Particle identification at an EIC

- Why is it so important?

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Stony Brook University

EIC PID workshop, CFNS,
Stony Brook University,
July 9-10, 2019.

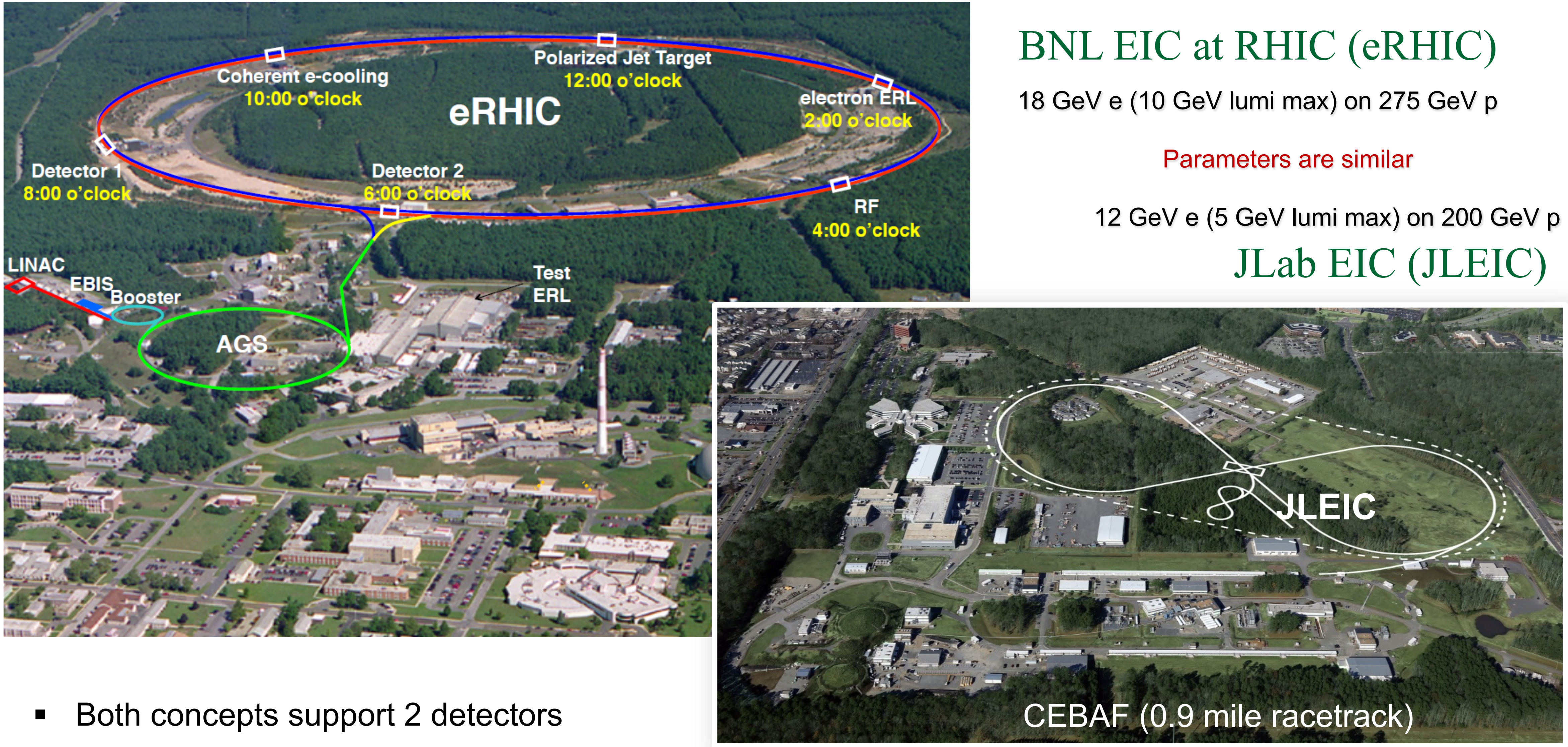
The EIC in the 2015 NSAC LRP and the recent NAS review

arXiv:1212.1701
(2012)

NSAC: **“We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.”**

NAS: **“The committee unanimously finds that the science that can be addressed by an EIC is compelling, fundamental, and timely.”**

Proposed EIC implementations at JLab and BNL



CEBAF (0.9 mile racetrack)

BNL EIC at RHIC (eRHIC)

18 GeV e (10 GeV lumi max) on 275 GeV p

Parameters are similar

12 GeV e (5 GeV lumi max) on 200 GeV p

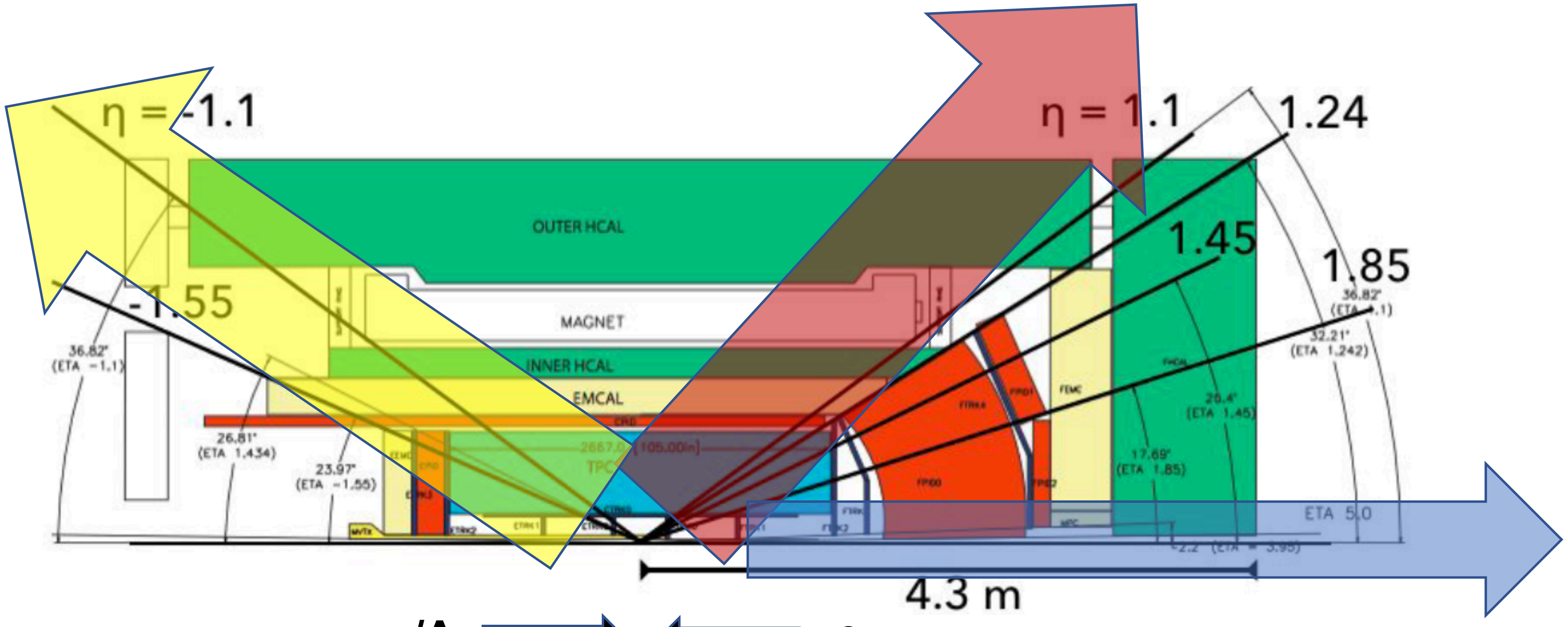
JLab EIC (JLEIC)

- Both concepts support 2 detectors

What do we measure?

Current jet (or hadron)

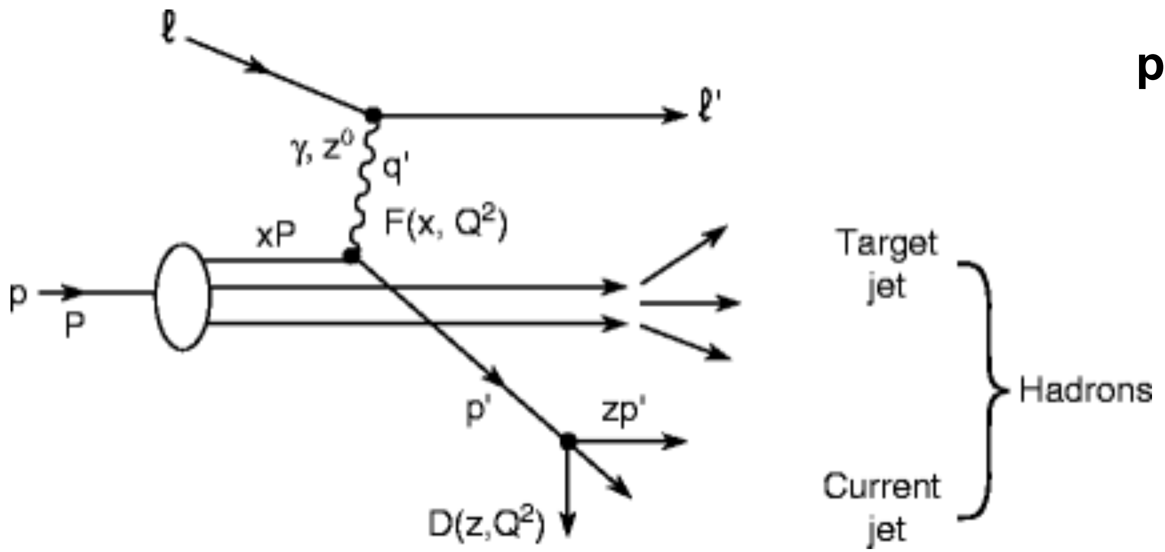
Scattered electron



p/A → ← **e**

Target fragments

Lepton scattering on a proton

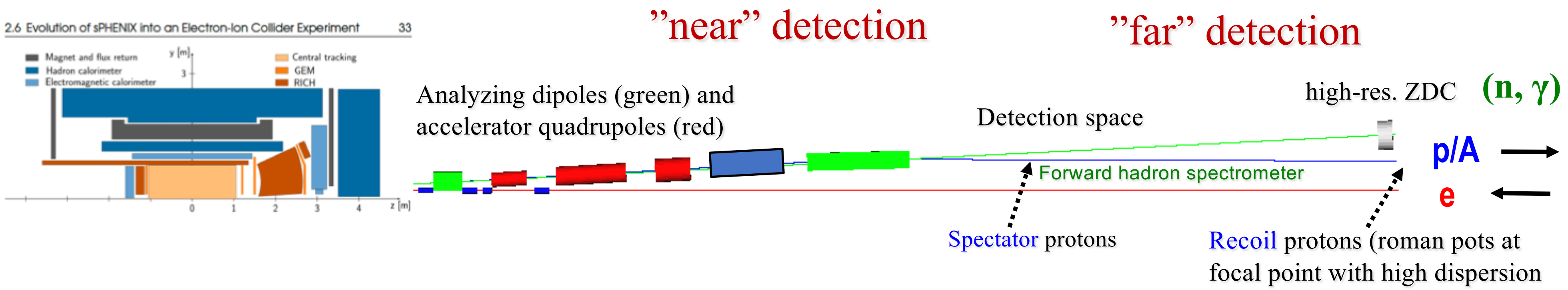


Inclusive DIS: only electron is detected

Semi-Inclusive DIS (SIDIS): electron and current jet (hadron) are detected.

Exclusive reactions: all particles are detected

Detection of target fragments



"near" detection

"far" detection

Analyzing dipoles (green) and
accelerator quadrupoles (red)

Detection space

high-res. ZDC

(n, γ)

p/A →

e ←

Forward hadron spectrometer

Spectator protons

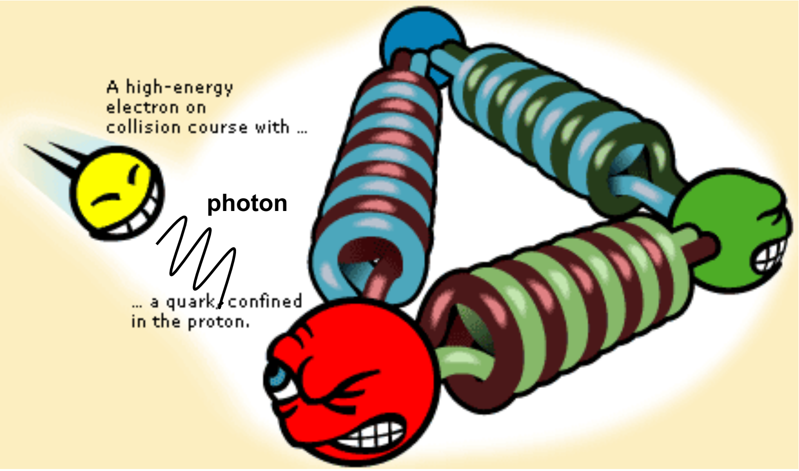
Recoil protons (roman pots at
focal point with high dispersion

- A large part of the EIC program relies on detecting recoil baryons and target fragments
  - Spatial imaging through *exclusive* meson/photon production on the proton, and in coherent diffraction on nuclei
  - Neutron structure through spectator tagging in light nuclei
  - Various incoherent processes on heavy nuclei, including SRC and EMC studies

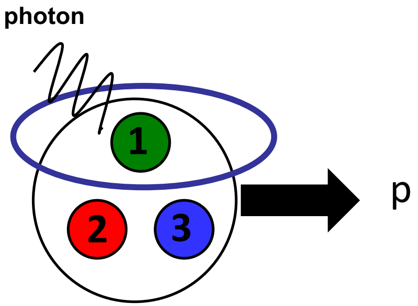
- Forward detection requirements for the EIC are very demanding
  - Need to detect particles very near the beam (down to $p_T = 0$ for $dp/p > 1\%$)
  - Need to detect protons with p_T up to at least 1 GeV/c and spectators with A/Z very different from that of the beam (*e.g.*, spectator protons from deuterium)
  - Need excellent momentum resolution, detection of neutrals, and **PID for ions**

Electron scattering: *x*, *t*, and Q^2

- **Q^2** is the (four-)momentum transfer *from* the electron, and is a measure of the resolving power of the probe.
- ***t*** is the (four-)momentum transfer *to* the nucleon.
- In *elastic* scattering, *t* and Q^2 are equivalent.



