Outline of EIC Detector Requirements

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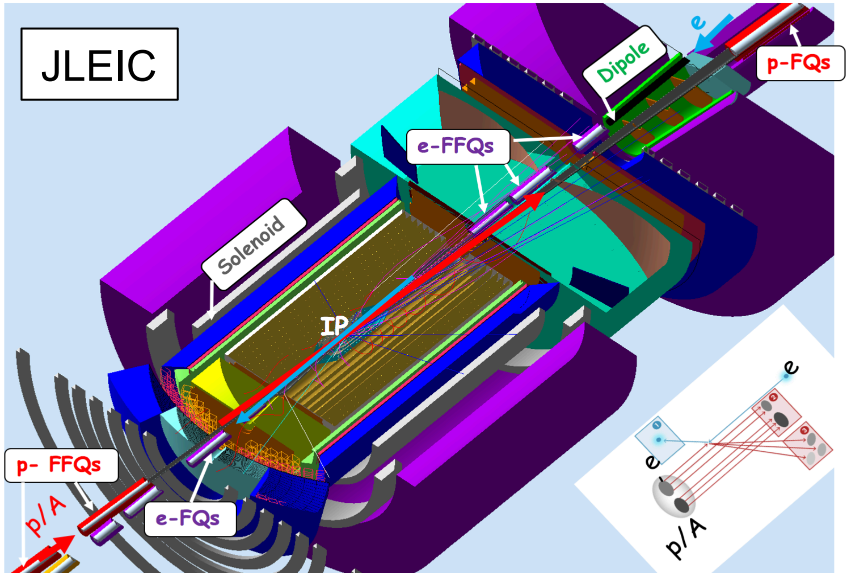
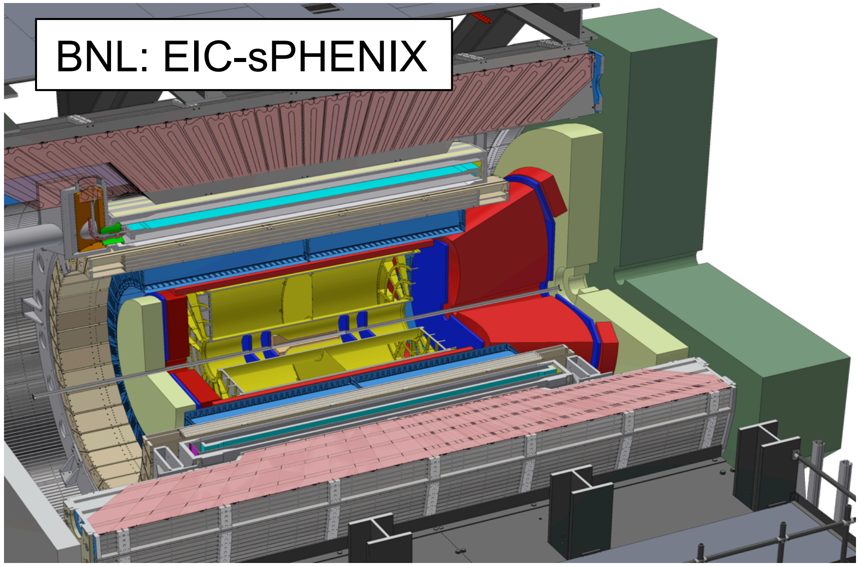
BROOKHAVEN NATIONAL LABORATORY

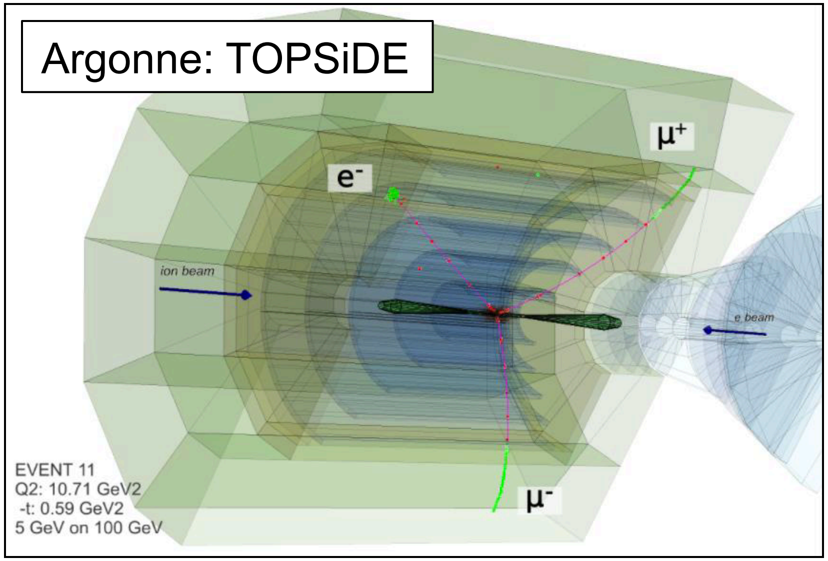
U.S. DEPARTMENT OF ENERGY | Office of Science

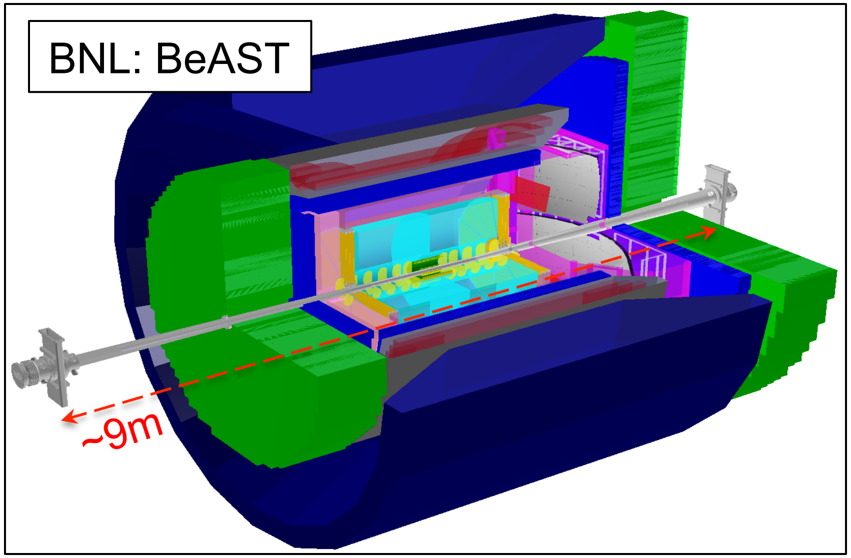
Jefferson Lab
Thomas Jefferson National Accelerator Facility

EIC detector concepts in one slide







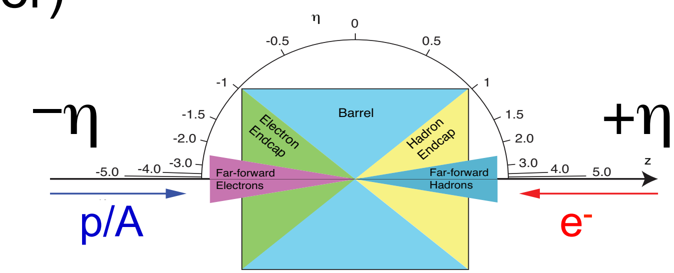


EIC Detector Concepts overview

- **Key features:**
  - Vertex + central + forward/backward tracker layout
  - Central detector: hermetic coverage in tracking/calorimetry/PID for $|\eta|<4$

  - Advanced far forward instrumentation (Roman Pots, ZDC, etc)
  - Far backward instrumentation (Low Q^2 tagger)

  - Low material budget in the tracker volume
  - 1.4 – 4.0 T central solenoid field



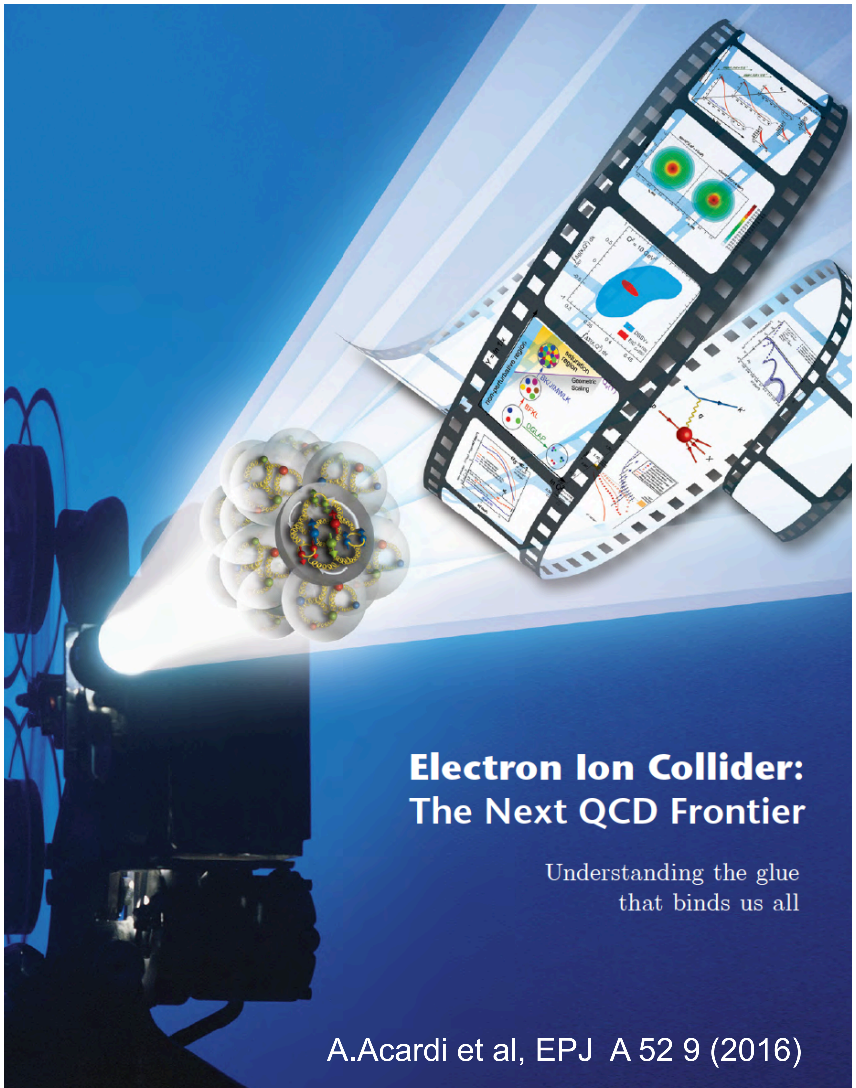
$-4<\eta<4 \sim [2^0 .. 178^0]$

  - Moderate momentum resolution (~1% level)
  - Moderate-to-high vertex resolution (<20 μm or so)
  - Moderate EmCal and HCal energy resolution

- **As stated at e.g. Temple UG meeting in Nov'2017, community wants *two* general-purpose detectors**

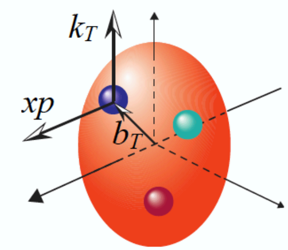
EIC physics case in one slide

<u>Precision study of quark and gluon dynamics inside nucleon and nuclei</u>

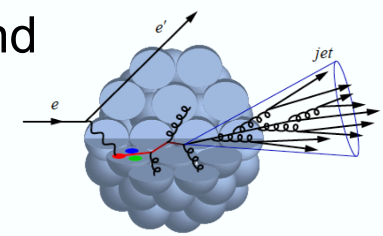


Key questions:

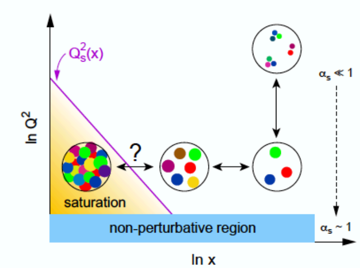
- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?



- How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?



- Where does the saturation of gluon densities set in? Does this saturation produce matter with universal properties?

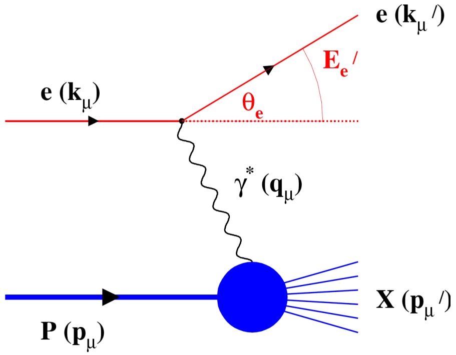


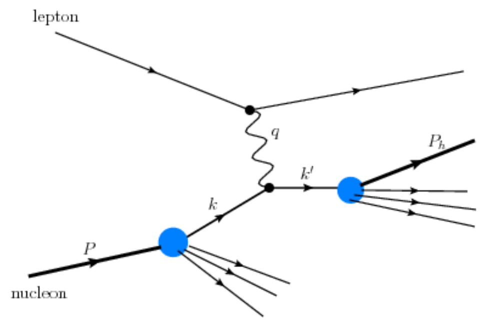
EIC physics measurements in one slide

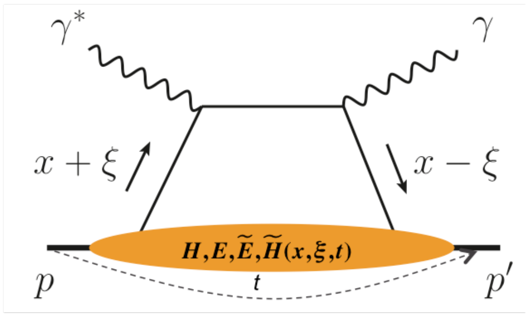
Parton Distributions in nucleons and nuclei

Spin and Flavor structure of nucleons and nuclei / **Tomography Transverse Momentum Dist.**

QCD at Extreme Parton Densities - Saturation / **Tomography Spatial Imaging**







inclusive DIS (ep/eA)

- measure scattered lepton
- two-dimensional binning: $\{x, Q^2\}$
  - → large kinematic coverage (where reach to lowest x,Q^2 also impacts IR design)
  - → event kinematics reconstruction (tracking, e/m calorimetry)
  - → high quality electron ID in the whole acceptance

semi-inclusive DIS (ep/eA)

