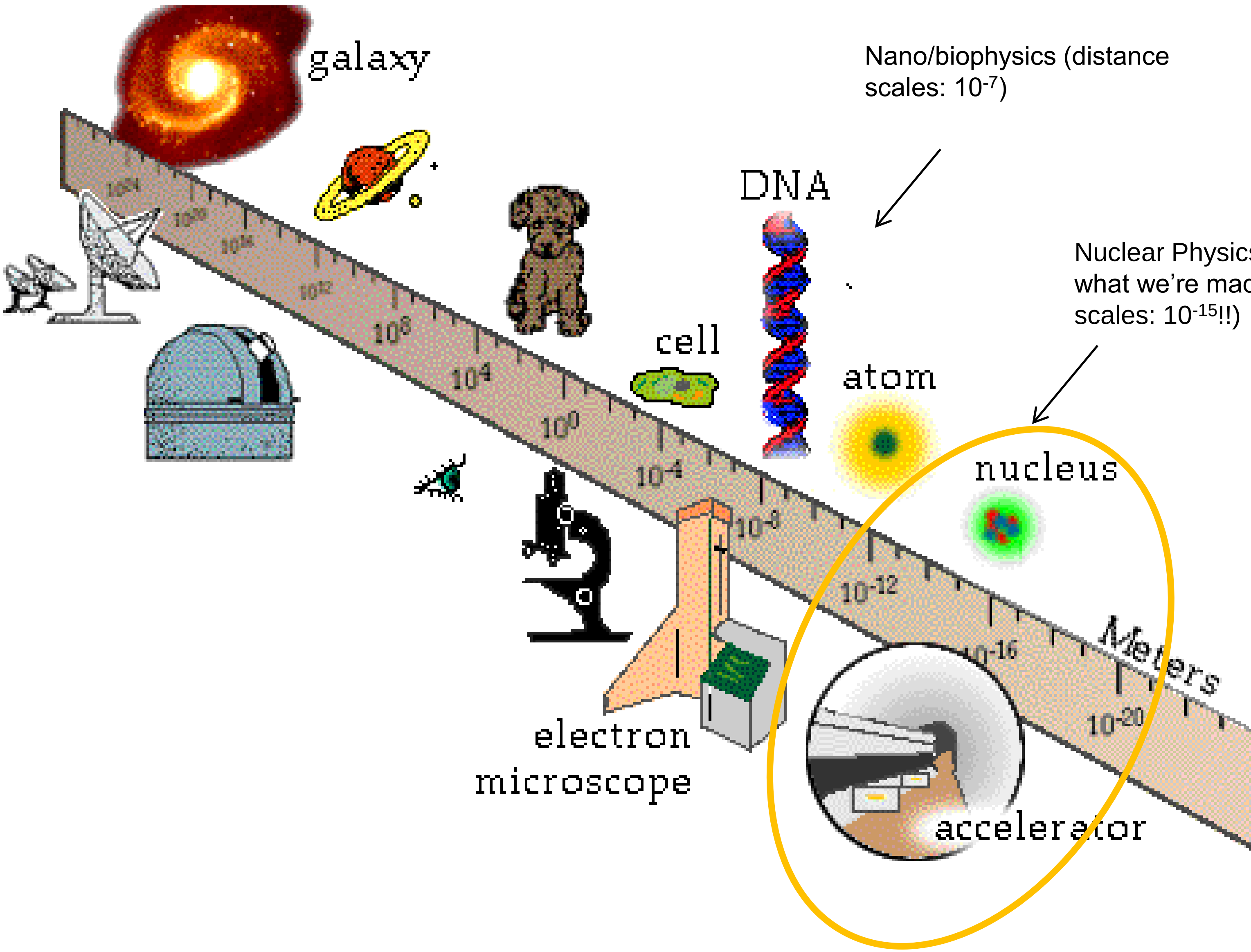
How do we see different size objects:



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

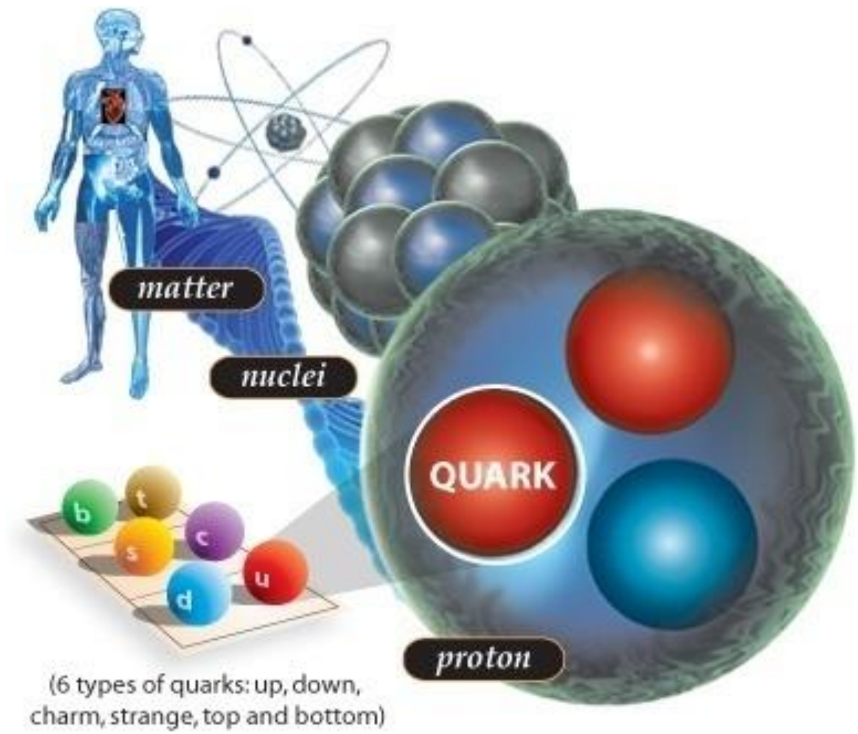
Nuclear Physics: understand what we're made of (distance scales: 10^{-15}!!)

Fundamental Matter

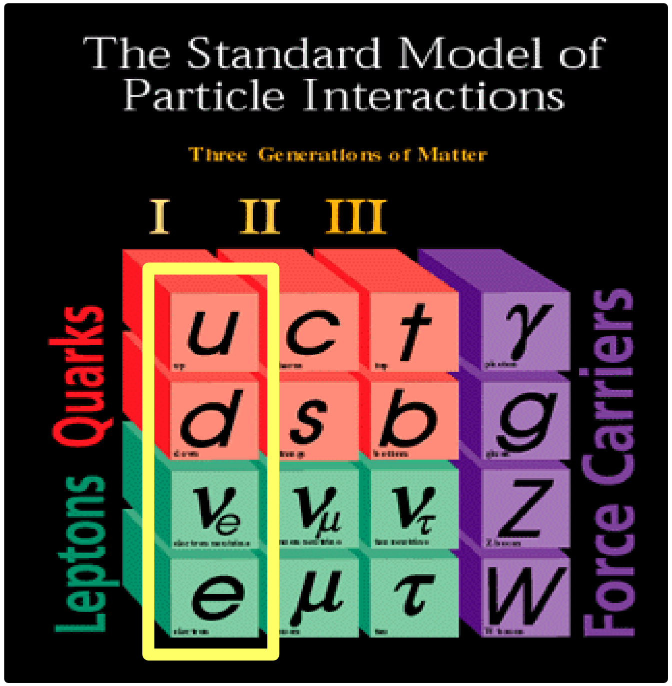
- Ordinary matter (atoms and molecules) is made up of protons, neutrons and electrons

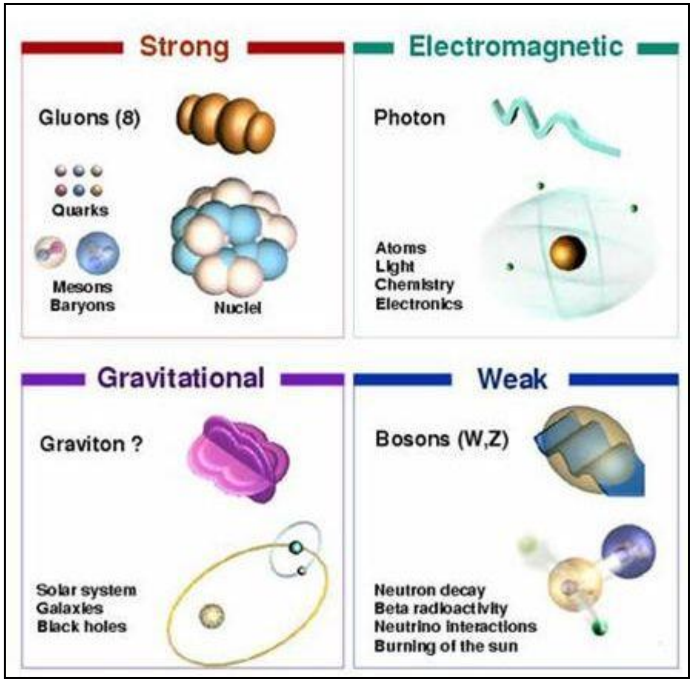
- Over 99.9% of the atom's mass is concentrated in the nucleus