- ***x*** is the fraction of the nucleon momentum carried by the struck quark in a frame where the nucleon is moving quickly. With 3 quarks, one would naively expect *x* = *1/3*.
- Reaching smaller values of *x* requires higher energy!

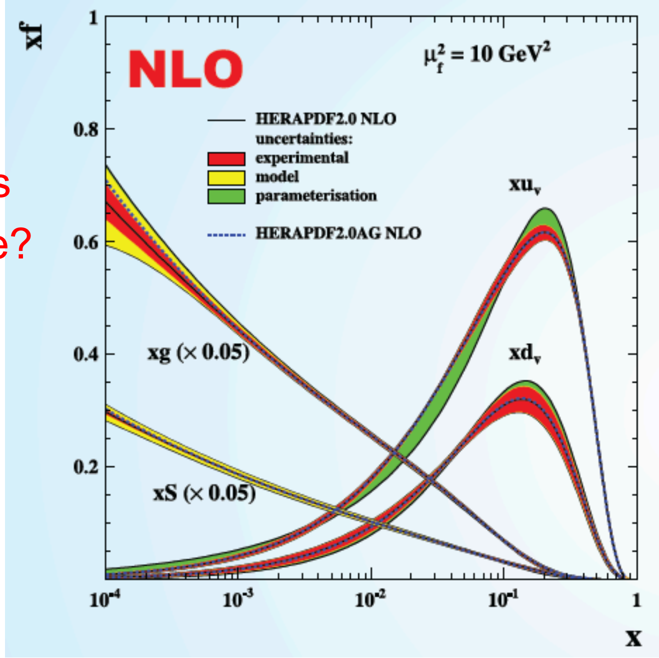


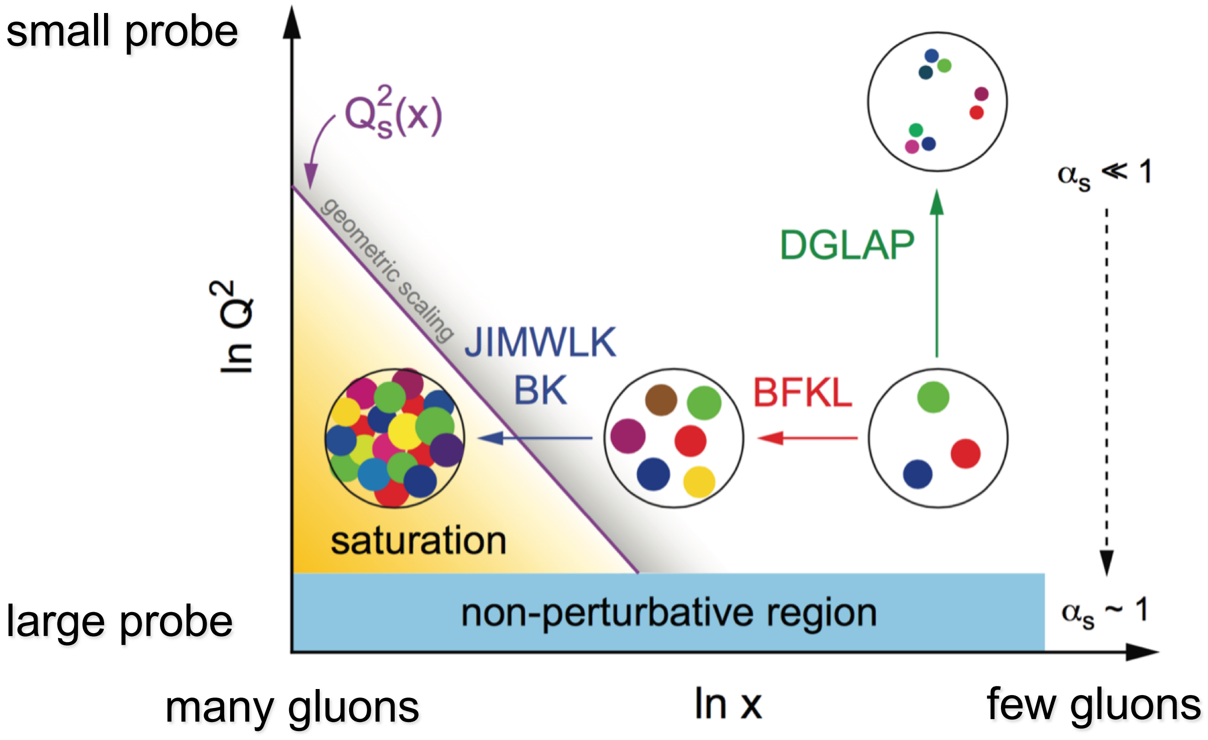
$x = p_1 / p_{proton}$

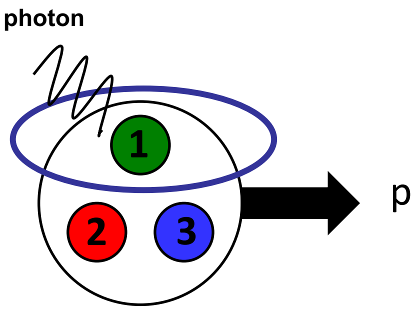
$x = Q^2 / sy$

Inclusive DIS: Momentum distributions of quarks and gluons

Gluons
saturate?





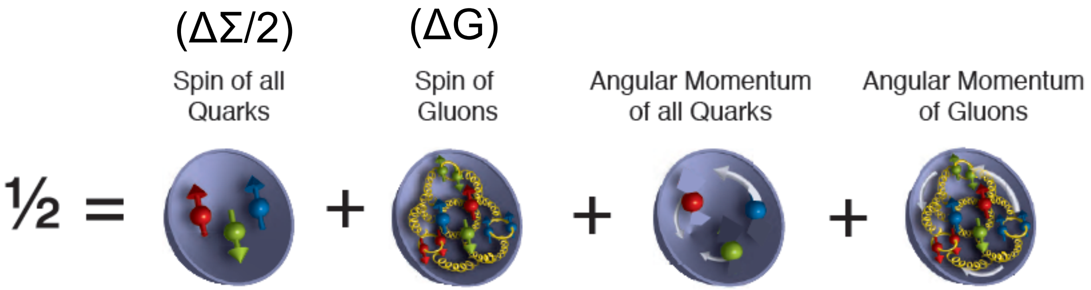


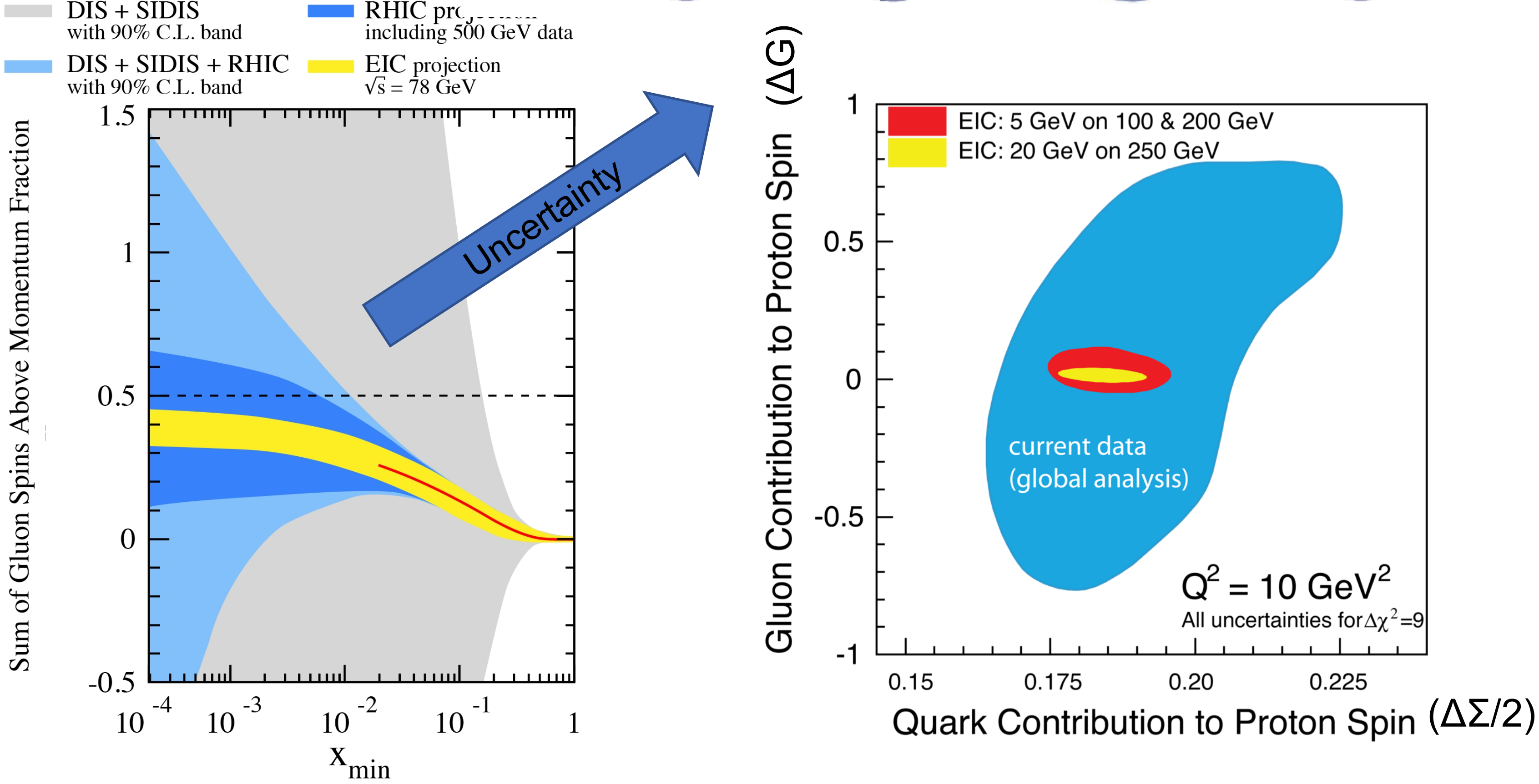
$x = p_1 / p_{proton}$

$x = Q^2 / sy$

- Parton Distribution Functions (PDFs) tell us about the densities of quarks and gluons inside the proton as function of their momentum (fraction) x.
- To reach saturation at the lowest x, the inelasticity y needs to be large (~1), producing low-energy scattered electrons in the lab frame.

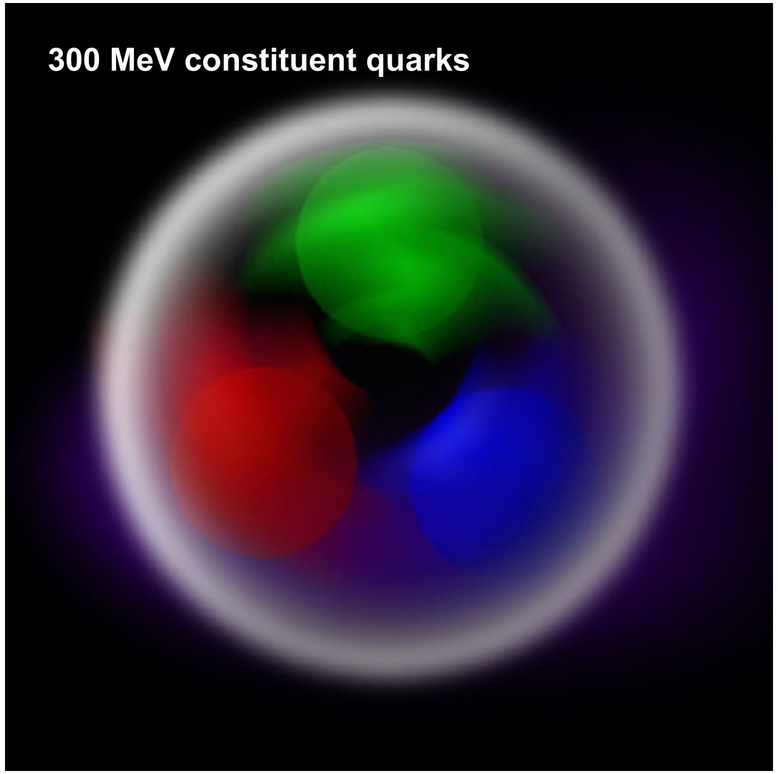
Inclusive DIS:
Gluon polarization

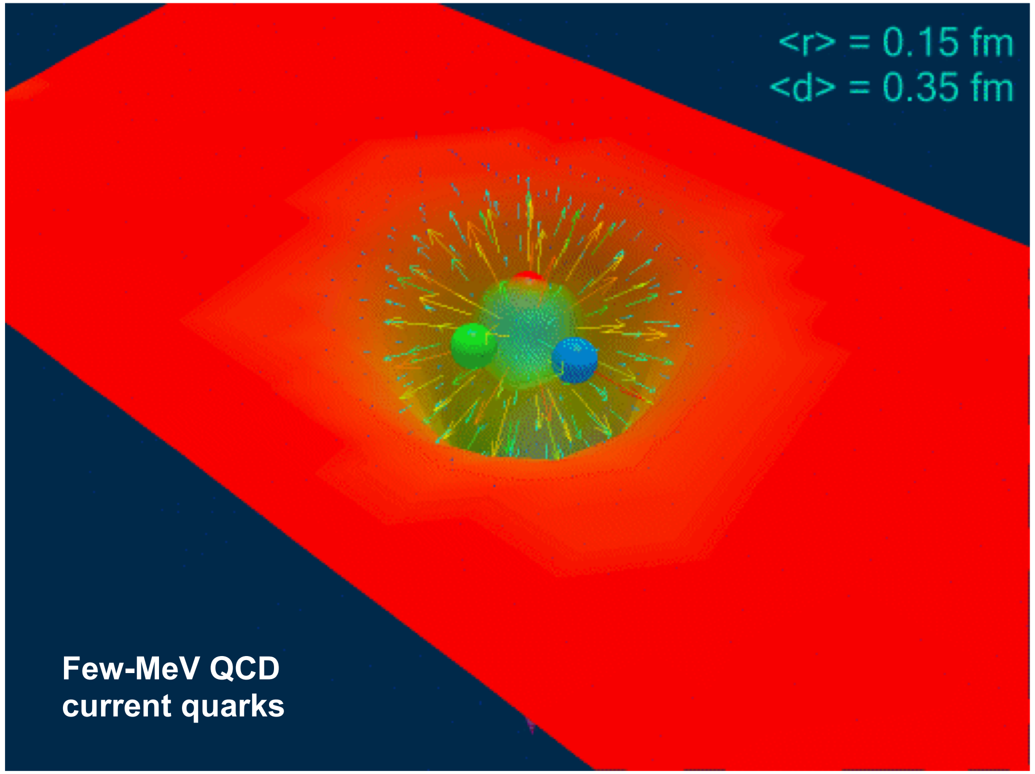




- Large uncertainties at low x require input from the EIC in addition to RHIC spin

