A New Era of Electron-Ion Collider Physics
The ePIC detector

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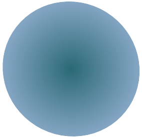
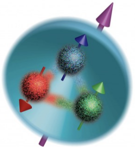
Back to the basics!

Where we are:

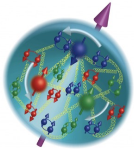
- Elastic lepton scattering determined the nucleon's charge & magnetism distributions in sphere with $\langle r_{ch} \rangle \approx 0.84$ fm
- Large fraction of momentum in proton (x) carried by 3 valence quarks (2u,d), but very small fraction of proton spin
- Nucleons contain additional dynamically generated quark-antiquark pairs & gluons each carrying low fraction of momentum
- Quark & gluon longitudinal momentum fractions well mapped out
- Nucleon spin & mass have large contributions from quark-gluon dynamics, described by QCD



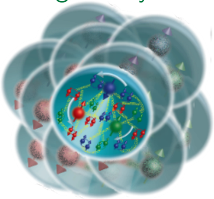
Proton
early 1900s



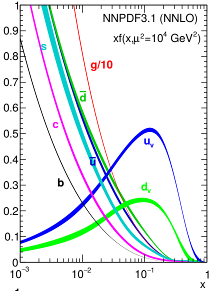
Proton
1975

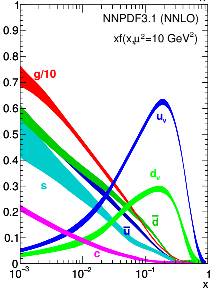


Proton
2015



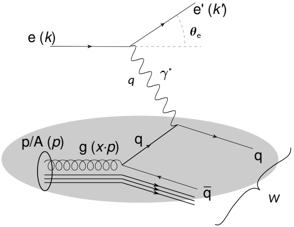
Proton
in a nucleus





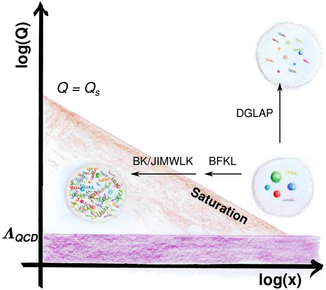
How did we learn this?

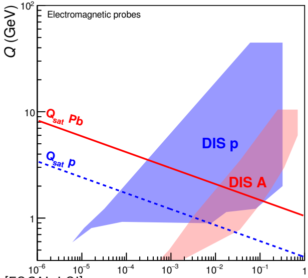
Deep Inelastic Scattering (DIS)



$$Q^2 = s \cdot x \cdot y$$

- s center-of-mass energy squared
- Q^2 resolution power
- x the fraction of the nucleon's momentum carried by the struck quarks ($0 < x < 1$)
- y inelasticity





[FOCAL LOI]

- As a probe, electron beams provide unmatched precision of the electromagnetic interaction
- Event-by-event, model independent leading order determination of parton kinematics including sensitivity to particle's spin is possible
- Data at higher Q^2 obtained indirectly from hadron-collider measurements

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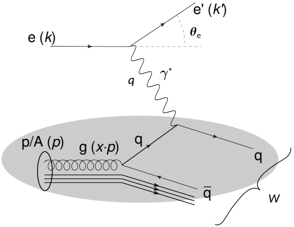

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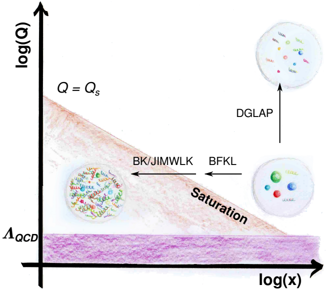
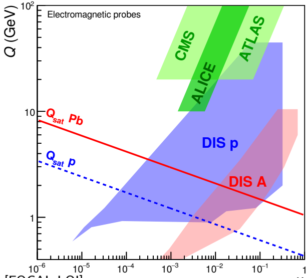
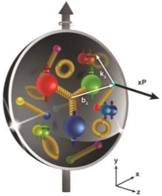




[FOCAL LOI]

What we don't know yet

- The 3D distributions of sea quarks & gluons and their spins in nucleon
- How do the nucleon mass & spin emerge from them and their interactions?
- The details of interactions of color-charged quarks and gluons with a nuclear medium
- How are nuclear bindings and hadronic states created from quark, gluons and their interactions?
- How does a dense nuclear environment affect the quarks and gluons and their interactions?
- The gluon density in nuclei
- Is there a Color Glass Condensate?



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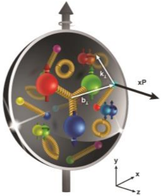

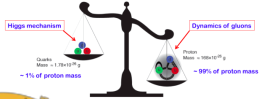

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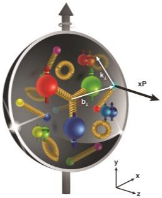

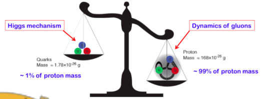

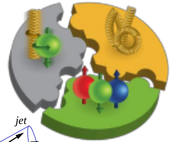

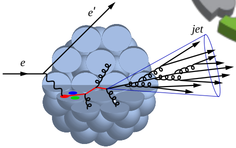

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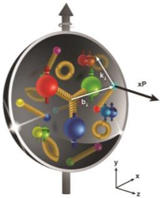

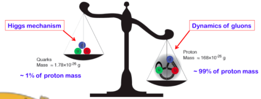

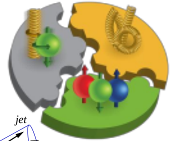

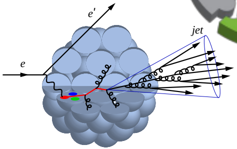

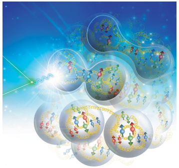

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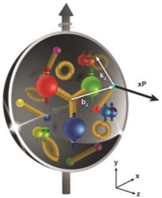

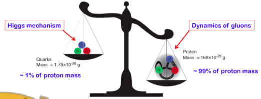

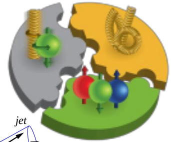

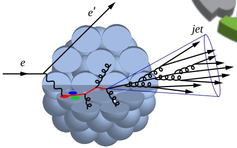

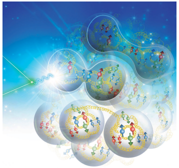

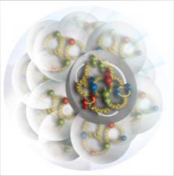

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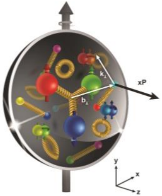
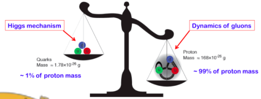
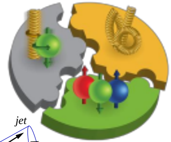
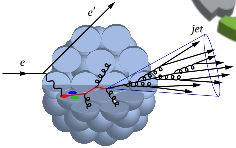
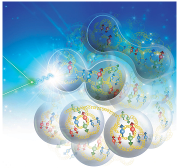
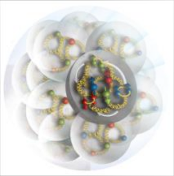