- The proton internal structure is complex
  - No exact definition for quantum mechanical reasons
  - Typically use concept of mass, energy, and particles



Matter and Forces

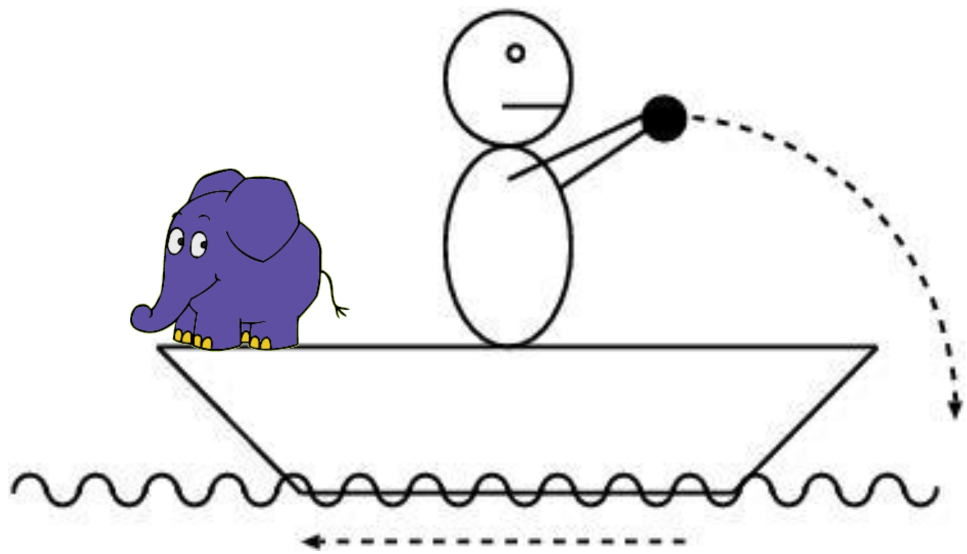




- Fermions are the building blocks
  - Conserve particle number
  - Try to distinguish themselves from each other by following the Pauli principle

- Bosons form the force carriers that keep it all together

Virtual Particles as Force Carriers

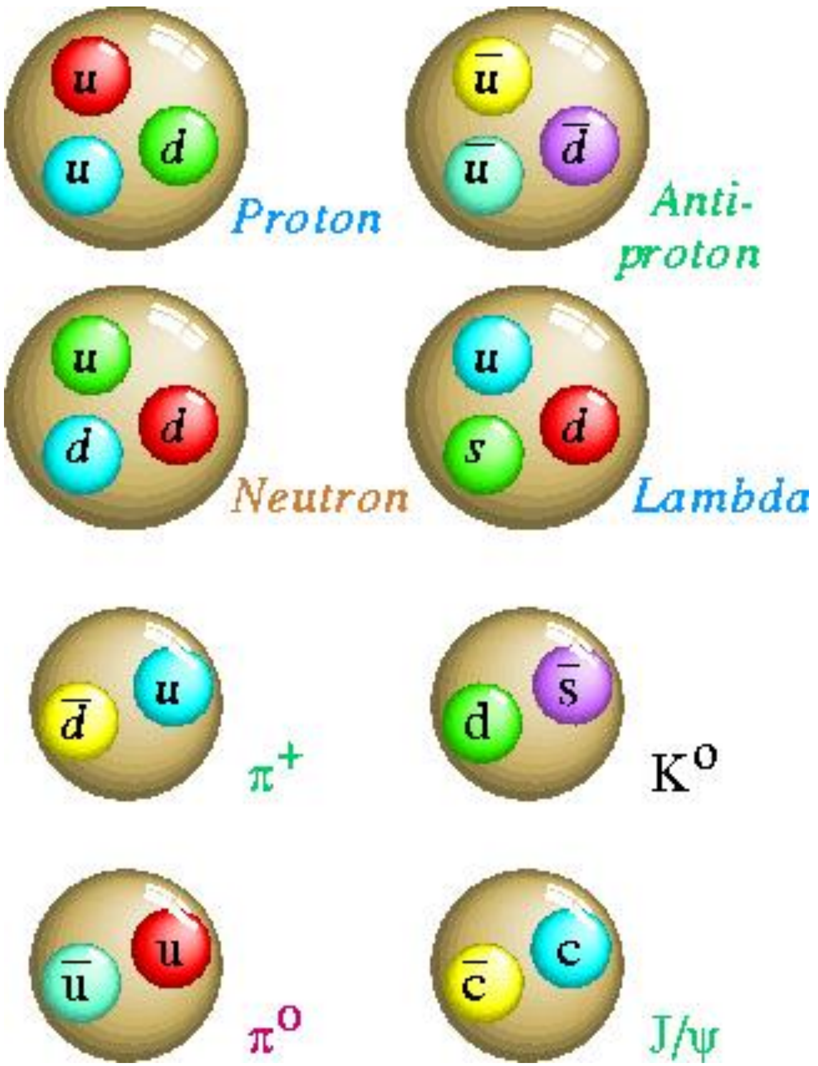


- Exchanged/thrown particles can create attractive and repulsive forces
- These particles are not real, but virtual
- Virtual particles can exist by the Heisenberg principle: $\Delta E \Delta t \geq \frac{\hbar}{2}$
  - Even elephants may show up, if they disappear quickly enough

Hadrons

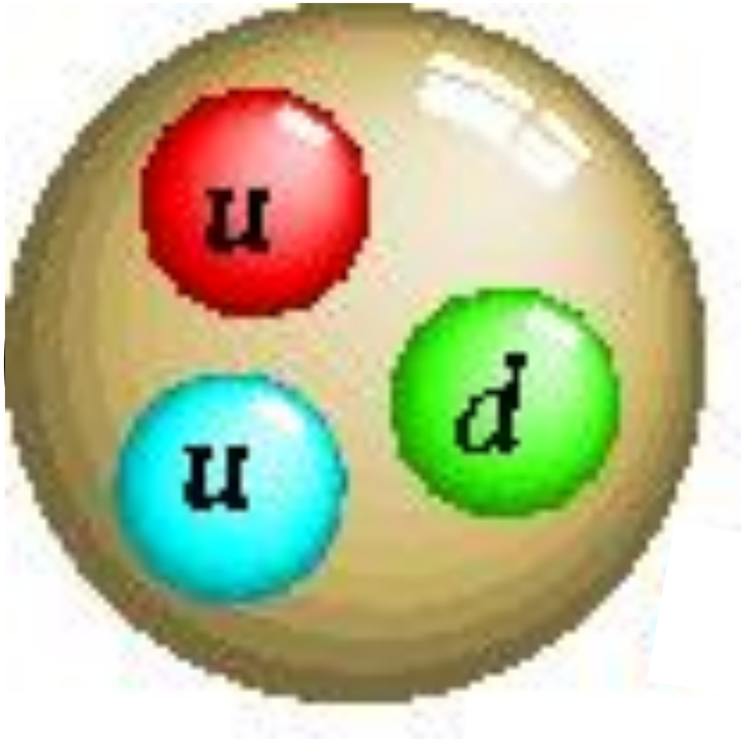
- Hadrons are composed of quarks with:
  - Flavor: u, c, t (charge +2/3) and d, s, b (charge -1/3)
  - Color: R, G, B
  - Spin: ½ (fermions)

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



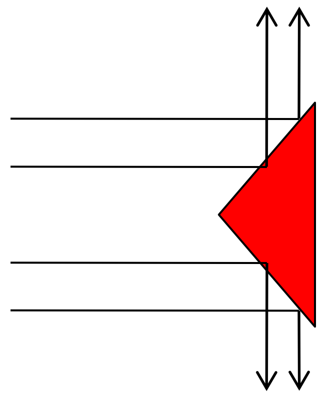
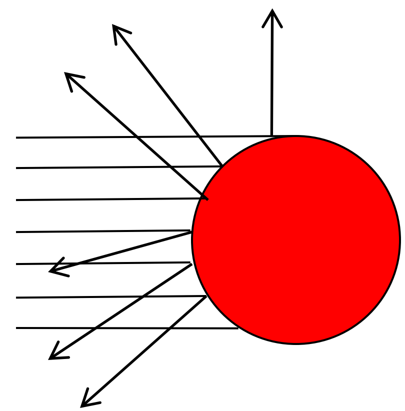
The target and how we study it…

- How do we measure the structure of particles that make up the atomic nucleus?

