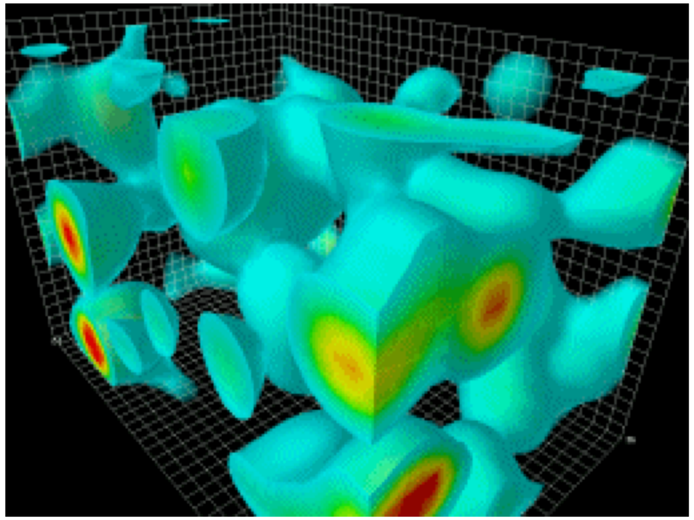
# A novel compact detector concept for the Electron-Ion Collider (EIC)



The QCD vacuum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Stony Brook University

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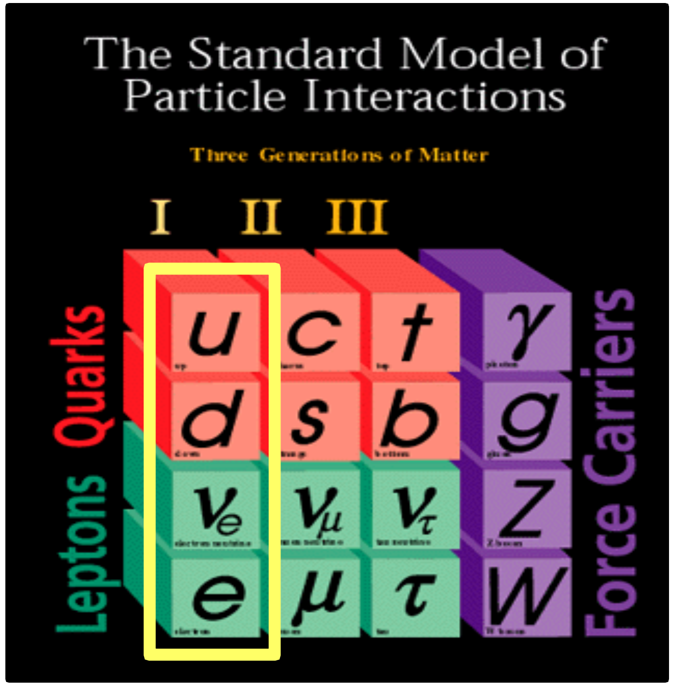
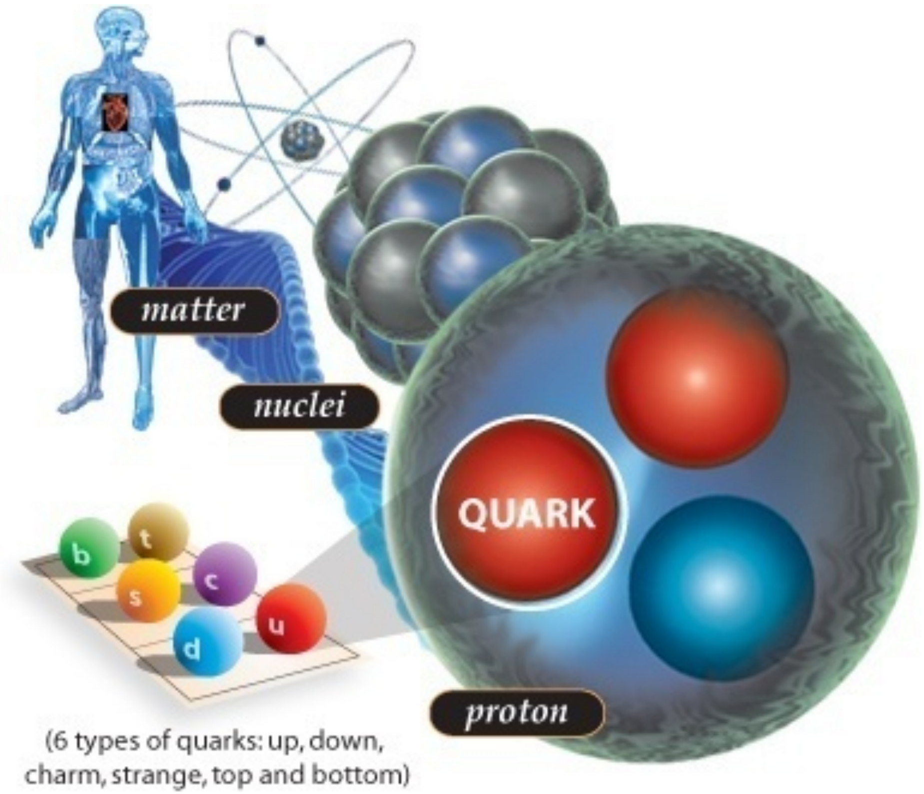
Old Dominion University


EIC PID consortium meeting, September 21, 2020

# Visible matter according to the standard model



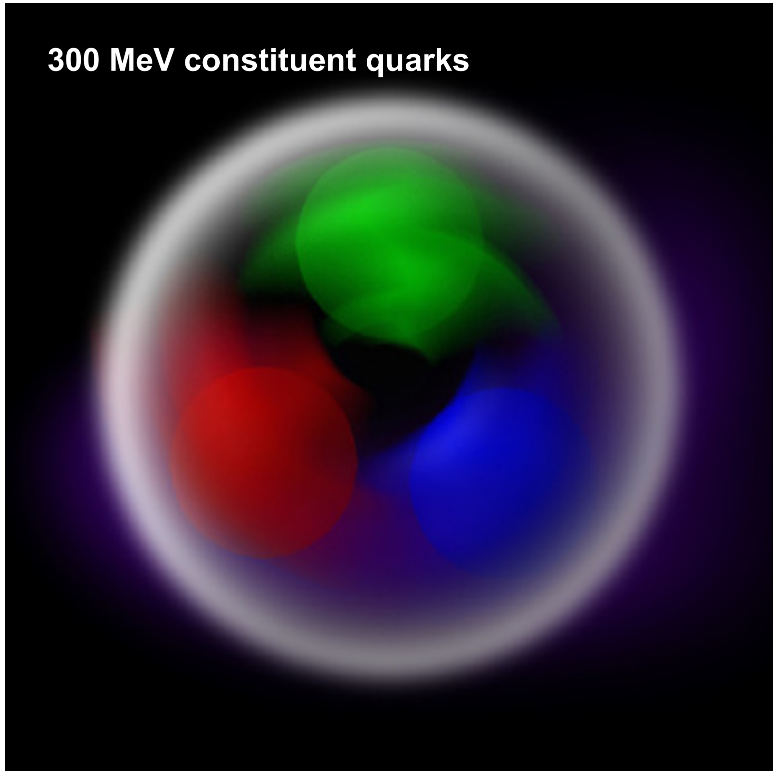



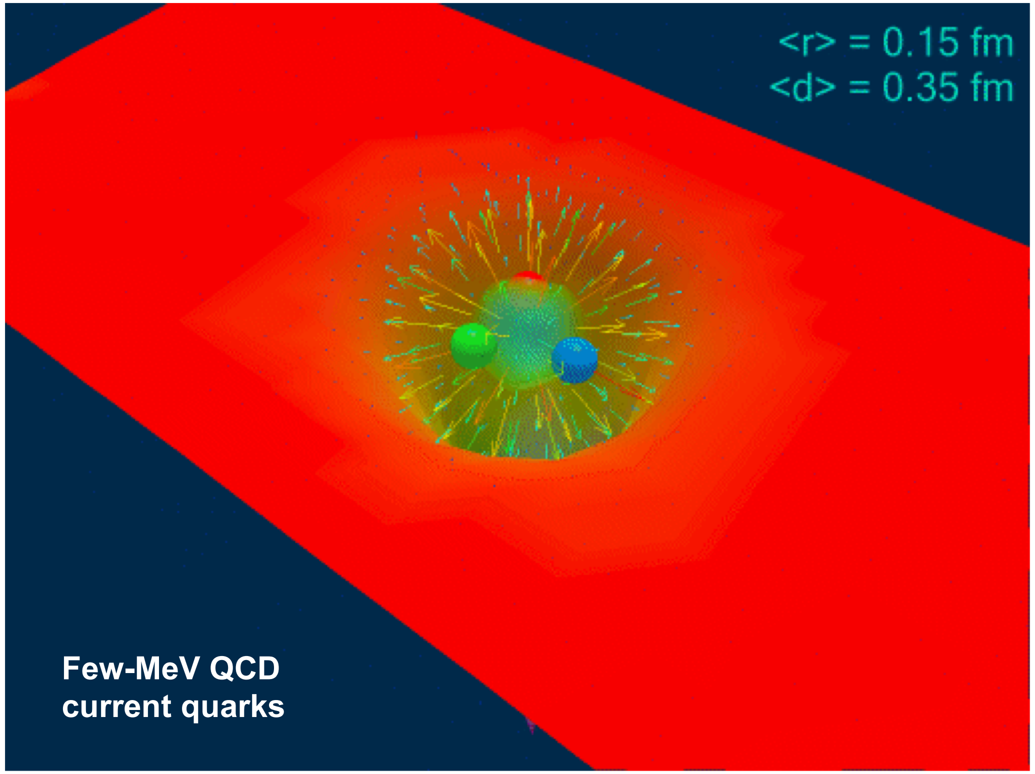

Fermions (matter)

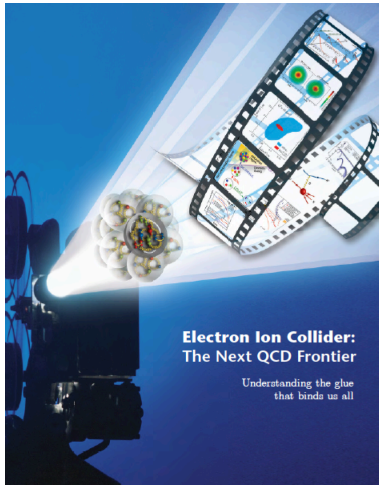
Bosons (force)

- Almost all mass is dynamically generated by the strong interaction (QCD). The Higgs mechanism contributes a few percent.

