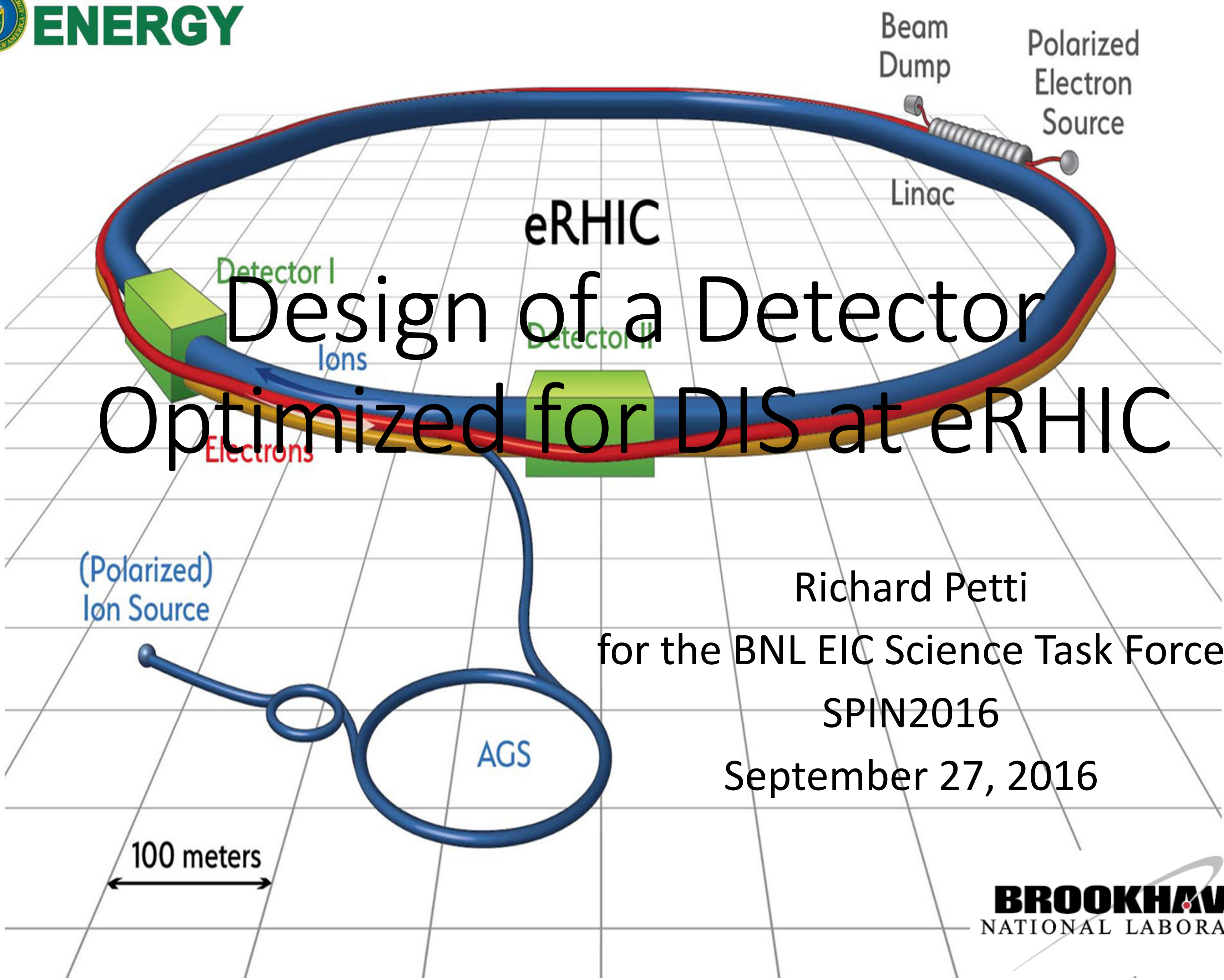
Design of a Detector Optimized for DIS at eRHIC



Richard Petti
for the BNL EIC Science Task Force

SPIN2016

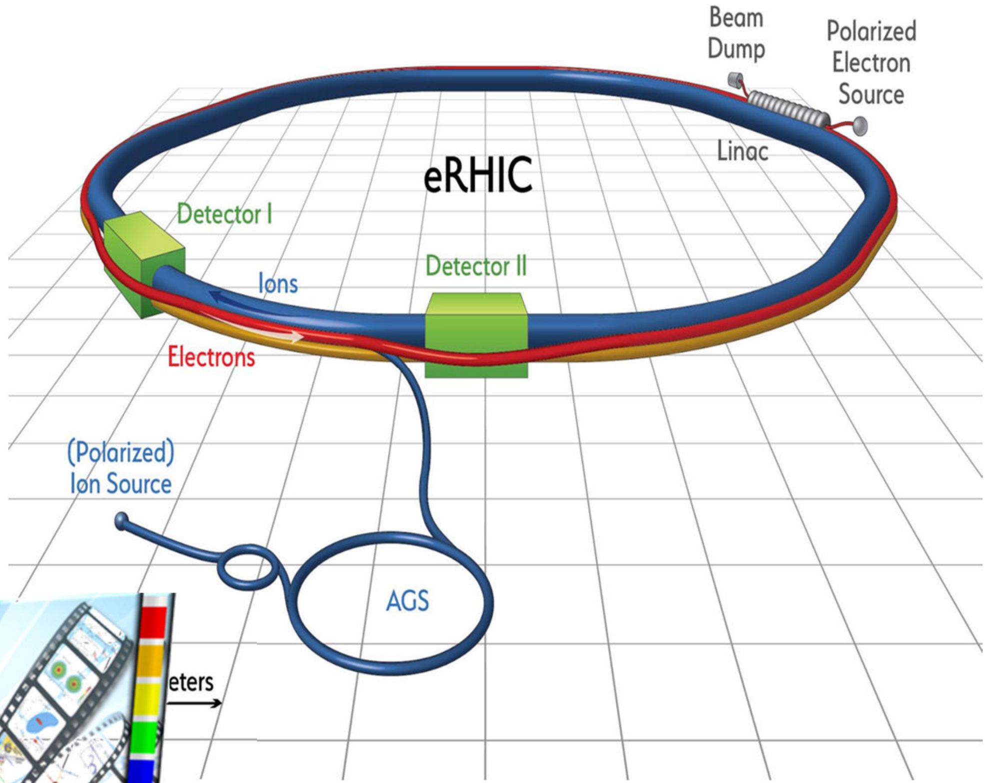
September 27, 2016

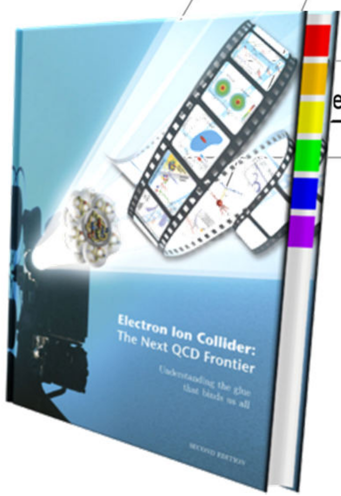
U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

Convert RHIC to eRHIC

- Add an electron ring to the RHIC tunnel
- Main features:
    - Collides electrons with protons, light and heavy ions
    - Polarized electron and proton/light ion beams
    - High luminosity 10^{33}-10^{34} $cm^{-2}s^{-1}$
    - Wide range in collision energy $\sqrt{s} = 20 - 140\ \text{GeV}$
- Main physics goals (non-exhaustive list)
    - Proton spin
    - Proton tomography
    - Gluon saturation



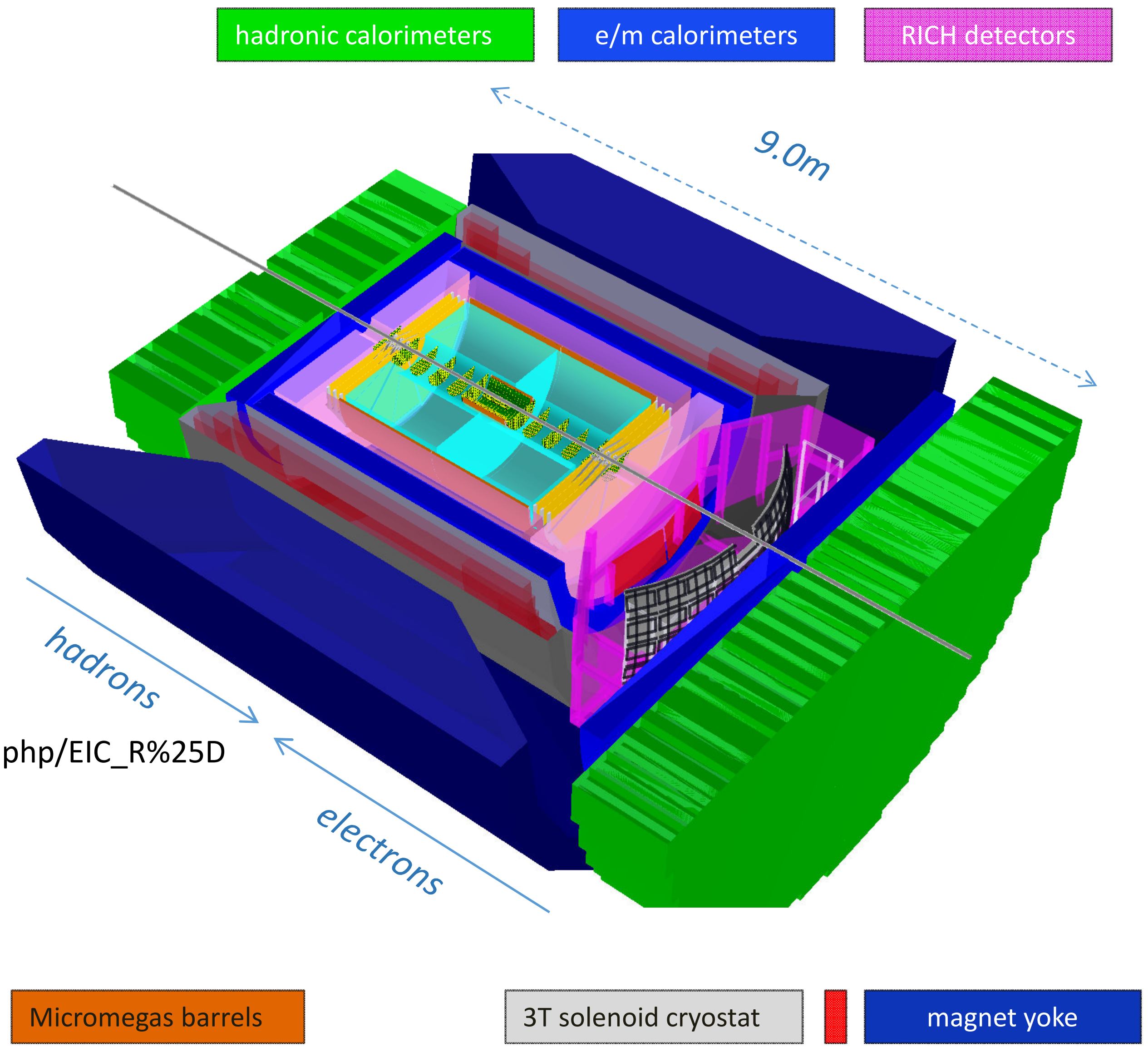


arxiv:1212.1701

Detector and IR requirements

- Main detector coverage over $-3.5 < \eta < 3.5$
  - Electron ID from $-3.5 < \eta < 1$; π suppression up to $1:10^4$
  - π/K/p separation with suppression factors ~100 required
  - Spatial resolution of primary vertex ~10-20 microns
  - Hcal at forward η for jet studies
- Close-to-beam-line acceptance
  - Recoil protons
  - Neutrons in hadron going direction
  - Low Q^2 electrons
- Luminosity and polarization measurement
  - photons from Bethe-Heitler for lumi
  - photons and/or electron from Compton scattering for e pol

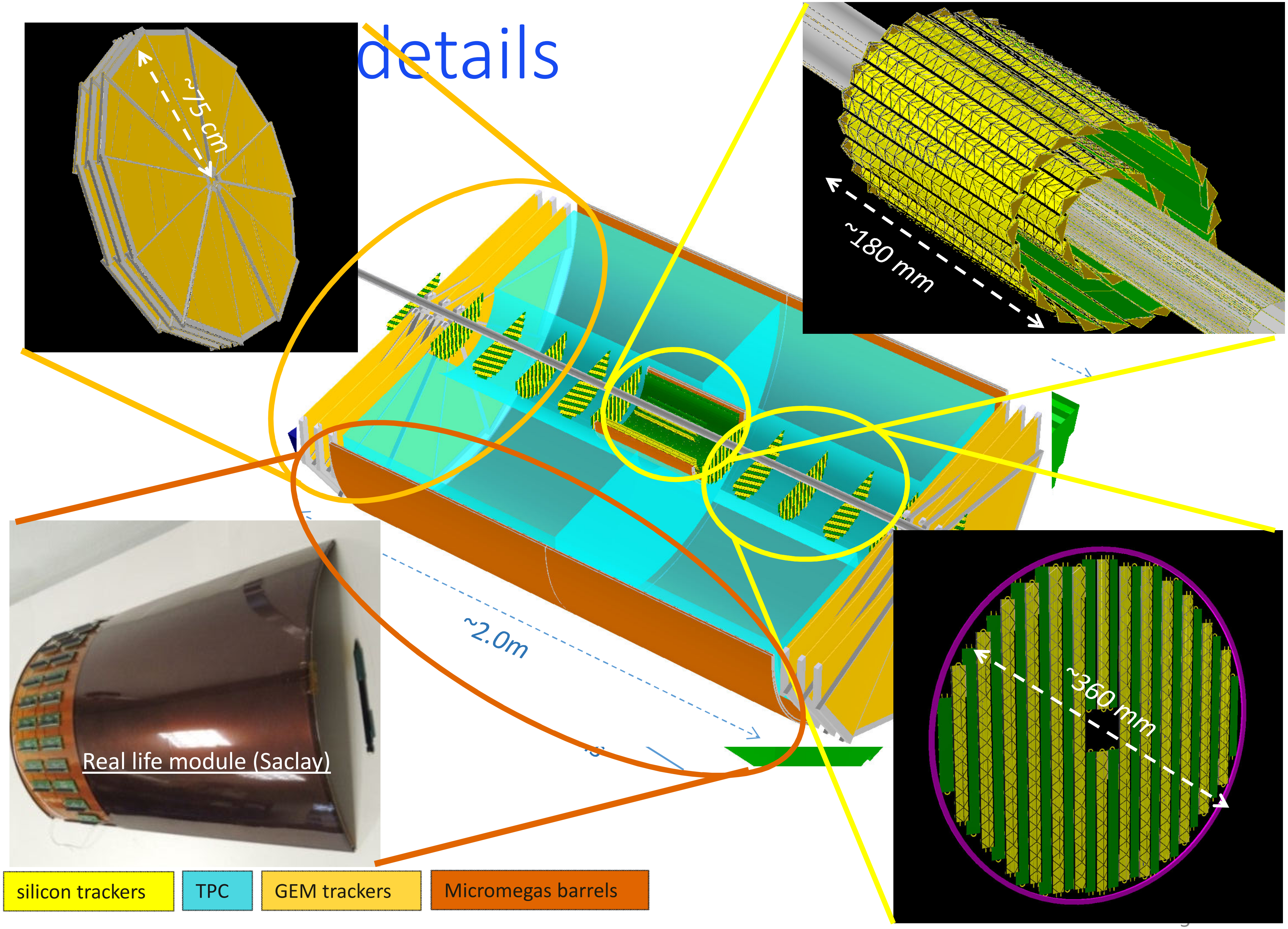
Reference detector layout: BeAST



- BeAST: Brookhaven eA Solenoidal Tracker
- Hermetic coverage
- Tracking and e/m calorimetry in the range $|\eta| < 3.5$
- Active R&D for detector components

