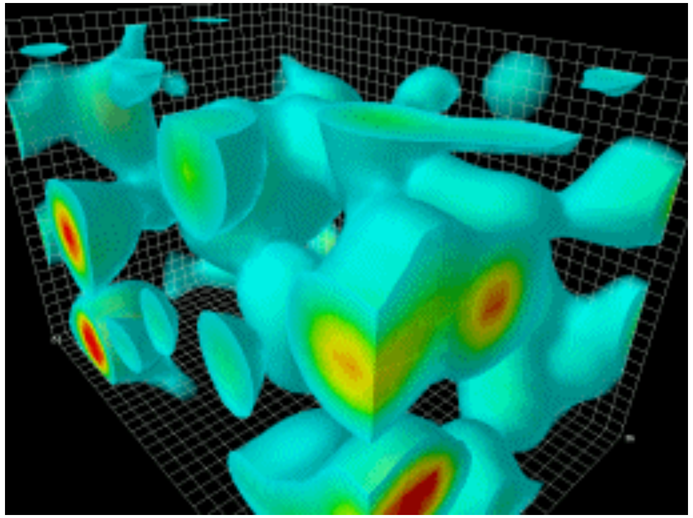
A novel compact detector concept for the Electron-Ion Collider (EIC)



The QCD vacuum

Pawel Nadel-Turonski

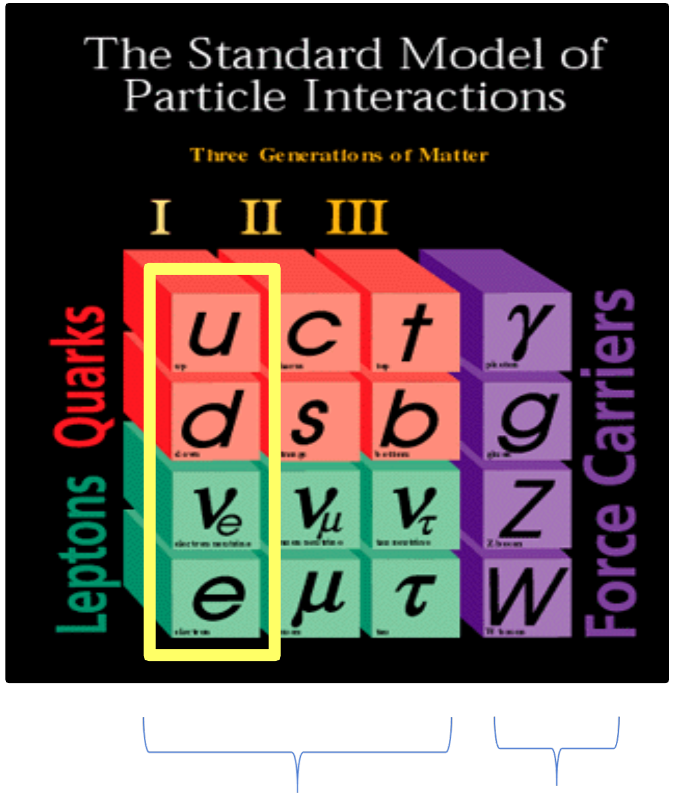
Stony Brook University

Charles Hyde

Old Dominion University

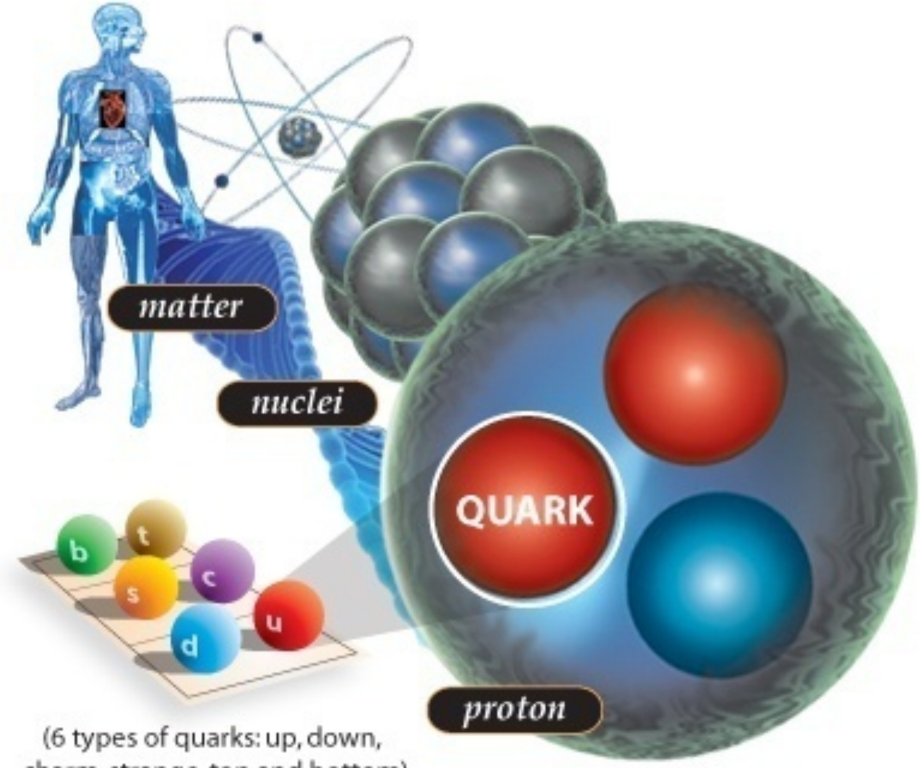
Oak Ridge seminar, September 17, 2020

Visible matter according to the standard model



Fermions (matter)

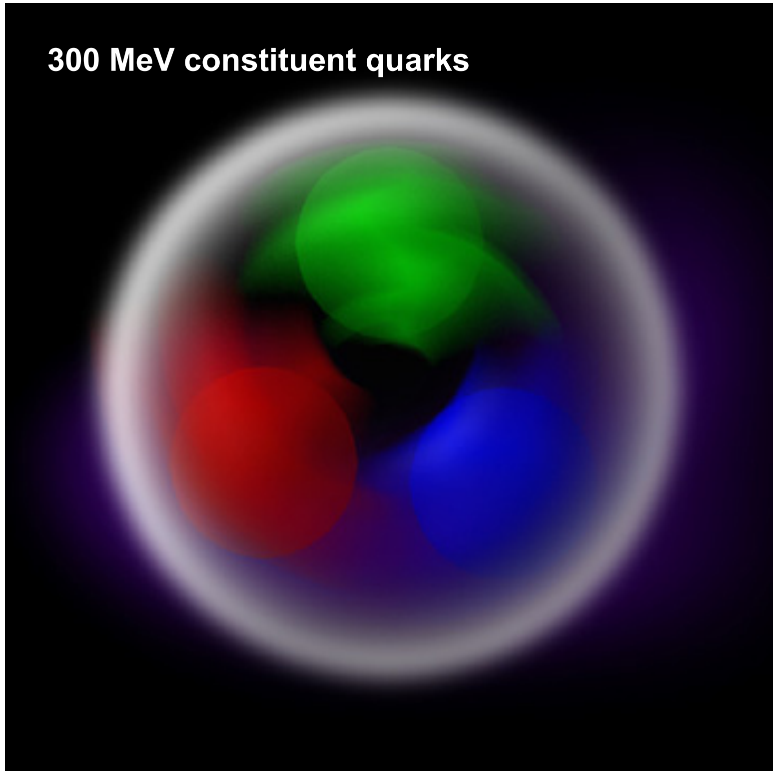
Bosons (force)

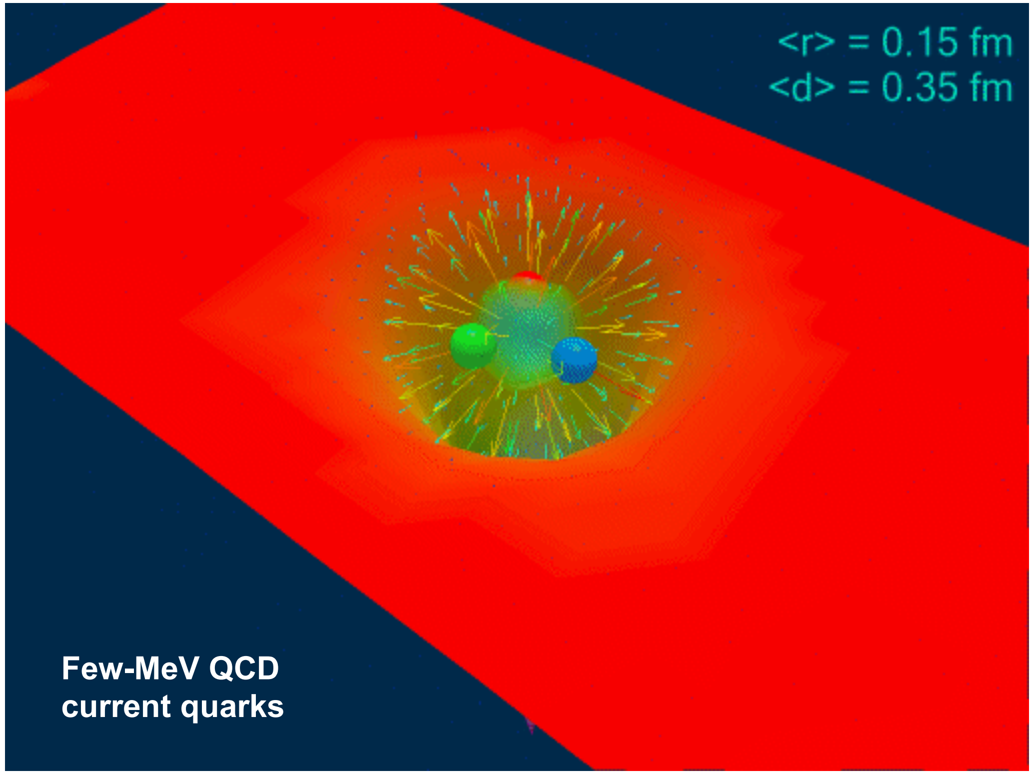


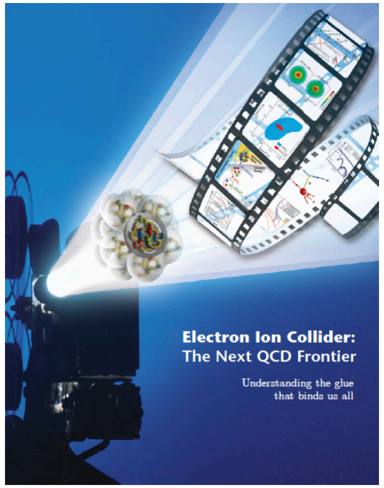
(6 types of quarks: up, down, charm, strange, top and bottom)

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

Understanding the glue that binds us all



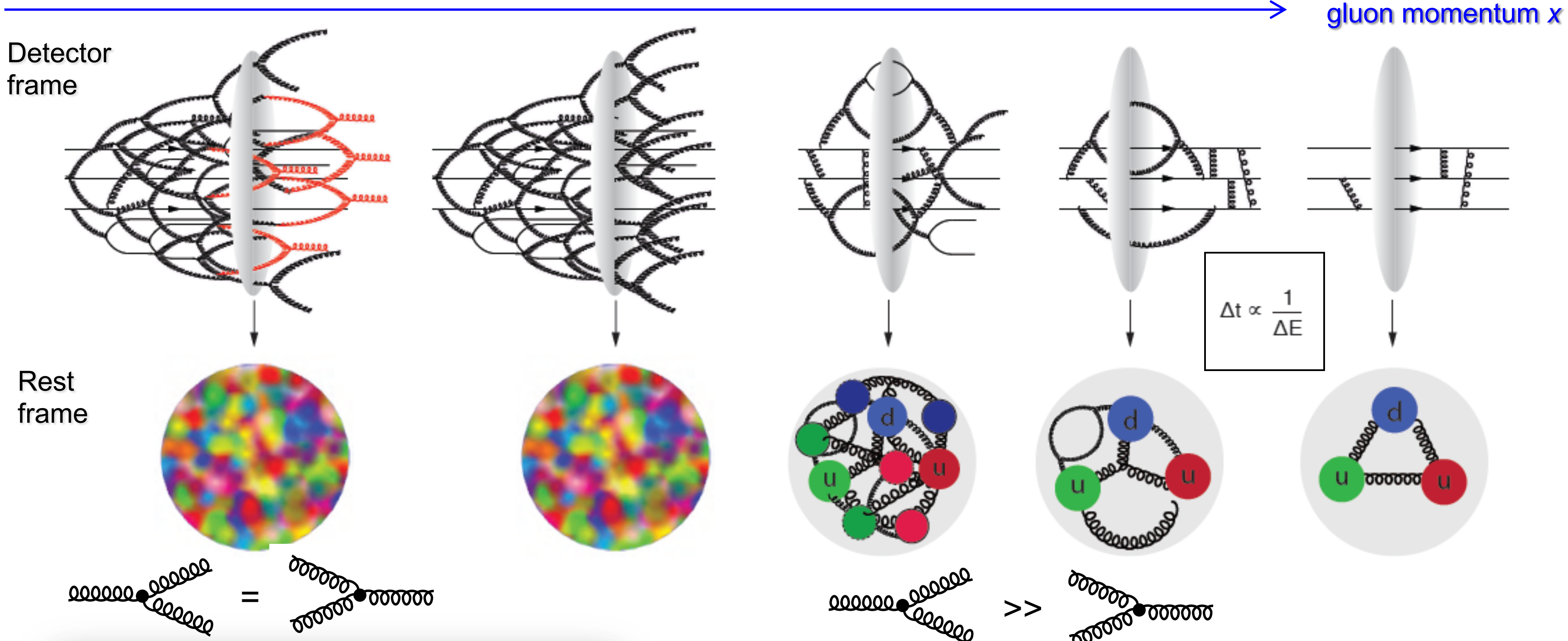


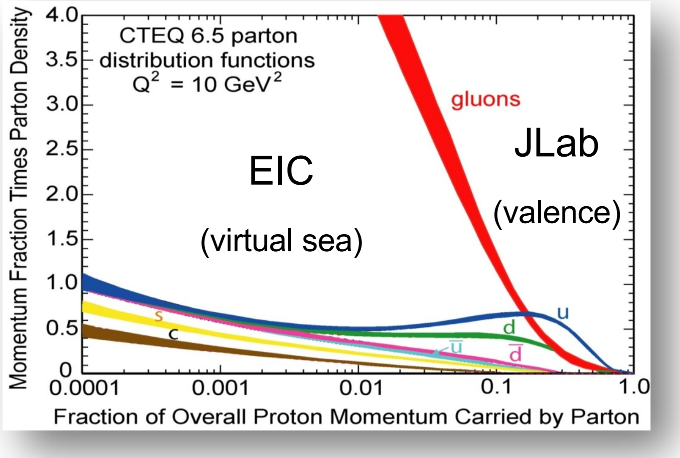


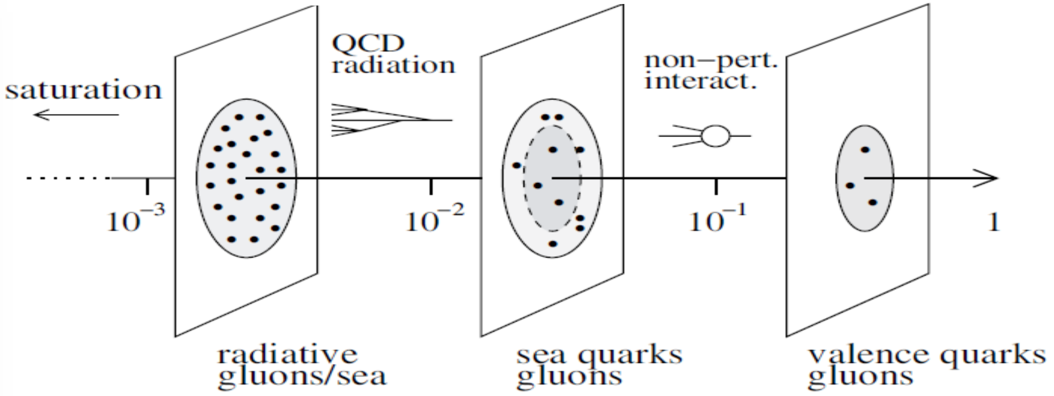
EIC white paper

- 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

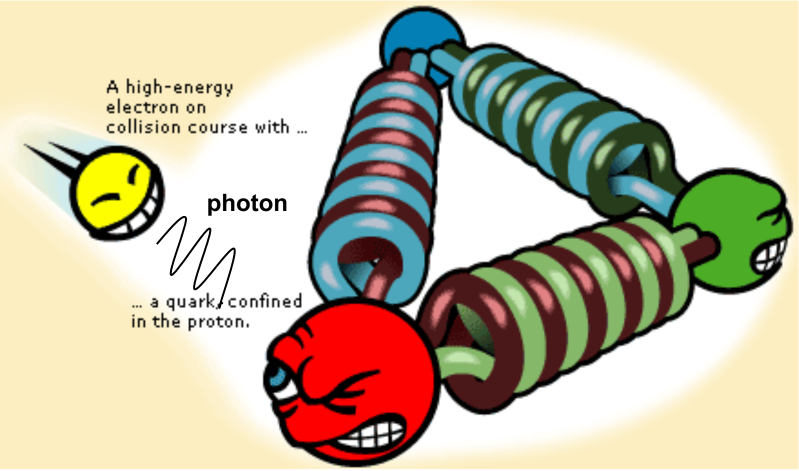




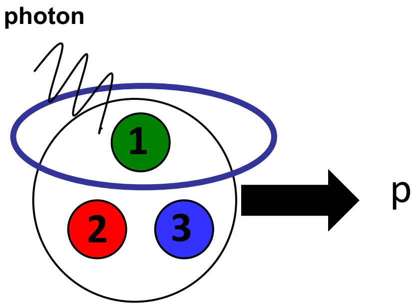


Electron scattering: *x*, *t*, and *Q²*

- **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.



