Kaon Detection Upgrade on SoLID

Zhihong Ye

10/12/2018

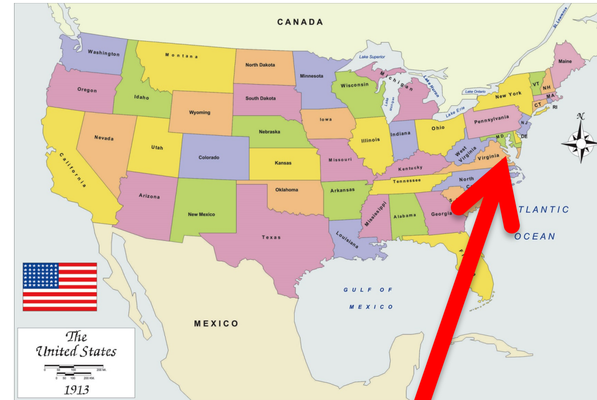
Self-Introduction

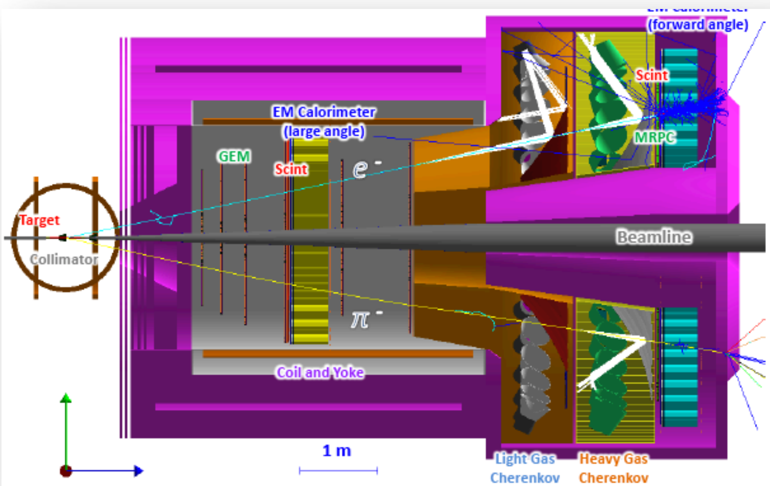
- Education:
  - Lanzhou University (Bachelor in Theoretical Physics)
  - University of Virginia (Ph.D in Experimental Nuclear Physics)
- Work History:
  - Postdoc at Duke University (Nov. 2013 ~ Sep. 2015
  - Postdoc at Argonne National Lab (Oct. 2015~Sep. 2018)
  - Senior Research Associate at Argonne National Lab (Oct. 2018 ~ current)
- Professional Experience:
  - Big Data Analysis, detection calibration, efficiencies study
  - Monte-Carlo simulation using self-developed programs and/or Geant4
  - Detector design, construction, operation and maintained
  - Design, propose and carry-out large-scale nuclear physics experiments
  - Publish physics results and present in international workshops and conferences
  - Abundant experience from working in large-size collaborations, organizing research activities and supervising students.