# Understanding the glue that binds us all



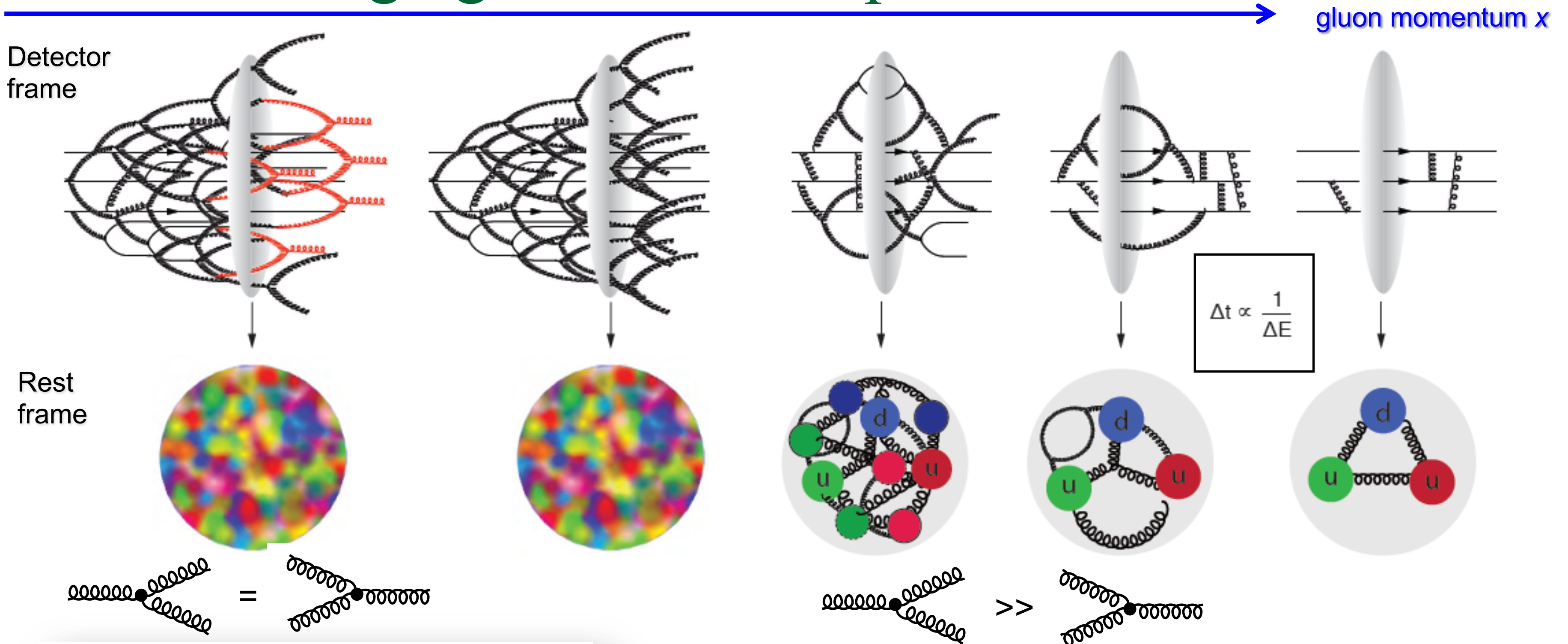



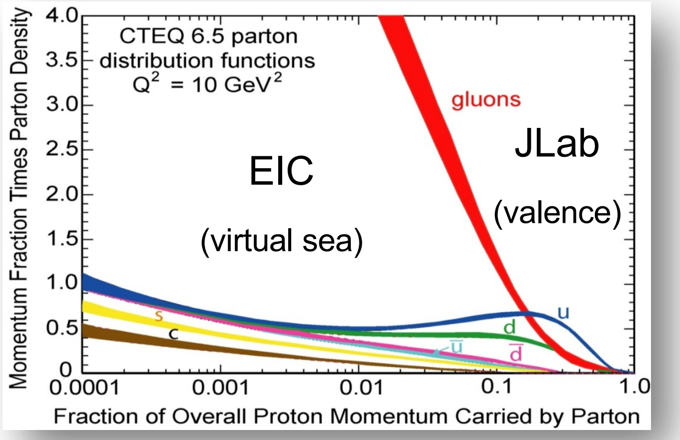



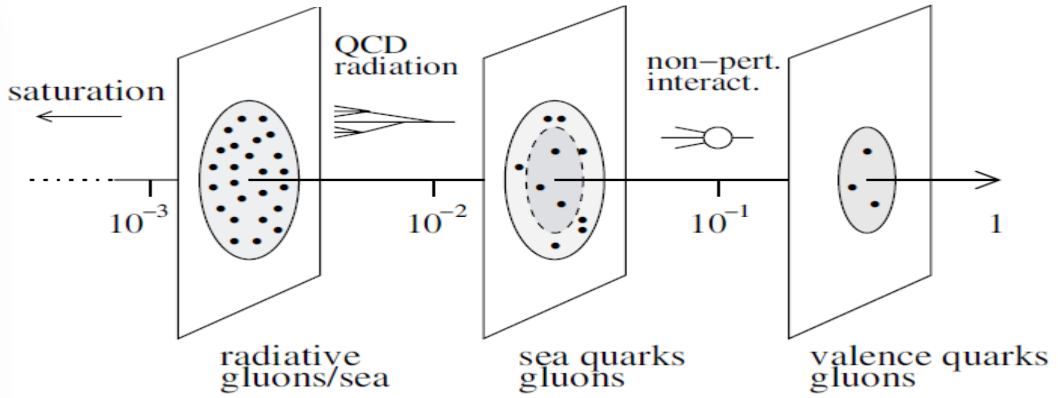

EIC white paper

- What is the spatial distribution of gluons and sea quarks in the proton?
- How do the quarks and gluons make up the proton spin?
- What happens at high gluon densities? Do gluons recombine and saturate?

# The changing nature of the proton

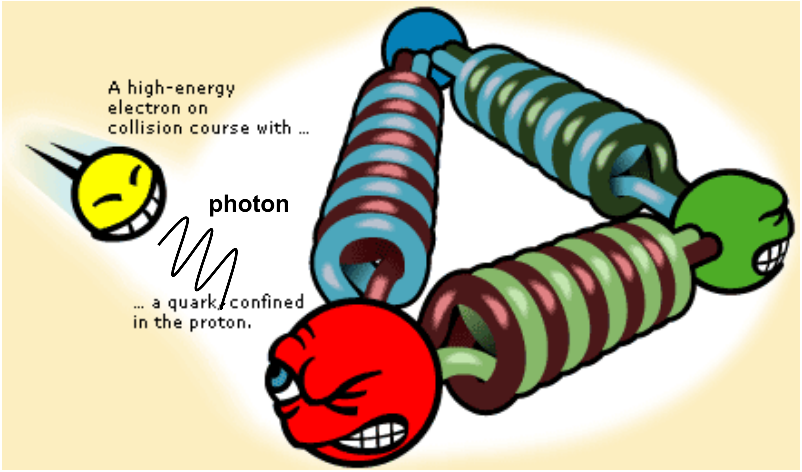


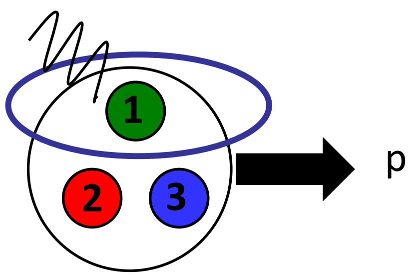



# Electron scattering: *x*, *t*, and *Q²*

- **$Q^2$** 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 a higher collision energy!