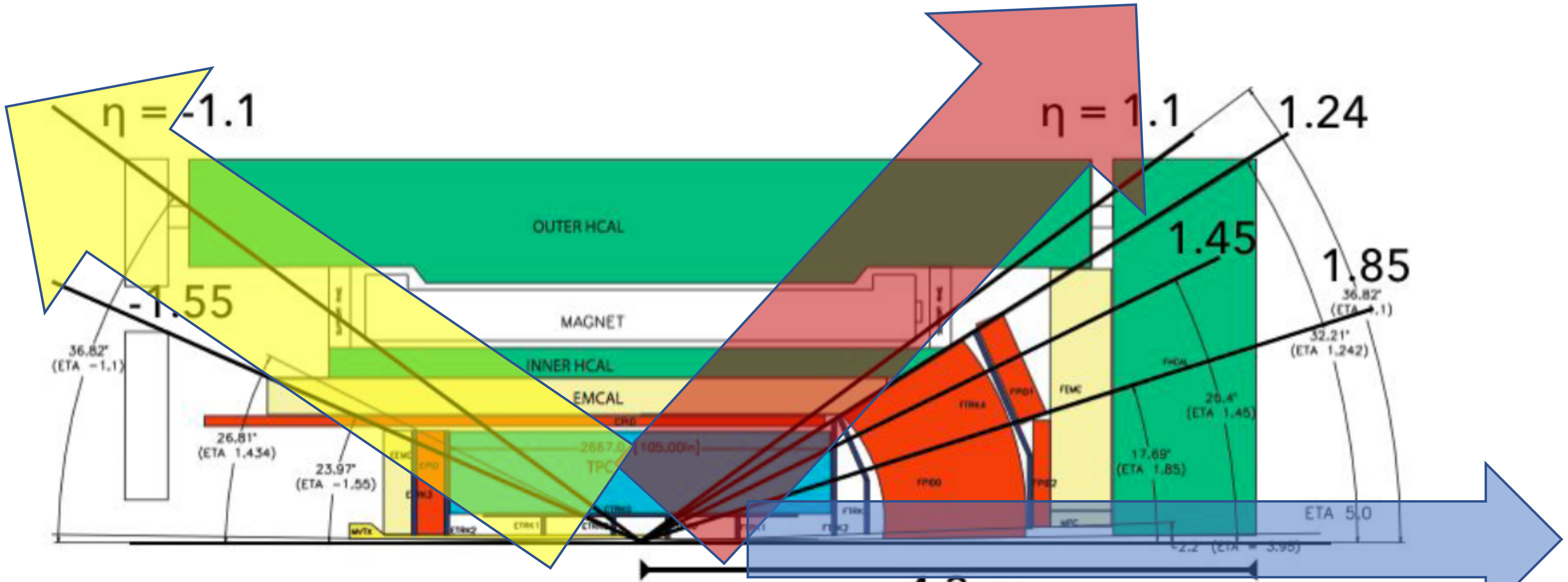
- ***x*** is the fraction of the nucleon momentum carried by the struck quark in a frame where the nucleon is moving quickly. With 3 quarks, one would naively expect *x* = *1/3*.
- Reaching smaller values of *x* requires a higher collision energy!



$x = p_1 / p_{proton}$

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

What do we detect?

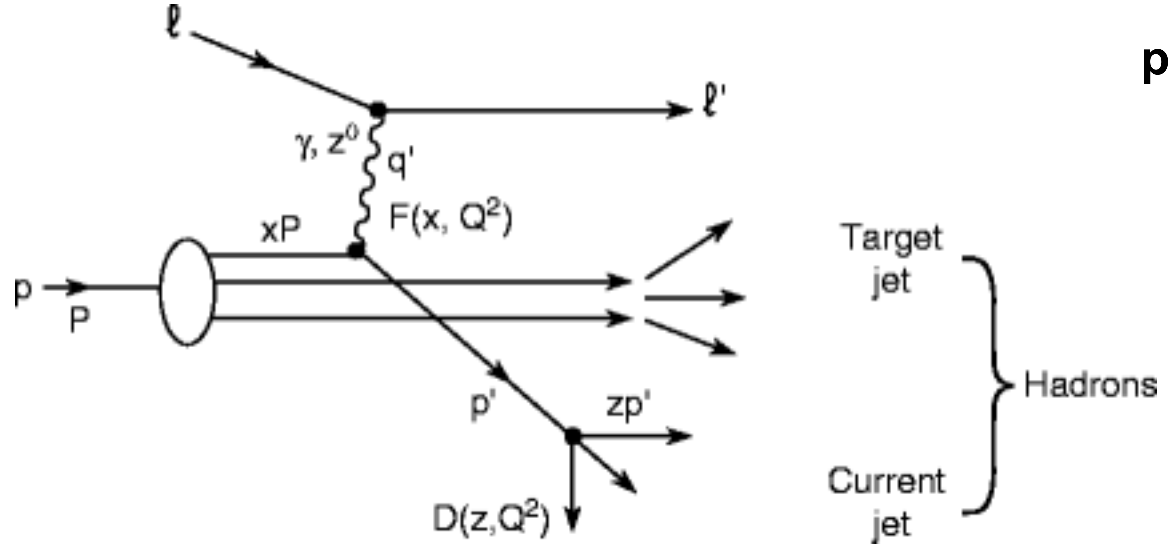


Current jet (or hadron)

Scattered electron

Target jet (or hadron)

Lepton scattering on a proton



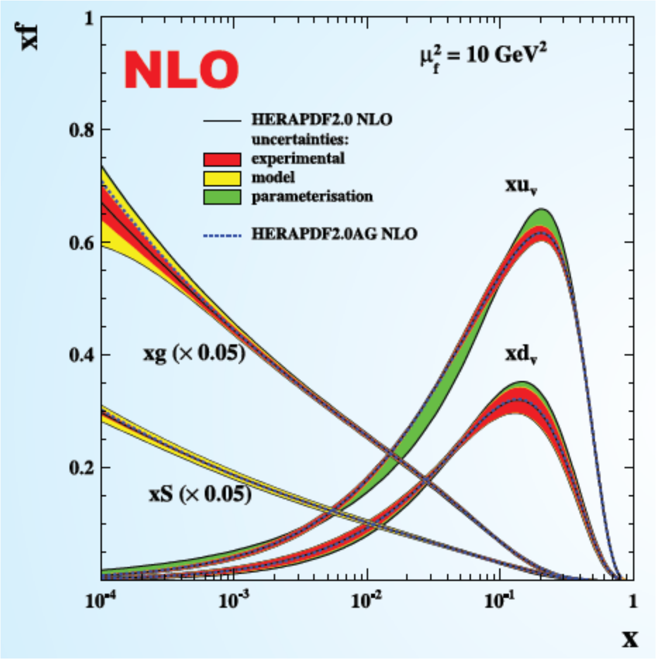
Inclusive DIS: only electron is detected

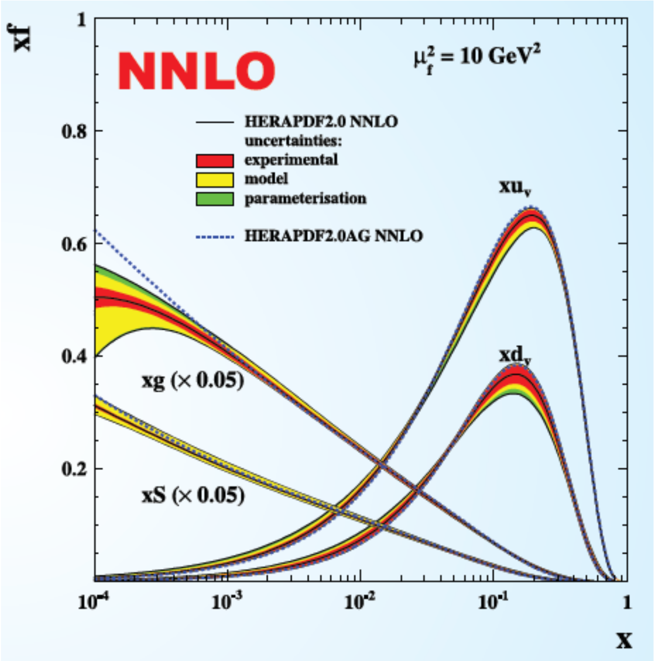
Semi-Inclusive DIS (SIDIS): electron and current jet (hadron) are detected.

Exclusive reactions: all particles are detected

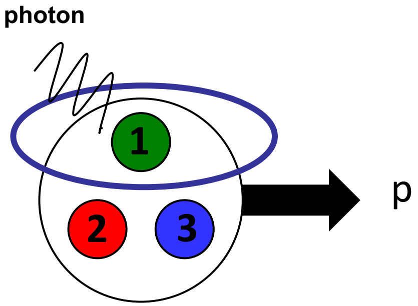
Momentum distributions of quarks and gluons

Gluons saturate?





Accessed through
inclusive reactions

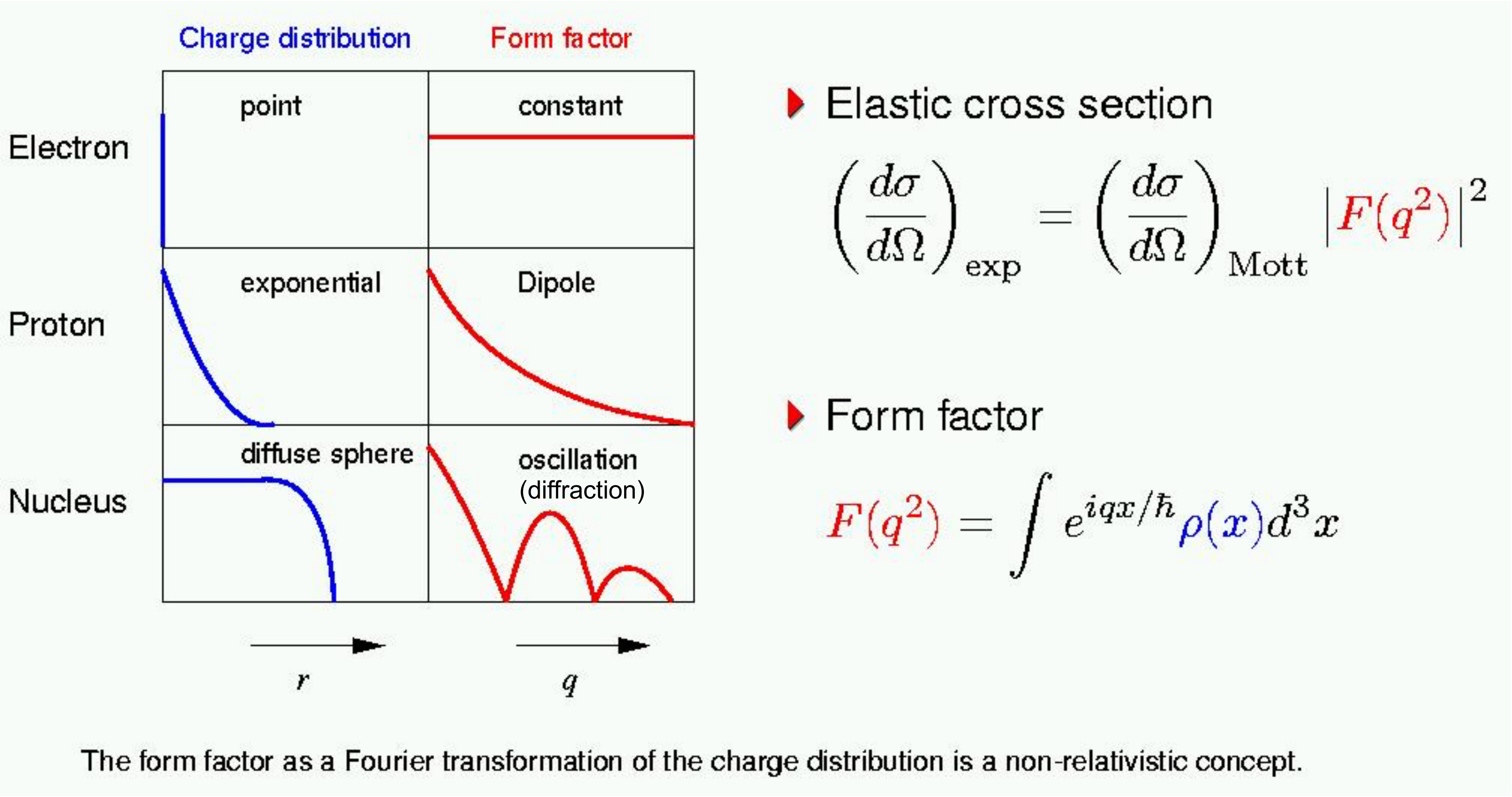


$x = p_1 / p_{proton}$

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

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

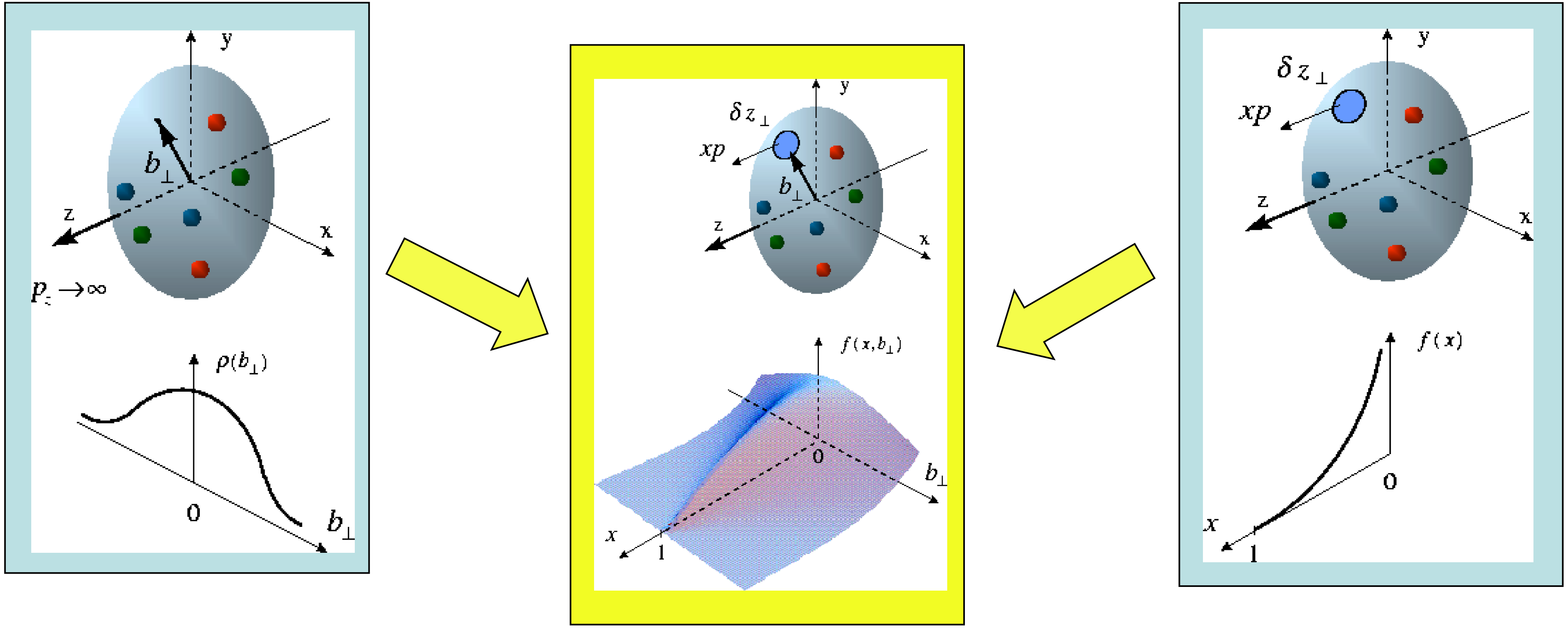
- Form factor

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

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)

