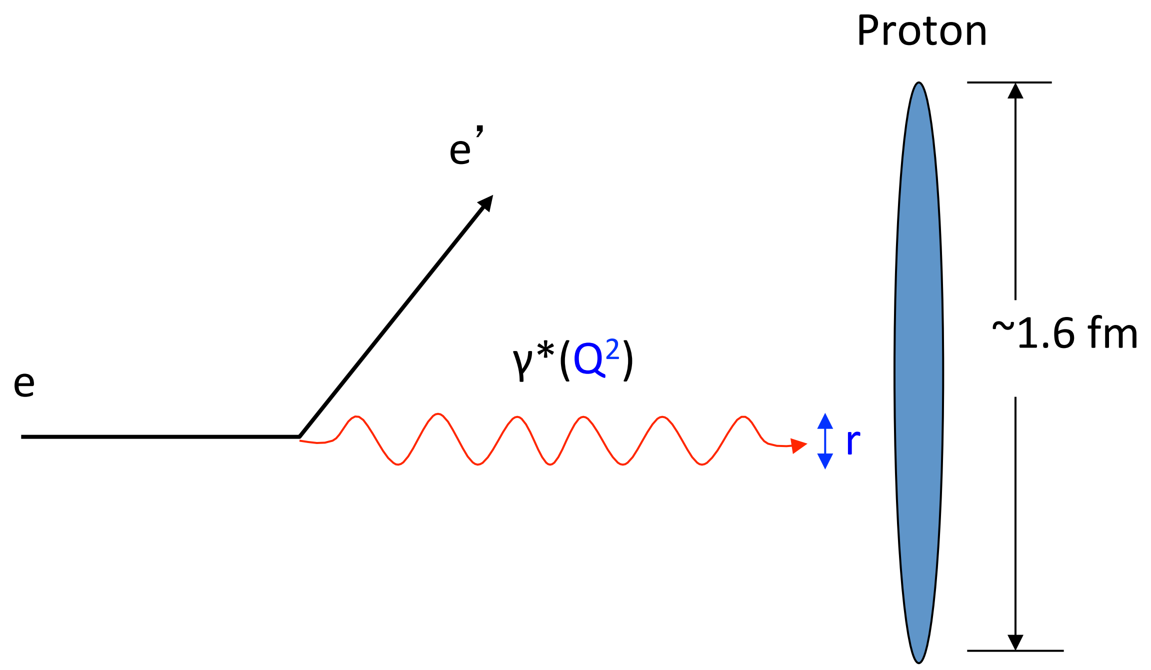
- Scattered electron
- Particles Associated with Initial Ion
- Particles associated with struck parton

These become more forward boosted and harder to measure with increasing E_{ion} and $E_{ion}/E_{electron}$

Complicated dependence on beam energies, detector capability and physics goals.

This optimization is on-going: depends on the physics program!

Deep Inelastic Scattering II



Virtuality (4-momentum transfer) Q gives the distance scale r at which the proton is probed.

$r \approx \hbar c/Q = 0.2\text{fm}/Q[\text{GeV}]$

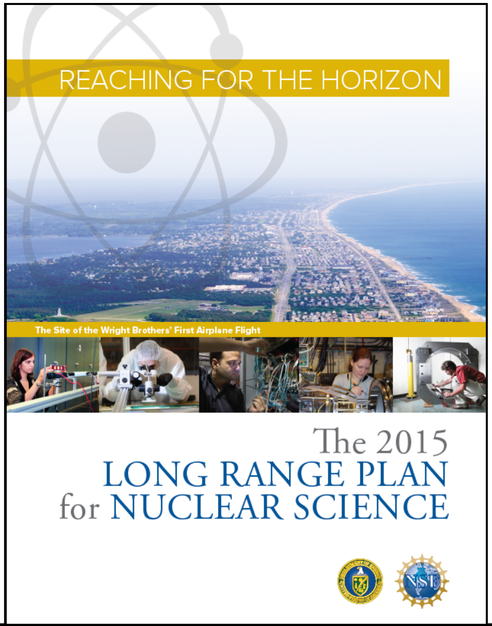
HERA ep collider DIS: $r_{min} \approx$ 1/1000 proton dia.

Nuclear Science Long-Range Planning

- Every 5-7 years the US Nuclear Science community produces a Long-Range Planning (LRP) Document
- The final document includes a *small* set of recommendations for the field of Nuclear Science **for the next decade**
- For instance, 12 GeV construction was the highest recommendation of the 2007 plan.

