MEIC Interaction Region and Detector Design

Pawel Nadel-Turonski

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Outline

- Part 1: Detectors at JLab and RHIC
- Part 2: Physics requirements and Central detector(s) for the (M)EIC
- Part 3: MEIC small-angle detection

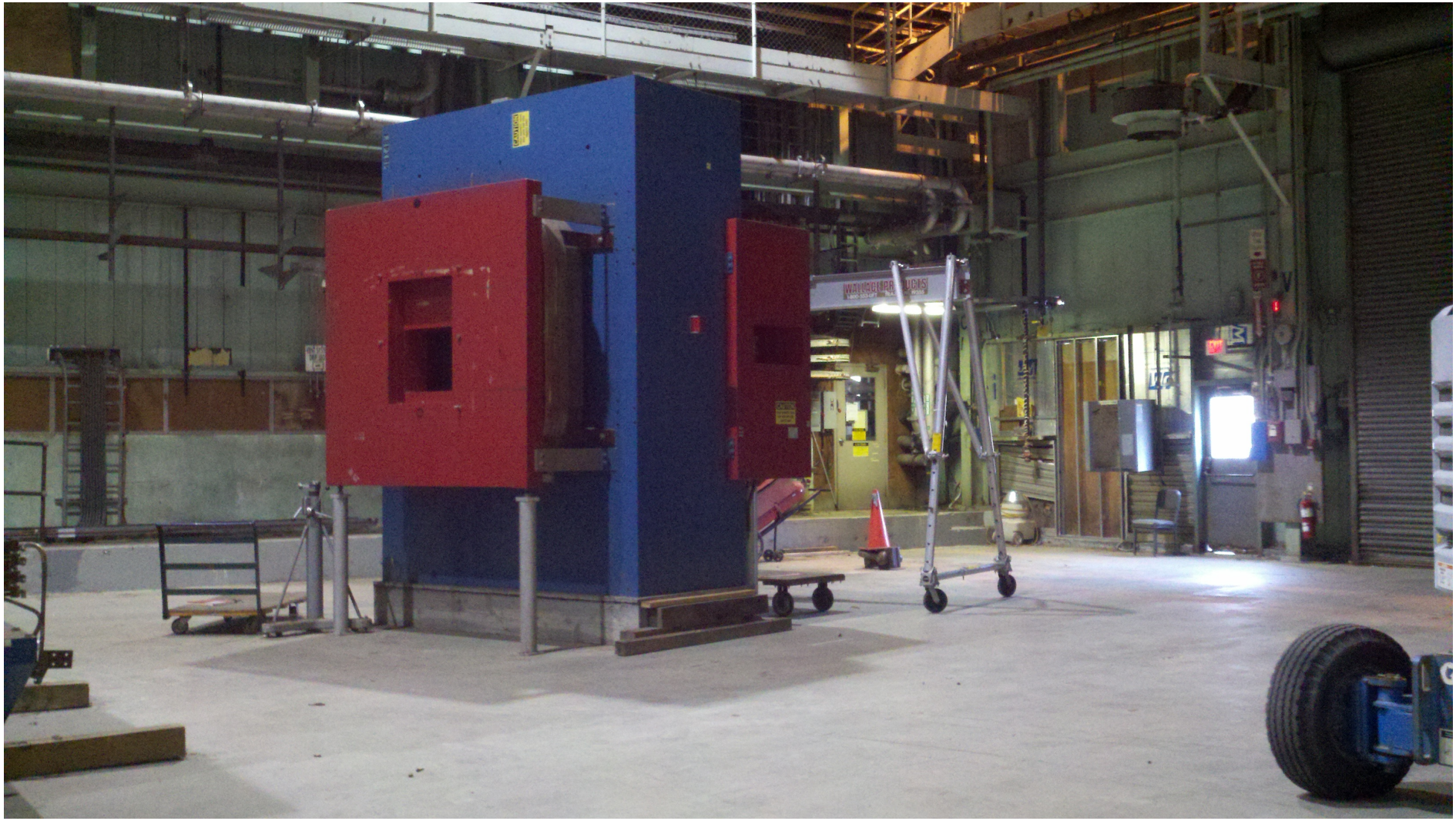
What particles do we detect?

- Charged particles
  - Only long-lived particles can be detected:
  - Leptons: ***electrons*** and ***muons***
  - Mesons: ***pions*** and ***kaons***
  - Baryons: ***protons***
  - Detection is based on *magnetic* fields: **F = v** x **B**

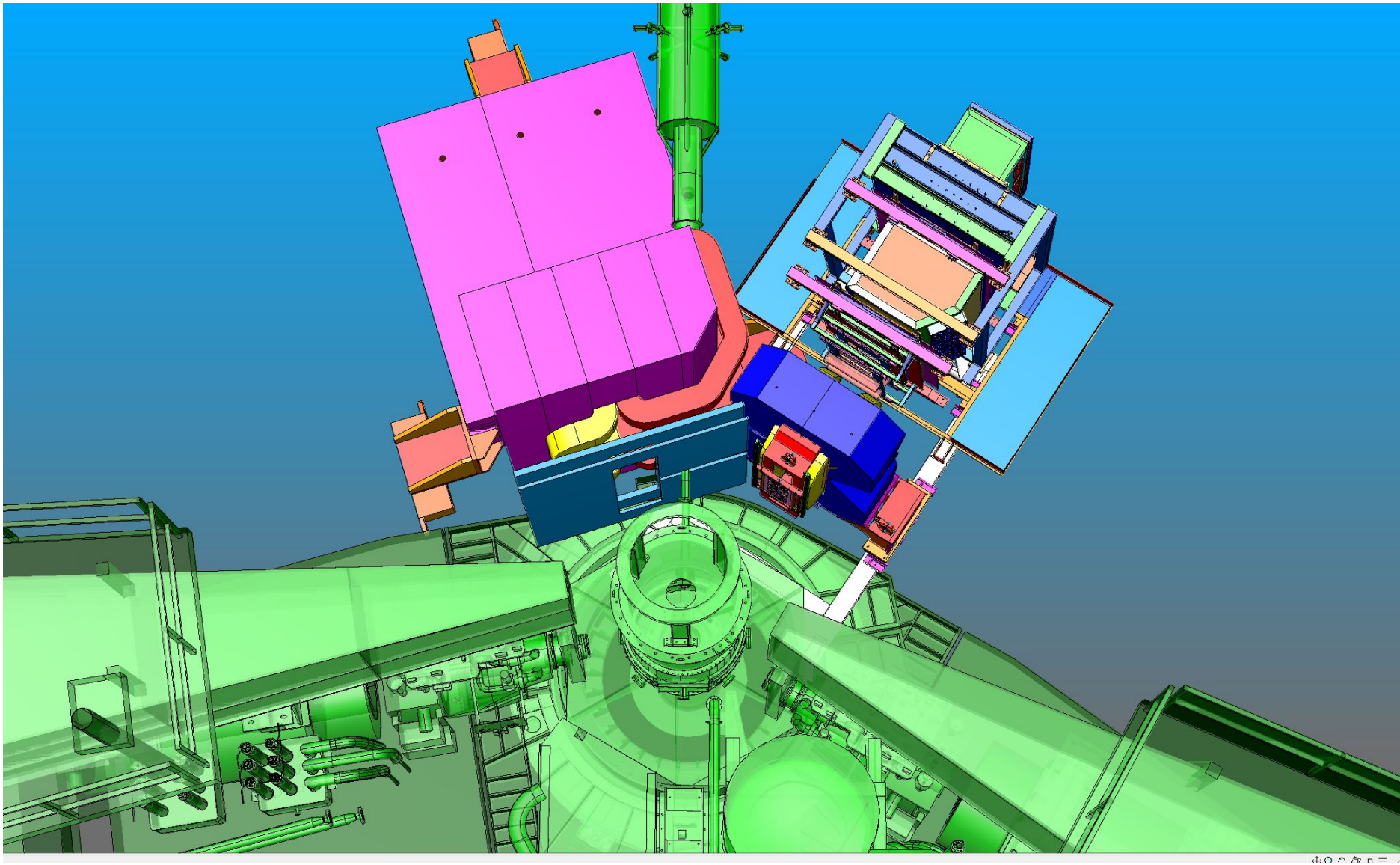
- Neutral Particles
  - Detection is based on energy deposited in materials (*calorimetry*)
  - **Photons** and electrons create electromagnetic (EM) *showers*
  - **Neutrons** (and charged hadrons) can be detected using hadronic calorimeters

- Particle Identification (PID)
  - Many techniques, usually aimed at relating velocity with mass (but not only)
  - Time-of-flight, emission of Cherenkov light, dE/dx, etc

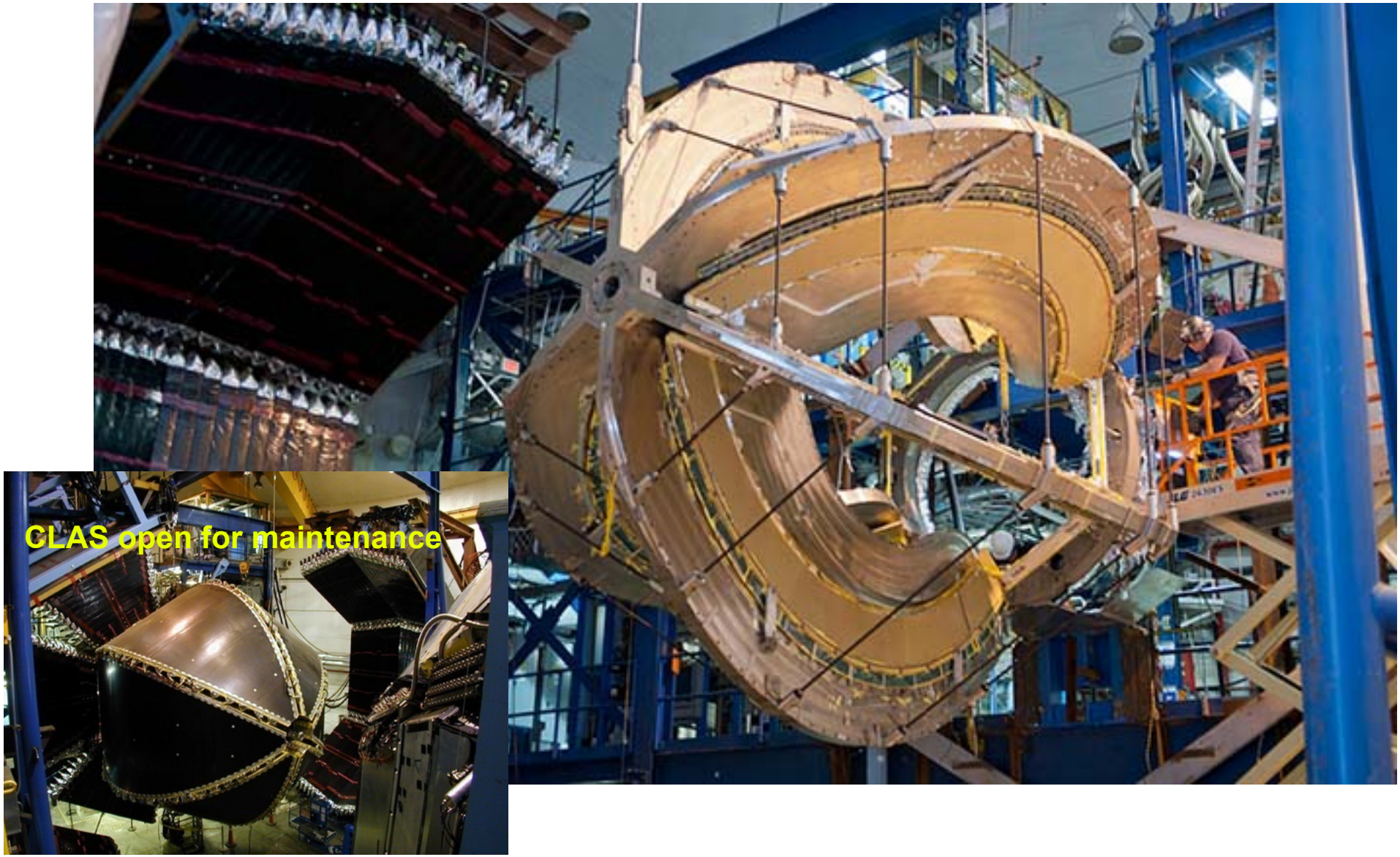
Super BigBite (SBS) dipole for Hall A



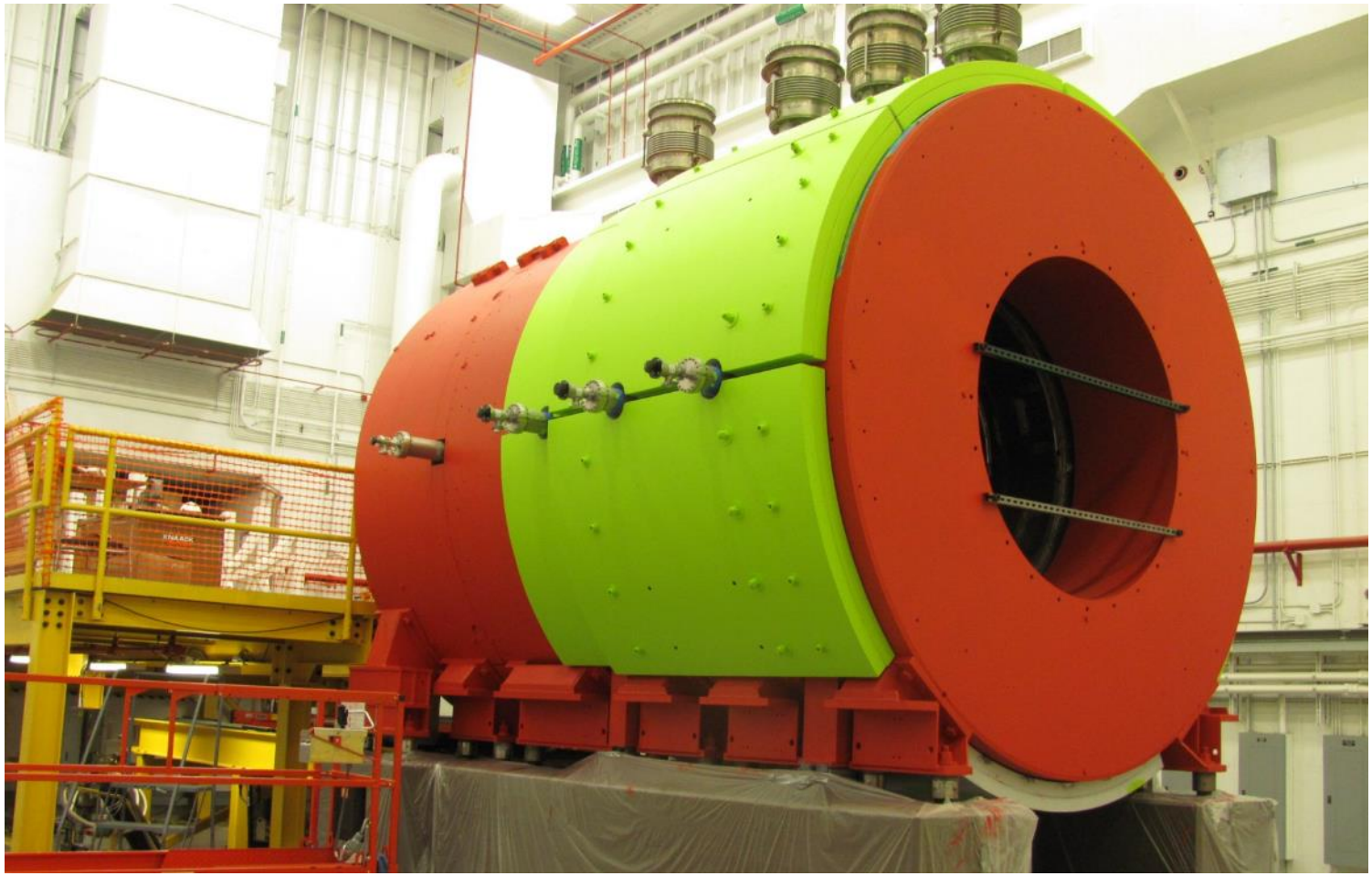
SBS in Hall A after the 12 GeV upgrade



The old CLAS torus in Hall B

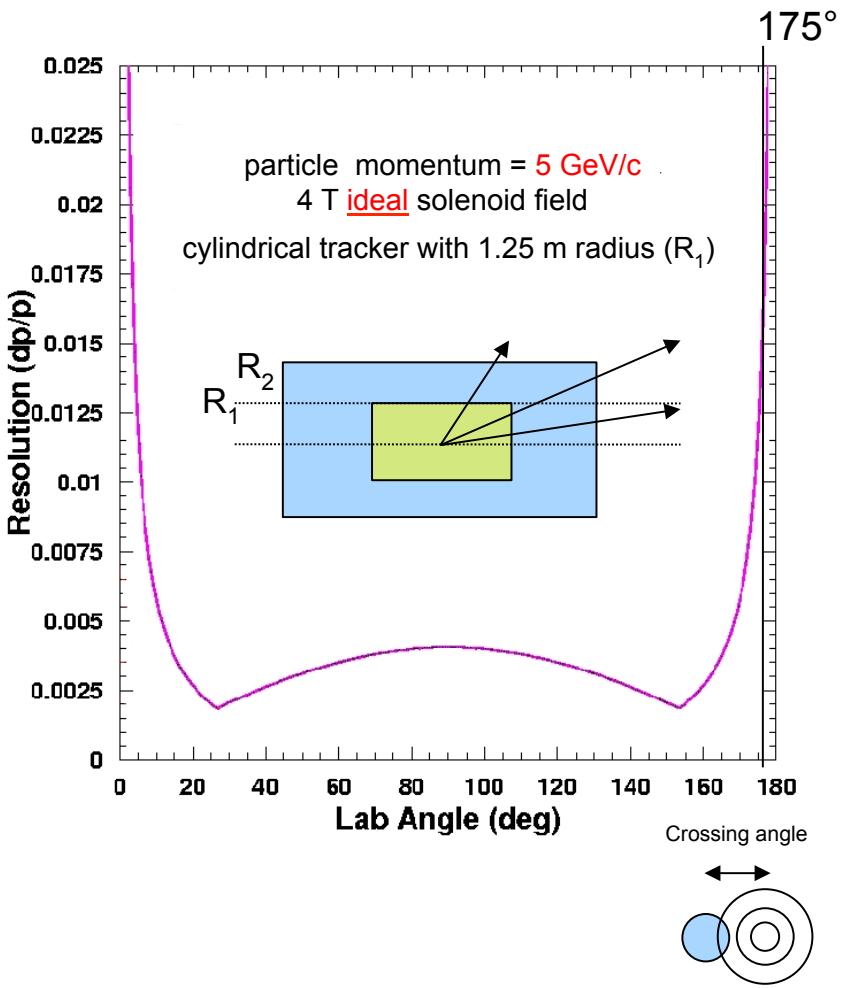


GlueX solenoid in Hall D



- Used for LASS at SLAC, for MEGA at Los Alamos, refurbished for Hall-D
- Bore inner diameter 1.85 m, length 4 m, B_{MAX} 2.0 T @ 1350 A

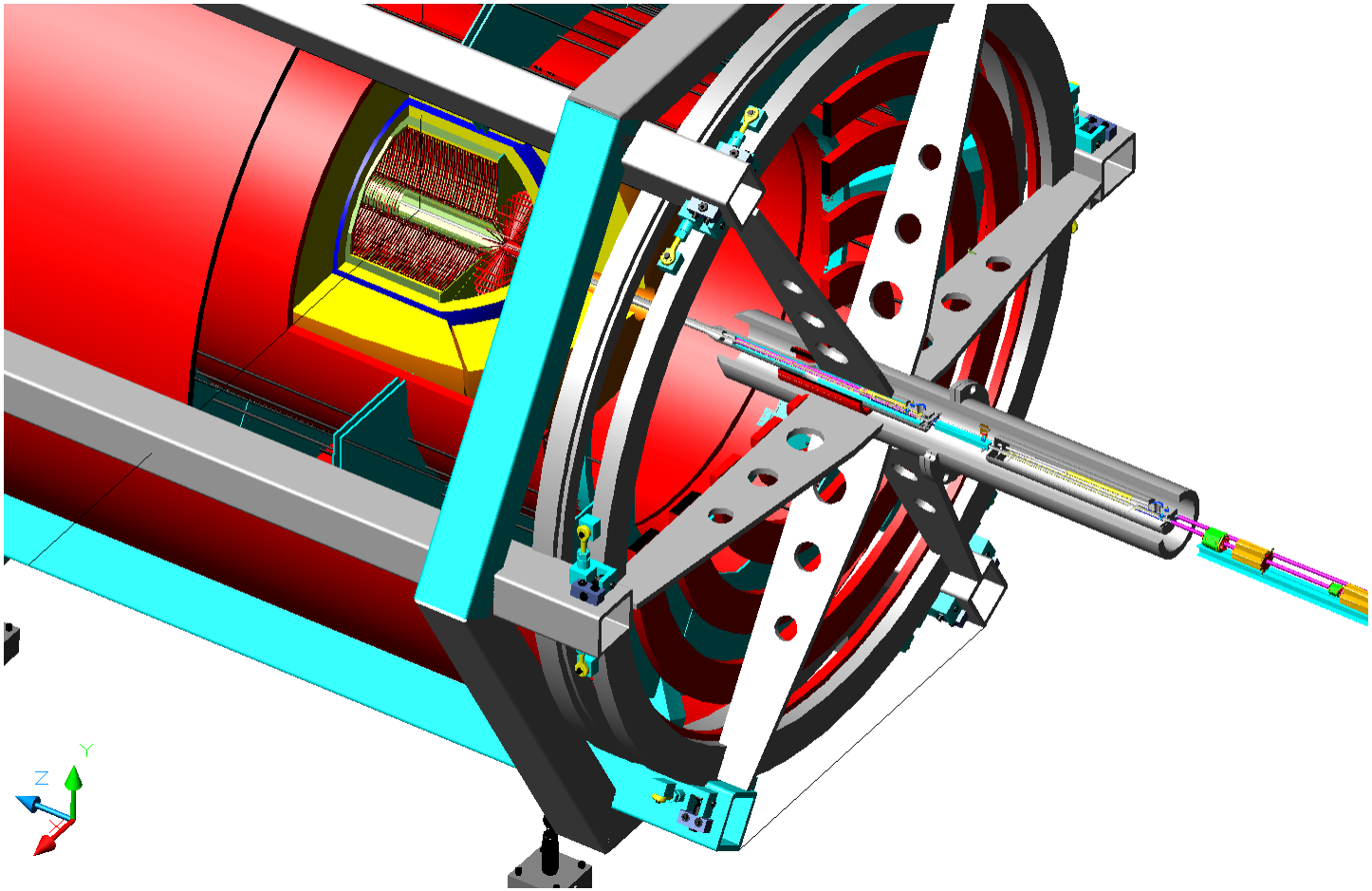
Momentum resolution in a solenoid



$$\Delta p/p \sim \sigma p / BR^2$$

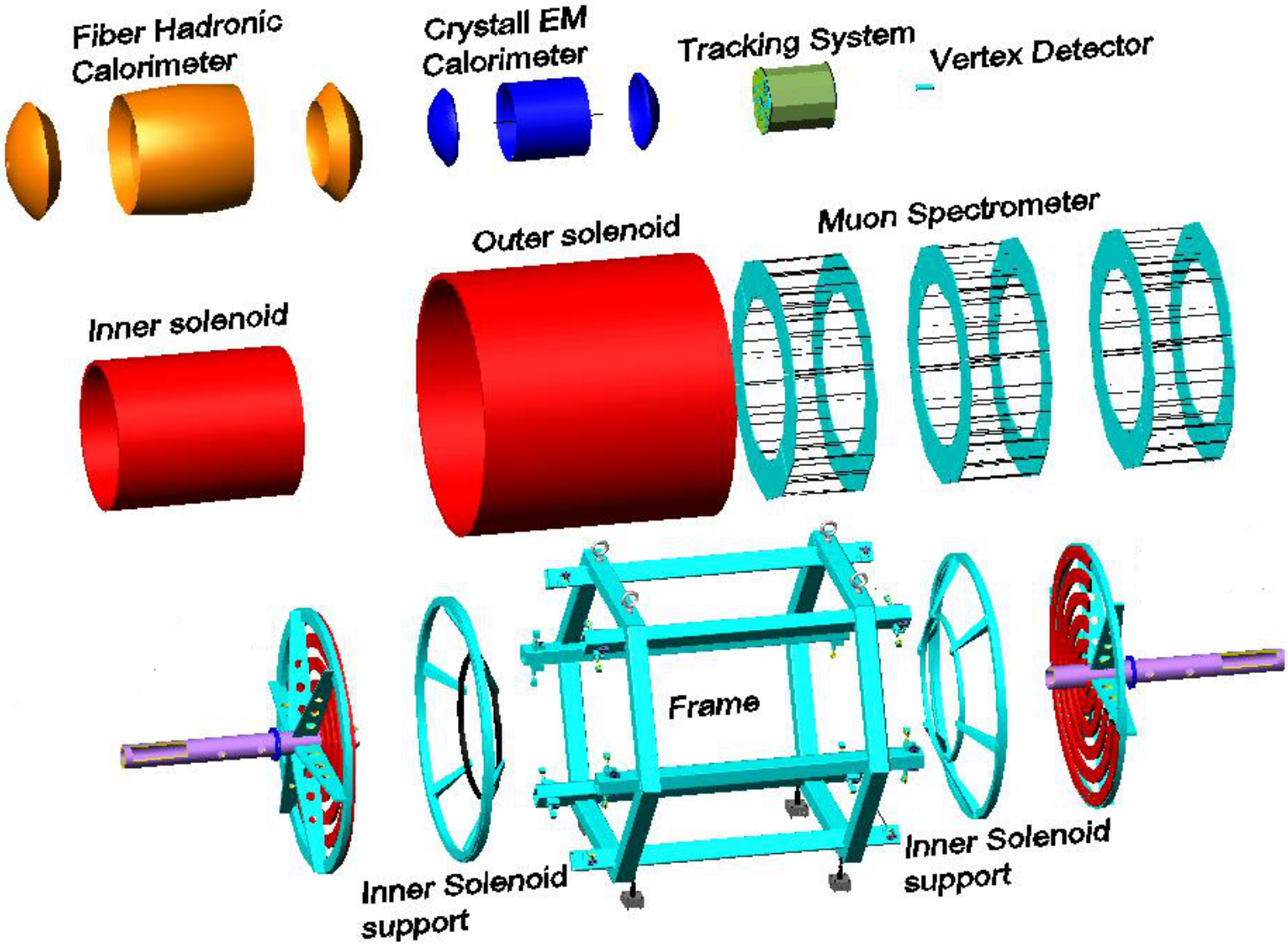
- Tracker (not magnet!) radius R is important at central rapidities
- Only solenoid field B matters at forward angles (rapidities)
- A 2 Tm dipole covering 3-5° can eliminate divergence at small angles
- A beam crossing angle moves the region of poor resolution away from the ion beam center line.
  - 2D problem!

ILC "4th" detector – dual solenoid



- Small, lightweight dual-solenoids are quire popular, but the first proposed large-scale application was the 4th detector concept for the International Linear Collider (ILC).

ILC "4th" detector – components



DIRC detector for particle identification

Detection of Internally Reflected Cherenkov Light (DIRC)

- Charged particle traversing radiator with refractive index n with $\beta = v/c > 1/n$ emits Cherenkov photons on cone with half opening angle $\cos\theta_c = 1/\beta n(\lambda)$.

- For $n > \sqrt{2}$ some photons are always totally internally reflected for $\beta \approx 1$ tracks.

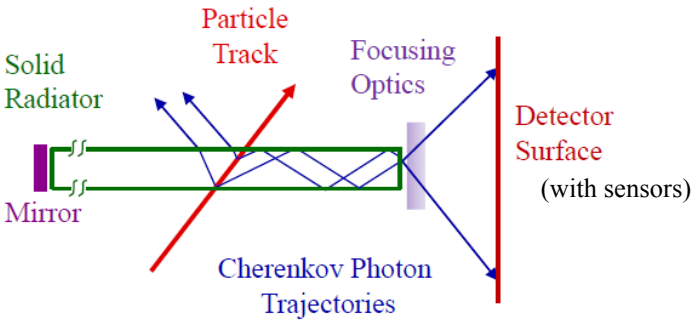
- Radiator and light guide: bar made from synthetic fused silica

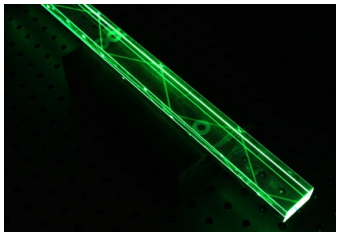
- Magnitude of Cherenkov angle conserved during internal reflections (provided optical surfaces are square, parallel, highly polished)

- Photons exit radiator into expansion region, detected on photon detector array

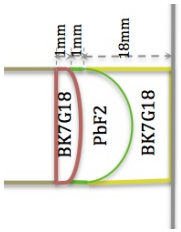
- A DIRC is intrinsically a 3-D device, measuring: x, y, and time of Cherenkov photons, defining θ_c, ϕ_c, $t_{propagation}$ of each photon.

