Introduction CUA NP Research Group

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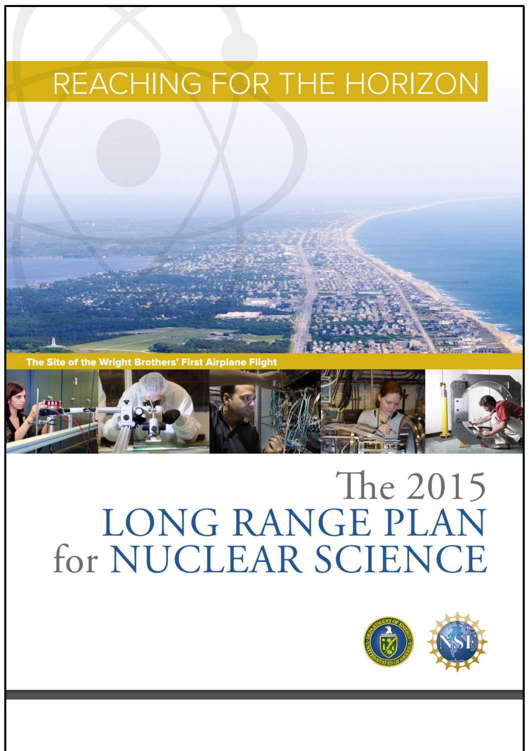
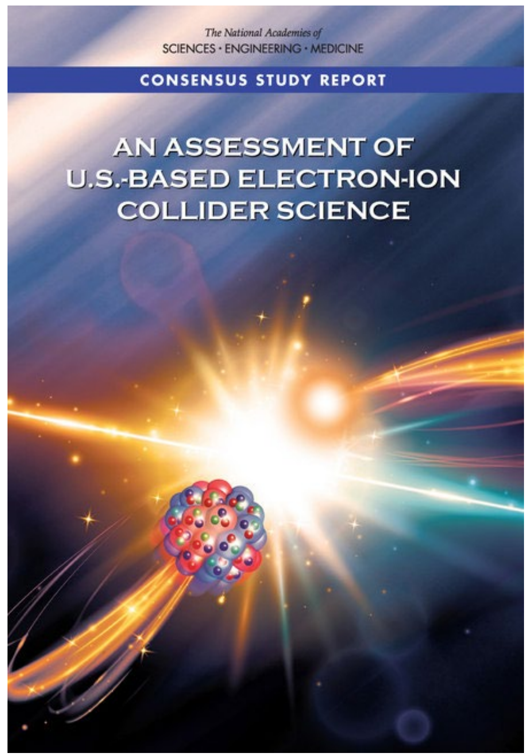
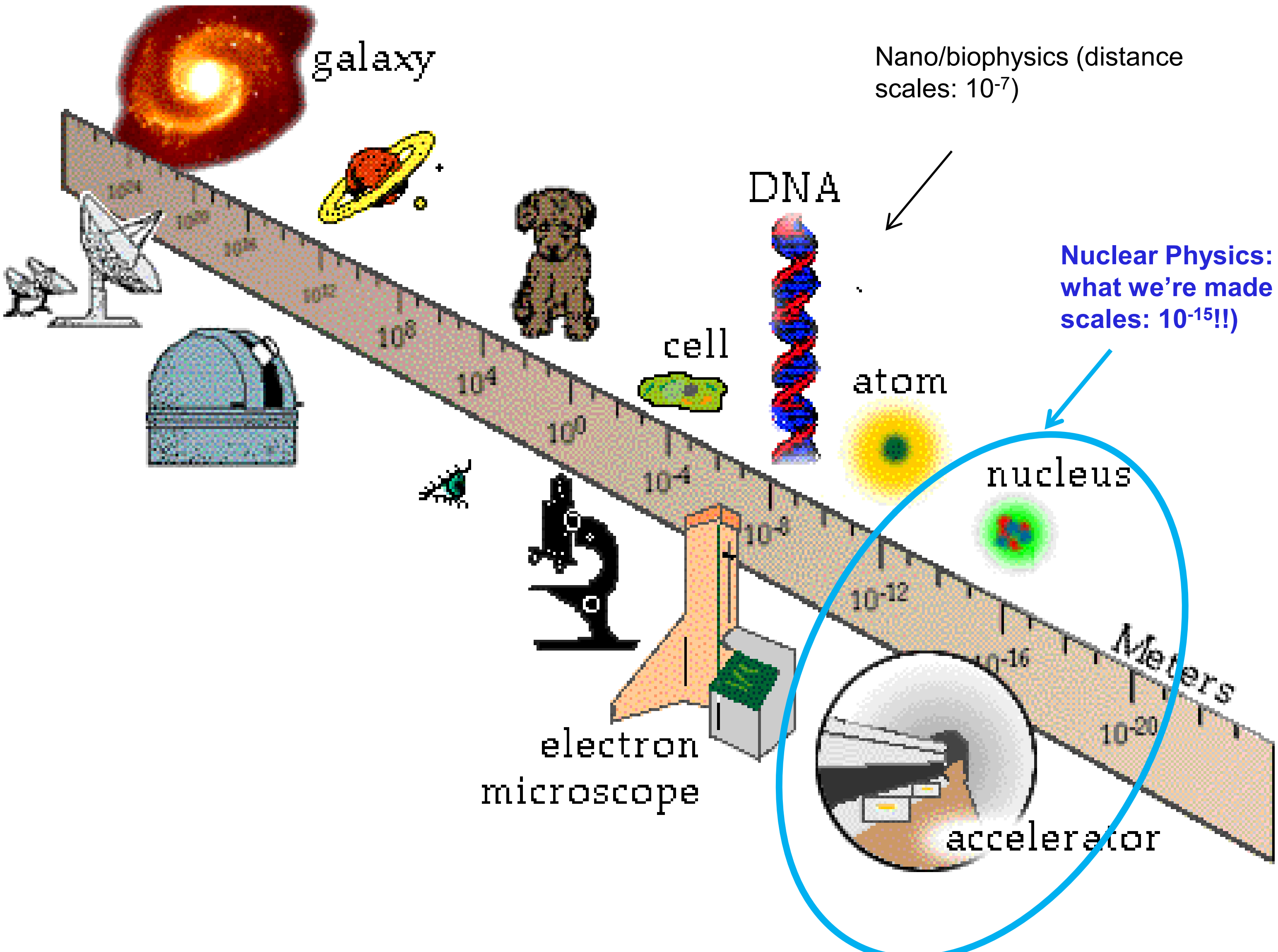




How do we see different size objects:

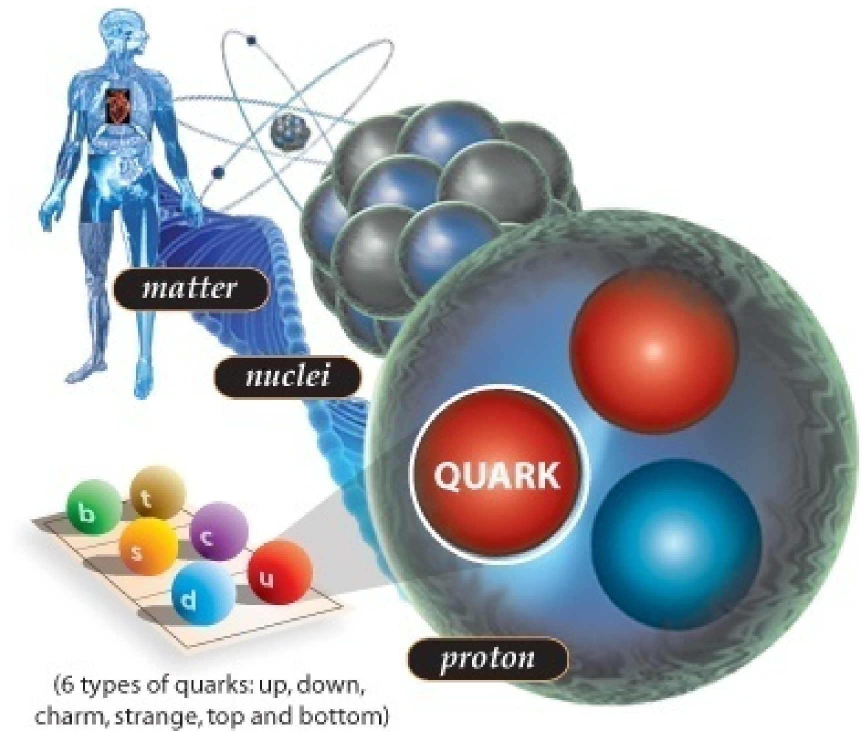
Nano/biophysics (distance scales: 10^{-7})

Nuclear Physics: understand what we're made of (distance scales: 10^{-15}!!)



Fundamental Matter

- Ordinary matter (atoms and molecules) is made up of protons, neutrons and electrons
- Over 99.9% of the atom's mass is concentrated in the nucleus
- The proton internal structure is complex
  - No exact definition for quantum mechanical reasons
  - Typically use concept of mass, energy, and particles

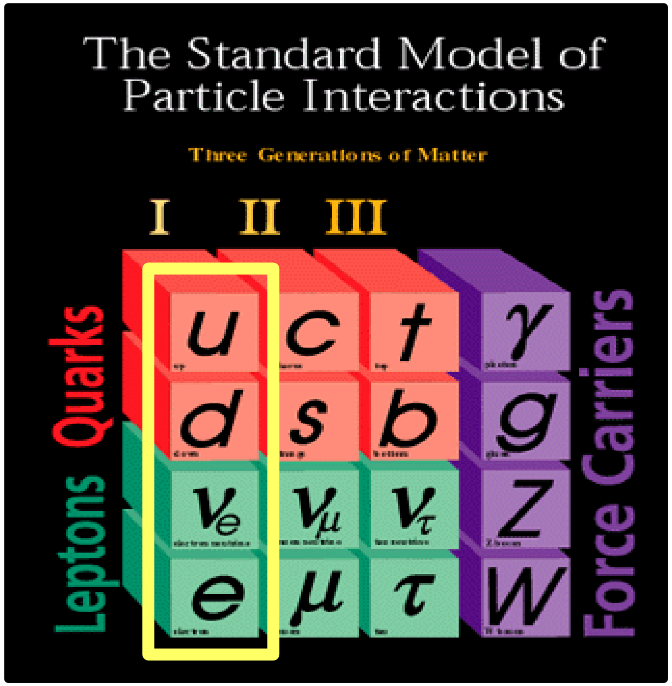


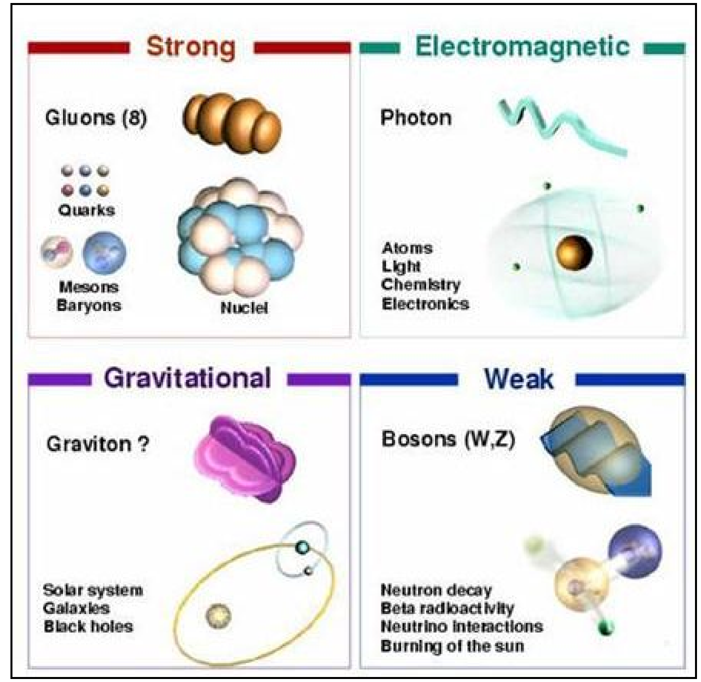
$$
\begin{aligned}
M^2 &= (E_1 + E_2)^2 - \|\mathbf{p}_1 + \mathbf{p}_2\|^2 \\
&= [(p_1, 0, 0, p_1) + (p_2, 0, p_2 \sin\theta, p_2 \cos\theta)]^2 \\
&= (p_1 + p_2)^2 - p_2^2 \sin^2\theta - (p_1 + p_2 \cos\theta)^2 \\
&= 2 p_1 p_2 (1 - \cos\theta).
\end{aligned}
$$

$E^2 = p^2c^2 + m^2c^4$

where E is energy;
c is the speed of light;
p is momentum, equal to γmv;
γ (pronounced "gamma") = $1/(1-(v/c)^2)^{1/2}$;
v is velocity;
and m is mass.