October 2015 -> Report Finalized
(Including cost review of EIC)
Note: Totally separate from
High Energy Physics planning process (P5)
HEP and NP funds in US are decoupled to first order

USDOE (NP) is acting based on this planning
National Academy Science Review being commissioned
(Larger science case must be endorsed)



Recommendations - shorthand

1. **The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.**
    - **12 GeV** – unfold quark & gluon structure of hadrons and nuclei
    - **FRIB** – understanding of nuclei and their role in the cosmos
    - **Fundamental Symmetries Initiative** – physics beyond the SM
    - **RHIC** – properties and phases of quark and gluon matter

    The ordering of these four bullets follows the priority ordering of the 2007 plan

2. **We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.**

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

4. **We recommend increasing investment in small and mid-scale projects and initiatives that enable forefront research at universities and laboratories.**

EIC Realization Imagined

With a formal NSAC/LRP recommendation, what can we speculate about any EIC timeline?

- A National Academy of Sciences study has been initiated and the committee is being formed. Charge: "assess the scientific justification for a U.S. domestic electron ion collider facility, " (Wider Science Community) Likely to take ~12-18 months. Our next challenge.

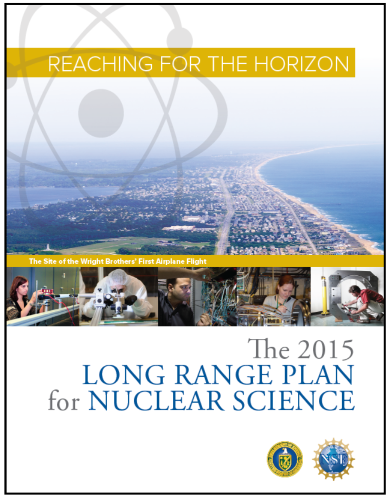
- DOE project "CD0" (Establish Mission need established) will be after the NAS study: i.e end 2017, early 2018.

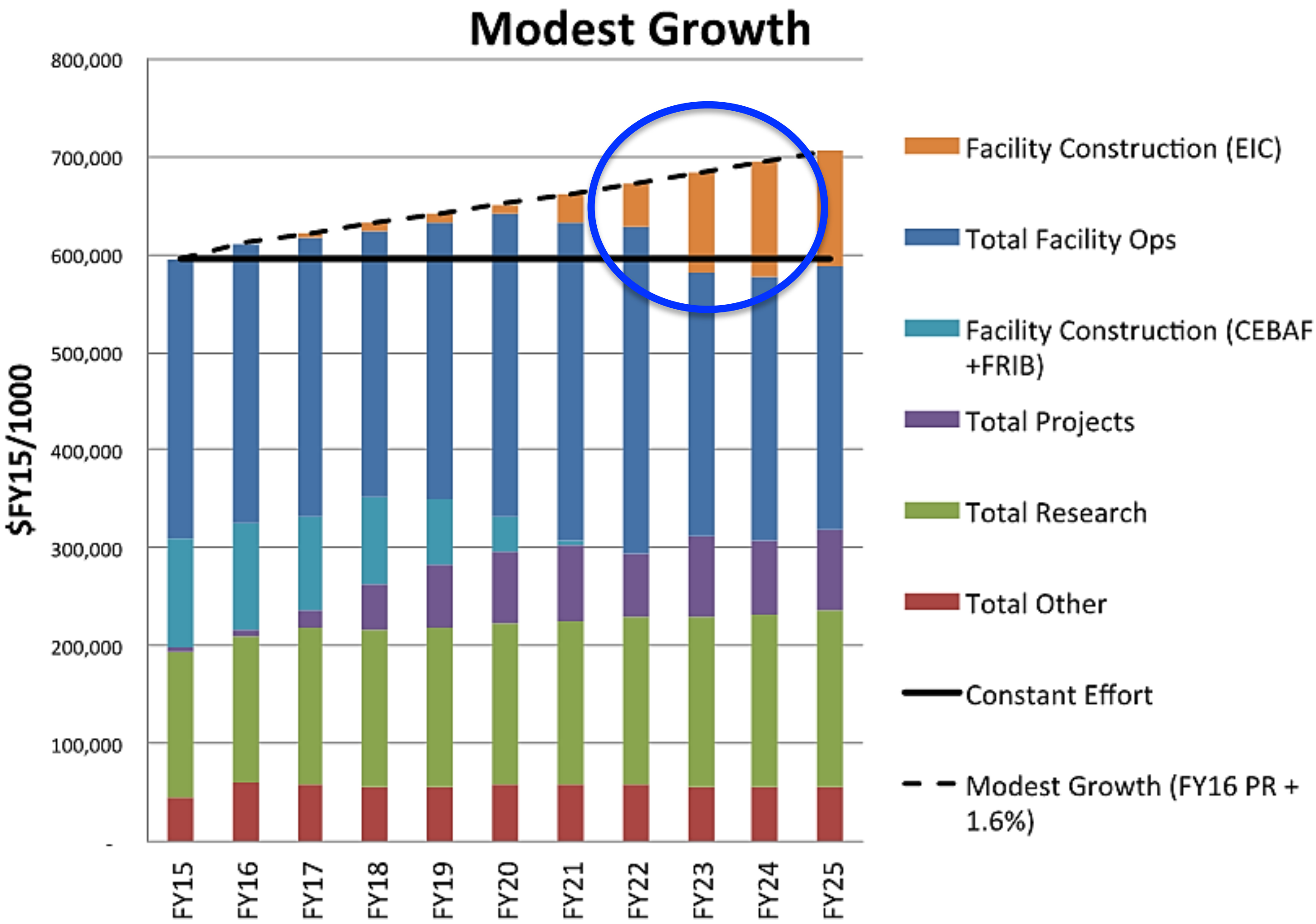
- EIC construction has to start **after FRIB completion**, with FRIB construction anticipated to start ramping down near or in FY20.

