Electron Scattering Experiments, Data-Analysis and Monte-Carlo Simulation

Section 1

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Head-Up

- It is a very brief introduction of Nuclear Experiments via Electron-Scattering examples.
- Do not intend to give a lecture about detector technologies (but do cover most of common use detectors)
- Highly related to some of the Physics topics discussed in other Sections and the upcoming Hadron-Workshop
- Only give experimental programs that I involved at JLab/EIC but the ideas behind are common for all particle physics experiments
- Welcome to discuss with me in the next few days

Outline

- Quick Introduction to Experimental Particle Physics Method

- Selected Experimental Examples:
  - Example 1: High resolution Magnet Spectrometer, HRS, Hall-A, JLab

Section 1

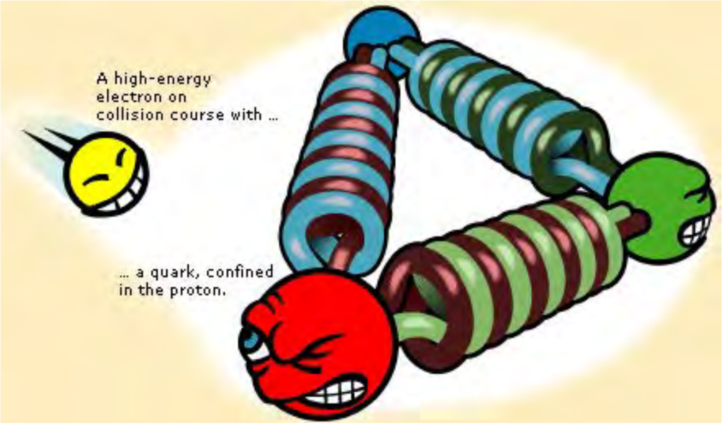
  - Example 2: General Purpose 4π Detector System, SoLID, Hall-A, JLab

  - Example 3: General Purpose 4π Detector System on Electron-Ion Collider

Section 2

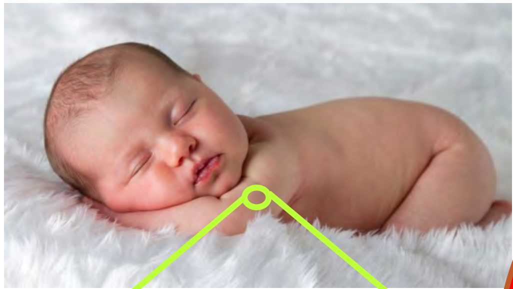
- Data Analysis and Simulation

Experimental Particle Physics Method



The Structure of Matters

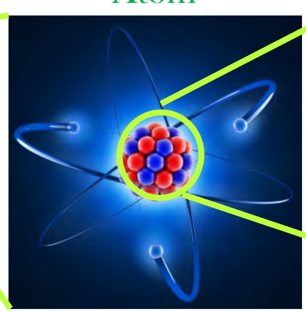
Baby



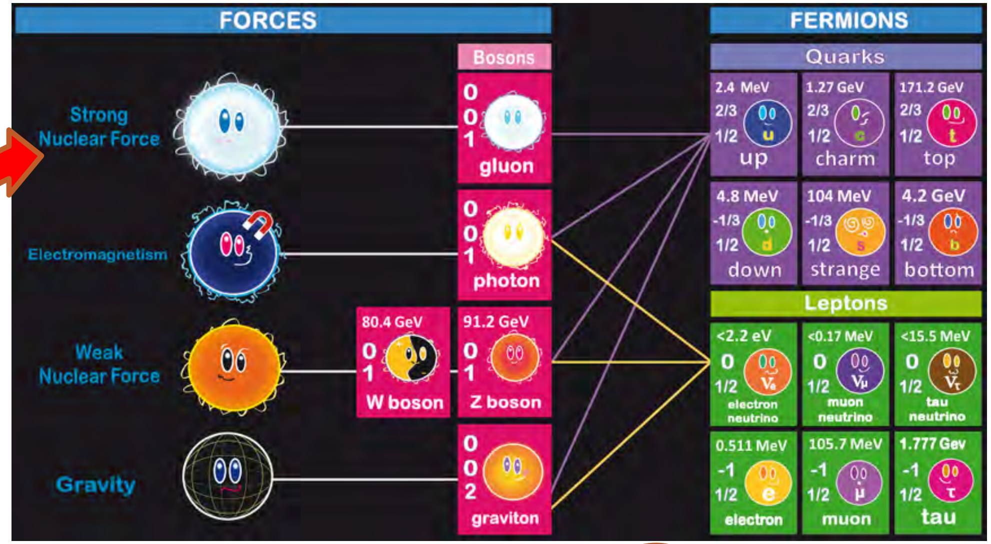
Cells, DNA ...

Molecular

Atom



The Standard Model:



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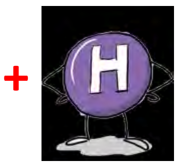
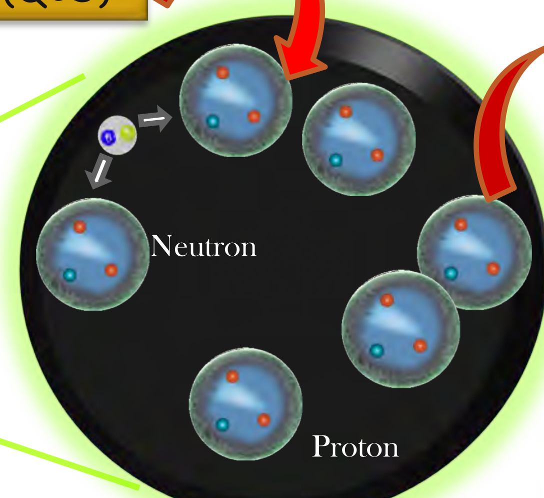
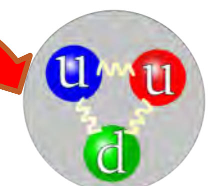
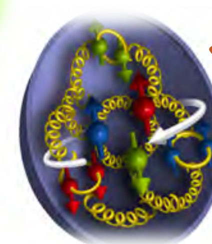


Quantum ChromoDynamcs (QCD)







Hydrogen-Size: 5.3×10^{-11} m
Carbon-Size: 9.0×10^{-11} m

Carbon-Nucleus-Size: 2.7×10^{-15} m
Proton-Size: $< 1.0 \times 10^{-15}$ m

Experimental Particle Physics Method

➢ **How we "see" this world?**

The wavelength of visible light is 400～700nm（ $1nm=10^{-9}$ m）;
The radius of an atom is 1～10fm ($1fm=10^{-15}$ m); A nucleus is 2000 times smaller than a atom;

See the daily stuffs

See nuclei, nucleons, quarks ...

Visible light

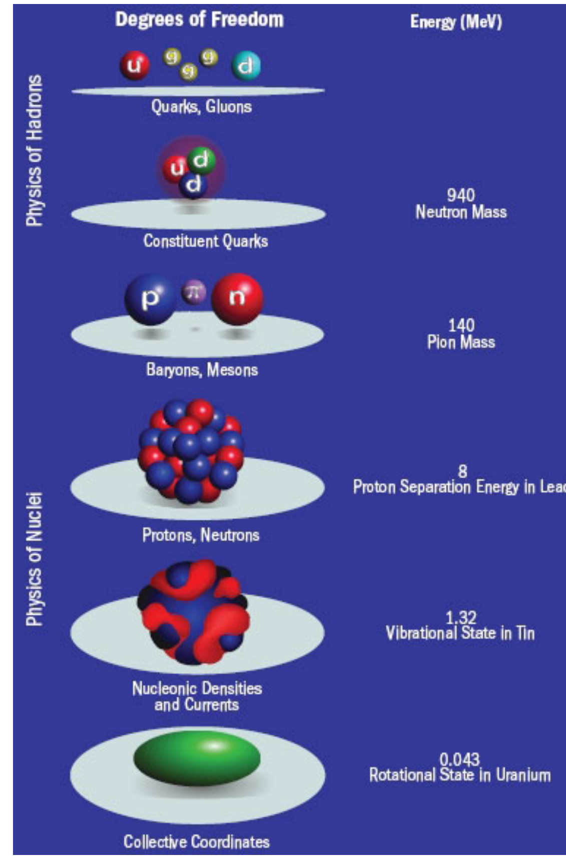
x-ray

$$E = {hc}/{\lambda} = mc^2$$

1/Wavelength

Energy Transfer

SEE – using eyes directly, or via certain devices → receive photons → generate bio-signals in the brain → use the brain to reconstruct the image



The shorter the wavelength, the more detailed structure we can see

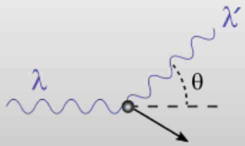
The higher the energy transfer, the deeper structure we can "see" inside the nuclues

Tools in Particle Physics

- **Main particle scattering processes:**

Compton scattering

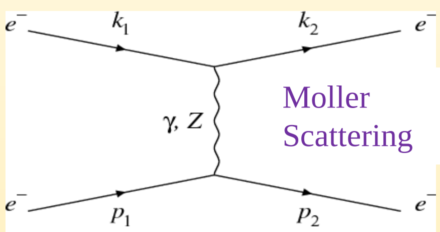
real photons

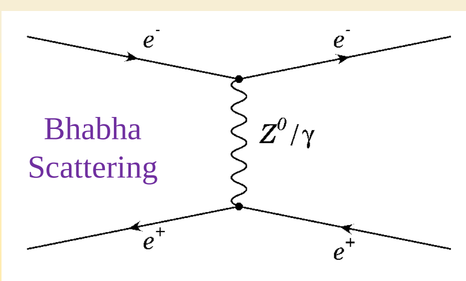


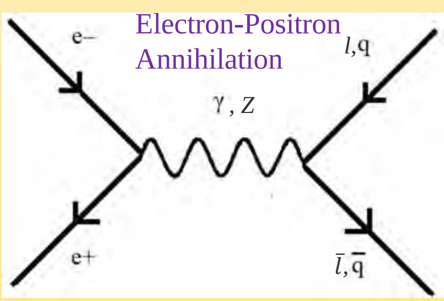
electrons or other charged particles

Lepton-Lepton scattering

lepton=electrons, muons, neutrinos

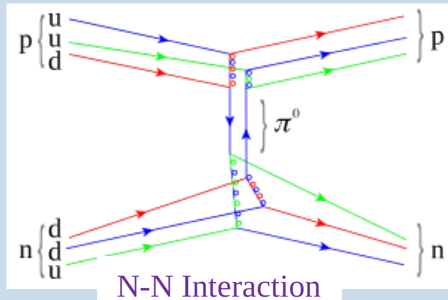




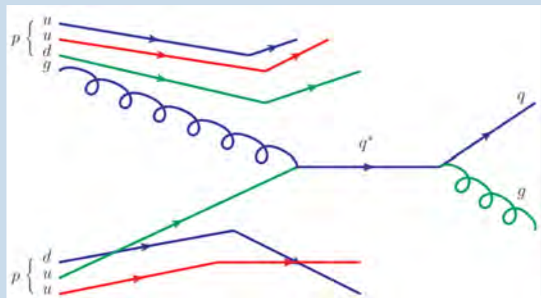


Hadron-Hadron scattering

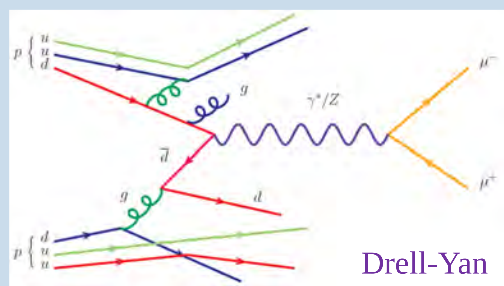
Hadron=mesons, protons, neutrons, nuclei



N-N Interaction

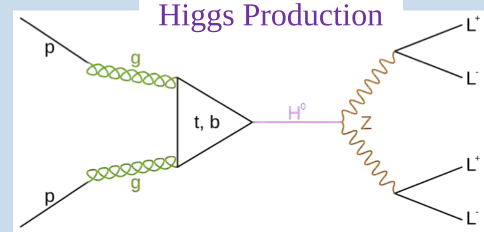


Quark/Gluon Scattering

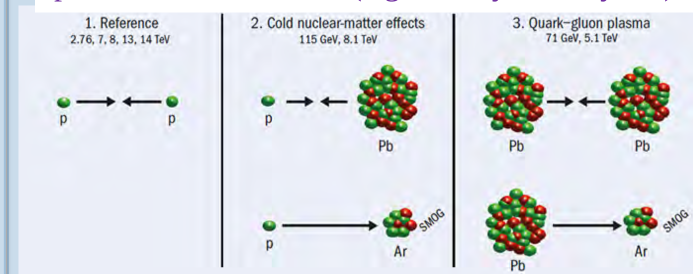


Drell-Yan

Higgs Production

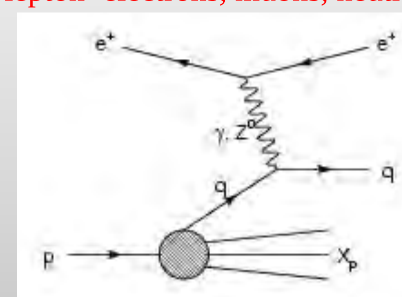


p-A and A-A Collision (e.g., Heavy Ion Physics)



Lepton-Hadron scattering

lepton=electrons, muons, neutrinos

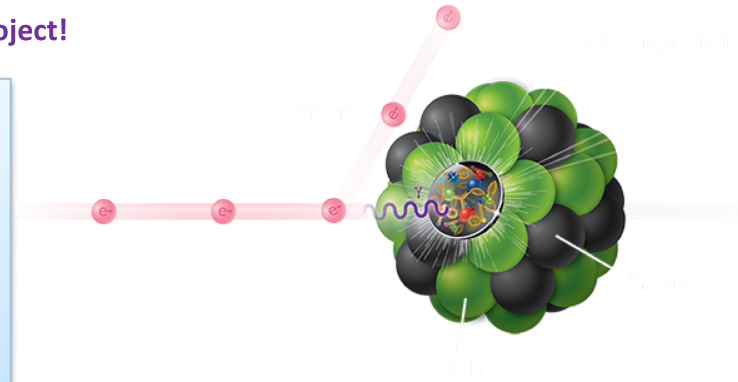


Hadron=mesons, protons, neutrons, nuclei

Experimental Particle Physics Method

➢Electron Scattering – A high precision EM probe!

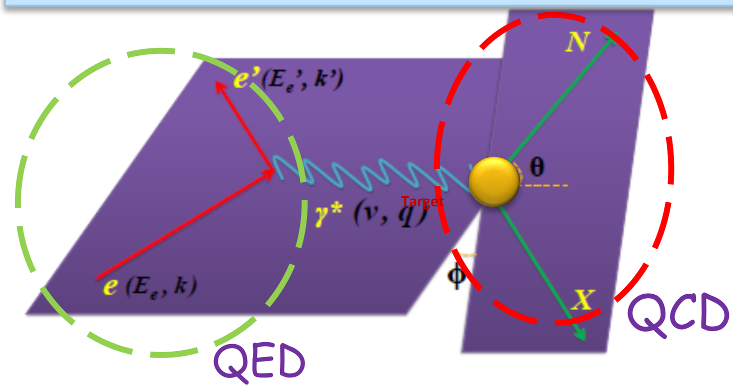
To study a complicated subject, the tool can not be more complicated than this project!



- ❖ Electrons are easier to accelerate, manipulate, and control the polarization
- ❖ Electrons interact with others via EM interaction (and also small probabilities of Week-Interaction)

  (Protons and other hadrons interact via both EM and Strong-Interactions!)
- ❖ Electrons are fundamental particles, and won't break into smaller pieces

  （Protons will break up into many fragments due to their quark and gluons)
- ❖ Weakness：Hard to reach high energy (tens of GeV)



QED (Quantum Electromagnetic Dynamics):
Precisely calculate EM interaction; Agree well with experiments

QCD (Quantum Chromo-Dynamics):
Calculate strong interaction; Non-perturbative parts are not directly calculatable; Need model approximation combined with experimental measurements as inputs;

- ❖ Control the resolution of the probe → (Q^2, ν) or (Q^2, x_{bj}):

Four Momentum Transfer (probe resolution)

$$Q^2 = 4E_0E'\sin^2(\theta/2)$$

Energy Transfer (probe depth)

$$\nu = E_0 - E'$$

Momentum Fraction of knock-out quark (probe depth)

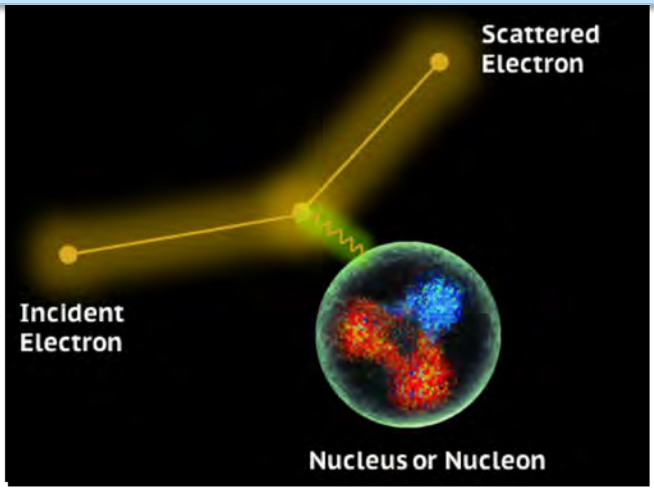
$$x_{bj} = \frac{Q^2}{2m_p\nu}$$

- ❖ By playing with (Q^2, ν) or (Q^2, x_{bj}), we can adjust the probe resolution ("sharpness") and probe depth ("view-zoom") to study the the different degree of freedom of the QCD interaction.

Experimental Particle Physics Method

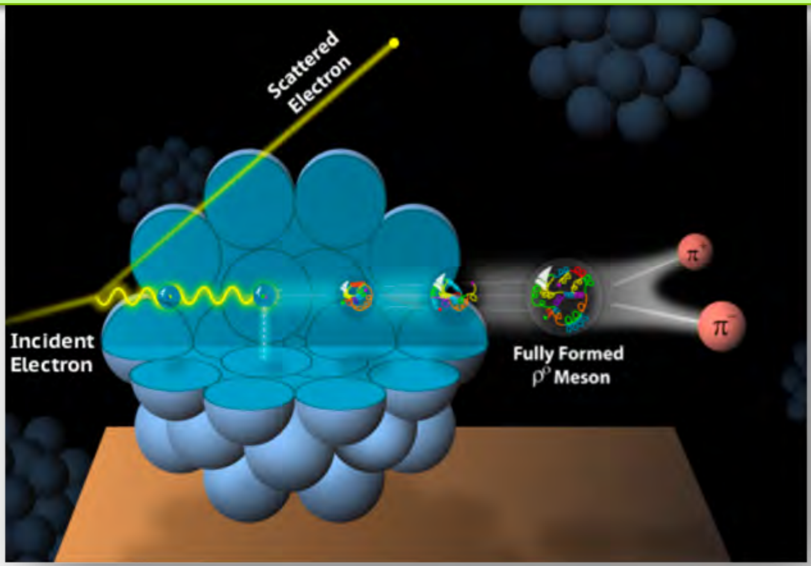
➢ **Major Electron Scattering Processes:**

Elastic Scattering: Energy Transfer is not enough to break up a nucleon or a nucleus; Study the collective EM structure of the nucleon or nucleus (like seeing the "skin")

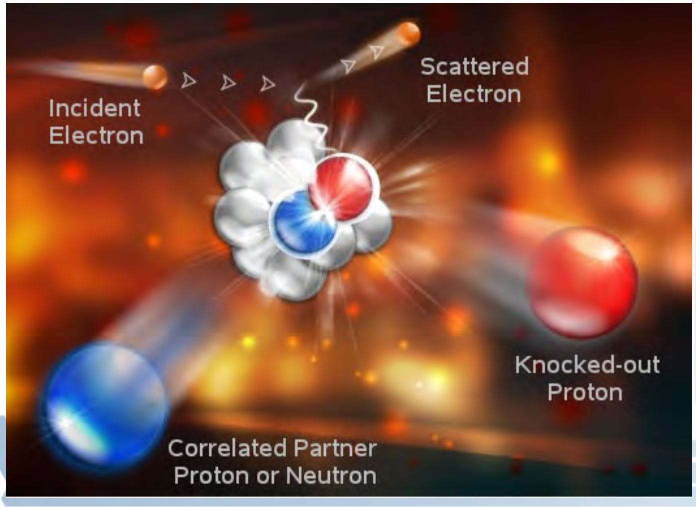


probe the "skin"

Deep Inelastic Scattering (DIS): Energy
The energy transfer is high enough to break up nucleon, and knock out a quark (or gluon); See the internal QCD structure of the nucleon (like seeing the "cells")



probe the "cell"

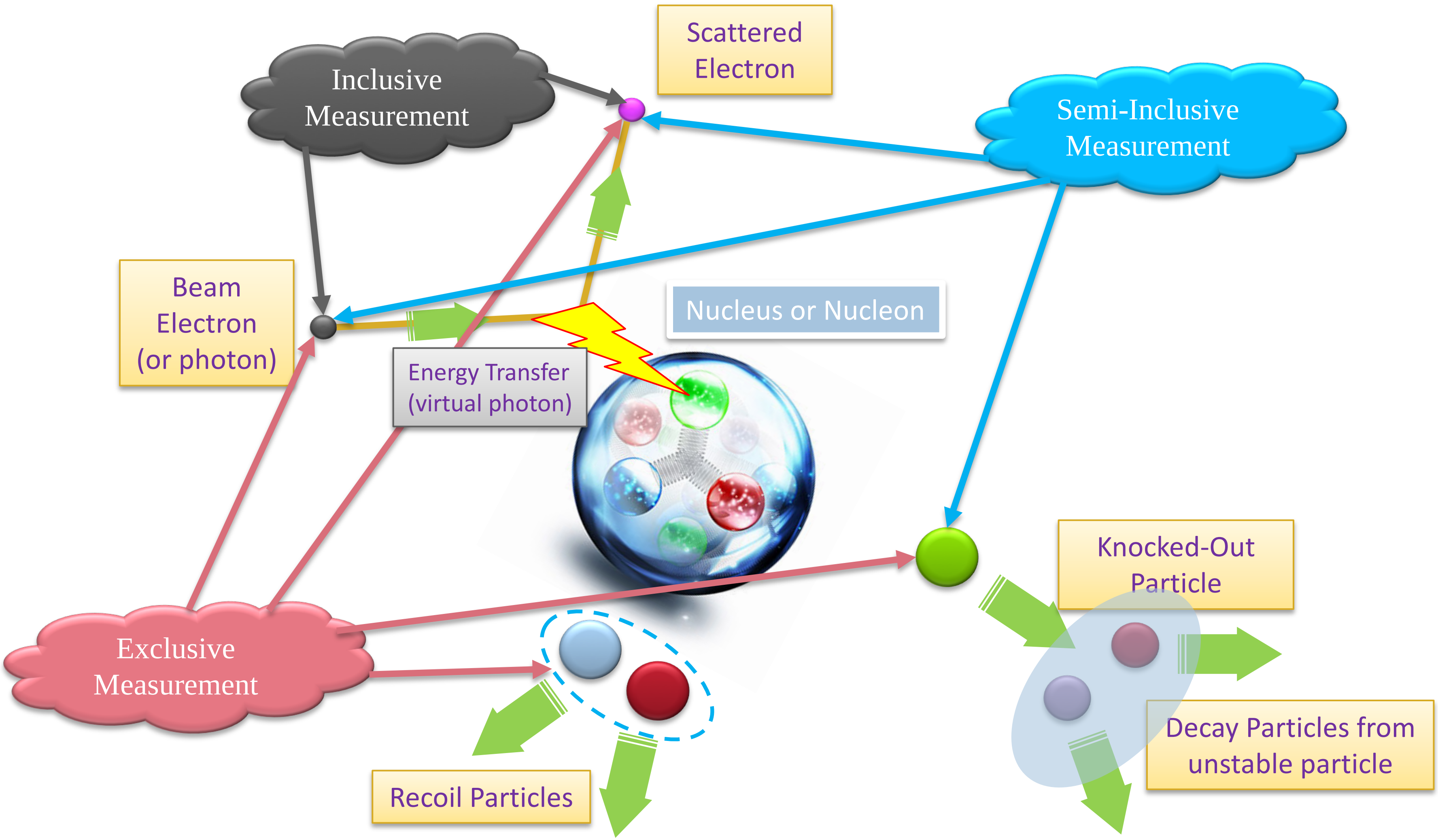


Quasi-Elastic Scattering (QES): The energy transfer is high enough to break up a nucleus and knock out a proton or a neutron; Study nucleon-nucleon interaction and nuclear structures (like seeing muscles or skeleton)

probe the "muscles"

Experimental Particle Physics Method

➢ **Major Detection Methods:**



General Idea: The more particles (and their kinematic quantities) we measure, the detailed mechanism we can learn from the reaction, but the less information we collect, and also the more challenging to measure!

