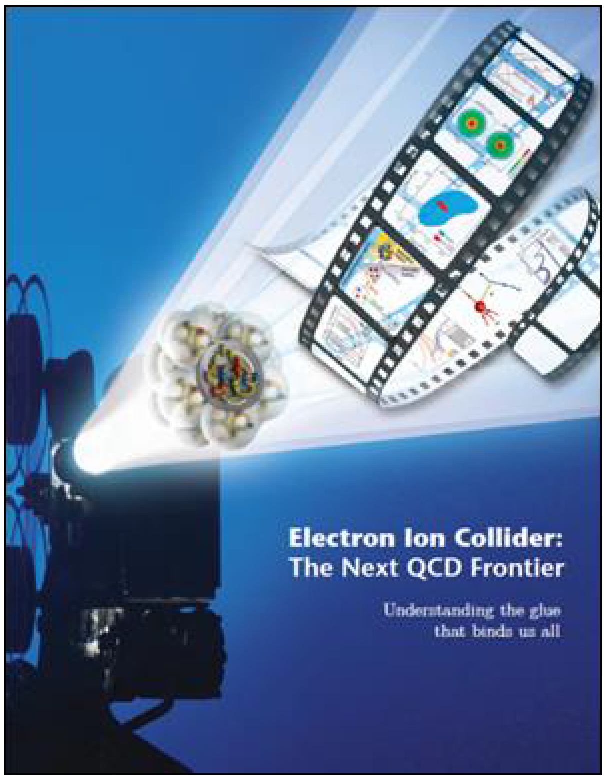
Physics with polarized light ions at an Electron-Ion Collider (EIC)



Pawel Nadel-Turonski

Jefferson Lab

EFB22, Krakow, Poland, September 12, 2013

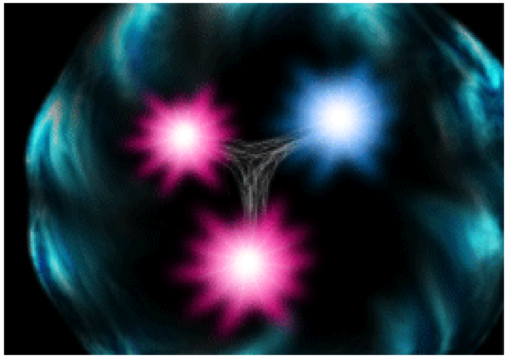
Outline

Physics highlights of an Electron-Ion Collider

Polarized light ions

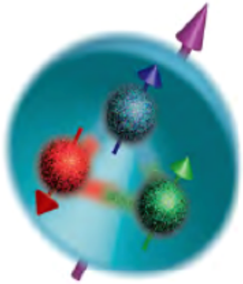
Accelerators and detectors

Physics highlights from the EIC program



- 3D structure of nucleons and nuclei is not trivial
  - Confinement

How do gluons and quarks bind into 3D hadrons?



- Gluon dynamics plays a large role in proton spin
  - Spin = intrinsic (parton spin) + motion (orbital angular momentum)

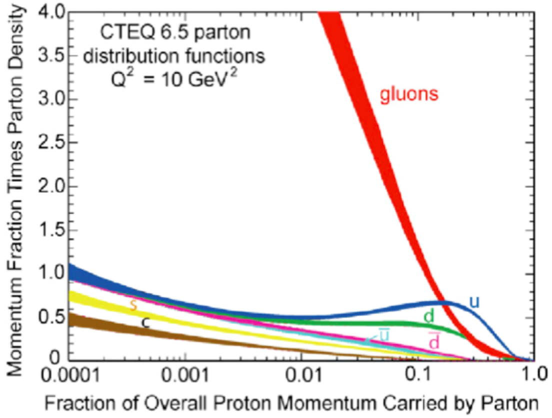
Why do quarks contribute so little (~30%) to proton spin?

- Gluons in nuclei

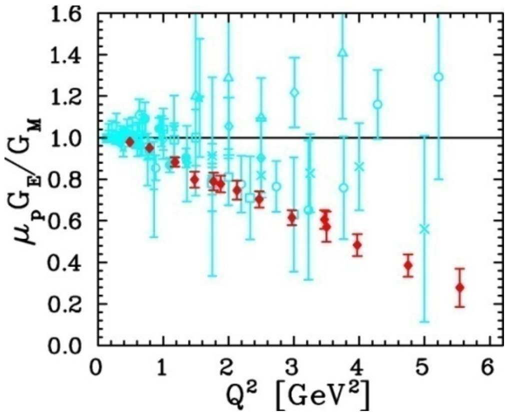
EIC stage I measurement

Does the gluon density saturate at small x?

EIC stage II measurement

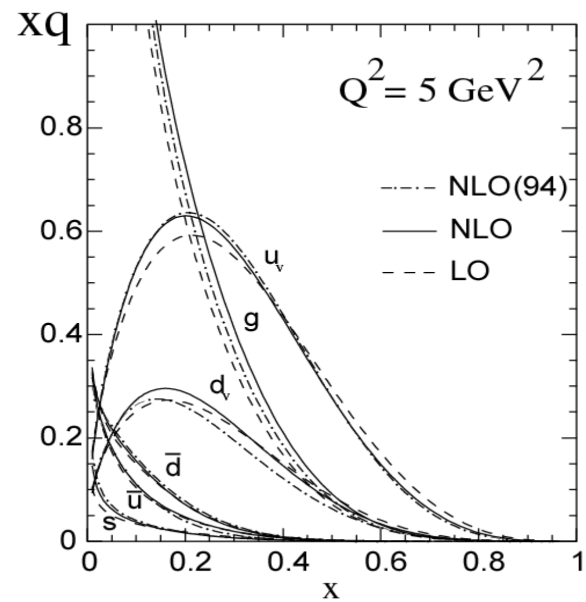


3D structure

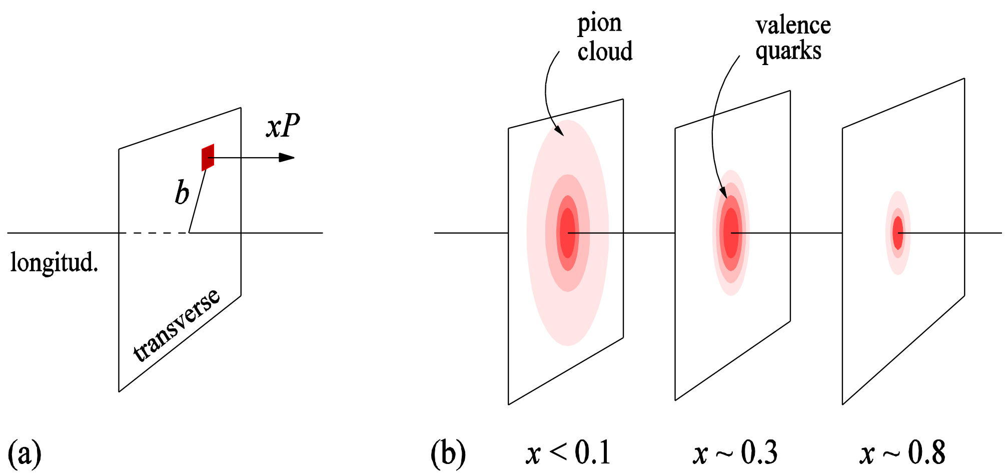


Elastic form factors

Transverse spatial distributions
(Naively Fourier transform of Q^2 or t)



Parton Distribution Functions
Longitudinal momentum distributions



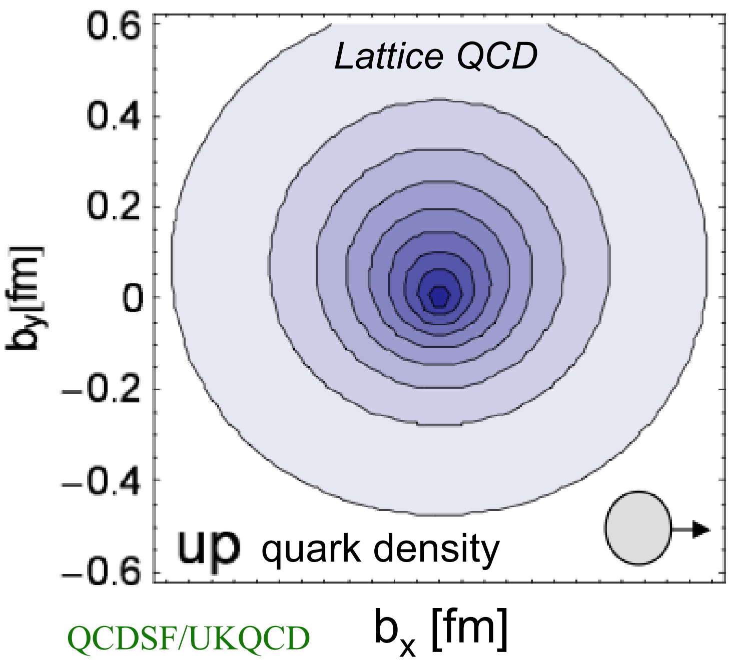
Generalized Parton Distributions

A unified descriptions of partons (quarks and gluons) in momentum and impact parameter space

Imaging in coordinate and momentum space

GPDs

2+1 D picture in **impact-parameter space**

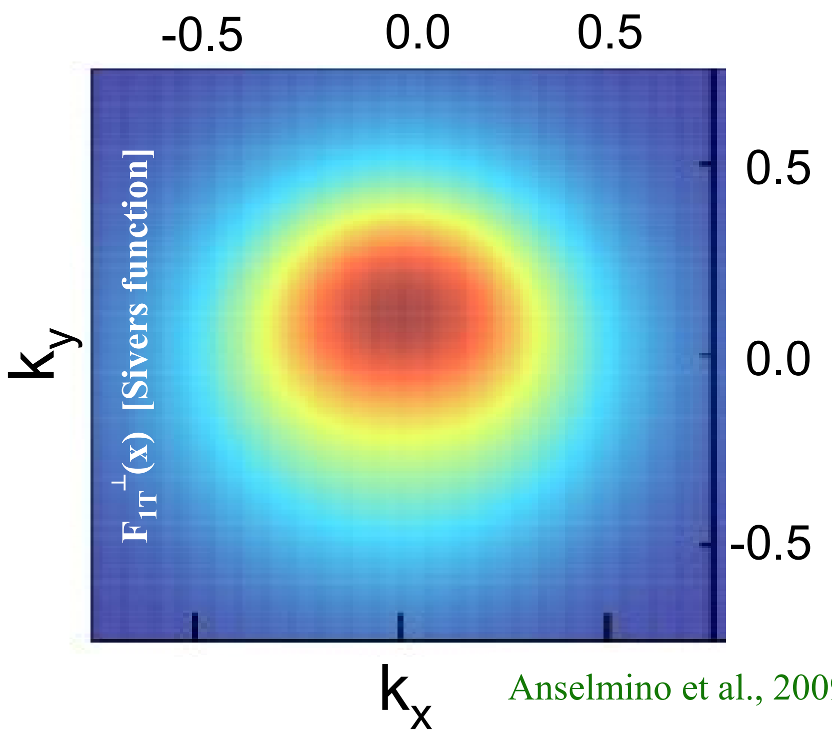


QCDSF/UKQCD Coll., 2006

- Accessed through *exclusive* processes
- Ji sum rule for nucleon spin

TMDs

2+1 D picture in **momentum space**



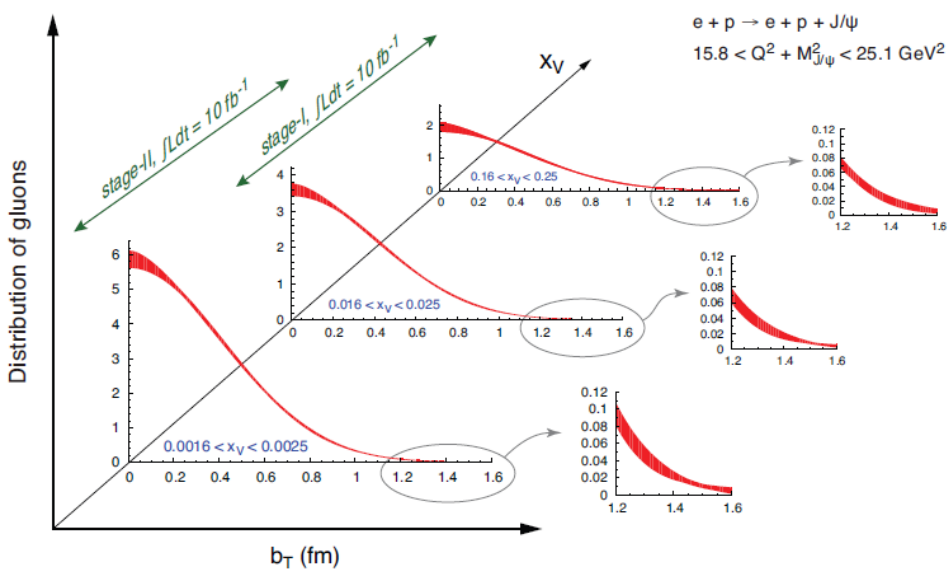
Anselmino et al., 2009

- Accessed through *Semi-Inclusive* DIS
- OAM through spin-orbit correlations?