→ Most optimistic scenario would have EIC construction start (CD3) in FY20, perhaps more realistic FY22-23 timeframe

→ Best guess for EIC completion assuming formal NSAC/LRP recommendation would be 2025-2030 timeframe

DOE budget in FY 2015 dollars for Modest Growth scenario





The EIC Users Group: EICUG.ORG

651 collaborators, 27 countries, 142 institutions.

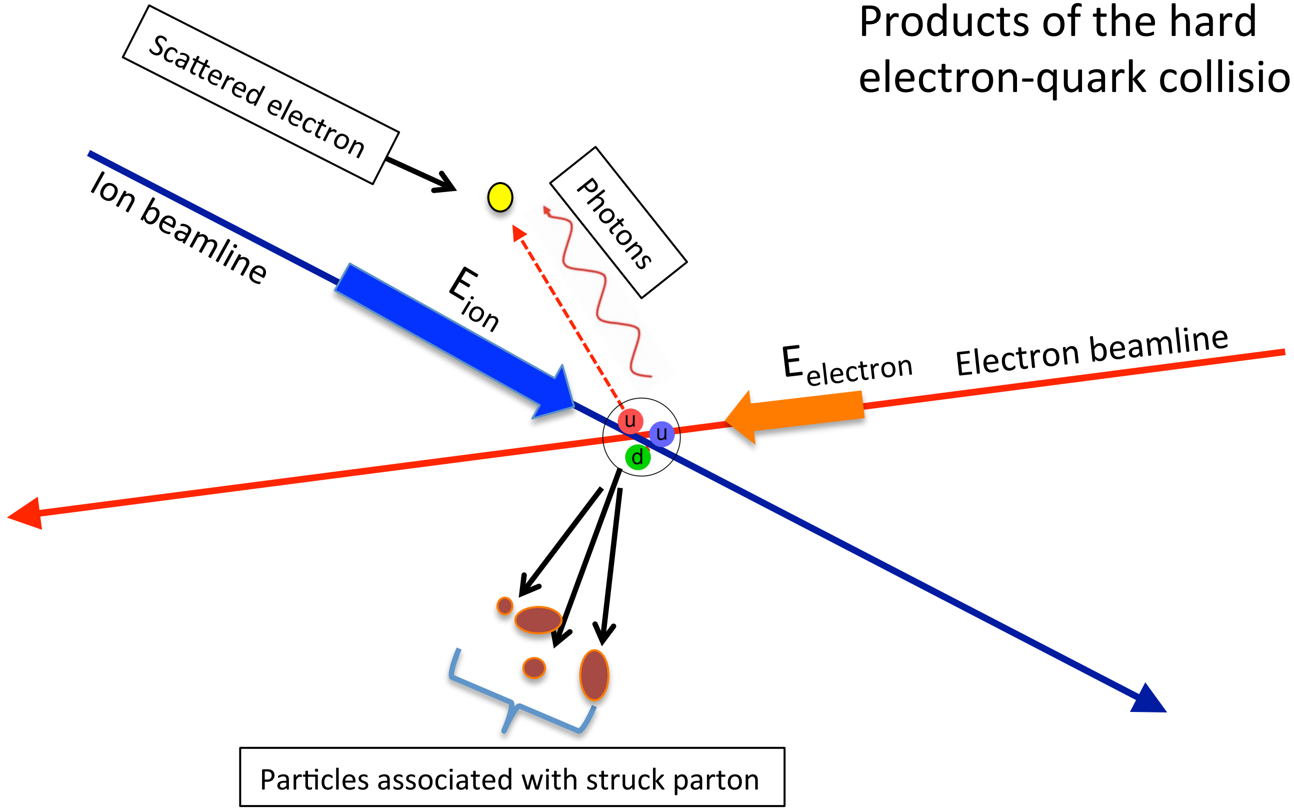
An incomplete picture of institution's locations…

And growing….

Join Us!