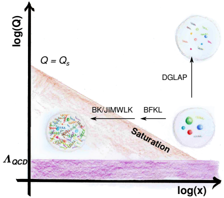












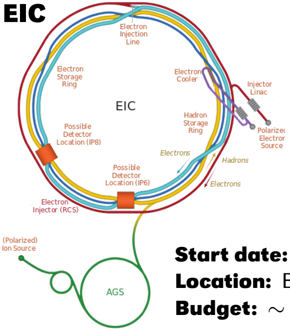
EIC vs HERA

[EIC CDR]

Machine parameters

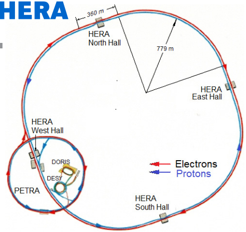
- **Center-of-mass energy**: 20 - 140 (318) GeV
  - electrons: 2.5 - 18 (27.5) GeV
  - protons: 40- 275 (920) GeV (ions: $Z/A \times E_p$)
- **Luminosity**: 10^{34} (10^{31}) cm^{-2} s^{-1}
- **Polarization**: up to 70% (e & ion) (only $e^{\pm}$ up to 60%)
- **Ion species**: p $\rightarrow$ U ($A > 1$ only in fixed target)
- **Detectors**:
  - full coverage: 1-2 (2)
  - fixed target: 0 (2 - limited far-forward coverage)

EIC



Start date: ~ 2031
Location: BNL
Budget: ~ $2.4 billion

HERA



[HERA proposal]

EIC will have:

- lower energy
- variable C-o-M energy w/o significant loss in luminosity
- higher luminosity

+ Hadron polarization
+ Nuclear beams
+ Modern detector(s)

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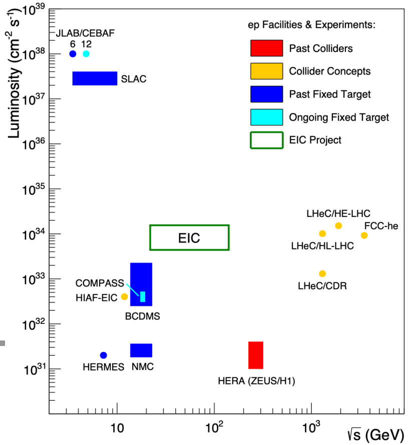

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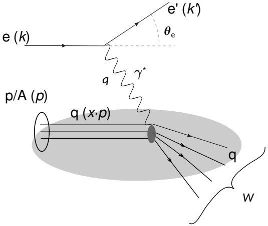
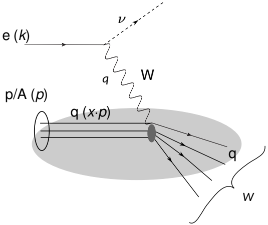
How to access partons at EIC

Neutral current (SI)DIS



Charged current DIS



Neutral current (SI)DIS

- Detect scattered lepton (DIS) in coincidence with identified hadrons (SIDIS)
  - measure correlation between different hadrons as fct. of p_T, z, η
  - needs FF to correlate hadron type with parton

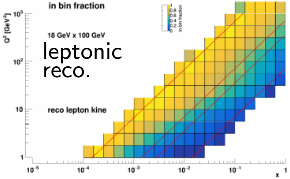
Charged current DIS - W-exchange

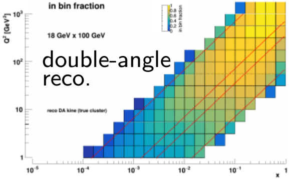
- direct access to the quark flavor no FF – complementary to SIDIS

Jets

- best observable to access parton kinematics
- tag partons through the sub-processes and jet substructure
  - di-jets: relative $p_T \rightarrow$ correlated to k_T
  - tag on PDF

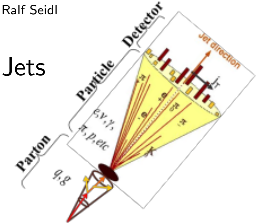
New Simulations



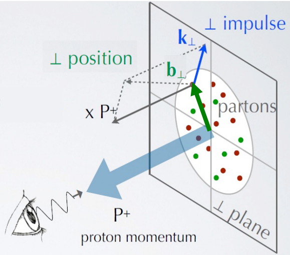


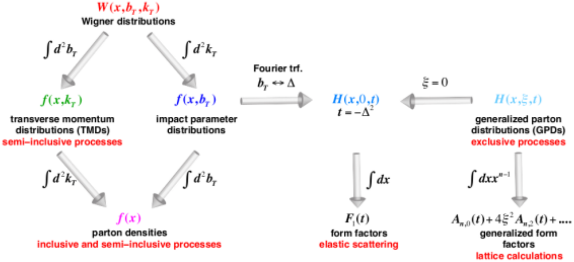
Ralf Seidl

Jets



2+1 dimensional Imaging of Quarks & Gluons





Nuclear Femtography

- Structure mapped in terms of:
  b_T = transverse position
  k_T = transverse momentum
- use different processes to access different aspects of distribution functions

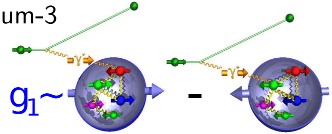
- **PDFs**: (SI)DIS cross sections
- **GPDs**: Deep Exclusive Scattering (DES) cross sections like: deeply virtual Compton scattering (DVCS) $\gamma^\star + p \rightarrow \gamma + p$ or production of a vector meson $\gamma^\star + p \rightarrow V + p$
  Spin-dependent 2+1D coordinate space images
- **TMDs**: SIDIS cross sections
  Spin-dependent 3D momentum space images

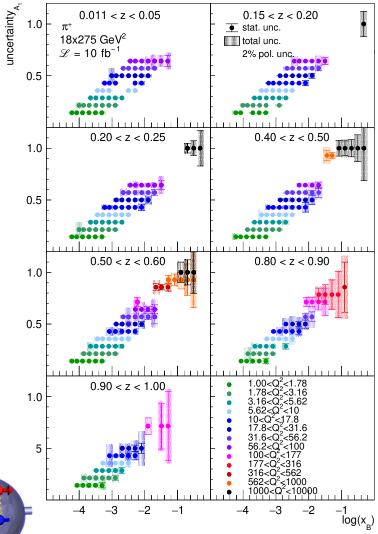
[EIC YR]

Nucleon Spin

$$\frac{1}{2}\hbar=\left\langle P,\frac{1}{2}\middle| J^z_{QCD} \middle| P,\frac{1}{2}\right\rangle=\overbrace{\frac{1}{2}\int_0^1 dx\Delta\Sigma(x,Q^2)}^{\text{total quark spin}}+\overbrace{\int_0^1 dx\Delta G(x,Q^2)}^{\text{gluon spin}}+\overbrace{\int_0^1 dx(\sum_q L_q^z+L_g^z)}^{\text{angular momentum}}$$

- quark contribution: integral of g_1 over x from 0 to 1
- gluon contribution: $dg_1(x,Q^2)/dlnQ^2 \rightarrow \Delta g(x,Q^2)$
- Measured through DIS cross section asymmetry in oppositely polarized collisions
- Improved constraints on the spin of quarks/gluons
  ⇒ Constrain contribution of orbital angular momentum (OAM) of partons to proton spin
- Collisions with polarized deuterons/helium-3
  ⇒ Access to neutron spin

