Physics capabilities at the MEIC at JLab

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for JLab's MEIC Study Group

XXII. Int'l Workshop on DIS and Related Subjects
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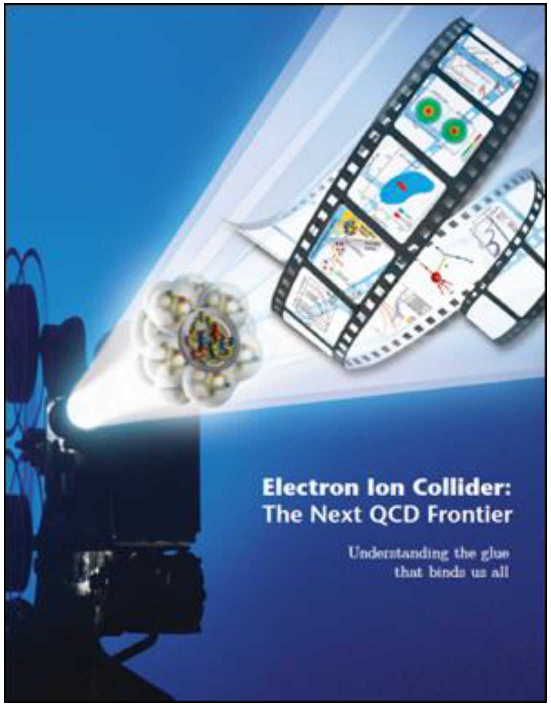
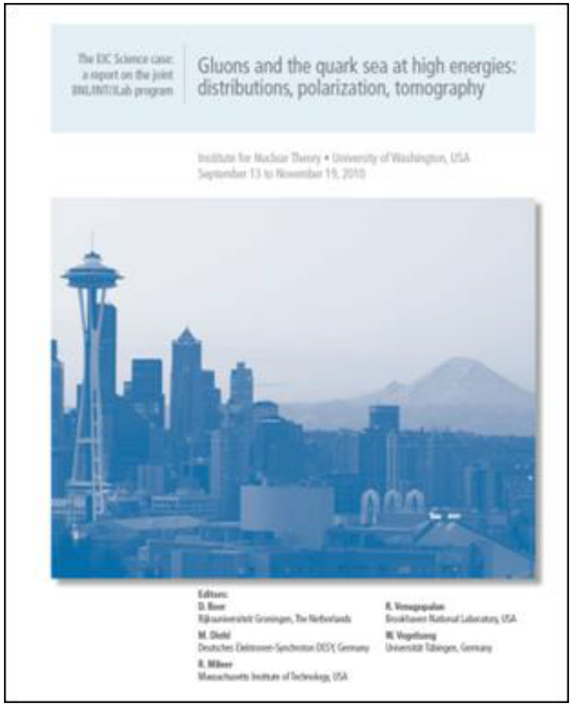
Outline

- Introduction
- The JLab EIC implementation
- Central detector
- Extended interaction region and detector integration

EIC physics program



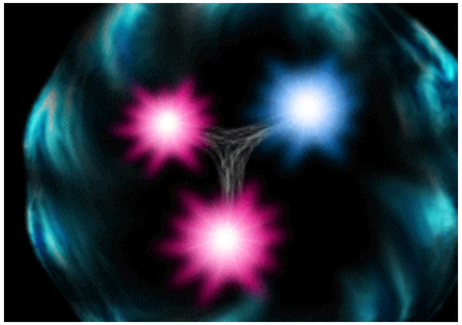


- The EIC at JLab supports the full physics program for a generic EIC
  - White paper, INT report, etc
- The JLab EIC implementation offers some unique capabilities
  - Detector integration is a key feature

EIC physics highlights

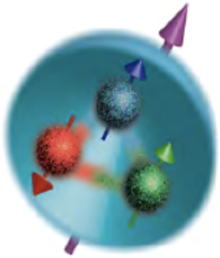
- 3D structure of nucleons is not trivial

  How do gluons and quarks bind into 3D hadrons?



- Orbital motion and gluon dynamics play a large role in the proton spin

  Why do quarks contribute only ~30%?

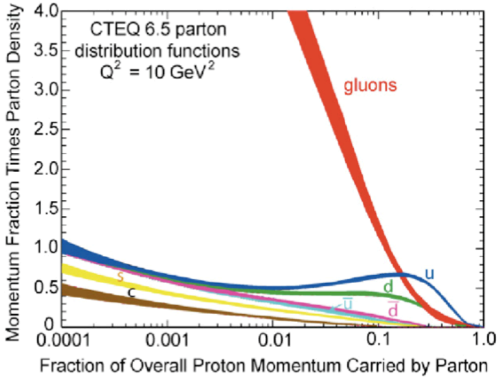


- Gluons in nuclei (light and heavy)

  ➔ *Talk on spectator tagging with light polarized nuclei on Thursday*

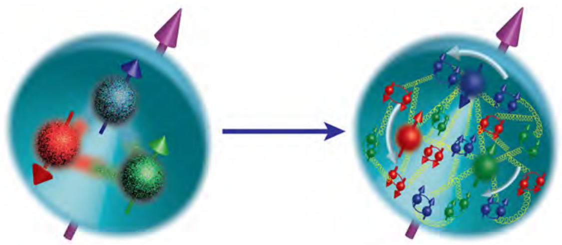
  Does the gluon density saturate at small x?

  Impact parameter dependence of Q_s ? (from fragment detection)



The spin of the proton

➔ *Introductory talk by Jianwei Qiu*



The number ½ reflects both intrinsic parton properties and their interactions

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

quarks: polarization + orbit; gluons: polarization + orbit

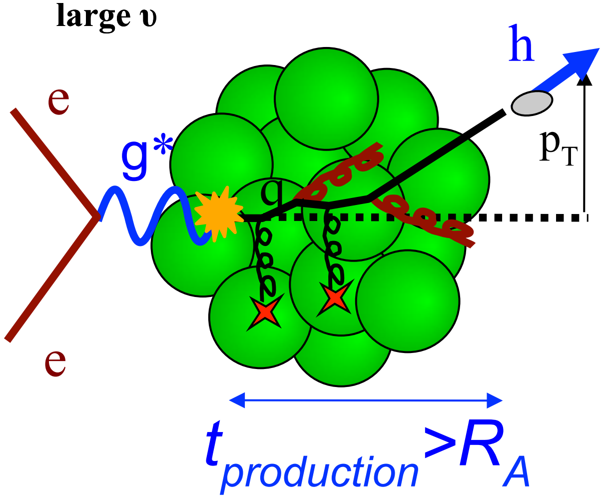
- Two complementary approaches required to resolve the spin puzzle

  Measure ΔG - gluon polarization (longitudinal structure)

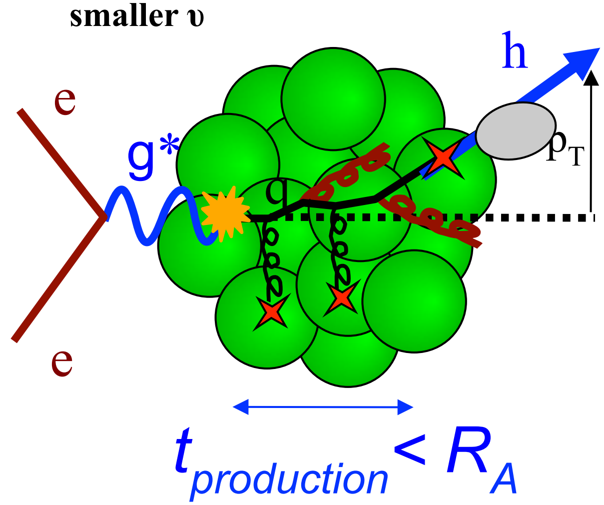
  Measure TMD and GPDs - orbital motion (3D structure)

Quark propagation in matter

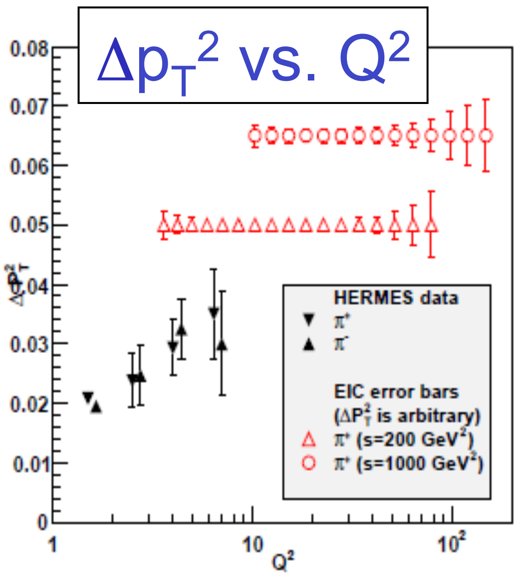
large υ



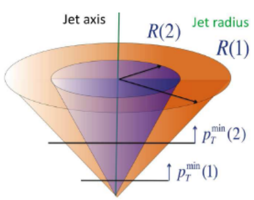
smaller υ



Accardi, Dupre

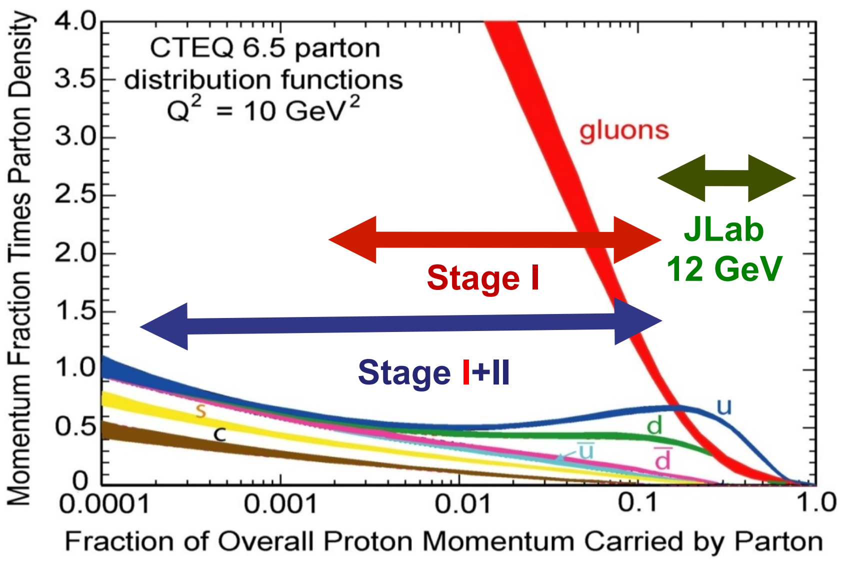


- Broadening of p_T distribution
- Heavy flavors: B, D mesons, J/Ψ
- Hadron jets at s > 1000 GeV^2
- *Impact parameter dependence?*
  - *Fragments and "wounded nucleons" can help understanding the path length*

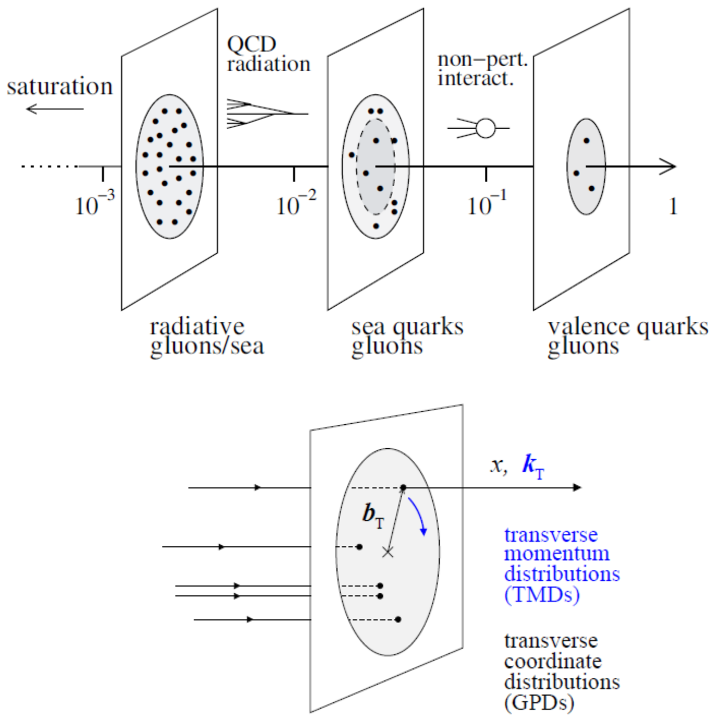


Energy staging

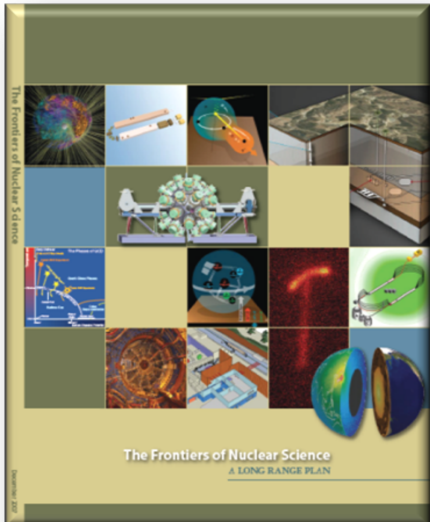
- JLab 12 GeV: valence quarks
- EIC stage I (MEIC): non-perturbabative sea quarks and gluons
- EIC stage II: extends coverage into radiation-dominated region