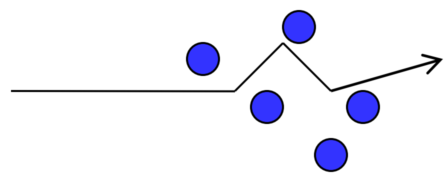
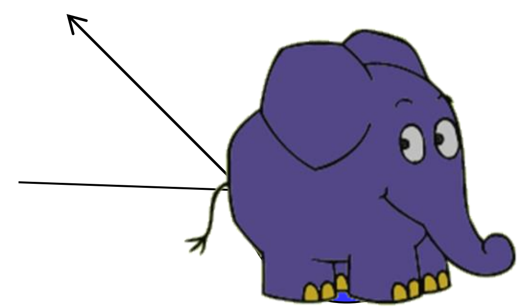


Scattering Experiments

- Measure the substructure of matter
- Shapes of target particles:

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

- Measure scattering cross sections, $d\sigma$= probability for beam particles to scatter by an angle θ

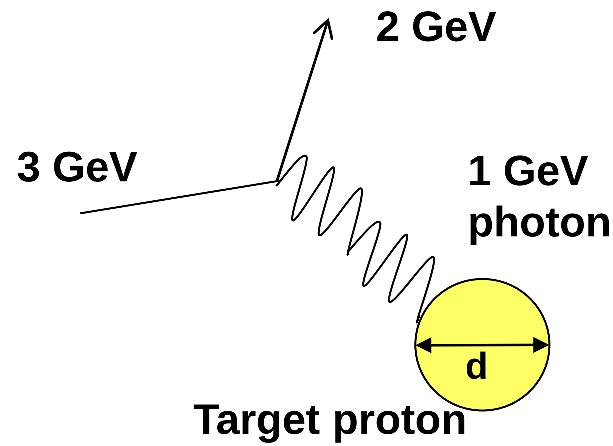
Elastic Electromagnetic Scattering

- 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

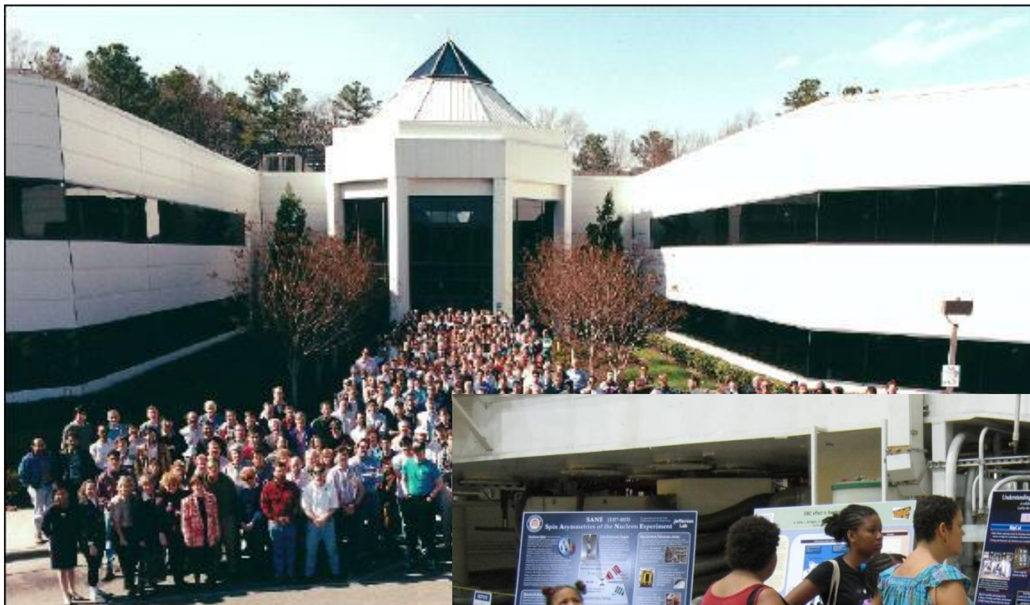
- The solution: Accelerating charged particles emit photons
  - Accelerate electrons to 3 GeV and scatter them off a proton target
  - Electrons deflected (accelerated), and emits a 1 GeV photon



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

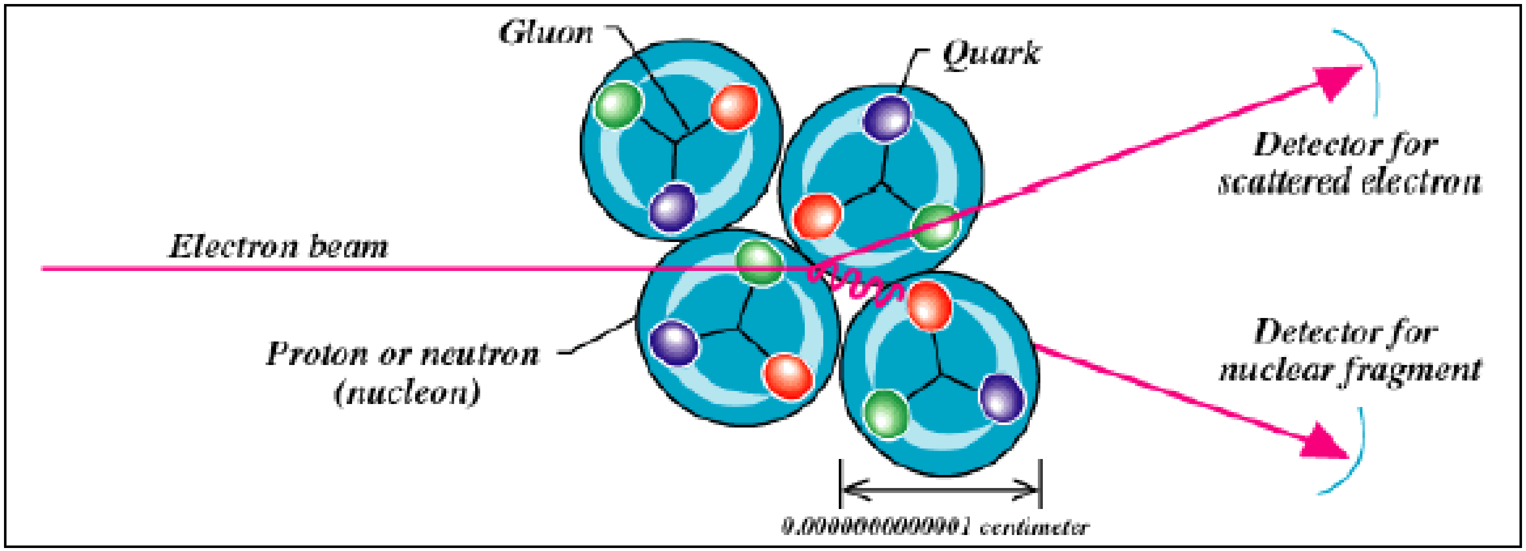
Welcome to Jefferson Lab

- 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.



How do scientists study quarks?

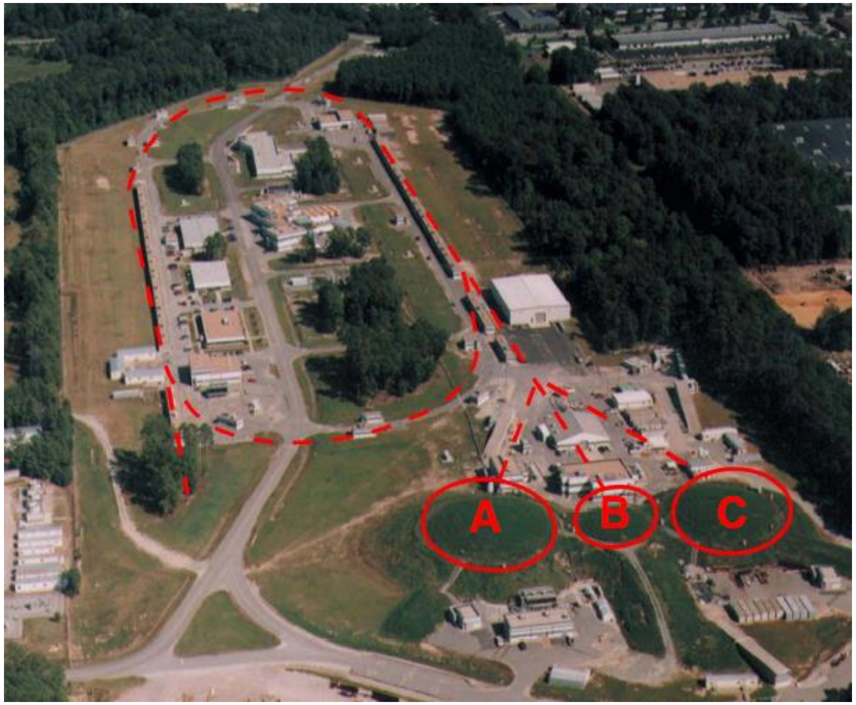
- A sheet of aluminum foil is about 250,000 atoms thick. If you took one of those atoms and enlarged it so that it was the size of the earth, a quark inside the nucleus of that atom would be no larger than your fist. How can we possibly study something that small?



- 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.