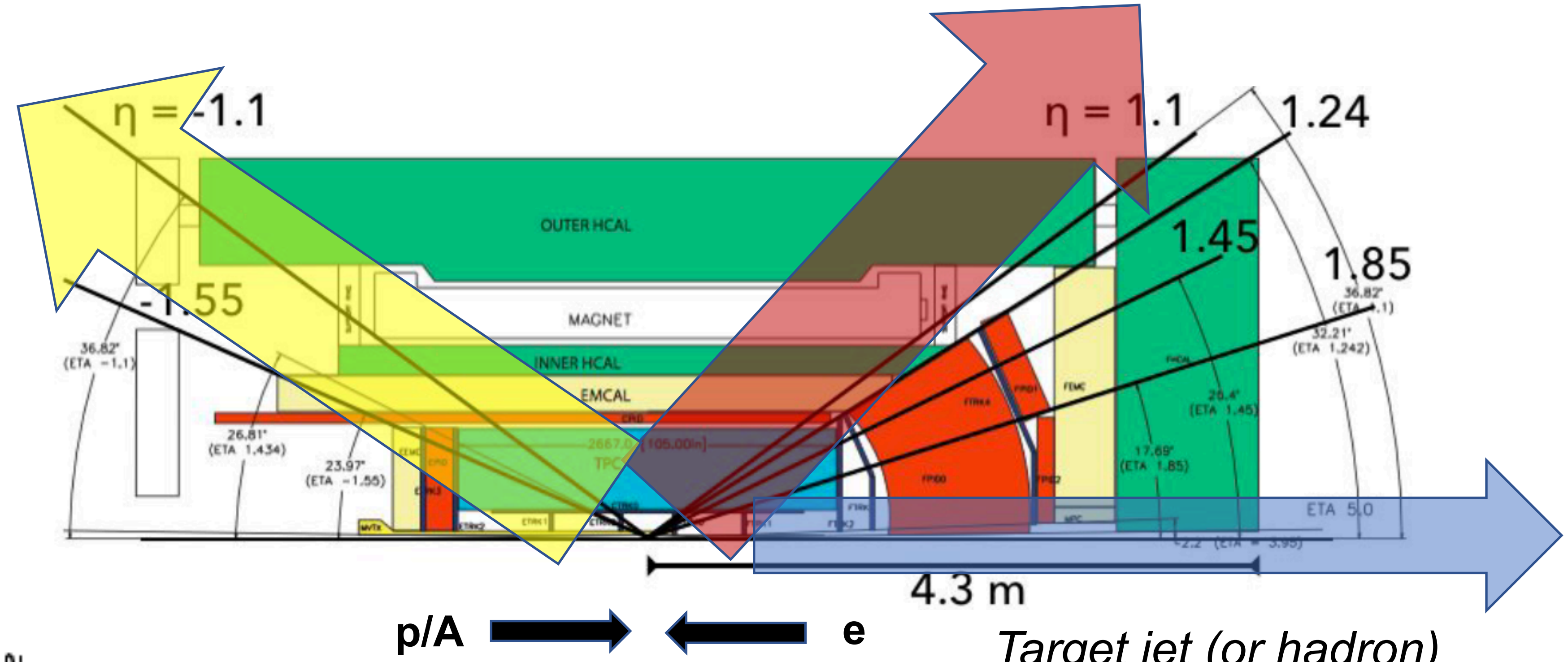

$$x = p_1 / p_{proton}$$

$$x = Q^2 / 2\, m_{proton}\, E_{photon}$$

# What do we detect?

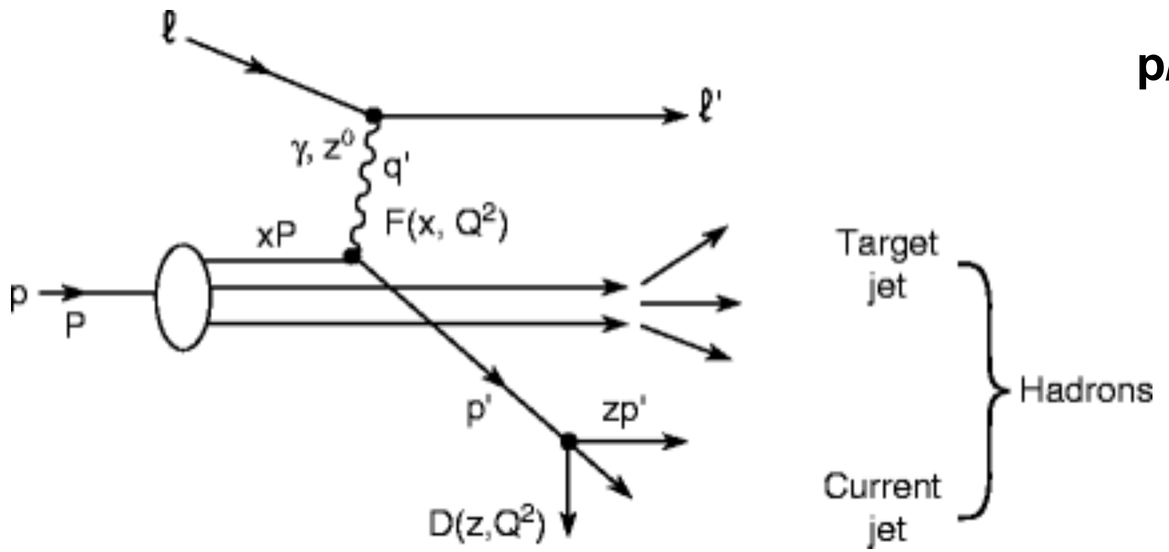
*Current jet (or hadron)*

*Scattered electron*




*Target jet (or hadron)*

Lepton scattering on a proton



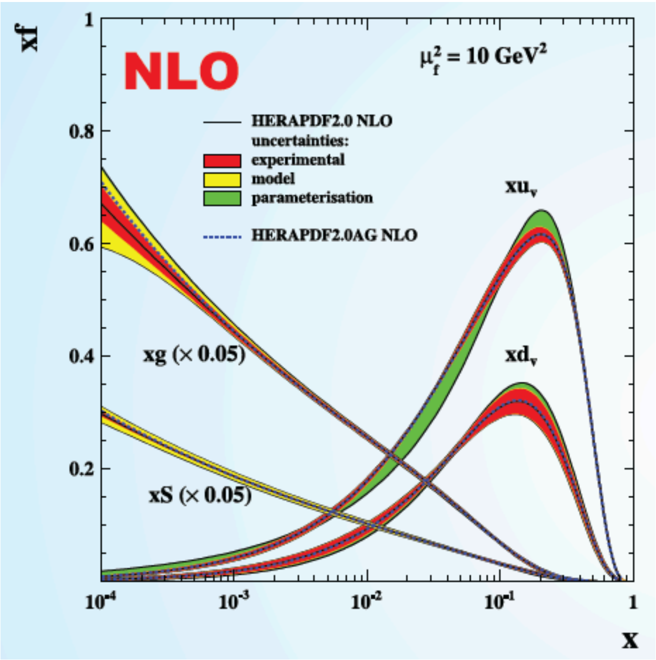

**Inclusive DIS:** only electron is detected

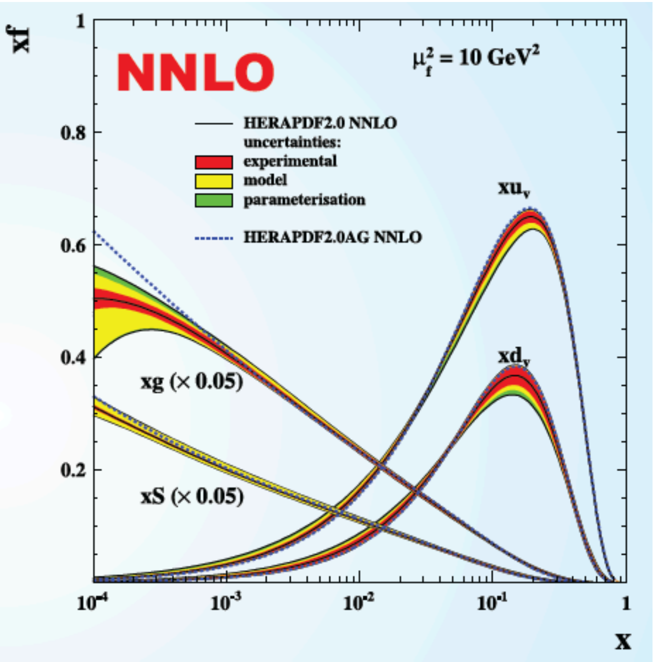
**Semi-Inclusive DIS (SIDIS):** electron and current jet (hadron) are detected.

**Exclusive reactions:** all particles are detected

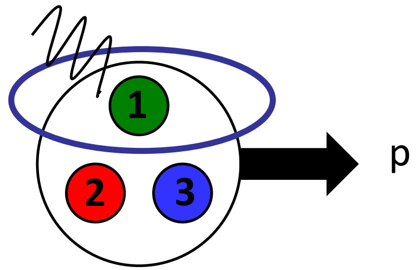
# Momentum distributions of quarks and gluons

Gluons saturate?




Accessed through **inclusive** reactions

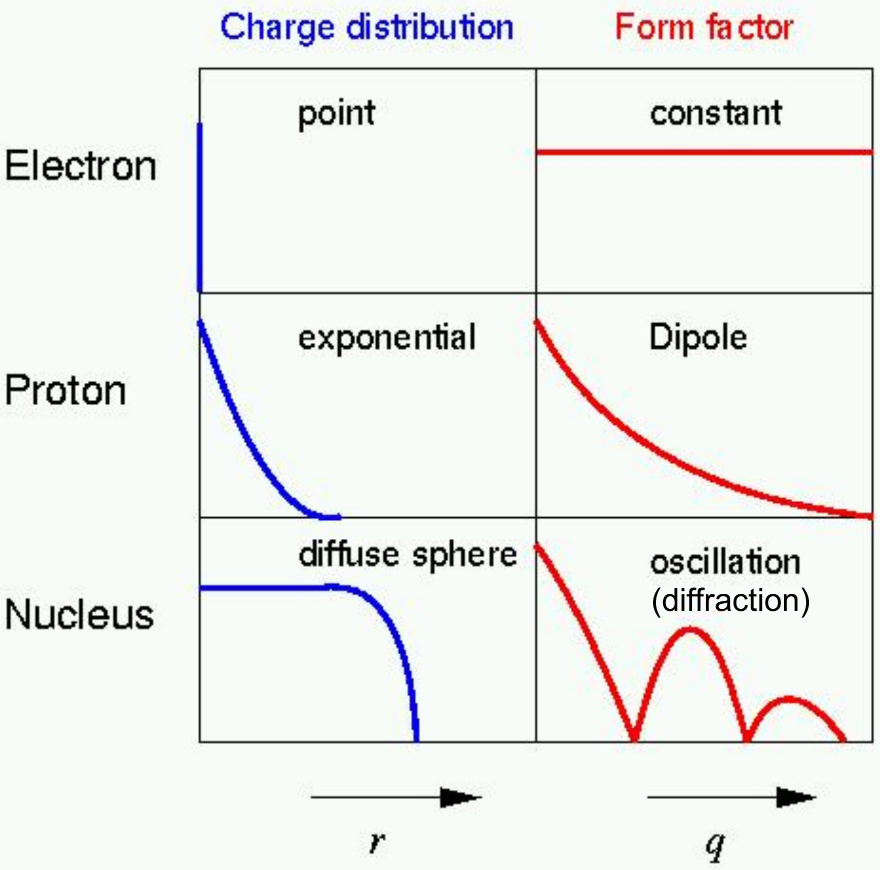



$\mathbf{x = p_1 / p_{proton}}$

Parton Distribution Functions (PDFs) tell us about the densities of quarks and gluons inside the proton as function of their momentum (fraction) x.

# Spatial charge distributions (form factors)

Form Factors characterize internal spatial structure of particles




- Elastic cross section

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left|F(q^2)\right|^2$$

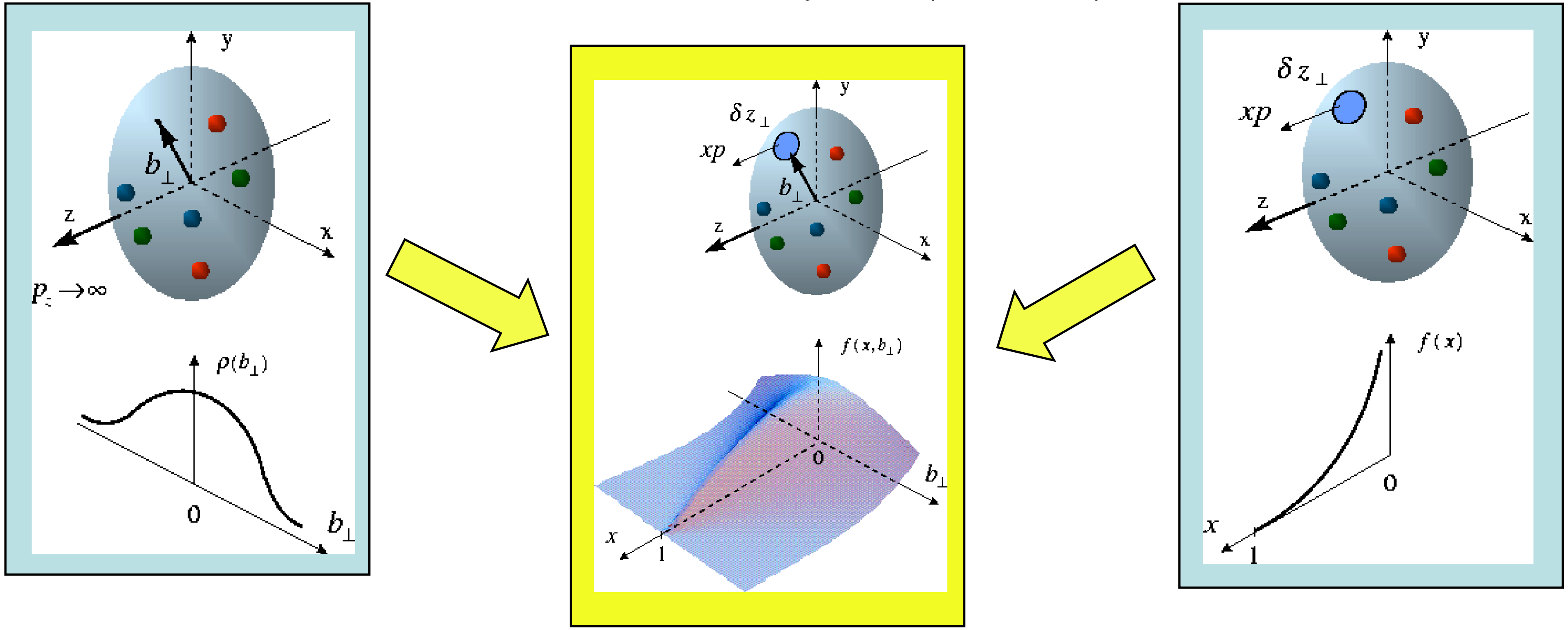
- Form factor

$$F(q^2) = \int e^{iqx/\hbar}\rho(x)d^3x$$

The form factor as a Fourier transformation of the charge distribution is a non-relativistic concept.

# Tomography of the nucleon (and nuclei)

X. Ji,  D. Mueller, A. Radyushkin (1994-1997)




Transverse charge & current densities (Form Factors)

Correlated quark momentum and transverse spatial distributions (Generalized Parton Distributions)

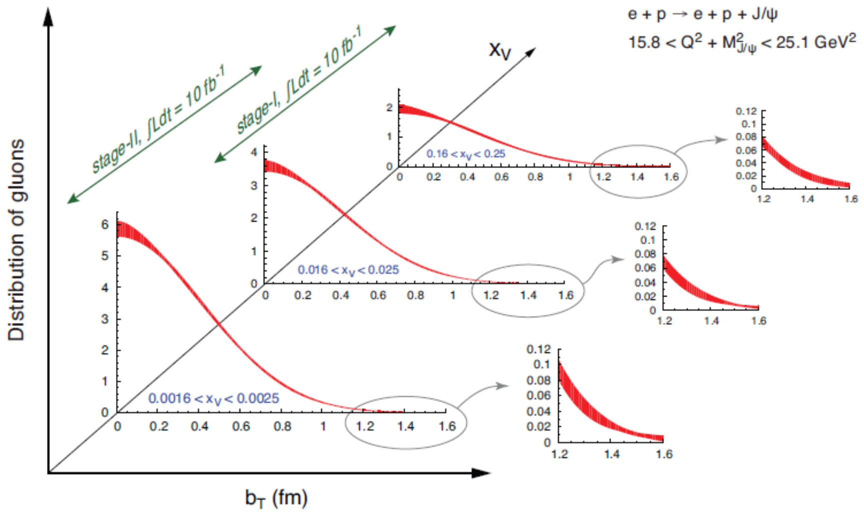
Longitudinal momentum distributions (Parton Distribution Functions)