General layout of a DIRC with lens focusing



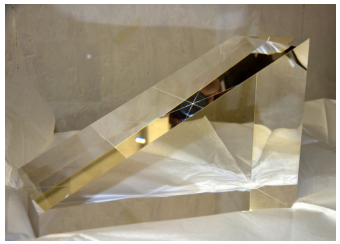


Quartz bar



Lens with no air gaps

~ 30 cm



Compact expansion volume of quartz

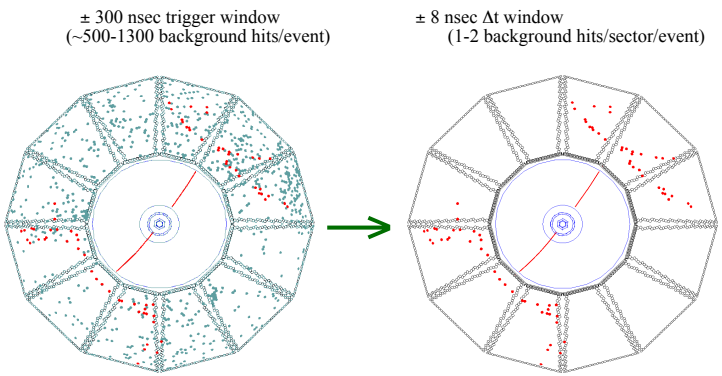
DIRC: event reconstruction

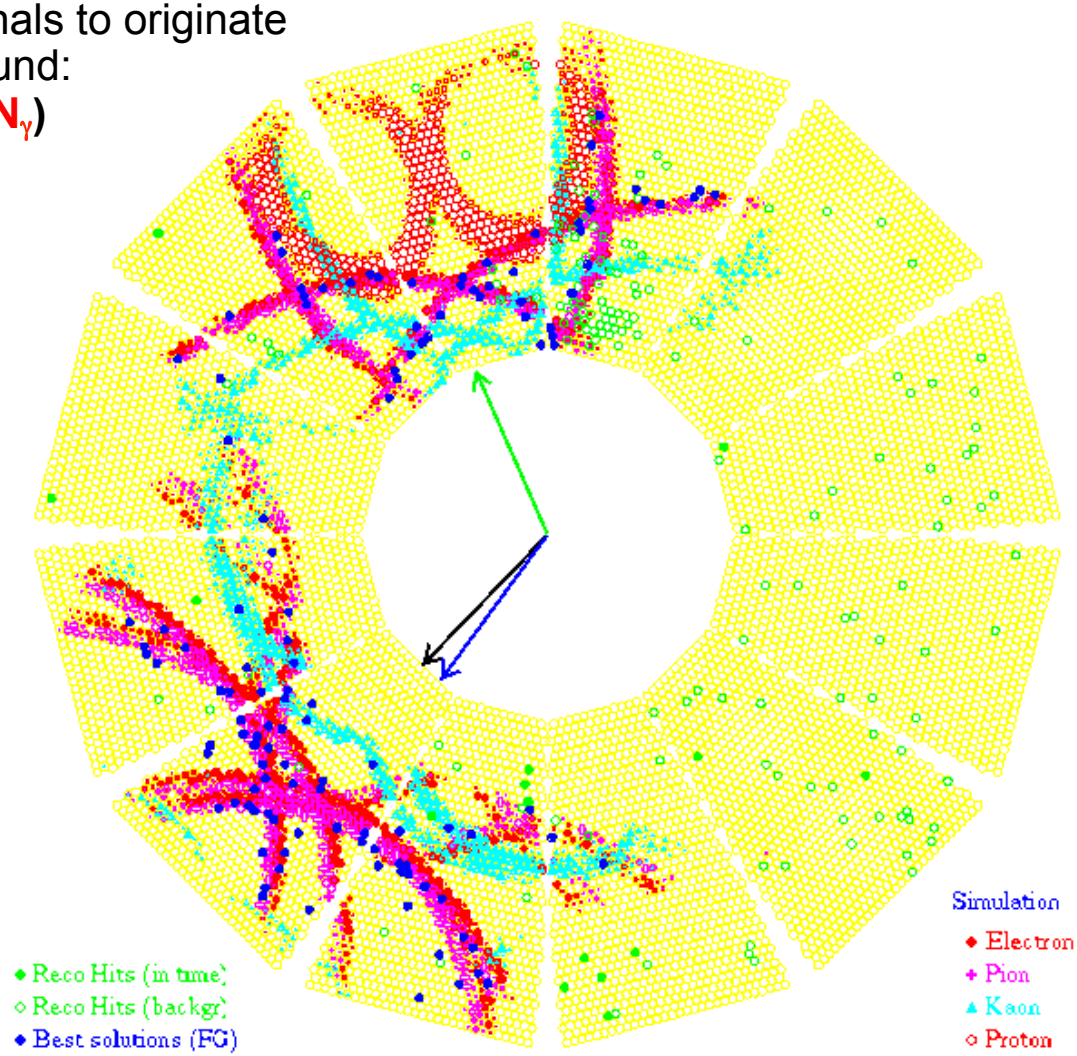
Calculate unbiased likelihood for signals to originate from e/μ/π/K/p track or from background:
Likelihood: **Pdf(θ_c) ⊗ Pdf(Δt) ⊗ Pdf(N_γ)**

Pdf = Probability distribution function

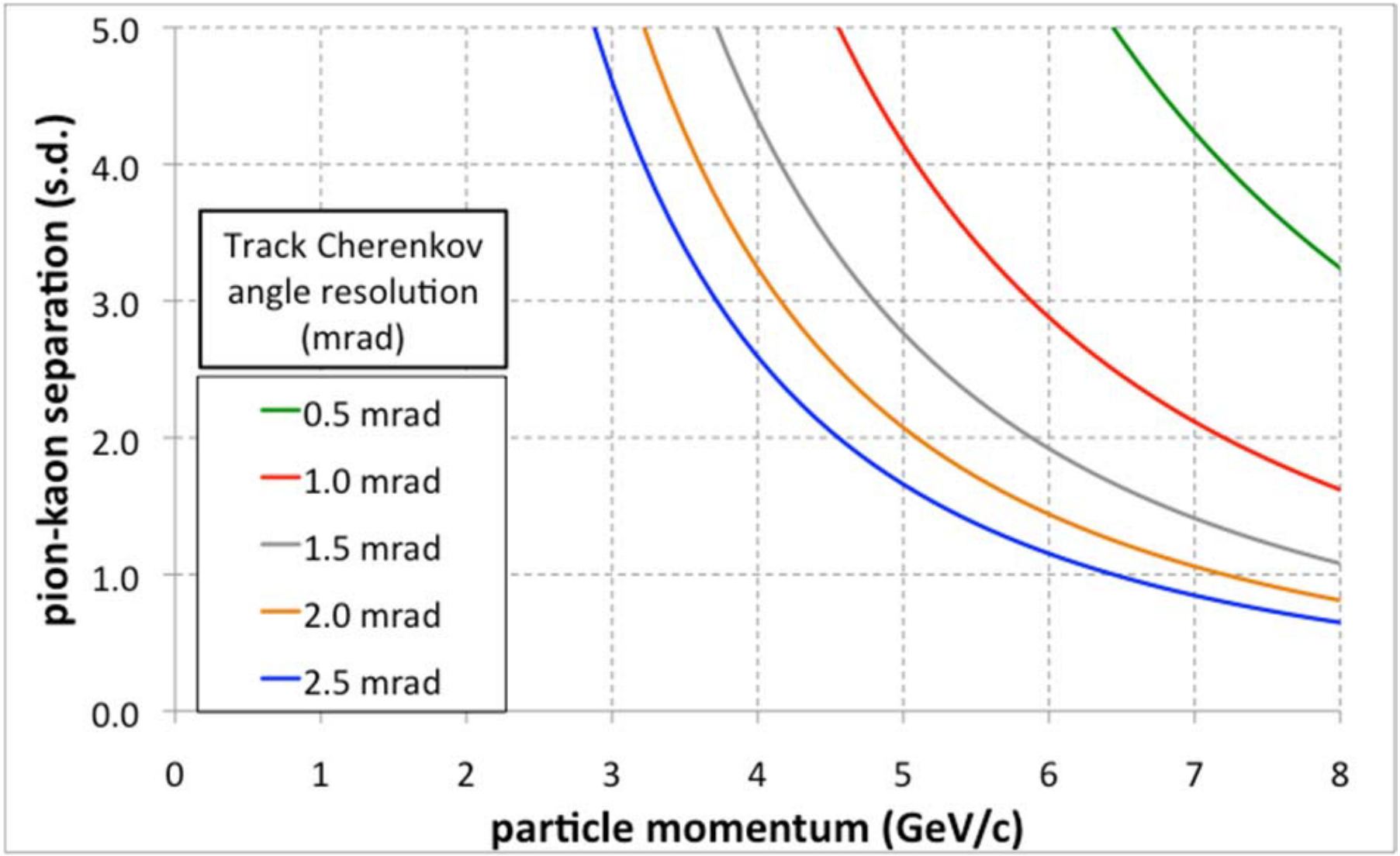
Example: comparison of real event to simulated response of BABAR DIRC to e/π/K/p.

Time resolution important for background suppression

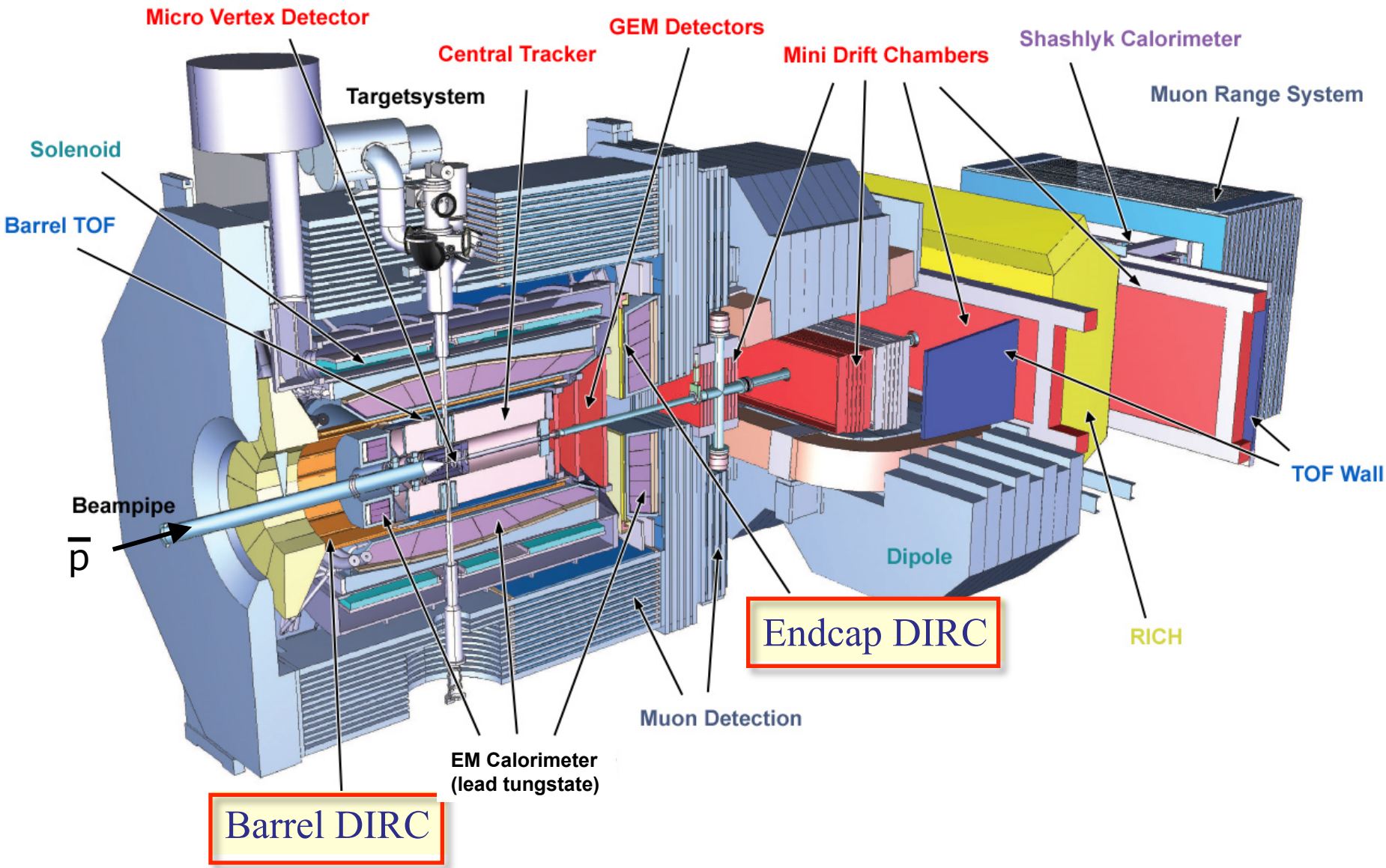




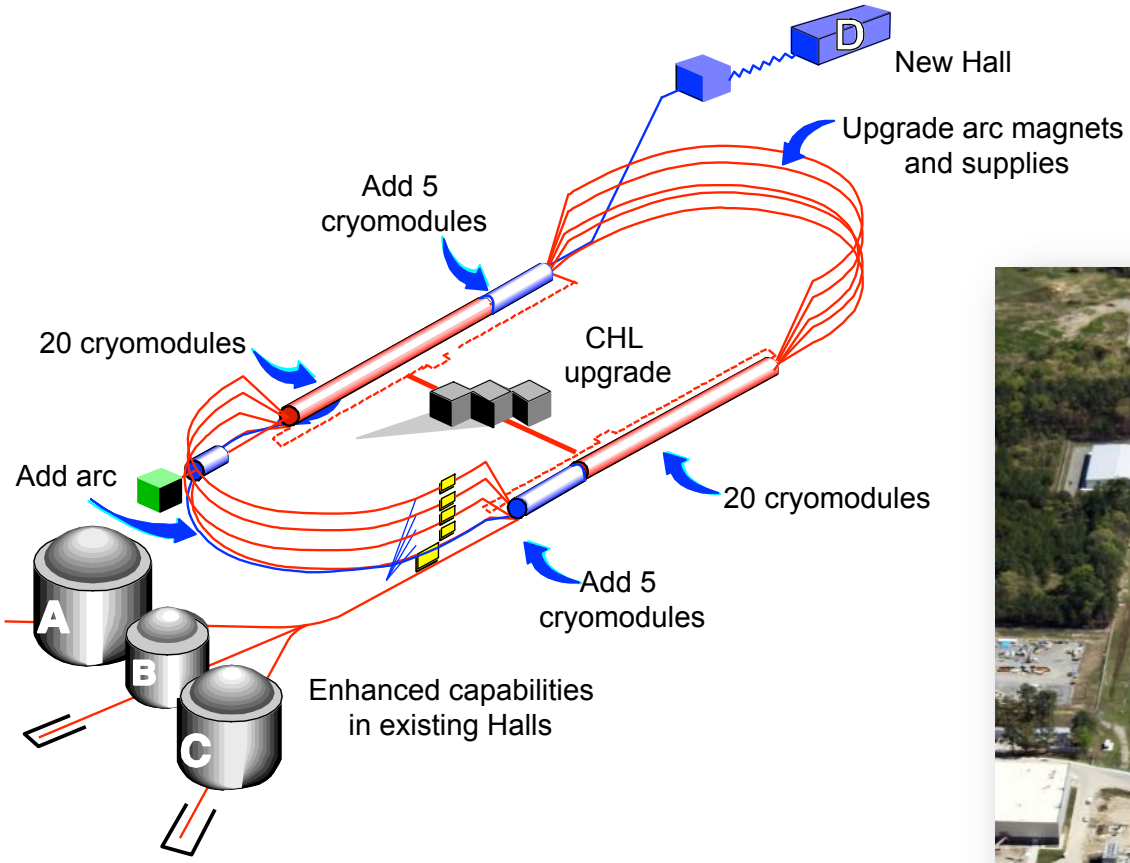
DIRC: π/K separation as function of *p*

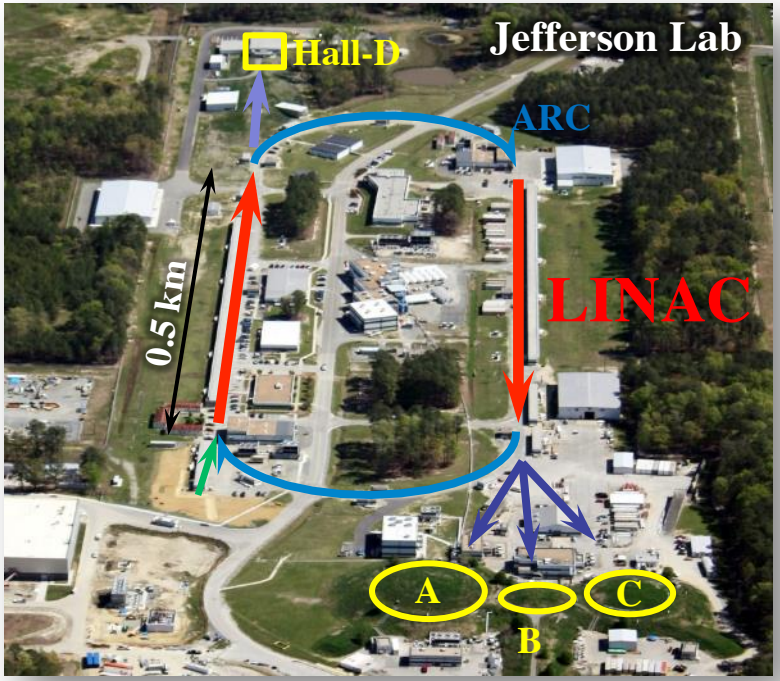


The PANDA barrel DIRC @ GSI



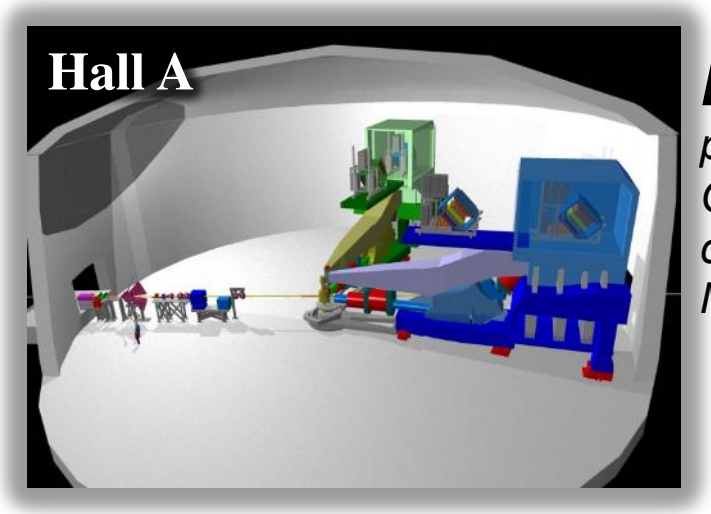
JLab 12 GeV upgrade





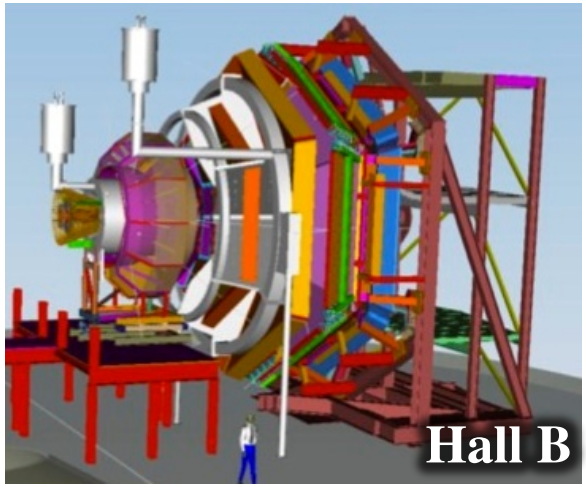
Scope of the project includes:
- Doubling the accelerator beam energy
- New experimental Hall and beamline
- Upgrades to existing Experimental Halls

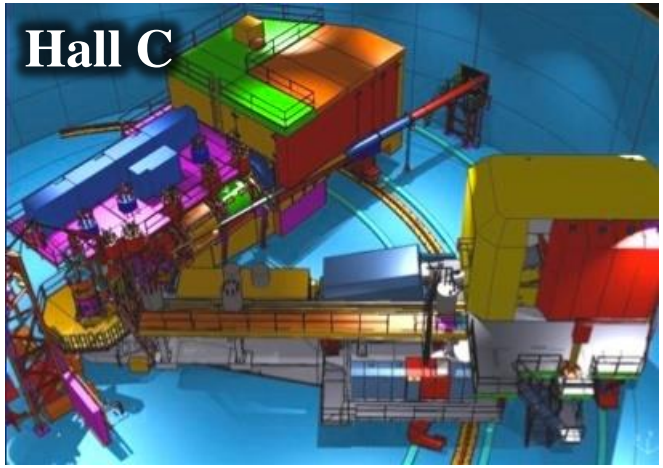
EIC



Hall A *– form factors, parton distributions (TMDs, GPDs), short range correlation, tests of Standard Model*

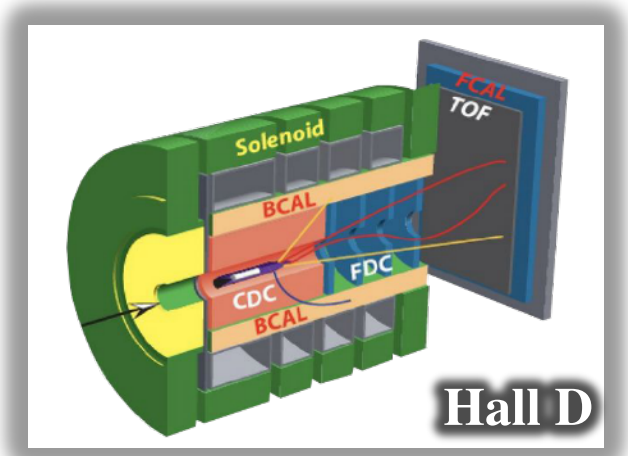
Hall B - *3D nucleon structure via GPDs & TMDs, meson and baryon spectroscopy*





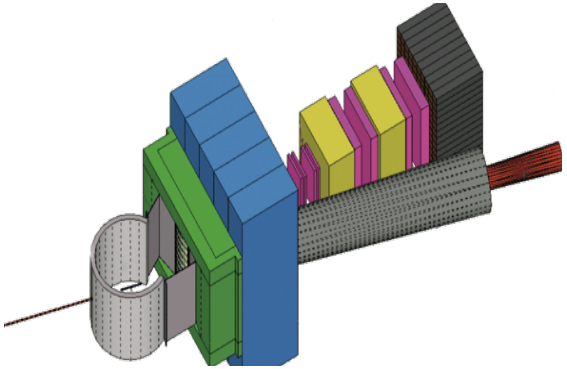
Hall C *– valence quark properties in nucleons and nuclei, Hyper-nuclei*

Hall D - *exploring origin of confinement by studying exotic mesons using real photons*

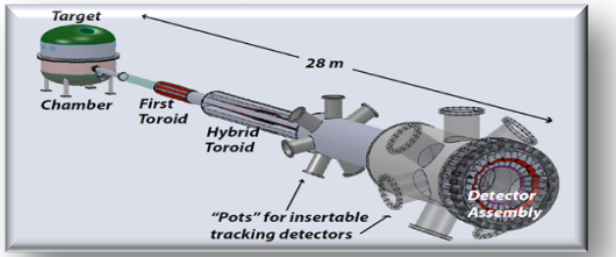


New experiments in the 12 GeV era

- **Super BigBite Spectrometer**

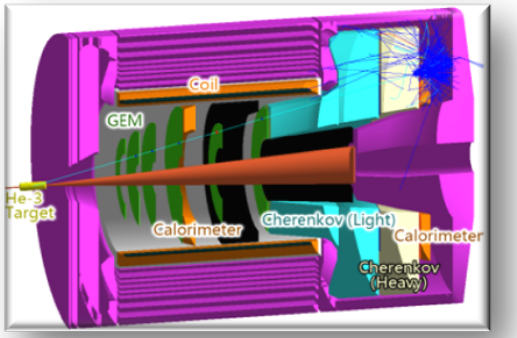


- **MOLLER experiment**



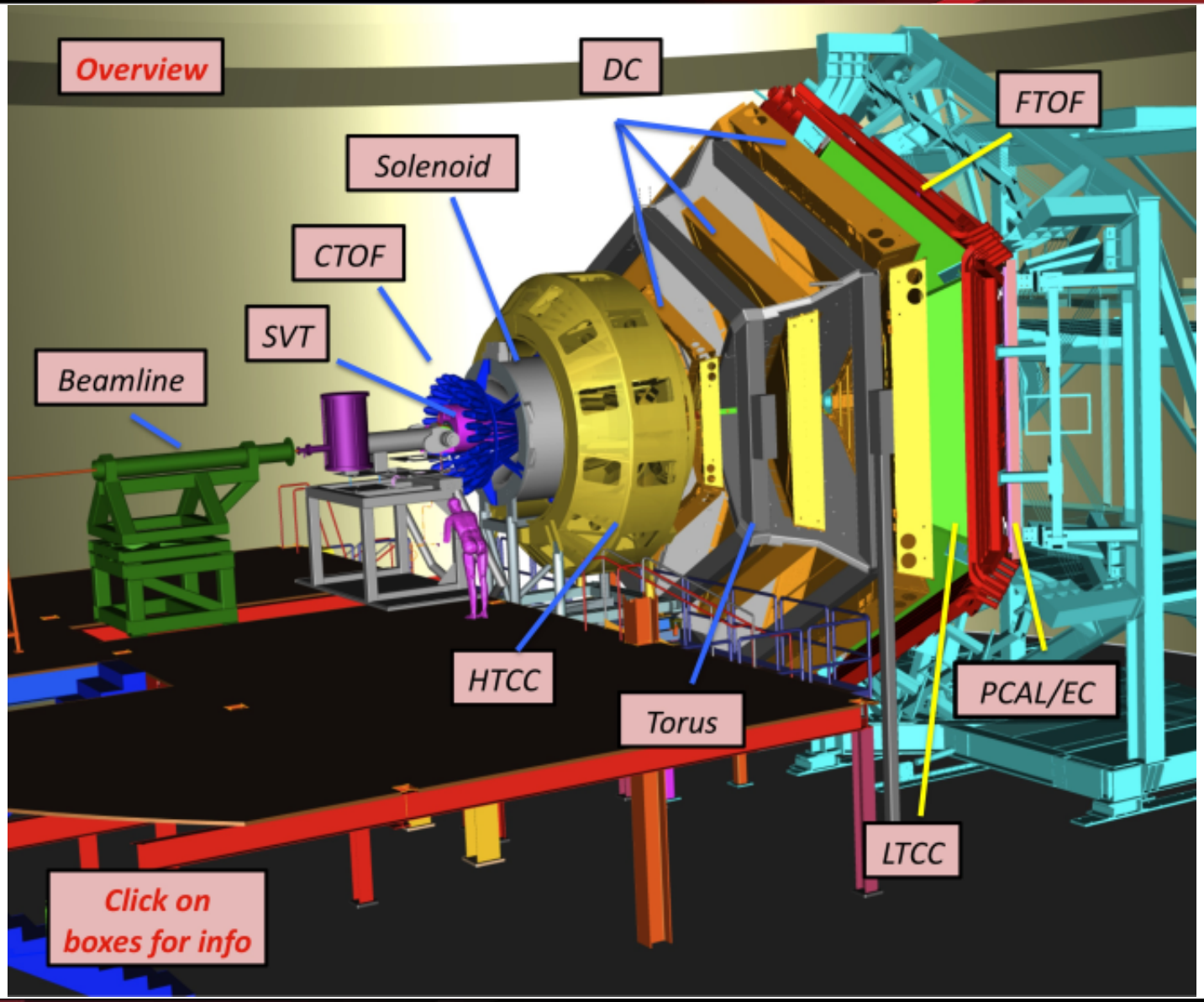
- **SoLID**

  Chinese collaboration
  CLEO Solenoid

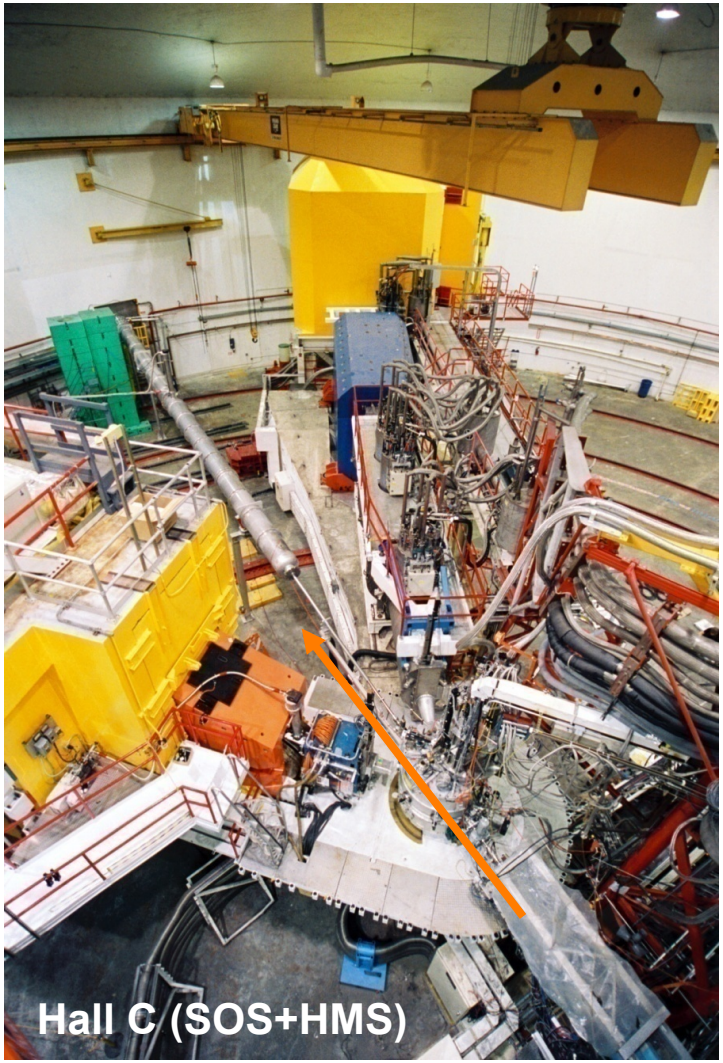


CLAS12 EM Calorimeter (EC)