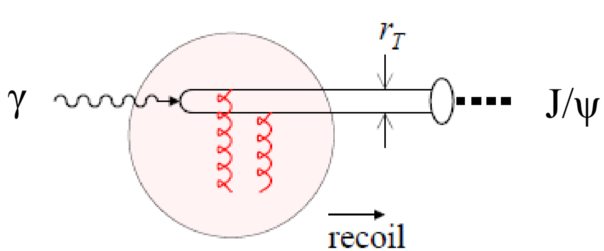
Imaging in coordinate and momentum space

GPDs

2+1 D picture in **impact-parameter space**

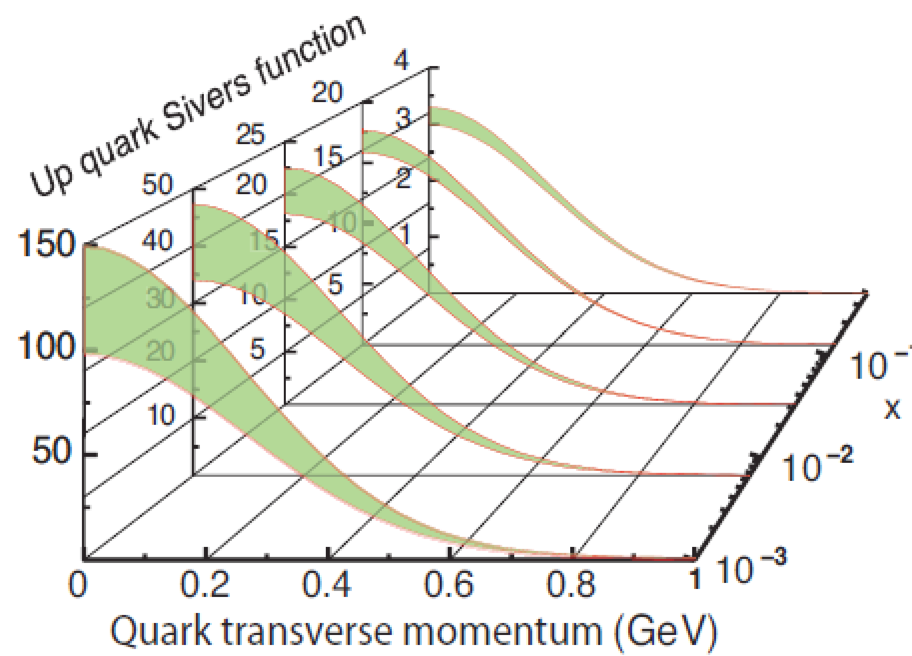


Transverse gluon distribution from J/ψ production

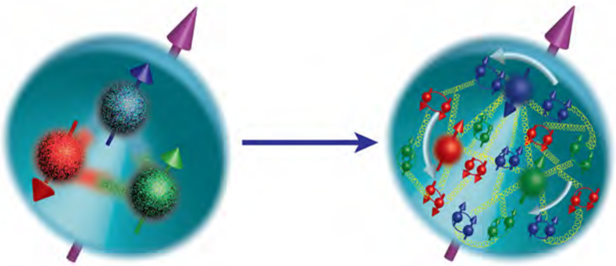


TMDs

2+1 D picture in **momentum space**



The spin of the proton



The number ½ turns out to be a complicated interplay between the intrinsic properties and interactions of quarks and gluons

$$\frac{1}{2} = \underbrace{\overbrace{\frac{1}{2}\Delta\Sigma(\mu)}^{\sim 0.35}_{\text{polarization}} + \overbrace{L_q(\mu)}^{?}_{\text{orbit}}}_{\text{quarks}} + \underbrace{\overbrace{\Delta G(\mu)}^{\text{small ?}}_{\text{polarization}} + \overbrace{L_g(\mu)}^{?}_{\text{orbit}}}_{\text{gluons}}$$

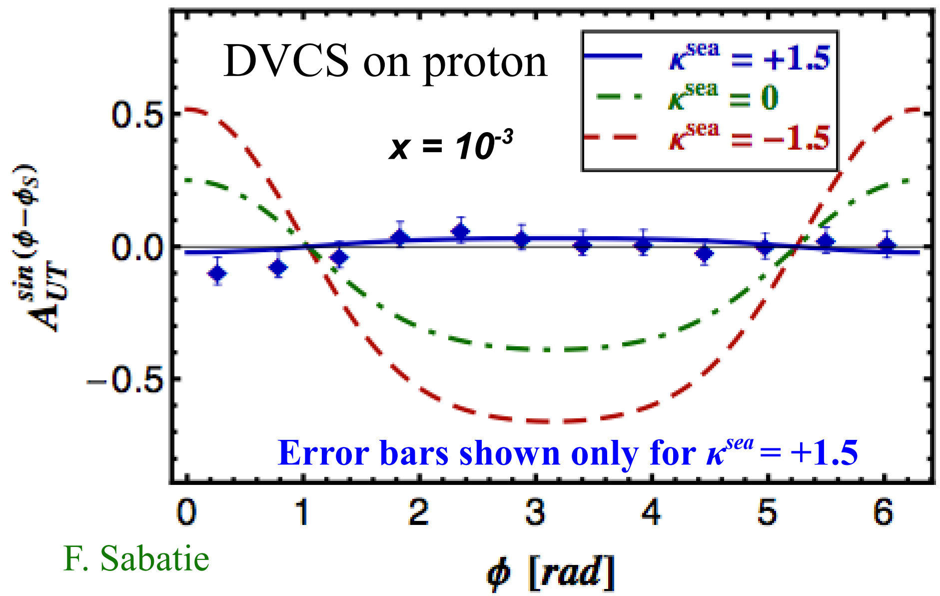
Two complementary approaches to resolve proton spin puzzle

Measure ΔG - gluon polarization

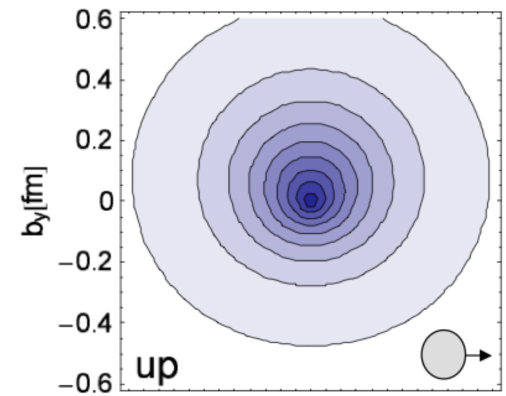
Measure TMD and GPDs - orbital motion

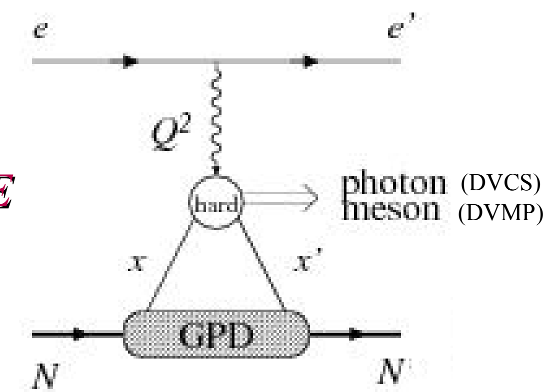
GPDs and angular momentum

Model: $E^i(x, \xi, t) = \kappa^i(t)\, H^i(x, \xi, t)$



F. Sabatie

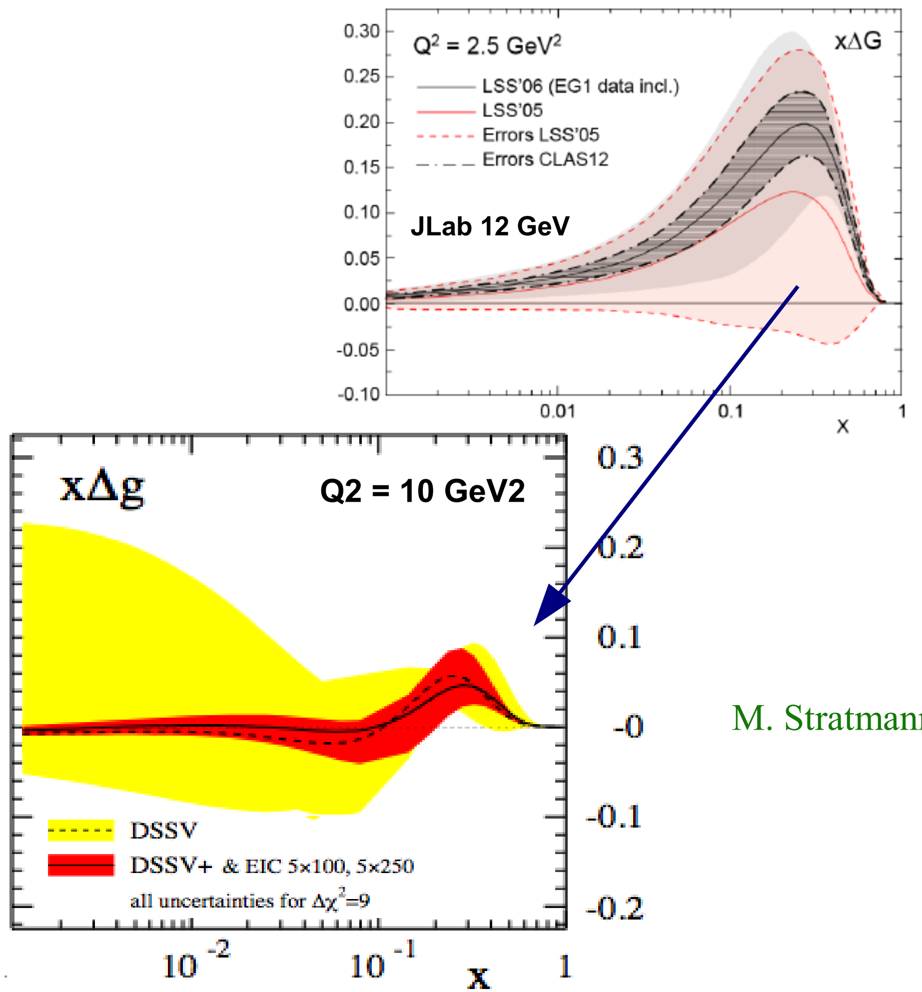




- DVCS on a transversely polarized target is sensitive to the *GPD E*
  - *GPD H* can be measured through the beam spin asymmetry
  - Opens up opportunity to study spin-orbit correlations:

$$J^q = \frac{1}{2}\int_{-1}^{+1} dx\, x\left[H^q(x,\xi,t) + E^q(x,\xi,t)\right]$$

Longitudinal spin – ΔG (gluon polarization)

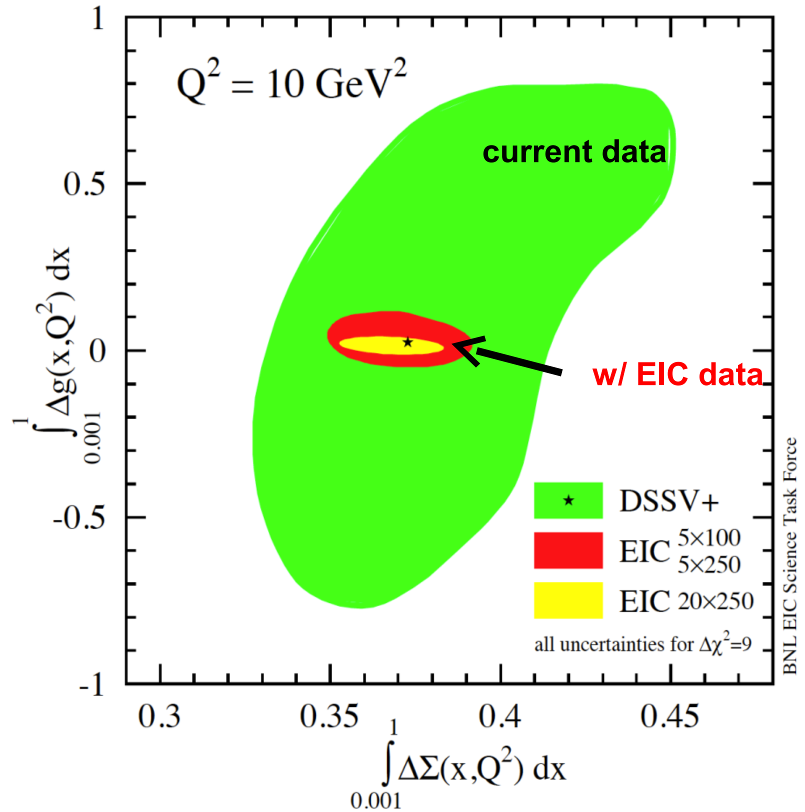


M. Stratmann

Green: RHIC spin, etc

Red: EIC Stage I (MEIC or eRHIC)

Yellow: EIC Stage II

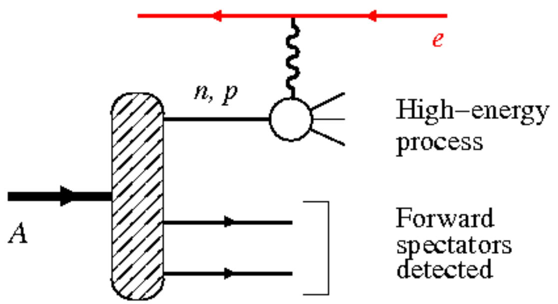


- EIC stage I will greatly improve our understanding of ΔG
  - Stage II will further reduce the uncertainty

Opportunities with polarized light ions

Experiment: requires excellent forward detection and spectator tagging
Theory: combines high-momentum-transfer processes and low-energy nuclear structure

Partonic structure of the neutron (including spin)



- Quark flavor decomposition of the nucleon spin
- Extraction of flavor non-singlet sea quark distributions
  - Sensitive to non-perturbative QCD interactions

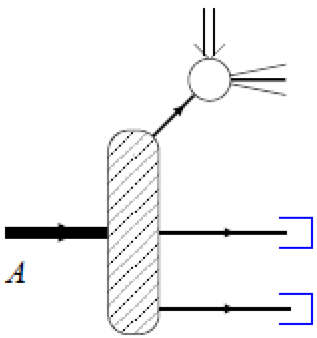
The bound nucleon in QCD

- Modifications of nucleon's quark/gluon structure due to nuclear binding
  - Quark/gluon origin of nuclear force
  - Control the effects of final-state interactions

Collective quark/gluon fields

- Coherent scattering probes the quark/gluon field of the entire nucleus
  - Similar information comes from diffractive scattering on deuterium
- Tensor-polarized structure function of deuterium is zero in single-nucleon scattering and precisely identifies the QCD double-scattering contribution.
  - Provides insight into the onset of gluon saturation at higher energies

Nuclear structure in high–energy processes [Summary by C. Weiss]



"Conditional" LF spectral function

- Low–energy nuclear structure affects high–energy $eA/\gamma A$ scattering processes

  Factorization in long–distance nuclear structure $\sim R_A$ and short–distance nucleon structure $\sim 1/Q$

  Light–front formulation essential: Momentum conservation, sum rules

- Inclusive deep–inelastic scattering on nuclei

  Nuclear structure functions: EMC effect, antishadowing, shadowing

- Spectator tagging with light nuclei ^{2}H, ^{3}He
  Becomes feasible with medium–energy Electron–Ion Collider!

  Neutron structure functions: Spin/flavor decomposition of parton densities

  Bound nucleon structure: Off–shellness controlled by kinematics, comparison of bound and free proton

  Nuclear polarization as additional handle: Spin filtering, tensor polarized ^{2}H for multiple scattering beyond IA

  Needs theory input: Conditional spectral functions, final–state interactions
  New applications of low–energy nuclear structure techniques. Expect developments in next years!