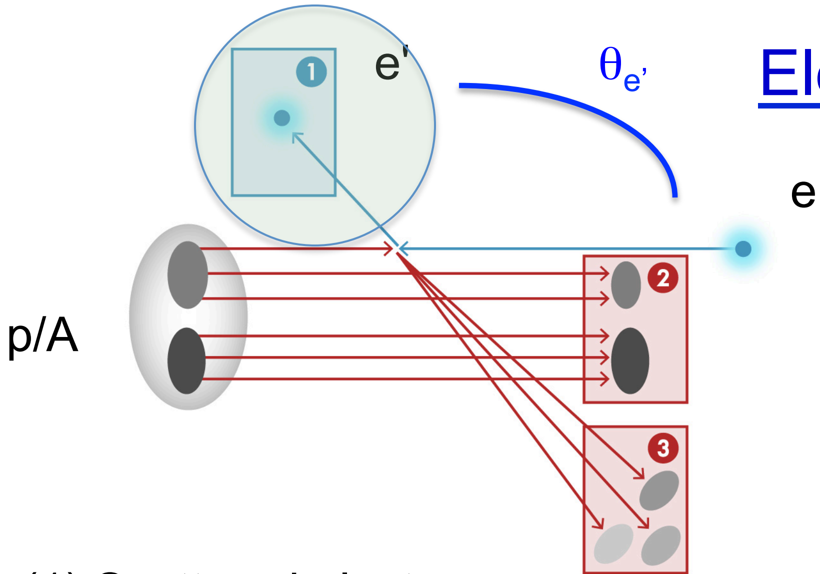
- measure scattered lepton and hadrons in coincidence
- multi-dimensional binning: $\{x, Q^2, z, p_T, \Phi\}$
  - → hadron identification over entire acceptance
  - → tracking
  - → hadronic calorimetry (jets)
  - → vertexing (charm)

exclusive processes (ep/eA)

- measure all particles in event
- multi-dimensional binning: $\{x, Q^2, t, \Phi\}$
  - → rapidity gap: hermeticity
  - → far forward instrumentation (recoil protons, exclusivity)

Inclusive measurements

DIS kinematics reconstruction: electron



(1) Scattered electron
(2) Proton (ion) remnants
(3) Struck quark fragmentation products

Electron method -> only scattered electron information is used

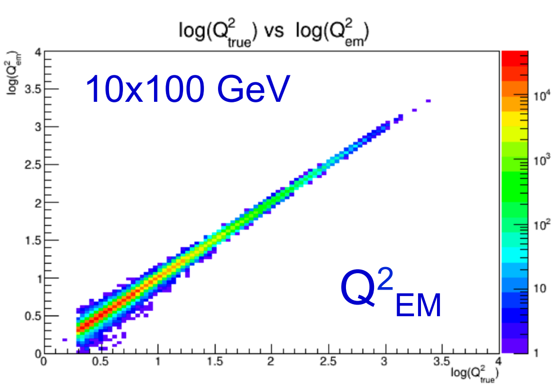
$$Q^2_{\text{EM}} = 2E_e E_{e'}\,(1+\cos\theta_{e'})\,,$$

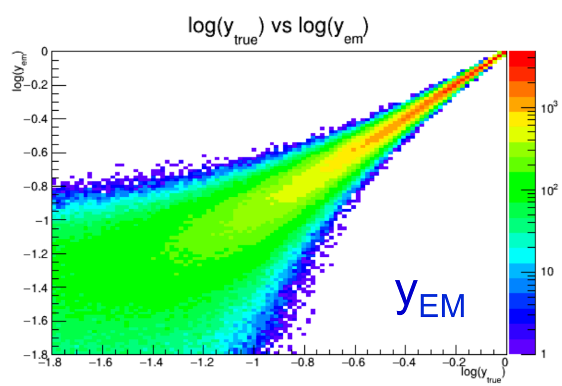
$$y_{\text{EM}} = 1 - \frac{E_{e'}}{2E_e}(1-\cos\theta_{e'})\,,$$

$$x = \frac{Q^2}{4E_e E_{\text{ion}}}\boxed{\frac{1}{y}}$$

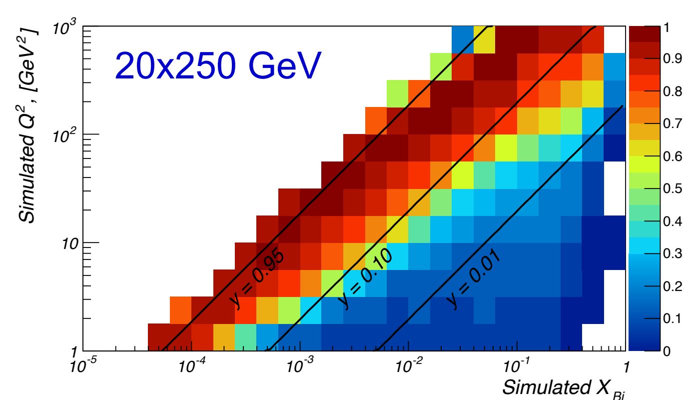
"Classic" way to determine $\{x,Q^2\}$

Obviously diverges at small y





Q^2 & y reconstruction quality (electron method)

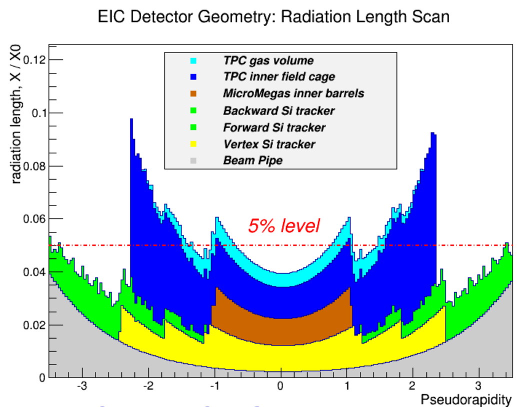


$\{x,Q^2\}$ bin migration

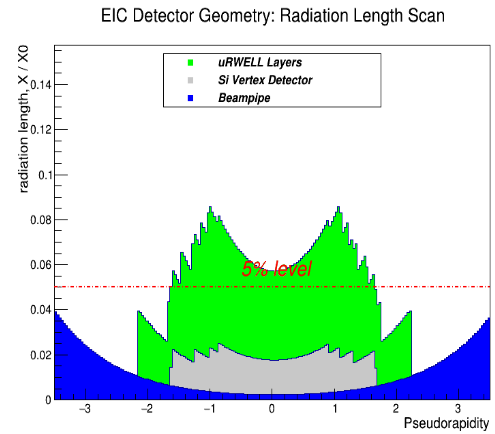
EIC tracker: systems & options

- **Vertex detector**
  - (D)MAPS, DEPFET, …
- **Central tracker**
  - TPC (+ MM)
  - All-silicon tracker
  - Curved MM (μRWELL)
  - Drift chamber
  - Straw tube tracker
- **Endcap trackers**
  - Flat GEMs (MM, μRWELL, sTGC)
- **Forward & backward trackers**
  - (D)MAPS, “traditional” silicon, …
  - (Very) high resolution GEMs

Material budget

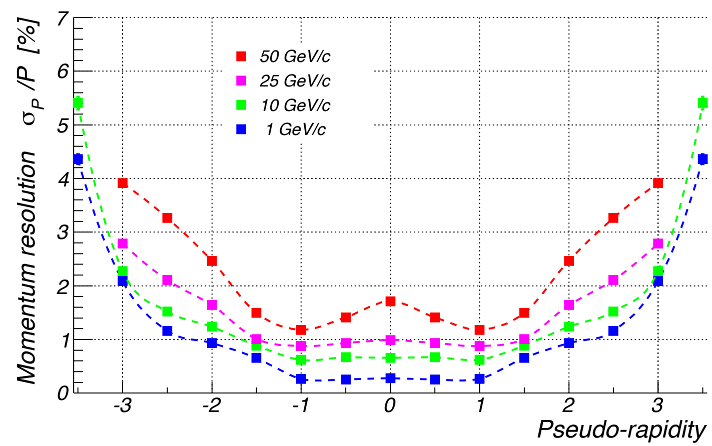


Si+TPC+GEM setup



Si+μRWELL setup

Momentum resolution for a Si+TPC+GEM setup



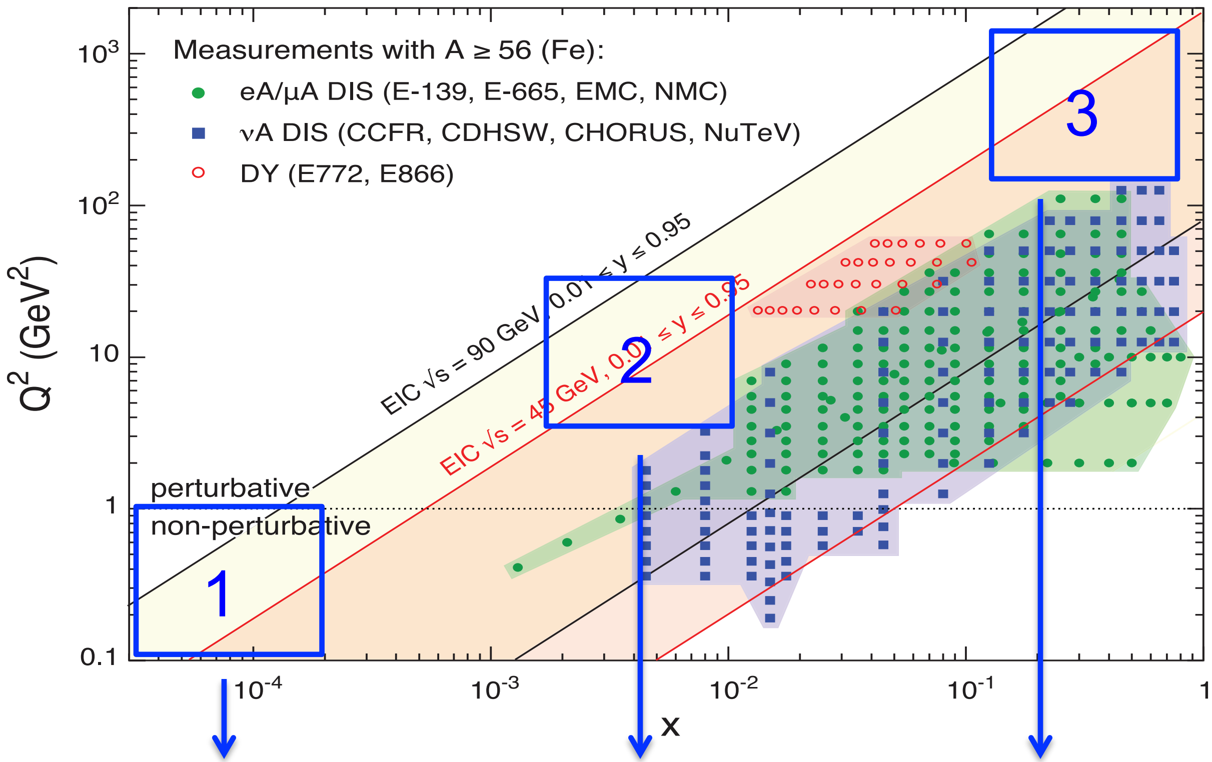
- All options favorably compare to the performance of HERA collider experiments:

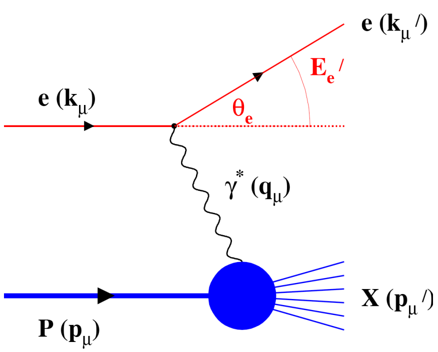
→ H1 : $0.6\%*P_t + 1.5\%$

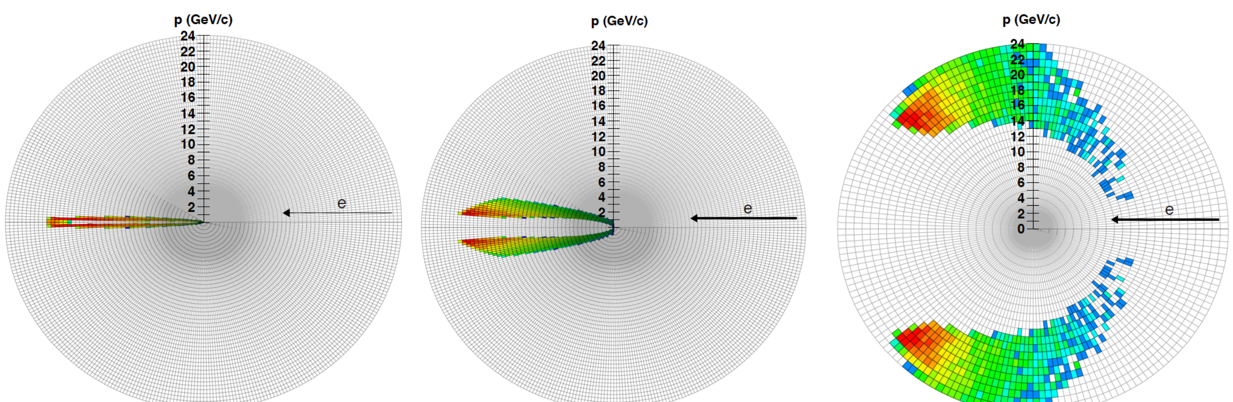
→ ZEUS : $0.5\%*P_t + 1.5\%$

Where does the scattered electron go?