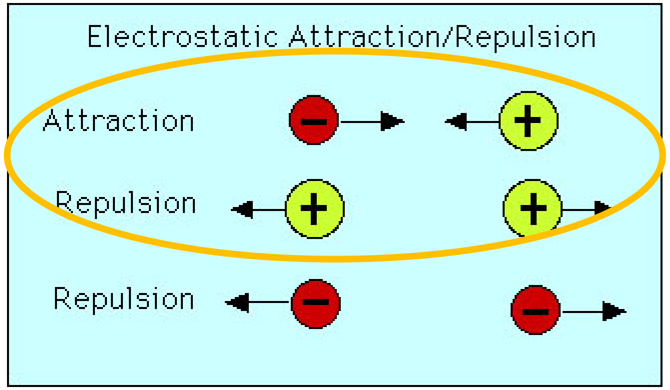


- Jefferson Lab's accelerator is about 1.4 kilometers around (about 7/8 of a mile) and was built in a tunnel 8 meters (about 25 feet) underground.
    - Electrons gain energy as they pass through the straight sections of the accelerator
    - and are steered by large electromagnets as they pass through 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 6 billion volts, it is directed to one of the three large, hill-like experimental halls where it collides with the target.

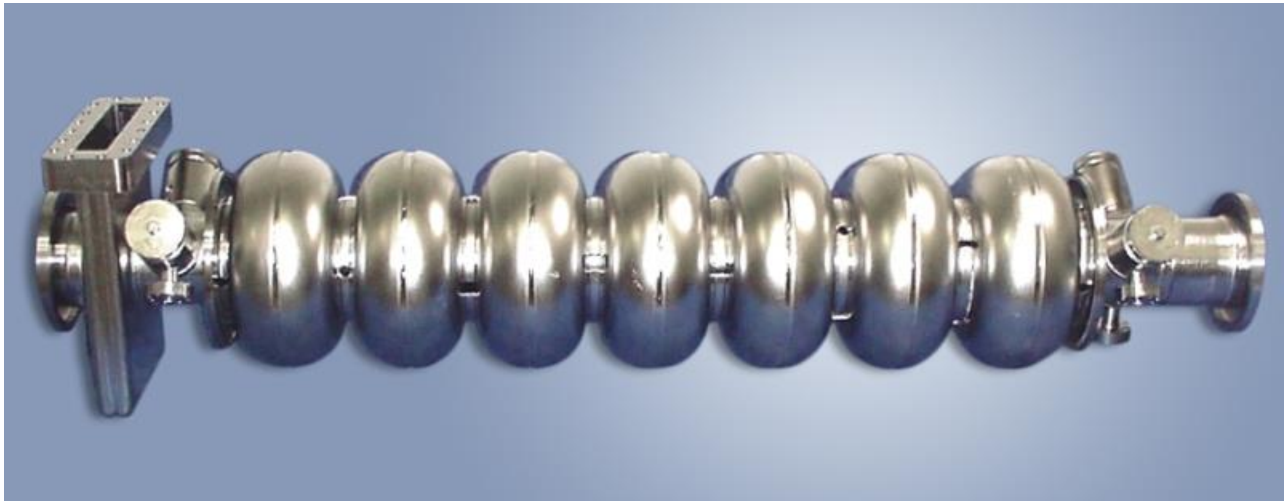
How does an accelerator work?

- 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.



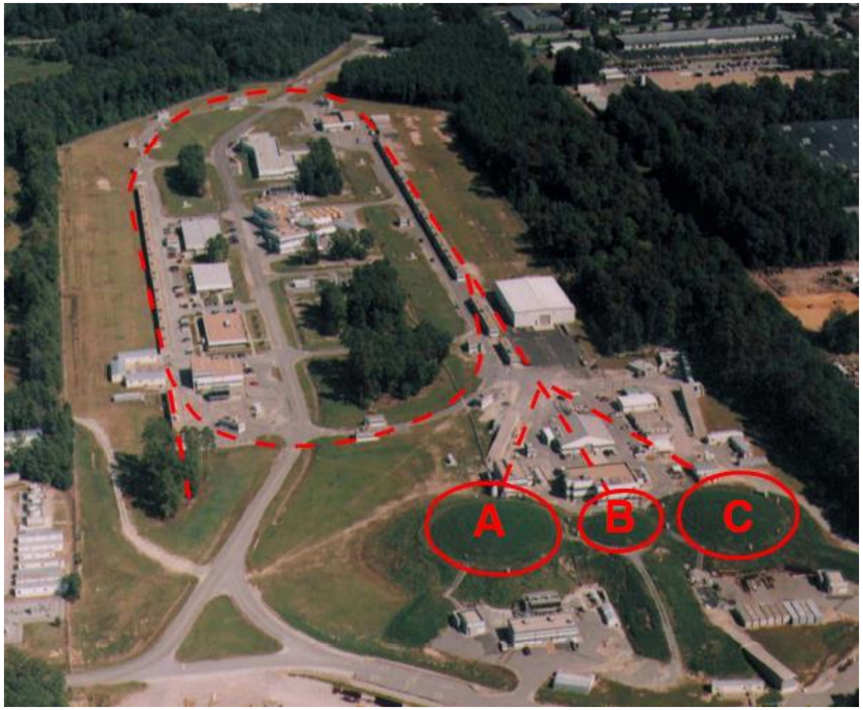
How does an accelerator work?

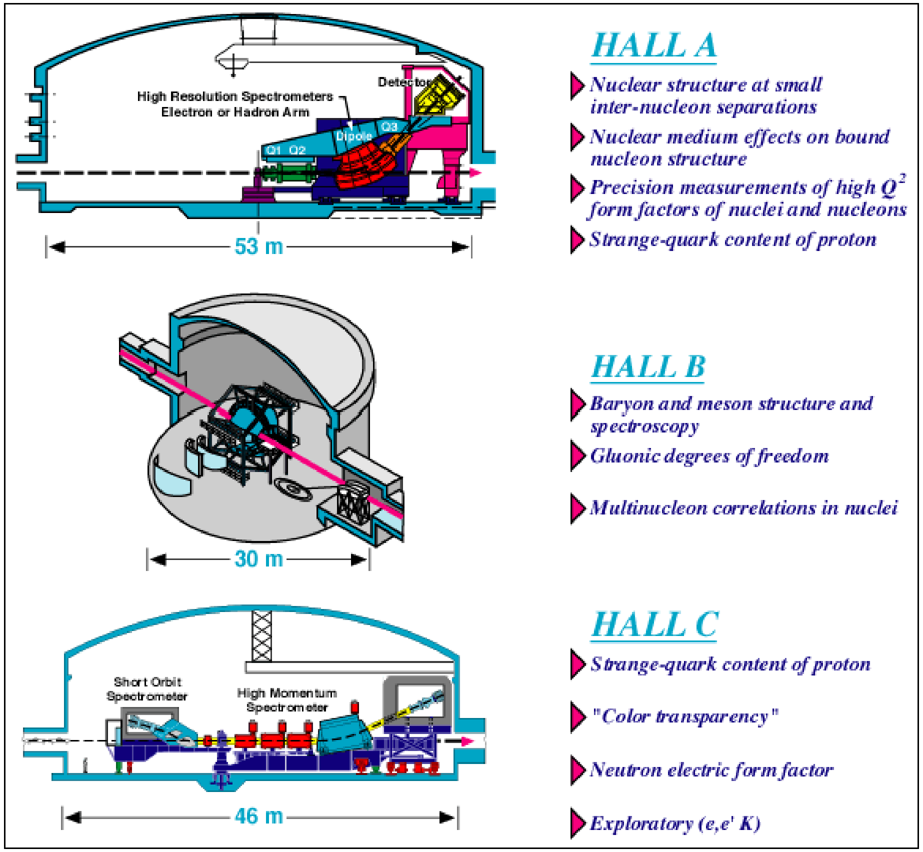
- Cavities are hollow shells made from the element niobium. Jefferson Lab's accelerator uses 338 cavities, mostly in the two long, straight sections. Microwaves are directed into the cavities and cause the electrons in the niobium metal to concentrate in certain areas. Since these areas have extra electrons, 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)



Where are experiments done?

- Three large experimental halls sit at the end of Jefferson Lab's accelerator. The halls can conduct three 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.