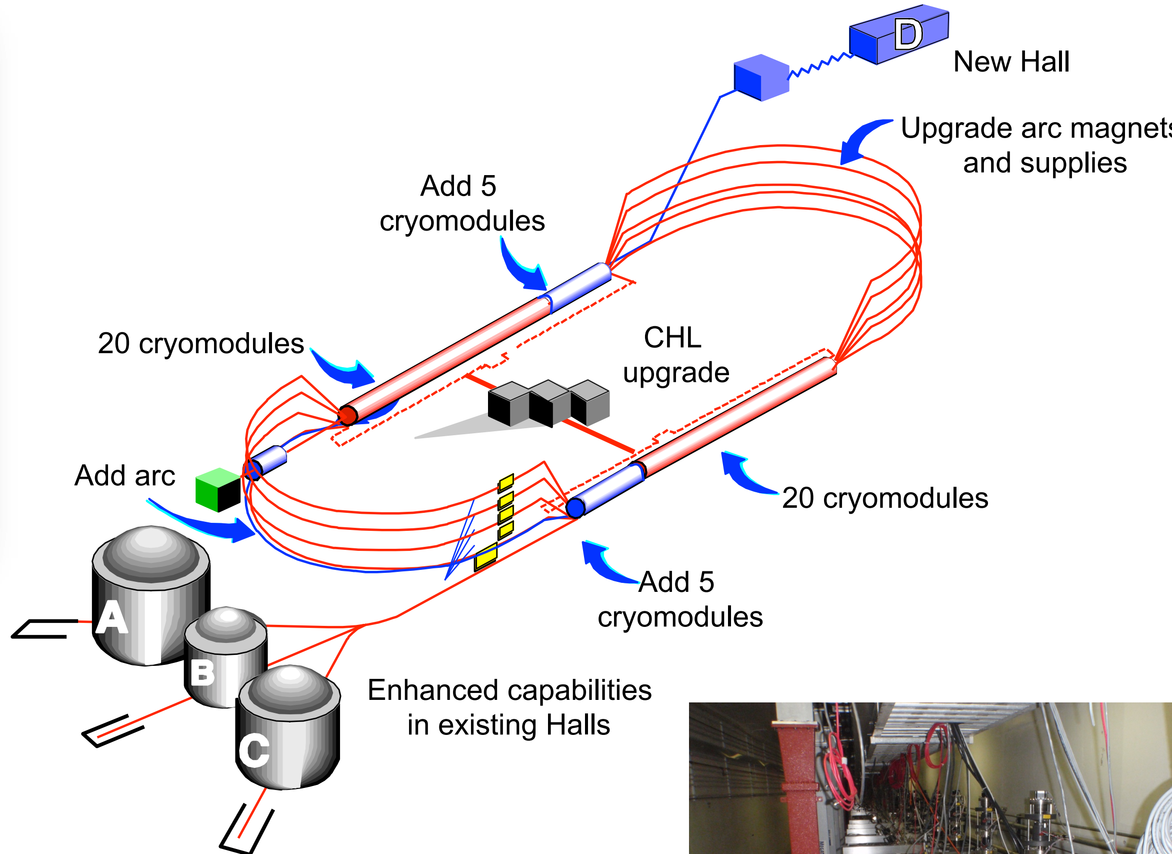
The MEIC (JLab stage I) provides excellent performance for all x and Q^2 between JLab 12 GeV and HERA (or a future LHeC)



JLab 12 GeV upgrade

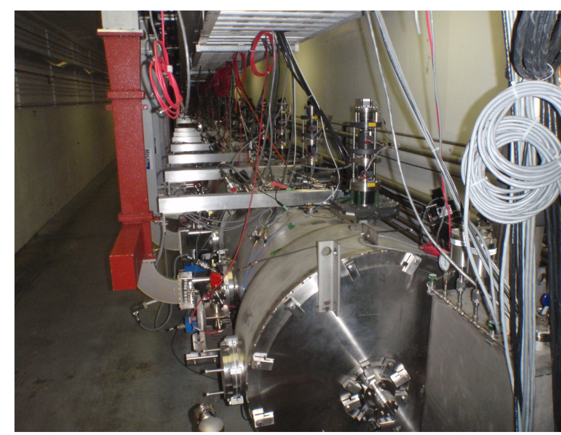


The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan.



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

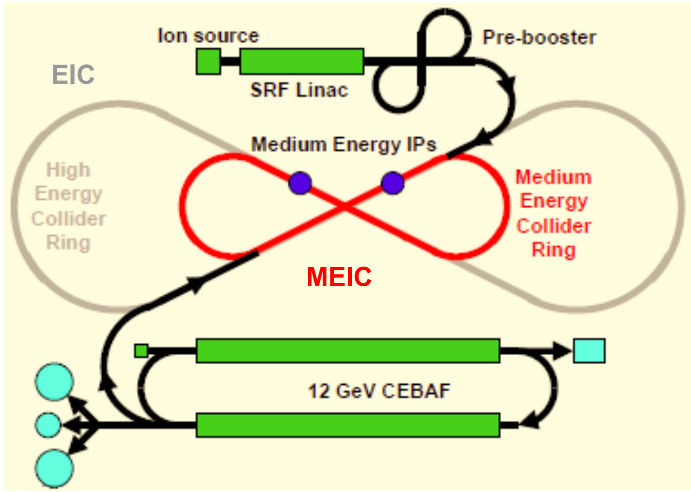
New C100 cryomodules in linac tunnel

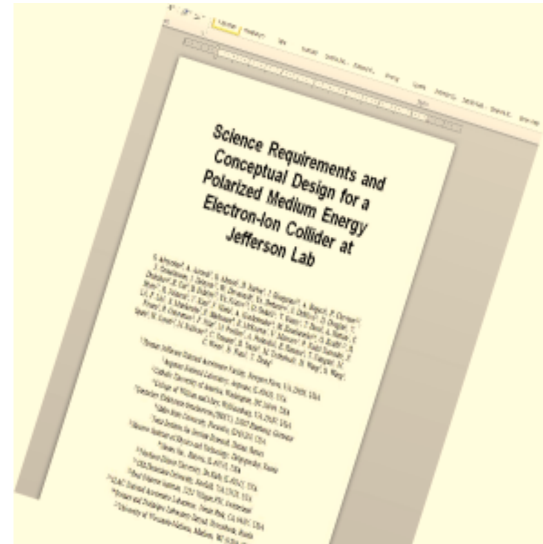


The EIC at JLab

- 12 GeV CEBAF is a full-energy lepton injector
  - Parallel running with fixed target possible
- MEIC and CEBAF both 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 ePHENIX*

MEIC – specific design goals




Science Requirements and Conceptual Design for a Polarized Medium Energy Electron-Ion Collider at Jefferson Lab

(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

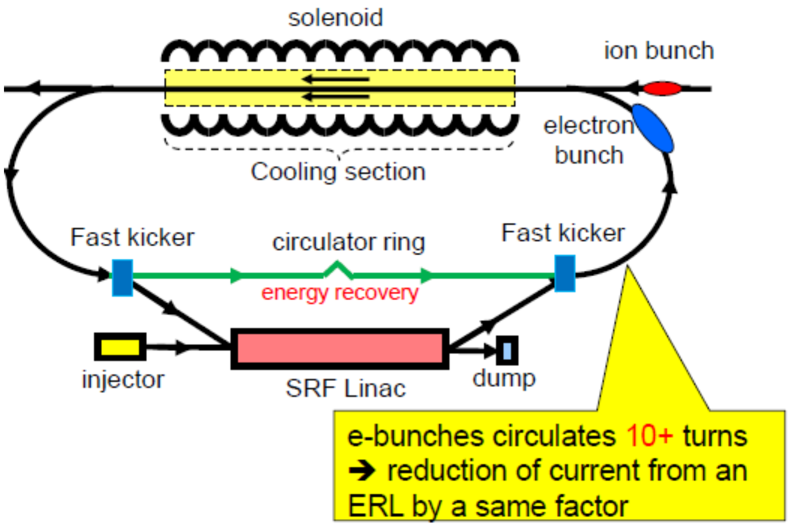
MEIC luminosity at 50 and 100 GeV

		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*	$cm^{-2}s^{-1}$	**2.4×10^{33}**		**8.3×10^{33}**	

* Includes space-charge effects and assumes conventional electron cooling

Red indicates parameters specific to the full-acceptance detector

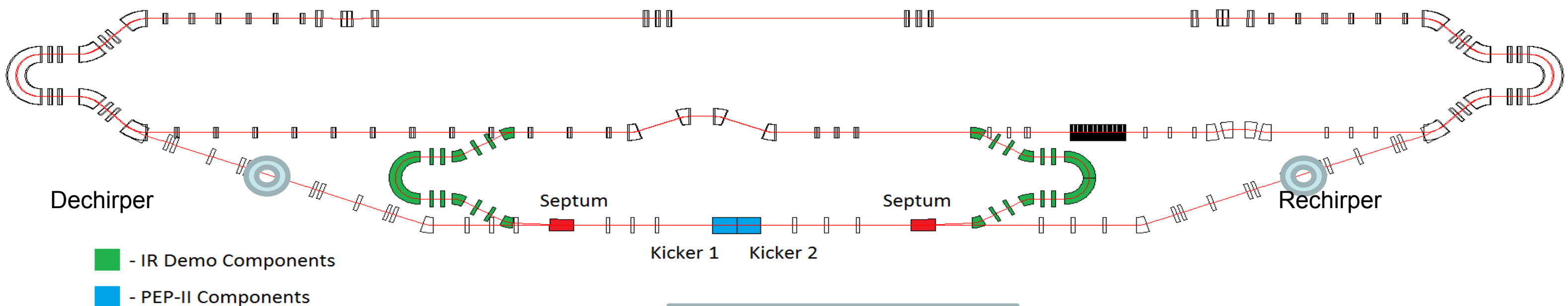
Conventional electron cooling (55 MeV)



- Electron cooling using an accelerating high-voltage is a well-established technique
- A single-pass Energy-Recovery Linac (ERL) allows reaching higher current and energy

  55 MeV is required for 100 GeV protons

- A circulator ring is not needed for the ready-to-build MEIC cooling scheme, but would reduce (unpolarized) source current.
- Circulator tests are planned at the JLab Free-Electron Laser (FEL) ERL

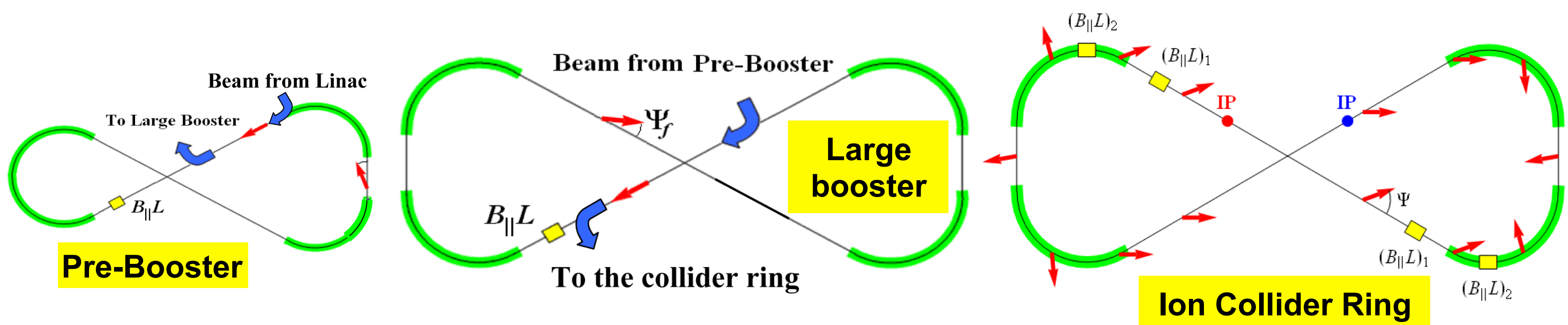


Cooler Test Facility @ JLab FEL ERL

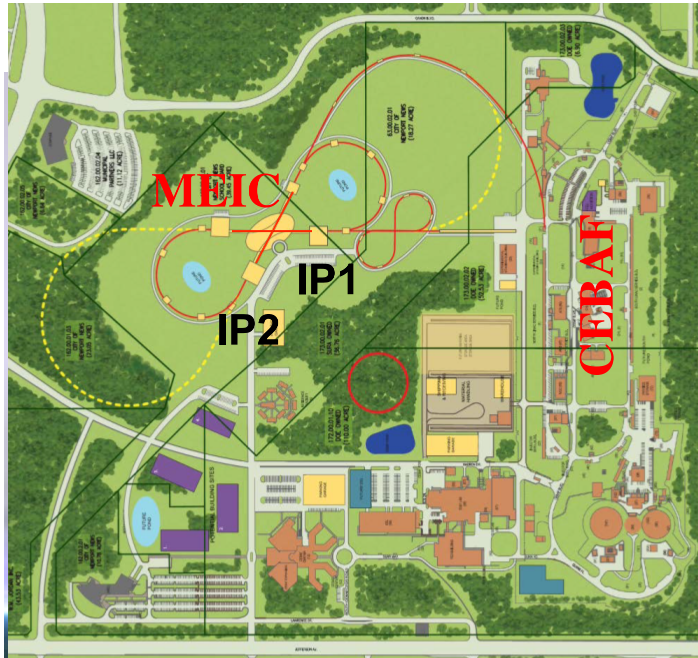
Polarization in a figure-8 ring

- Science program requires highly polarized electrons and light ions (p, D, ^{3}He, Li, ...)
- All MEIC rings have a figure-8 shape, which offers several important features
  - Spin precessions in the left & right parts of the ring are exactly cancelled
  - Net spin precession (***spin tune***) is zero, thus energy independent
  - Spin is easily controlled and stabilized by small solenoids or other compact spin rotators
- The figure-8 shape provides advantages for both ions and electrons
  - Ion spin preservation during acceleration for all ion species
  - Easy spin manipulation over multiple interaction points
  - Only practical way to accommodate **polarized deuterons** (very small g-2)
  - Strong reduction of quantum depolarization due to energy independent spin tune

