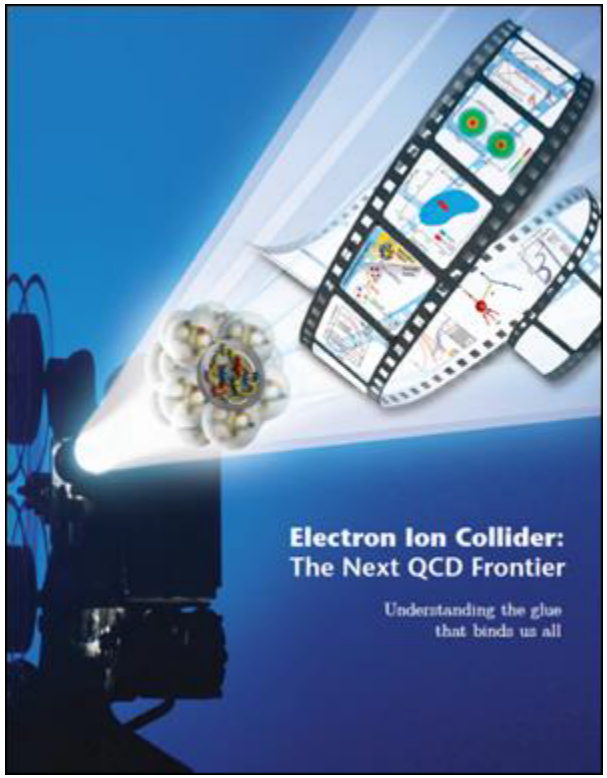
What is possible at the (M)EIC?



Pawel Nadel-Turonski

Jefferson Lab

Exploring Hadron Structure with Tagged Structure Functions
Jefferson Lab, Newport News, VA, January 16–18, 2014

Outline

The Electron-Ion Collider

Some physics highlights

Accelerator and detectors

Requirements for a generic EIC

The EIC project is pursued by BNL and JLab

From base EIC requirements in the INT report

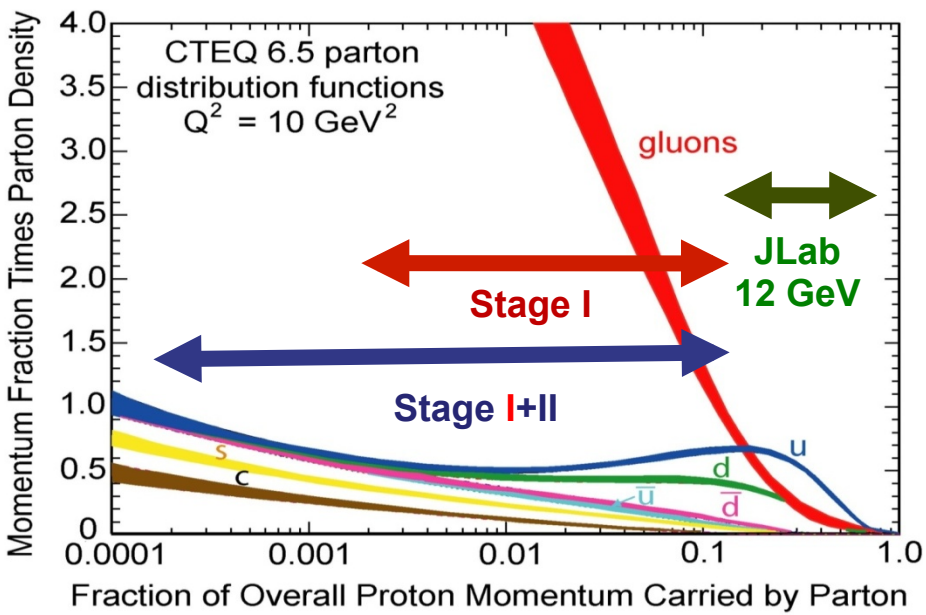
- Polarized electron, nucleon, and light ion beams
  - Electron and nucleon polarization > 70%
  - Transverse polarization at least for nucleons
- Ions from hydrogen to A > 200
- Luminosity reaching 10^{34} $cm^{-2}s^{-1}$
- Stage I energy: $\sqrt{s}$ = 20 – 70 GeV (variable) (MEIC)
- Stage II energy: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

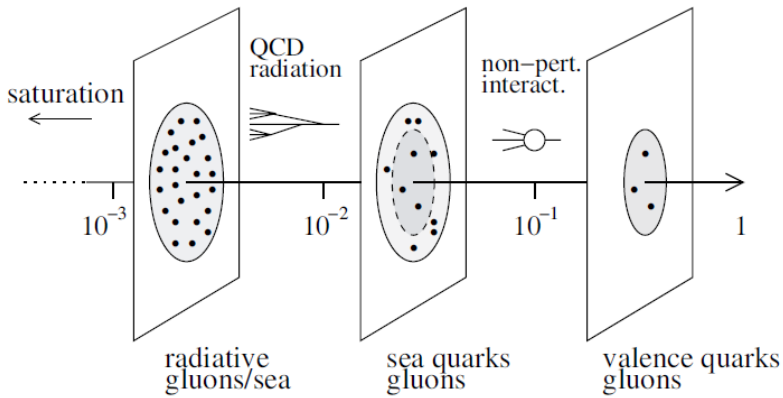
EIC staging

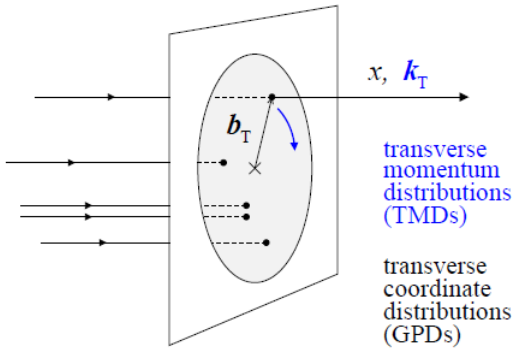
Already the first stage of an EIC gives access to sea quarks and gluons

Need polarization and good acceptance to detect spectators & fragments

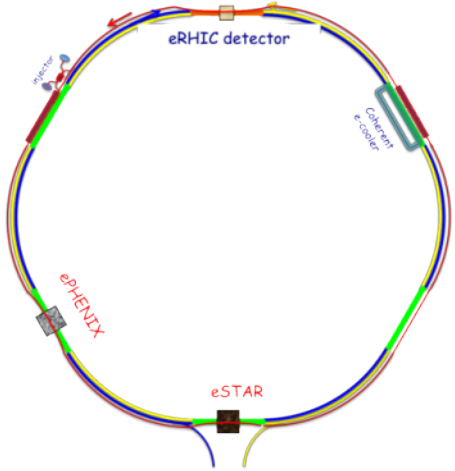
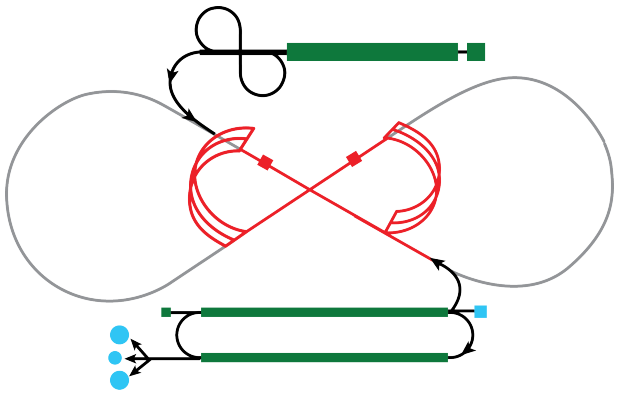
An EIC aims to study the sea quark and gluon-dominated matter.



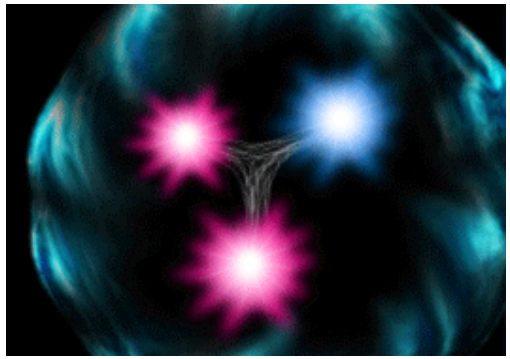




EIC staging at BNL and JLab

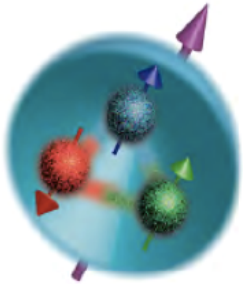
	Stage I	Stage II
eRHIC @ BNL 	$\sqrt{s}$ = 34 – 71 GeV E_e = *3 – 5 GeV (?)* E_p = 100 – 255 GeV E_{Pb} = up to 100 GeV/A	$\sqrt{s}$ = up to ~180 GeV E_e = *up to ~30 GeV (?)* E_p = up to 275 GeV E_{Pb} = up to 110 GeV/A
MEIC / EIC @ JLab 	$\sqrt{s}$ = 13 – 70 GeV E_e = 3 – 12 GeV E_p = 15 – 100 GeV 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)

Physics highlights from the EIC program



- 3D structure of nucleons and nuclei is not trivial

  How do gluons and quarks bind into 3D hadrons?



- Gluon dynamics plays a large role in proton spin

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

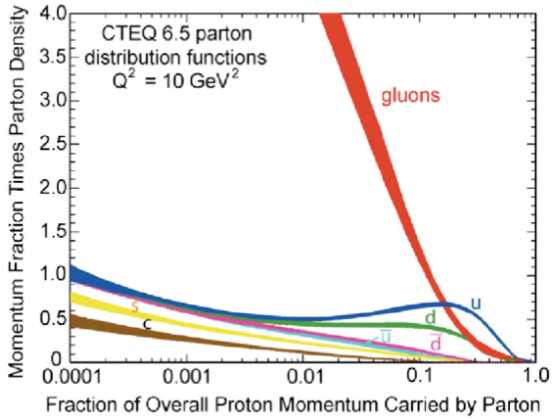
- Gluons in nuclei *(light and heavy)*

  EIC stage I measurement

  Does the gluon density saturate at small x?

  EIC stage II measurement?

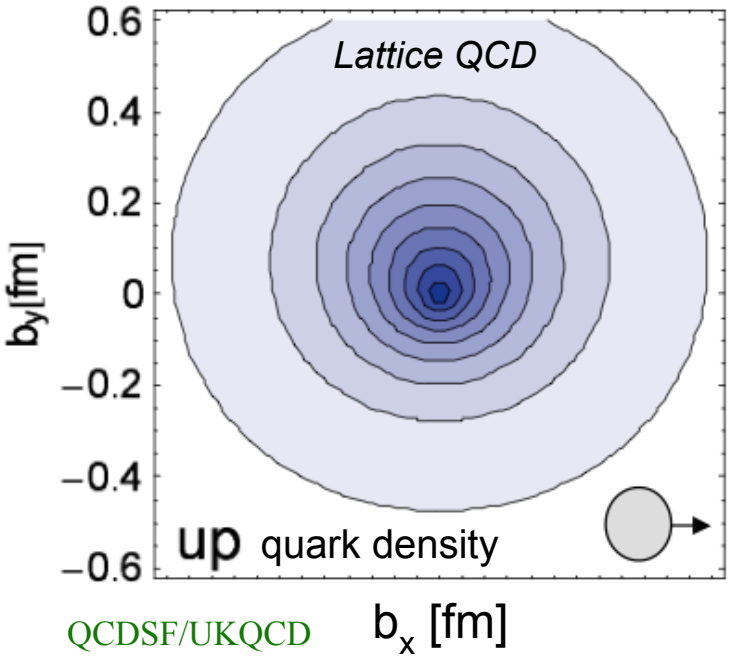
  Saturation-scale dependence on centrality of collision (from fragnent detection)?



Imaging in coordinate and momentum space

GPDs

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

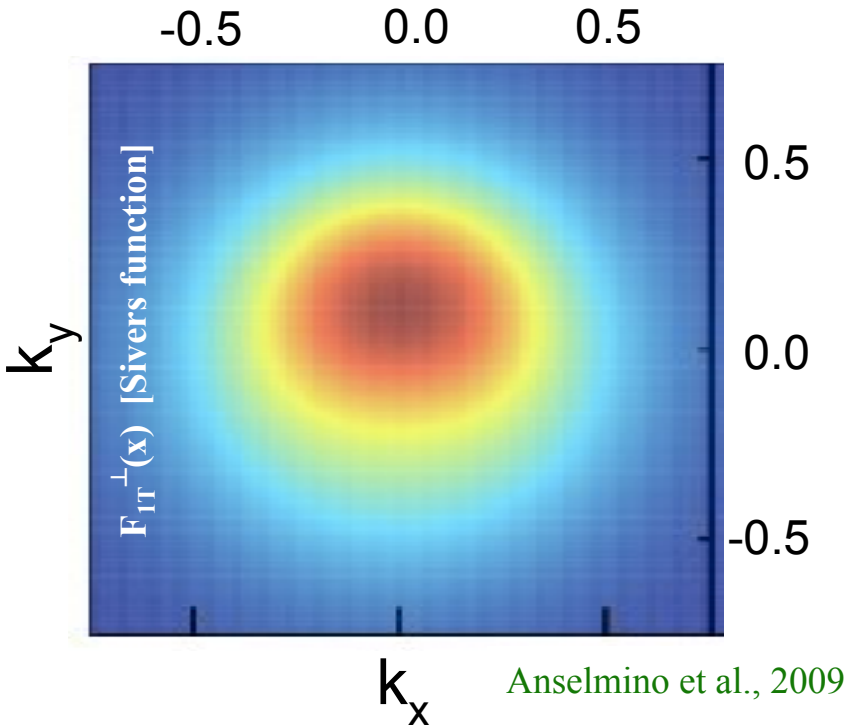


QCDSF/UKQCD Coll., 2006

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

TMDs

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



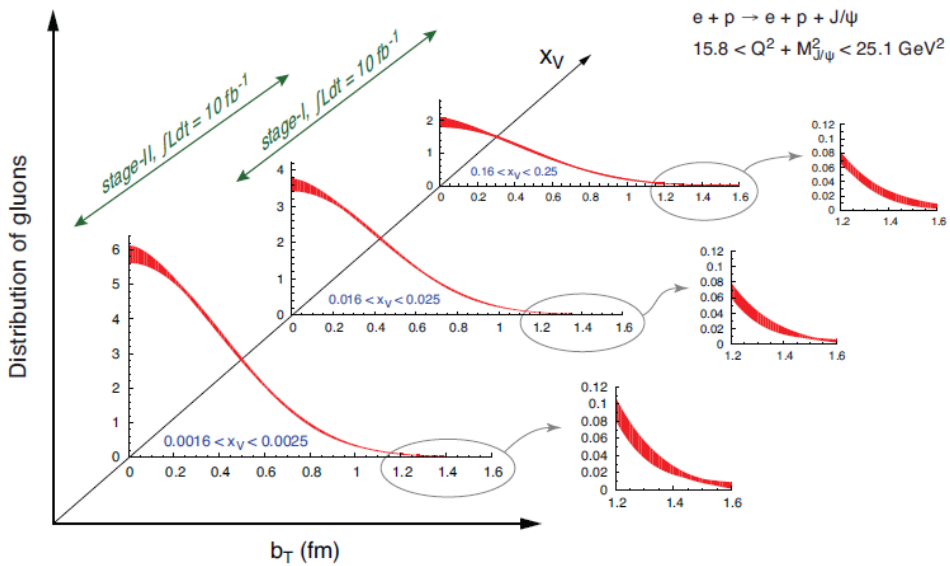
Anselmino et al., 2009

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

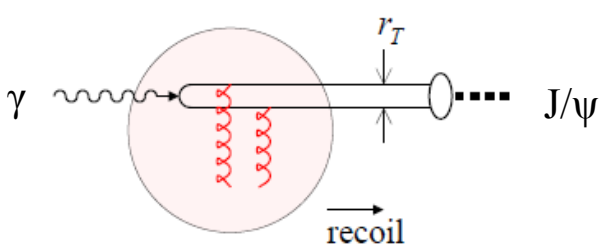
Imaging in coordinate and momentum space