Matter and Forces

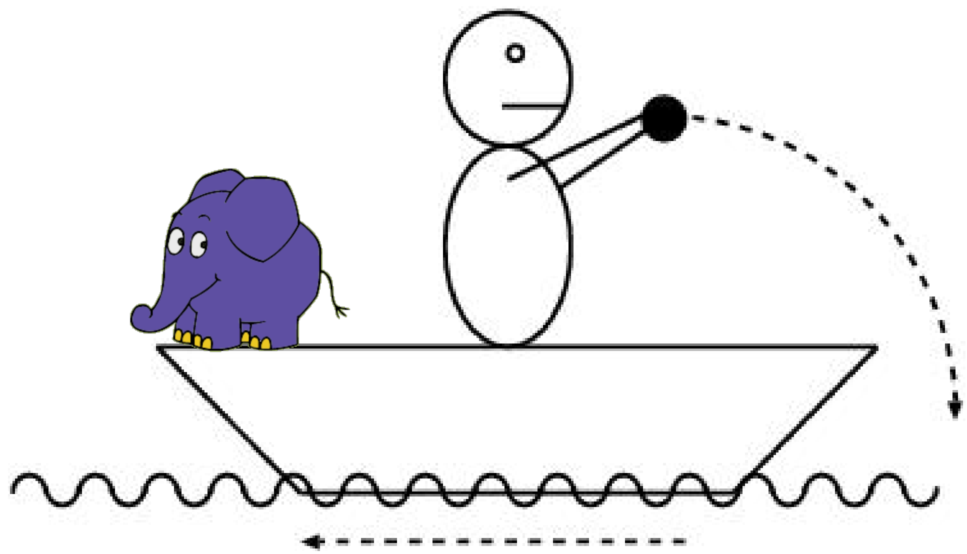




- Fermions are the building blocks
  - Conserve particle number
  - Try to distinguish themselves from each other by following the Pauli principle

- Bosons form the force carriers that keep it all together

Virtual Particles as Force Carriers



- Exchanged/thrown particles can create attractive and repulsive forces

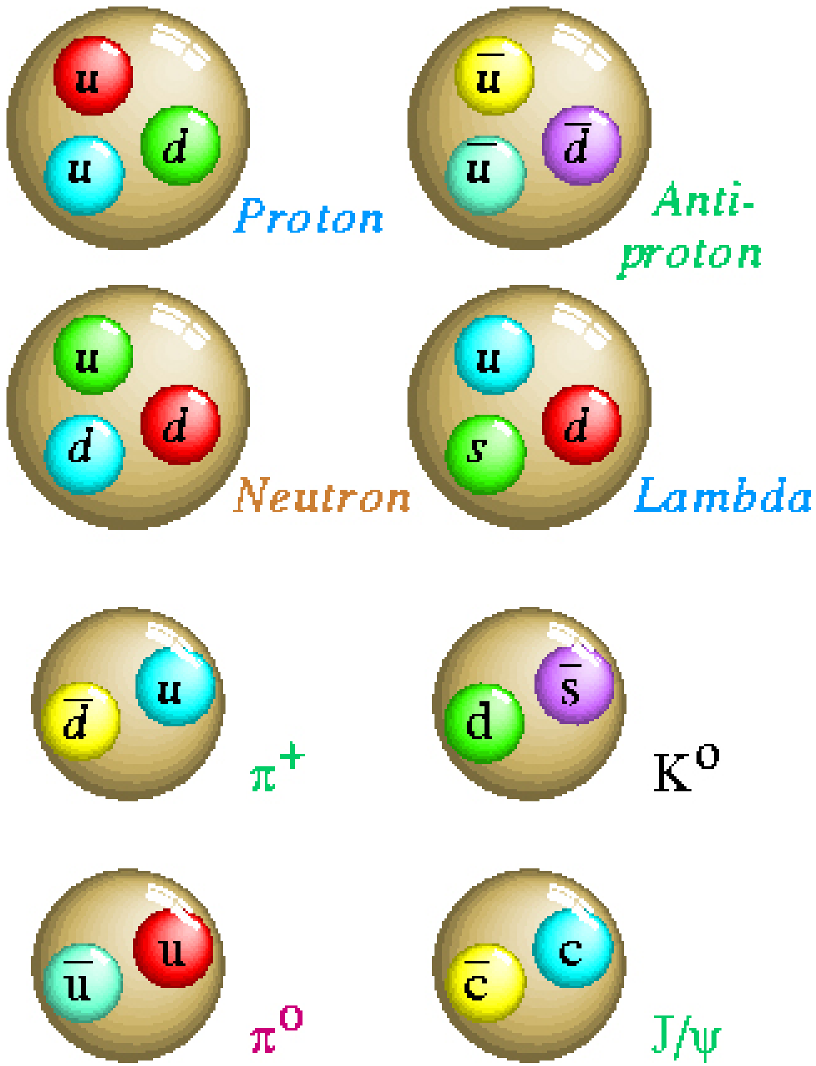
- These particles are not real, but virtual

- Virtual particles can exist by the Heisenberg principle: $\Delta E \Delta t \geq \frac{\hbar}{2}$
  - Even elephants may show up, if they disappear quickly enough

Hadrons

- Hadrons are composed of quarks with:
  - Flavor: u, c, t (charge +2/3) and d, s, b (charge -1/3)
  - Color: R, G, B
  - Spin: ½ (fermions)

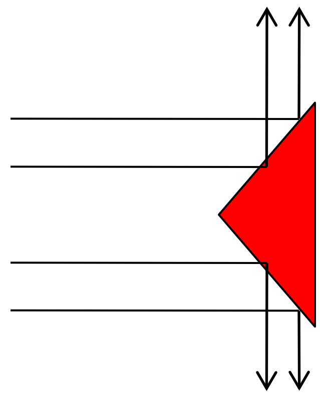
- Two families of hadrons:
  - Baryons: valence *qqq*
  - Mesons: valence $\bar{q}q$

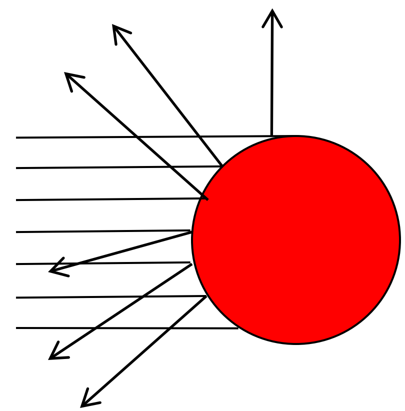


Scattering Experiments

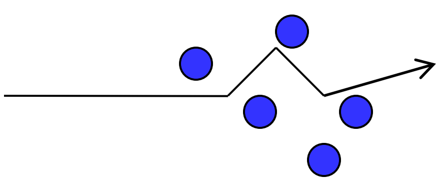
- Measure the substructure of matter

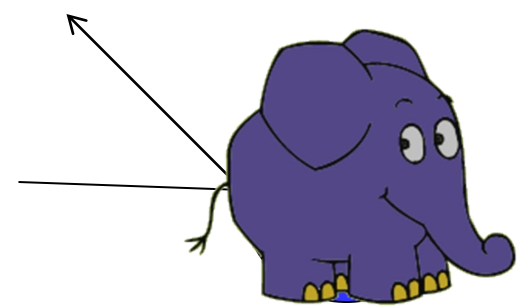
- Shapes of target particles:





- Mass of target particles
  - Light: small deflections
  - Heavy: large deflections





- **Measure scattering cross sections, dσ= probability for beam particles to scatter by an angle θ**

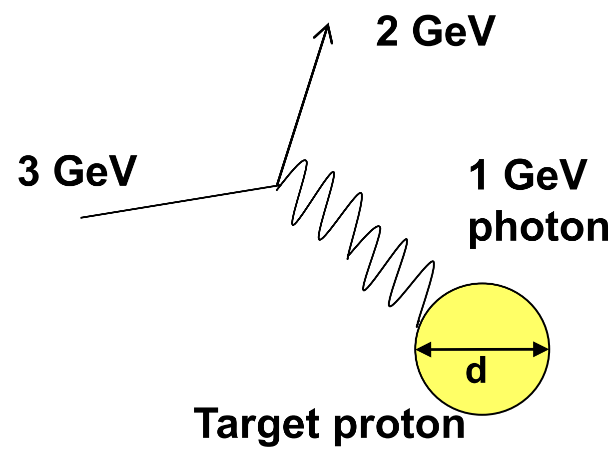
Elastic Electromagnetic Scattering

- The higher the beam energy, and the shorter the wavelength of the photon, the more detail in the target structure is revealed

- Visible light → λ=500 nm=5×10^{-7} m, E_γ=2 eV

- BUT we want to study nucleons=protons and neutrons, whose radius is about 10^{-15} m!
  - Need photons with E=1 keV·nm/λ=10^9 eV=1 GeV

- The solution: Accelerating charged particles emit photons
  - Accelerate electrons to 3 GeV and scatter them off a proton target
  - Electrons deflected (accelerated), and emits a 1 GeV photon



- Instead of photon energy, we typically use: $Q^2 = p^2 - E^2$

Jefferson Lab - flagship NP Lab in the US

The Thomas Jefferson National Accelerator Facility is a basic physics research laboratory operated for the U.S. Department of Energy by the Jefferson Science Associates, LLC. Jefferson Lab is located in Newport News, Virginia.

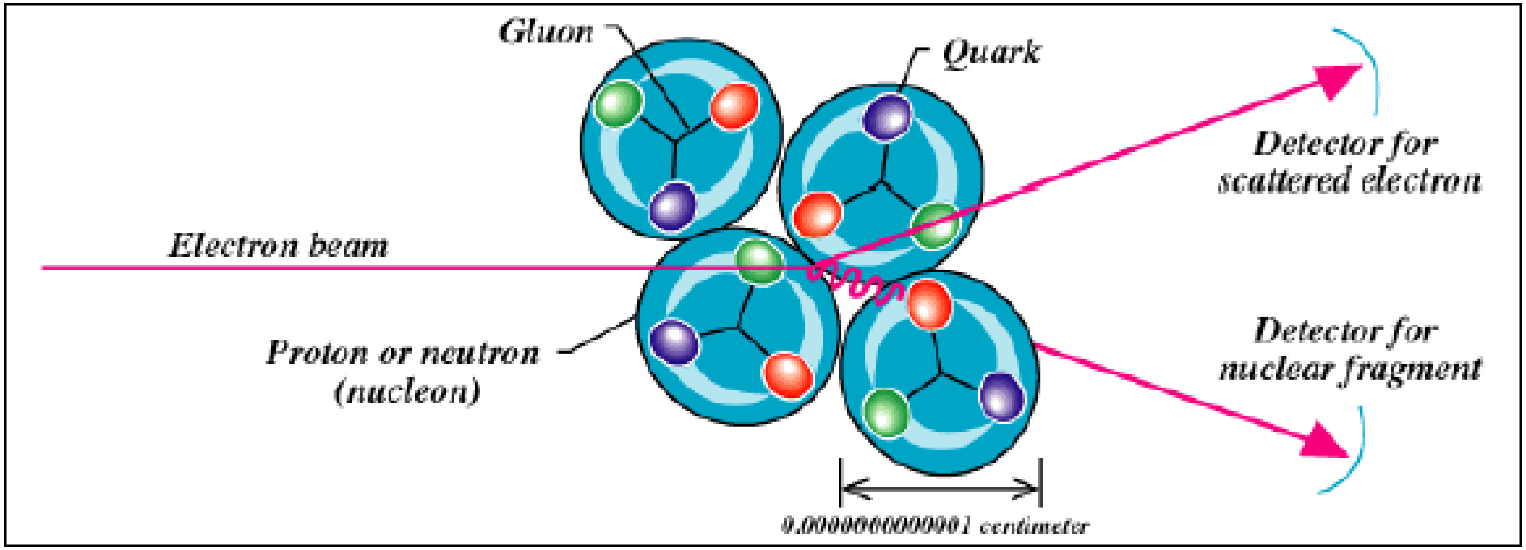
- **Read more here: https://www.jlab.org/research/science**

Objective for this summer: learn about

- **NP Research**
- **Supporting technologies**
- **Experiments start-to-finish**

How do scientists study quarks?

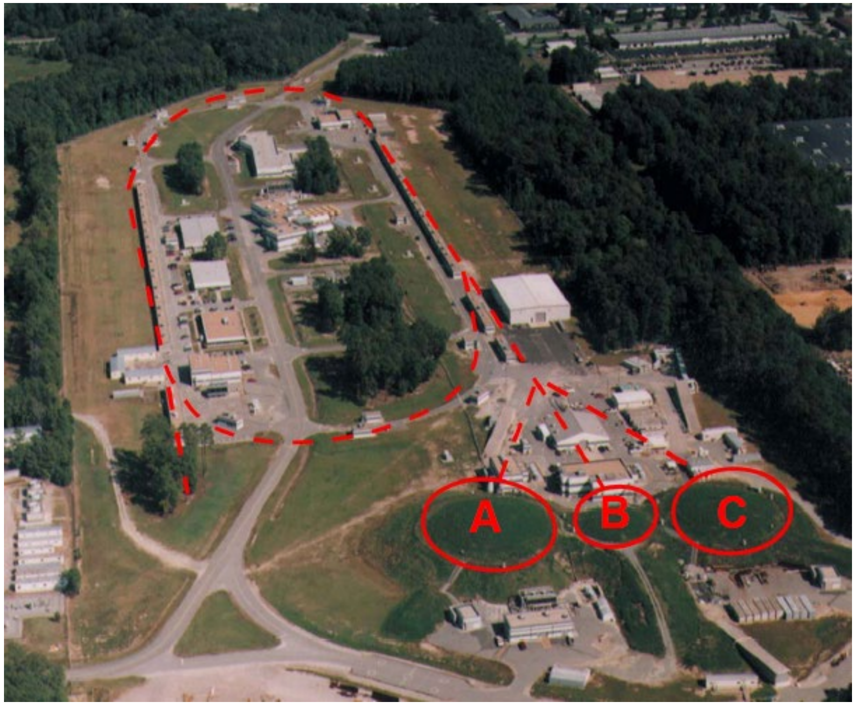
- A sheet of aluminum foil is about 250,000 atoms thick. If you took one of those atoms and enlarged it so that it was the size of the earth, a quark inside the nucleus of that atom would be no larger than your fist. How can we possibly study something that small?



- Scientists at Jefferson Lab use electrons to study quarks. They direct a beam of electrons at a sample of matter and observe how the electrons interact with it.
- This requires very high energy electrons to be able to detect details small enough to 'see' quarks.
- A machine called an accelerator is used to produce a beam of electrons with the energy the scientists need.

What is an accelerator?

- An accelerator is a device used to make something go faster. Jefferson Lab's accelerator is a racetrack-shaped machine used to make electrons travel at nearly the speed of light.