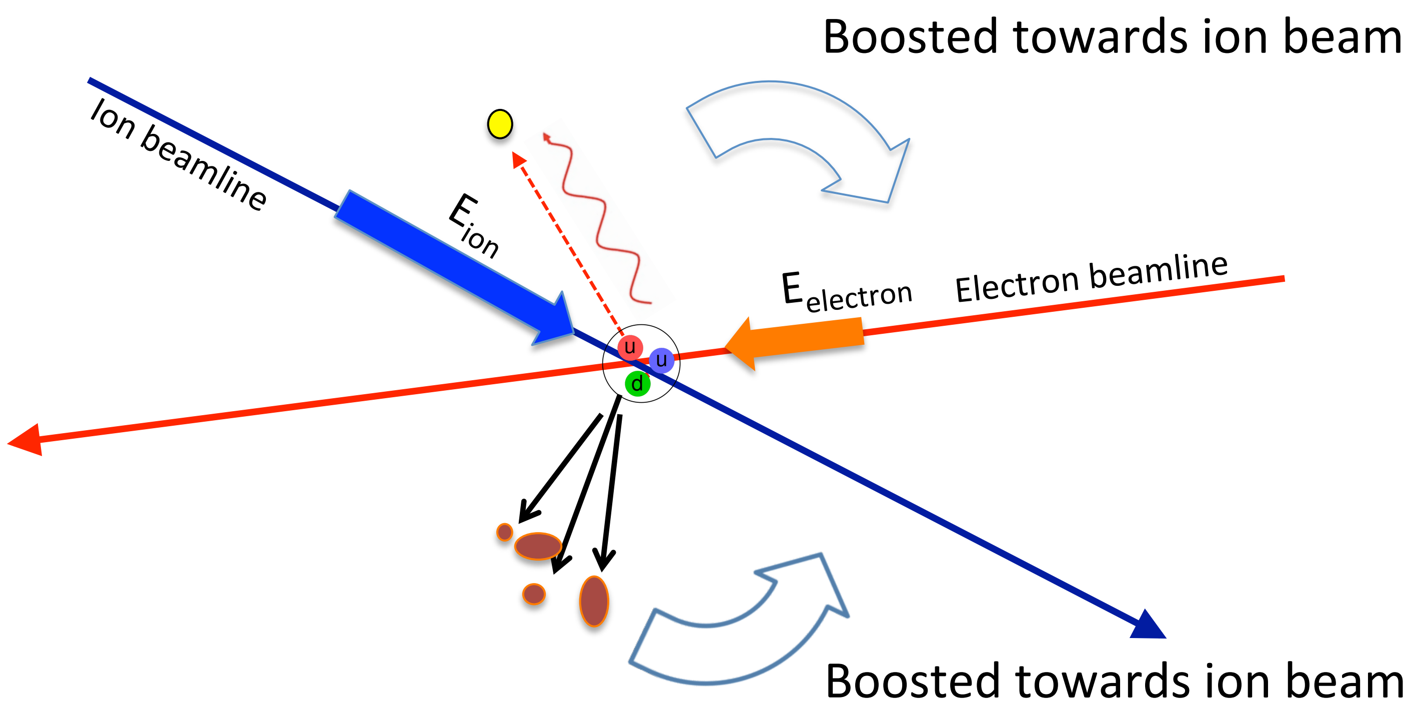
Final State Particles in the Central Rapidity

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 ($Q_2 \sim \Lambda_{QCD}$). **Particle ID much more important than at HERA**