EIC – consensus on global EIC requirements

The EIC project is pursued jointly by BNL and JLab, and both labs work towards implementing a common set of goals

From base EIC requirements in the INT report

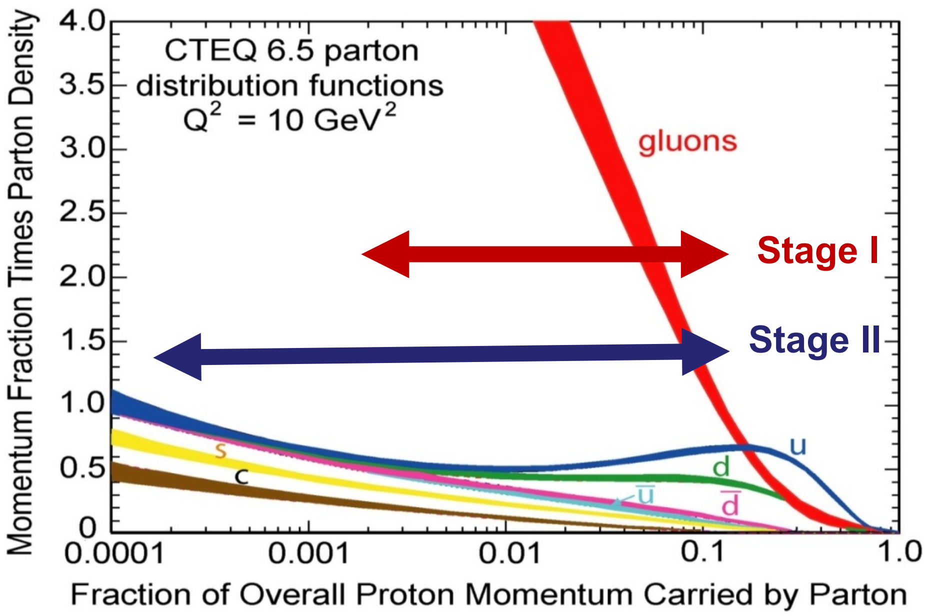
- Polarized electron, nucleon, and light ion beams
  - Electron and nucleon polarization > 70%
  - Transverse polarization at least for nucleons
- Ions from hydrogen to A > 200
- Luminosity reaching 10^{34} $cm^{-2}s^{-1}$
- Stage I energy: $\sqrt{s}$ = 20 – 70 GeV (variable) (MEIC)
- Stage II energy: $\sqrt{s}$ up to about 150 GeV (EIC)

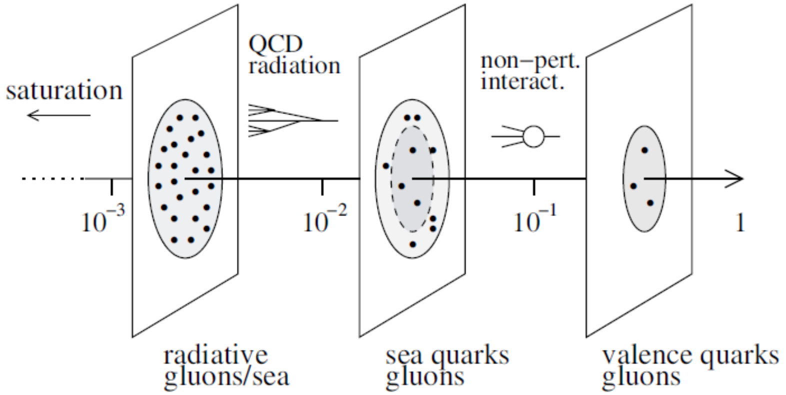
EIC staging

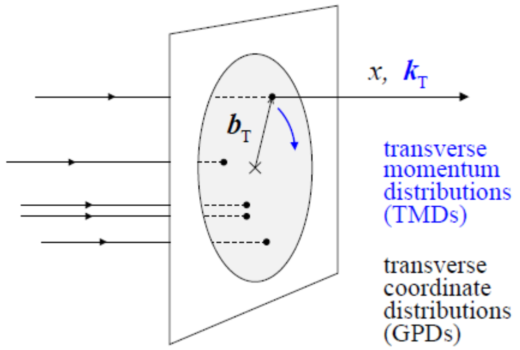
Already the first stage of an EIC gives access to sea quarks and gluons

Need polarization and good acceptance to detect spectators & fragments

An EIC aims to study the sea quarks and gluon-dominated matter.

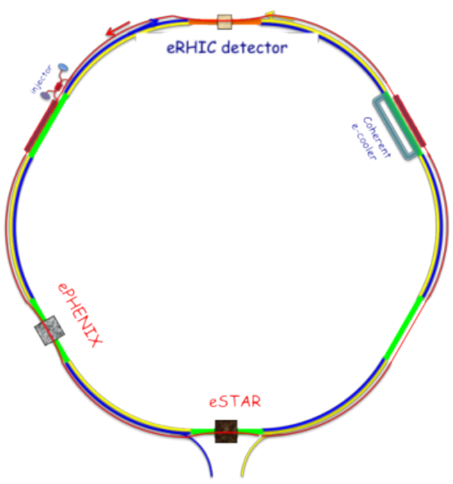






EIC – staging at BNL and JLab

eRHIC @ BNL



Stage I

$\sqrt{s}$ = 34 – 71 GeV

E_e = 3 – 5 (10 ?) GeV

E_p = 100 – 255 GeV

E_{Pb} = up to 100 GeV/A

Stage II

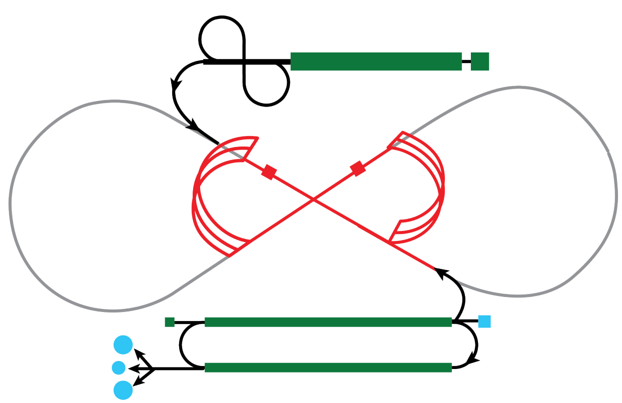
$\sqrt{s}$ = up to ~180 GeV

E_e = up to ~30 GeV

E_p = up to 275 GeV

E_{Pb} = up to 110 GeV/A

MEIC / EIC @ JLab



$\sqrt{s}$ = 13 – 70 GeV

E_e = 3 – 12 GeV

E_p = 15 – 100 GeV

E_{Pb} = up to 40 GeV/A

(MEIC)

$\sqrt{s}$ = up to ~140 GeV

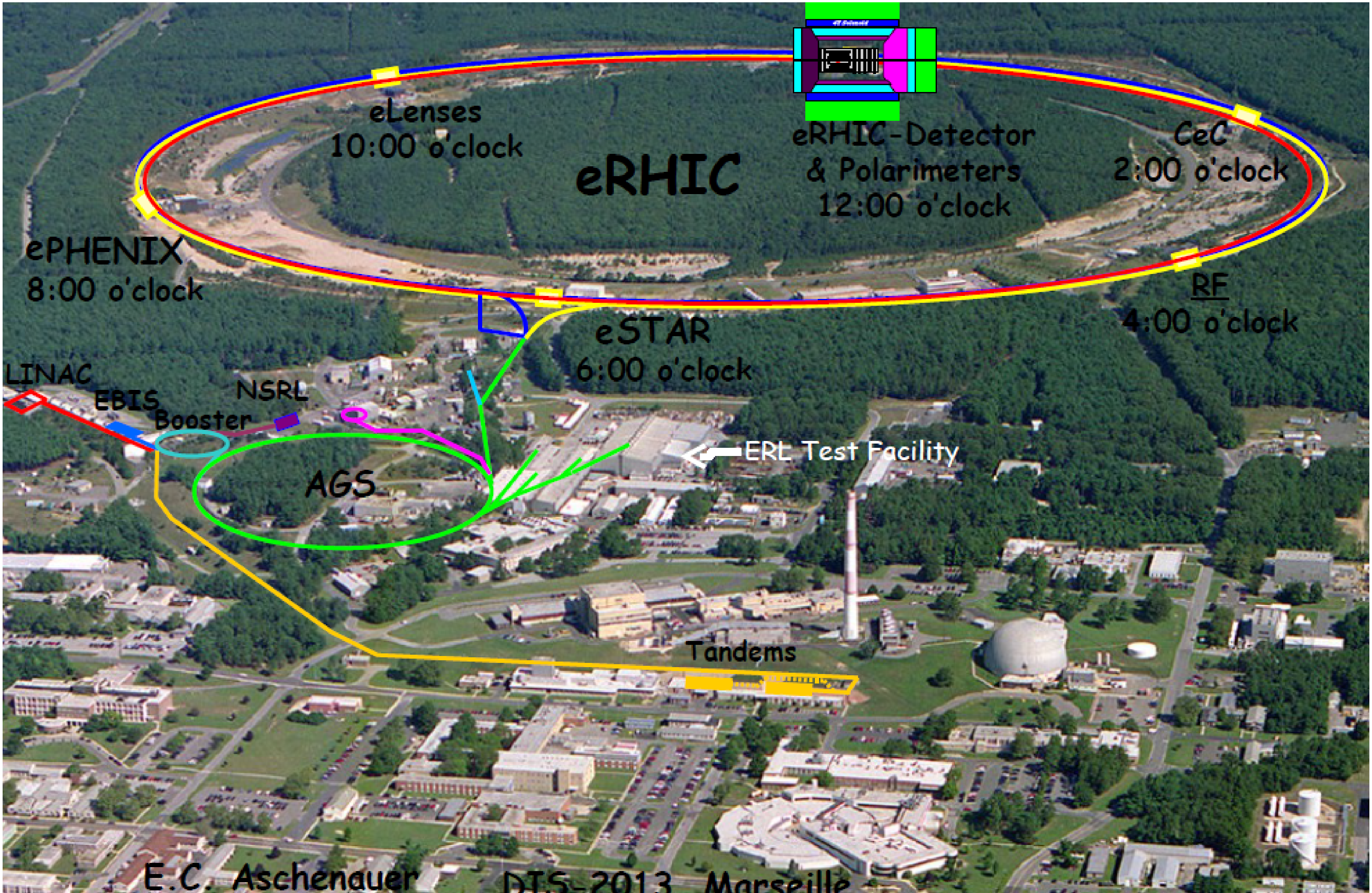
E_e = up to 20 GeV

E_p = up to at least 250 GeV

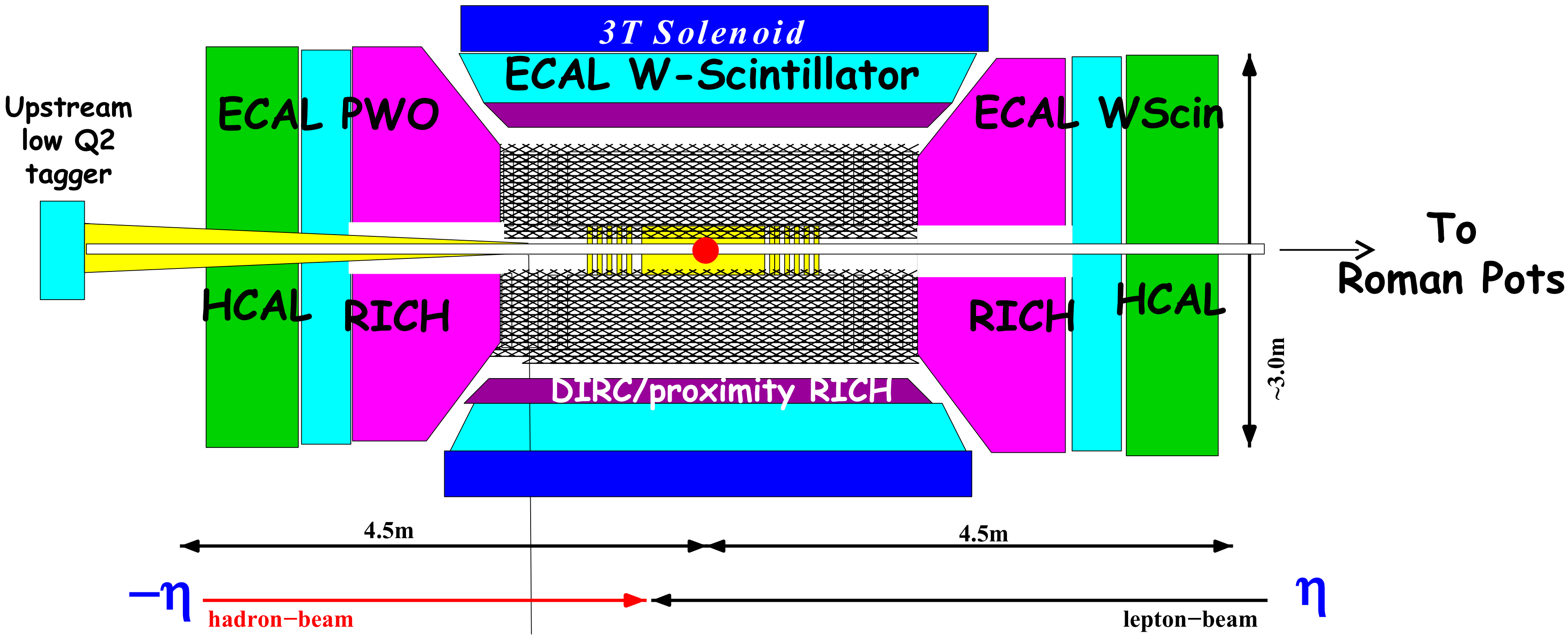
E_{Pb} = up to at least 100 GeV/A

(EIC)

eRHIC at Brookhaven Lab (BNL), NY



BNL: 1st Detector Design Concept



PID:

-1<η<1: DIRC or proximity focusing Aerogel-RICH

1<|η|<3: RICH

Lepton-ID:

-3 <η< 3: e/p

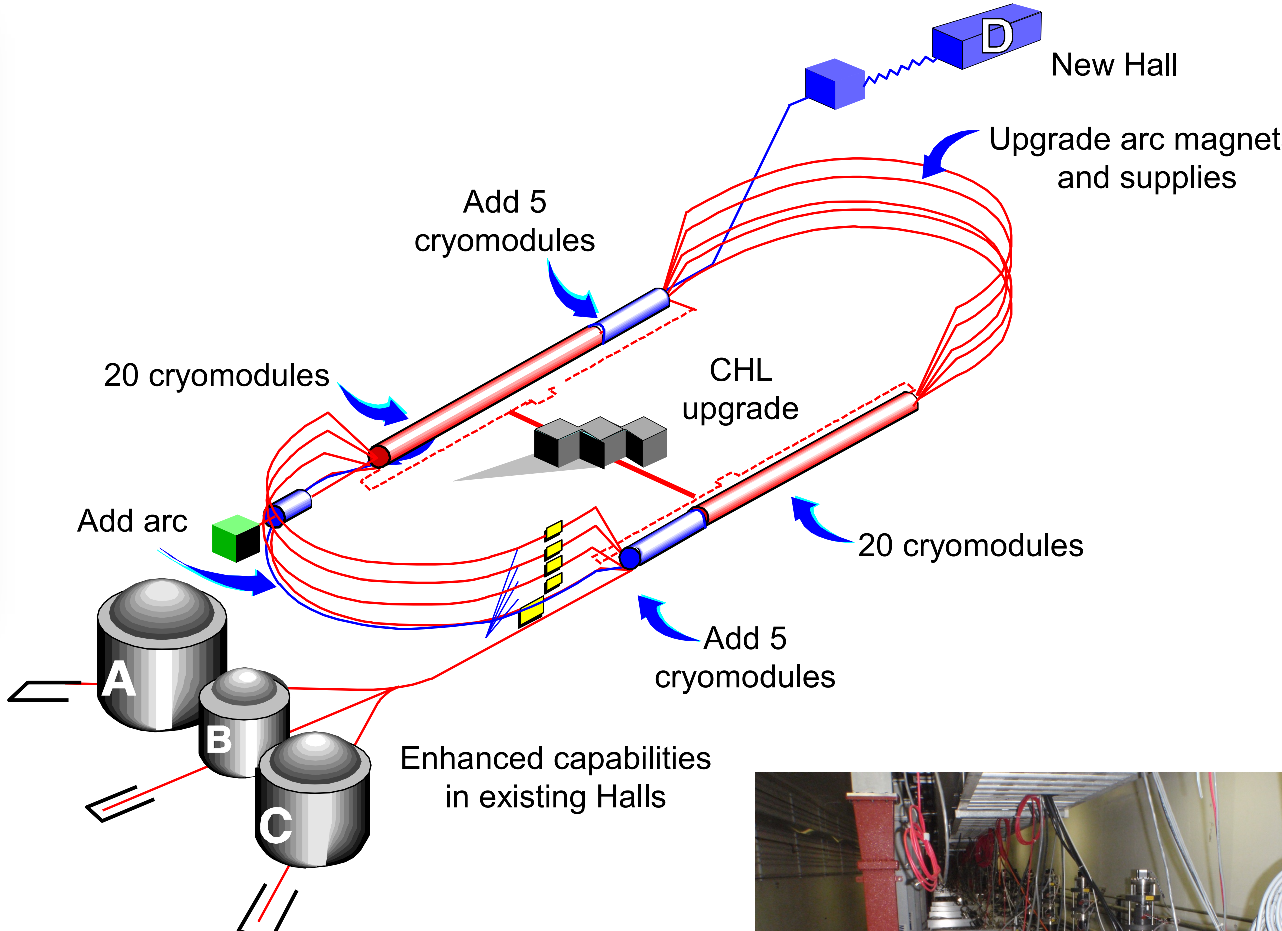
1<|η|<3: in addition Hcal response & γ suppression via tracking

|η|>3: ECal+Hcal response & γ suppression via tracking

-5<η<5: Tracking (TPC+GEM+MAPS)

JLab 12 GeV upgrade – probing the valence quarks

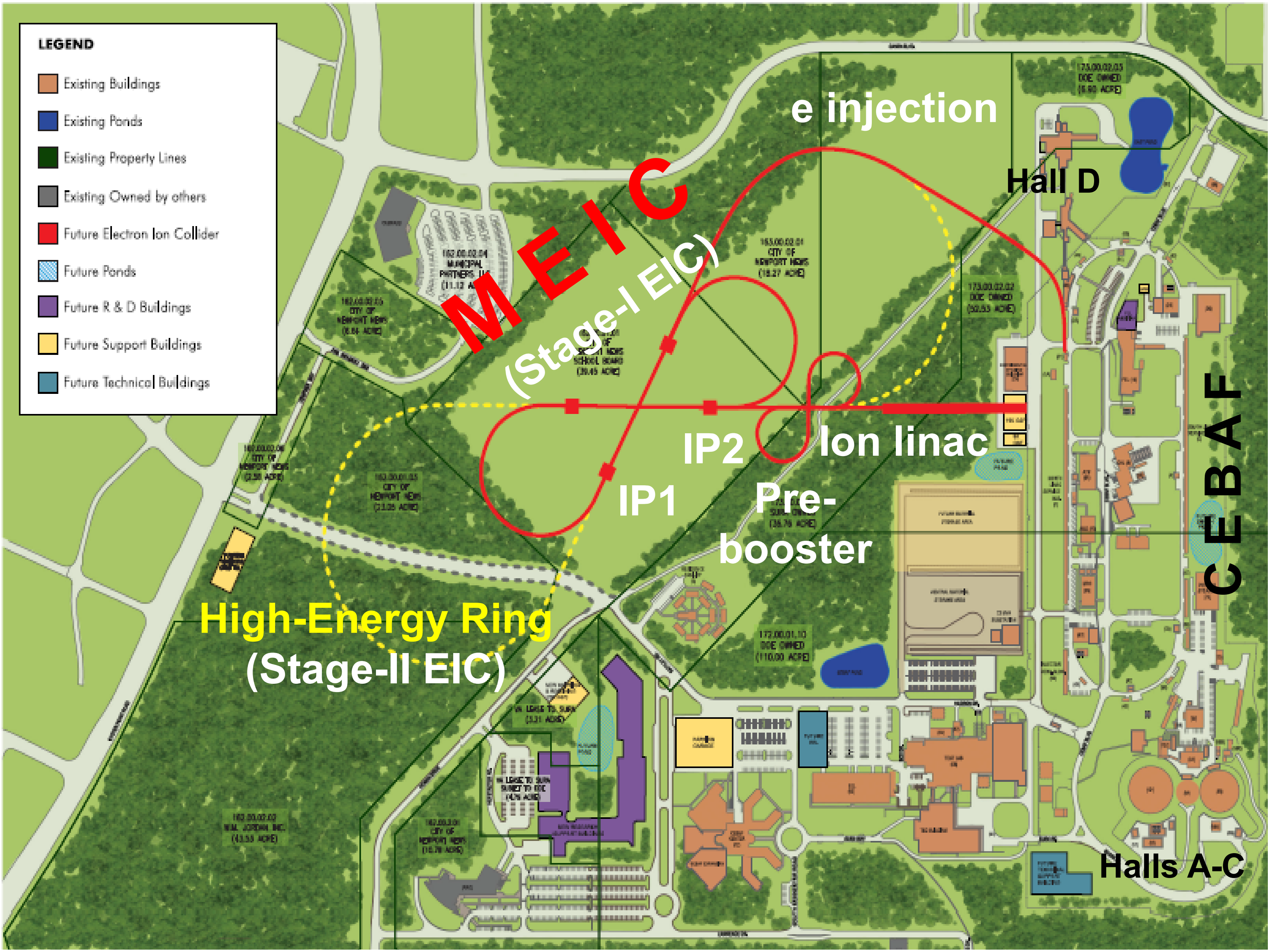
The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan.



Scope of the project includes:
- Doubling the accelerator beam energy
- New experimental Hall and beamline
- Upgrades to existing Experimental Halls

New C100 cryomodules in linac tunnel

The EIC at Jefferson Lab (JLab), VA

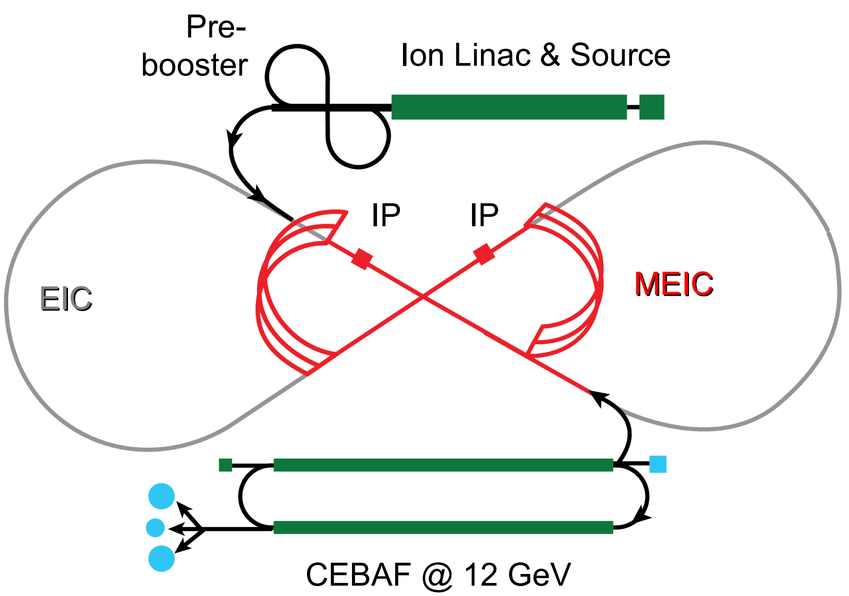


- The MEIC has a circumference similar to CEBAF (1.4 km)

MEIC – a figure-8 ring-ring collider

Baseline design

- Two high-luminosity, full-acceptance detectors
  - Simultaneous use (total beam-beam tune shift < 0.03)
- Highly polarized e, p, and light ion beams
  - Figure-8 ring provides exceptional spin control
  - Vector- and tensor polarized deuterium
- New ion complex: source, linac, boosters
  - Ions up to and above A=200 (Au, Pb)
- 12 GeV CEBAF linac used as full-energy injector
  - Possible to run in parallel with fixed-target experiments

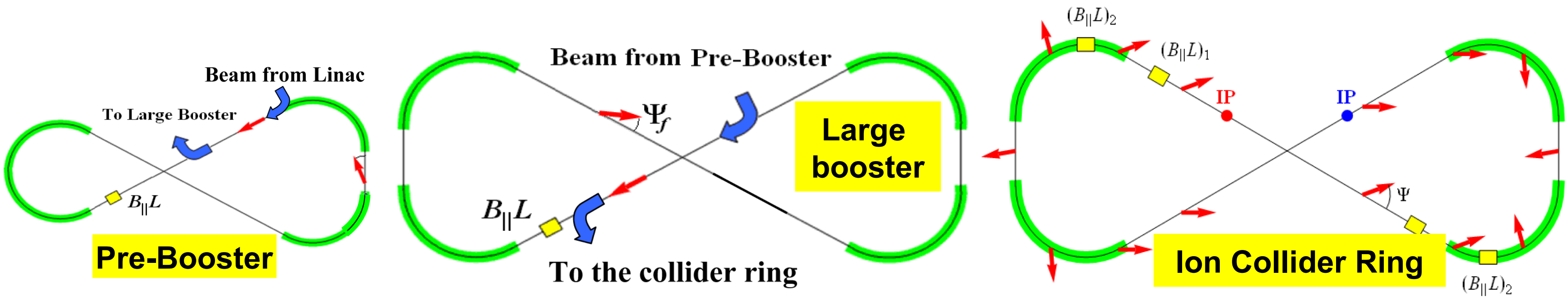


Minimized technical risk and R&D challenges

- Regular electron cooling
- Regular polarized electron source
- No multi-pass ERL needed
- No space-charge compensation assumed

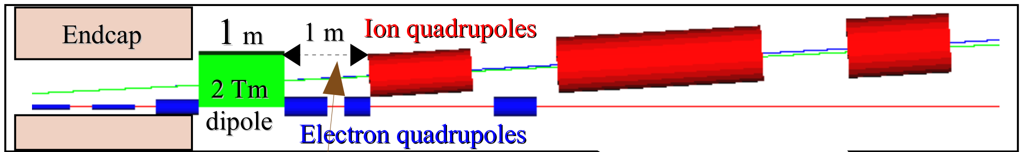
MEIC – ion polarization in figure-8 ring

- Science program demands highly polarized (>70%) light ion beams (p, D, ^{3}He, Li, ...)
- Figure-8 shape used for all ion booster and collider rings
  - Spin precession in one arc is canceled by the other arc
  - No preferred periodic spin direction
  - Energy-independent spin tune
  - Simplified polarization control and preservation for all ion species
  - Needs only small magnetic fields (instead of Siberian Snakes) to control polarization at Ips
  - The electron ring has a figure-8 shape because it shares a tunnel with the ion ring
- Figure-8 ring is the only practical way to accelerate ***polarized deuterons***

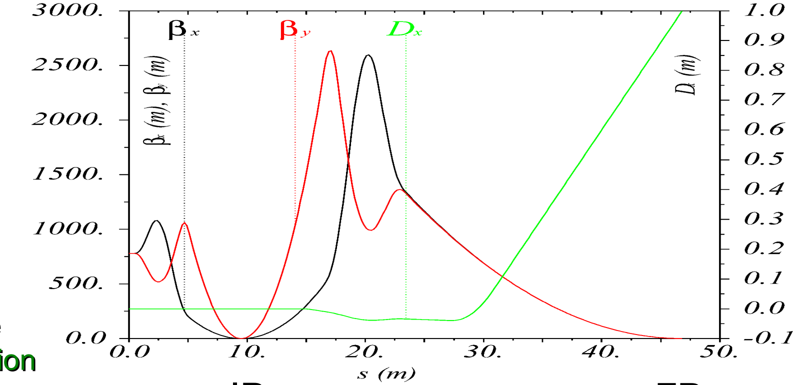


The JLab full-acceptance detector concept

No other magnets or apertures between IP and FP!