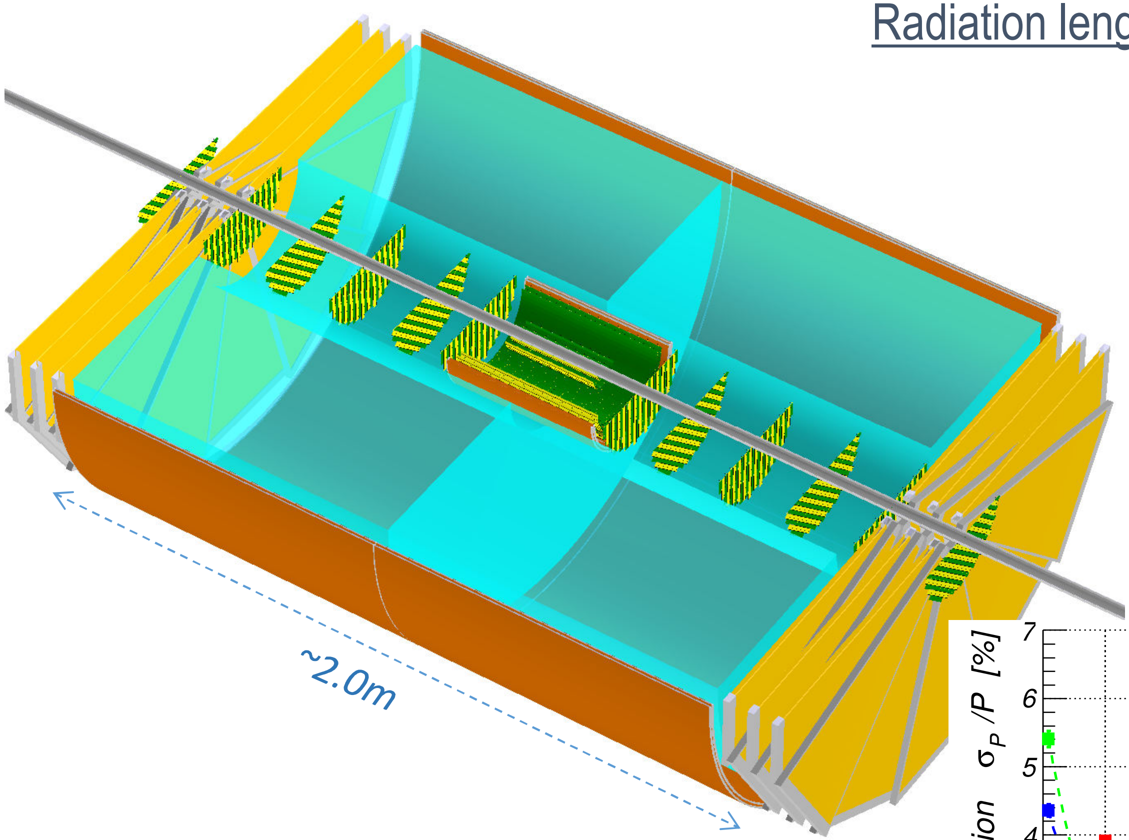
https://wiki.bnl.gov/conferences/index.php/EIC_R%25D

details

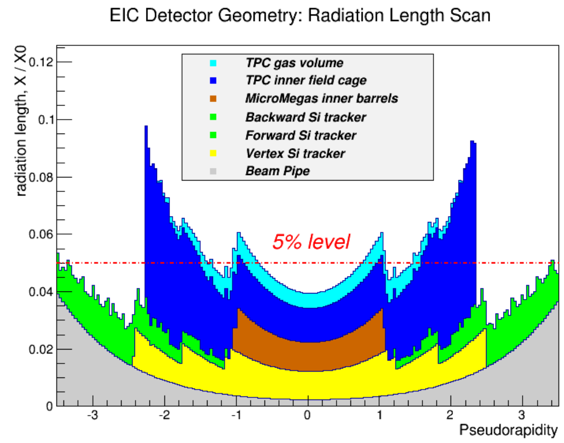


~75 cm
~180 mm
~2.0m
~360 mm
Real life module (Saclay)
silicon trackers
TPC
GEM trackers
Micromegas barrels

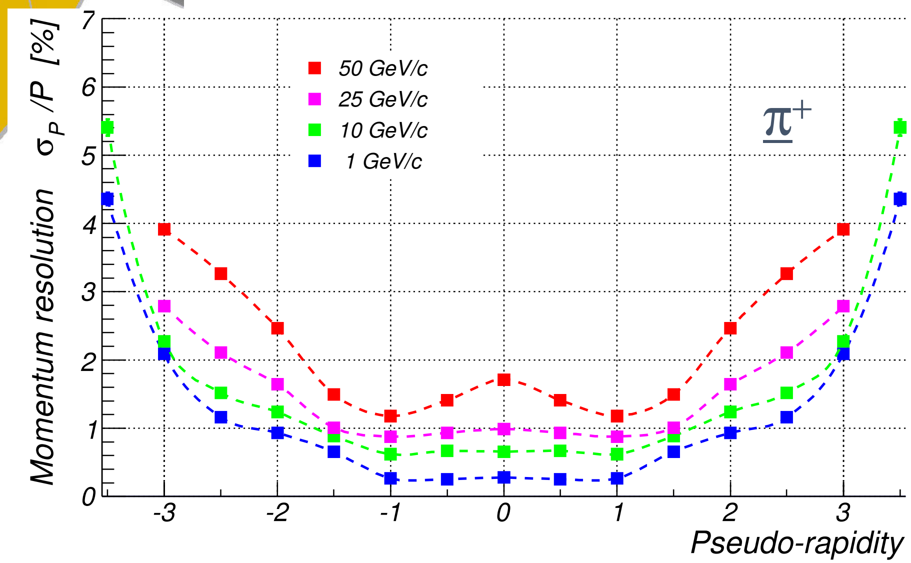
Tracker performance in simulation



<u>Radiation length scan (inner tracking elements only)</u>



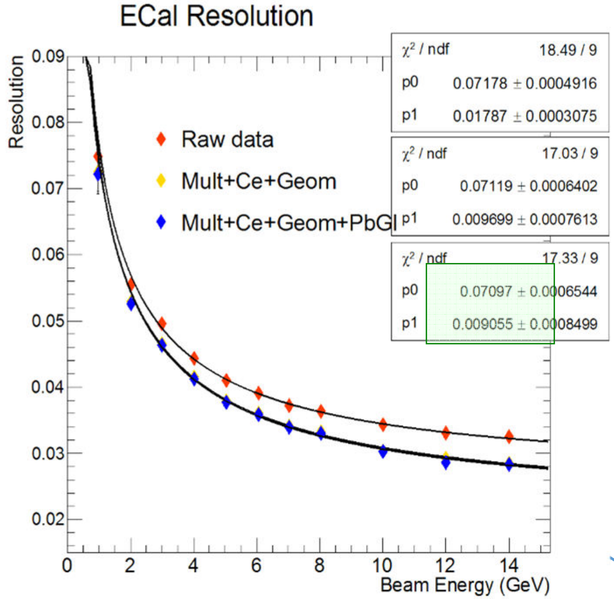
<u>Momentum resolution</u>

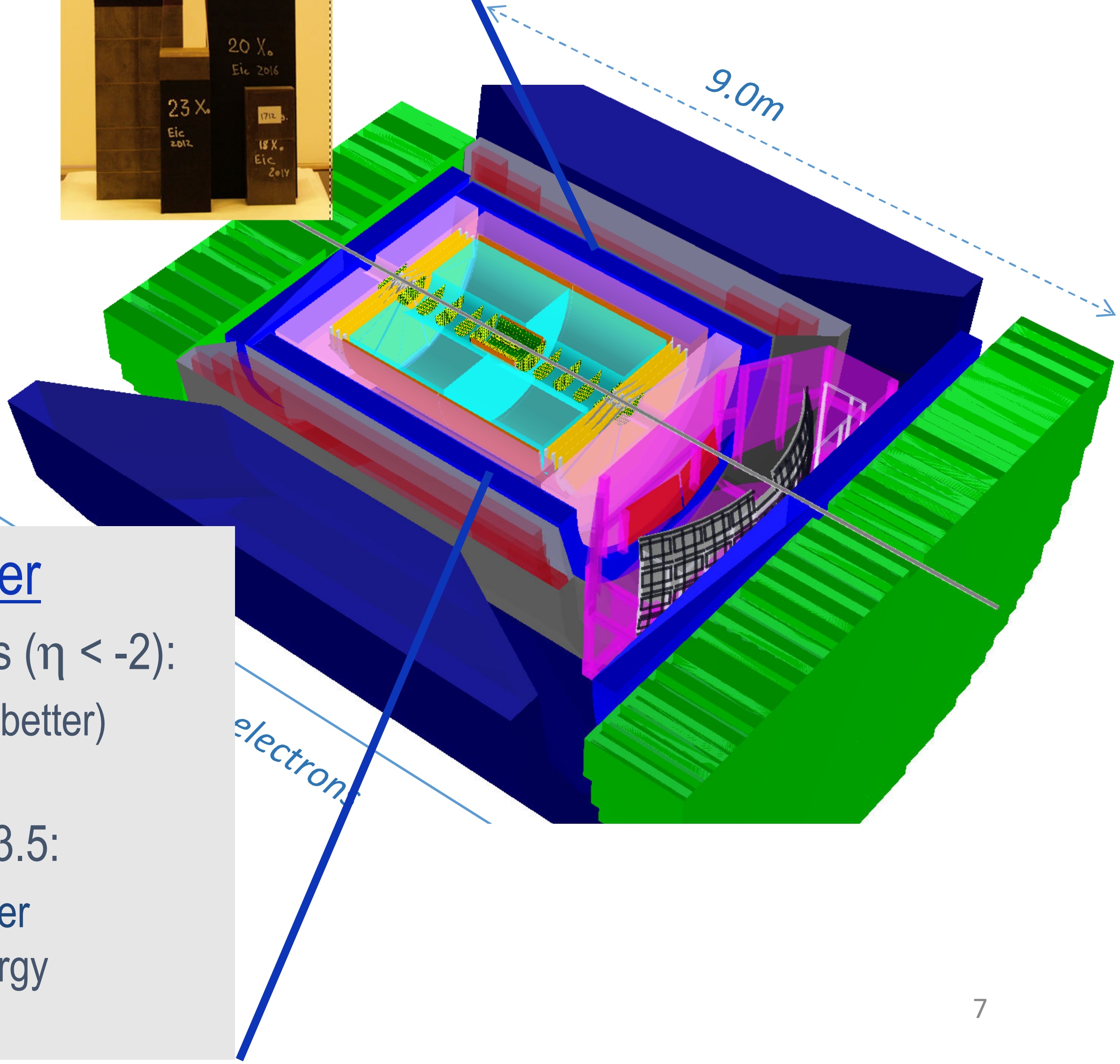


- High redundancy
- Low material budget
- High resolution up to (at least) |η|~3

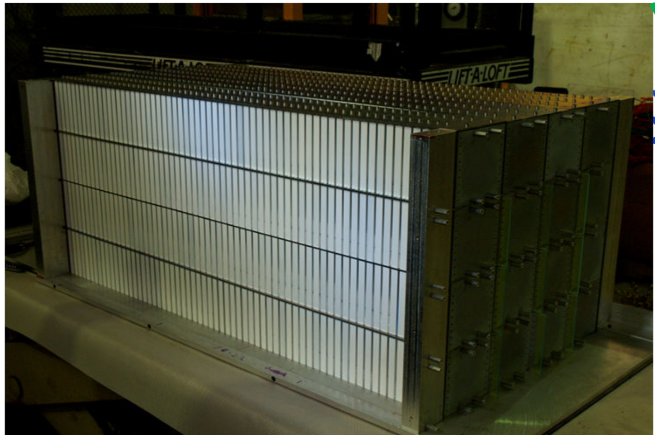
Calorimeters

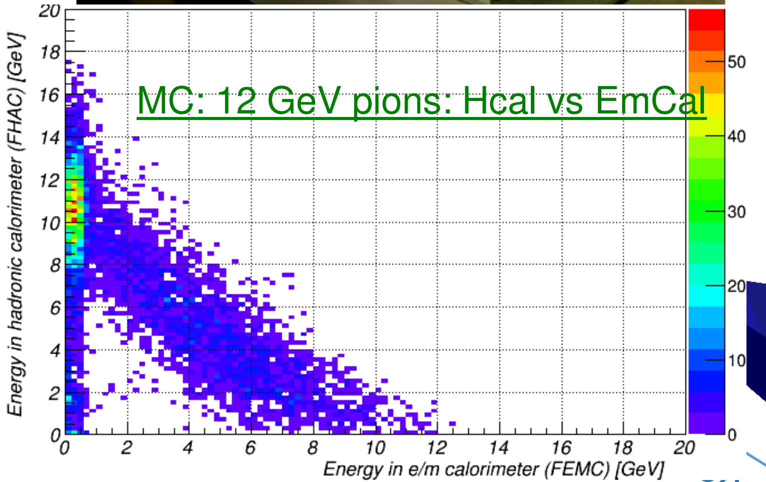
May'2016 test run in FNAL

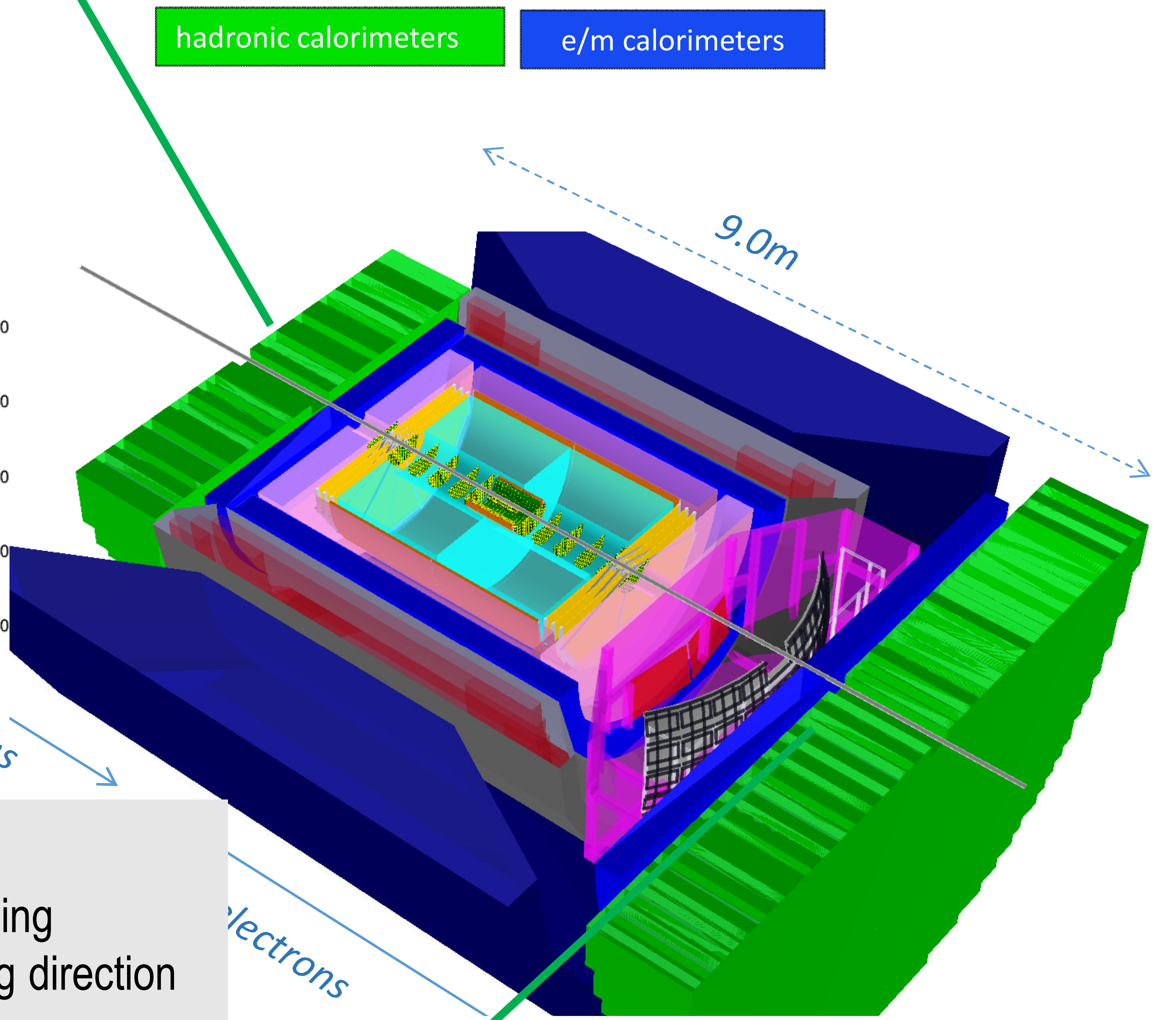




- Electromagnetic Calorimeter
- Very backward pseudo-rapidities ($\eta < -2$):
  - PWO crystals with ~2%/√E (or better) energy resolution
- Pseudo-rapidity range $-2 < \eta < 3.5$:
  - Tungsten powder scintillating fiber technology with ~7-10%/√E energy resolution







- Hadronic Calorimeter Endcaps
  - Electron identification in electron-going direction; jet physics in hadron-going direction
  - Lead absorber scintillating plate sandwich technology
  - ~50%/√E energy resolution looks fine
  - Monte-Carlo model exists in GEANT