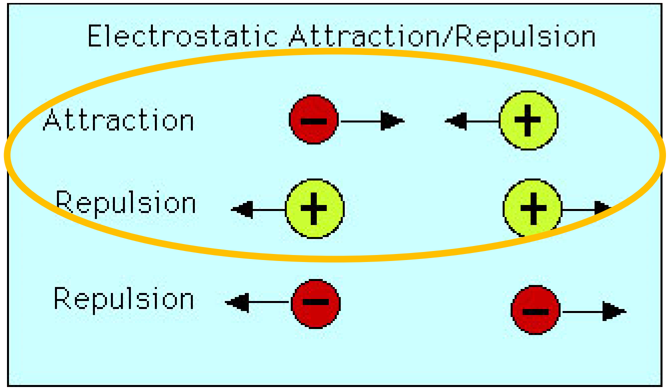


- Jefferson Lab's accelerator is about 1.4 kilometers around (about 7/8 of a mile) and was built in a tunnel 8 meters (about 25 feet) underground.
  - Electrons gain energy as they pass through the straight sections of the accelerator
  - and are steered by large electromagnets as they pass through the curved sections.

- An electron can travel around the accelerator as many as five times, gaining energy with each trip. Once an electron has enough energy, which can be as much as 12 billion volts, it is directed to one of the four large, hill-like experimental halls (shown here are Hall A, B, and C) where it collides with the target.

How does an accelerator work?

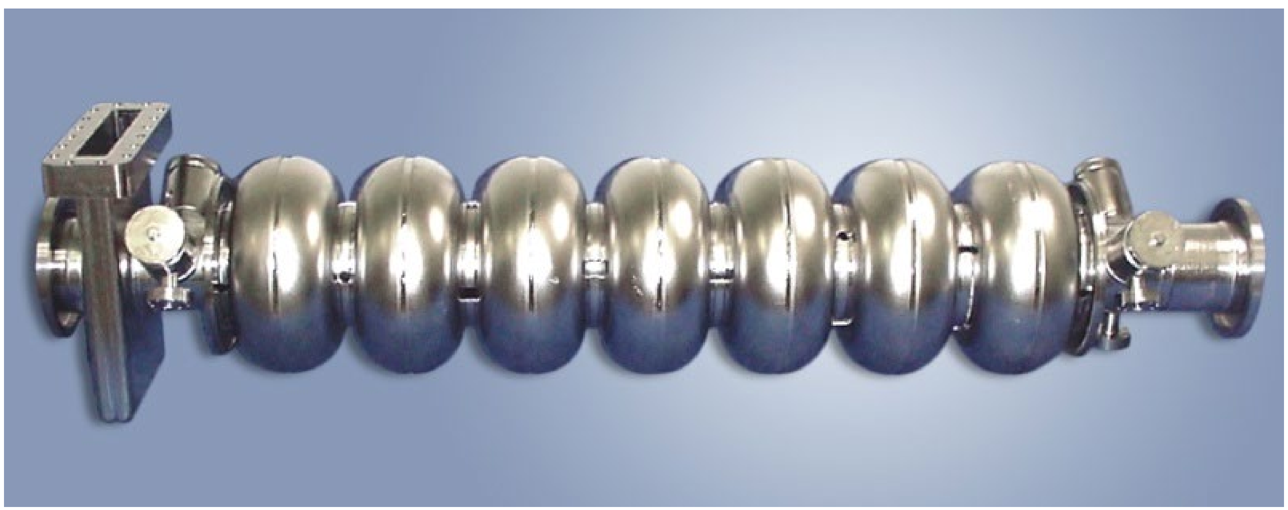
- Jefferson Lab's accelerator makes electrons go faster by placing negative charges behind them and positive charges in front of them.
- Since electrons have a negative electrical charge, they are repelled by the other negative charges and are attracted towards the positive charges.
- Devices called cavities, like the two shown in the photo, are used to place positive and negative charges around the electrons in the beam.



Standard textbook: J.D. Jackson, “Classical Electrodynamics”, 3rd ed.

How does an accelerator work? (cont.)

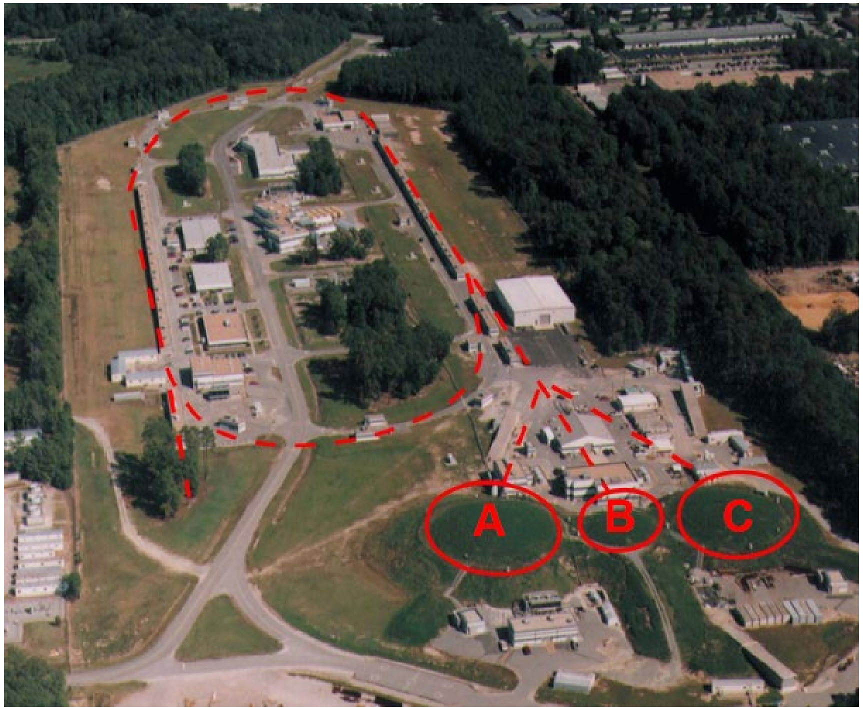
- Cavities are hollow shells made from the element niobium. Jefferson Lab's accelerator uses 338 cavities, mostly in the two long, straight sections.
- Microwaves are directed into the cavities and cause the electrons in the niobium metal to concentrate in certain areas.
- Since these areas have extra electrons, they become negatively charged. Other areas of the cavities have too few electrons, so they become positively charged.
- The electrons in the beam are pulled towards the positively charged areas and are pushed away from the negatively charged areas. (Cavities)

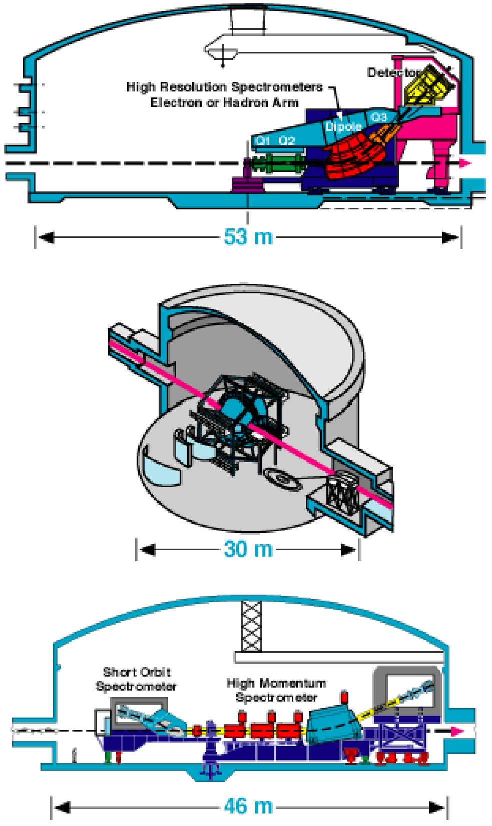


Standard textbook: J.D. Jackson, “Classical Electrodynamics”, 3rd edition

Where are experiments done?

Four large experimental halls sit at the end of Jefferson Lab's accelerator. The halls can conduct four different experiments, each with its own beam energy, at the same time. Each experimental hall is equipped with huge electromagnets and particle detectors that the scientist use to study their experiments.





HALL A

- *Nuclear structure at small inter-nucleon separations*
- *Nuclear medium effects on bound nucleon structure*
- *Precision measurements of high Q^2 form factors of nuclei and nucleons*
- *Strange-quark content of proton*

HALL B

- *Baryon and meson structure and spectroscopy*
- *Gluonic degrees of freedom*
- *Multinucleon correlations in nuclei*

HALL C

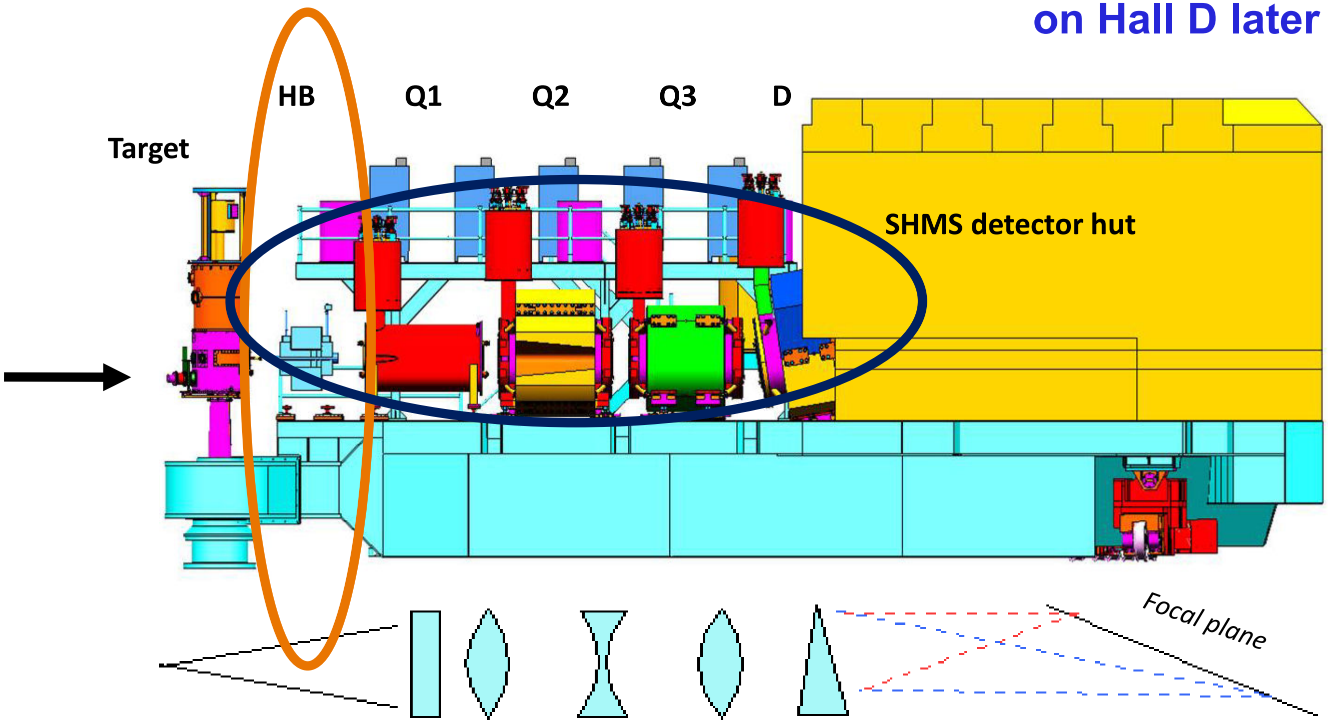
- *Strange-quark content of proton*
- *"Color transparency"*
- *Neutron electric form factor*
- *Exploratory (e,e' K)*

More detail on our experiments later

+ Hall D

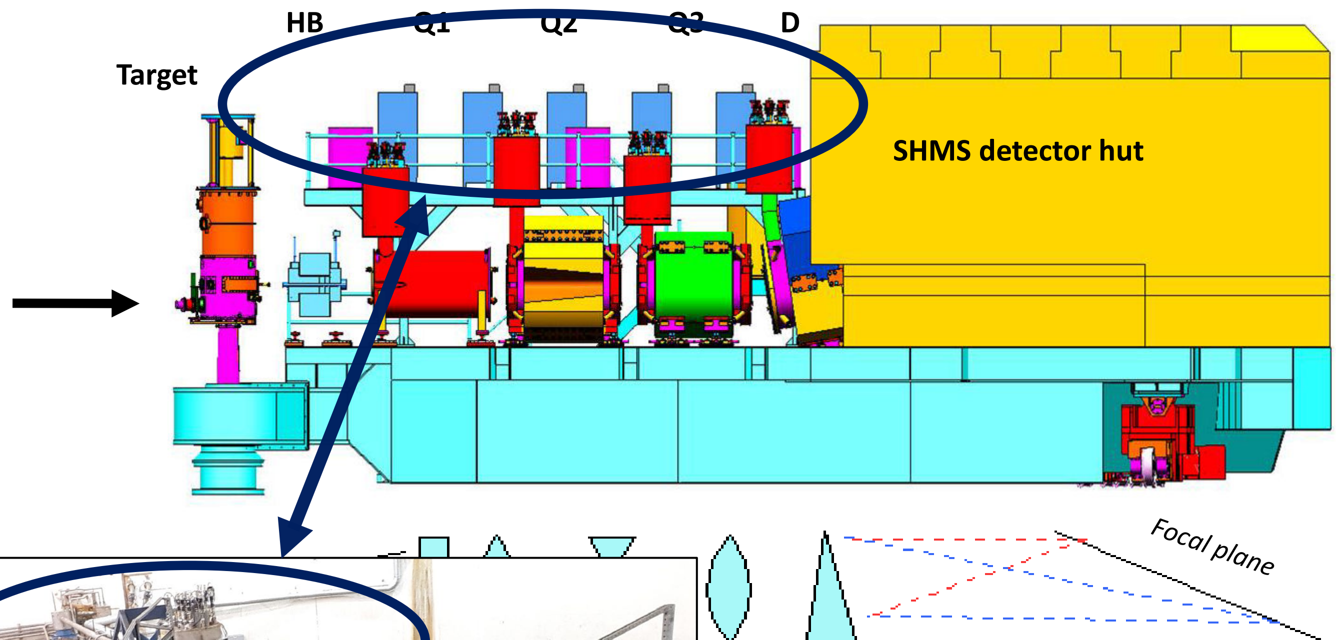
Example of an electromagnetic optics system (Hall C)