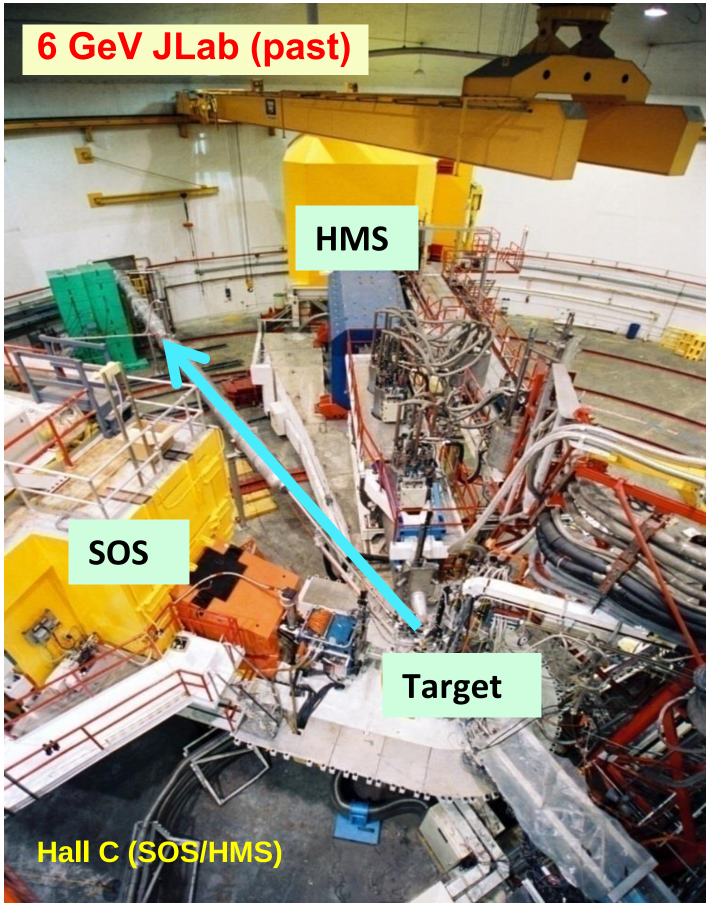


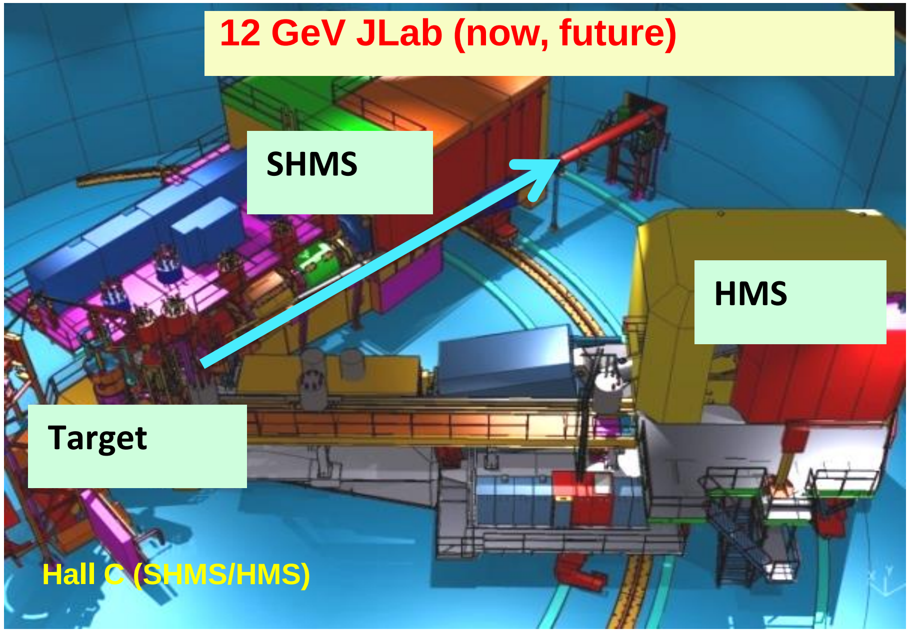


Example: Hall C: past and present

Two focusing spectrometers

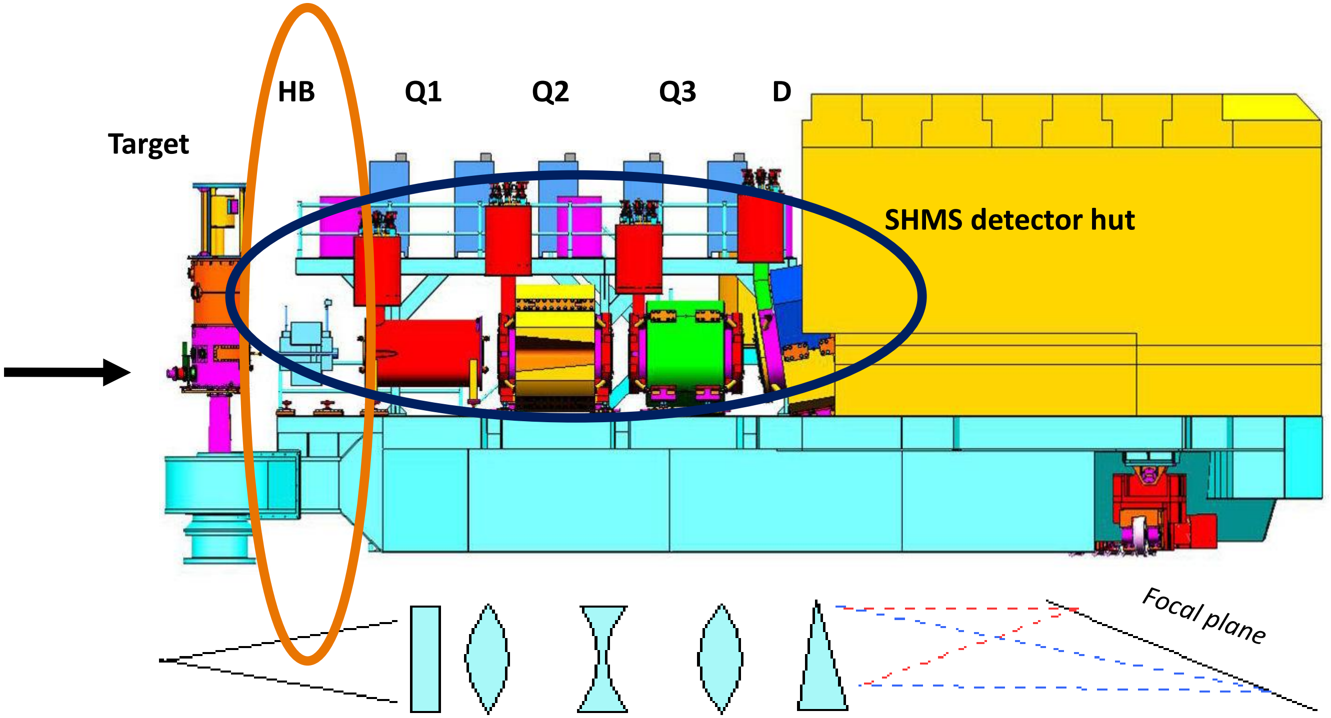
Retain HMS spectrometer
Remove SOS spectrometer
Add SHMS spectrometer





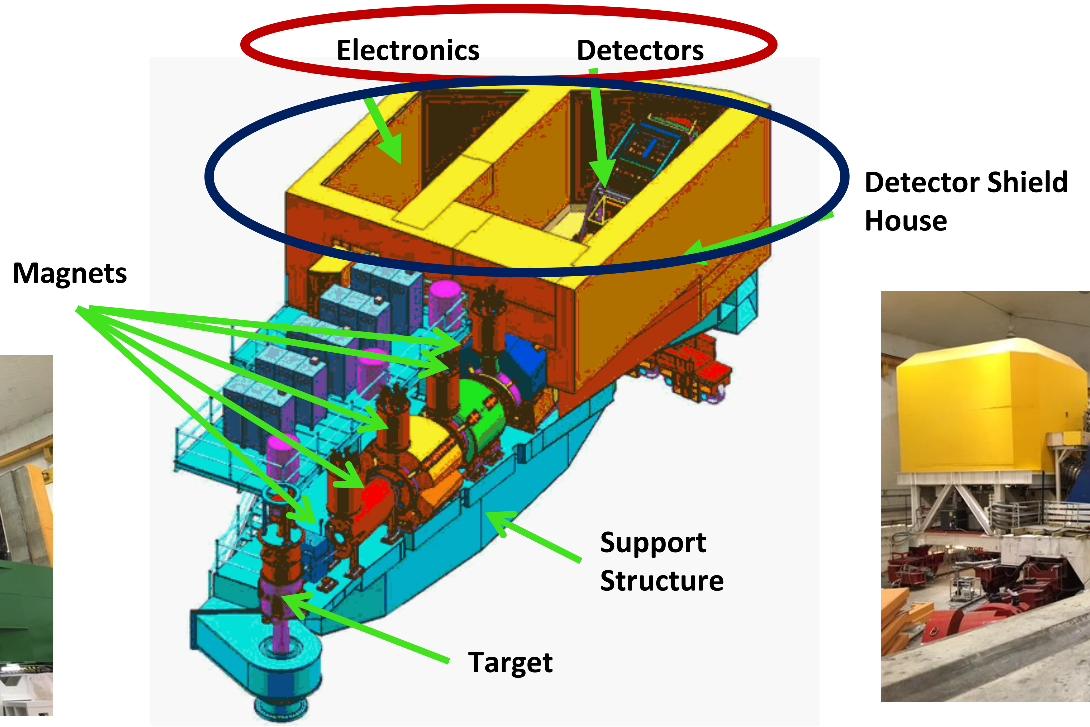
- **Key Features of the SHMS:**
  - 3 quadrupole & 1 dipole & 1 horizontal bend magnet
  - new 6 element detector package
  - complementary to existing spectrometer (HMS)
  - rigid support structure
  - well-shielded detector enclosure