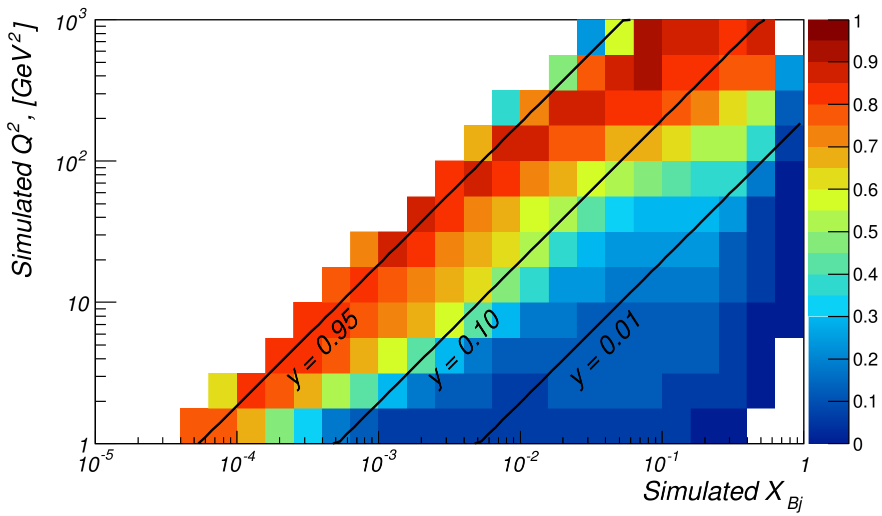
"Purity" in (x,Q^2) kinematic bins

$$Purity = \frac{N_{gen} - N_{out}}{N_{gen} - N_{out} + N_{in}}$$

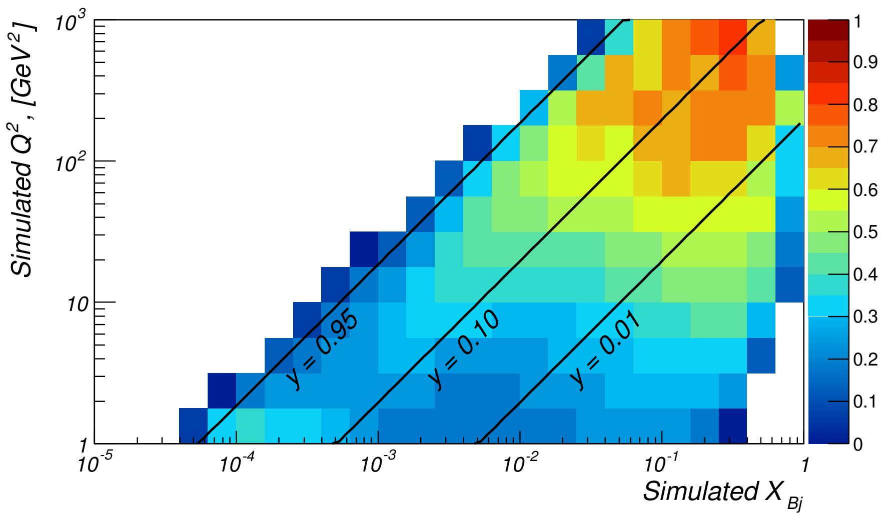
- Describes migration between kinematic bins
- Important to keep it close to 1.0 for successful unfolding

- {PYTHIA 20x250 GeV} -> {GEANT} -> {Kalman filter track fit}
- Bremsstrahlung turned on here (and it matters even for detector with ~5% X/X_0!)

Lepton tracking only



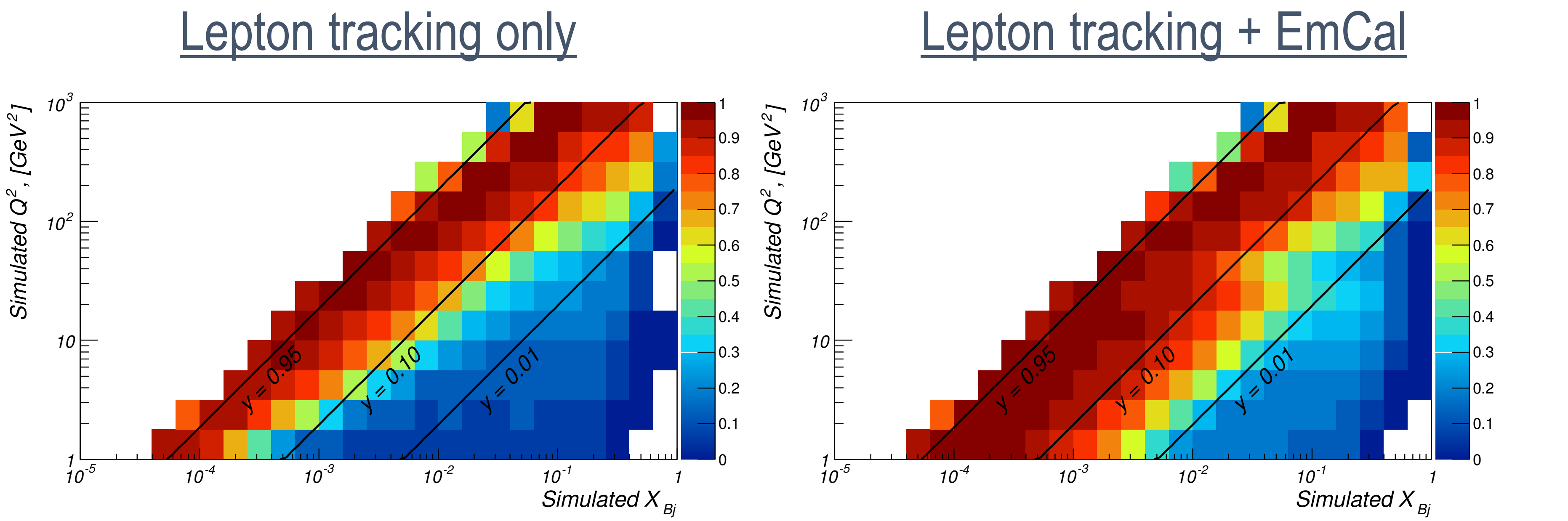
Double-angle method



- "Straightforward" lepton tracking can hardly help at Y<0.1
- Hadronic final state accounting allows to recover part of the high Q^2 range

"Purity" in (x,Q^2) kinematic bins, cont'd

- Assume e/m calorimeter is used in addition to tracking
  - ~2%/√E energy resolution for η < -2 (PWO crystals)
  - ~7%/√E energy resolution for 1 < η < 2 (tungsten powder scint. fiber sampling towers)
- Consider "bremsstrahlung off " case here for simplicity

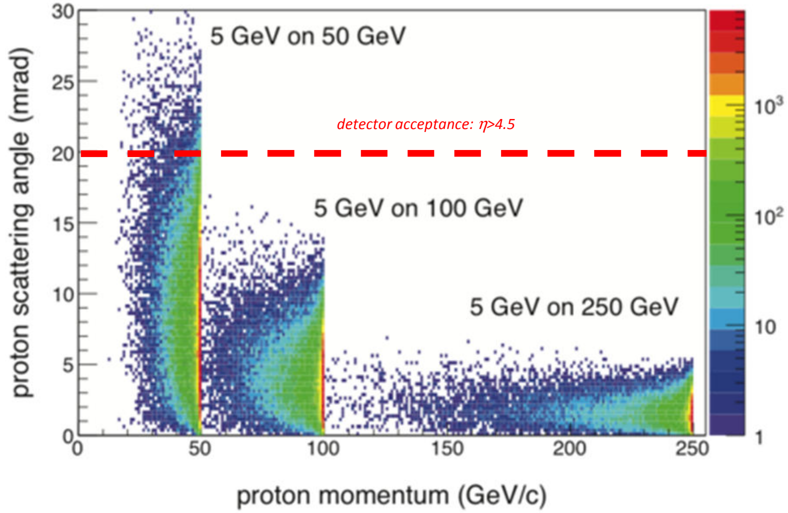


- High-resolution e/m calorimeter allows to noticeably increase available Y range

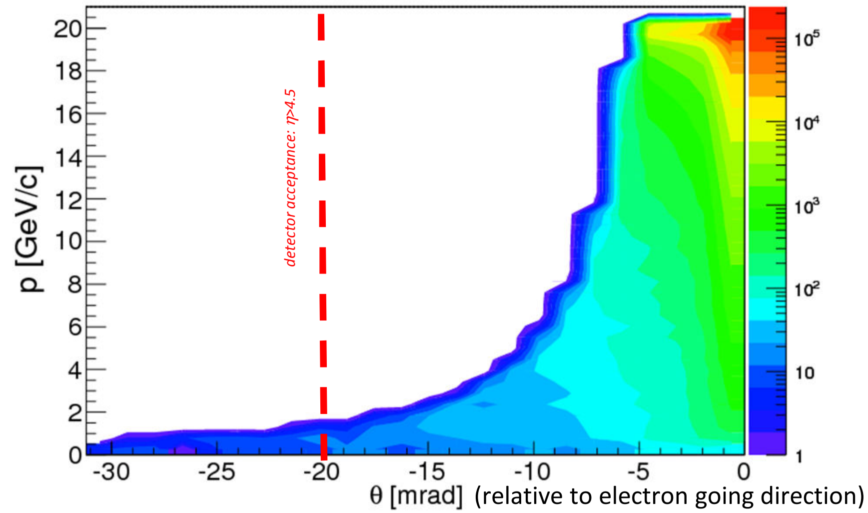
Auxiliary Detectors

- In addition to the main detector, there are several auxiliary components being developed which are critical to the program
  - Forward proton tagger (Roman Pots, small angle scattered protons)
  - Low Q^2-tagger (small angle scattered electrons)
  - Luminosity monitor
  - Electron beam polarimetry

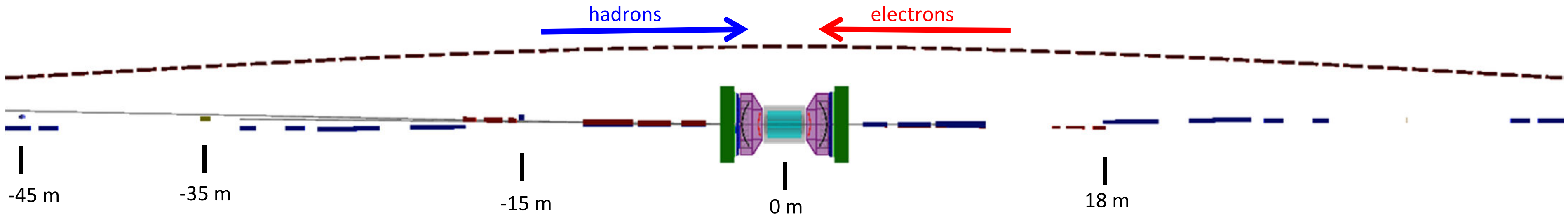
p beam energy dependence from DVCS simulation



PYTHIA 20x250 GeV ep simulation $Q^2 < 0.01$ GeV^2

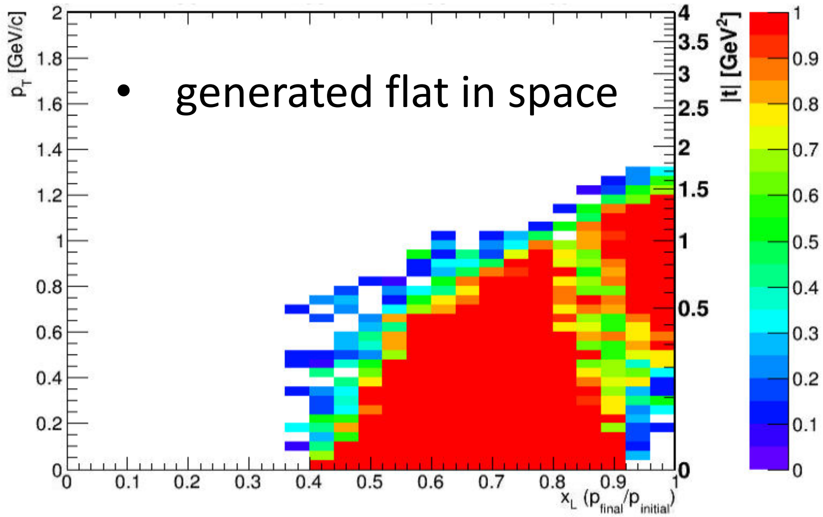


Auxiliary Detectors and the IR

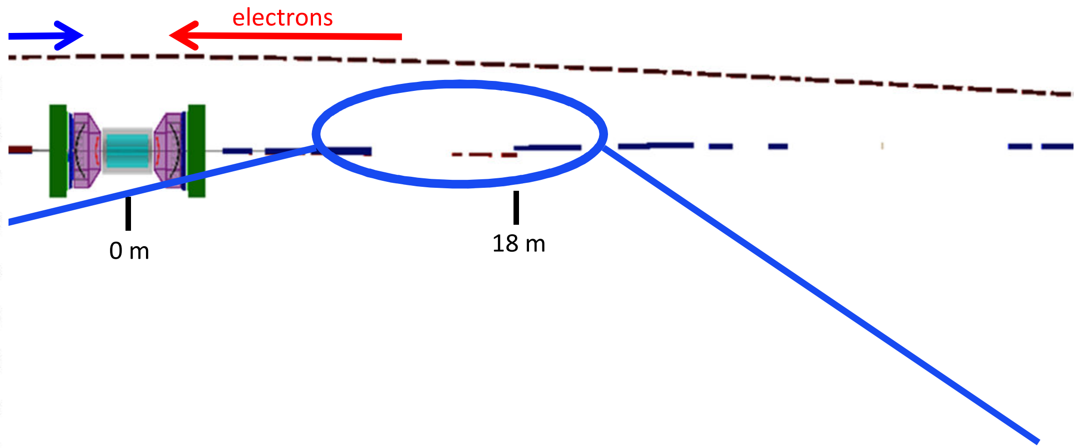


- Ongoing R&D and optimization of the IR layout with the machine design group
- Much attention given to allow acceptance of forward and backward going particles close to the beam
  - Scattered protons and neutrons
  - Scattered electrons
  - Photons for luminosity measurement
- Active R&D for machine induced backgrounds that may be present
  - Synchrotron radiation from the electron beam
  - Beam-gas interactions

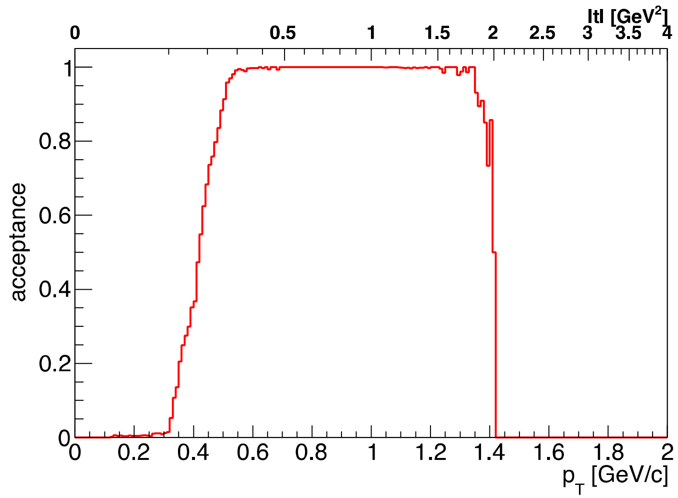
Auxiliary Detectors and the IR



- generated flat in space

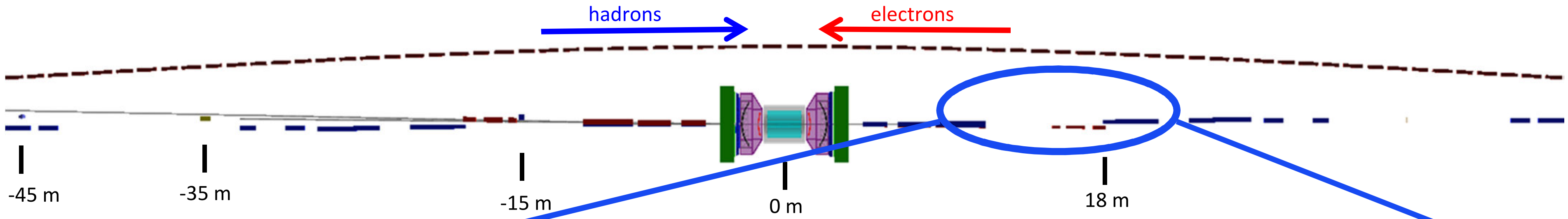


- One station at ~20 m
- MILOU 20x250 GeV DVCS sent into sim



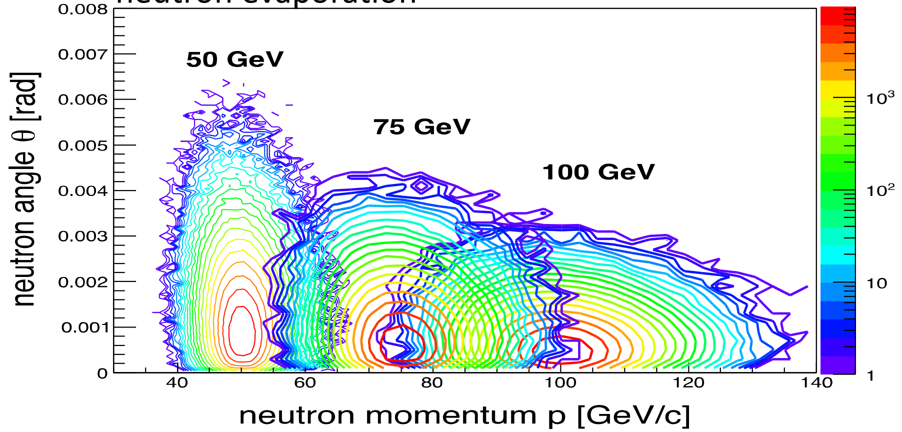
- Roman Pots
  - Sensors integrated into the vacuum system
  - Retractable to move into the beam after stable
  - Allows to move sensors as close to beam as possible
    - Typically around 10sigma beam width
    - Defined by beam optics (beta function) at the location of the roman pot
    - Want small beta function with large dispersion to pull scattered protons out of the beam
  - Ongoing R&D with machine developers to give access