➢ More from Greg/Nilanga on Hall D later



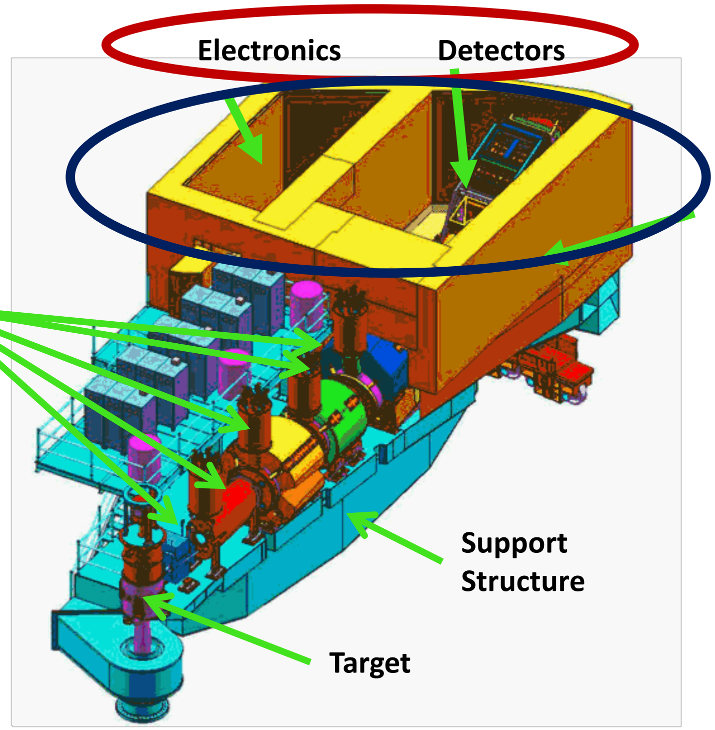
- Design magnetic fields so that they focus charged particles onto a focal plane inside the detector hut
- To reach very small angles, a horizontal bend magnet (HB) is needed

Example of an electromagnetic optics system (Hall C)



2017: On top of one of the Hall C magnetic spectrometers looking down at the cryostats of the other one

Example of a detector shielded enclosure

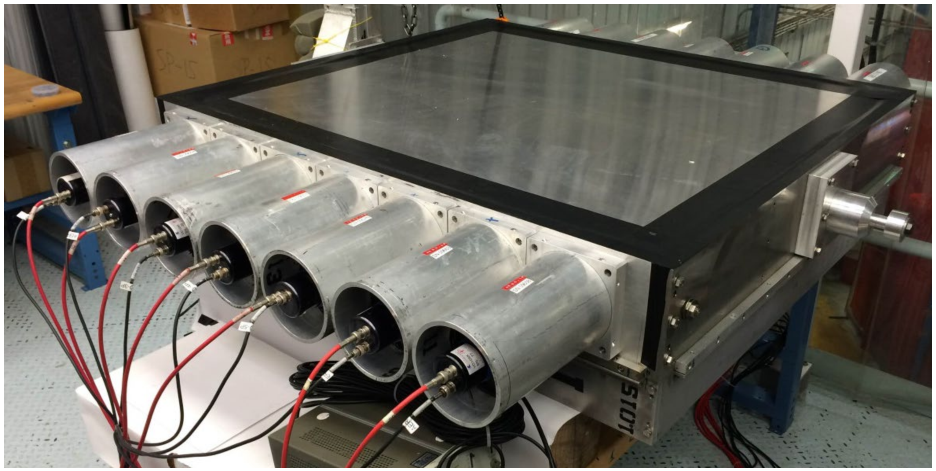


Detectors and electronics also operate in a high radiation environment and need to be protected

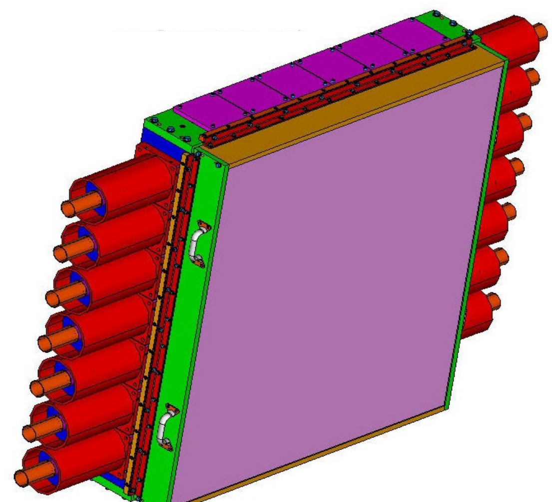
Detector Example: Kaon Aerogel Cherenkov

Detector design and construction (2012-2014)

NSF MRI PHY-1039446



- ❑ Four aerogel refractive indices covering kaon momentum range 3-7 GeV/c
- ❑ 5-inch PMTs
  - 14+6 PMTs with one HV and one signal cable each



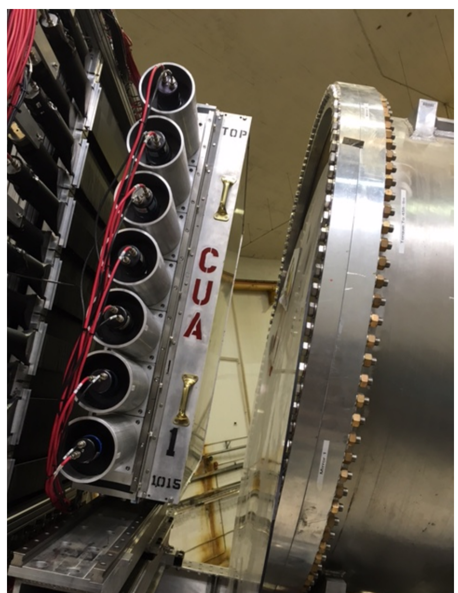
Detector design drawing

Detector Example: Kaon Aerogel Cherenkov

Detector installation, operation, and maintenance (2015+)







ELSEVIER
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 842, 11 January 2017, Pages 28-47

The Aerogel Čerenkov detector for the SHMS magnetic spectrometer in Hall C at Jefferson Lab

T. Horn [a, c], H. Mkrtchyan [b], S. Ali [a], A. Asaturyan [b], M. Carmignotto [a], A. Dittmann [f], D. Dutta [d], R. Ent [c], N. Hlavin [a], Y. Illieva [e], A. Mkrtchyan [a], P. Nadel-Turonski [c], I. Pegg [a], A. Ramos [g], J. Reinhold [g], I. Sapkota [a], V. Tadevosyan [b], S. Zhamkochyan [b], S.A. Wood [c]

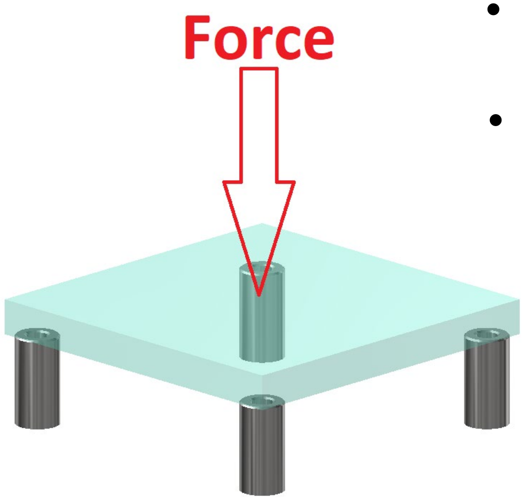
[a] The Catholic University of America, Washington, DC 20064, USA
[b] A.I. Alikhanyan National Science Laboratory, Yerevan 0036, Armenia

Novel aerogel composites for Cherenkov Detectors

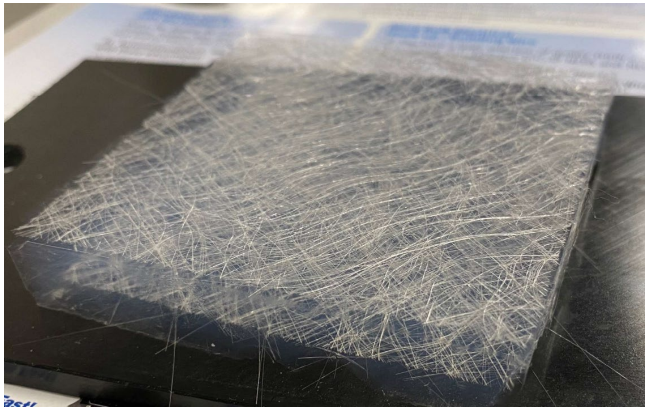
➢ More from Josh later

Aerogel is very fragile and breaks easily during manufacturing and handling

- ➢ New aerogel material for aerogel based detectors.
- ➢ **Summer 2021: Design and evaluation of fiber reinforced aerogel for nuclear physics experiments**



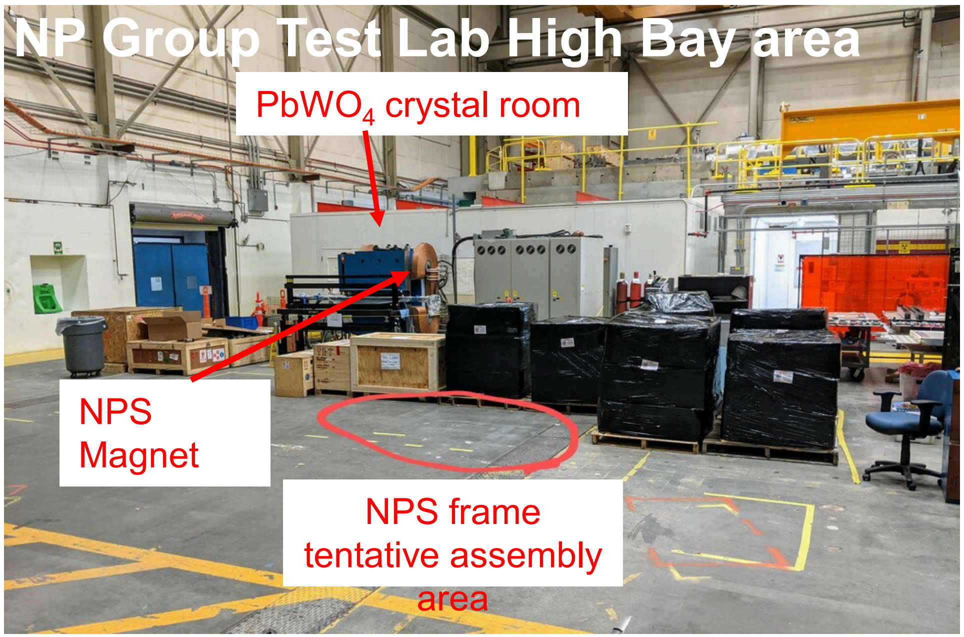
- Optical properties
- **Mechanical properties**

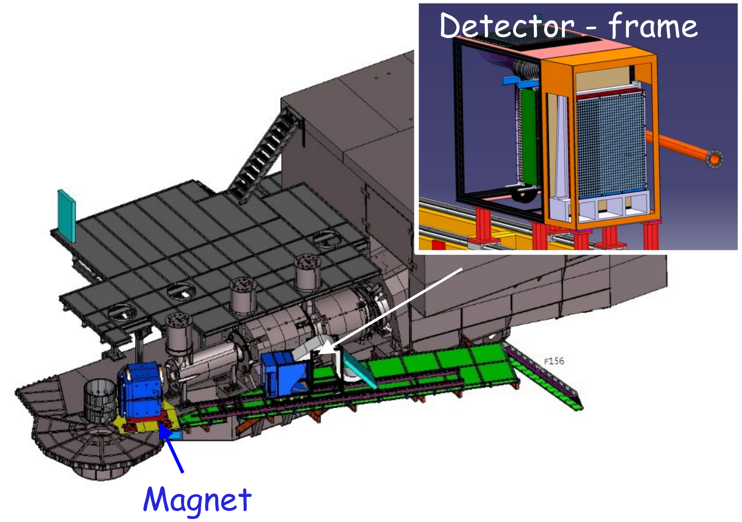


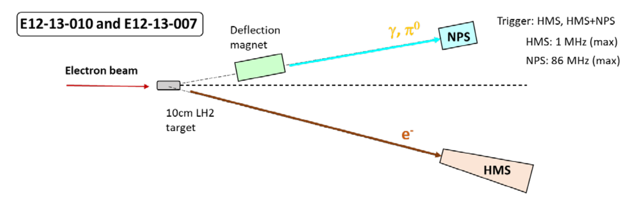
Neutral Particle Spectrometer (Hall C)