Exclusive: spatial structure of nucleons



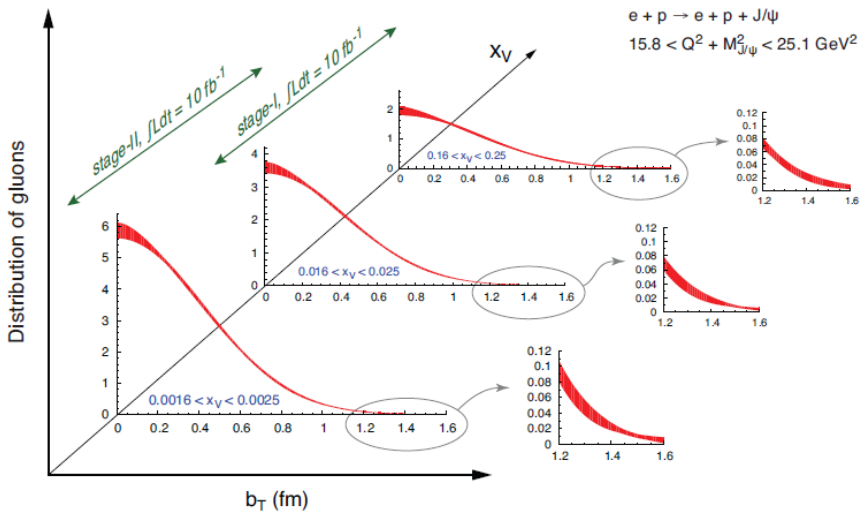


- Understanding the spatial structure of nucleons and nuclei is a key goal of the EIC
- For instance, do the gluons form “clouds” around the quarks, or are they mostly in-between?
- The transverse spatial structure can be probed through *exclusive* diffractive processes

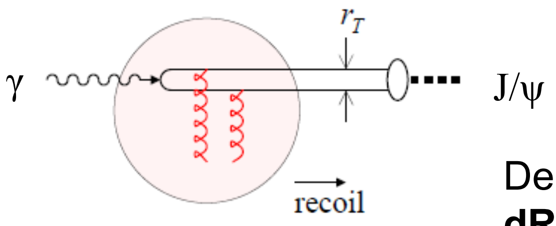
3D imaging the nucleon and light nuclei in coordinate and momentum space

GPDs (exclusive)

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



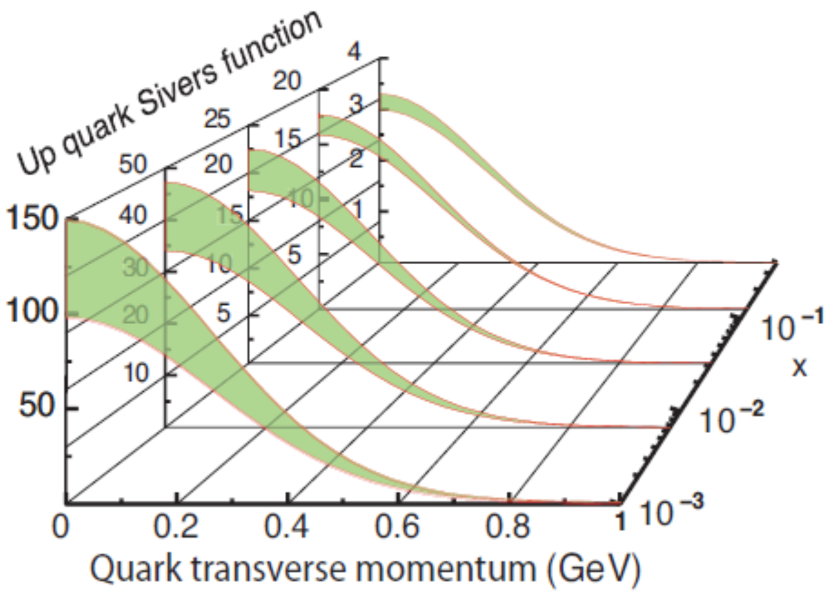
Transverse gluon distribution from J/ψ production



Decays into leptons
dRiCH eID

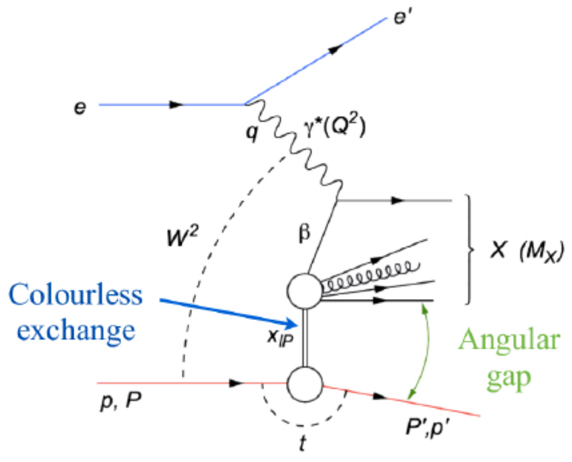
TMDs (SIDIS)

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



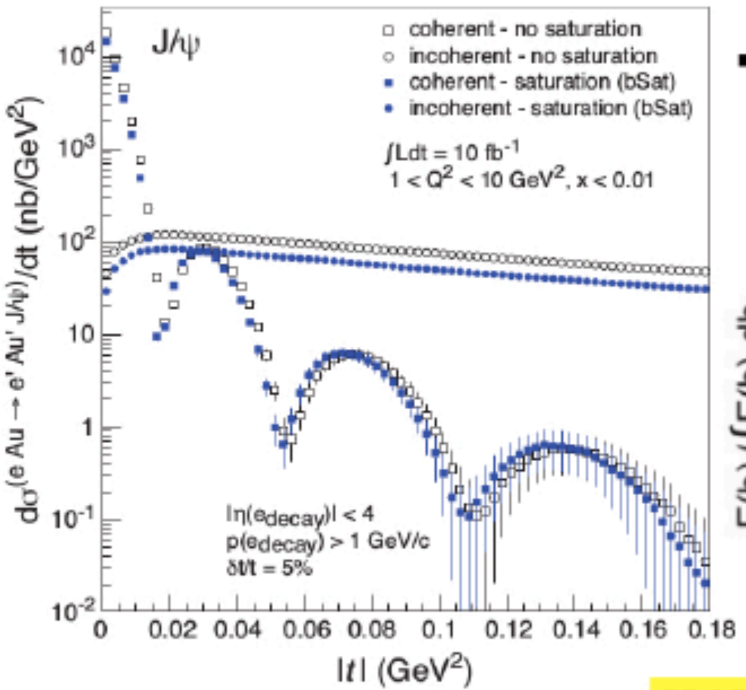
Projections from EIC white paper

2D spatial gluon imaging in heavy nuclei through coherent diffraction



Fragment detection and ID important for efficient veto

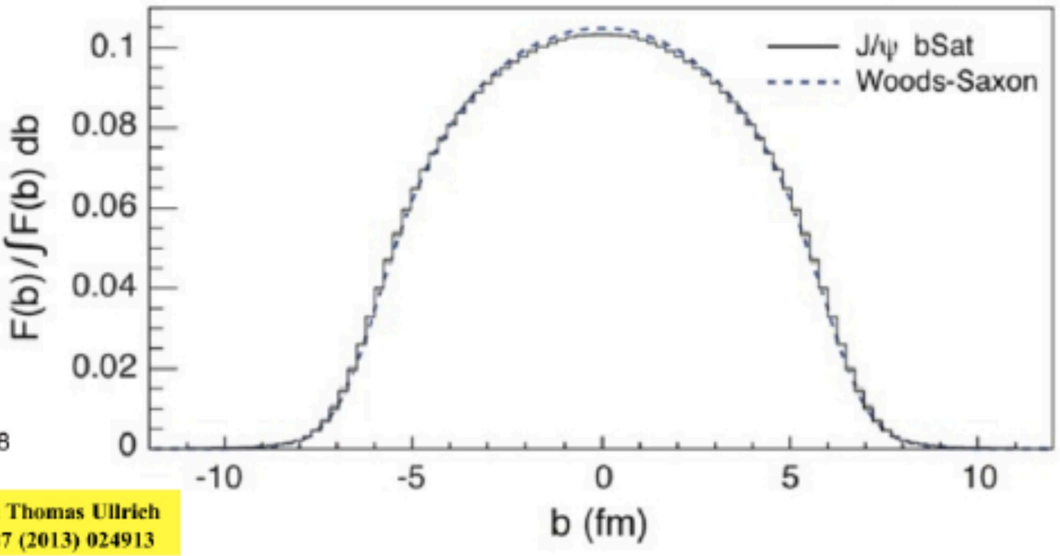
Momentum transfer *t* conjugate to transverse coordinate *b*



T.T. & Thomas Ullrich
PRC 87 (2013) 024913

$$\rightarrow F(b) \propto \int \mathrm{d}\Delta \Delta J_0(\Delta b) \sqrt{\frac{\mathrm{d}\sigma}{\mathrm{d}t}}$$

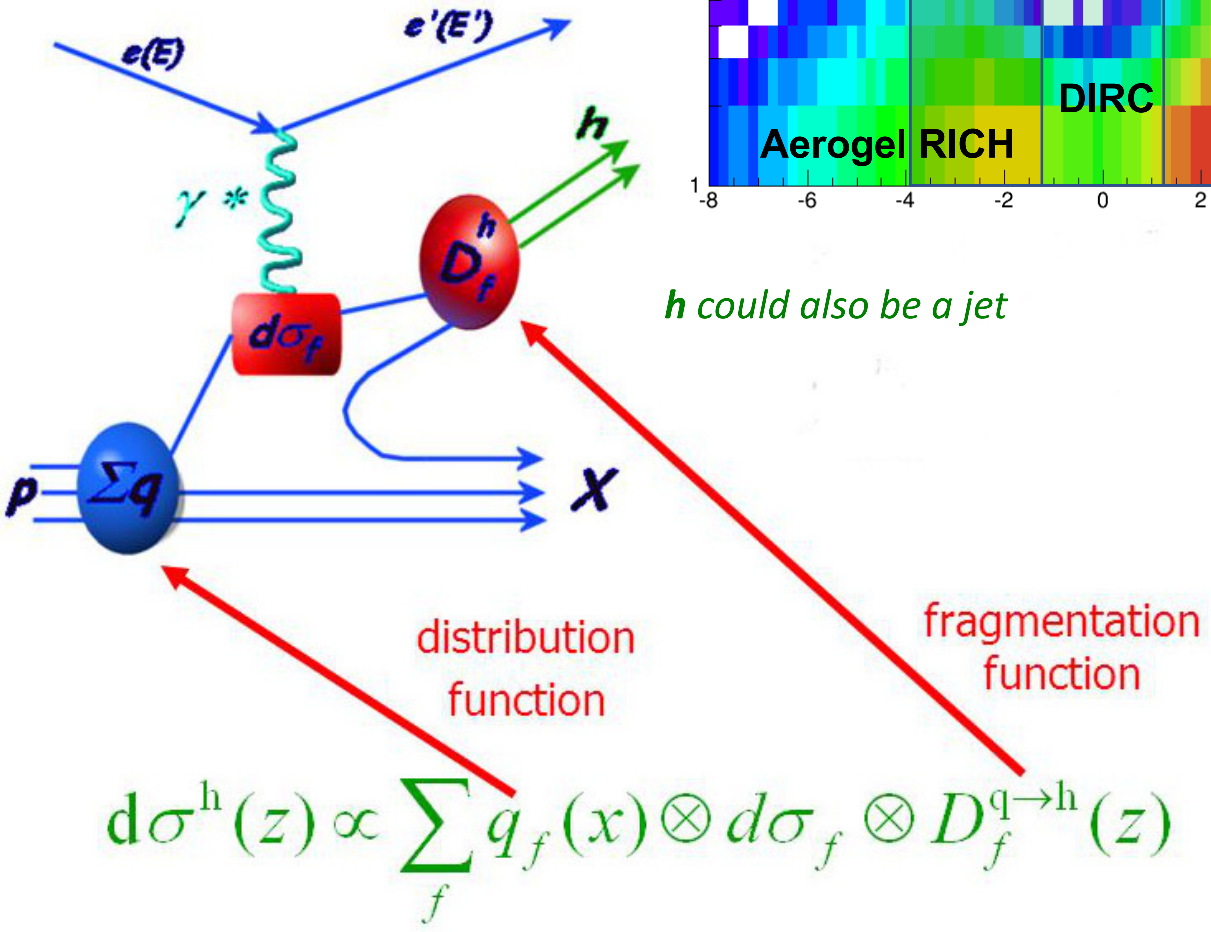
$t = \Delta^2/(1-x) \approx \Delta^2$



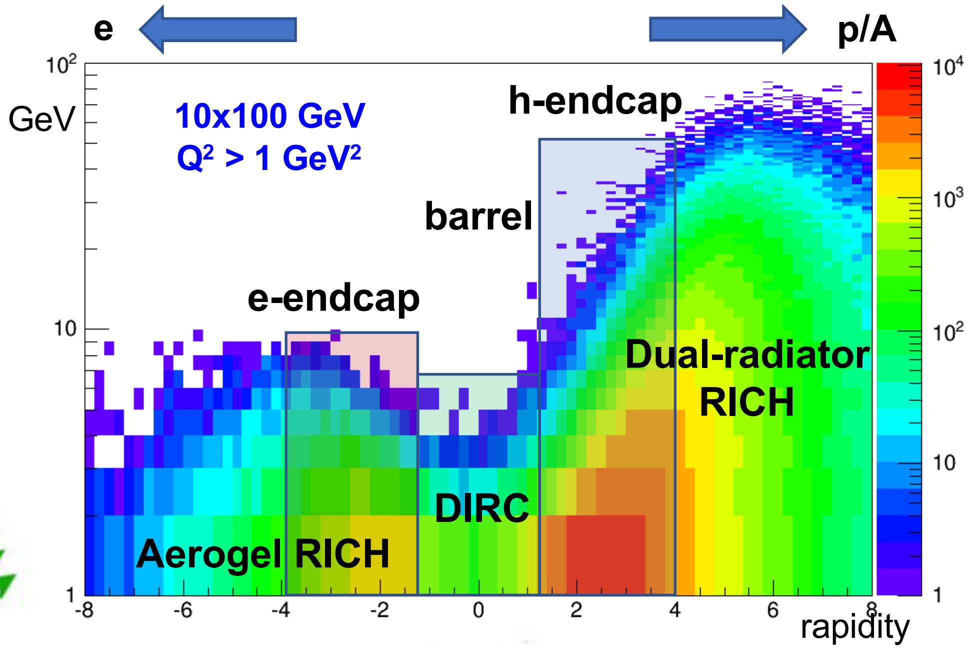
- Important input for the initial state in heavy ion collisions
- Sensitivity to gluon saturation