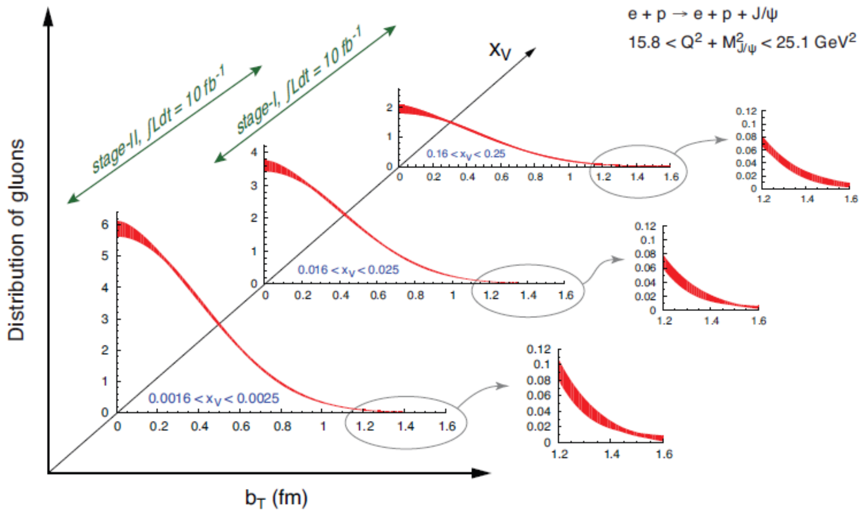
Longitudinal momentum distributions (Parton Distribution Functions)

Transverse imaging in coordinate and momentum space

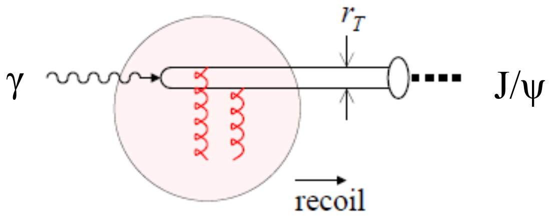
GPDs

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

Accessed through
exclusive reactions

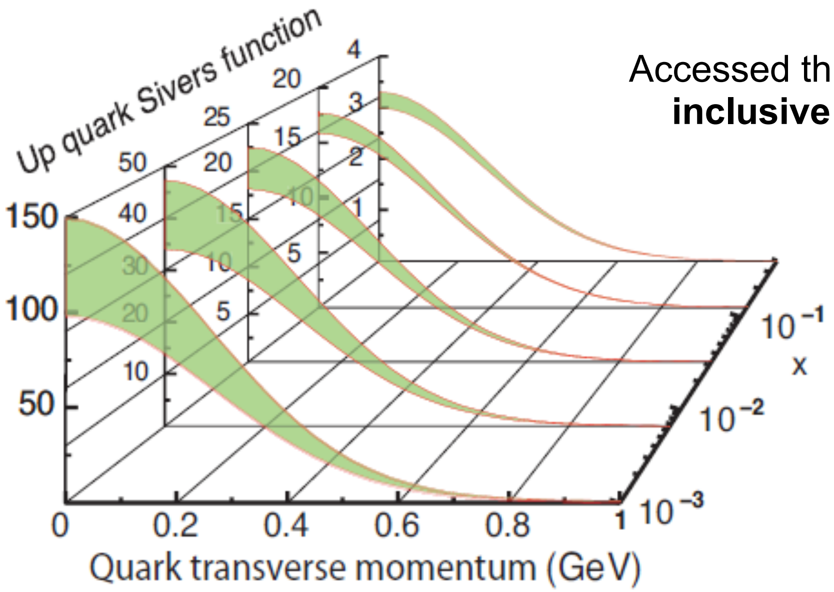


Transverse gluon distribution from J/ψ production



TMDs

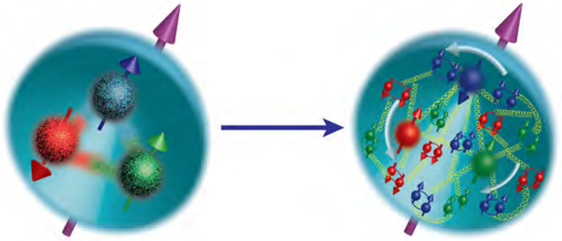
2+1 D picture in **momentum space**



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.

$$\frac{1}{2} = \underbrace{\overset{\text{polarization}}{\frac{1}{2}\Delta\Sigma(\mu)} + \overset{\text{orbit}}{L_q(\mu)}}_{\text{quarks}} + \underbrace{\overset{\text{polarization}}{\Delta G(\mu)} + \overset{\text{orbit}}{L_g(\mu)}}_{\text{gluons}}$$

Two complementary approaches needed to resolve proton spin puzzle

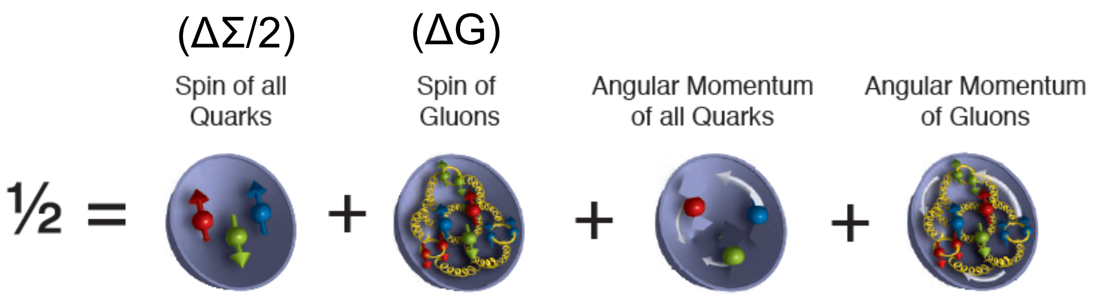
Measure ΔG - gluon polarization

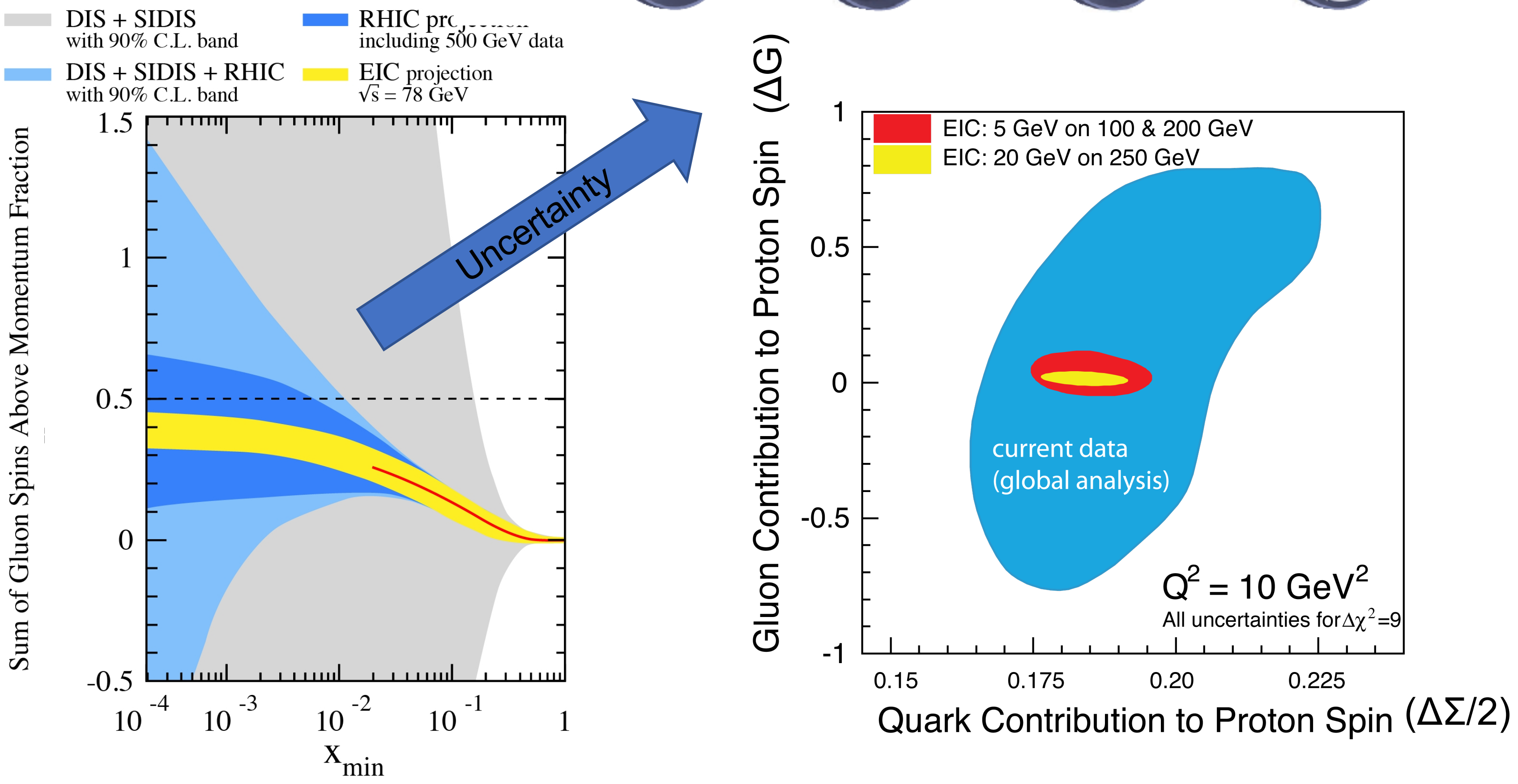
Measure GPDs and TMDs - orbital motion

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

Ji sum rule for GPDs H and E

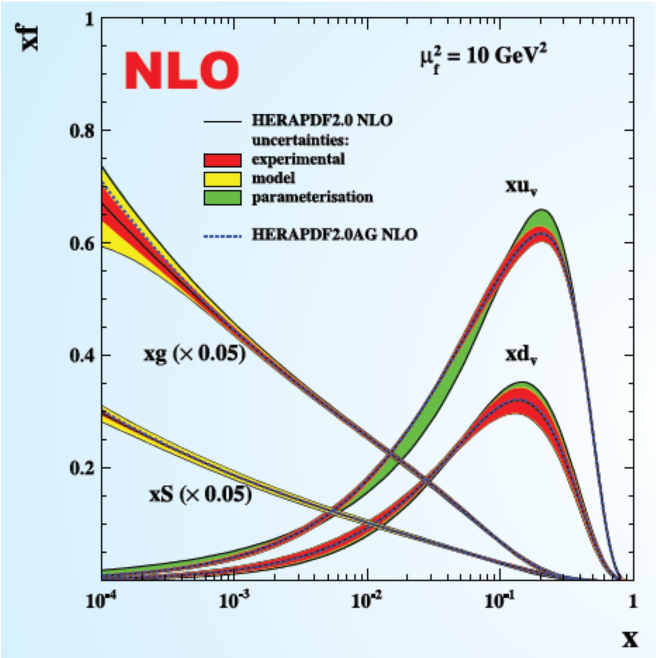
Gluon polarization

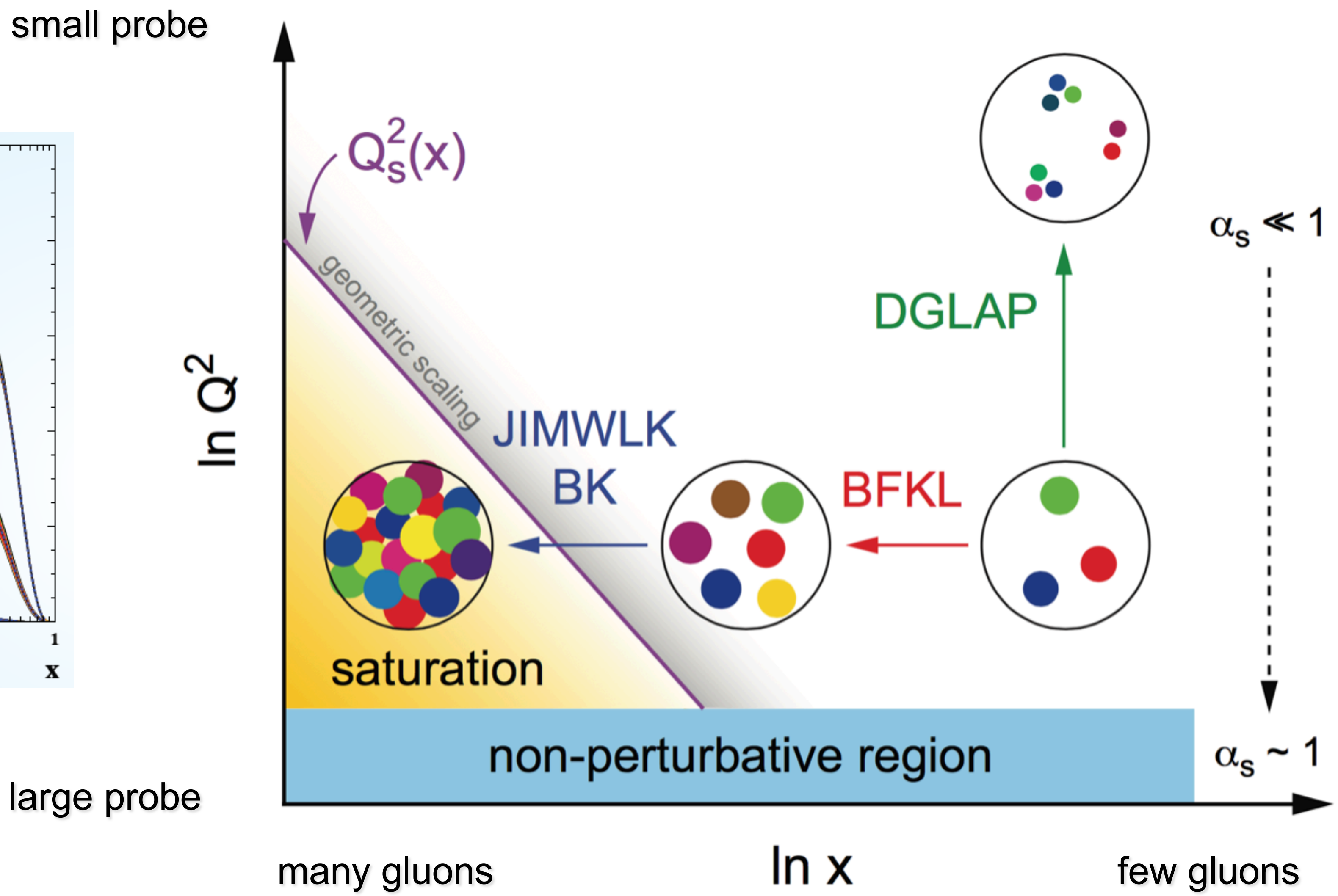




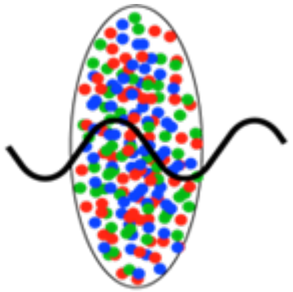
- Large uncertainties at low x require input from the EIC in addition to RHIC spin