Scattered electron kinematics is very different depending on {x,Q^2}

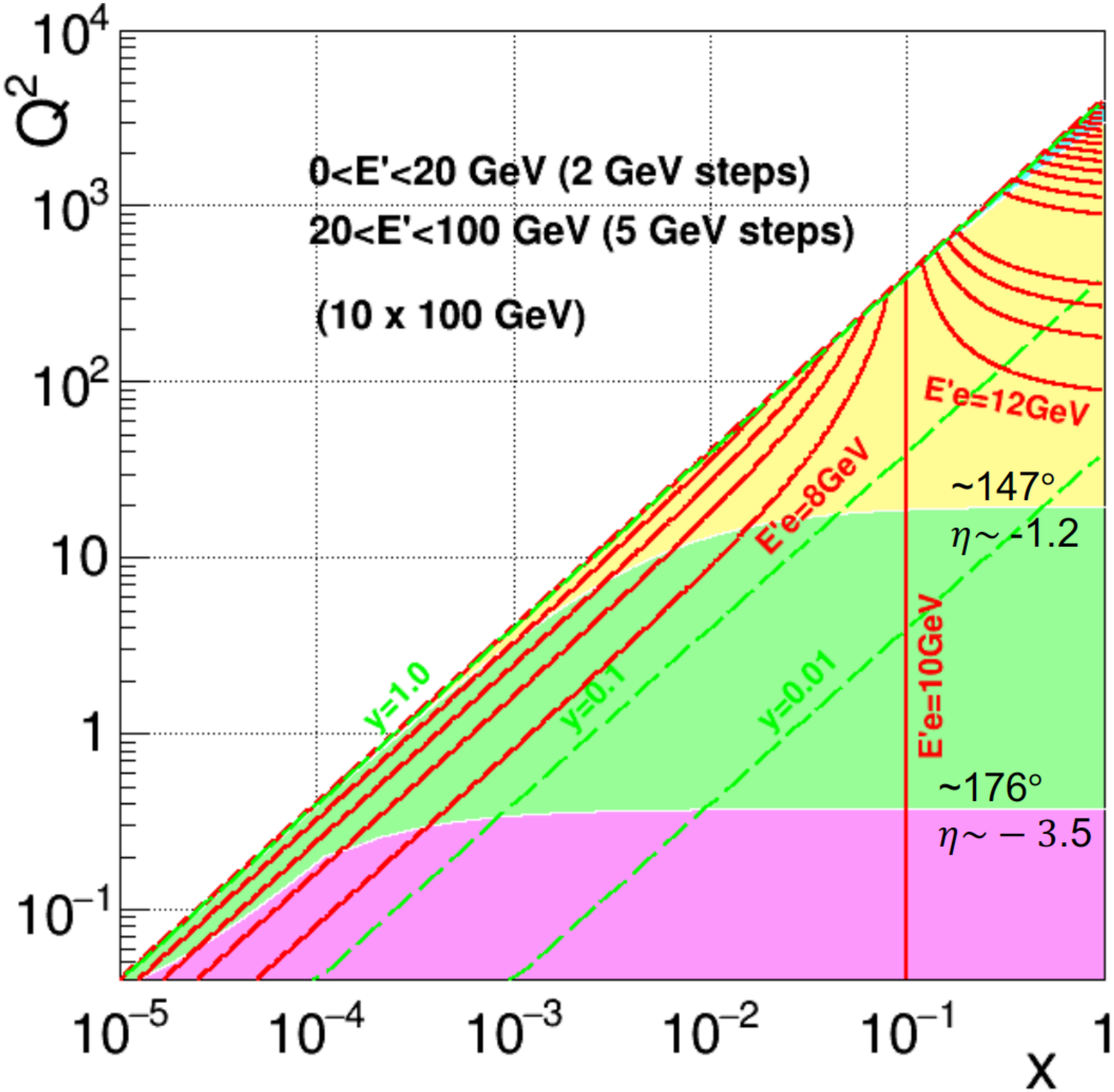


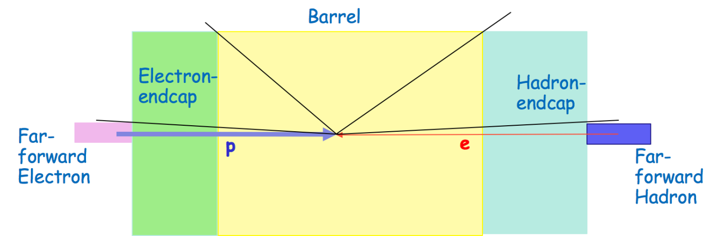




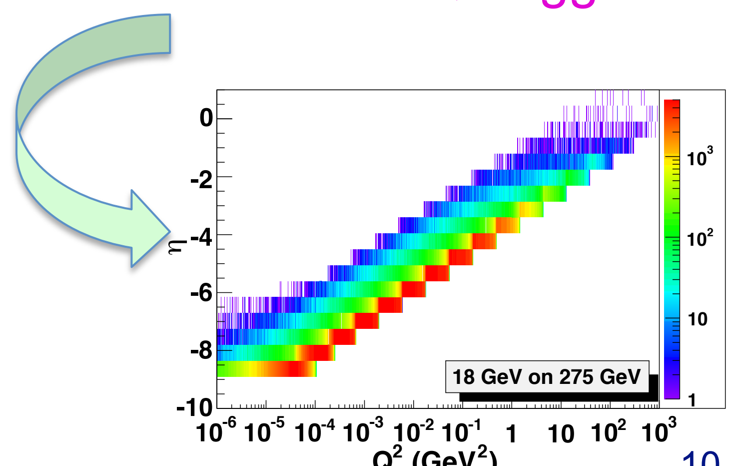
- Need excellent electron ID in a wide range of energies and polar angles
  - → equal rapidity coverage for tracking and e/m calorimeter
  - → low material budget to reduce bremsstrahlung
- Momentum (energy) and angular resolution of scattered electron is critical

Where does the scattered electron go?





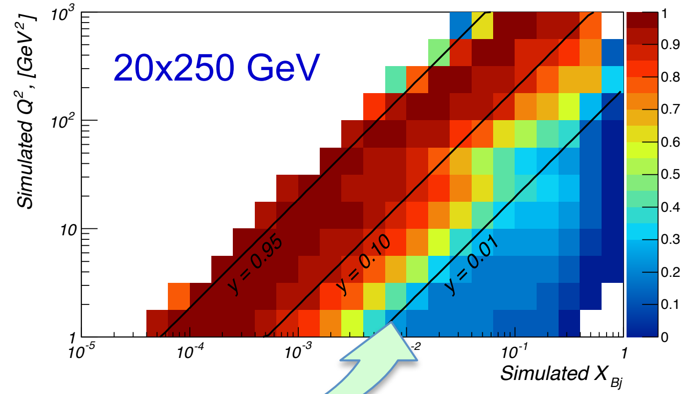
- Electrons typically go to electron endcap, except for large (barrel) and very large (hadron endcap) Q^2
- Photoproduction ($Q^2 < 0.1$ GeV^2) physics require a dedicated low Q^2 tagger



EIC e/m calorimetry: systems & options

- **Inner EmCal at η < -2 (at least)**
  - Scattered electron *energy* measurement at rear angles, where solenoid bending power runs out of stem; resolution ~1.5%/√E + 0.5% required to improve kinematic coverage in ***y***; radiation hardness!

  Technology: PWO crystals

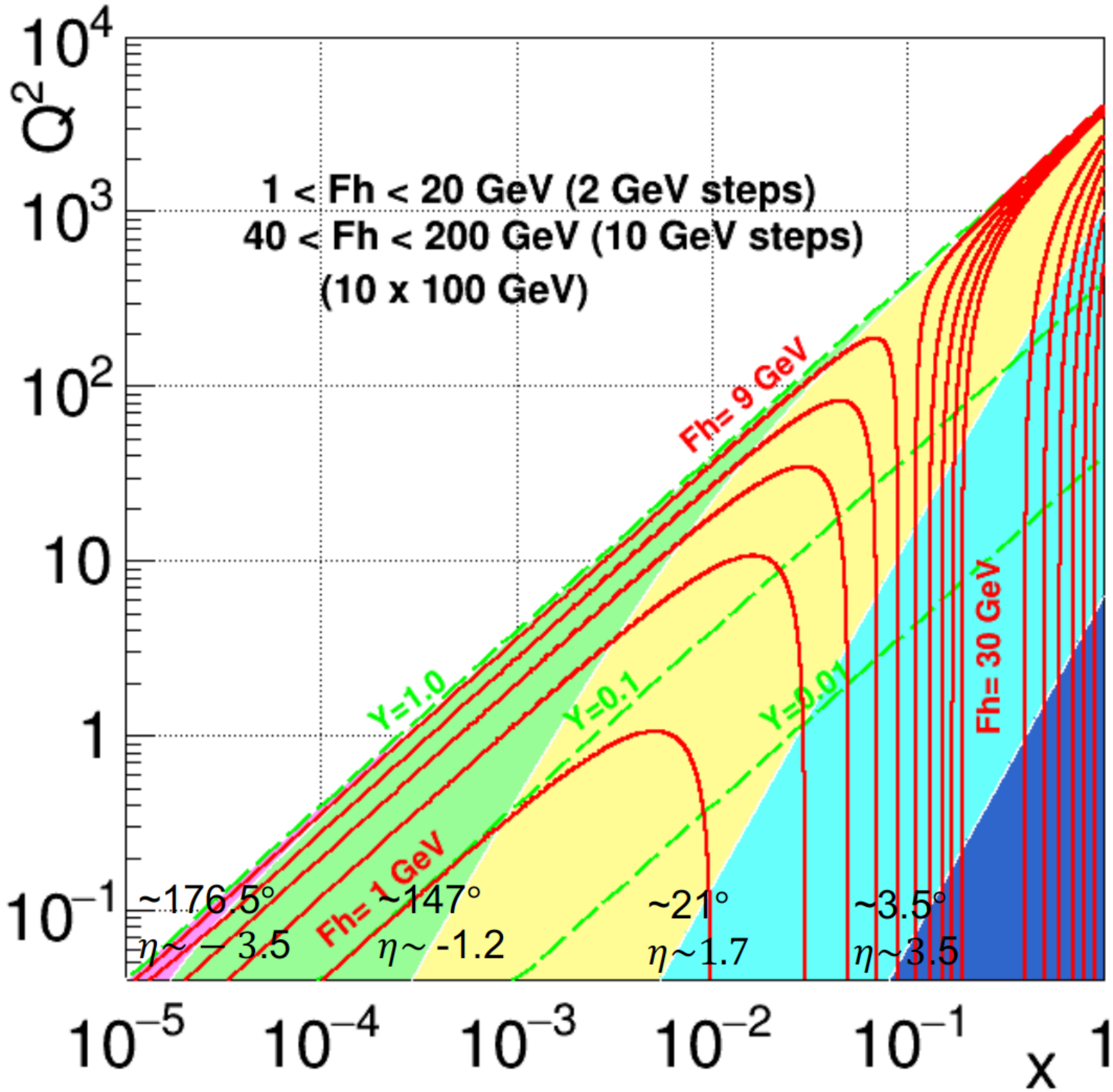


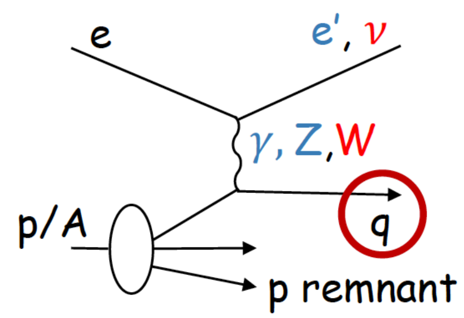
{x,Q^2} bin migration

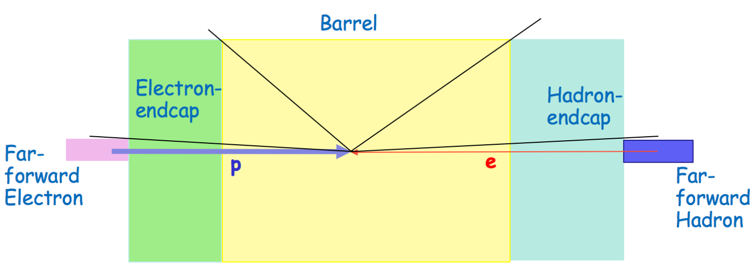
- **Electron-going endcap at -2 < η < -1**
  - As tracker takes over the scattered electron *momentum* measurement, modest *energy* resolution ~7-10%/√E suffices
- **Barrel (-1 < η < 1) and Hadron-going endcap (1 < η < 4)**
  - Energy resolution ~10-12%/√E may suffice; limited radial space!

Technology: sampling W/SciFi spaghetti or W/Cu/SciTile shashlik

Where does the struck quark go?

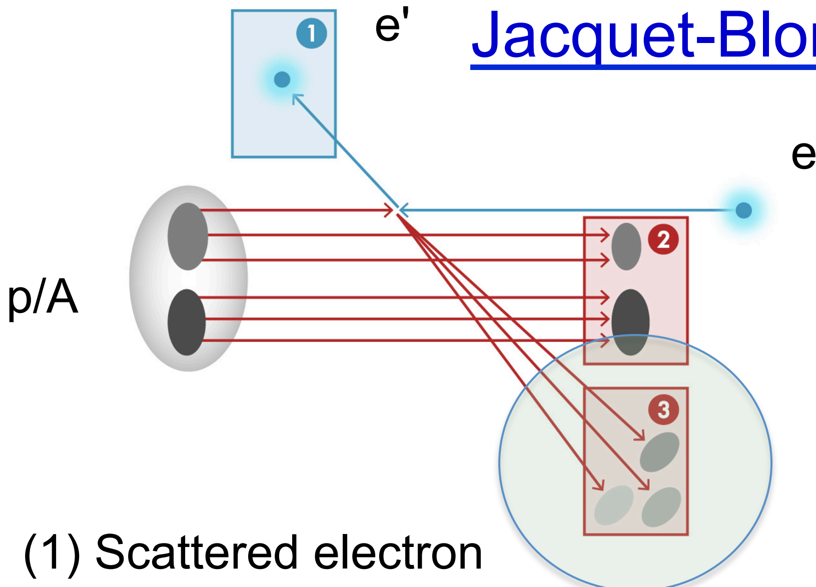






- Quarks (and their proxies: leading hadrons, jets) basically go everywhere: electron endcap, barrel, hadron endcap

DIS kinematics reconstruction: struck quark



Jacquet-Blondel method

-> only hadronic final state information is used

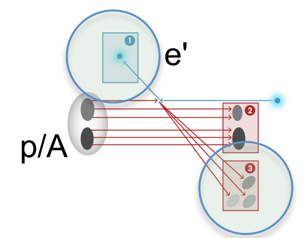
$$y_{JB} = \frac{1}{2E_e}\sum_h (E_h - p_{z,h}),$$

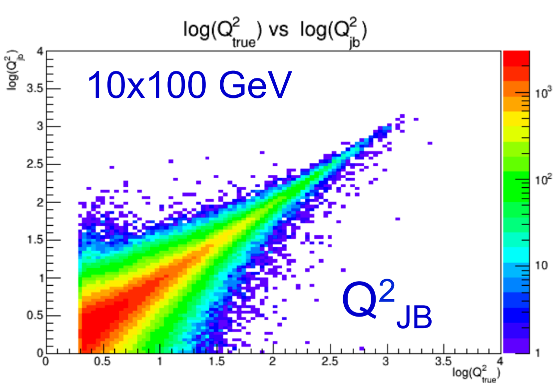
$$Q^2_{JB} = \frac{1}{1-y_{JB}}\left[\left(\sum_h p_{x,h}\right)^2 + \left(\sum_h p_{y,h}\right)^2\right].$$

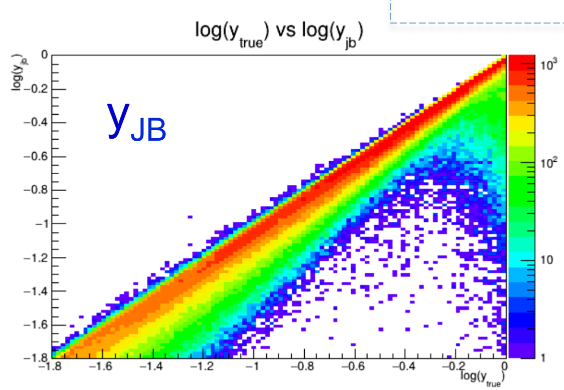
The only way to reconstruct $\{x,Q^2\}$ for charged current events (since neutrino in the final state can not be detected)