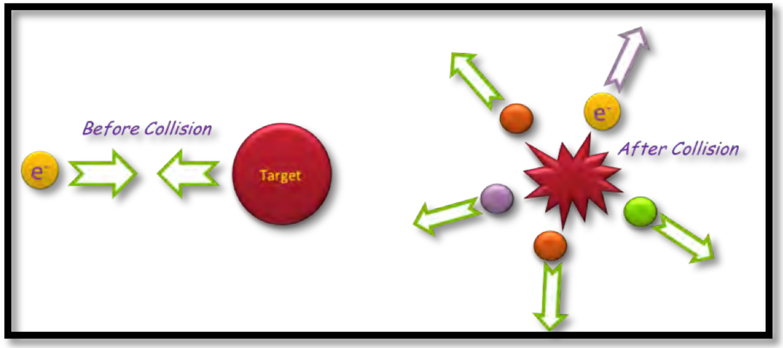
Experimental Particle Physics Method

➢ **The Detection of Particles:**

What to measure?		How to measure?
✓ Position and Direction	(x, y, z, θ, ϕ) →	❖ Position and Tracking Reconstruction
✓ Momentum	$\lvert\vec{P}\rvert$ →	❖ Tracking Reconstruction in a magnetic field
✓ Energy	E →	❖ Calorimetry
✓ Mass	m →	❖ Particle Identification; Mass Spectroscopy
✓ Velocity	v, β →	❖ Time of Flight; Cherenkov Radiation
✓ Spin	$\Leftarrow, \Uparrow, \Rightarrow, \Downarrow$ →	❖ Polarimetry
✓ Life-time	τ →	❖ Vertex Reconstruction
✓ …		❖ …

Fixed Target Experiments:

High Resolution Magnetic Spectrometers



Center of Mass Frame

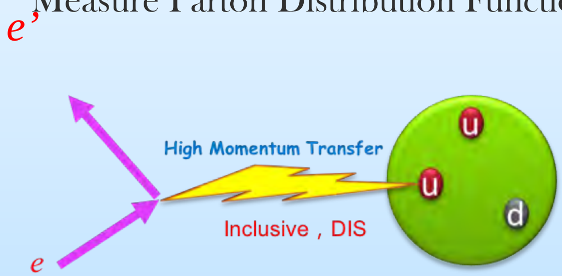
Lab Frame

Experimental Example 1

➢ **Hall-A Tritium Experimental Run-Group**

E12-10-103 (MARATHON)

- Inclusive (only measure scattered electrons)
- DIS (Q^2>1 GeV^2, x_B<1, W>2 GeV)
- Measure Parton Distribution Functions



E12-11-112 (Inclusive SRC)

- Inclusive (only measure scattered electrons)
- QES (Q^2~1, x_B>=1)
- Measure Cross Sections

E12-17-003 (Hypernucleus)

- Exclusive (measure electrons and Kaons)
- DIS ((Q^2>1 GeV^2, x_B<1)
- Measure Lambda-Hypernuclear (Nuclear Force, Shell Structure)

E12-14-009 (Exclusive SRC)

- Exclusive (measure electrons + protons)
- QES (Q^2~1, x_B>=1)
- Measure Nucleon Momentum Distributions, Nuclear Force and Nucleon Shell Structures

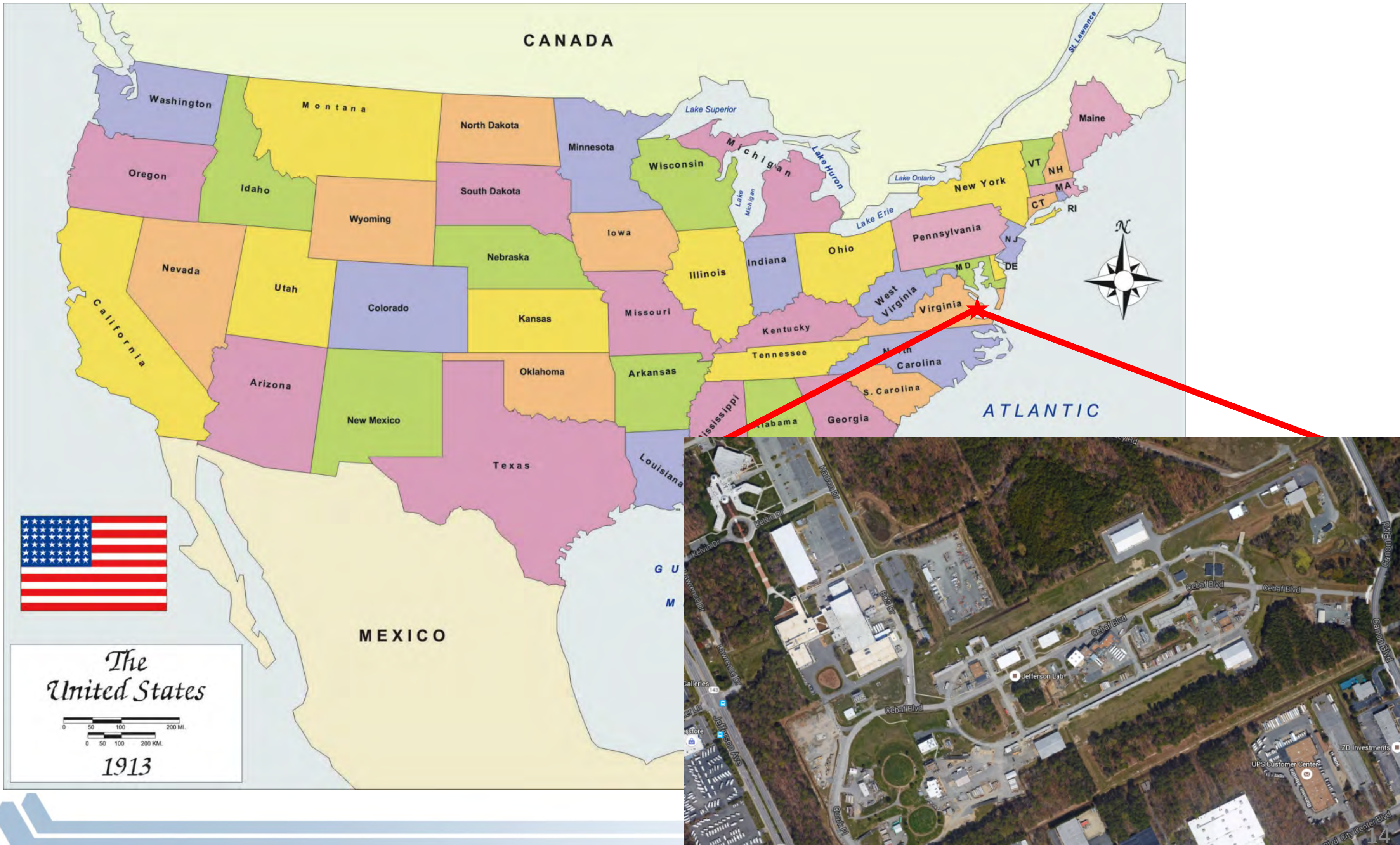
Thomas Jefferson Lab

Jefferson Lab
Thomas Jefferson National Accelerator Facility

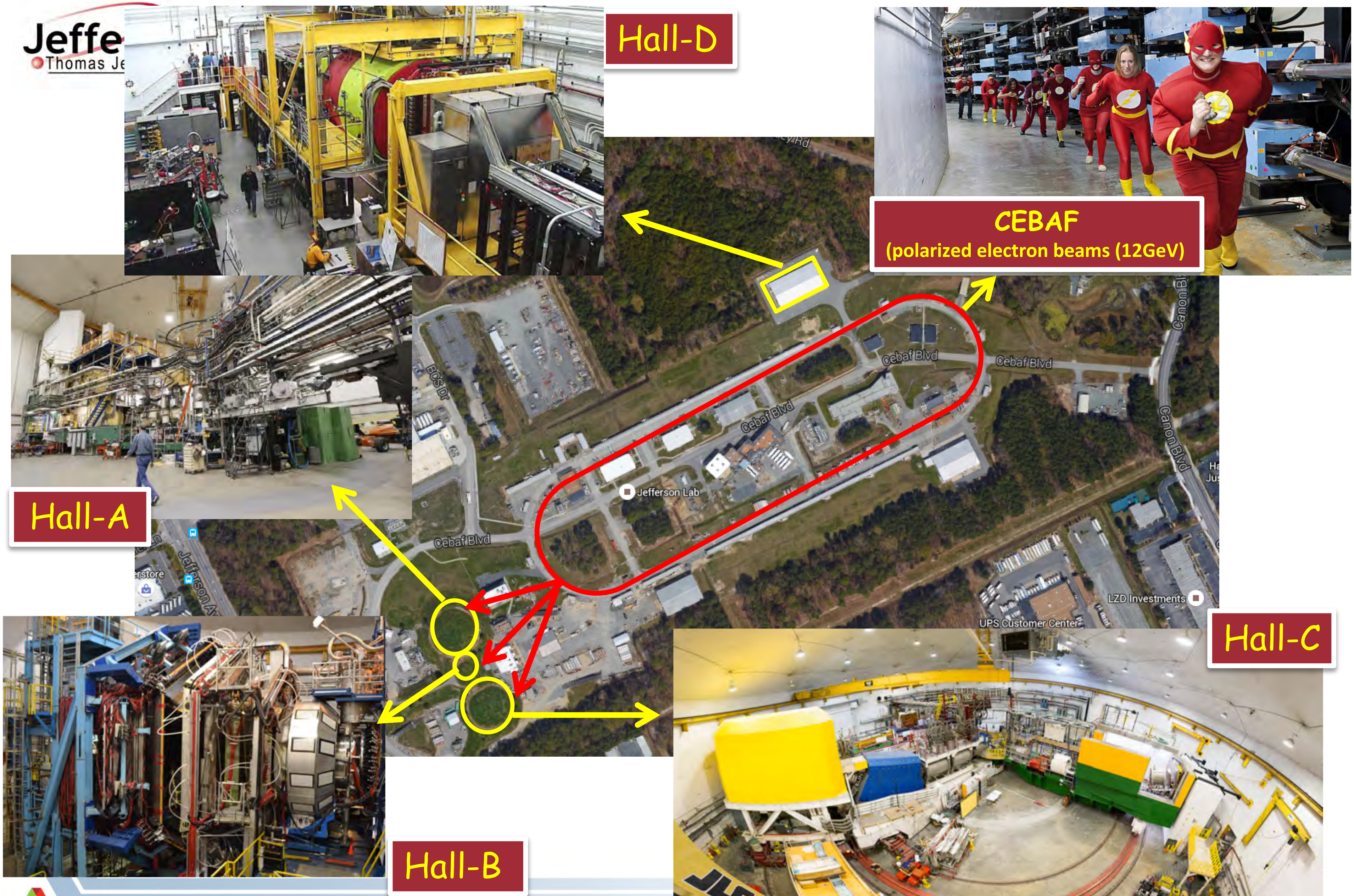
JSA

U.S. DEPARTMENT OF ENERGY

Located at Newport News, Virginia; Funded by Department of Energy; First operation in 1990s

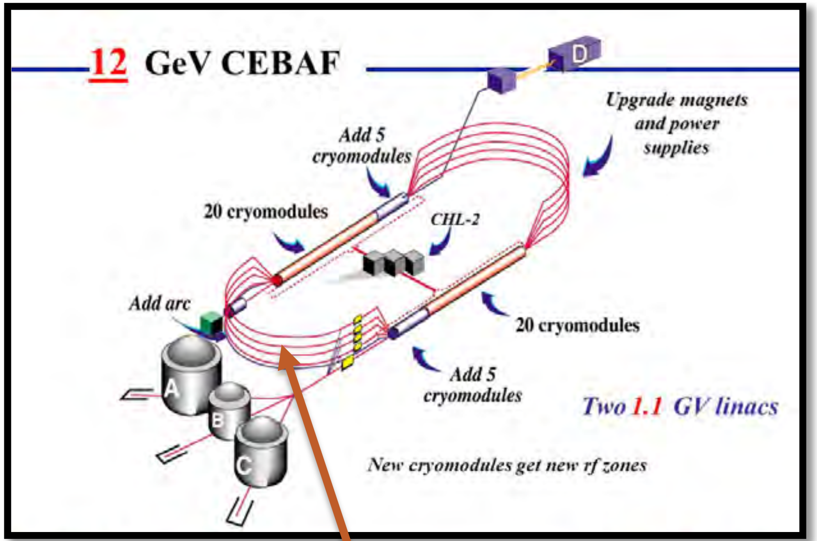


Thomas Jefferson Lab



Thomas Jefferson Lab

➢ Continuous Electron Beam Accelerator Facility:



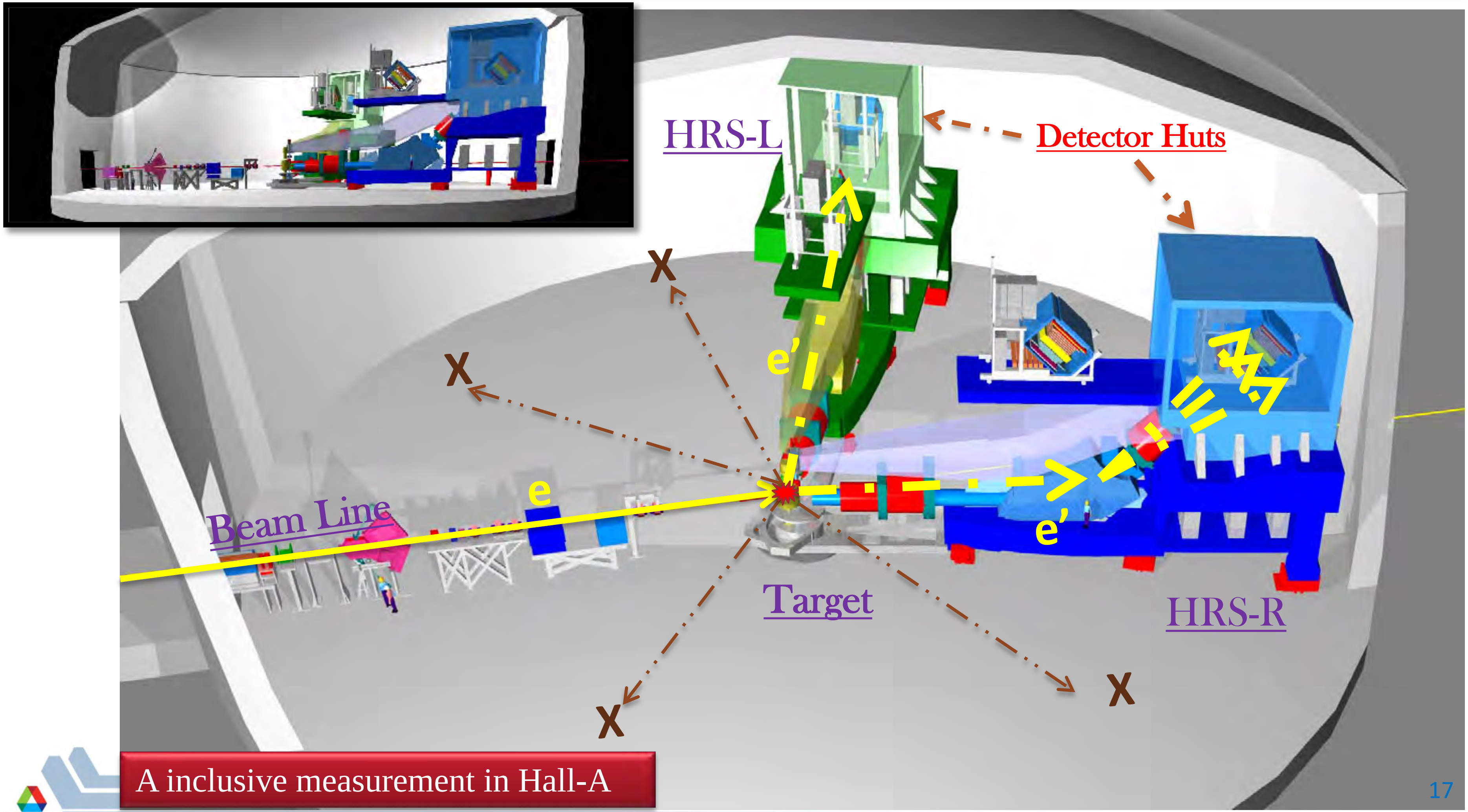
ARC

- ❖ High luminosity Electron Linear Accelerator
- ❖ Superconducting Cavity
- ❖ Longitudinal Polarization
- ❖ Continues Wave Beam Current up to 200uA to each Hall
- ❖ Radio-Frequency Technique to send beam with different energies and polarization to individual halls, simultaneously

Superconducting Radio-Frequency Cavity

High Resolution Magnetic Spectrometer

- Hall-A HRS Spectrometers:
  - ✓ A magnetic spectrometer provides precise measurements at selected (limited) kinematic phase-space
  - ✓ Mostly single purpose, i.e. one experiment is optimized to measure one type of physics
  - ✓ Can handle very high luminosity (due to small acceptance and large particle flight-length)



A inclusive measurement in Hall-A

High Resolution Magnetic Spectrometer

- Hall-A HRS Spectrometers:
  - ✓ A magnetic spectrometer provides precise measurements at selected (limited) kinematic phase-space
  - ✓ Mostly single purpose, i.e. one experiment is optimized to measure one type of physics
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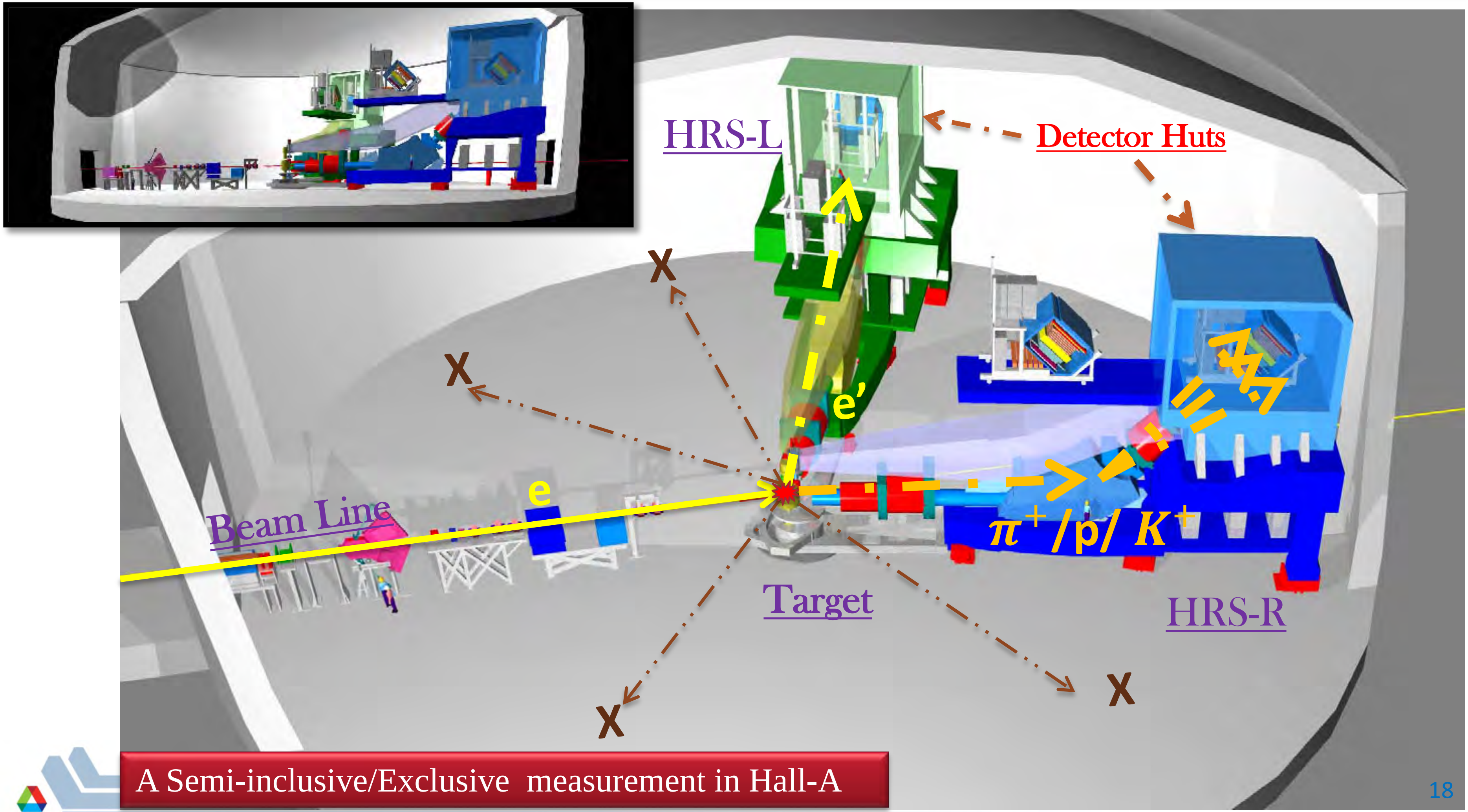
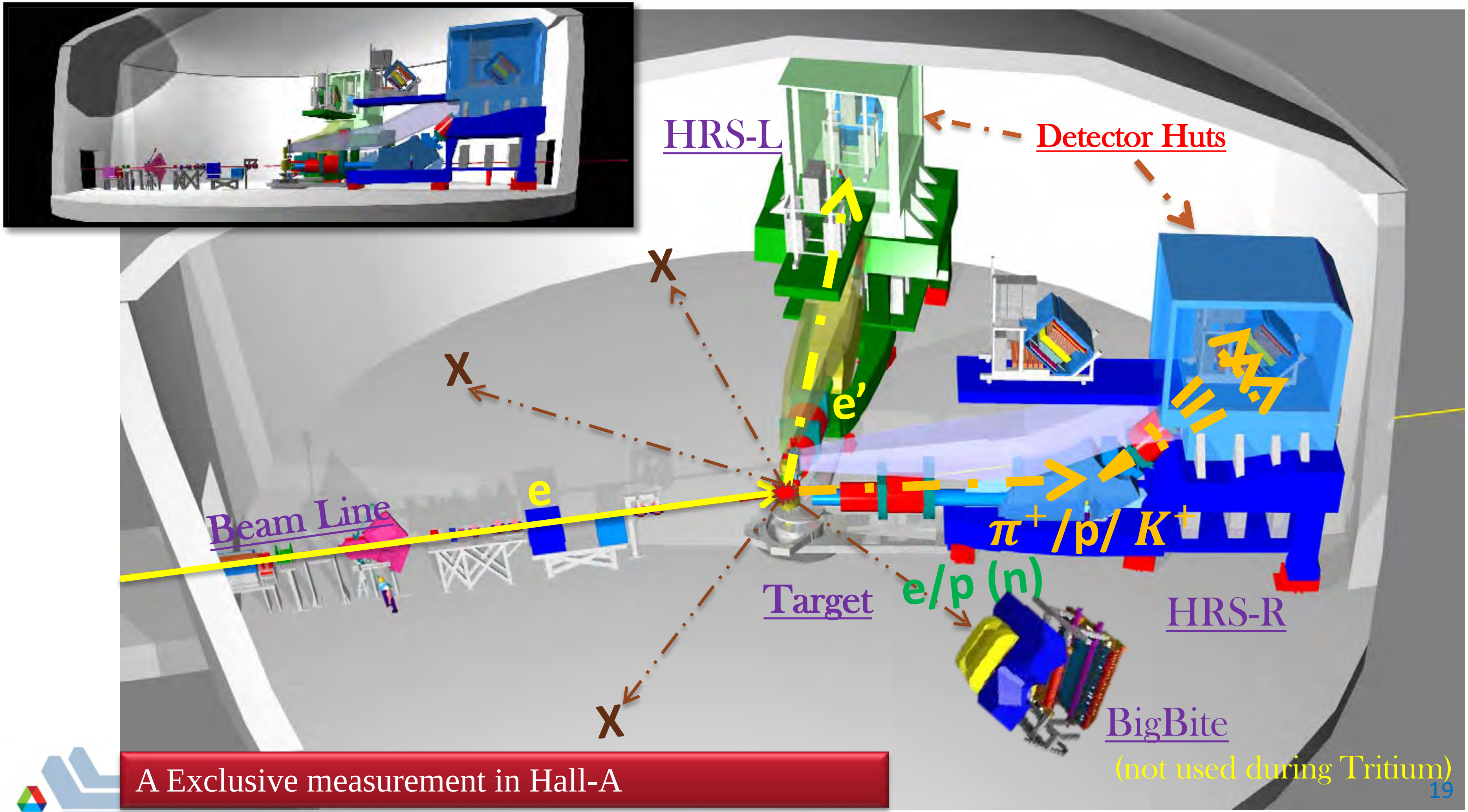


A Semi-inclusive/Exclusive measurement in Hall-A

High Resolution Magnetic Spectrometer

- Hall-A HRS Spectrometers:
  - ✓ A magnetic spectrometer provides precise measurements at selected (limited) kinematic phase-space
  - ✓ Mostly single purpose, i.e. one experiment is optimized to measure one type of physics
  - ✓ Can handle very high luminosity (due to small acceptance and large particle flight-length)

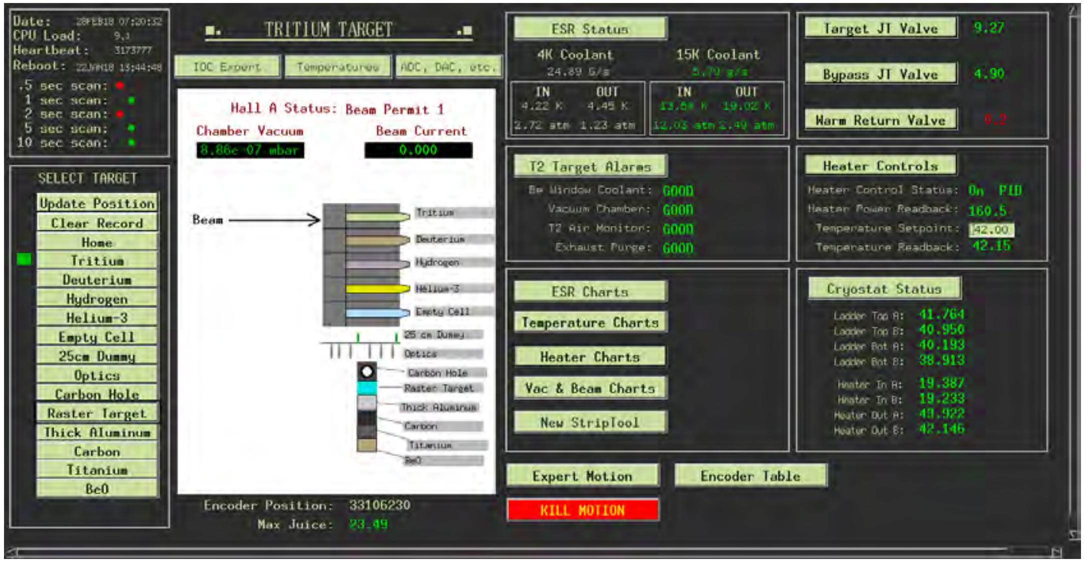


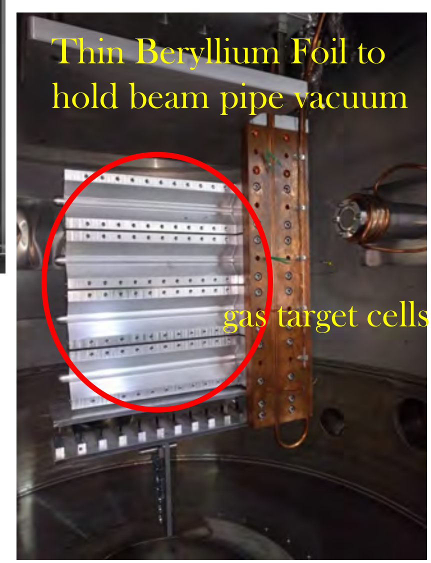
A Exclusive measurement in Hall-A

High Resolution Magnetic Spectrometer

➢ Target System:

- ❖ A vacuum chamber to house gas, liquid and solid targets
- ❖ Beam goes through the chamber (and the targets)
- ❖ Remotely change targets by moving up and down



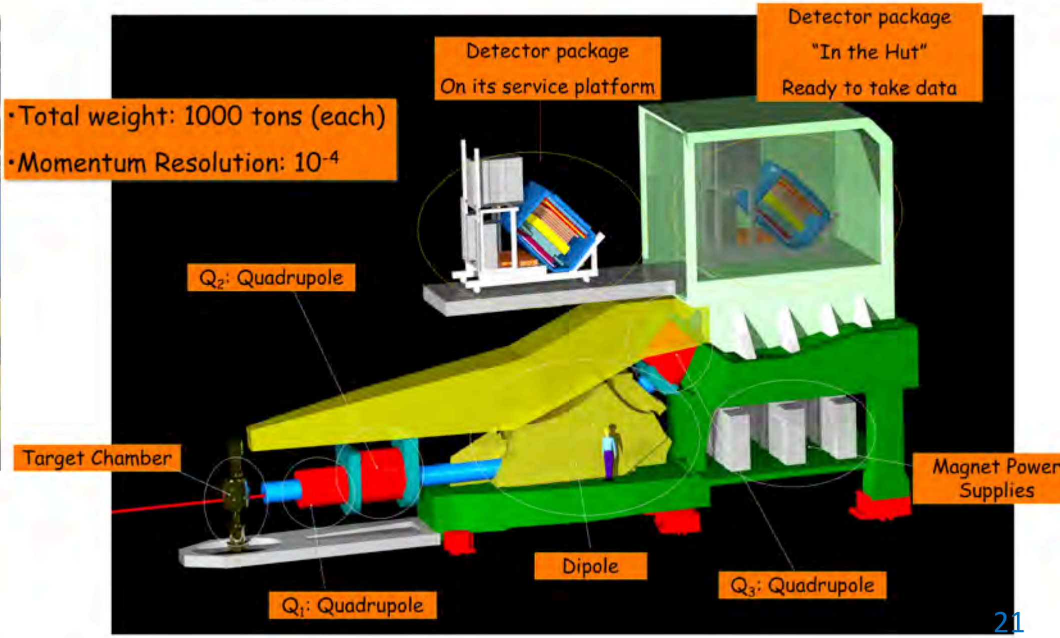


High Resolution Magnetic Spectrometer

- Hall-A HRS Spectrometers:

Hight Resolution Spectrometers

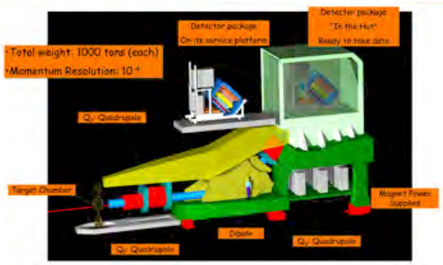
- Two identical spectrometers, HRS-L optimized for electrons and HRS-R optimized for hadrons
- Each HRS includes 3 Quadrupoles (Q) + 1 Dipole
  QQDQ setup to obtain high momentum resolution (10^{-4})
- A ~20 meter flight path allows us to precise measure the angles and positions info of charged particles
- The detector-hut is ~10 meter above the floor to avoid radiation damage and background.