Gluon saturation in the proton



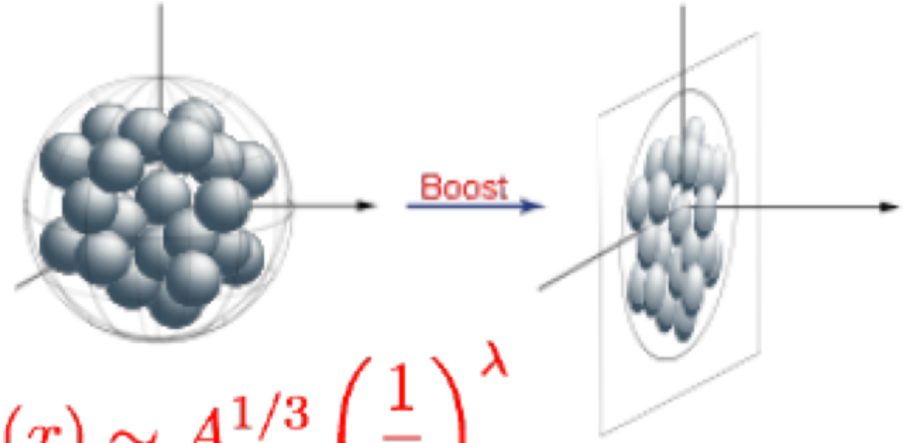


Gluon saturation in nuclei

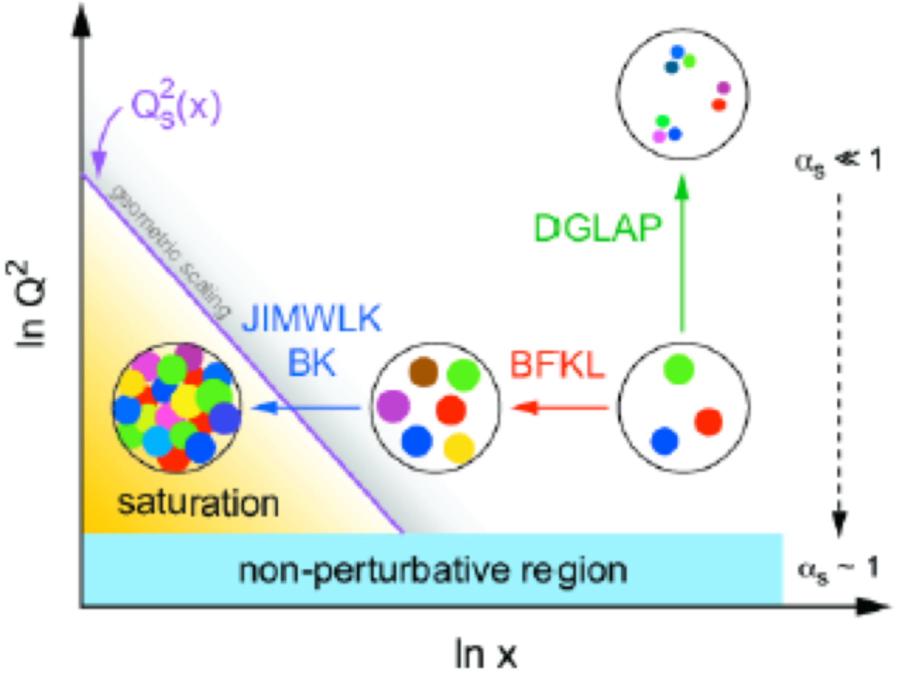


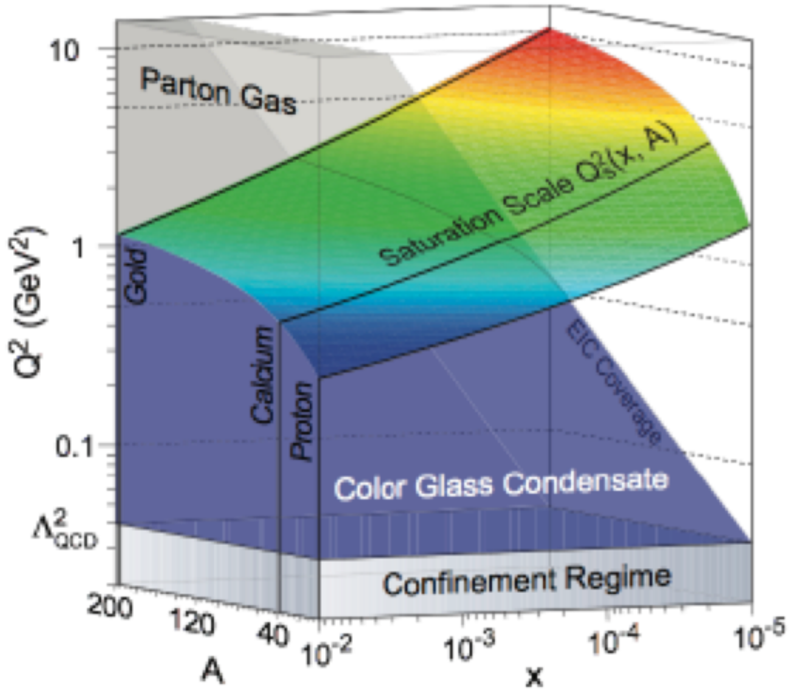
At low x the coherence length of the photon is larger than the nucleus (rest frame).

Detector frame: the nucleus is compressed into a pancake



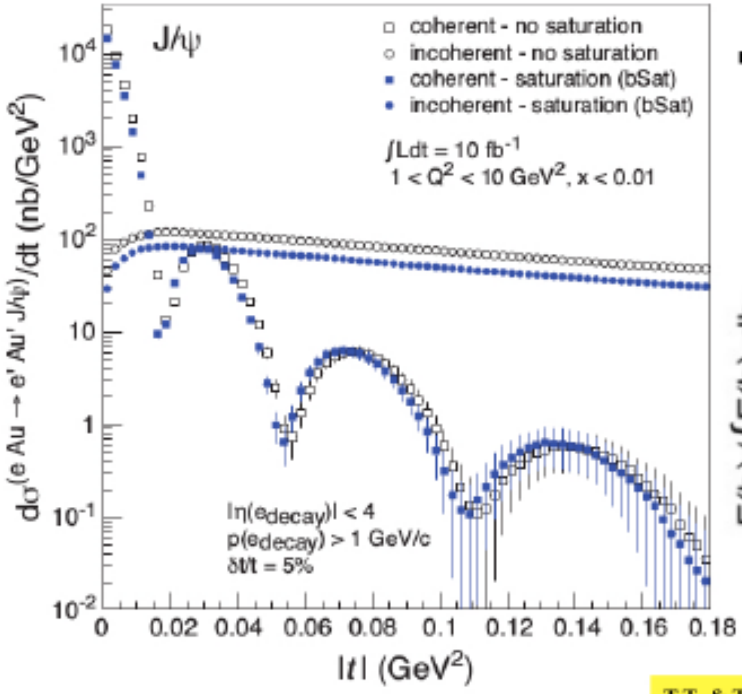
$$Q_s^2(x) \sim A^{1/3}\left(\frac{1}{x}\right)^{\lambda}$$





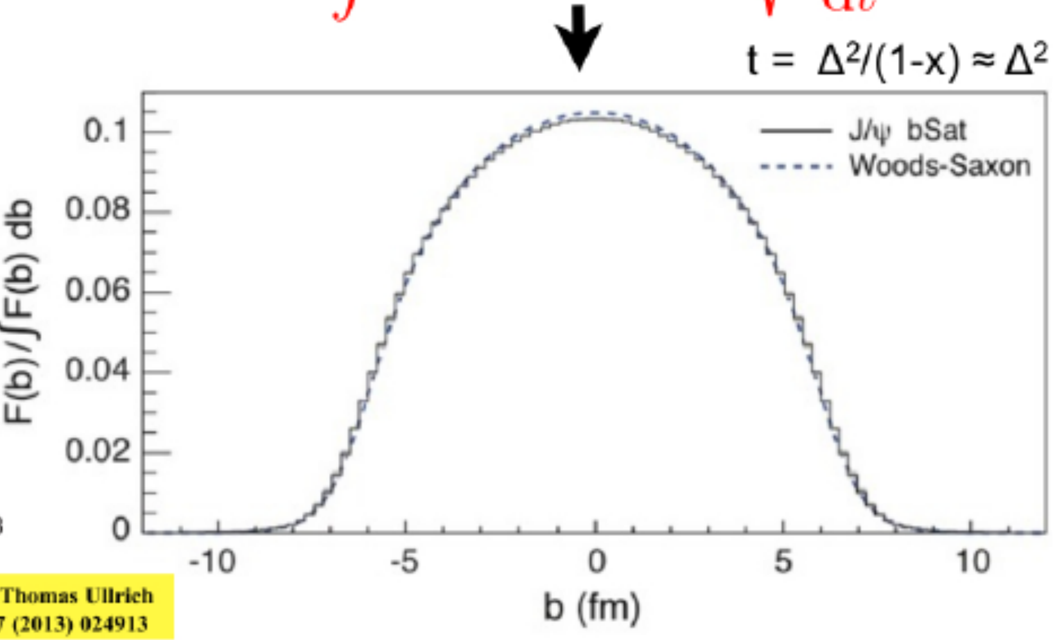
2D spatial gluon imaging in heavy nuclei through coherent diffraction

Momentum transfer t conjugate to transverse coordinate b



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

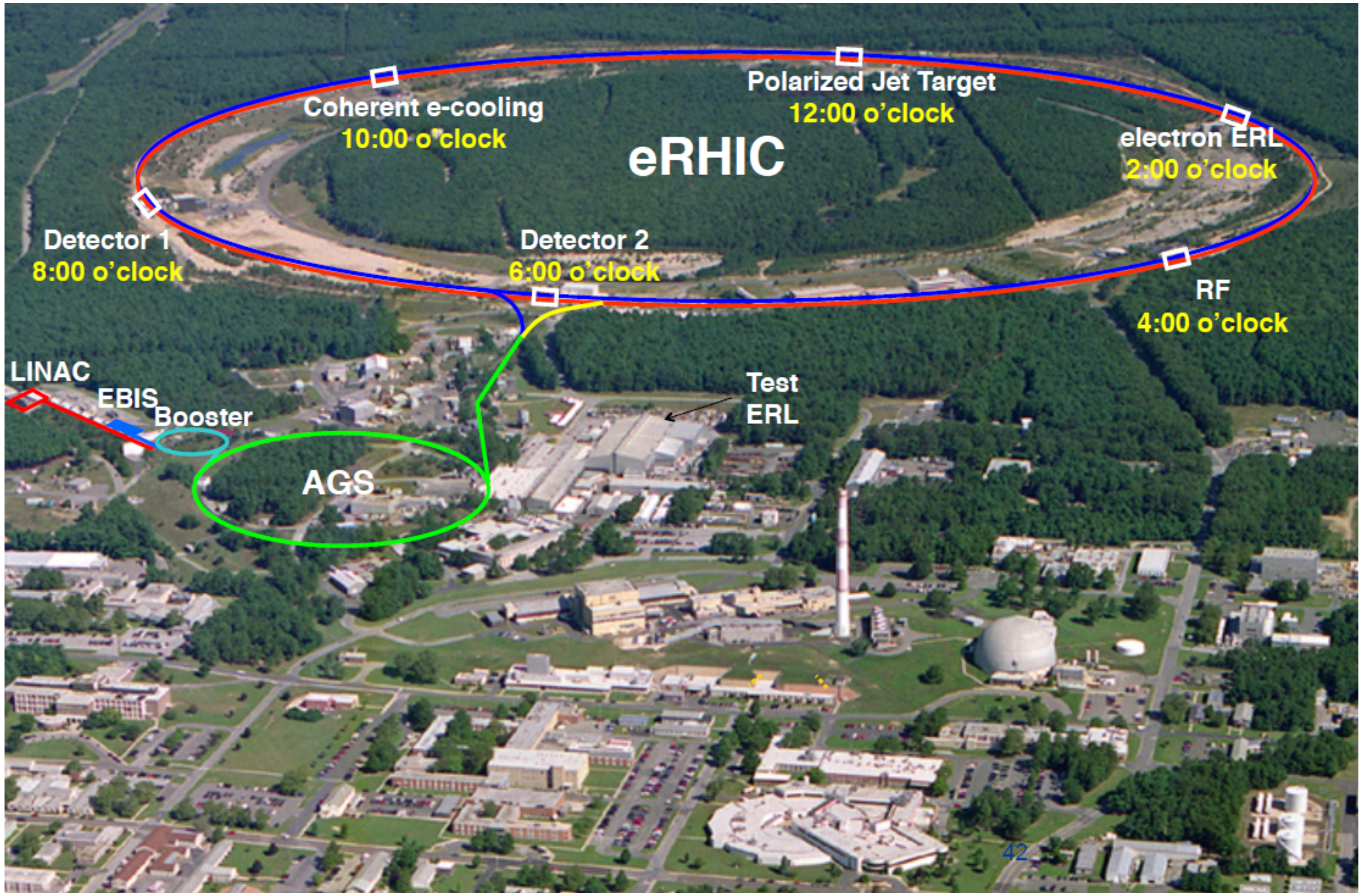
$t = \Delta^2/(1-x) \approx \Delta^2$



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

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

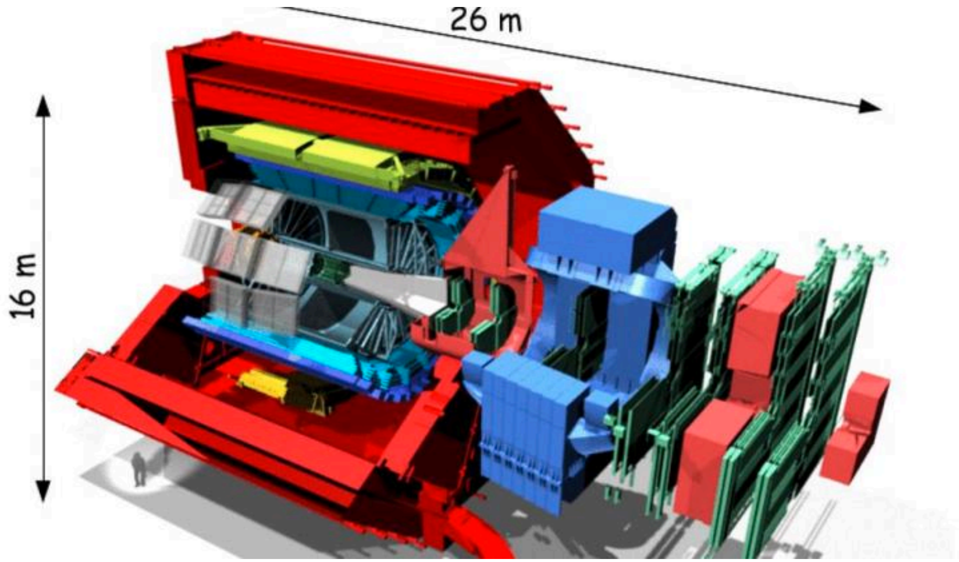
The Electron-Ion Collider at BNL



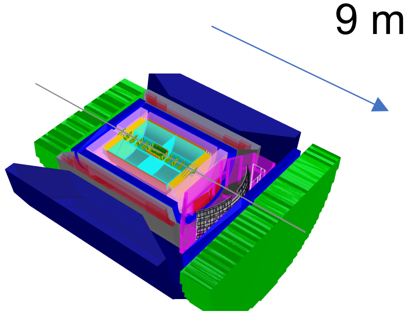
- 5-18 GeV polarized e- beams
  - 10 GeV luminosity maximum.
- 41-275 GeV polarized p beams
  - Luminosity max at top energy
- Ion beams up to 110 GeV/A
  - Any ion species in principle possible from d to U
- One detector is included in the project, but two would be desirable if funding permits

EIC detector requirements are diverse and demanding

ALICE

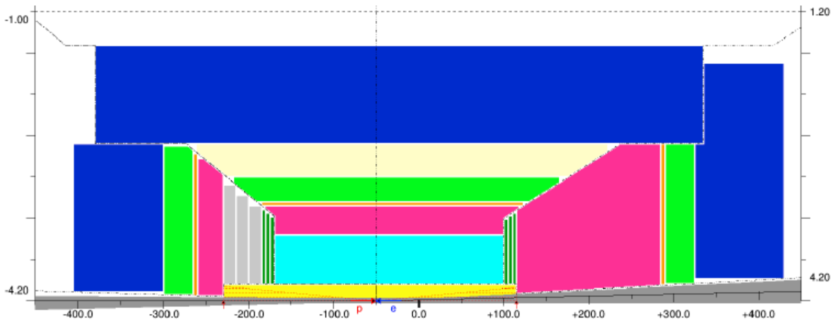


EIC detector

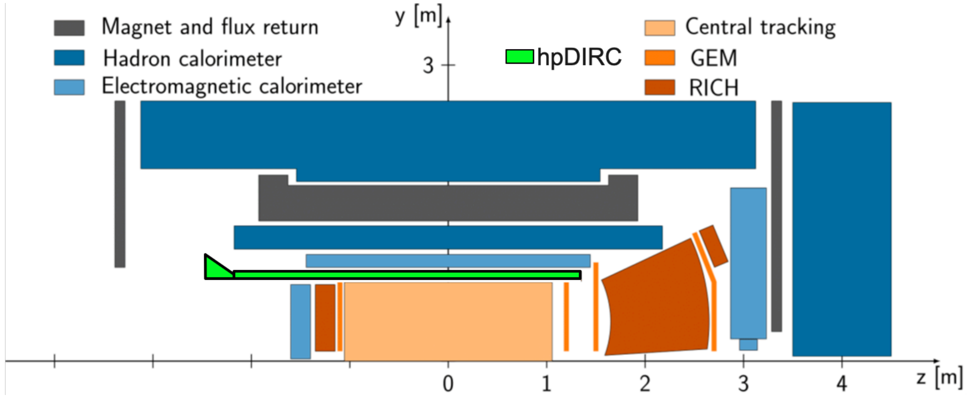


- In order to reach the luminosity goal, the EIC detector is limited to a length of 9 m.
- The physics require a hermetic detector with a full suite of subsystems allowing for precise measurement and identification of anything from single photons and mesons to jets
- The collision kinematics are very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

A two detector scenario?