GPDs

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

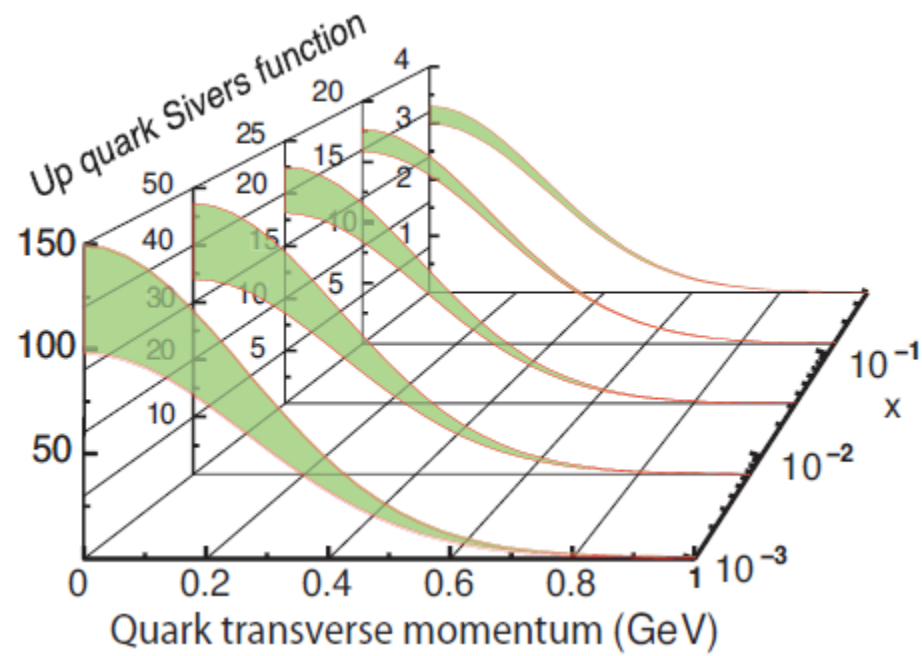


Transverse gluon distribution from J/ψ production



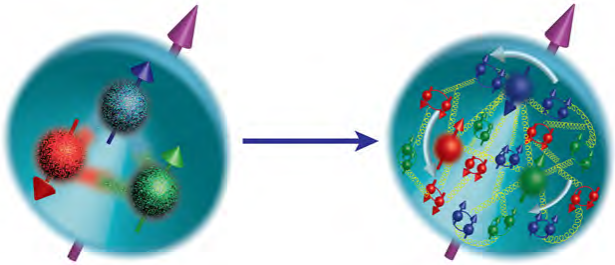
TMDs

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



Projections from EIC white paper

The spin of the proton



The number ½ reflects both intrinsic parton properties and their interactions

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

polarization orbit polarization orbit

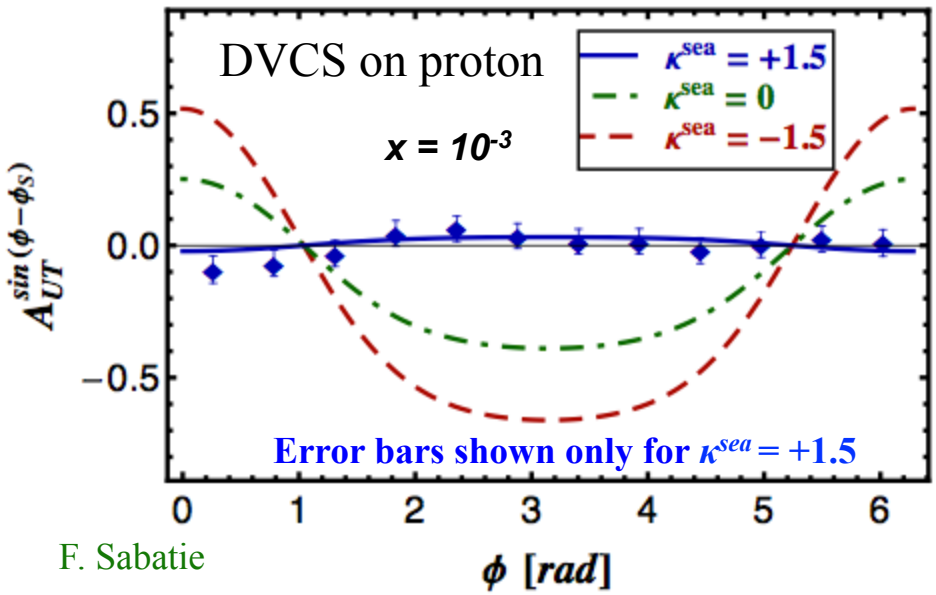
Two complementary approaches to resolve proton spin puzzle

Measure ΔG - gluon polarization

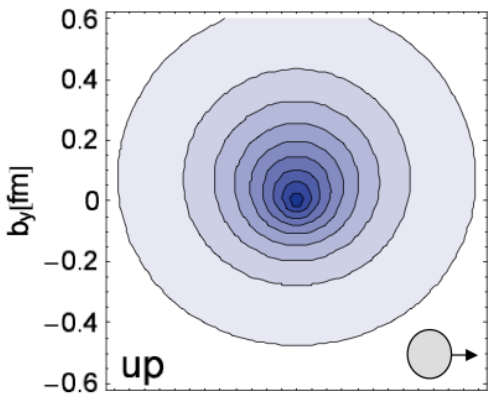
Measure TMD and GPDs - orbital motion

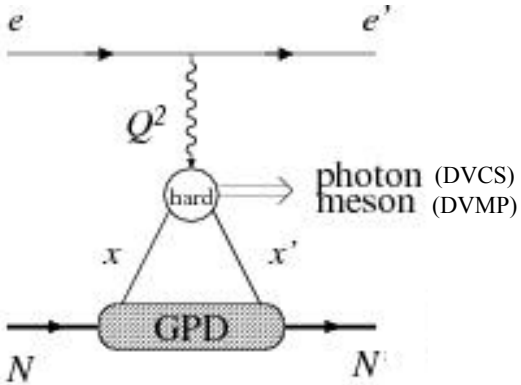
GPDs and angular momentum

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



F. Sabatie

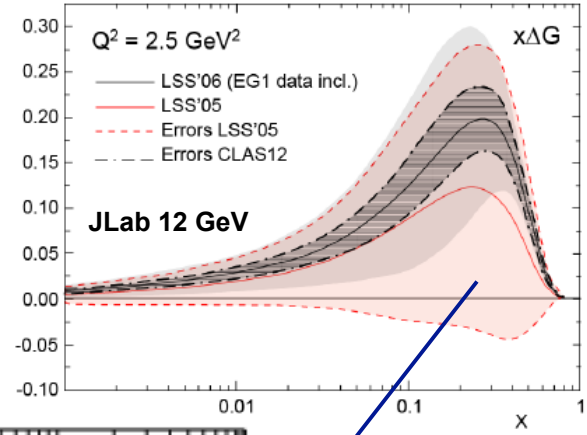


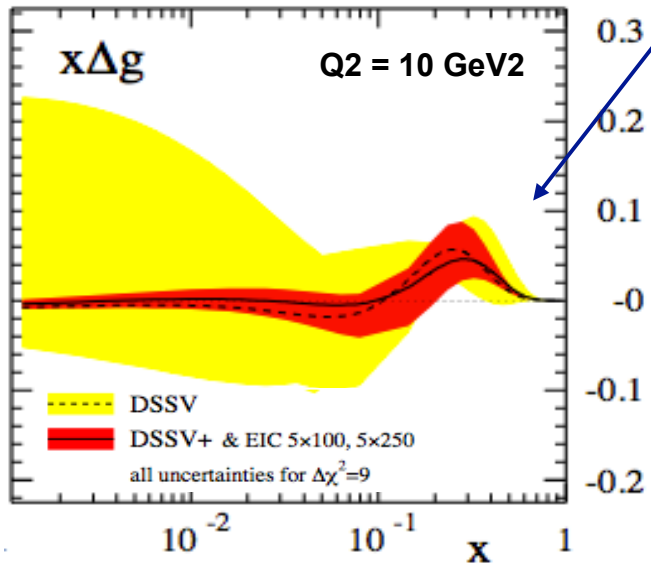


- DVCS on a *transversely* polarized target is sensitive to the *GPD E*
  - *GPD H* can be measured through the beam spin asymmetry
  - Opportunity to study spin-orbit correlations (Ji sum rule)

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

Longitudinal spin – ΔG (gluon polarization)



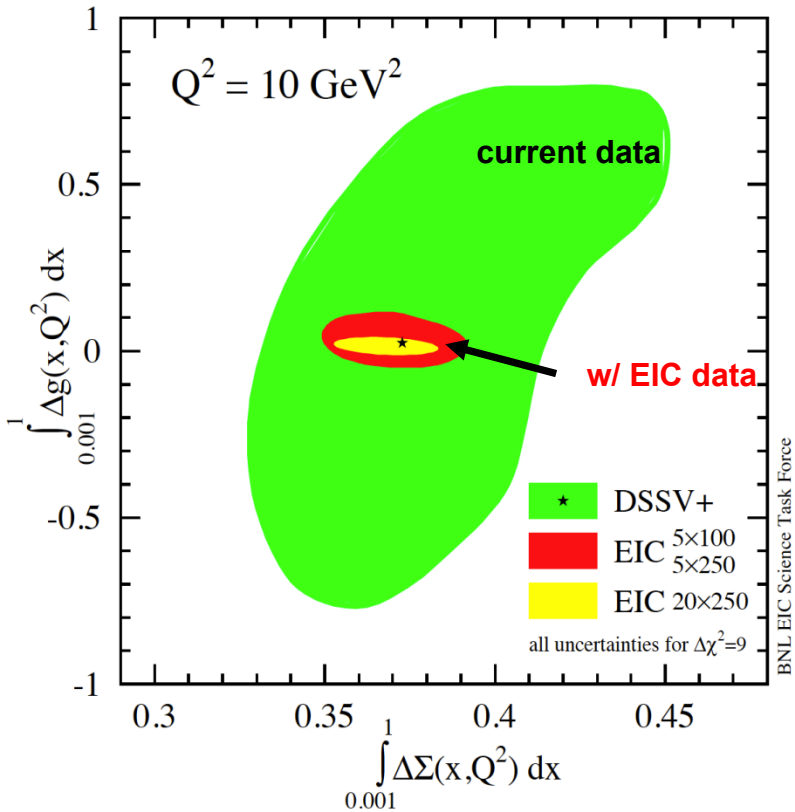


M. Stratmann

Green: RHIC spin, COMPASS, etc

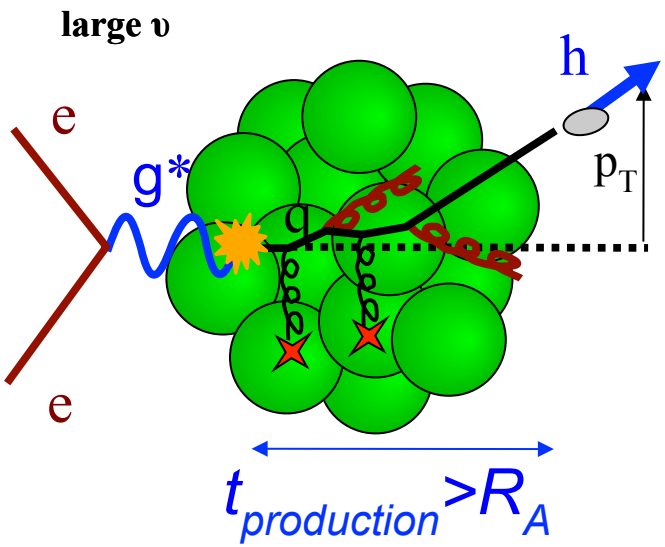
Red: EIC Stage I (MEIC or eRHIC)

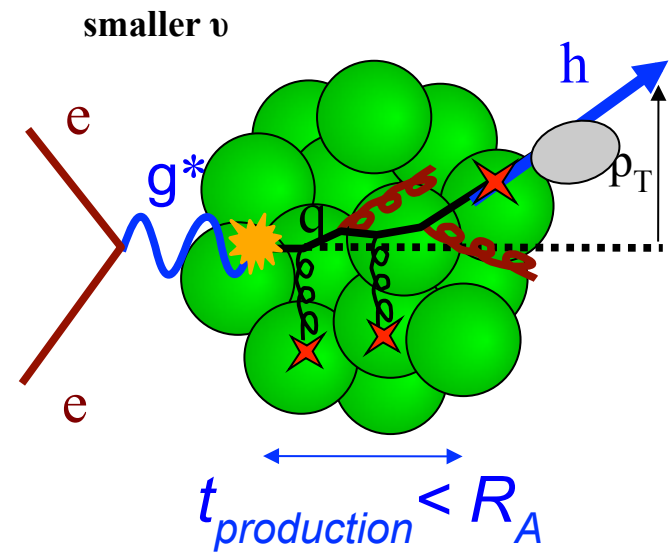
Yellow: EIC Stage II



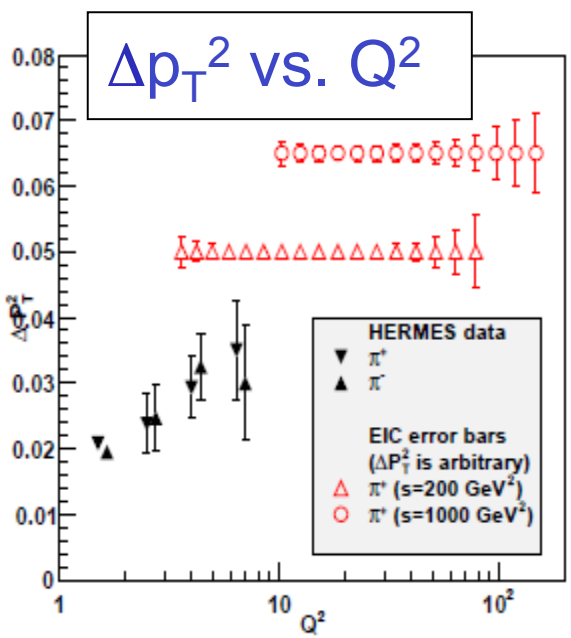
- EIC stage I will greatly improve our understanding of ΔG
  - Stage II will further reduce the uncertainty

Quark propagation in matter (hadronization)

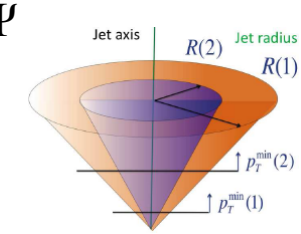




Accardi, Dupre



- Broadening of p_T distribution
- Heavy flavors: B, D mesons, J/Ψ
- Hadron jets at s > 1000 GeV^2



- *Impact parameter dependence?*
  - *Fragments and "wounded nucleons" can help understanding the path length*

Detection requirements for forward processes

Recoils in deep-exclusive (diffractive) processes

- Large t (p_T) range desirable for recoil baryons
- Coherent nuclear processes
  - Recoiling heavy ions are difficult to detect
  - Good acceptance at small p_T extends the mass range

Partonic fragmentation in SIDIS

- Also decays of strange and charmed baryons

Nuclear spectators and fragments

- Measure *complete* final state (all fragments) in heavy-ion reactions
  - Centrality of collision (shadowing, saturation, hadronization, etc)
- Spectator tagging with polarized light ions
  - p_T resolution < Fermi momentum
  - LDRD proposal approved at JLab in FY13