Final State Particles in the Central Rapidity

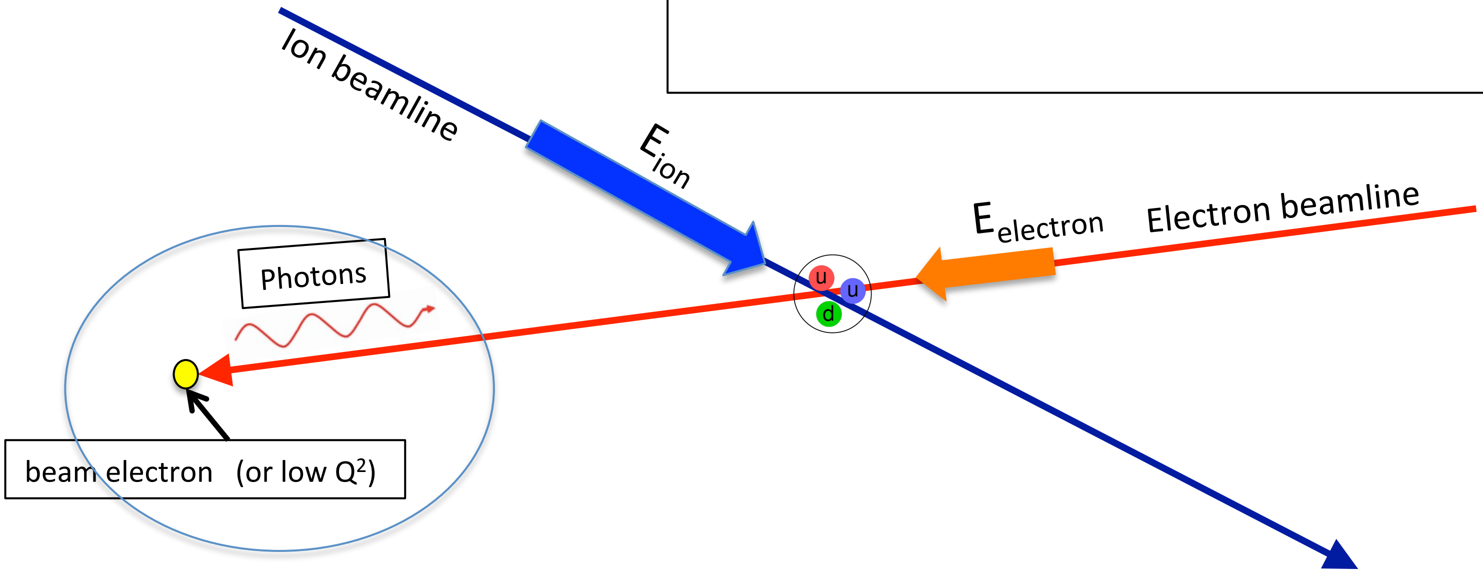


Asymmetric collision energies will boost the final state particles in the ion beam direction: **Detector requirements change as a function of rapidity**

Particles Associated with the Initial Electron

Forward Electron area:

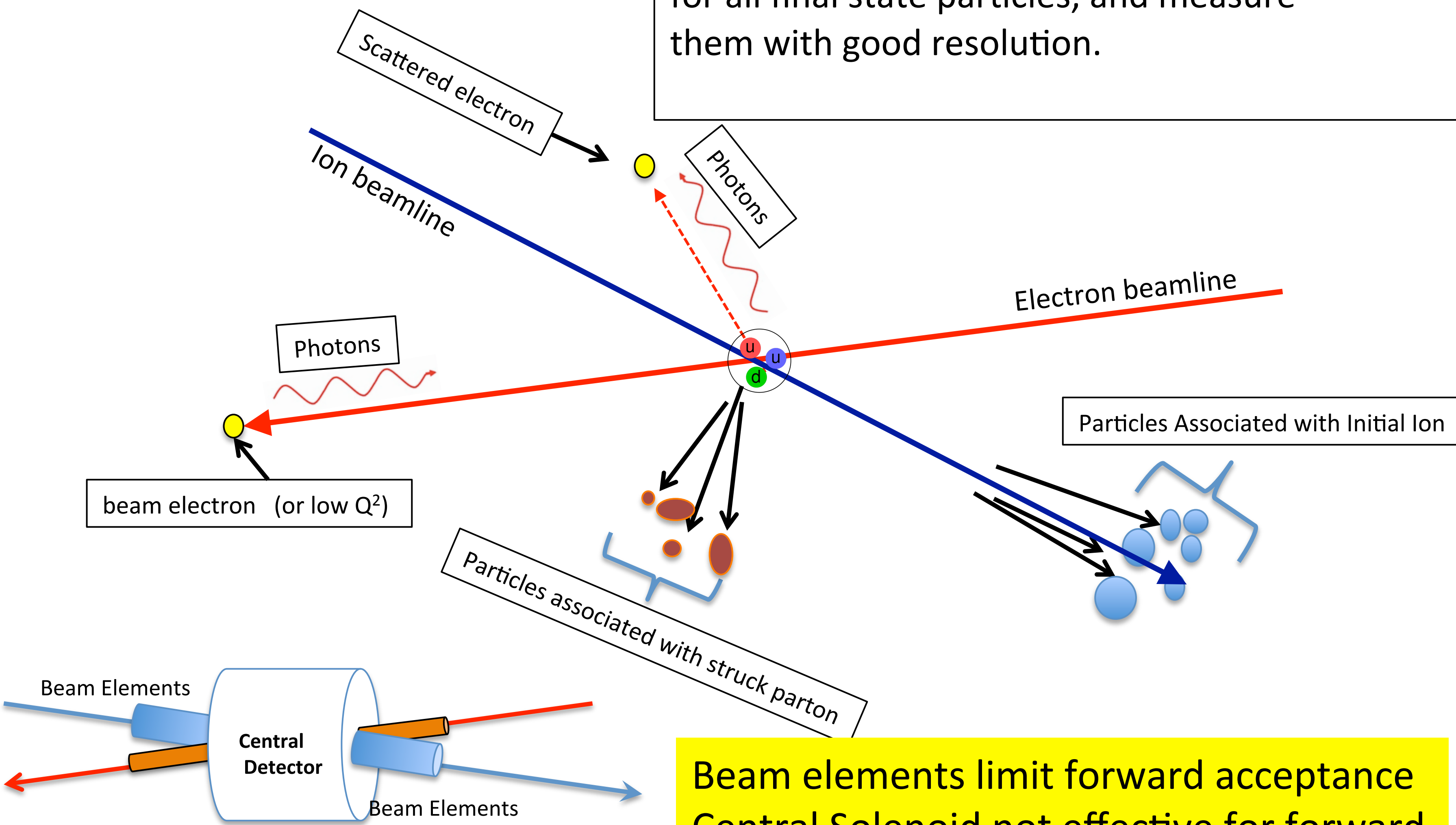
- Tag photoproduction ($Q^2 \approx 0$)
- Measure Luminosity
- Measure electron polarization