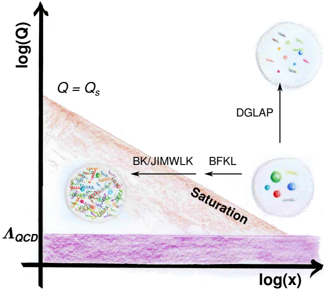


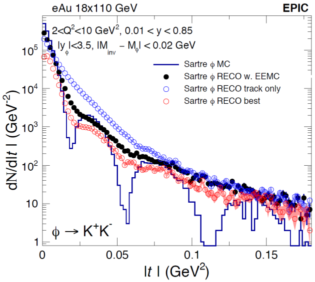


New Simulations

Charlotte v. Hulse

Imaging Nuclei





DGLAP

- predicts Q^2 but not A-dependence and x-dependence

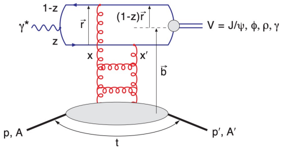
Saturation models

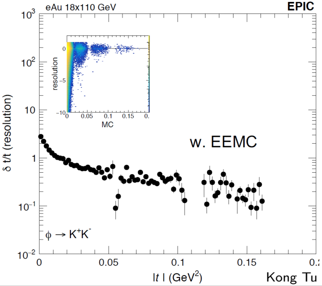
- predict A-dependence and x-dependence but not Q^2

Need: large Q^2 lever-arm for fixed x, A-scan

- Measure different structure function in eA $\rightarrow$ constrain nPDF
- Does the nucleus behave like a proton at low-x?
- Diffractive J/ψ production for imaging nucleus
- Diffractive ϕ/ρ production as saturation probe

Diffractive vector meson production





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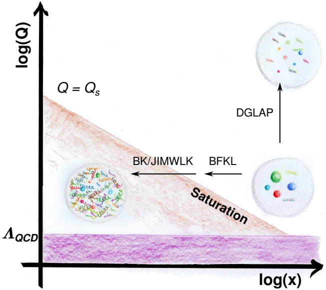
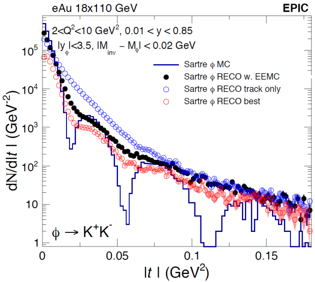




DGLAP

- predicts Q^2 but not A-dependence and x-dependence

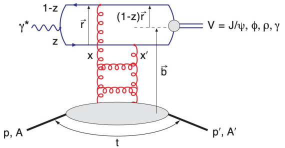
Saturation models

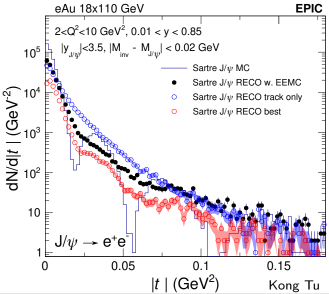
- predict A-dependence and x-dependence but not Q^2

Need: large Q^2 lever-arm for fixed x, A-scan

- Measure different structure function in eA $\rightarrow$ constrain nPDF
- Does the nucleus behave like a proton at low-x?
- Diffractive J/ψ production for imaging nucleus
- Diffractive ϕ/ρ production as saturation probe

Diffractive vector meson production



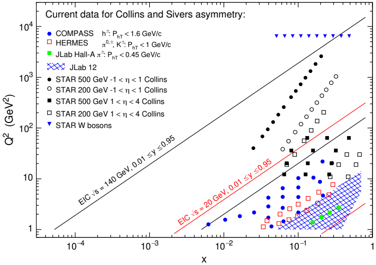


Kong Tu

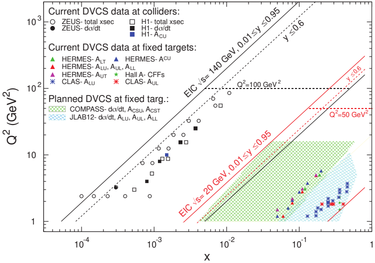
New Simulations

Kinematic Coverage

Collins & Sivers

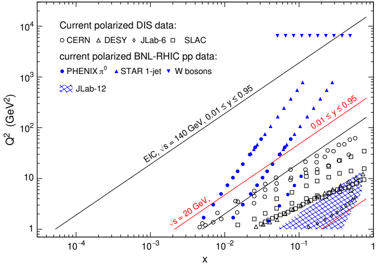


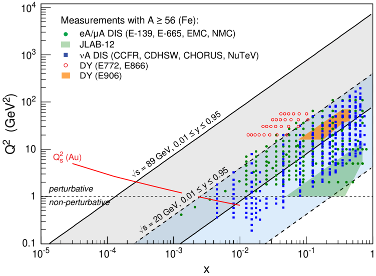
DVCS



polarized DIS

[EIC YR]

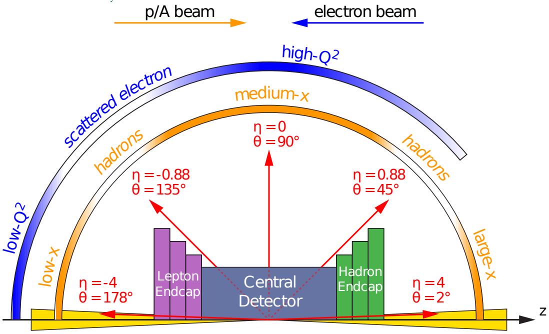




Accelerator gives access to extensive kinematic range

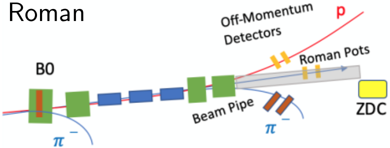
⇒ Now we need a detector to match

Generalized detector design considerations



- Large rapidity coverage for central detector
- Specialized far-forward detectors for *p* kinematics measurements
- High precision low mass tracking
- Hermetic coverage of tracking, electromagnetic & hadronic calorimetry
- High performance single track PID for π, K, p separation

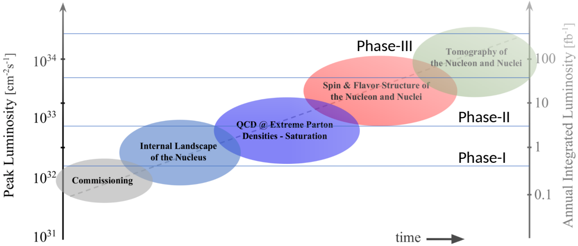
- Large acceptance for diffraction, tagging, neutrons from nuclear breakup many auxillary detectors integrated in beam line: low-Q^2 tagger, Roman pots, ZDCs ...
- High control of systematics luminosity monitors, electron & hadron polarimetry



Highly integrated design between detector and machine for IR

[EIC YR]

Luminosity dependence - Main measurements



design luminosity:

$L = 10^{34}$ cm^{-2} s^{-1}

$\int Ldt = 100$ fb^{-1} per year

$\int$ Ldt 1 fb^{-1}

inclusive DIS

- measure scattered electron
- → precision EM-Calorimetry
- multi-dimensional binning: x, Q^2
- → maximize x, Q^2 coverage & determines interaction region design

10 fb^{-1}

semi-inclusive DIS

- measure scattered electron in coincidence with identified hadrons
- multi-dimensional binning: x, Q^2, z, θ, p_T
- → maximize PID detector coverage in whole phase space

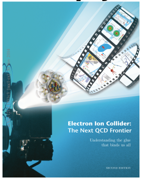
10-100 fb^{-1}

Exclusive processes

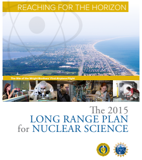
- measure all particles in event
- → hermetic tracking + hadronic calorimetry
- multi-dimensional binning: x, Q^2, z, θ, p_T
- measure proton kinematics
- → strong constraints on far-forward detector & interaction region