(1) Scattered electron
(2) Proton (ion) remnants
(3) Struck quark fragmentation products

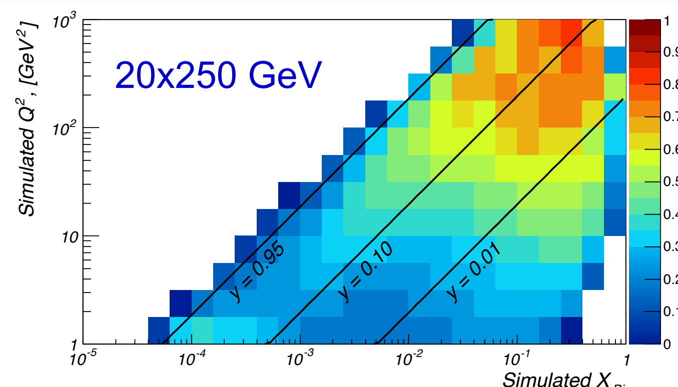
"Mixed" versions exist (**sigma** and **double-angle** methods in particular)







Q^2 & y reconstruction quality (Jacquet-Blondel method)

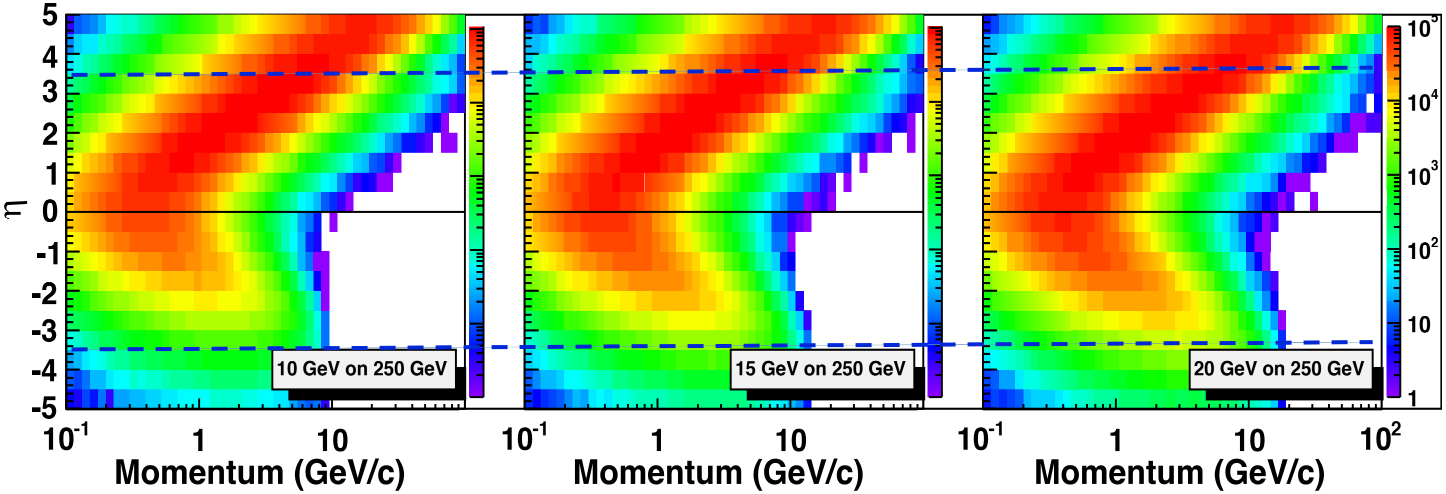


$\{x,Q^2\}$ bin migration (double-angle method)

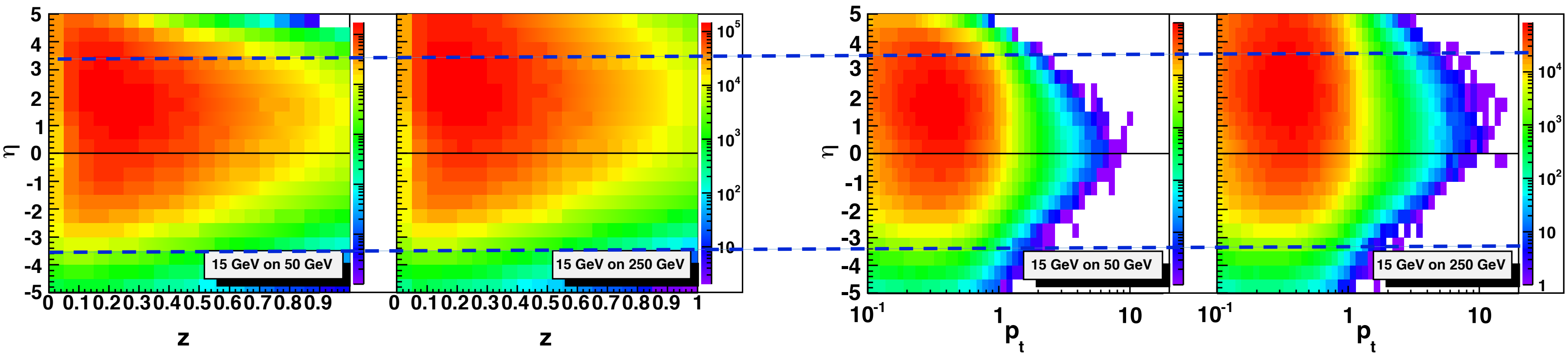
Semi-Inclusive Physics

Kinematics of SIDIS pions

Cuts: $Q^2>1$ GeV^2, $0.01<y<0.95$, $z>0.1$ ($\pi^\pm$, $K^\pm$, $p^\pm$ look similar)



Increasing lepton beam energy boosts hadrons more to negative rapidity



-> $-3.5 < \eta < 3.5$ covers entire kinematic region in hadron **z** (virtual photon energy fraction) and $\mathbf{p_t}$ (transverse momentum), basically for all proton beam energies

Particle ID for an EIC detector

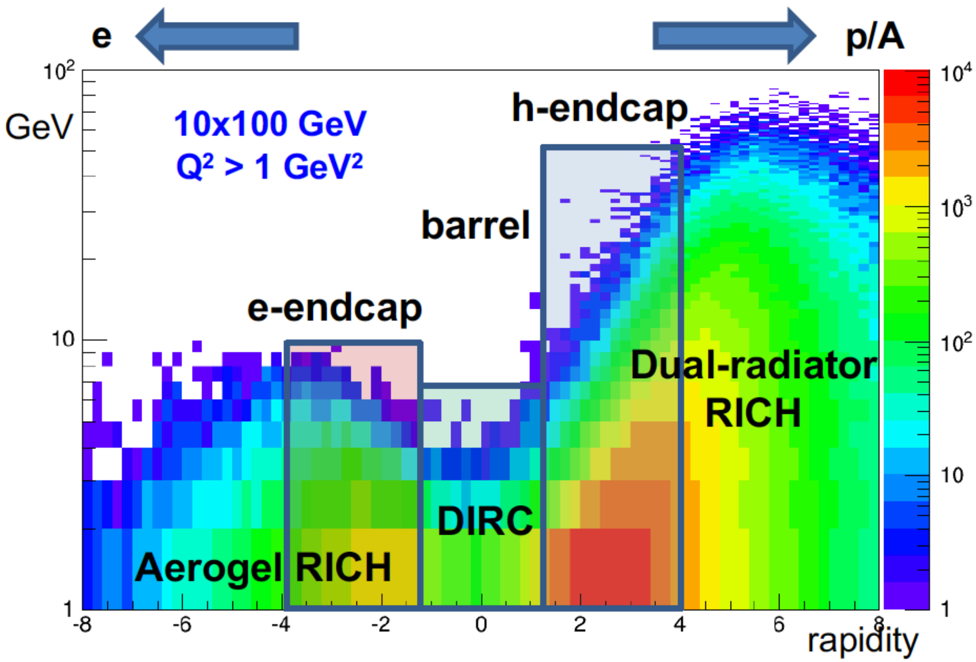
Focus on electron and charged hadron identification

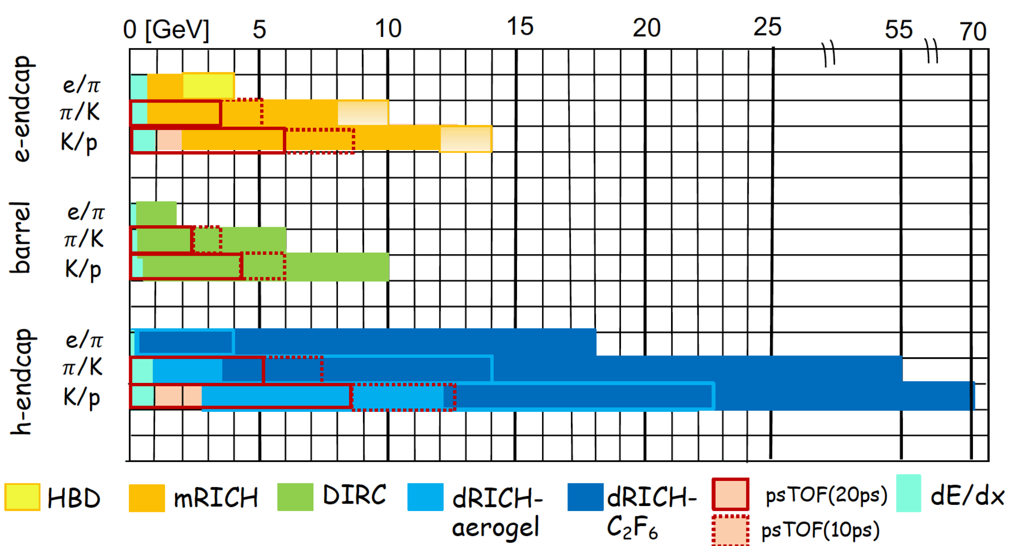
- **In general, need to separate:**
  - Electrons from photons
  - Electrons from charged hadrons
  - Charged pions, kaons and protons from each other

- **Use available physics processes and the detector arrangement(s) to do so:**
  - Cerenkov radiation (e/π/K/p in a certain momentum ranges)
  - Time of flight (π/K/p up to several GeV/c)
  - dE/dx (π/K/p up to ~1 GeV/c)
  - Transition radiation (e/h above ~2 GeV/c)

  - {e/m + hadronic} segmentation of the calorimeter setup (e/h)

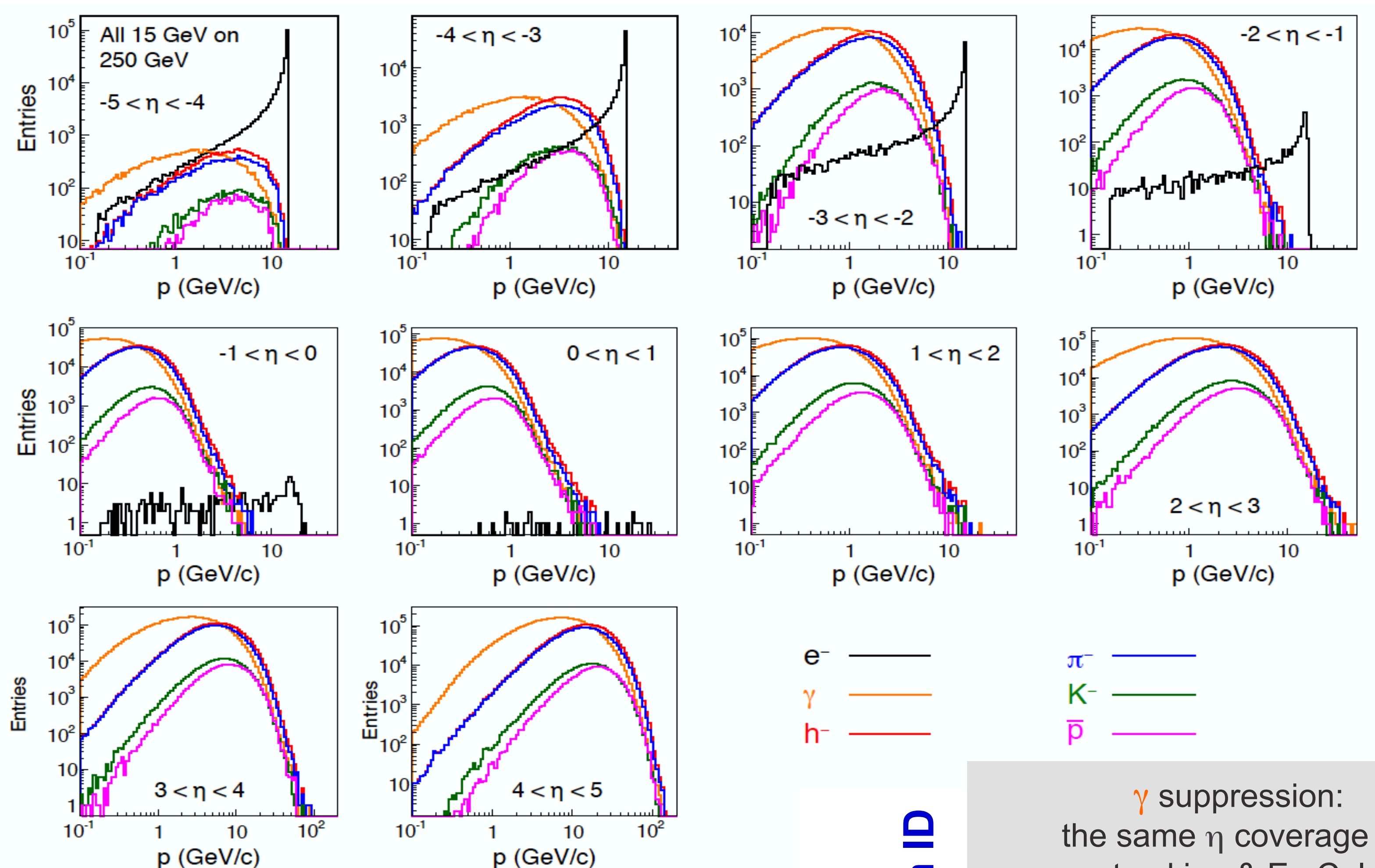
Hadron PID solution for EIC





- **h-endcap:** a RICH with two radiators (gas + aerogel) is needed for π/K separation up to ~50 GeV/c
- **e-endcap:** A compact aerogel RICH with π/K separation up to ~10 GeV/c
- **barrel:** A high-performance DIRC provides a compact and cost-effective way to cover the area with π/K separation up to ~6-7 GeV/c
- TOF and/or dE/dx in a TPC can cover lower momenta