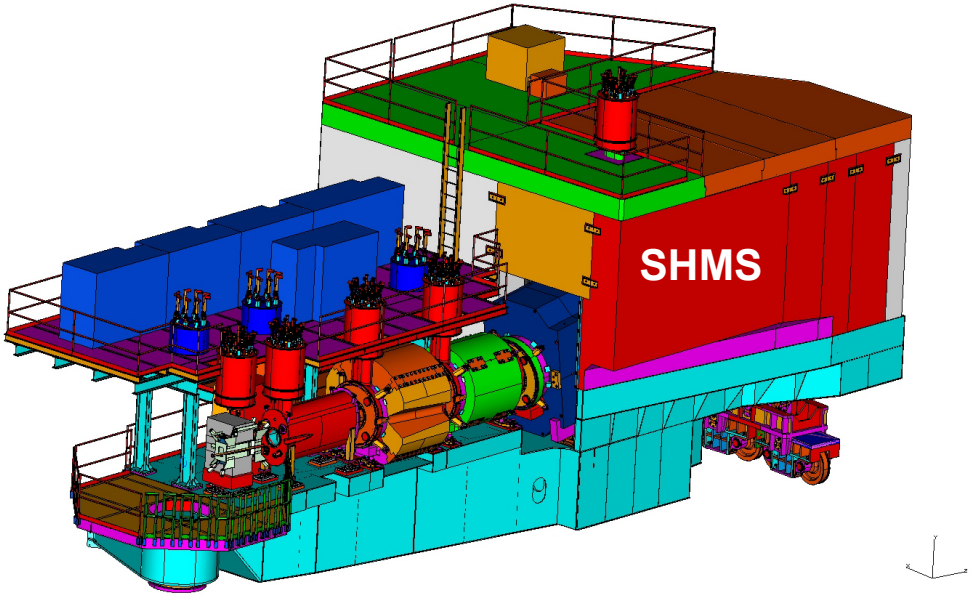
CLAS12 in Hall B



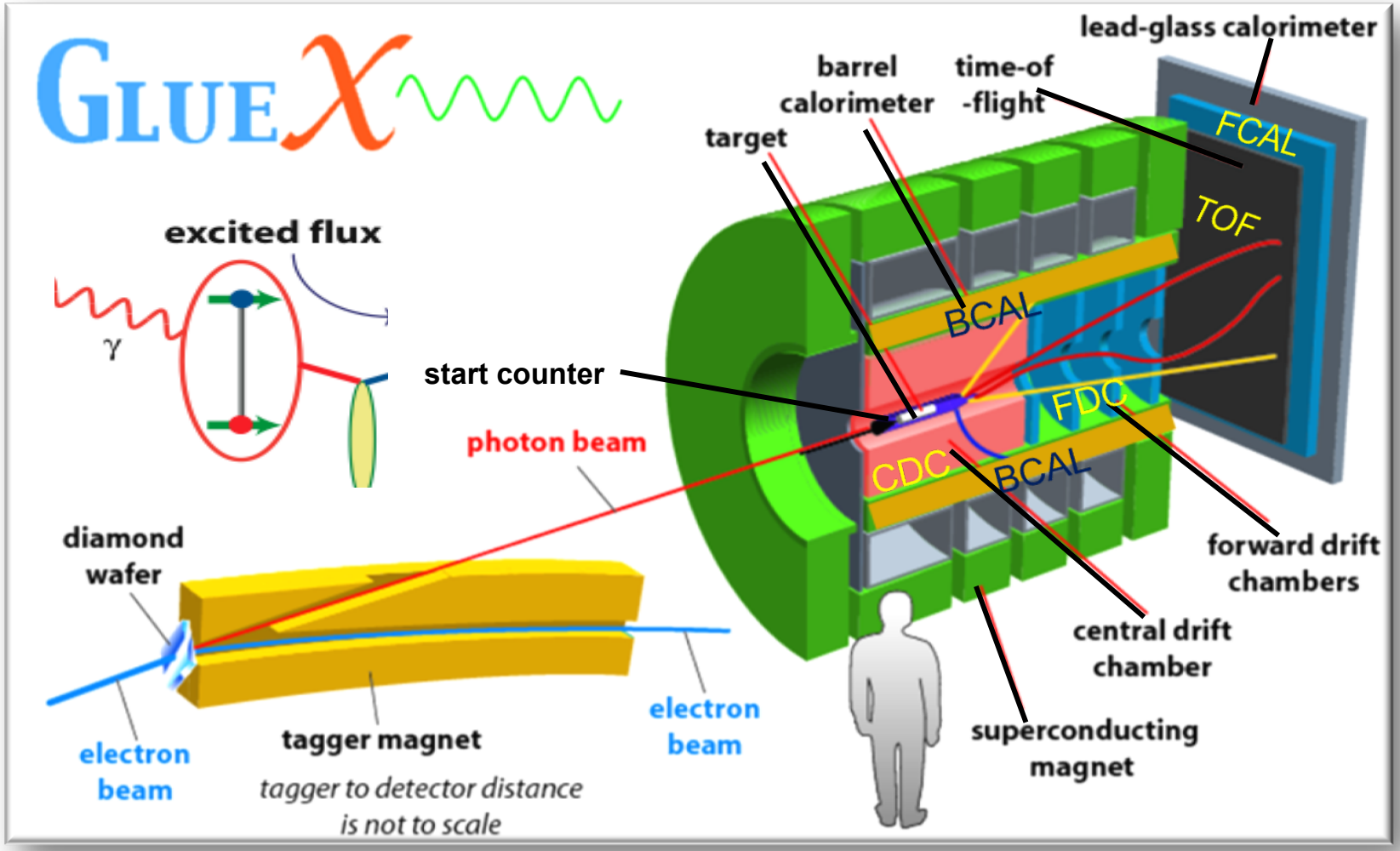
Hall C spectrometers



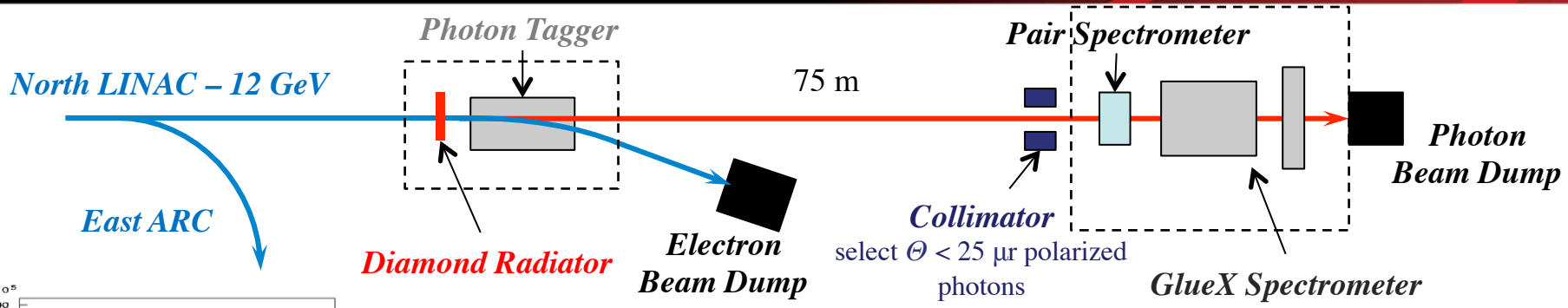
- Retain the High-Momentum Spectrometer (HMS)
- SOS spectrometer replaced by new Super-HMS
  - Luminosities reaching at least 10^{38} $cm^{-2}s^{-1}$
  - PID and momentum analysis up to 11 GeV/c

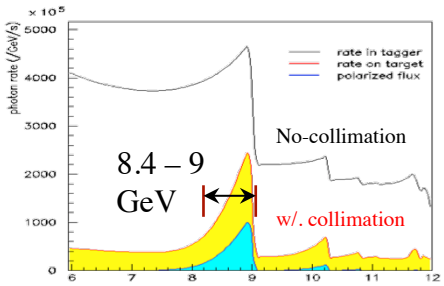


GlueX detector in Hall D

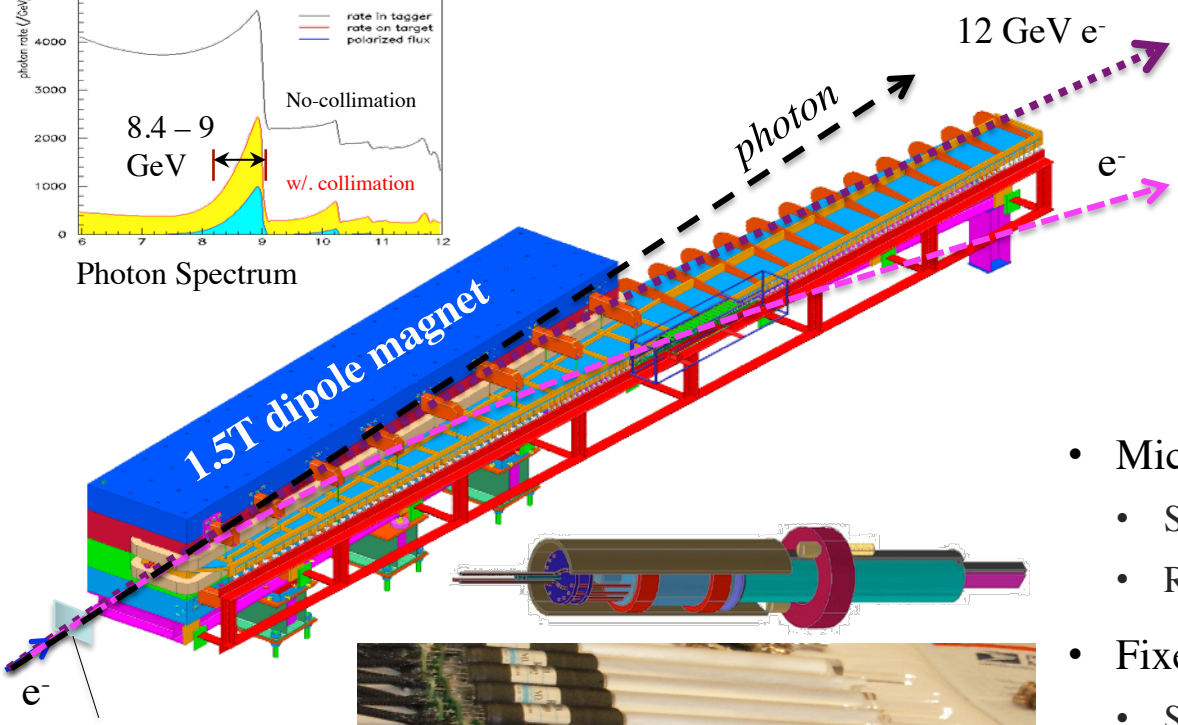


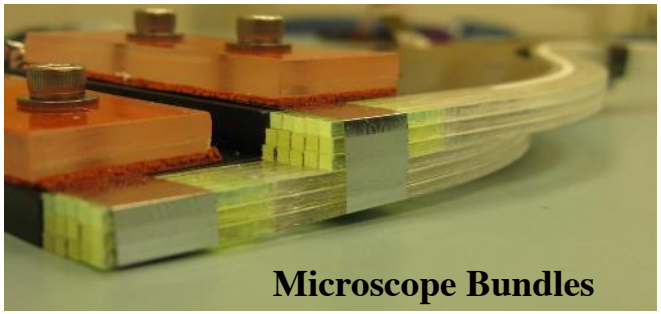
Hall D photon tagger





Photon Spectrum

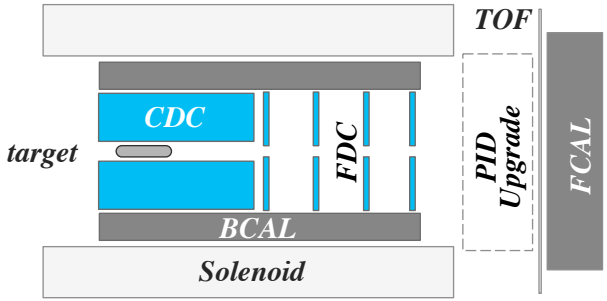


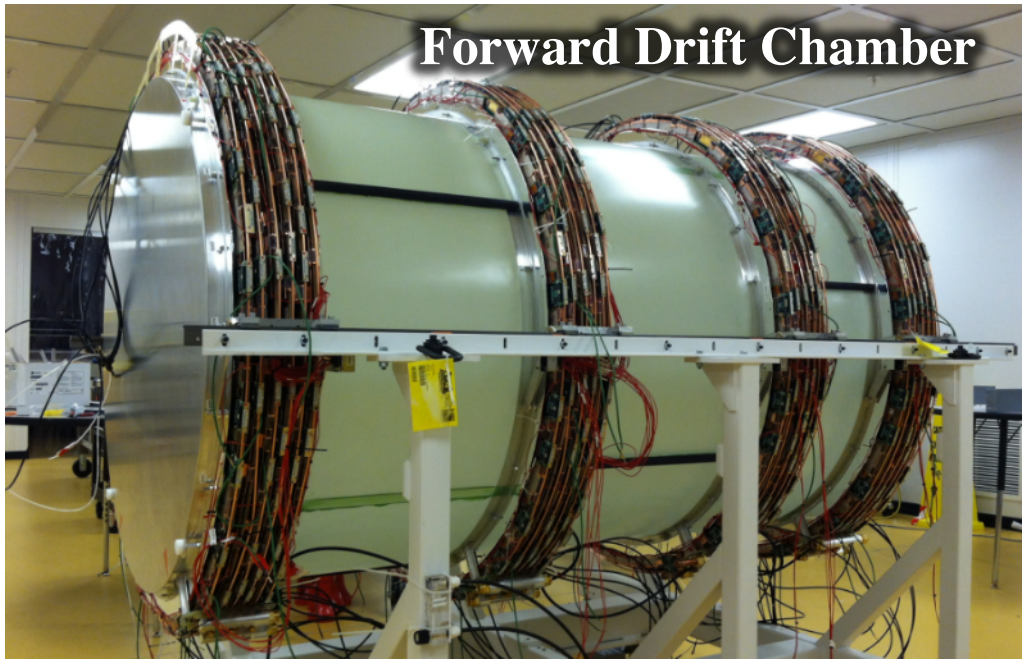


- Microscope (Coherent Peak) – U Conn
  - Scintillating fibers – 120 channels
  - Readout by Silicon Multipliers (SiPM)
- Fixed Array (E_γ = 3 – 11.6 GeV) – CUA
  - Small scintillators
  - JLab designed active divider – high rate

GlueX charged particle tracking

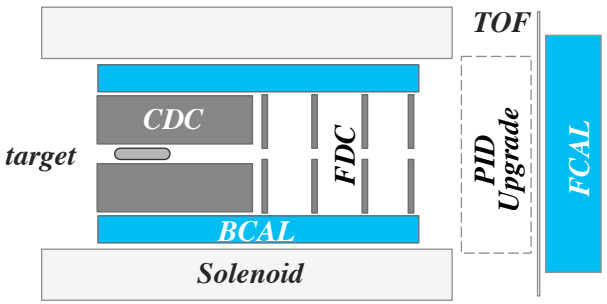
- Central Drift Chamber (CDC) – CMU
  - Straw tube design – single end readout
  - 28 layers (16 stereo layers – ± 6º), 3522 tubes
- Forward Drift Chamber (FDC) – JLab
  - Traditional drift chamber, readout from both cathode strips and anode wires
  - 4 packages, 24 readout planes – 3 orientations, 10368 channels

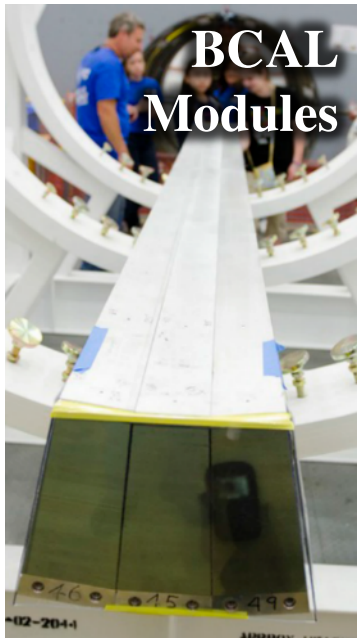


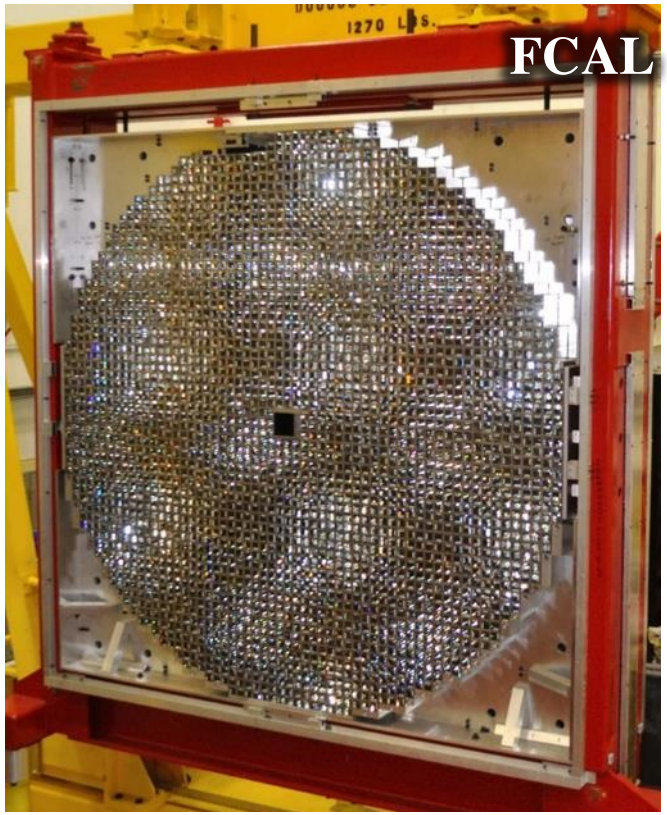


GlueX Electromagnetic Calorimeter

- Barrel Calorimeter (BCAL) – U Regina
  - 48 4-m Scintillator Fiber (SciFi) modules
  - Readout by Silicon Photomultiplier (SiPM)
- Forward Calorimeter (FCAL) – Indiana U
  - 2800 4×4×45-cm^3 Lead glass blocks

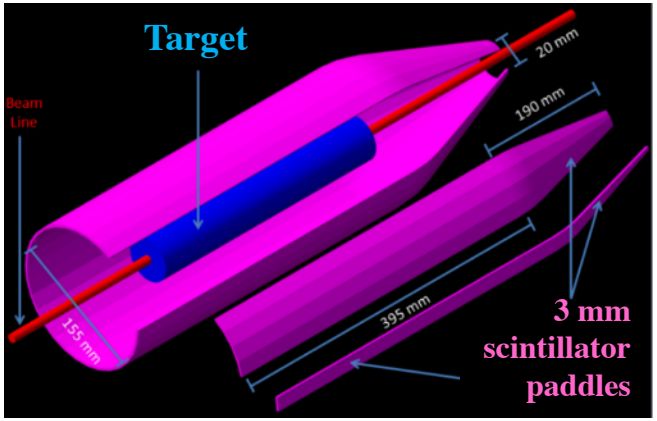




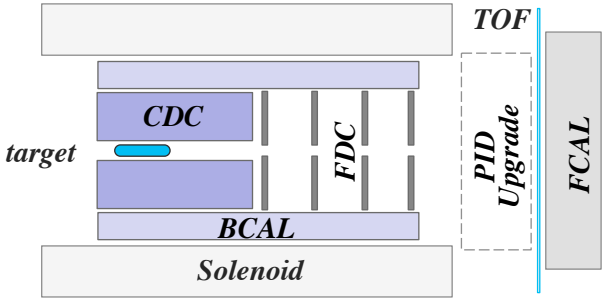


GlueX particle identification

- Time of flight measurement
  - Start Counter (SC) – FIU
    - 3-mm scintillators, 30 sectors
    - determine originating RF bunch (2 ns)
    - Readout by SiPM
  - Time-of-flight (TOF) – FSU
    - 1” thick scintillators, 2 layers
    - 80 ps resolution, forward K/π separation up to 2 GeV
  - Barrel Calorimeter
    - Large angle, 200 ps
- dE/dx measurement in CDC
  - proton identification

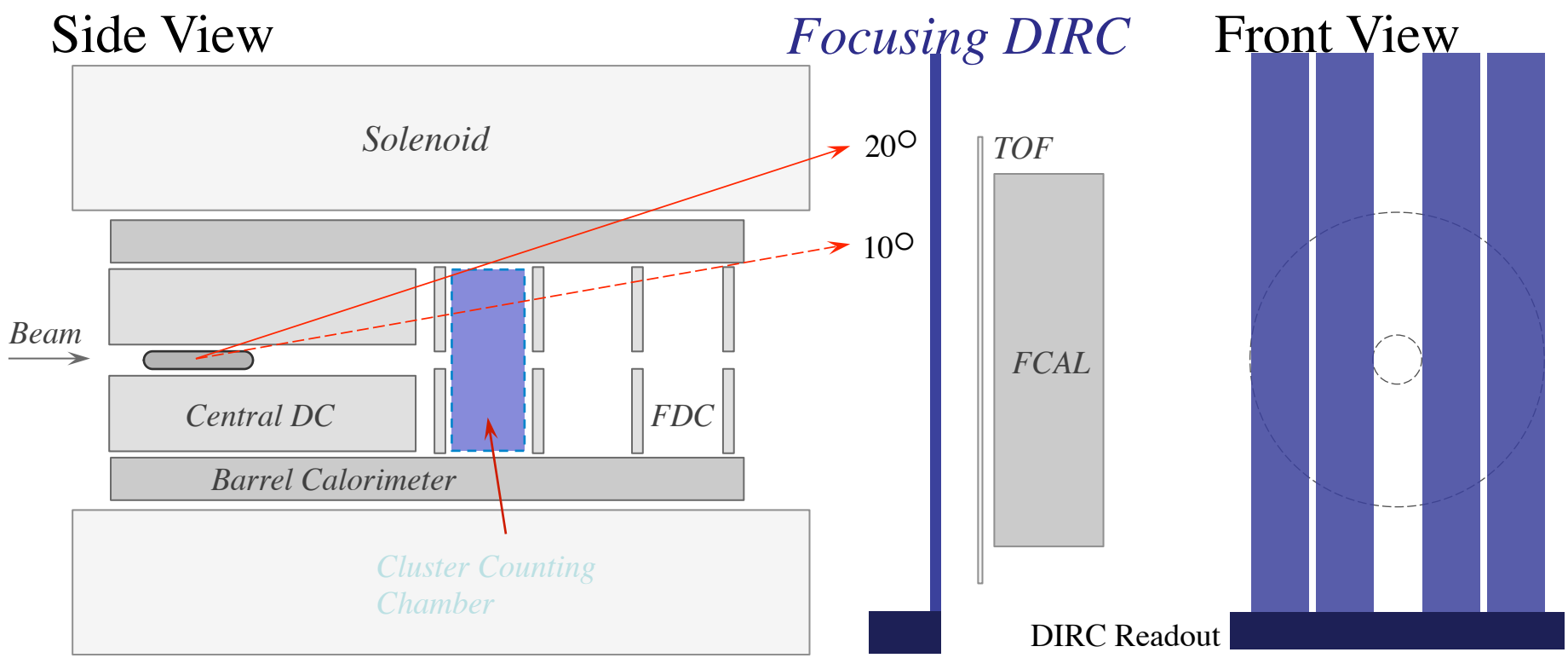


Start Counter

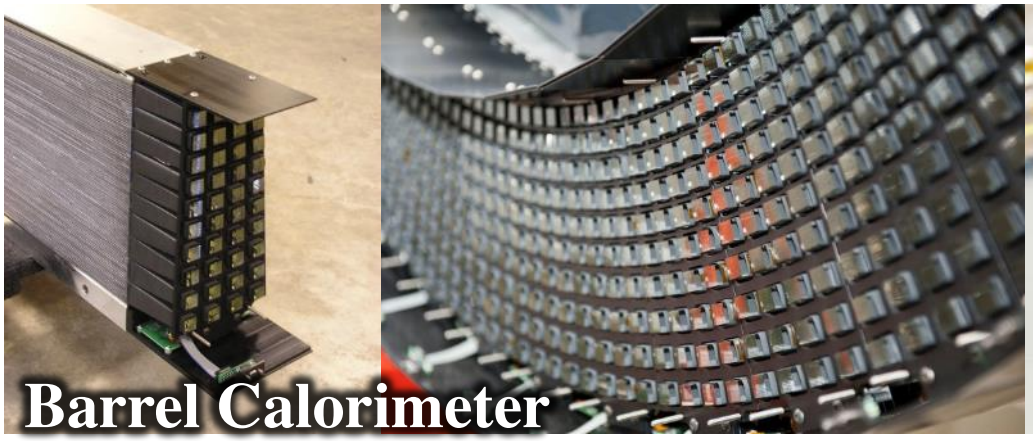


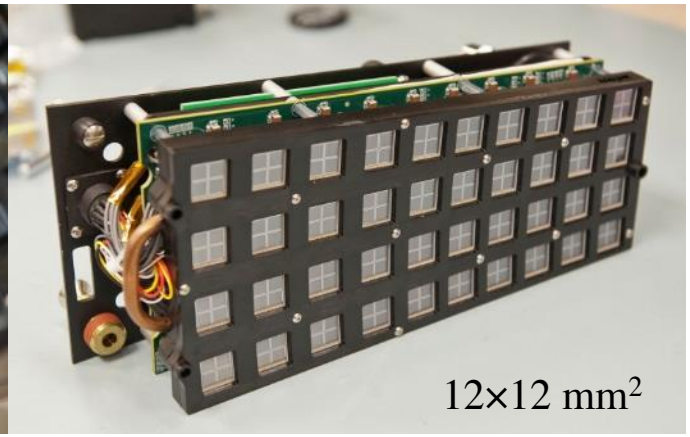
GlueX PID upgrade using a DIRC

- 12 BaBar DIRC bar boxes available: 490×43 cm^2 each
- Need 4 boxes for GlueX: forward region
- K/π separation up to 4 GeV