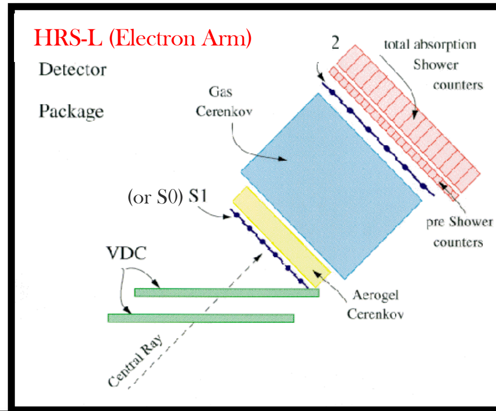


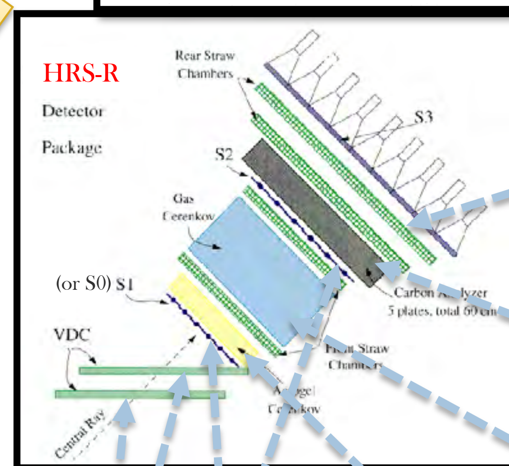
High Resolution Magnetic Spectrometer

- HRS Detectors:

  The detector hut contains a set of detectors hold in a retractable rack, protected by a thick concrete door from radiations (e.g. neutrons).







Calorimeters

Polarimetry (Proton Polarization, not in used)

Front-End Electrons + Trigger System

Positions and Angles Tracking

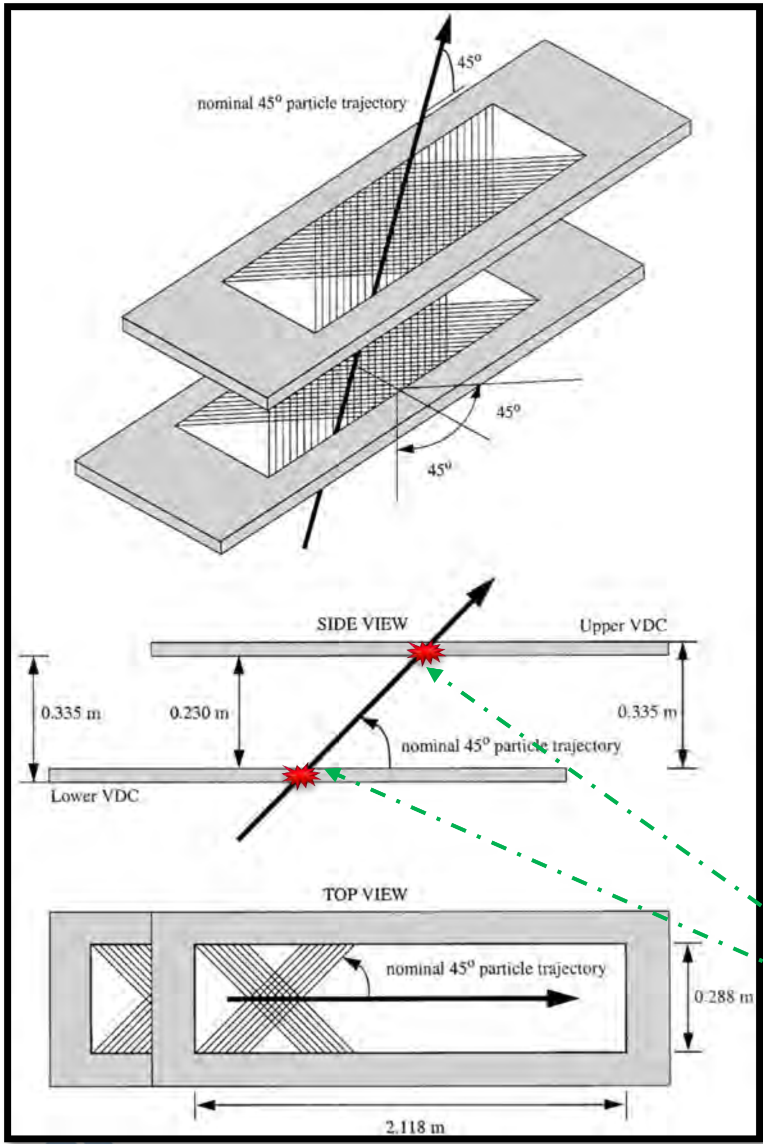
Timing

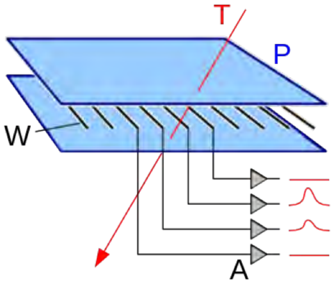
$\pi^{+/-}$ and $K^{+/-}$ Separation

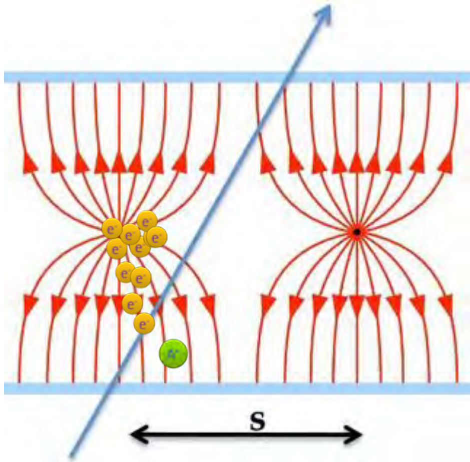
$e^{+/-}$and $\pi^{+/-}$ Separation

High Resolution Magnetic Spectrometer

➢ Vertical Drift Chambers:





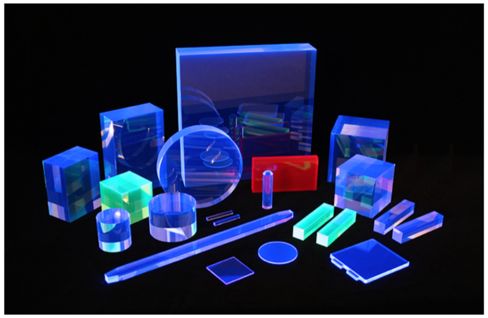


- A charged particle passing through gases can ionize gas-atom
- In a strong electric field, ionized electrons develop cascade toward the anode-wire,
- Electric-pulse is amplified, converted into digital signal and read-out by front-end electronics

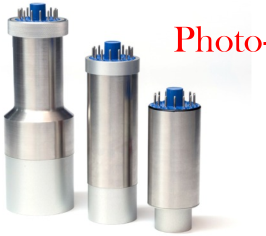
- The location of anode-wires which receive pulse signals (corrected by the drift-time) tell the location of the hit
- Each HRS VDC have to wire planes. Two VDCS give four hit positions to extract the position *(x, y)* and angle (θ, ϕ)

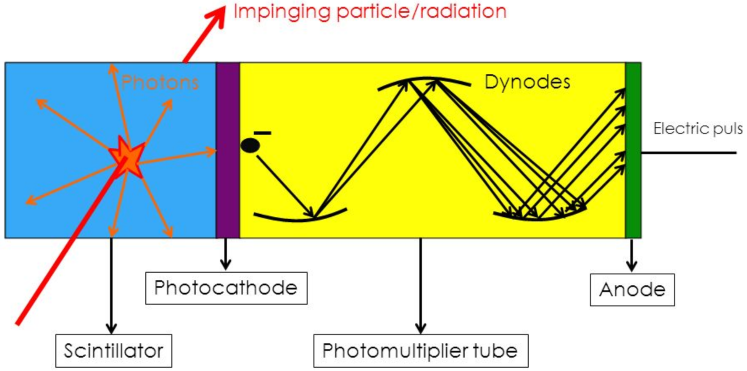
High Resolution Magnetic Spectrometer

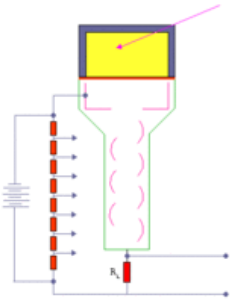
➢ (Plastic) Scintillator Counters:

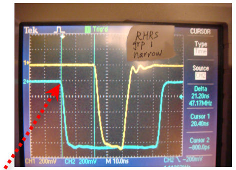


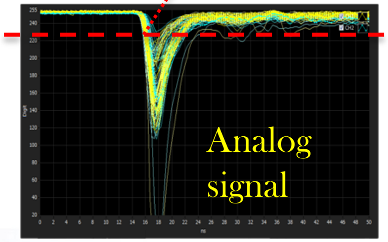
- ❖ Plastic scintillating materials are mixed with fluorescent emitter, which produces light when charged particles ions the materials.
- ❖ Light is reflected by the inner layer to the end and collected by Photon-Multiplier Tube (PMT).
- ❖ Generally have very fast arising time and short decay time (2-4 ns)
- ❖ Great application in timing measurement.
- ❖ Key components in the trigger system.









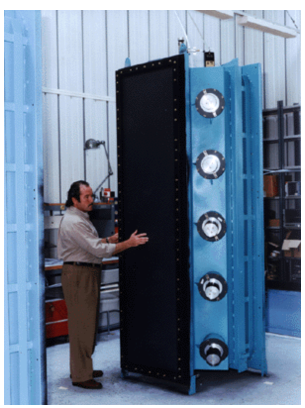


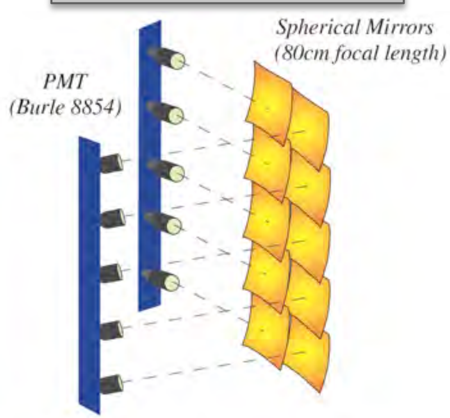
High Resolution Magnetic Spectrometer

- Gas Cherenkov Detector (GC):

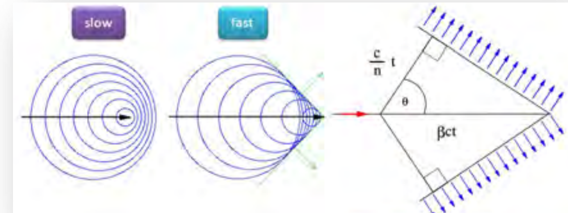
Charged Particles

Cherenkov lights are focused by mirrors and reflected to the PMT





- Charged particle radiates Cerenkov light in a medium with speed faster than that of light.
  - ✓ Gas particle are polarized and become dipoles
  - ✓ Oscillation of these dipole moments emits light

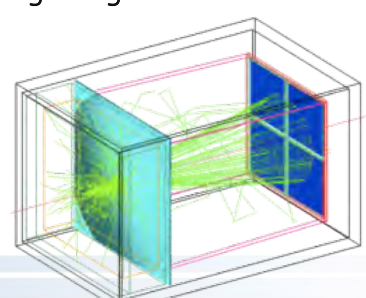


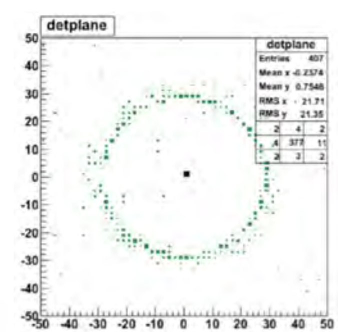
- Cherenkov radiation angle depends on the speed and the index of reflection of the medium: $cos\theta = \frac{1}{\beta n}$
- The momentum threshold for a particle to produce a Cherenkov light depends on its mass: $P_{threshold} = \frac{mc}{\sqrt{n^2 - 1}}$

Hall-A Gas Cherenkov Detector was tuned to allow electrons with 18 MeV/c to emit light, while pions requires 4.3 GeV/c

- Increasing index of reflection (i.e. materials), one can set the threshold to be between pion mass and kaon mass, such as Aerogel.
- Can be extended to a more powerful detector: RICH

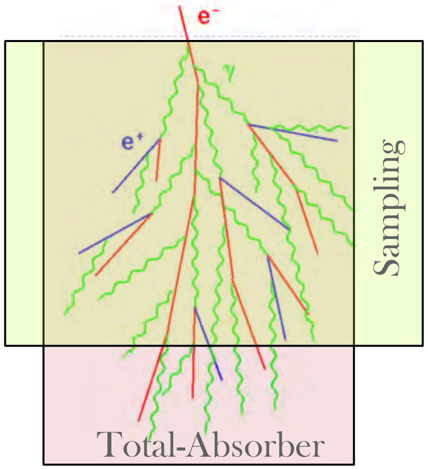
Ring Image Cherenkov Detector





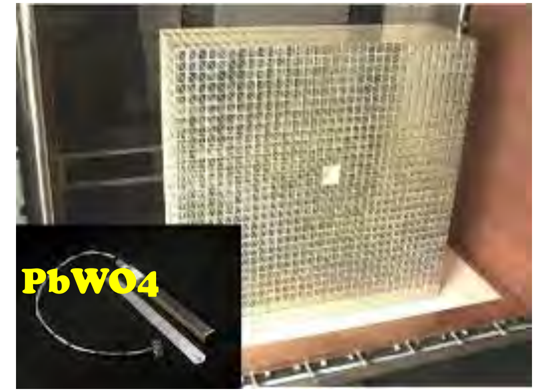
High Resolution Magnetic Spectrometer

- Electromagnetic Calorimeters (ECal):

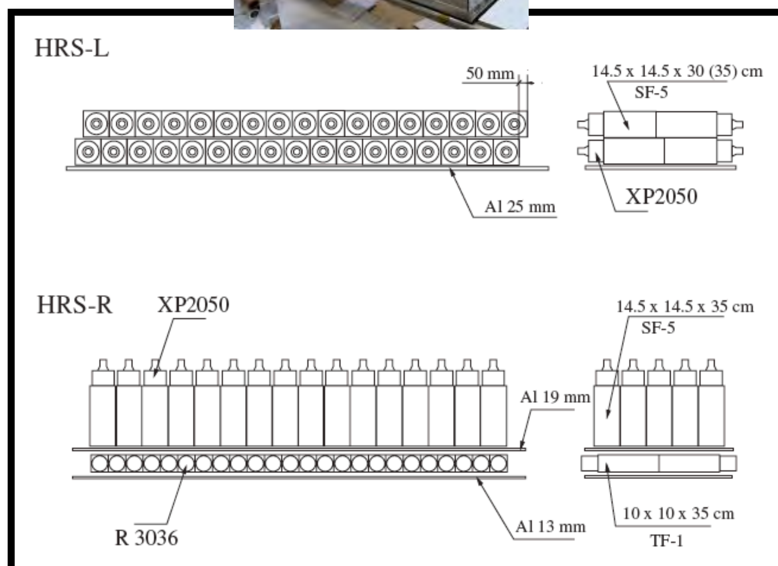


- ❖ An electron (or positron, photon) passing through a dense material deposits most of its energy via the EM cascade process.
- ❖ Hadrons require much longer radiation length to develop cascade (only deposit ionizing energy in ECal).
- ❖ Typically choose PbWO4 Crystal or Pb-Glass (transparent materials) to guide the light out to PMTs.

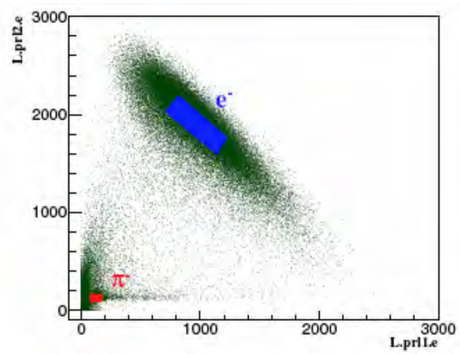
HyCal for PRAD in Hall-B



- ❖ HRS-R has a thicker (longer radiation length) ECal, called Showers, which is a Total-Absorber (i.e. an electron's energy is totally deposited inside the ECal and it stops
- ❖ HRS-L has a thinker ECal, called Pion-Rejectors, which is a Sampling-ECal (some electrons escape)
- ❖ Each ECal contains two layers (PreShower+Shower, Pion-Rejection 1 and 2), to perform e/pi separation.



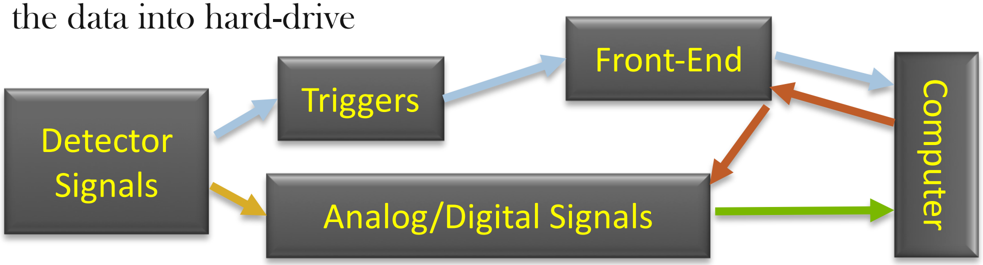
Pions most likely develop their energy only via ionization in the first layer;



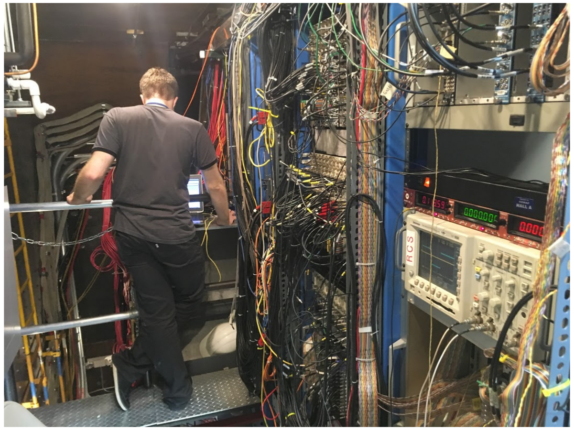
Electrons are more easily develop EM cascade even in the first layer

High Resolution Magnetic Spectrometer

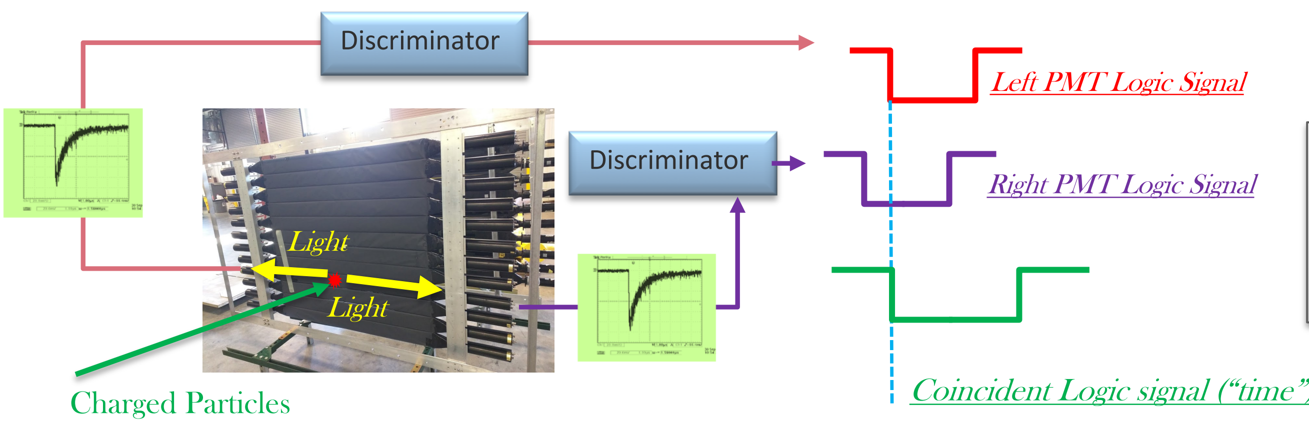
- Data Acquisition System and Triggers:
  - ❖ A Data-Acquisition System includes:
    - Front-end electronic modules to read and process signals from detectors (e.g., analog signals from PMTs)
    - A Computer which communicate with the front–end modules and save the data into hard-drive



Front-End Electronics in the HRS Detector Hut



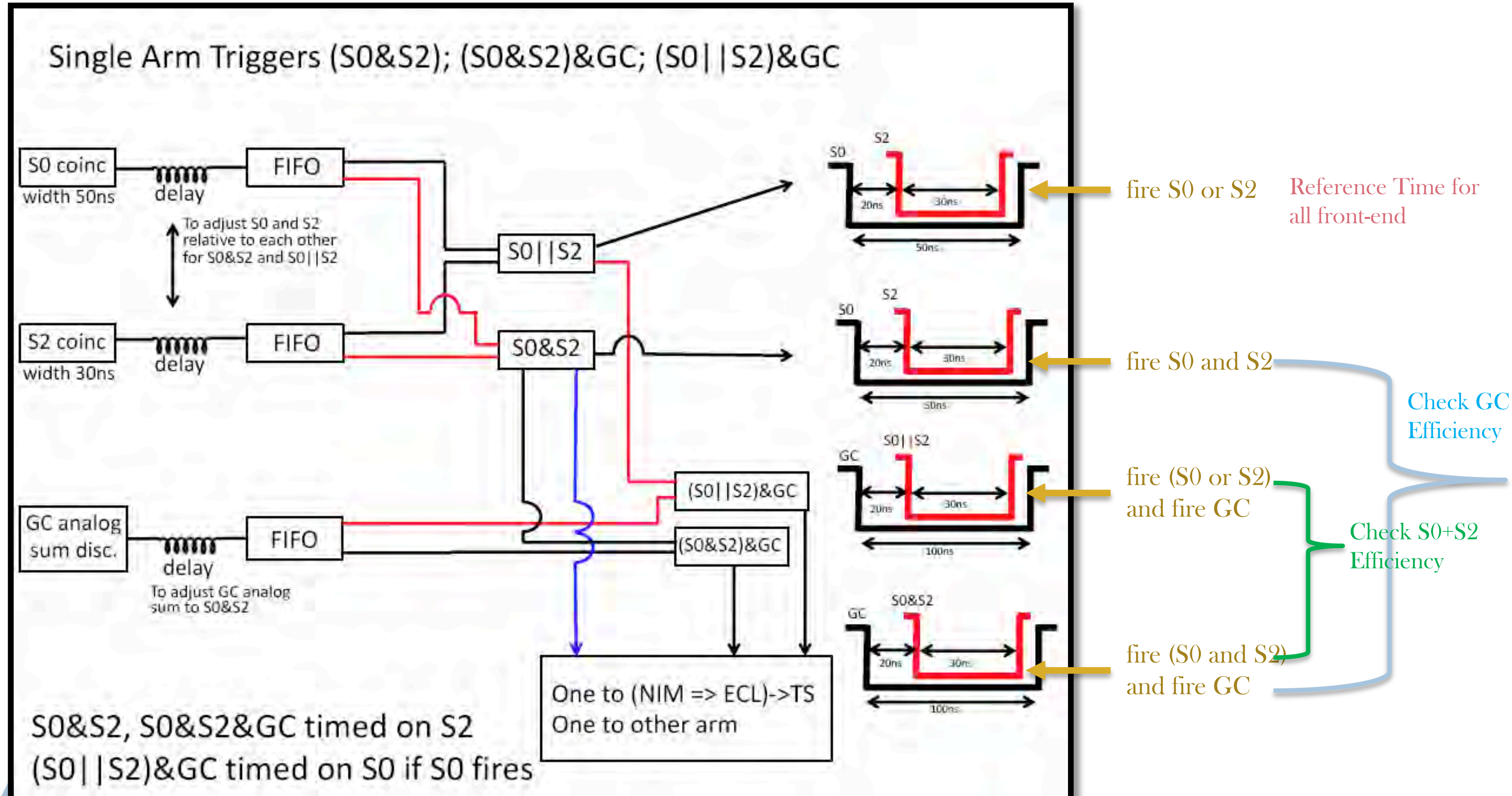
- ❖ A trigger is a digital signal to tell DAQ system when to record signals coming from detectors and elsewhere (e.g., target info, beam info, spectrometer info, etc.)
- ❖ Designing a trigger for a dedicated experiment is very essential and also complicated.
- ❖ On HRS, we heavily reply on two Scintillator counter planes (which have very good time response for charged particles). How we determine a particle hit a detector plane ("trigger")?