The detector design process

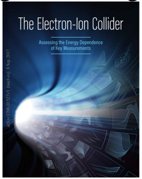
Define physics objectives & generic design parameters



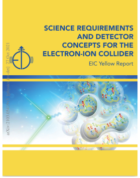
2012



2015

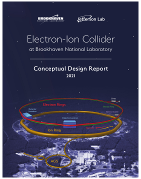


2017

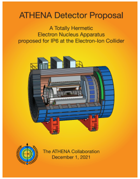


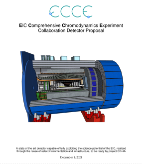
2020

Realistic machine & detector concepts



Feb. 2021



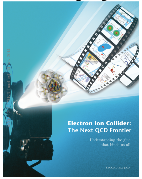


Dec. 2021

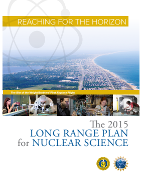
- Detector & machine design driven by physics objectives
- Jan. 2020: BNL site selection
- Extensive generic detector R&D for EIC for PID, tracking & calorimetry
- YR outlines general detector requirements for benchmark physics observables
- Mar. 2021: Call for Detector Proposals
- Mar. 2022: ECCE chosen as reference design for detector 1
- **Jul. 2022: ePIC collaboration**
- **now: TDR preparations**

The detector design process

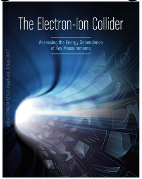
Define physics objectives & generic design parameters



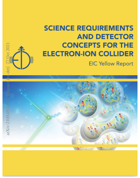
2012



2015



2017



2020

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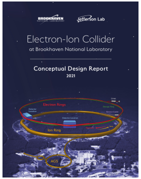

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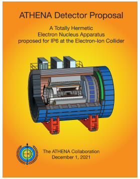

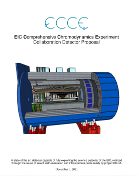

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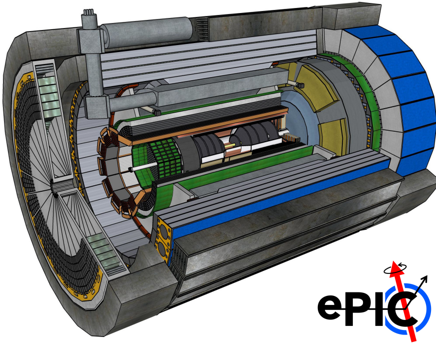
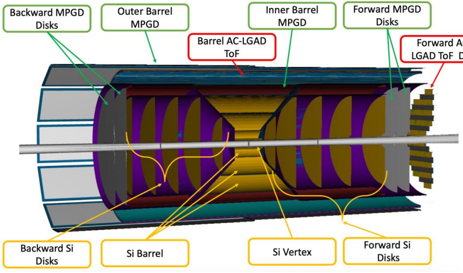


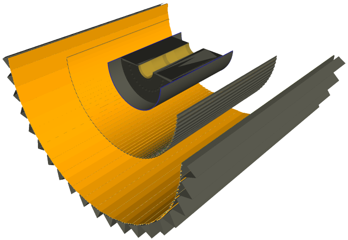
Tracker layout

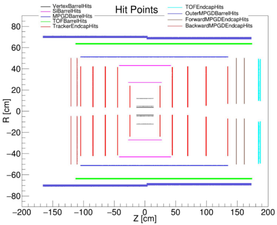


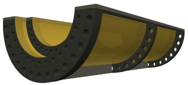
Technology mix

- **ITS3 MAPS based Si-detectors**: $\sigma = 10\mu\text{m},\ X/X_0 \sim 0.05 - 0.55\%/\text{layer}$
- **Gaseous tracker**: $\sigma = 55\ \mu\text{m},\ X/X_0 \sim 0.2\%/\text{layer}$
- **AC-LGADs**: $\sigma = 30\ \mu\text{m},\ X/X_0 \sim 1.5 - 6\%/\text{layer}$

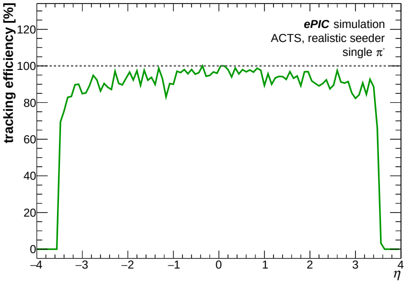
- Ultra thin MAPS based Si-detectors, gaseous detectors & AC-LGADs
- Outer layers placed to provide seeds for tracking & ideal track points before/after PID detectors
- New Magnet with BABAR dimensions B = 1.7-2T

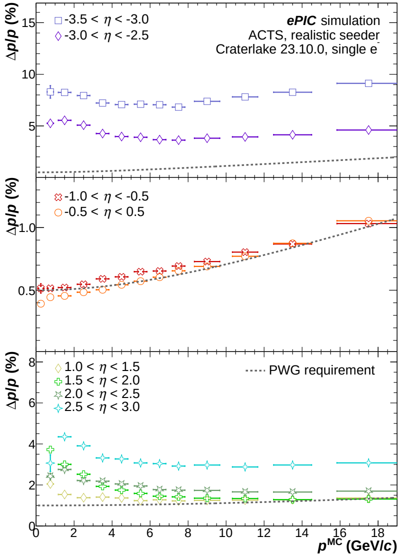






Tracking performance



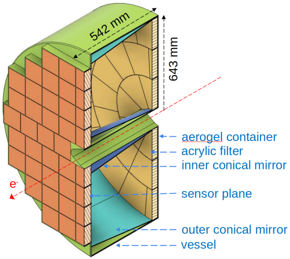


E. Yeats, R. Cruz-Torres, N. Schmidt, S. Maple

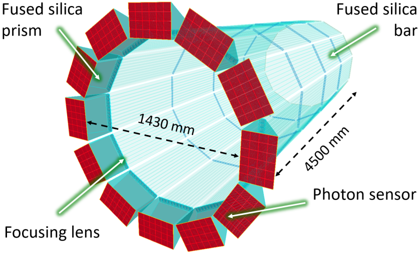
- Stringent requirements from Yellow Report for electron resolution
- Backward momentum resolution requirement hard to meet, complemented by calorimetric resolution
- YR requirement assumes Calorimetry & Tracking need to fullfill requirements independently
- Rapidly evolving tracker design, including background and pattern recognition

Cherenkov-PID

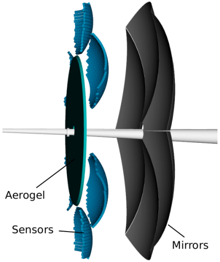
pfRICH



hpDIRC



dRICH



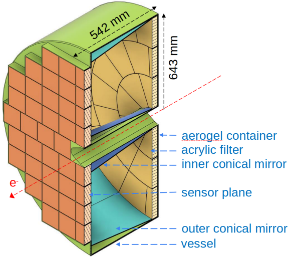
- Optimized for charged pion, kaon & proton separation
- Particular focus on large η coverage
- Complemented by calorimetry & TOF

$\Rightarrow$ Global optimization process ongoing

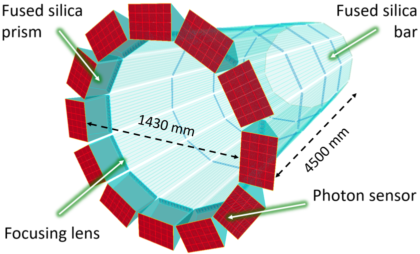
[ATHENA prop] [ECCE prop]