Apply lessons from HERA, JLab and elsewhere

Final State Particles

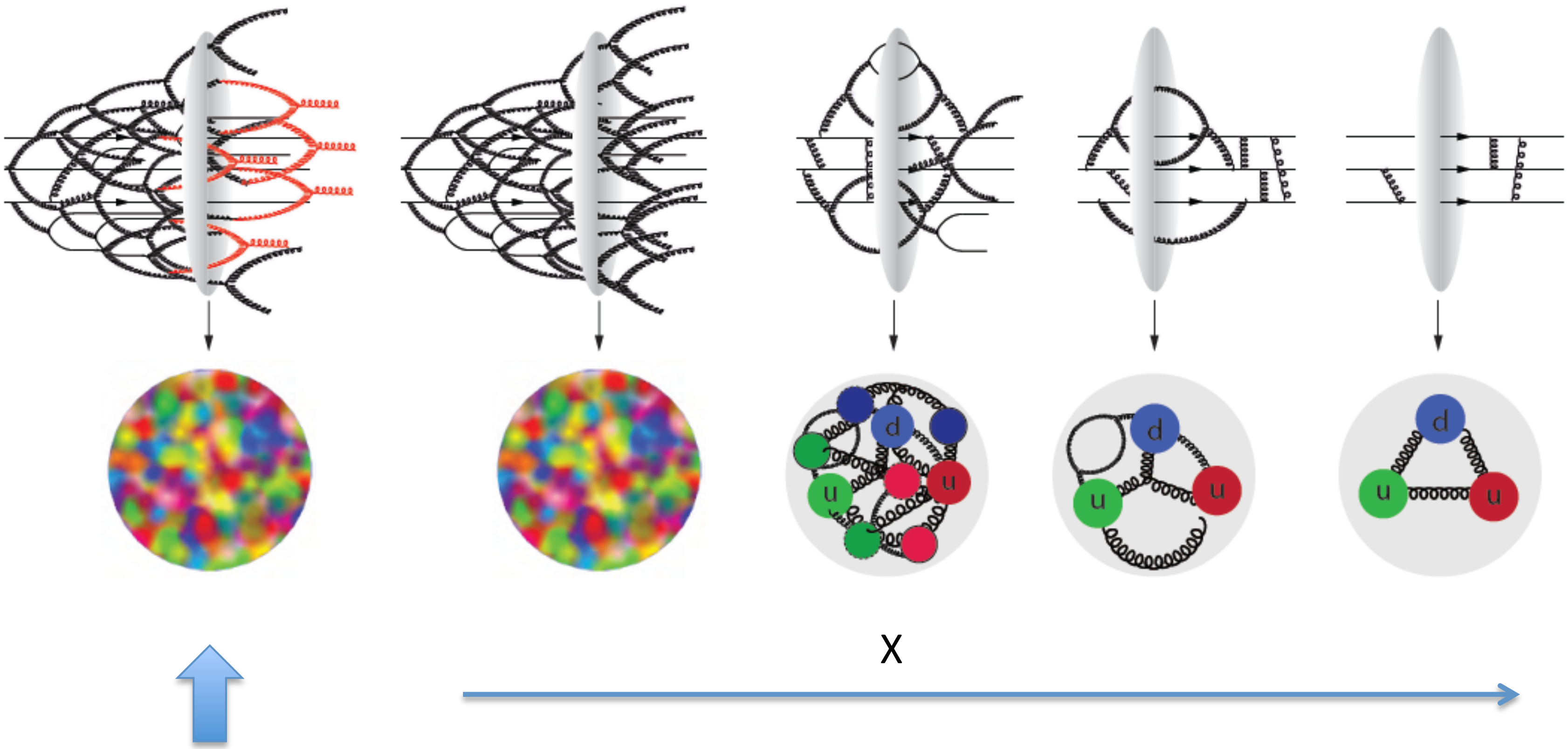
The aim is to get ~100% acceptance for all final state particles, and measure them with good resolution.