Opportunities with polarized light ions

Experiment: requires excellent forward detection and spectator tagging

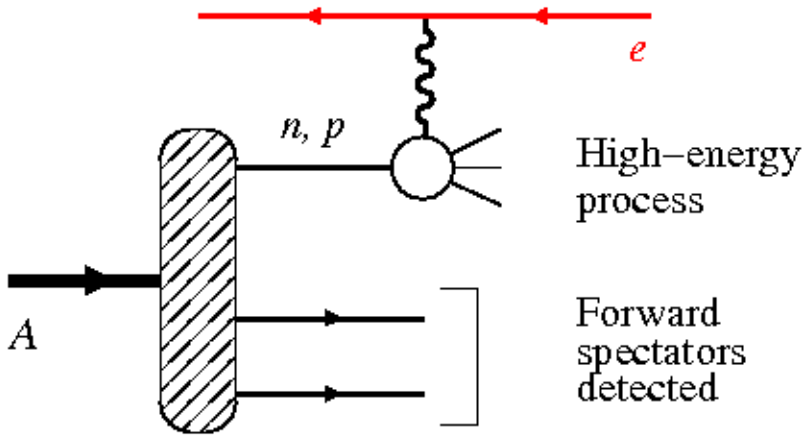
Theory: combines high-momentum-transfer processes and low-energy nuclear structure

Partonic structure of the neutron (including spin)

- Spin/flavor decomposition of parton densities

The bound nucleon in QCD

- Modifications of nucleon's quark/gluon structure due to nuclear binding
  - Off–shellness controlled by kinematics

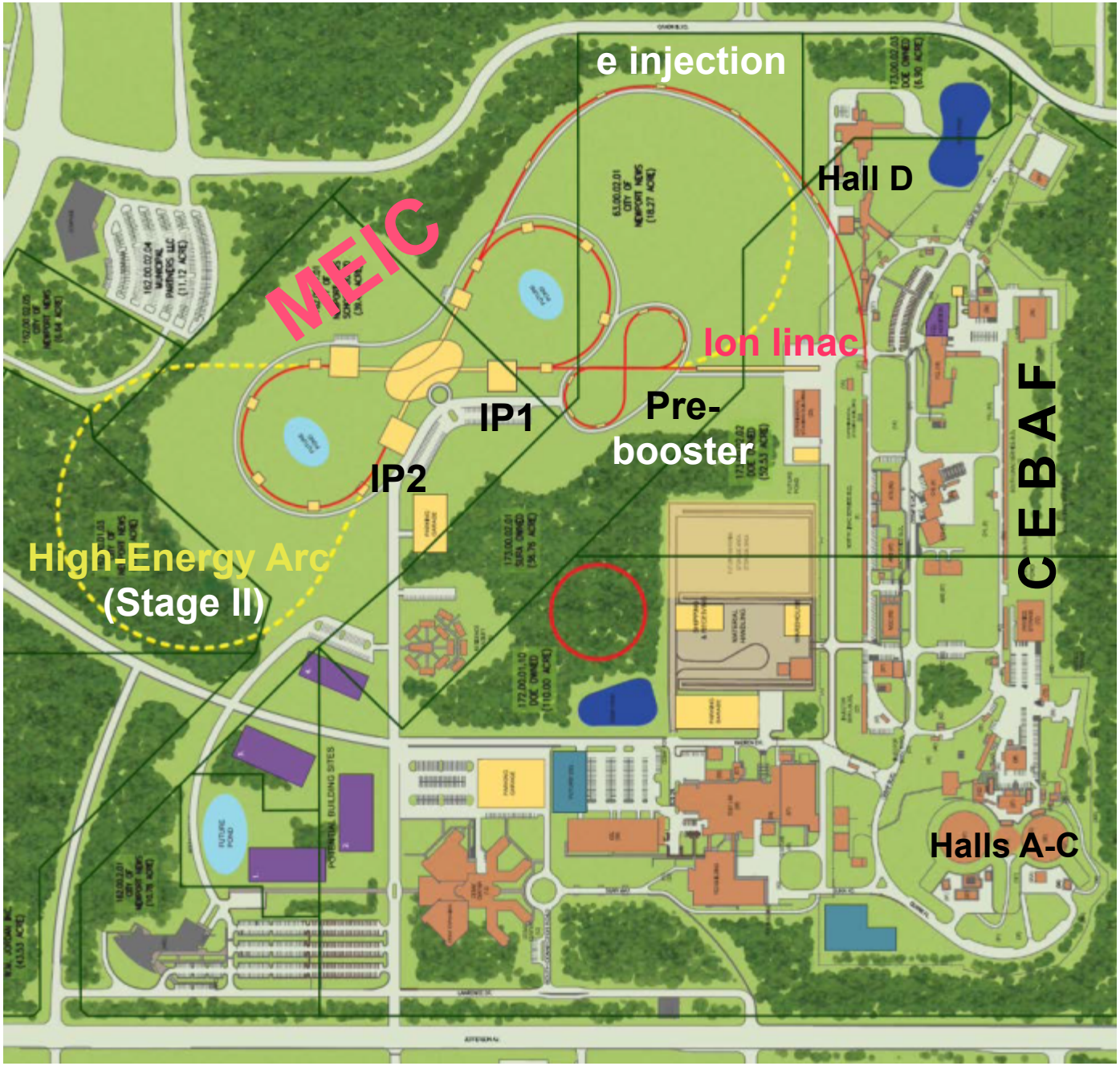


Collective quark/gluon fields

- Coherent scattering probes the quark/gluon field of the entire nucleus
- Tensor-polarized structure function of deuterium identifies the QCD double-scattering contribution - insight into onset of gluon saturation

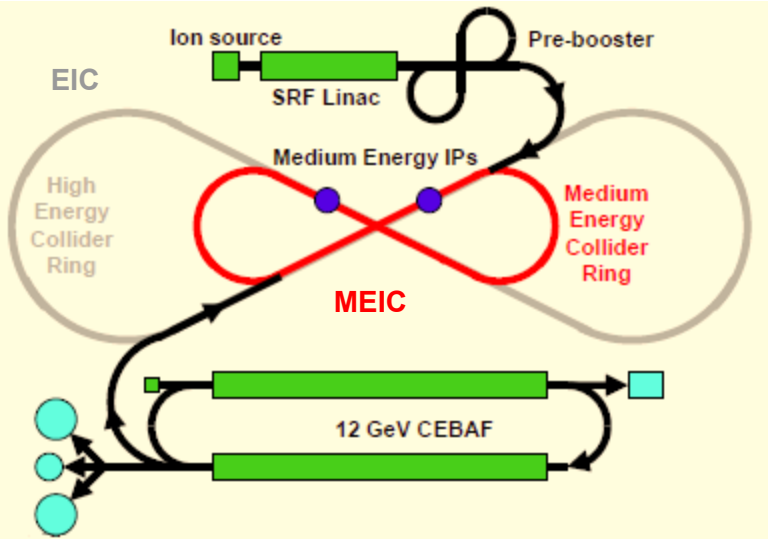
➔ ***Talk by C. Hyde tomorrow!***

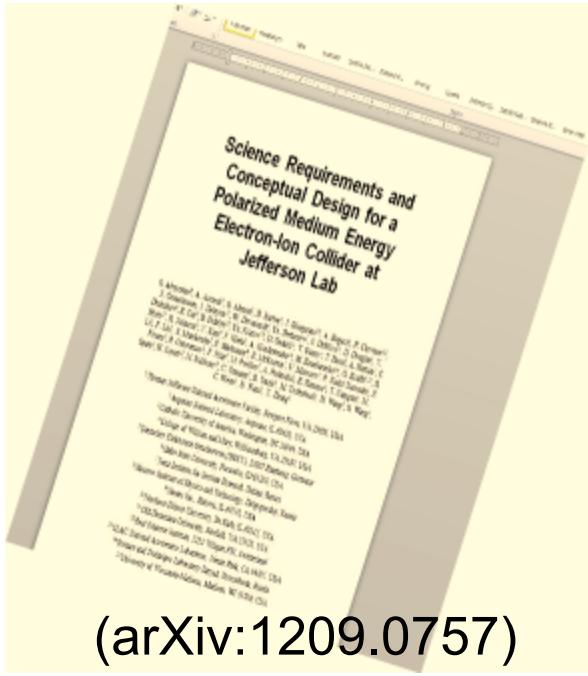
The EIC at Jefferson Lab



- 12 GeV CEBAF is a full-energy e-injector
  - Continuous injection as at SLAC (~50 nA)
  - Parallel running with fixed target possible
- Both the MEIC and CEBAF have a 1.4 km circumference
- MEIC can store 20-100 GeV protons, or heavy ions up to 40 GeV/A.
- The stage II EIC will increase the energy to 250 GeV for protons and 20 GeV for electrons.
- Two detectors
  - *IP2 could host sPHENIX*

MEIC – specific design goals





(arXiv:1209.0757)

Spin control for all light ions

- Figure-8 layout
- Vector- and tensor polarized deuterium

Full-acceptance detector

- Ring designed around detector requirements
- Detection of all fragments – nuclear and partonic

Minimized technical risk

Stable concept – detailed design report released August 2012

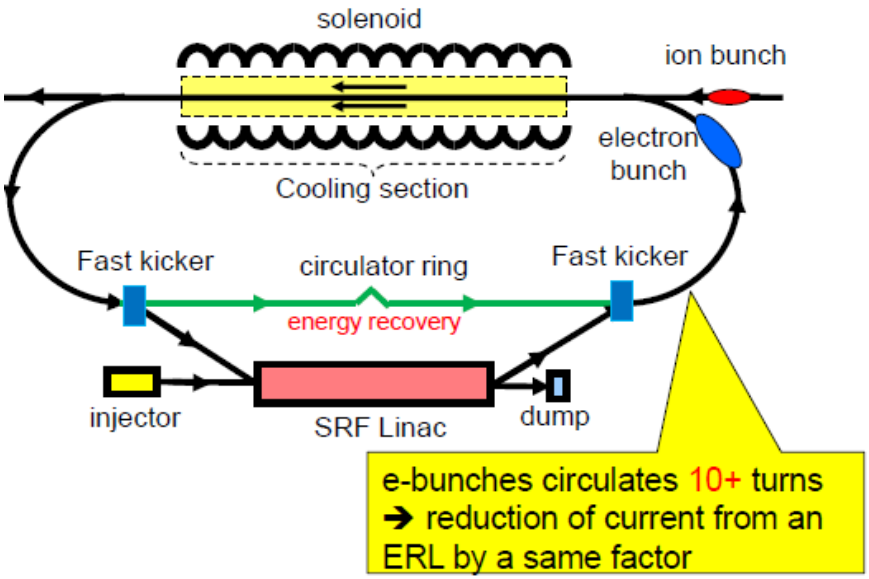
MEIC accelerator parameters

		50 × 5 GeV^2		100 × 5 GeV^2	
		Proton	Electron	Proton	Electron
Beam energy	GeV	50	5	100	5
Collision frequency	MHz	748.5	748.5	748.5	748.5
Particles per bunch	10^{10}	*0.21*	*2.2*	*0.42*	*2.5*
Beam Current	A	*0.25*	*2.6*	*0.5*	*3*
Polarization	%	~80	>70	~80	>70
Energy spread	10^{-4}	~3	7.1	~3	7.1
RMS bunch length	mm	10	7.5	10	7.5
Horizontal emittance, normalized	μm rad	*0.3*	54	*0.4*	54
Vertical emittance, normalized	μm rad	*0.06*	5.4	*0.04*	5.4
Horizontal and vertical β*	cm	10 and 2	10 and 2	10 and 2	10 and 2
Vertical beam-beam tune shift		*0.015*	*0.014*	*0.014*	*0.03*
Laslett tune shift		*0.053*	*<0.0005*	*0.03*	*<0.001*
Distance from IP to 1st quad	m	7 (downstream) 3.5 (upstream)	3	7 (downstream) 3.5 (upstream)	3
Luminosity per IP*	$cm^{-2}s^{-1}$	**2.4 x 10^{33}**		**8.3 x 10^{33}**	

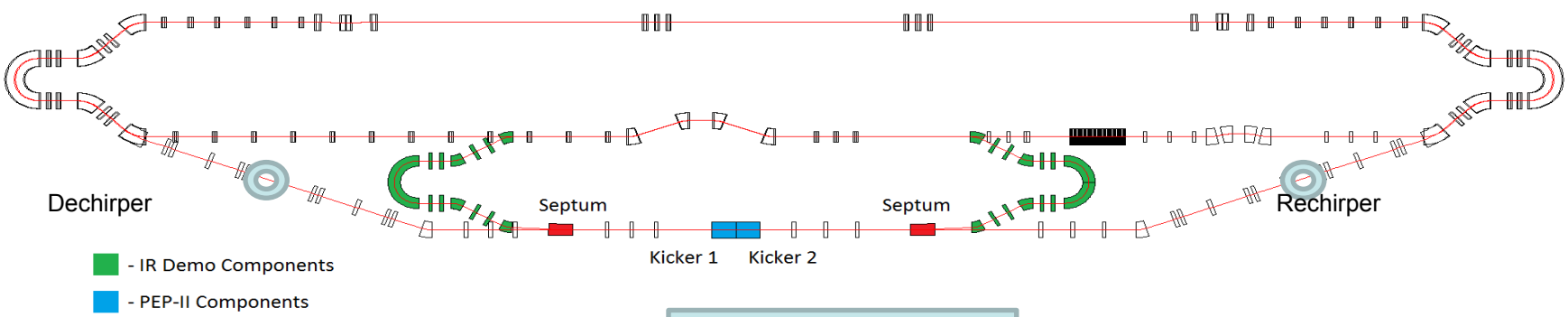
* Includes space-charge effects and assumes conventional electron cooling

Red indicates parameters specific to the full-acceptance detector

Conventional electron cooling using a 55 MeV ERL



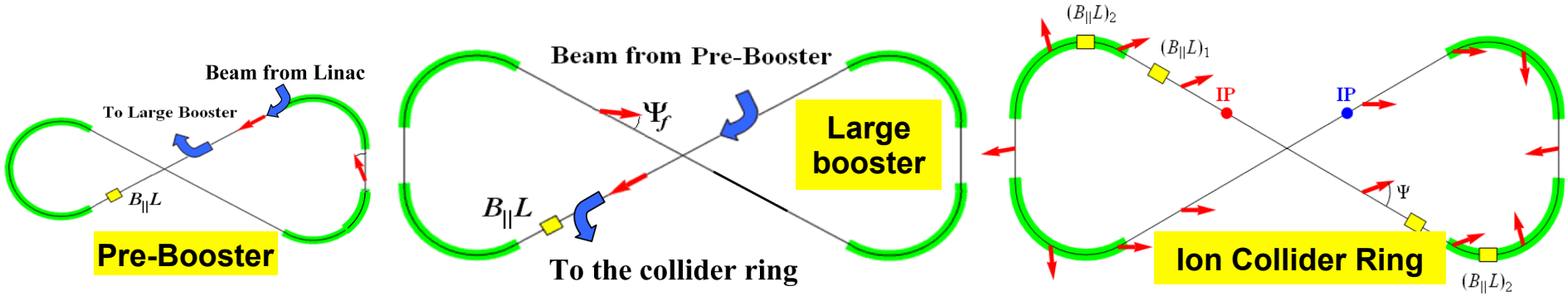
- Conventional electron cooling using an accelerating high-voltage is a well-established technique (*e.g.* at Fermilab)
- A single-pass Energy-Recovery Linac (ERL) allows reaching higher electron energies and currents
- A recirculator ring is not needed for the ready-to-build MEIC cooling scheme, but would reduce source current requirements
- Recirculator tests are planned at the JLab Free-Electron Laser (FEL) ERL