Cherenkov-PID

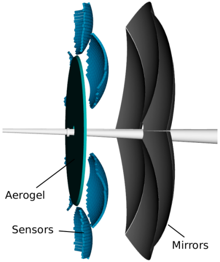
pfRICH

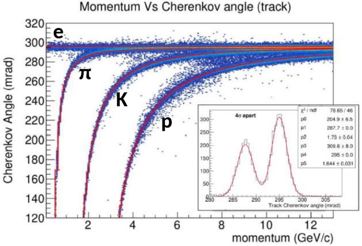


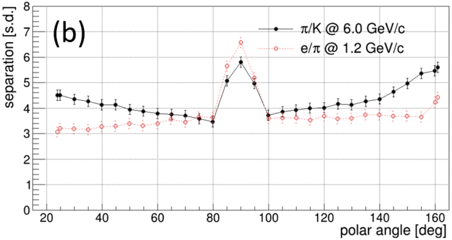
hpDIRC

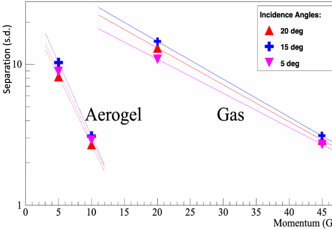


dRICH



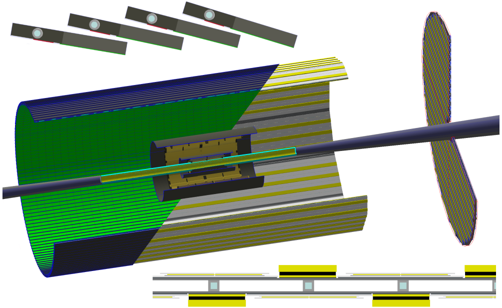


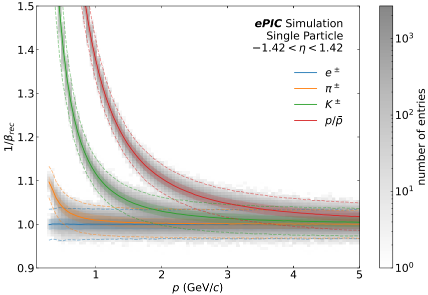


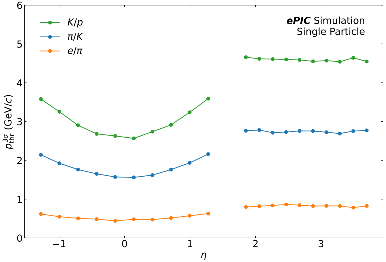


[ATHENA prop] [ECCE prop]

Time of flight (TOF)



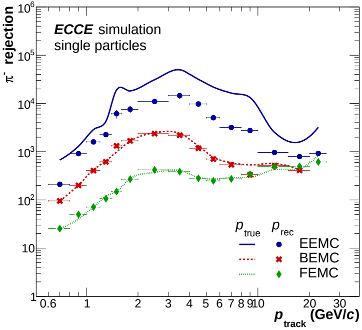


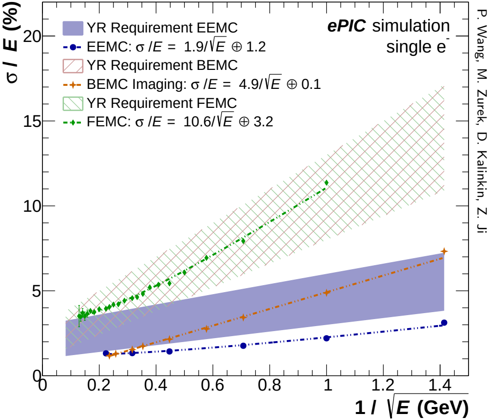


- Analog Coupled - Low Gain Avalanche Detectors (AC-LGADs) with 25 ps time resolution resolution
- Combined PID & tracking detector
- Positions optimized for low momentum e/π, π/K, K/p separation
- Full η-coverage for simultaneous start time determination
- Alternative barrel design with less X/X_0

O. Hartbrich, N. Schmidt, Z. Ye

Electromagnetic Calorimetry (1)



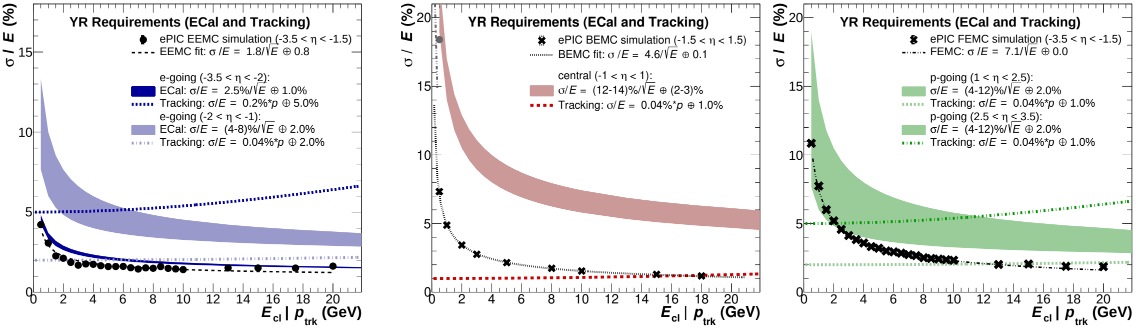


Optimization criteria

- Minimal acceptance gaps
- Scattered electron detection & identification (energy resolution & E/p)
- Shower separation within jets & good energy resolution (h-endcap)
- Most stringent constraints in e-endcap & barrel
- h-endcap with high granularity & good energy resolution

Electromagnetic Calorimetry (1)

[ECCE prop]



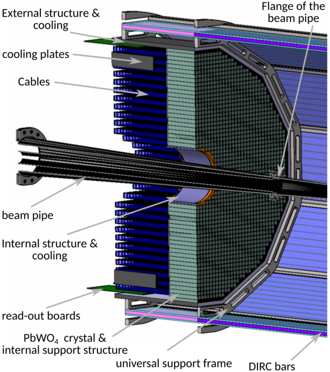
P. Wang, M. Zurek, D. Kalinkin, Z. Ji

Optimization criteria

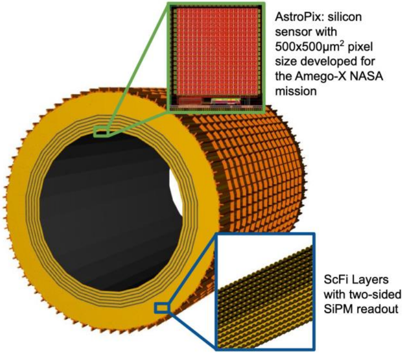
- Minimal acceptance gaps
- Scattered electron detection & identification (energy resolution & E/p)
- Shower separation within jets & good energy resolution (h-endcap)
- Most stringent constraints in e-endcap & barrel
- h-endcap with high granularity & good energy resolution

Electromagnetic Calorimetry (2)