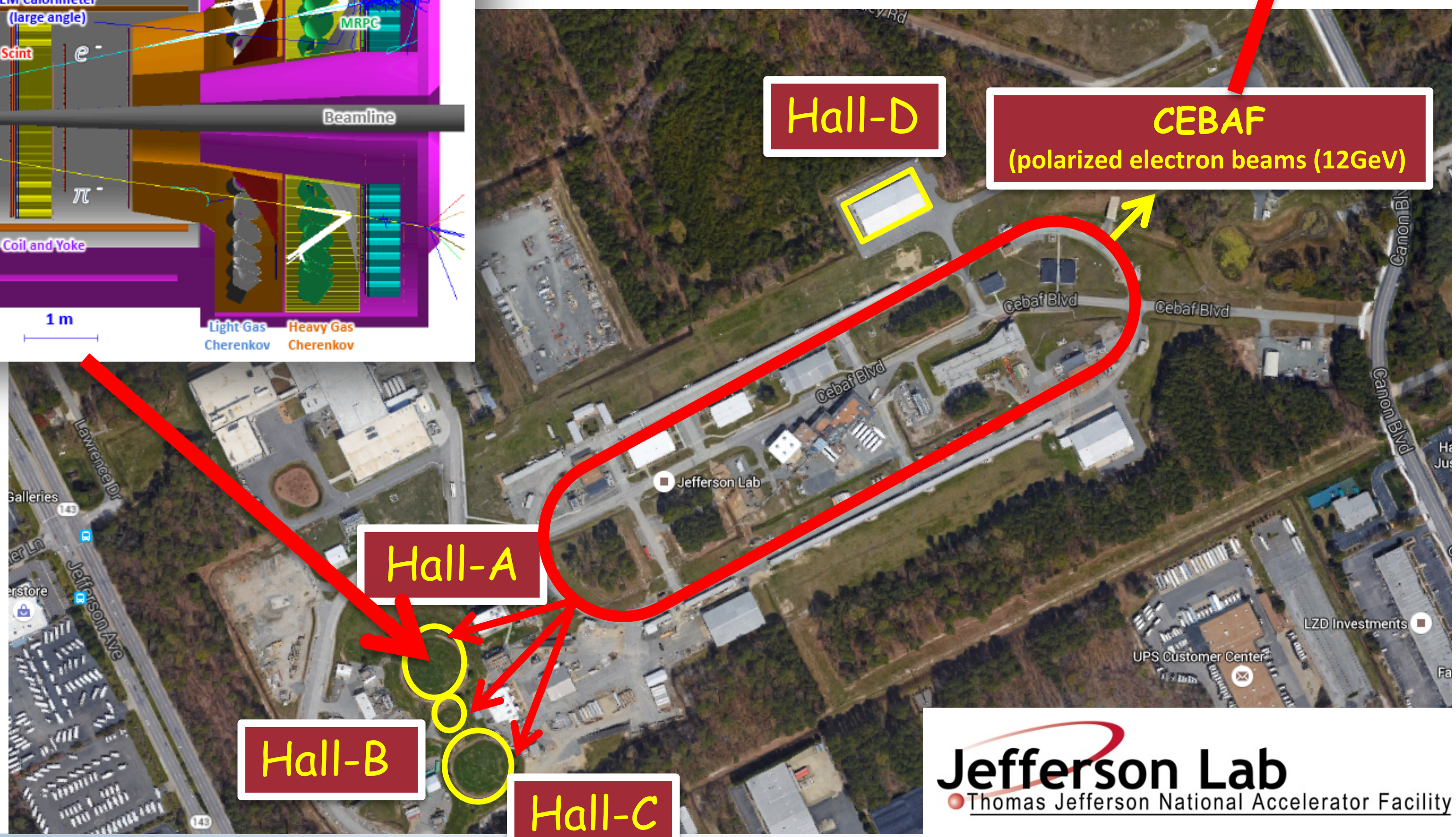
Introduce to SoLID

➢ **S**o**l**enoidal **L**arge **I**ntensity **D**evice:

✓ SoLID is the next generation detector system in Hall-A at Jefferson Lab (Newport