Relative particle yields



- π/K/p distributions at the same η look similar ...
- … and π/K ratio is about 3:1

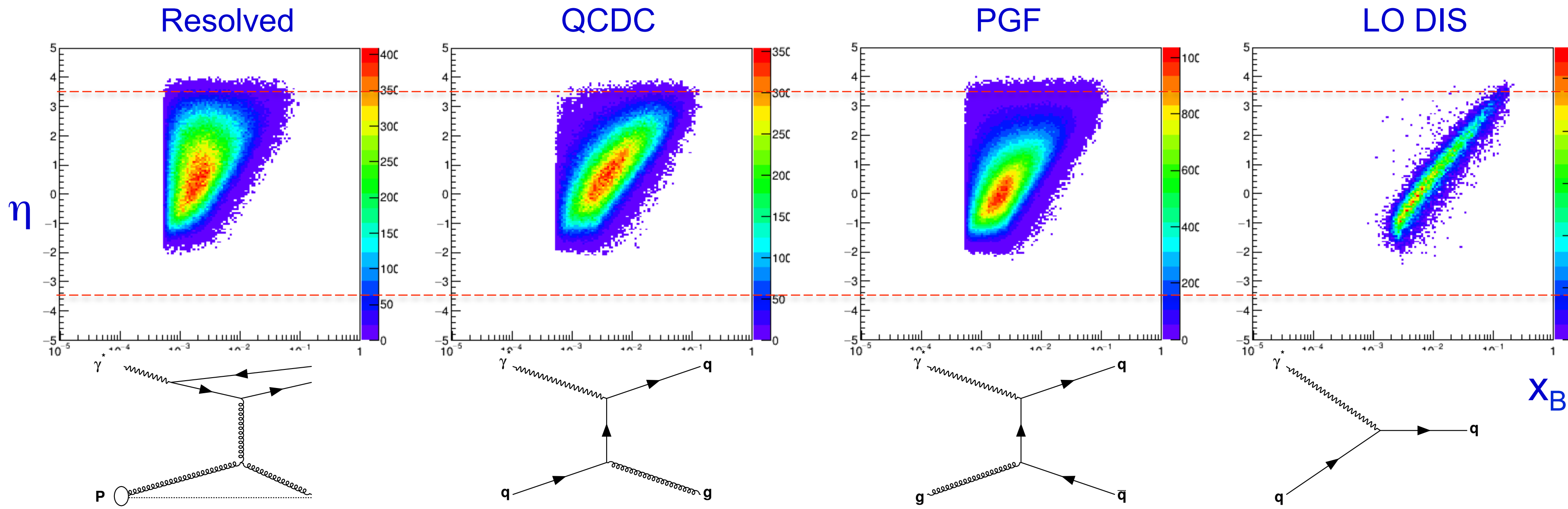
- electrons from decays are *not* shown here

Electron ID

γ suppression:
the same η coverage for
tracking & EmCal

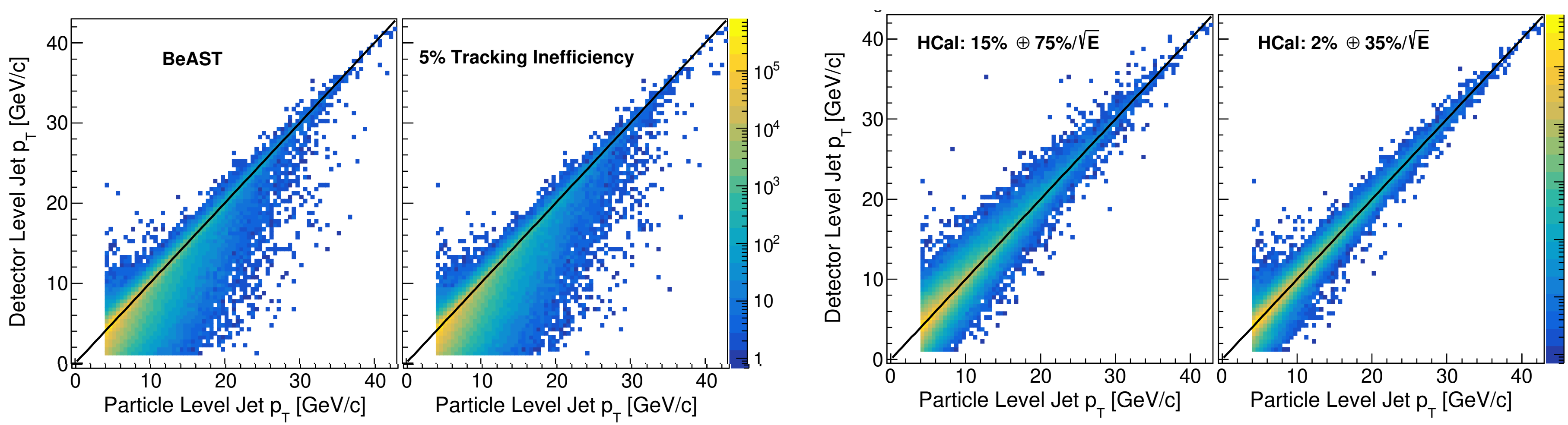
h^- suppression: through E/p and
a combination of other
technologies, η range dependent

Physics with jets at an EIC



Example study: jets at mid-rapidities, ep 20 x 250 GeV, 10 < Q^2 < 100 GeV^2

- eic-smear pass in a PFA-like fashion (check P_t reconstruction quality)



-> So a high resolution HCal does make a difference

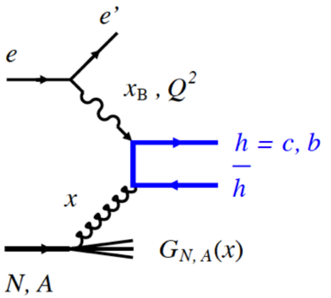
EIC hadronic calorimetry: systems & options

- **Hadron-going endcap ($1 < \eta < 4$)**
  - High-performance system most likely required for forward jet measurements, energy resolution <40%/√E with a small constant term
  - Compactness (little space available, so 5-7 λ deep) is also an issue

- **Electron-going endcap and barrel ($-4 < \eta < 1$)**
  - Case needs to be justified; modest energy resolution may suffice

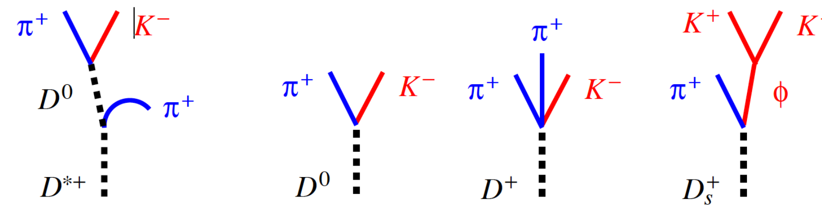
- **Possible implementations**
  - Pb/Sci tile compensated sandwich design
  - High granularity calorimetry?
  - Dual readout (Scintillation/Cerenkov) or dual gate (late neutrons)?

Open charm reconstruction



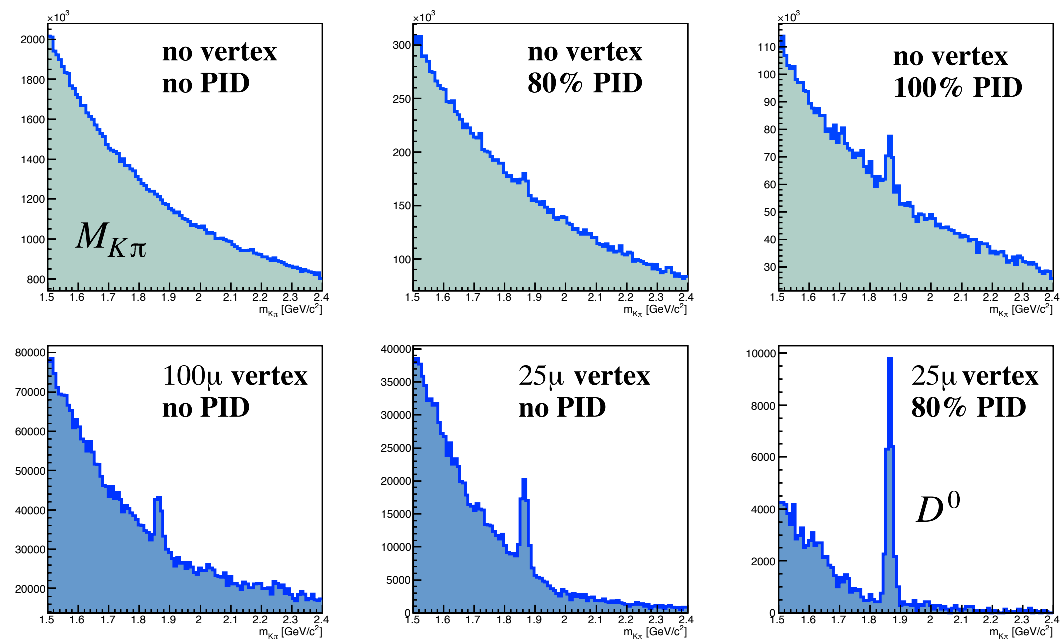
D0	1864,8 MeV	123 μm
D*	2010.2 MeV	-
D+	1869.5 MeV	315 μm
Ds+	1967 MeV	147 μm
Λc	2286.5 MeV	60μm
Ξc		132 μm

Signature: displaced secondary vertex



- Vertex tracker: closest to the IP detector to provide vertex resolution better than ~20 μm
- Low material budget detector (to reduce multiple scattering)
- Beam-induced background could cause radiation damage (proper shielding / masking of synchrotron radiation required)
- Provides stand-alone measurements of low-Pt particles (potentially with dE/dx measurements for PID ?)
- Prefer relatively small solenoid field

Example study: exclusive decay $D^0 \to K^- \pi^+$
ep 10 GeV x100 GeV, selection: $Q^2 > 10$ GeV^2, $x_B > 0.05$

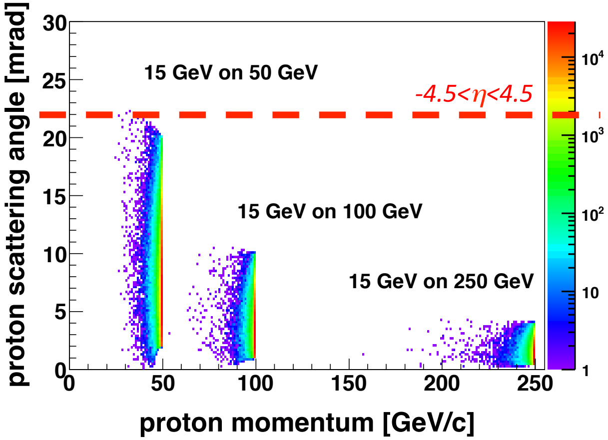


Exclusive Reactions

Exclusive reactions in ep/eA

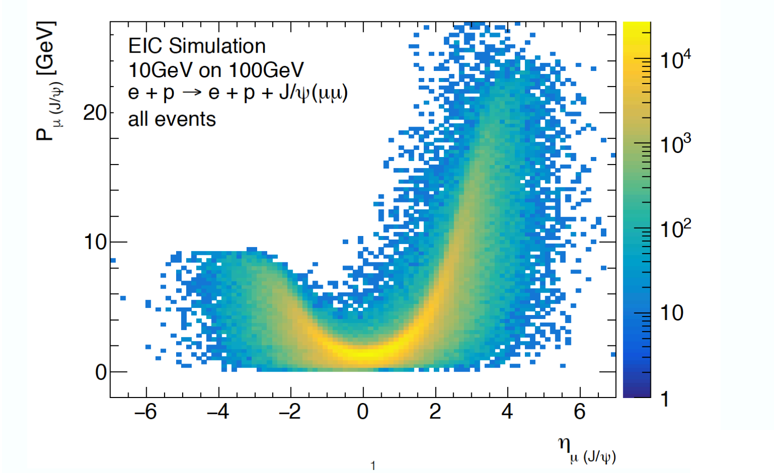
- Diffraction: establish rapidity gap
  - Hermetic acceptance
  - HCal for $1<\eta<4.5$
- Exclusivity: measure all final state particles
  - wide coverage in t ($=p_t^2$) → Roman pots for recoil protons
- eA: veto nucleus break-up by ZDC
- Sufficient acceptance for other reaction products (DVCS photons, e^+e^- pairs from J/ψ decay, etc)

scattered protons



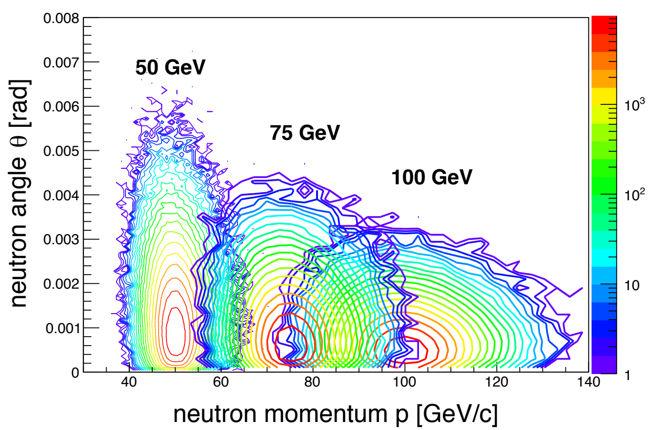
- Defines acceptance of the far forward magnetic spectrometers