# Transverse imaging in coordinate and momentum space

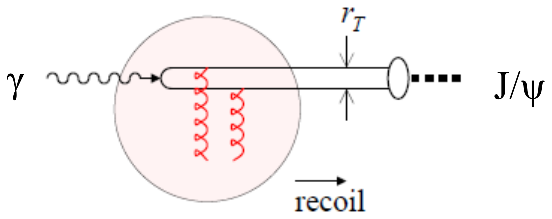
<u>GPDs</u>

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

Accessed through **exclusive** reactions



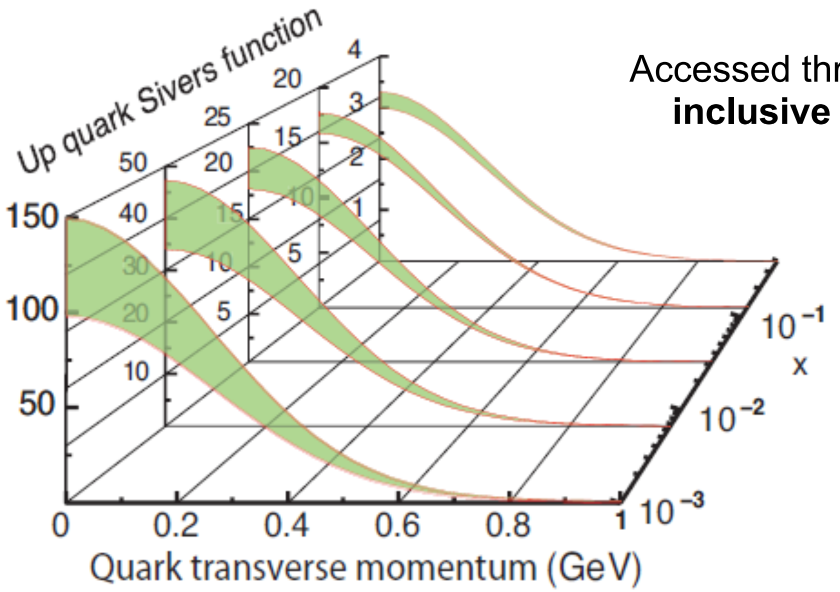

Transverse gluon distribution from J/ψ production




<u>TMDs</u>

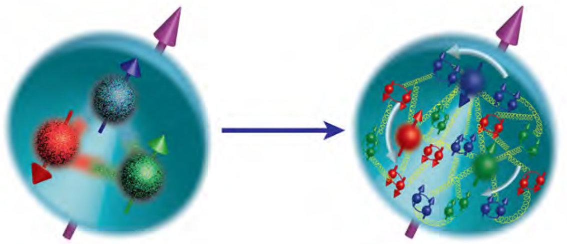
2+1 D picture in **momentum space**

Accessed through **semi-inclusive** reactions




*Projections from EIC white paper*

# The spin of the proton



The nucleon spin reflects both the polarization of quarks and gluons, and their orbital motion.

$$\tfrac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + L_q(\mu) + \Delta G(\mu) + L_g(\mu)$$

polarization orbit polarization orbit

quarks gluons

Two complementary approaches needed to resolve proton spin puzzle

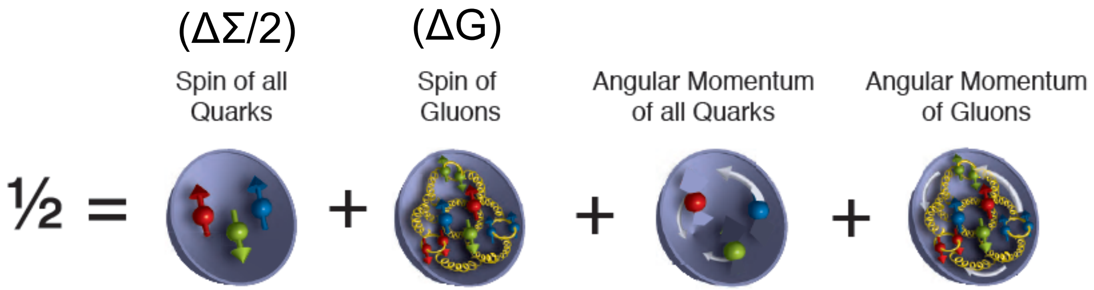
Measure $\Delta G$ - gluon polarization

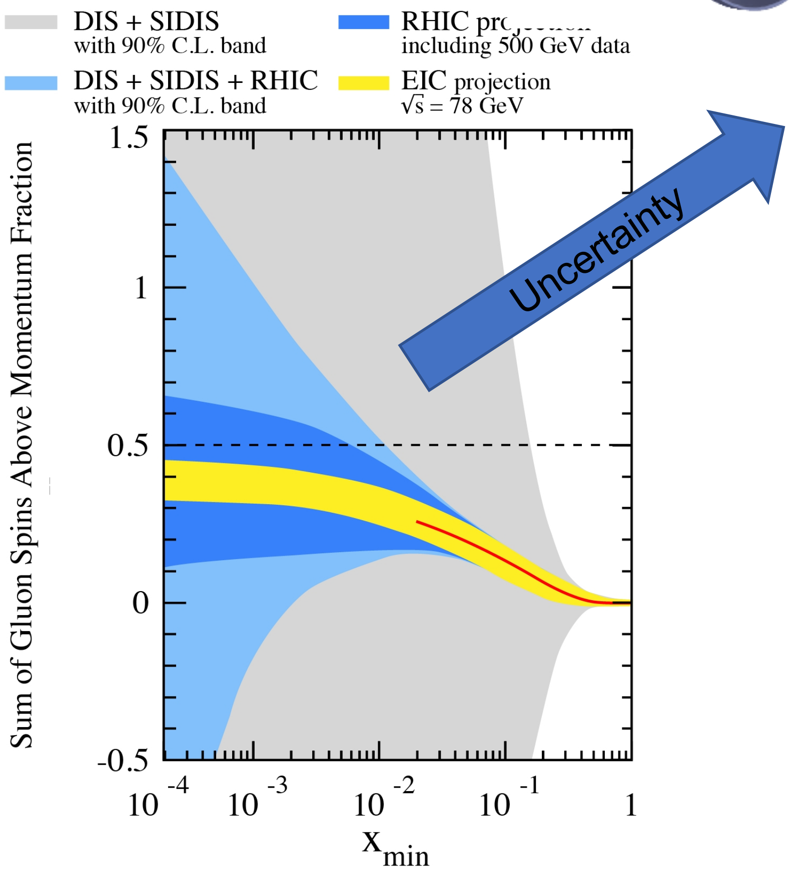
Measure GPDs and TMDs - orbital motion

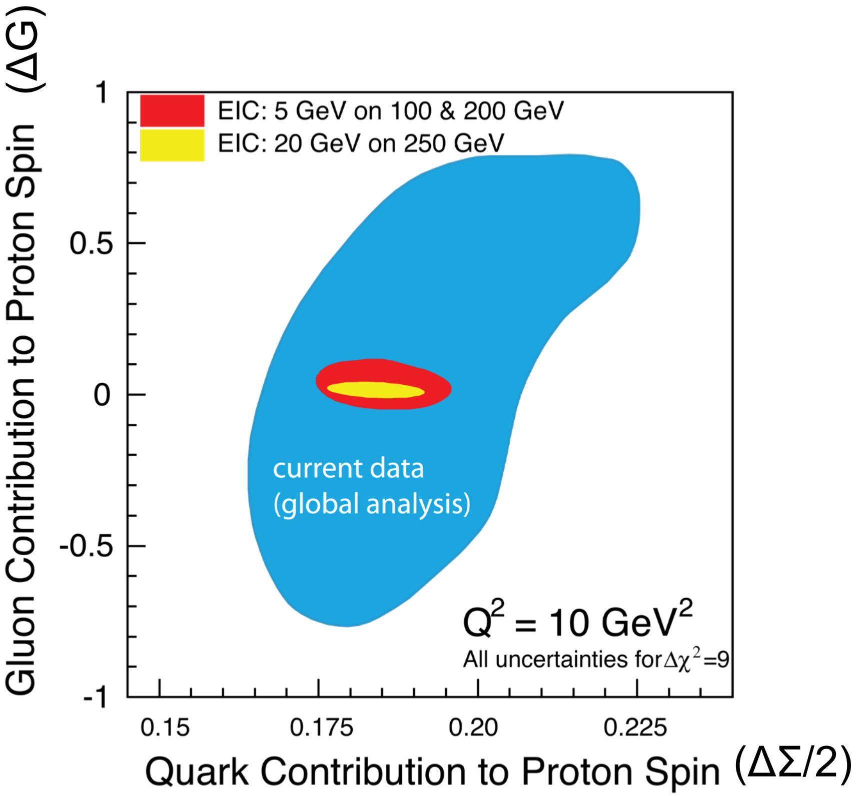
$$J = \frac{1}{2}\int_{-1}^{1} dx\, x[H(x,\xi,t) + E(x,\xi,t)]$$