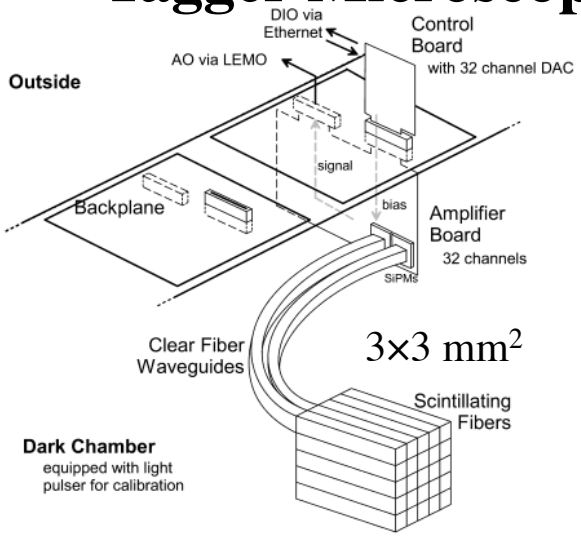


GlueX SiPM photon sensors

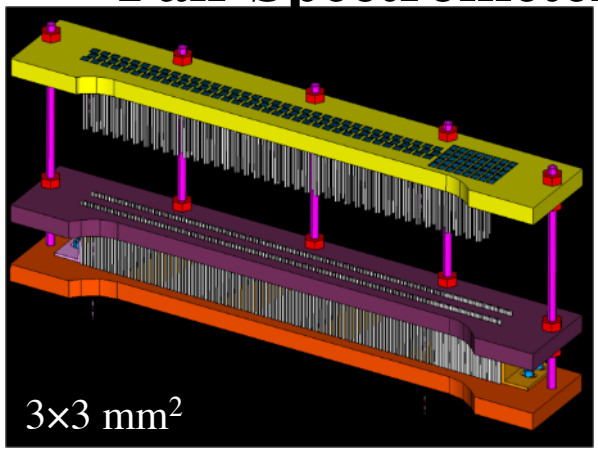




Tagger Microscope

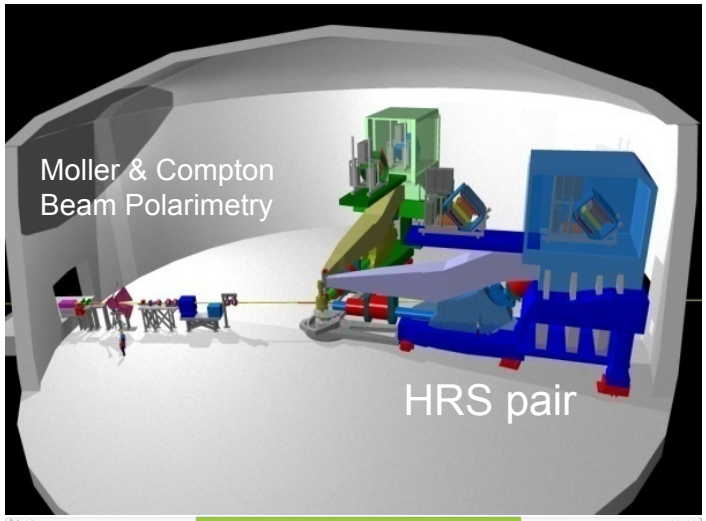


Pair Spectrometer

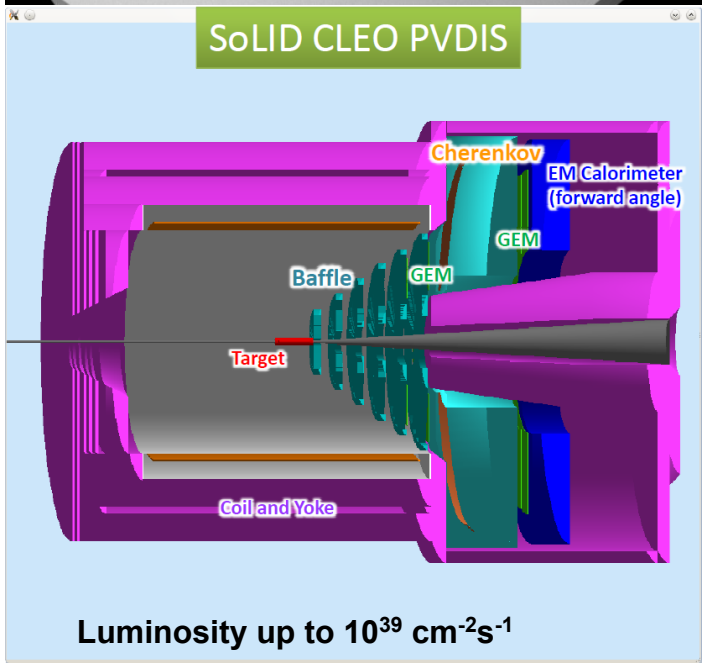


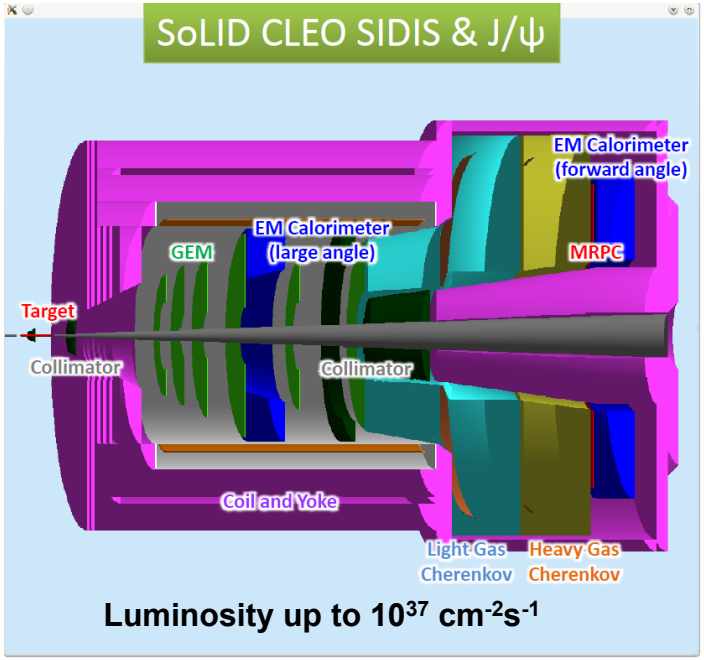
Start Counter

SoLID detector in Hall A



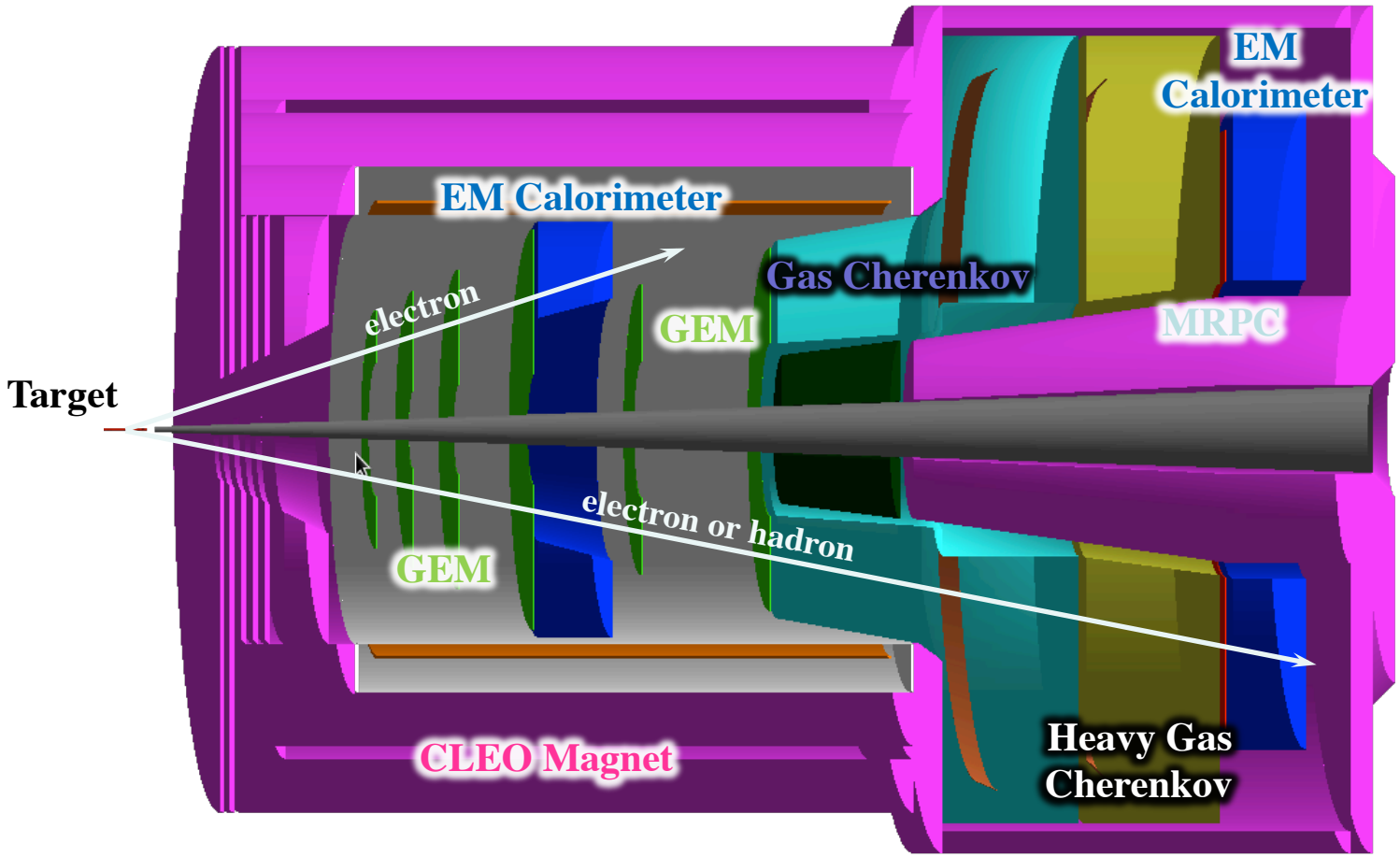
- Large acceptance detector based on CLEO solenoid
- GEM-based tracking will allow reaching very high luminosities
- Envisioned to run in two configurations





SoLID Setup for SIDIS and J/Ψ

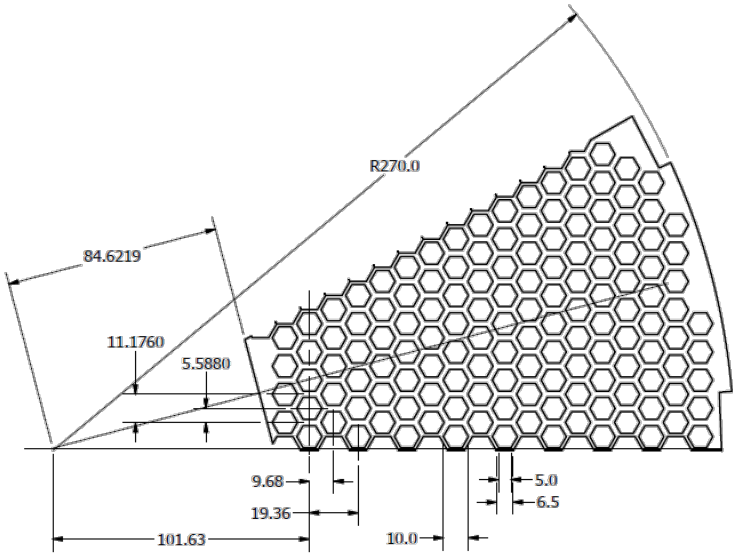
- Polarized ^{3}He and proton targets
- Luminosity ~ 10^{37}/cm^2/s (open geometry)

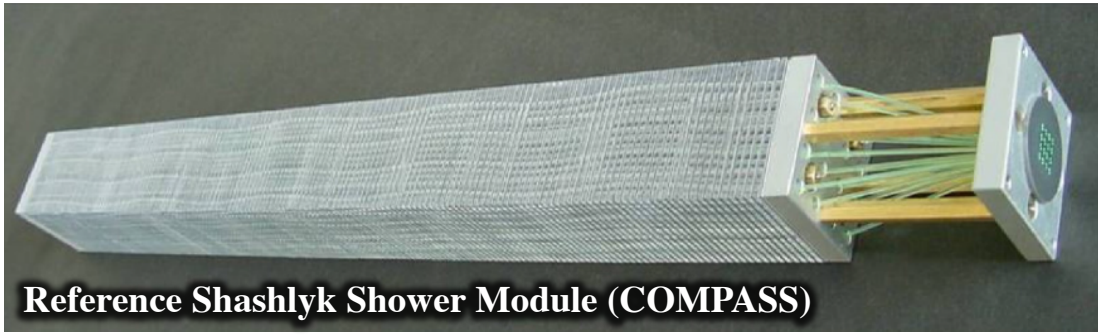


SoLID EM calorimeter

- Pre-shower/Shower configuration for better electron identification
- Pre-shower: Wavelength shifting fiber embedded in scintillator blocks, being tested at UVa

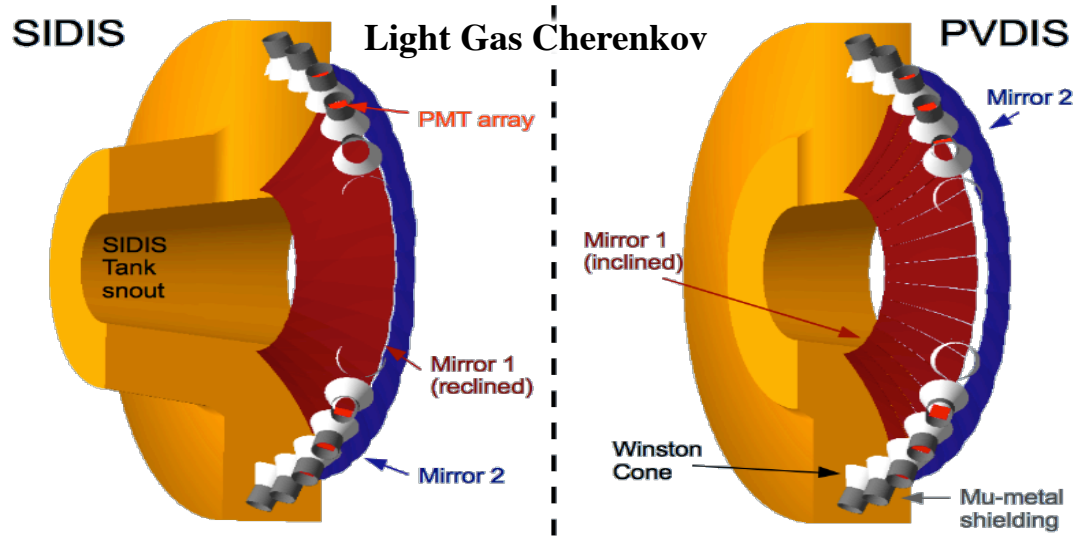
- Shower: Shashlyk module for better radiation tolerance, tested at JLab
- Hexagon segmentation

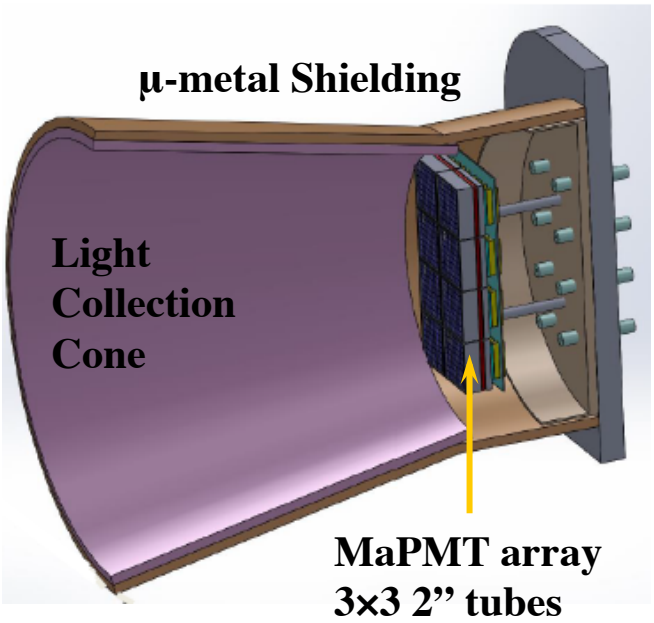


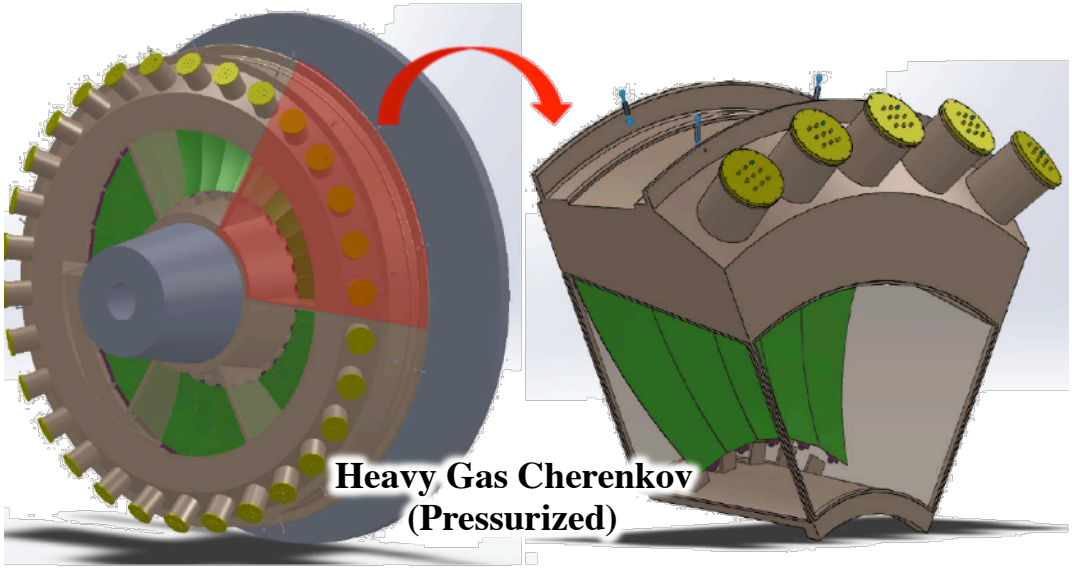


SoLID gas Cherenkov detectors

- Being Developed by Temple U (Light Gas Cherenkov) and Duke U (Heavy Gas)
- Readout by MaPMT arrays

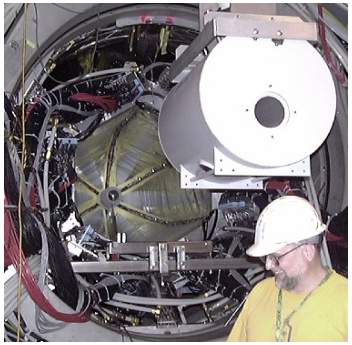




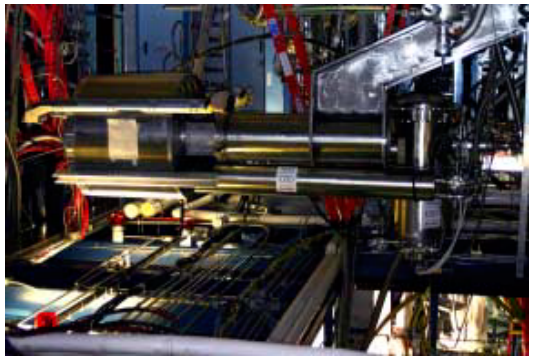


Generic EIC detector R&D – example

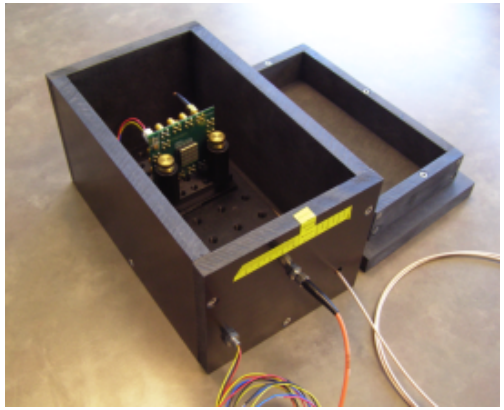
- As part of the EIC R&D program, a new, permanent facility for tests of photosensors in high magnetic fields is being set up at JLab
  - Two 5T magnets provided by JLab
- MCP-PMTs (or LAPPDs) with small pore size (2-10 μm) could provide a radiation hard, low-noise, baseline sensor suitable for single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



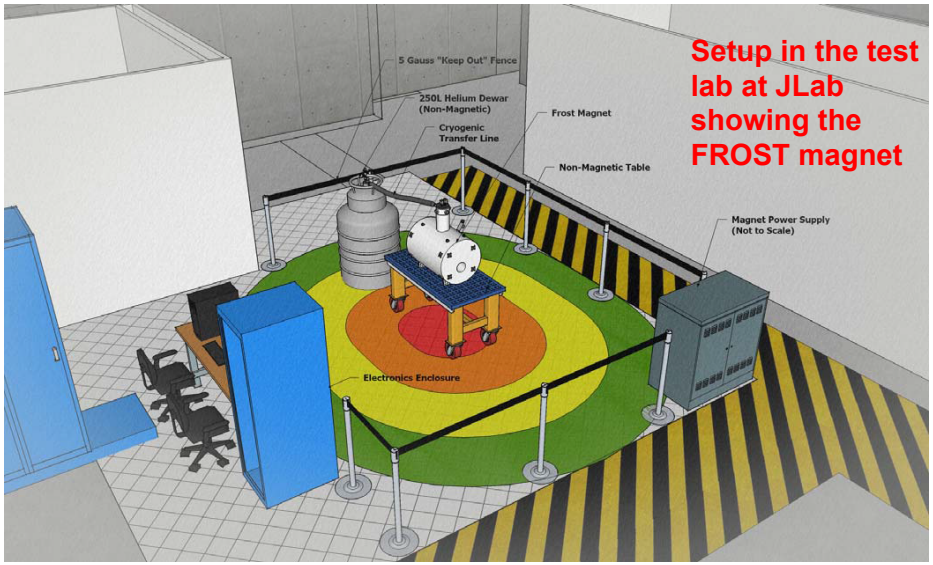
CLAS FROST solenoid with 5” bore



CLAS DVCS solenoid with 9” bore

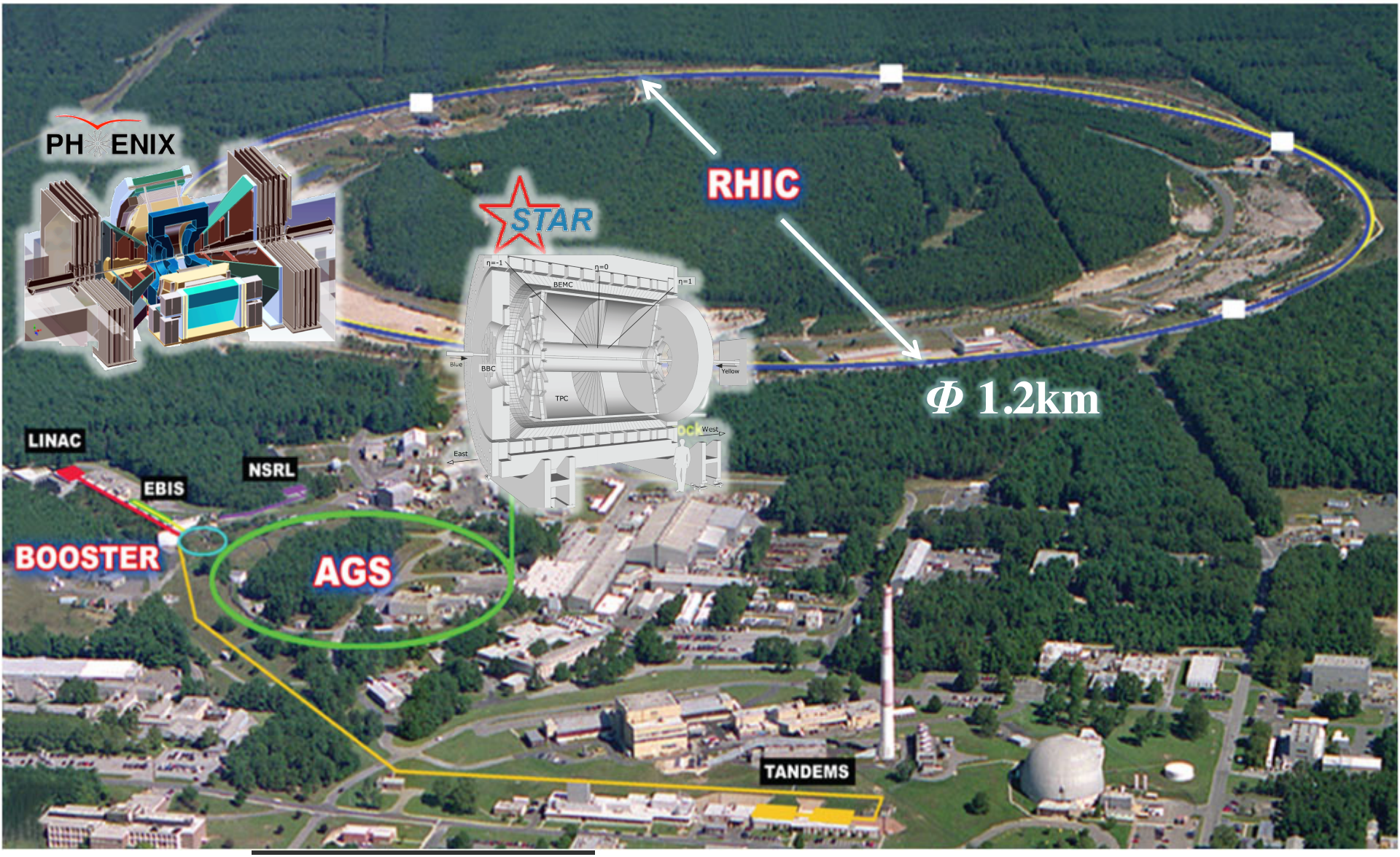


Non-magnetic dark box with pulsed LED for the DVCS solenoid – note the GlueX SiPM (Hamamatsu S11064-050P(X))

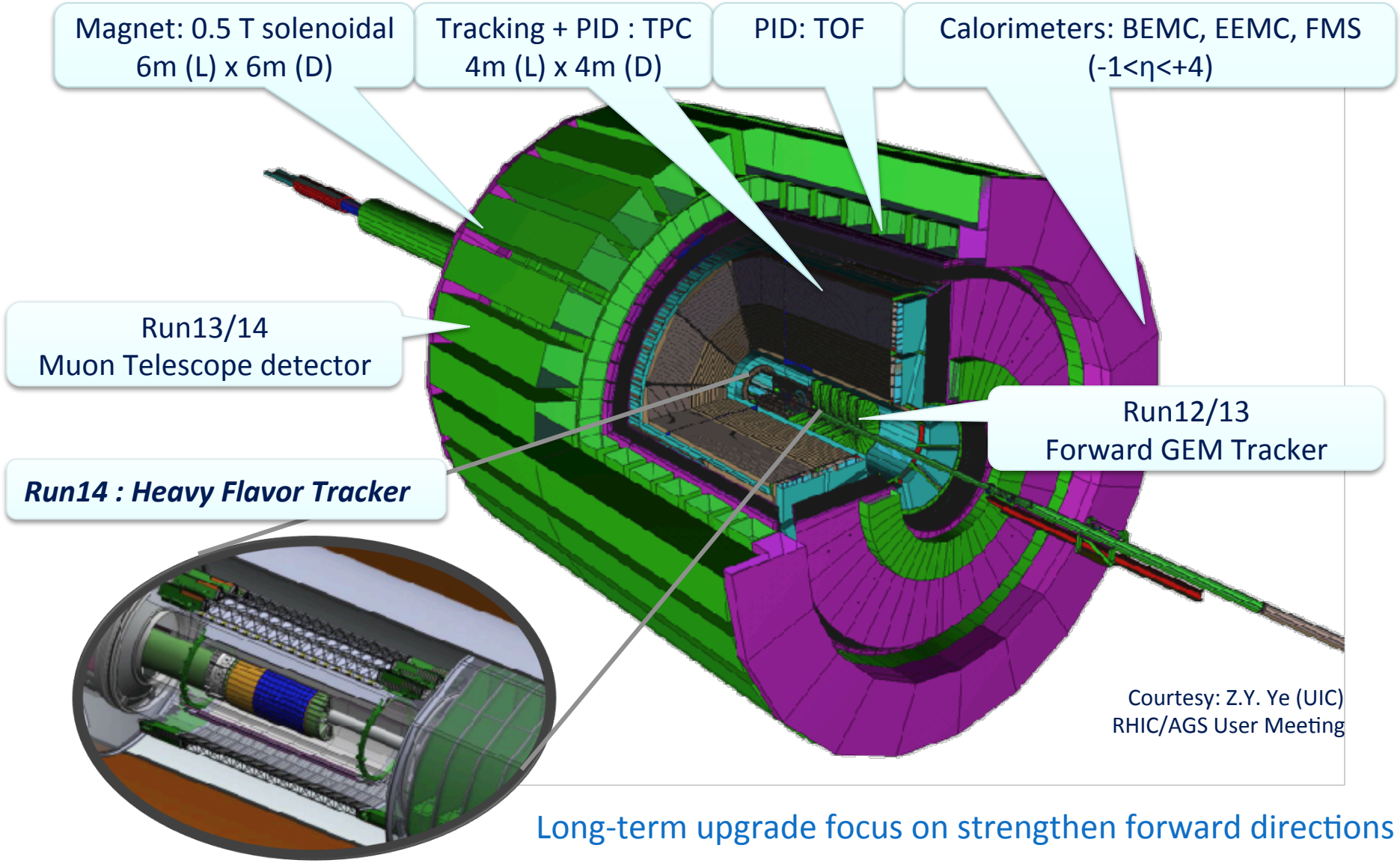


Setup in the test lab at JLab showing the FROST magnet

RHIC at Brookhaven



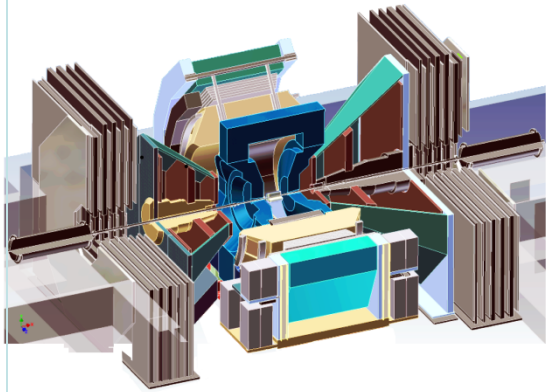
STAR at RHIC

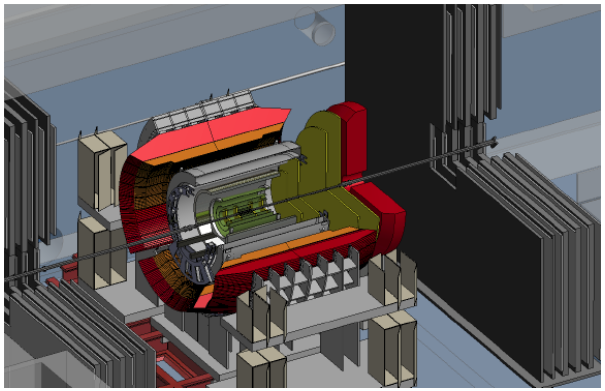


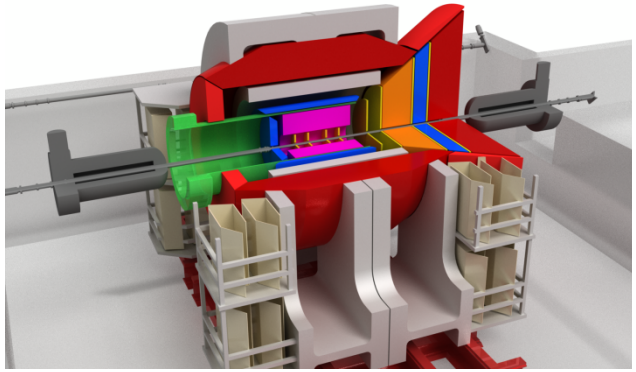
Long-term upgrade focus on strengthen forward directions