CUA led Major Research Instrumentation Project

Supported by NSF MRI PHY-1530874

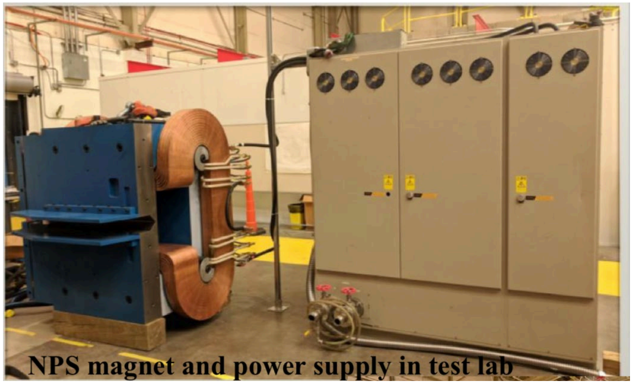






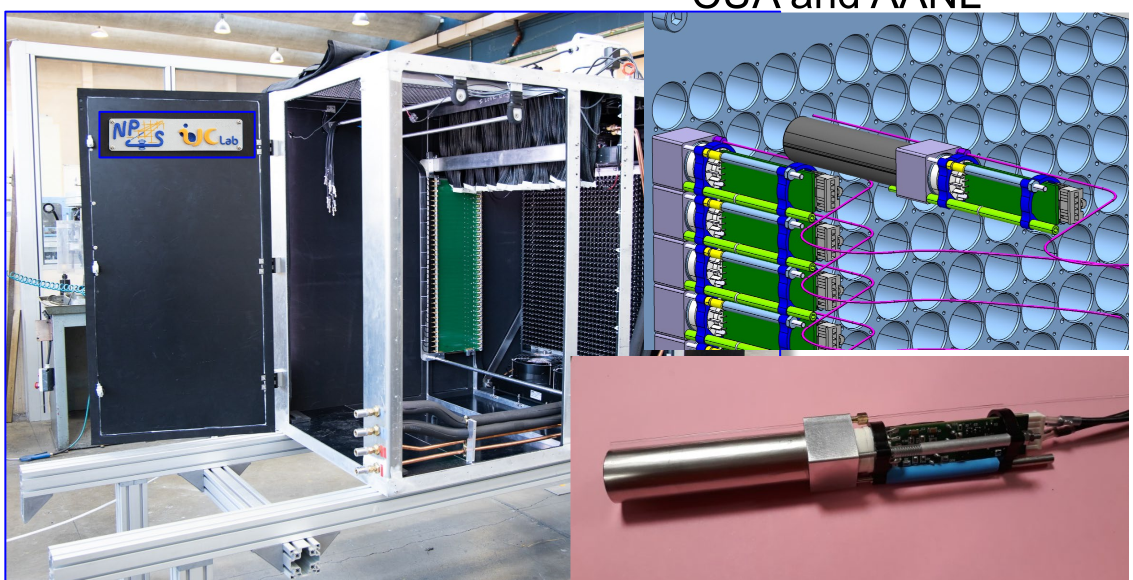
- **1080 PbWO4 crystals (30x36 matrix) (CE)** in a temperature controlled frame including gain monitoring and curing systems
- A vertical-bend sweeping magnet for charged background suppression
- Cantilevered platforms off the SHMS carriage to allow for remote rotation.
- A beam pipe with a large opening/critical angle for the beam exiting

NPS: Some Highlights & Status



Sweep Magnet : fully assembled and being tested at JLAB

PbWO4 crystals: testing performed by CUA and AANL



Frame infrastructure: assembed at IJCLab-Orsay

PbWO4 crystals

- 30x36 (1080) PbWO4 crystals of size: 2x2x20 cm3

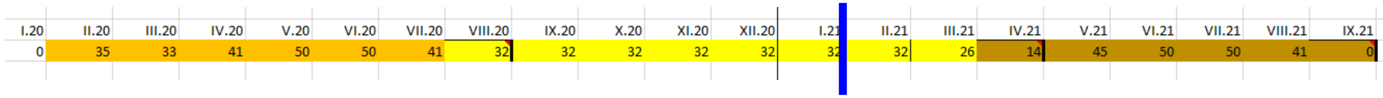
PbWO4 crystal properties and performance tests

- NIM A **956** (**2020**) 163375

Beam test program in Hall D with 12x12 NPS prototype

- Baseline tests completed in 2019
- Streaming readout tests in 2020
- Initial energy resolution: ~2.83%/E+2.23%/√E+0.73%

- ❖ Sweeper magnet ready for full current test in Hall C
- ❖ Frame is on-site
- ❖ PMT's on-site and spot checked - no rejections – **evaluate data for crystal tower characteristics**
- ❖ All (1100) active bases assembled
- ❖ Calorimeter assembly scheduled to begin in fall 2021



NPS Crystal Status

- ❑ PbWO4 crystals (~1100) – suitable quality and uniformity

Vendor	Crystals tested	Manufactured
SICCAS	460*	2017
CRYTUR	827+100	2018-present

*Rejection rate ~30-50%

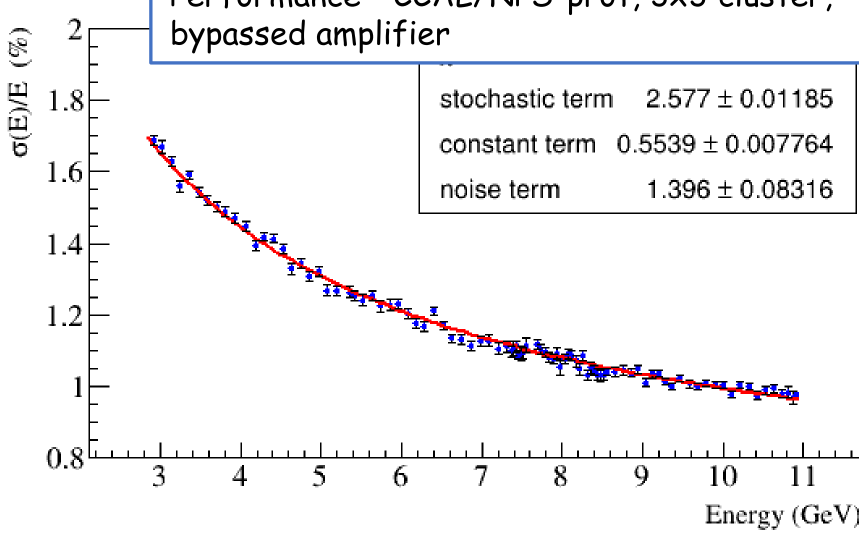
- ❑ Crytur production rate: ~20-50 crystals/month
  - ○ By the end of August 2021: 1150 Crytur crystals

Measurement	CRYTUR	SICCAS
Visual Inspection	✓	✓
Dimensions	✓	✓
Transmittance	✓	✓
Light Yield	✓	✓
Radiation resistance	✓	X

➢ **Summer 2021: Digitize crystal data and evaluate calorimeter tower characteristics (tool: Python?)**

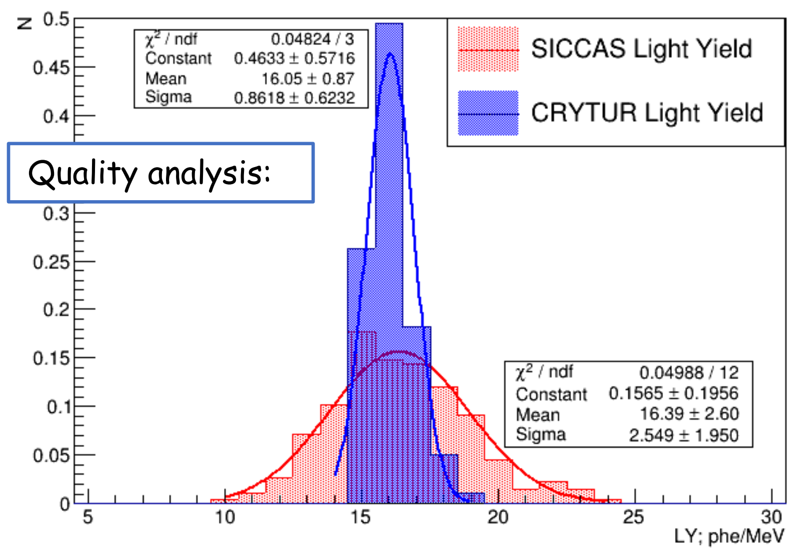
➢ **More from Vladimir later**

Performance – CCAL/NPS-prot, 3x3 cluster, bypassed amplifier



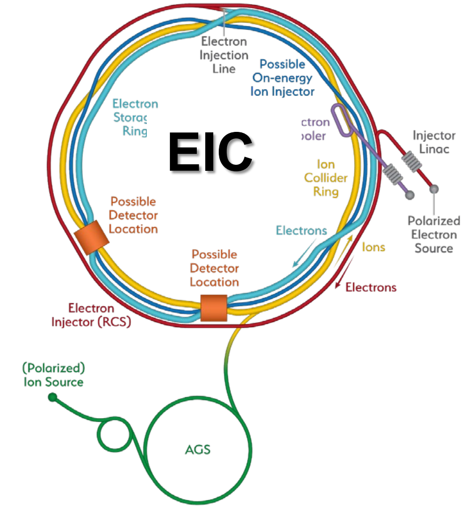
https://halldweb.jlab.org/DocDB/0047/004784/003/ccal_nps.pdf

Quality analysis:



Electron-Ion Collider (EIC)

The EIC will illuminate the dynamical basis of hadron structure in terms of the fundamental quark and gluon fields



The EIC addresses three central scientific issues:

- the mechanisms by which the mass of nucleons, and thus the mass of all the visible matter in the universe, is generated.
- the origin of internal angular momentum or spin of nucleons, a fundamental property that underlies many practical applications, including magnetic resonance imaging (MRI).
- the nature of gluons in matter—potentially revealing new states resulting from the close packing of many gluons in nucleons and nuclei.

CD-0 was approved by DOE in December 2019

Site selection at BNL announced in January 2020

- **Read more here: http://www.eicug.org/**

Example: Electron-Ion Collider (EIC) – hadron physics measurements with electromagnetic reactions

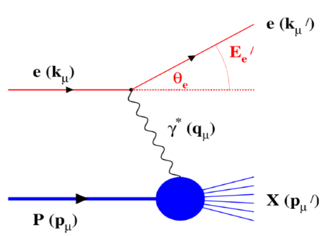
Scattered electron and final-state photon detection are crucial at the EIC

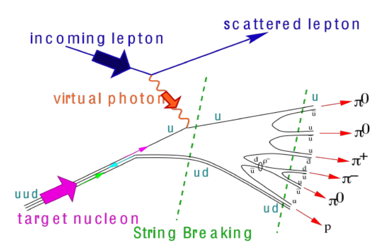
- Nearly all physics processes require the *detection of the scattered electron*
  - The requirement of *high-precision detection is driven mainly by inclusive DIS* where the scattered electron is critical to determine the event kinematics.
- DVCS, where a real photon is additionally detected in the final-state, is one of the fundamental processes to image and understand proton and nuclear structure at EIC.
- Precision detection of EM showering is essential to optimal particle ID and to determination of radiative corrections.

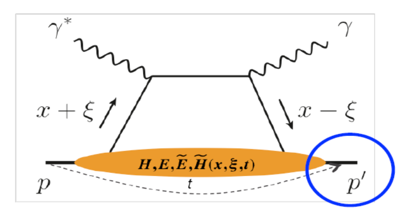
Parton Distributions in nucleons and nuclei

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

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







inclusive DIS
- measure scattered lepton
- multi-dimensional binning: x, Q^2

→ reach to lowest x, Q^2 impacts Interaction Region design

semi-inclusive DIS
- measure scattered lepton and hadrons in coincidence
- multi-dimensional binning: x, Q^2, z, p_T, Θ

→ particle identification over entire region is critical

exclusive processes
- measure all particles in event
- multi-dimensional binning: x, Q^2, t, Θ
- proton p_t: 0.2 - 1.3 GeV

→ cannot be detected in main detector

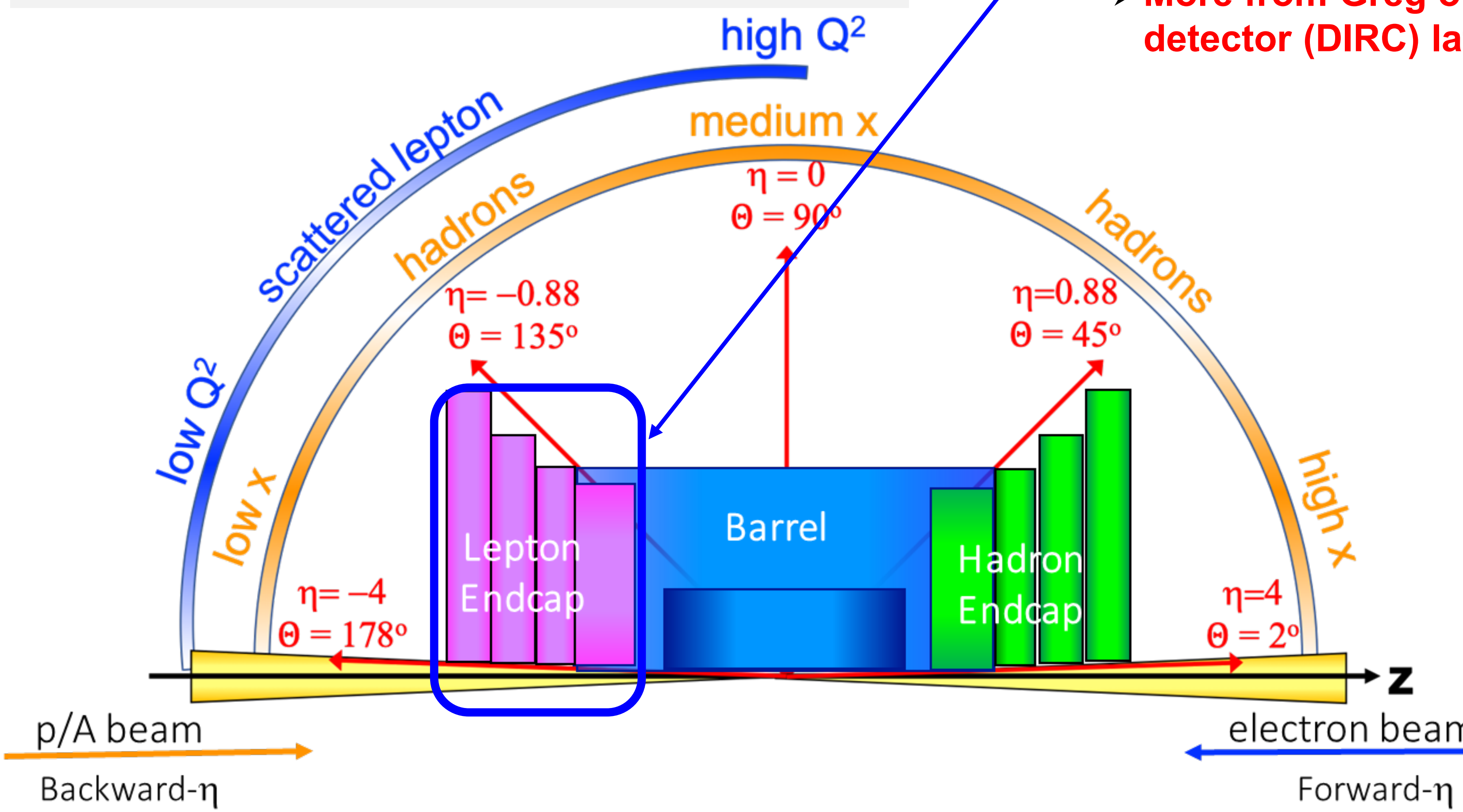
→ strong impact on Interaction Region design