News, Virginia) for experimental nuclear physics

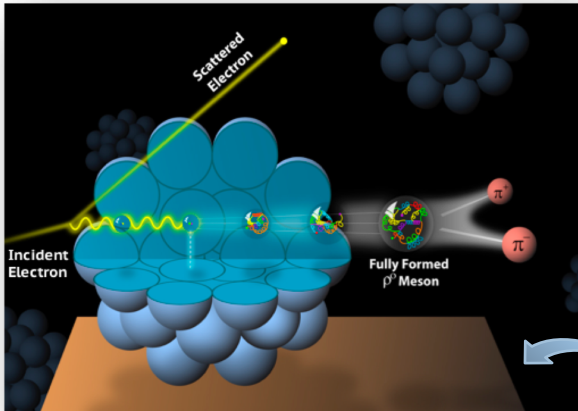






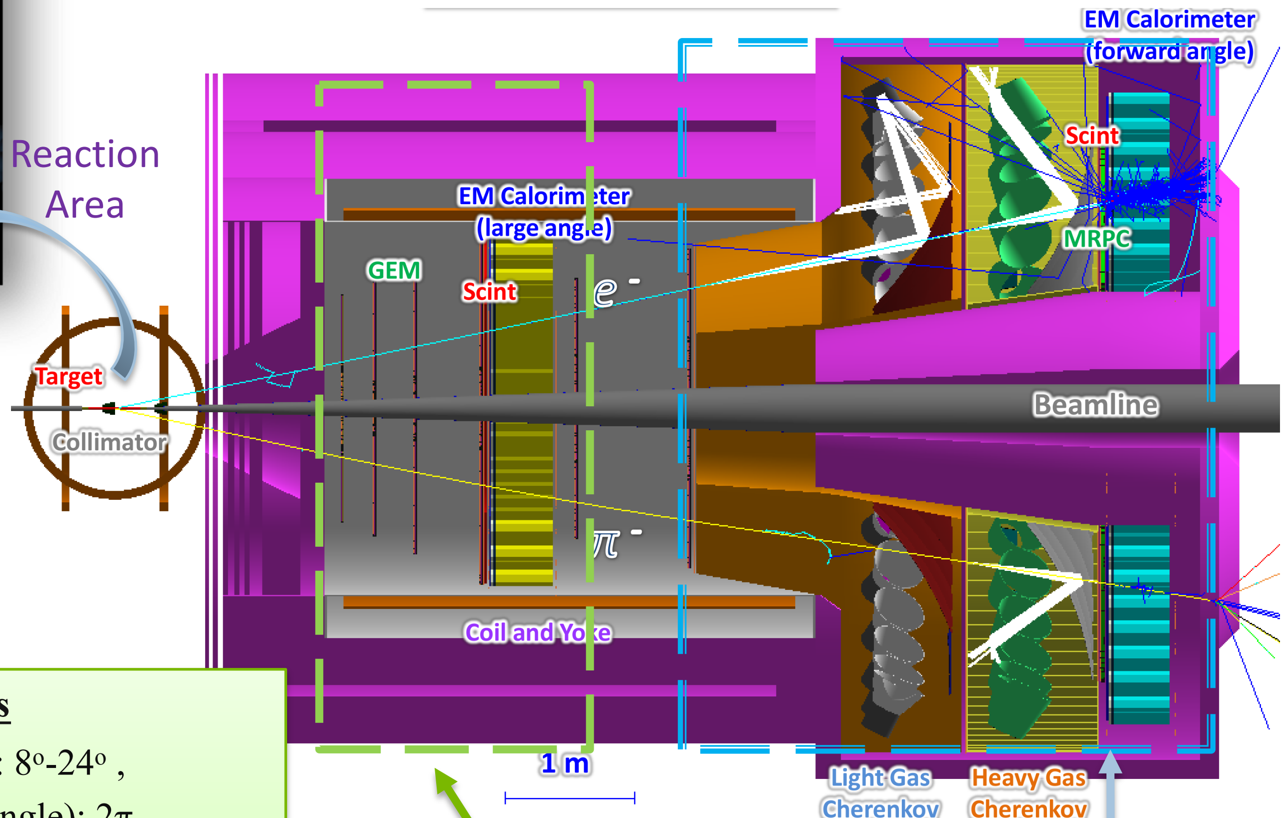
Jefferson Lab
Thomas Jefferson National Accelerator Facility