PHENIX at RHIC

Current PHENIX	*f*/*s*PHENIX	Future EIC detector
▸ 14+ years of operation ▸ Last run in 2016	▸ New detector based on solenoid magnet from the BaBar detector ▸ Opportunity for forward upgrade ▸ Jet detector with Hadronic Calorimeter (covering $-1<\eta<4$) ▸ Cost $75M	▸ Path of PHENIX upgrade leads to a capable EIC detector ▸ Large coverage of tracking, calorimetry, and PID ▸ Can be used at BNL or JLab





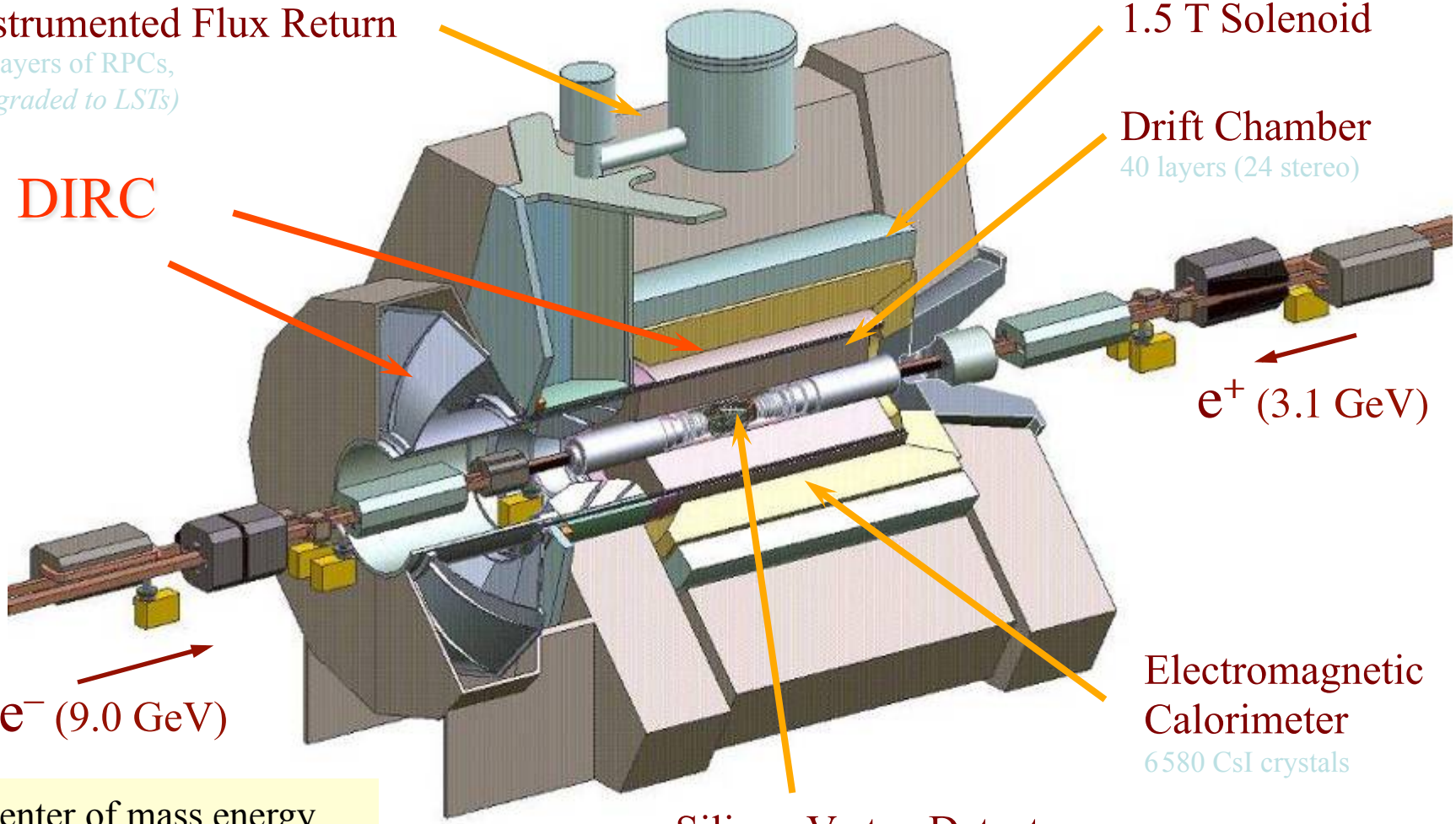


~2000 ~2020 ~2025 Time

RHIC: A+A, spin-polarized p+p, spin-polarized p+A

EIC: e+p, e+A

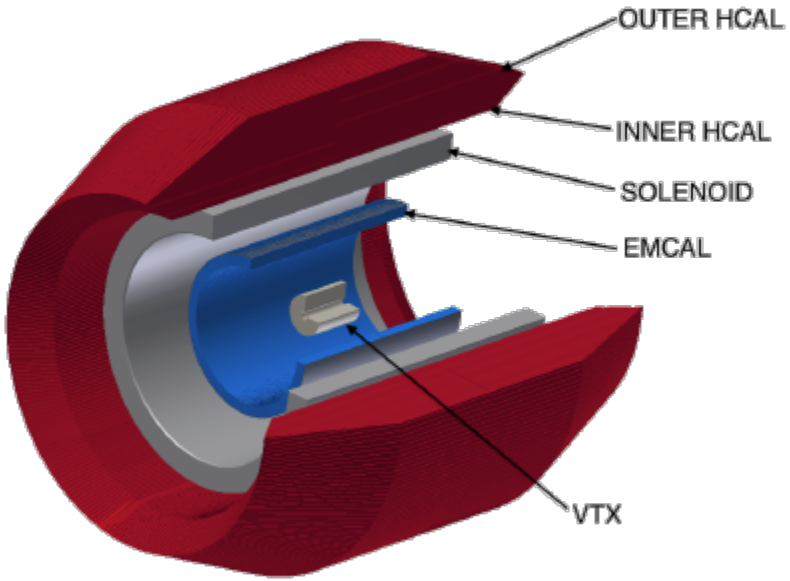
The BaBar detector at SLAC



center of mass energy
$\approx M_{\Upsilon(4S)} = 10.58\ \mathrm{GeV}/c^2$

BaBar solenoid and sPHENIX


BaBar solenoid packed for shipping, May 17 2013



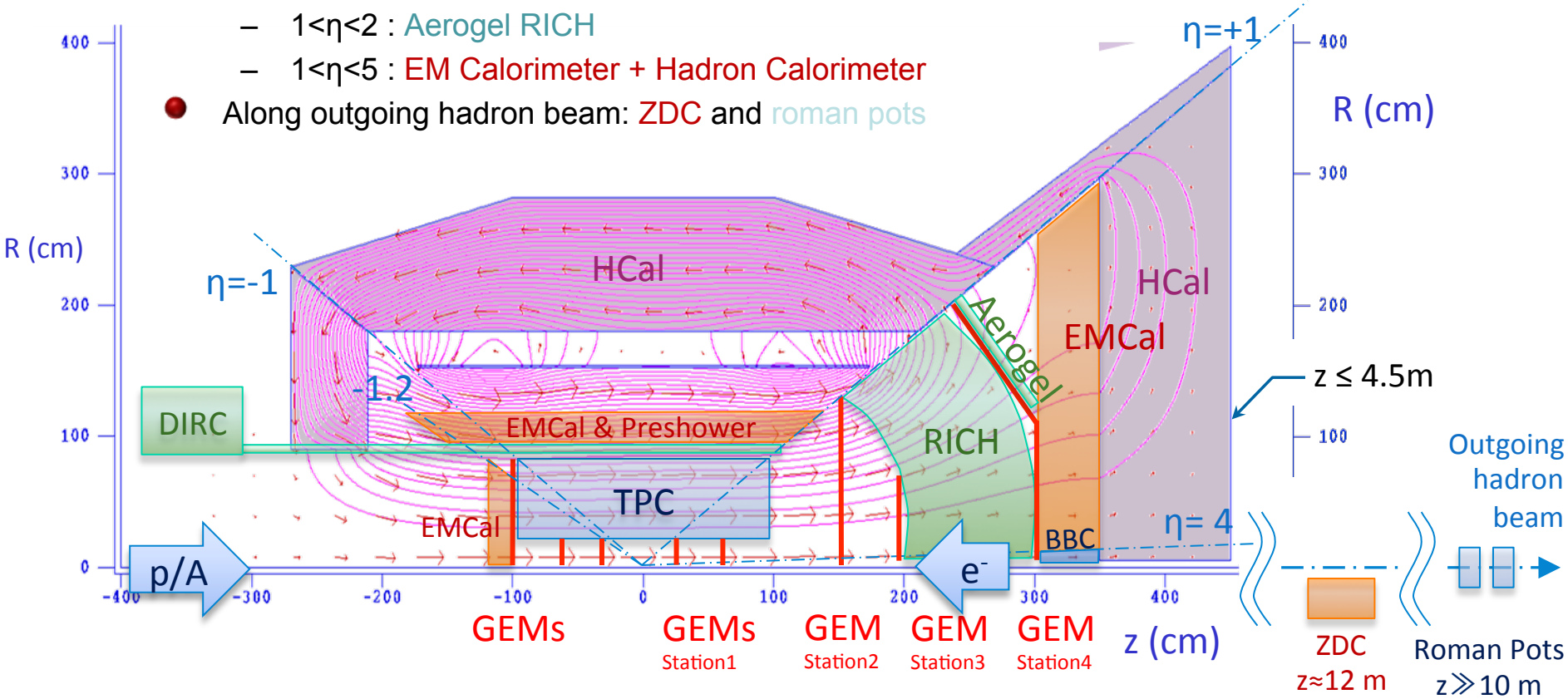
Baseline detectors for sPHENIX

sPHENIX MIE, http://www.phenix.bnl.gov/plans.html

EIC detector based on BaBar solenoid

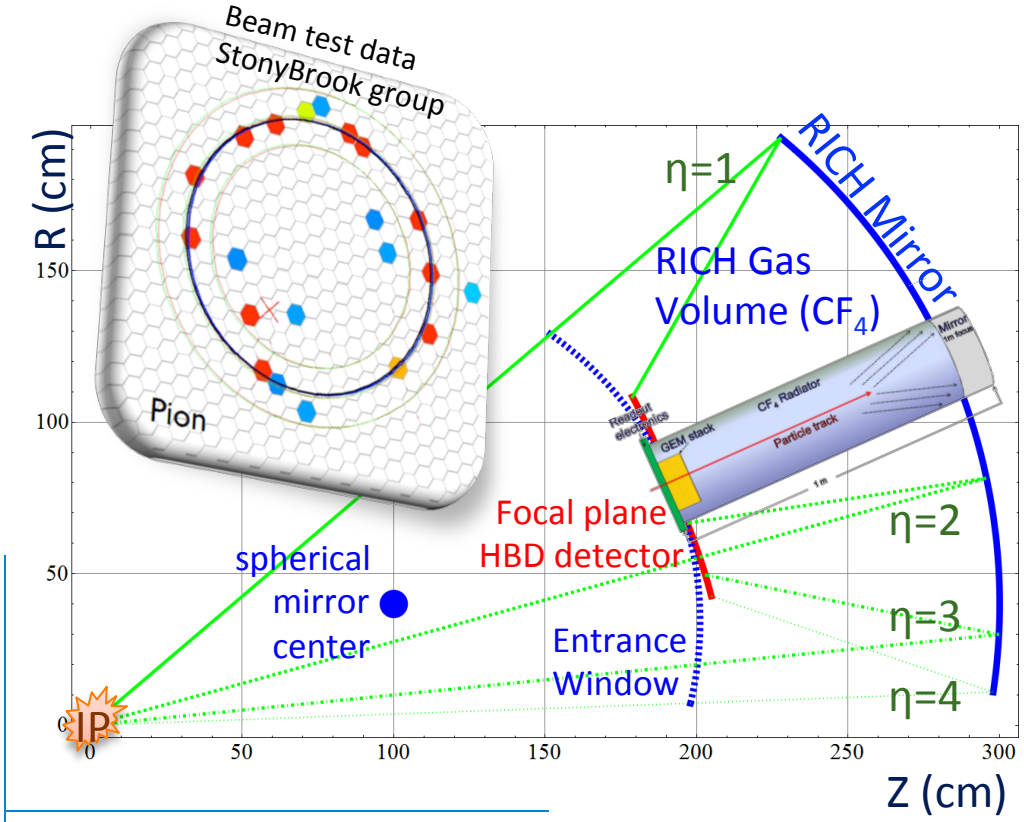
- -1<η<+1 (barrel) : sPHENIX + Compact-TPC + DIRC
- -4<η<-1 (e-going) :
  High resolution calorimeter + GEM trackers
- +1<η<+4 (h-going) :
  - 1<η<4 : GEM tracker + Gas RICH
  - 1<η<2 : Aerogel RICH
  - 1<η<5 : EM Calorimeter + Hadron Calorimeter
- Along outgoing hadron beam: ZDC and roman pots

- Caveat: hadronic calorimeter (Hcal) limits forward opening!
- Complementary detector needed

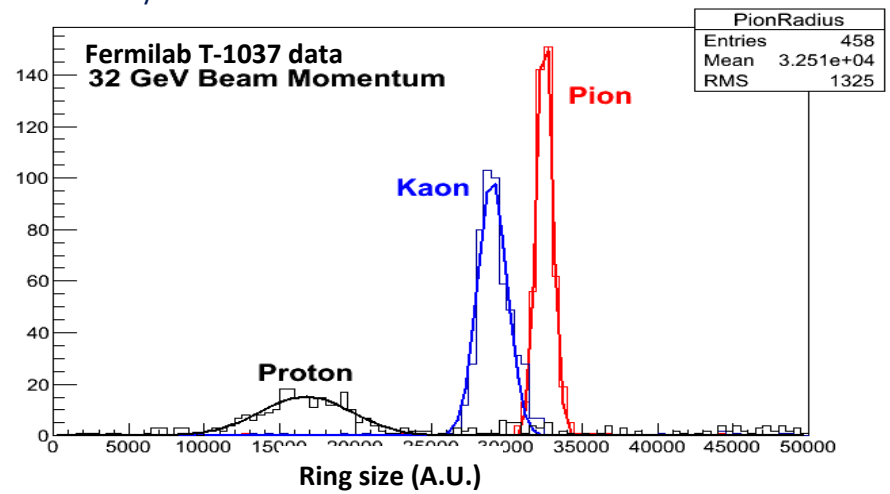


Gas RICH
- The Design

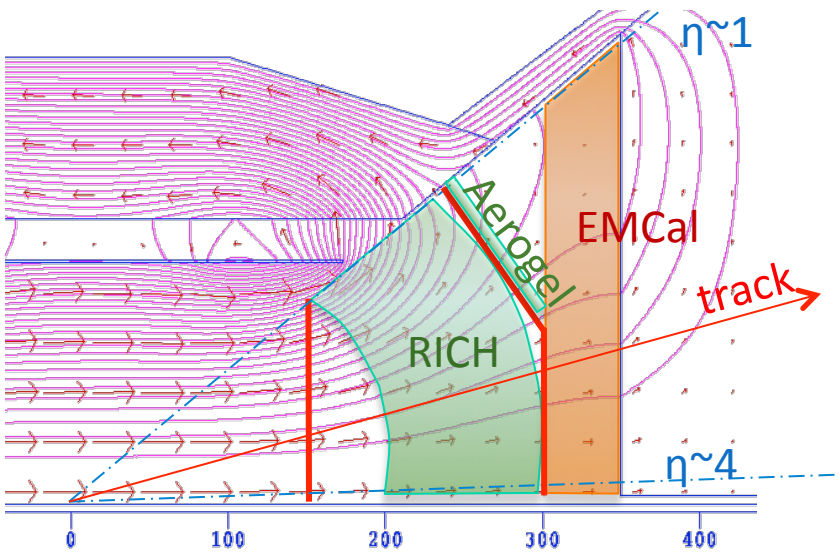
- Hadron ID for p>10GeV/c require gas Cherenkov
  - CF_4 gas used, similar to LHC_b RICH
- Beautiful optics using spherical mirrors
- Photon detection using CsI –coated GEM in hadron blind mode
  - thin and magnetic field resistant
- Active R&D:
  - Generic EIC R&D program
  - recent beam tests by the stony brook group



Courtesy : EIC RD6 TRACKING & PID CONSORTIUM

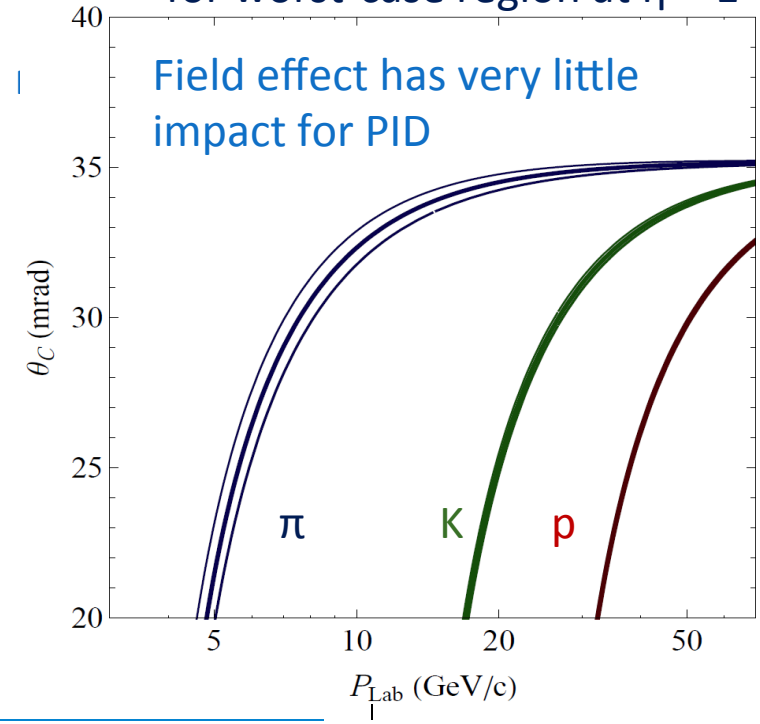


Gas RICH
- performance in ePHENIX

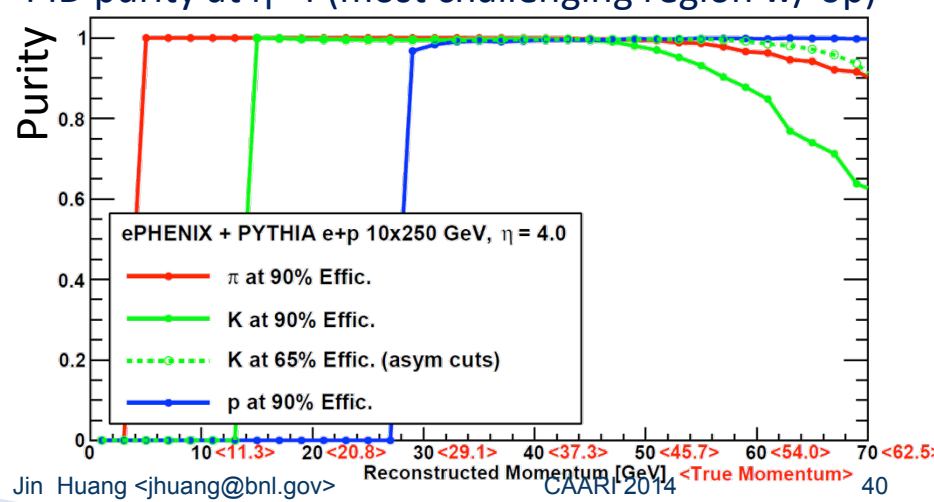


- Strong fringe field unavoidable
  Tuned yoke → magnetic field line most along track within the RICH volume
  → very minor ring smearing due to track bending
- Reached good hadron ID to high energy

Ring radius ± 1σ field effect for worst-case region at η~+1



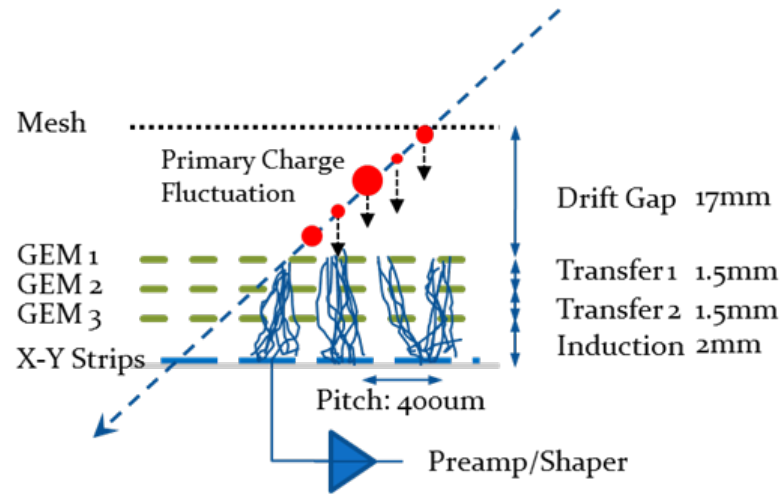
PID purity at η=4 (most challenging region w/ δp)



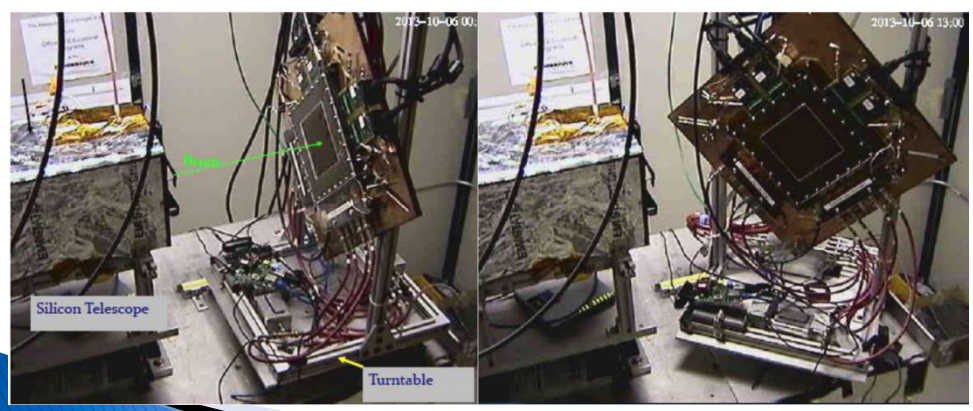
On-going detector R&D : mini-Drift GEM

Courtesy : EIC RD6 TRACKING & PID CONSORTIUM

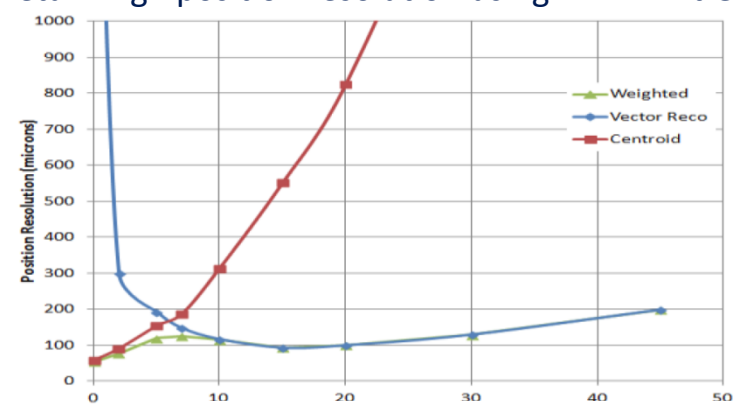
- Challenge in GEM tracking to achieve high precession with large indenting angle in the lower η region
- One innovation: use thicker drift gap in GEM as a mini-TPC and measure the tracklet
- Successful test beam data for mini-Drift GEM
- Large area GEM developments



Beam test in Fermi-Lab: October 2013

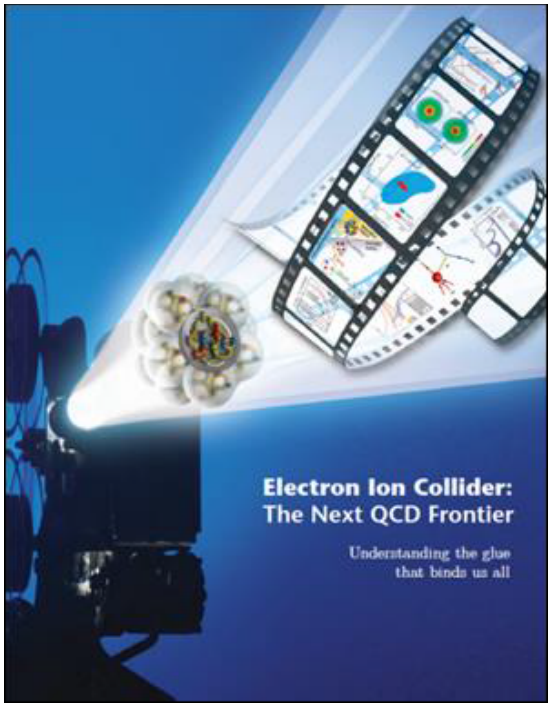


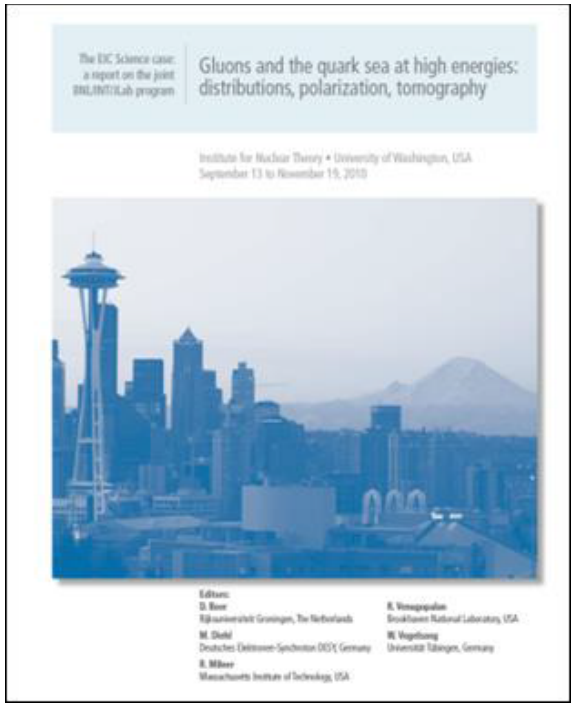
Retain high position resolution using mini-Drift GEM



Beam incident angle (degree)

EIC physics program



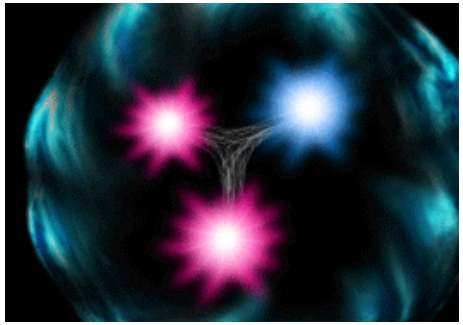


- The EIC at JLab supports the full physics program for a generic EIC
  - White paper, INT report, etc
  - JLab implementation offers some unique features
- Many detector concepts can be applied to both BNL and JLab
  - At JLab detector integration with the accelerator has been a key feature

EIC physics highlights

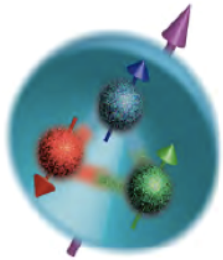
- 3D structure of nucleons

  How do gluons and quarks bind into 3D hadrons?



- Role of orbital motion and gluon dynamics in the proton spin

  Why do quarks contribute only ~30%?

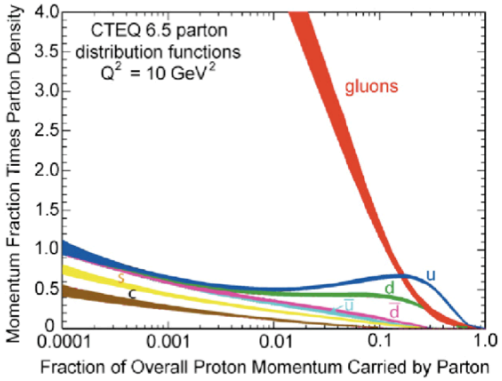


- Gluons in nuclei (light and heavy)

  Example: spectator tagging with light polarized nuclei

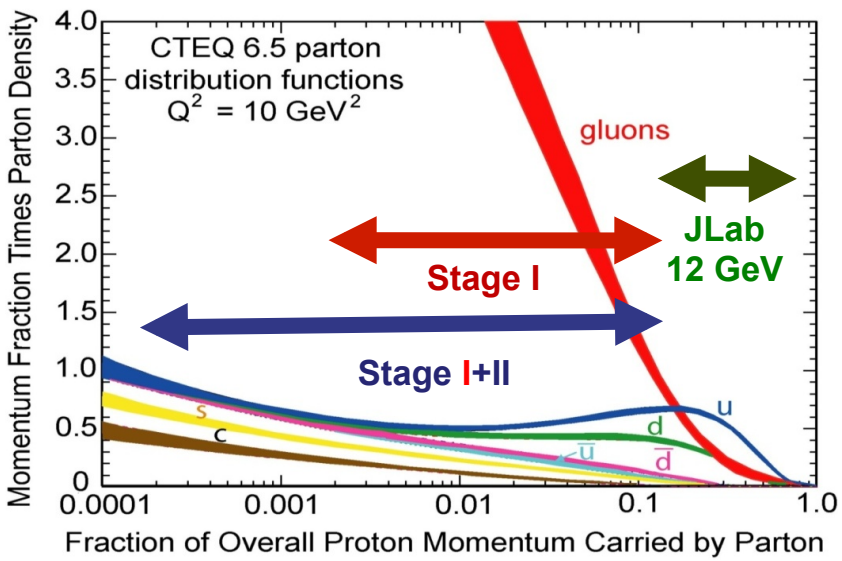
  Does the gluon density saturate at small x?