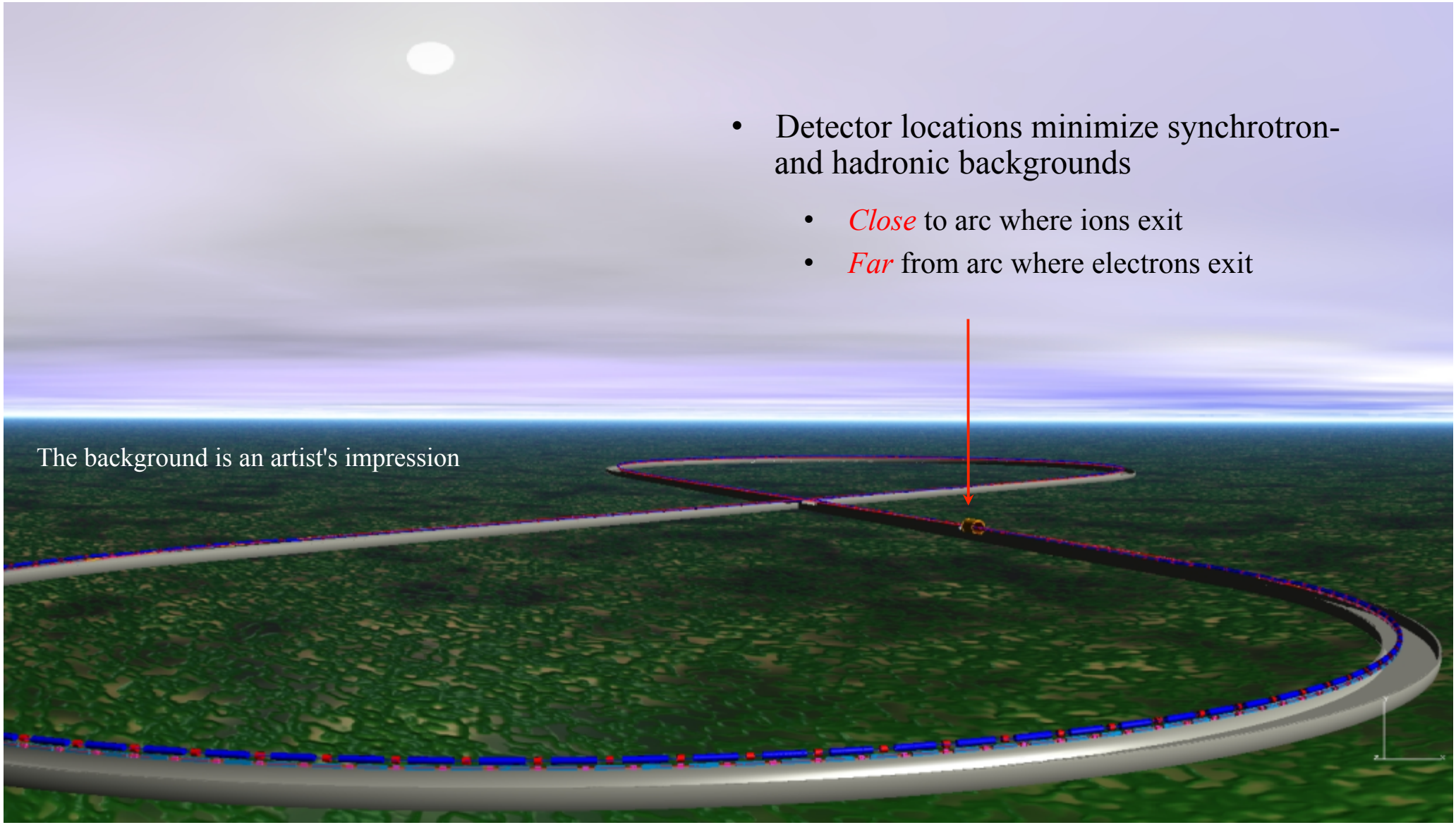
Cooler Test Facility @ JLab FEL ERL

MEIC – ion polarization in figure-8 ring

- Science program demands highly polarized (>70%) light ions (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 MEIC detector locations (in CAD)



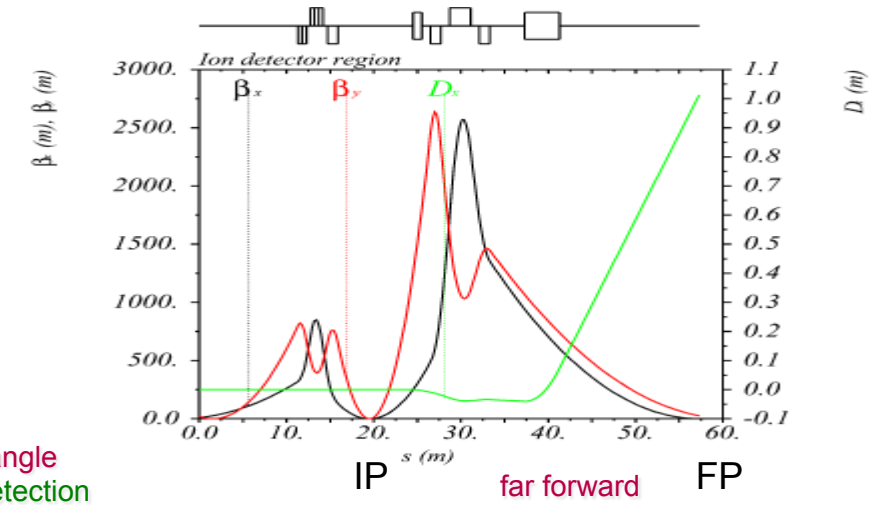
- Detector locations minimize synchrotron- and hadronic backgrounds
  - *Close* to arc where ions exit
  - *Far* from arc where electrons exit

- The MEIC magnetic lattice design is complete

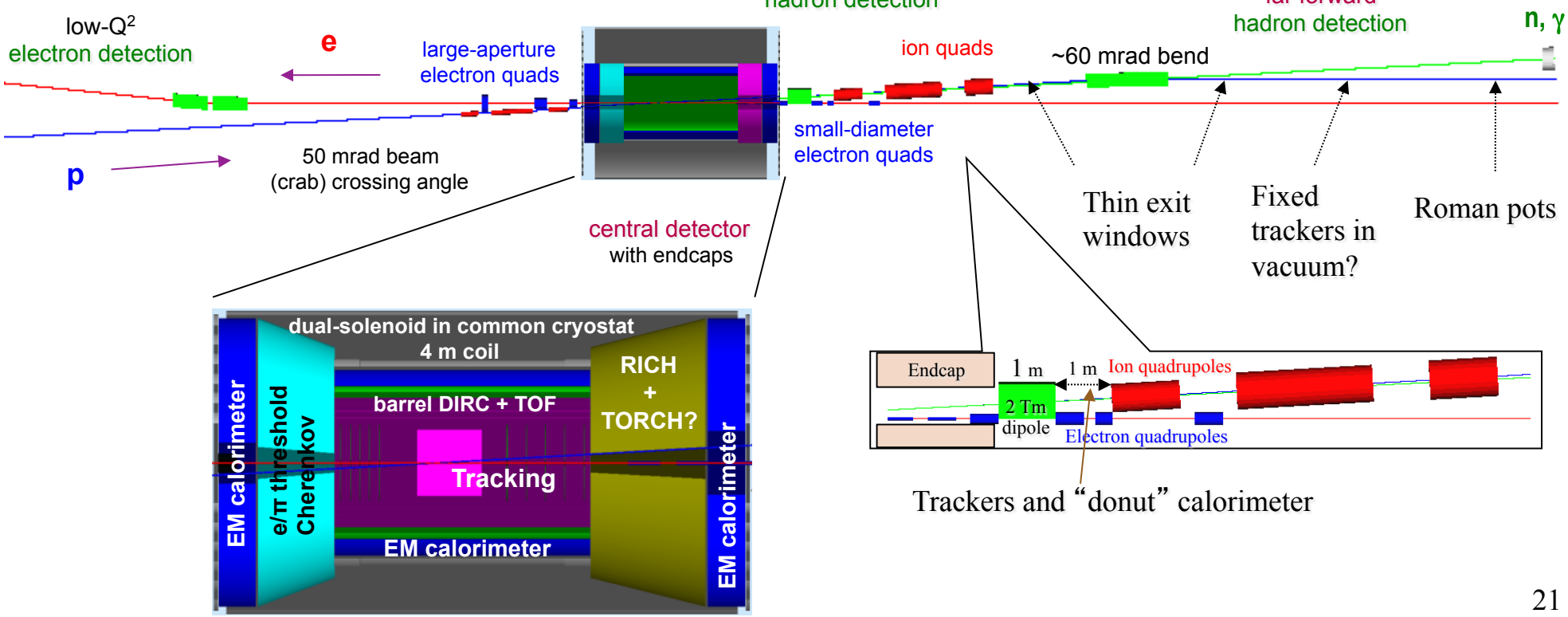
The MEIC full-acceptance detector concept

Forward hadron detection in three stages:

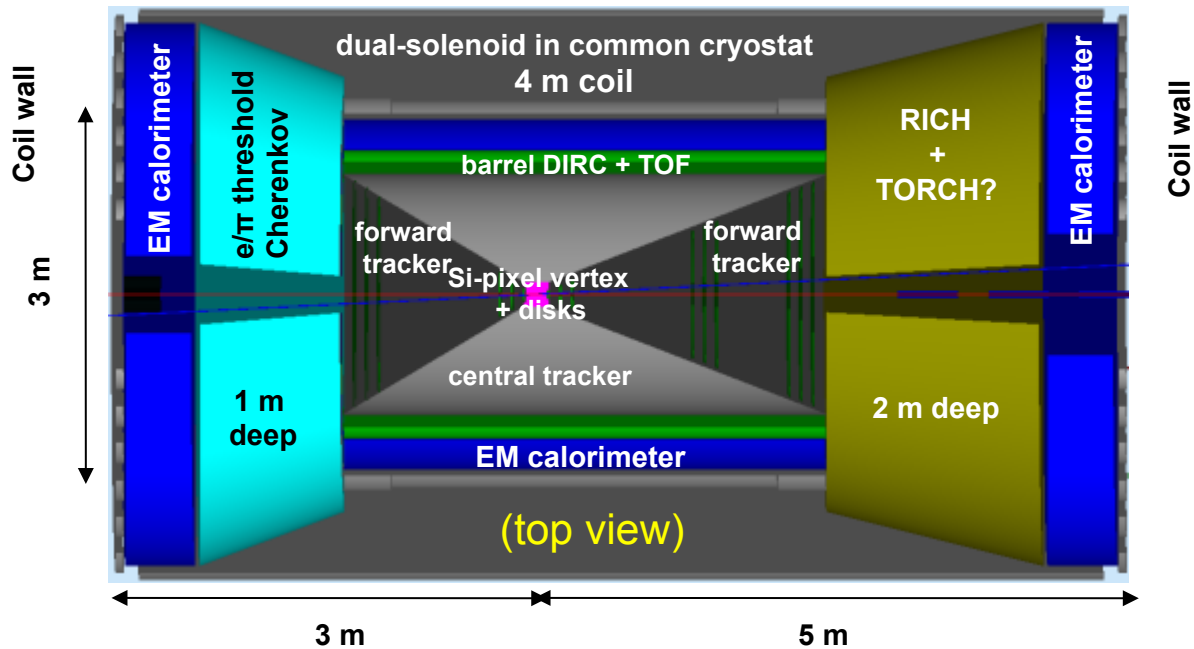
1. **Endcap with 50 mrad crossing angle**
2. **Small dipole covering angles up to a few degrees**
3. **Far-forward, up to one degree, for particles passing the accelerator quads**

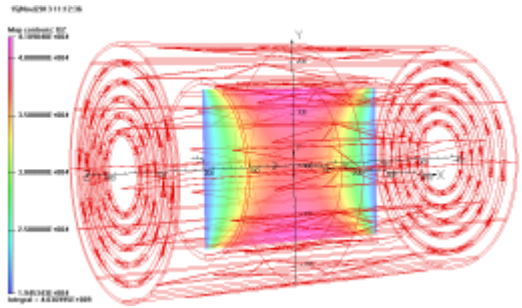


(from GEANT4)



Central detector options

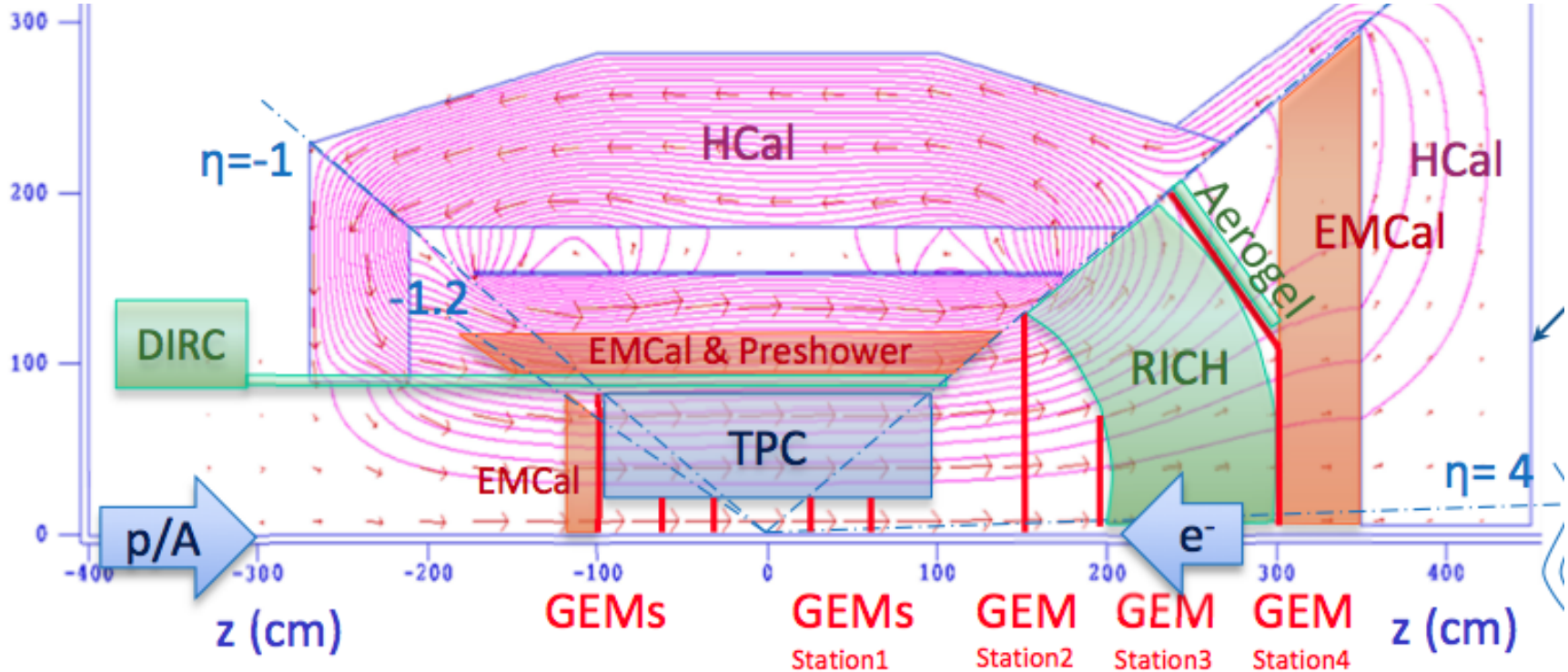




- First TOSCA model of 3T dual solenoid.
  - Inspired by ILC 4th concept detector