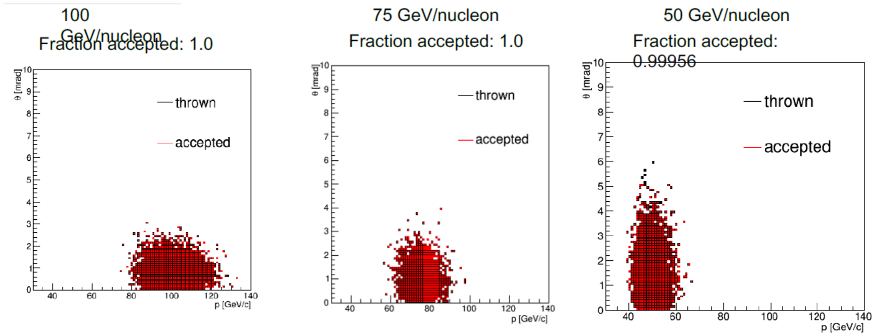
Auxiliary Detectors and the IR



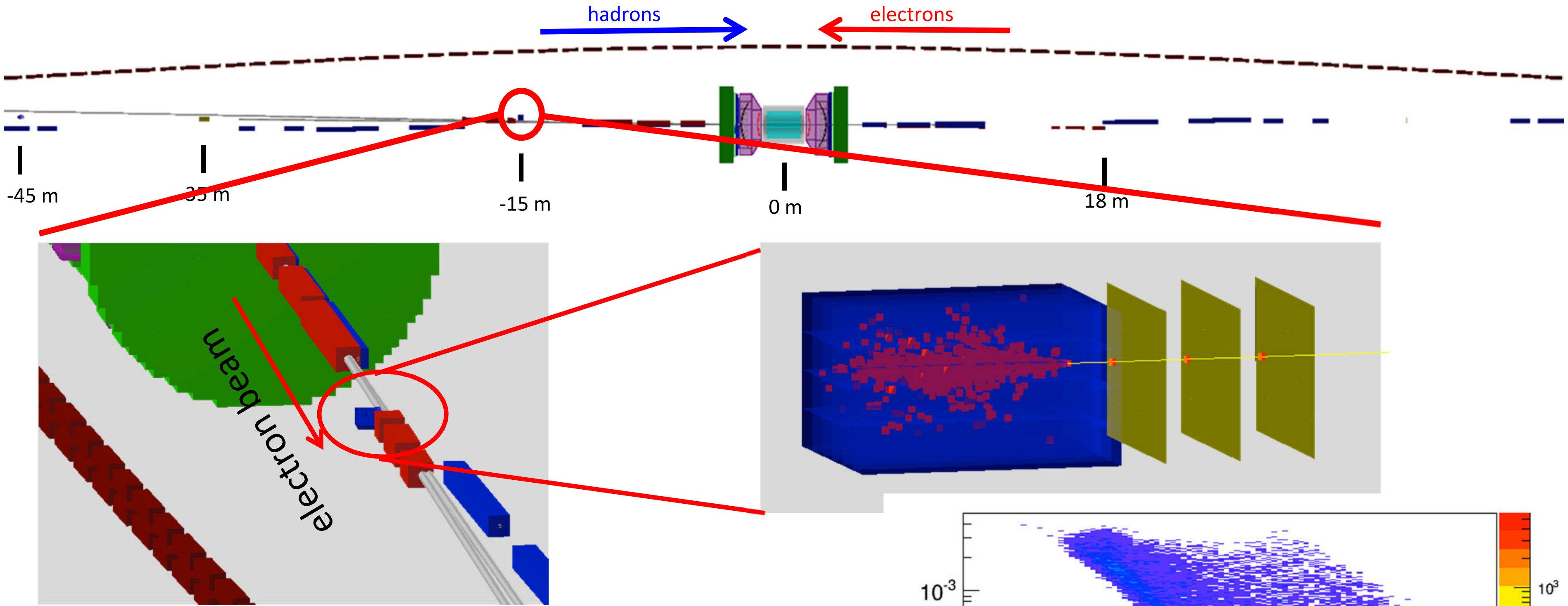
- ZDC
- Need acceptance for outgoing neutrons
  - Centrality determination in e+Au collisions
  - Tagging for diffractive events

Expected distributions from DPMJet simulation of neutron evaporation

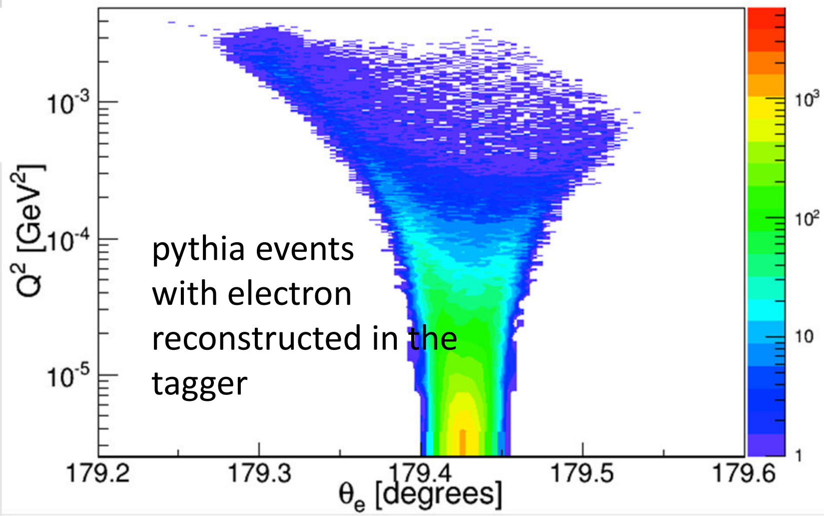




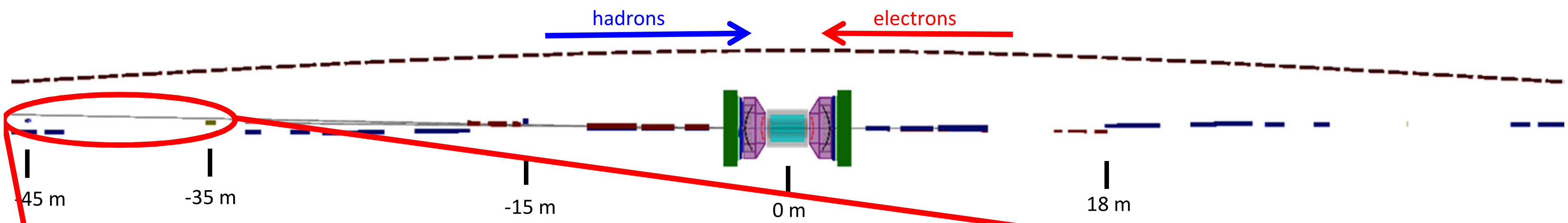
Auxiliary Detectors and the IR



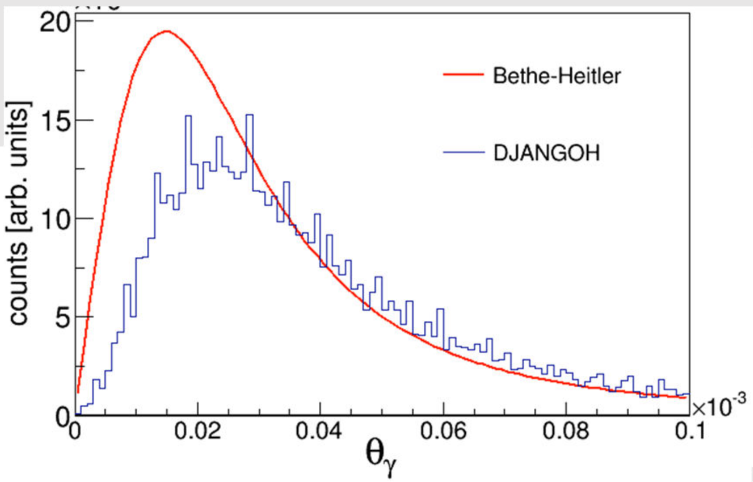
- <u>Low Q^2-Tagger</u>
  - Acceptance for electrons from events with Q^2<0.01 GeV^2
  - Sits close to the beam line

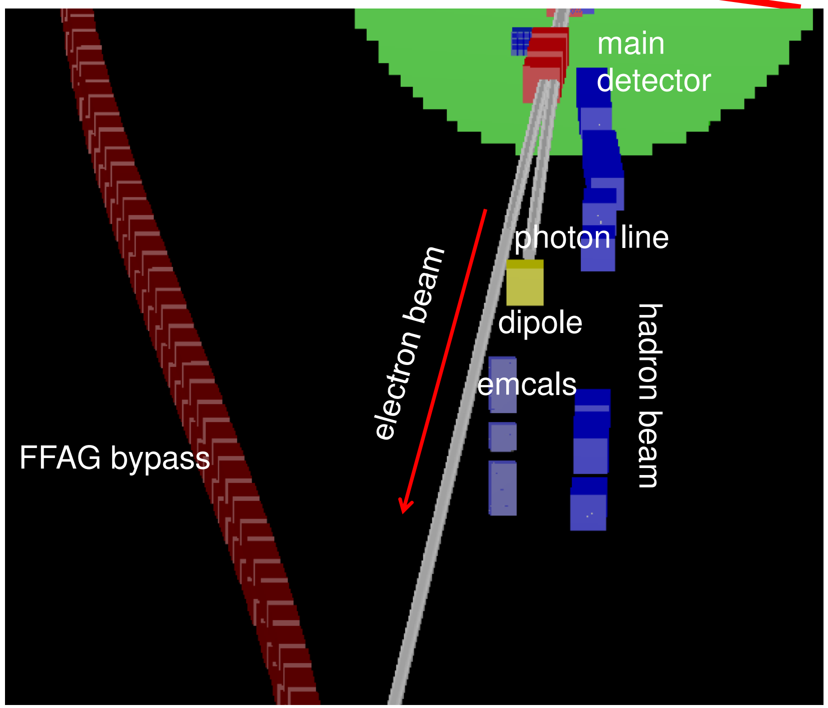


Auxiliary Detectors and the IR



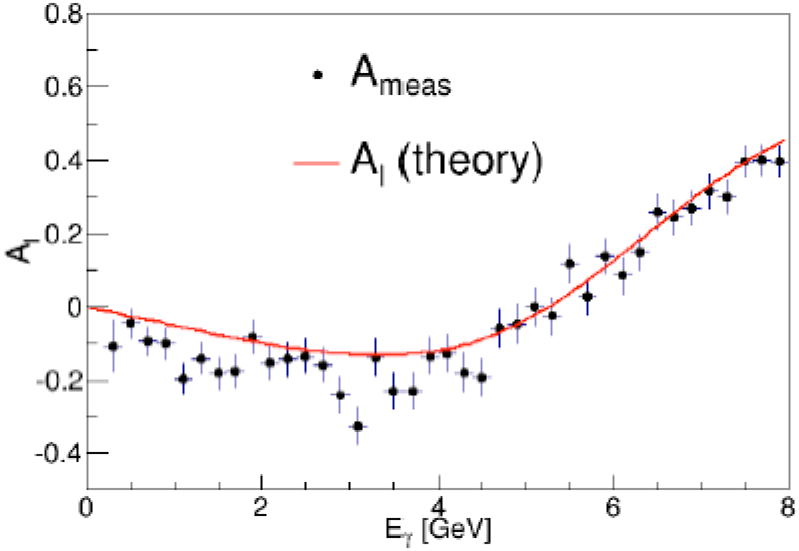
- <u>Luminosity Monitor</u>
  - Measure via Bethe-Heitler
    - e+p -> e+p+gamma
  - Emission cone dominated by beam optics