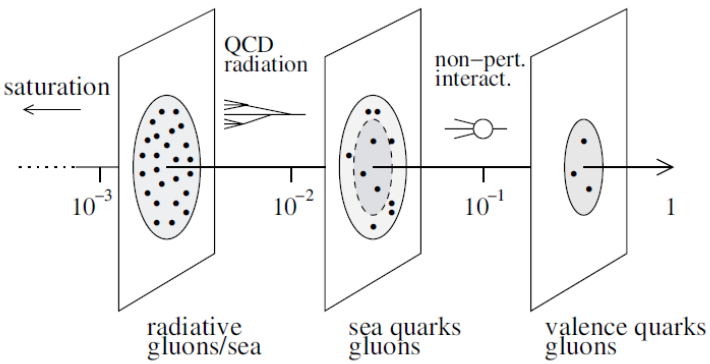
  Impact parameter dependence of Q_s ? (from fragment detection)

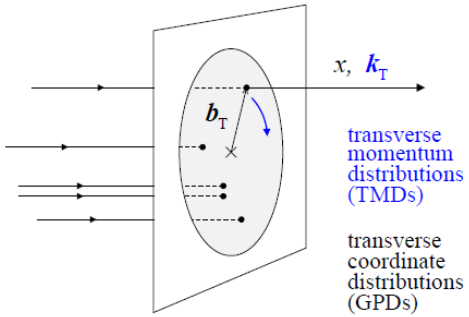


Physics coverage and energy staging

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



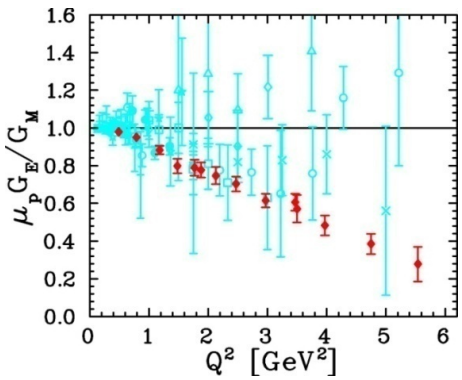


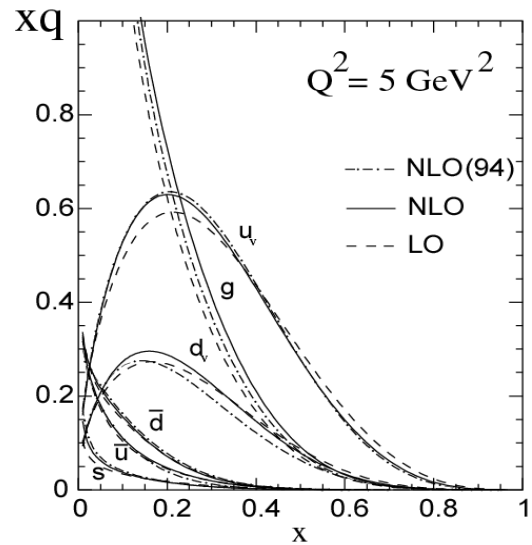


The MEIC (JLab stage I) provides excellent performance for all x and Q^2 between JLab 12 GeV and HERA (or a future LHeC)

3D structure of the nucleon

➔ *see also JLab 12 GeV*





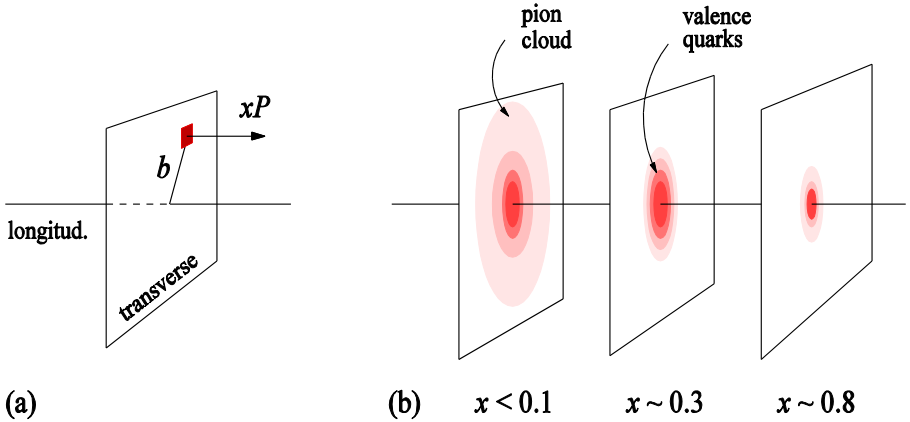
Elastic form factors

Transverse spatial distributions

(Naively Fourier transform of Q^2 or t)

Parton Distribution Functions

Longitudinal momentum distributions



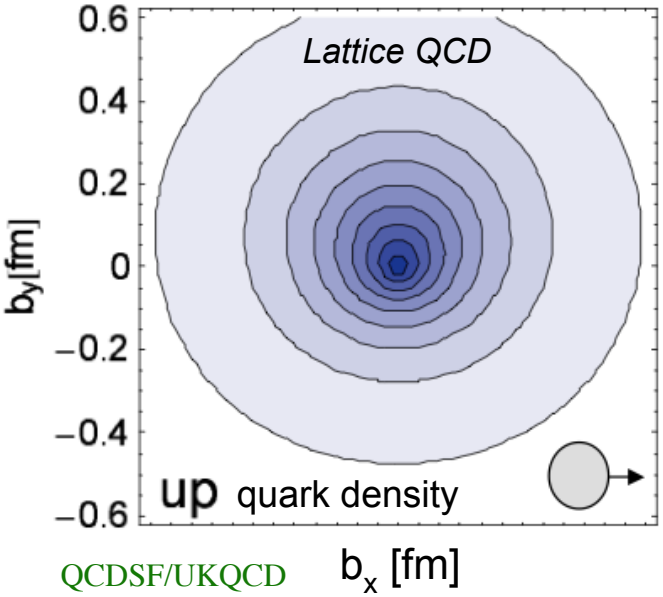
Generalized Parton Distributions

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**

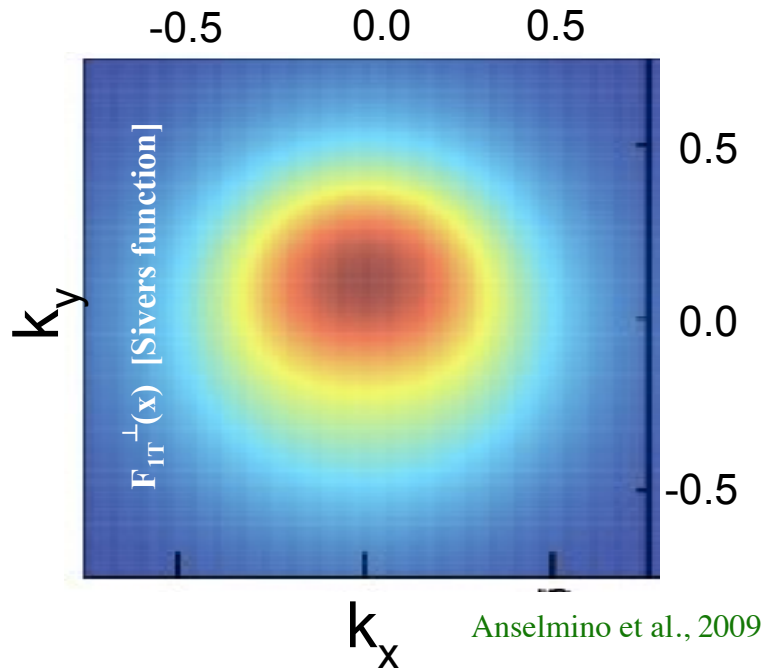


QCDSF/UKQCD Coll., 2006

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

TMDs ➔ *see also JLab 12 GeV*

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



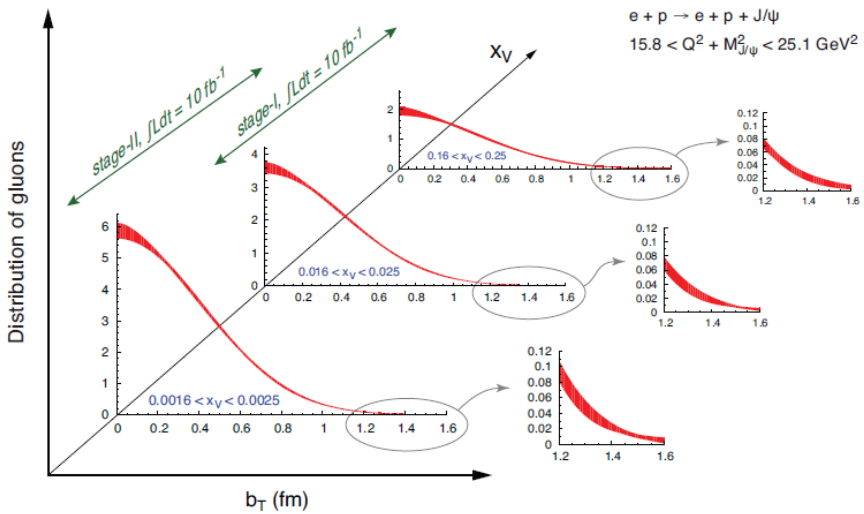
Anselmino et al., 2009

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

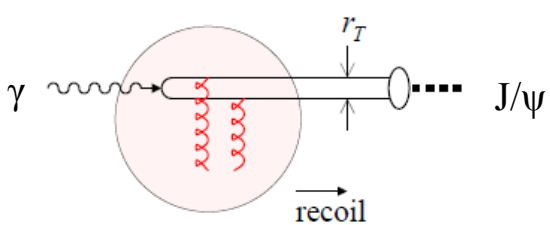
Spatial- and momentum imaging

GPDs

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

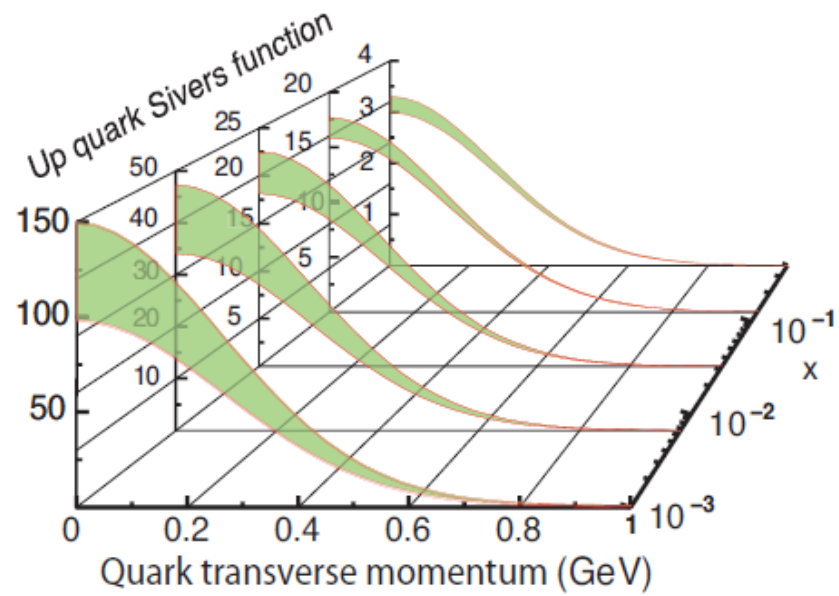


Transverse gluon distribution from J/ψ production



TMDs

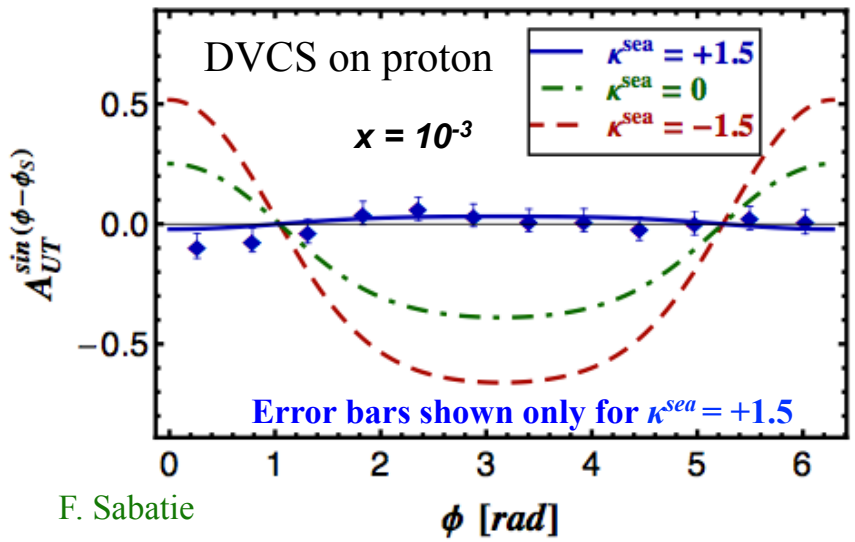
2+1 D picture in **momentum space**



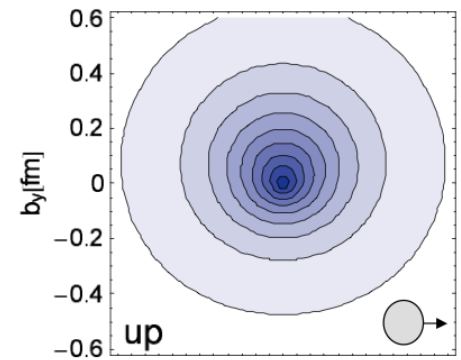
Projections from EIC white paper

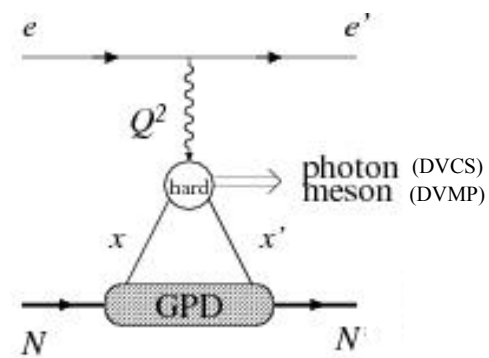
GPDs and angular momentum

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



F. Sabatie



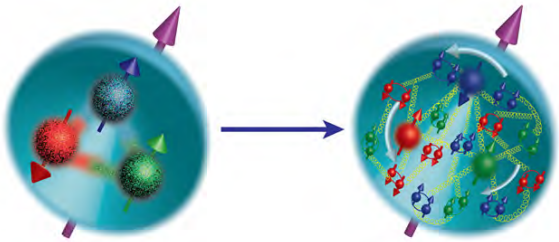


- DVCS on a *transversely* polarized target is sensitive to the *GPD E*
  - *GPD H* can be measured through the beam spin asymmetry
  - Opportunity to study spin-orbit correlations (Ji sum rule)

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

The spin of the proton

The number ½ reflects both the intrinsic properties of quarks and gluons as their interactions



$$\frac{1}{2} = \underbrace{\overset{\sim 0.3}{\frac{1}{2}\Delta\Sigma(\mu)} + \overset{?}{L_q(\mu)}}_{J\ \text{quarks}} + \underbrace{\overset{\text{small ?}}{\Delta G(\mu)} + \overset{?}{L_g(\mu)}}_{J\ \text{gluons}}$$

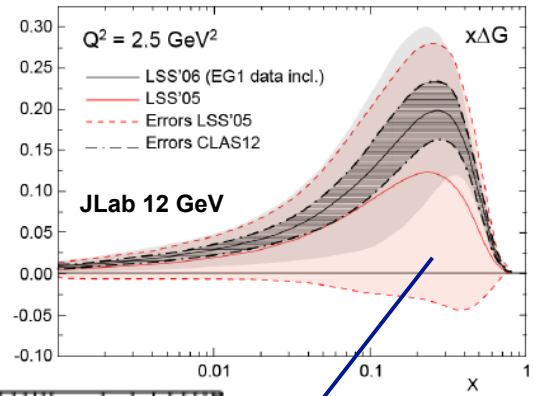
quark spin, orbit; polarization, orbit

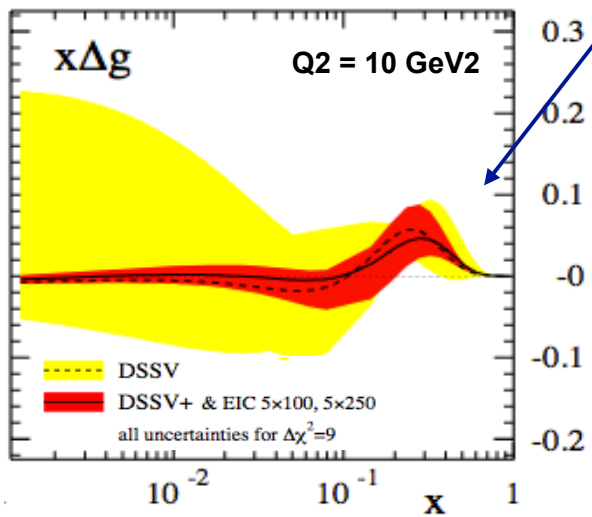
- Two complementary approaches required to resolve the spin puzzle

Measure ΔG - gluon polarization (longitudinal structure)

Measure TMD and GPDs - orbital motion (3D structure): $J^q = \frac{1}{2}\int_{-1}^{+1} dx\, x\left[H^q(x,\xi,t) + E^q(x,\xi,t)\right]$ GPDs

Gluon polarization (ΔG)



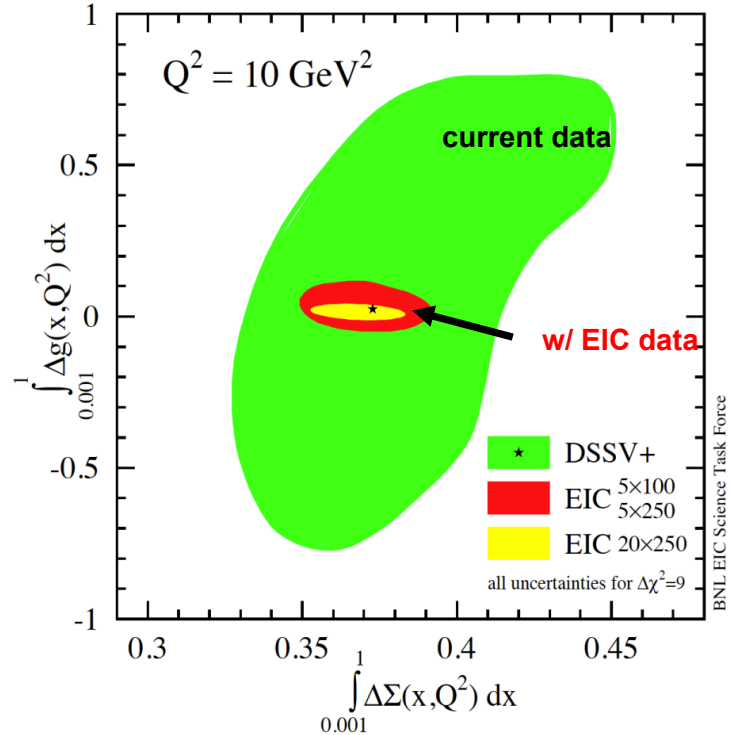


M. Stratmann

Green: RHIC spin, COMPASS, etc

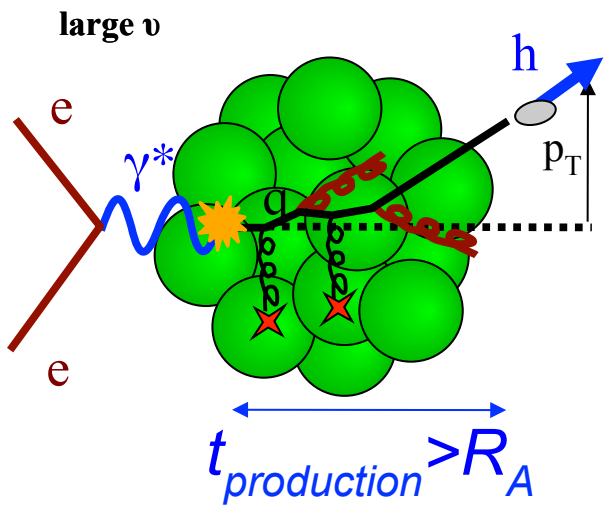
Red: EIC Stage I (MEIC or eRHIC)

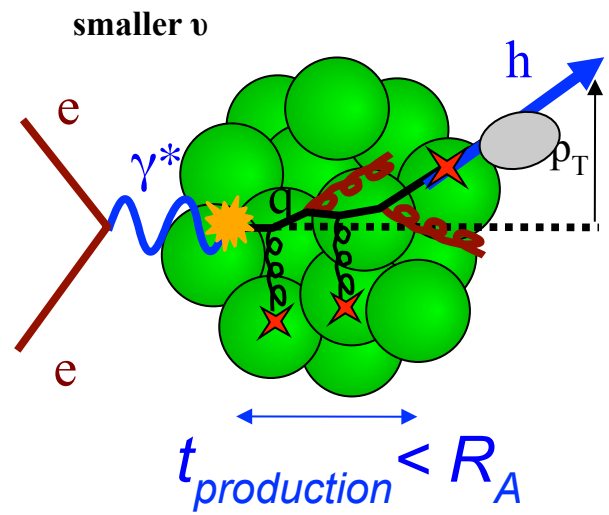
Yellow: EIC Stage II



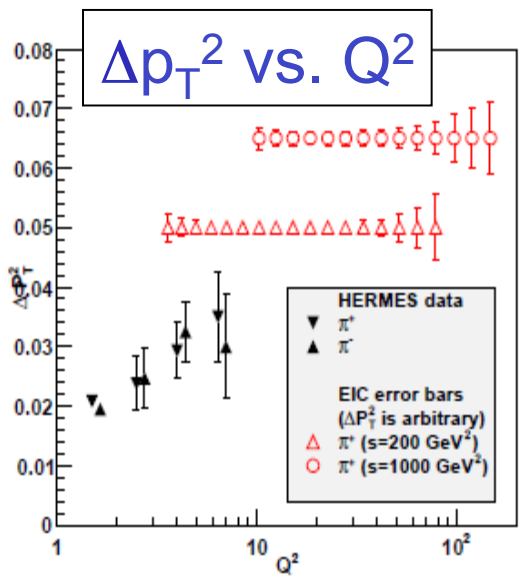
- EIC stage I will greatly improve our understanding of ΔG
  - Stage II will further reduce the uncertainty

Quark propagation in matter





Accardi, Dupre

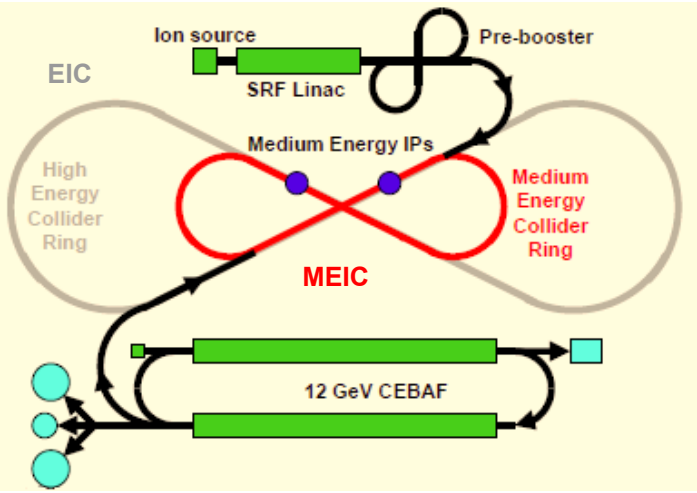


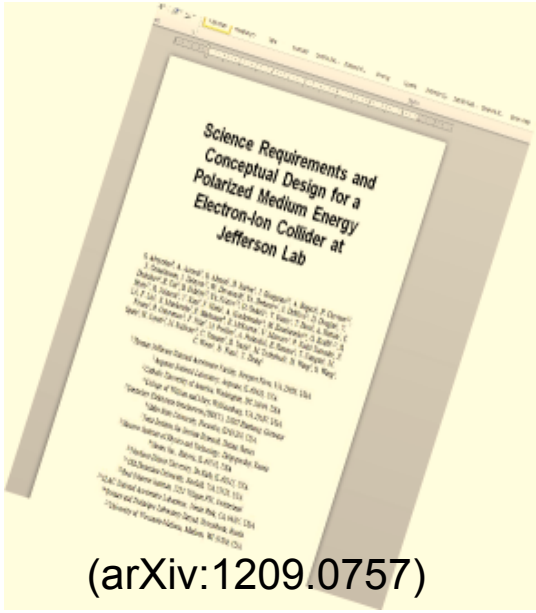
- Broadening of the outgoing meson's (h) p_T distribution gives insight into hadron formation
- Also interesting to look at heavy flavor mesons (B, D, J/Ψ) and jets
- *Impact parameter dependence?*
  - *Fragments and "wounded nucleons" can help understanding the path length*

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 a BaBar-based EIC detector*

MEIC – design goals and features



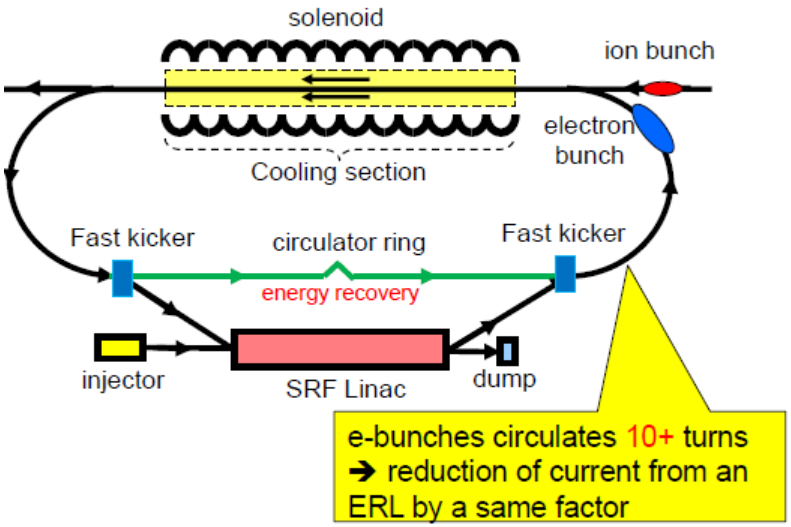


(arXiv:1209.0757)

Stable concept – detailed design report released August 2012

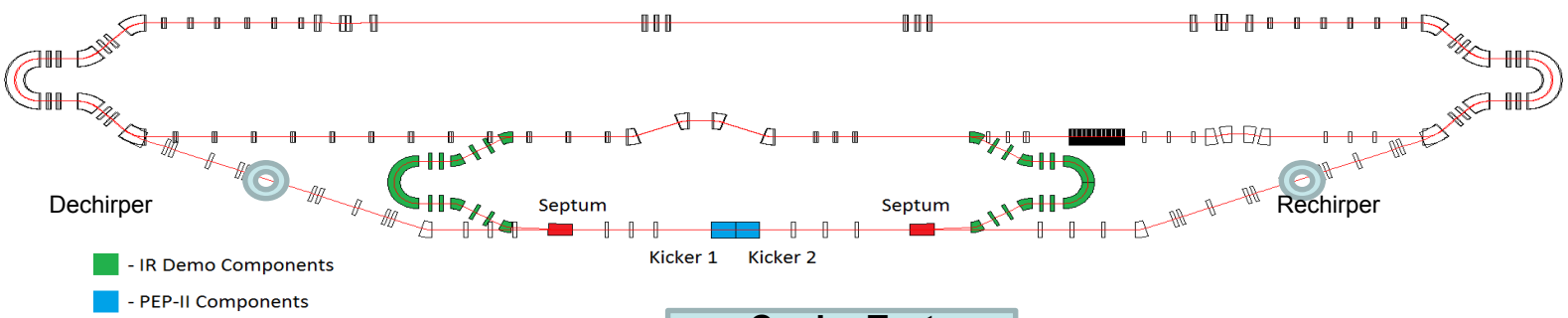
- **Spin control for all light ions**
  - Figure-8 layout
  - Vector- and tensor polarized deuterium
- **Full-acceptance detector**
  - Ring designed around detector requirements
  - High-resolution detection of all fragments – nuclear and partonic
- **Minimized technical risk**

Ion beam cooling with 55 MeV electrons



- Conventional electron "cooling" is a well-established technique to reduce emittance
- An Energy-Recovery Linac (ERL) provides higher current and energy than electrostatic devices