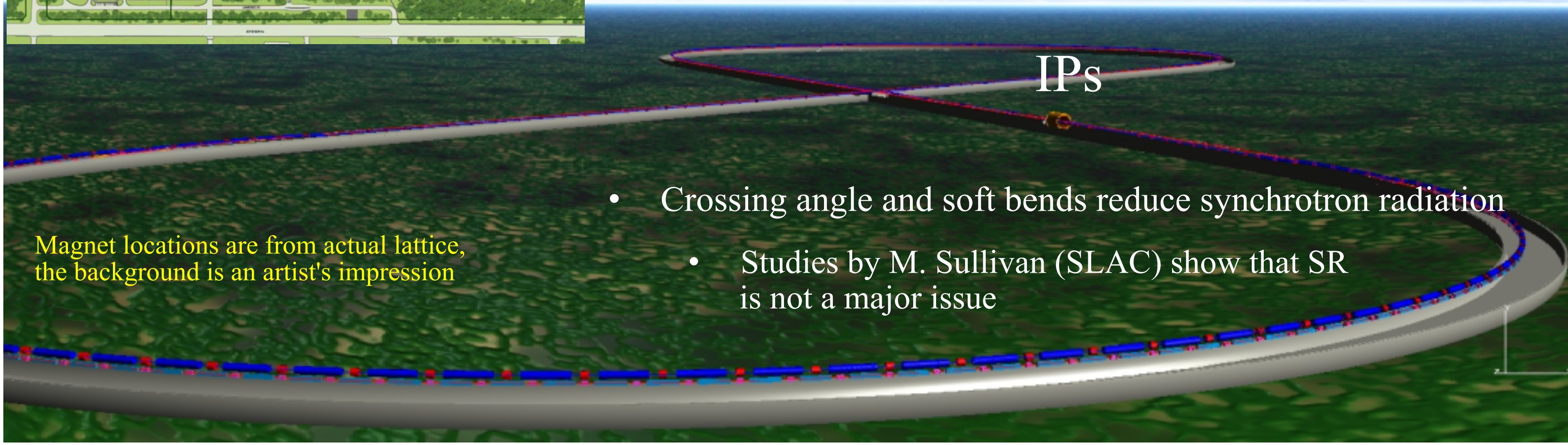
    Helps to preserve polarization of the top-off electrons injected from CEBAF every minute



Detector locations and backgrounds



- IP locations reduce synchrotron- and hadronic backgrounds
  - *Far* from arc where electrons exit (synchrotron)
  - *Close* to arc where ions exit (hadronic)
- Scaling from HERA (pp cross section, multiplicity, current) suggest comparable hadronic background at similar vacuum
  - Should be possible to reach better vacuum (early HERA: 10^{-7} torr, PEP-II/BaBar: 10^{-9} torr)
  - MEIC luminosity is more than 100 times higher
  - *Signal-to-background (random hadronic)* should be 10^3-10^4 times better



Magnet locations are from actual lattice, the background is an artist's impression

- Crossing angle and soft bends reduce synchrotron radiation
  - Studies by M. Sullivan (SLAC) show that SR is not a major issue

Detector development overview

- Central Detector – evolutionary
  - Basic requirements and technologies/solutions understood
  - Need to optimize performance and cost of subsystems
  - Use innovative design features to relax specs and/or improve performance

    Large crossing angle, dual solenoid
  - Important to explore full phase space of technologies/configurations
  - Ultimately, we would want to have two complementary detectors

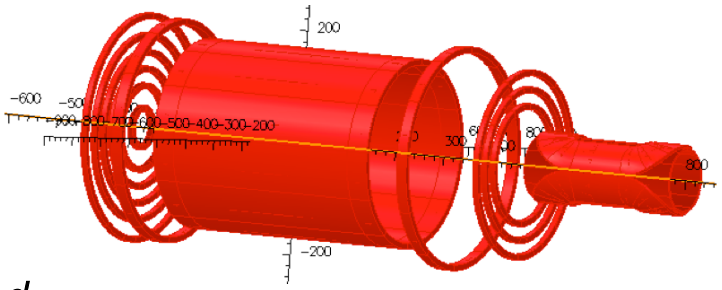
    At the MEIC both can run simultaneously without beam time sharing
- Small-angle hadron and electron detection – new opportunities
  - Accelerator integration is the highest priority

    Allows the storage ring to be designed around the detector needs
  - Novel design allows reaching unprecedented acceptance and resolution
- Detector R&D – in collaboration with BNL
  - Most detector technologies can be applied both at JLab and BNL
  - The Generic Detector R&D for an EIC program is open to everyone!

Central detector solenoid options

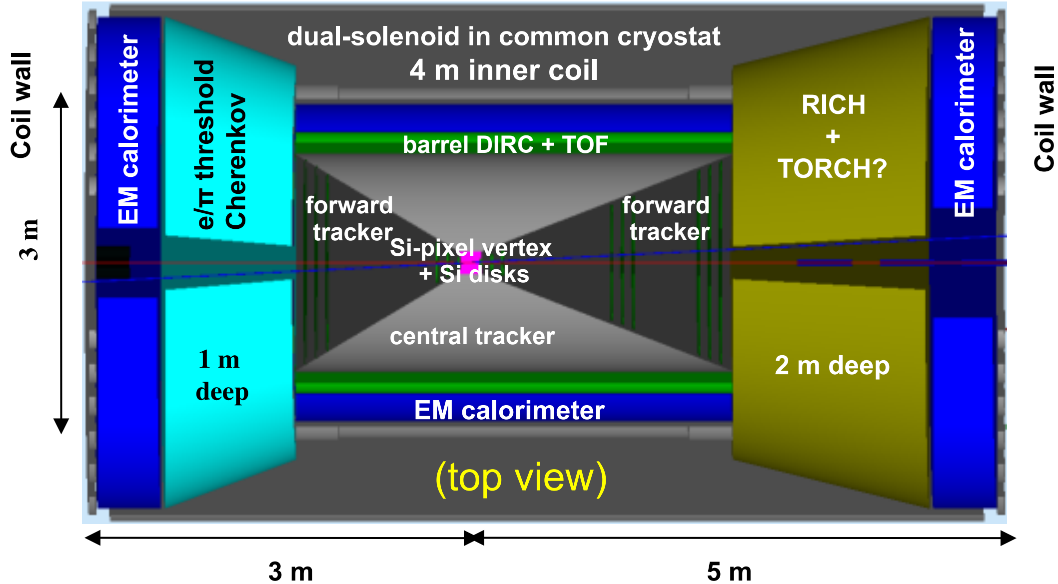
- Existing magnets
  - The CLEO and BaBar would be suitable for use in the MEIC at either IP
  - The magnets are very similar:
    4 m long, 3 m diameter, 1.5 T field, iron yoke
  - In the near term it is planned to use the CLEO magnet for SoLID at JLab, and BaBar for an upgrade to PHENIX at BNL
    Both should be in good condition and available for use in the EIC

- Option: iron-free dual solenoid for IP1
  - Inner and outer solenoids have opposite polarity
    Space in-between provides an iron-free flux return
  - Proposed for the ILC 4th detector concept
  - **Advantages:** *light weight, high field (3 T), improved endcap acceptance, compact endcaps (coils instead of iron), easy detector access, low external field, precise internal field map (no hysteresis)*
  - Ideal for a detector optimized for SIDIS and exclusive processes
  - Initial (magnetic) design is ready



TOSCA model of the dual solenoid showing inner solenoid, shaping coils, endcap coils, and one possible version of the forward dipole. The outer solenoid is not shown.

Central detector design



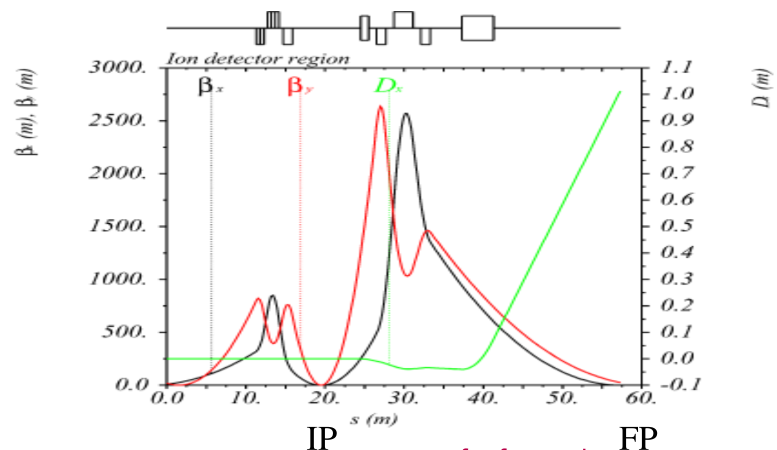
- Dual-solenoid-based detector in GEMC (a GEANT4 package also used for JLab 12 GeV)
- Configuration shown with forward- and central trackers based on micropattern gas detectors (GEM/micromegas).
- Central tracker could also include a low-mass, cluster-counting, He-filled drift chamber (ILC 4th concept).

- **Primary focus:** One detector compatible with the full-acceptance interaction region, optimized for SIDIS and exclusive reactions
- Current tracker layout is compatible with both a dual solenoid and the CLEO magnet (but the latter would restrict the endcaps)
- A 2nd detector could use a TPC and focus on hadronic calorimetry (jets)
- An explicit design of the 2nd IR will begin soon.

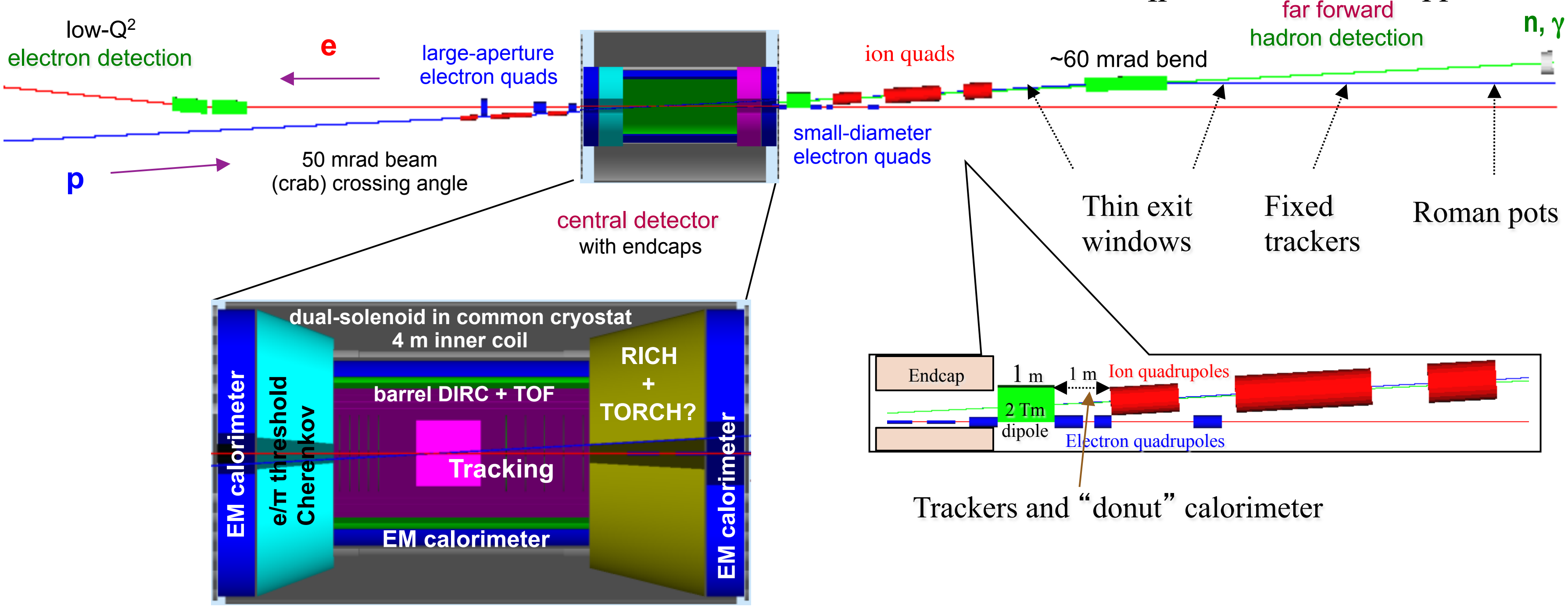
The MEIC *full-acceptance* detector

Design goals:

1. Detection/identification of complete final state
2. Spectator p_T resolution << Fermi momentum
3. Low-Q^2 electron tagger for photoproduction

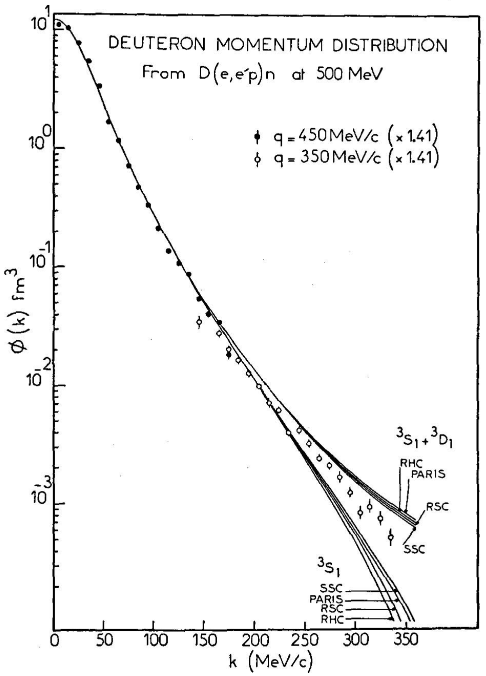


(from GEANT4, top view)