2020 Yellow Report “Reference Detector”



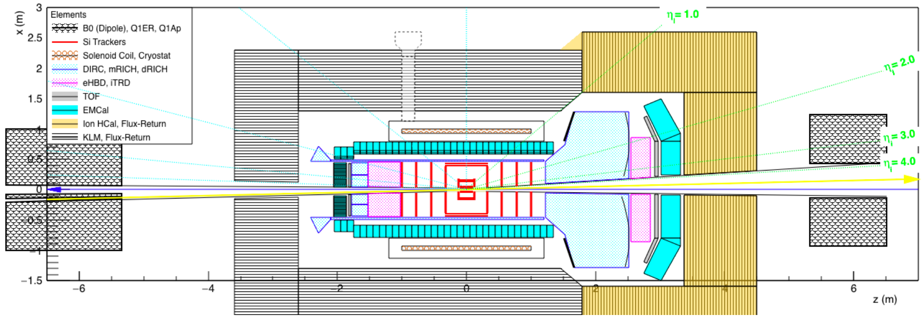
EIC-sPHENIX from 2018 LOI

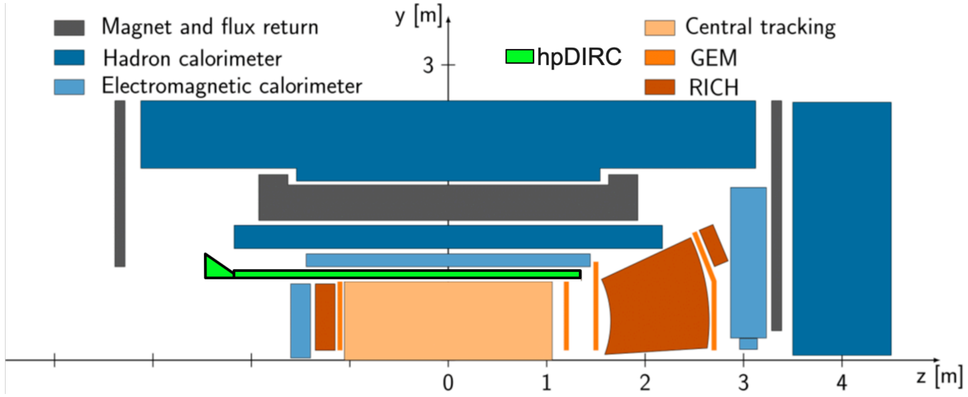
- To realize a two-detector scenario, we need three ingredients
  - A primary detector that can satisfy the key EIC physics goals within a moderate budget
  - A second detector that save costs by re-using suitable existing components (e.g., magnet, barrel Hcal, and TPC from sPHENIX).
  - A complementarity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

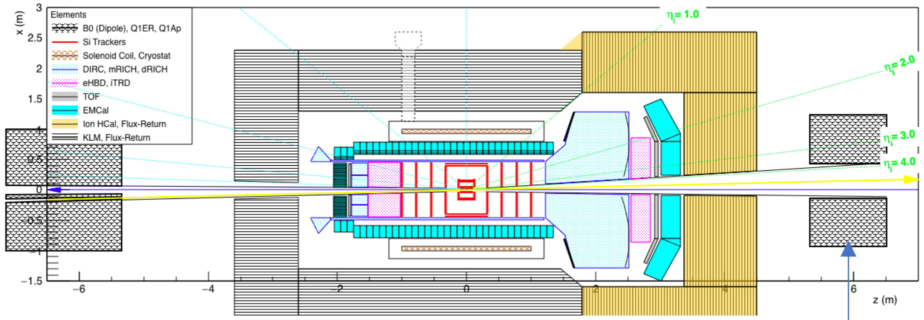




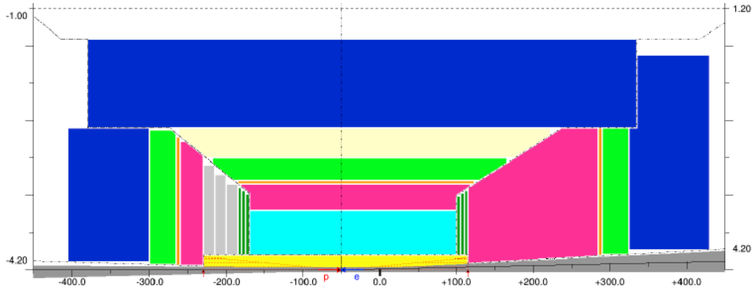
EIC-sPHENIX from 2018 LOI

- A hermetic general-purpose detector that fulfills all physics requirements that 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)

Integration

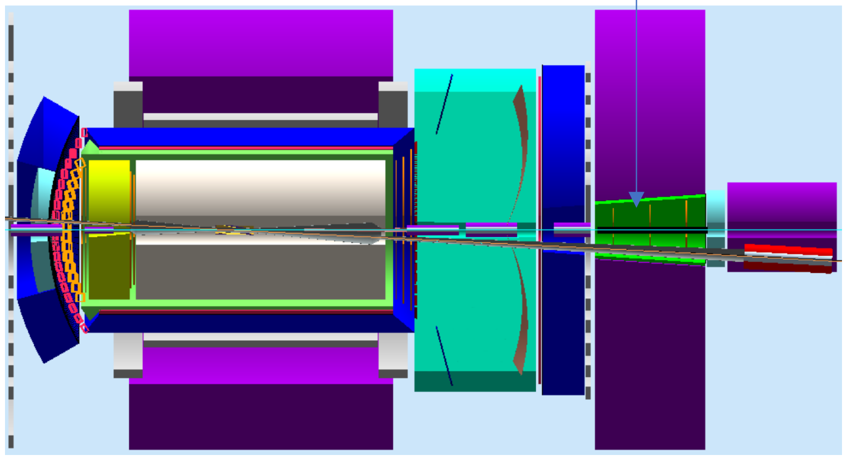


Compact EIC detector



Yellow Report “Reference Detector”

Two options for “B0” dipole integration

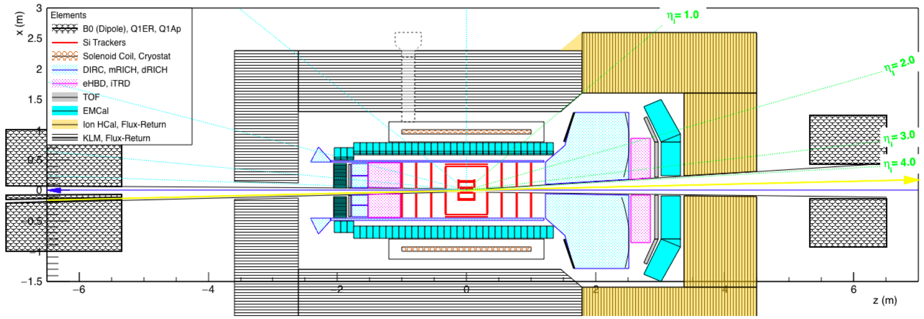


2015 JLab EIC detector

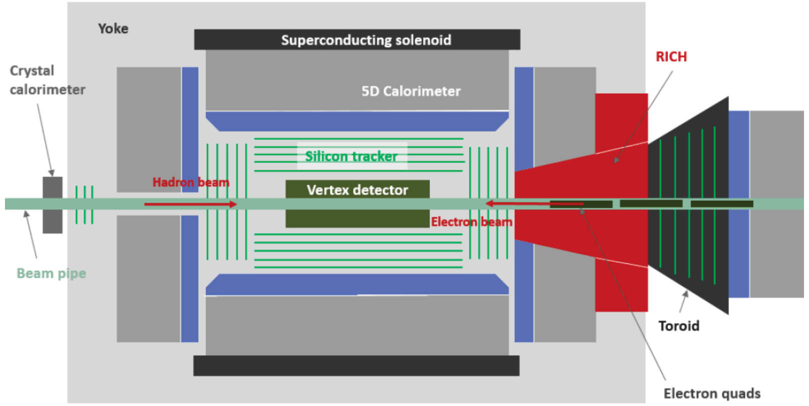
- Integration of all subsystems of the detector within the limited space provided by the 9 m long interaction region can be challenging
- The compact detector provides a simple solution to this problem
- An alternative approach, making maximum use of the available space, was chosen for the JLab detector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

Why not an “all-silicon” detector?

Compact EIC detector



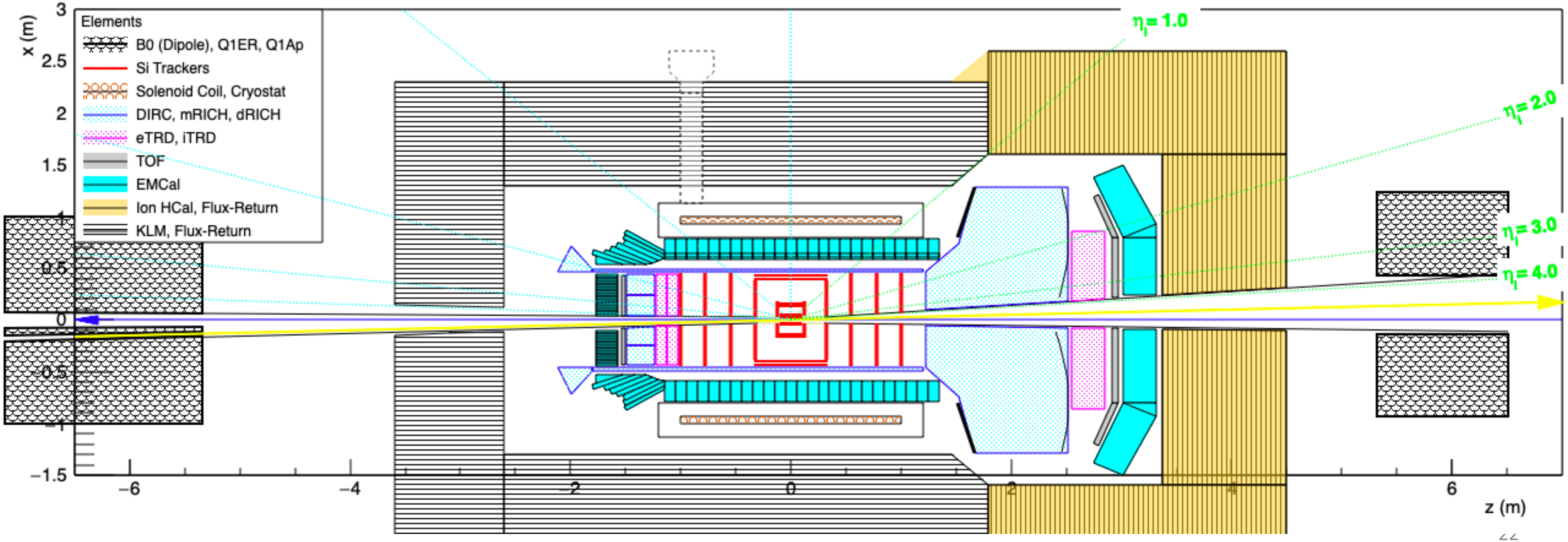
ANL “TOPSiDE” detector



- 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.