Introduce to SoLID



Reaction Area

12GeV electrons (beam)



Electron Protons, Photons

Electrons, Protons, Photons, Pions

Key Requirements

- $e/\pi^{\pm}$ Coverage: θ (Polar Angle): 8^o-24^o ,
  ϕ (Azimuthal Angle): 2π
  P (Momentum): 1.0 – 7.0 GeV/c
- Resolution: $\delta P/P \sim 2\%$, $\theta \sim 0.6$mrad, $\phi \sim 5$mrad
- Trigger Rate: 100 KHz
- Magnetic Field: 1.5 T
- Overall Detector Efficiencies : 85%
- High Radiation Tolerance (neutrons)

Introduce to SoLID

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

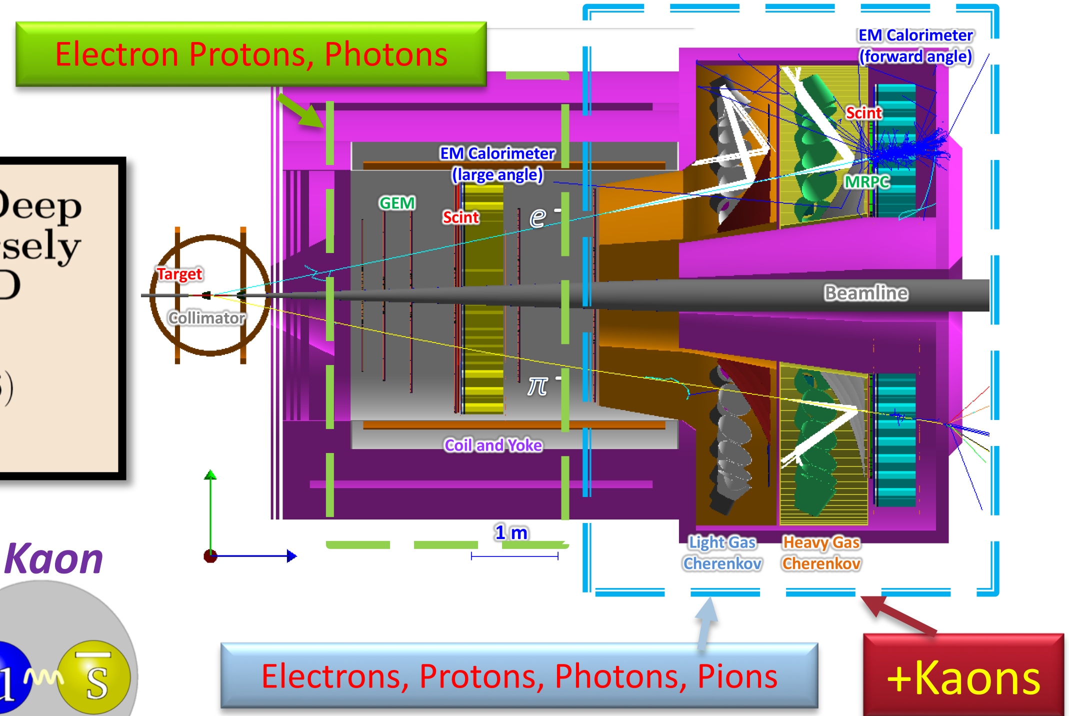
Upgrade on SoLID: Kaon Detection

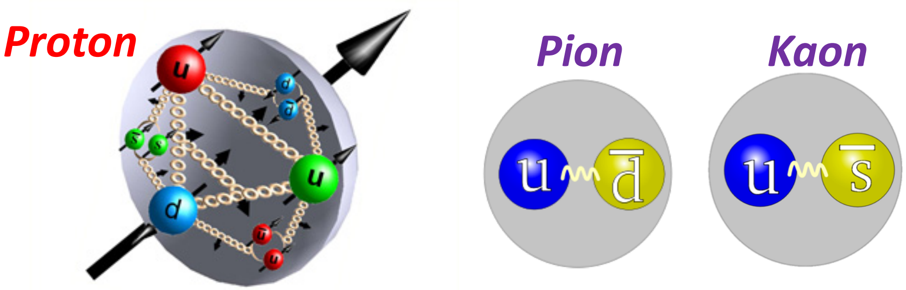
Spokespeople: Z. Ye*, T. Liu, S. Park, Y. Wang, Z. Zhao

$K^{\pm}$ Production in Semi-Inclusive Deep Inelastic Scattering using Transversely Polarized Targets and the SoLID Spectrometer

(A Run-Group Proposal Submitted to PAC 46)

June 4, 2018





Motivation of Upgrade: On top of pions (contain u and d-quark), detecting kaons (contain anti-u-, anti-d-, s- and anti-s-quark) can extend experimental goal to study how different quarks build protons and neutrons.

Constraints: Can't modify the basic configurations; No enough space for extra detectors (e.gl RICH); Can't dramatically increase the total cost of SoLID; Can't interference with other physics topics.

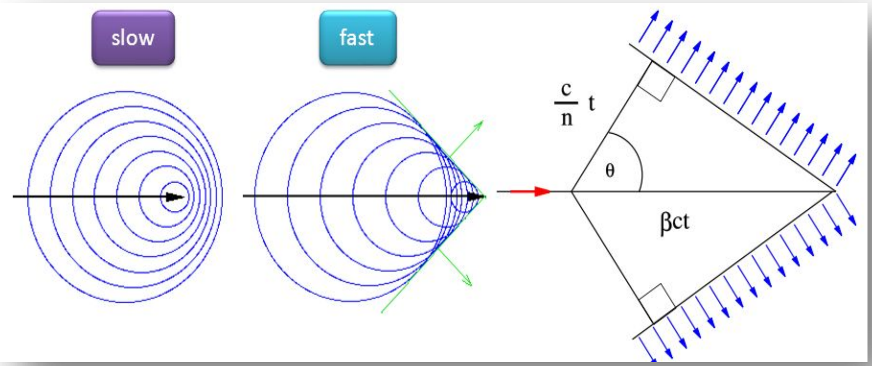
Solutions: Improve the timing resolution of MRPC and apply the veto-signal from Heavy-Gas Cherenkov Counter (HGC)

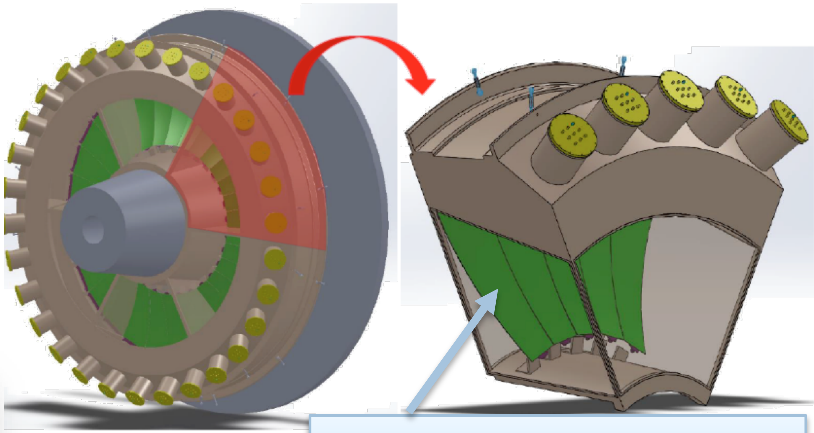
Kaon Detection on SoLID

➢ **Heavy Gas Cherenkov Counter (HGC):**

❖ Cherenkov Radiation:

A high energy charged particle radiates Cerenkov light when it travels in a medium with its speed faster than that of light.