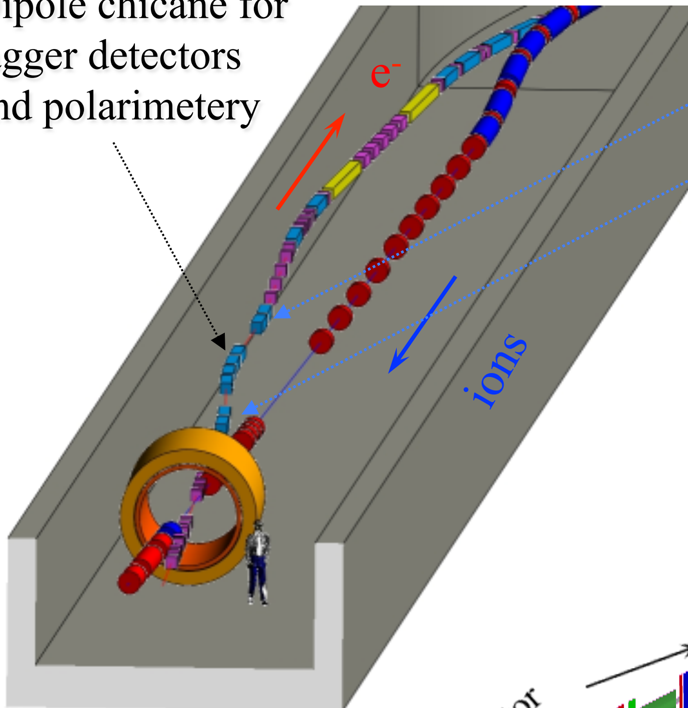
Forward detection – processes

- Recoils in exclusive (diffractive) processes
  - Recoil baryons
    - *Large t (p_T) range and good resolution desirable*
  - Coherent nuclear processes
    - *Good small-p_T acceptance extends detectable mass range*
    - *Suppression of incoherent background for heaviest nuclei through detection of all fragments and photons*
- Partonic fragmentation in SIDIS
  - Correlations of current and target jets
  - Decays of strange and charmed baryons
- Nuclear spectators and fragments
  - Spectator tagging with polarized light ions
    - *p_T resolution < Fermi momentum*
  - Final state in heavy-ion reactions
    - *Centrality of collision (hadronization, shadowing, saturation, etc)*
- Heavy flavor photoproduction (low-Q^2 electron tagging)

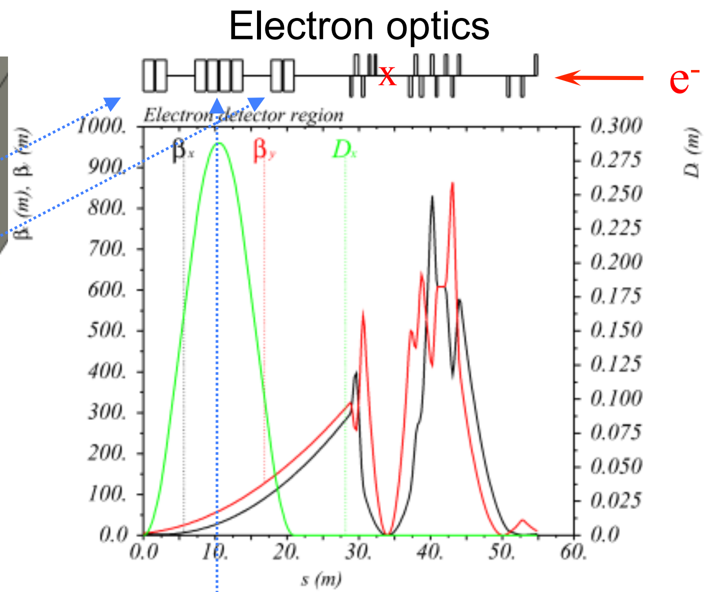


Low-Q^2 electron tagger

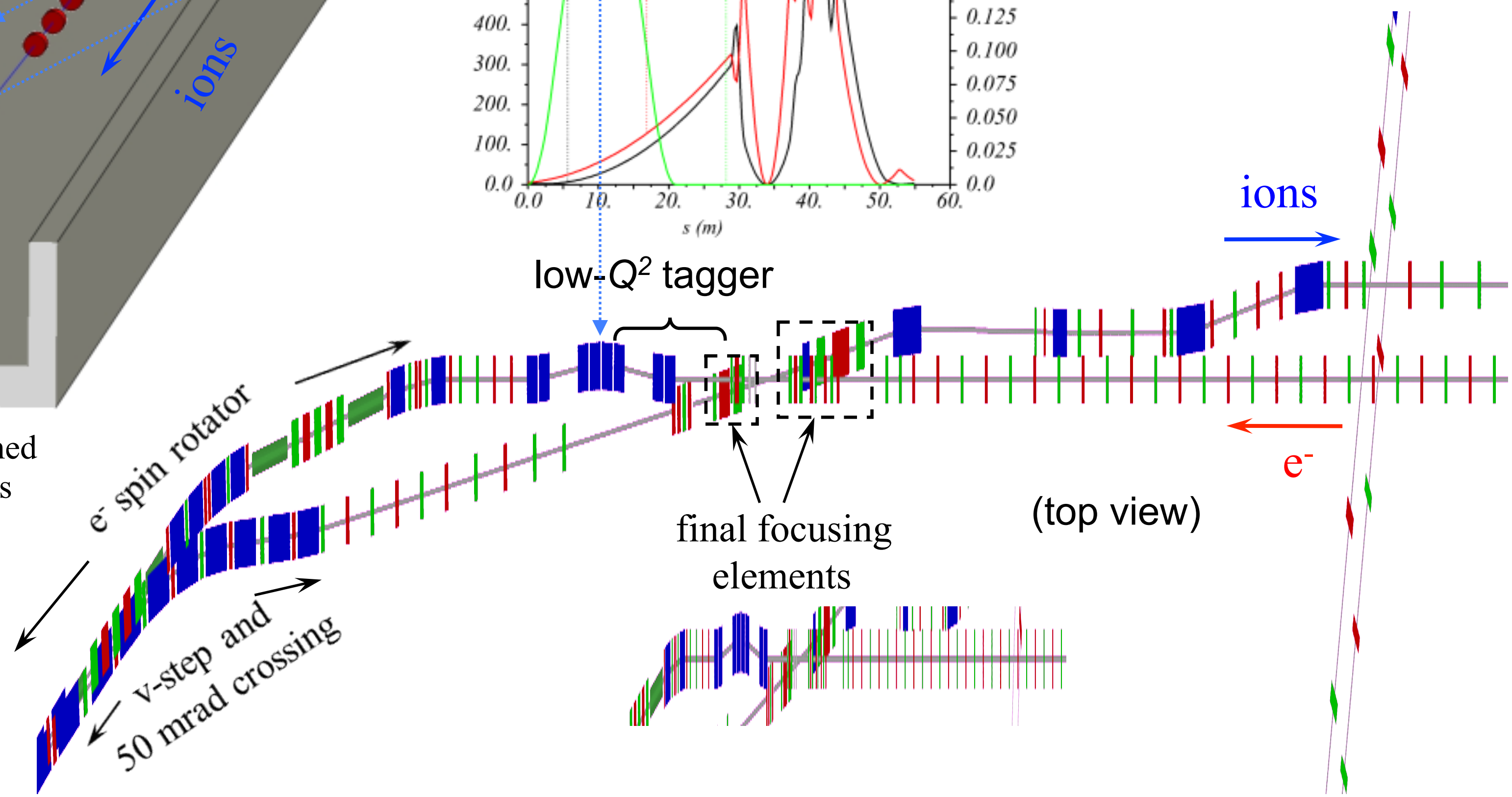
Dipole chicane for tagger detectors and polarimetery



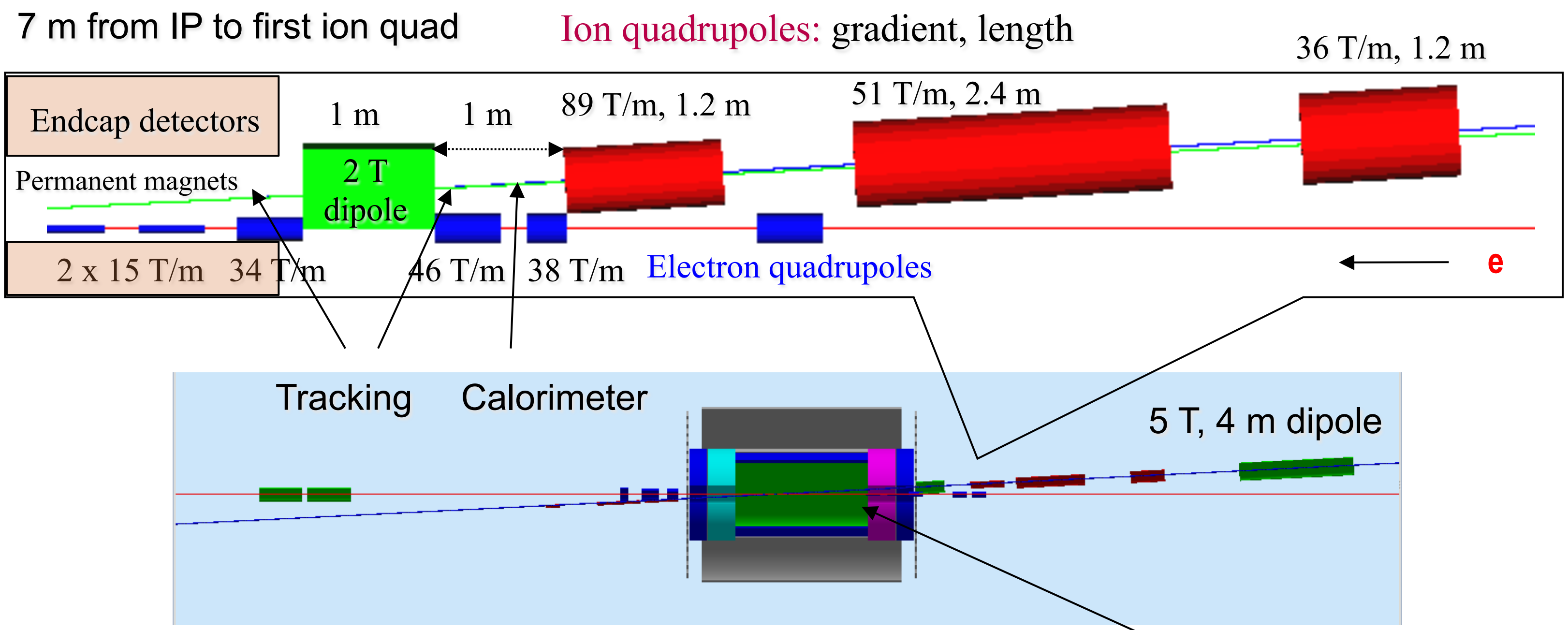
Electron beam aligned with solenoid axis

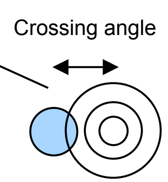


The tagger chicane will have a Compton polarimeter and be instrumented for luminosity monitoring.



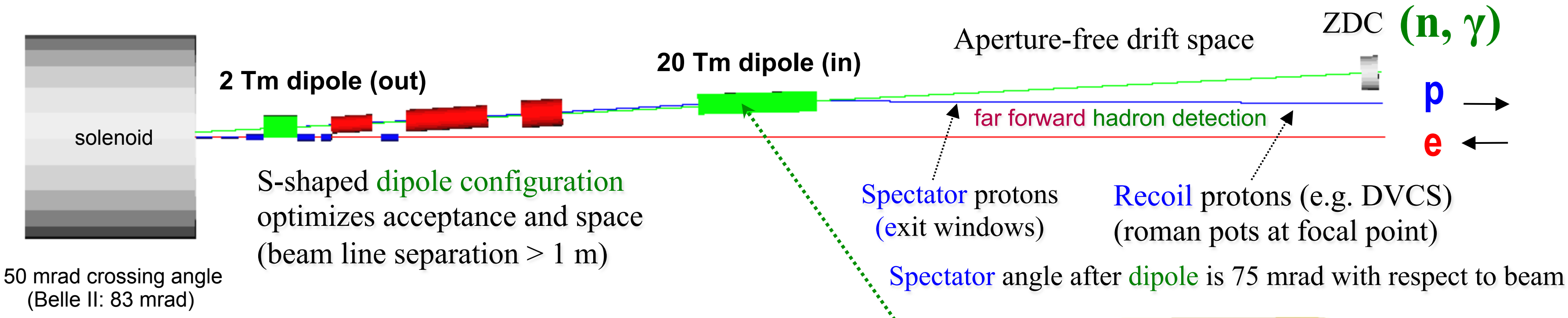
Forward detection *before* ion quads

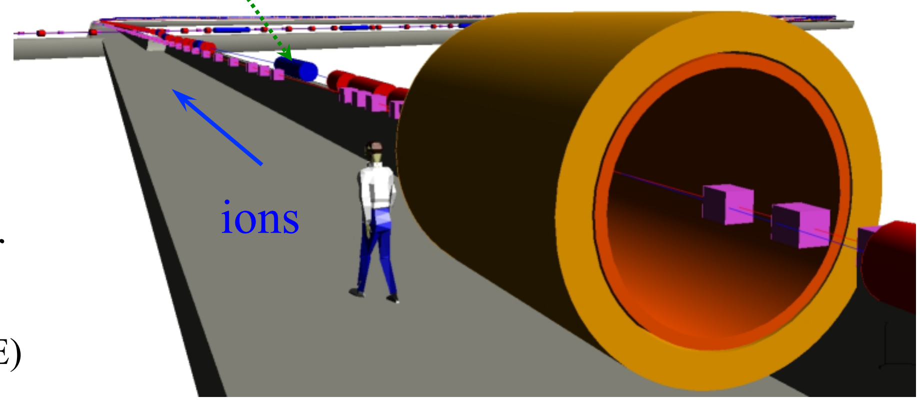




- 50 mrad crossing angle
  - Moves spot of poor resolution along solenoid axis into the periphery
  - Minimizes shadow from electron FFQs
- Dipole before quadrupoles further improves resolution in the few-degree range
- Low-gradient quadrupoles allow large apertures for detection of *all* ion fragments
  - **Peak field** = quad **gradient** x aperture **radius**

Forward detection *after* ion quads



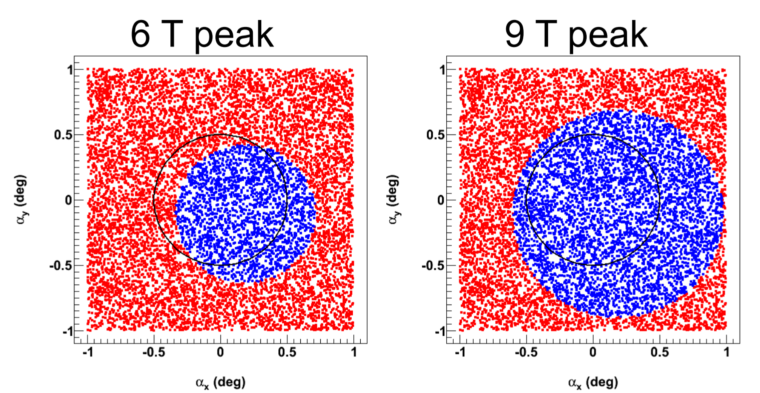


- S-shaped transport optimizes acceptance for both neutrals and charged particles.
- Lots of space for Zero-Degree Calorimeter (ZDC) on the outside of the ring
  - EMcal and high-resolution Hcal (~30%/√E)

    CERN RD52 "DREAM" or particle flow type
- Quad acceptance for neutrals depends on peak field (6 T baseline), but in ±10 mrad range.