PID for the EIC (SIDIS shown)

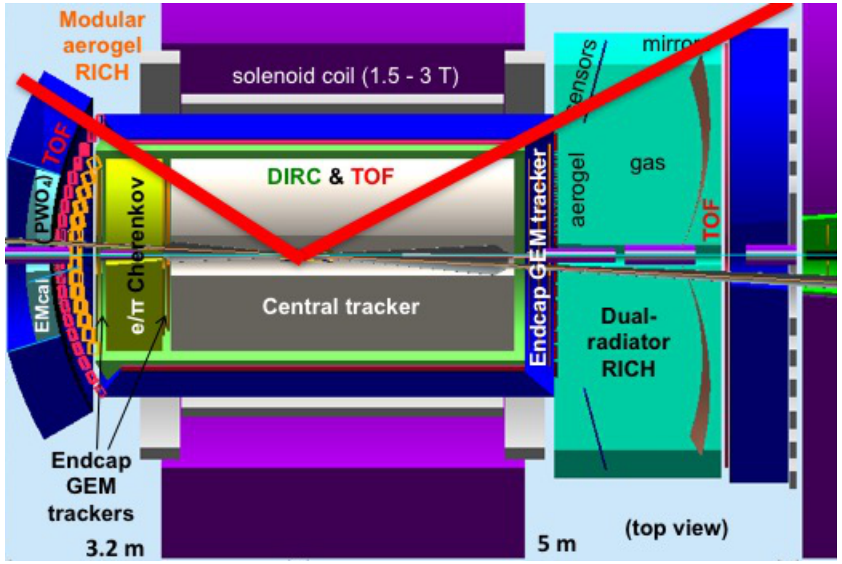
Semi-Inclusive DIS (SIDIS)



$$d\sigma^{h}(z) \propto \sum_{f} q_{f}(x) \otimes d\sigma_{f} \otimes D_{f}^{q\rightarrow h}(z)$$

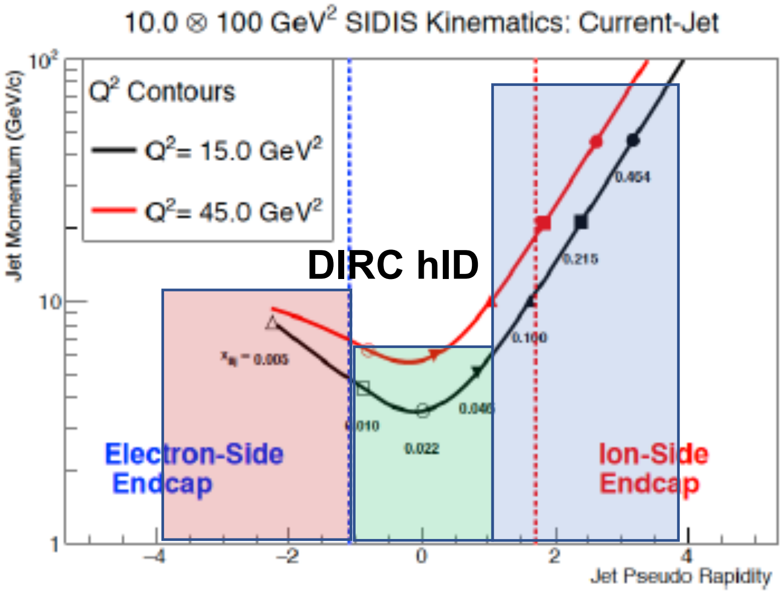


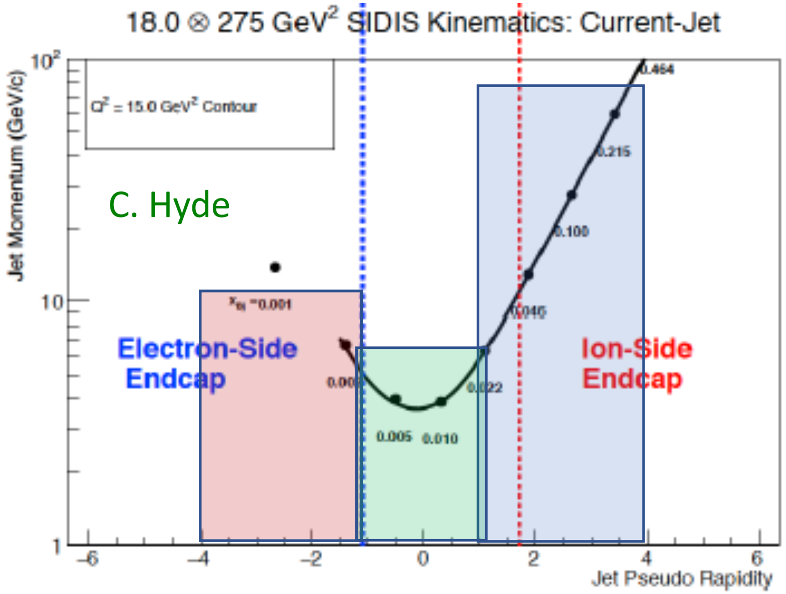
h could also be a jet



- Particle ID is an essential capability required for the EIC physics program
  - also beyond SIDIS and open charm
- Imaging Cherenkov detectors are the primary technology
  - Photosensors and electronics are also key R&D areas for the consortium

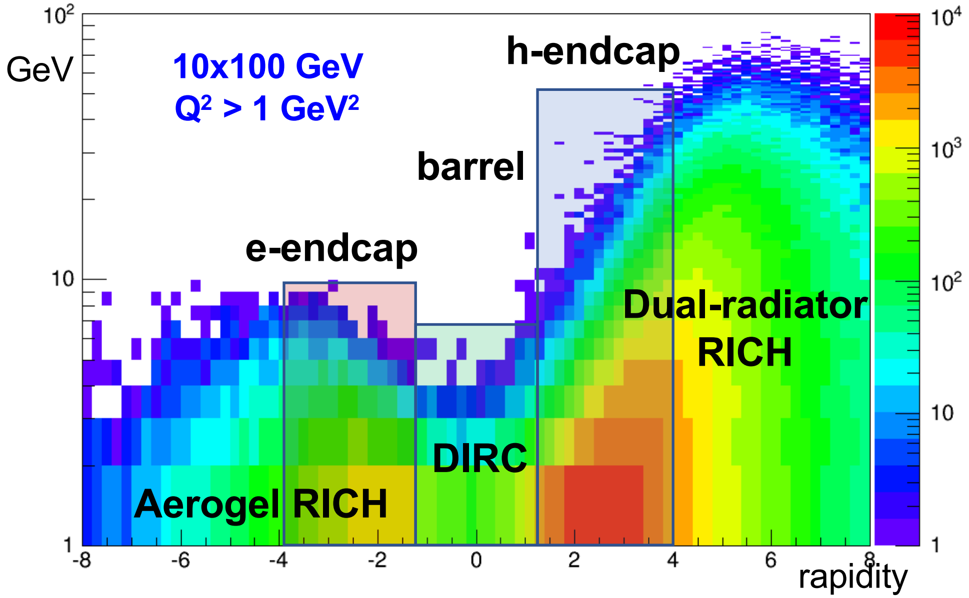
Hadron kinematics at an EIC





C. Hyde

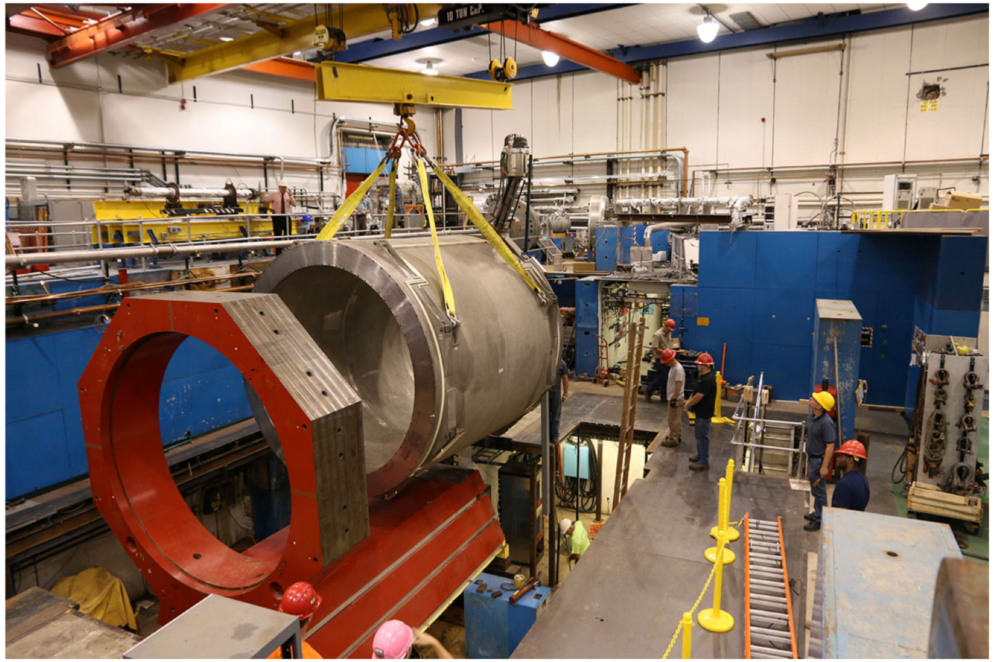
e ← → **p/A**



- The maximum hadron momentum in the endcaps is close to the electron and ion beam energies, respectively.
- The momentum coverage need in the central barrel depends on the desired kinematic reach, in particular in Q^2 – important for QCD evolution, etc.
  - Weak dependence on beam energies

Two existing 1.5 T solenoids – both ideal for the EIC

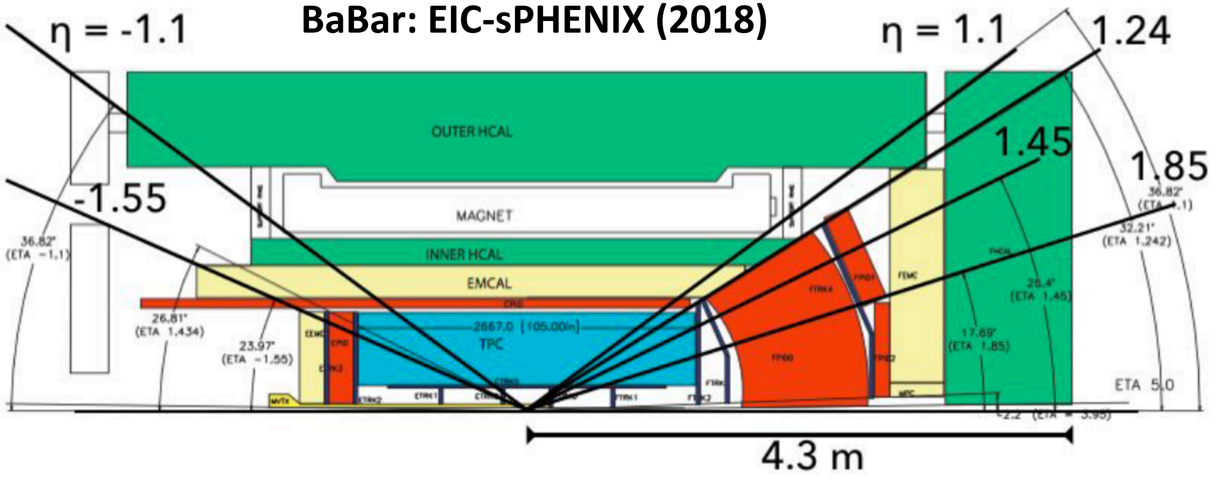
- The solenoids also have identical dimensions: 4 m long and 3 m diameter



- The Babar solenoid is now at BNL for use in the sPHENIX detector, which would be available from the beginning of EIC operations.
- The CLEO solenoid is now at JLab for use in the SoLID detector. It will be available upon completion of the SoLID program.