Technology and Performance Overview of a Compact Detector Concept

- access door: 27’ by 27’ =(8.23 m)^2
- IR magnet clear zone: IP±4.5 m

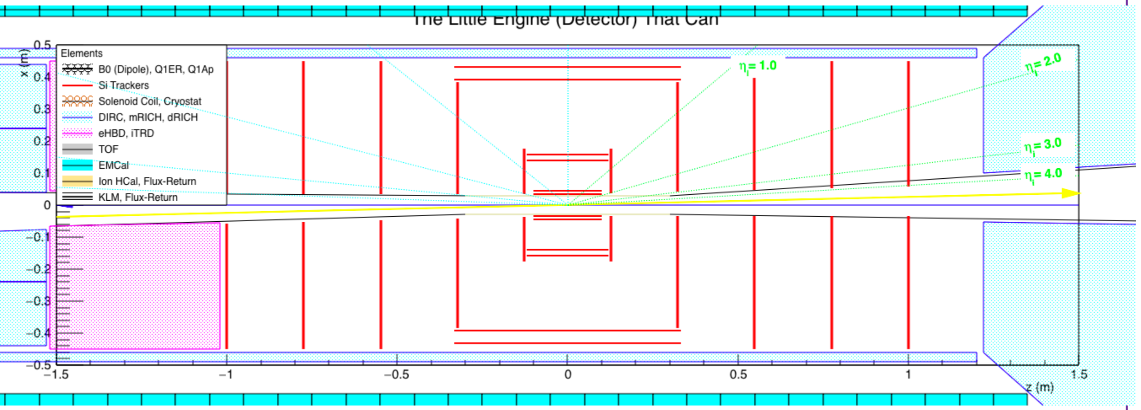


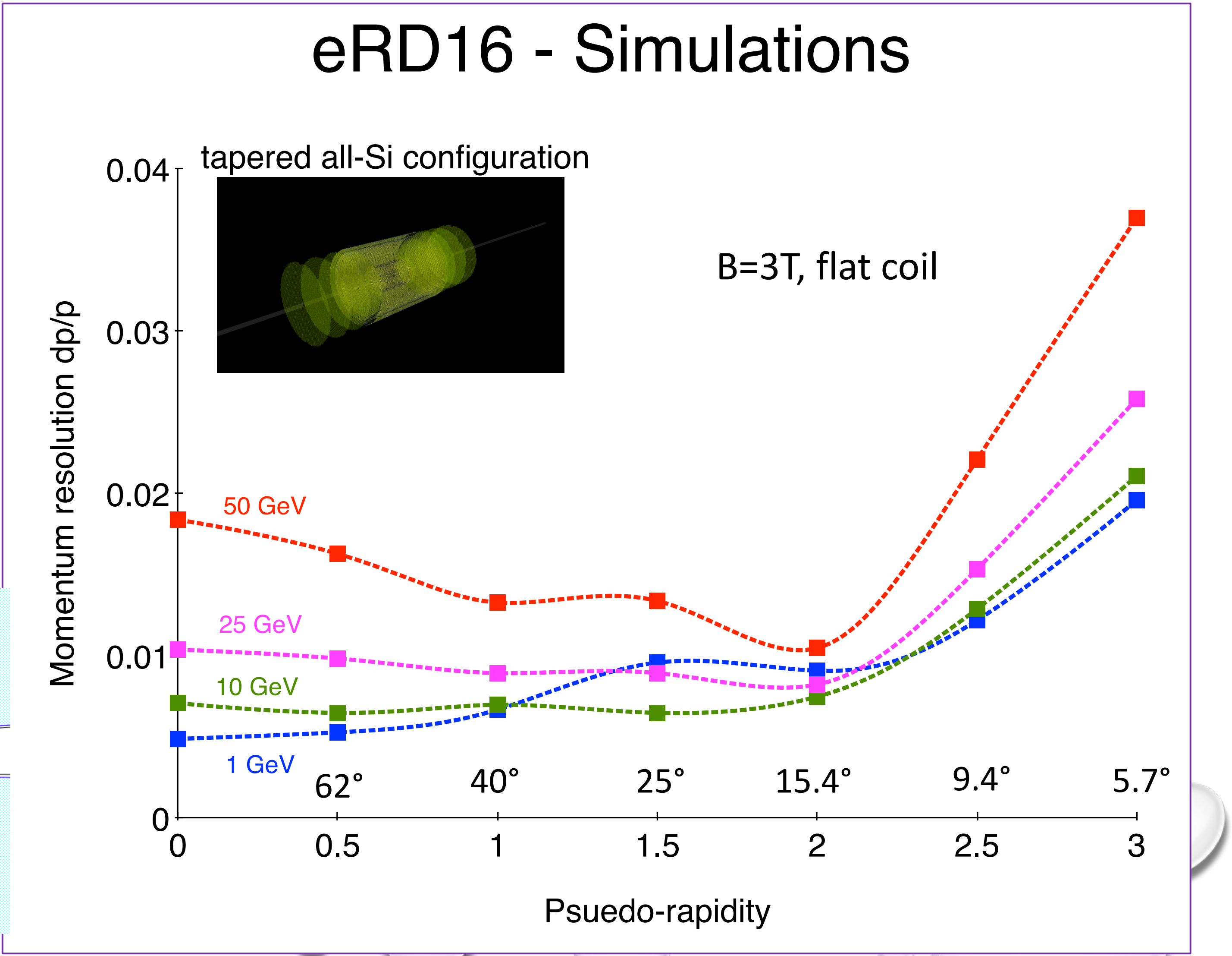
The Little Engine (Detector) That Can

Si Tracking Performance

https://wiki.bnl.gov/conferences/images/2/23/20190711-eRD16.v1.pdf

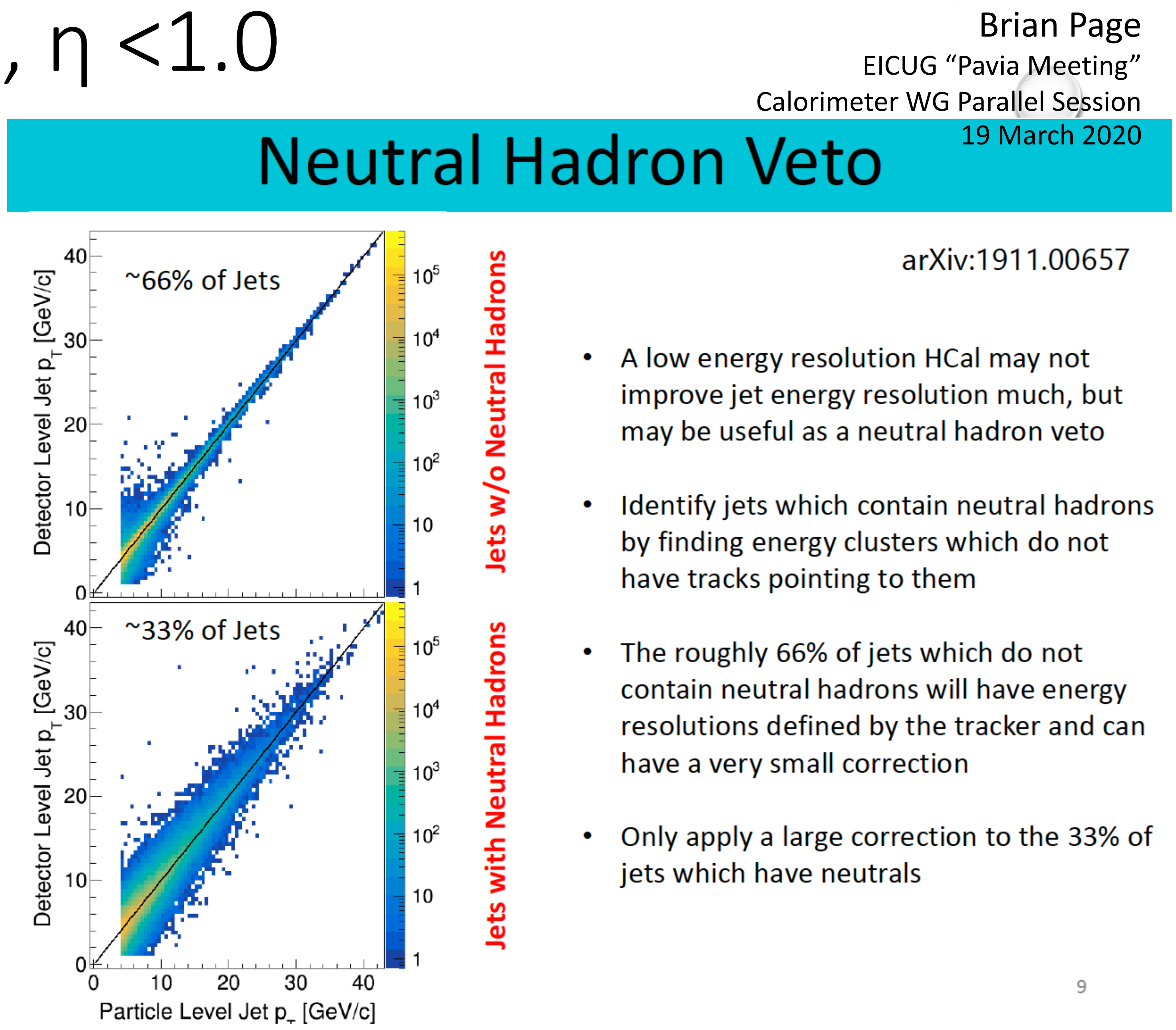
- Si Vertex Tracker:
  - Two MAPS layers
  - 20x20 μm^2 pixels
- Magnet Bore 160 cm diam.
  - 4 Si-strip Barrel Layers
  - Maximum radius 45 cm
  - 5 Si-strip Disk Layers, each endcap
- Performance ≥ Si+TPC





Jet Reconstruction, η <1.0

- EIC events have modest multiplicity.
- Charged particles via tracking, PID
  - $\delta p/p$ ~ 1% to 3%
- Photons in EM Calorimeters
  - 12%/sqrt(E) for $-1.5 < \eta < 2.0$
  - 2%/sqrt(E) for $-4 < \eta < -1.5$
  - 10%/sqrt(E) for $\eta > 2.0$
- Muons, K_L^0, neutrons tagged in BELLE-II $K_{Long}\mu$ (KLM) instrumented flux return
  - Muons: PID in KLM, tracking in central Si
  - K_L^0: Veto events with large shower in KLM, correct with K_S^0 sample
  - Neutrons, (rare) vetoed by KLM (PID by TOF, or mis-identified as K_L^0)



Brian Page
EICUG "Pavia Meeting"
Calorimeter WG Parallel Session
19 March 2020

Neutral Hadron Veto

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

9

HCAL in Forward Ion Endcap

- Design includes coverage $1<\eta<4$
- What range is needed?
- Jet cluster: $|\Delta\eta| <\pm0.5$
- *$E_{Jet} < 50$ GeV* for $\eta<2$

Jets and Calorimetry: First Look

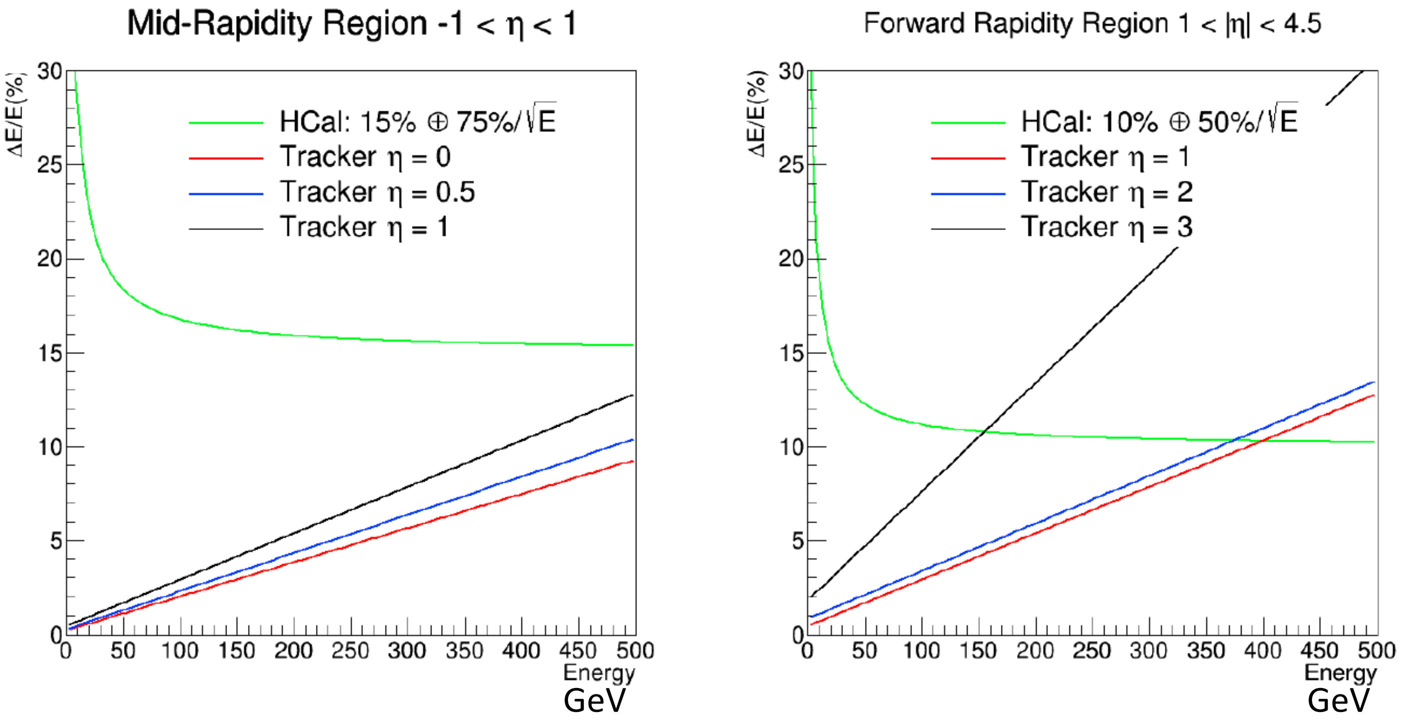
Brian Page
Calorimeter WG Parallel Session
3/19/2020

Hcal in barrel and e-endcap serves only as a K^0_L veto
- nn-bar pairs are very rare

Not clear if *any* measurement would specifically require independent determination of K^0_L and K^0_S rather than just inferring total K^0 from K^0_S
- K^0_s can be measured w/o Hcal

$1.0 < \eta <4.0$

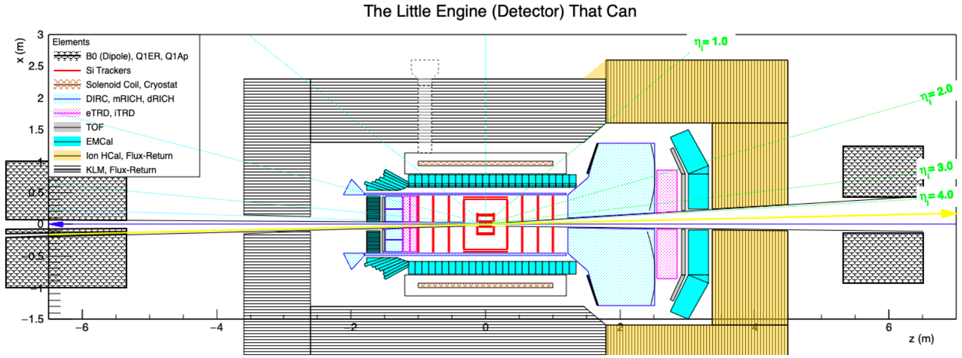
Tracker Vs HCal Resolution



- 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_Ls

A scintillator based endcap KL and muon detector for the Belle II experiment

[Https://arxiv.org/pdf/1406.3267.pdf](https://arxiv.org/pdf/1406.3267.pdf)



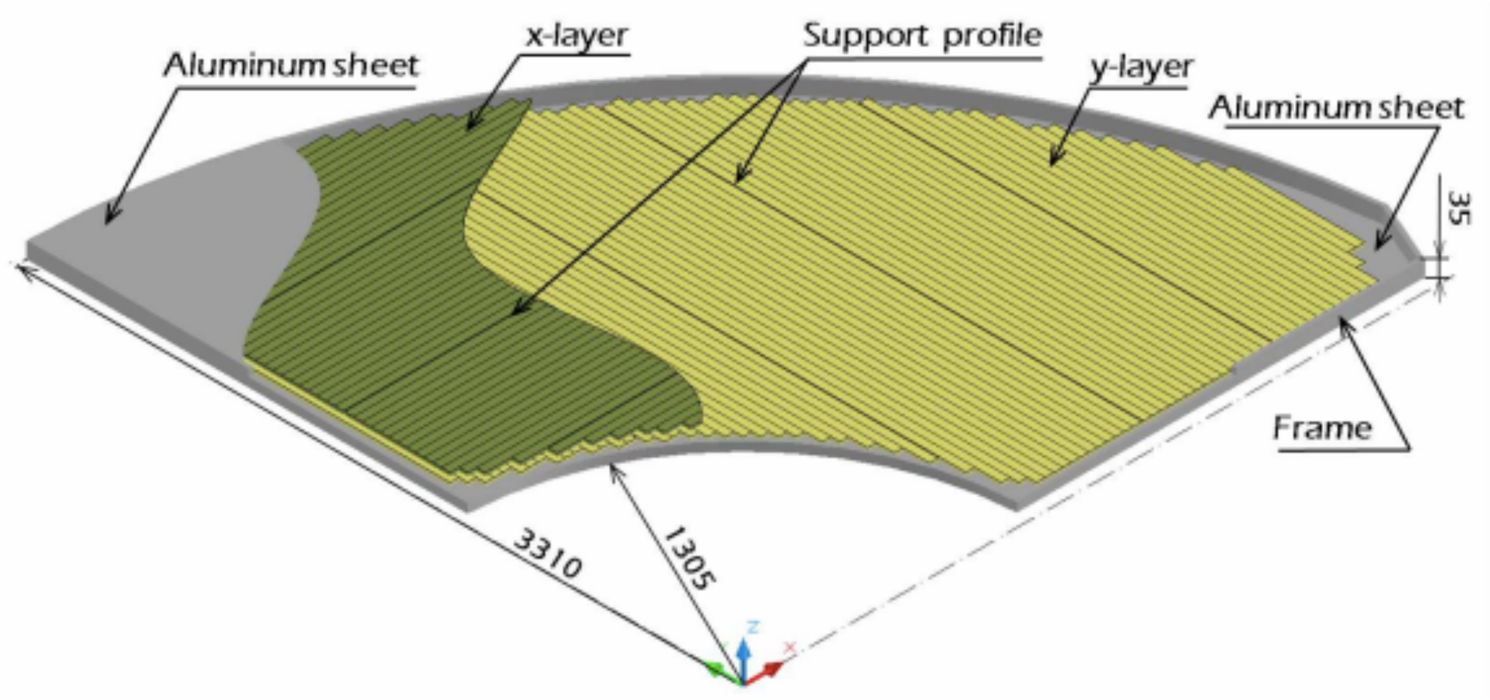


Figure 2: Schematic view of one superlayer formed by scintillator strips. Sizes are given in mm.

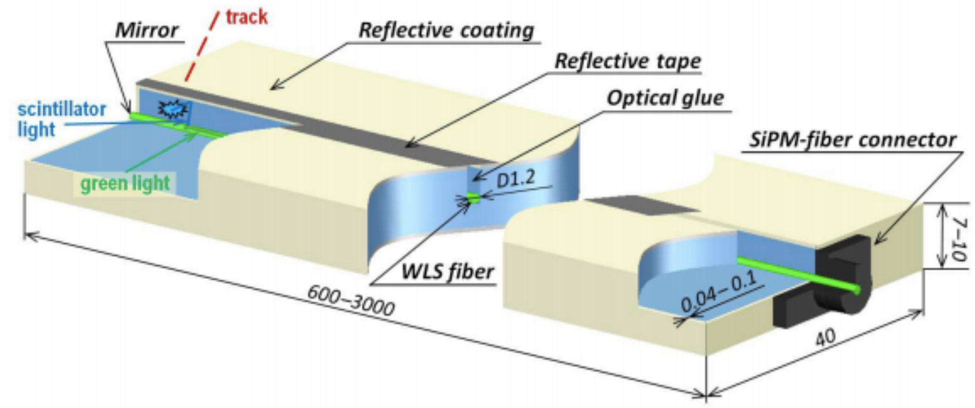
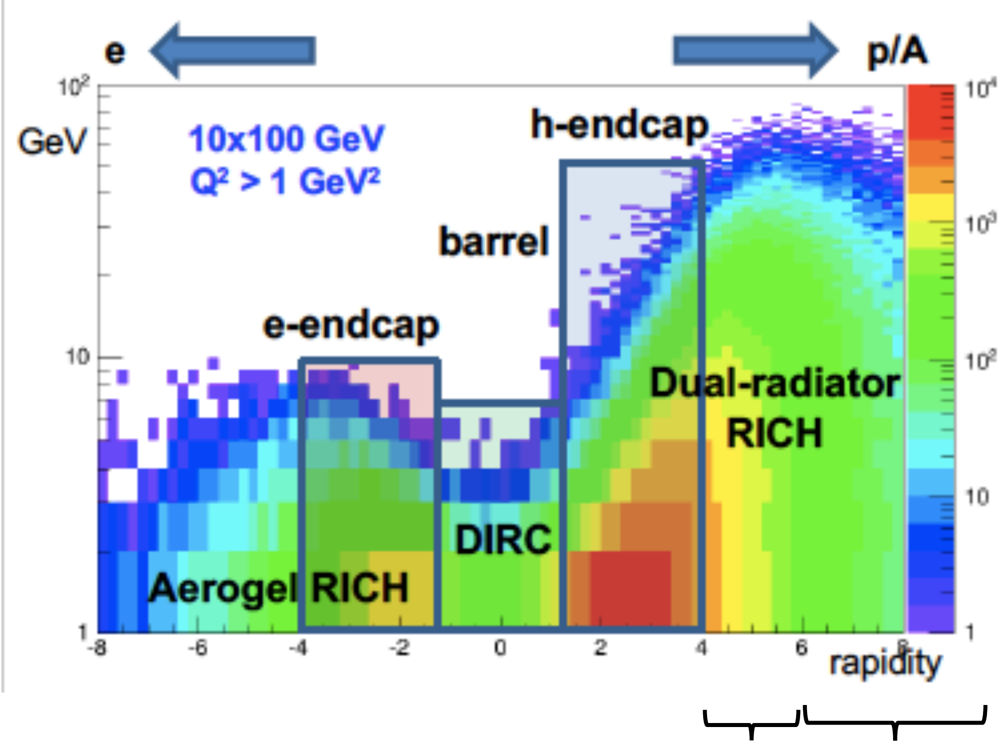


Figure 1: Schematic view of the scintillator strip. Dimensions are in mm.