Red: **neutrals** detected *before* ion quadrupoles

Blue: **neutrals** detected *after* ion quadrupoles



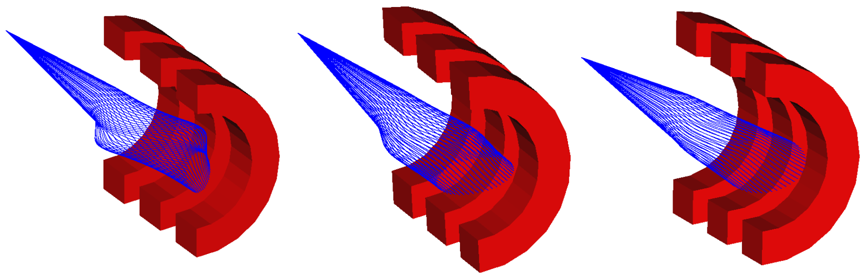
Far-forward detection summary

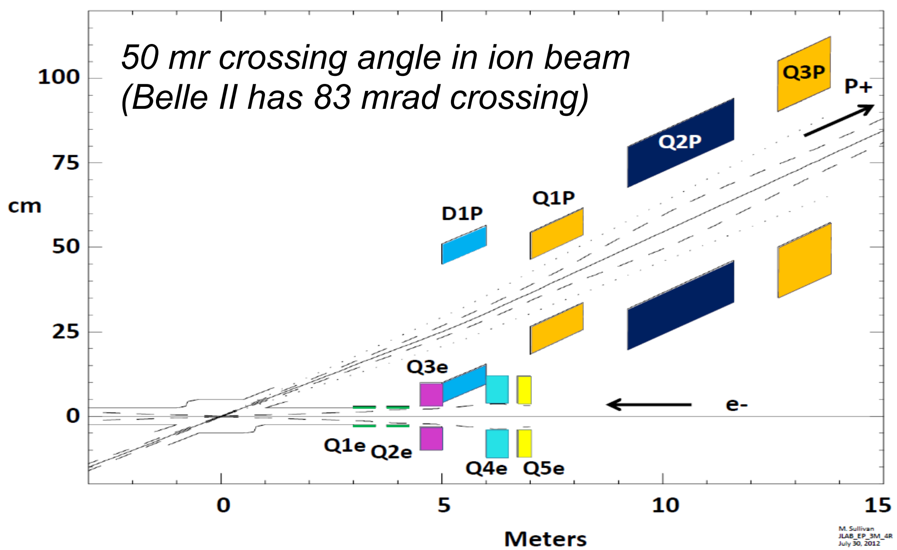
- Good acceptance for *all* ion fragments – *rigidity different from beam*
  - **Large magnet apertures** (*i.e.*, small gradients at a fixed maximum peak field)
  - *Roman pots not needed for spectators and high-p_T fragments*
- Good acceptance for low-p_T recoils – *rigidity similar to beam*
  - **Small beam size** at detection point (downstream focus, efficient cooling)
  - **Large dispersion** (generated *after* the IP, D = D' = 0 at the IP)
  - With a 10σ beam size cut, the low-p_T recoil proton acceptance at the MEIC is:
    - **Energy:** up to **99.5%** of the beam for *all angles*
    - **Angular *(θ)*:** down to **2 mrad** for *all energies*
- Good momentum- and angular resolution
  - Should be limited only by initial state (beam). At the MEIC:
    - ***Longitudinal (dp/p): 4x10^{-4}***
    - ***Angular (θ, for all φ): 0.2 mrad***
    - ***~15 MeV/c resolution for a tagged 50 GeV/A deuterium beam!***
  - Long, instrumented drift space (no apertures, magnets, etc)
- Sufficient beam line separation (~ 1 m)

Fragment acceptance

proton-rich fragments
"spectator protons from ^2H"

neutron-rich fragments
"tritons from N=Z nuclei"

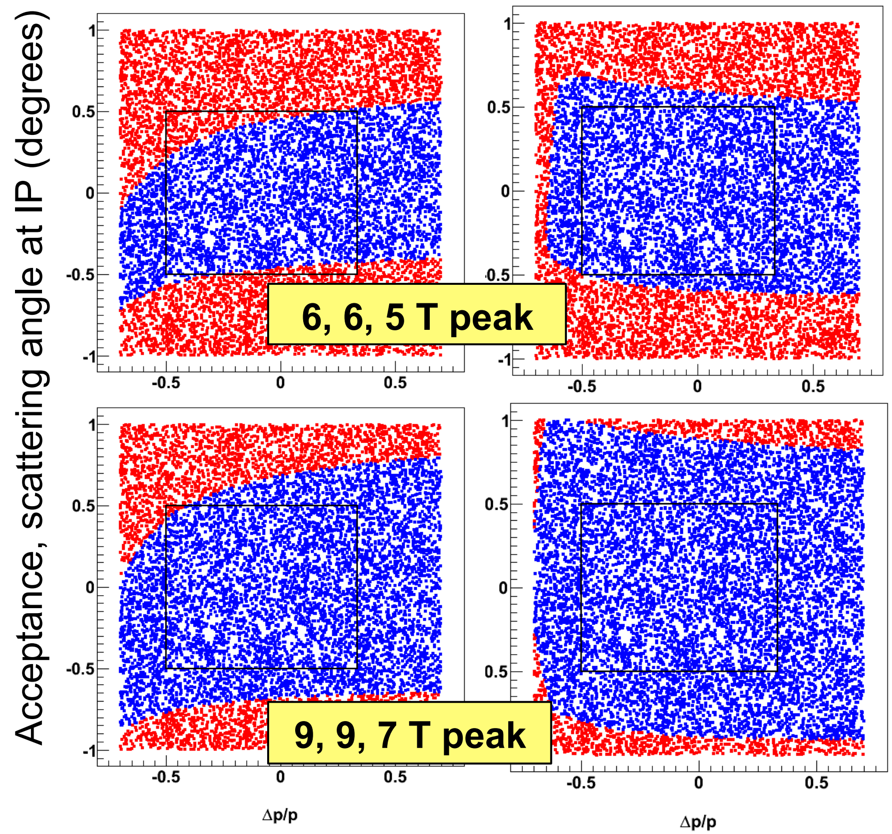




- Baseline: Q1p and Q2p with 6 T peak fields

Forward acceptance vs.magnetic rigidity

horizontal plane | **vertical plane**

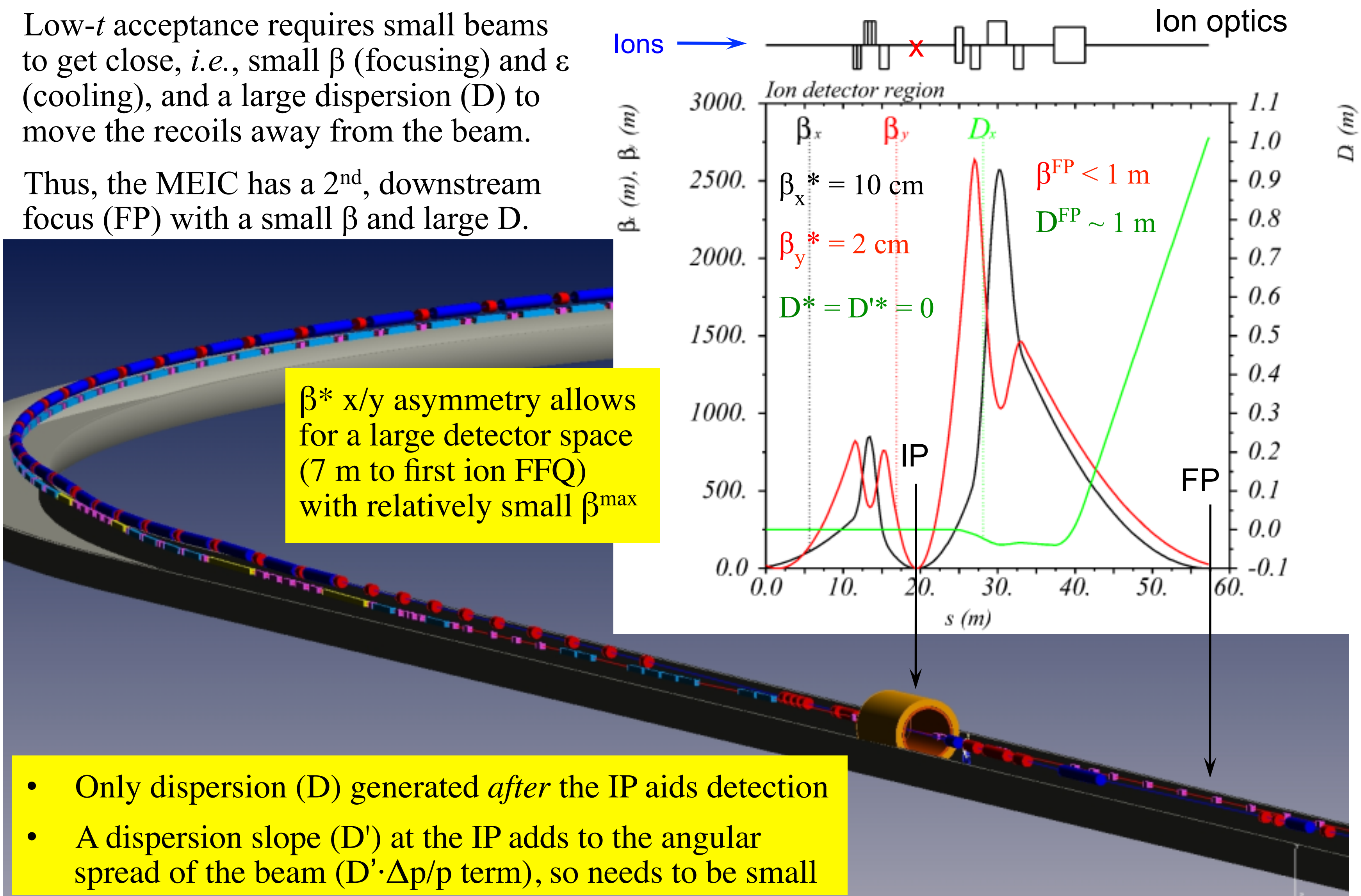


Red: Detection *before* ion quadrupoles

Blue: Detection *after* ion quadrupoles

Low-t (p_T) recoil baryon acceptance

- Low-t acceptance requires small beams to get close, *i.e.*, small β (focusing) and ε (cooling), and a large dispersion (D) to move the recoils away from the beam.
- Thus, the MEIC has a 2nd, downstream focus (FP) with a small β and large D.