Note: delay time due to different cable lengths should be considered

Charged Hadrons Interacting with Matters

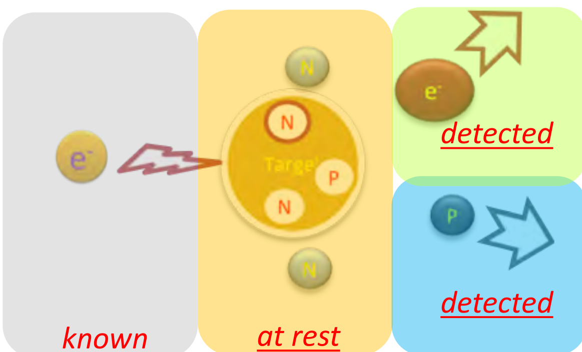
- Data Acquisition and Triggers:
  - To reject background particles, we use at lease two detector planes to form a trigger
  - To reject pions and only keep electrons, we add the Gas-Cherenkov into the trigger as well
  - We design different trigger types for multiple purpose (e.g., evaluate the efficiencies of the detectors)



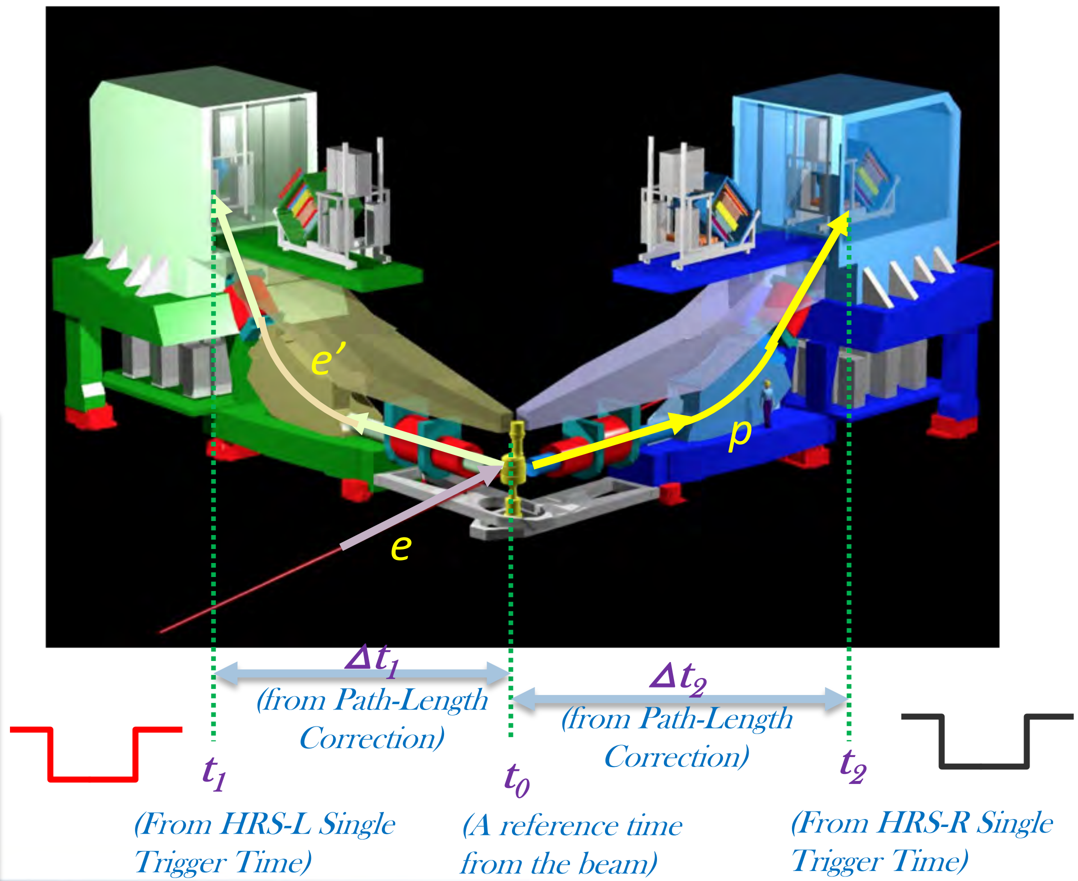
High Resolution Magnetic Spectrometer

- A coincidence experiments (e.g., e + H3 → e' + p + n +n):
  - In a coincidence experiment, we need to determine two or more particles coming from the same reaction in the target region
  - The reaction time can be from the beam RF time (i.e. when the beam-electron was sent to Hall-A)
  - The target region to the detector region has a ("roughly") fixed path length; Hence fixed travel-time for known particles

Electron beam does come continuously, but in every 2 ns (1/RF)

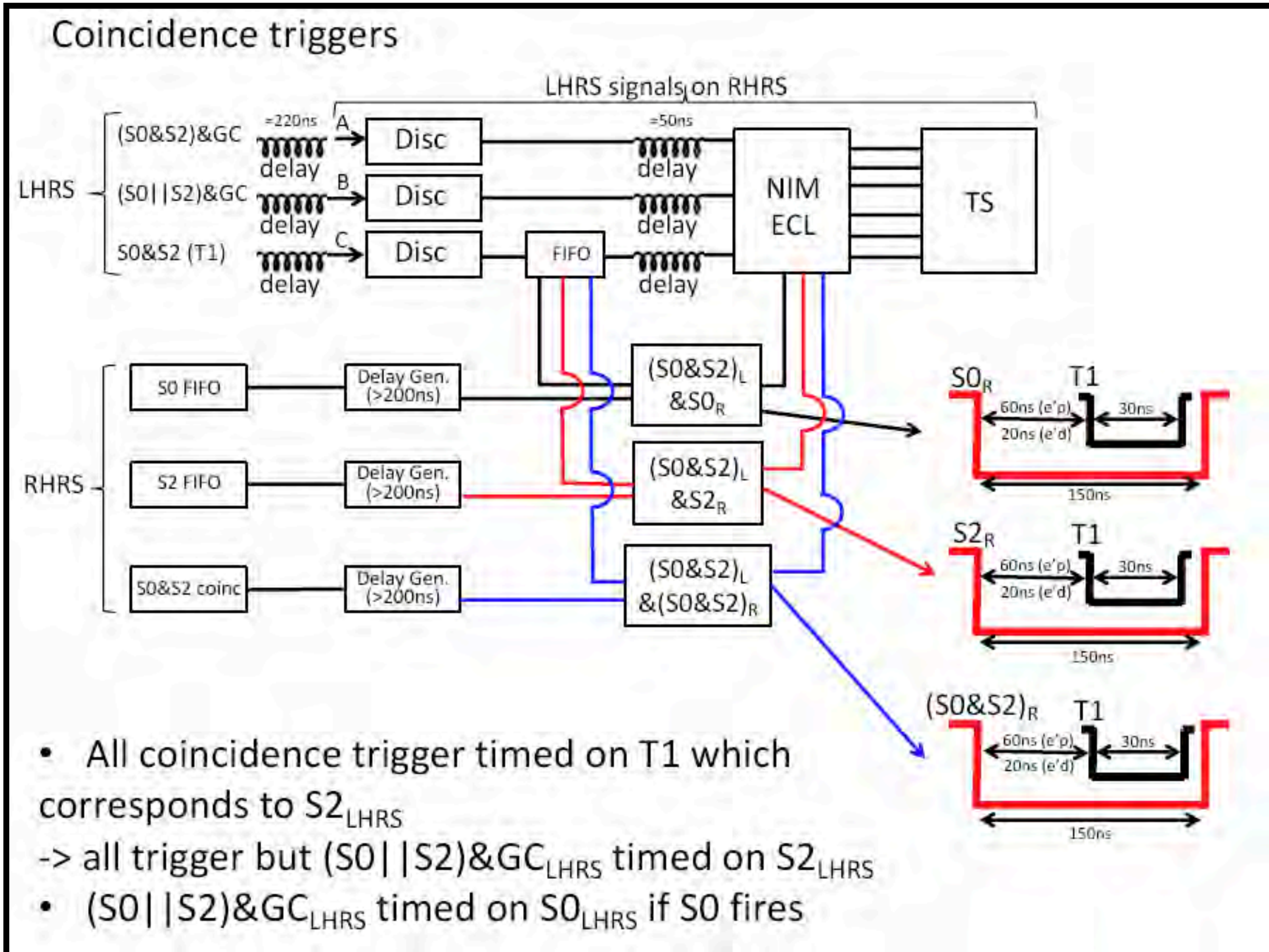


Note:
- Times are all relevant (not absolute)
- Required to reference to a common time(normally use HRS-L trigger time as the reference ($\Delta t_1 = 0$)
- HRSs have set central momenta; hence set central velocities; hence roughly know travel-time for known particle
- Cable lengths (between HRS-L and HRS-R) have to be calculated correctly



High Resolution Magnetic Spectrometer

- Triggers for a Coincidence Experiment:



High Resolution Magnetic Spectrometer

➢ Control Room (Counting House):

When the experiment runs, it is 24/7 for weeks or months

❖ Shift-workers (8 hrs shift) are:
- Execute run-plans
- Monitoring status of all instrumentation
- Running DAQ to take data
- Analyzing data to check quality and find issues
- Make changes (spectrometer settings, targets, beam, etc.)
- Communicating with Accelerator Machine Control Center
- Log all activities and Report issues to experts

❖ Experts (mainly PHD students) are in the back room :
- Assisting shift-works;
- Perform more sophisticated analysis
- Fixed issues or work with JLab scientists to fix issues.

❖ Other folks:
- Spokespeople and lab managements are working together to design run-plane, define actitivies;
- Run-Coordinator communicate among spokespeople and different division; Make sure run-plans are well executed
- Support groups (beam-line, target, electric engineer, radiation-control, etc...)

Electron Scattering Experiments, Data-Analysis and Monte-Carlo Simulation

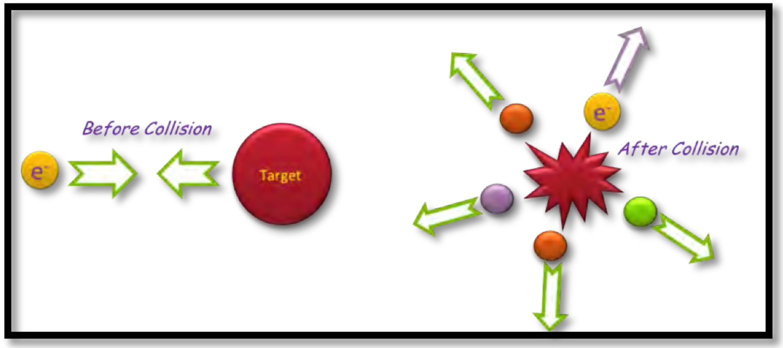
Section 2

Zhihong Ye (叶志鸿)
Medium Energy Group, Physics Division,
Argonne National Lab
07/24/2018

Pre-School, Hadron Workshop, 2018, Weihai, Shandong

Fixed Target Experiments:

General Purpose 4π Detector Systems



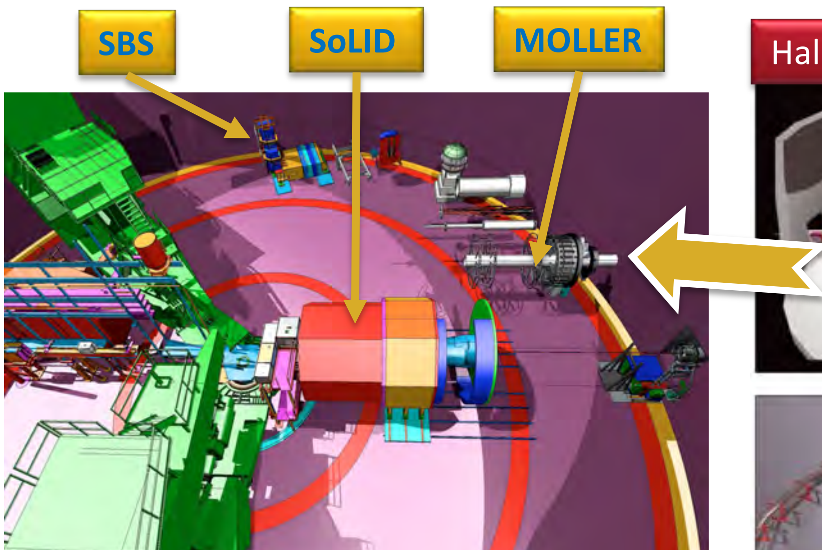
Center of Mass Frame

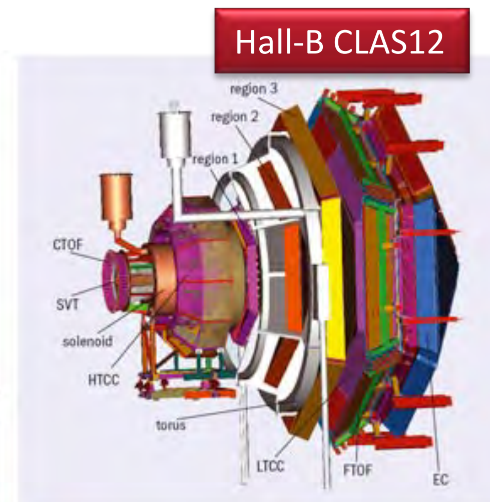
Lab Frame

General Purpose 4π Detector Systems

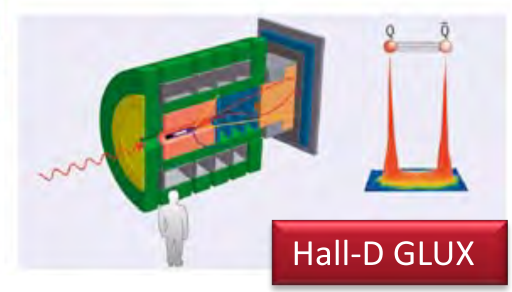
➢ Four Experimental Halls:

- ❖ Hall-A: HRS, then Super-BigBite Spectrometer (SBS), then MOLLER are for dedicated purpose experiments
- ❖ Hall-B: CLAS12 is a multiple purpose 4 π detector (low luminosity, large acceptance, limited resolution)
- ❖ Hall-C: HMS and Super-HMS are high-luminosity, limited acceptance, for precision measurement at limited region.
- ❖ Hall-D: GLUX detector system is for real-photon production experiment to search exotic gluon states



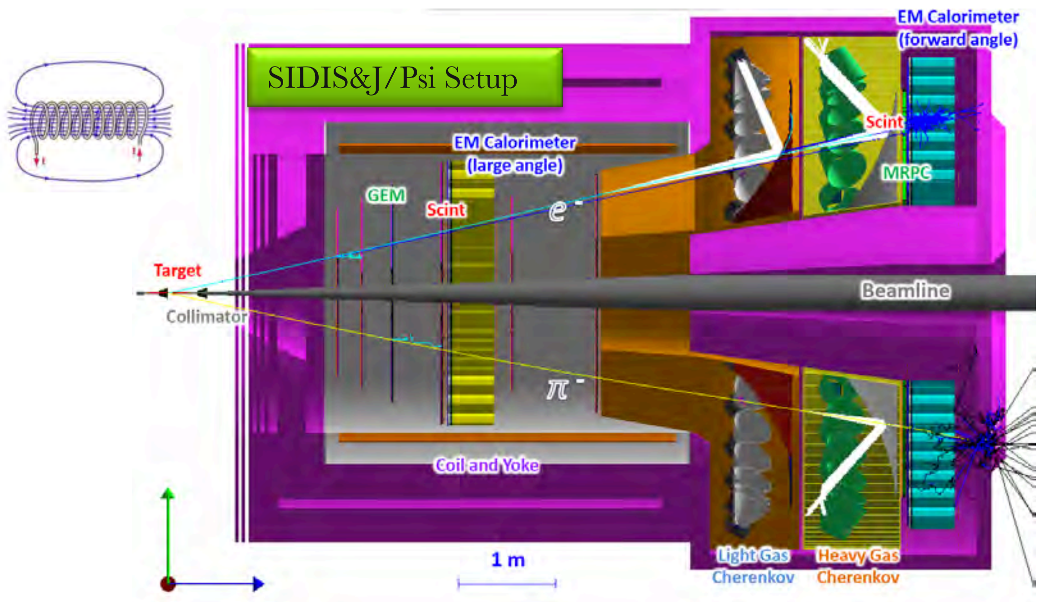


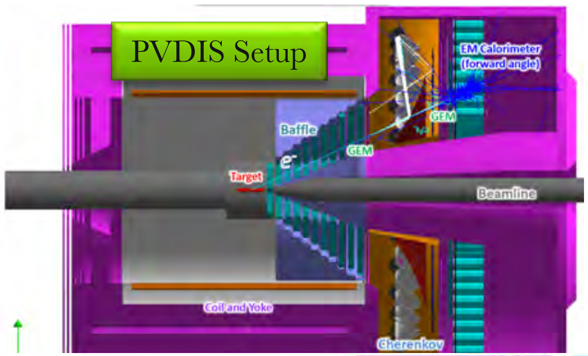
Hall-A is going to build an advanced Detector System, ***SoLID***, which will have both high-luminosity and large acceptance for general purpose experiments.

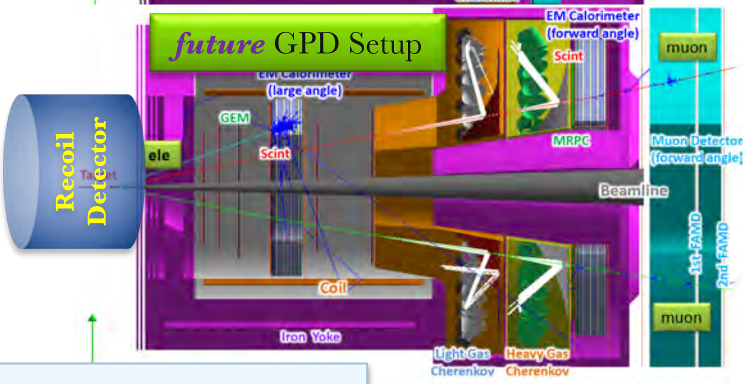


General Purpose 4π Detector Systems - SoLID

- **So**lenoidal **L**arge **I**ntensity **D**evice (SoLID) in Hall-A:







One Inclusive PVDIS experiment (PDF, new physics):

- E12-10-007, Parity Violation Deep Inelastic Scattering, 90 days

Four SIDIS experiments (TMD):

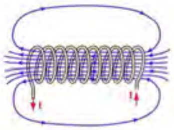
- E12-10-006, Pion SIDIS with Transversely Polarized He3, 90 days
- E12-11-007, Pion SIDIS with Longitudinally Polarized He3, 35 days
- E12-11-108, Pion SIDIS with Transversely and Longitudinally Polarized Proton, 120 days
- E12-11-108A/E12-10-006B, Kaon SIDIS with Polarized Proton and Neutron , in parallel
- E12-10-006A, Pion Dihadron-Production in SIDIS with Polarized He3 , in parallel

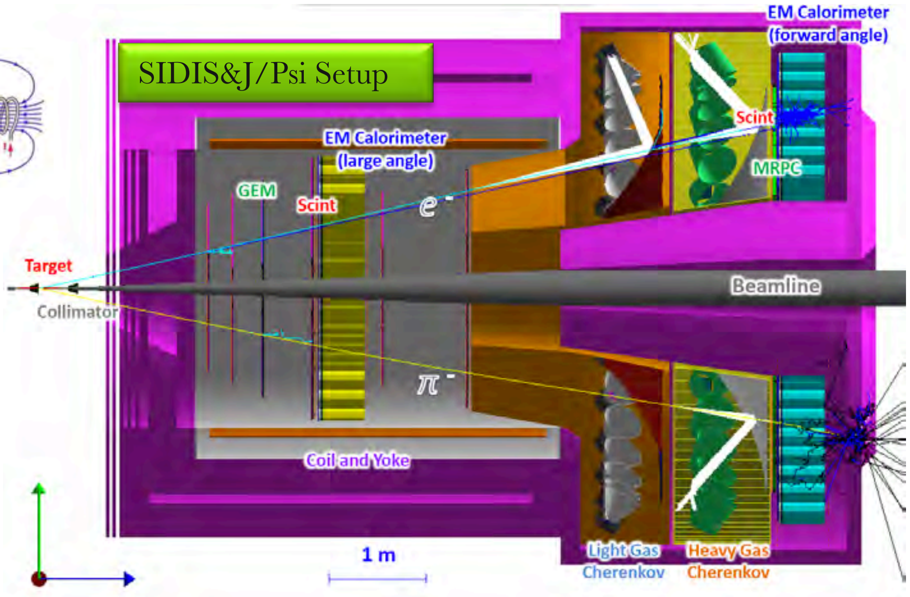
Three Exclusive experiments (proton-mass, GPD):

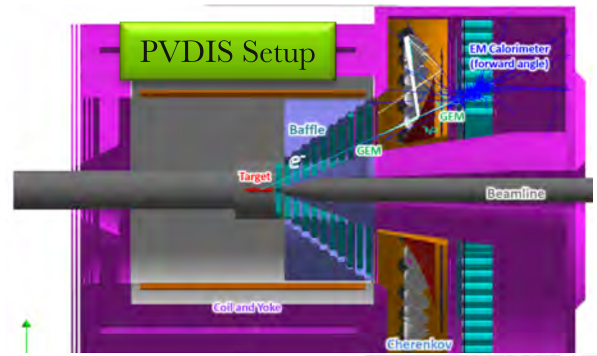
- E12xxxxxxxxx, J/Psi Production near Threshold with unpolarized proton target, 60 days
- E12-------B, Time-like Compton Scattering with unpolarized proton target, in parallel
- E12-10-006B, Pi- Production Deep Exclusive Meson Production with polarized He3 , in parallel

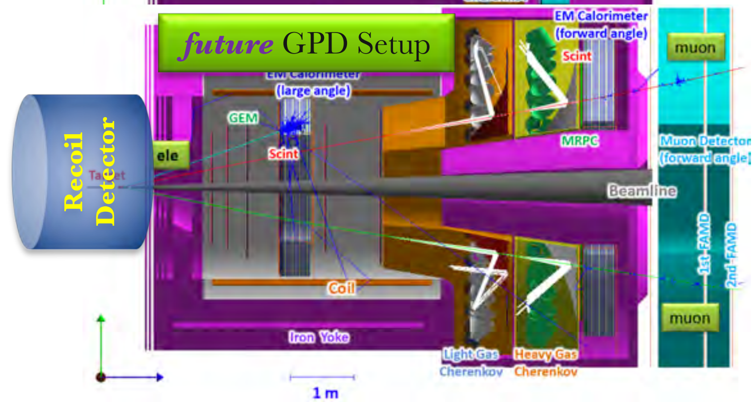
General Purpose 4π Detector Systems - SoLID

- Solenoidal Large Intensity Device (SoLID) in Hall-A:







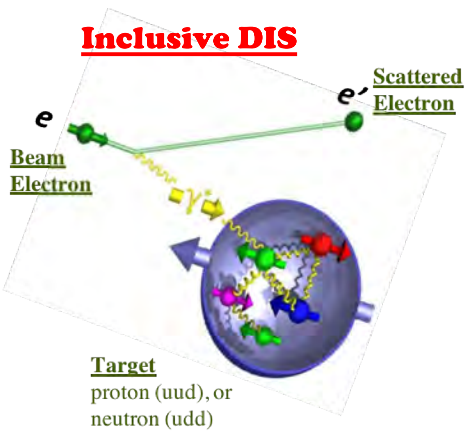


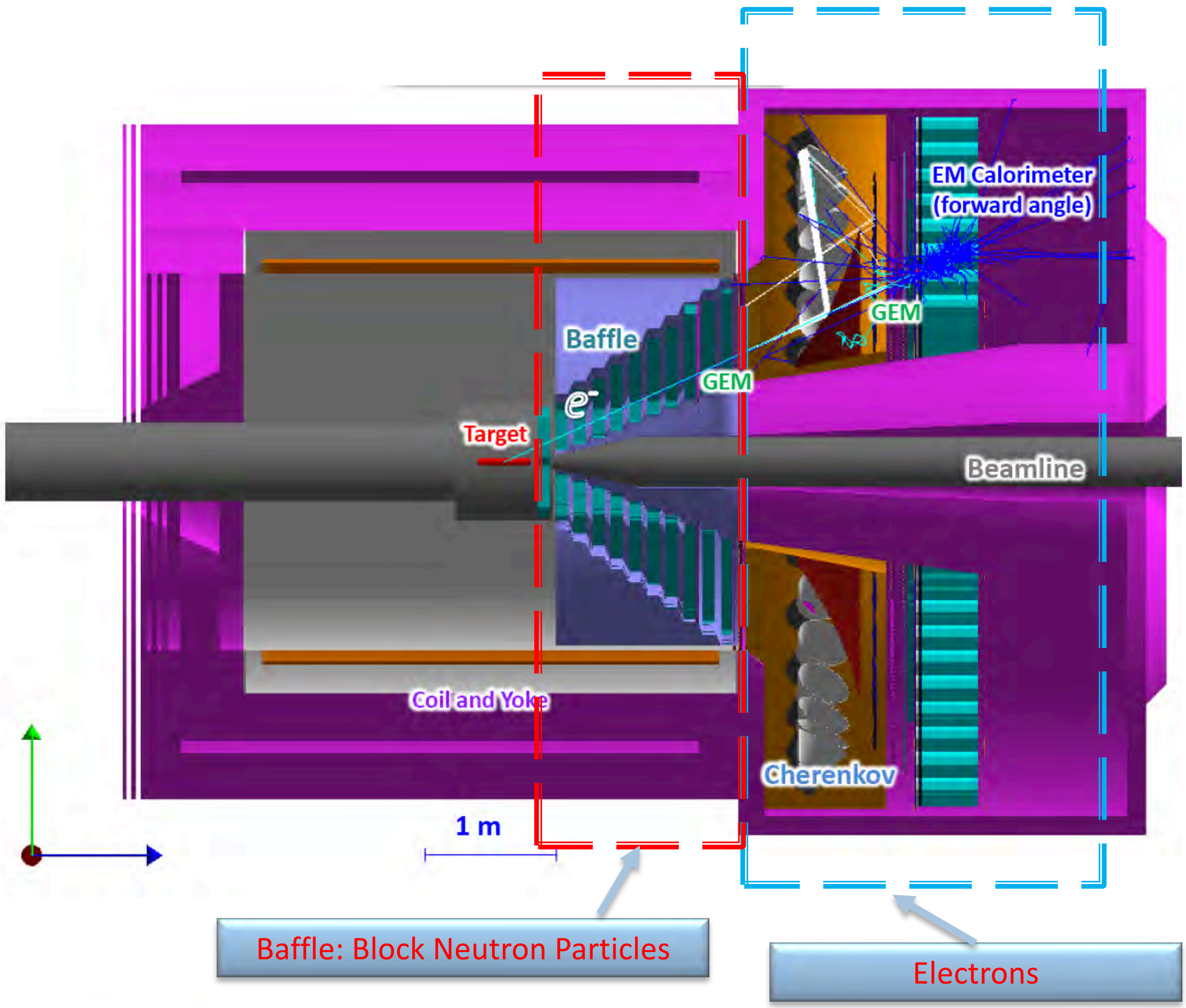
Status:

- ✓ Three Original Physics Programs→ SIDIS, J/Psi and PVDIS; + newly developed GPD
- ✓ On December 2014, pre-Conceptual Design was submitted;
- ✓ On March 2015, Passed the JLab Director's Review on;
- ✓ In 2016, CLEO Solenoidal Magnet was transported from Cornell University to JLab;
- ✓ In 2017, Sent Conceptual Design and R&D Plan to Department of Energy;
- ✓ In 2018, to request to DOE Science Review; Project starts (Critical Decision Stage 0, CD0);
- ✓ In 2019 or 2010, to request to DOE for Critical Decision Stage 1 (CD1); Project officially starts;
- ✓ Significant contributions from Chinese collaborators.