muons from J/ψ decay



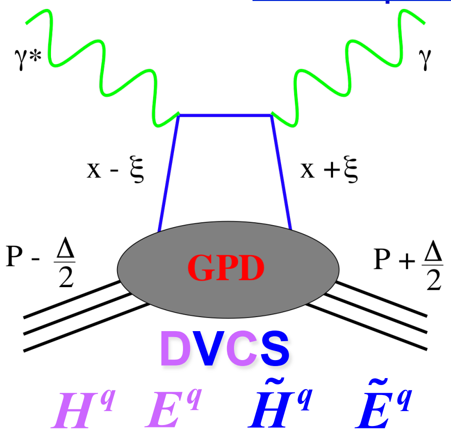
- Mostly seen in the main detector

break-up neutrons

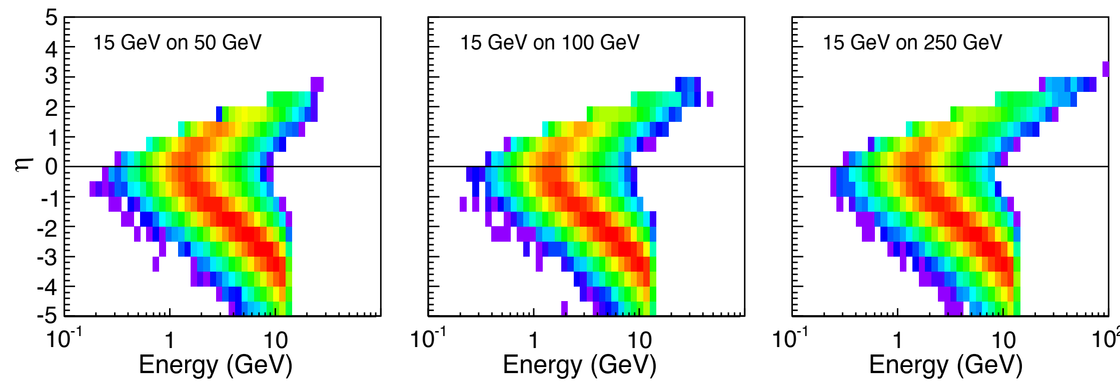


- Up to ~4-6 mrad cone opening to ZDC required

DVCS

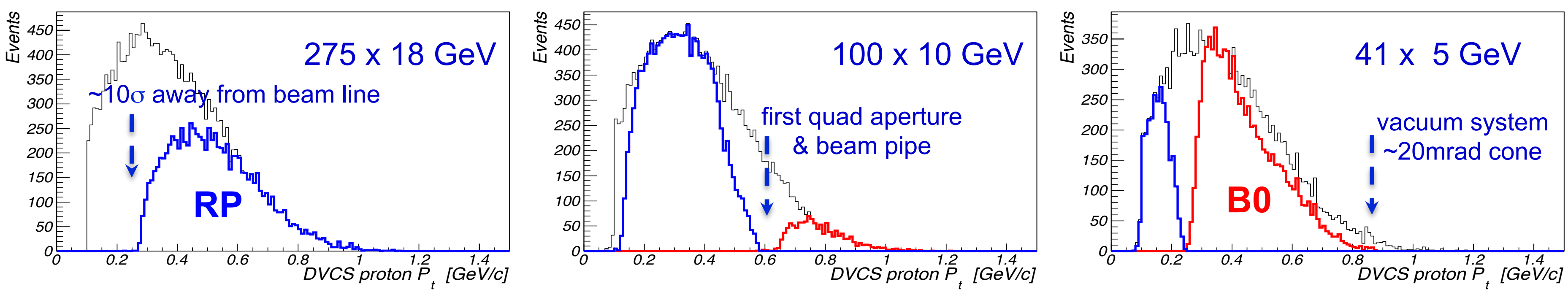


DVCS photon {η,E} for 15 GeV electrons and various proton beam energies



- Need e/m calorimetry coverage in $-4 < \eta < 2$ range

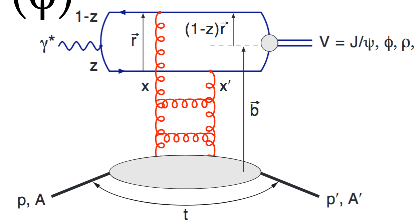
Example study: DVCS proton P_t acceptance (by far forward spectrometers)

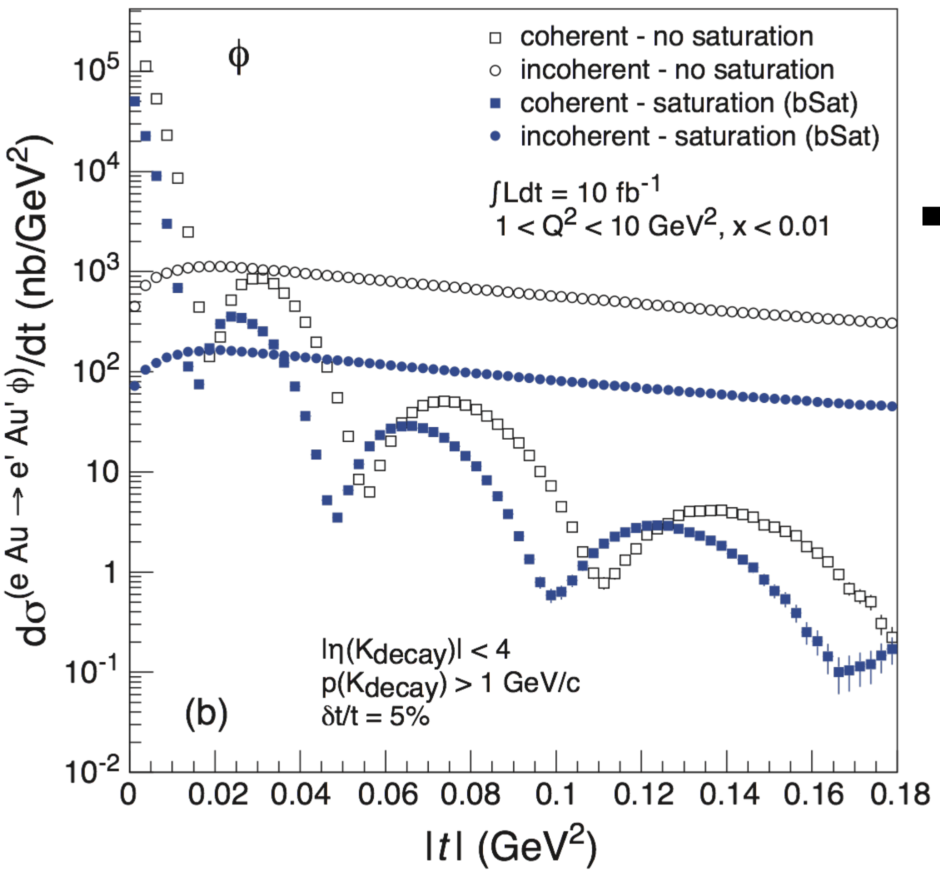


- Realized as a combination of large acceptance dipole (B0) and traditional Roman Pots (RP)

Gluon imaging

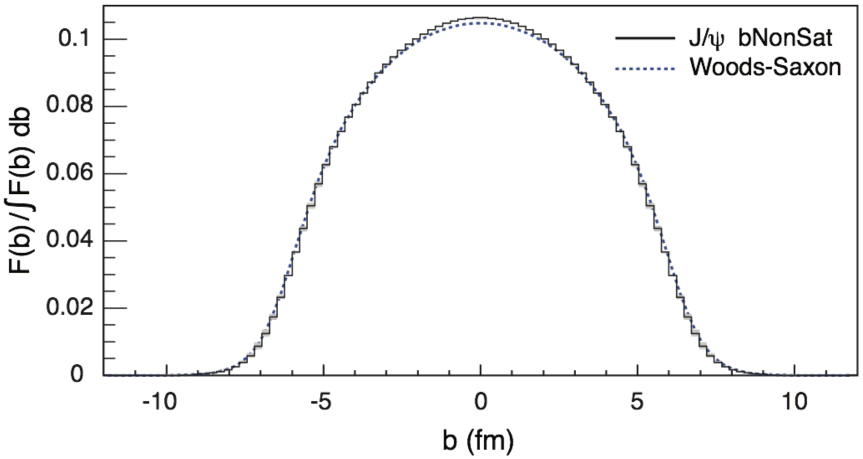
Diffractive vector meson production: e + Au → e′ + Au′ + J/ψ (ϕ)





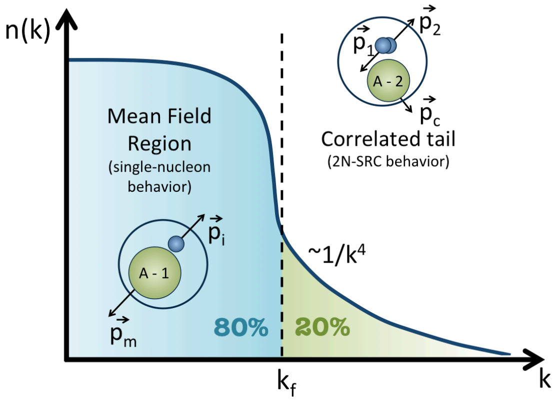
$$F(b) \sim \frac{1}{2\pi}\int_0^\infty d\Delta\, \Delta\, J_0(\Delta b)\sqrt{\frac{d\sigma}{dt}}$$

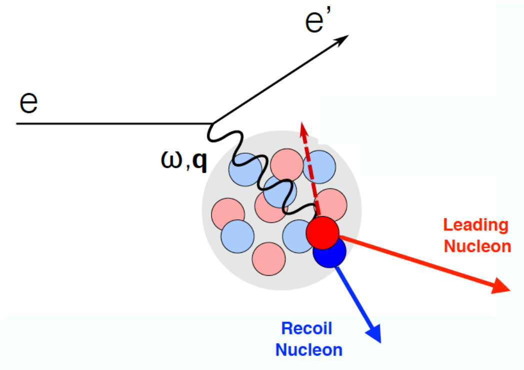
$t = \Delta^2/(1-x) \approx \Delta^2$

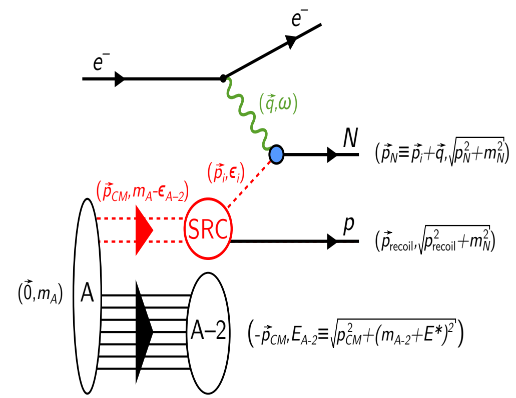


- veto nucleus break-up by ZDC
- detect scattered electron in the main spectrometer
- detect e^+e^- ($\mu^+\mu^-$) pairs from J/ψ decay, or K^+K^- from ϕ decay elsewhere

Short range correlations

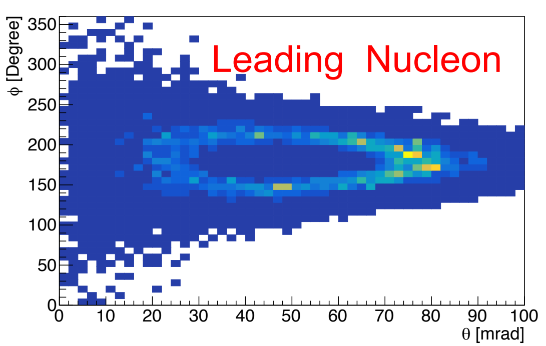


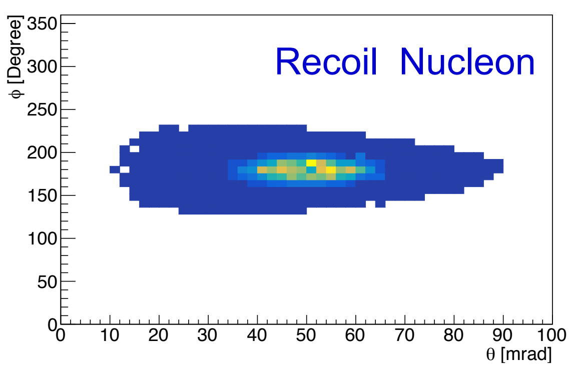


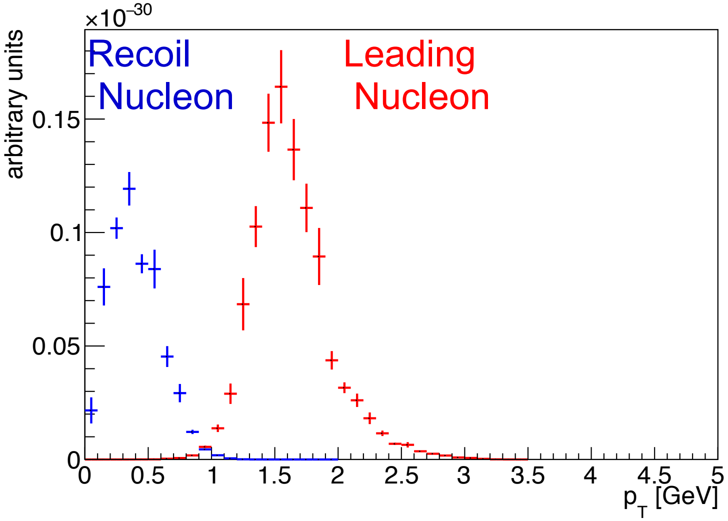


- Need to have enough of the forward acceptance to detect leading and recoil nucleons