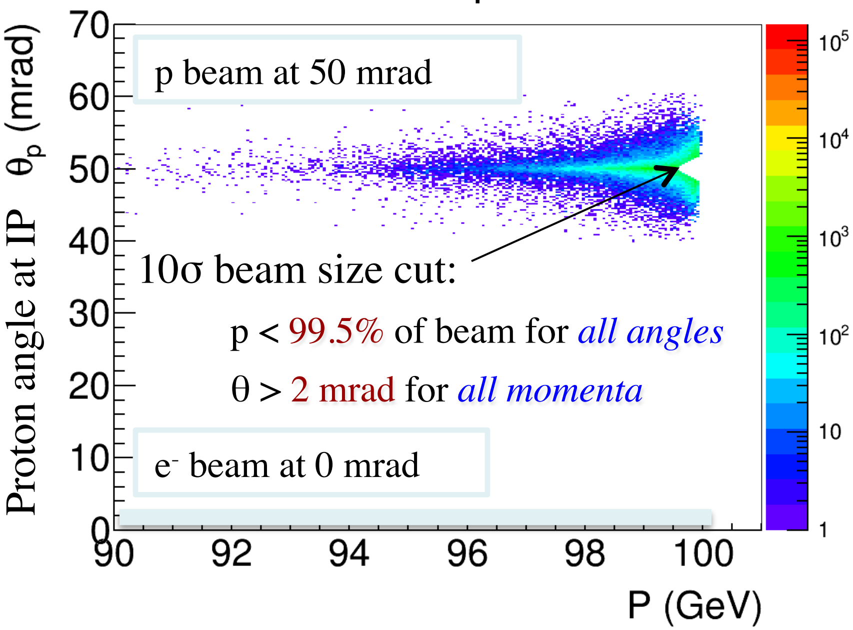
β^* x/y asymmetry allows for a large detector space (7 m to first ion FFQ) with relatively small β^{max}

- Only dispersion (D) generated *after* the IP aids detection
- A dispersion slope (D') at the IP adds to the angular spread of the beam (D'·Δp/p term), so needs to be small

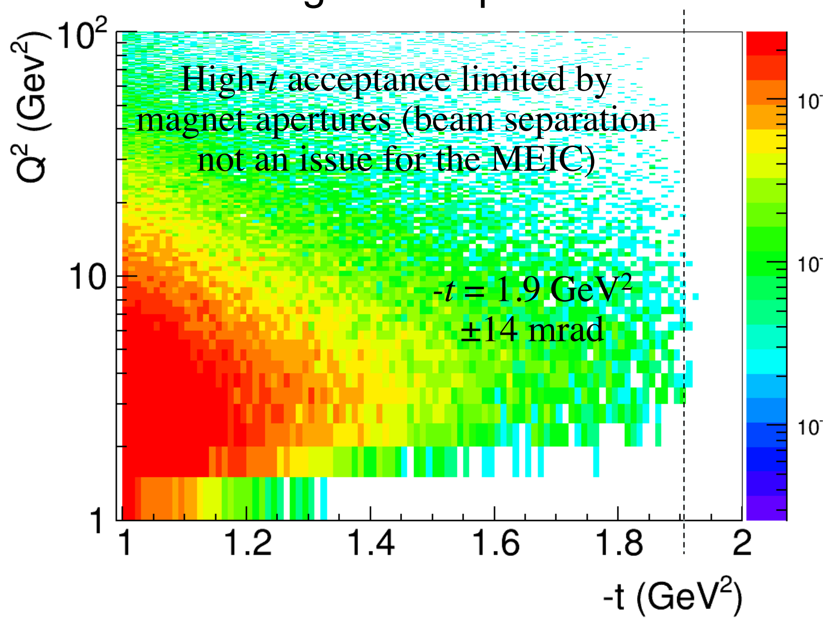
DVCS recoil proton acceptance

- **Kinematics:** 5 GeV e^- on 100 GeV p at a crossing angle of 50 mrad.
  - Cuts: $Q^2 > 1$ GeV^2, $x < 0.1$, $E'_e > 1$ GeV, recoil proton 10σ outside of beam
- **DVCS generator:** MILOU (from HERA, courtesy of BNL)
- **GEANT4 simulation:** tracking through all magnets done using the JLab GEMC package

low-*t* acceptance



high-*t* acceptance



- Recoil proton angle is independent of electron beam energy: $\theta_p \approx p_T/E_p \approx \sqrt{(-t)}/E_p$
- The wide angular distribution at E_p = 100 GeV makes precise tracking easier

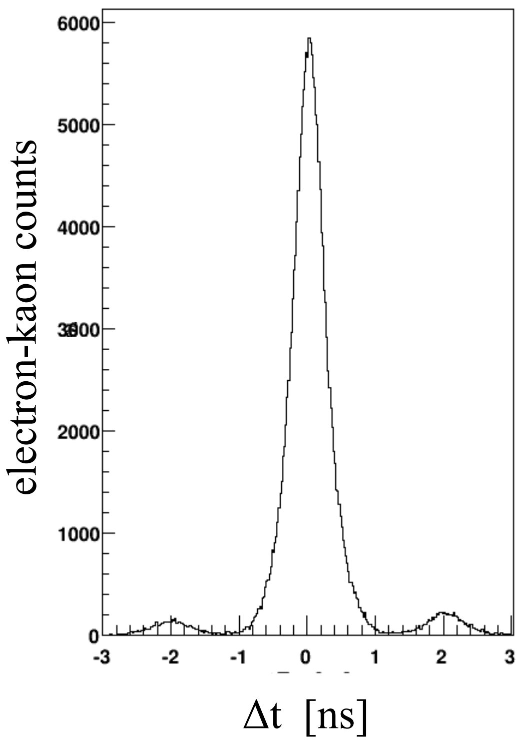
Bunch spacing and identification

- Existing detectors (CLAS, BaBar, etc) at machines with high bunch crossing rates have not had problems in associating tracks with a specific bunch.
  - Having more bunches lowers the average number of collisions per crossing

- Example: CLAS detector at JLab 6 GeV
  - 2 ns bunch spacing (500 MHz rep. rate)
  - 0.2 ns TOF resolution (0.5 ns FWHM)
  - The figure shows time matching of kaons in CLAS with electrons in the (low-Q^2) tagger, in turn matched to the accelerator RF signal

    The 2 ns bunch structure is clearly resolved
  - CLAS12 aims at a TOF resolution of 80 ps

K-e coincidence time in CLAS 6 GeV data



- The bunch spacing in the MEIC is similar to CLAS and most e^+e^- colliders
  - PEP-II/BaBar, KEKB/Belle: **8 ns**
  - Super KEKB/Belle II: **4 ns** *(2 ns with all RF buckets full)*
  - MEIC: **1.3 ns** [750 MHz]
  - CERN Linear Collider (CLIC): **0.5 ns** [2 GHz]

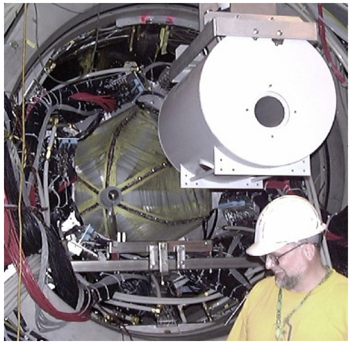
Asynchronous trigger

- The MEIC will use a "smart" asynchronous trigger and pipelined electronics
  - The MEIC L1 rate is expected to be comparable to GlueX (200 kHz)
    - *Low-Q^2 (photoproduction) events will be pre-scaled*
  - Simple tracking at L2 will suppress random background (not from vertex)
    - *Already planned for CLAS12*

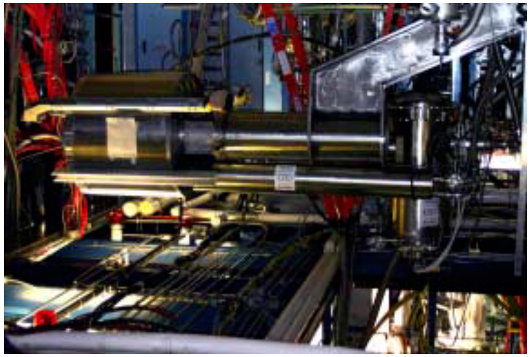
- Data-driven, asynchronous triggers are well-established
  - If the number of collisions of interest per bunch crossing is << 1, synchronizing the trigger to each RF clock cycle becomes inefficient
  - Sampling rate requirements for the pipelined electronics depend on signal properties and backgrounds, not the bunch crossing frequency
    - *JLab 12 GeV uses flash ADCs with 250 MHz (4 ns) sampling*
  - When a trigger condition is fulfilled (*e.g.*, e^- found), memory buffers are written to disk or passed to L3 (at PANDA signals will go directly to L3)
  - Correlations with the RF are made offline
  - T0 is obtained from tracking high-β particles (*e.g.*, electrons in CLAS)

Generic detector R&D – an example

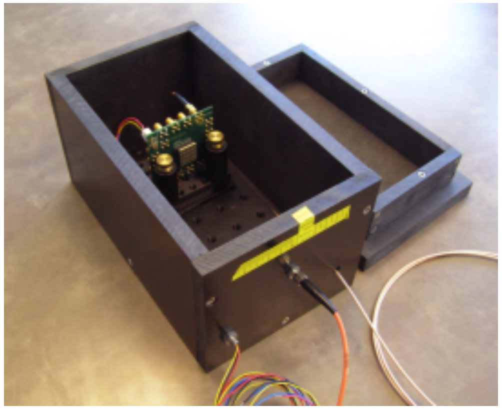
- As part of the R&D program, a new, permanent facility for tests of photosensors in high magnetic fields is being set up at JLab
  - Two 5T magnets provided by JLab
- MCP-PMTs (or LAPPDs) with small pore size (2-10 μm) could provide a radiation hard, low-noise, baseline sensor suitable for single photon detection (DIRC, RICH, etc).



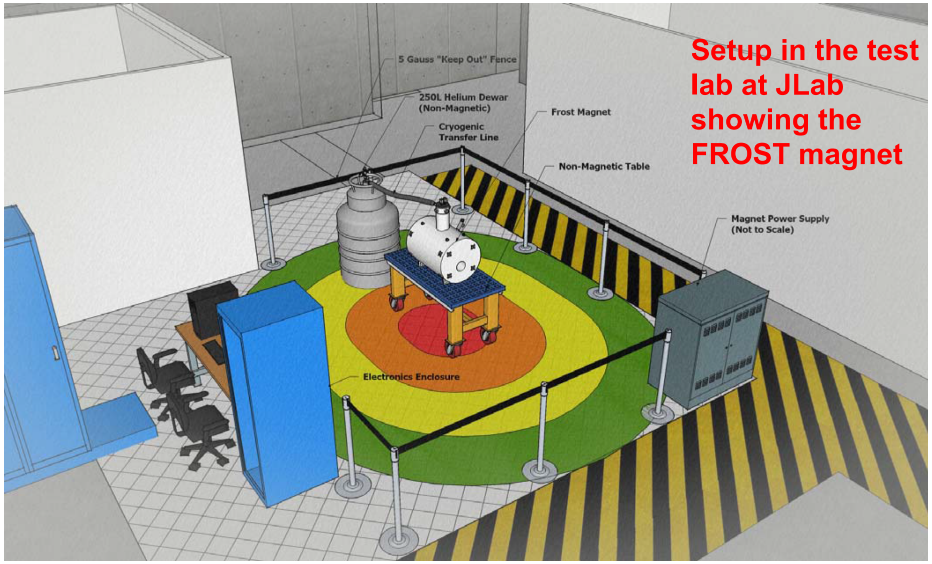
CLAS FROST solenoid with 5” bore



CLAS DVCS solenoid with 9” bore



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



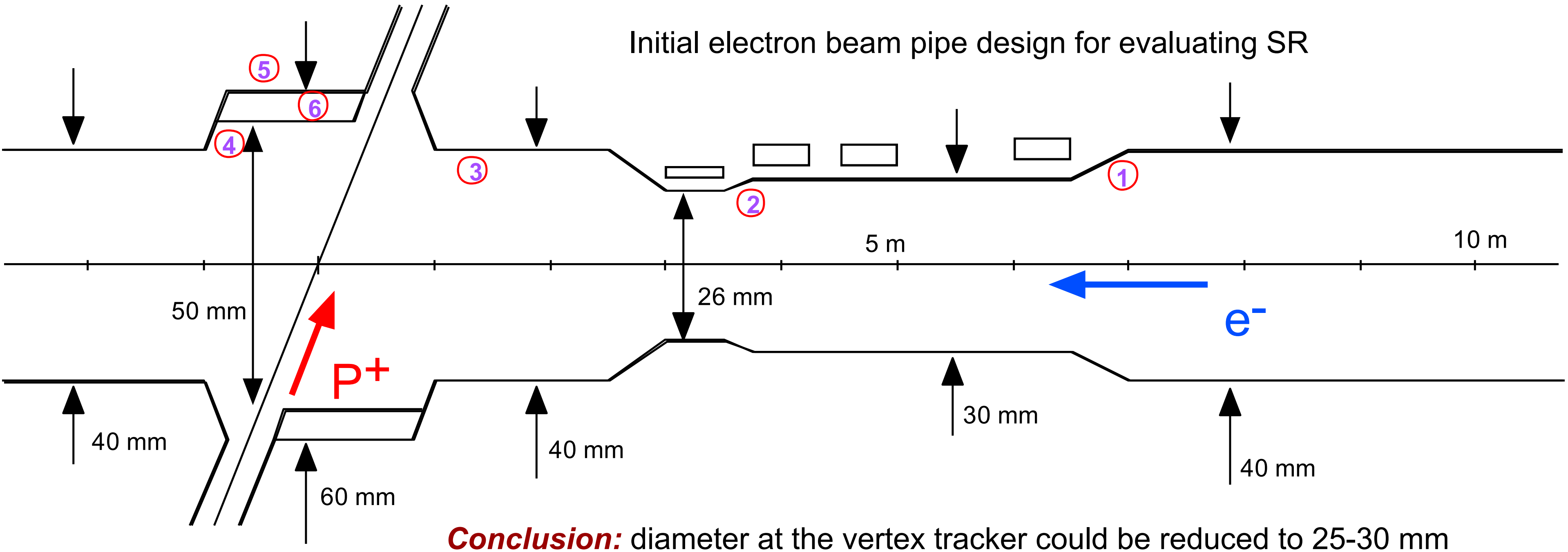
Setup in the test lab at JLab showing the FROST magnet

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

Backup

Synchrotron radiation background



Conclusion: diameter at the vertex tracker could be reduced to 25-30 mm

Surface:	1	2	3	4	5	6
Power (W) @ 5 GeV	3.0	5.7	0.2	0.8	-	0.03
γ >10 keV @ 5GeV	5.6×10^5	3.4×10^5	1.4×10^4	5.8×10^4	167	3,538
Power (W) @ 11 GeV	4.2	8.0	0.3	1.1	-	0.04
γ >10 keV @ 11 GeV	5.6×10^5	2.8×10^5	9.0×10^4	3.8×10^5	271	13,323

Photon numbers are per bunch

Simulation by M. Sullivan (SLAC)