General Purpose 4π Detector Systems - SoLID

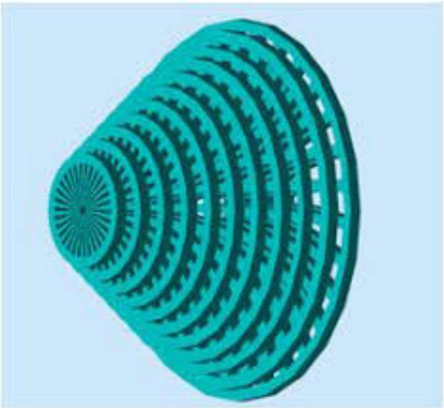
- SoLID PVDIS Setup (inclusive DIS with polarized beam):





General Purpose 4π Detector Systems - SoLID

- Baffle Collimator:



Goals:

→ For PVDIS only

→ 11 layers of 9cm thick lead and one layer of 5cm lead

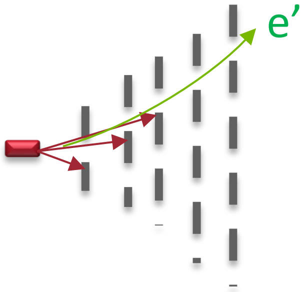
→ Right after the target, to block neutral particles and secondary low-energy particles.

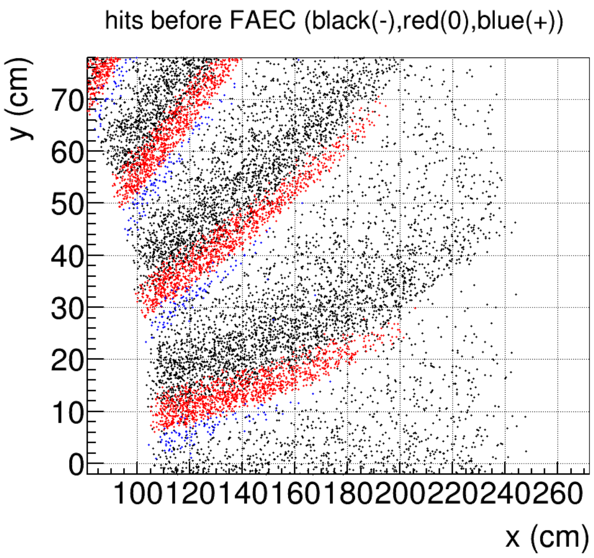
→ Follow charge particle bending in the field, preserve the same azimuthal slice and block line of sight.

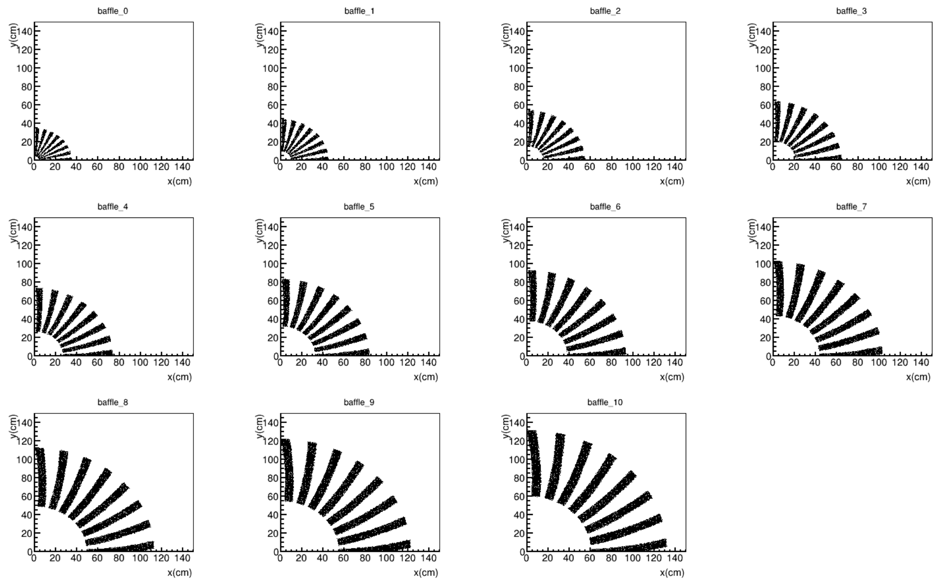
✓ During the experiment, dominate particles are low energy charged particles from secondary scattering, as well as photons.

✓ Neutral particle (photons) and low energy charged particles are mostly blocked by any layers of baffle;

✓ ~50% of high energy electrons can pass all layers





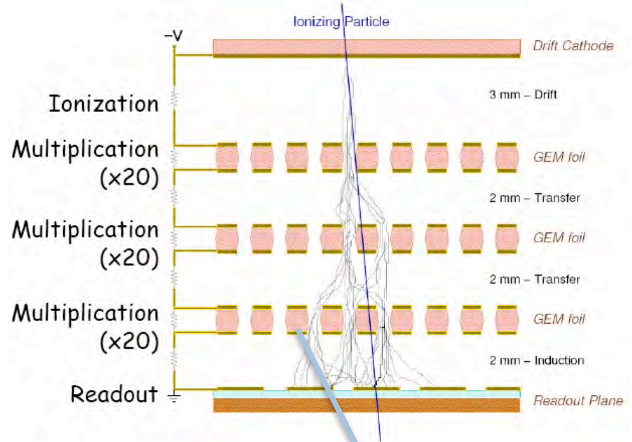


General Purpose 4π Detector Systems - SoLID

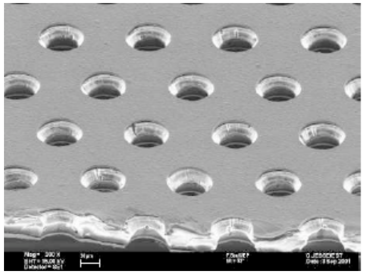
- Gas Electric Multiplier (GEM):

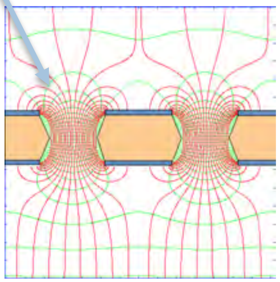
- ✓ Can handle very high rate (50MHz per mm^2)
- ✓ Can also work in a high magnetic field

- ❖ Strong electric field inside the holes
- ❖ Charged particles ionize atoms
- ❖ Drifting electrons are amplified during cascade
- ❖ Signals are read out in the back panel



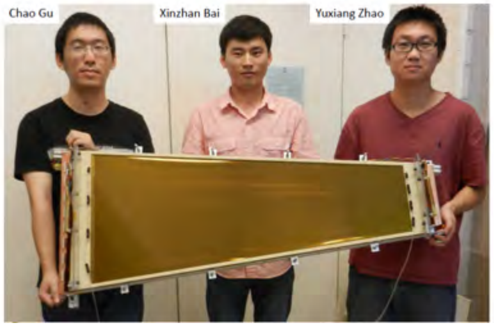
- ❖ GEM foil: 50 mm Kapton + few mm copper on both sides with 70 mm holes, 140 mm pitch

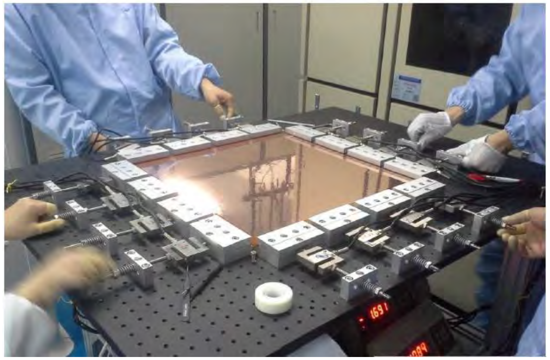




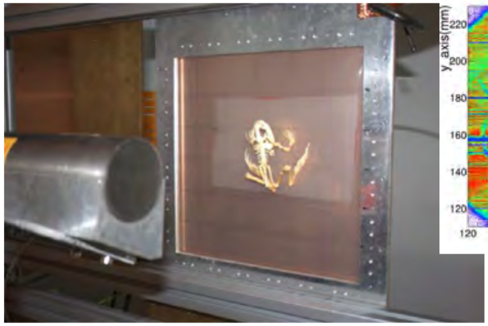
- ❖ Easily built into different shapes based detector geometry

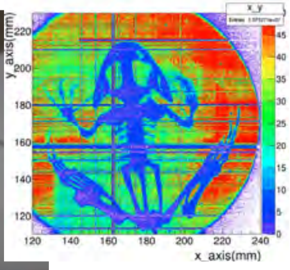
The "real" SoLID-GEM Chinese collaboration





- ❖ Provide good position resolution (80um)



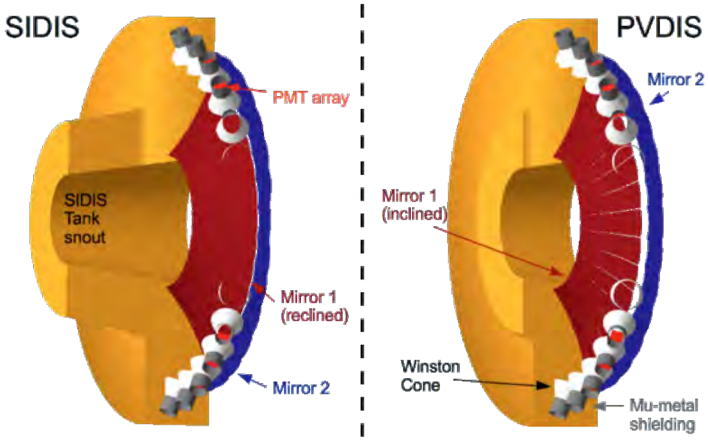


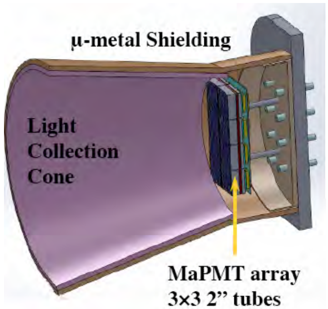
General Purpose 4π Detector Systems - SoLID

- Gas Cherenkov Detectors:

Light Gas Chernekov (LGC) Detector:

→2 m CO_2 (SIDIS/Jpsi), 1 atm
→1 m C_4F_8O (65%)+N_2 (35%) (PVDIS), 1 atm
→30 sectors, 60 mirrors, 270 PMTs, Area~20m²
→N.P.E>10, electron detection efficency>90%,
→π suppresion > 500:1
→Work at 200G field (100G after shielding)



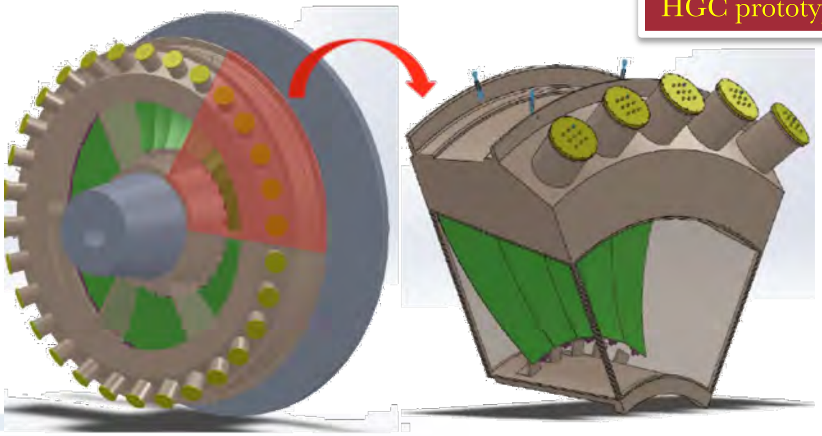


"Bazooka" LGC prototype

HGC prototype

Heavy Gas Cherenkov (HGC) Detector:

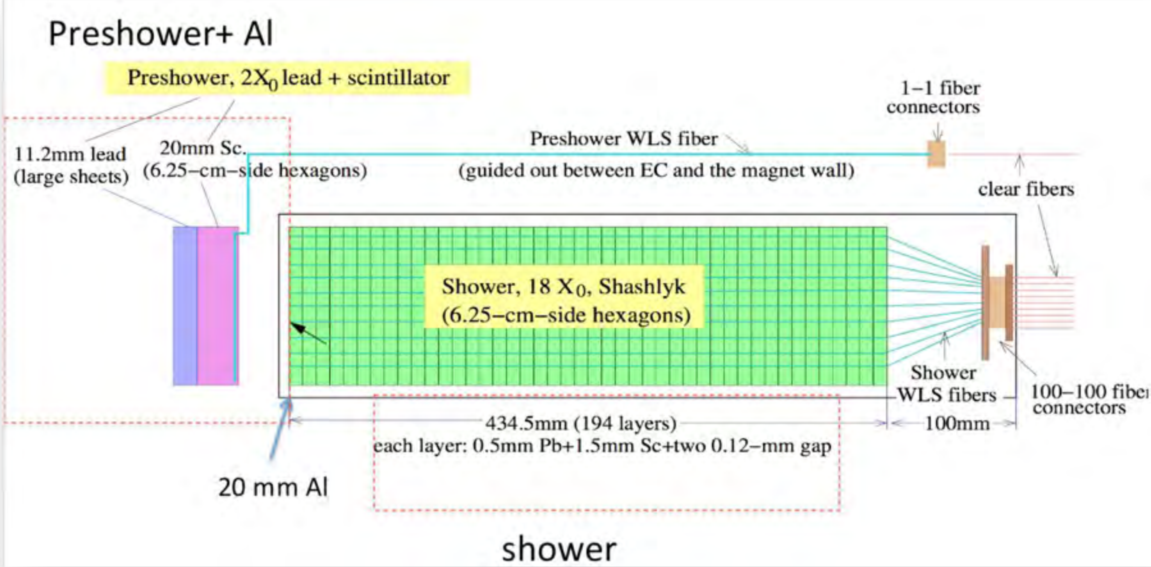
→for SIDIS only
→1 m C_4F_8O at 1.5 atm
→30 mirrors, 480 PMTs, area~20 m²
→N.P.E>10, pion detection efficiency>90%
→Kaon suppresion > 10:1,
→Work at 200G field (100G after shielding)

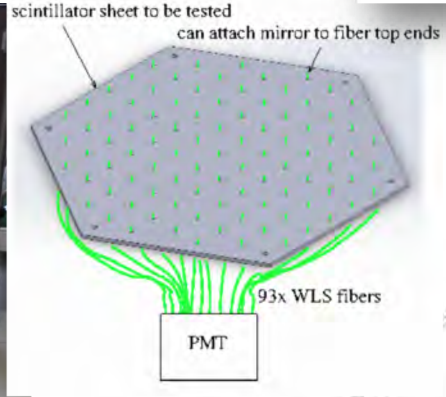


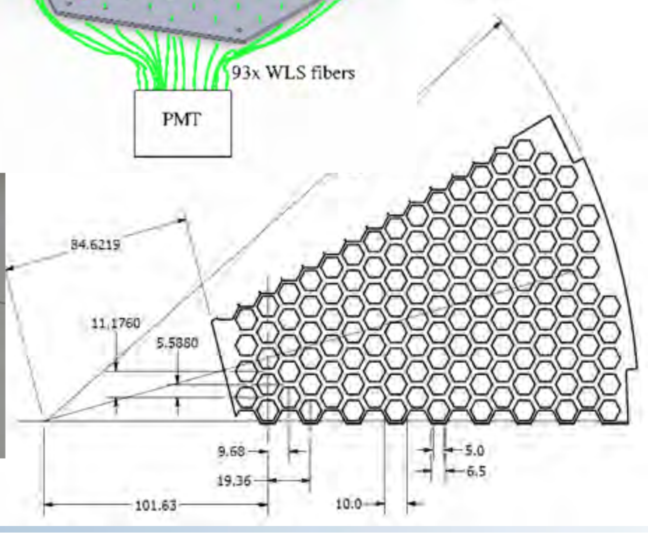
General Purpose 4π Detector Systems - SoLID

➢ **Shashlyk Electromagnetic Calorimeters:**

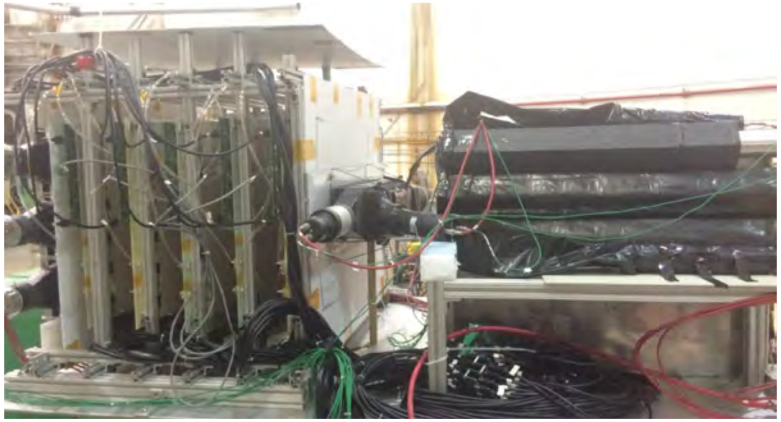
- Sandwich layers of Lead-plates and Scintillator-plates
- Lights are guided out by clear fibers to PMTs
- A sampling ECal
- Also have two-layers to perform e/pi separation
- A hexagon shape ECal for SoLID to match the geometry



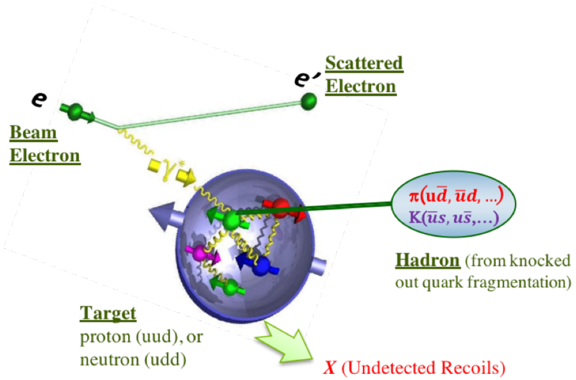


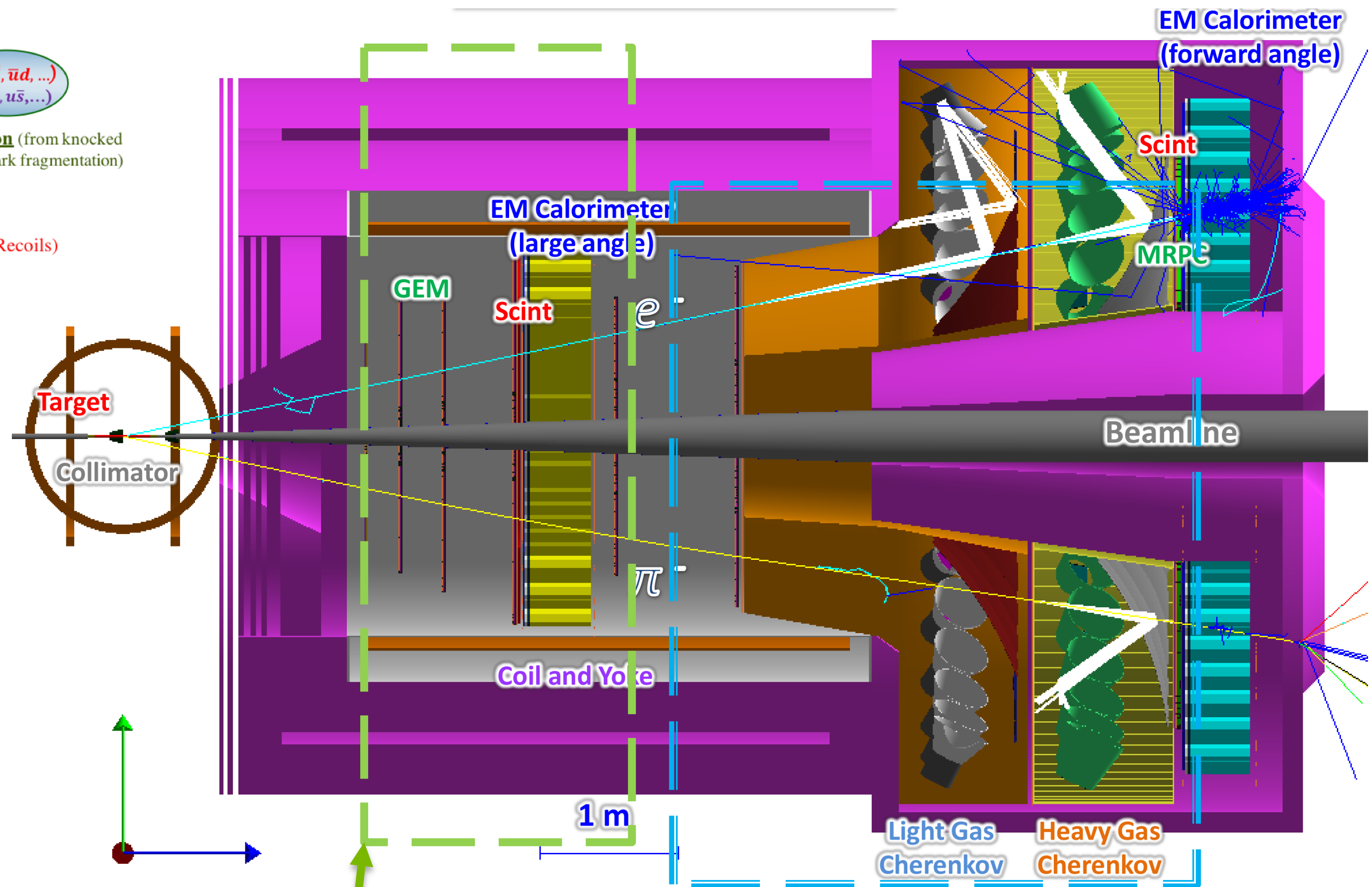


- Shandong University and Tsinghua University have built three modules to be tested at JLab



General Purpose 4π Detector Systems - SoLID





Detect Electrons

Detect Electrons, Pions and Kaons

SoLID Overview

Polarized He3 Targets
"neutron"