Beam elements limit forward acceptance
Central Solenoid not effective for forward

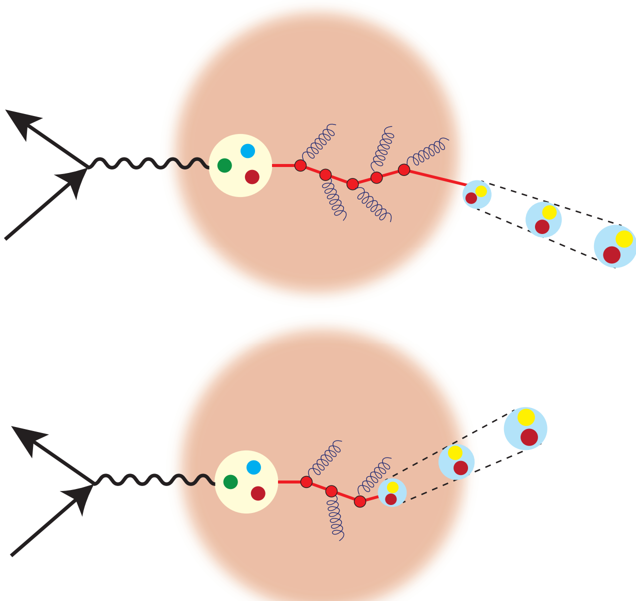
Picture of the Proton

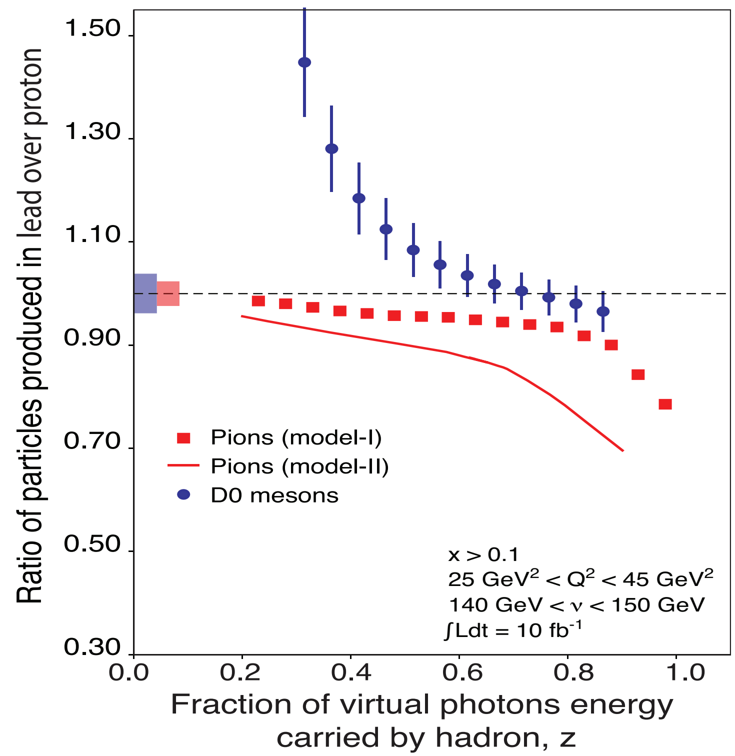
When probed at high resolution



Saturation?
Not clearly seen at HERA

Jets, Hadronization





ν = E-E' = 100-200 GeV to keep jet within nucleus

√s = 32-45 GeV for y=0.1 (keeping jet in the central region of the detector)