Example study: BEAGLE, e+C, 5x50 GeV

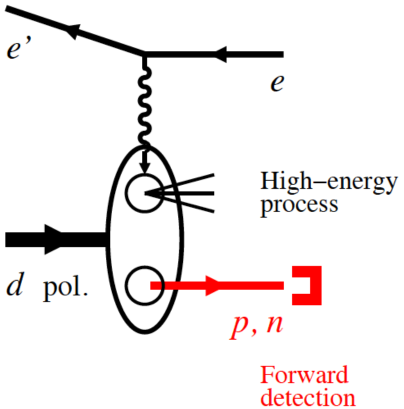


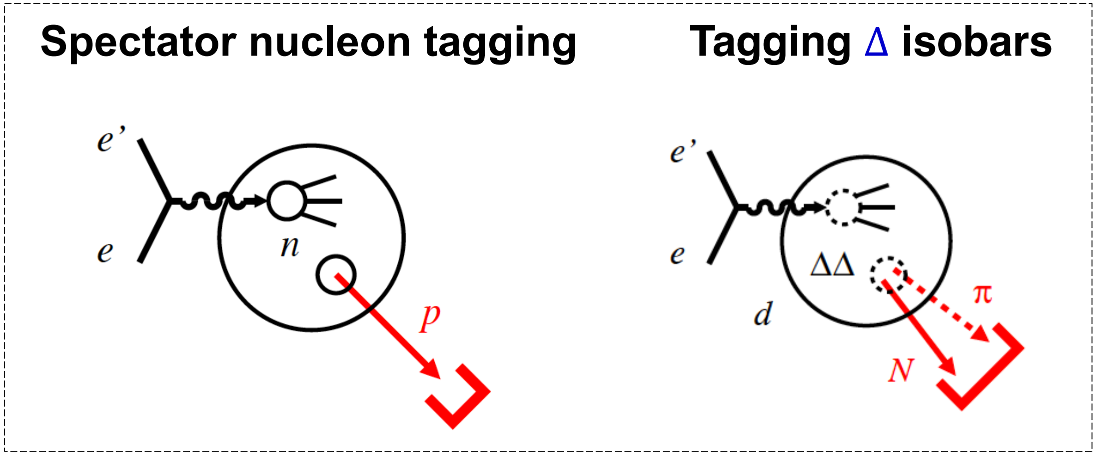


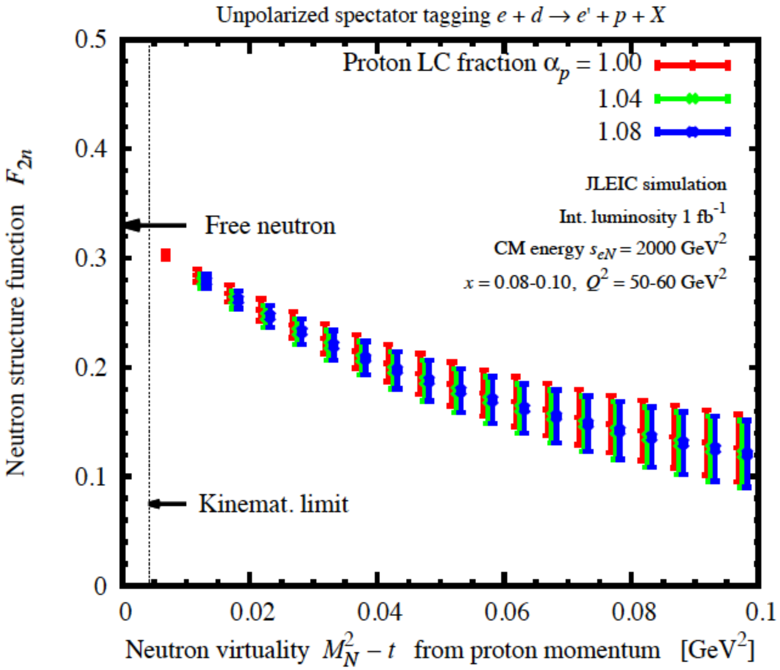


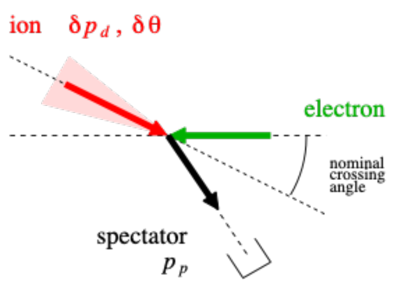
Tagged DIS

Tagged-DIS on Deuteron









- Neutron structure
- Origin of EMC effect
- Shadowing and coherent phenomena

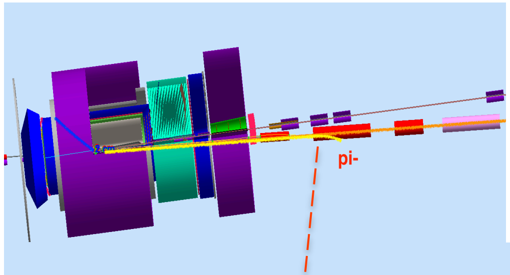
Challenges for forward detection:

(a) spectator rigidity different from beam

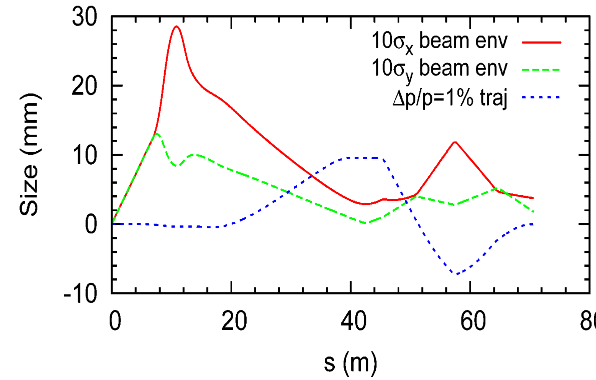
(b) need momentum resolution ~ few 10 MeV

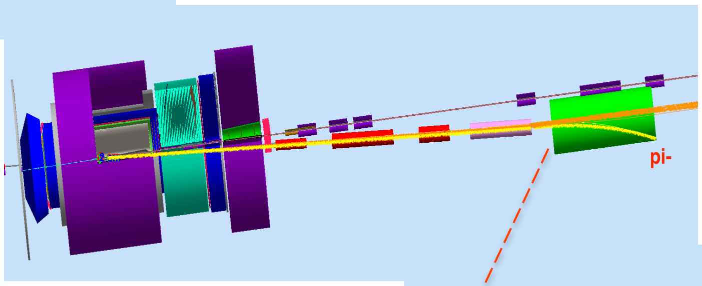
(c) ion beam momentum spread

Pion/Kaon structure functions

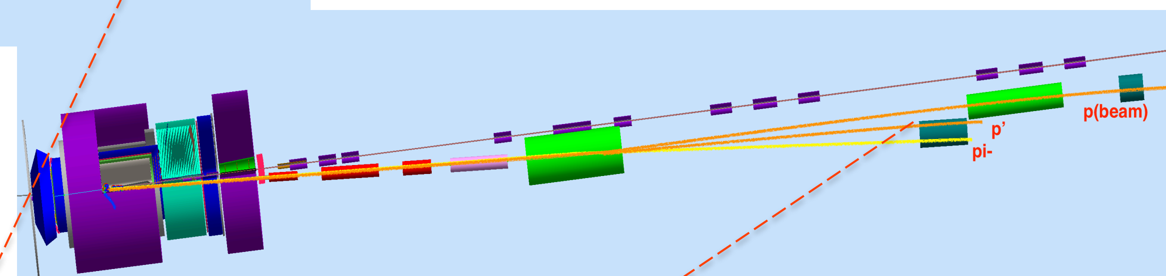


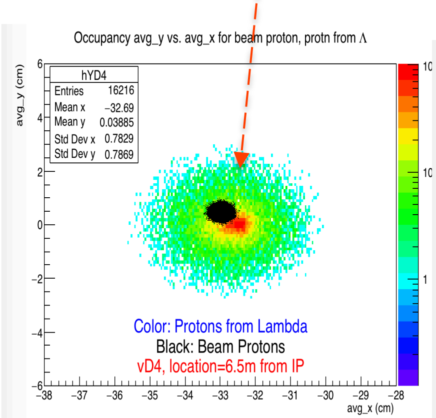
Example study: pions & protons from Λ decay

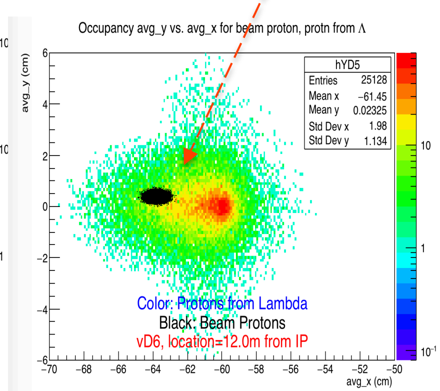


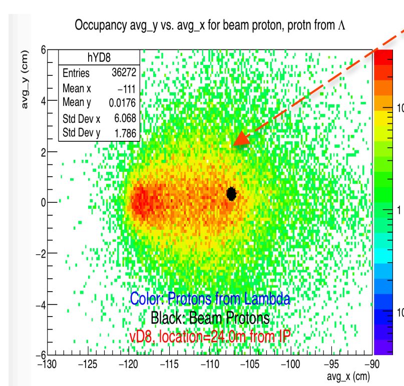


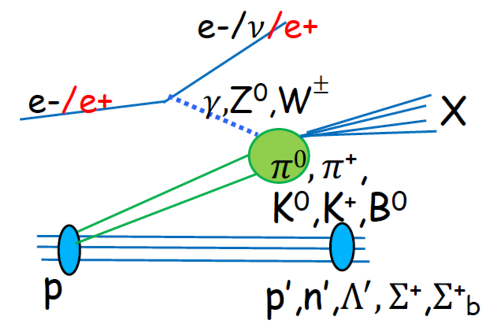
- Main beam is focused
- High dispersion for off-momentum particles





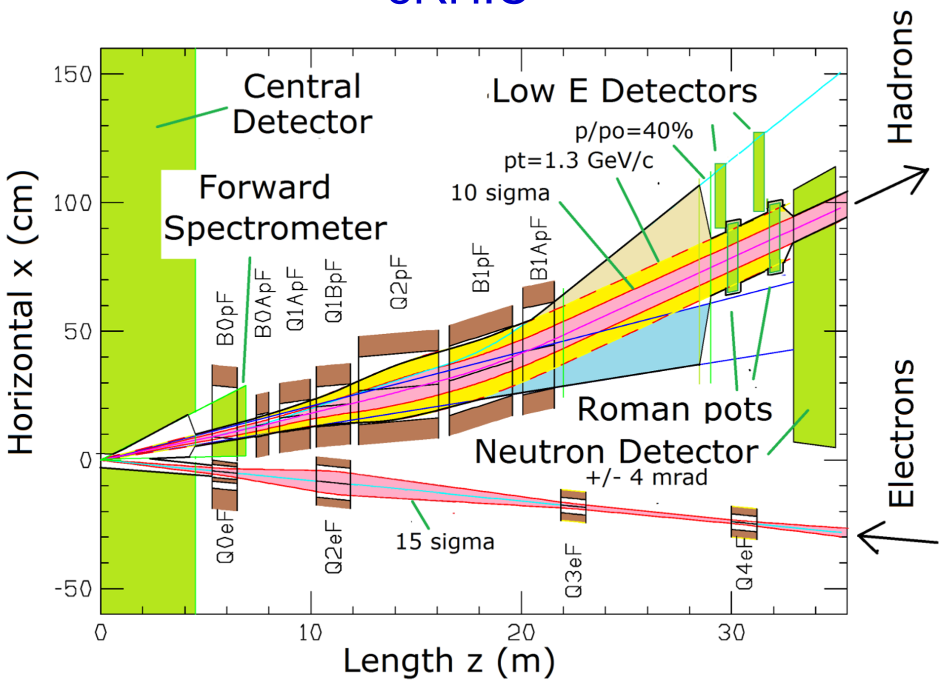




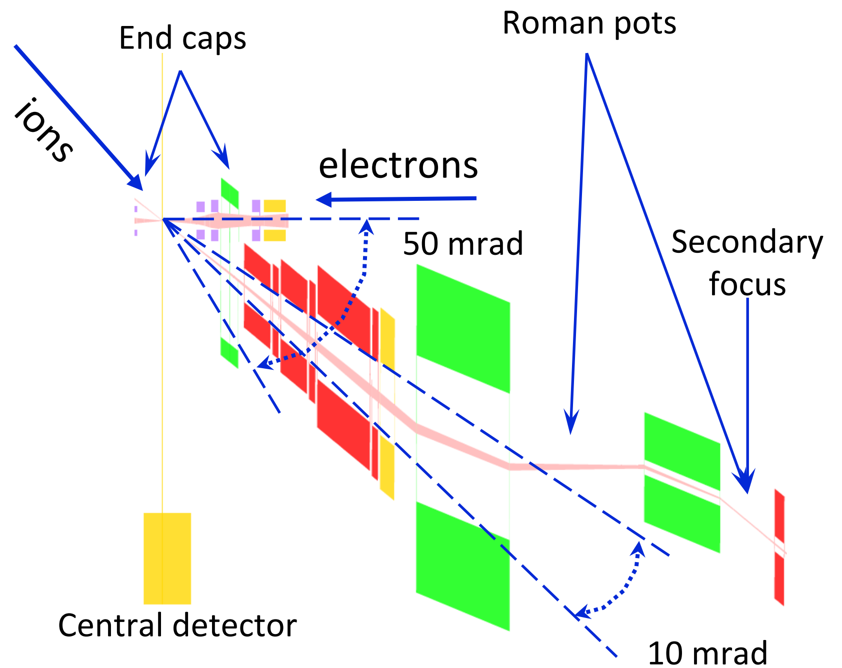


IR far forward design

eRHIC



JLEIC



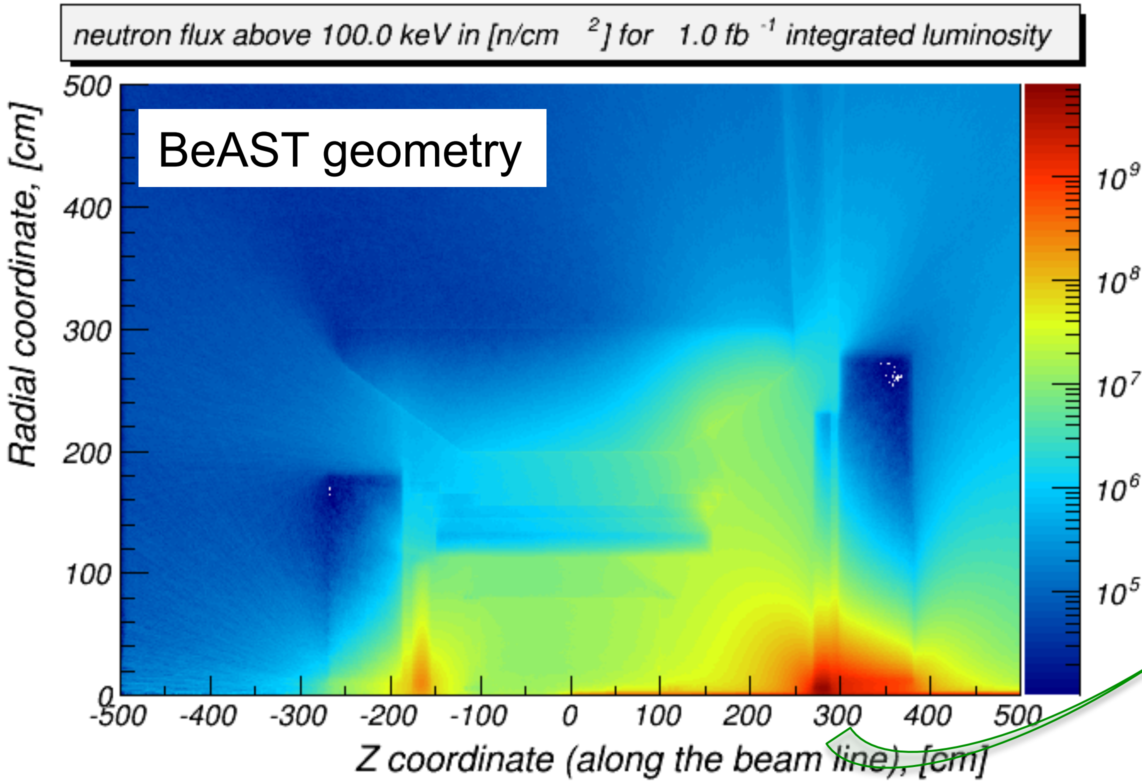
- 25 mrad crossing angle
- Spectrometer dipole (B0) : ~20mrad acceptance
- 2nd dipole (B1) to separate hadrons from neutrons: ±4mrad neutron cone to ZDC