Scattered Electrons – special detection requirements

Scattered electrons have to be detected in the <u>Lepton Endcap</u> (-3.5 < η < -1.0)

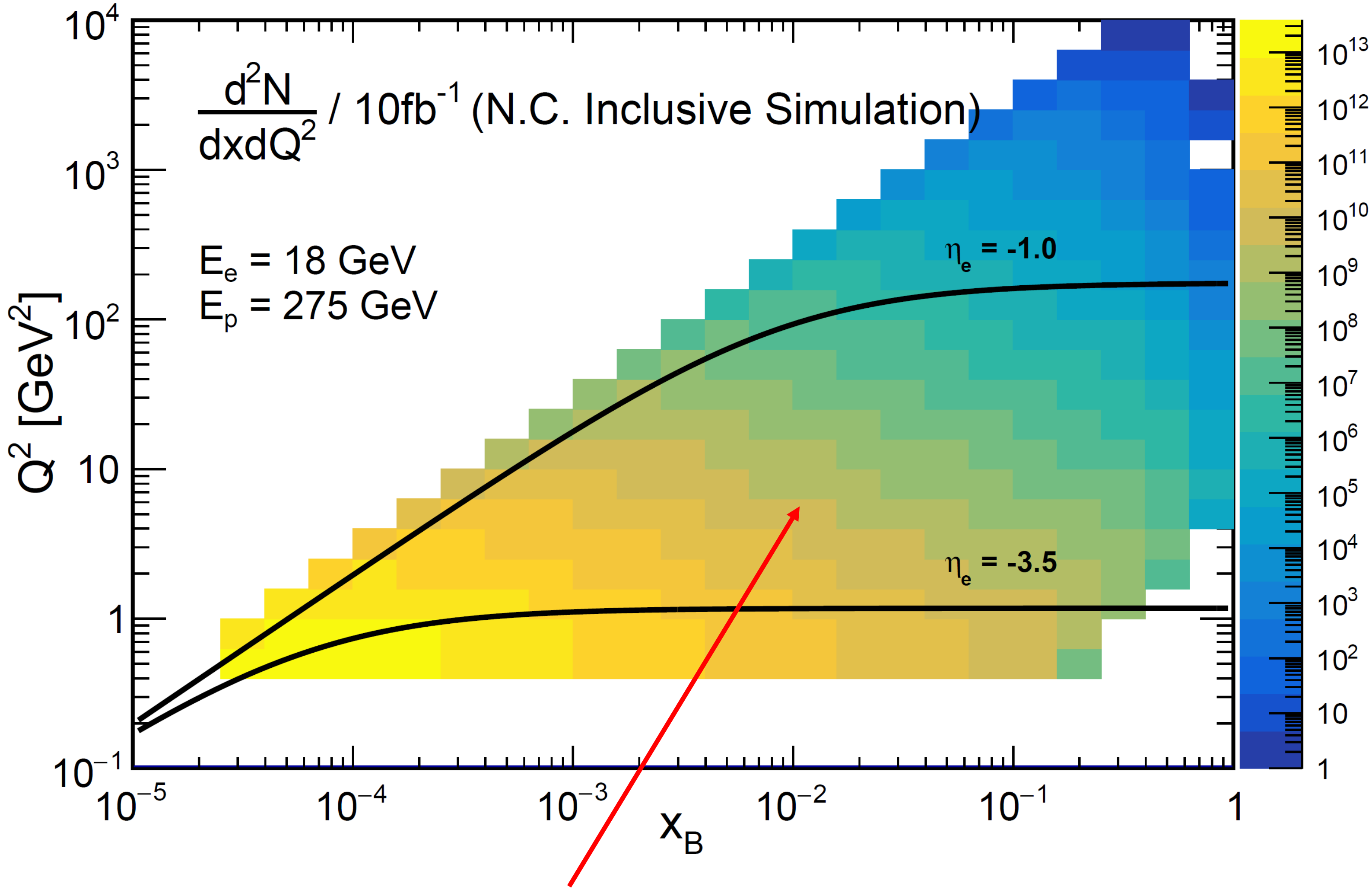
High resolution important in region -3.5 < η < -2
- Determines electron kinematics
- Physics requires (1-2%)/√E
- Particle E: ~0.02 – 18 GeV

➢ **More from Greg on Barrel detector (DIRC) later**



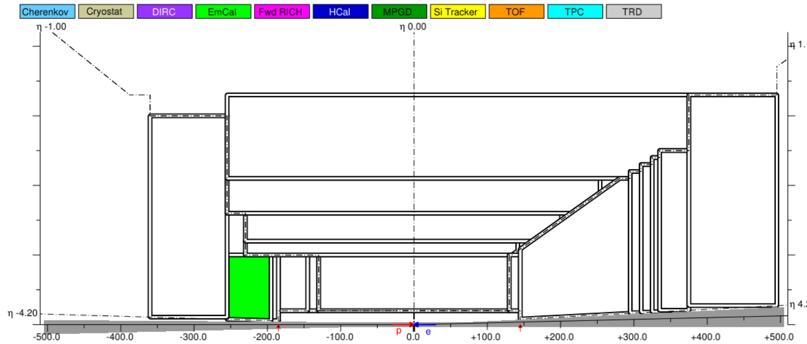
Scattered Electrons – special detection requirements

Scattered electrons have to be detected in the Lepton Endcap (-3.5 < η < -1.0)



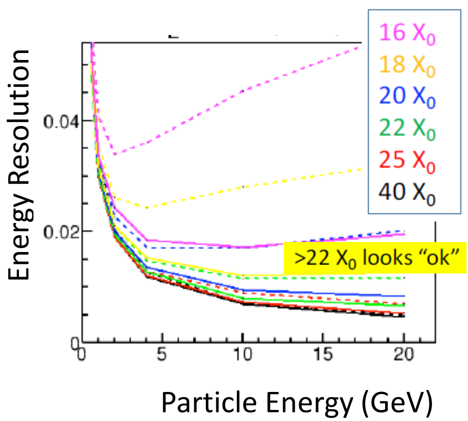
Region of physics enabled by the EEEMCal

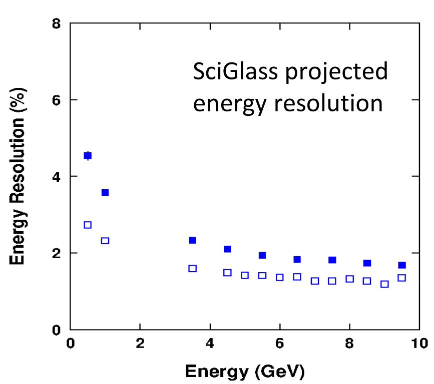
Electron Endcap EM Calorimeter for Electron Detection - Goal



We aim to design and construct the scattered electron detection in the Lepton Endcap covering pseudorapidity -3.5 to -1 with an electromagnetic calorimeter (**EEEMCal**).

➢ **Read more here: https://wiki.jlab.org/cuawiki/index.php/Electron-Ion_Collider_Detectors:_EEEMCal**





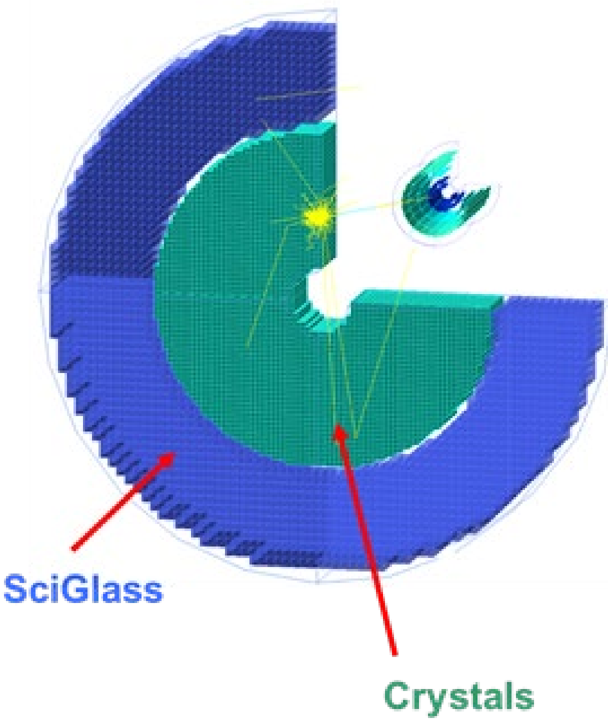
REFERENCE

$PbWO_4$ crystals (inner)

- compact, radiation hard, luminescence yield to achieve high energy resolution, including the lowest photon energies
- Sensor: SiPMs (TBC)

SciGlass (outer)

- EIC eRD1
- radiation hard, luminescence yield similar or better than crystals depending on longitudinal length
- Sensor: SiPMs (TBC)



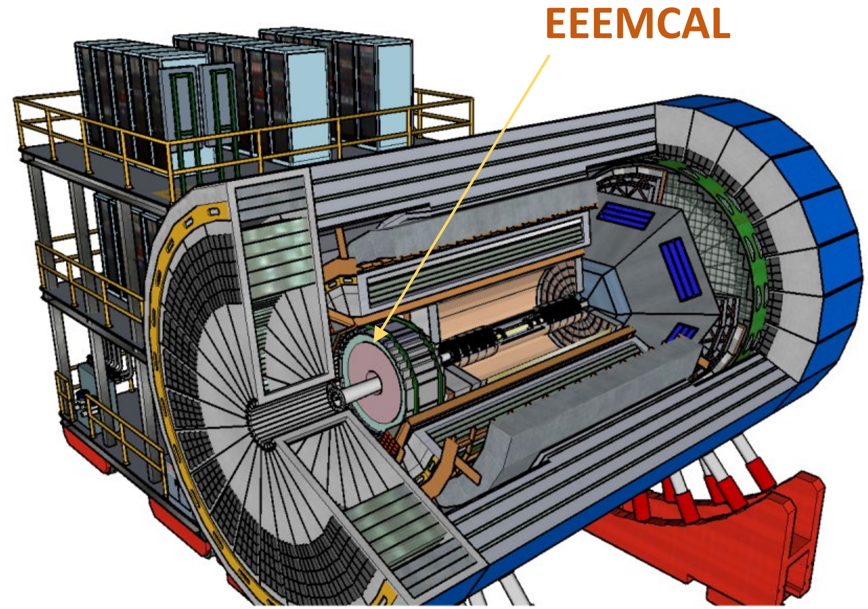
Electron Endcap EM Calorimeter for Electron Detection –
Support Structure and scientific modeling

➢ More from Josh/Petr later

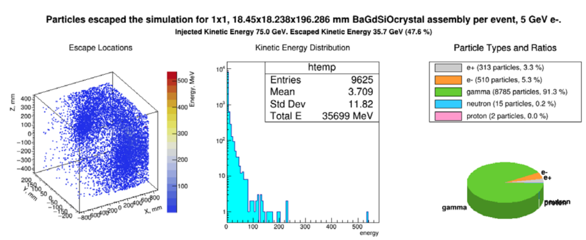
❑ **EEEMCal model** – scintillator support

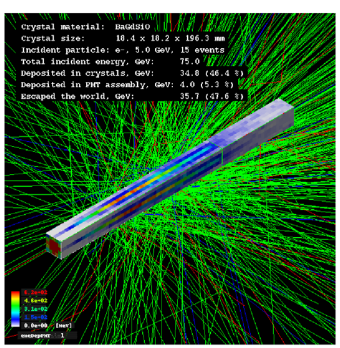
- ➢ **Crystals: 1628 blocks (2cm x 2cm)**
- ➢ **SciGlass: ~11000 blocks (2cm x 2cm)**

  Or 2778 blocks (4cm x 4cm)
- ➢ **Total radiator weight: 8573 kg (9.5 US tons)**

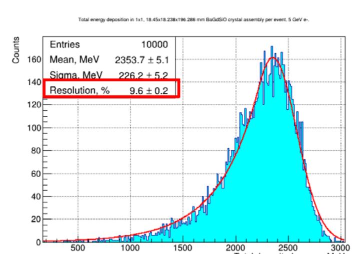


Energy resolution of 1x1 18.45x18.24x196.29mm BaGdSiO





Vladimir mentioned that we can compare the simulated Energy Resolution of the above sample to some reference value.