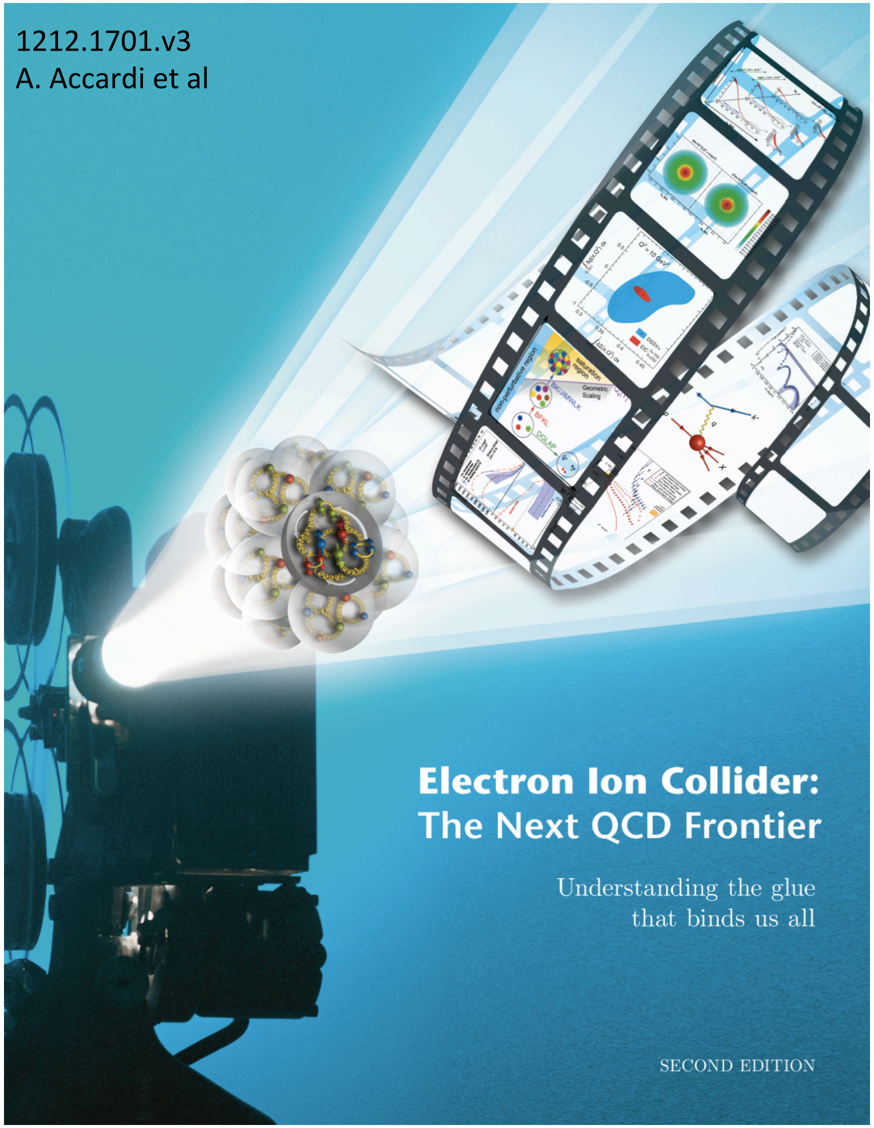
The Electron Ion Collider

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

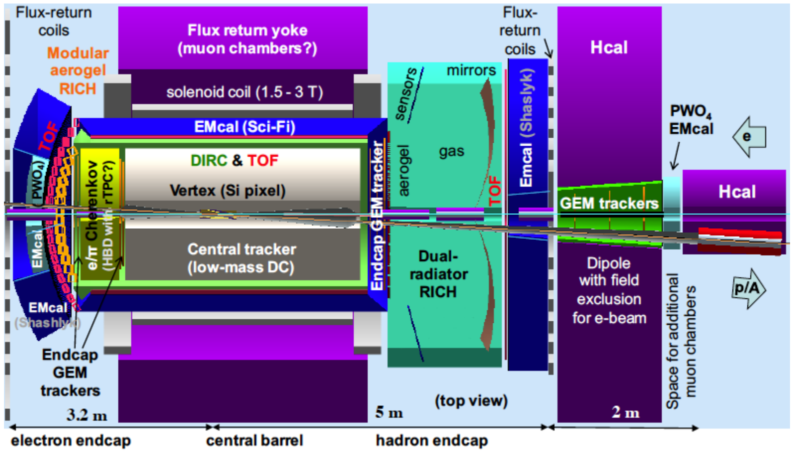
World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

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

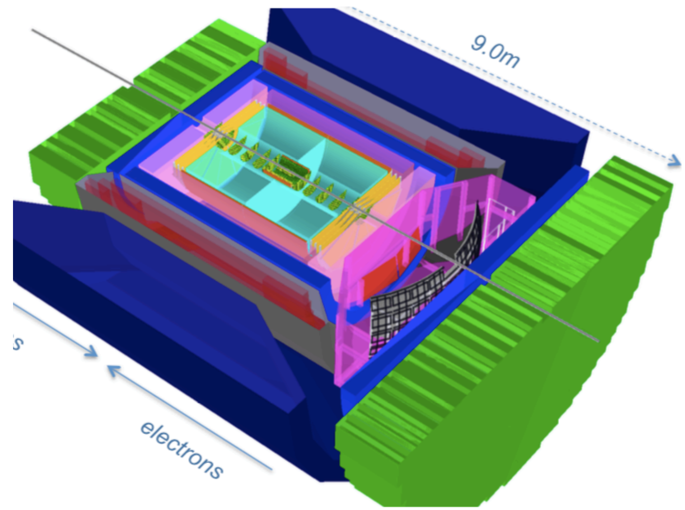


Current Detector Concepts

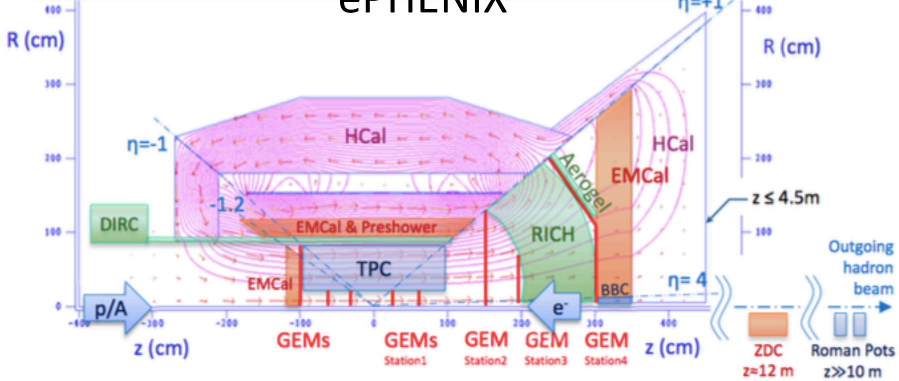
JLEIC



BEAST



ePHENIX



Much work to be done in developing detectors!
Come join us!