*Ji sum rule for GPDs H and E*

# Gluon polarization

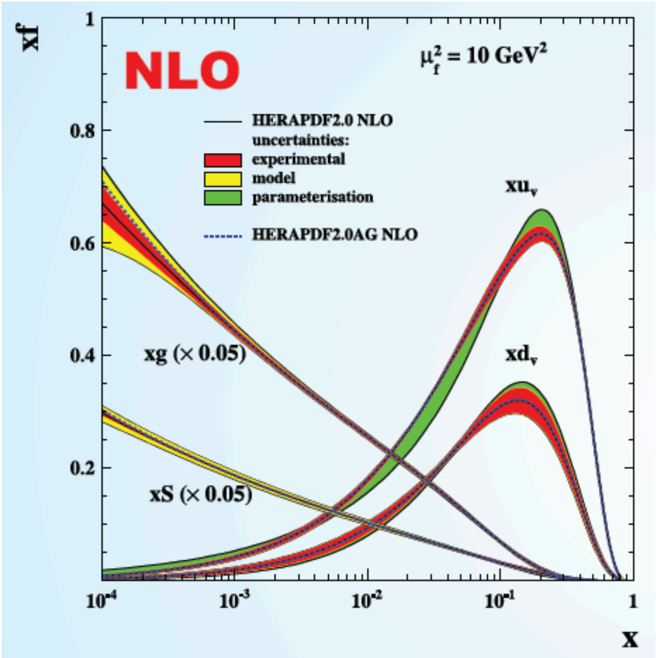


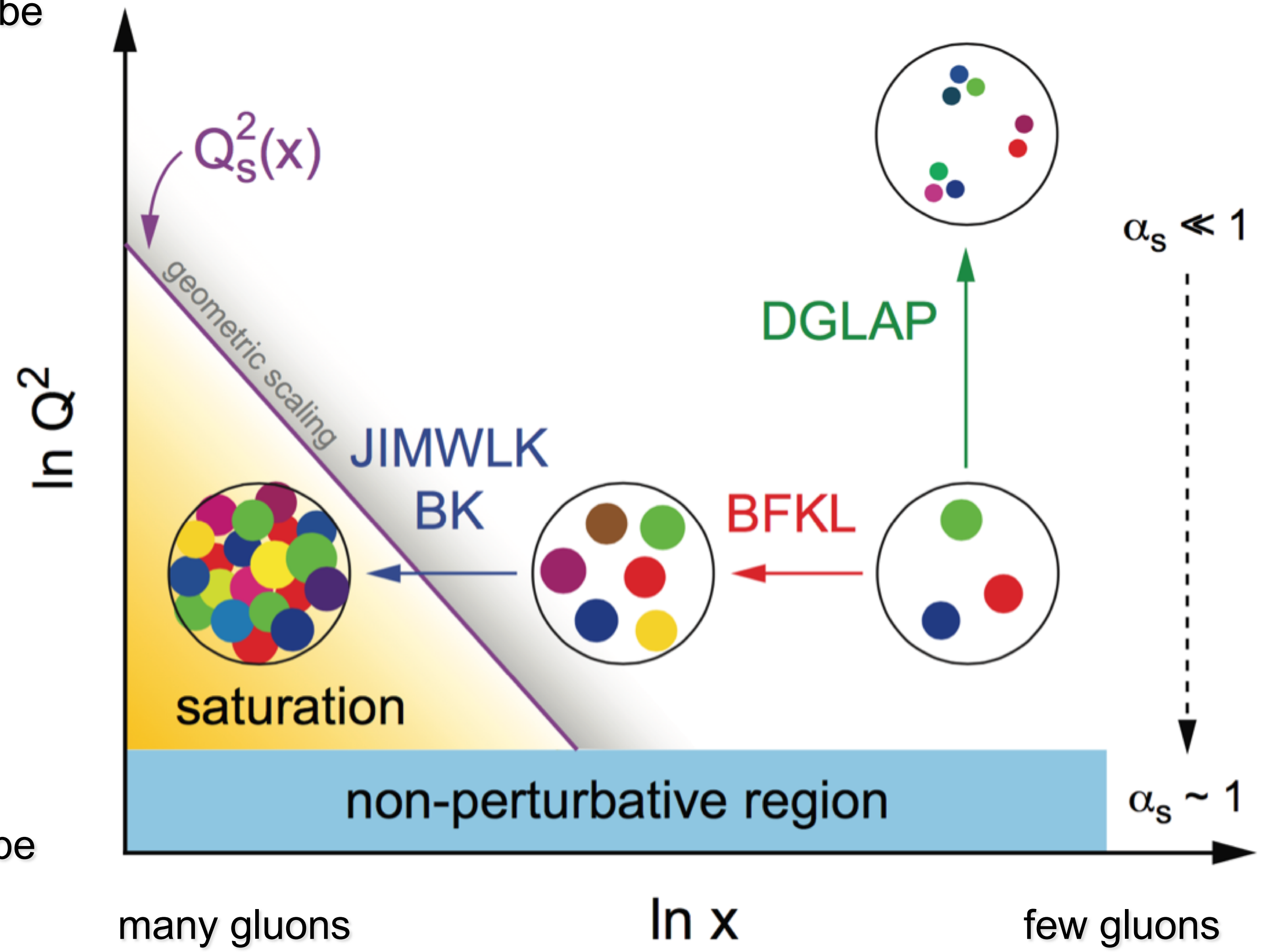

- Large uncertainties at low x require input from the EIC in addition to RHIC spin

# Gluon saturation in the proton

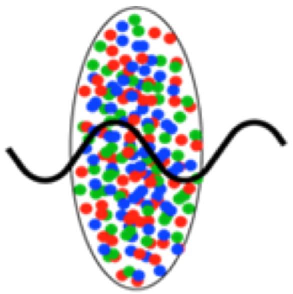



small probe

large probe

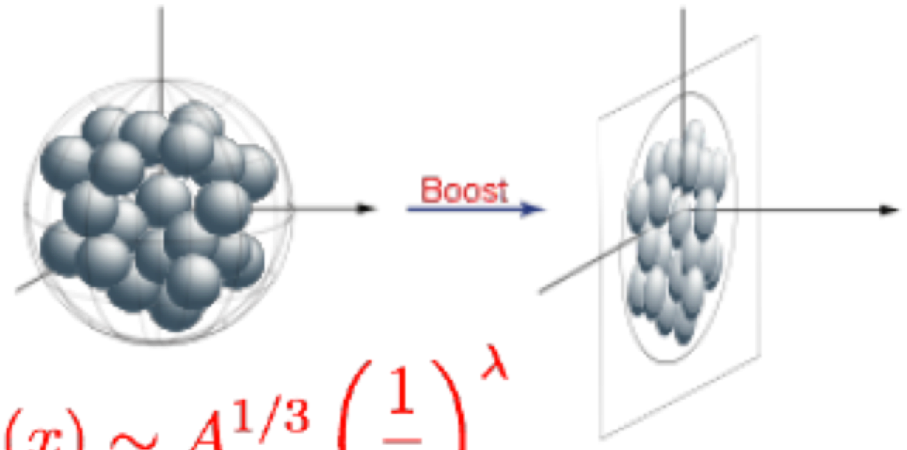


# Gluon saturation in nuclei

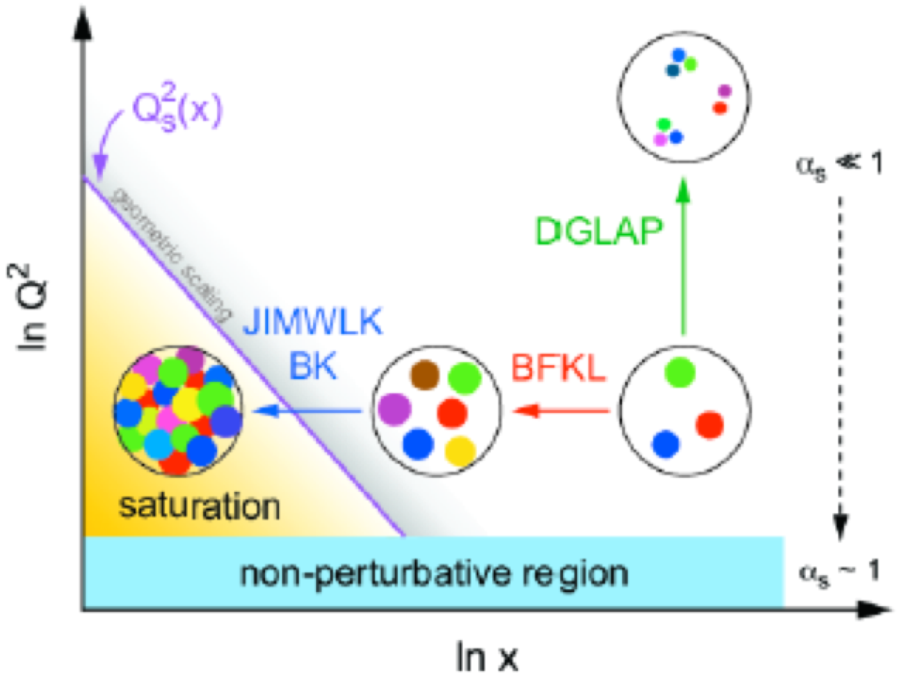


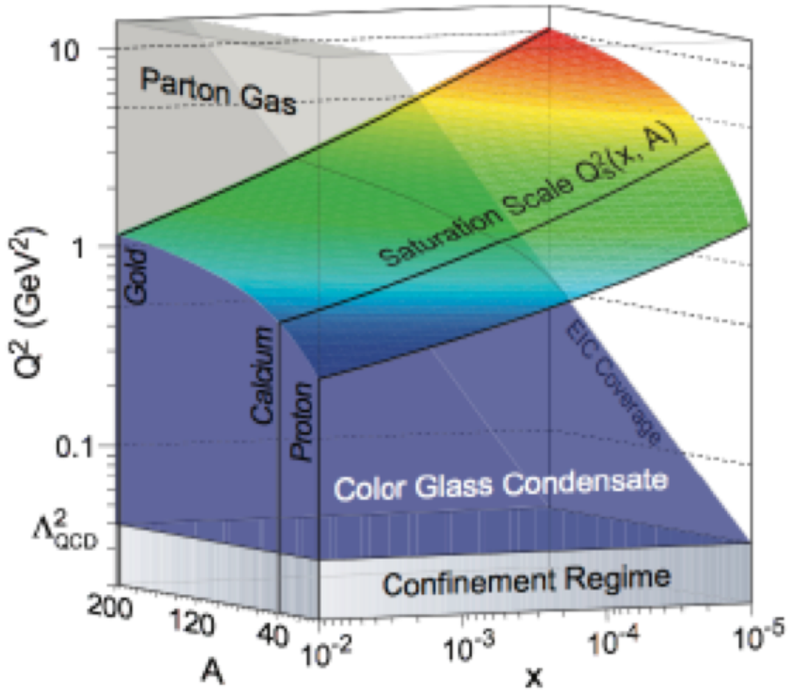
At low x the coherence length of the photon is larger than the nucleus (rest frame).