- **Goal:** two sufficiently different, complementary central detectors
  - No need to for beam sharing at a ring-ring collider!
- **IP1 (shown above):** new 3T dual solenoid and large tracker
  - Si-pixel disks and micropattern gas detector (GEM/micromega) forward trackers
  - Low-mass cluster-counting He-filled DC, and/or micropattern central tracker
- **IP2** can be instrumented using an old magnet (CLEO or BaBar)
  - Focus on hadronic calorimetry + small TPC central tracker

The MEIC IP2 could host an upgraded PHENIX



- The planned PHENIX detector upgrade is based on the BaBar solenoid
  - Staged implementation denoted by various prefixes (s/fs/e)
  - Relatively small and can easily be moved
- Main physics focus of sPHENIX is jet physics using hadronic calorimeter
- MEIC IP2 is designed to be compatible with the new PHENIX
  - Good starting point for bringing the communities together

The MEIC full-acceptance detector concept

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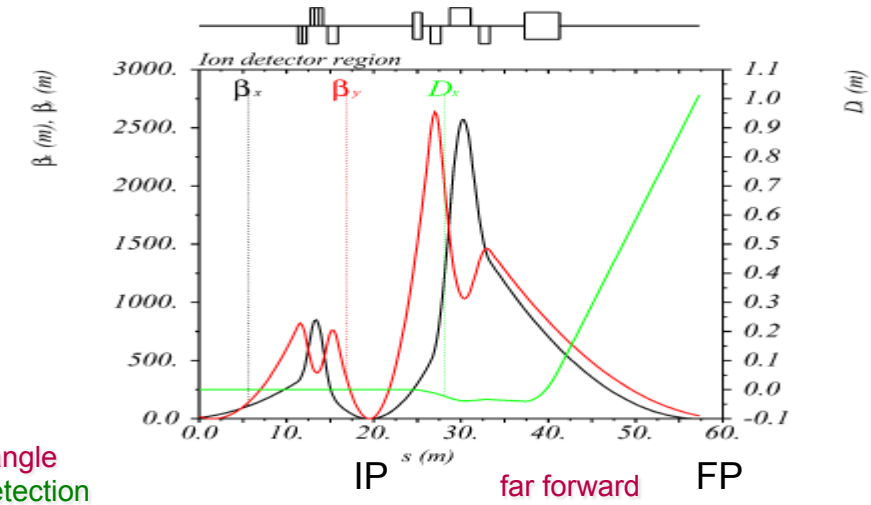
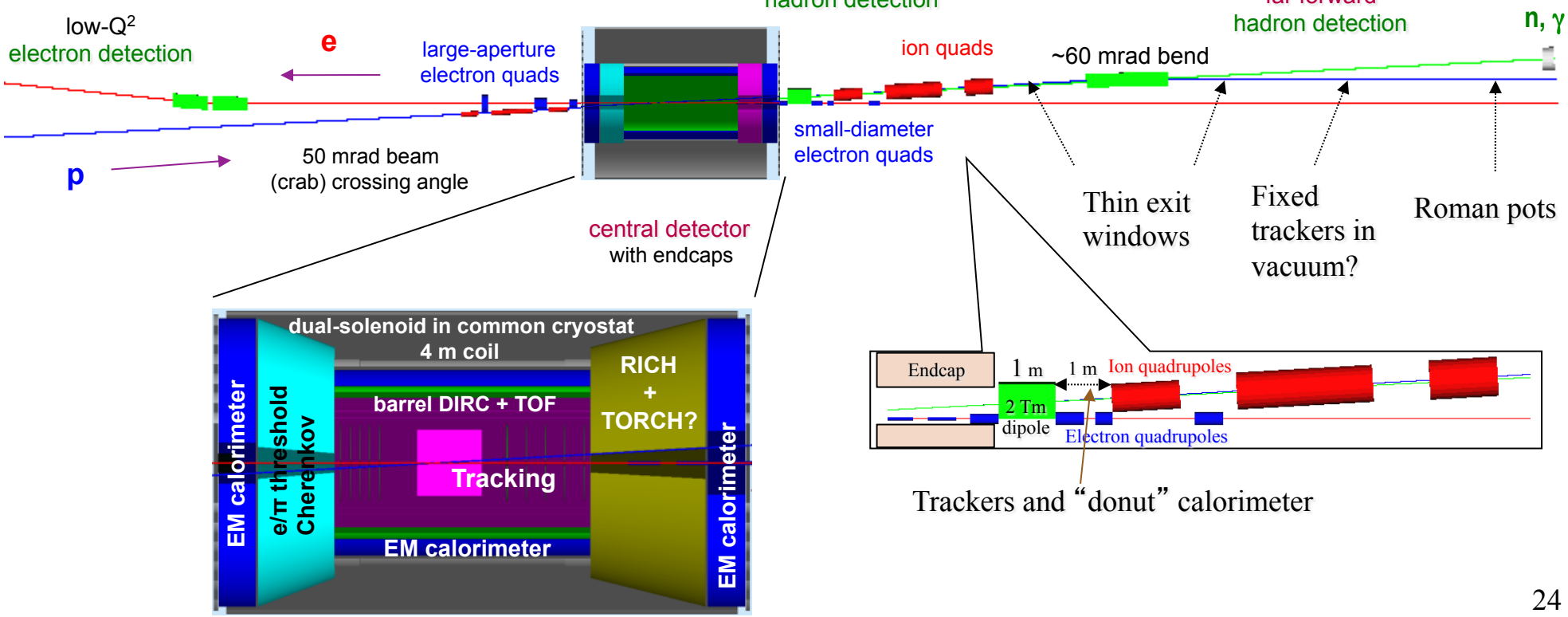
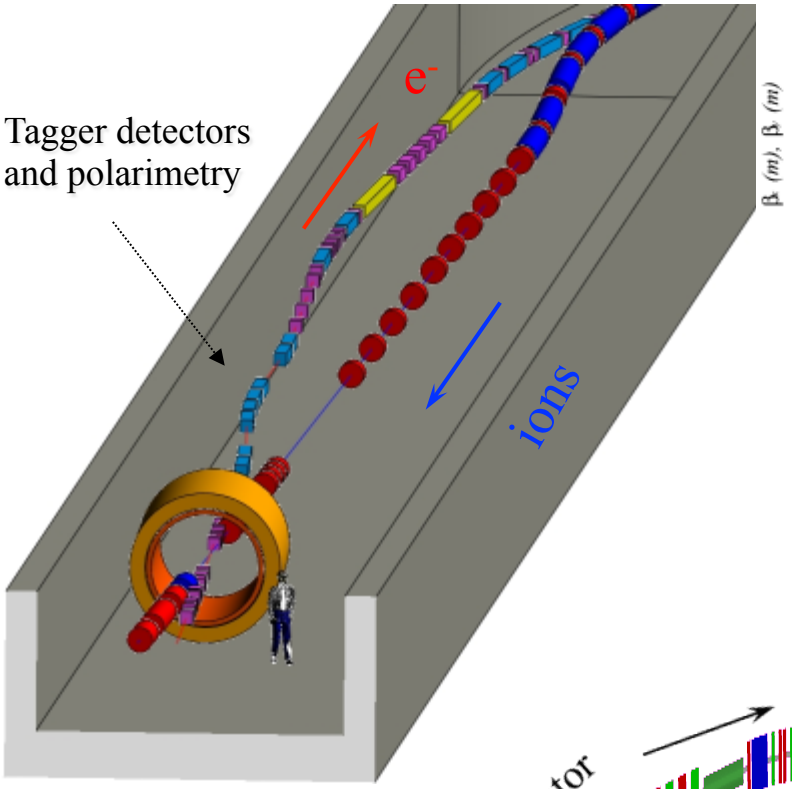
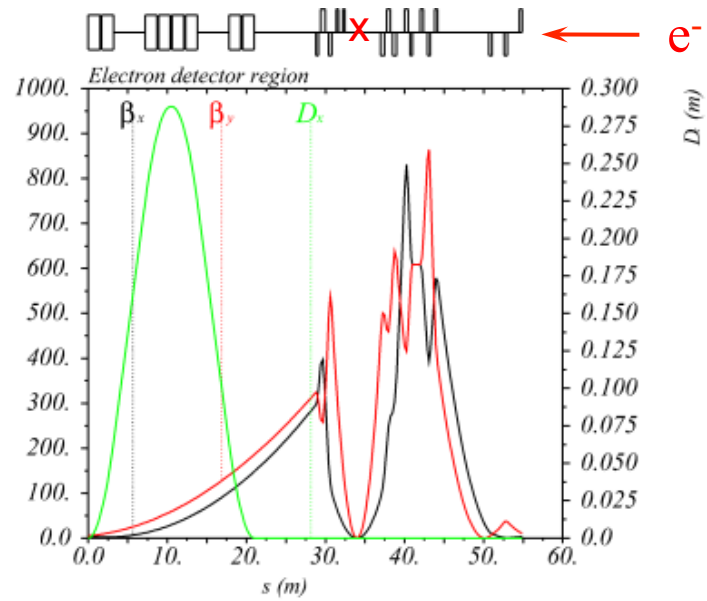


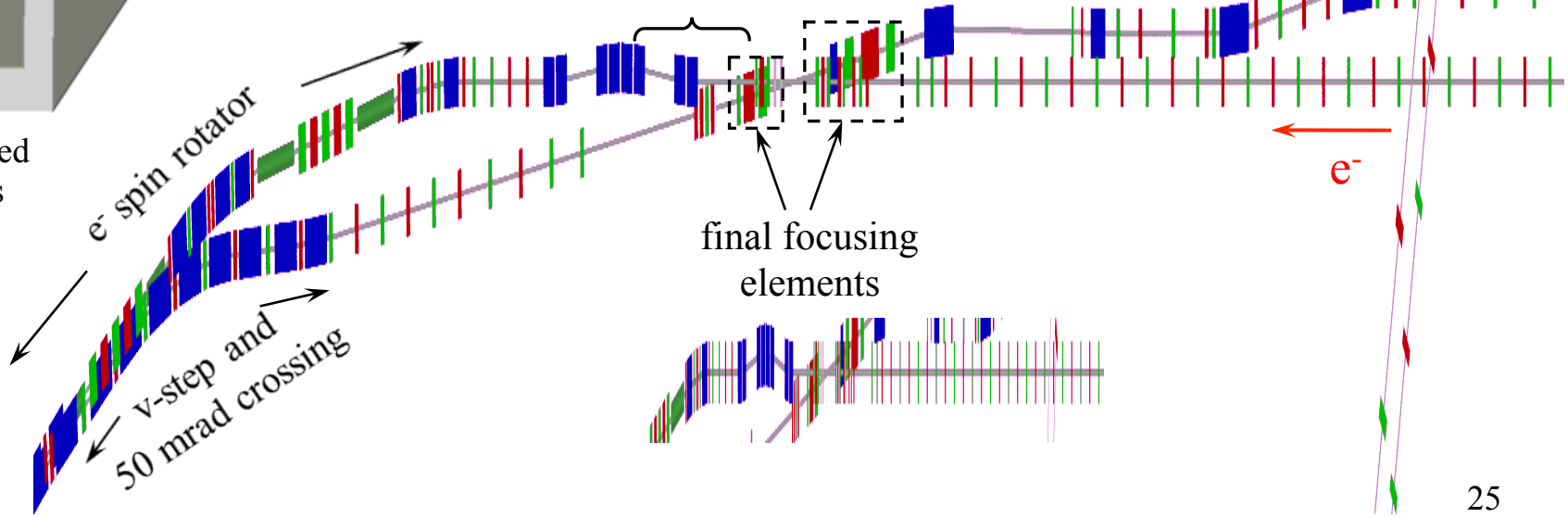
(from GEANT4)



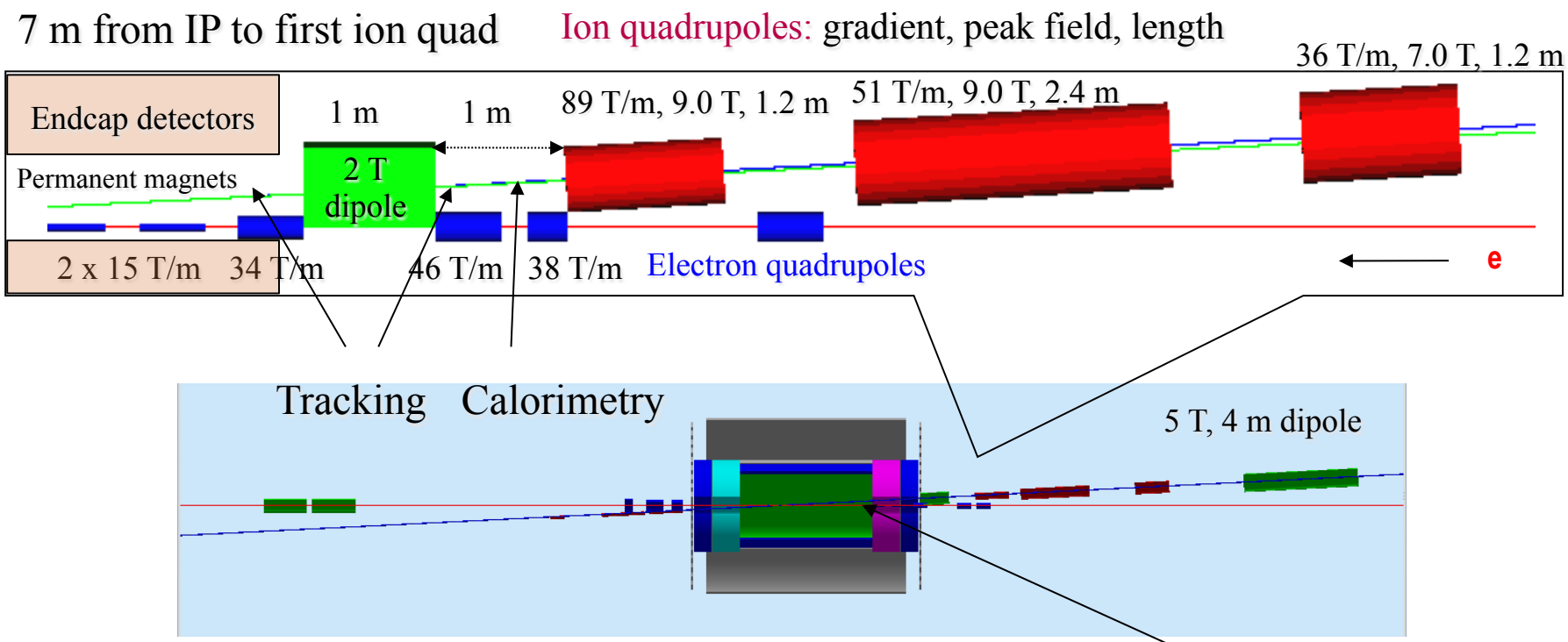
The low-Q^2 tagger – small angle electron detection