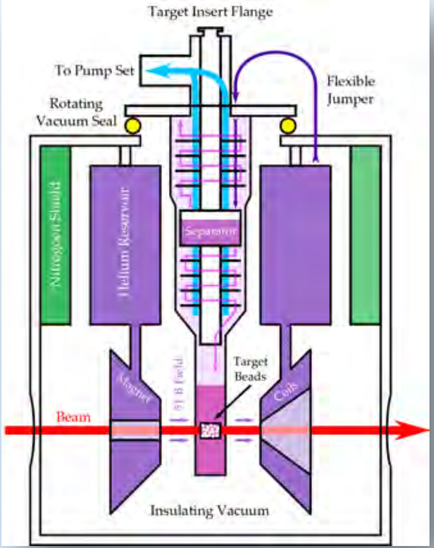
Specification

- ✓ System Size: R=1.83m(outer)
- ✓ Operation Field: 25~30 Gaus
- ✓ Target Length: 40 cm
- ✓ Target Lumi: 10^{36} cm^{-2} s^{-1}
- ✓ Maximum Pol: >70%
- ✓ Pol in Beam: ~60% @ 15uA
- ✓ Dilution: 0.3

- Built in 1998 @ Jlab
- Used by 13 experiments in 6GeV Era
- To be used by >7 approved 12GeV experiments
- Aim to increase the efficiency of flipping polarization.
- Both longitudinally and transversely polarized

http://hallaweb.jlab.org/equipment/targets/polhe3/polhe3_tgt.html

Polarized NH3 Targets
"proton"



Specification

- ✓ System Size: 1.2m(W) x2m(H)
- ✓ Maximum Field: 5 Tesla
- ✓ Target Length: ~3 cm
- ✓ Target Lumi: 10^{35} cm^{-2} s^{-1}
- ✓ Maximum Pol: >90%
- ✓ Pol in Beam: 70%
- ✓ Dilution: ~0.13
- ✓ Operation Temp: 1K

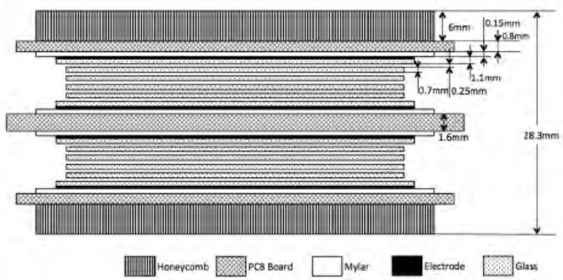
- Many years of developments and application
- The major polarized proton target at JLab
- Used by SLAC E143/E155, and many experiments in Hall-A/B/C at JLab
- Current opening angle for outgoing particles is +/- 17^{o}, and will be +/-25^{o} with new coils

https://userweb.jlab.org/%7Eckeith/Frozen/Frozen.html
http://twist.phys.virginia.edu/

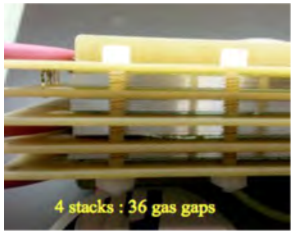
General Purpose 4π Detector Systems - SoLID

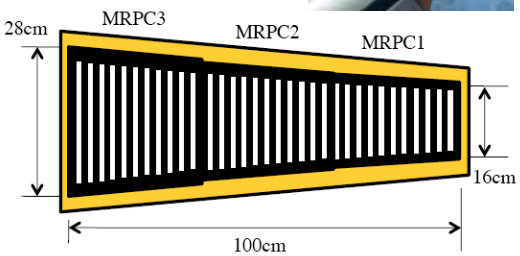
➢ Multi-gaps Resistant Plate Chamber(MRPC):

(a) The layout of the MRPC

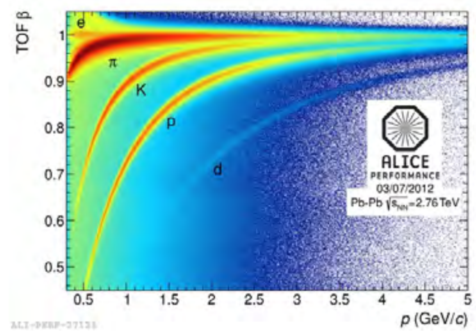


(b) The structure of the MRPC prototype





- The SoLID TOF detector is the MRPC (50 super-modules w/ 3MRPC modules for each super-module)
- Each MRPC contains 10 gas gaps (0.25mm each gas layer + 0.7mm each glass)
- Maximum rate capability – 50 KHz/cm^2.

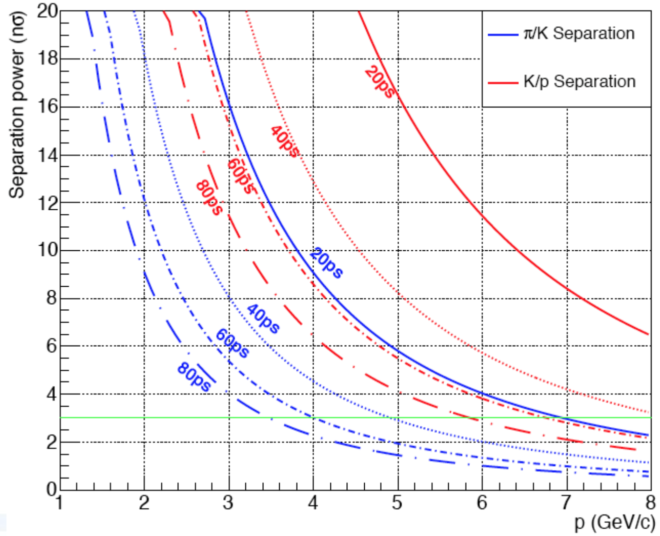


- MRPC is the key detector in the SoLID trigger system.
- The TOF-Beta has been a powerful quantities to perform PID:

$$\beta = \frac{p}{\sqrt{p^2 + m^2c^2}}$$

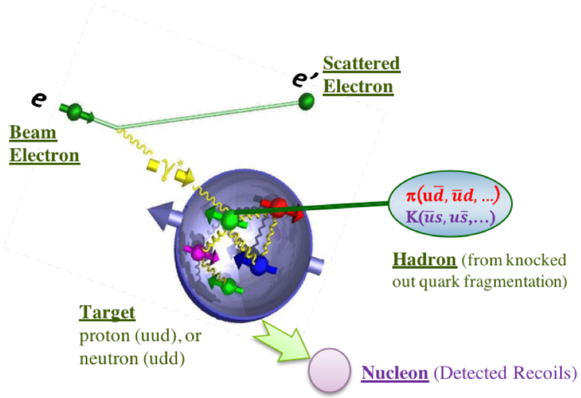
- Particles with same momenta but different masses spend different amount of time when travelling the same distance:

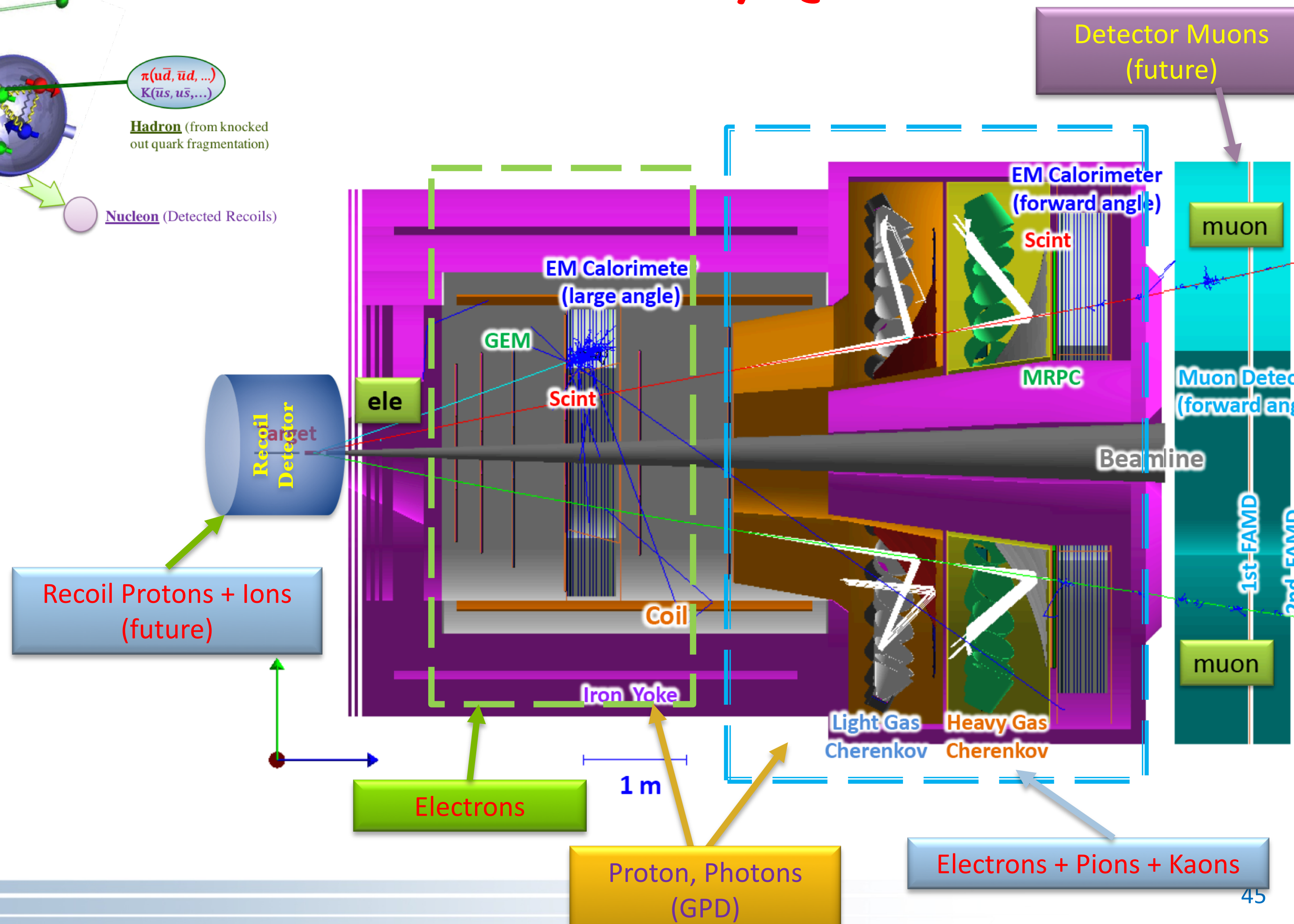
$$\Delta t = t_1 - t_2 \simeq \frac{Lc}{2p^2}(m_1^2 - m_2^2))$$



General Purpose 4π Detector Systems - SoLID

SoLID-SIDIS/Jpsi设置

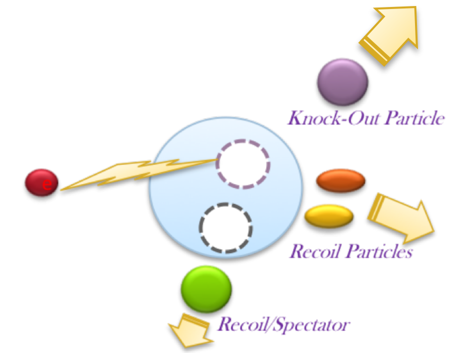




General Purpose 4π Detector Systems - SoLID

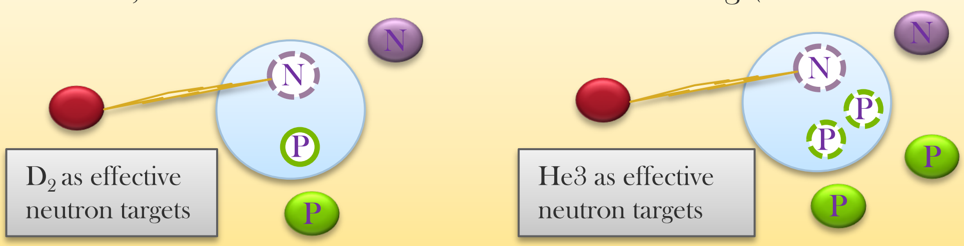
➢ **Recoil Detector:** Why do we need this for fixed target experiments?

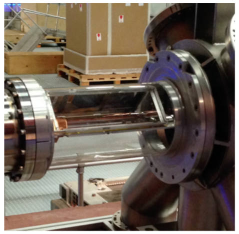
❖ Low energy knock-out particles can not get out from thick targets

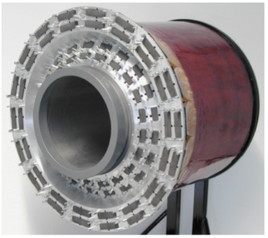


Spectator Nucleons move with Fermi-Momentum (<200 MeV/c)

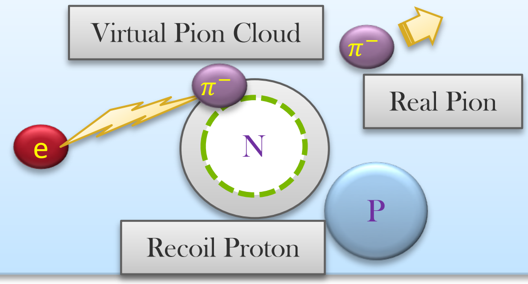
❖ Sometimes, we interest in electro—neutron scattering (no free neutron!!!)

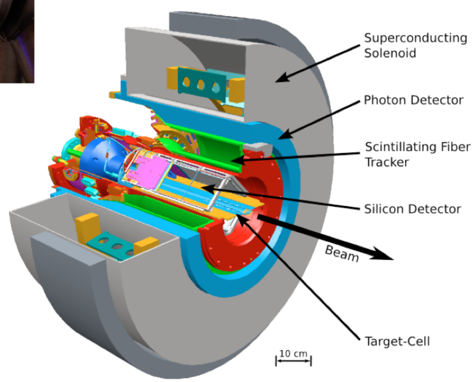






❖ Sometimes, we interest in electro—pion/kaon scattering (no pion/kaon targets!!!)

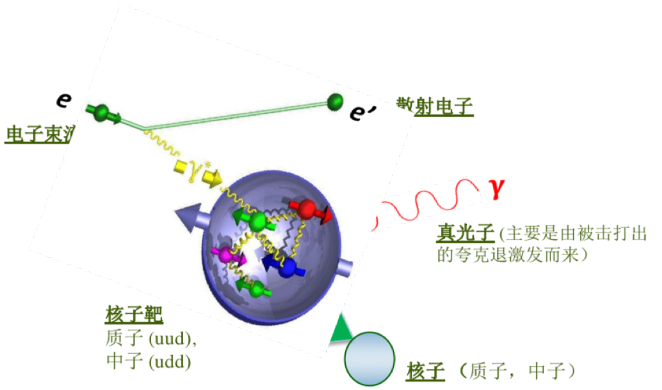




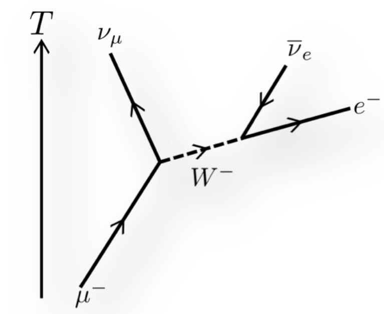
HERMES Recoil Detector

❖ In SoLID-DVCS experiments with He3 targets, we can use the recoil detector to detect protons: If P_p<200 MeV/c, we measure the nDVCS reaction; If 200 MeV/c<P_p<1.5GeV/c, we measure the pDVCS reaction

$$e + \vec{n} \rightarrow e' + n + \gamma$$

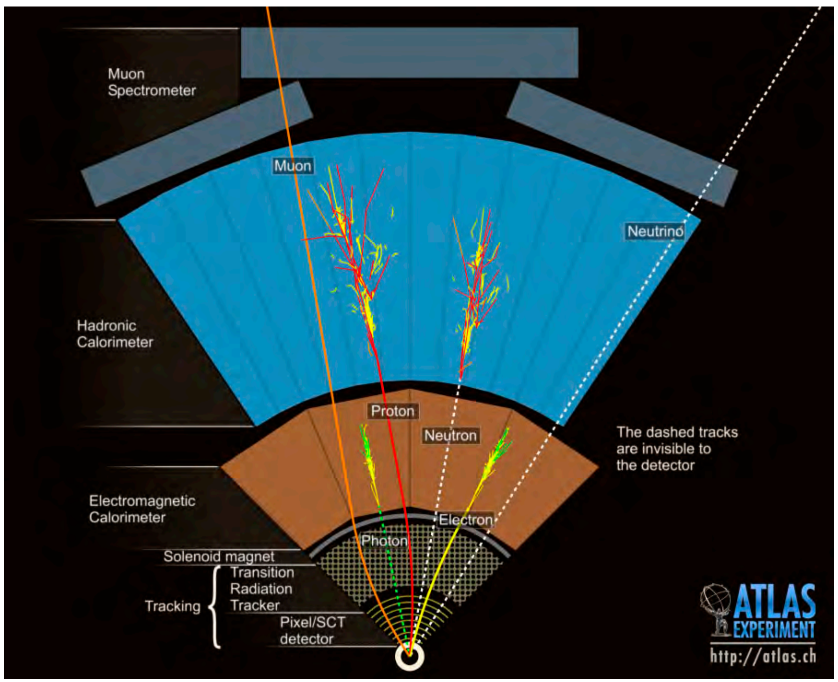


General Purpose 4π Detector Systems - SoLID

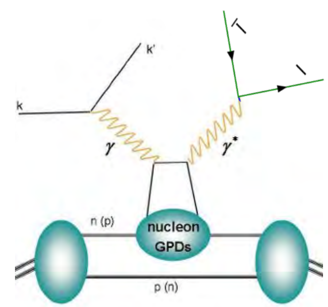


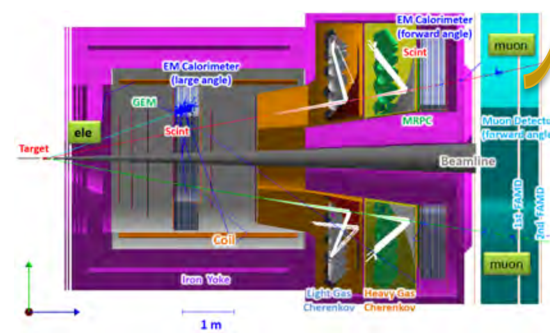
➢ Muon Detectors:

- ❖ Muons are very similar to electrons, except heavier (105.66 MeV) and unstable (2.2 us)
- ❖ Muons are not easily to be stopped even in thick materials (no easy to radiate Bremsstrahlung photons)
- ❖ Muons do deposit Ionization energy (hence can be tracked and counted).

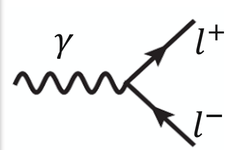


Double DVCS on SoLID





- ❑ Muons have their own interesting physics (e.g, anomalous magnetic dipole momentum, g-2)
- ❑ In nuclear physics, we "take advantage of" their penetrating-power to do clean measurements



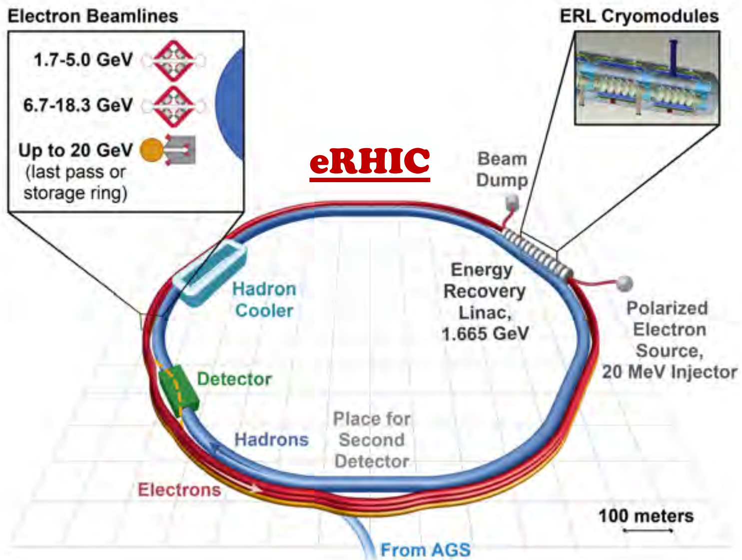
- ✓ Lepton pairs can be (e^+, e^-) or (μ^+, μ^-)
- ✓ However, electron-pairs are easily mixed with many other background sources

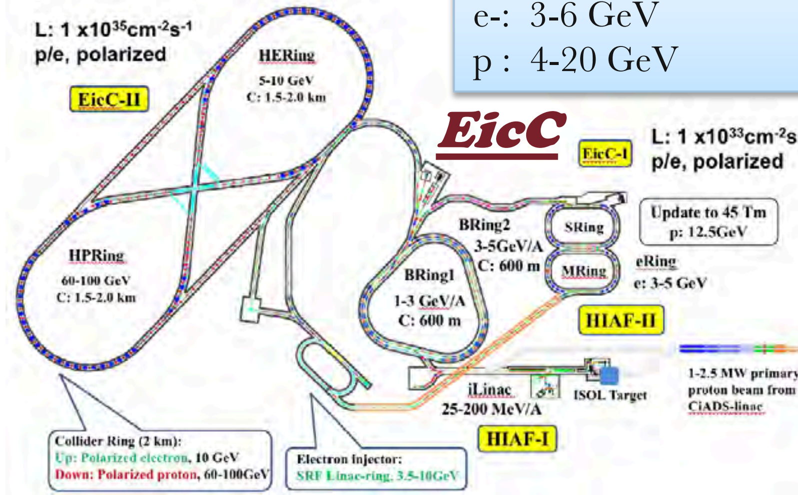
Collider Experiments:

Interaction Region in A Electron-Ion Collider

General Purpose 4π Detector Systems - EIC

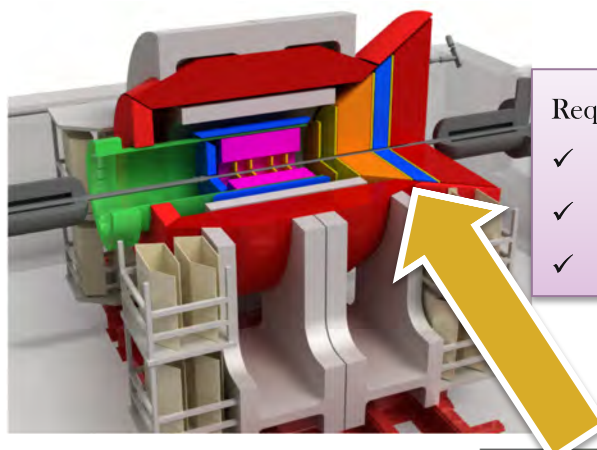
- Electron-Ion Collider (EIC):





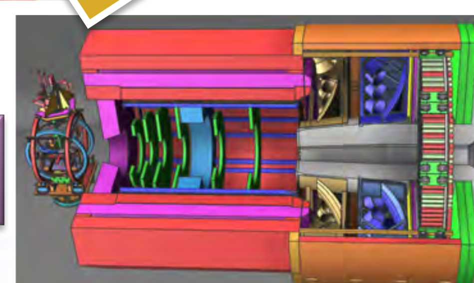
EicC energy range:
e-: 3-6 GeV
p : 4-20 GeV

US EIC Energy Range:
e-: 3-10 GeV
p : 20-100 GeV

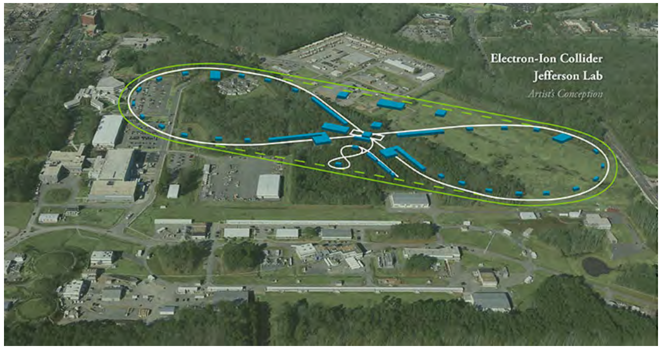


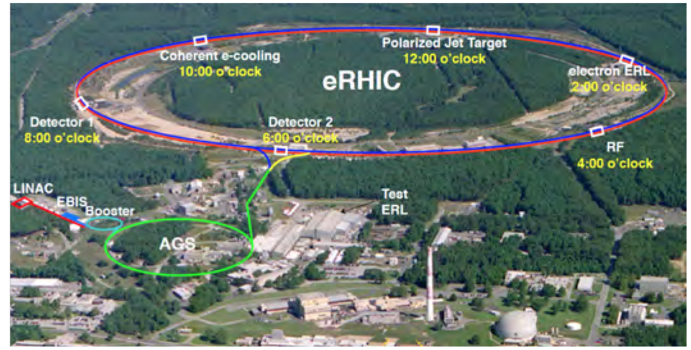
Requirement of an EIC :
- ✓ High Lumosity ~10^{34} cm^{-2} s^{-1}
- ✓ Polarized Electrons, Proton, Ions
- ✓ Full 4pi Azimuthal Coverage

SoLID可以直接成为EIC
的其中一个探测器系统

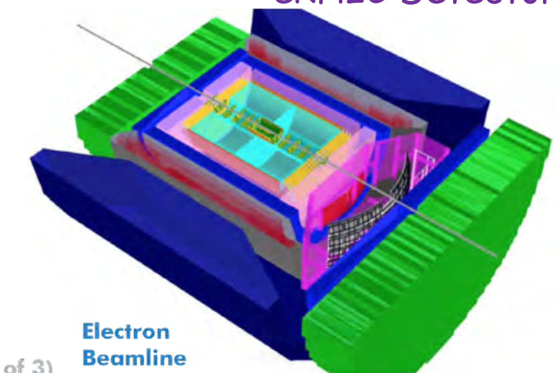


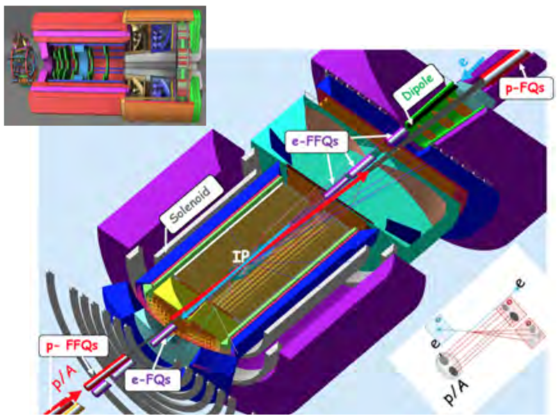
General Purpose 4π Detector Systems - EIC