Detector frame: the nucleus is compressed into a pancake

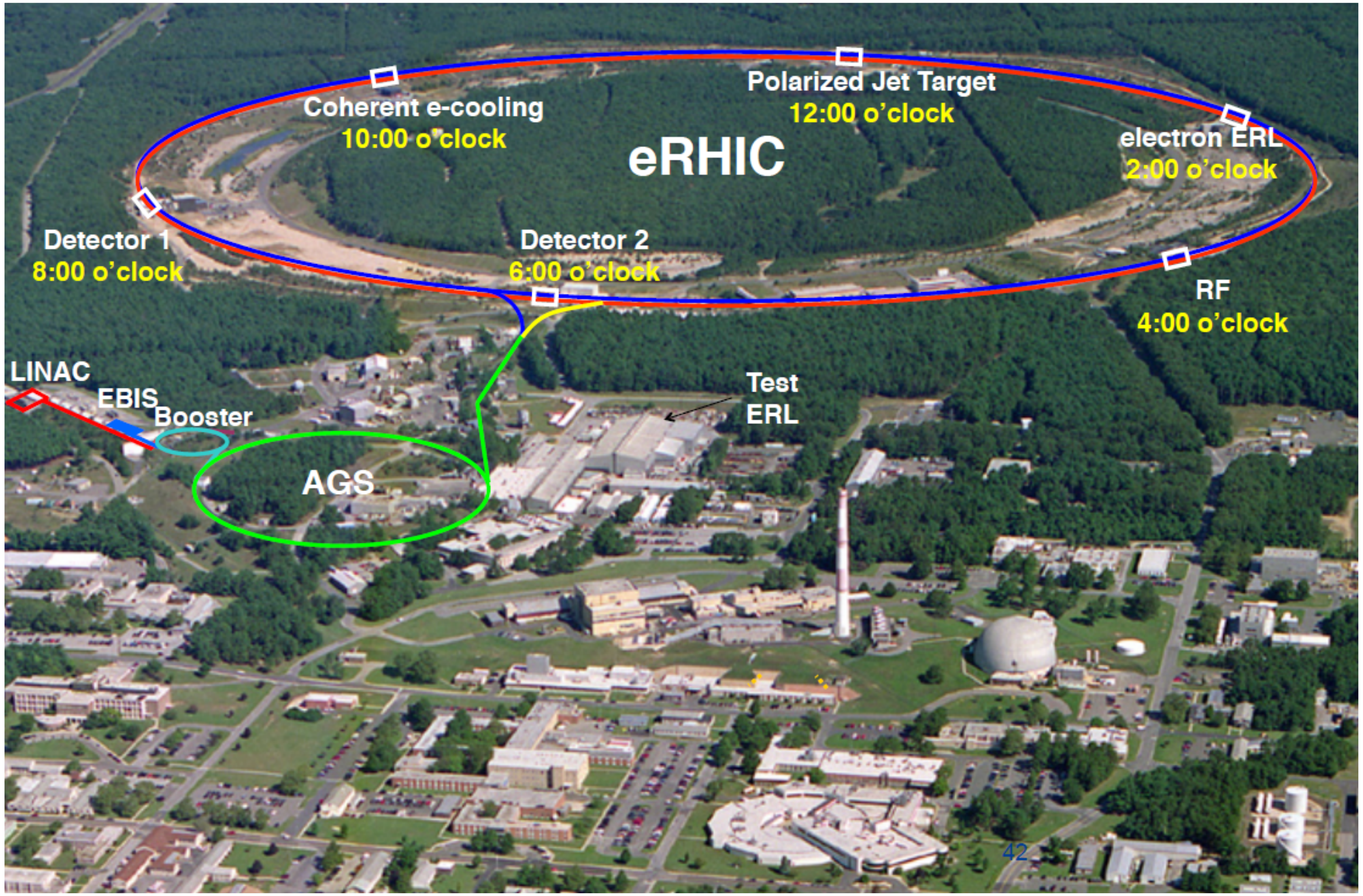



$$Q_s^2(x) \sim A^{1/3}\left(\frac{1}{x}\right)^{\lambda}$$



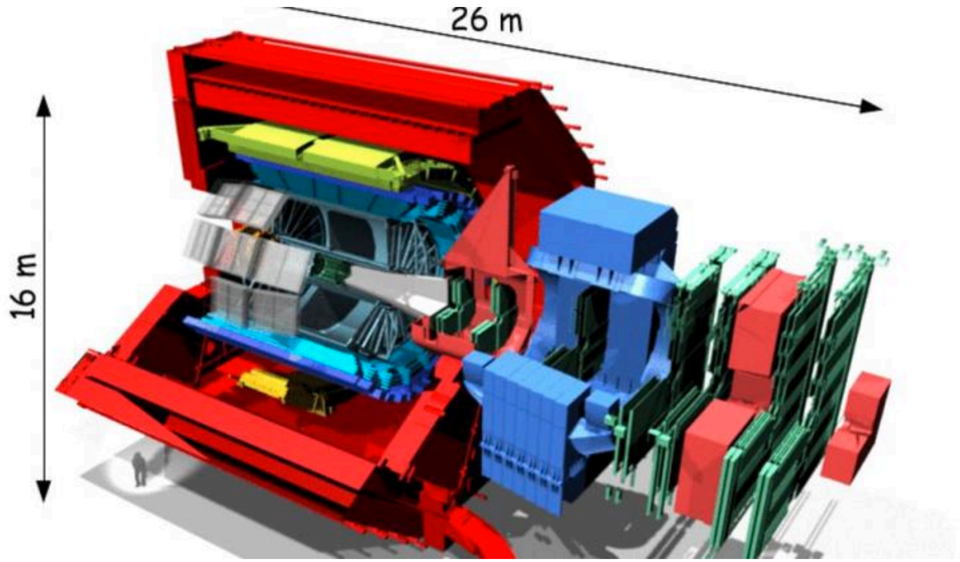
# The Electron-Ion Collider at BNL



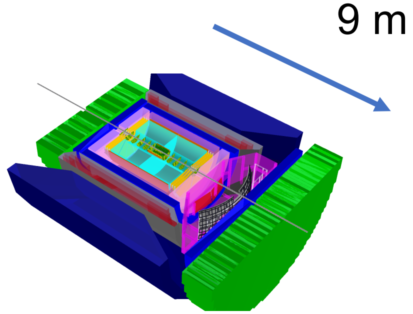

- 5-18 GeV polarized e- beams
  - 10 GeV luminosity maximum.
- 41-275 GeV polarized p beams
  - Luminosity max at top energy
- Ion beams up to 110 GeV/A
  - Any ion species in principle possible from d to U
- One detector is included in the project, but two would be desirable if funding permits

# EIC detector requirements are diverse and demanding

ALICE

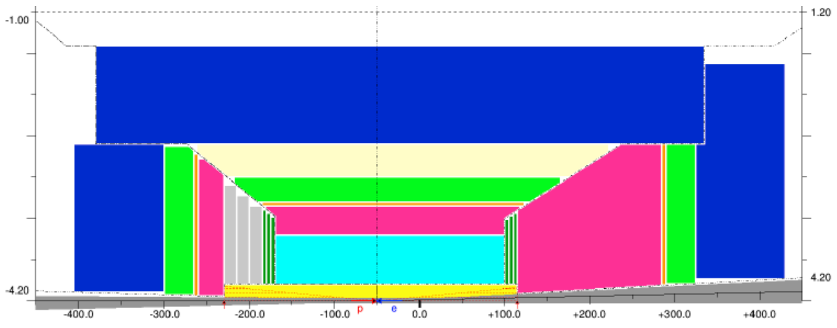


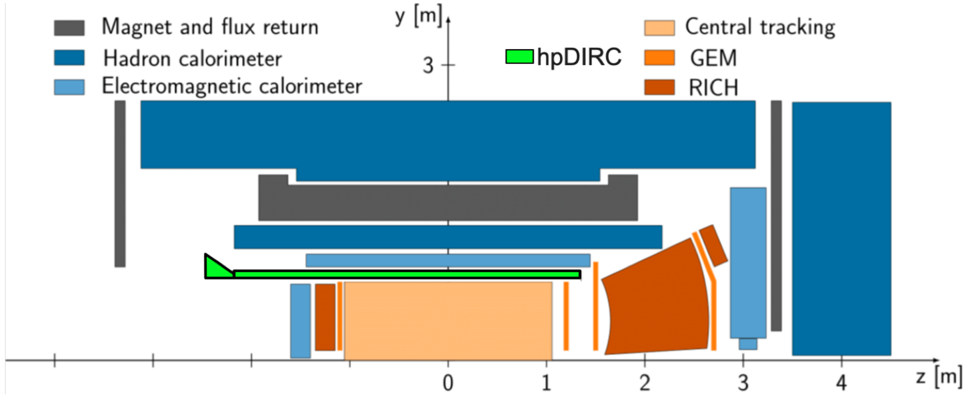

EIC detector




- In order to reach the luminosity goal, the EIC detector is limited to a length of 9 m.
- The physics require a hermetic detector with a full suite of subsystems allowing for precise measurement and identification of anything from single photons and mesons to jets
- The collision kinematics are very asymmetric, requiring different technologies in different parts of the detector

# A two detector scenario?


2020 Yellow Report "Reference Detector"



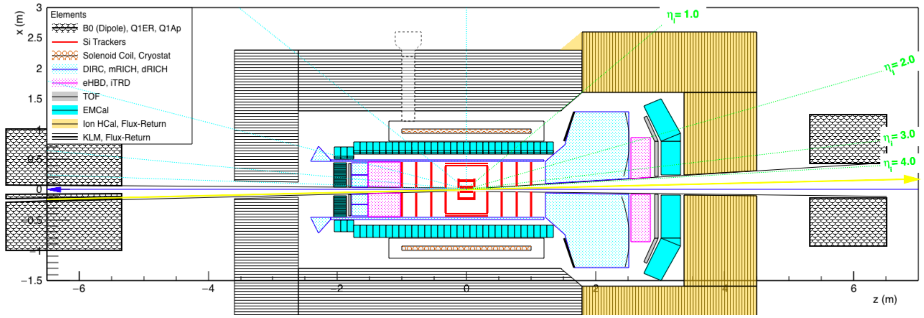
EIC-sPHENIX from 2018 LOI

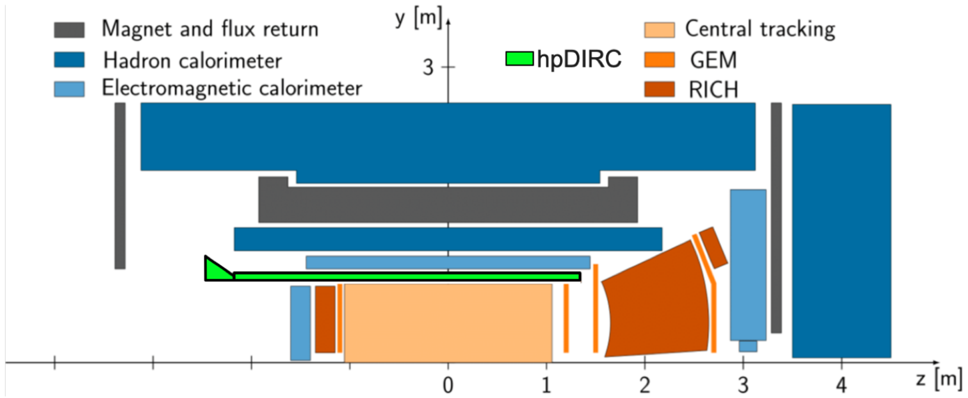
- To realize a two-detector scenario, we need three ingredients
  - A primary detector that can satisfy the key EIC physics goals within a moderate budget
  - A second detector that save costs by re-using suitable existing components (e.g., magnet, barrel Hcal, and TPC from sPHENIX).
  - A complementarity between the two focusing on function rather than just technology

- The Yellow Report "reference detector" is, however, generally similar in size and layout to the "EIC-sPHENIX" proposal from 2018.
  - The main differences are that the "reference detector" has less space for PID, may have an electron-side Hcal, and envisions using more expensive subsystems.

# The compact EIC detector

Compact EIC detector



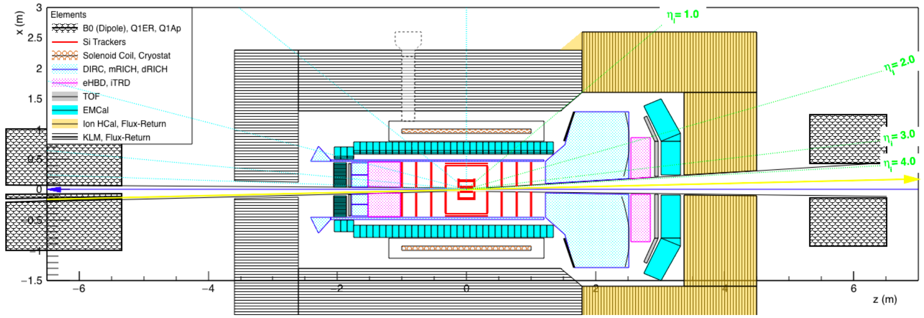



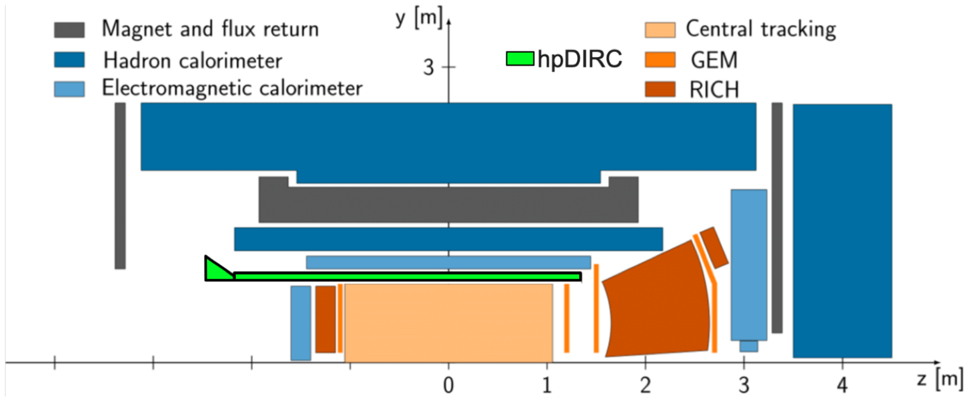

EIC-sPHENIX from 2018 LOI

- A hermetic general-purpose detector that fulfills all physics requirements. It saves cost by reducing the size, but not performance of its subsystems:
  - Risk minimized by utilizing components from Generic EIC R&D program
- Key concepts:
  - A small (ALICE-inspired) central Si-tracker and ultra-compact DIRC barrel Cherenkov
  - An inexpensive barrel muon ID system integrated with the flux return of a new, small solenoid that can also provide a neutral particle veto for jets (like the Belle II KLM)
  - A high-resolution Hcal (yellow) and a dual-radiator RICH (with outward-reflecting mirrors) at forward rapidities (to the right, in the ion beam direction)

# Complementarity

Compact EIC detector



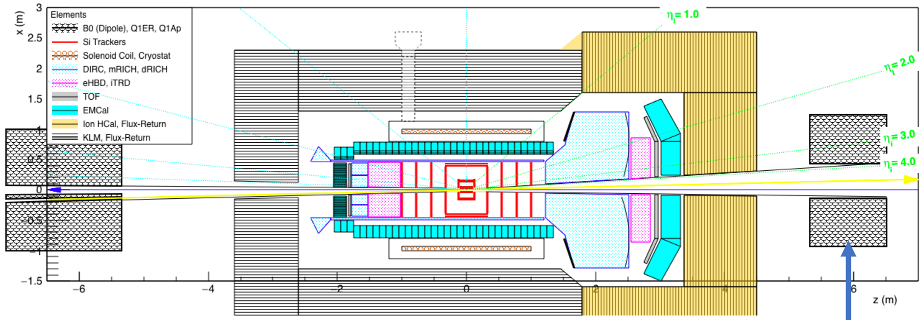

EIC-sPHENIX from 2018 LOI

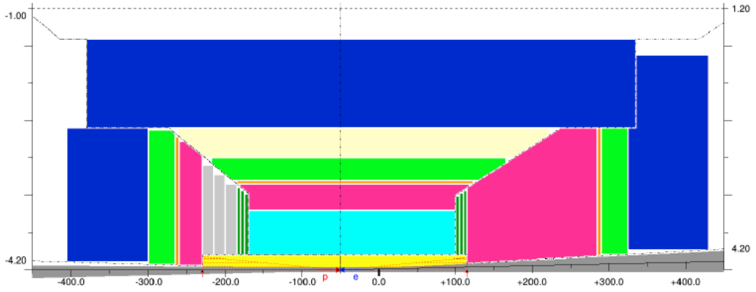
- The compact detector can support all aspects of the EIC physics program, but the concept is naturally complementary with an EIC upgrade of sPHENIX.