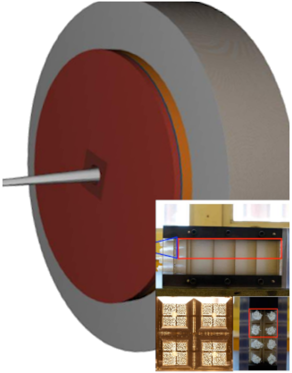
EEMC



BEMC



FEMC

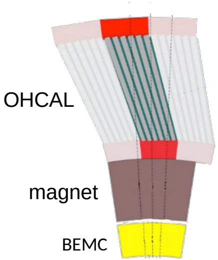


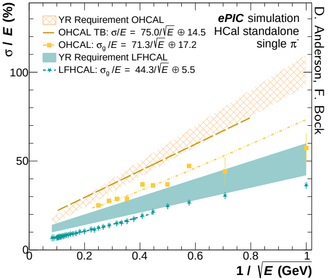
- **EEMC** - homogenous high resolution $PbWO_4$ crystal ECal
- **FEMC** - highly granular W-Scintilating Fiber calalorimeter
- **BEMC:** - 6 layers of 0.5x0.5mm Astro-Pix Silicon layers, interleaved with Pb-SciFi calorimeter

Hadronic Calorimetry

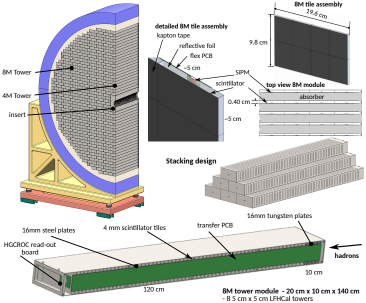
- Designed to complement tracking in Particle-Flow algorithm
- **OHCAL/IHCAL**
  - Fe/Scint sampling calorimeter
  - partial sPHENIX re-use & magnet flux return
- **LFHCAL**
  - Fe/Scint & W/Scint sampling calorimeter
  - Highly segmented (7 long. segments)
  - W-segment as colimator
- High granularity inserts for forward E&HCal to extend η coverage to $\eta = 4$
- Electron end-cap HCAL as neutral veto, shallow Fe/Scint calo

OHCAL





LFHCAL



	Barrel HCal	LFHCAL
η	[-1 .. 1]	[1 .. 4]
σ_E/E	~75%/√E + 15%*	~ 43% √E + 5.5%
depth	~4-5 λ_I	~7-8 λ_I

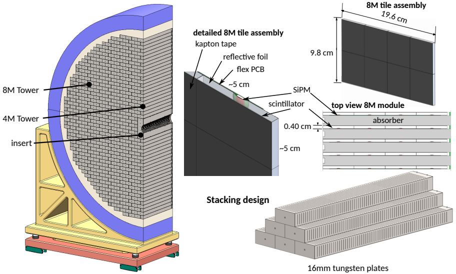
*Based on prototype beam tests and earlier experiments

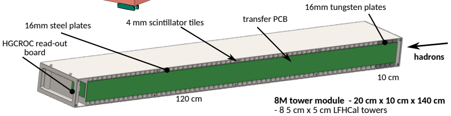
[ECCE prop]

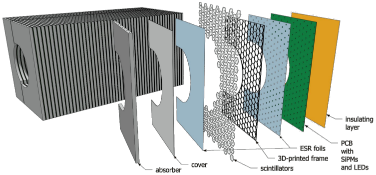
LFHCAL: The General Idea

Concept:

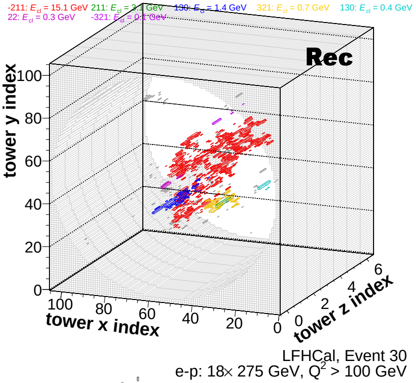
- CALICE AHCal inspired W/Fe-Scintillator calorimeter with SiPM on-tile-readout
- Three construction units:
  - 8M modules 10x20x140 cm^3
  - 4M modules out of 10x10x140 cm^3
  - Insert modules built out of 2 halves surrounding the beam pipe
- **8M & 4M modules :**
  - 4 layers of tungsten + 61 layers of steel interleaved with scintillator material
  - Transverse tower size 5x5 cm^2
  - Multiple consecutive tiles summed to 7 longitudinal segments per tower
- **Insert modules:**
  - 10 layers of tungsten + 54 layers of steel interleaved with scintillator
  - Hexagonal tiles of 8 cm^2 each read-out individually

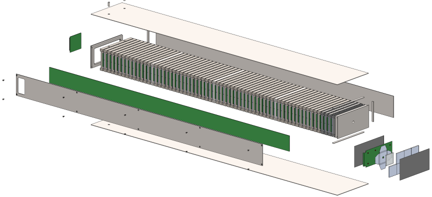






LFHCal: General Facts on the Read-out





- High granularity needed to try to distinguish shower maxima close to beam pipe
- **8M & 4M modules**:
  read out in 7 layers longitudinally (5 or 10 SiPMs summed)
  desirable min measurable tower energy < 0.5 MIP/segment, max. ≈ 1500 MIP/segment
- **insert modules**:
  read out every single tile
  desirable min measurable energy < 0.5 MIP/tile , max. ≈ 500 MIP/tile
- SiPMs mounted to flexible PCBs, passive signal transfer to back side of calorimeter using long transfer PCB
- 1 SiPM-HGCROC (up to 70 channels) per 8M module (56 channels) in the back, 320 HGCROCs for insert readout

LFHCal in Numbers

8M & 4M modules

- Acceptance: $1.2 < \eta < 3.5$
- Inner modules ($R < 1$m): machined scintillator tiles & 3mm SiPMs $\rightarrow \sim 11\% = 83200$ tile/ SiPMs
- Outer modules: injection molded tiles & 1.3mm SiPMs $\rightarrow \sim 89\% = 482560$ tile/ SiPMs

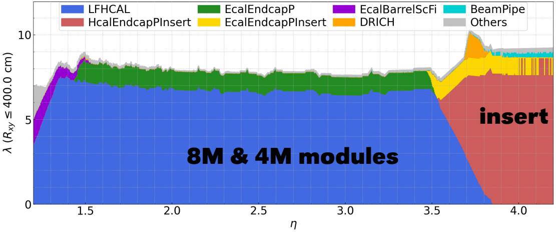
$\rightarrow$ 565,760 SiPMs, 60,928 read-out channels

Insert modules

- Acceptance: $3.5 < \eta < 4.4$
- 360 hexagonal tiles/layer, staggered positions in different layers

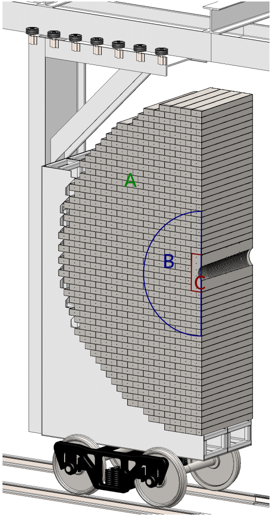
$\rightarrow$ 23400 SiPMs/tiles & read out channels

parameter	LFHCal 8M & 4M modules	insert modules
inner x,y (R)	-20 cm $> x > 40$ cm, -30 cm $> y > 30$ cm	$R > 17$ cm
outer R (x,y)	$R < 270$ cm	-20 cm $> x > 40$ cm, -30 cm $> y > 30$ cm
η acceptance	$1.2 < \eta < 3.5$	$3.5 < \eta < 4.4$
tower information		
x, y	5 cm	≈ 3 cm
z (active depth)	130 cm	130 cm
z read-out	≈ 7 cm	≈ 7 cm
interaction lengths	$6.5\ \lambda/\lambda_0$	$7.5\ \lambda/\lambda_0$
# towers	8704	
# modules		2
8M	1050	
4M	76	
# read-out channels	7 x 8704 = 60,928	23400