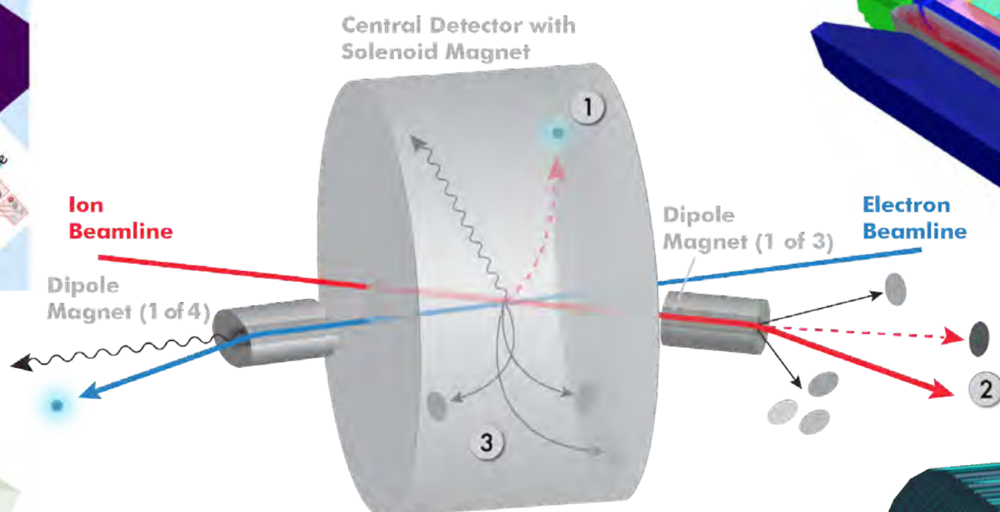


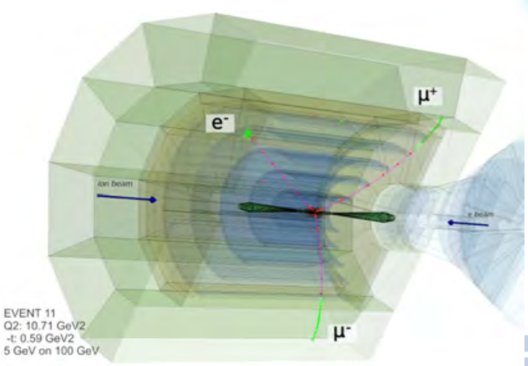
eRHIC Detector



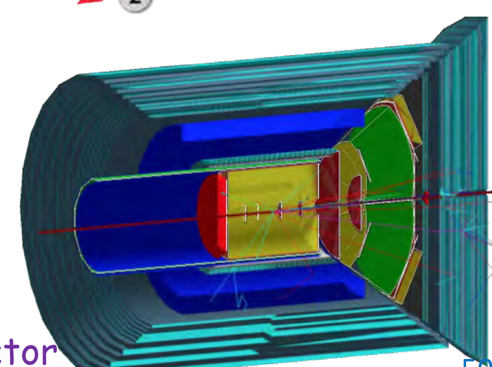


JLEIC Detector





TOPSiDE by ANL

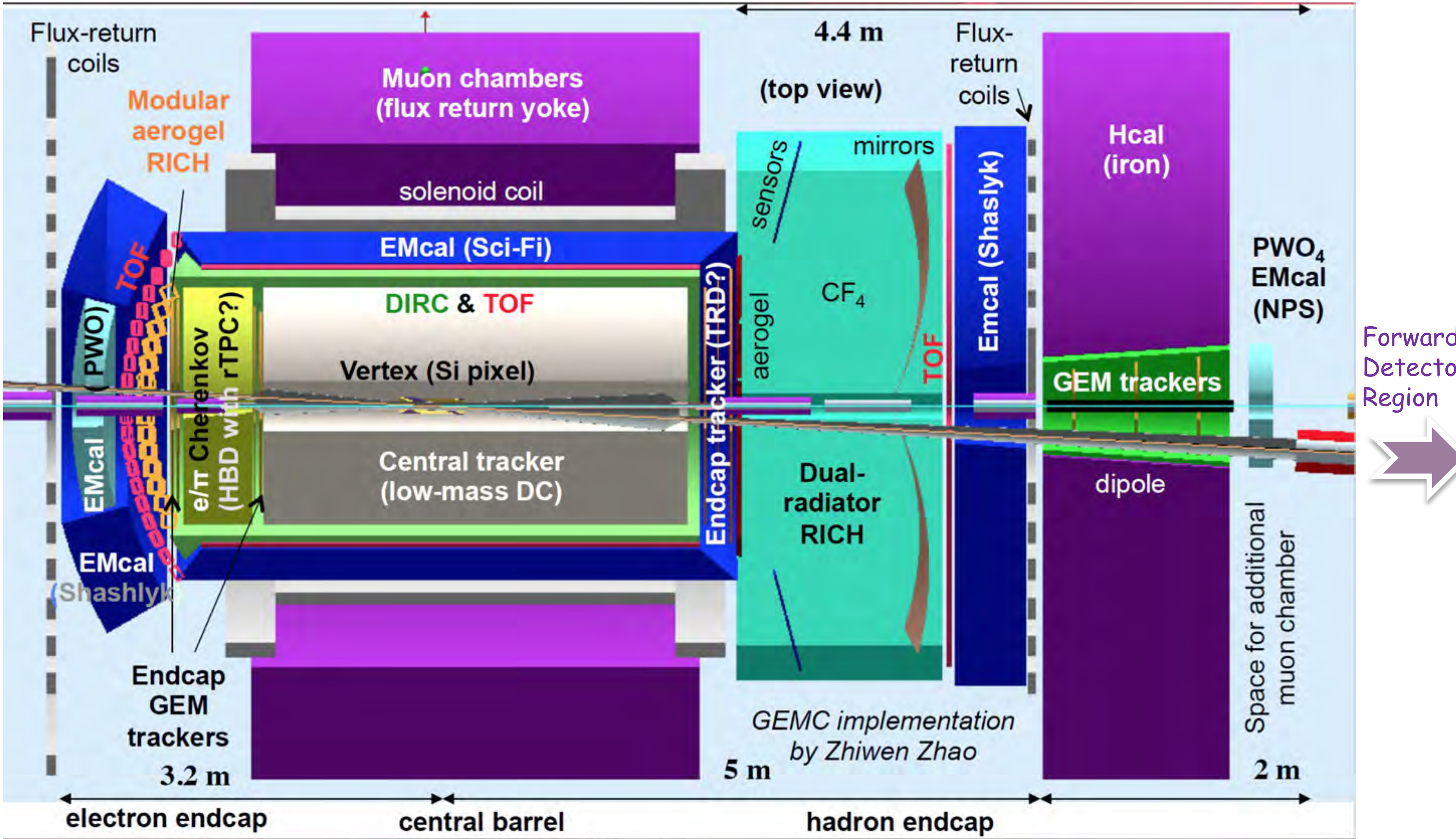


ePhoenix Detector

General Purpose 4π Detector Systems - EIC

- JLab MEIC Detector Design:

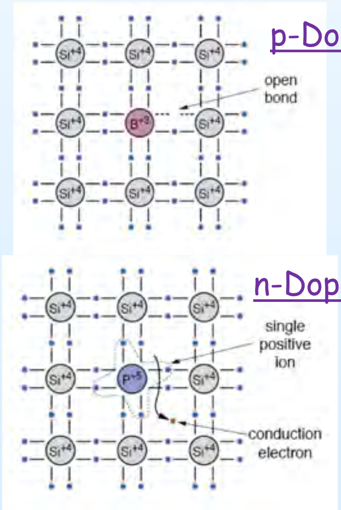
Other Detector designs share very similar idea but with slightly different detectors

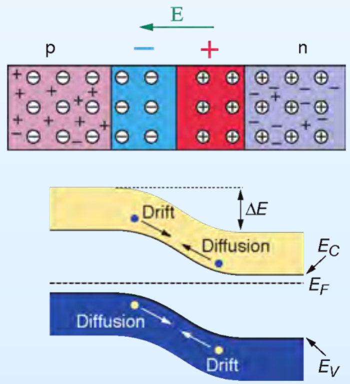


General Purpose 4π Detector Systems - EIC

➢ Silicon Detectors:

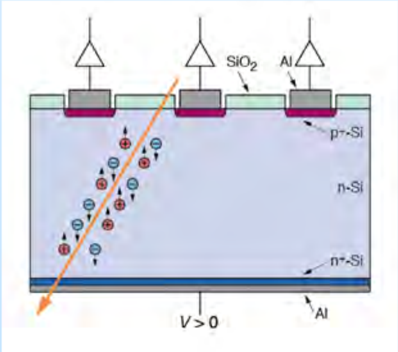
❖ Silicon semiconductor with p/n doping form a pn-Junction





pn-Junction

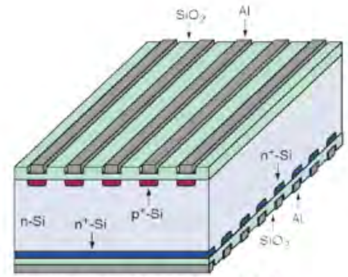
❖ w/ a strong voltage applied, ionized electrons/ions by charged particle form avalanche cascade in Si.



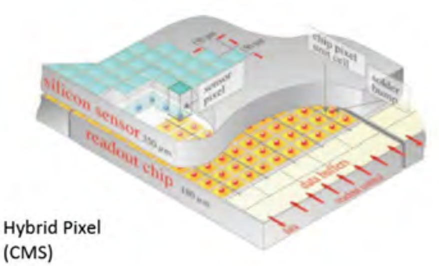
✓ Voltage < 200 V
✓ Amplification~10^7

❖ Electron signals was read-out and amplified.

❖ Strip- and Pixel Detector

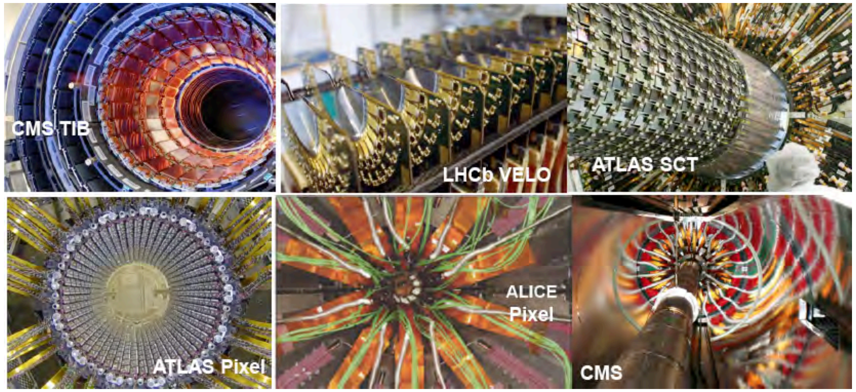


Scheme of a double sided strip detector (biasing structures not shown)

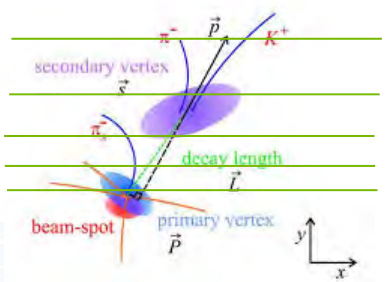


Hybrid Pixel (CMS)

❖ Great Application



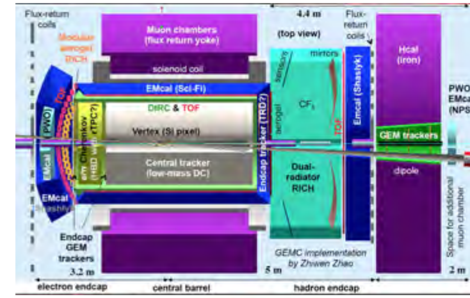
e.g., Vertex Tracker for detecting decayed particles



Multiple-layer Si Pixel Detector

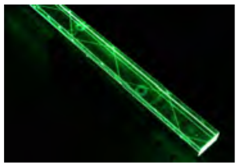
General Purpose 4π Detector Systems - EIC

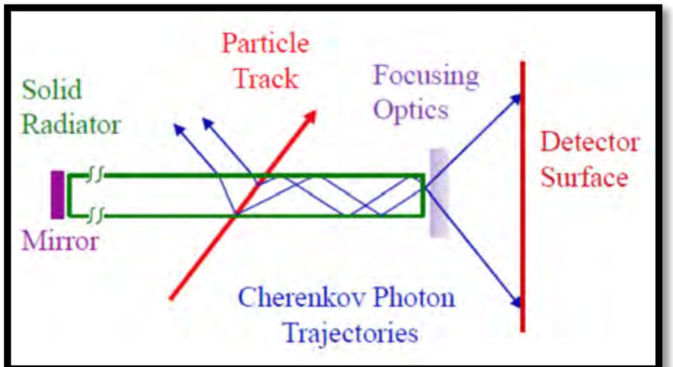
➢ Detection of Internally Reflected Cherenkov Light (DIRC):

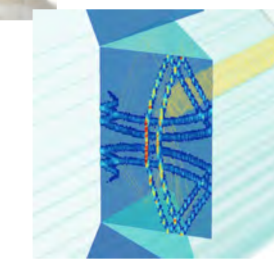


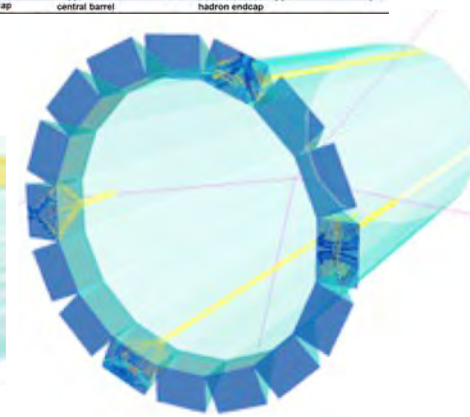
❖ DIRC is also a Cherenkov detector (half opening angle $\cos \theta_c = 1/\beta n(\lambda)$).

❖ Radiator and light guide: bar made from synthetic fused silica





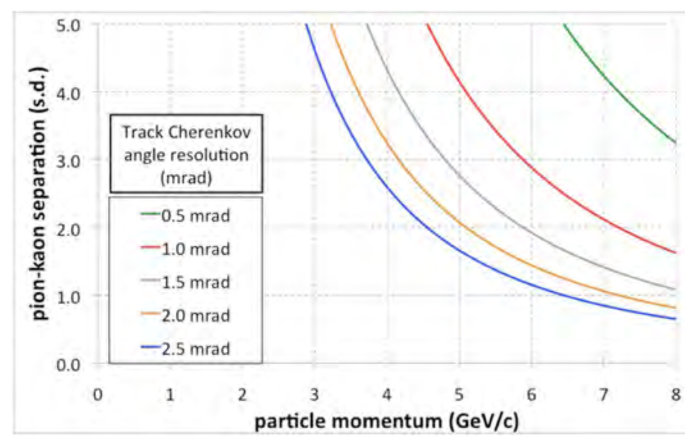




❖ w/ $n > \sqrt{2}$ some photons are totally internally reflected for $\beta \approx 1$ tracks.

❖ Magnitude of Cherenkov angle conserved during internal reflections (provided optical surfaces are square, parallel, highly polished)

❖ Photons exit radiator into expansion region, detected on photon detectors



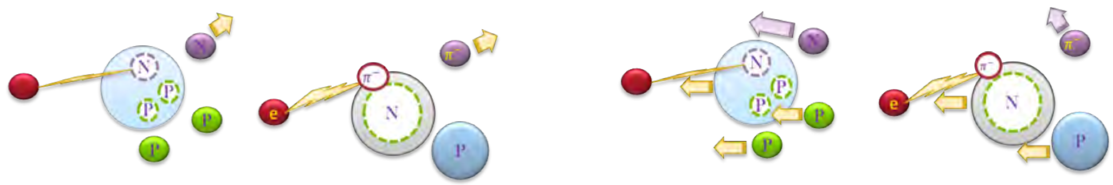
❖ A DIRC is intrinsically a 3-D device, measuring: x, y, and time of Cherenkov photons, defining θ_c, ϕ_c, propagation of each photon.

❖ Increase pi/K separation by improving angular resolution

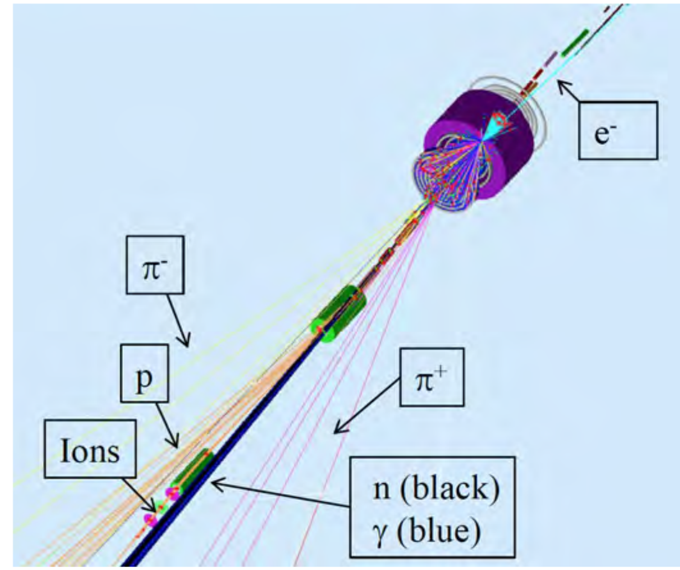
General Purpose 4π Detector Systems - EIC

➢ Forward Detector Region:

❖ Motivation: direct and better detection of recoil particles which move close to Ion-Beam direction.



Fixed Target (Recoil Detector)   Collider (Forward Detector)

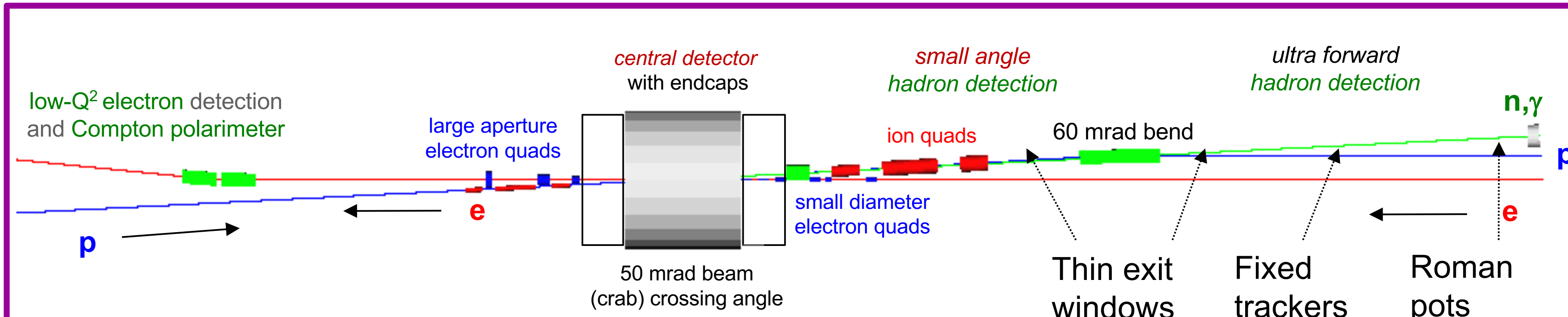


❖ Neutrals detected in a 25 mrad (total) cone down to zero degrees

❖ Need excellent acceptance for all ion fragments

- *Recoil baryon* acceptance:
  - ✓ up to *99.5%* of beam energy for *all angles*
  - ✓ down to at least *2-3 mrad* for *all momenta*
  - ✓ *full* acceptance for x > 0.005

- Resolution limited only by beam
  - ✓ longitudinal $\Delta p/p \sim 3\times10^{-4}$
  - ✓ angular $\varphi \sim 0.2$ mrad



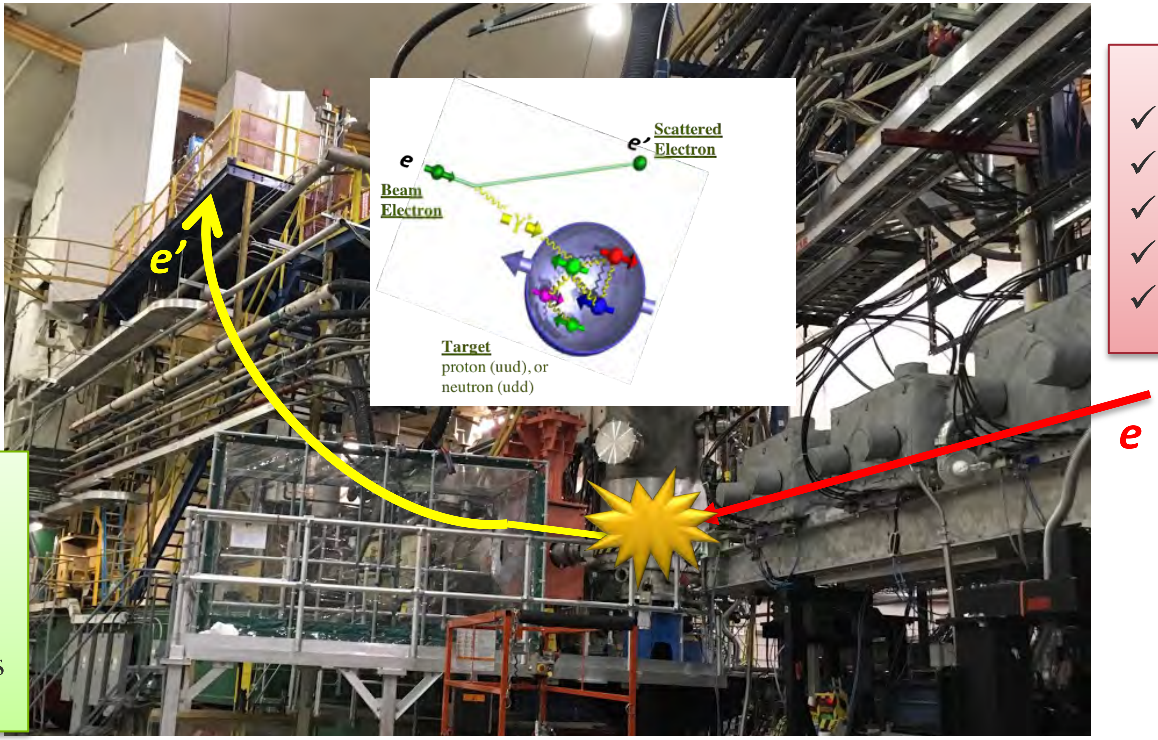
❖ Building a Forward Detector is also very challenging (but in a different way) as a recoil detector but way more advantage!