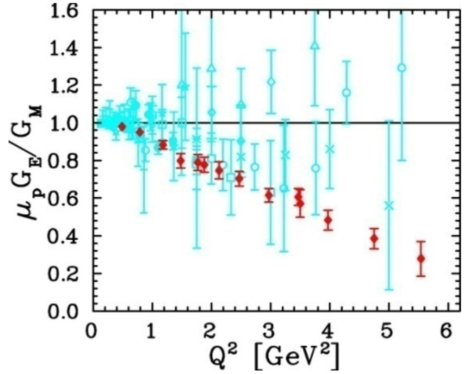
Hadronic backgrounds

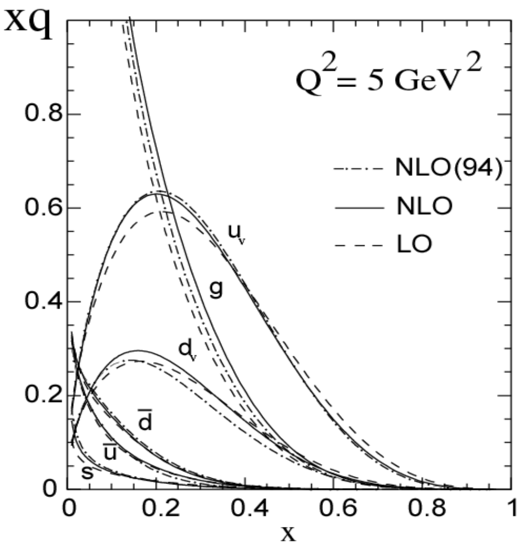
- Random hadronic background
  - Assumed to be dominated by scattering of beam ions on residual gas (mainly ^2H) in the beam pipe between the ion exit arc and the detector.
  - Correlated background from photoproduction events is discussed separately

- The conditions at the MEIC compare favorably with HERA
  - Typical values of *s* are 4,000 GeV^2 at the MEIC and 100,000 GeV^2 at HERA
  - Distance from arc to detector: 65 m / 120 m = 0.54
  - p-p cross section ratio σ(100 GeV) / σ(920 GeV) < 0.8
  - Average hadron multiplicity per collision $(4000 / 100000)^{1/4} = 0.45$
  - Proton beam current ratio: 0.5 A / 0.1 A= 5
  - At the *same vacuum* the MEIC background is 0.54 * 0.8 * 0.45 * 5 = 0.97 of HERA
  - But MEIC vacuum should be closer to PEP-II (10^{-9} torr) than HERA (10^{-7} torr)

- The signal-to-background ratio will be even better
  - HERA luminosity reached ~ 5 x 10^{31} cm^{-2}s^{-1}
  - The EIC (and the MEIC in particular) aims to be close to 10^{34} cm^{-2}s^{-1}

3D structure of the nucleon





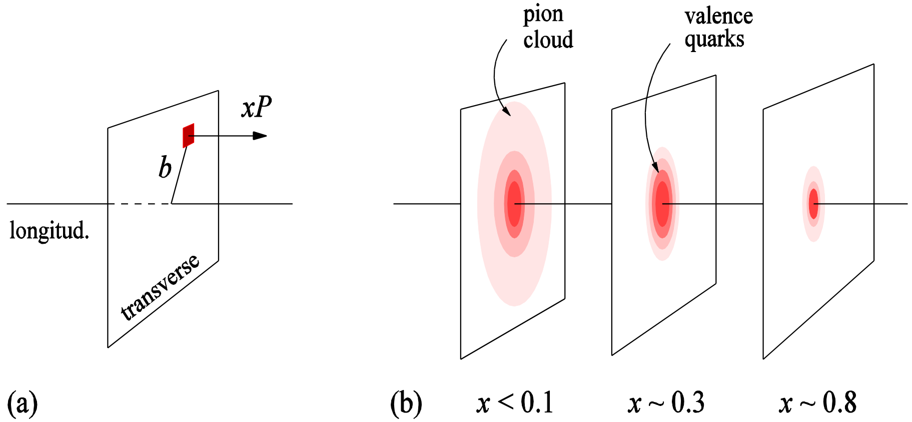
Elastic form factors

Transverse spatial distributions

(Naively Fourier transform of Q^2 or t)

Parton Distribution Functions

Longitudinal momentum distributions



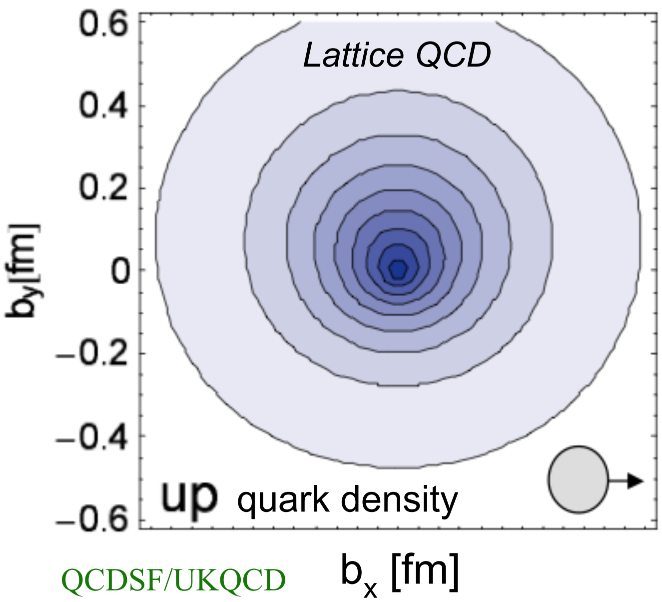
Generalized Parton Distributions

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

Spatial- and momentum imaging

GPDs

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

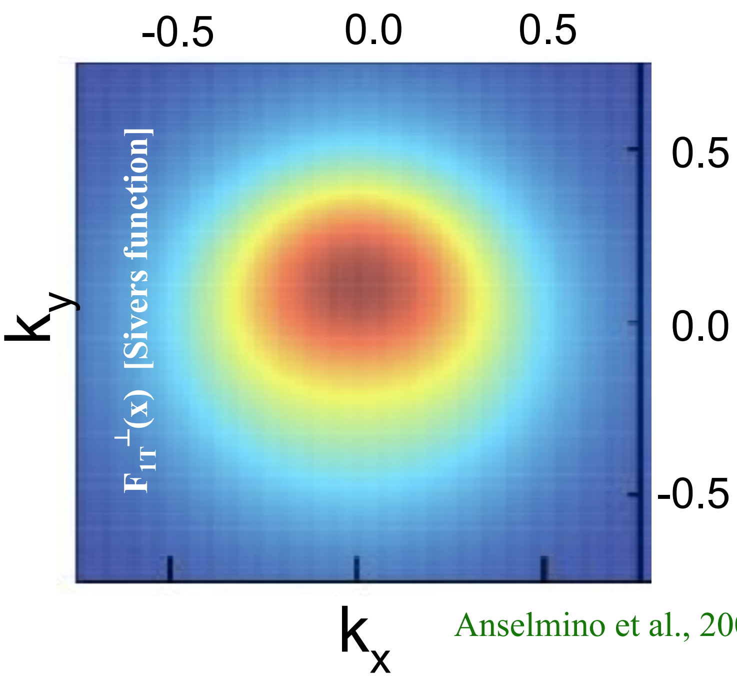


QCDSF/UKQCD Coll., 2006

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

TMDs

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



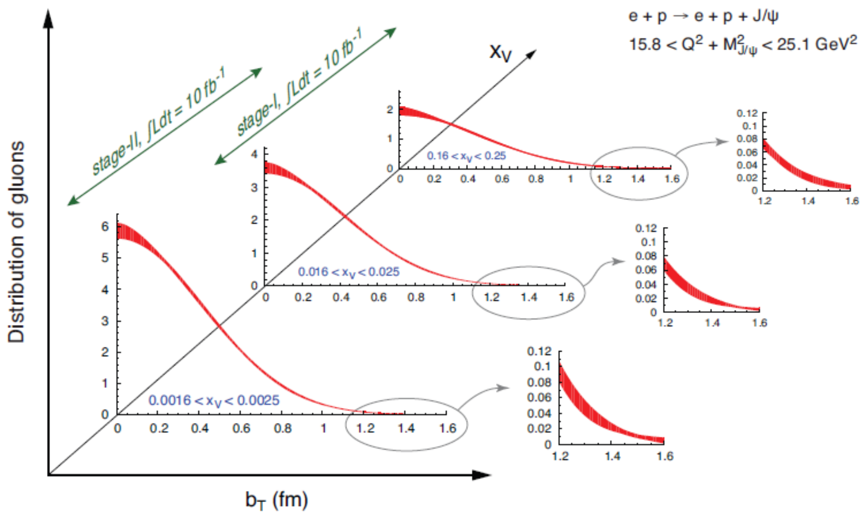
Anselmino et al., 2009

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

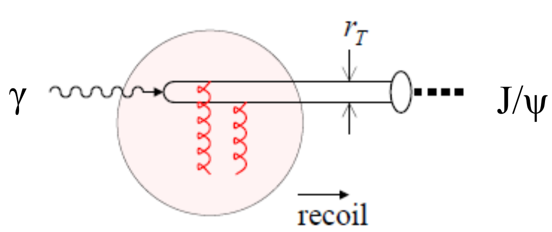
Spatial- and momentum imaging

GPDs

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

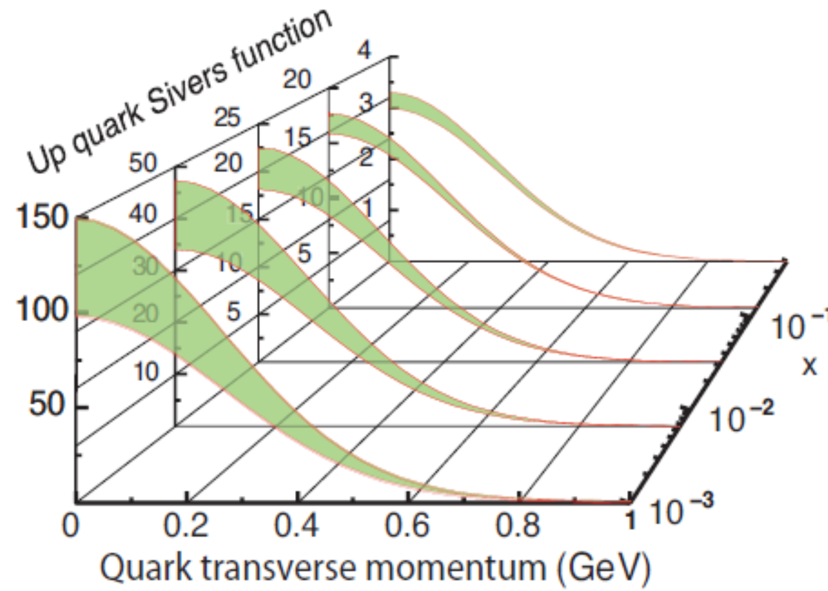


Transverse gluon distribution from J/ψ production



TMDs

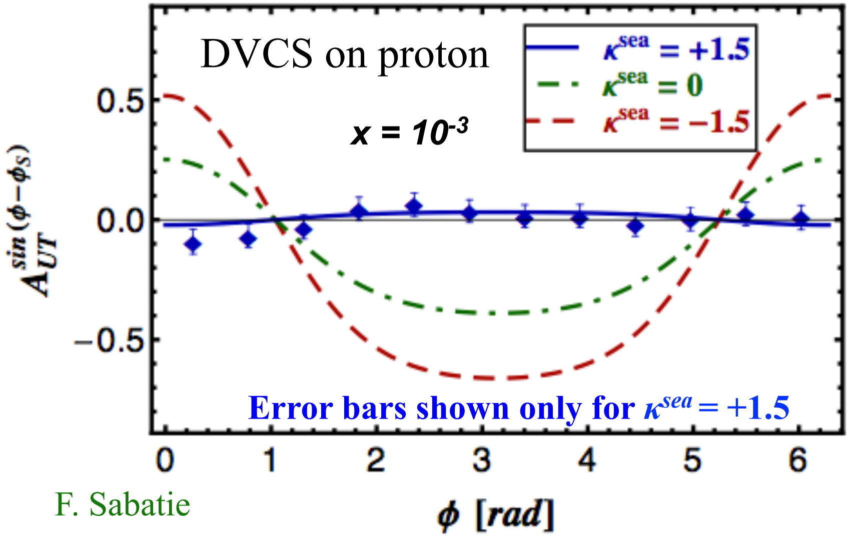
2+1 D picture in **momentum space**

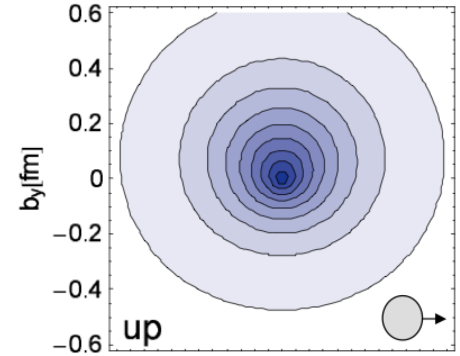


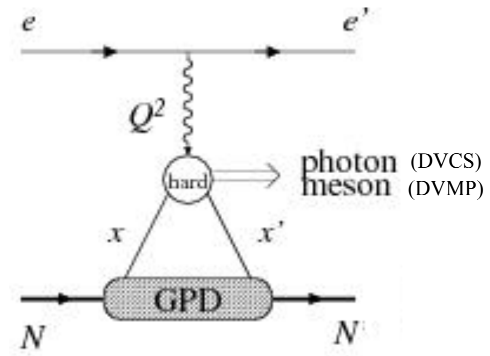
Projections from EIC white paper

GPDs and angular momentum

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



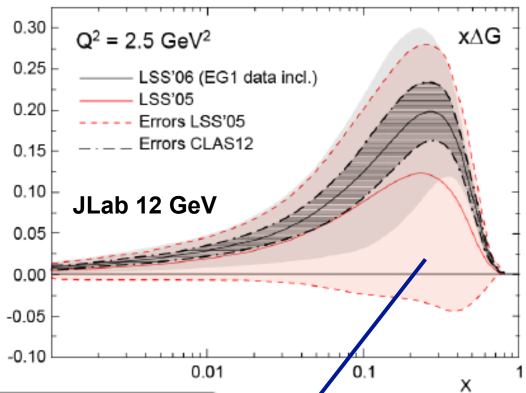


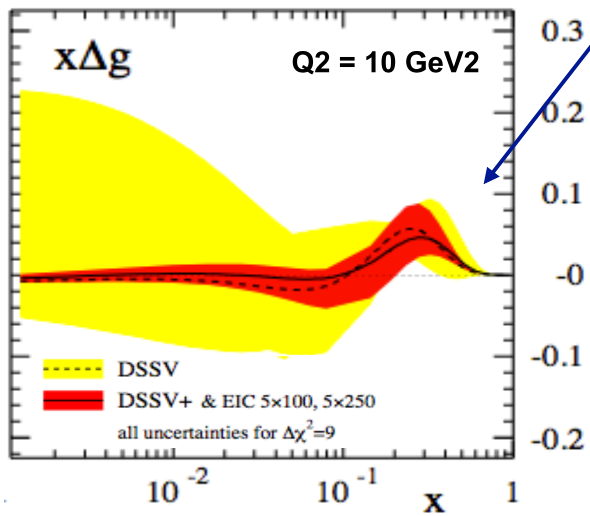


- DVCS on a *transversely* polarized target is sensitive to the *GPD E*
  - *GPD H* can be measured through the beam spin asymmetry
  - Opportunity to study spin-orbit correlations (Ji sum rule)