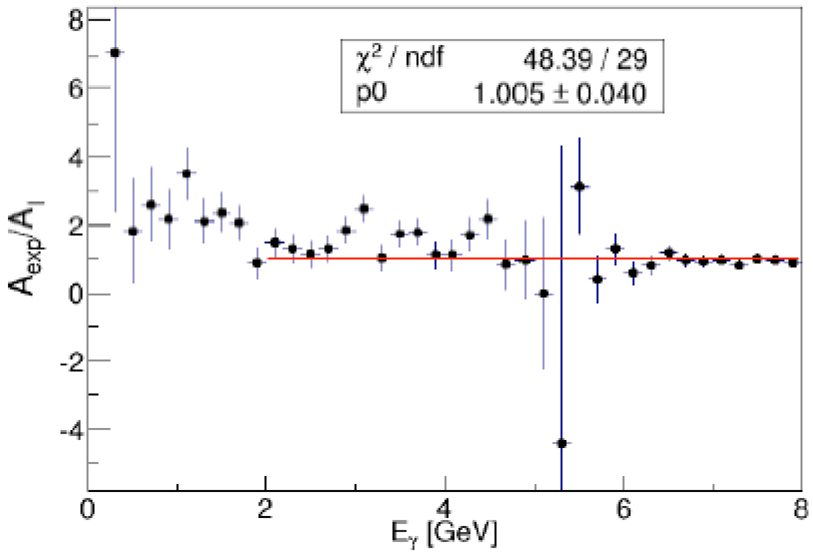




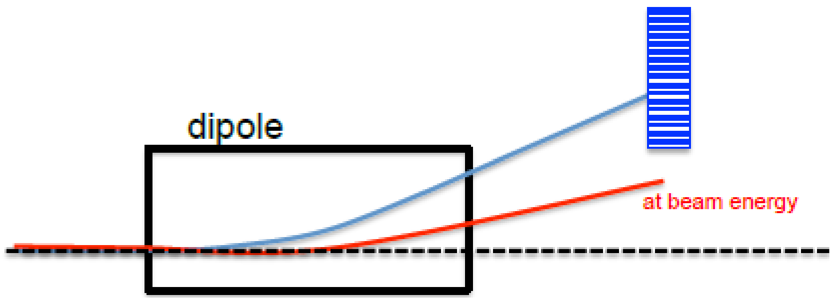
Auxiliary Detectors and the IR

measure via single photons

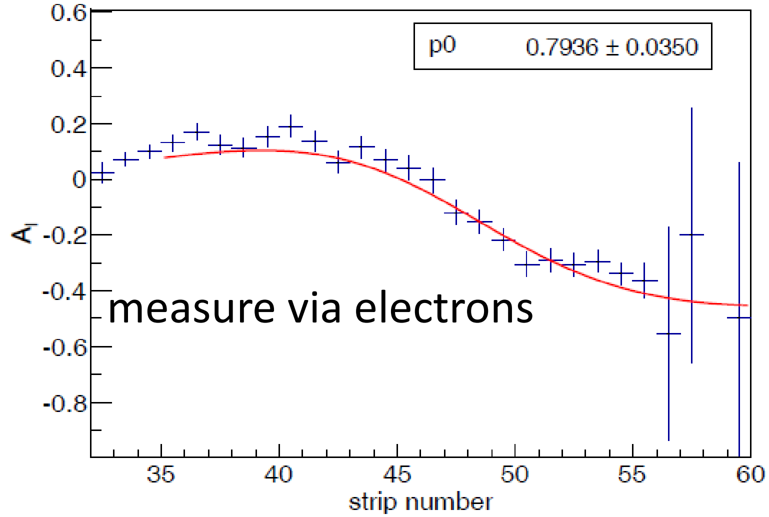




- Shine laser on electron beam, flip helicity state and measure asymmetry in



by a 2D fit in angle and energy of photon



measure via electrons

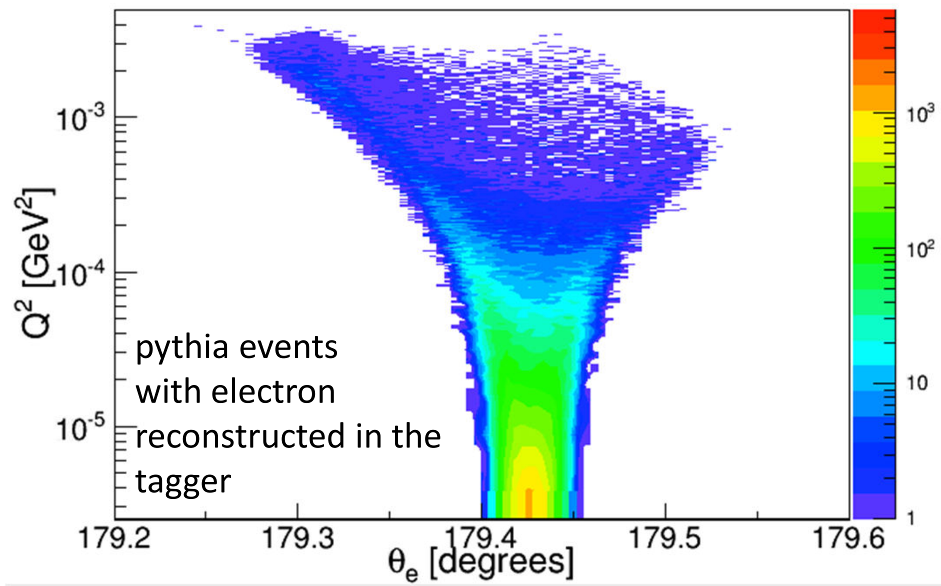
Summary

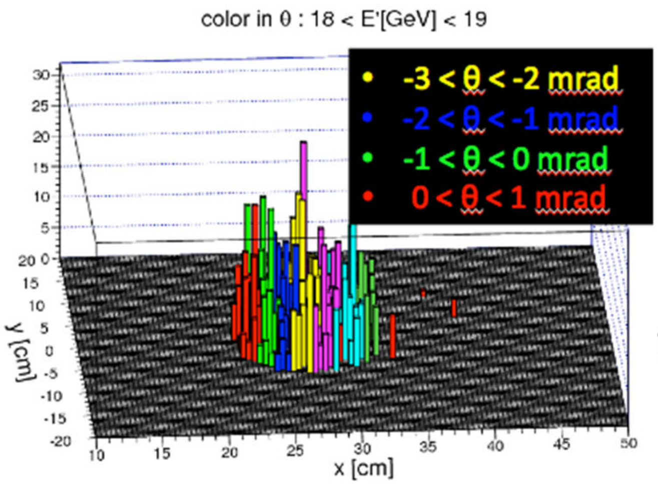
- Construction of an EIC is deemed a top priority in major facility construction in the US by the NSAC
- Major detector R&D programs underway for detector technologies and the planning of the detector to meet the physics goals of the facility
- A new detector is being developed to carry out the next generation DIS measurements (BeAST)
- The design of detector components, configuration, and technologies guided by physics requirements
  - Main DIS detector
  - Auxiliary support through down stream close to beam line detectors, luminosity monitors and polarimeters

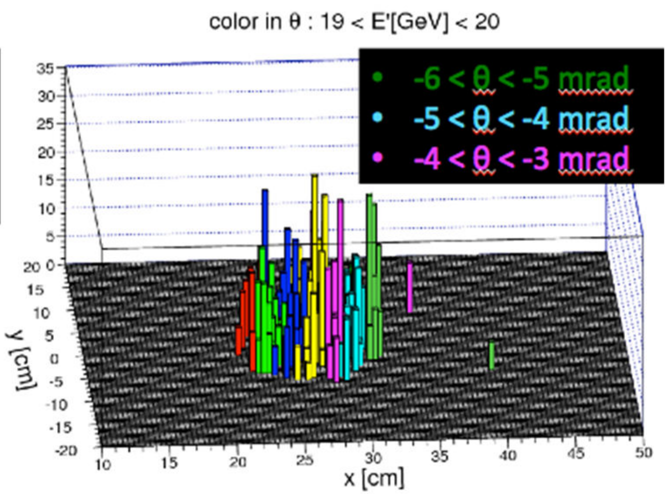
Backups

Physics with a low Q^2-tagger

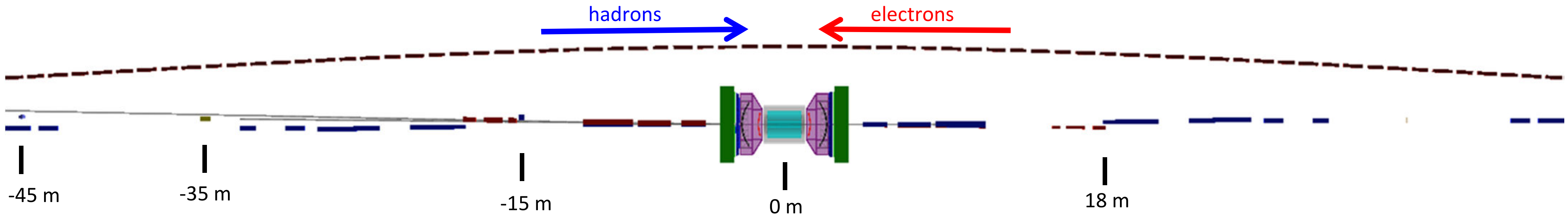
- acceptance of electrons from events down to $Q^2 \sim 10^{-5}$ GeV^2
- allows for further study of photoproduction physics
  - represents large portion of total cross section
  - probing the quark structure of photons
    - direct vs resolved photon
  - look for change in event properties associated with transition of real to virtual photon





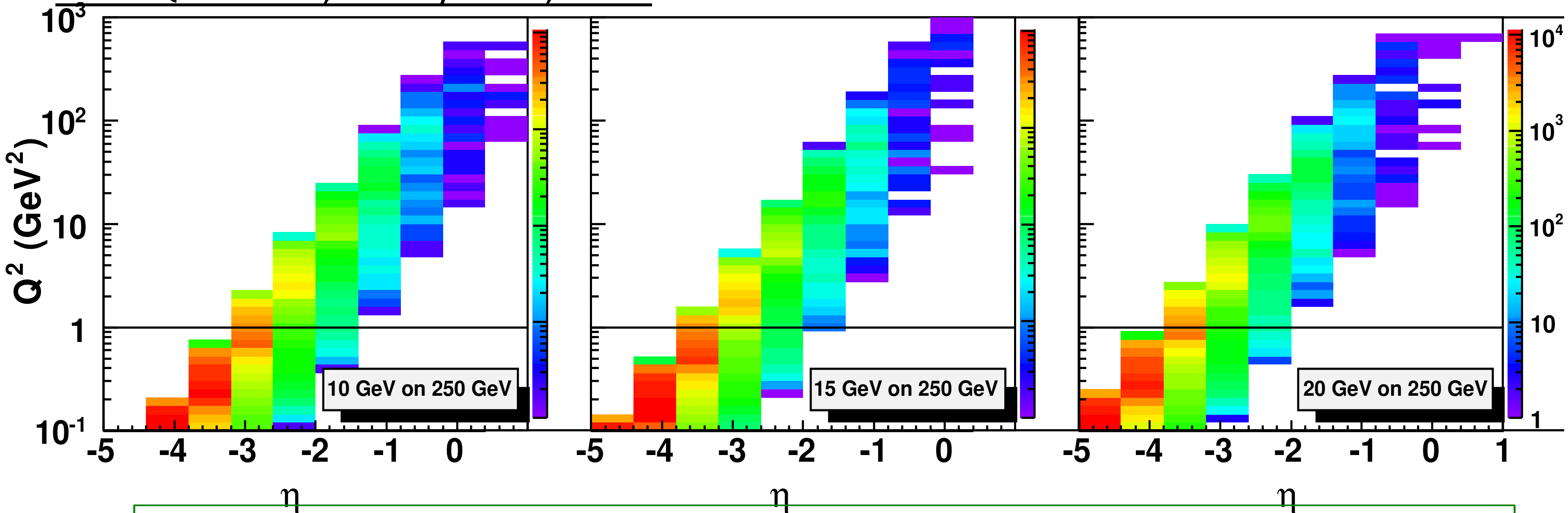


Auxiliary Detectors and the IR



Scattered Lepton Kinematics

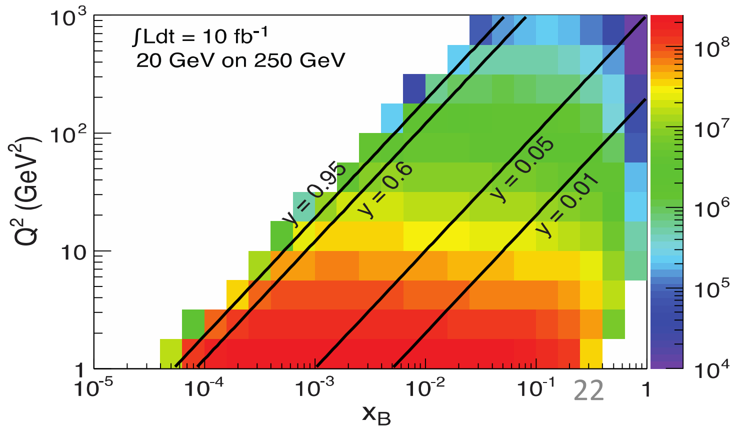
Cuts: Q^2>1 GeV^2, 0.01<y<0.95, z>0.1



Q^2 > 1.0 GeV^2: rapidity coverage -4 < η < 1 is sufficient

Q^2 < 0.1 GeV^2: a dedicated low-Q^2 tagger is required anyway

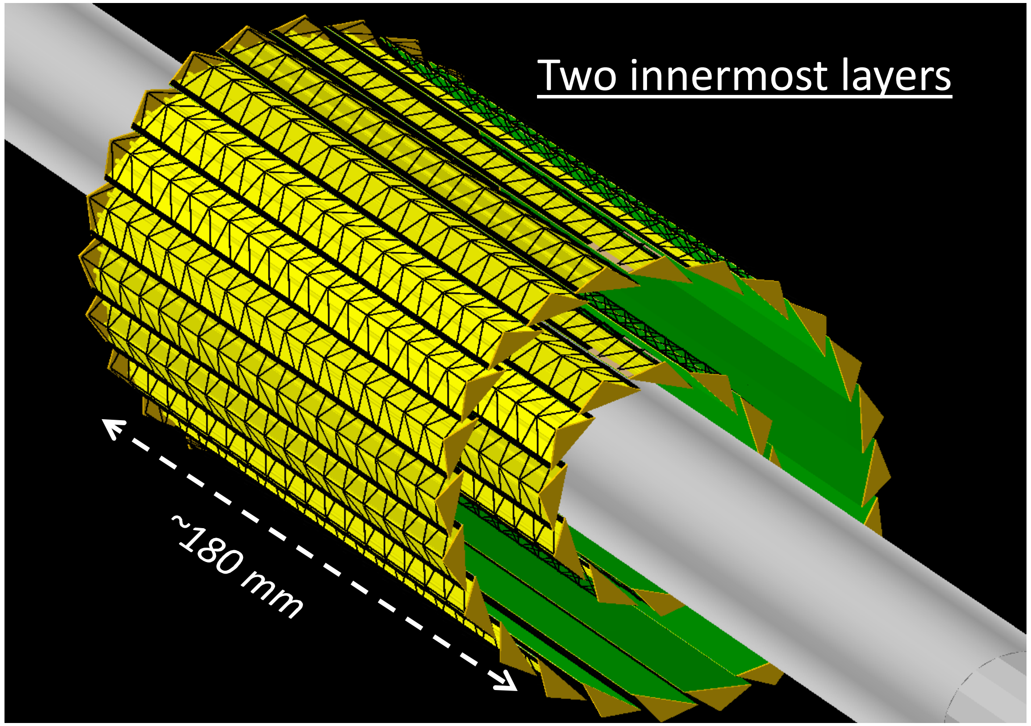
Also notice: as lepton beam energy goes up scattered lepton is boosted to negative η



Silicon Vertex Tracker

ALICE ITS design

- 2x2 barrel layers with high resolution MAPS
- assume discrete 20x20 μm^2 pixels and ~0.3% X_0 per layer



The prototype (ALICE ITS TDR page)

J. Phys. G: Nucl. Part. Phys. **41** (2014) 087002 The ALICE Collaboration

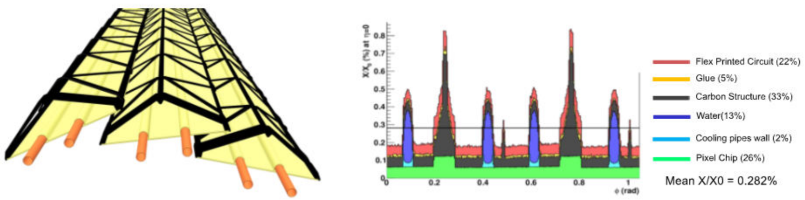
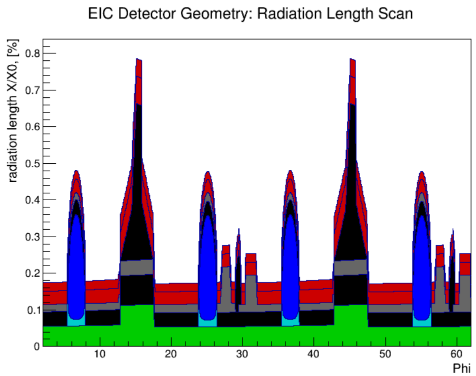


Figure 4.3: A detail of the Stave overlaps of the Inner Layers (left) and the corresponding material budget distribution (right). The highest peaks correspond to the overlap of the reinforced structures at the edges of the Space Frame, while the narrow spikes to the reinforcement at the upper vertex. The peaks around 0.5 % X_0 are due to the polyimide cooling pipes fully filled of water.

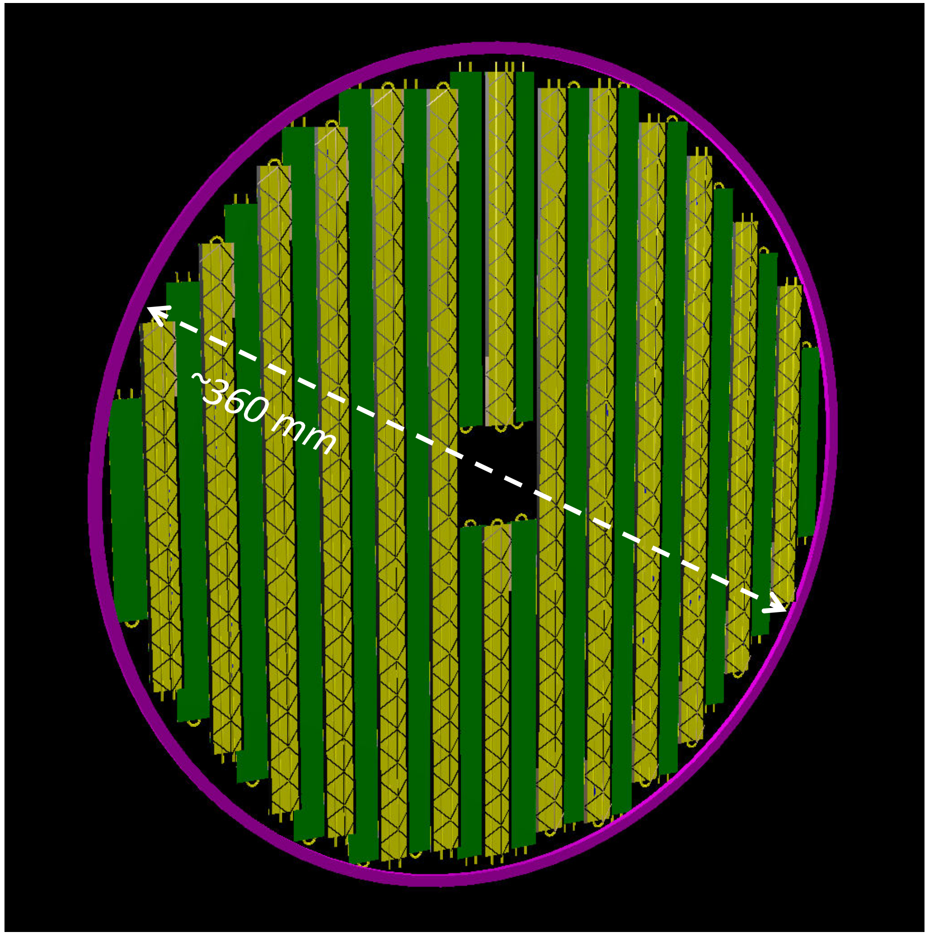


- Radiation length scan (single layer)

Forward & backward Silicon Trackers

- 2x7 disks with 30 .. 180 mm radius
- for now assume the same building blocks (complete staves) as in the vertex tracker
- Final configuration can be a combination of ALICE ITS and MFT upgrades