SHMS Optics



- 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

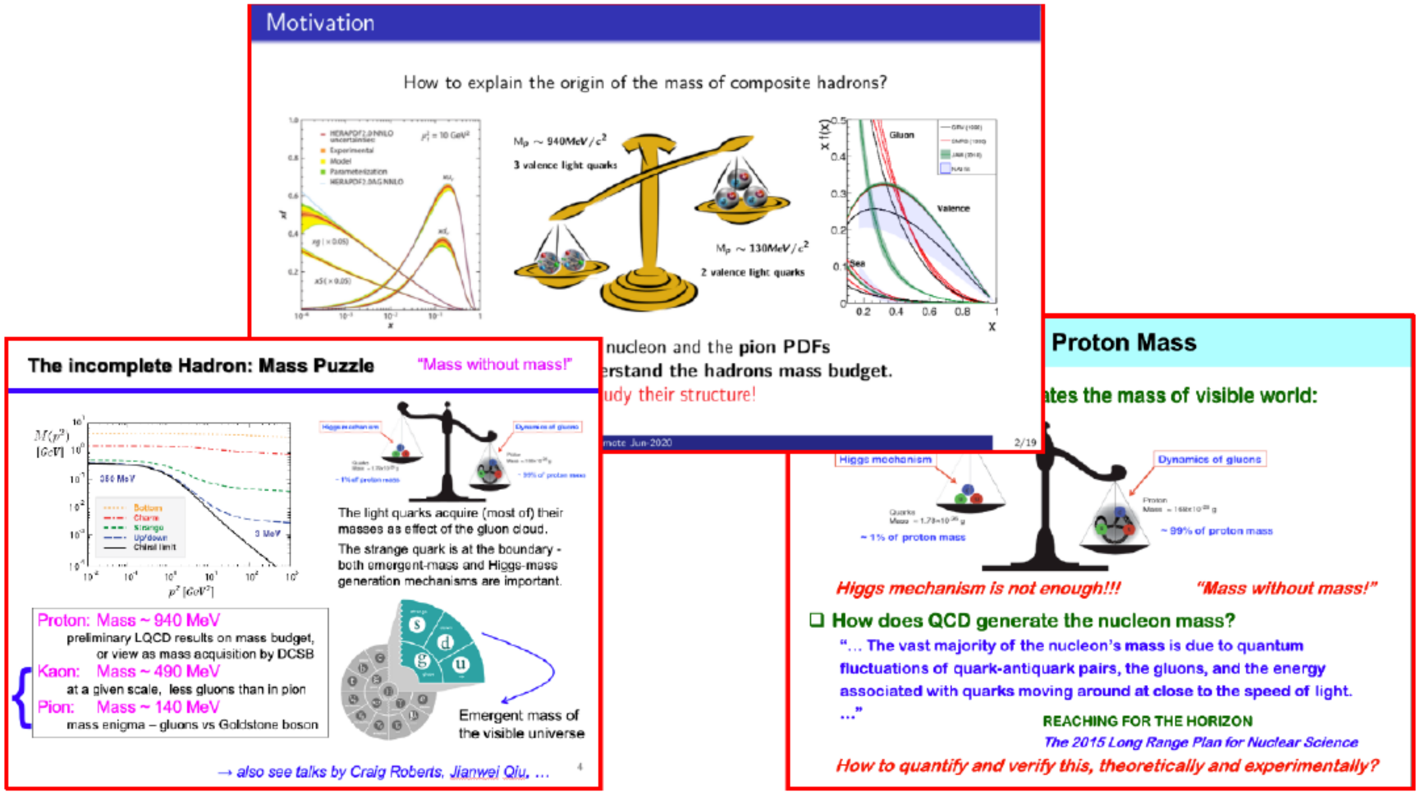
SHMS Detector Shield House



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

Our Research and Experiments

Pions and Kaons are fundamental

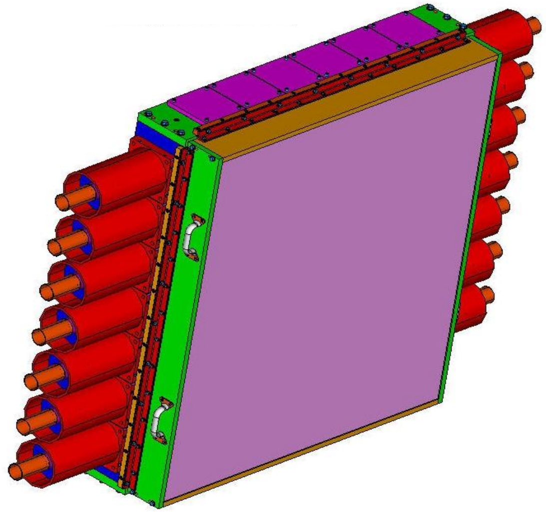


Experiment E12-09-011 – complete, data analysis ongoing

Electron-Ion Collider – simulations for physics and detector requirements

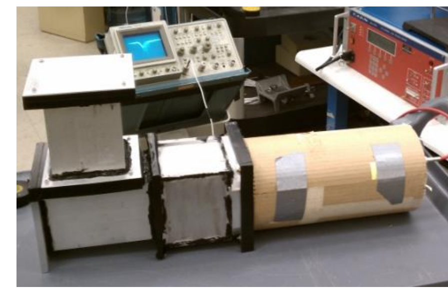
Detector Example: Kaon Aerogel Cherenkov

Detector design (2010/11)

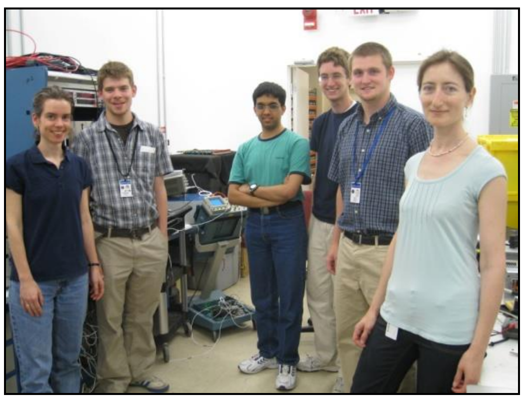


Aerogel and PMTs from BLAST ready for shipping

- Detector component evaluation with summer students from CUA, South Carolina, and MSU



Prototype to test aerogel tiles for detector



Profs Tanja Horn and Yordanka Illieva with summer students Nathaniel Hlavin, Prajwal Mohanmurthy, Robert Jacobson, and Kevin Wood

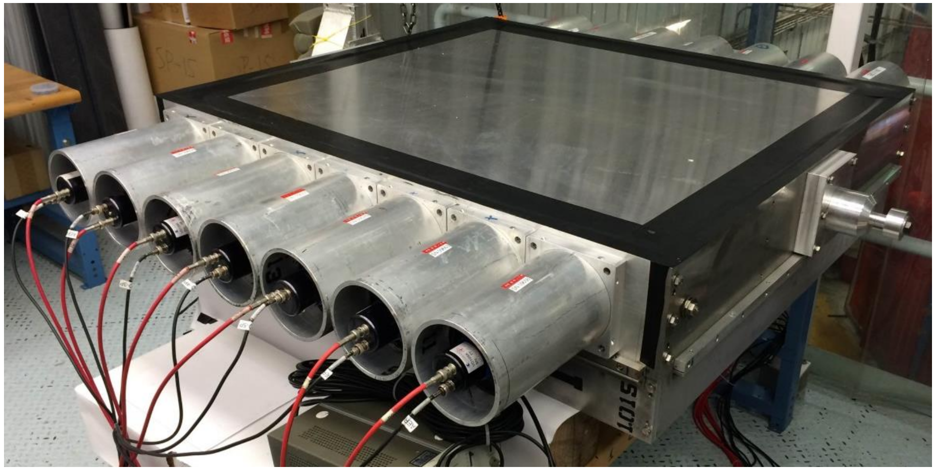
Prof. Illieva explains the test setup while Prof Horn works with students on the analysis

Postdoc Ibrahim Albayrak explains data to students

Detector Example: Kaon Aerogel Cherenkov

Detector construction (2012-2014)