- Key areas of complementarity :
  - Barrel: KLM for muon ID and low-energy jets vs Hcal for high-energy jets
  - Hadron endcap: dual-radiator RICH for optimal momentum coverage vs gas-only RICH, which could cover larger angles (if the inner Hcal was removed from sPHENIX) and more easily deal with higher-multiplicity jets
  - Technological complementarities include tracking (Si vs TPC). Different choices EM calorimetry in the barrel and both EMcal and Hcal in the hadron endcap are also possible.

# Integration

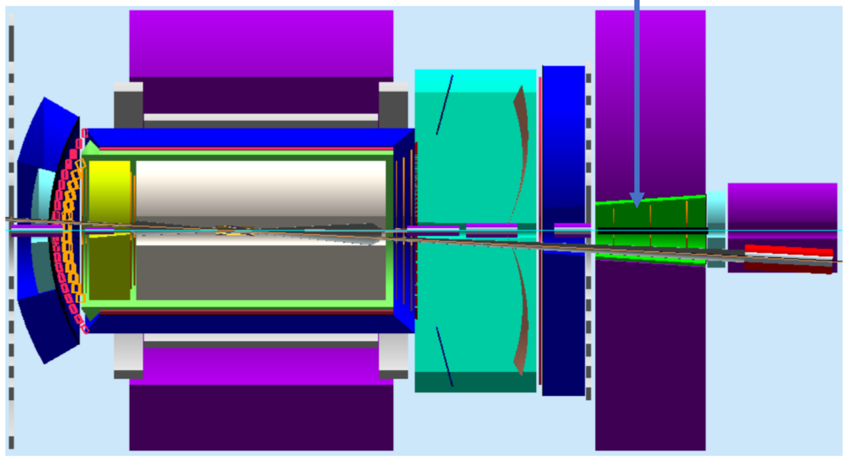
Compact EIC detector



Yellow Report “Reference Detector”

Two options for “B0” dipole integration

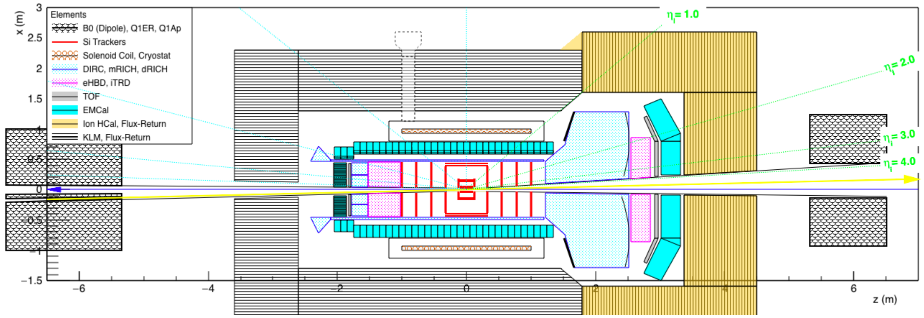


2015 JLab  EIC detector

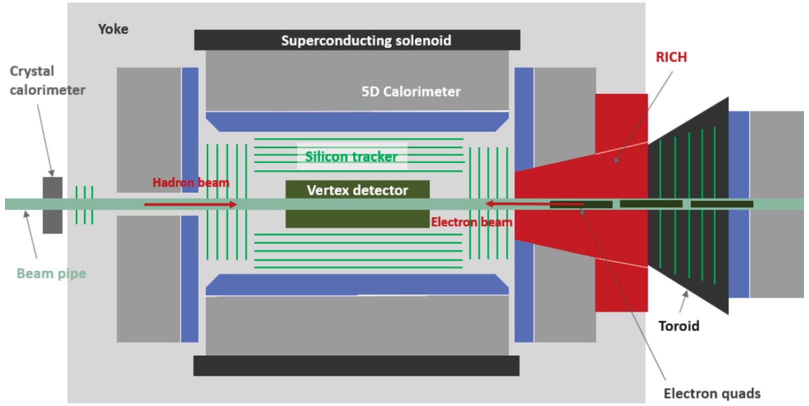
- Integration of all subsystems of the detector within the limited space provided by the 9 m long interaction region can be challenging
- The compact detector provides a simple solution to this problem
- An alternative approach, making maximum use of the available space, was chosen for the JLab detector concept
    - But the larger size would likely increase cost

# Why not an "all-silicon" detector?

Compact EIC detector

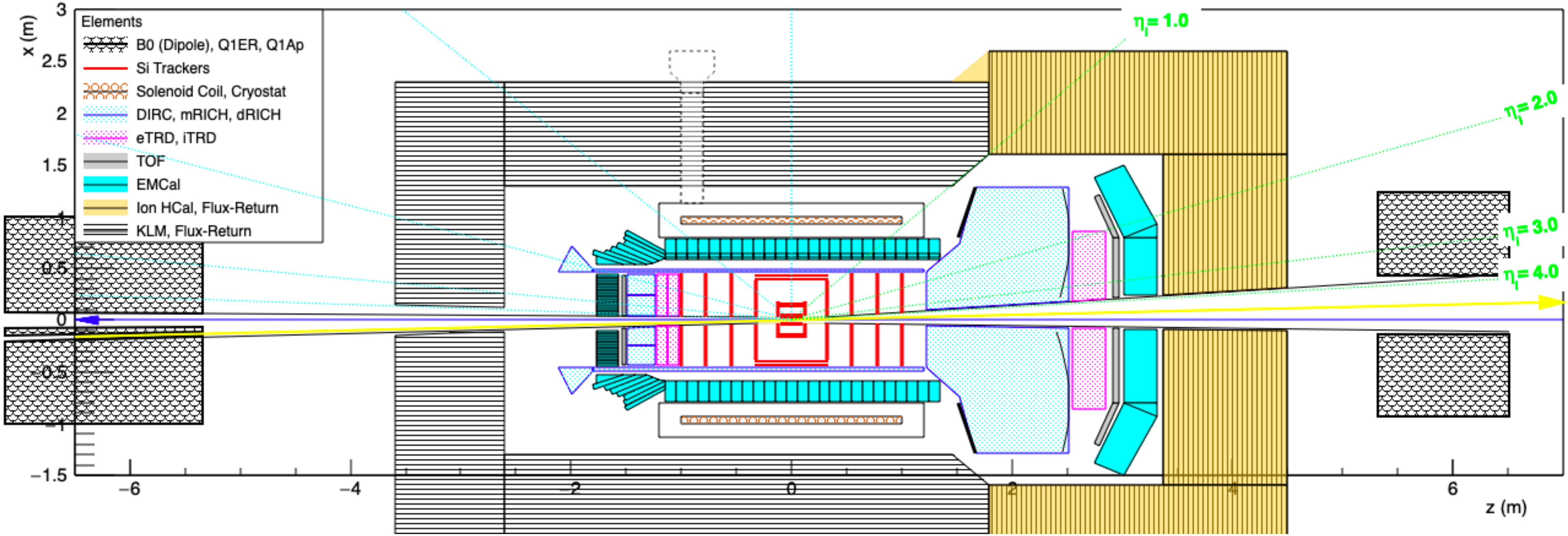



ANL "TOPSiDE" detector



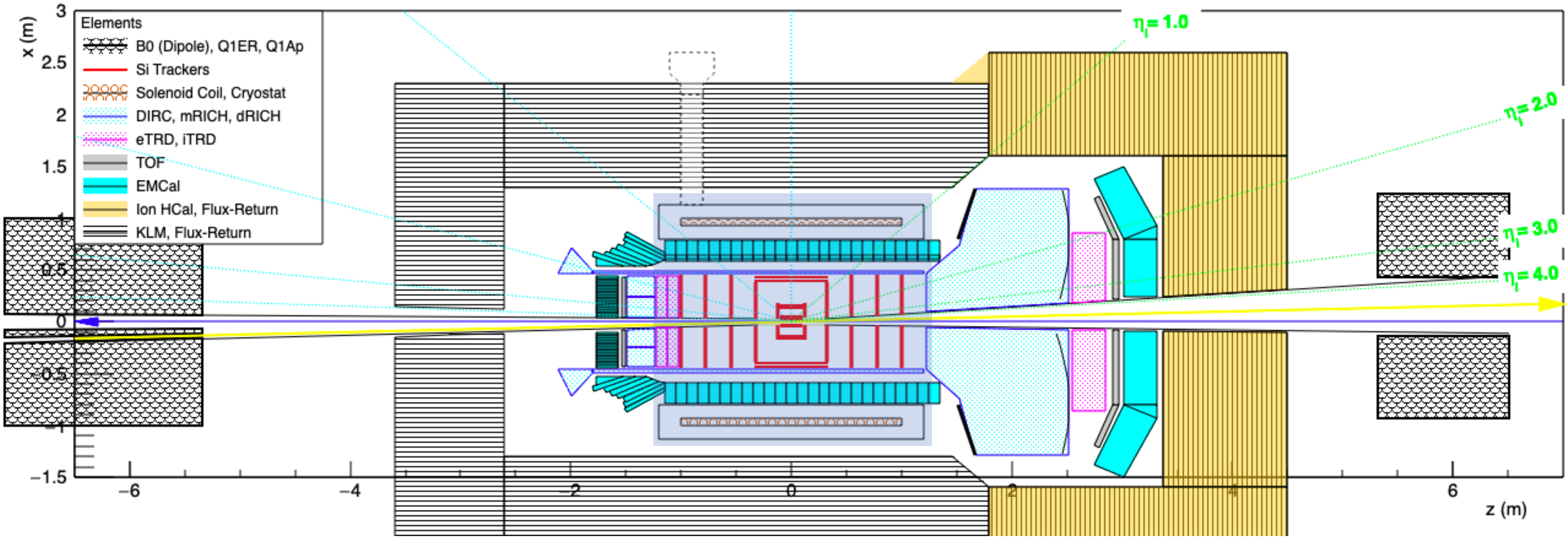

- In the compact detector, the main benefit provided by the central Si-tracker is a smaller size, which in turn reduces the cost of the outer systems.
- Since Cherenkov detectors do not rely on a long flight path, they are a natural choice for high-performance PID in any EIC detector, but in particular a compact one.
- Replacing the Cherenkov-based PID with high-resolution (10 ps) timing, would require a much larger and more expensive detector, which would still not reach the same level of performance.

# The compact EIC detector – overview




- The picture shows an HBD in front of the mRICH and a TRD behind the dRICH. A more ideal configuration would likely be a TRD behind the mRICH but none behind the dRICH.
  - This is still a concept detector that can be optimized in many ways!