EIC central detector

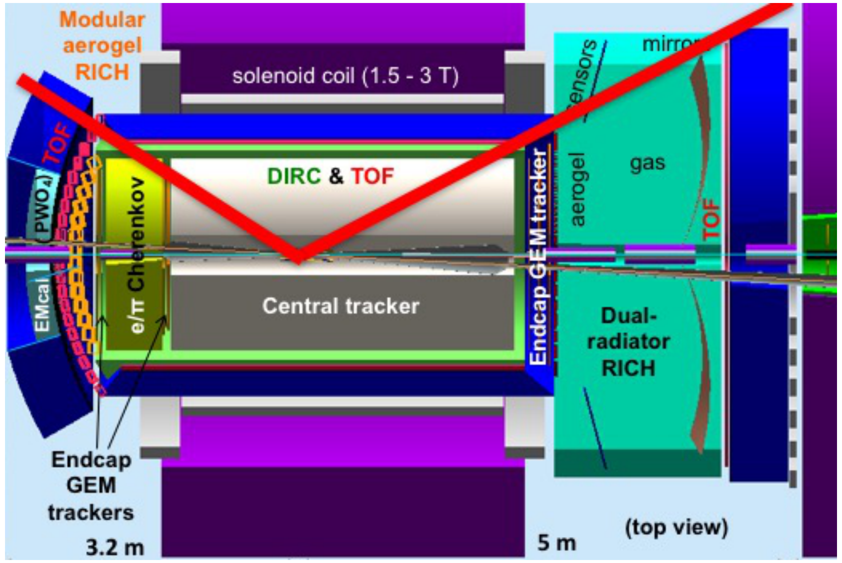
BaBar: EIC-sPHENIX (2018)



- Need 4pi acceptance to catch the electron and the hadron(s) from the struck parton (and the target at very small angles).
- Low multiplicities mean that tracking and particle identification (also for electrons) are essential
  - Hadronic calorimetry is important on the (outgoing) hadron endcap
- Very asymmetric collisions lead to very different requirements in different parts of the detector.

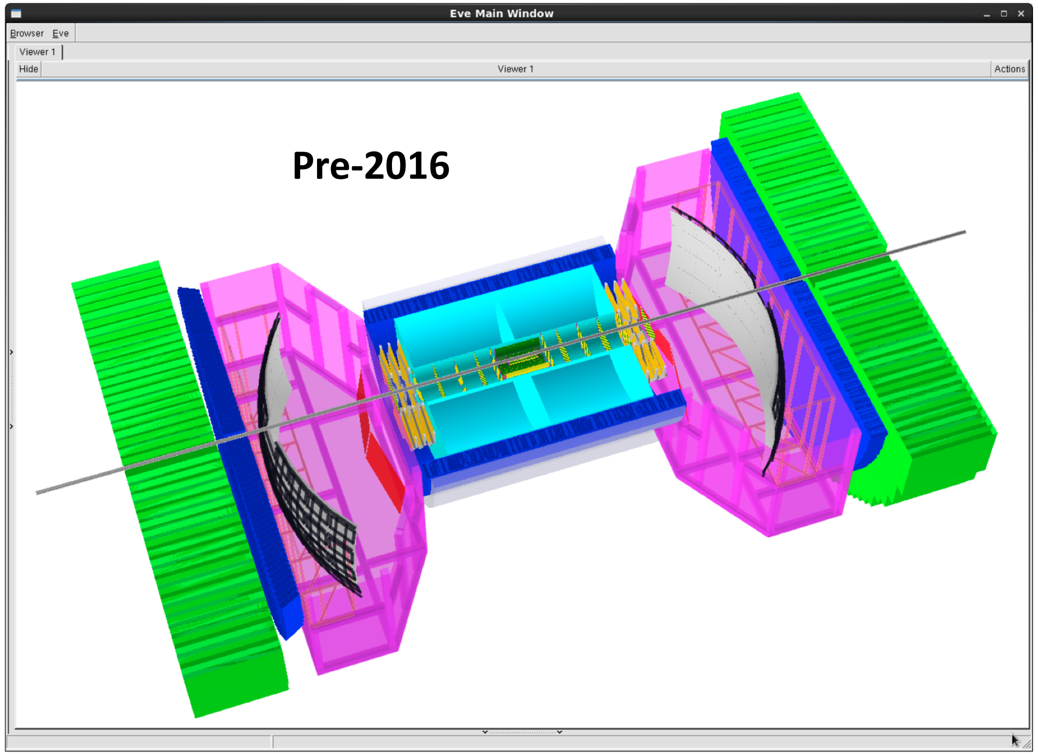
p/A → ← **e**

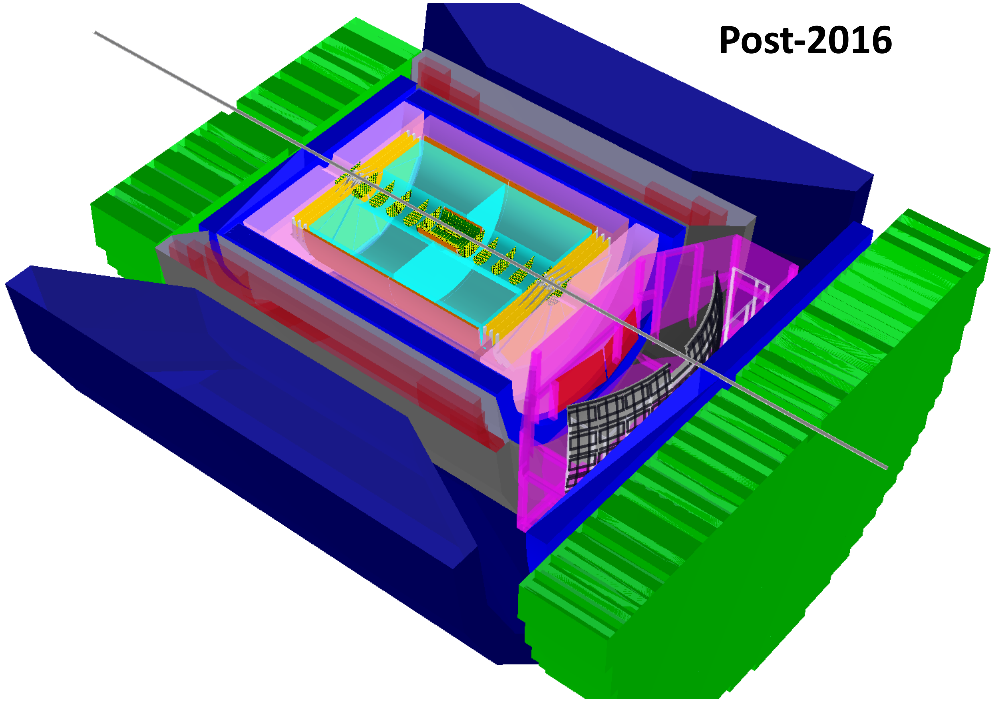
CLEO: JLab (2015)



- Doubly asymmetric design makes more efficient use of available space
  - IP is shifted within the solenoid and the solenoid within the IR

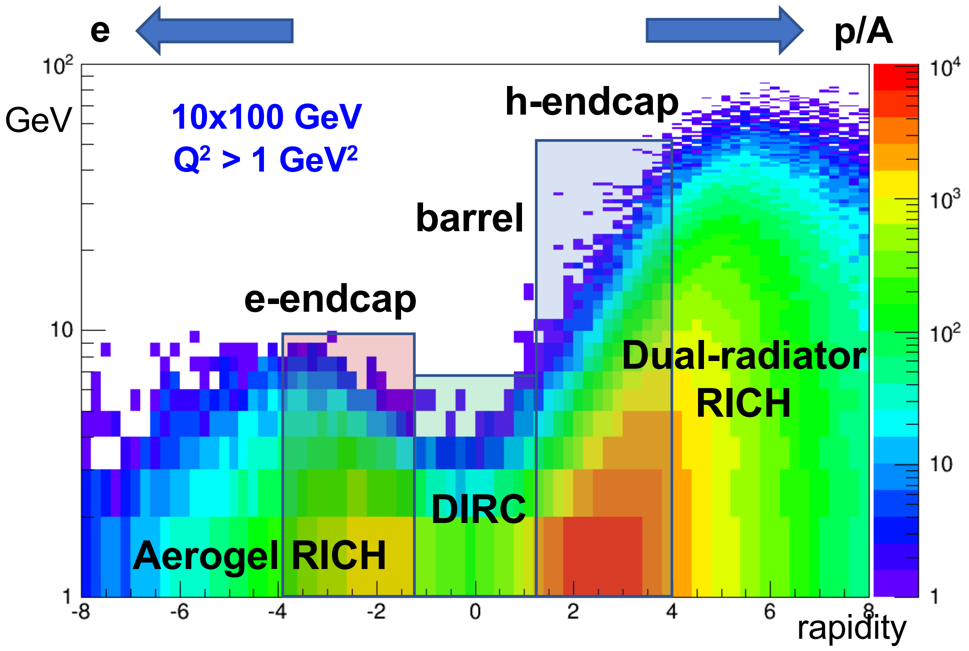
BNL BeAST detector concept

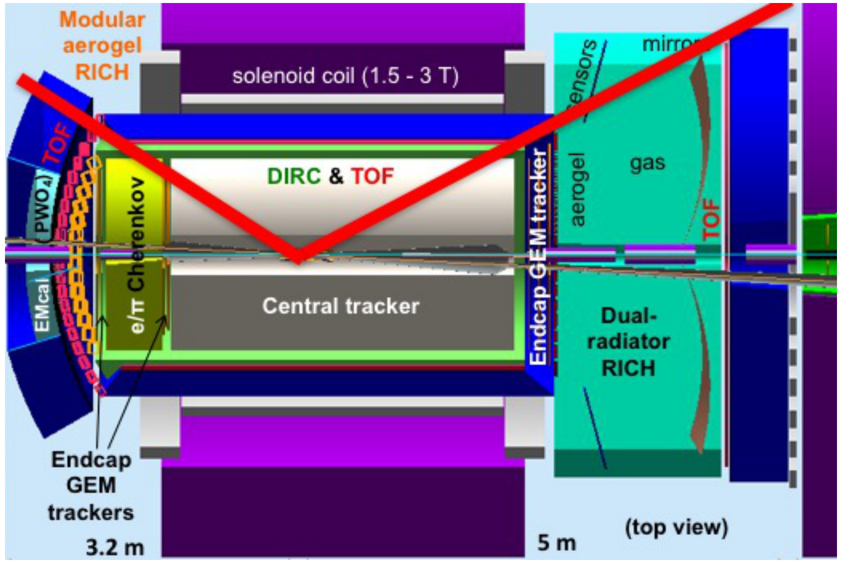




- The original BeAST was a very different, completely symmetric detector using a new, small 3 T solenoid
- Today, BeAST looks much more similar to the JLab and sPHENIX detectors, and has room for all the PID systems developed in the EIC R&D program. The 3 T field could easily be changed to 1.5 T.
- In the future, two central detectors based on BaBar and CLEO could share features of all three concepts.

A PID solution for the EIC central detector (eRD14)

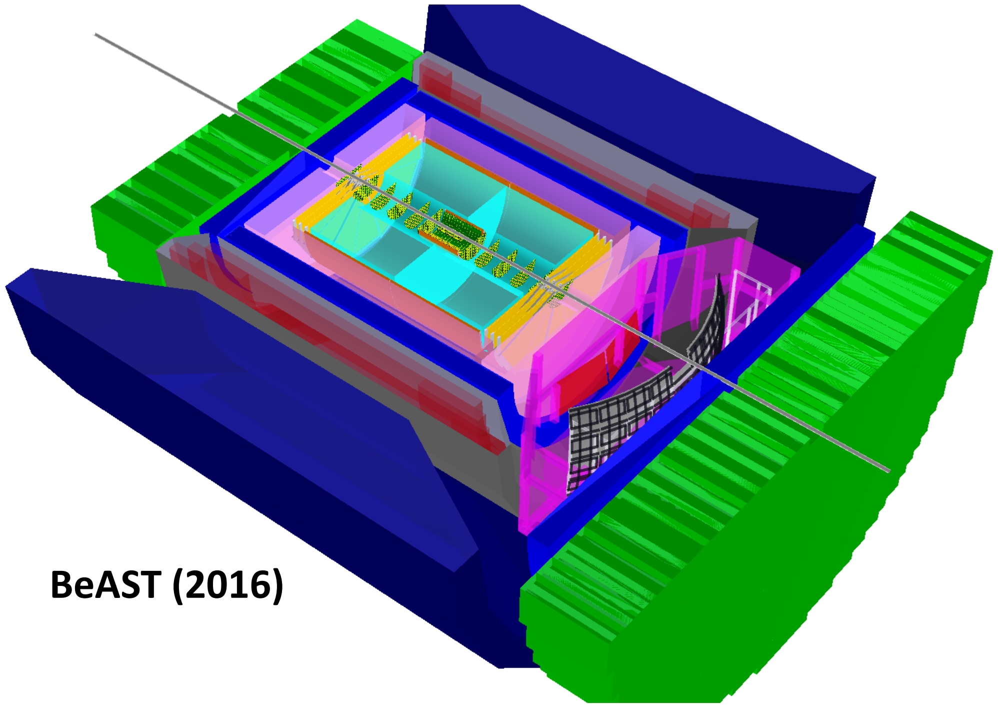




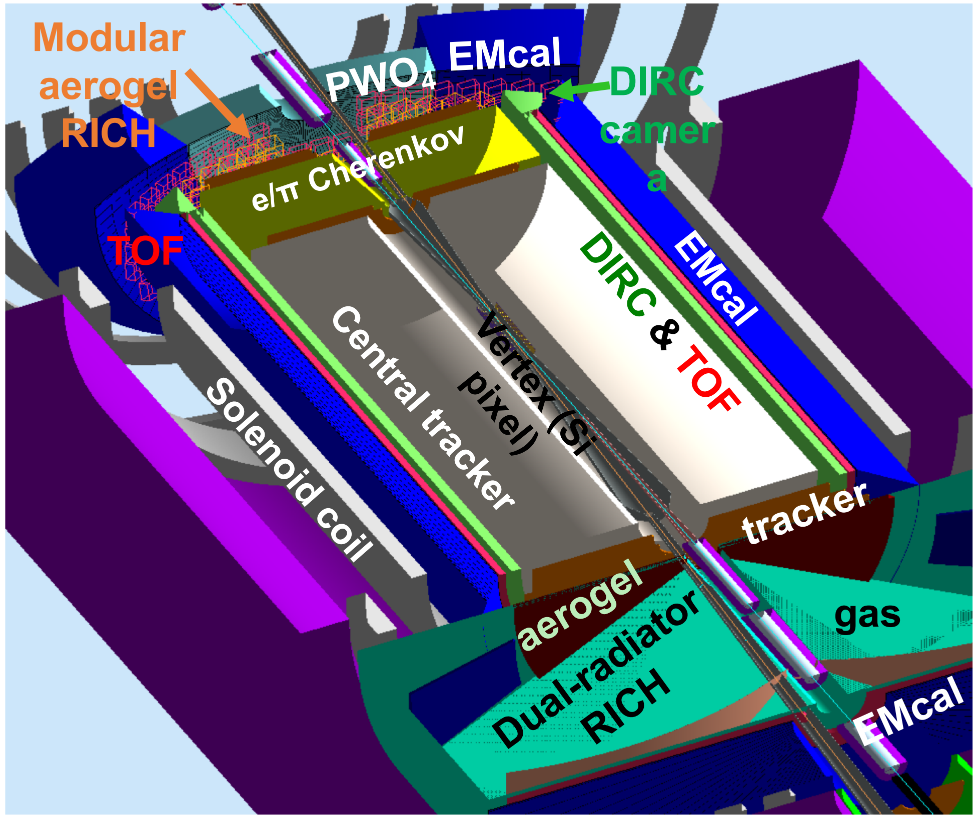
- **h-endcap**: A RICH with two radiators (gas + aerogel) is needed for
  π/K separation up to ~50 GeV/c
- **e-endcap**: A compact aerogel RICH which can be projective
  π/K separation up to ~10 GeV/c
- **barrel**: A high-performance DIRC provides a compact and cost-effective way to cover the area.
  π/K separation up to ~6-7 GeV/c
- **TOF and/or dE/dx in a TPC**: can cover lower momenta.
- **Photosensors and electronics**: need to match the requirements of the new generation devices being developed – both for the final system and during the R&D phase