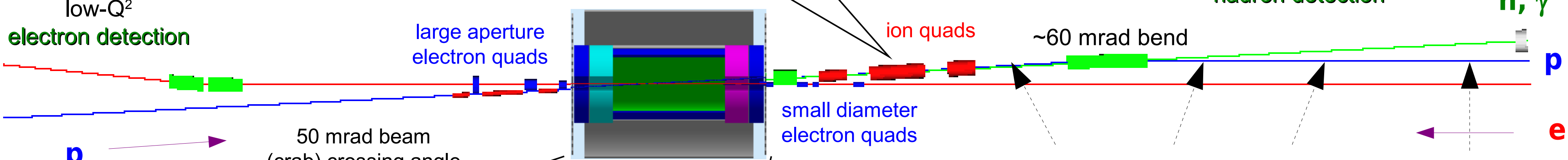


Trackers and “donut” calorimeter

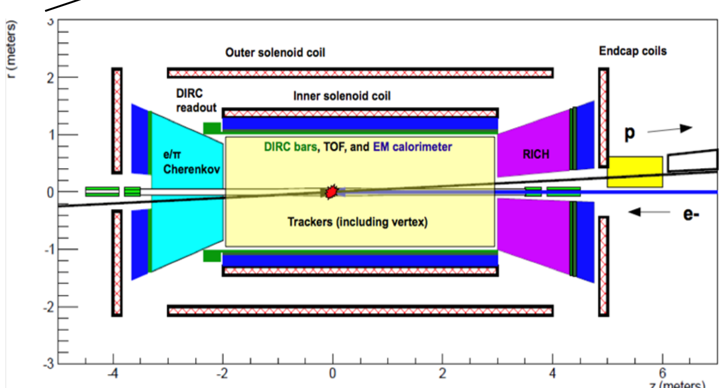


small angle
hadron detection

(from GEANT4)



central detector
with endcaps

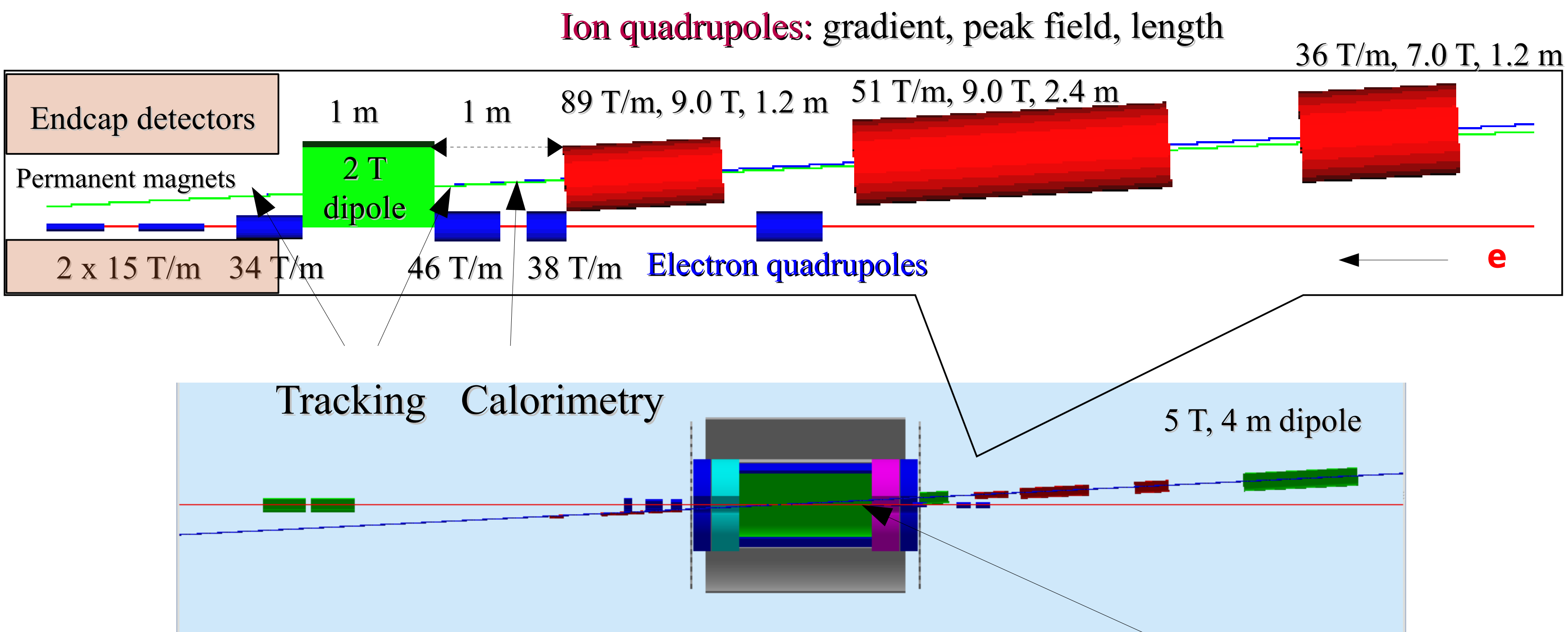


Cartoon based on previous iteration IR design

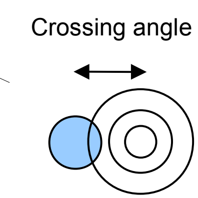
Forward hadron detection in three stages:

1. **Encap with 50 mrad crossing angle**
2. **Small dipole covering angles up to a few degrees**
3. **Ultra-forward, up to one degree, for particles passing the accelerator quads**

Hadron detection between endcap and ion quads



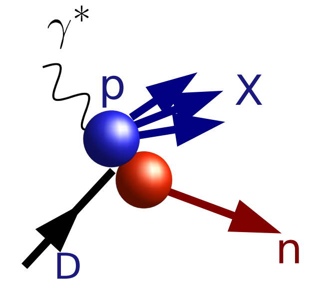
- Large crossing angle (50 mrad)
  - Moves spot of poor resolution along solenoid axis into the periphery
  - Minimizes shadow from electron FFQs



- Dipole before quadrupoles further improves resolution in the few-degree range
- Low-gradient quadrupoles allow large apertures for detection of *all* ion fragments
  - Peak field = quad gradient x aperture radius

Ultra-forward hadron detection – requirements

1. Good acceptance for ion fragments (rigidity different from beam)



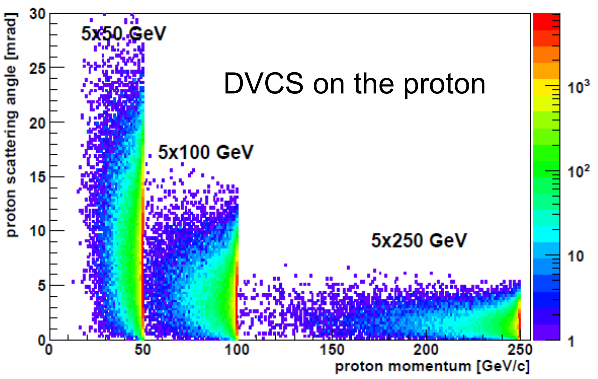
- Large downstream magnet apertures
- Small downstream magnet gradients (realistic peak fields)
- Roman pots not needed

2. Good acceptance for recoil baryons (rigidity similar to beam)

- Small beam size at second focus (to get close to the beam)
- Large dispersion (to separate scattered particles from the beam)
- Roman pots important

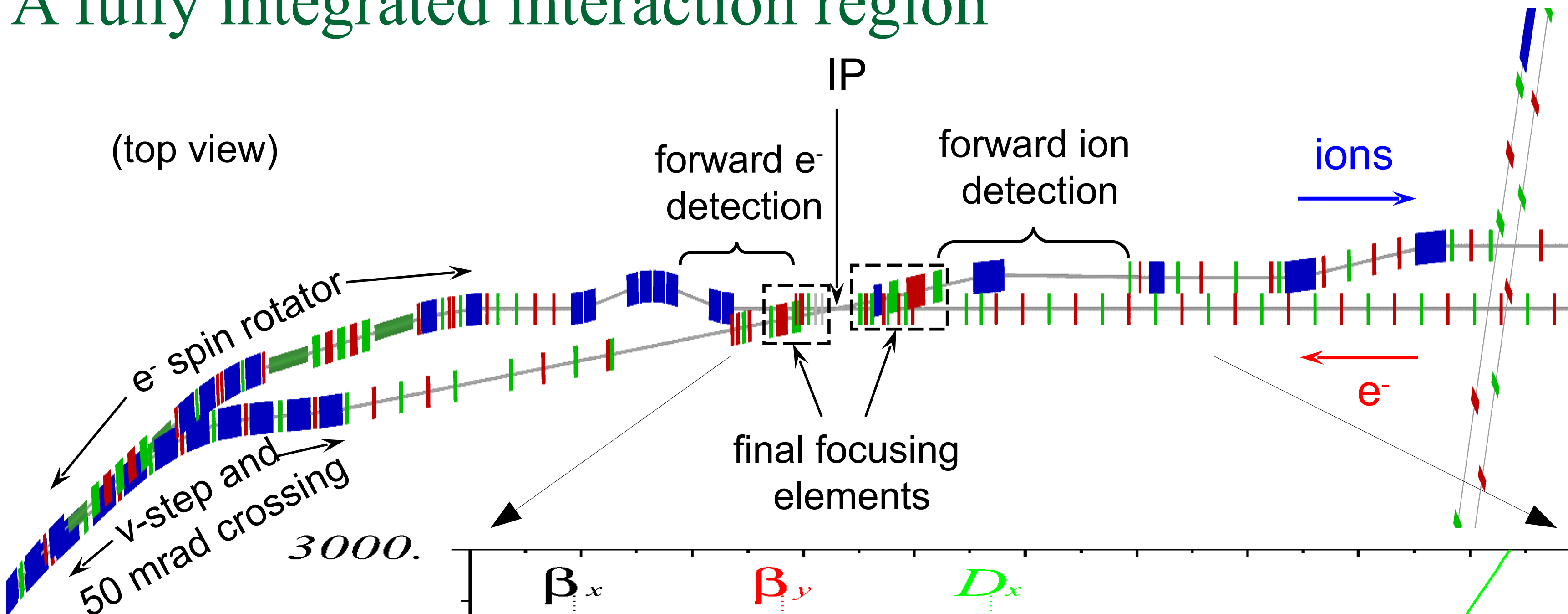
3. Good momentum- and angular resolution

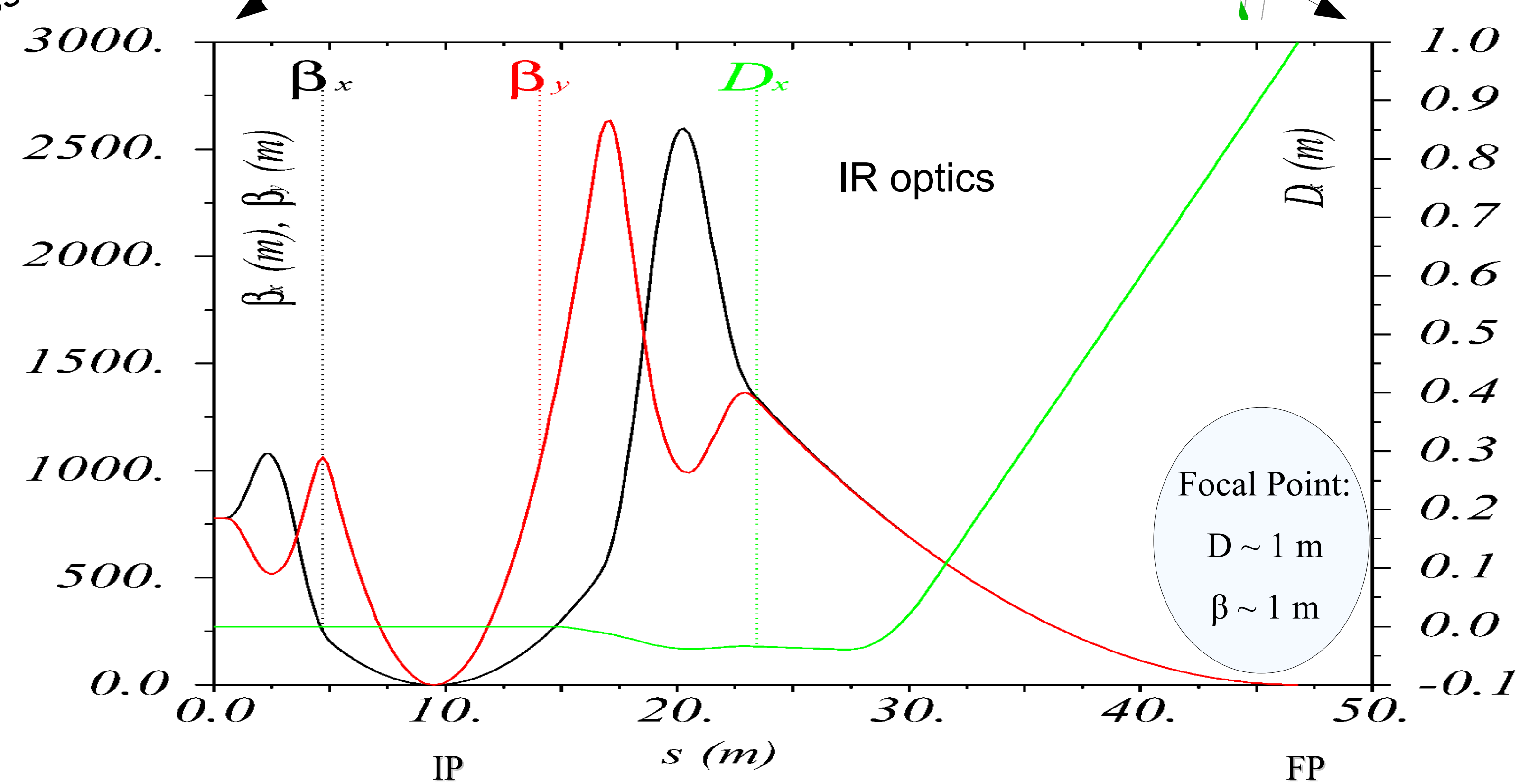
- Large dispersion (*e.g.*, 60 mrad bending dipole)
- Long, instrumented magnet-free drift space



4. Sufficient separation between beam lines (~1 m)

A fully integrated interaction region





Recoil baryon detection:

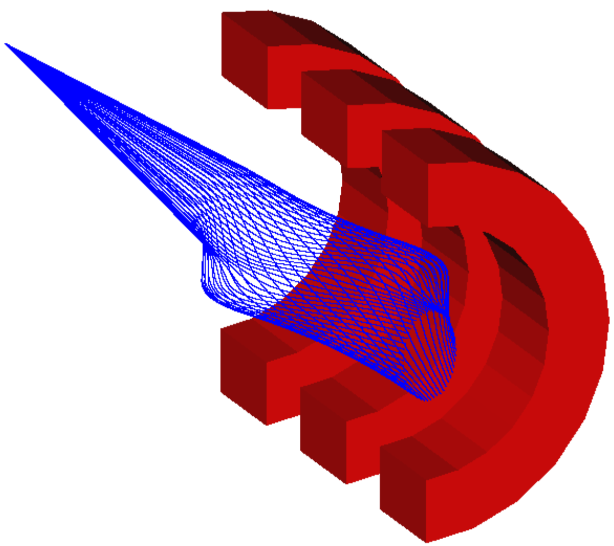
Small beam size (β) and large dispersion at the secondary focal point give superb resolution and acceptance at very small angles

Excellent t-coverage for all kinematics!