- Individual single channel SiPM readout

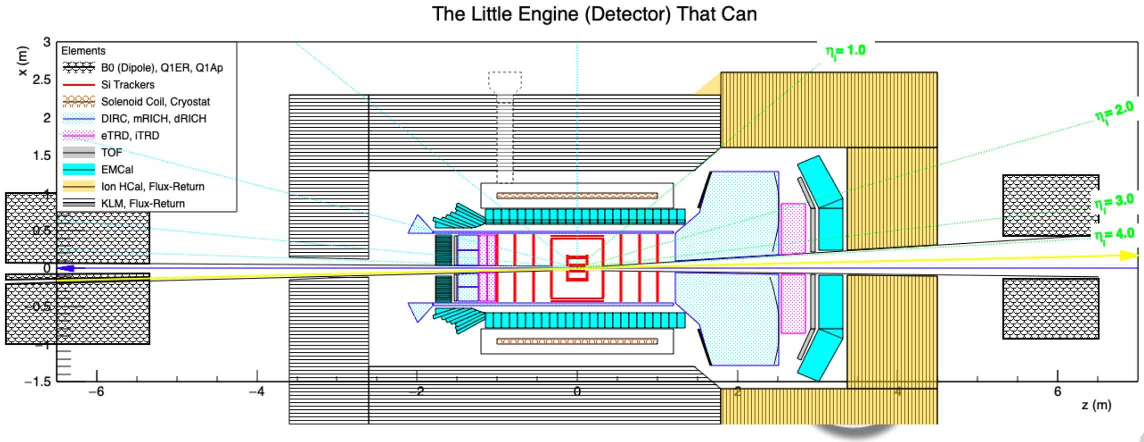
Hadron PID: eRD14 Concepts

- Hadron endcap Dual Cherenkov ($1.6 < \eta < 4.0$)
  - dRICH: Aerogel plus heavy gas
  - Common photo-sensors reduces cost
  - B-field must be shaped approximately projective to minimize “lighthouse” effect
- Barrel DIRC high performance PID goal ($|\eta|<1.8$): $\geq 3\sigma$ π/K for $p < 6$ GeV/c
- Electron Endcap Modular RICH (mRICH), Aerogel radiator (n= 1.02) and Fresnel lens (20 cm)[3]
  - $K^\pm/\pi^\pm$ separation $\geq 3\sigma$ for $p \leq 8$ GeV/c
  - $-4.0 < \eta < -1.5$



B0

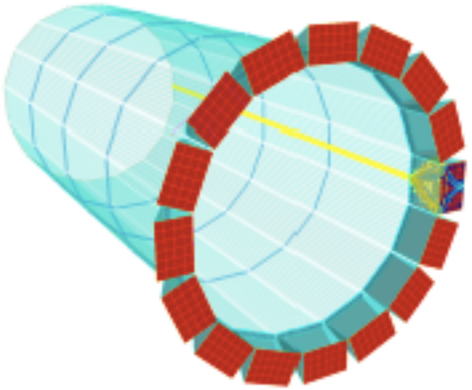
ZDC
RPot



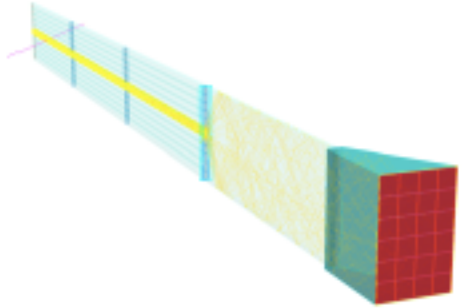
High Performance DIRC
$-2.1 \le \eta \le 1.6$

- 3σ pi/K separation up to 6 GeV/c
  - Focusing lens
  - (3 mm)^2 pixelated photo-sensors
  - Simulation validated by PANDA beam tests with lens and (6 mm)^2 pixels
  - Requires tracking precision 0.5 mr from central tracker
  - Details in eRD14 reports to R&D Committee
- New element for vetoing/correcting multiple scattering:
  - High spatial precision pre-shower in Barrel EMCal
  - 100 µm precision after 10 cm drift ≈ 1 mrad precision on m.s.

PANDA Barrel DIRC



hpDIRC:
"PANDA-like" design



hpDIRC:
"ultimate" design

$e^{\pm}/\pi^{\pm}$ and γ/π^0 Separation

- Forward Electron Endcap:
  - High-granularity, high resolution PbWO4 calorimeter
  - Two-layer (20 cm) Transition Radiation Detector (TRD) with GEM photo-cathode
  - KLM veto of hadronic showers correlated with electron-candidate track

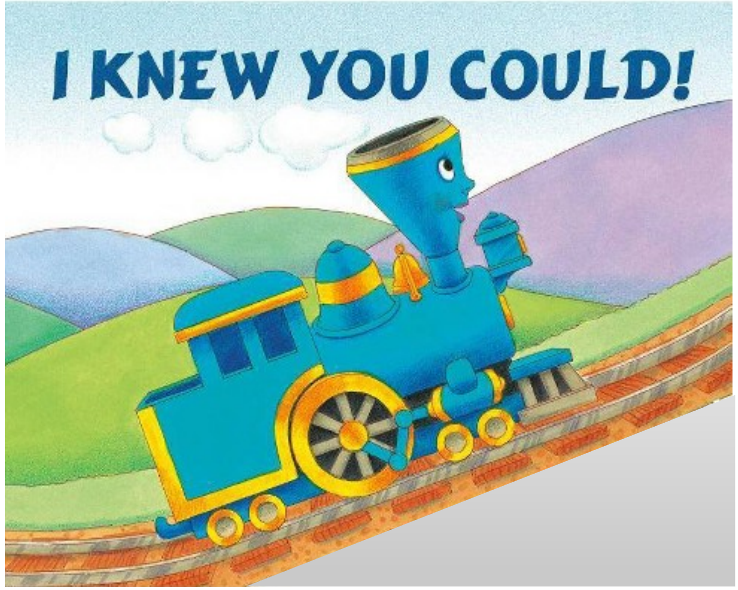
- Barrel region
  - EMCal, with high spatial resolution pre-shower layer (Si+W)
    - ALICE FOCAL pre-shower with Si pixel layers at $2X_0$ and $5X_0$
    - 1 mm spatial resolution of shower → > 6σ 2cluster separation for $E(\pi^0) \leq 14$ GeV
    - Total absorption, **any suitable technology** with $X_0 \leq 1$cm
    - DIRC (0.2<p<1.8 GeV/c at B = 1.5 Tesla)
  - KLM hadronic veto

- Forward Ion Endcap
  - EMCal Shashlyk ~ 10%/sqrt(E), or other with $X_0 < 2$cm
  - Transition Radiation Detector (3 layer, 30 cm)
  - HCal Veto

New Custom Solenoid

- Primary magnetic volume is π 2m^3. Compare with BaBar: π 7.8m^3
- Possibilities of shaping field
  - Projective field in track volume of dRICH
  - Field orthogonal to dRICH PhotoSensor plane
  - Field orthogonal to DIRC PhotoSensor plane
- Nominal field is 2.0 T
  - Slightly less than eRD16 tracking study
  - Could be increased if field shaping is sufficiently successful

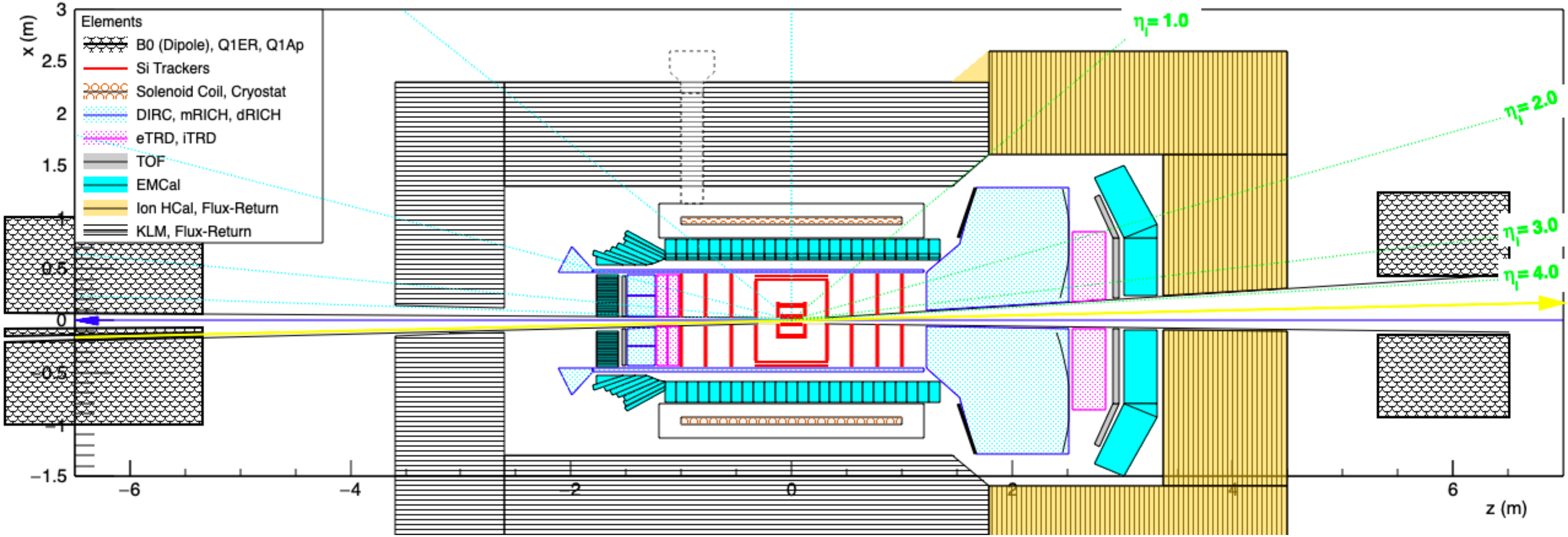
Implementation Summary



1) To reduce risk, the design is based on existing technologies and results from the EIC R&D program.
2) All Si-tracker from eRD25/eRD16 ➔ compact implementation of all PID systems from eRD14
3) Additional electron ID: e) HBD on the electron side and i) TRD on the hadron side
4) Hadronic Calorimetry matched to EIC kinematics/multiplicity
    A. HCal on the hadron side covering eta > 1.
    B. At central and backward rapidity, lower cost K_{Long} - Muon (KLM) detector, Muon ID and K_{Long} veto capability (the rest of the jet reconstructed from tracking, PID, and EM Cal.)
5) The Hcal and KLM: flux return for a new, small solenoid with a field of 1.5 - 3 T.
6) The compact size: Ample space for supports and services. 8 m length allows for up to 1 m adjustment in placement beamline elements.

Collaboration Desired !

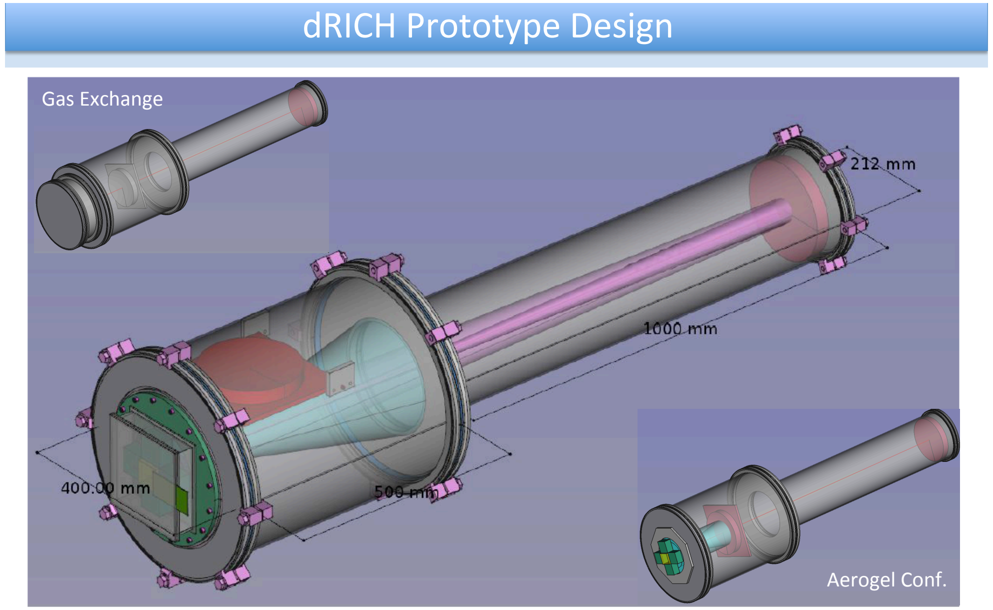
Detector proposals due in September 2021 !!

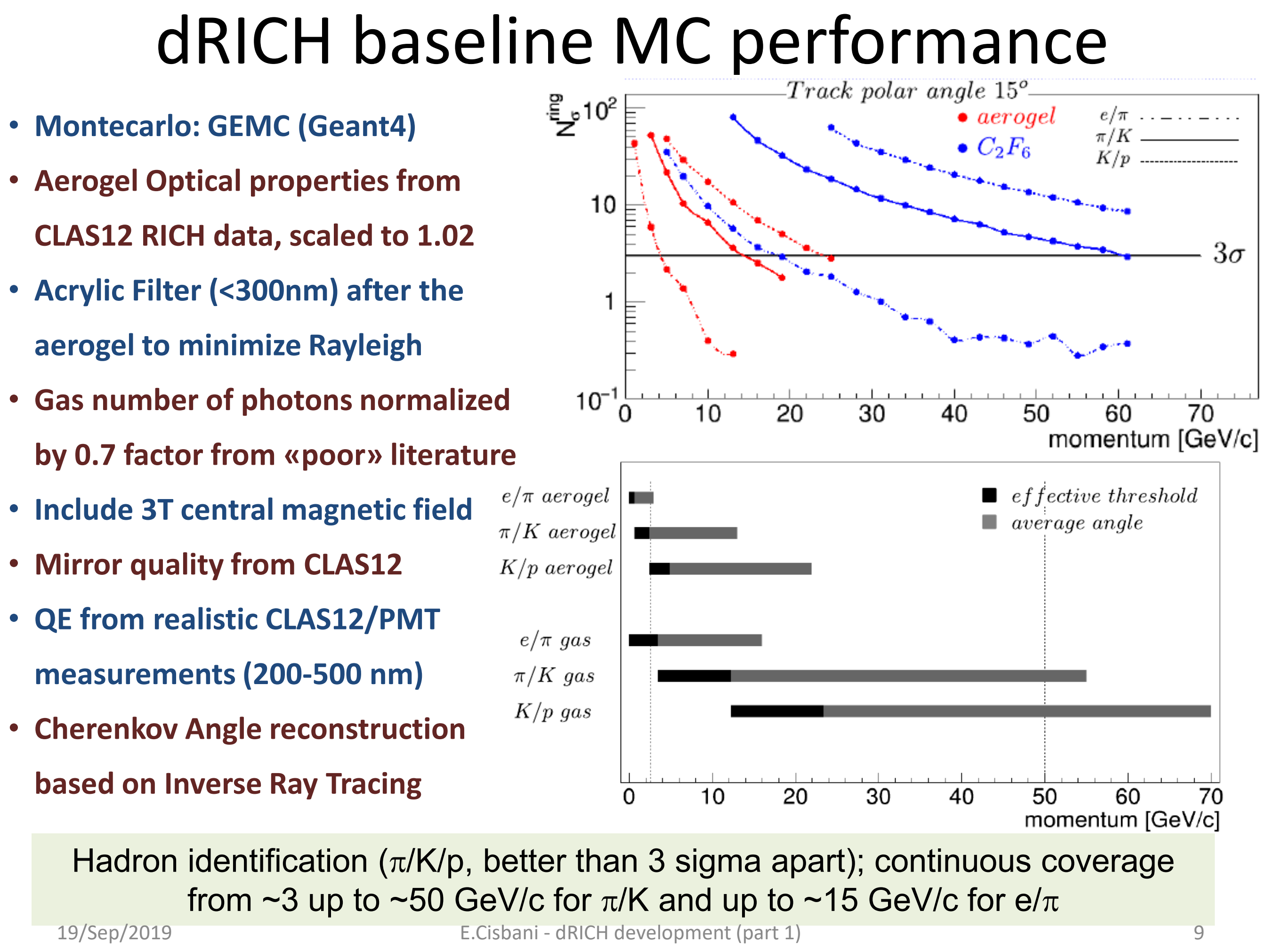


Backup

Dual RICH: Simulations and Prototyping

- eRD14 report, Sept 2019
- Evaristo Cisbani → https://indico.bnl.gov/event/6819/
- Marco Contalbrio ↓