  55 MeV is required for 100 GeV protons
- A circulator ring would reduce the (unpolarized) source current requirement
- Tests are planned at the JLab Free-Electron Laser (FEL) ERL



Cooler Test Facility @ JLab FEL ERL

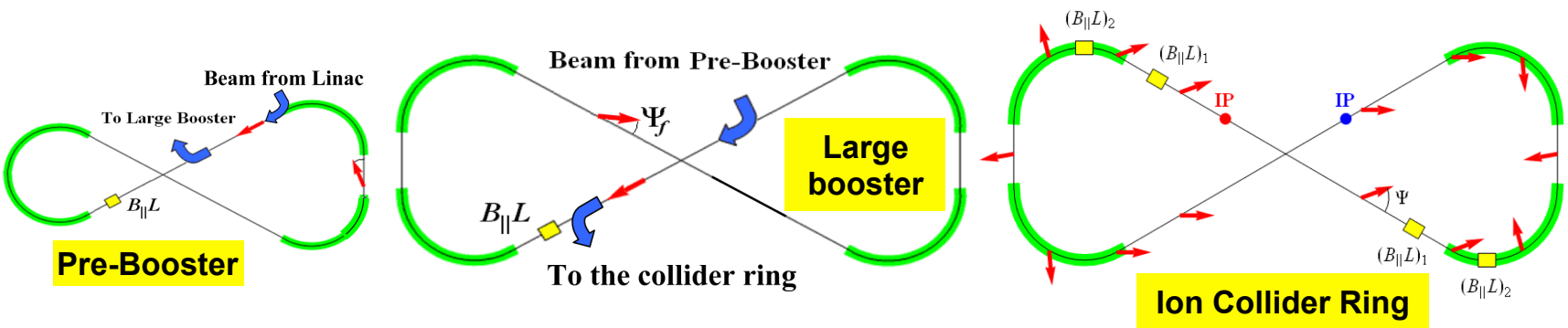
Polarization in figure-8 storage rings

- The EIC science program requires highly polarized electrons and light ions (p, D, ^{3}He, Li)

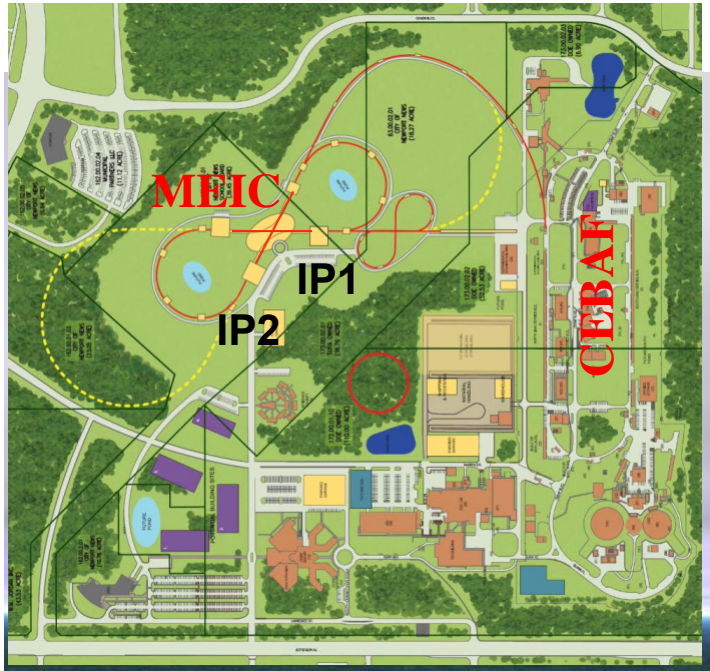
- Spin precession in left & right parts of the figure-8 ring cancel
  - Preserves polarization during acceleration (for all ion species)
  - Energy-independent spin tune
  - Spin is easily controlled by small solenoids (or other compact spin rotators)

    Spin orientation can be chosen independently at both IPs in the collider ring

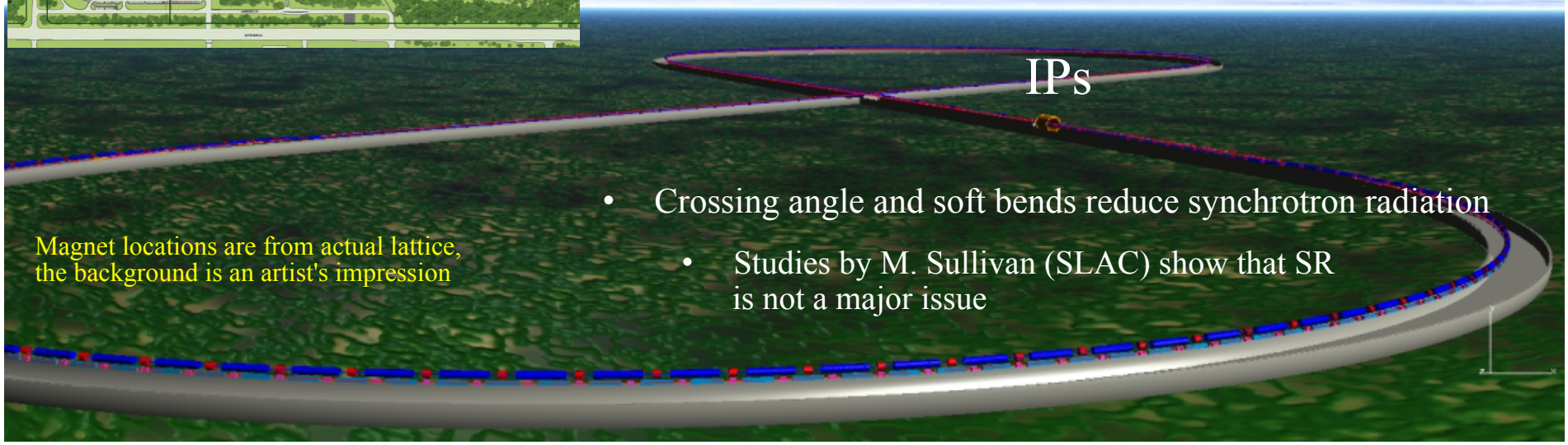
- A figure-8 ring allows vector- and tensor polarized deuterium (very small g-2)



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



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

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

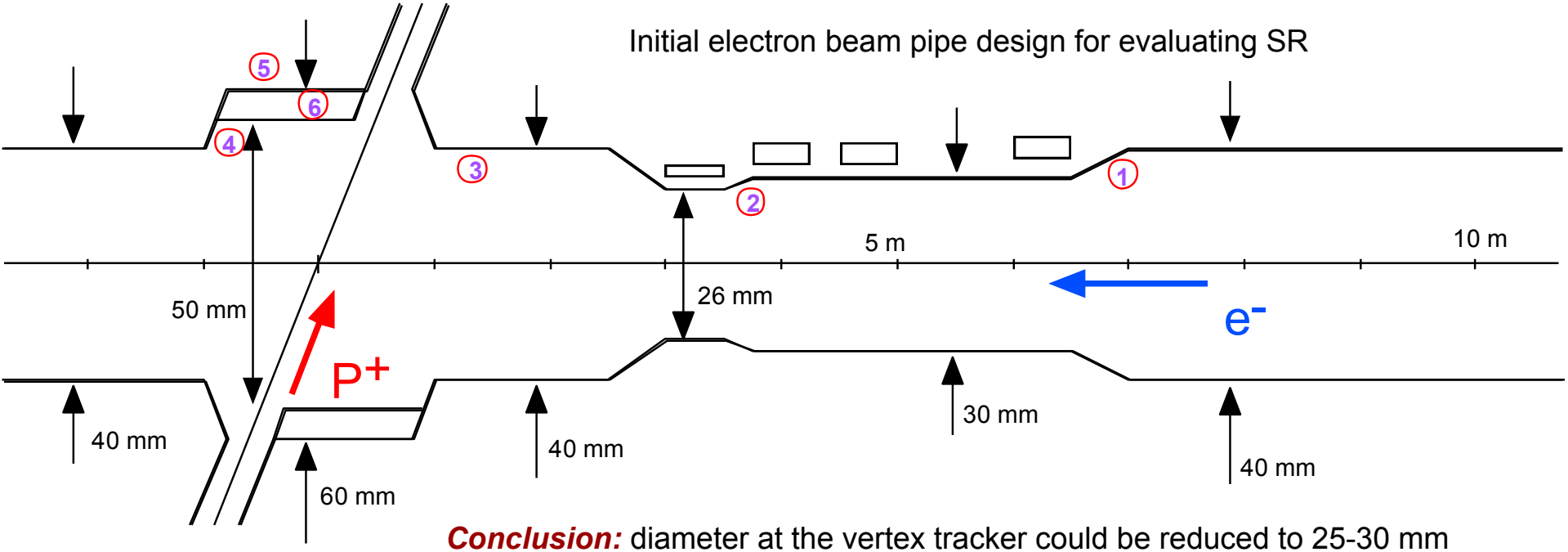
Hadronic backgrounds

- 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} $cm^{-2}s^{-1}$

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)

MEIC Detector development

- Central Detector
  - Basic requirements and technologies/solutions understood
  - Need to optimize performance and cost of subsystems
  - Innovative design features may improve performance
  - Ultimately, we would want to have two complementary detectors

    At the MEIC both can run simultaneously without beam time sharing

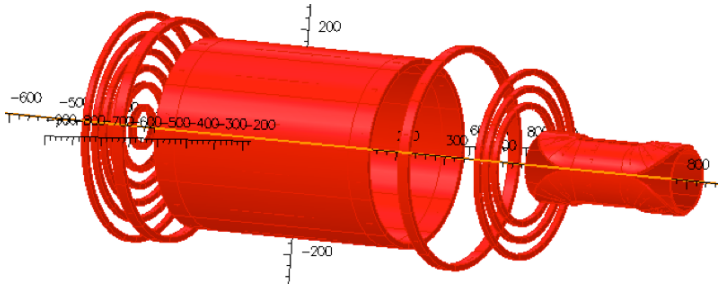
- Small-angle hadron and electron detection
  - Unprecedented acceptance and resolution possible
  - Integration with the accelerator is very important

    Allows the storage ring to be designed around the detector needs

- 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!

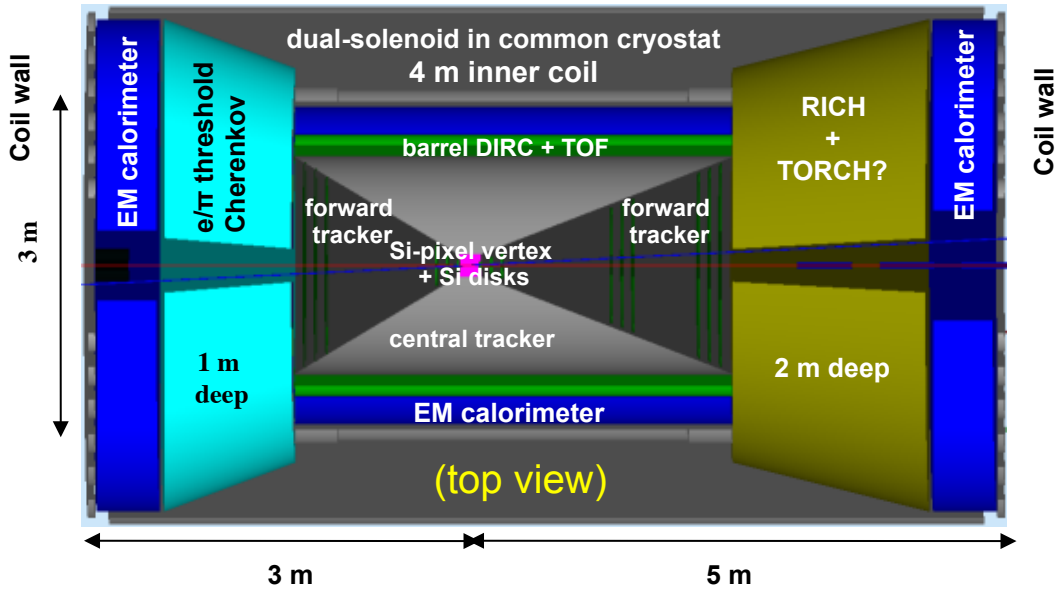
Central detector solenoid options

- 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
  - Was 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)*



TOSCA model of adual 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



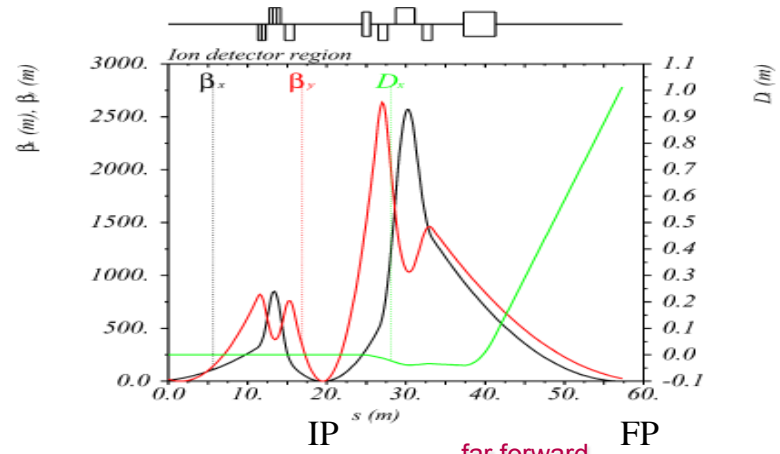
- Dual-solenoid-based detector in GEMC (a GEANT4 package also used for JLab 12 GeV)
- Configuration shown with forward- and central trackers based on micropattern gas detectors (GEM/micromegas).
- Central tracker could also include a low-mass, cluster-counting, He-filled drift chamber (ILC 4th concept).

- **Primary focus:** IP1 detector compatible with the full-acceptance interaction region, optimized for SIDIS and exclusive reactions
- The IP1 tracker layout is compatible with both a dual solenoid and the CLEO magnet (the latter with more restricted endcaps)
- The IP2 detector could use the BaBar magnet, have a TPC and focus on hadronic calorimetry (jets) – *similar to ePHENIX concept*

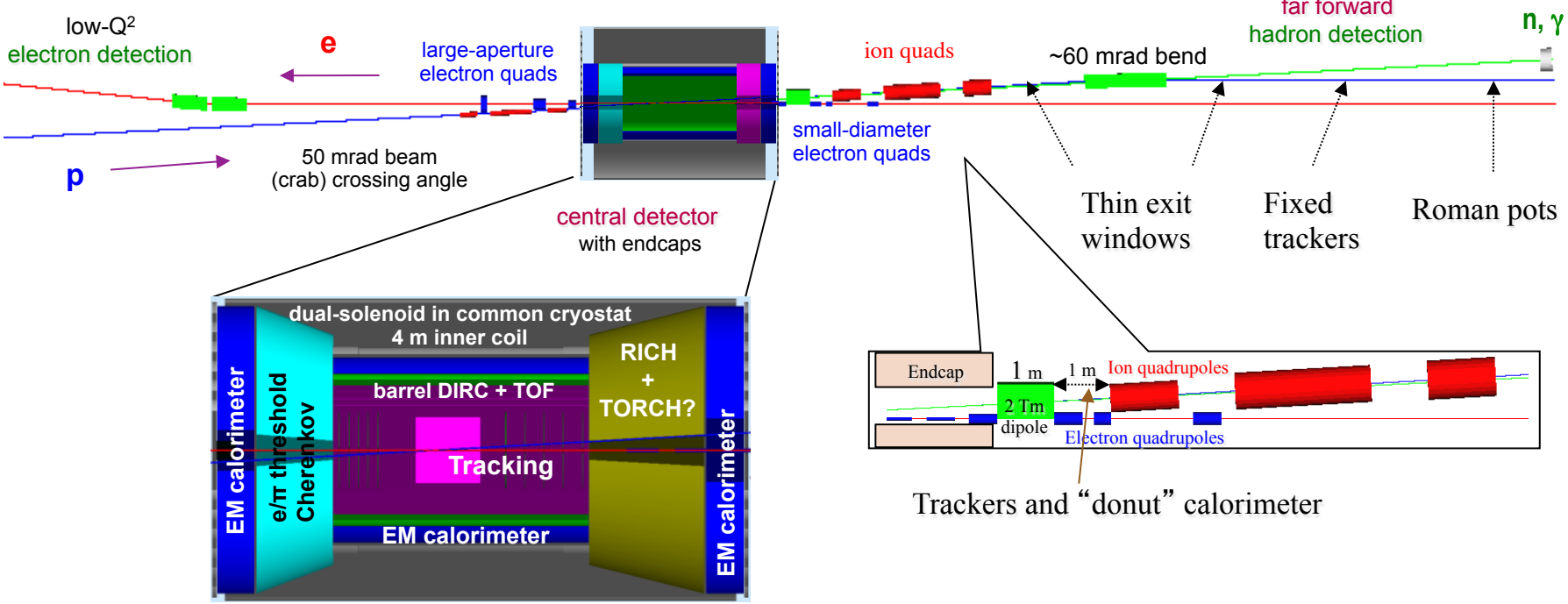
The MEIC *full-acceptance* detector

Design goals:

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

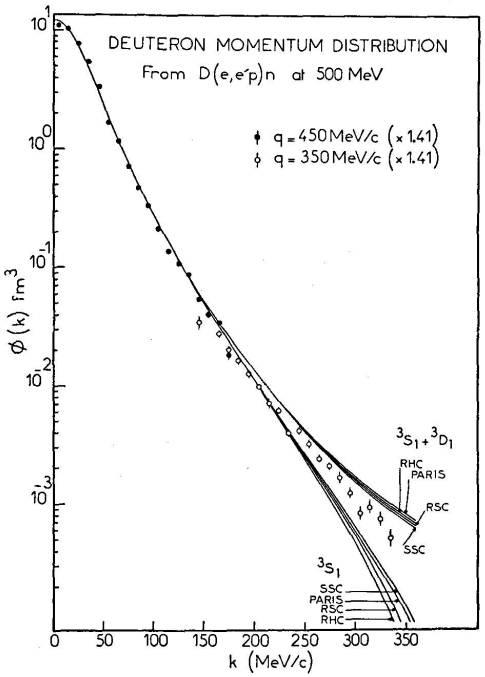


(from GEANT4, top view)



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)



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:

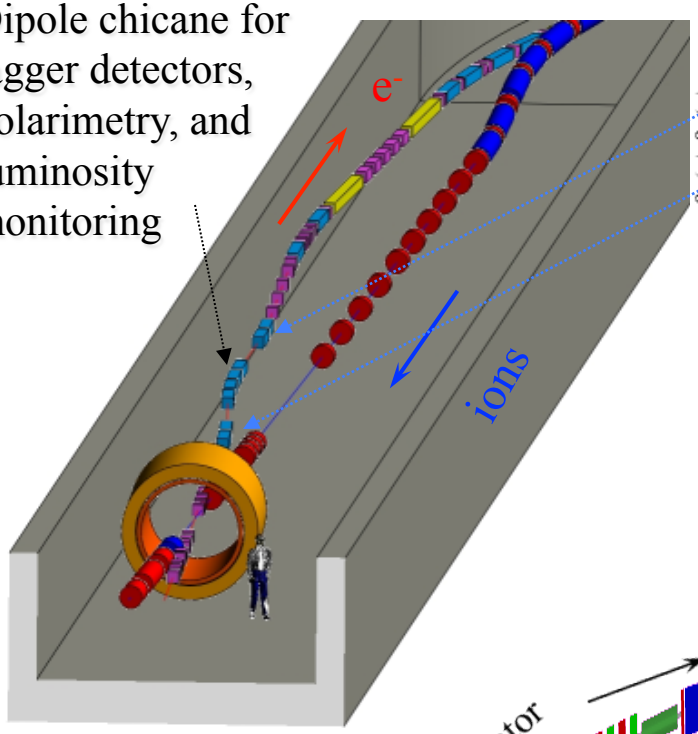
    Longitudinal (dp/p): 4×10^{-4}

    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)

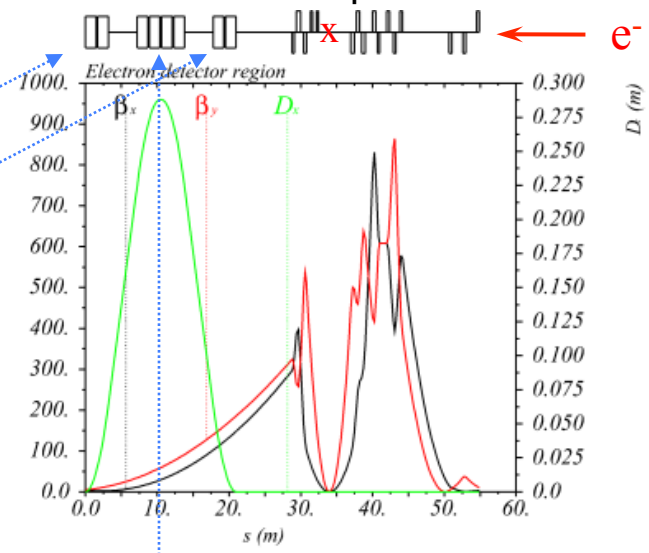
Low-Q^2 electron tagger

Dipole chicane for tagger detectors, polarimetry, and luminosity monitoring



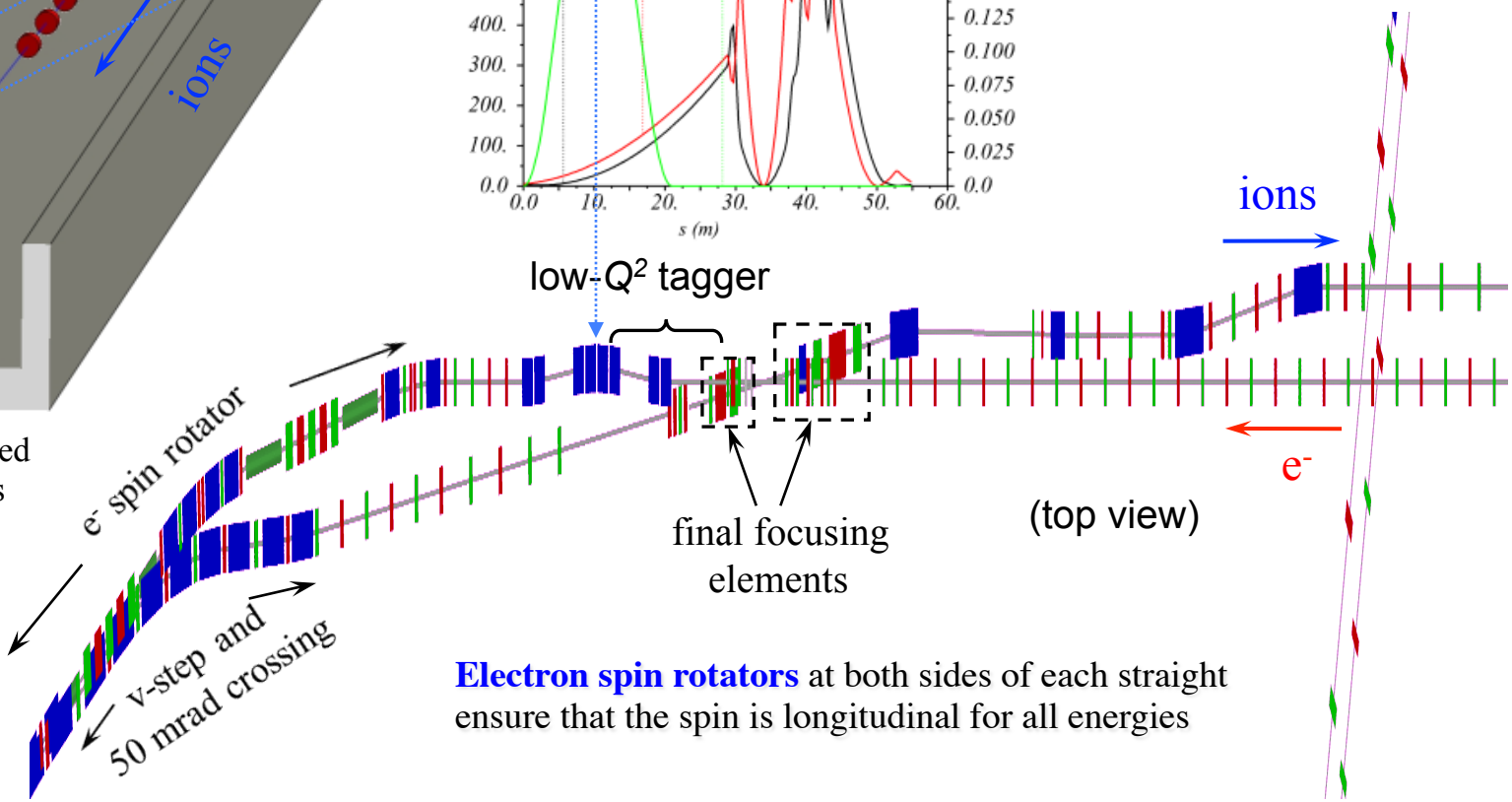
Electron beam aligned with solenoid axis

Electron optics



Compton polarimeter will detect both the photon *and* electron

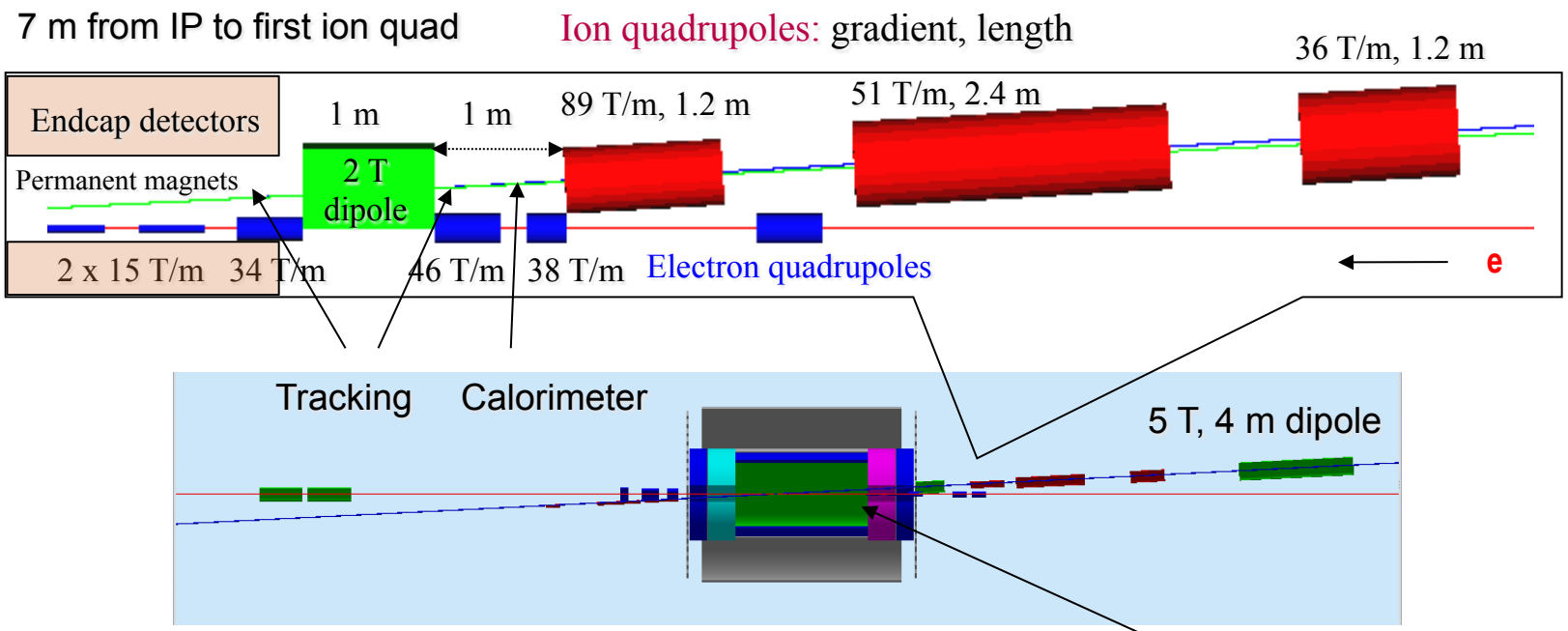
Laser in middle of chicane probes same polarization as at IP

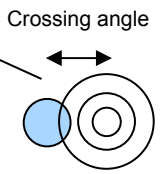


low-Q^2 tagger

Electron spin rotators at both sides of each straight ensure that the spin is longitudinal for all energies