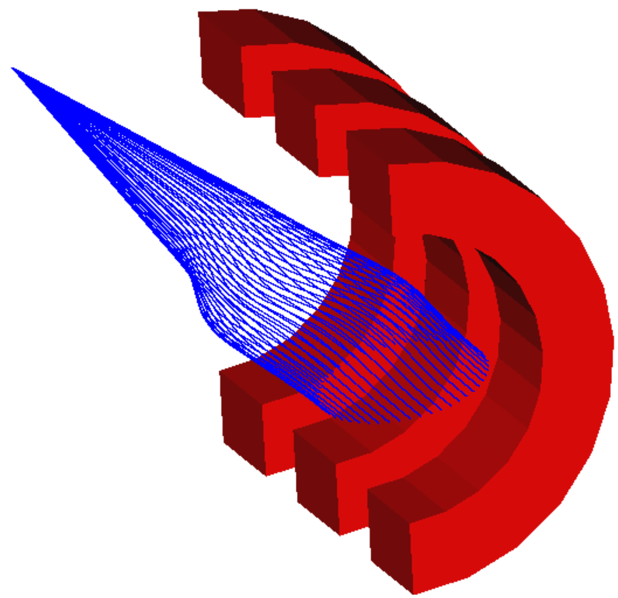
Tracking of ultra-forward charged particles

(protons rich fragments) ← → (neutron rich fragments)

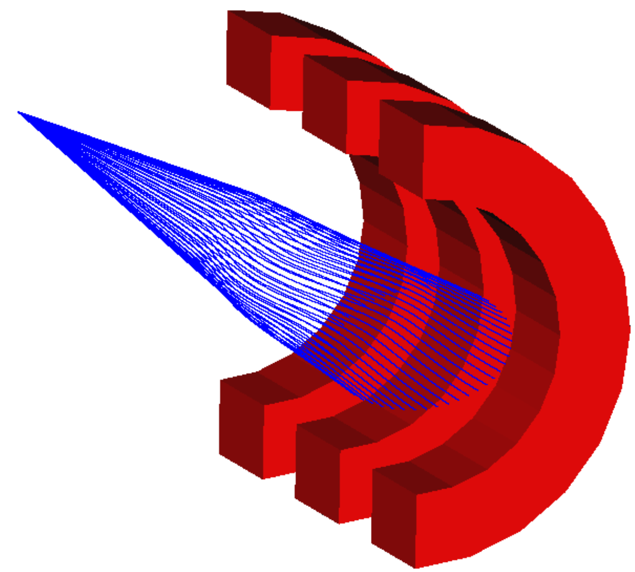
$\Delta p/p = -0.5$
(spectator protons from deuterium)



$\Delta p/p = 0.0$
(exclusive / diffractive recoil protons)

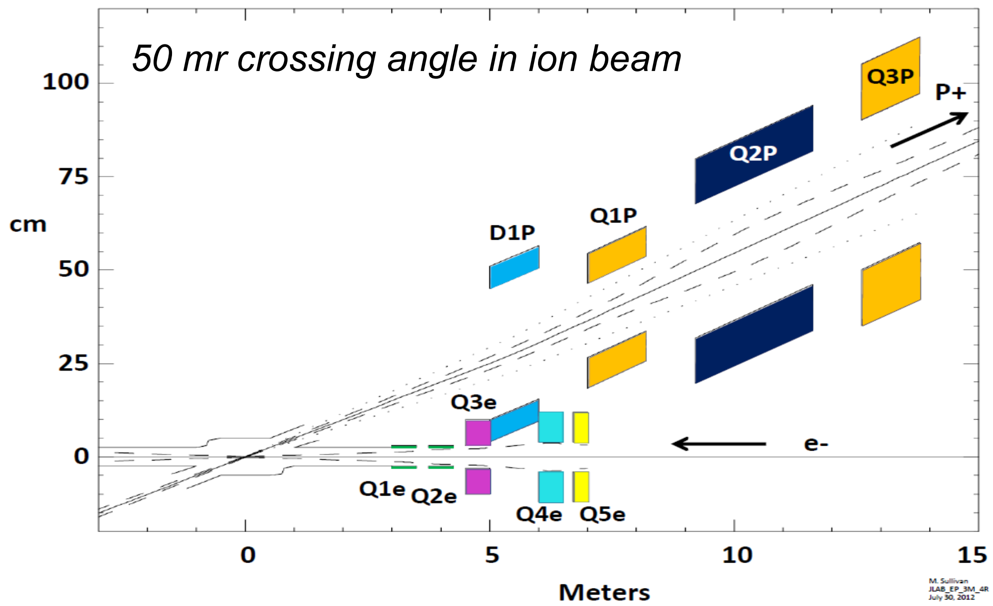


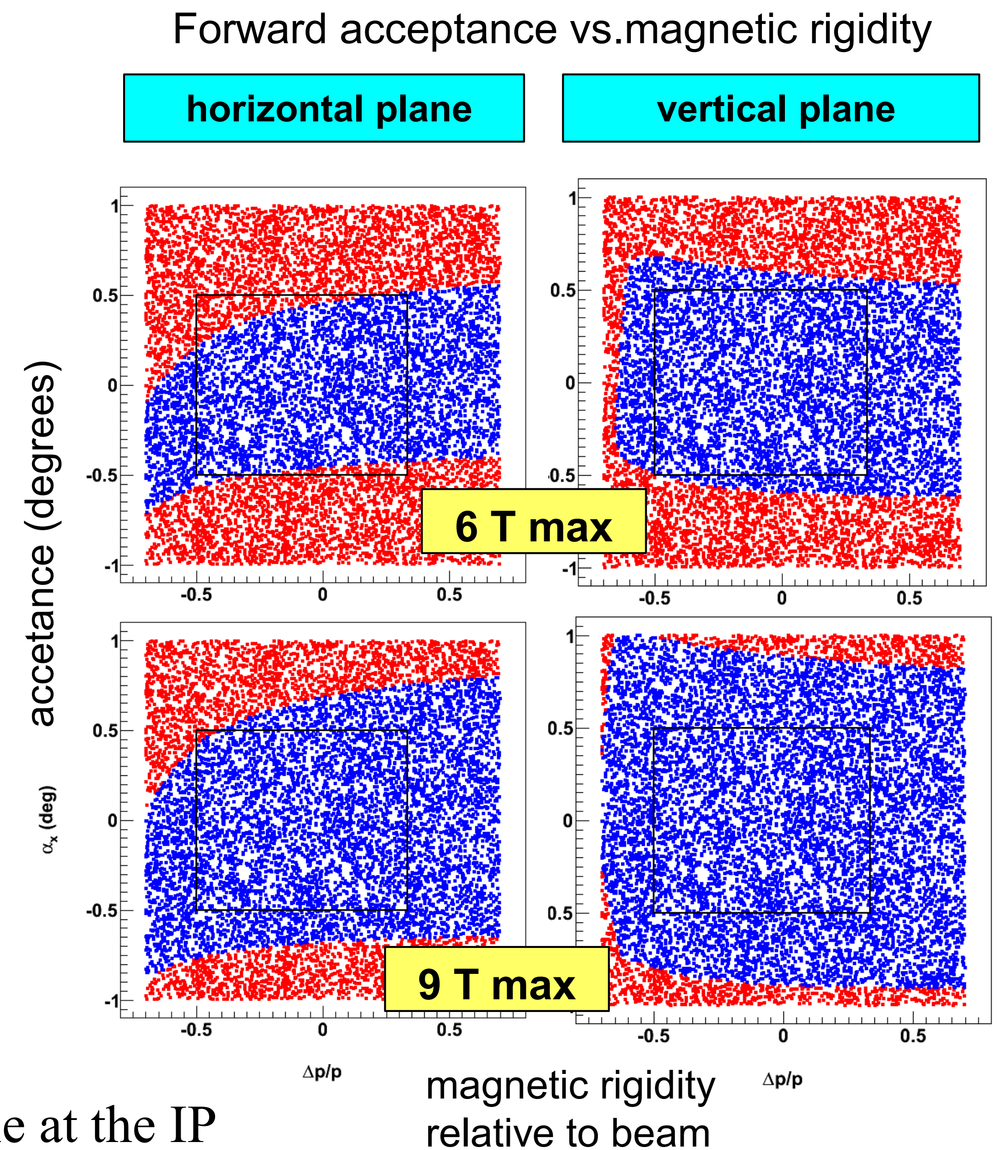
$\Delta p/p = 0.5$
(tritons from N=Z nuclei)



- Large apertures provide full acceptance for *all* nuclear fragments
  - The MEIC IR design combines excellent performance and low technical risk

Target fragment acceptance in the ion quadrupoles





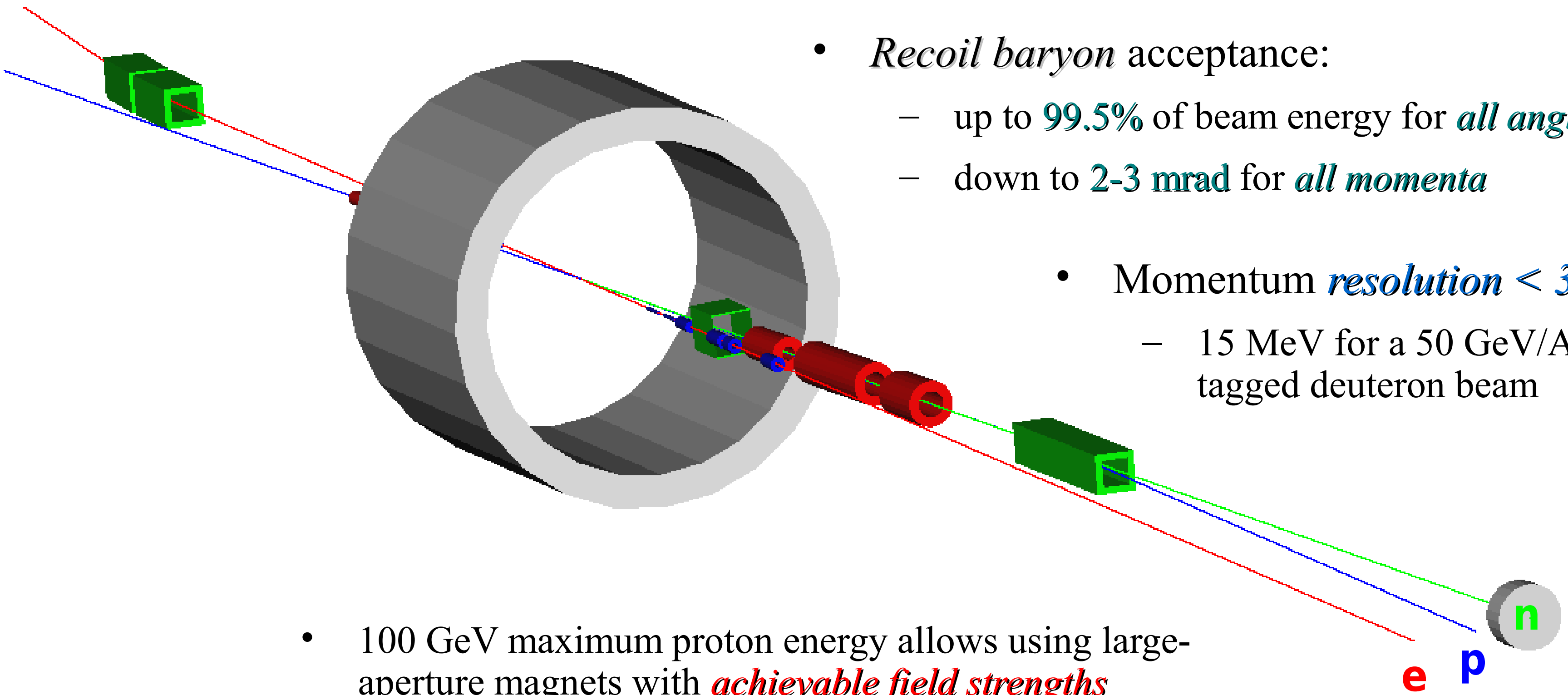
Red: Detection *before* ion quadrupoles

Blue: Detection *after* ion quadrupoles

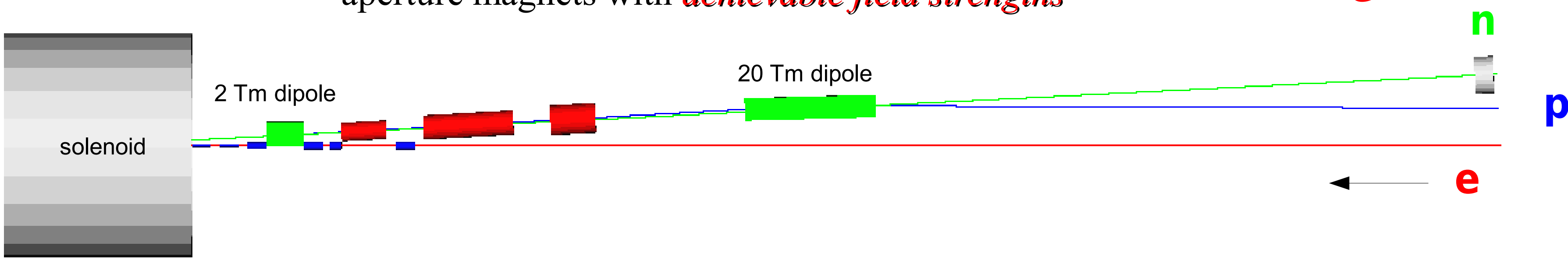
- Q3P can be weaker
  - "9 T" is actually 9, 9, and 7 Tesla
- The angle is the original scattering angle at the IP