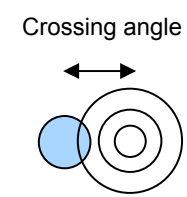




Hadron detection between endcap and ion quads

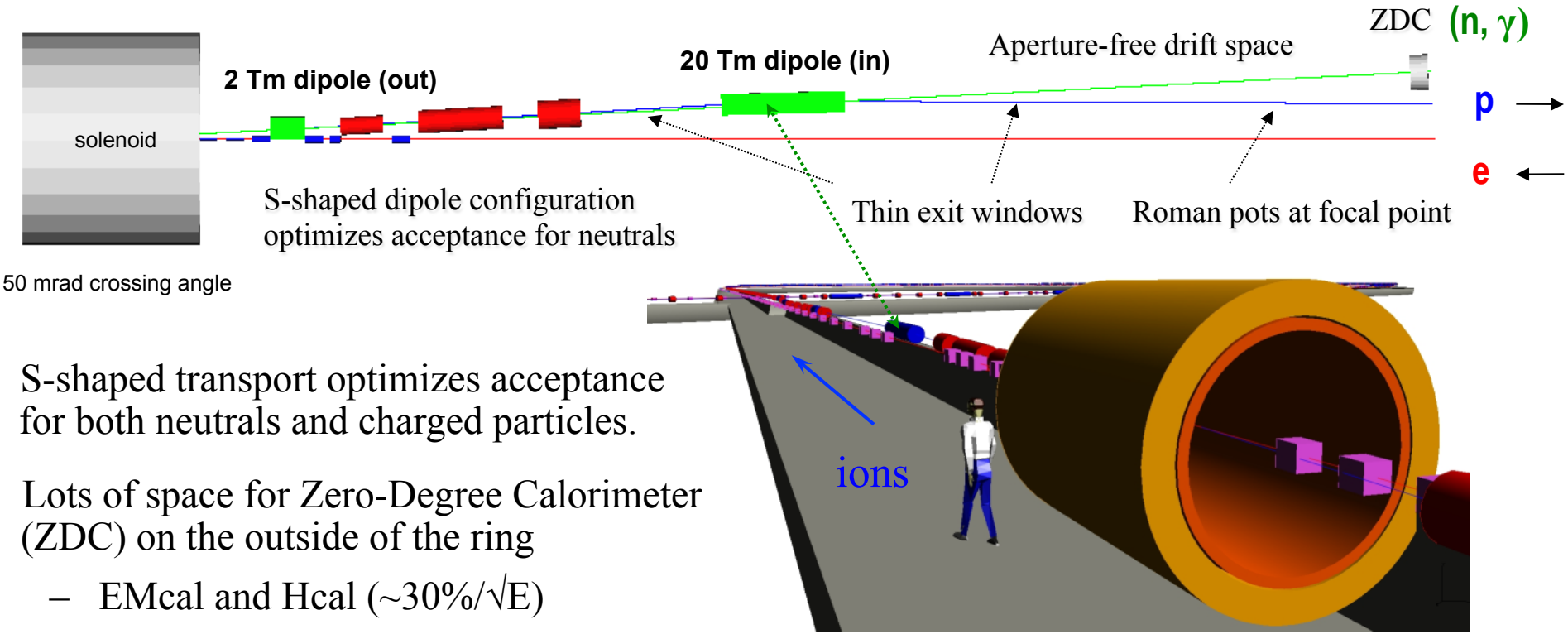


- Large crossing angle (50 mrad)
  - Moves spot of poor resolution along solenoid axis into the periphery
  - Minimizes shadow from electron FFQs



- 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

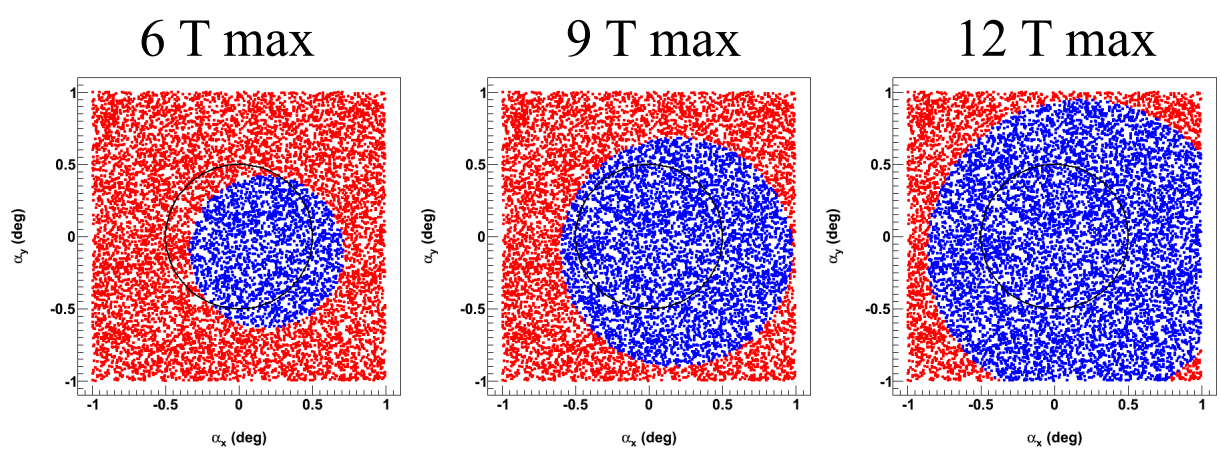
Detection after the ion quads



- S-shaped transport optimizes acceptance for both neutrals and charged particles.
- Lots of space for Zero-Degree Calorimeter (ZDC) on the outside of the ring
  - EMcal and Hcal (~30%/√E)
- Quad acceptance depends on peak field, but in 1-2° range.

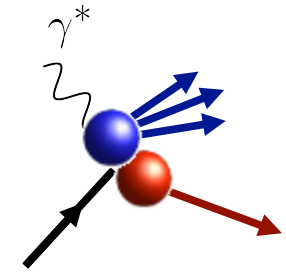
Red: Detection *before* ion quadrupoles

Blue: Detection *after* ion quadrupoles



Far-forward charged hadron detection – requirements

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



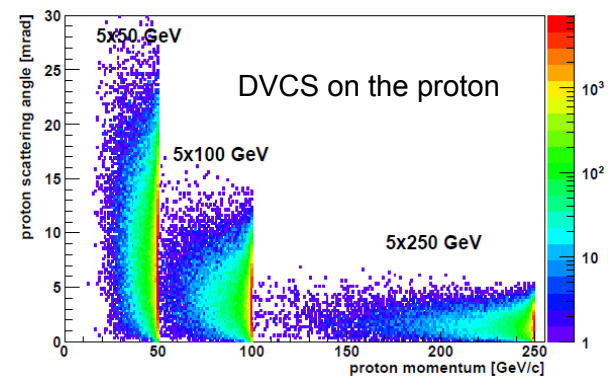
- Large downstream magnet apertures
- Small downstream magnet gradients (realistic peak fields)
- Roman pots not needed

2. Good acceptance for low-p_T 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

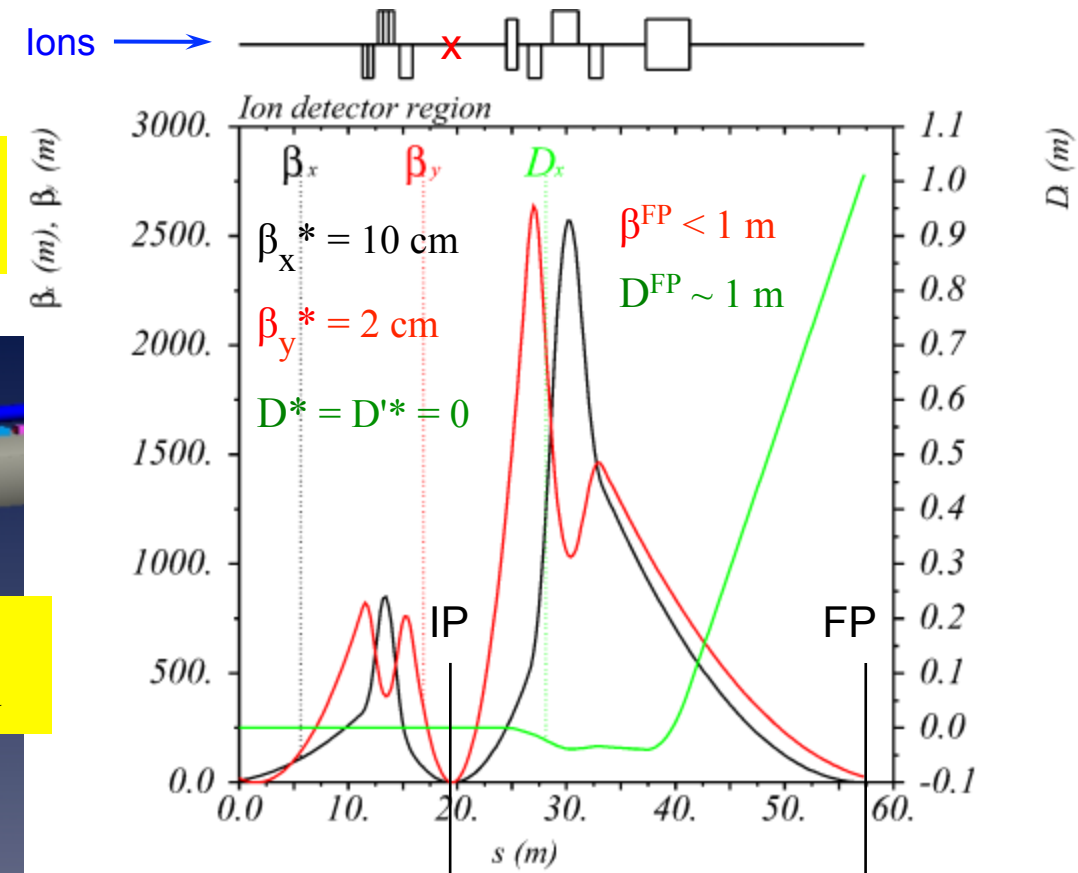
- Large dispersion (but with D = D' = 0 at IP)
- Long, instrumented, magnet-free drift space

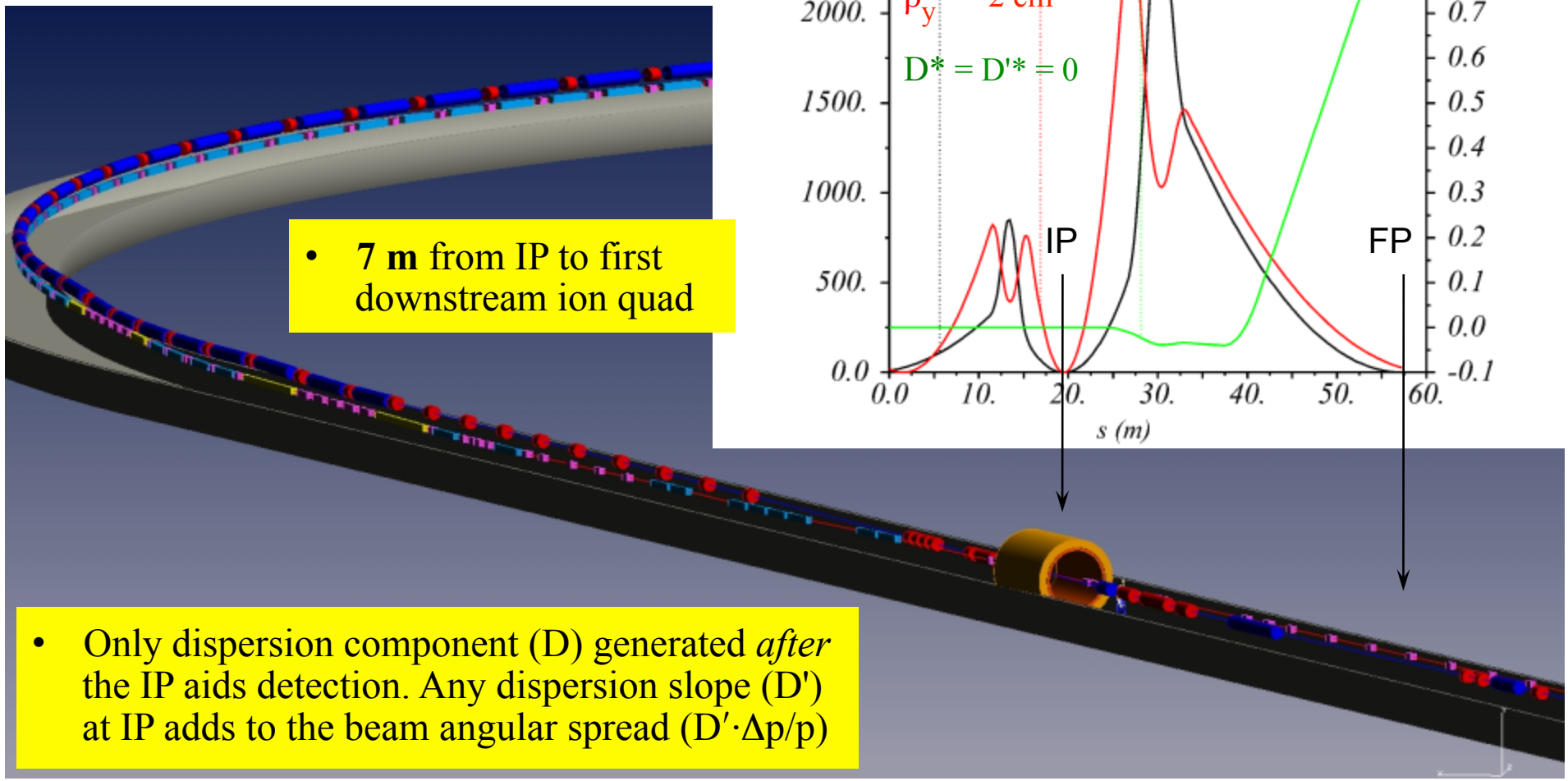


4. Sufficient separation between beam lines (~1 m)

Asymmetric ion optics

- β^* x/y asymmetry allows a high luminosity with relatively small β^{max}





- **7 m** from IP to first downstream ion quad

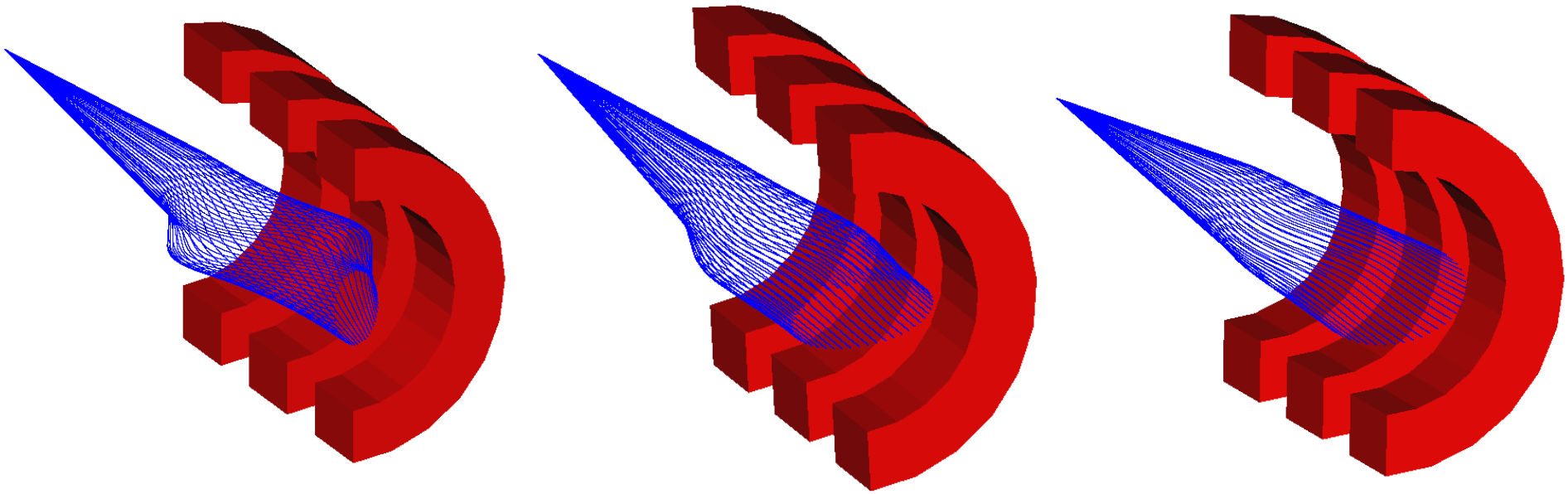
- Only dispersion component (D) generated *after* the IP aids detection. Any dispersion slope (D') at IP adds to the beam angular spread ($D' \cdot \Delta p/p$)