→1 m C_4F_8O at 1.5 atm

→30 mirrors, 480 PMTs, area~20 m^2

→N.P.E>10, pion detection efficiency>90%

→Kaon suppresion > 10:1,

→Work at 200G field (100G after shielding)

❖ Cherenkov radiation angle depends on the speed and the index of reflection of the medium: $cos\theta = \frac{1}{\beta n}$

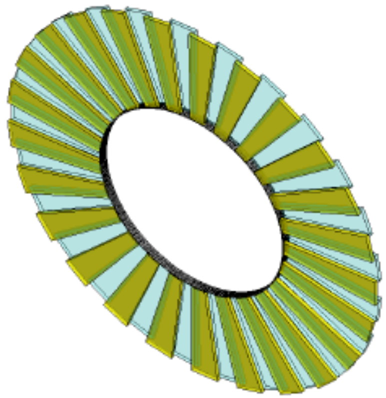
❖ The momentum threshold for a particle to produce a Cherenkov light depends on its mass: $P_{threshold} = \frac{mc}{\sqrt{n^2 - 1}}$

❖ w/ fixed index of reflection (i.e. materials), one can set the threshold to be between pion mass and kaon mass

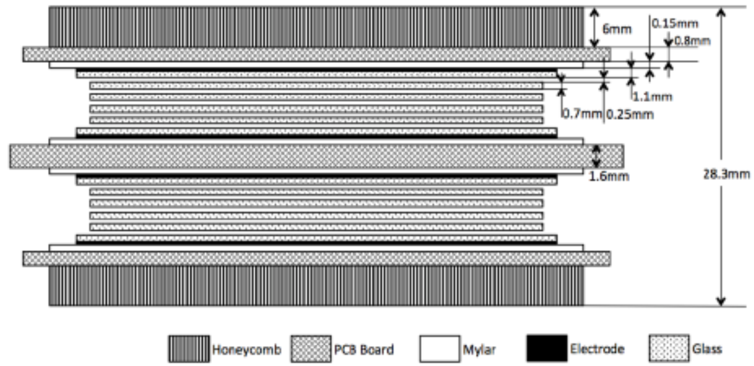
$$P^{\pi}_{threshold} = \frac{139.57 MeV/c}{\sqrt{1.0024^2 - 1}} = 2\ GeV/c \qquad P^{K}_{threshold} = \frac{493.68 MeV/c}{\sqrt{1.0024^2 - 1}} = 7\ GeV/c$$

Kaon Detection on SoLID

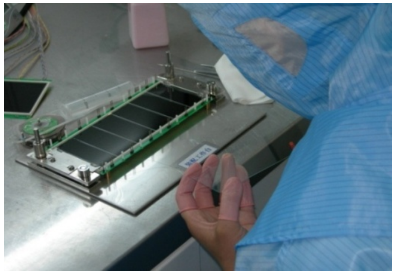
➢ Multi-gaps Resistant Plate Chamber(MRPC):

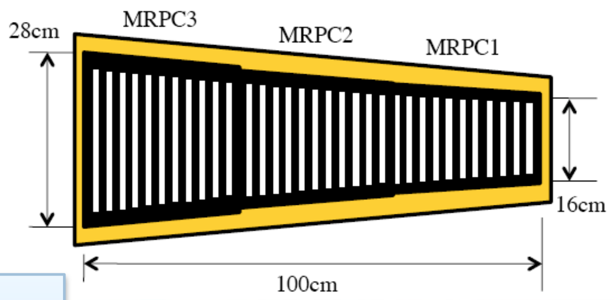


(a) The layout of the MRPC



(b) The structure of the MRPC prototype





- 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.
- Designed goal of timing resolution to be 150ns.

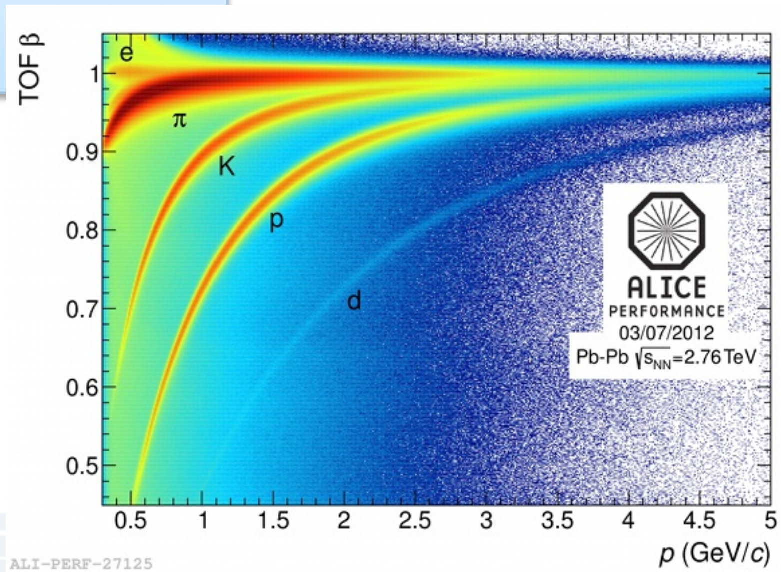
- MRPC is the key detector in the SoLID trigger system.
- The TOF-Beta has been a powerful quantities to perform PID:

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

from tracking reconstruction using GEM position info

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

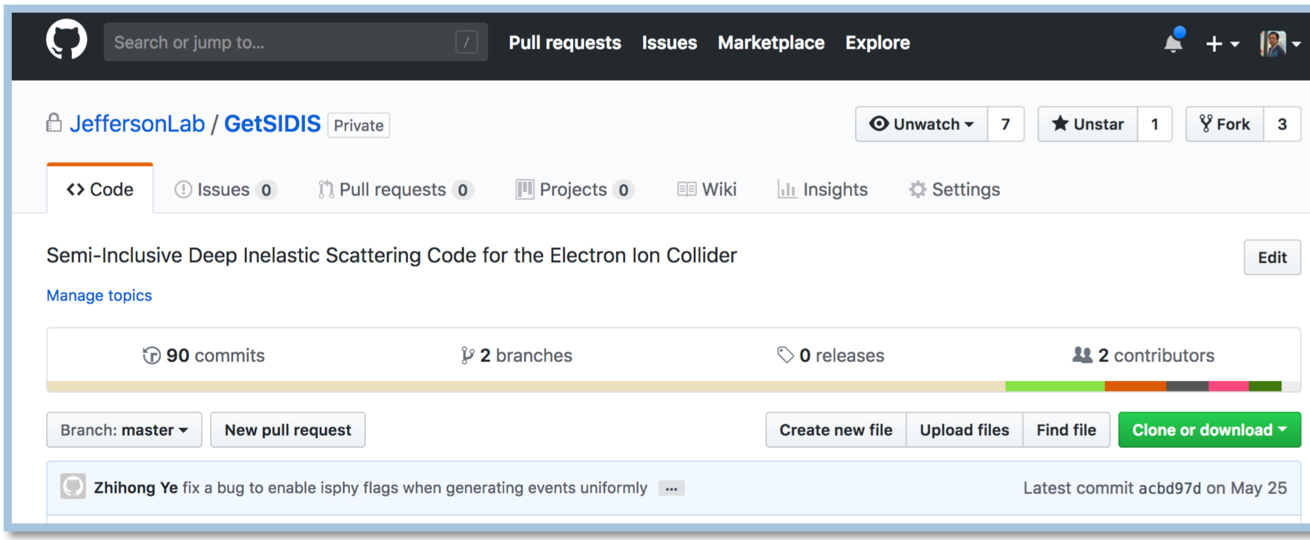
$$\Delta t = t_1 - t_2 \simeq \frac{Lc}{2p^2}(m_1^2 - m_2^2))$$



Geant4 Simulation for SoLID

➢ Step#1: Generate real physics events

Used the Monte-Carlo (MC) event generator (developed and maintained by myself) to randomly generate (electrons + pions) events and (electrons + kaons) events coming from the target region, w/ distributions are slightly wider than SoLID can detect.

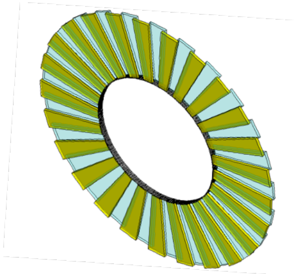


➢ Step#2: Generate background events

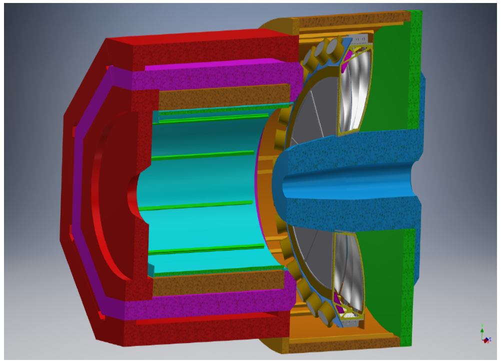
✓ Randomly generated electrons, pions, kaons and other particles coming from other reaction channels separately (i.e., random combination of (electrons + kaons), etc.), at/near the target region