Ultra-forward hadron detection – summary

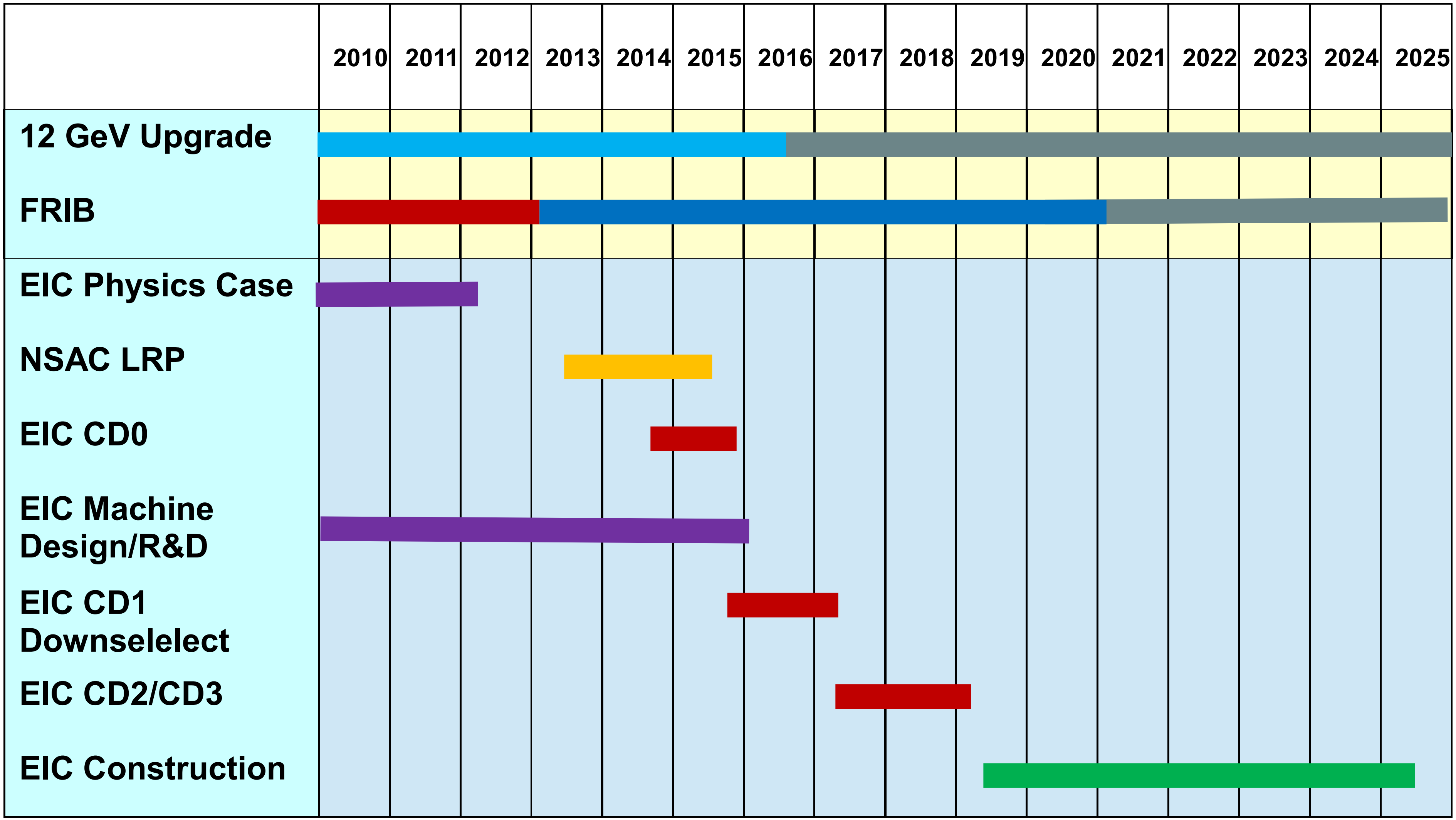
- *Neutron* detection in a 25 mrad cone ***down to zero degrees***
- Excellent acceptance for ***all ion fragments***
- *Recoil baryon* acceptance:
  - up to **99.5%** of beam energy for ***all angles***
  - down to **2-3 mrad** for ***all momenta***
- Momentum ***resolution < $3x10^{-4}$***
  - 15 MeV for a 50 GeV/A tagged deuteron beam



- 100 GeV maximum proton energy allows using large-aperture magnets with ***achievable field strengths***



EIC timeline



Assumes endorsement for an EIC at the next NSAC Long Range Plan
Assumes relevant accelerator R&D for down-select process done around 2016

Summary

The EIC is the next-generation US QCD facility

- JLab or BNL implementations possible
  - Agreement on global parameters
  - Collaboration on detector R&D

The EIC at JLab offers some unique capabilities

- Vector- and tensor polarized deuterium
- Excellent detection of recoil baryons, spectators, and target fragments
  - Full acceptance, high resolution

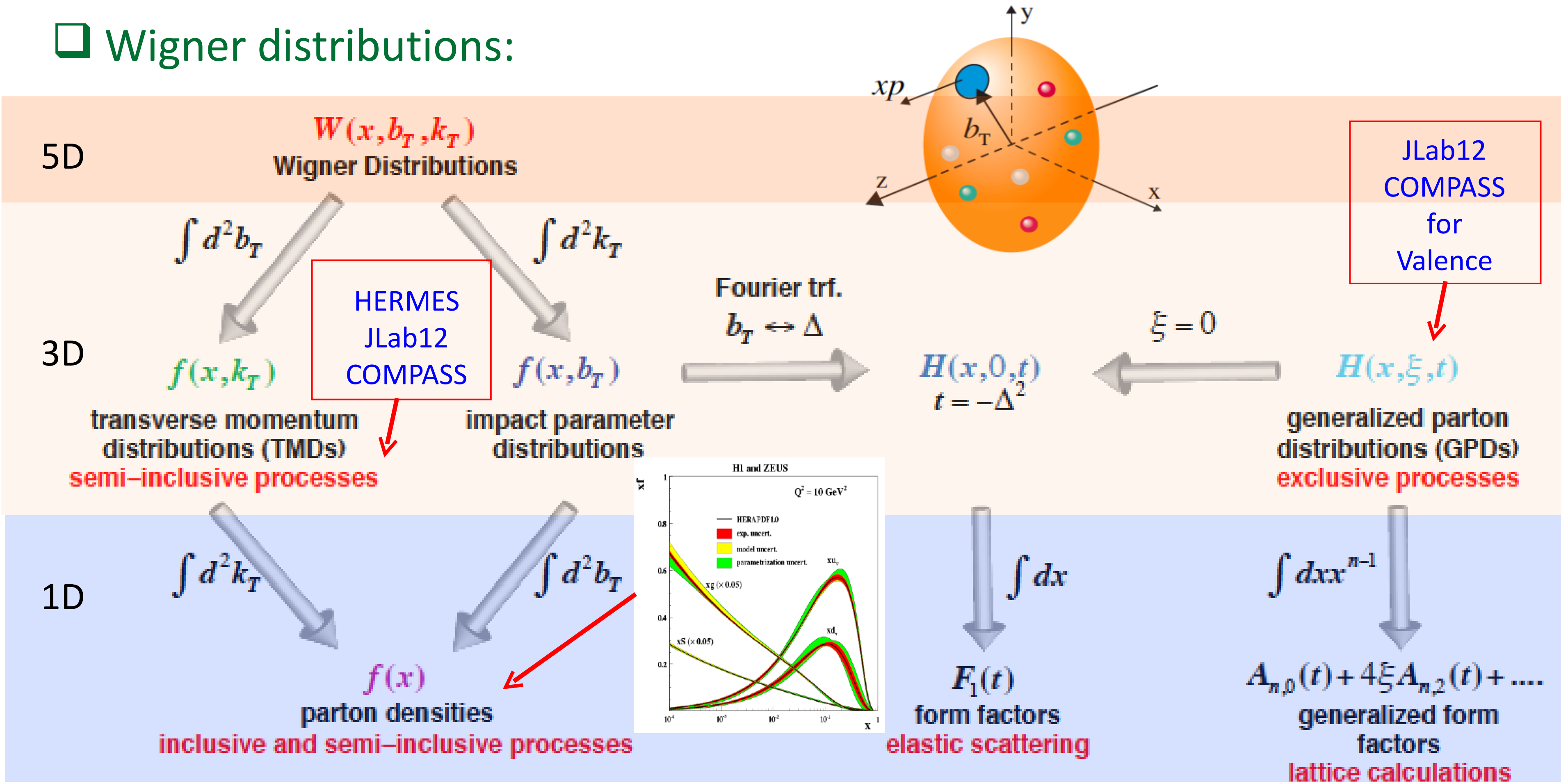
Exciting opportunities for program with polarized ions

- Combines high-momentum-transfer processes and low-energy nuclear structure
- Important input from few-body community needed!

Backup

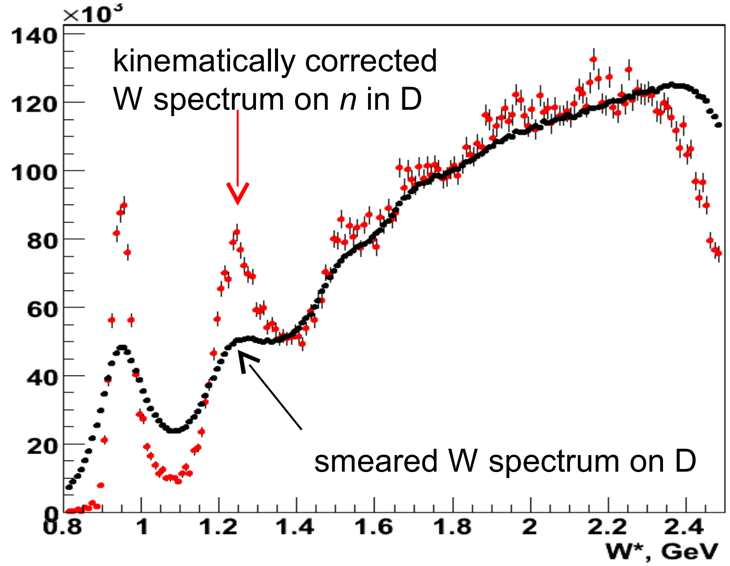
A unified picture of nucleon structure

- Wigner distributions:



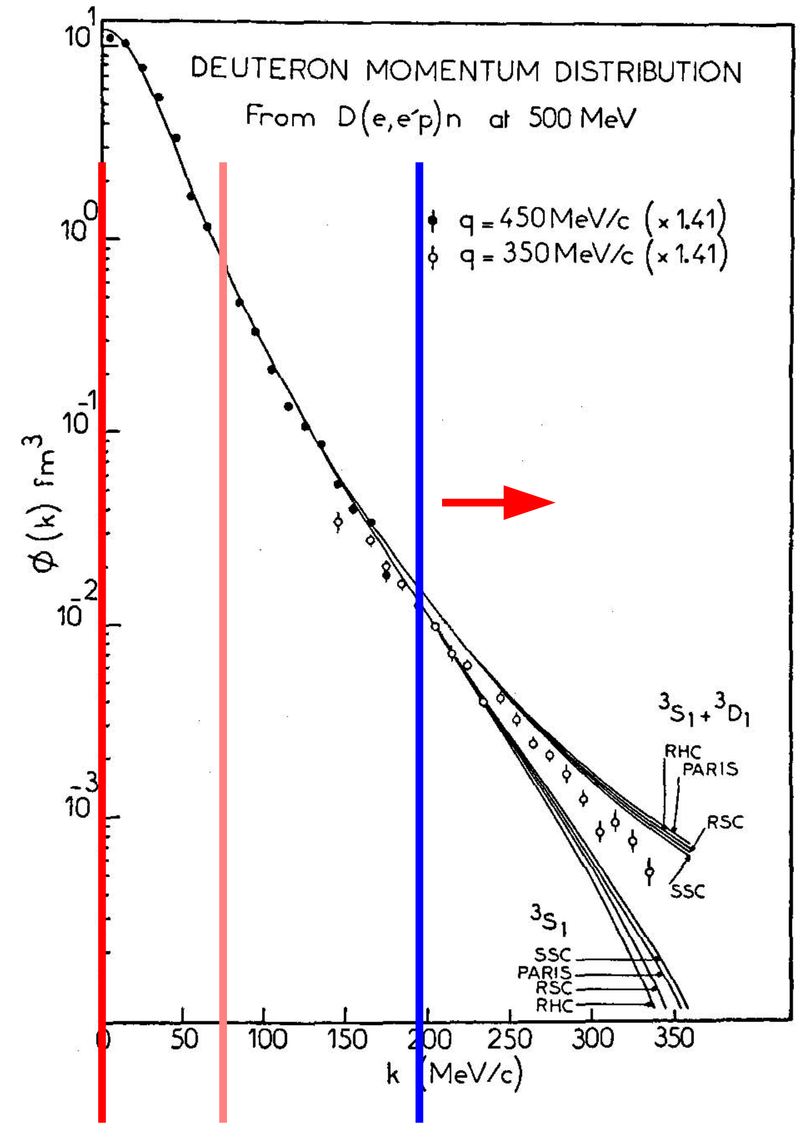
- EIC – 3D imaging of sea and gluons:
  - ✧ TMDs – confined motion in a nucleon (semi-inclusive DIS)
  - ✧ GPDs – Spatial imaging of quarks and gluons (exclusive DIS)

Neutron structure through spectator tagging

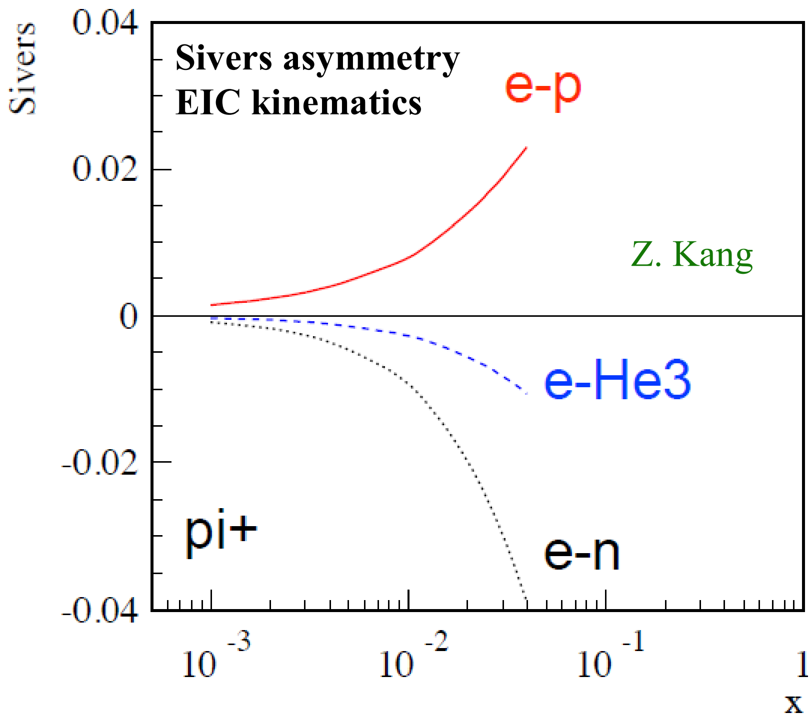


JLab CLAS BoNuS data with tagged spectators

- In fixed-target experiments, scattering on *bound neutrons* is complicated
  - Fermi motion, nuclear effects
  - Low-momentum spectators
  - No polarization
- The MEIC is designed from the outset to tag spectators, and all nuclear fragments.