Data Analysis and Simulation

Data Analysis

- General Idea: e.g., on a Spectrometers
  - Particles are only measured before/after the reaction happen, mostly are far from the reaction point (target region)
  - What we are interested is the **reaction** itself (e.g., cross-sections, asymmetries, spectroscopies, life-times, masses, etc.)
  - Data analysis is basically a process of understand what happen during the reaction based on detector signals

Detectors
- ✓ Position
- ✓ Angle
- ✓ Time
- ✓ Speed
- ✓ Momentum
- ✓ Energy
- ✓ Particle Type (Mass, Charge)

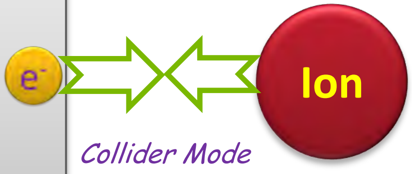


e Beam
- ✓ Current
- ✓ Energy
- ✓ Position
- ✓ Polarization
- ✓ Arrival Time

Physics
- ✓ Yield (Cross Section)
- ✓ Detection Efficiency
- ✓ Background
- ✓ Systematic Uncertainties

Target (fixed target experiment)
- ✓ In-Beam Density (boiling effect correction)
- ✓ Polarization (for a polarized target only)
- ✓ Target Atoms (if mixed materials)
- ✓ Reaction Point (for a long target)

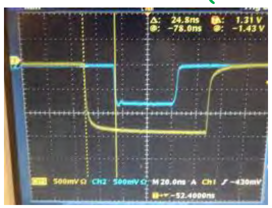
Ion Beam (EIC)
- ✓ Current
- ✓ Energy
- ✓ Position
- ✓ Angle
- ✓ Polarization
- ✓ Arrival Time

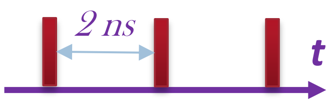


Data Analysis

- **Generalized Idea: e.g. Coincident Measurement**
  - On top of the data analysis for a single arm, the key is to find the two particles from both HRSs come from the same reaction, i.e. the times of two particles projected back to the target should align with the beam time (RF time):

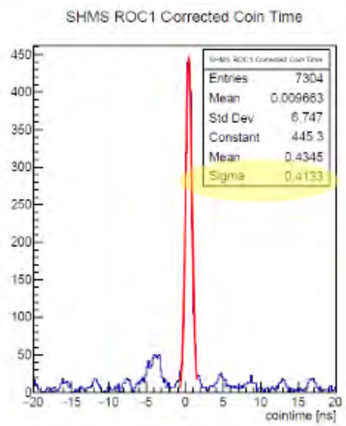
Coincidence time (Relative)

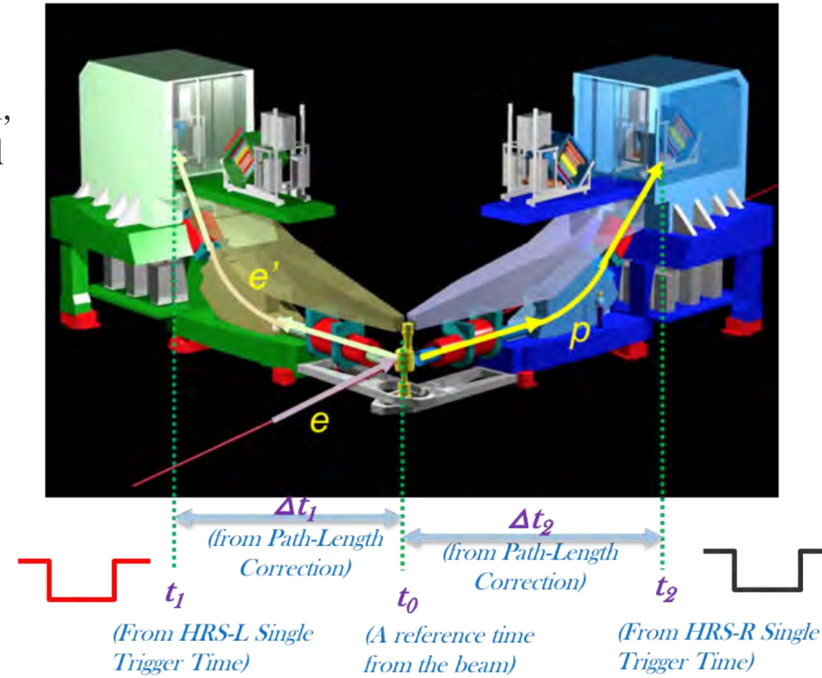




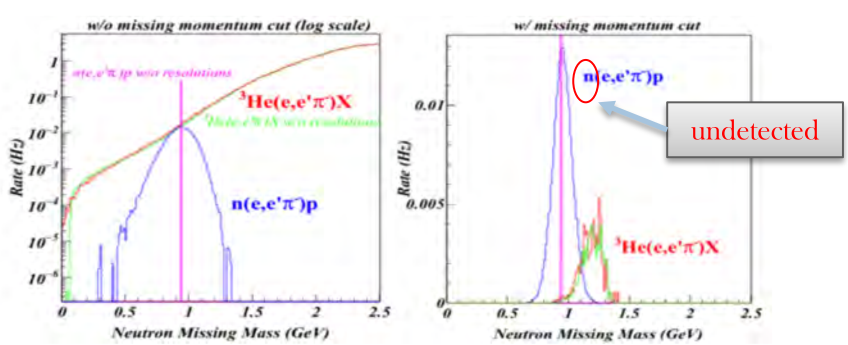
RF Time (absolute)

Match to show a RF structure with peaks

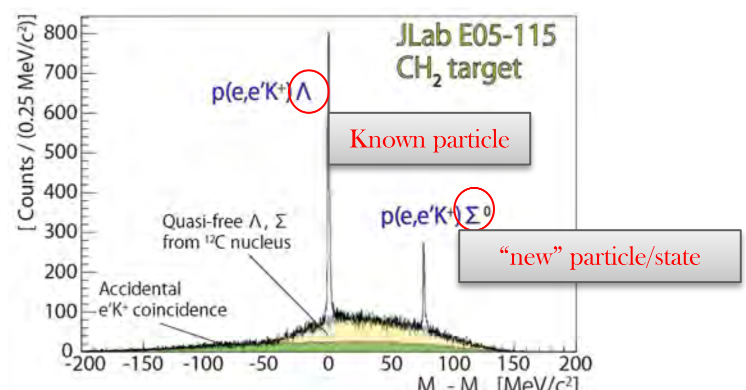




- In an Exclusive measurement, particles' total momenta and energy should be conserved which can be applied to reconstruct missing mass (and missing momentum)
  - ✓ Application 1: Clean up events with known mass (but undetected)



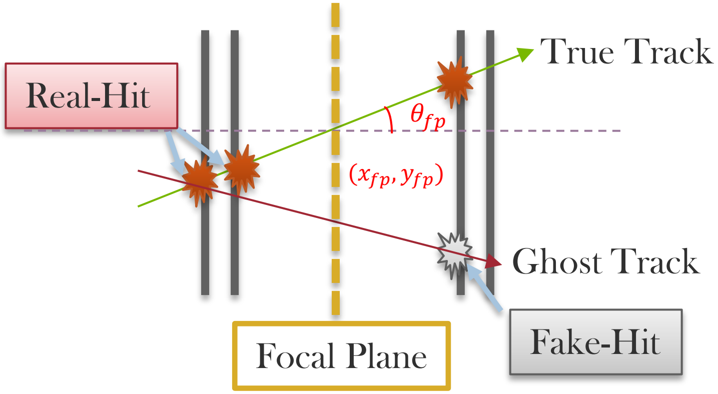
  - ✓ Application2: Search for new particles or new excited stages with unknown mass



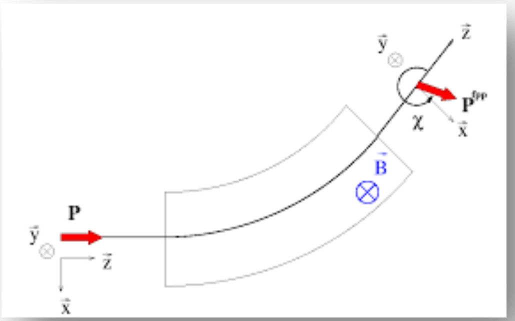
Data Analysis

➢ **Tracking Reconstruction:**

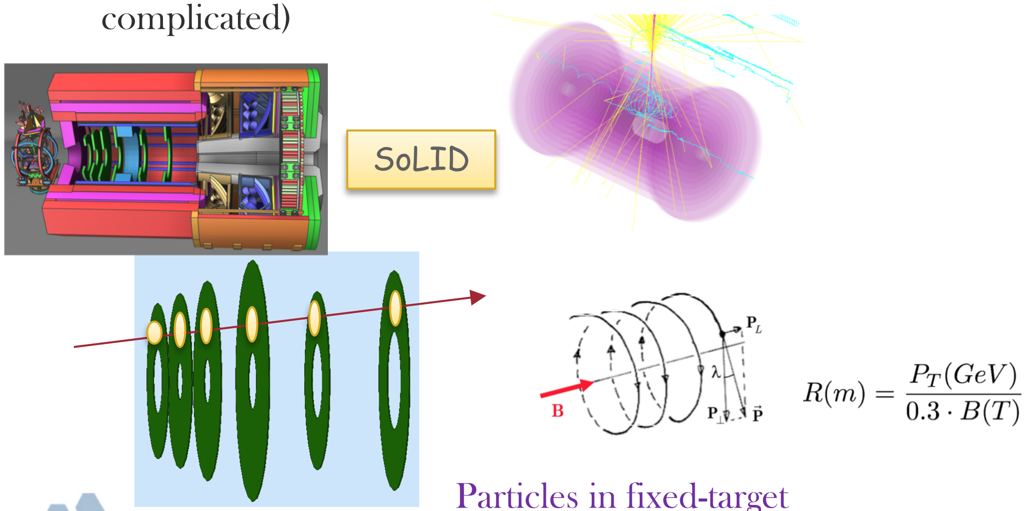
❖ In a non magnetic environment (e.g., the HRS detector hut), fit the linear pattern to obtain the positions (x,y) and angles (θ, ϕ)



❖ The charged particle's momentum is determined by the bending angle inside the dipole

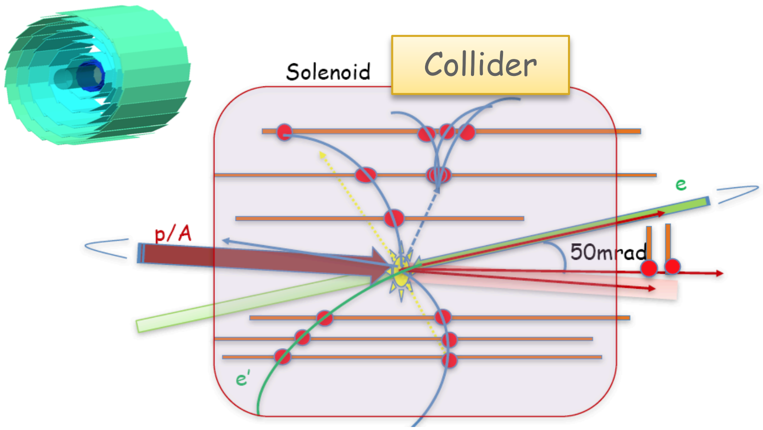


❖ In a Solenoid magnet (SoLID, EIC, or other collider detectors), tracking reconstruction are similar (but more complicated)



$$R(m) = \frac{P_T(GeV)}{0.3 \cdot B(T)}$$

Particles in fixed-target experiments mostly go forward



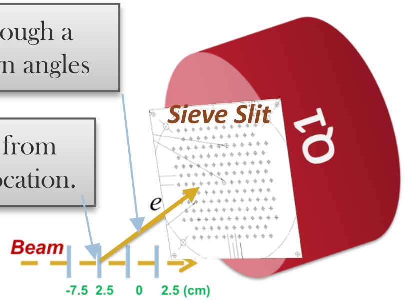
Particles in collider experiments go to any directions

Data Analysis

- **Optics Reconstruction for Spectrometers:**
  - Goal: based on the tracking reconstruction, trace back to the reaction point, and obtain the reaction location, angles and momenta. i.e., for HRS,
  - An optics calibration procedure is to obtain the parameters in the polynomial functions:

Events passing through a hole has the known angles

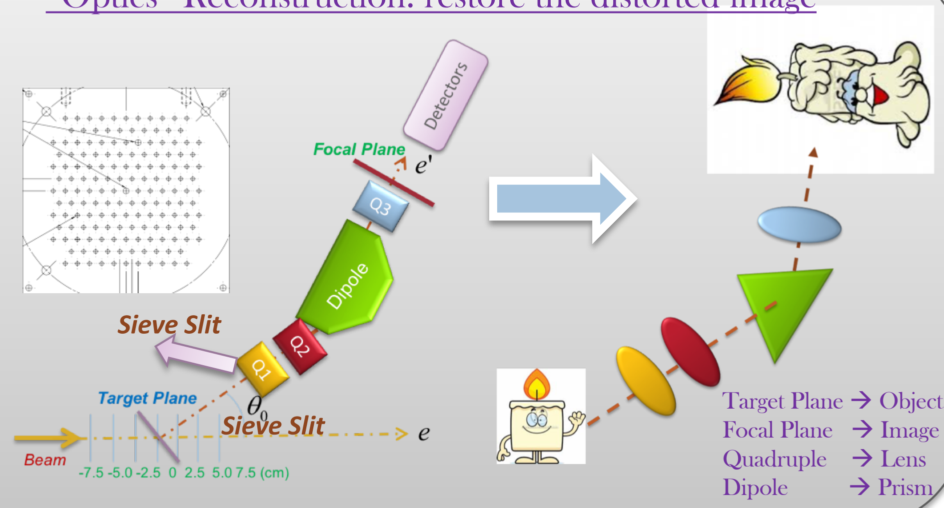
Position (x,y,z) is known from beam position and foil location.

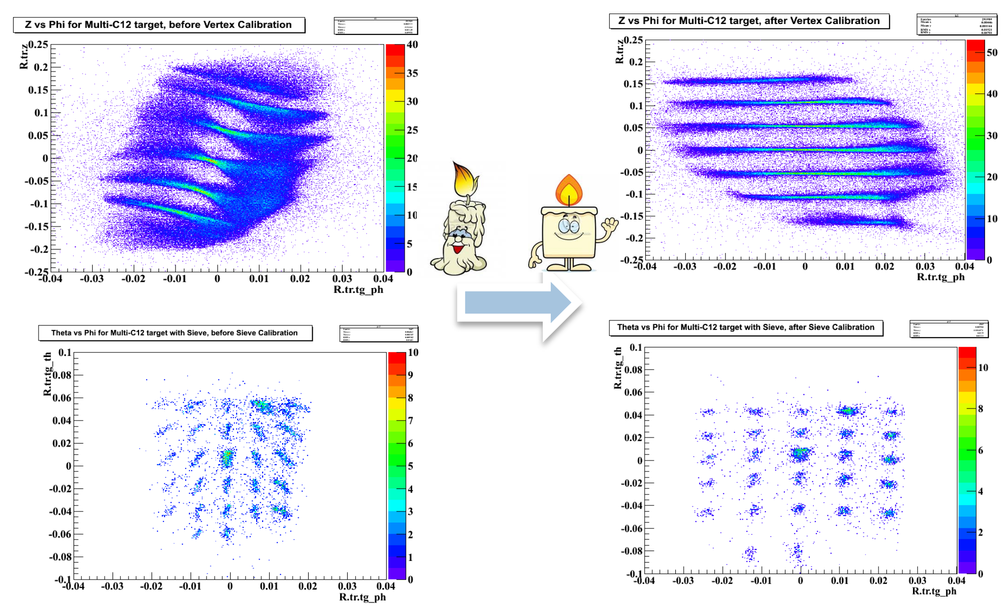


$$\begin{pmatrix} \delta p \\ y_{tg} \\ \theta_{tg} \\ \phi_{tg} \end{pmatrix} = \begin{bmatrix} Optics \\ Matrix \end{bmatrix} \begin{pmatrix} x_{fp} \\ y_{fp} \\ \theta_{fp} \\ \phi_{fp} \end{pmatrix} \Rightarrow \begin{cases} \delta p = \sum_{i,j,k,l} C^{D}_{ijkl} x^{i}_{fp} y^{j}_{fp} \theta^{k}_{fp} \phi^{l}_{fp} \\ y_{tg} = \sum_{i,j,k,l} C^{Y}_{ijkl} x^{i}_{fp} y^{j}_{fp} \theta^{k}_{fp} \phi^{l}_{fp} \\ \theta_{tg} = \sum_{i,j,k,l} C^{T}_{ijkl} x^{i}_{fp} y^{j}_{fp} \theta^{k}_{fp} \phi^{l}_{fp} \\ \phi_{tg} = \sum_{i,j,k,l} C^{P}_{ijkl} x^{i}_{fp} y^{j}_{fp} \theta^{k}_{fp} \phi^{l}_{fp} \end{cases}$$

w/ known focal plane quantities and target plane quantities, fit the matrices using minimization method.

"Optics" Reconstruction: restore the distorted image

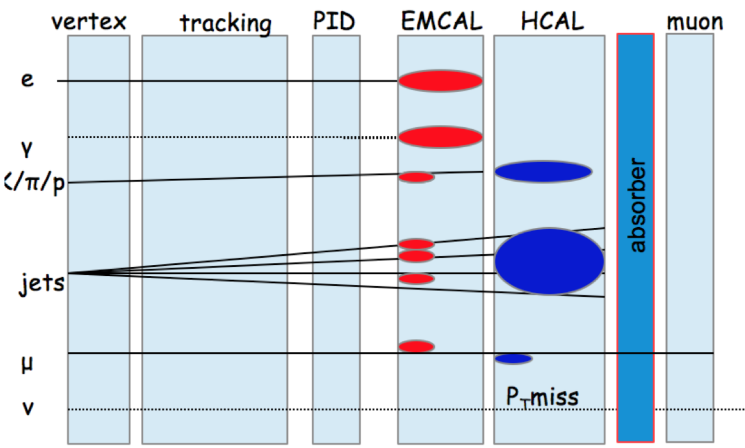


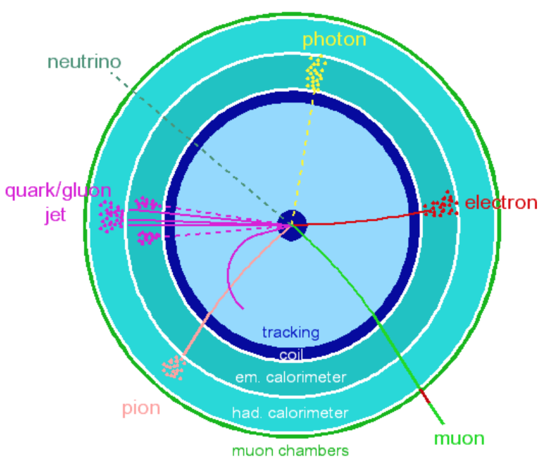


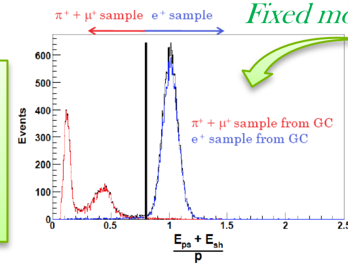
Data Analysis

- Particle Identification:

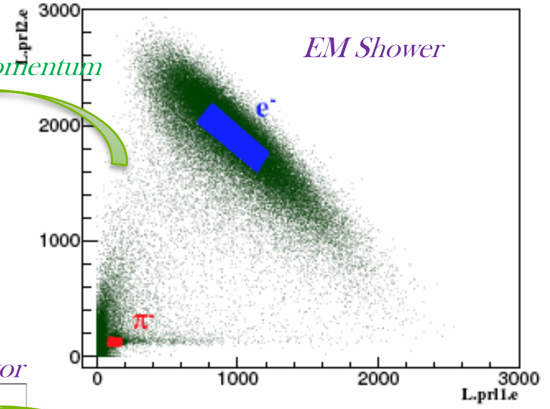
❖ How to know what type of particles coming from the target?
  - ✓ Charge → Bending direction in a magnet
  - ✓ Mass = Momentum / Speed (e.g. Time of Flight)
  - ✓ Interaction with materials (A, Z, M, etc.)



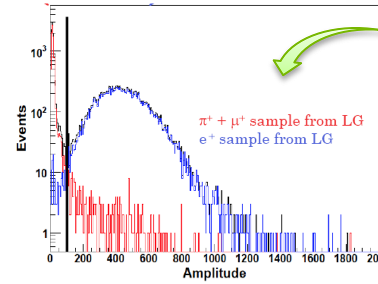




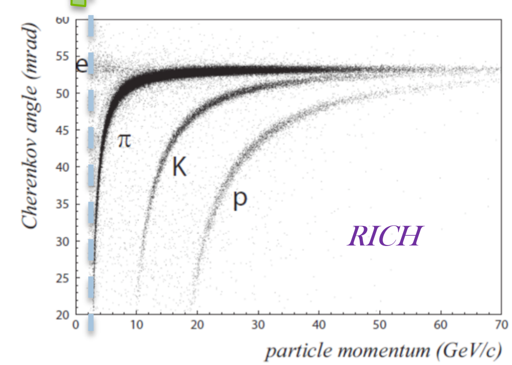
Fixed momentum

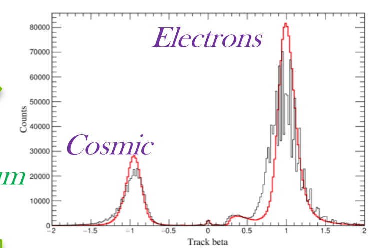


Threshold Cherenkov Detector



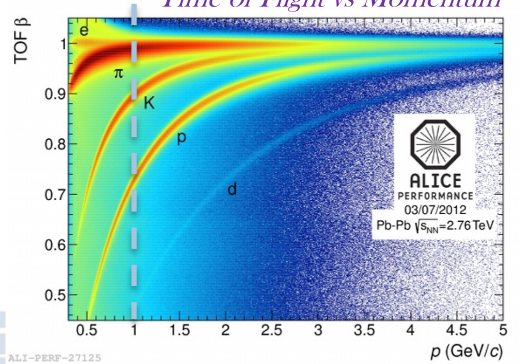
Fixed momentum



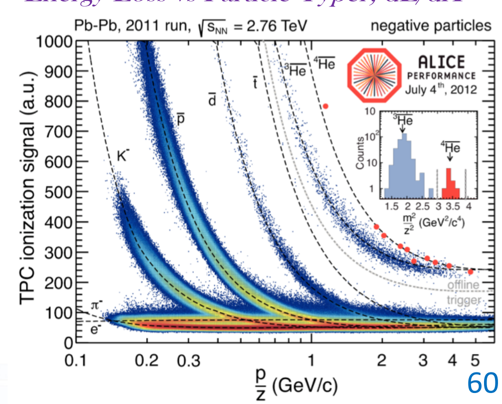


Fixed momentum

Time of Flight vs Momentum



Energy Loss vs Particle Typer, dE/dX



Data Analysis

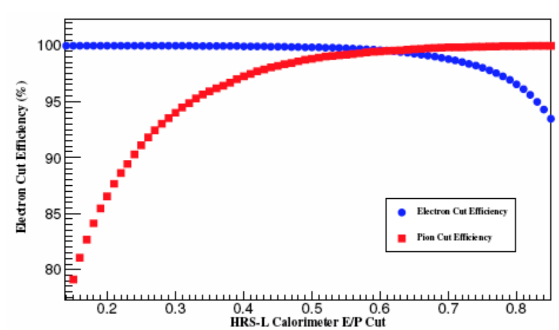
- **Efficiencies:**

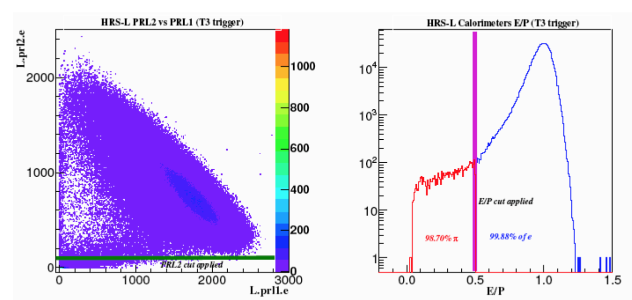
  - Efficiency → How well we measure the physics events?
    - Does a detector detects all particles passing through?
    - Does the tracking reconstruction find the right track?
    - Does the PID cut selects the right particles?
    - Does the Electronics/Computer convert/save all signals from detectors into disks?

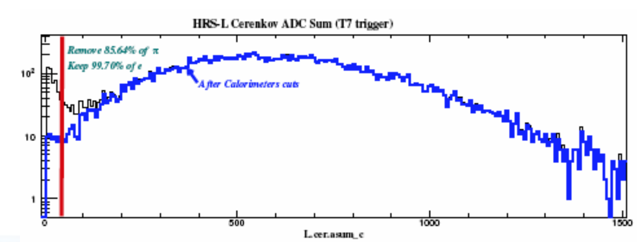
- ❑ Detectors are not perfect due to their performance, geometry → Detection Efficiencies
- ❑ Tracking Reconstruction may treat fake tracks as reall ones, vice versa → Tracking Efficiencies
- ❑ PID cuts we choose may remove good particles and keep bad ones → PID Cut Efficiencies
- ❑ Front-Electronics may be not fast enough to generate triggers → Trigger Efficiencies
- ❑ Computer is too busy to record the previous event and have to discard the → Dead Time

  - All Inefficiencies that cause us to "misunderstand" what actually happens at the reaction point, have to be evaluated, corrected or treated as systematic uncertainties.

e.g., to study PID efficiency, choose good particle samples from one detector, and study how many of them are removed by mistake in another detector, by changing the cuts



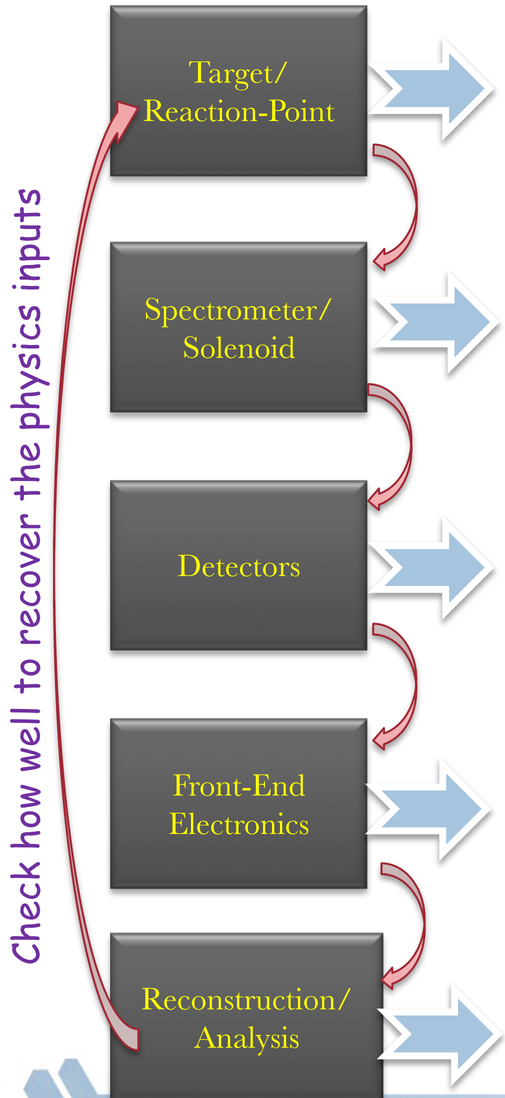




Monte-Carlo Simulation

➢ General Idea:

❖ A Monte-Carlo Simulation is basically like running an experiment in your computer



Simulate the physics reaction w/ model inputs

Simulate how particles travel in a EM field

Simulate how detectors respond to particles

Simulate how detectors signals converted into different electric signals

Reconstruct physics quantities after building in "actual effects" (energy-loss, background, detector resolution, etc.)

❖ Many application
- ✓ Design experiments
- ✓ Design detectors
- ✓ Evaluate detector/electronics performance
- ✓ Help pre-processing of the online experimental data
- ✓ Apply correction and evaluation uncertainties to real data

❖ Software and Tools
- ✓ Event Generators for dedicated physics processes (w/ theory models)
- ✓ Fast simulation to study particles propagating through EM fields and materials (DYI codes)
- ✓ Sophisticated MC simulation, using Geant4

Summary

[redacted]

Summary

- What I covered:
  - ✓ The general idea of particle physics experiments
  - ✓ Examples of fixed target experiments at Jlab Hall-A using HRSs
    - Magnetic Spectrometer
    - Targets
    - Detectors: Drift-Chambers, Scintillators, Cherenkov Detector, ECal
    - Trigger Design and DAQ
    - How to run an experiment
  - ✓ Examples of fixed target experiments at Jlab Hall-A using SoLID
    - Baffle Collimator
    - Polarized Targets
    - Detectors: GEM, Gas Cherenkov Shashlyk ECal, MRPC, Recoil Detector, Muon Detector
  - ✓ Examples of experiments on an Electron-Ion Collider
    - Detectors: Silicon Tracker, DIRC, Forward Detector System
  - ✓ Basic Data-Analysis
- ✓ Very Basic Monte-Carlo Simulation

- What I didn't cover:
  - ✗ Physics subjects
  - ✗ Detailed principle of particles interacting with matters
  - ✗ Scattering experiment other than electron-nucleon/nuclear scattering
  - ✗ Many other detectors
  - ✗ Many other data analysis tasks
  - ✗ Detailed Monte-Carlo Simulation