PID in the JLab/BNL EIC detector concepts

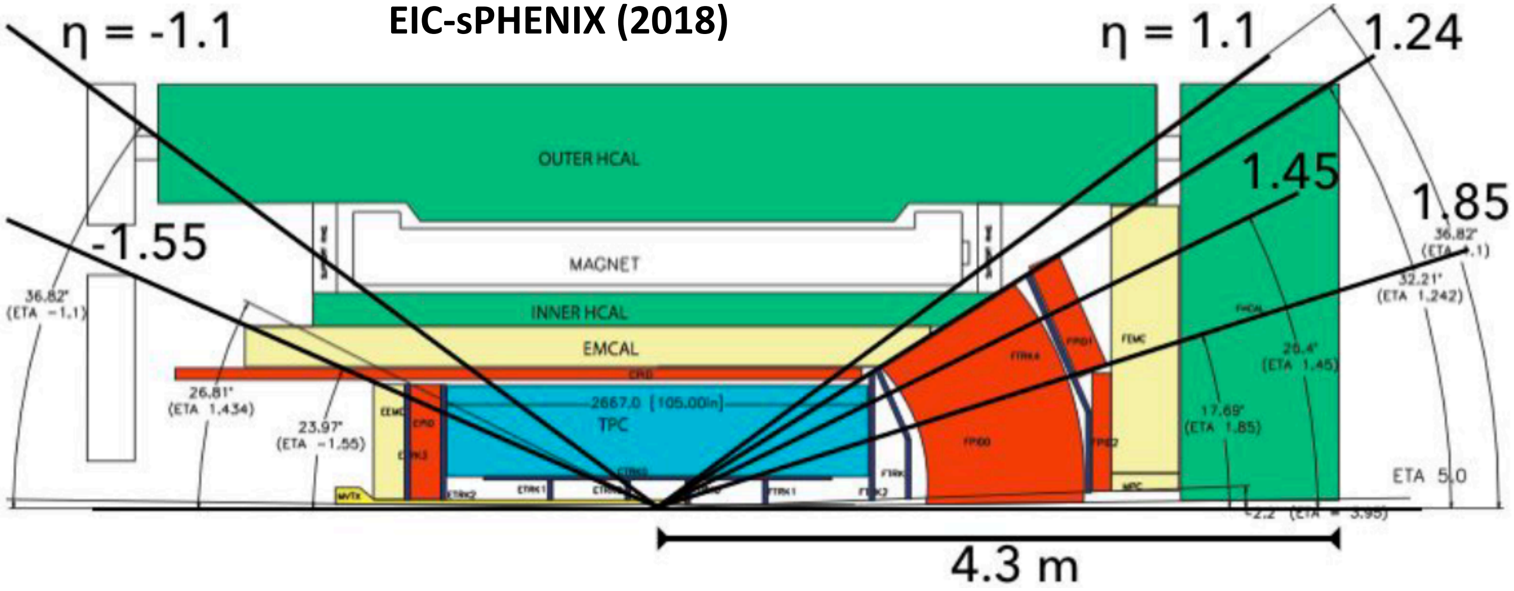
- All Cherenkov detectors developed by the PID consortium (DIRC, mRICH, dRICH) are the baseline options for the three detector concepts developed at JLab and BNL
  - Only exception is EIC-sPHENIX which has a gas-only RICH



BeAST (2016)

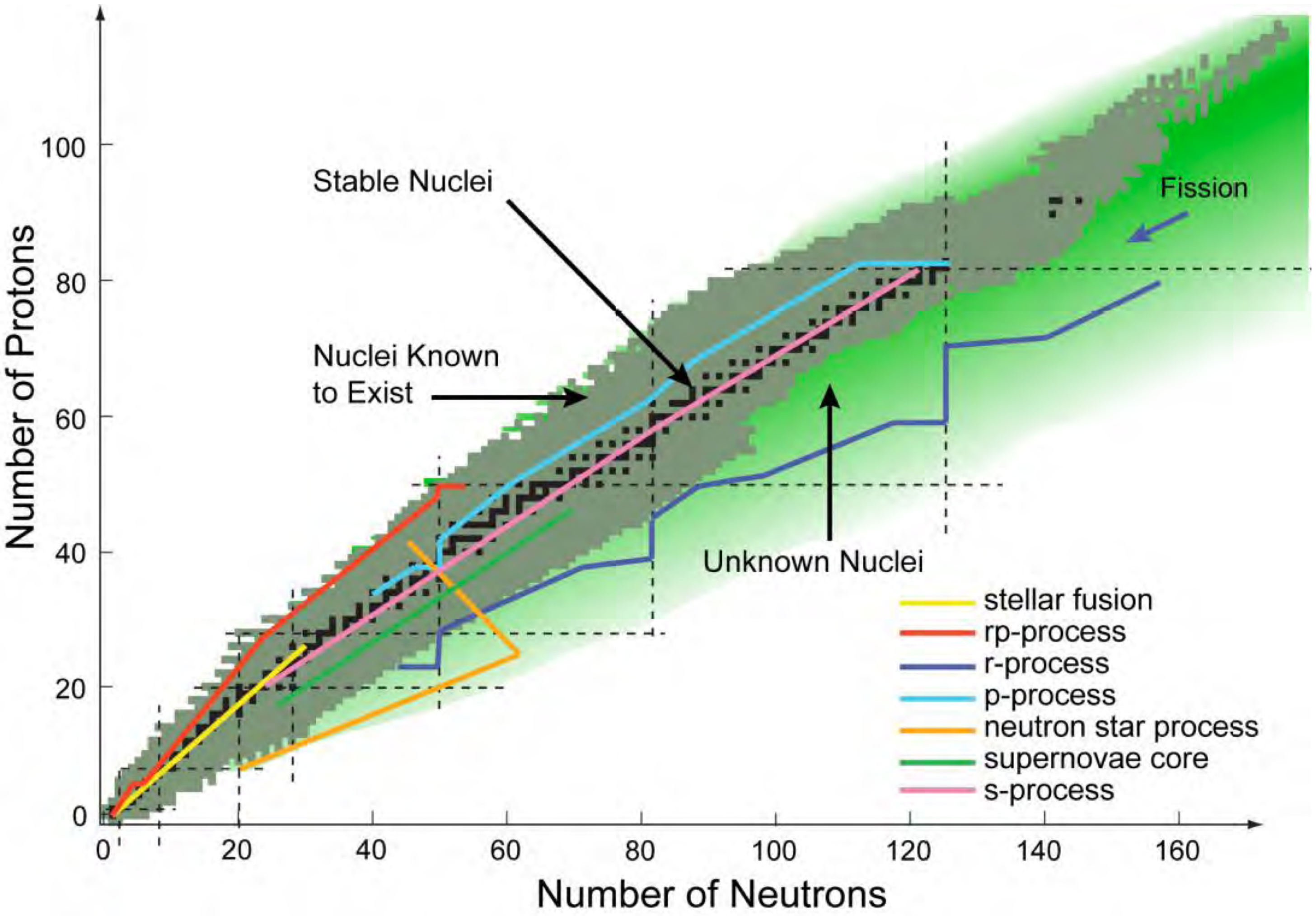


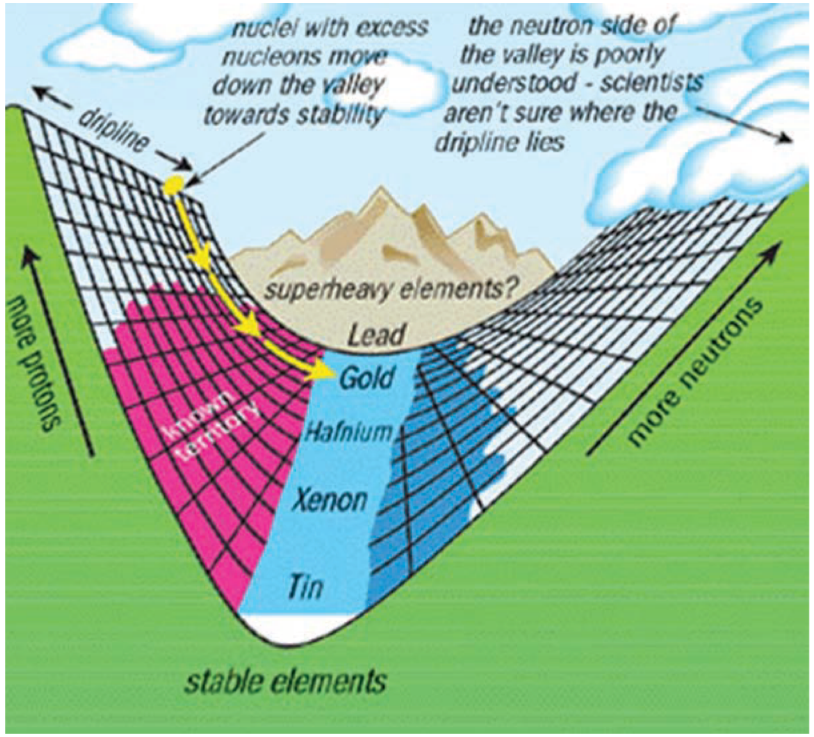
JLab (2015)

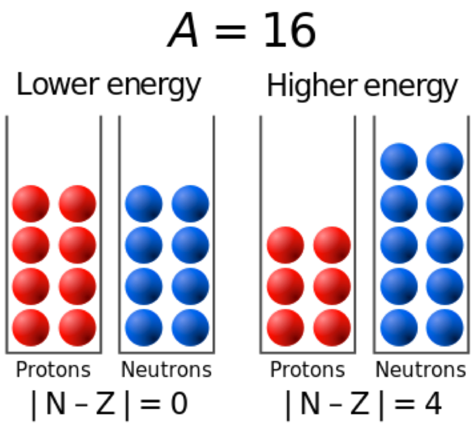


EIC-sPHENIX (2018)

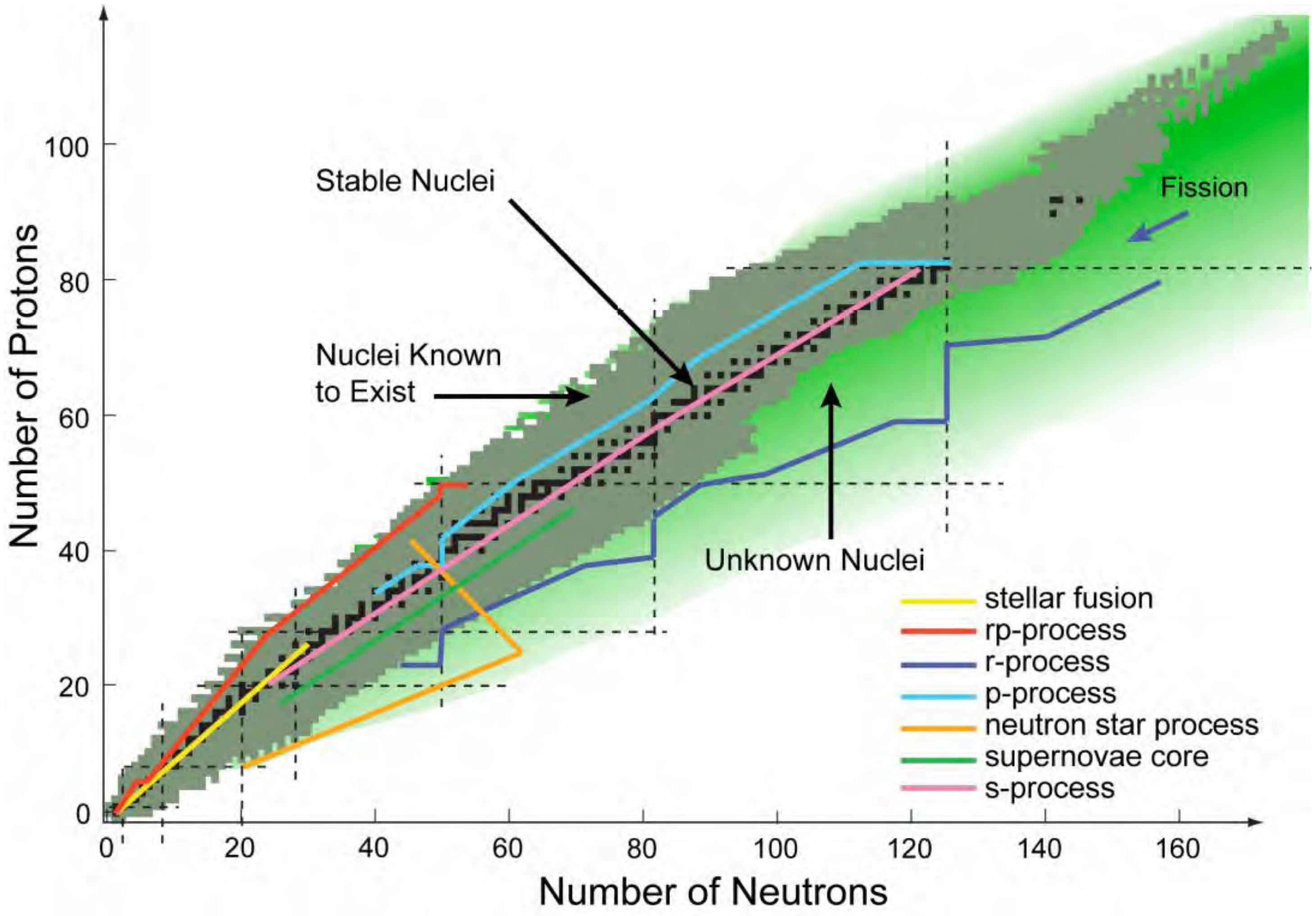
New opportunities: Rare isotopes at an EIC