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

Gluon polarization (ΔG)



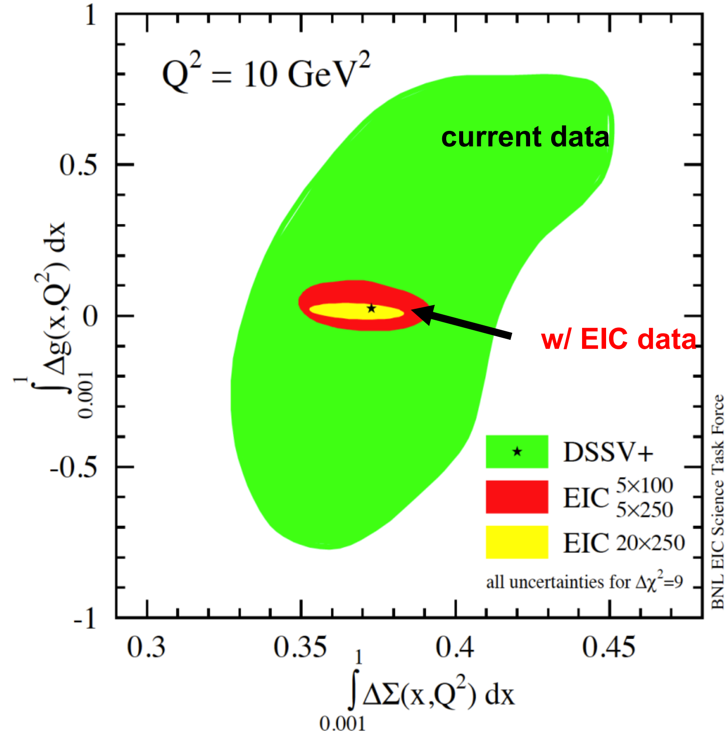


M. Stratmann

Green: RHIC spin, COMPASS, etc

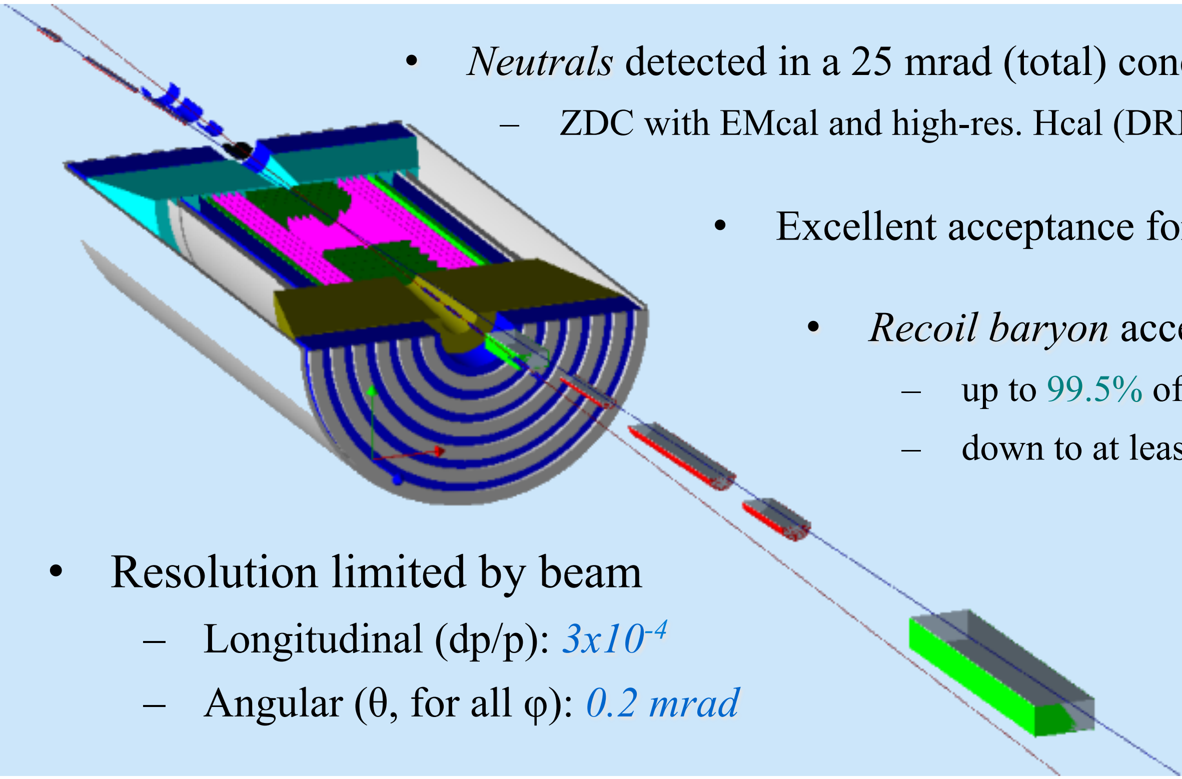
Red: EIC Stage I (MEIC or eRHIC)

Yellow: EIC Stage II

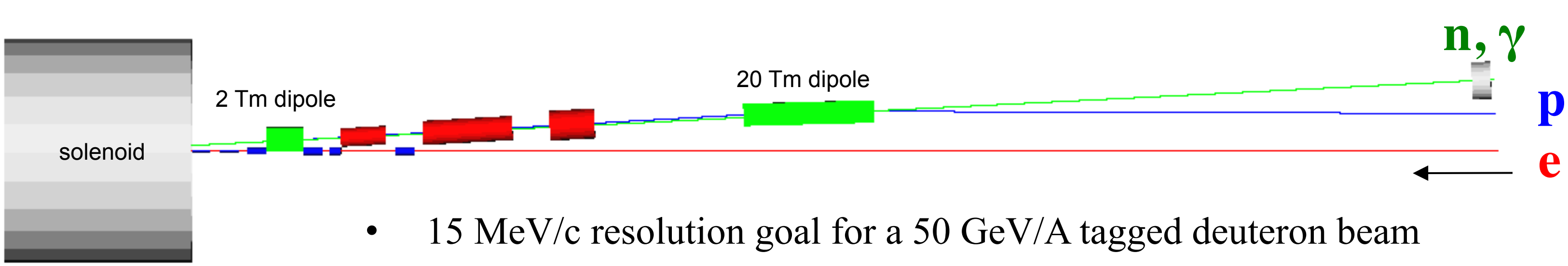


- EIC stage I will greatly improve our understanding of ΔG
  - Stage II will further reduce the uncertainty

Far-forward detection summary

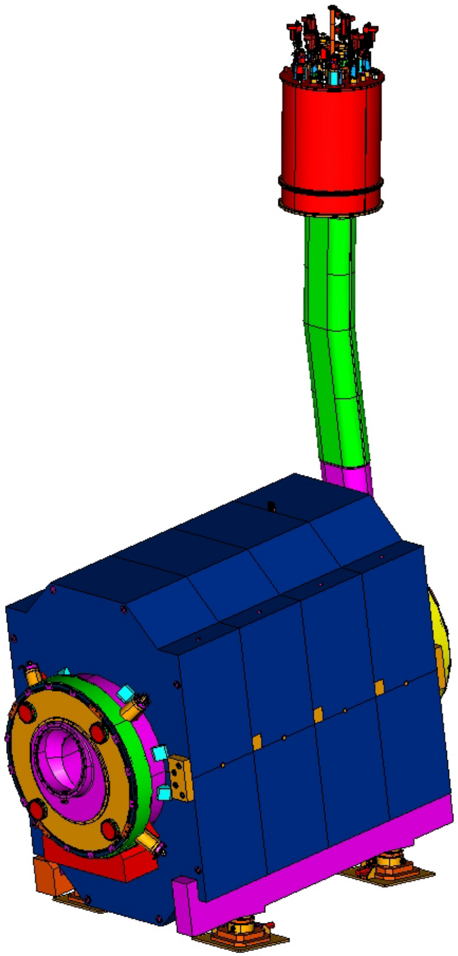


- *Neutrals* detected in a 25 mrad (total) cone *down to zero degrees*
  - ZDC with EMcal and high-res. Hcal (DREAM or particle flow).
- Excellent acceptance for *all ion fragments*
- *Recoil baryon* acceptance:
  - up to 99.5% of beam energy for *all angles*
  - down to at least 2-3 mrad for *all momenta*
- Resolution limited by beam
  - Longitudinal (dp/p): *$3x10^{-4}$*
  - Angular (θ, for all φ): *0.2 mrad*



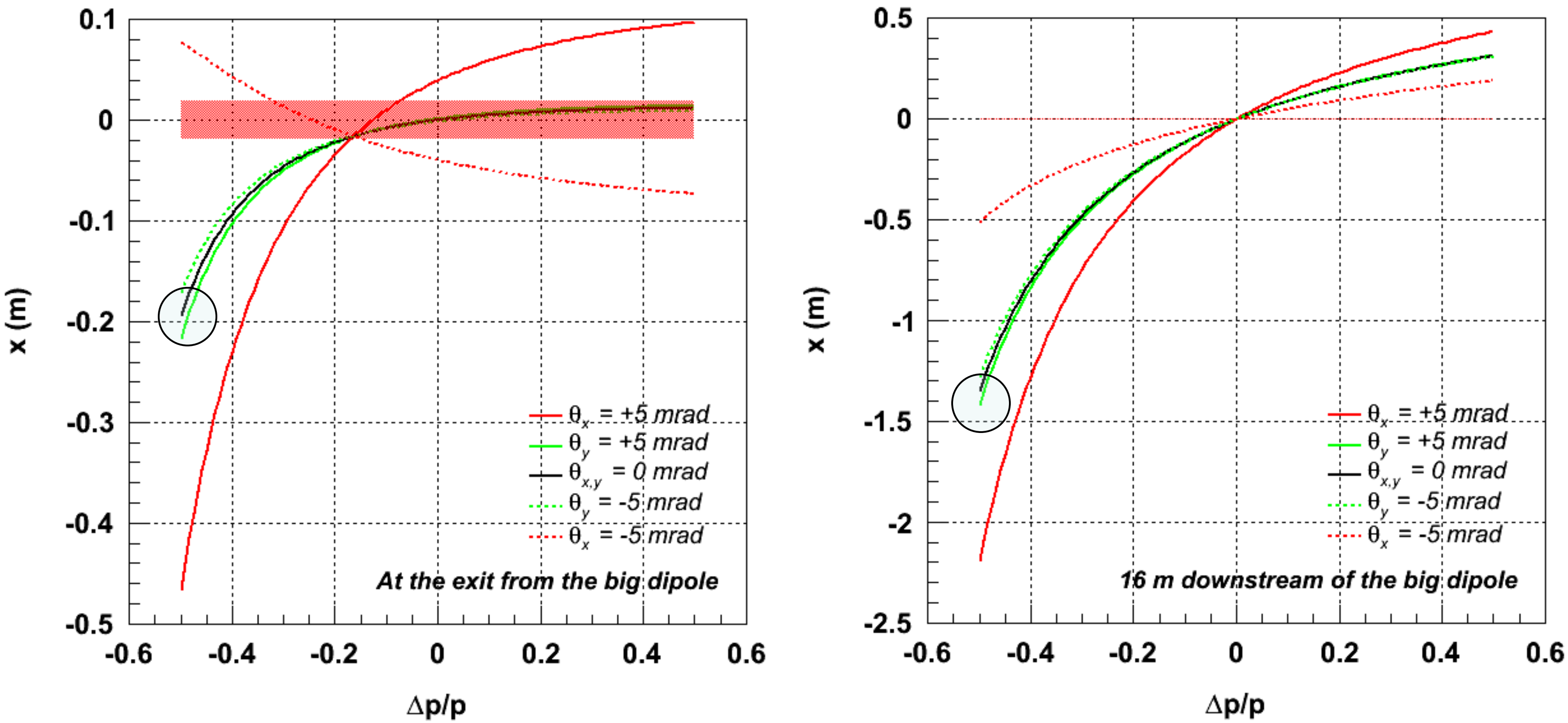
- 15 MeV/c resolution goal for a 50 GeV/A tagged deuteron beam

Large-aperture Hall C dipole



- 3.86 Tesla Cosine(Θ)dipole
- 60 cm warm bore
- 2.85 M EFL
- 11.2 TM Integral B.dL
- 10 % TEST margin
- 13.7 MJ stored Energy
- 4800 A/cm^2

Spectator angles *after* dipole



- True spectator fragments have very small scattering angles at the IP (black curve)
- Spectator protons from deuterium have $\Delta p/p$ = -0.5
- After passing the large bending dipole, the spectator angle with respect to the ion beam is large
- The angle in the magnet-free drift section after the dipole can be calculated from the displacement at the dipole exit and a point 16 m further downstream:
  - θ = atan ((1.4- 0.2)/16) = 75 mrad (= 4.3°)