LFHCal: Impact of Radiation Damage on Design

ePIC



Radiation Regions

A: $R > 1$ m: $< 5 \cdot 10^{9}$ neq/cm^2/year

B: $R < 1$ m: $10^{9} - 10^{11}$ neq/cm^2/year

C: $\sim 10^{11}$ neq/cm^2/year

Mitigation for different regions:

A: 8M & 4M modules with inaccesible SiPMs

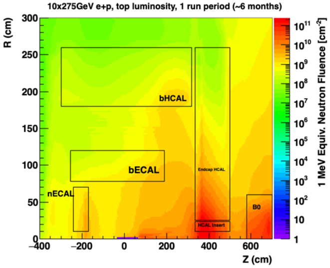
- 1.3×1.3 mm^2 SiPMs & injection molded scintillator

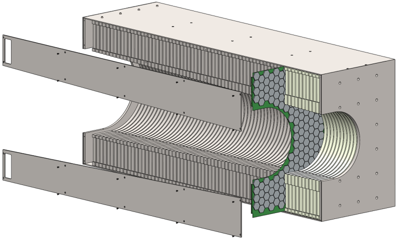
B: 8M & 4M modules with inaccesible SiPMs

- 3×3 mm^2 SiPMs & scint. mach. from cast material

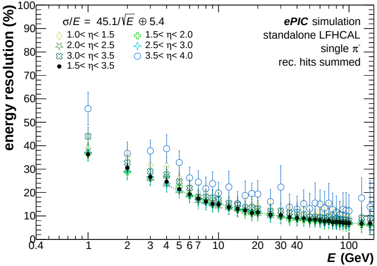
C: Insert modules

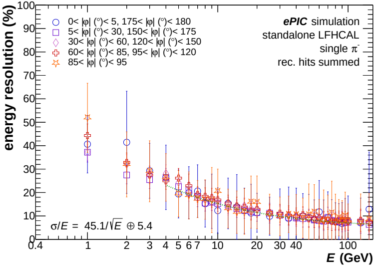
- **Scintillator & SiPM assemblies accessible during longer shutdowns** (after removal of dust cover)
- **Replacement or annealing of SiPMs & tiles possible**

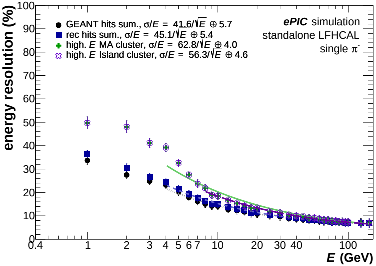




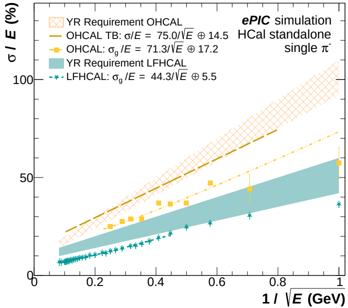
LFHCal simulations



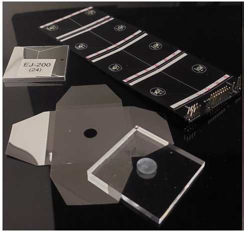


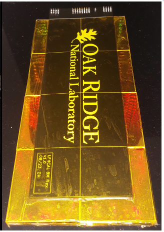


- No strong η or φ performance dependence
- Standalone standard LFHCal performance sufficient to $\eta \approx 3.2$ complemented by insert beyond that
- Ongoing studies to improve clusterization algorithm using ML started during several workshops
  - ePIC Calorimeter Workshop (Apr. 23')
  - HGS-HIRe Power Week - Machine Learning (Jul. 23')
- Meets YR requirements



LFHCal: Recent test beams





Dates:

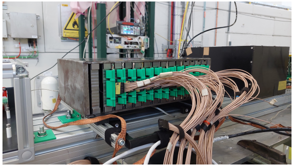
- **SPS**: 6^{th} – 13^{th} Sept.
- **PS**: 11^{th} – 18^{th} Oct.

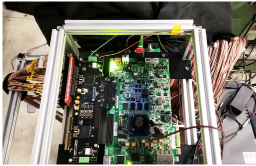
Setup:

- Parasitic to FoCal-H/FoCal-E at SPS and PS
- Setup consists out of maximum 14 layers of 8M tile assemblies
  Sept: w/o absorber layers
  Oct: w/ absorber layers (4 tungsten, 10 steel)
- Read-out: CAEN DT5202 64ch CITIROC SiPM readout unit or H2GCROC

Main expected measurements:

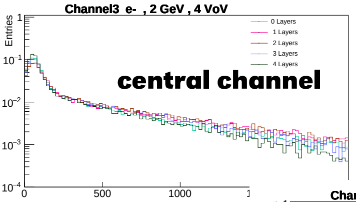
- Light yields per tile
- Shower profile measurements with different absorbers
- Cross talk estimates of different tiles
- Use it as testing setup for SiPM-H2GCROC
- If placed behind FoCal-H, measure part of leakage