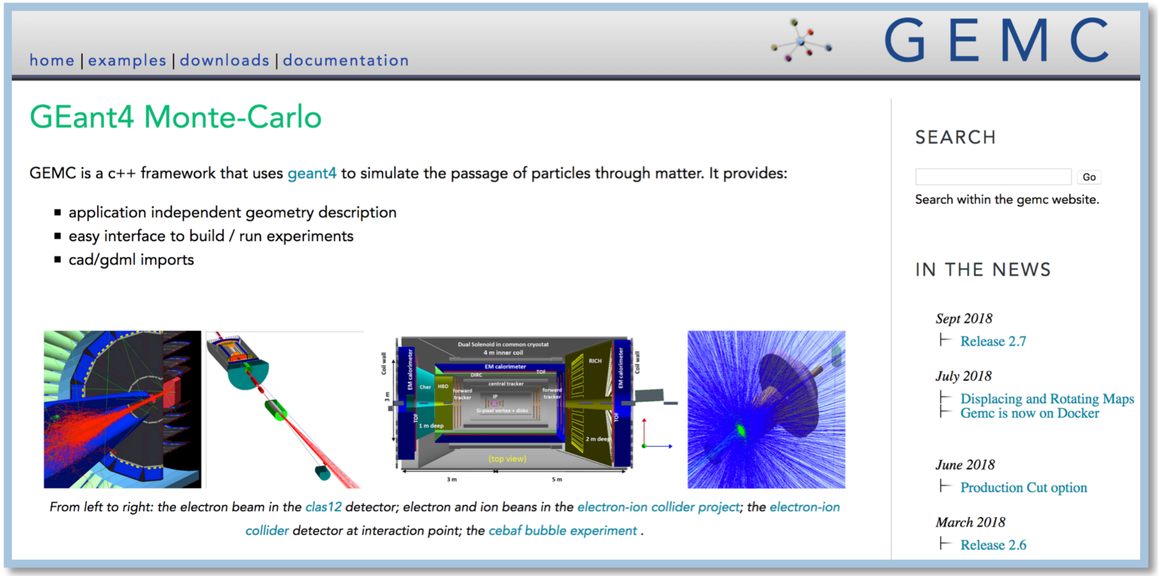
✓ Also used Geant4 to randomly secondary particles created when these particles passing through all materials including detectors

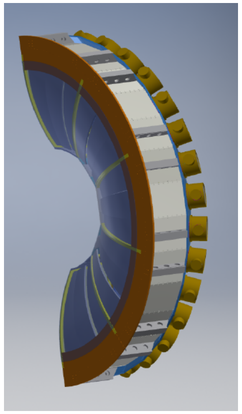
Geant4 Simulation for SoLID

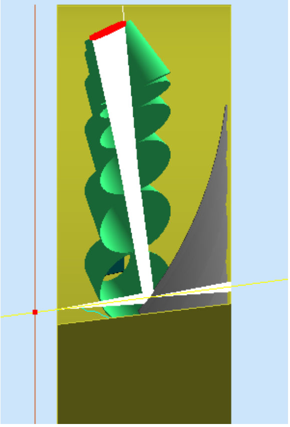


- Step#3: Define Structure of MRPC and HGC in Geant4:
  - ✓ We use a simulation toolkit developed at JLab which is a wrapper of Geant4 w/ easy geometry definitions;
  - ✓ Define the realistic locations and materials for all SoLID detectors and the magnetic field





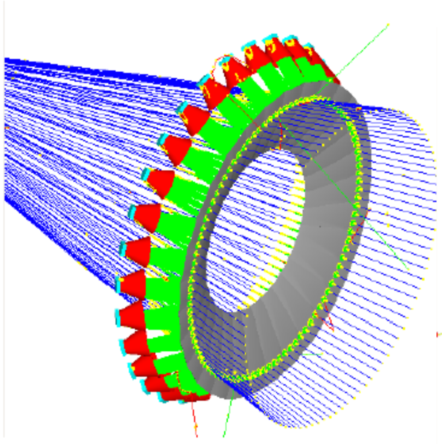


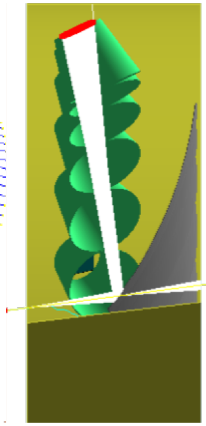


- Step#4: Propagate MC events through SoLID detectors in Geant4, and record detectors' responds (e.g., energy depositions) when particles coming from targets (and also from secondary scattering)