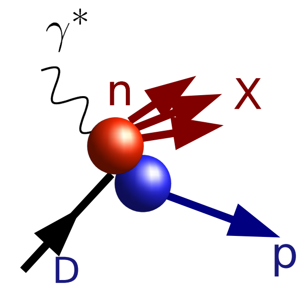


Spectator tagging with polarized deuterium



„If one could tag neutron, it typically leads to larger asymmetries“

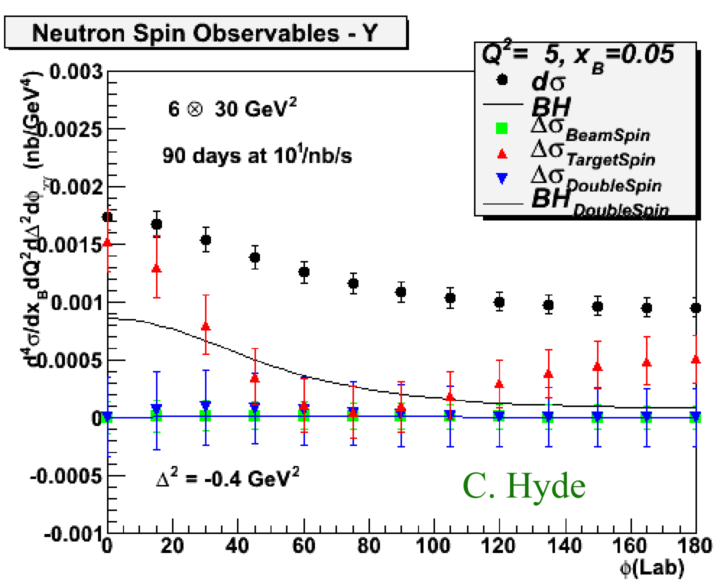
Z. Kang



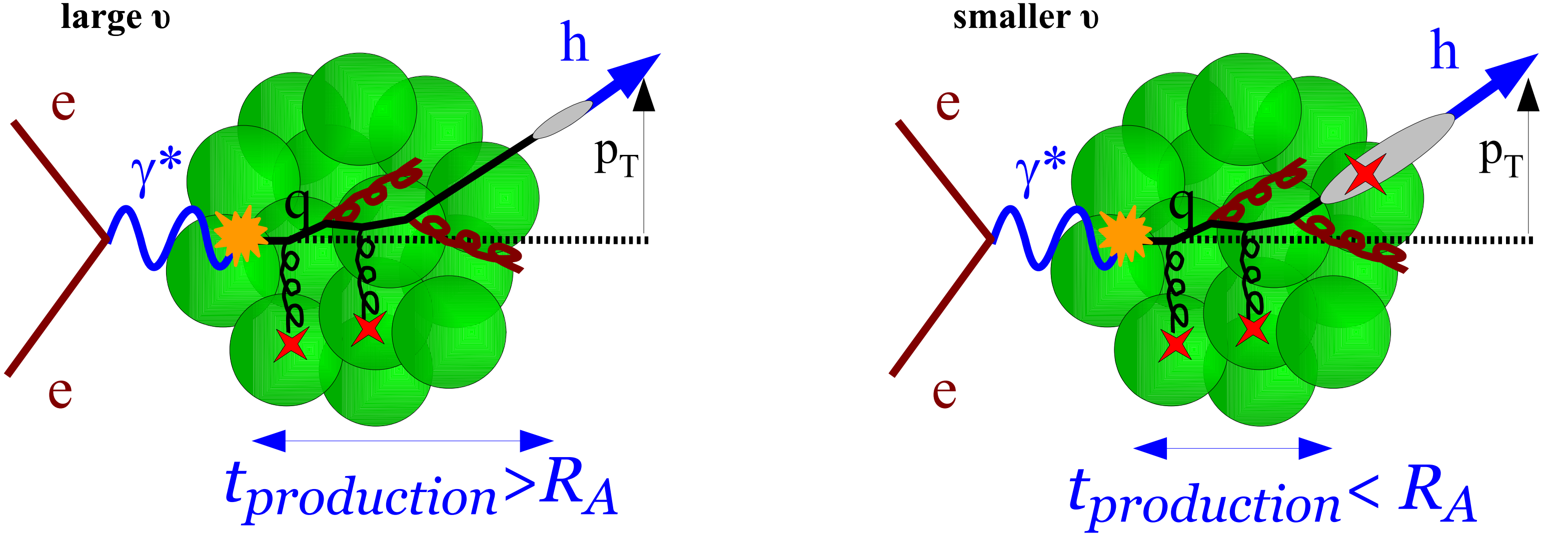
- Polarized neutrons are important for probing d-quarks through **SIDIS**

- Deeply Virtual Compton Scattering (DVCS) on a neutron target

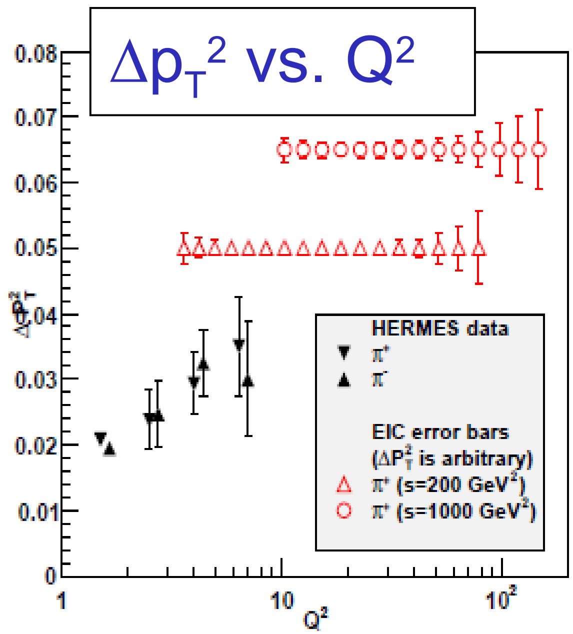
- Tagged, polarized *neutrons* are essential for the GPD program



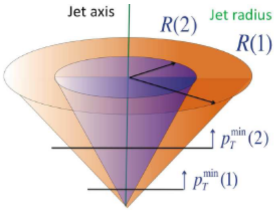
Quark propagation in matter (hadronization)



Accardi, Dupre

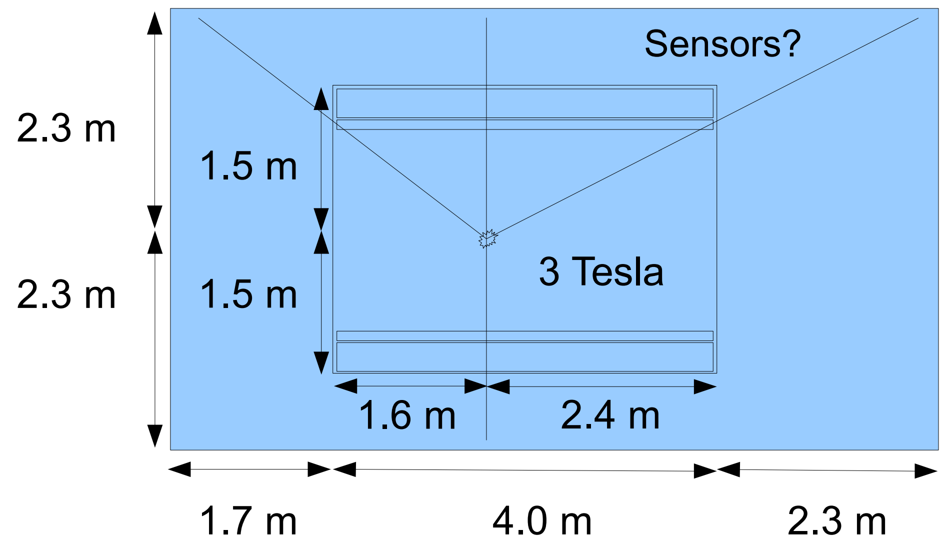


- Broadening of p_T distribution
- Heavy flavors: B, D mesons, J/Ψ …
- Hadron jets at s > 1000 GeV^2
- ***What happens to the nucleus?***
  - *Fragments hold the key to what happened „along the way“*



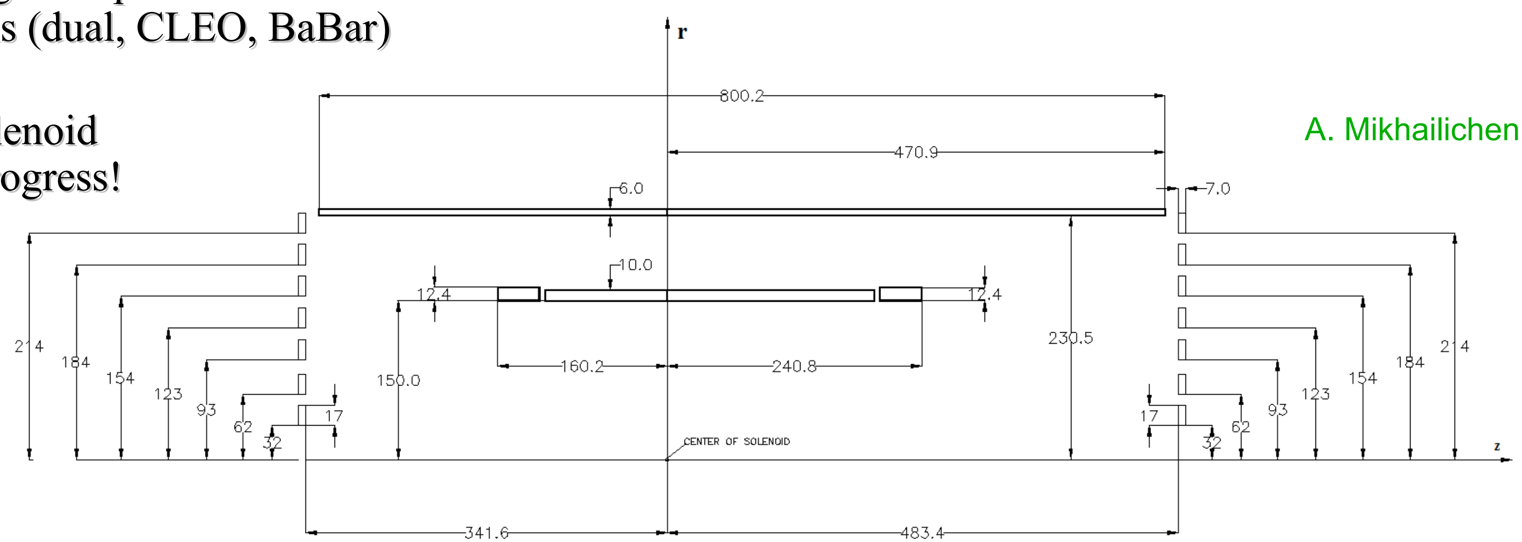
Dual-solenoid-based "ultimate SIDIS" detector

- Inspired by the „4th“ detector concept for the ILC
- Novel asymmetric layout for the MEIC
- Iron-free flux return allows more coverage for endcap detectors providing superior performance
- Easy access to endcap detectors through coil wall and gap between coils and outer solenoid
- Space for sensors outside of the "line-of-sight"
- Dimensions of inner solenoid follow the new unified MEIC magnet and IR geometry
  - Central detector can be designed as a package compatible with all solenoid options (dual, CLEO, BaBar)

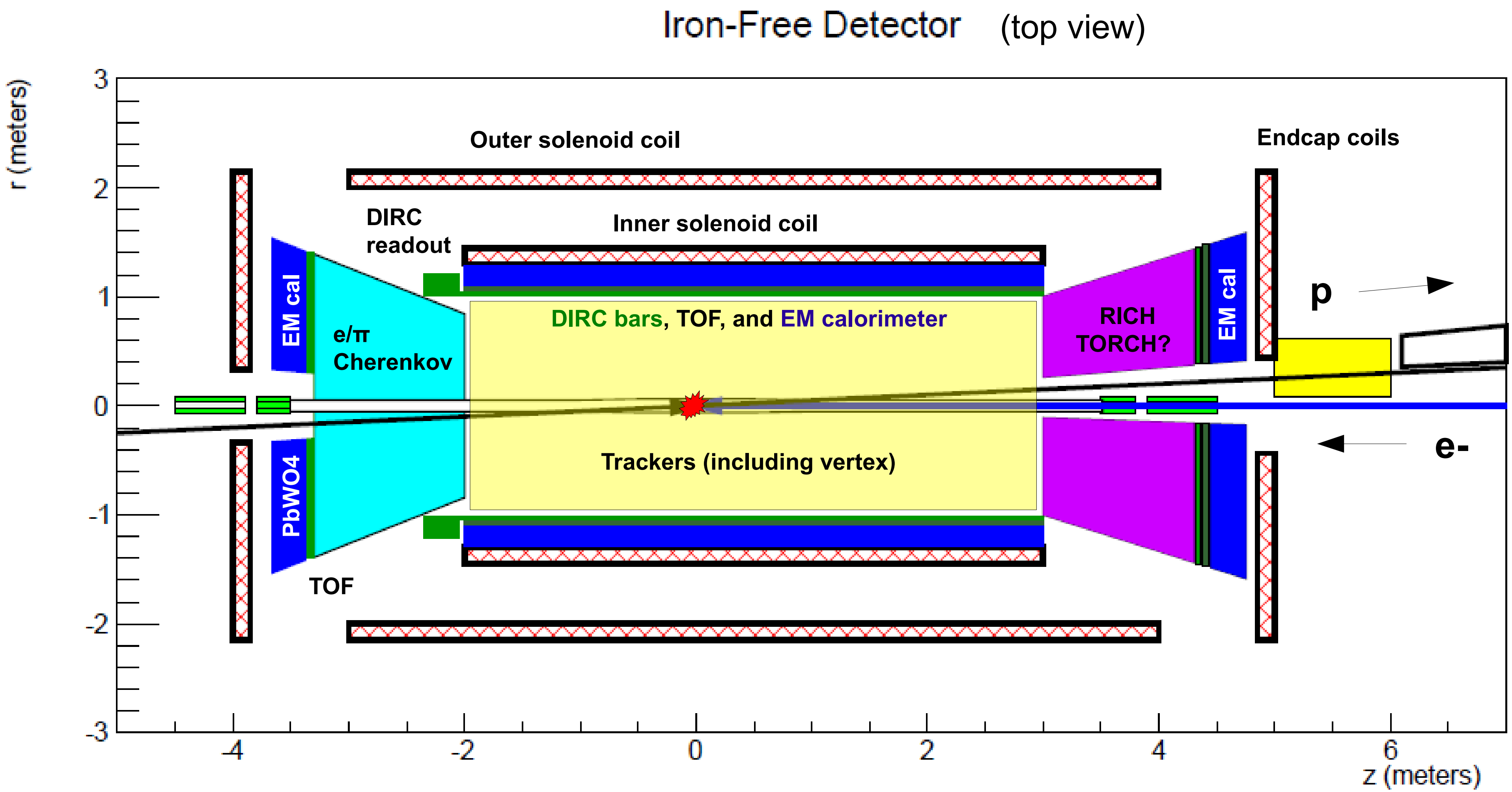


- Detailed solenoid design in progress!

A. Mikhailichenko



MEIC – (old) central detector cartoon



- MEIC detector is currently being implemented in GEANT4
- Baseline configuration will incorporate as many technologies as possible from the Generic Detector R&D for an EIC program *(coordinated by Tom Ludlam. BNL)*
  – Already more than $1 million per year available