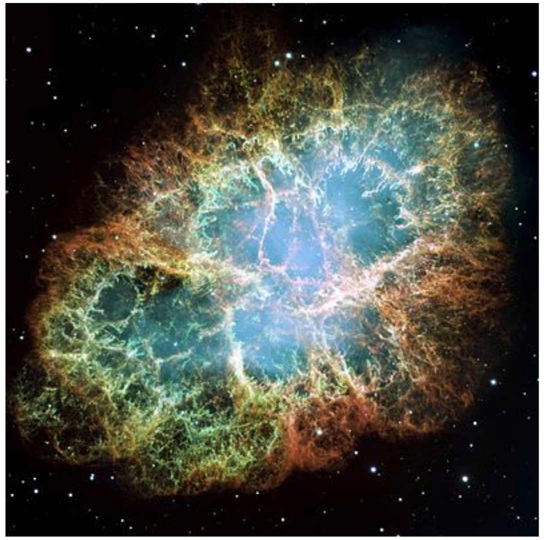






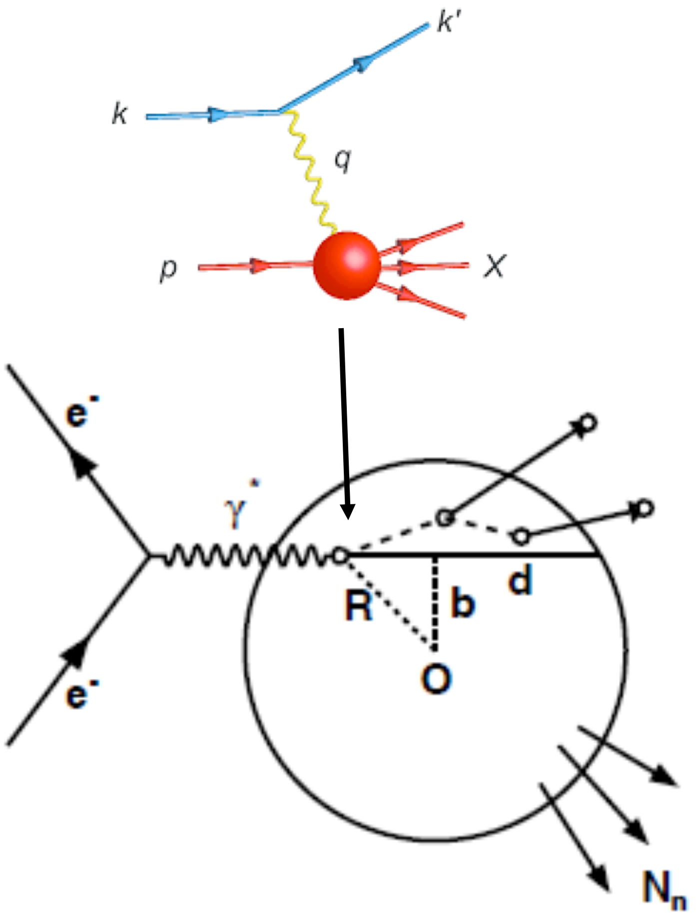
Importance for astrophysics





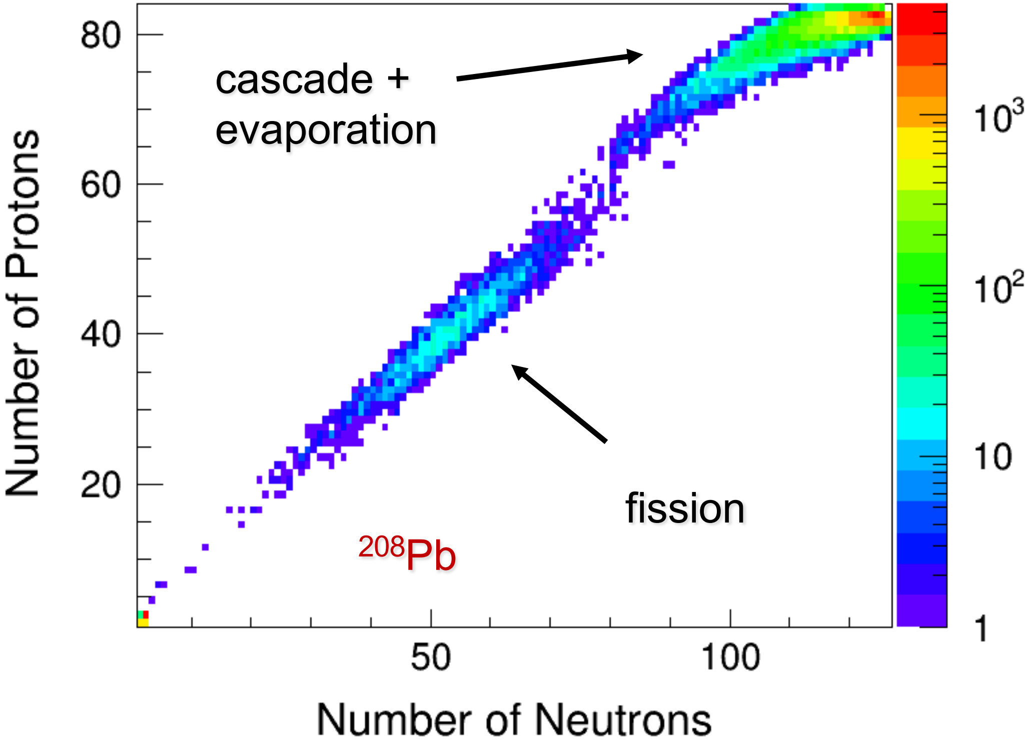
- All elements heavier than iron (the most tightly bound nucleus) have been created in stellar events like supernovae
- The most important mechanism is the rapid neutron capture (r-process) in equilibrium with beta-decay
- The drip-line difficult to reach on the neutron-rich side, which means that “all” produced isotopes are bound.

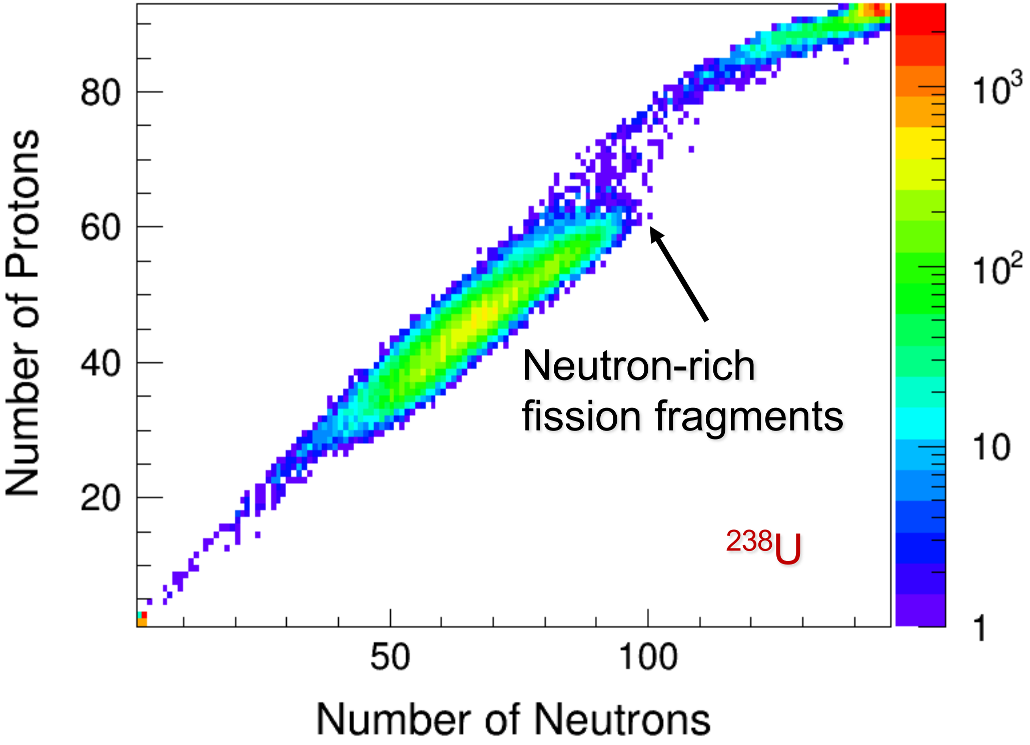
Deep Inelastic Scattering on nuclei



- DIS on nuclei is a multi-stage process.
- First, there is a scattering on a parton
- Debris from the interaction will propagate out of the nucleus, interacting along the way, causing an intra-nuclear cascade typically leading to the knock-out of several nucleons
- The daughter nucleus will usually be left in an excited state, leading to evaporation of nucleons and light nuclei, and sometimes fission.
- At high excitation energies there is no strong preference for emitting charged particles or neutrons, but at low energy neutrons are preferred.
- Finally, when below the nucleon separation energy, the nucleus will emit photons. These transitions between bound states offer detailed insight into the structure of the produced nucleus.

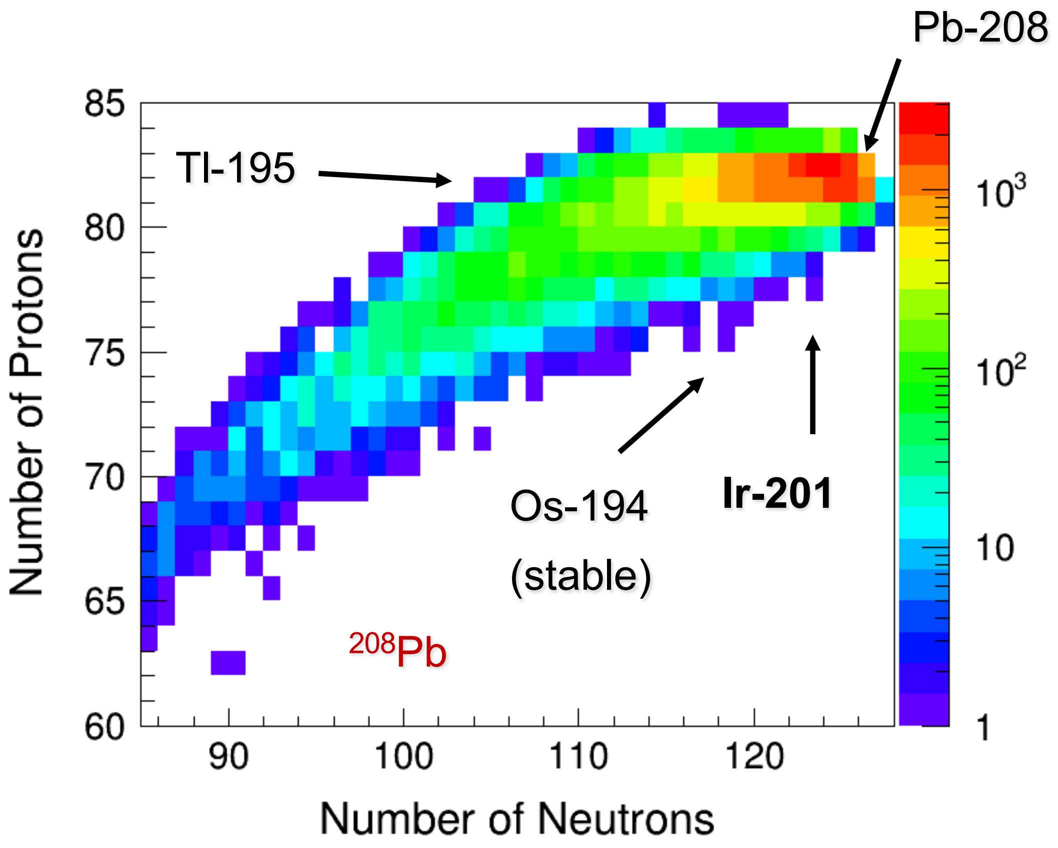
Nuclei from ^{208}Pb and ^{238}U (1s of simulated beam time)