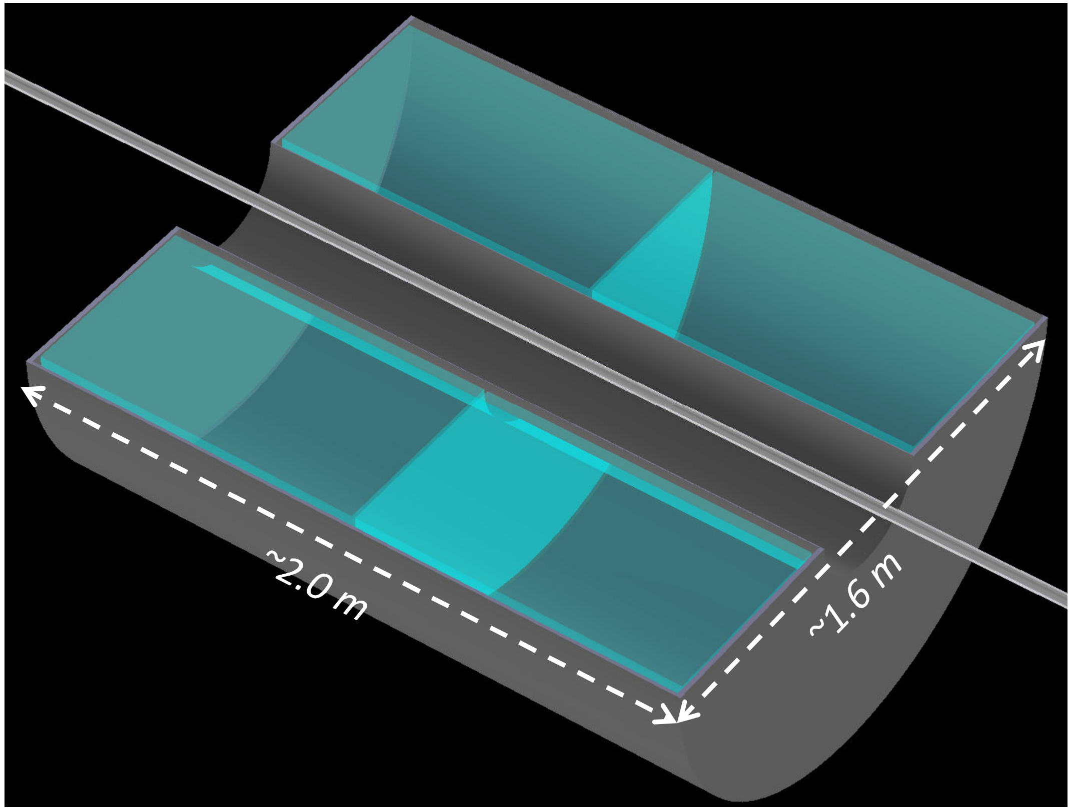
Design of this subsystem will likely become a topic for a separate R&D effort soon



TPC

Ongoing EIC R&D project

- ~2m long; gas volume radius [225..775] mm
- 1.2% X/X_0 IFC, 4.0% X/X_0 OFC; 15.0% X/X_0 end-caps
- assume 5 mm long GEM pads and ~250 μm single point {rϕ} resolution for the max. drift distance of ~1m
- A gas mixture like T2K at ~250 V/cm (very small transverse dispersion in 3T field) will do the job

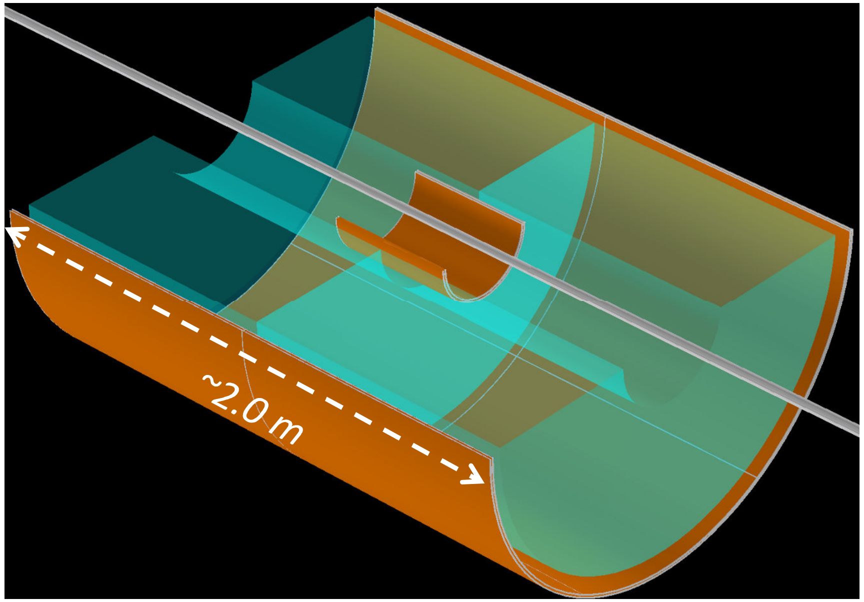


A medium size and medium resolution TPC, having in mind current status of the ILD R&D work

Micromegas barrel tracker

- 4 layers; technologically driven azimuthal and longitudinal segmentation
- 2D readout; assume ~100 μm spatial resolution

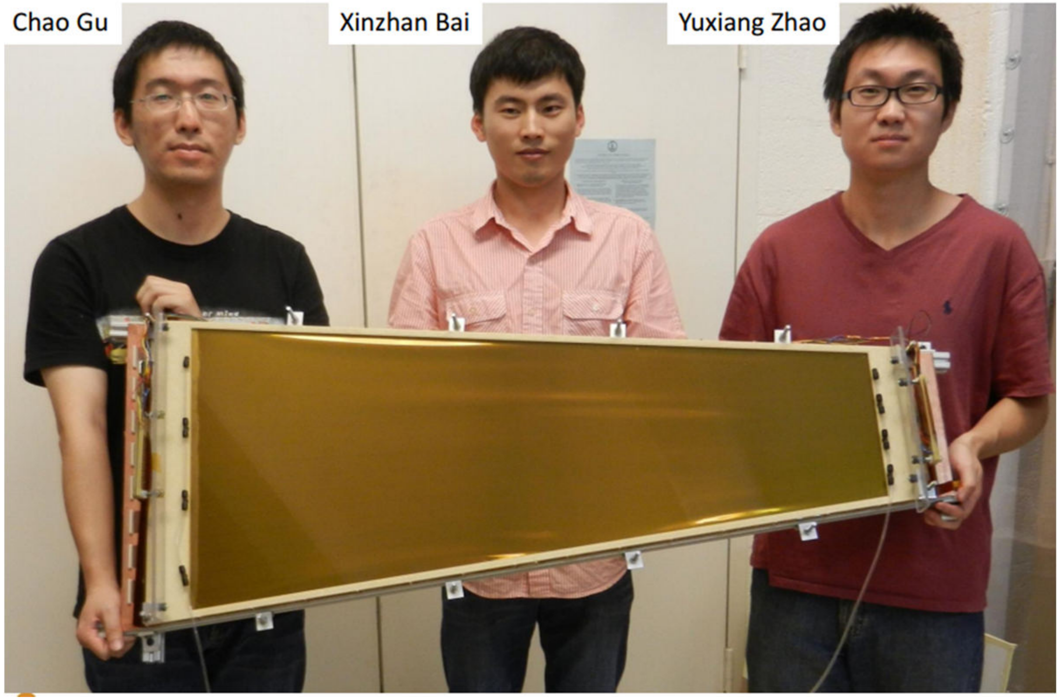
CLAS12 upgrade project



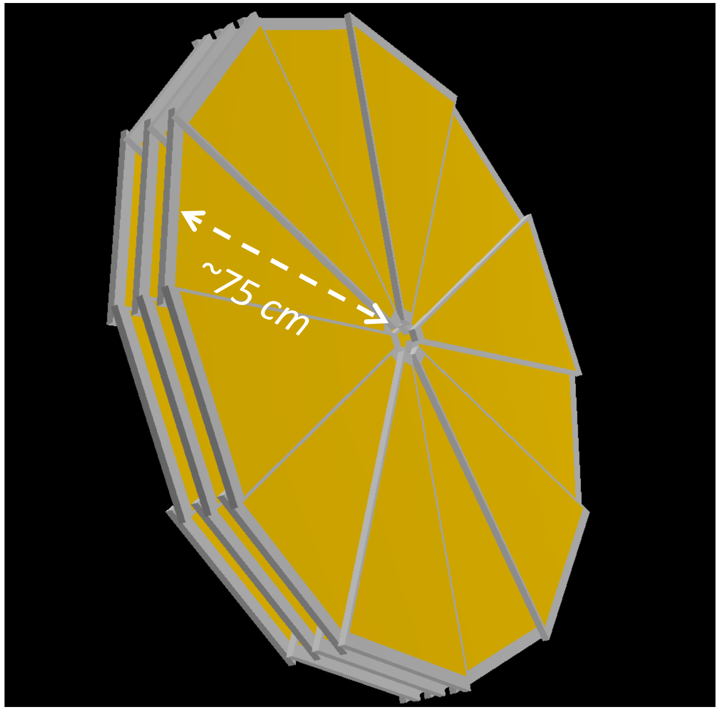
- Internal structure modeled according to the real-life prototypes
- ~0.5% X/X_0 per layer

GEM endcap trackers

- 3 disks behind the TPC end-caps; SBS internal design for now
- assume 50 μm $\{r\phi\}$ spatial resolution can be achieved



Ongoing EIC R&D project

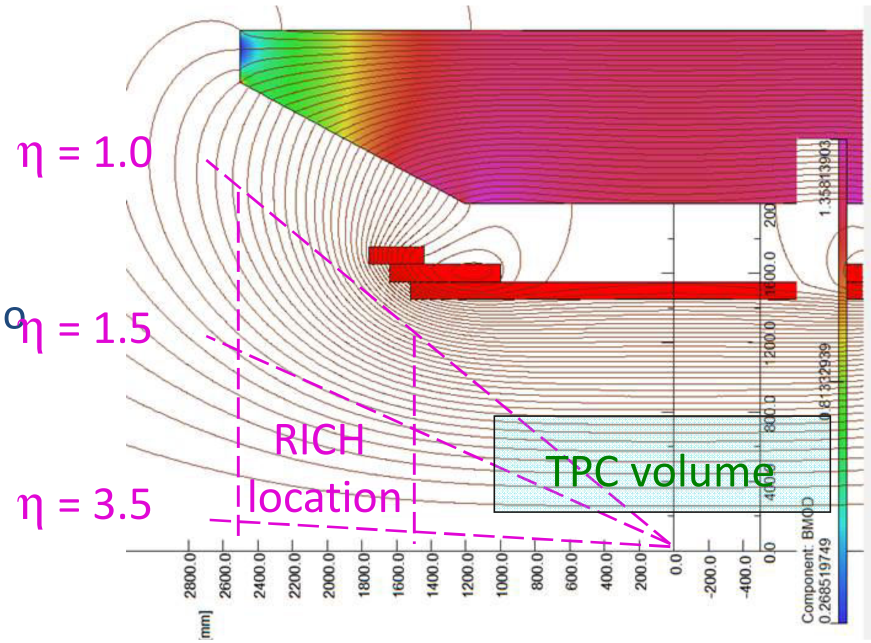


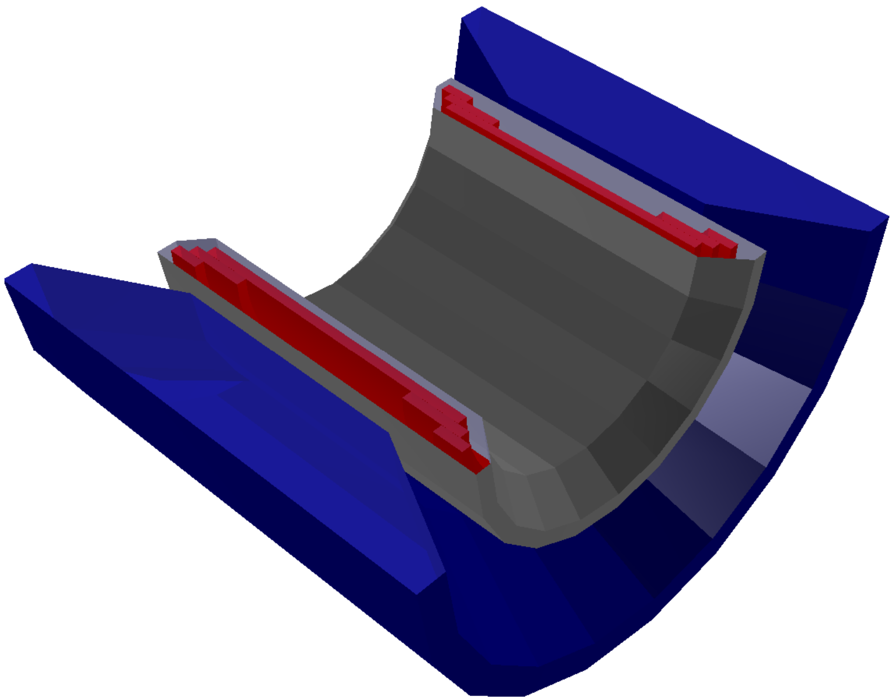
- Well advanced R&D program
- A couple of groups have their own large area GEM designs

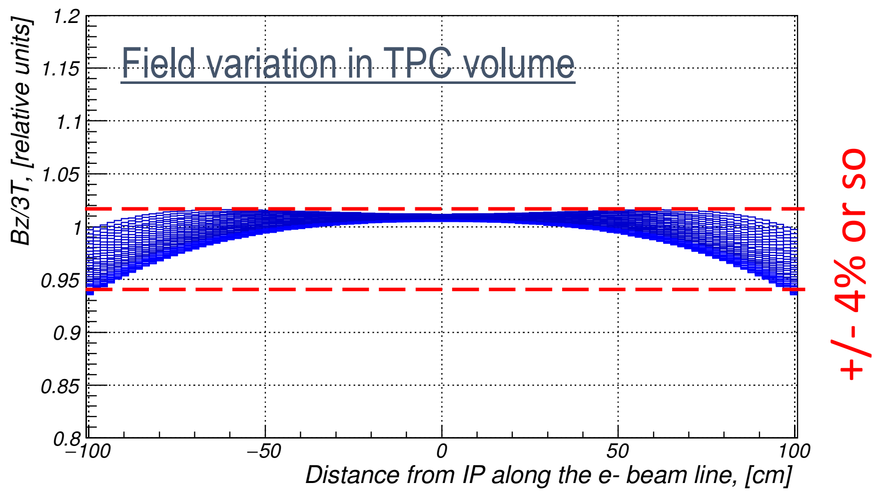
Superconducting solenoid

<u>Goal:</u>

- Implement in the same compact design:
  - homogeneous ~3T field in the TPC
  - hadron-track-aligned field in the RICH
- Keep it simple (no dual solenoid configuration; no reversed current coils; no flux return through HCal; no warm coils between RICH and EmCal)







Electromagnetic calorimeters

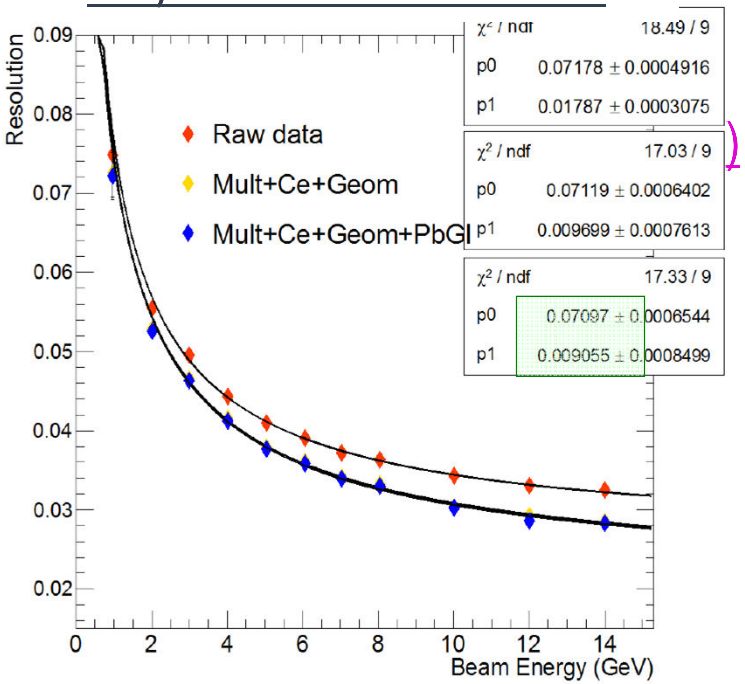
Ongoing EIC R&D projects

- Very backward pseudo-rapidities ($\eta < -2$):
  - PWO crystals with ~2%/√E (or better) energy resolution

e⁻ and γ energy measurement;
e/p electron ID

- Pseudo-rapidity range $-2 < \eta < 3.5$:
  - Tungsten powder scintillating fiber technology with ~7-10%/√E energy resolution