# The compact EIC detector – solenoid



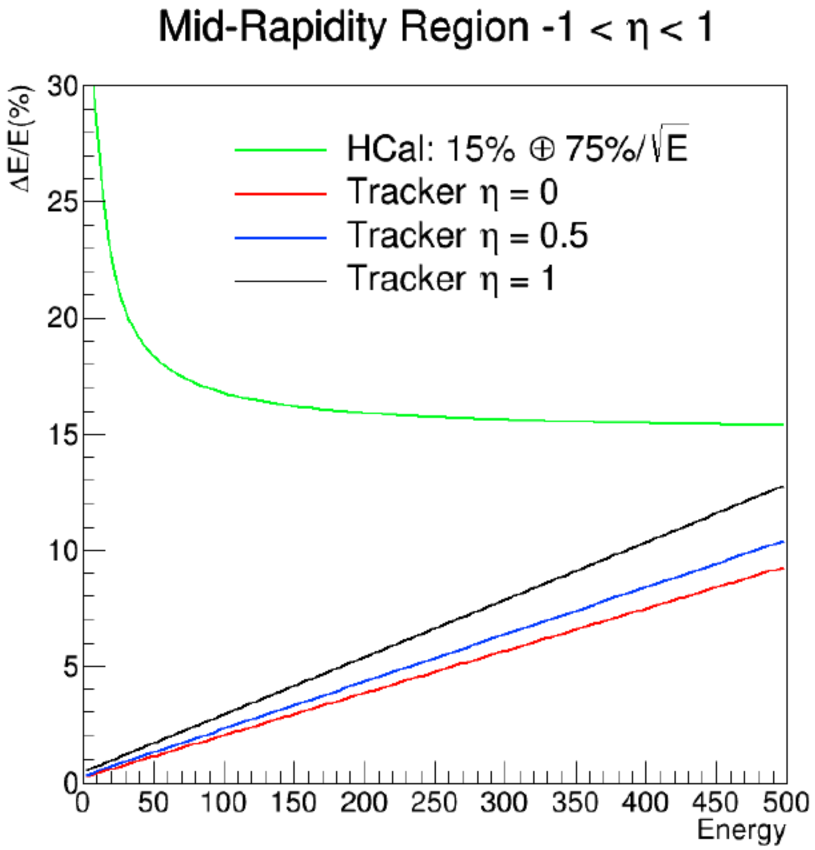

- New 2 T solenoid with a magnetic volume of about $2\pi$ m$^3$ compared with $7.8\pi$ m$^3$ in BaBar.
  - The Si-tracker does not require a flat field, which thus can be optimized for the Cherenkovs.
- The KLM can be integrated with the flux return at a moderate cost.

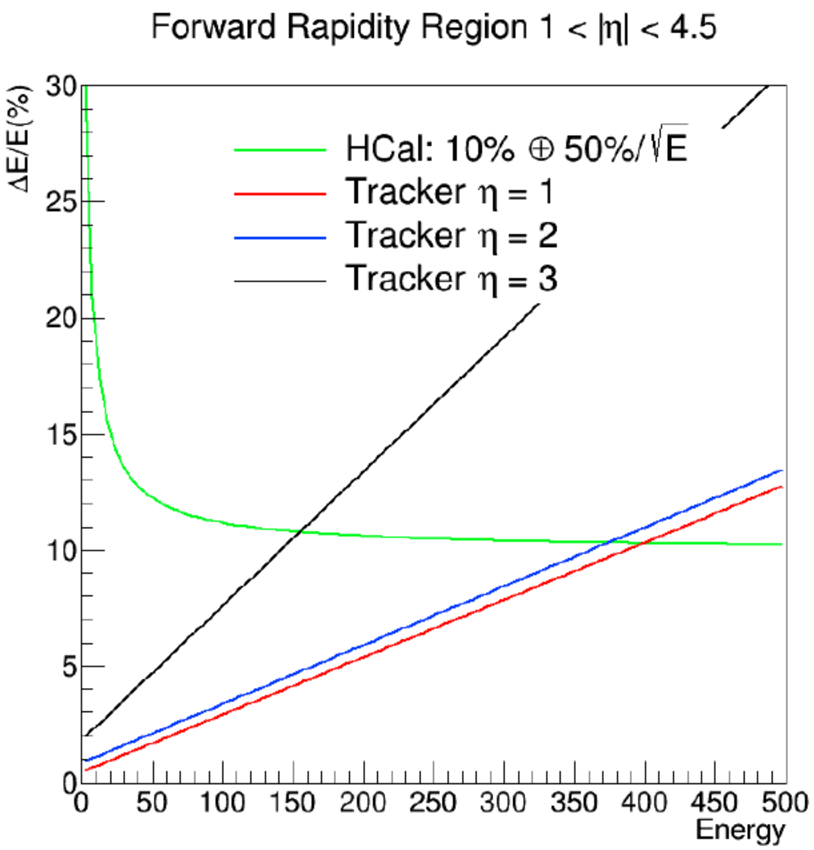
# Hadronic calorimetry

# Tracker Vs HCal Resolution

Brian Page

- At mid-rapidity, an Hcal does not reconstruct the jet energy as well as tracking and PID.
  - Both jet energies and multiplicities are low
- A high-resolution Hcal is needed in the hadron endcap.
  - In addition to jets, it is also needed for kinematic reconstruction (hadronic method)



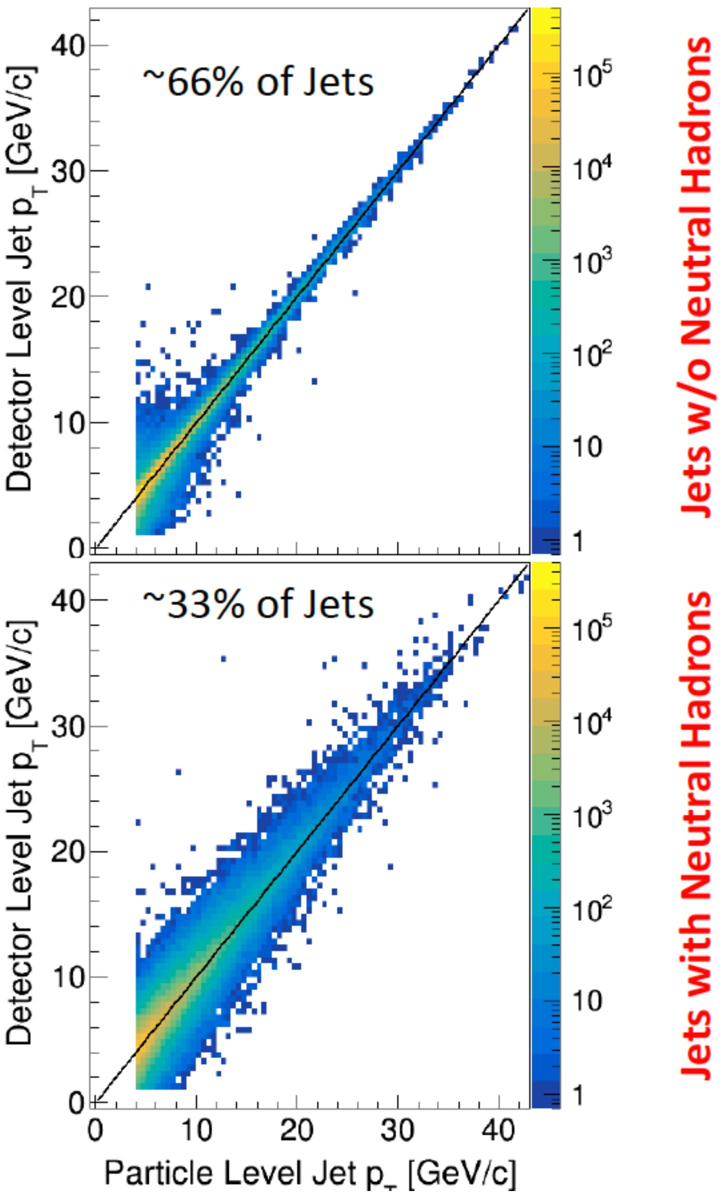

- Tracker provides better resolutions for nearly all energies and pseudorapidities
- Assumption: use tracker for all hadrons except long lived neutrals such as neutrons and $K^0_L$s

# Neutral Hadron Veto

Brian Page

## Hadronic calorimetry

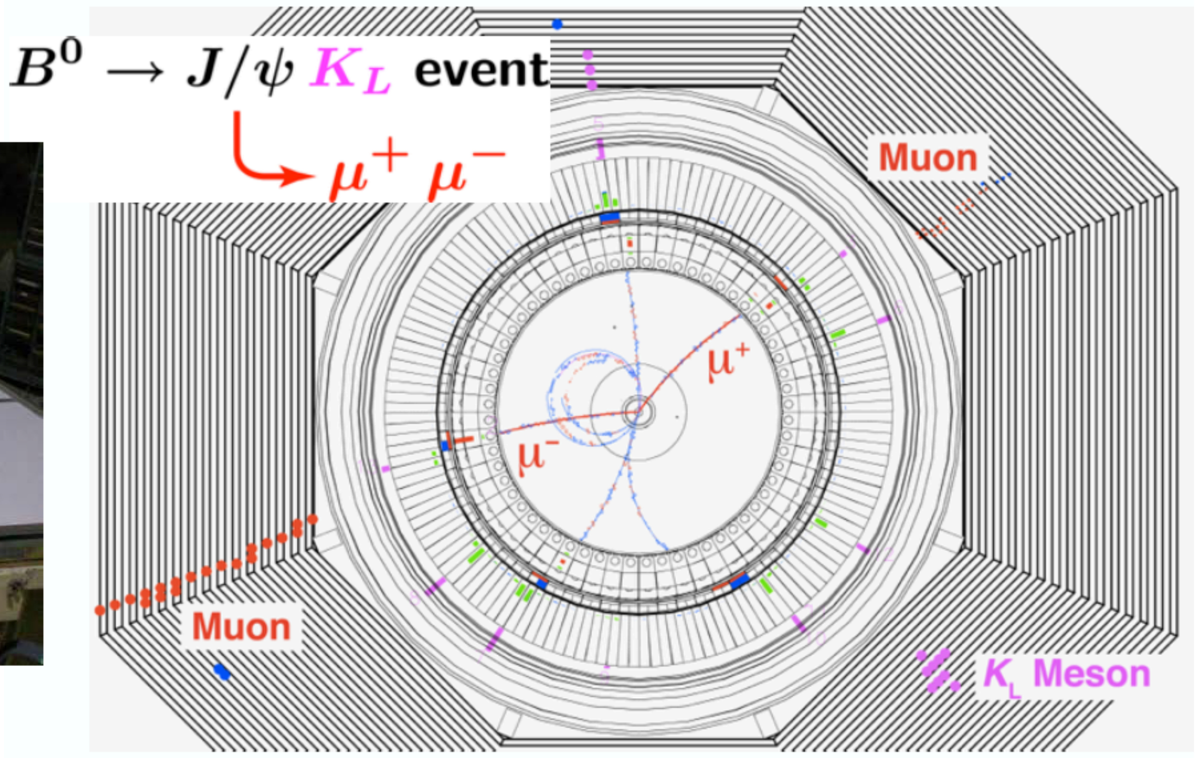
- Vetoing jets containing a $K_L$ improves resolution
- The veto efficiency can be determined precisely by comparing $K_L$ and $K_s$ yields.
- The energy information from a traditional Hcal does not improve the resolution for jets with a missing few-GeV $K_L$
  - Overall smearing remains comparable




arXiv:1911.00657

- A low energy resolution HCal may not improve jet energy resolution much, but may be useful as a neutral hadron veto
- Identify jets which contain neutral hadrons by finding energy clusters which do not have tracks pointing to them
- The roughly 66% of jets which do not contain neutral hadrons will have energy resolutions defined by the tracker and can have a very small correction
- Only apply a large correction to the 33% of jets which have neutrals

# The Belle (II) KLM




- The KLM provides muon ID and $K_L$ detection
  - The muon momentum is determined by the central tracker
  - The $K_L$ gives an isolated hit in the KLM without an associated charged track

- Mid-rapidity jets typically have low multiplicities and cover a large area in the detector
  - The KLM is ideal for vetoing such jets with high efficiency