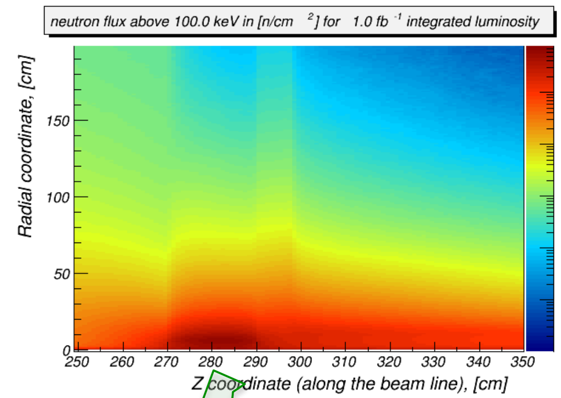
- 50 mrad crossing angle
- Spectrometer dipole (D1) : ~45mrad acceptance
- 2nd dipole (D2) to separate hadrons from neutrons: ±10mrad neutron cone to ZDC

Backgrounds

Neutron fluence from primary interactions

<u>The quantity</u>: Fluence = "a sum of neutron path lengths"/"cell volume" for N events





-> forward EmCal: up to ~5*10^9 n/cm^2 per fb^{-1} (*inside the towers*); perhaps ~5 less at the SiPM location;

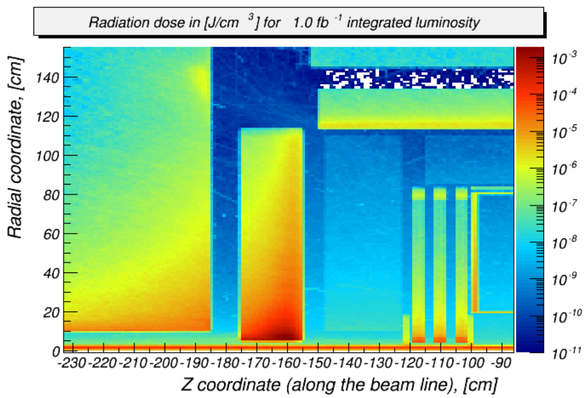
NB: "standard" EIC run at ~10^{33} cm^{-2}s^{-1} luminosity is 10 fb^{-1}

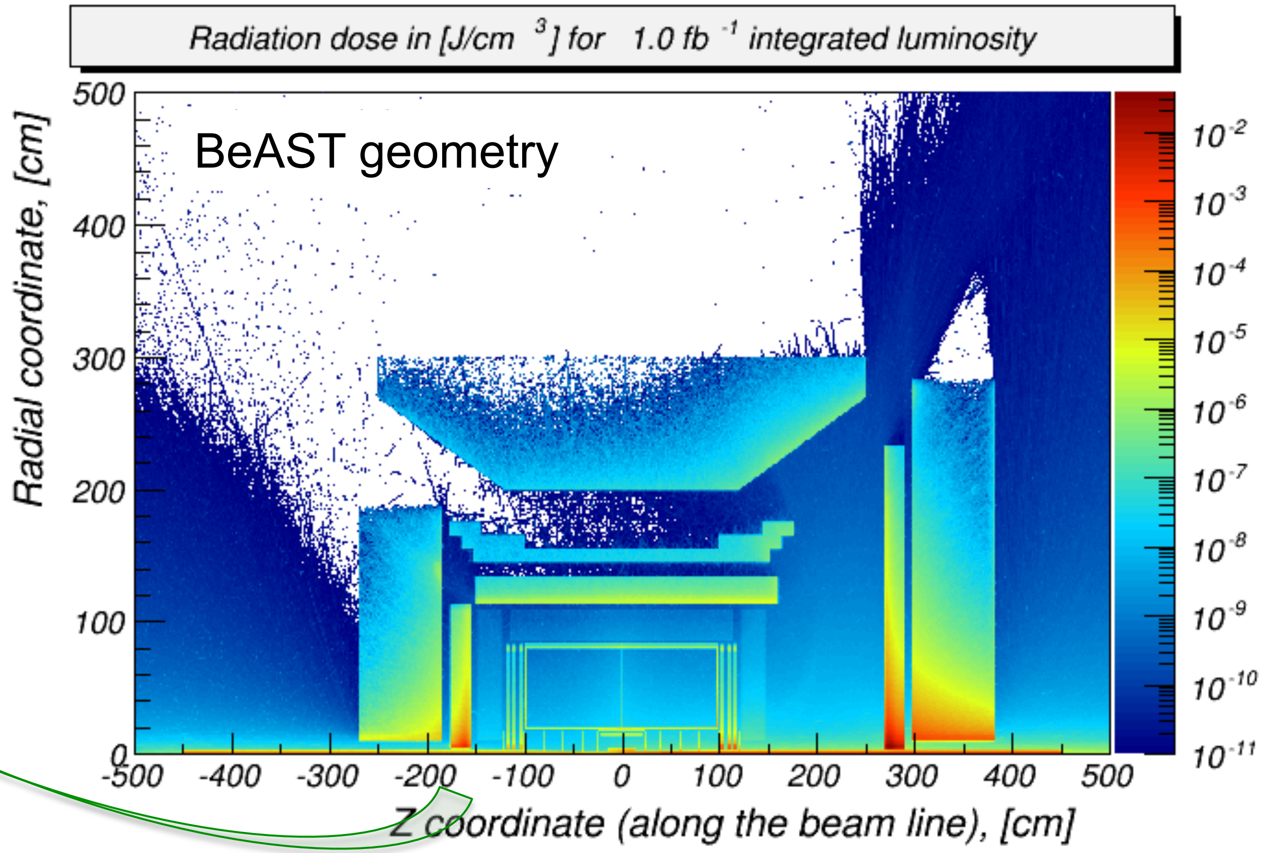
<u>The numbers look OK, but:</u>

- Beam line elements not incorporated in the simulation
- Thermal neutrons are not accounted
- Close to beam line: ~10^{34} cm^{-2}s^{-1} over ~10 years would exceed ~10^{11} n/cm^2

Radiation dose from primary interactions

<u>The (primary) quantity</u>: E_{sum} = "a sum of dE/dx"/"cell volume" for N events





-> crystal EmCal: up to $\sim 2*10^{-3}$ J/cm^3 per fb^{-1} (close to beam line)

1 rad = 0.01 Gy & [Gy] = [J/kg] & PWO density ~8g/cm^3 -> ~250 rad/year

(at "nominal" luminosity $\sim 10^{33}$ cm^{-2} s^{-1})

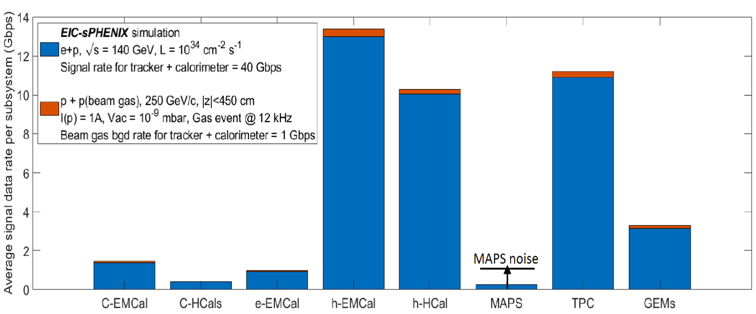
-> looks OK?

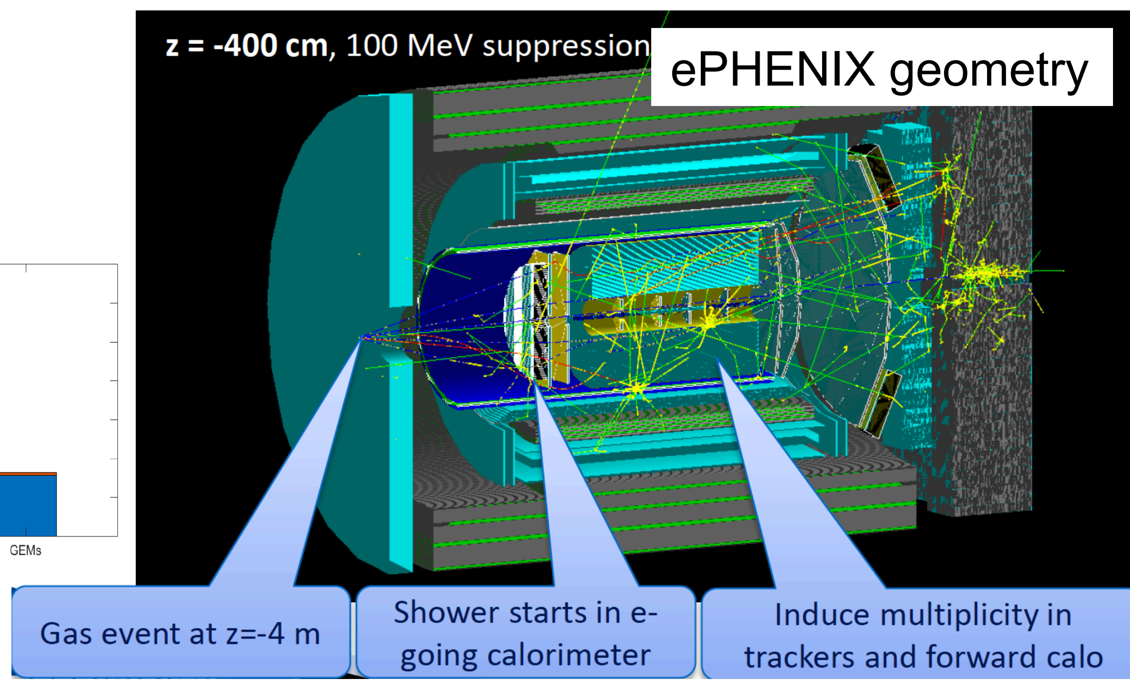
Beam-gas interaction

- Produced by hadron beam particles scattered off residual gas (mostly H_2) in the vacuum system
- Dynamic vacuum problem: synchrotron radiation heats the IR vacuum chamber walls, this causes outgassing, and subsequent hadronic scattering in a “fixed target” fashion, which floods the detector with secondary particles -> very hard to model!

Vacuum pressure	10^{-9} mbar
Beampipe temperature	Room temperature
Average atomic weight of gas	Hydrogen (H^2)
Molecular density (for 10 m pipe)	2.65×10^{10} molecules/cm^2
Luminosity (Ring-Ring)	10.05×10^{33} cm^{-2}s^{-1}
Bunch intensity (R-R) (e/p)	15.1 / 6.0×10^{10}
Beam Current (R-R) (e/p)	2.5 / 1 A
Bunch spacing (Ring-Ring)	8.7 ns → 1320 bunches
ElectronxProton beam energy	10 GeV x 275 GeV

Beam-gas events effect on the streaming readout @ EIC



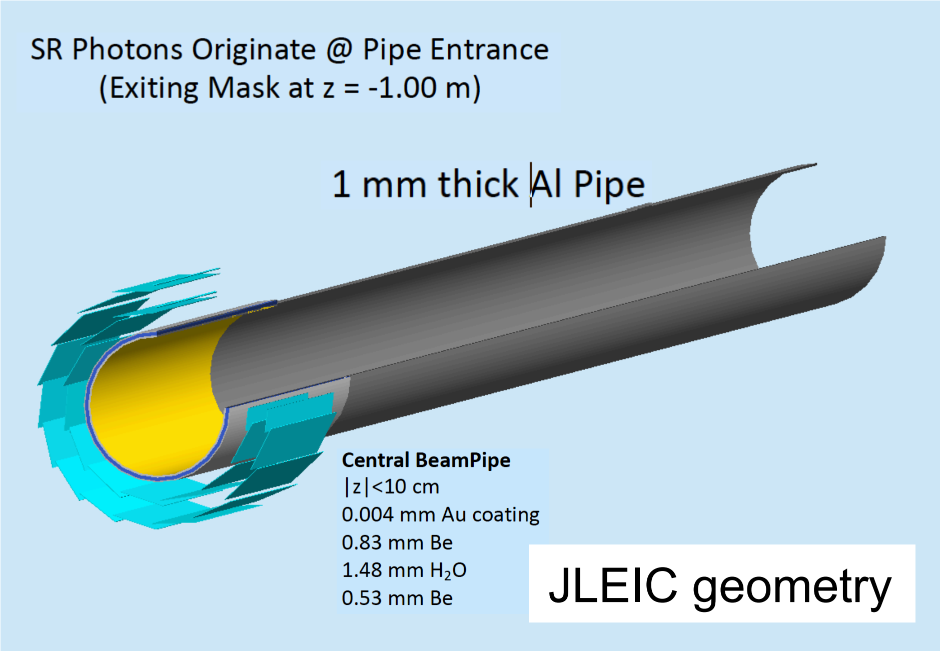


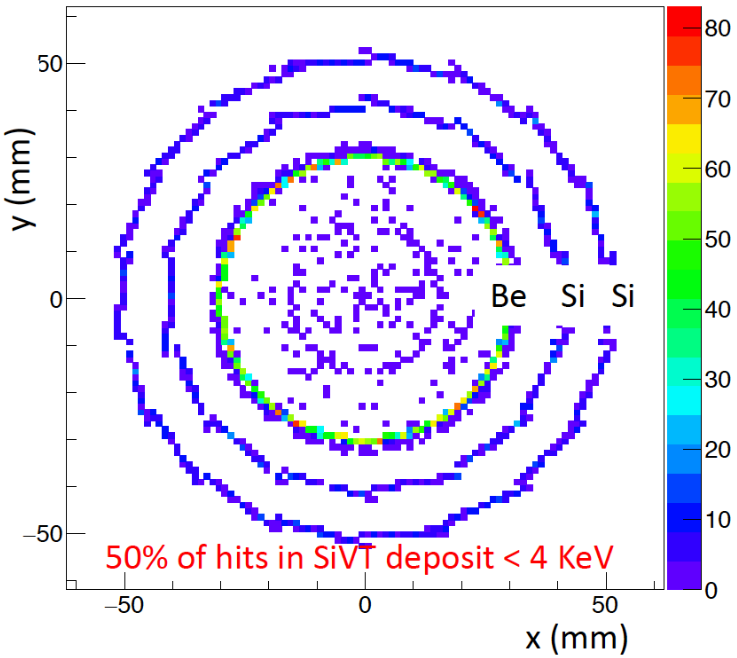
Synchrotron radiation

- Crossing angle (no strong electron bending at the IP) does not solve the synchrotron radiation problem completely ...
- ... because of the bending in Final Focusing Quads (FFQs)

- Need either to increase the beam pipe diameter at the IP or install masks or both

Synchrotron fan induced in FFQs hitting JLEIC SVT tracker after passing 24mm diameter mask at Z=-1m





-> tedious optimization work is ongoing for both JLAB and BNL EIC designs

Summary

- Various preliminary EIC detector concepts developed
- To first order both physics- and accelerator-driven requirements are defined and taken into account

- Design optimization work is ongoing
- Close collaboration between theorists, experimentalists and accelerator physicists is required ...
- ... and contributions from the US and international institutions are more than welcome!