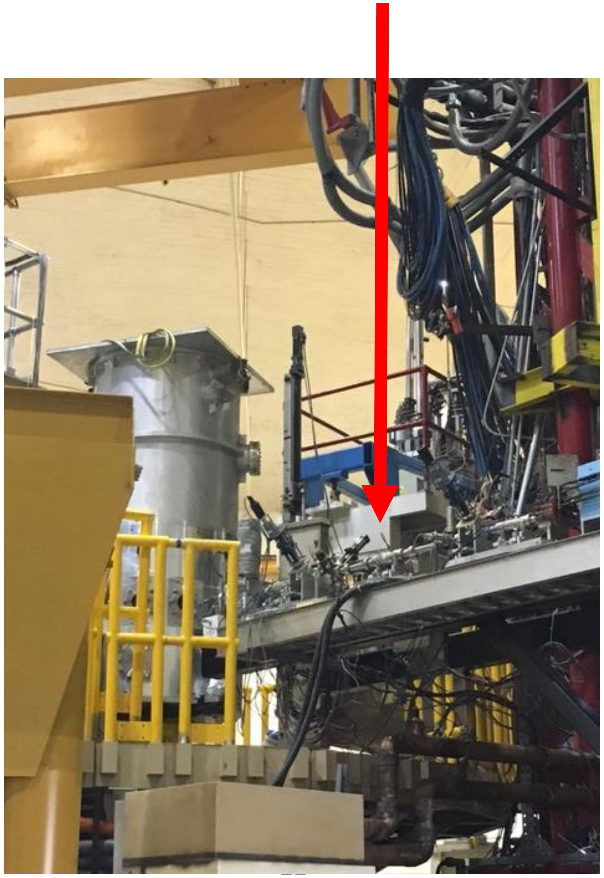
NSF MRI PHY-1039446



- ❑ 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

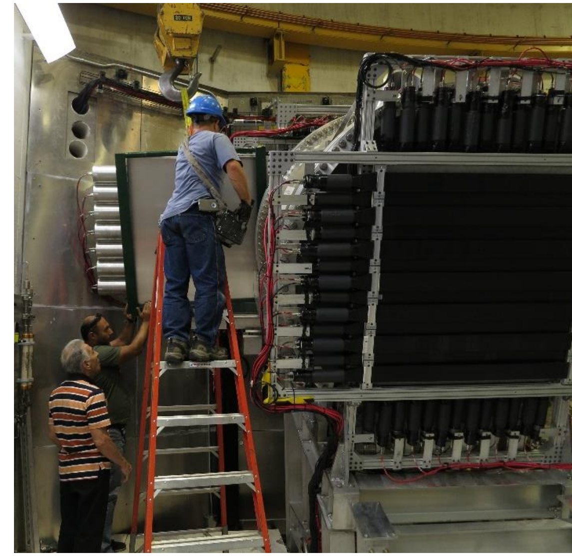
Detector Example: Kaon Aerogel Cherenkov

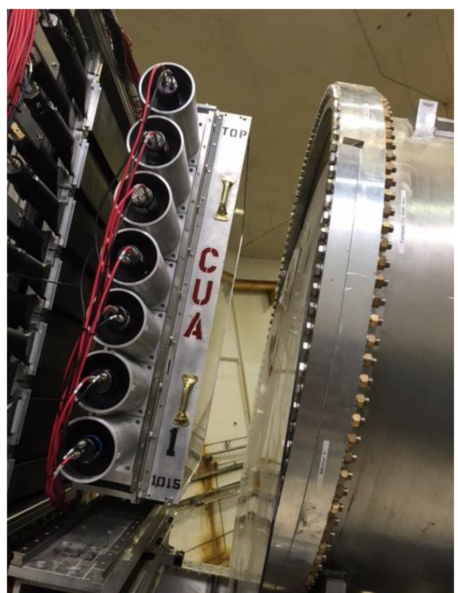
Detector installation planning (2010+)

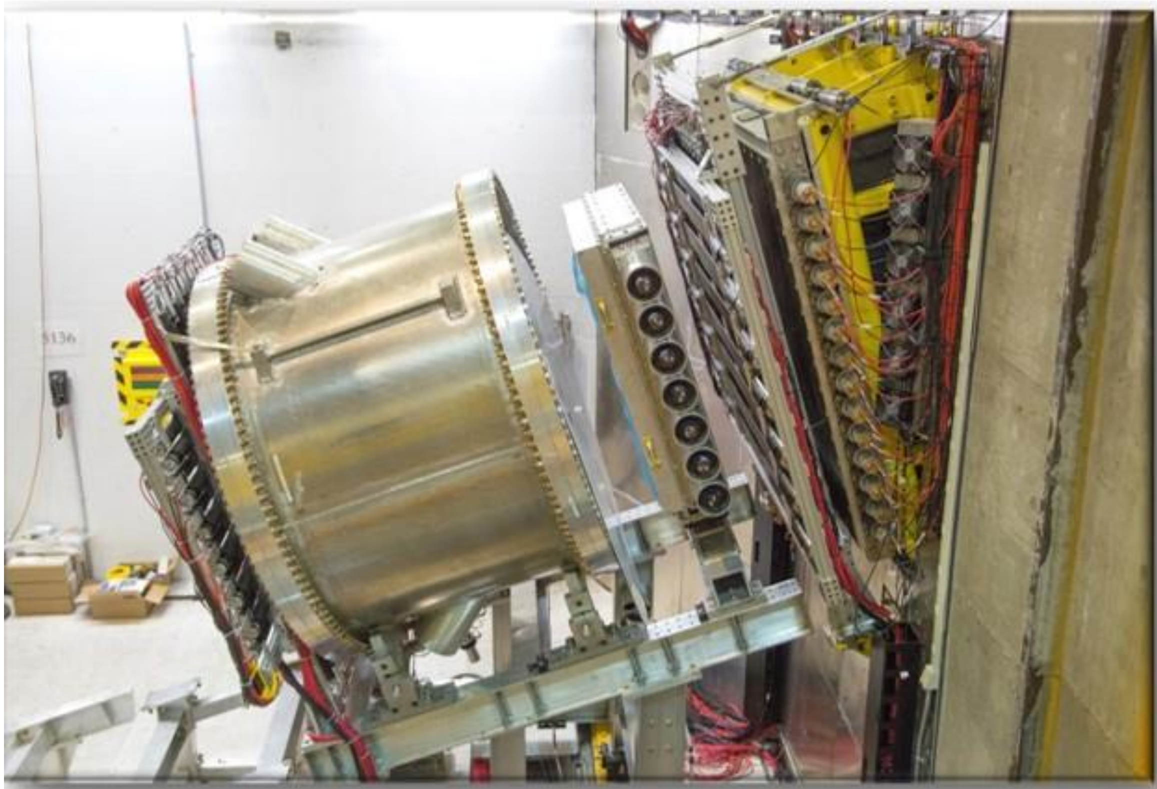


Detector Example: Kaon Aerogel Cherenkov

Detector installation, operation, and maintenance (2015+)







SHMS aerogel Cherenkov detector – built at CUA

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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

Detector Example: Kaon Aerogel Cherenkov

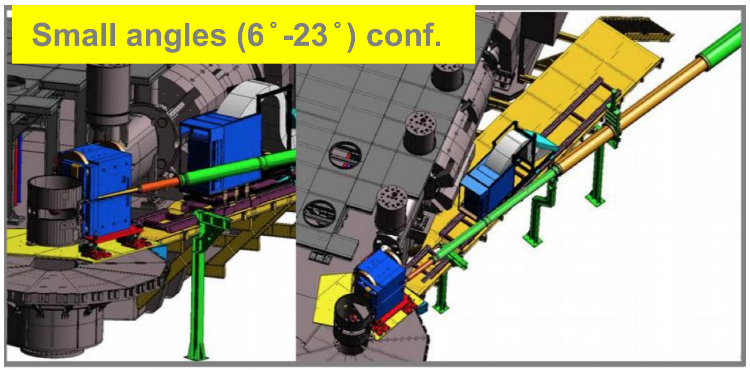
Detector improvement (2019+)

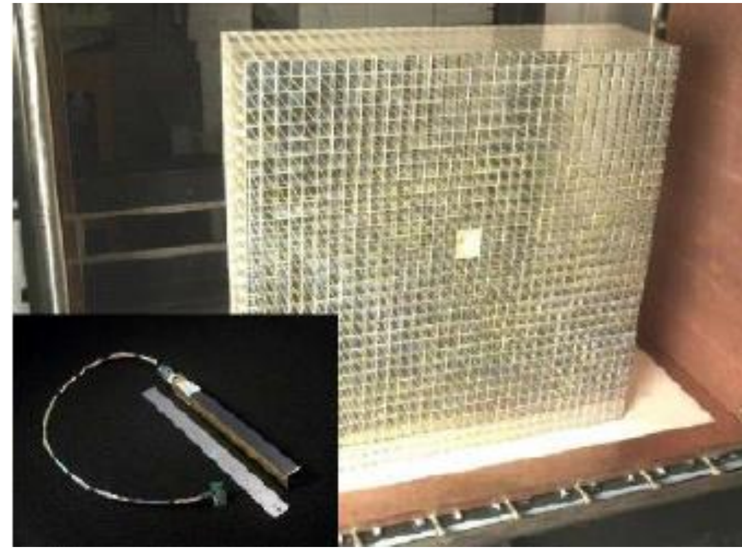
- Aerogel tray optimization
- **New aerogel material for aerogel based detectors**
  - **Optical properties**
  - **Mechanical properties**