- Beam angular spread is also proportional to $\sqrt{(\varepsilon/\beta^*)}$ → good ion beam cooling essential

Far-forward detection of charged fragments

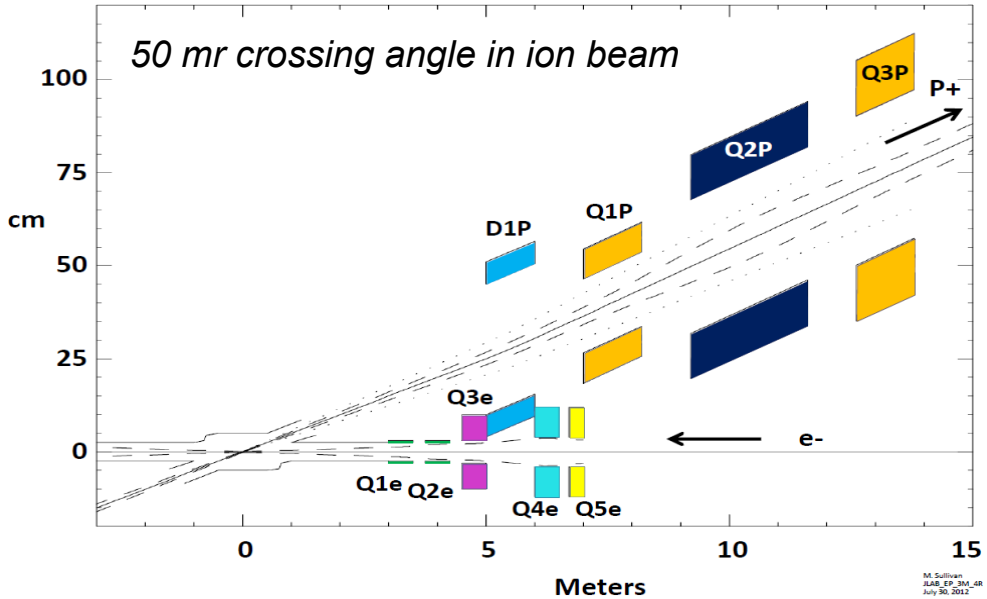
(protons rich fragments) ← → (neutron rich fragments)

$\Delta p/p = -0.5$	$\Delta p/p = 0.0$	$\Delta p/p = 0.5$
(spectator protons from deuterium)	(exclusive / diffractive recoil protons)	(tritons from N=Z nuclei)



- For light ions focus the mass/charge ratio of fragments is usually very different from the beam
- For heavy ions one needs both good acceptance and momentum resolution

Fragment acceptance vs quadrupole peak field

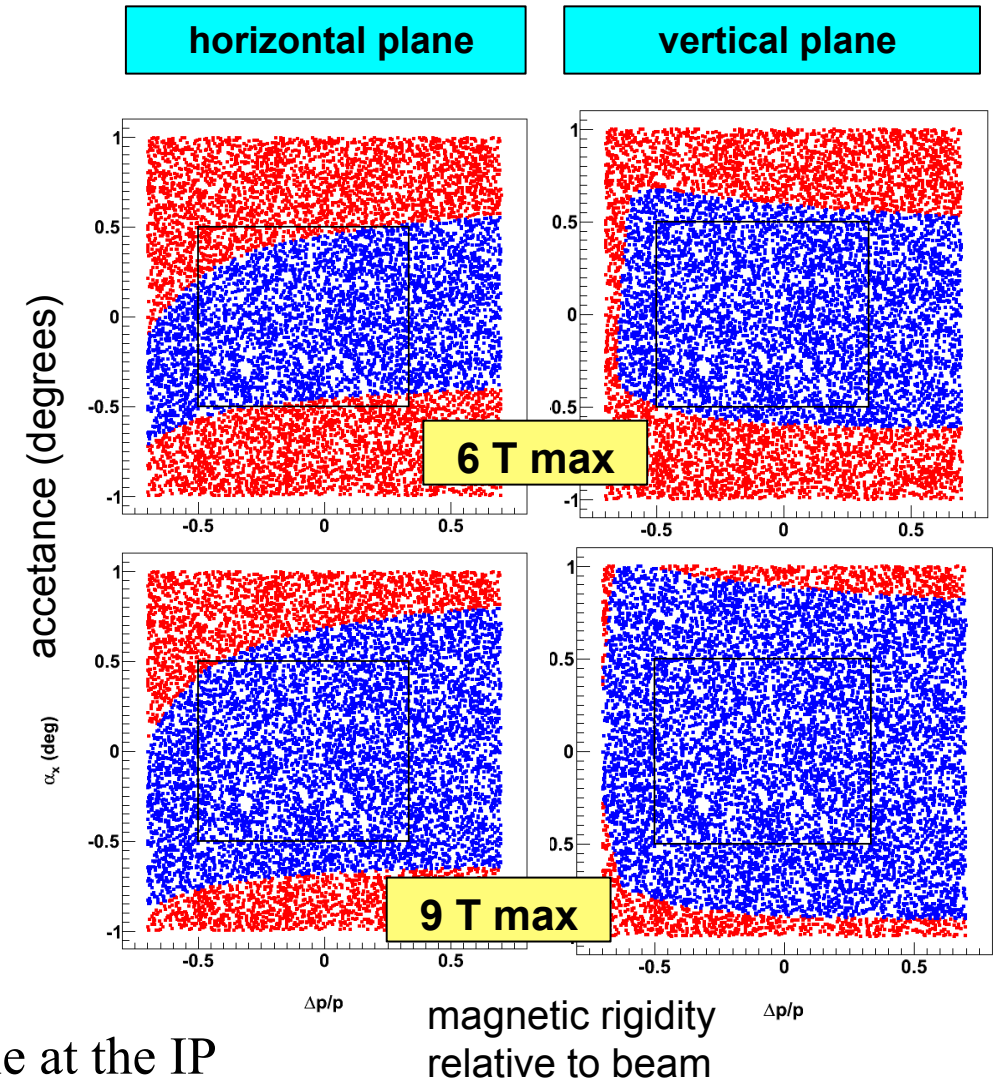


Red: Detection *before* ion quadrupoles

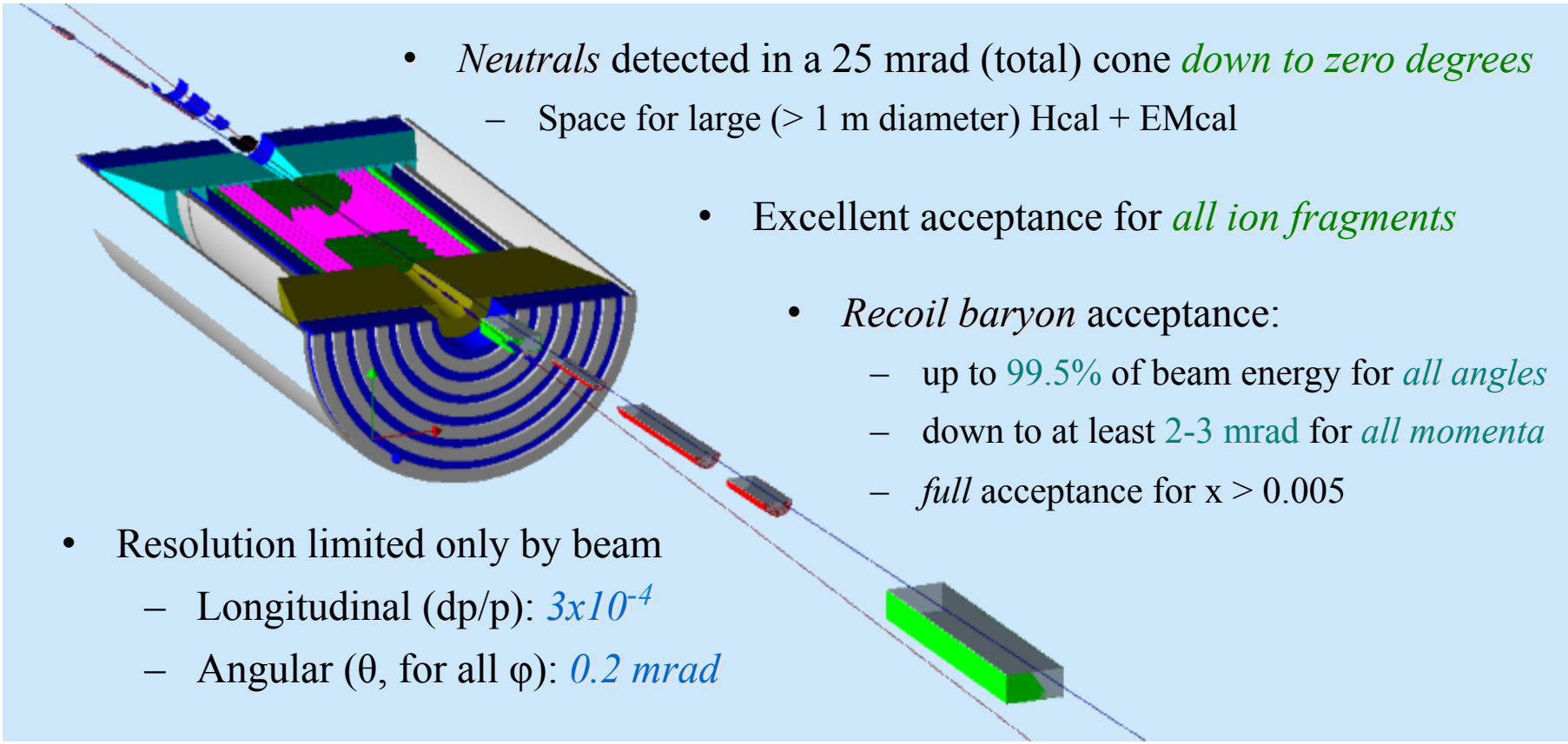
Blue: Detection *after* ion quadrupoles

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

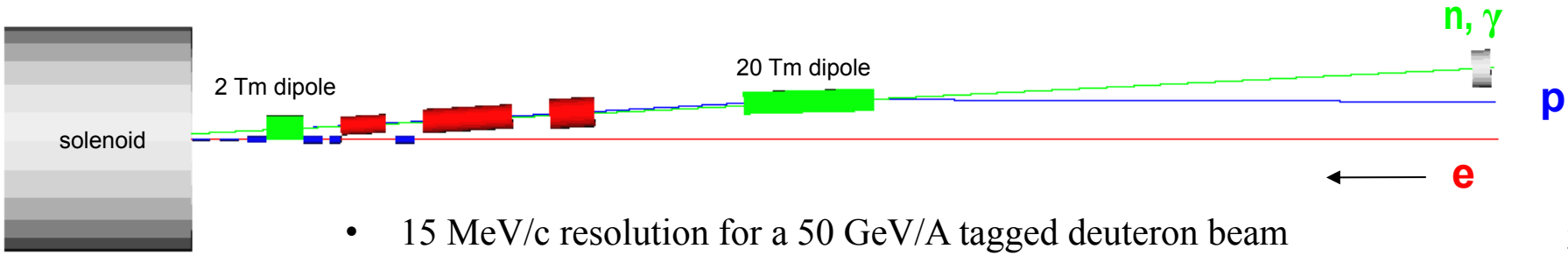
Forward acceptance vs.magnetic rigidity



Far-forward hadron detection summary



- *Neutrals* detected in a 25 mrad (total) cone *down to zero degrees*
  - Space for large (> 1 m diameter) Hcal + EMcal
- Excellent acceptance for *all ion fragments*
- *Recoil baryon* acceptance:
  - up to 99.5% of beam energy for *all angles*
  - down to at least 2-3 mrad for *all momenta*
  - *full* acceptance for x > 0.005
- Resolution limited only by beam
  - Longitudinal (dp/p): $3x10^{-4}$
  - Angular (θ, for all φ): *0.2 mrad*



- 15 MeV/c resolution for a 50 GeV/A tagged deuteron beam

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

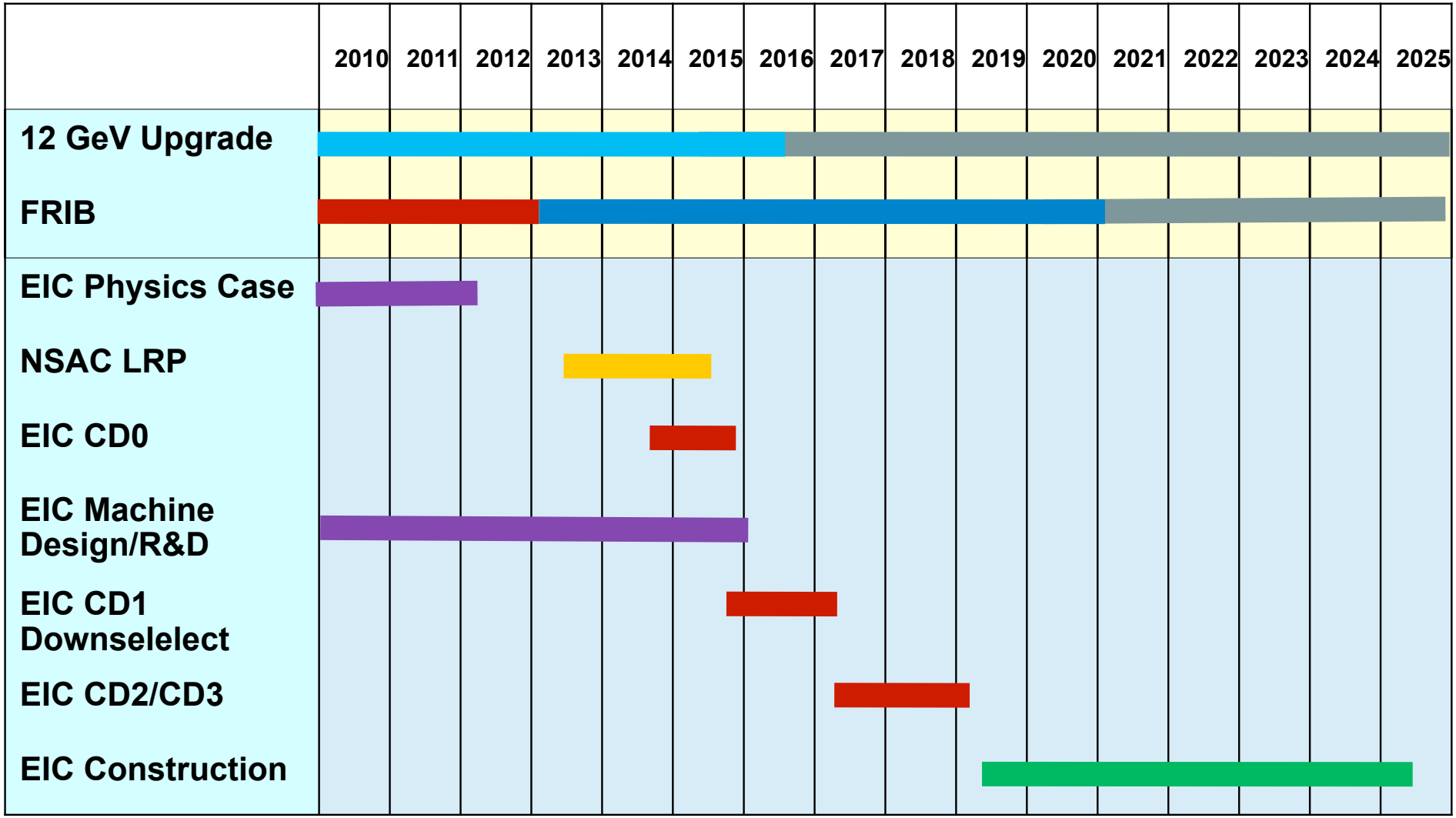
- Vector- and tensor polarized deuterium
- Excellent detection of recoil baryons, spectators, and target fragments
  - Full acceptance, high resolution