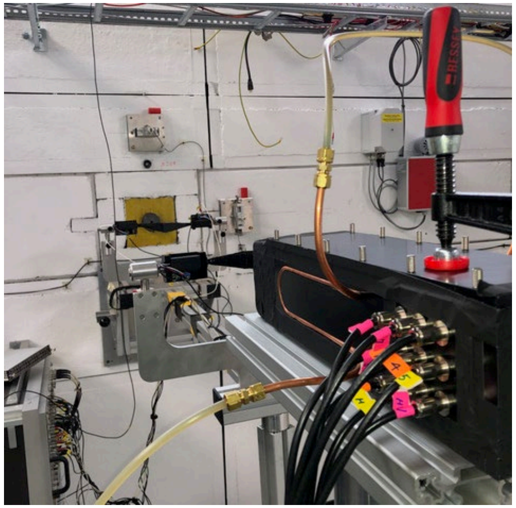
❑ **Summer 2021:**

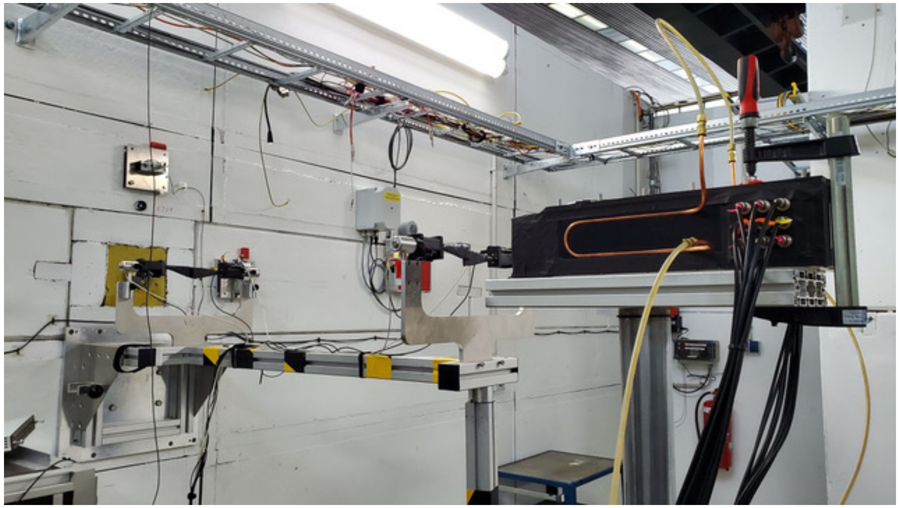
- ➢ **Design of a calorimeter cooling system**
- ➢ **Scientific Modeling of novel electromagnetic calorimeters (Monte Carlo methods) – Crystal + SciGlass**

EEEMCal – prototype beam test program

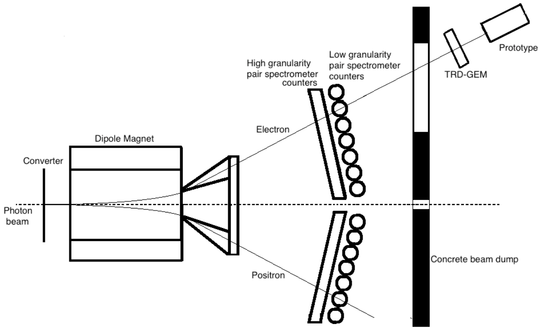
Tests of: EMCal characteristics, photosensor, readout

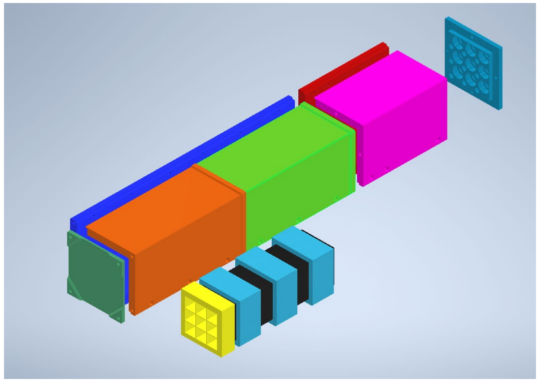
- ❑ Prototype beam tests at DESY

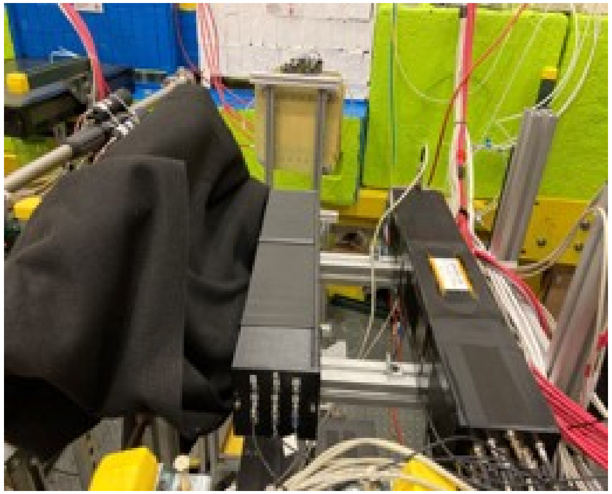




- ❑ Prototype beam tests in Hall D at Jlab

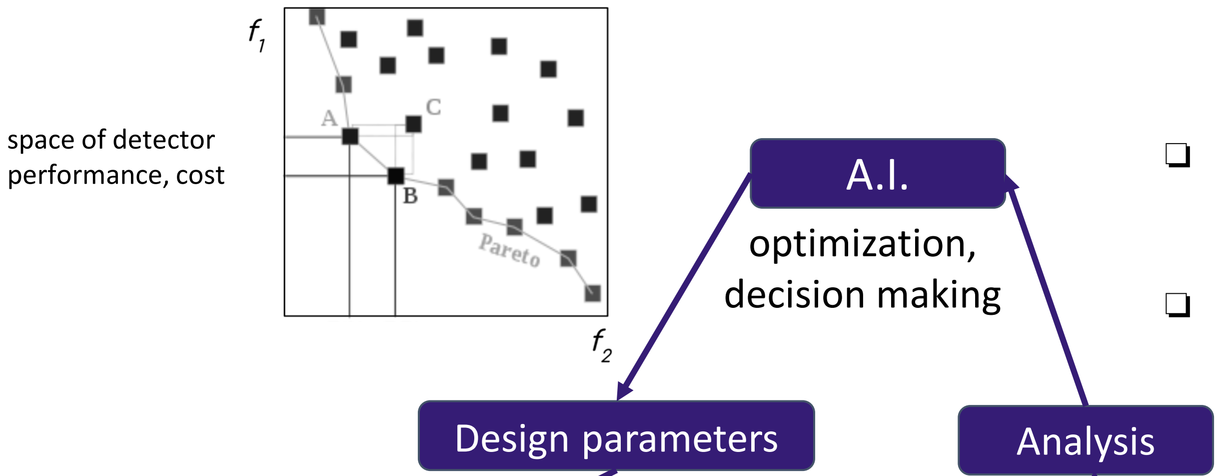


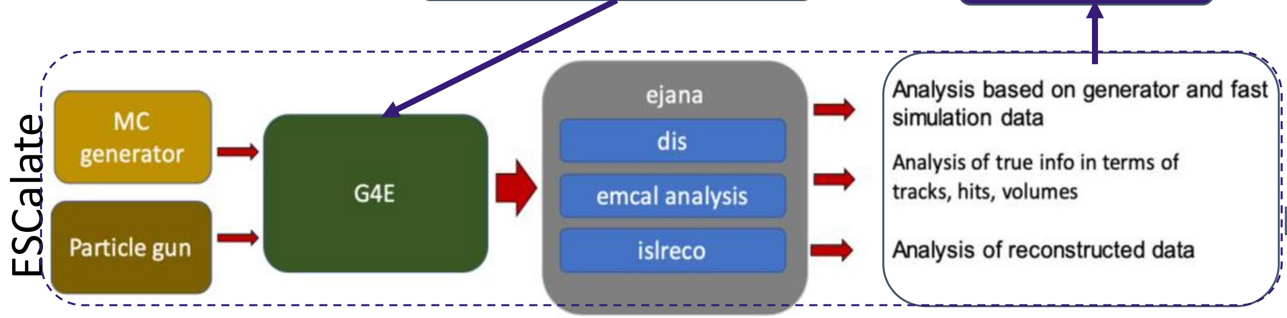


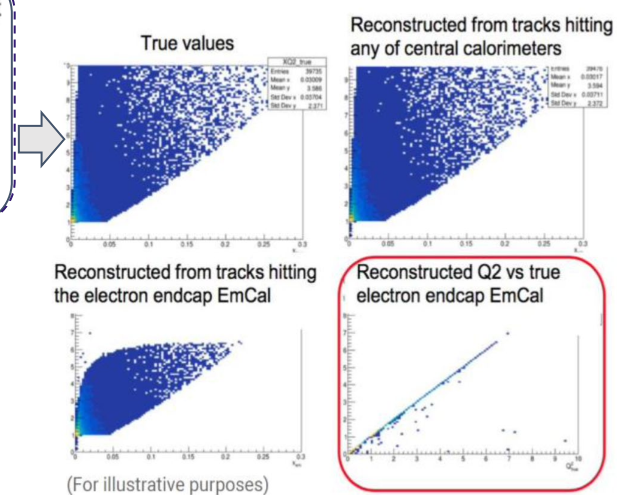


EEEMCal – Simulations to further optimize material and configuration

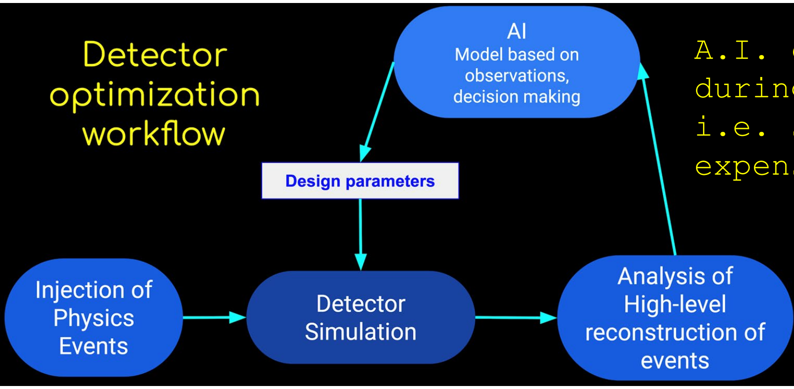
- ❑ GEANT4 simulation including geometry, readout digitization, and reconstruction algorithms
- ❑ Analysis plugins for studies of the EEEMCal performance
- ❑ Artificial Intelligence Framework to optimize crystal/glass material selection in the shared rapidity region





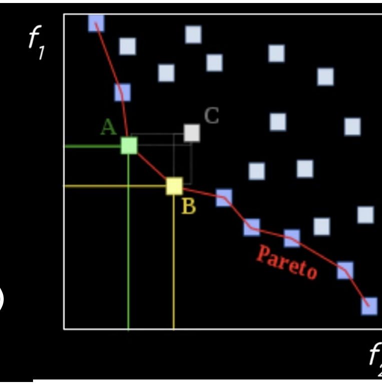


Examples: Detector Design Optimization

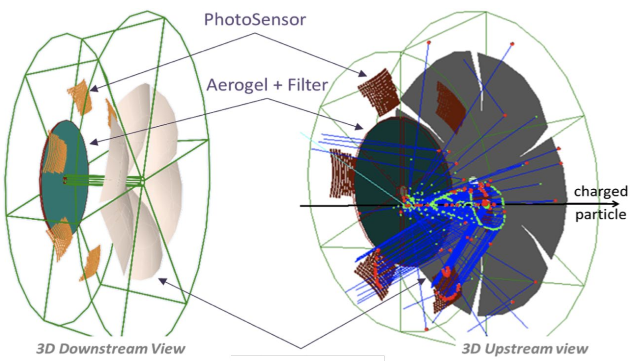


A.I. can optimize the design of complex during the R&D of large-scale detectors, i.e. simulating noisy and computationally expensive black-box functions

- **Bayesian Optimization (BO), Evolutionary Algorithms (EA), etc**
- **Multi-objective optimization (MOO) in multi-dimensional design space**

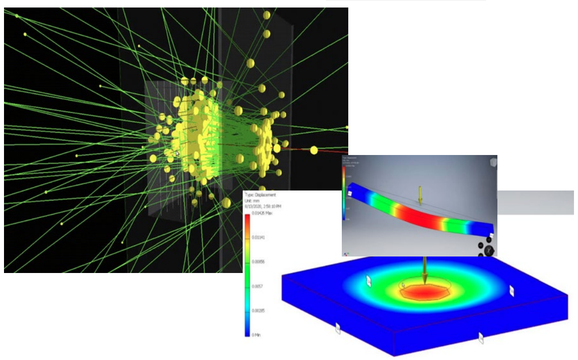


Dual-RICH @EIC: **First EIC paper using AI**, an automated, highly parallelized, self-consistent framework based on BO+ML to optimize the Geant simulation of the dual-RICH. O(10)parameters optimized.



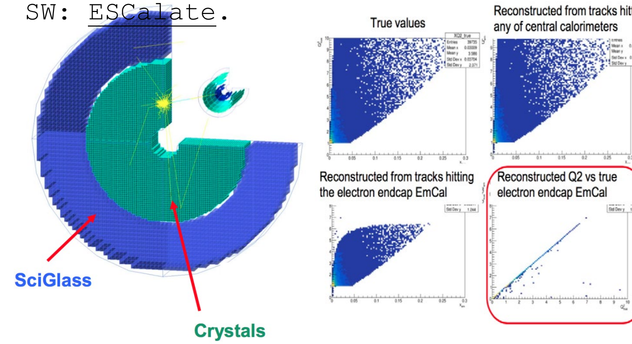
E. Cisbani, A. Del Dotto, C. Fanelli, M. Williams et al 2020 JINST 15 P05009

R&D of novel composite aerogel+fibers: Aerogels with low refractive index are very fragile. We are designing with the AI optimizing **mechanical strength** and **resolution** using evolutionary MOO. Geant4 + Autodesk (gmsh+elmer)



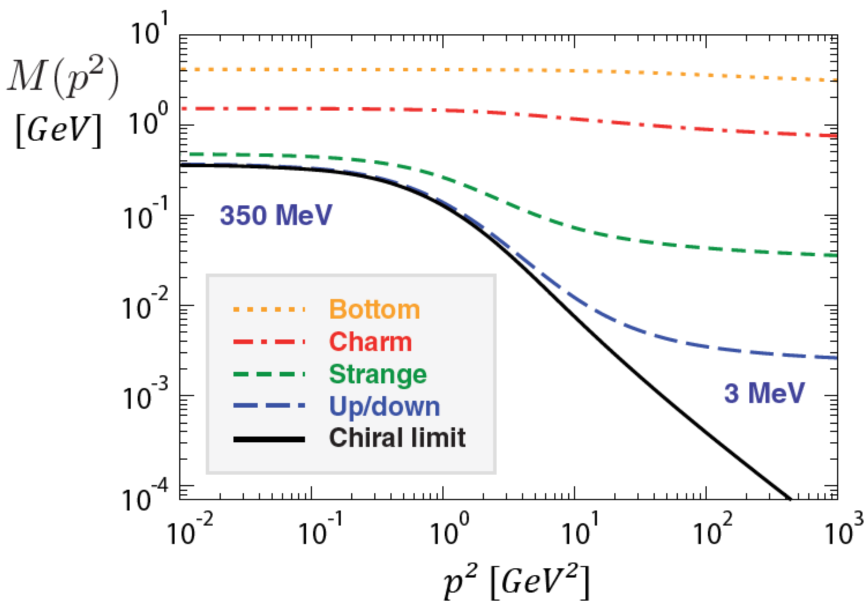
The team: V. Berdnikov, J. Crafts, E. Cisbani, C. Fanelli, T.H. , R.. Trotta

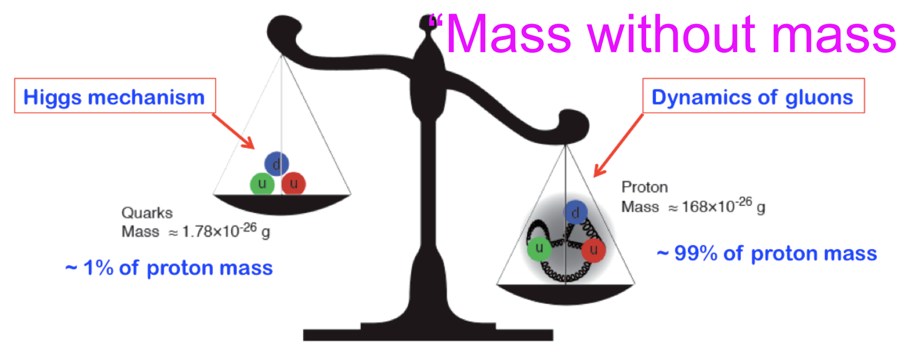
EIC Electron Endcap EM Calorimeter: Optimization of glass/crystal material selection in shared rapidity regions including mechanical constraints from EIC detector. MOO to make decision on EEemCAL resolution (how it affects physics of interest), and crystal/glass cost optimization. EIC SW: EScalate.