dRICH baseline MC performance

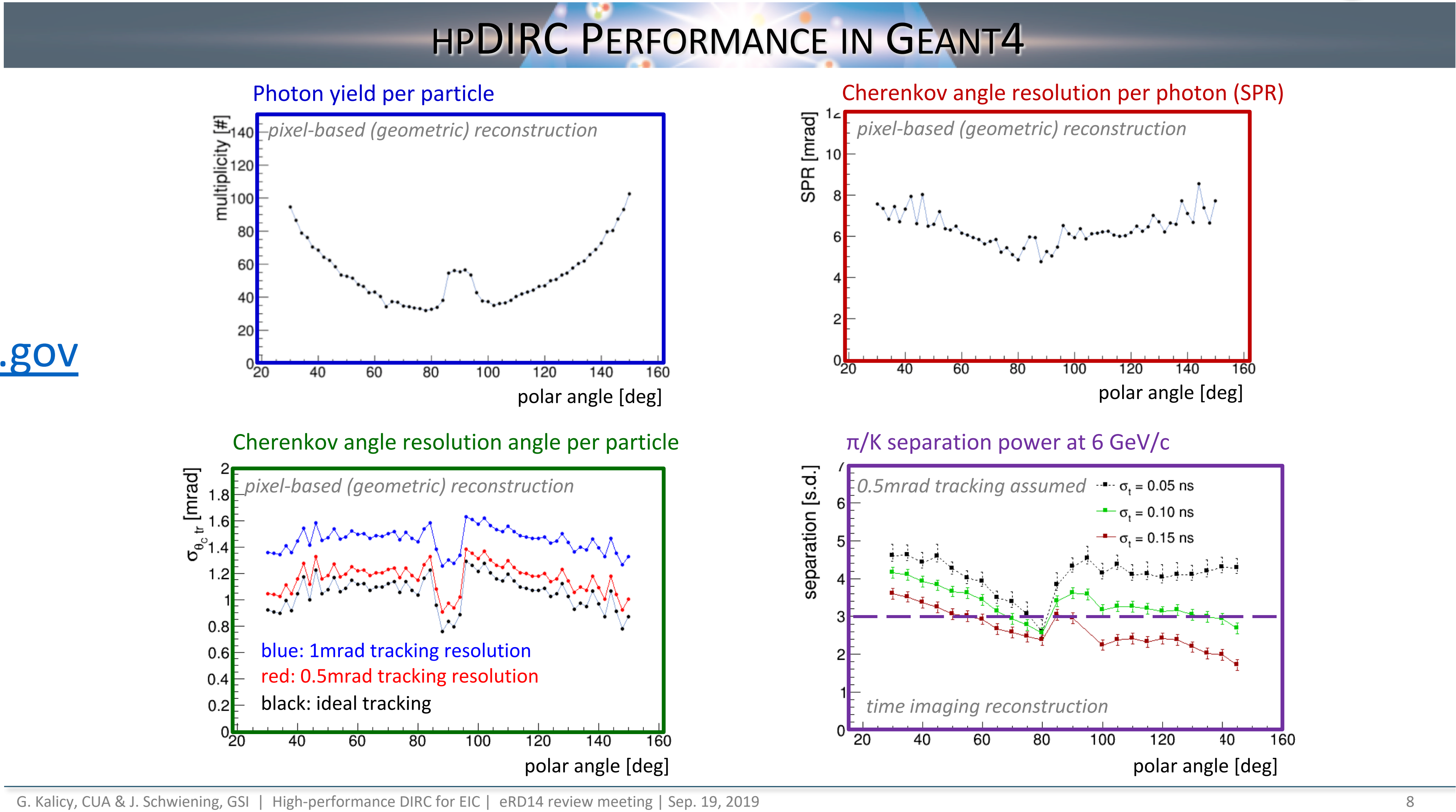
- **Montecarlo: GEMC (Geant4)**
- **Aerogel Optical properties from CLAS12 RICH data, scaled to 1.02**
- **Acrylic Filter (<300nm) after the aerogel to minimize Rayleigh**
- **Gas number of photons normalized by 0.7 factor from «poor» literature**
- **Include 3T central magnetic field**
- **Mirror quality from CLAS12**
- **QE from realistic CLAS12/PMT measurements (200-500 nm)**
- **Cherenkov Angle reconstruction based on Inverse Ray Tracing**

Hadron identification (π/K/p, better than 3 sigma apart); continuous coverage from ~3 up to ~50 GeV/c for π/K and up to ~15 GeV/c for e/π

19/Sep/2019 E.Cisbani - dRICH development (part 1) 9

DIRC Simulation Status

- eRD14 report
  Sept 2019
- https://indico.bnl.gov/event/6819/



HPDIRC PERFORMANCE IN GEANT4

Photon yield per particle

pixel-based (geometric) reconstruction

Cherenkov angle resolution per photon (SPR)

pixel-based (geometric) reconstruction

Cherenkov angle resolution angle per particle

pixel-based (geometric) reconstruction

blue: 1mrad tracking resolution

red: 0.5mrad tracking resolution

black: ideal tracking

π/K separation power at 6 GeV/c

0.5mrad tracking assumed

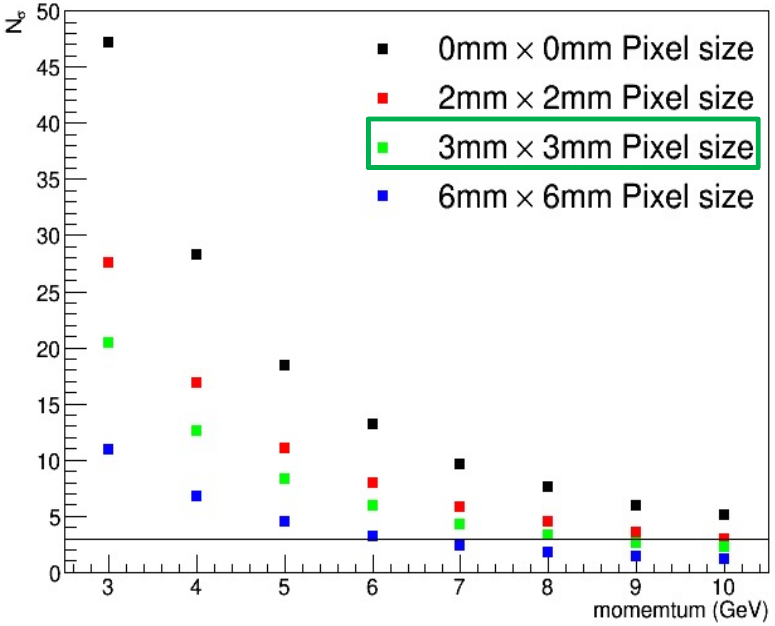
time imaging reconstruction

G. Kalicy, CUA & J. Schwiening, GSI | High-performance DIRC for EIC | eRD14 review meeting | Sep. 19, 2019 8

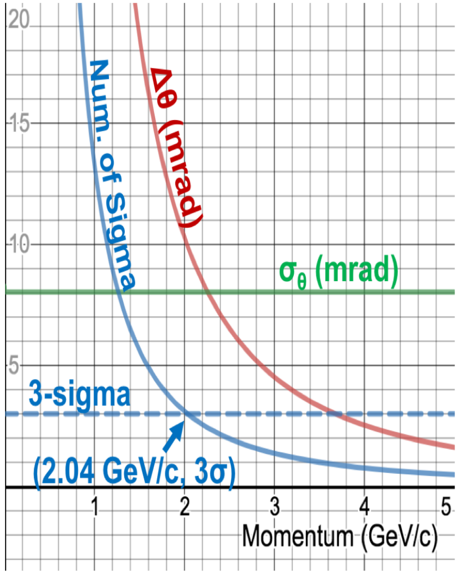
mRICH PID (electron EndCap)

Projected mRICH Performance

- $K^{\pm}/\pi^{\pm}$ separation $\geq 3\sigma$ for $p \leq 8$ GeV/c
- $-4 < \eta < -1.5$
  - Switch mRICH and eTRD from cartoon

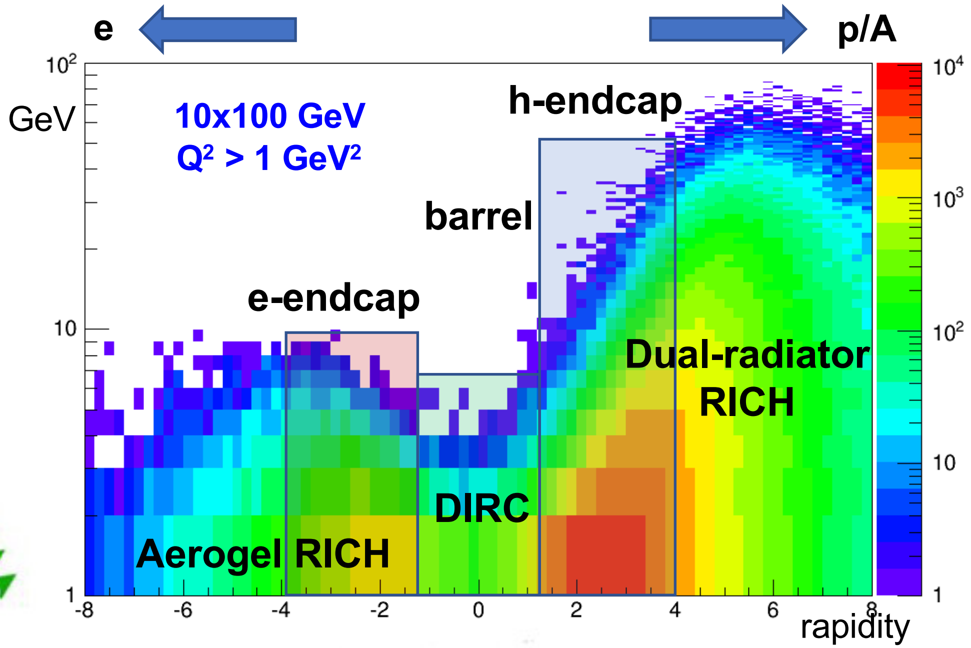


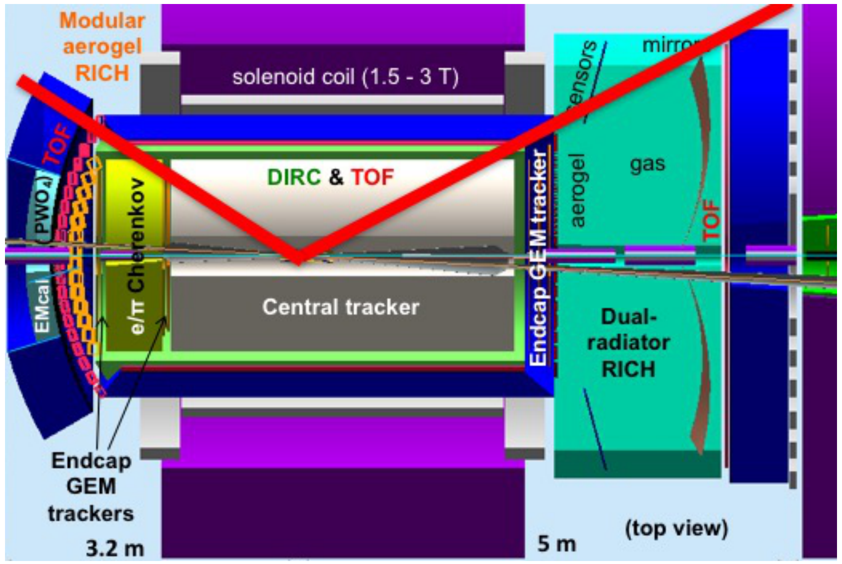
- Projected K/pi separation of mRICH 2nd prototype detector (**Green dots**)
- 2nd prototype detector can achieve 3-sigma K/pi separation up to 8 GeV/c



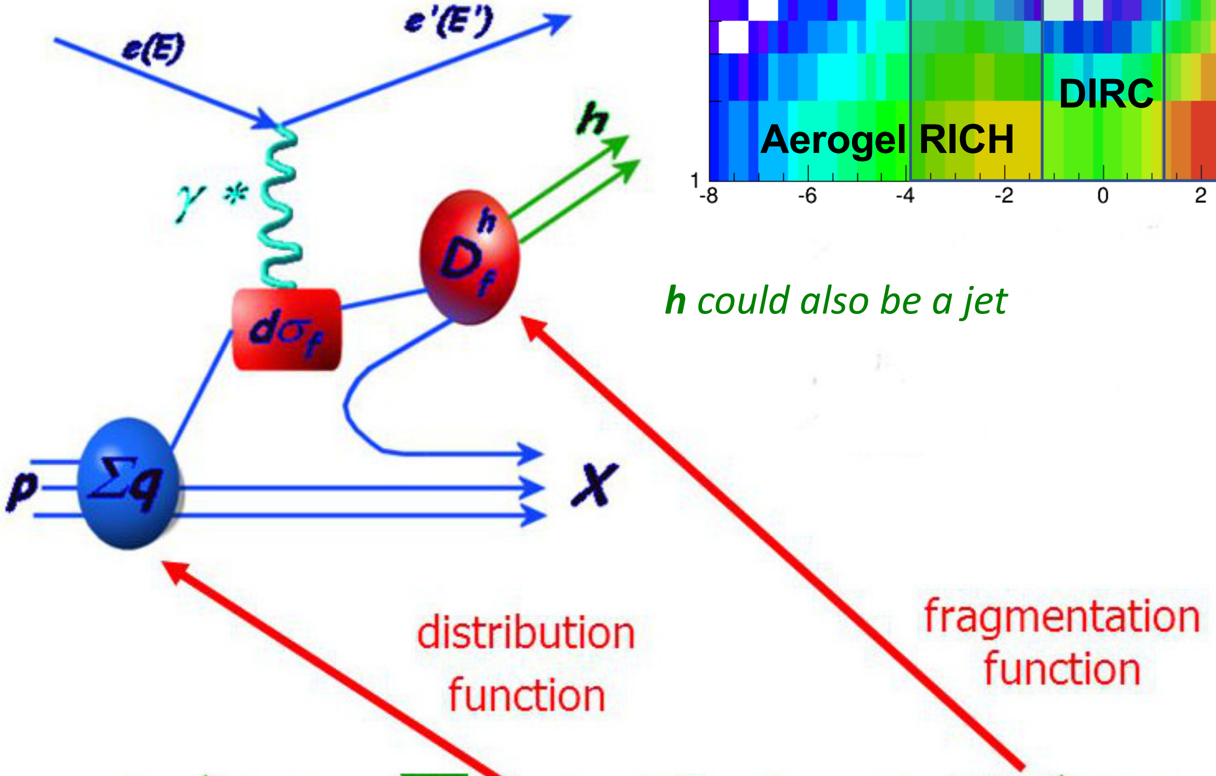
- Projected e/pi separation of mRICH 2nd prototype detector (**blue solid line**)
- 2nd prototype detector can achieve 3-sigma e/pi separation up to 2 GeV/c

PID for the EIC





Semi-Inclusive DIS (SIDIS)



h could also be a jet

$$d\sigma^h(z) \propto \sum_f q_f(x) \otimes d\sigma_f \otimes D_f^{q\to h}(z)$$

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

ALICE Inner Tracking System (ITS) and Upgrade

- ALICE ITS: http://alice.web.cern.ch/detectors/more-details-alice-its#
- ITS upgrade: https://ep-news.web.cern.ch/content/alice-its-upgrade-pixels-quarks
- The MAPS-based ITS Upgrade for ALICE: https://arxiv.org/pdf/2001.03042.pdf
- 2018 ITS EOI and cost estimate of 5.3 MCHF: https://cds.cern.ch/record/2644611/files/ITS3%20EoI.1.pdf

ALICE ITS Upgrade

- All MAPS (ALPIDE chip)
  - Si layer thicknesses from 50 to 100 µm
  - 40 mW/cm^2
  - Low mass carbon fiber support/cooling staves
- 7 cylindrical layers at radii from 2.3 cm to 39.3 cm
- 10 m^2, 12.5 Gpixels
- Data rate: 50 KHz Pb-Pb collisions