Neutral Particle Spectrometer (Hall C)

- **Another CUA Detector Project**

Supported by NSF MRI PHY-1530874





~25 msr Neutral Particle detector consists of :

- **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

PbWO4 crystals

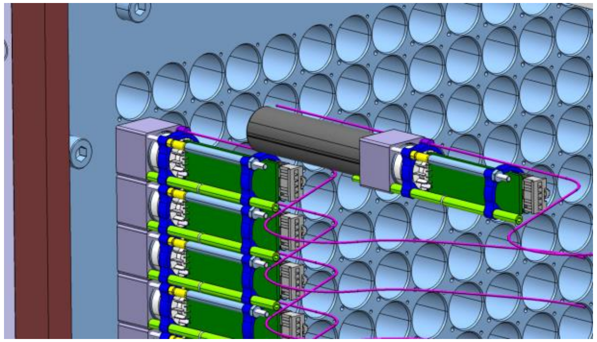
- 30x36 (1080) PbWO4 crystals of size: 2x2x20 cm3 – goal is to have all Crytur crystals

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%



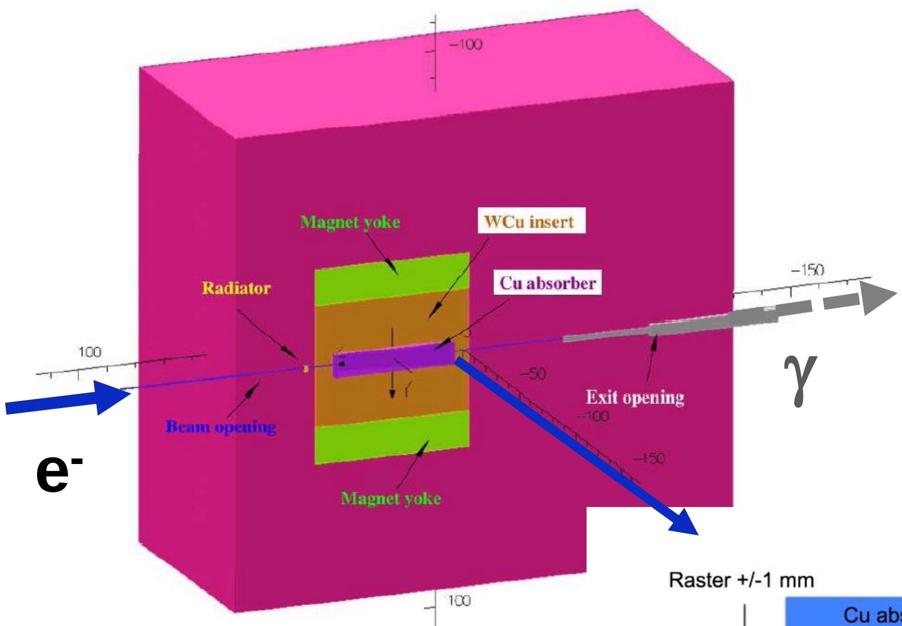
Frame infrastructure: being assembed at IPN-Orsay

- ❖ Sweeper magnet ready for full current test in Hall C
- ❖ Frame scheduled to be on-site in December 2020
- ❖ PMT`s received and spot checked - no rejections
- ❖ All (1100) active bases assembled
- ❖ Calorimeter assembly scheduled to begin in January 2021

Compact Photon Source (Hall C)

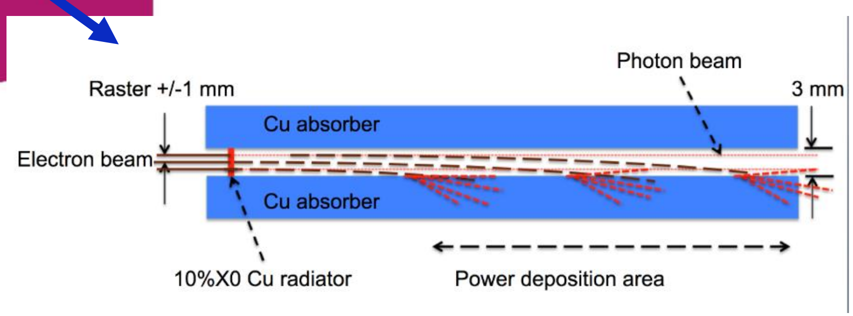
A high-intensity compact photon source that could provide a factor of 30 gain in figure-if-merit for photo-production experiments of solid-state polarized targets

High-energy photoproduction in 3D dynamic proton structure – **two approved experiments to date (Polarized Wide-Angle Compton Scattering and Timelike Compton Scattering)**



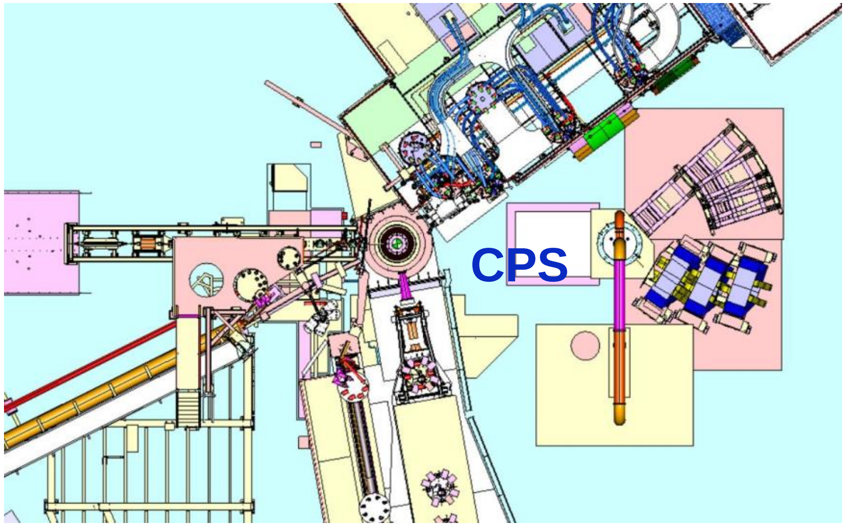
CPS conceptual design:

- a radiator to produce photons
- a magnet to dump the electrons with a small photon collimator
- a central copper absorber to handle the power deposition
- tungsten powder and borated plastic to hermetically shield the induced radiation dose as close to the source as possible.



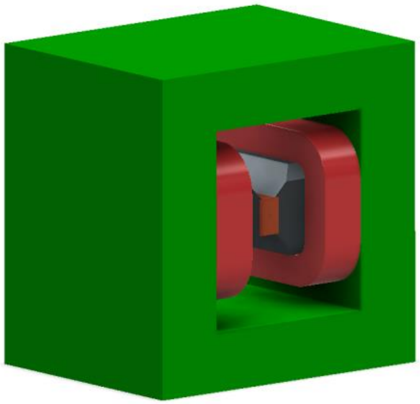
Compact Photon Source Status

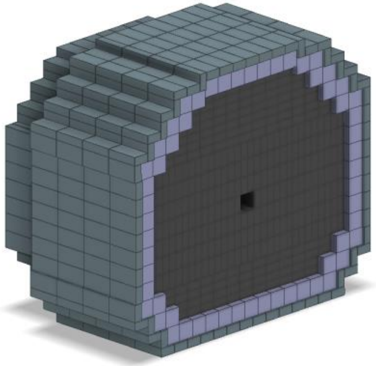
- CPS simulations give light-weight shielding configuration that fulfill all radiation requirements
- Design modeling of CPS magnet and shielding configuration has started
- Mechanical evaluation of CPS implementation completed – location will be downstream
- Information gathering on shielding material and vendors started
- An adaptation of the concept to the Kaon Long Facility (KLF) in Hall D has been developed
- CPS concept successfully passed a Technical Review in 2018
- Conceptual Design for Hall C CPS published in NIMA **957**, 163429 (**2020**)



CPS in Hall C: mechanical design model

The CE CPS project could include the magnet and/or the infrastructure to contain the swept-away electrons.





CPS magnet and shielding model: the optimized shielding has rounded edges and replaces a fraction of tungsten with lead

Summer 2020 Projects

Experiment E12-09-011 – data analysis, reference time

➡ Global fit of kaon and pion data

➡ Simulations of pion/kaon structure functions at an EIC and detector requirements

Performance of novel scintillators for EIC calorimeters

➡ Performance of new aerogel material for Cherenkov detectors

Schedule and Communications

Weekly group meetings – status updates, brainstorming, planning

Tutorials on physics, detectors, data analysis and simulation software

- **First tutorial on Thursday 7/9 (Richard Trotta)**

Questions any time: Slack

"Homework for week 7/6"

Read the background material

Review data/material provided and ask questions

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

Familiarize yourself with the software

Prepare 2-3 slides of your project, e.g. what you will be doing, for the next group meeting on Monday 7/13

Questions any time: Slack