The team: V. Berdnikov, M. Bondi', C. Fanelli, Y. Furletova, T.H., I. Larin, D. Romanov, R. Trotta

EIC Science Example: The incomplete Hadron: Mass Puzzle





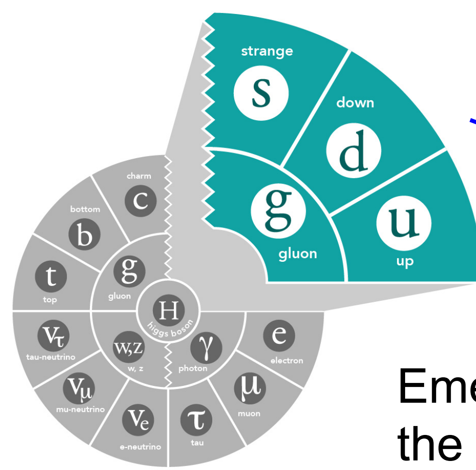
The light quarks acquire (most of) their masses as effect of the gluon cloud.

The strange quark is at the boundary - both emergent-mass and Higgs-mass generation mechanisms are important.

Proton: Mass ~ 940 MeV
preliminary LQCD results on mass budget, or view as mass acquisition by DCSB

Kaon: Mass ~ 490 MeV
at a given scale, less gluons than in pion

Pion: Mass ~ 140 MeV
mass enigma – gluons vs Goldstone boson



Emergent mass of the visible universe

Key Experimental Efforts at the EIC

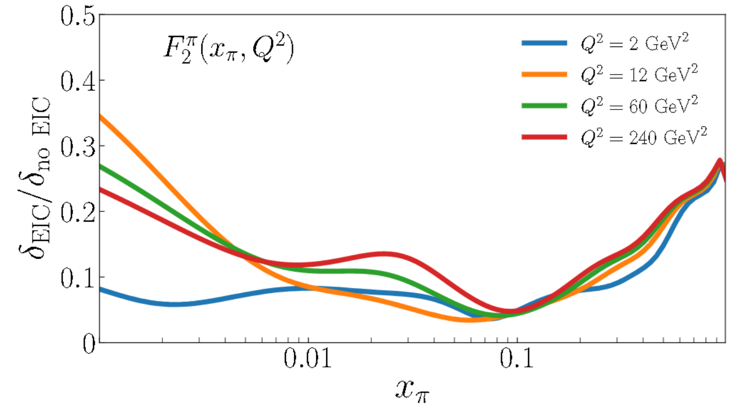
- **Read more here: EIC Yellow Report (http://www.eicug.org/web/sites/default/files/Yellow_Report_v1.1.pdf)**

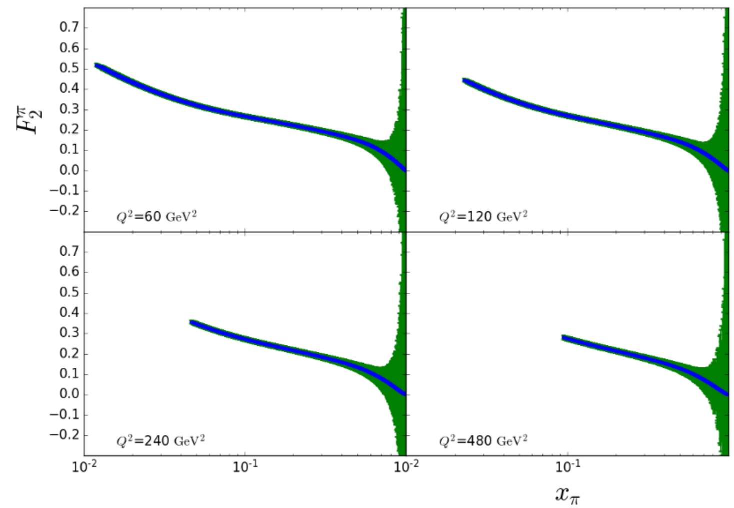
- Hadron masses in light quark systems
  - Pion and kaon parton distribution functions (PDFs) and generalized parton distributions (GPDs)
- Gluon (binding) energy in Nambu-Goldstone modes
  - Open charm production from pion and kaon
- Mass acquisition from Dynamical Chiral Symmetry Breaking (DCSB)
  - Pion and kaon form factors
- Strong vs. Higgs mass generating mechanisms
  - Valence quark distributions in pion and kaon at large momentum fraction x
- Timelike analog of mass acquisition
  - Fragmentation of a quark into pions or kaons

Pion SF Projections

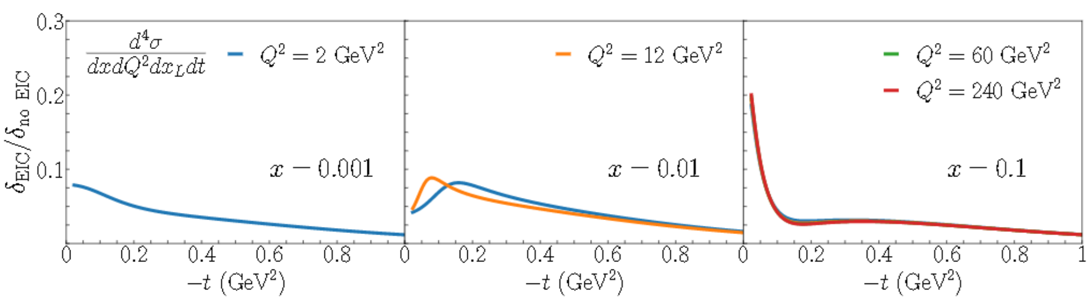
➢ **More from Richard later**

- Reasonable uncertainties in the mid-to-large x region but increasing rapidly as x→1
  - Even with these restrictions, the coverage in mid to high x is unprecedented
- Access to a significant range of Q^2 and x, for appropriately small−t
  - Allows for much-improved insights in the gluonic content of the pion.





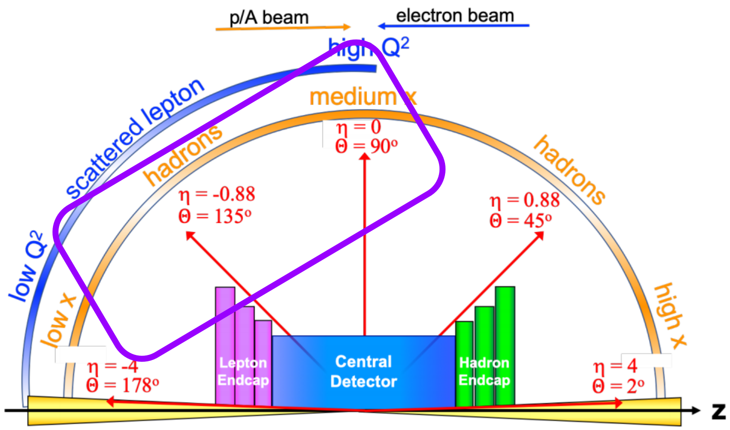
NLO through pion PDFs

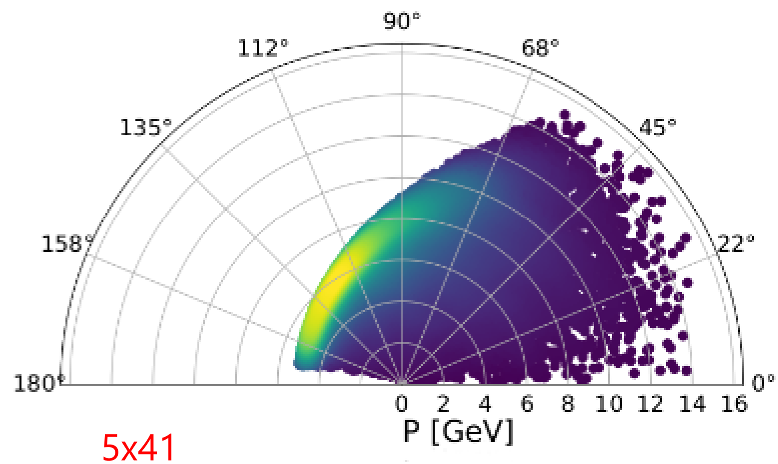


J Arrington, et al., J. Phys. G (2021) arXiv:2102.11788

Meson Structure Functions – Scattered Electron

➢ **More from Richard later**

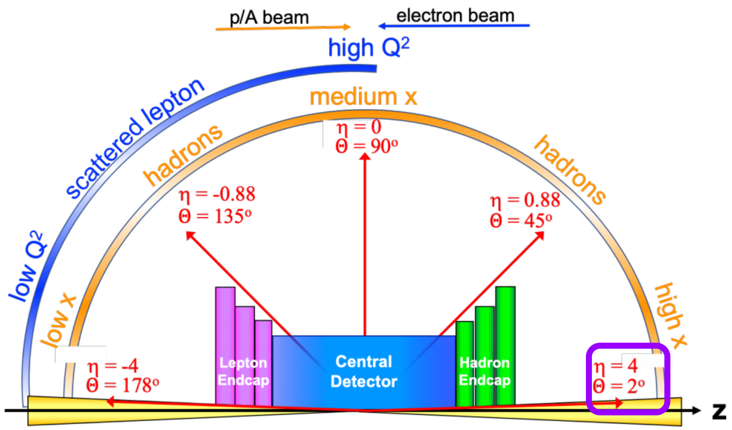




- Scattered electrons can be detected in the central detector

Meson Structure Functions – Forward Baryon

➢ More from Richard later



5x41

- Baryon (neutron, lambda) at very small forward angles and nearly the beam momentum

Future F_2^π projections

➢ **More from Richard later**

- Only ZEUS parameterization for F_2^π is currently implemented
  - next step would be checking with other pion SF parameterizations
  - parameterizations depend on how pion SF is regulated
  - varying theory inputs for models and checking how they fit MC pseudo-data
- Goal is to achieve more comprehensive control/quantification of theory/model uncertainties
  - explore limitations of Sullivan and single-pion exchange framework
  - implement additional contributions; e.g., Regge-theoretic modes
  - these uncertainties are entangled in simulations with the pion structure function (PDF) errors; the combined theory uncertainty must be mapped

Future F_2^K projections

- **More from Richard later**

- Goal is to extend to tagged kaon structure function
- Very limited data on F_2^K
- Kaon projected structure function data will be of similar quality as the projected pion structure function data for the small-t geometric forward particle detection acceptances at EIC - studies in progress
- To determine projected kaon structure function data from pion structure function projections
  - one method...scale the pion to the kaon case with the coupling constants while taking the geometric detection efficiencies into account

S. Goloskokov and P. Kroll, Eur.Phys.J. A ***47*** *(2011) 112:*

$g_{\pi NN}=13.1$ $g_{Kp\Lambda}=-13.3$ $g_{Kp\Sigma^0}=-3.5$

(these values can vary depending on what model one uses, so sometimes a range is used, *e.g.*, 13.1-13.5 for $g_{\pi NN}$)

Summer 2021 Projects

Weverton **Design of a Calorimeter cooling system –** contact: Josh

Design and evaluation of fiber reinforced aerogel – contact: Josh

David **Scientific modeling of novel EM Calorimeters (Monte Carlo Methods) –** contact: Peter

Ciaran **$\phi \rightarrow K^+K^-$ as a probe for π/K separation power –** contact: Greg/Nilanga

Akshitha **Detector evaluation and optimization using scientific computing (AI/ML) –** contact: Vladimir/Richard

Weverton **Towards the origin of mass with light mesons – KaonLT Analysis –** contact: Richard

Zach **Optimizing event selection for $\Lambda(1405) \rightarrow \Sigma^0\pi^0$ –** contact: Greg/Nilanga

David **Projections of meson structure at the Electron-Ion Collider –** contact: Richard

Schedule and Communications

Weekly group meetings – status updates, brainstorming, planning

Tutorials on physics, detectors, data analysis and simulation software

- **First tutorial on Tuesday 6/1 (Petr Stepanov)**

Questions any time: Slack

Homework for week 6/1

Read the background material

Review data/material provided and ask questions

Create needed computer accounts (Wiki, JLab, etc.)

Familiarize yourself with the software

Prepare 1 slide with an overview of your project for the REU meeting on Friday 6/4

Prepare 2-3 slides of your project, e.g. what you will be doing, for the next group meeting on Tuesday 6/8

Questions any time: Slack