May'2016 test run in FNAL



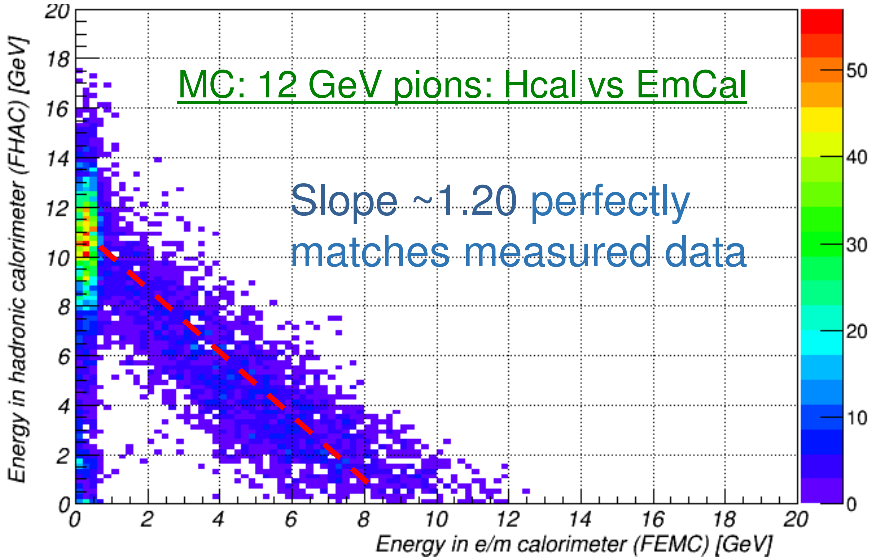
→ H1 : (7..12)%/√E+1%
→ ZEUS : 18%/√E+1%

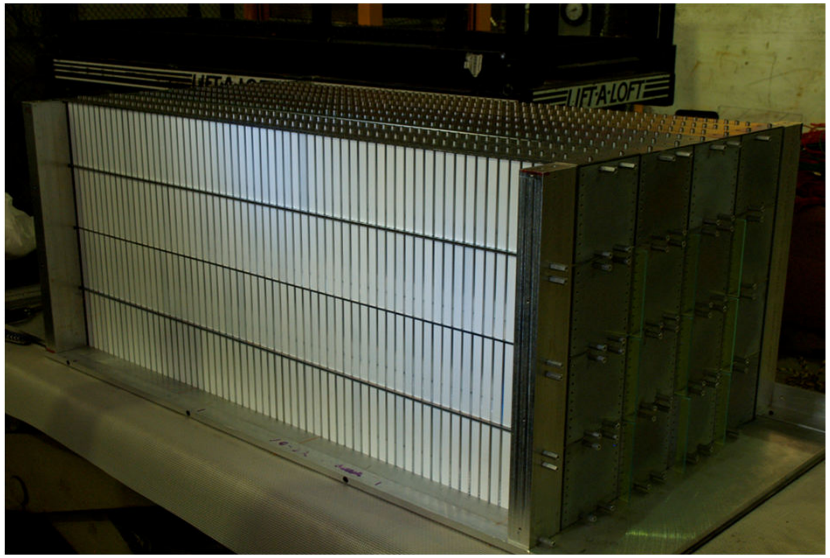
- Several configurations tested since 2012
- Reach energy resolution level of ~{7%/√E + 1%} with the PMTs
- See clear path towards getting similar level of performance with a compact readout

Hadronic calorimeter(s) in the end-cap(s)

Electron identification in electron-going direction;
jet physics in hadron-going direction

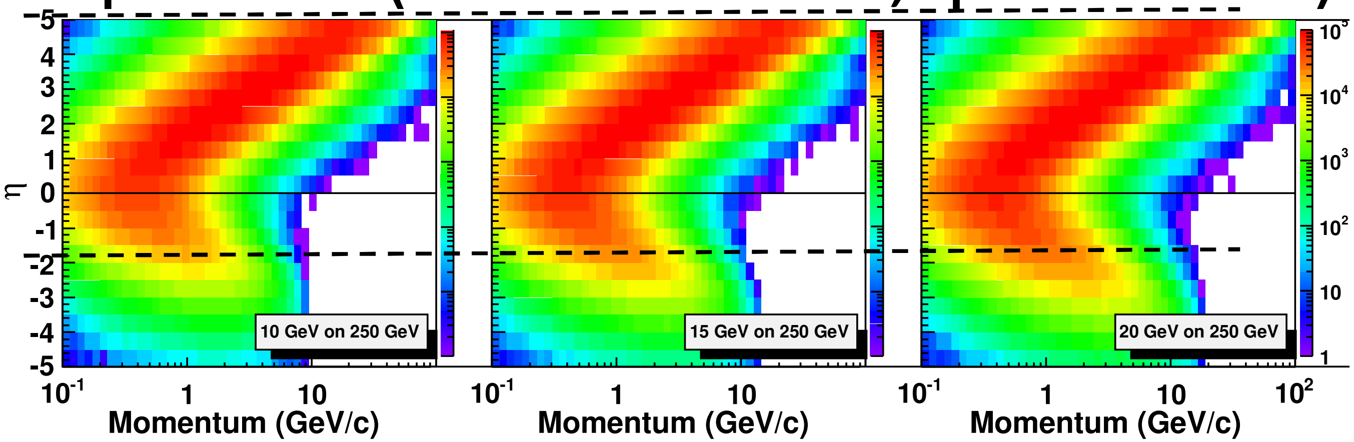
EIC R&D project



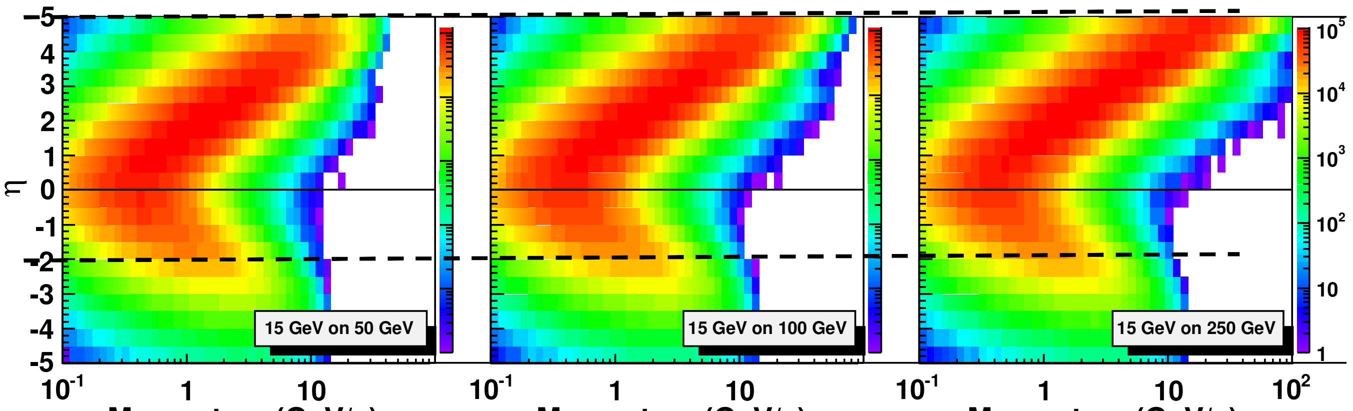


- Lead absorber scintillating plate sandwich technology
- ~50%/√E energy resolution looks fine
- Adequate Monte-Carlo model exists in GEANT
- Cost optimization and further R&D may be required (use steel plates instead of lead?)

SIDIS: kinematic coverage for pions (and kaons, protons)



Increasing lepton beam energy boosts hadrons more to negative rapidity

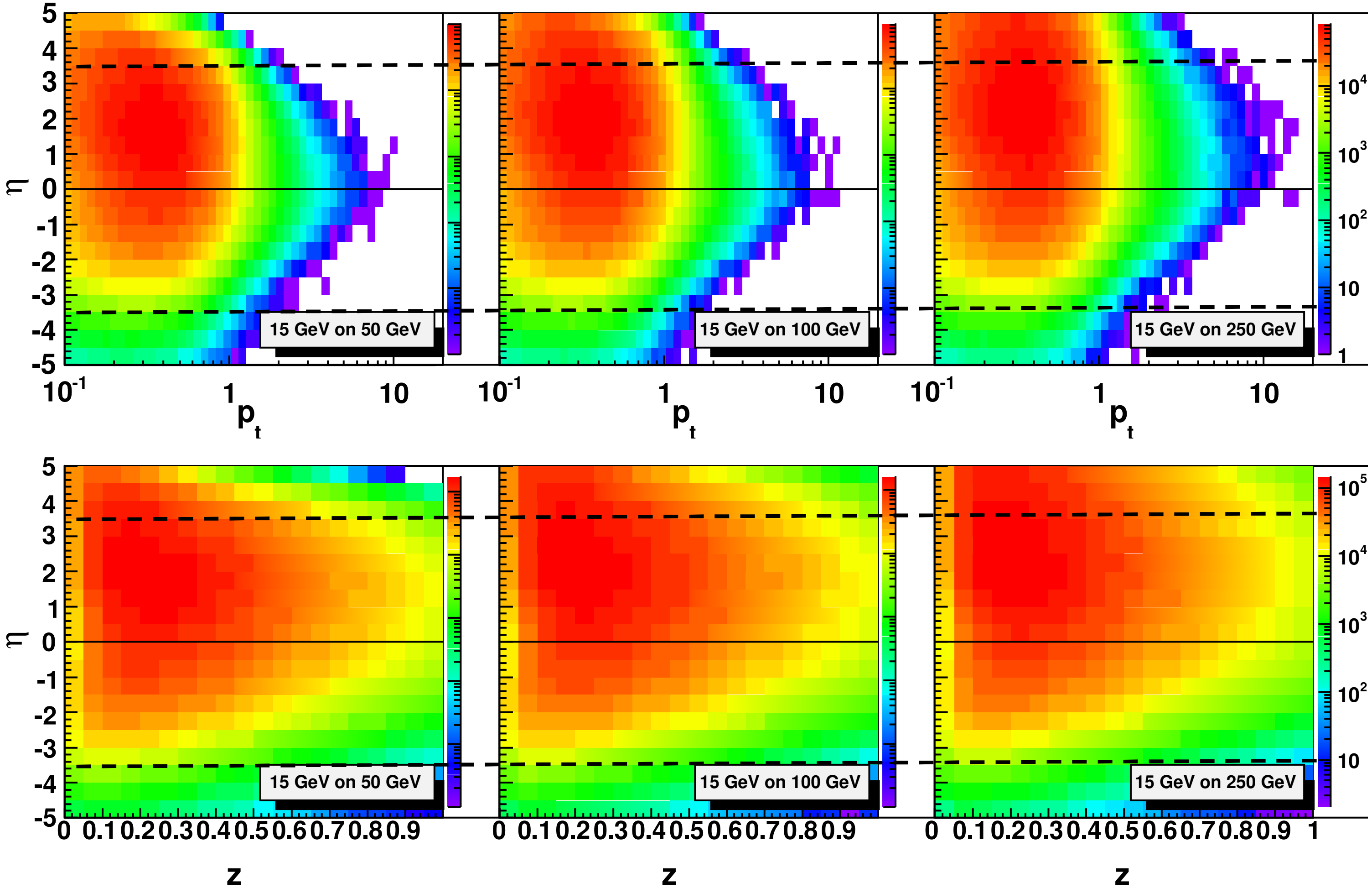


Increasing hadron beam energy influences max. hadron energy at fixed η

except for the highest η values ($1.5 < \eta < 3.5$ range)
π/K/p separation below ~5 GeV/c or so is sufficient

SIDIS: kinematic coverage for pions (and kaons, protons)

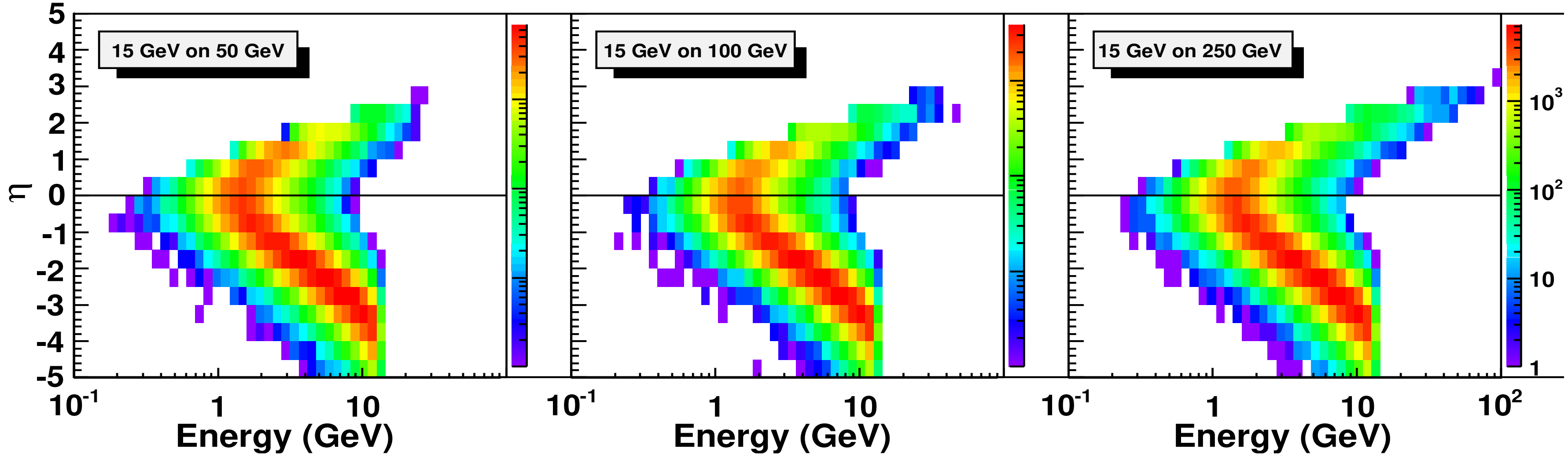
Cuts: Q^2>1 GeV^2, 0.01<y<0.95, p>1GeV (no difference between $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$)



-3.5 < η < 3.5 covers entire kinematic region in p_t & z important for physics

DVCS photon kinematics

Cuts: Q^2>1 GeV, 0.01<y<0.85

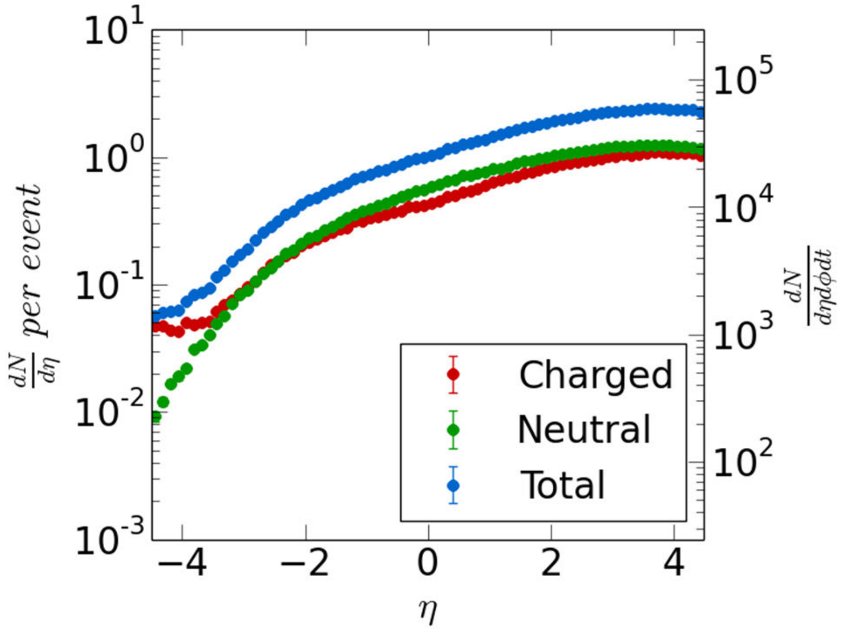


EmCal pseudo-rapidity coverage -4 < η < 1 is sufficient

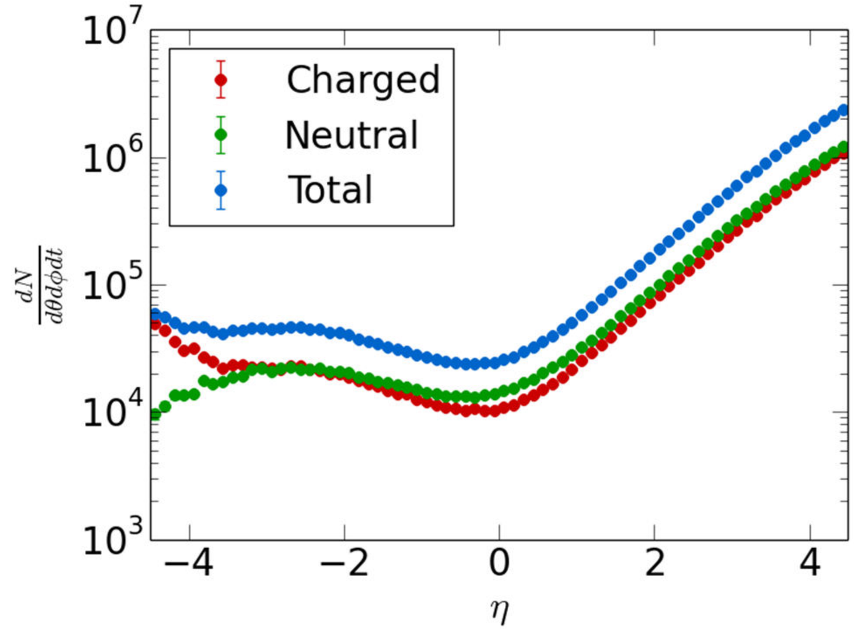
Also notice: increasing hadron beam energy influences max. photon energy at fixed η photons are boosted to negative rapidities (lepton direction)