Complementarity with the LHC/LHeC

- The MEIC will cover all kinematics between JLab 12 GeV and the LHeC

Backup

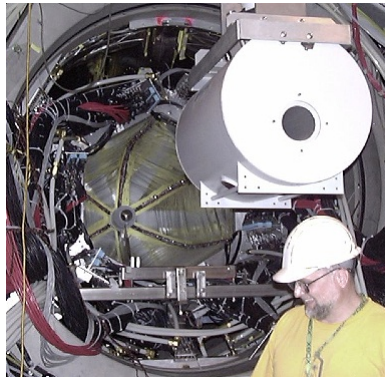
EIC timeline



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

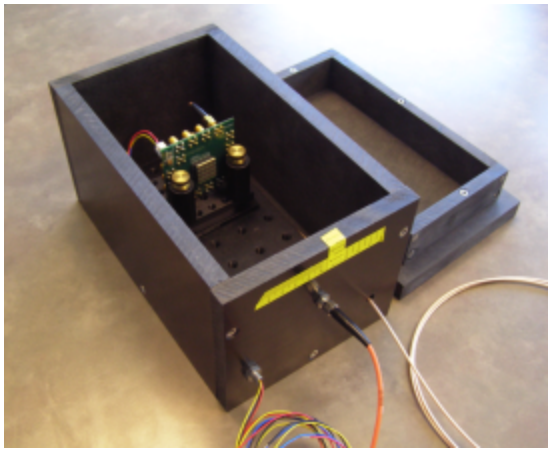
Generic detector R&D for an EIC – example

- R&D program not site specific
  - Coordinated by Tom Ludlam (BNL)
- As part of the program, a new, permanent EIC facility for sensor tests in high magnetic fields is being set up at Jefferson Lab
  - Two 5T magnets provided by JLab
- Tests will include MCP-PMTs with small pore size (2-6 μm), SiPMs and LAPPDs

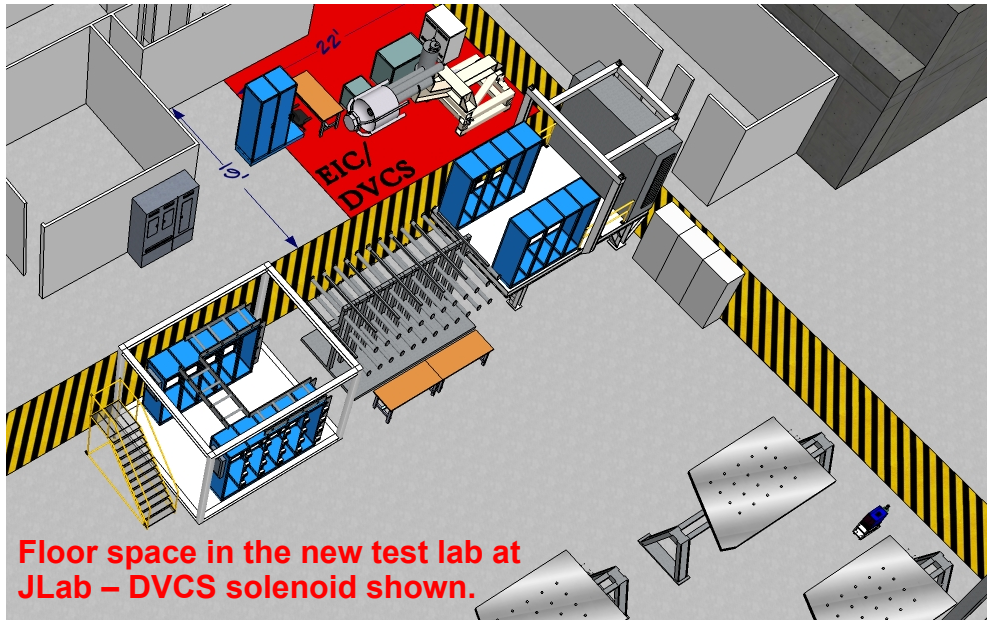


CLAS FROST solenoid with 5 inch bore

CLAS DVCS solenoid with 9 inch bore

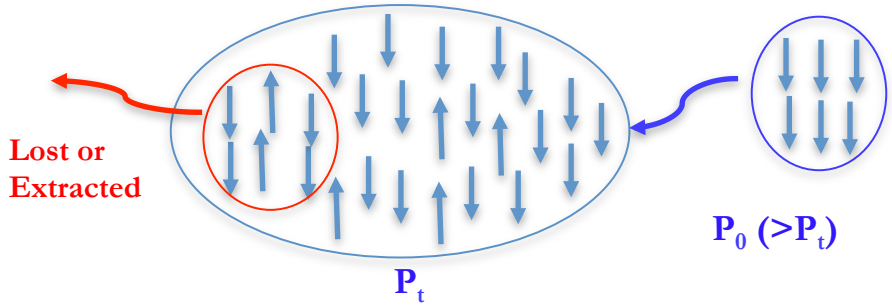


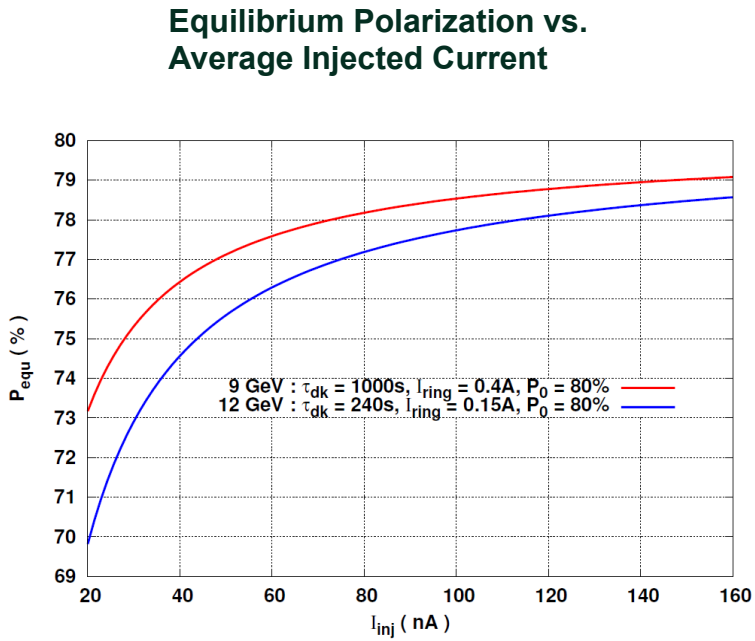
Non-magnetic dark box with pulsed LED for the DVCS solenoid – note the GlueX SiPM (Hamamatsu S11064-050P(X))



Floor space in the new test lab at JLab – DVCS solenoid shown.

Electron polarization – continuous injection





- Polarization at t+Δt

$$P_{t+\Delta t} = (1 - \frac{\Delta N}{N})(P_t + \frac{\Delta P_t}{\Delta t}\Delta t) + \frac{\Delta N}{N} P_0$$

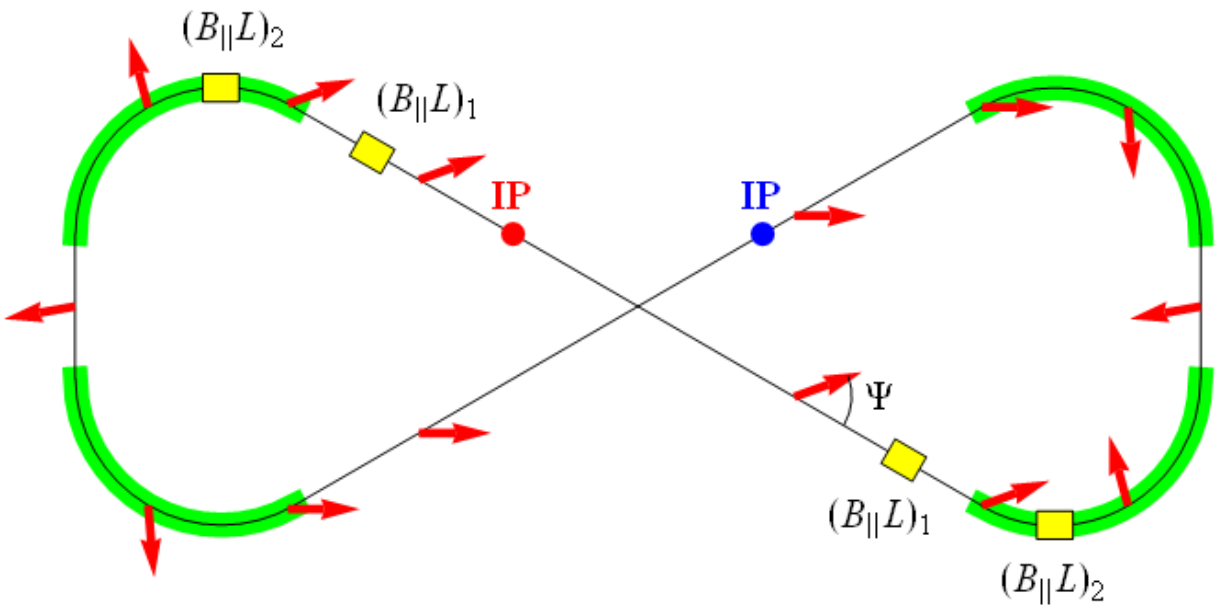
- Equilibrium Polarization

$$P_{equ} = P_0 (1 + \frac{T_{rev} I_{ring}}{\tau_{dk} I_{inj}})^{-1}$$

- Note that:
  - Polarization lifetime at 5 GeV is 1 or 3 hours depending on helicity (Sokolov-Ternov)
  - 50-100 nA beam injected from CEBAF can maintain polarization close to its initial value of 80% indefinitely for any elevtron beam energy.

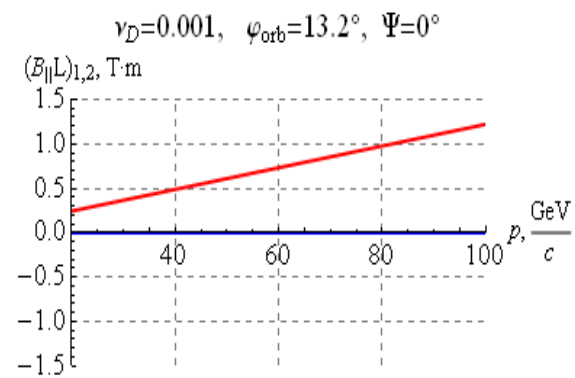
Deuteron polarization in figure-8 ring

- Beam injected longitudinally polarized, accelerated and then desired spin orientation adjusted

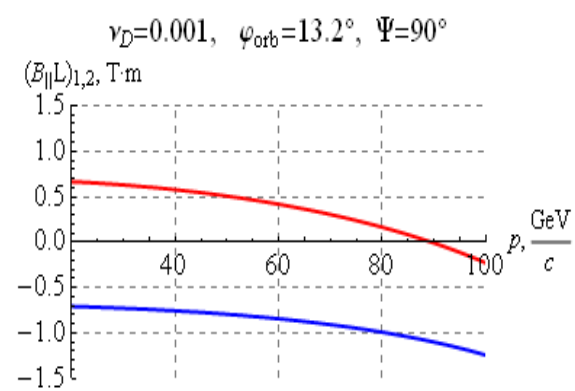


$(B_{||}L)_{1,2}$ (T·m) vs. p (GeV/c)

longitudinal polarization



radial polarization



$$\varphi_{z1} = \pi\nu \frac{\sin(\varphi_y - \Psi)}{\sin\varphi_y} \qquad \varphi_{z2} = \pi\nu \frac{\sin\Psi}{\sin\varphi_y} \qquad \varphi_{zi} = (1+G)\frac{(B_{||}L)_i}{B\rho}$$

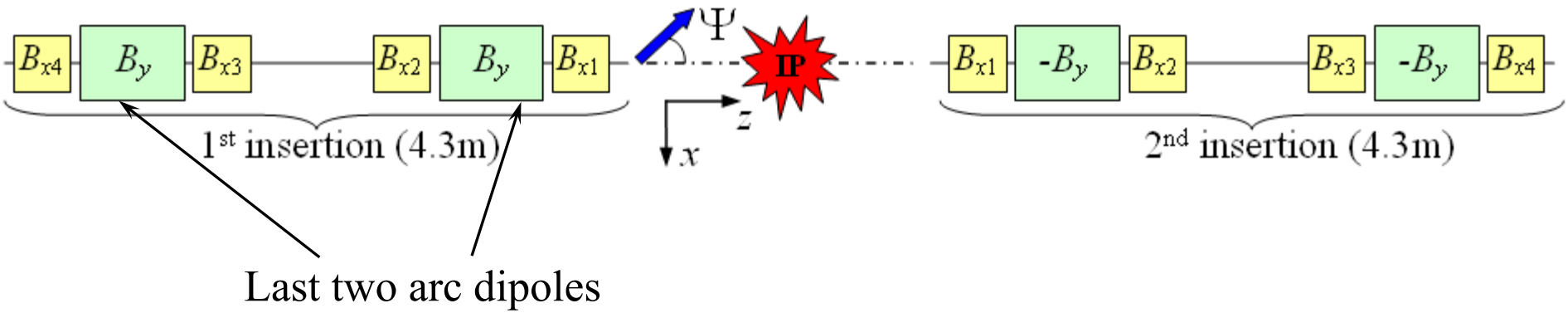
φ_{z1}, φ_{z2} are the spin rotation angles in the solenoids

$\varphi_y = \gamma G\alpha$ is the spin rotation angle between the solenoids

α is the orbit rotation angle between the solenoids

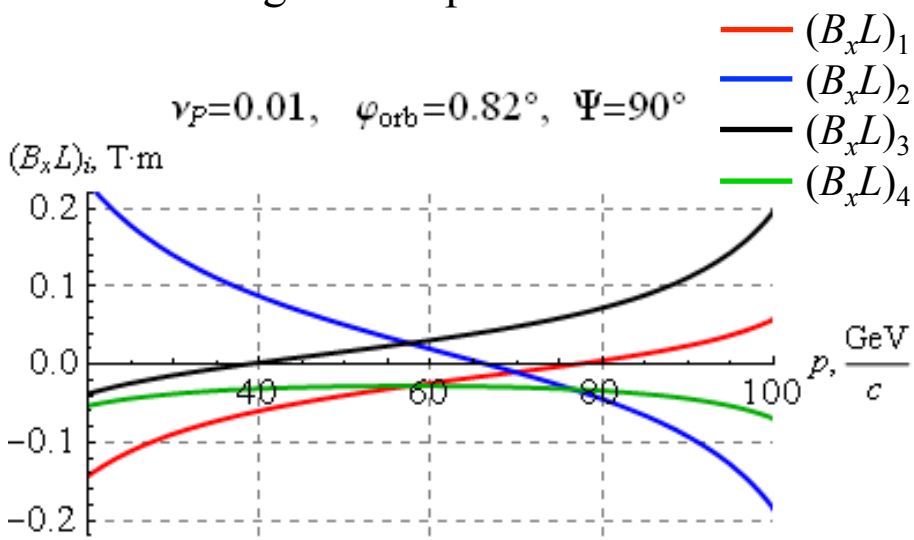
Ψ is the angle between the polarization and velocity directions

Proton polarization in figure-8 ring



$(B_\perp L)_i$ (T·m) vs. p (GeV/c)

longitudinal polarization



radial polarization