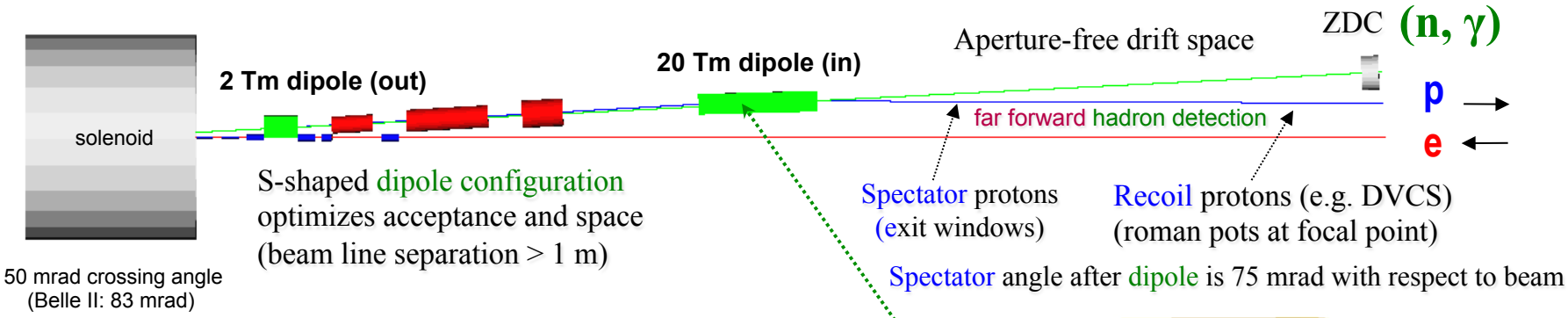
Forward detection *before* ion quads

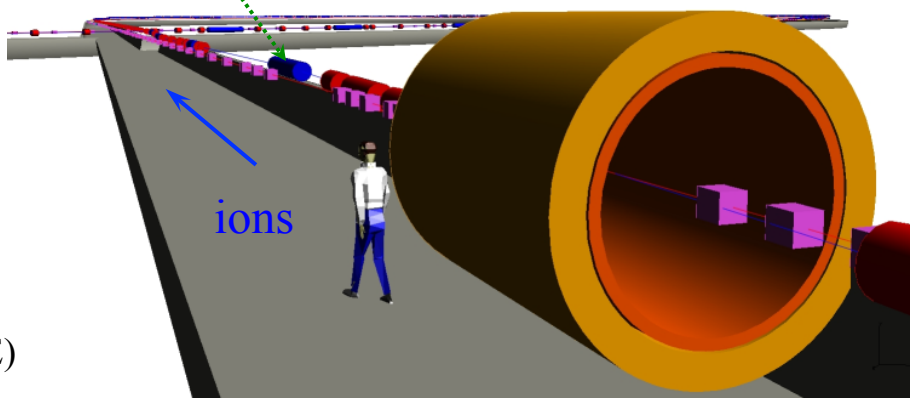




- 50 mrad crossing angle
  - Moves spot of poor resolution along solenoid axis into the periphery
  - Minimizes shadow from electron FFQs
- Dipole before quadrupoles further improves resolution in the few-degree range
- Low-gradient quadrupoles allow large apertures for detection of *all* ion fragments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

Forward detection *after* ion quads



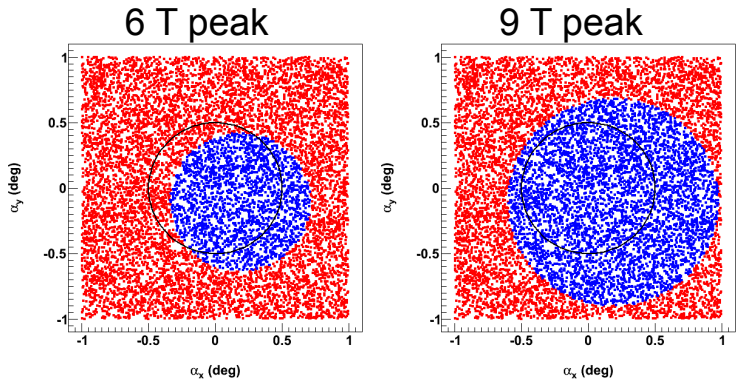


- S-shaped transport optimizes acceptance for both neutrals and charged particles.
- Lots of space for Zero-Degree Calorimeter (ZDC) on the outside of the ring
  - EMcal and high-resolution Hcal (~30%/√E)

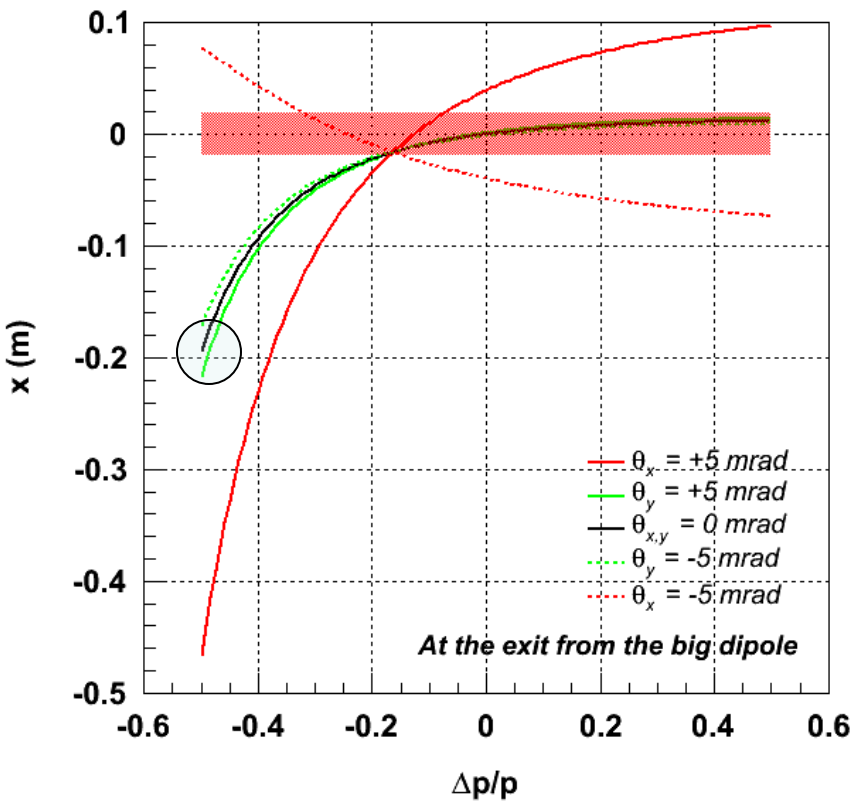
    CERN RD52 "DREAM" or particle flow type
- Quad acceptance for neutrals depends on peak field (6 T baseline), but in ±10 mrad range.

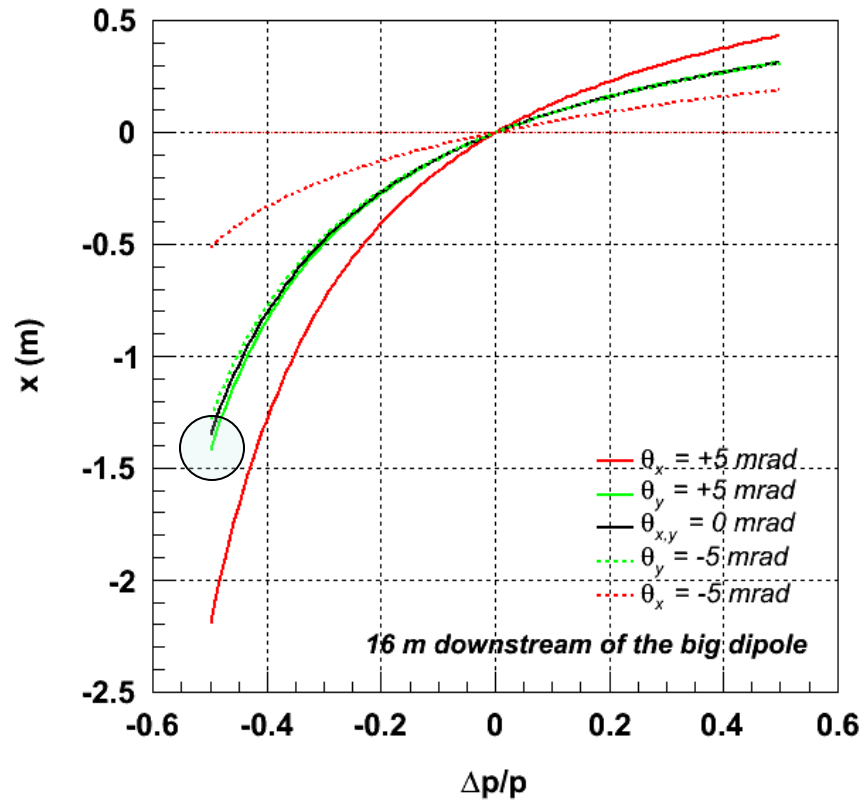
Red: **neutrals** detected *before* ion quadrupoles

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



Spectator angles *after* dipole



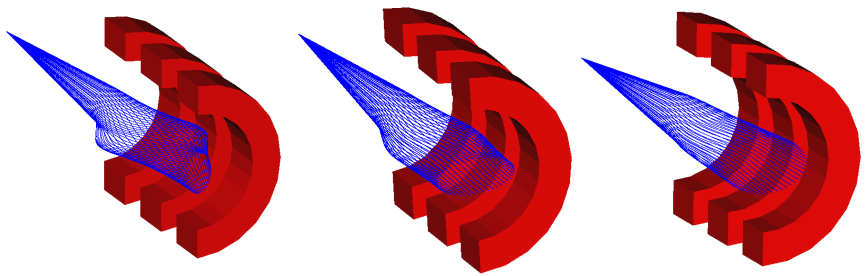


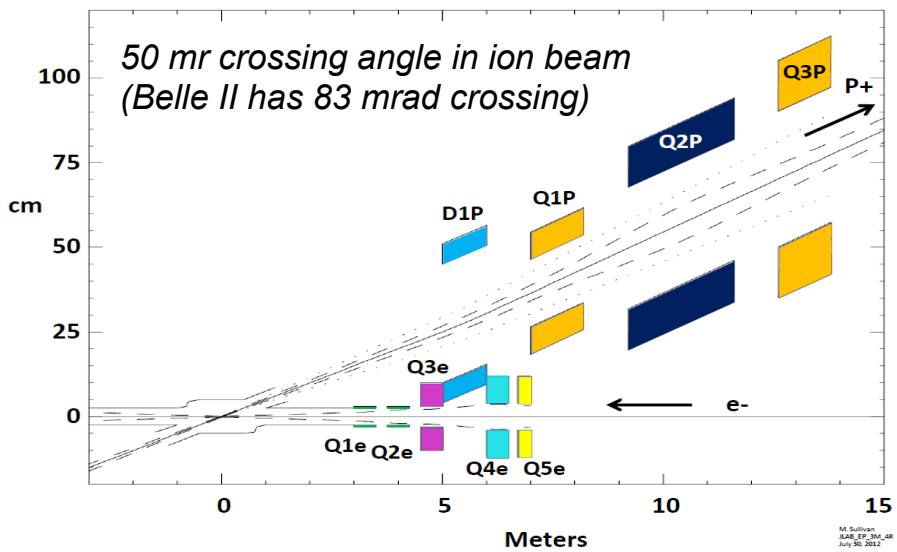
- True spectator fragments have very small scattering angles at the IP (black curve)
- Spectator protons from deuterium have Δp/p = -0.5
- After passing the large bending dipole, the spectator angle with respect to the ion beam is large
- The angle in the magnet-free drift section after the dipole can 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°)

High-t (p_T) and fragment acceptance

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

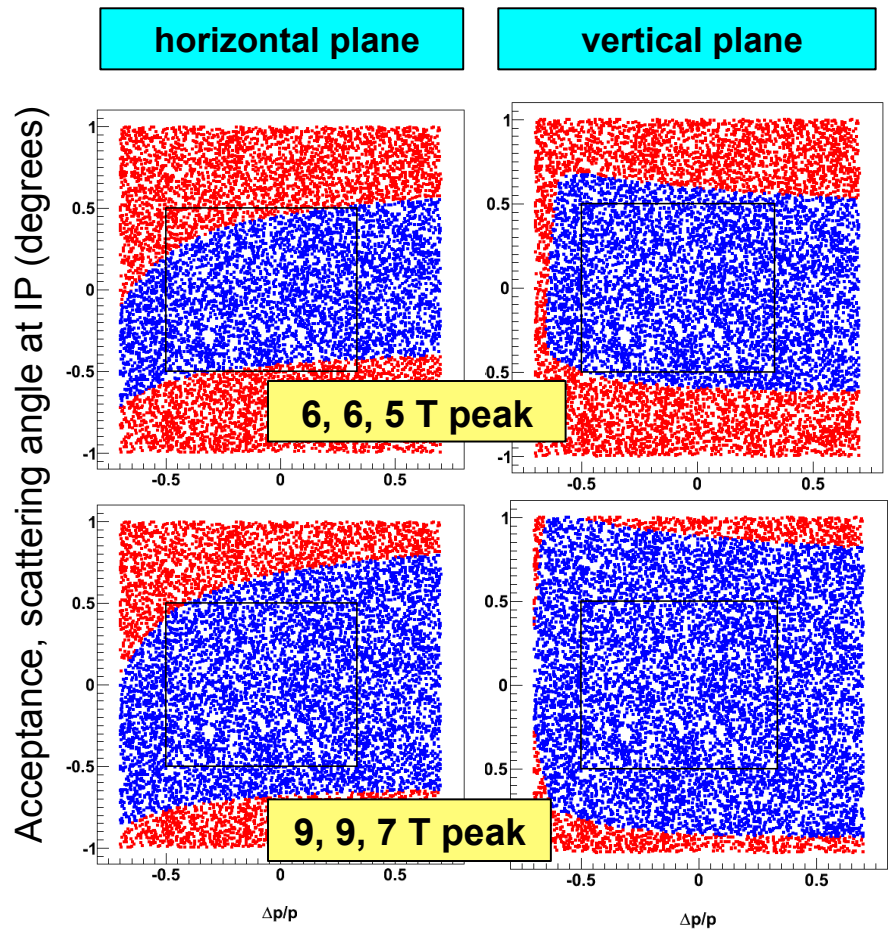
neutron-rich fragments
"tritons from N=Z nuclei"





- Baseline: Q1p and Q2p with 6 T peak fields

Forward acceptance vs.magnetic rigidity

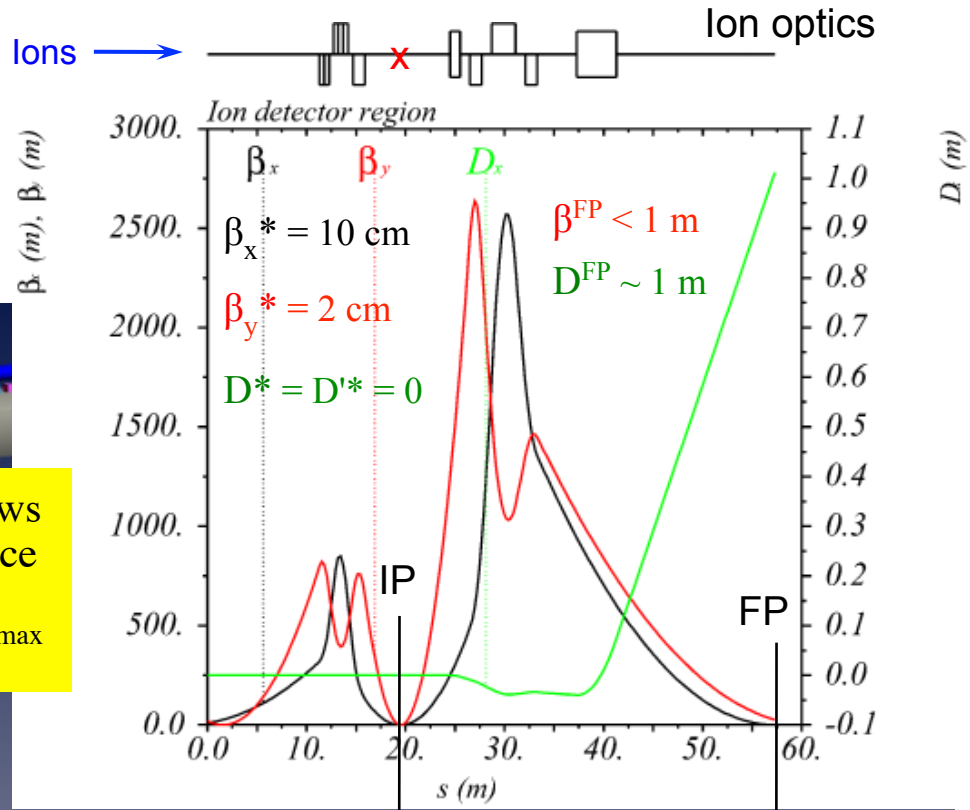


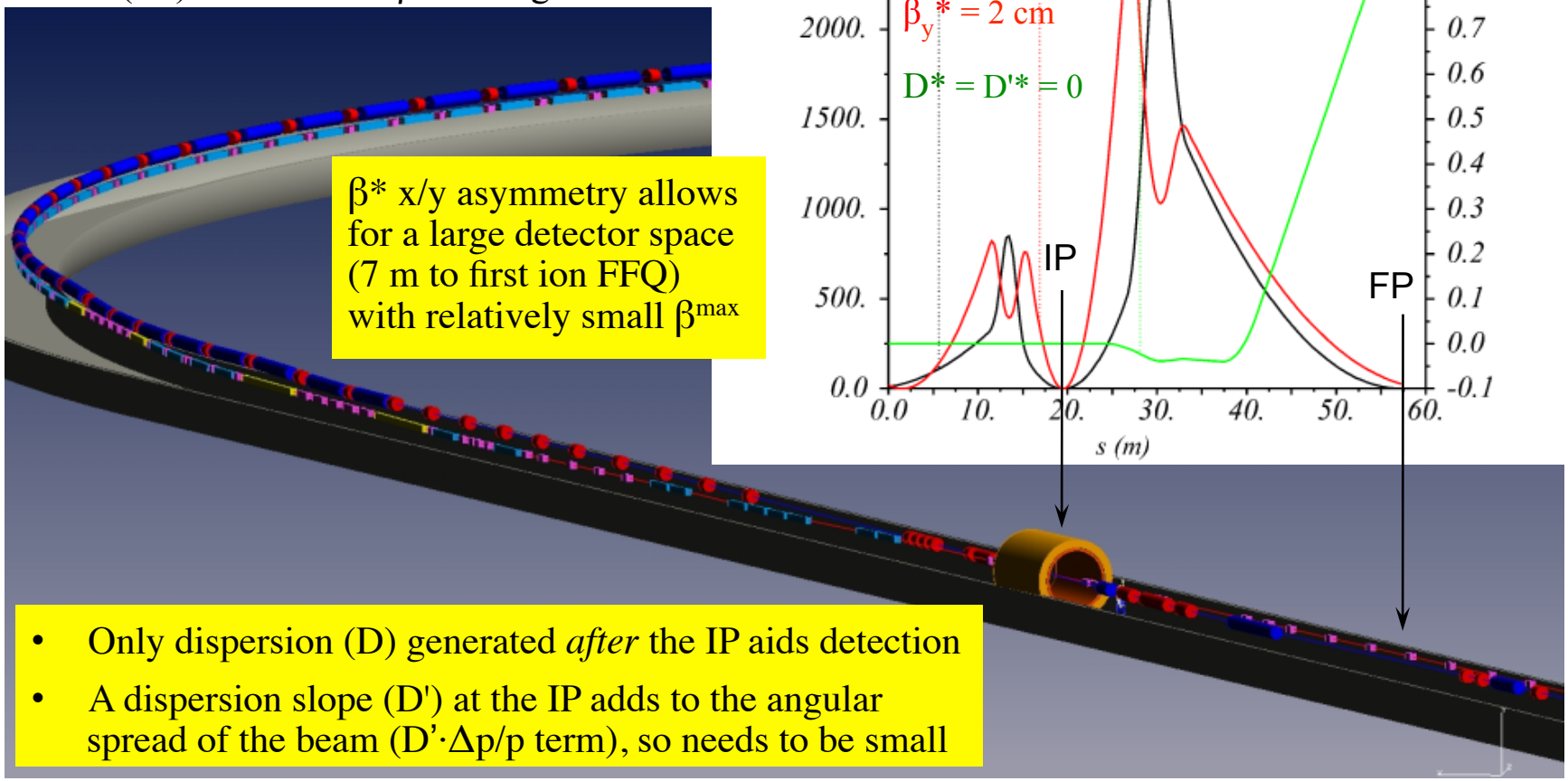
Red: Detection *before* ion quadrupoles

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.





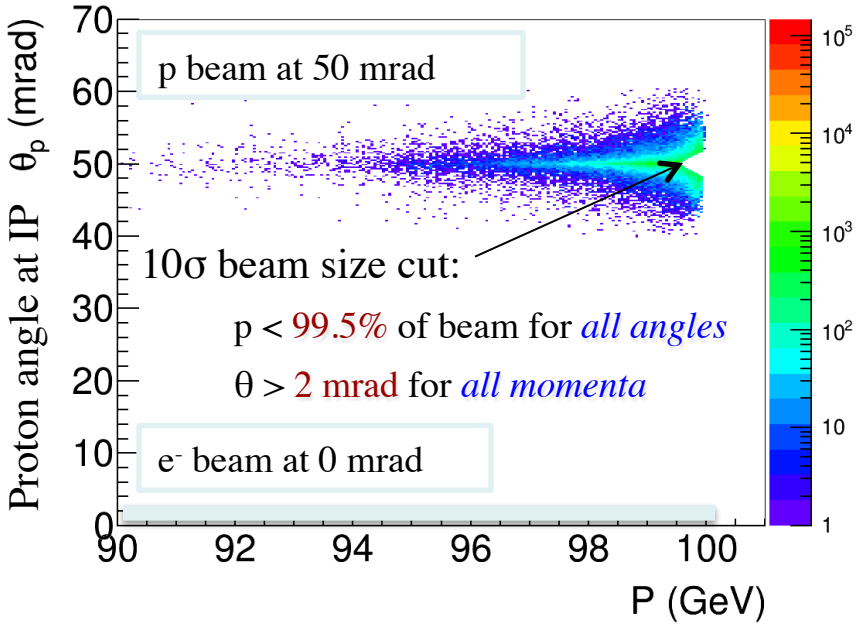
β* x/y asymmetry allows for a large detector space (7 m to first ion FFQ) with relatively small β^{max}

- 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

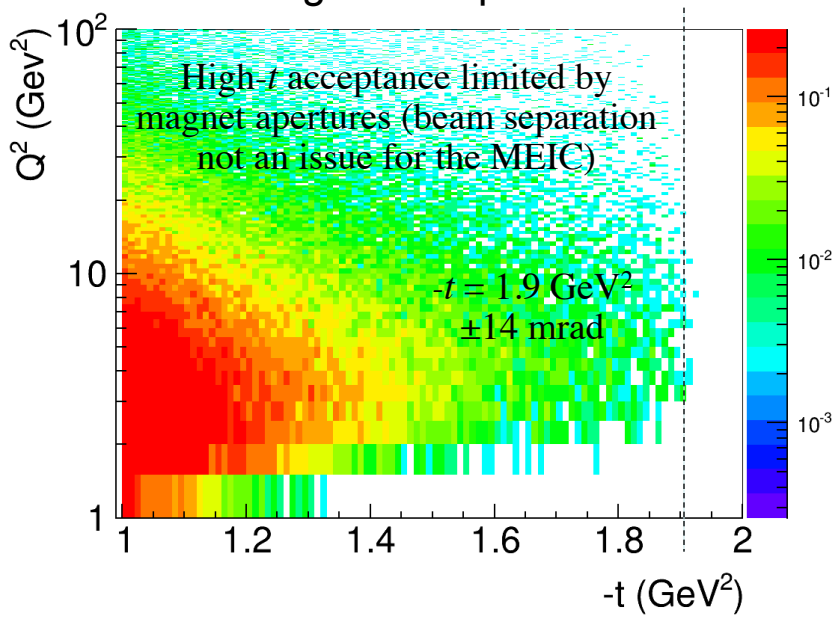
DVCS recoil proton acceptance

- **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

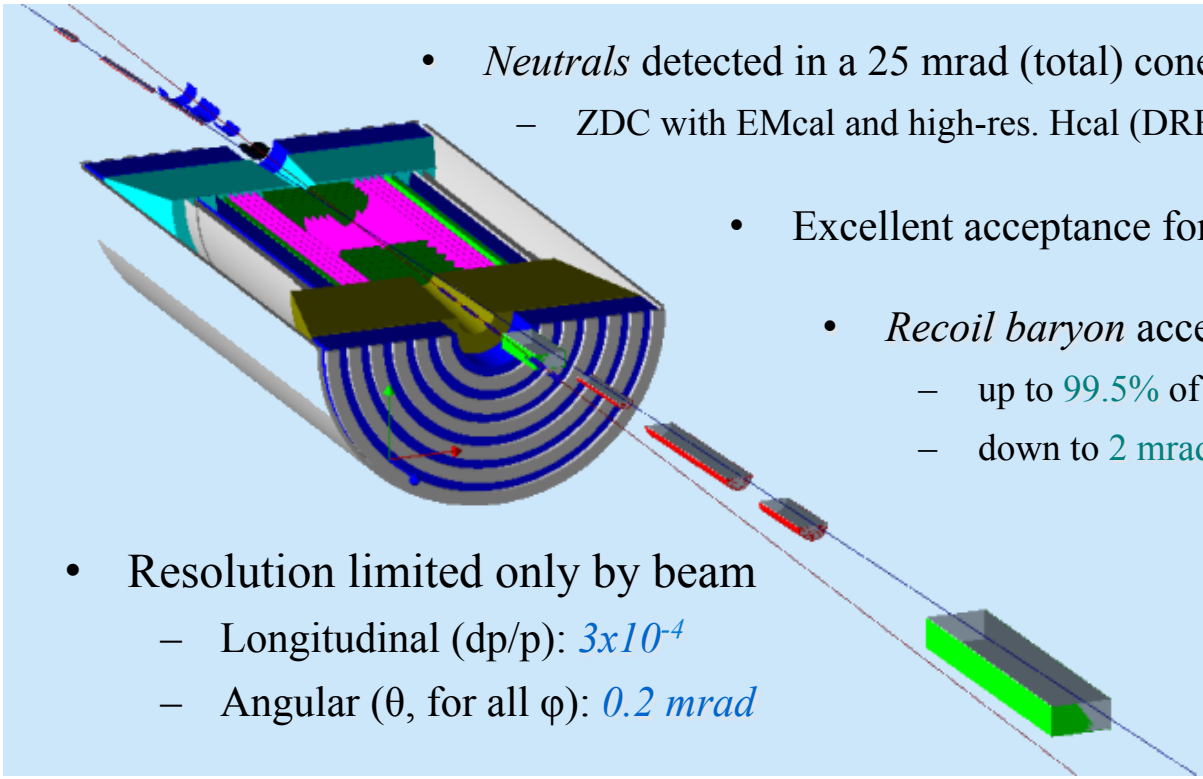


high-*t* acceptance

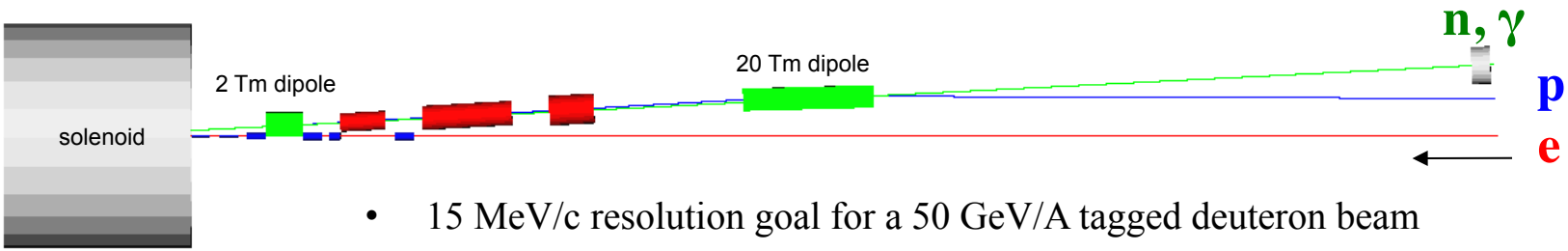


- Recoil proton angle is independent of electron beam energy: $\theta_p \approx p_T/E_p \approx \sqrt{(-t)}/E_p$
- The wide angular distribution at E_p = 100 GeV makes precise tracking easier

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 2 mrad for *all momenta*
- Resolution limited only 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

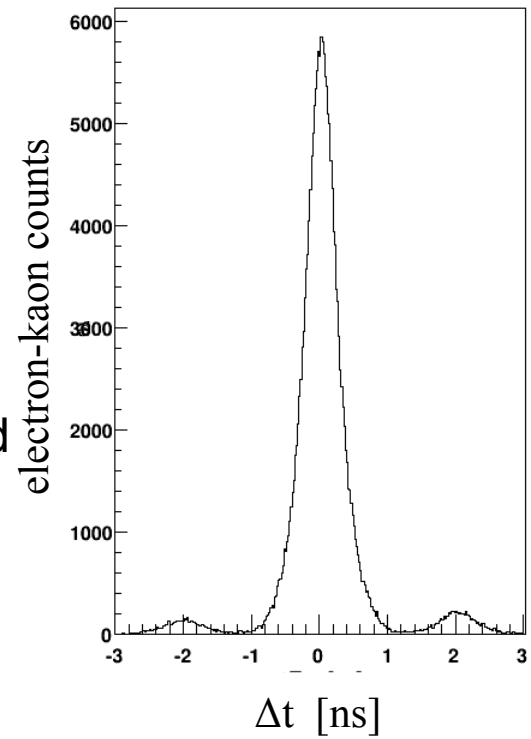
Bunch spacing and identification

- Detectors (CLAS, BaBar, etc) at machines with high bunch crossing rates have not had problems in associating particle 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 triggering

- 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)

Backup

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

Multi-gap Resistive Plate Chamber

- Developed by Tsinghua U, China. Tested at Jlab
- ~ 75 ps resolution, K/π separation up to 2.8 GeV