Interaction rate & absolute yields

PYTHIA 20x250 GeV configuration; absolute particle yields for L=10^{33} cm^{-2} s^{-1}



Per unit of {η,ϕ}



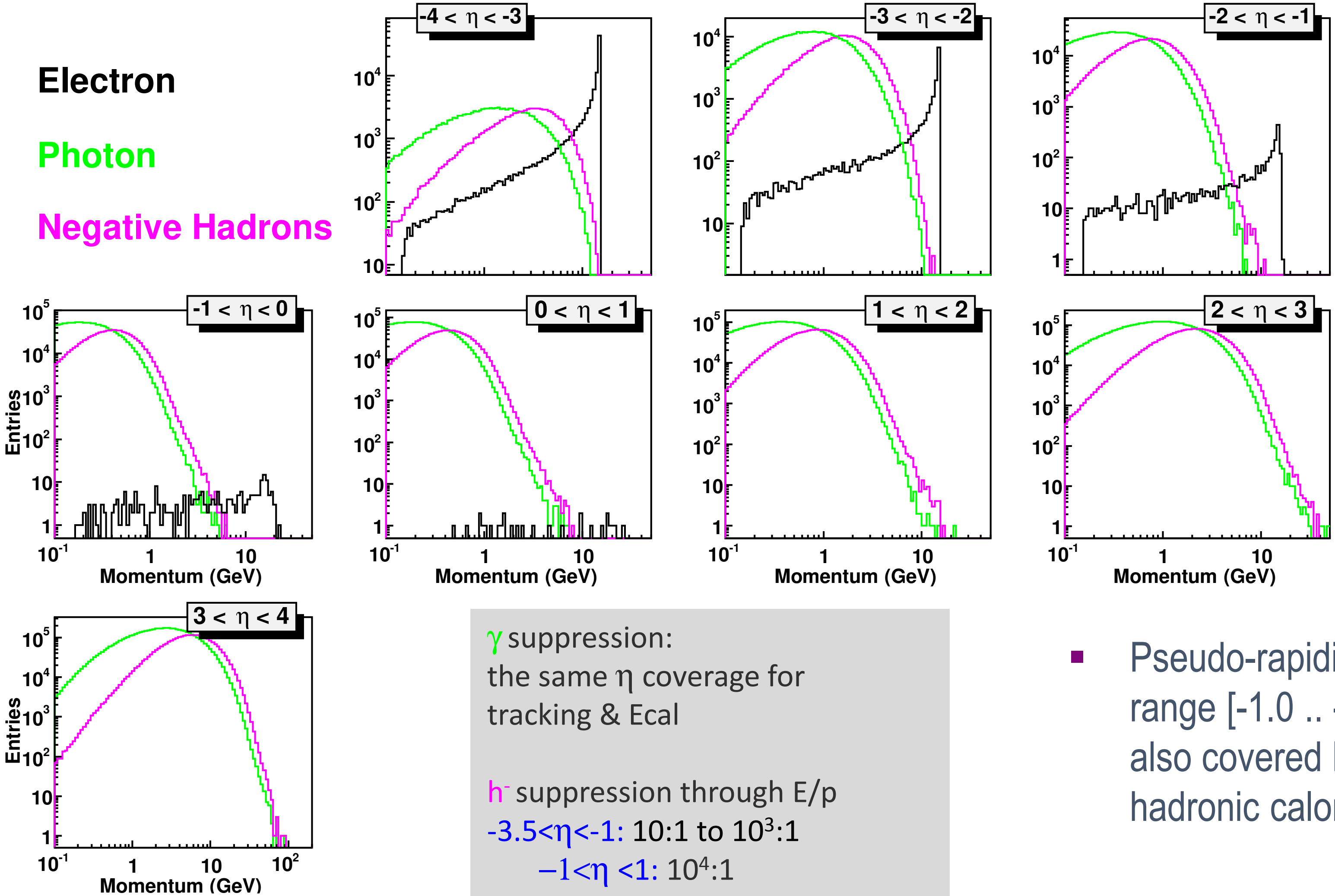
Per unit of {θ,ϕ}

- Interaction rate ~50kHz (so 1:200 at ~10MHz bunch crossing frequency)
- At most few particles per unit of η per event
- Correspondingly low particle fluxes per unit of time

Not even close to LHC-HL upgrade (to say the least)

Electron ID

15x250 GeV configuration; particle yields versus momentum in the -4 < η < 4 range:



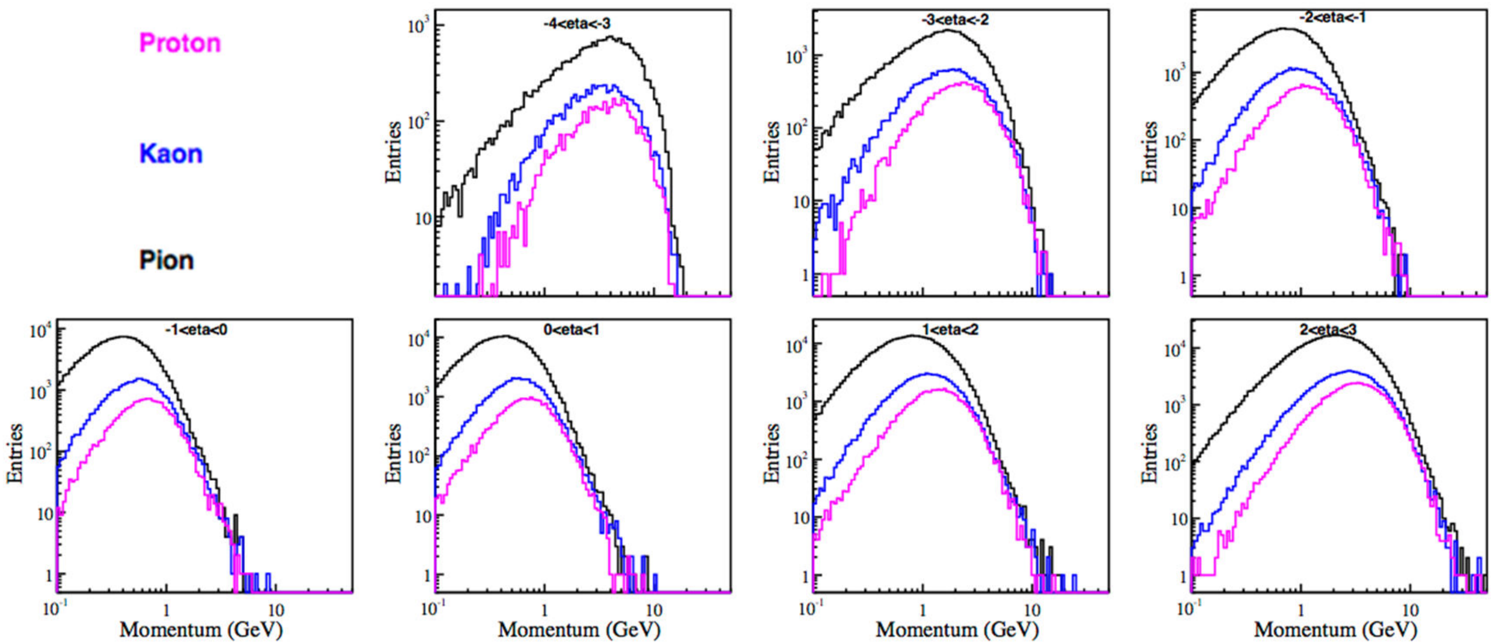
γ suppression:
the same η coverage for tracking & Ecal

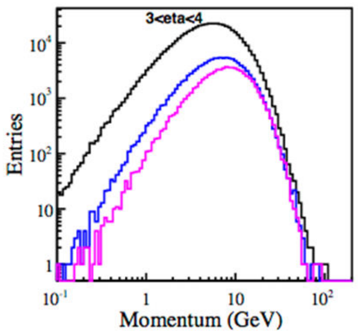
h⁻ suppression through E/p
$-3.5<\eta<-1$: 10:1 to 10^3:1
$-1<\eta<1$: 10^4:1

- Pseudo-rapidity range [-1.0 .. -3.5] is also covered by the hadronic calorimeter

Relative pion/kaon/proton yields

20x250 GeV configuration; yields versus momentum in the 4 < η < 4 range:





- π/K/p distributions at the same η look similar

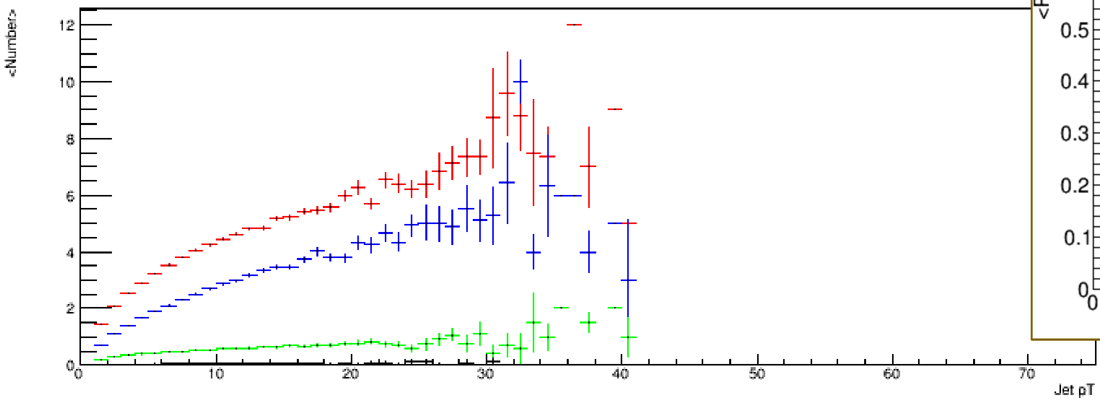
π/K ratio is about 3:1 -> depending on the desired efficiency and contamination this defines the required suppression factors

Jets at mid-rapidities

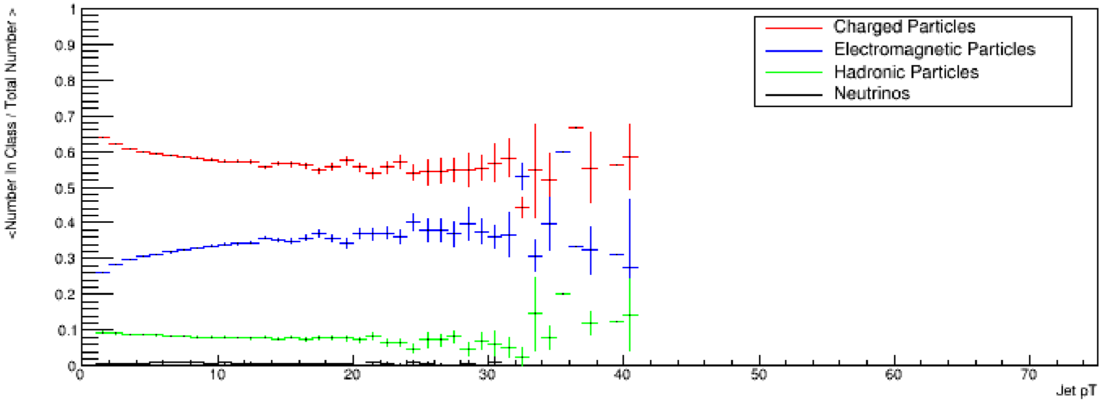
20x250 GeV; Q^2 [10 .. 100] GeV^2 ; $-1 < \eta < 1$

EIC jets at |η|<1 are "jetlets"

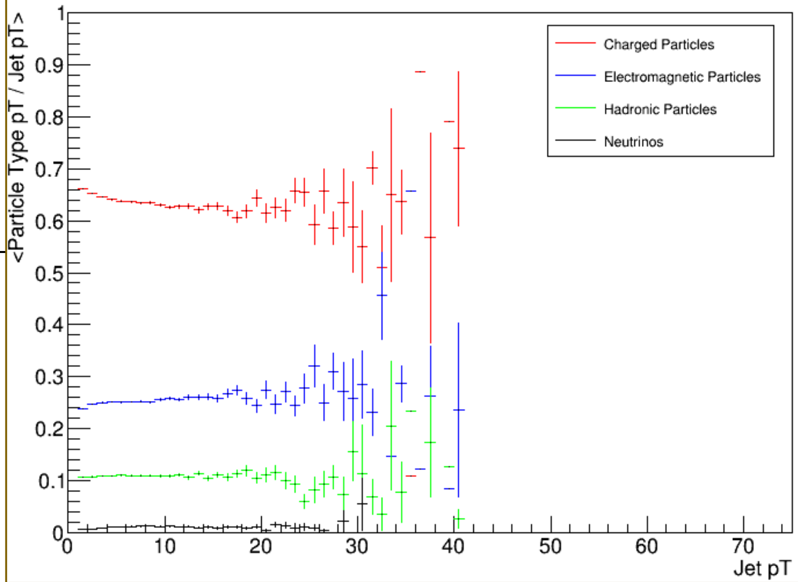
Absolute number of particles in each class



Fractional number of particles in each class

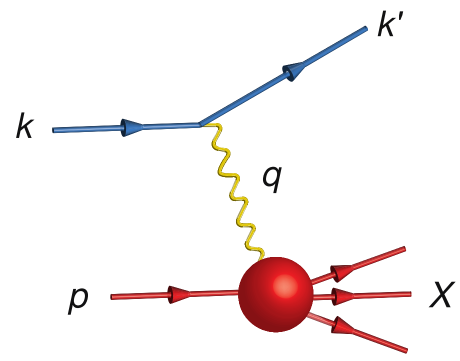


Fraction of jet P_t carried by different particles classes



- Fraction of P_t carried by neutral hadrons is small
- No way ~50%/√E hadronic calorimeter energy resolution at <40 GeV/c can beat tracker momentum resolution

Kinematic variable definitions: reminder



- Kinematic variables:
  - k, k' are the four-momenta of the incoming and outgoing lepton
  - p is the four-momentum of the nucleon
- Lorentz invariants (related by $Q^2 = xys$):
  - $s = (p + k)^2 = 4E_p E_e$, squared collision energy
  - $Q^2 = -q^2 = -(k - k')^2$, squared momentum transfer to the lepton (equal to the virtuality of the exchanged photon)
  - $x_B = Q^2/(2p \cdot q)$, determines the momentum fraction of the parton on which the photon scatters
  - $y = (q \cdot p)/(k \cdot p)$, the inelasticity which determines the polarization of the virtual photon, fractional energy transfer
- Other variables:
  - $W^2 = (p + q)^2 = Q^2(1 - 1/x)$, squared invariant mass of the produced hadronic state
  - $\nu = q \cdot p/M = ys/(2M)$, the energy lost by the lepton (i.e. energy carried away by the virtual photon) in the proton rest frame

Kinematic Variable Reconstruction

- Lepton method
  - Use only the scattered lepton to determine event kinematics

$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 2E_e E'_e(1-\cos\Theta_{e'})$$

Measure of resolution power

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

  - Resolution goes as:

$$\frac{\delta x_e}{x_e} = \frac{1}{y_e}\frac{\delta E'_e}{E_e} \oplus \left[\frac{x_e}{E_e/E_p} - 1\right]\tan\frac{\theta'_e}{2}\delta\theta'_e$$

$$\frac{\delta y_e}{y_e} = \left(1 - \frac{1}{y_e}\right)\frac{\delta E'_e}{E_e} \oplus \left[\frac{1}{y_e} - 1\right]\cot\frac{\theta'_e}{2}\delta\theta'_e$$

diverges for $y_e \rightarrow 0$ depends on E'_e

$$\frac{\delta Q_e^2}{Q_e^2} = \frac{\delta E'_e}{E_e} \oplus \tan\frac{\theta'_e}{2}\delta\theta'_e$$

diverges for $\theta'_e \rightarrow 180^o$ depends on E'_e and θ'_e

- Double angle method
  - Use a combination of information from the scattered lepton and hadronic state

$$Q^2_{DA} = \frac{4E'^2_e cos^2(\theta'_e/2)}{sin^2(\theta'_e/2) + \sin(\theta'_e/2)\cos(\theta'_e/2)\tan(\theta'_p/2)}$$

$$y_{DA} = 1 - \frac{\sin(\theta'_e/2)}{\sin(\theta'_e/2) + \cos(\theta'_e/2)\tan(\theta'_p/2)}$$