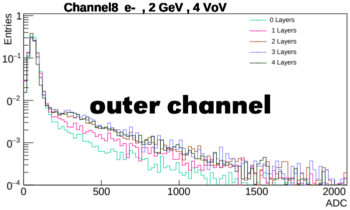




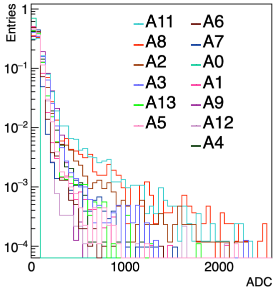
LFHCal test beam: First Results

CAEN read-out



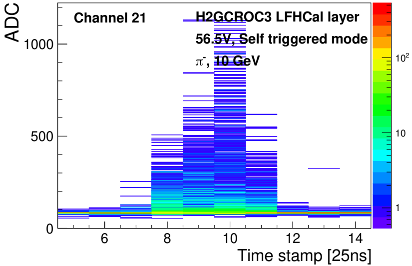


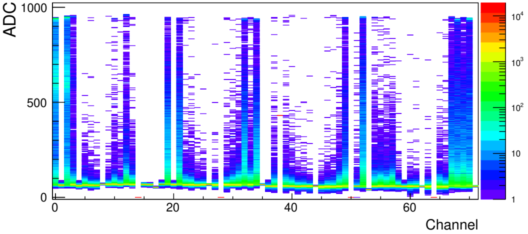
e-, E= 5GeV, V_{ov} = 5V, 1 W-plate



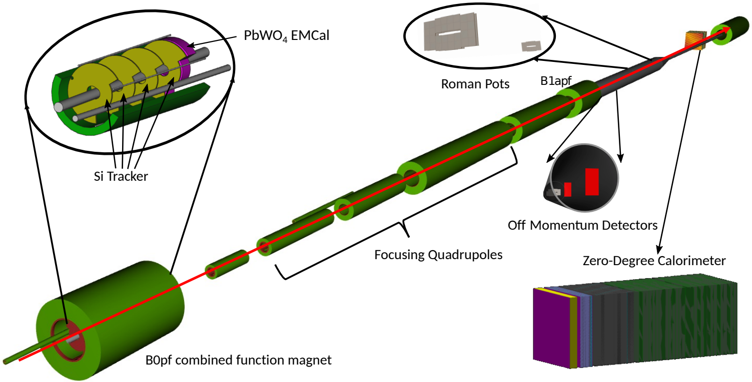
shower development

H2GCROCv3a in self triggered mode





Far-forward Region

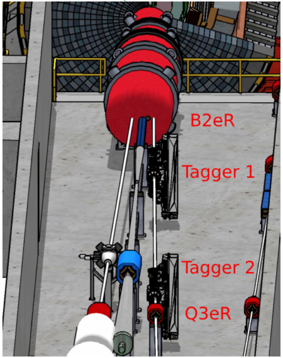


Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	$\theta < 5.5$ mrad ($\eta > 6$)
Roman Pots (2 stations)	$0 < \theta < 5.0$ mrad ($\eta > 6$)
Off-Momentum Detectors (2 stations)	$\theta < 5.0$ mrad ($\eta > 6$)
B0 detector	$5.5 < \theta < 20.0$ mrad ($4.6 < \eta < 5.9$)

- **B0 system** for charged-particle measurement in forward direction & neutral-particle tagging
- **off-momentum detectors** measure charged particles with different rigidity than the beam, e.g., those following decay and fission.
- **roman pot detectors** charged particles measurement close to beam envelope
- **zero-degree calorimeter** measures neutral particles at small angles.

[ECCE prop]

Far-backward Region

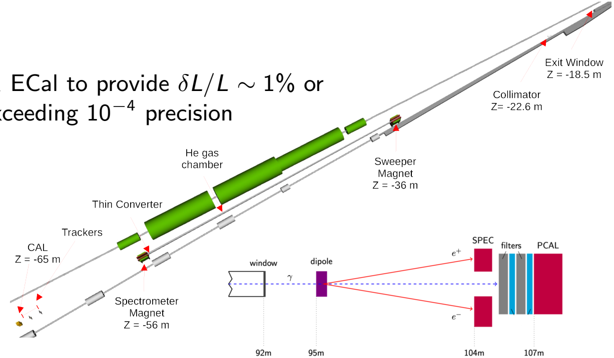


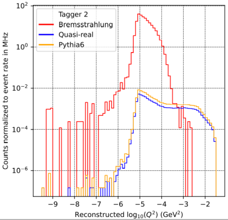
Luminosity Monitor

e + p → e γ p

e + Au → e γ Au

AC-LGAD and $PbWO_4$ ECal to provide $\delta L/L \sim 1\%$ or rel. L determination exceeding 10^{-4} precision





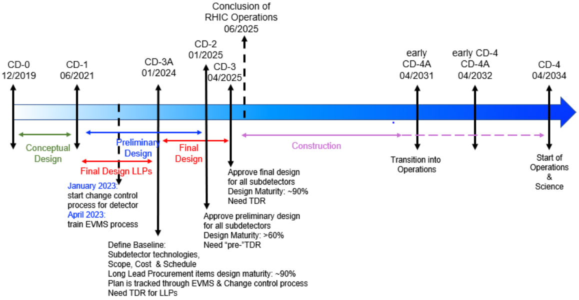
Low Q2-tagger

clean photo-production signal for $10^{-3} < Q^2 < 10^{-1}$

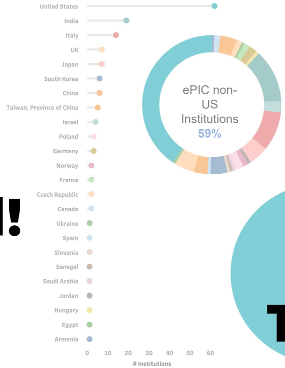
- Double-layer AC-LGAD tracker at 24 & 37m from IP
- $PbWO_4$ ECal ($20cm \times 2cm^2$ crystals)

- This area is designed to measure scattered electrons at small, far-backward angles
- Strong technology synergies with central detector systems

[EIC YR] [ECCE prop]



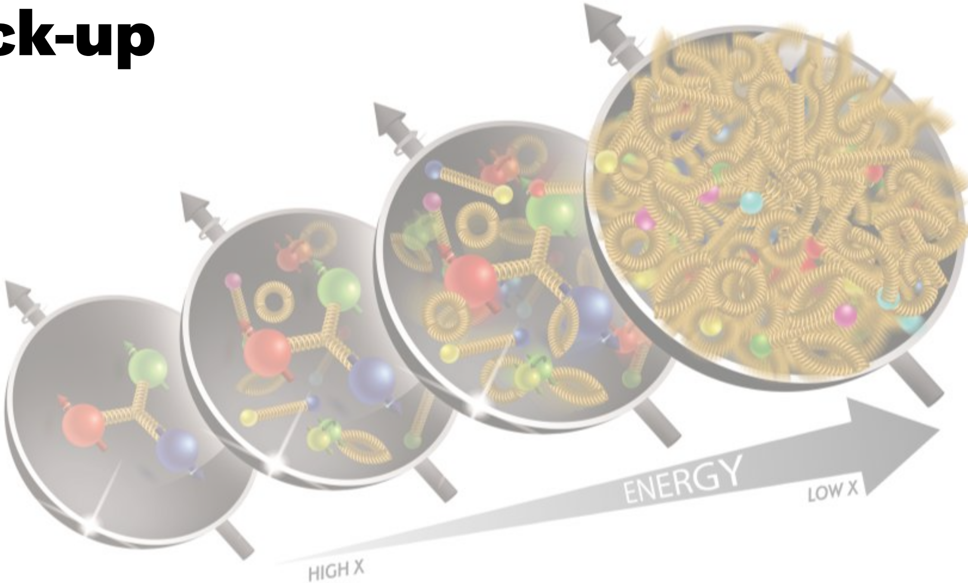
The EIC is coming fast!



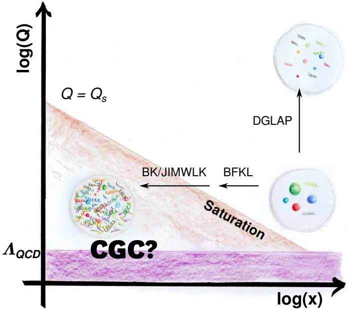
Exiting times ahead!

Thank you!

Back-up



Color Glass Condensate?

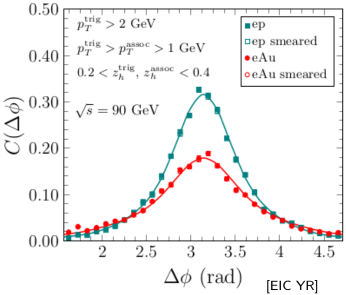


- e interacts over distances $L \sim (2mNx)^{-1}$
- For $L > 2R_A \sim A^{1/3}$ probe cannot distinguish between nucleons in front or back
- Probe interacts coherently with all nucleons

$\Rightarrow$ **Enhancement of Q_s with $A \rightarrow$ non-linear QCD regime reached at significantly lower energy in A than in proton**

Di-Hadron or Di-Jet Correlations

- Low p/A gluon n density (ep): pQCD $2 \rightarrow 2$ process predicts $\Rightarrow$ back-to-back di-jet
- High gluon density (eA): $2 \rightarrow$ many process $\Rightarrow$ expect broadening of away-side
- **EIC allows to study the evolution of Q_s with x**



[EIC YR]

Diffractive Vector Meson Production