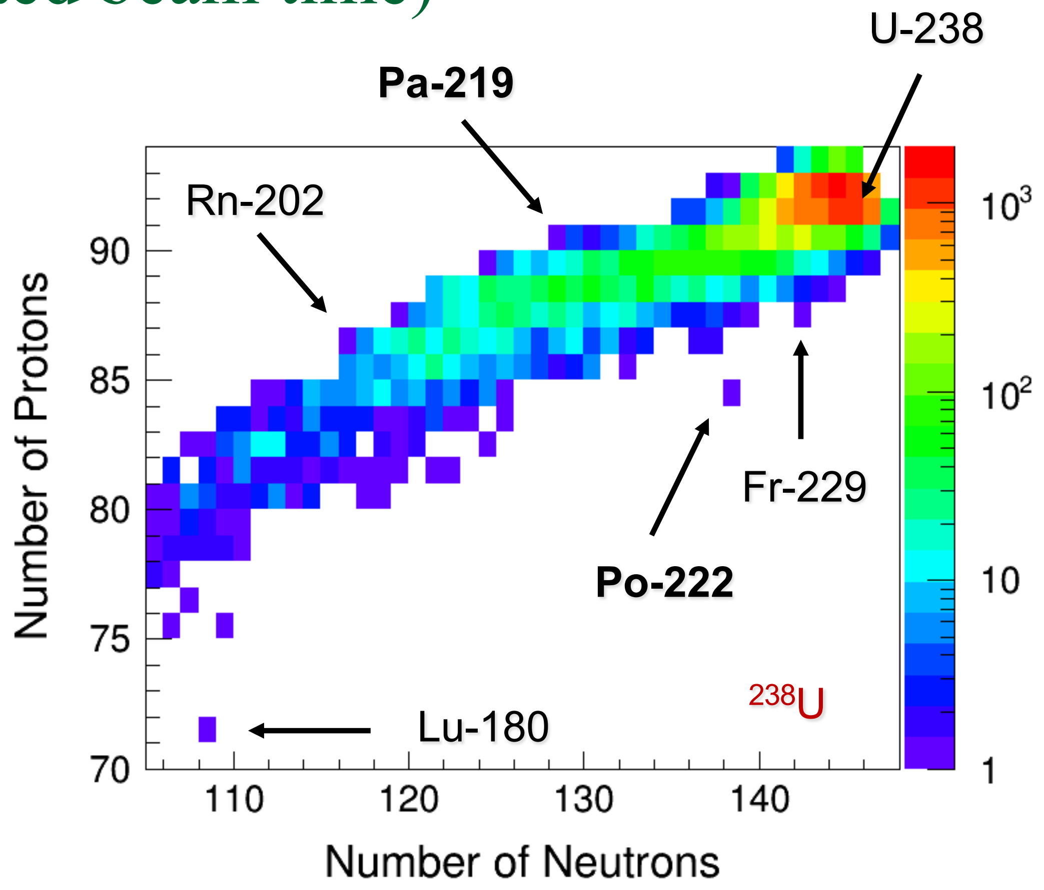




- ^{208}Pb (left) produces mainly heavy isotopes from evaporation
- ^{238}U (right) produces fewer, but heavier isotopes from evaporation. It also produces very neutron-rich fission fragments (medium-mass nuclei have fewer neutrons).

Nuclei from ^{208}Pb and ^{238}U (1s of simulated beam time)





- ^{208}Pb (left) produces mainly heavy isotopes from evaporation
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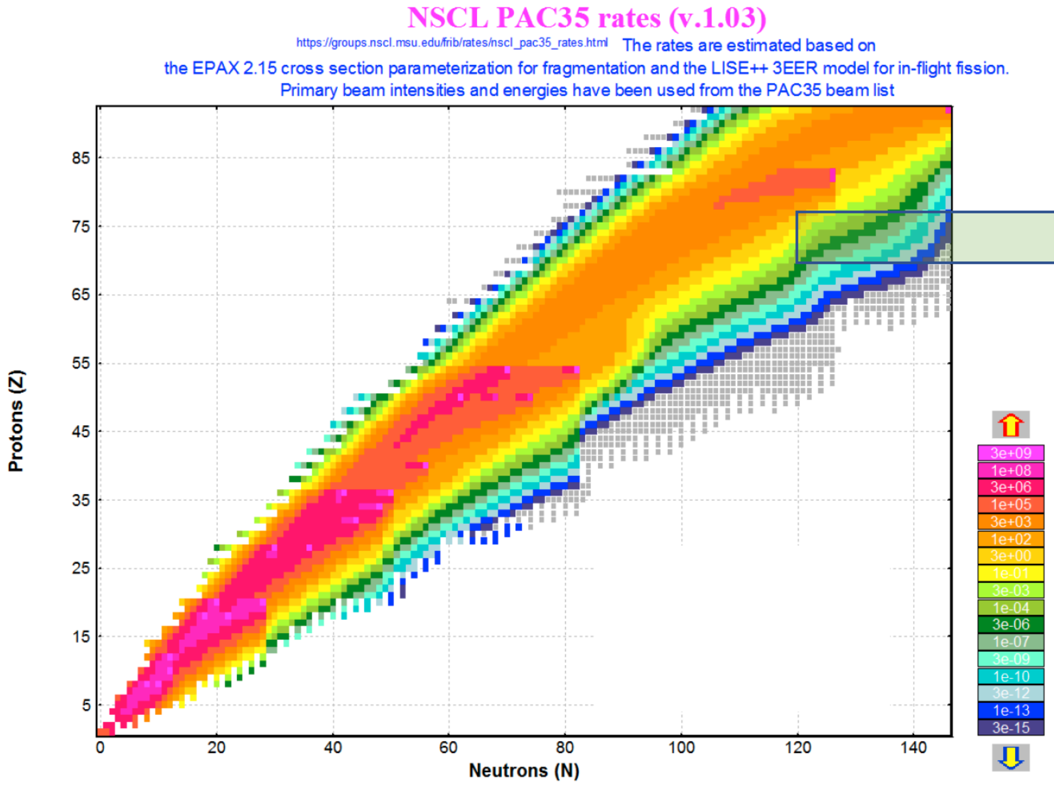
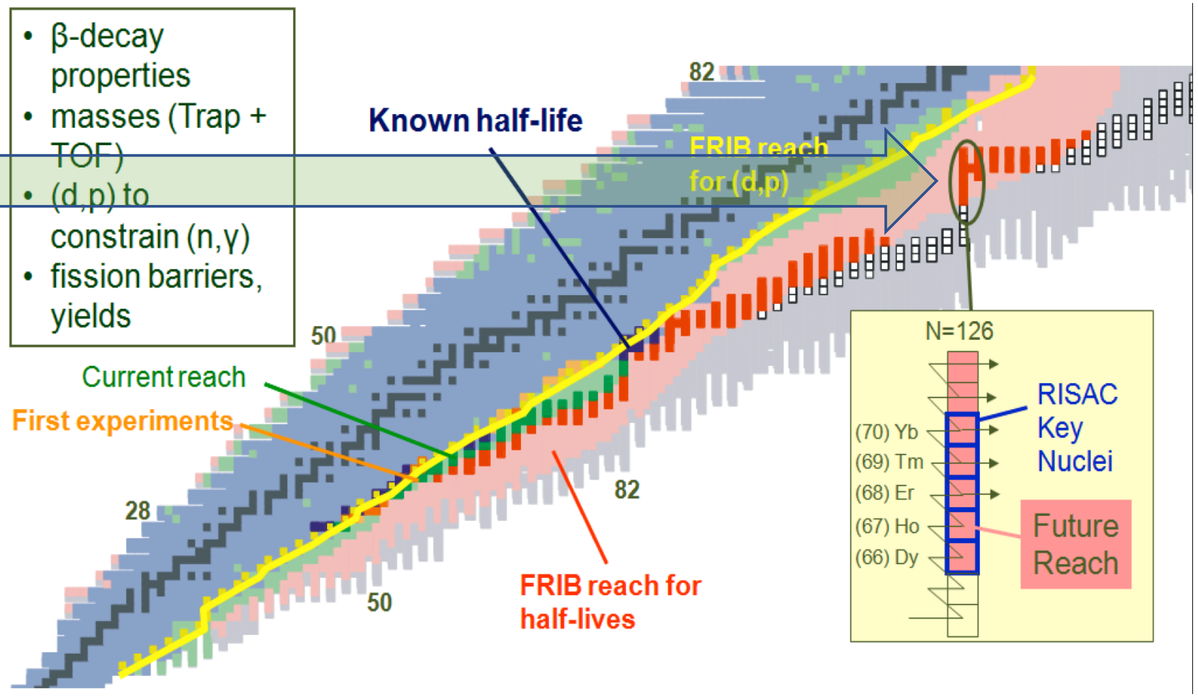
How does this compare with FRIB?



NSCL PAC35 rates (v.1.03)

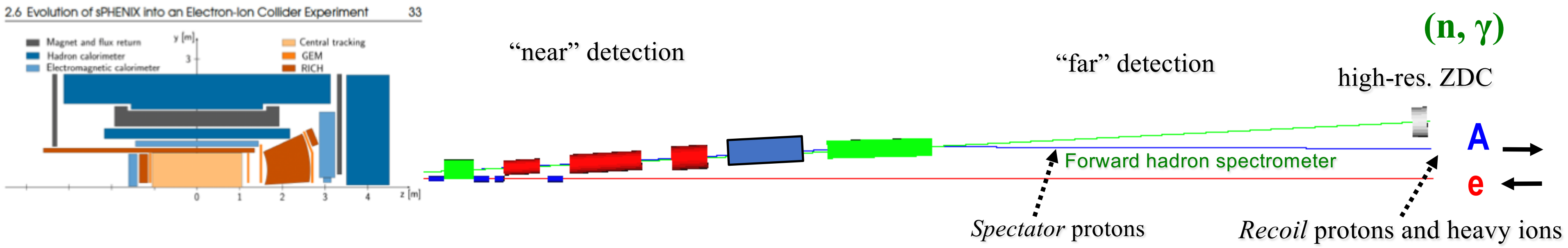
https://groups.nscl.msu.edu/frib/rates/nscl_pac35_rates.html The rates are estimated based on the EPAX 2.15 cross section parameterization for fragmentation and the LISE++ 3EER model for in-flight fission. Primary beam intensities and energies have been used from the PAC35 beam list



- β-decay properties
- masses (Trap + TOF)
- (d,p) to constrain (n,γ)
- fission barriers, yields

- With very large uncertainties, a year of heavy-ion running at the EIC should make it possible to probe parts of the neutron-rich red area on the right where FRIB plans to measure half lives.
- It will also at the same time provide information on proton-rich isotopes

Detection and identification of the produced nuclei



"near" detection

"far" detection

(n, γ)

high-res. ZDC

A →

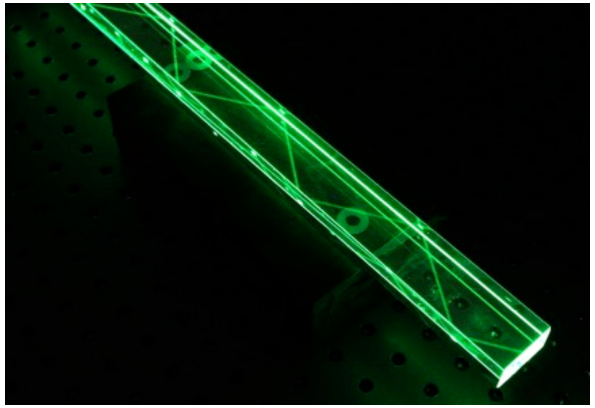
e ←

Forward hadron spectrometer

Spectator protons

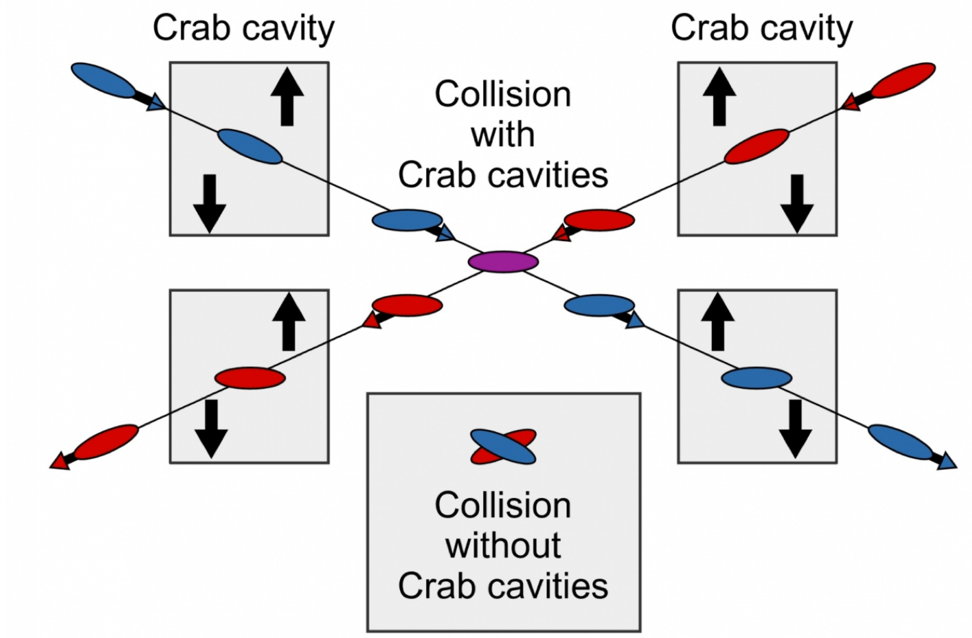
Recoil protons and heavy ions

- Detection of nuclei with rigidities (A/Z) close to that the beam require a dedicated "far" spectrometer where the beam is small and dispersion large.
- But to identify the ion we need both A/Z and an independent measurement of Z (since all fragments travel with the same velocity, TOF is not ideal). The requirement for sensitivity in Z^2 is a little more than 2%.
- A "mini-DIRC" can produce close to 100,000 photons (<< 1% error) in a few mm of fused silica – but which photosensor would be best at counting them precisely?
- A pilot study will be proposed as a new R&D project this year by the EIC PID consortium.



A "mini-DIRC" inside a Roman pot at the downstream focus can identify ions to ~1% in Z^2

Future of precision TOF for the EIC?



- The luminosity of a collider with a crossing angle between the beams can be increased by using a crab cavity, which orients the bunches ”head on” near the collision point.
- The crab cavity acts as dipole with a time-dependent strength, providing more kick at the edges and none in the middle.

- For measurements within the crab cavities, this creates a p_T smearing – unless one can know where in the bunch the collision took place (a vertex tracker does not help since it tells you where in the detector the collision took place, but not where in the bunch).
- Electron bunches are short and carry little momentum, so they key challenge is to resolve the structure of the ion bunch, which would typically require ps timing resolution.

Thank you!