Geant4 Simulation for SoLID

- Step#5: Study Light Collection of HGC for pions and kaons



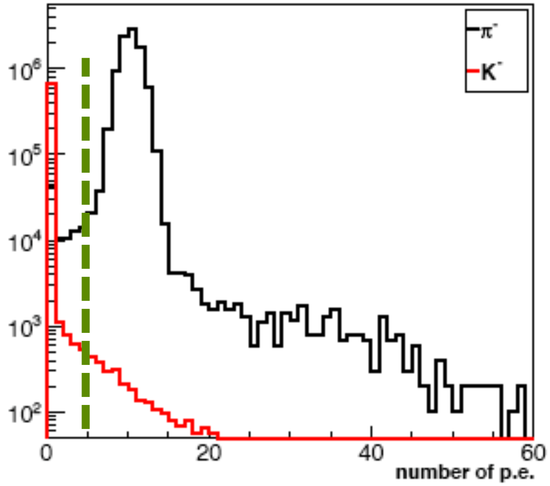


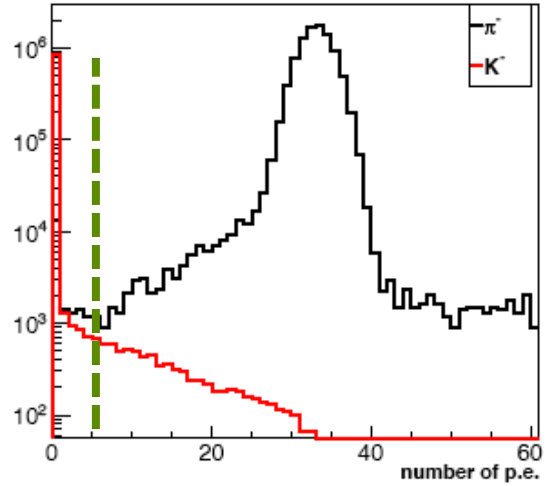
- ✓ Pion and Kaon rates strongly depend on their momenta and angles
- ✓ In high rate environments, kaons can produce "fake" signals when coming together with high-rate secondary particles ("pile-up")
- ✓ When momenta become higher (>7GeV), kaons can also fire HGC
- ✓ Light collection efficiencies dependence w/ given geometry
- ✓ Performance reduction of PMTs in strong magnetic fields after shielding

Cherenkov light production and collection in Geant4

All such effects consider in the Geant4 simulation!

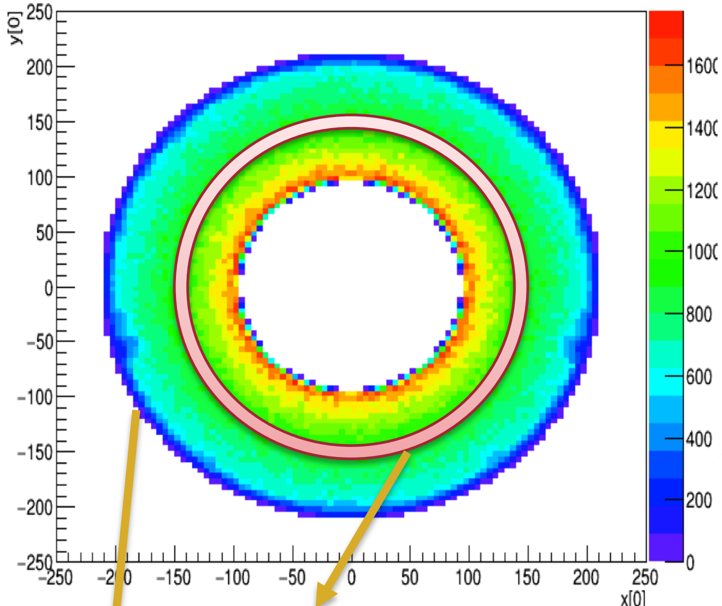
- Geant4 simulation shows that w/ 5 N.P.E, the HGC can suppress pions by 1/100 at 2.5 GeV/c and by 1/400 at 7 GeV/c





Geant4 Simulation for SoLID

- Step#6: Study “realistic” time resolution of MRPC with fine segments and background

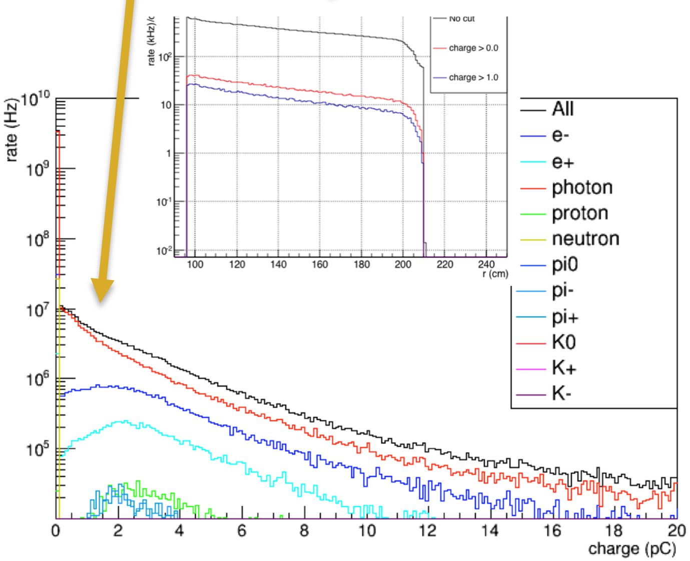


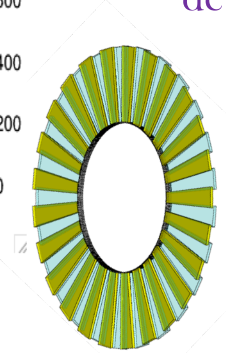
✓ Pi/K and K/p separation power depends on momenta

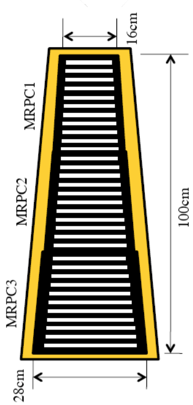
$$\Delta t = t_1 - t_2 \simeq \frac{Lc}{2p^2}(m_1^2 - m_2^2))$$

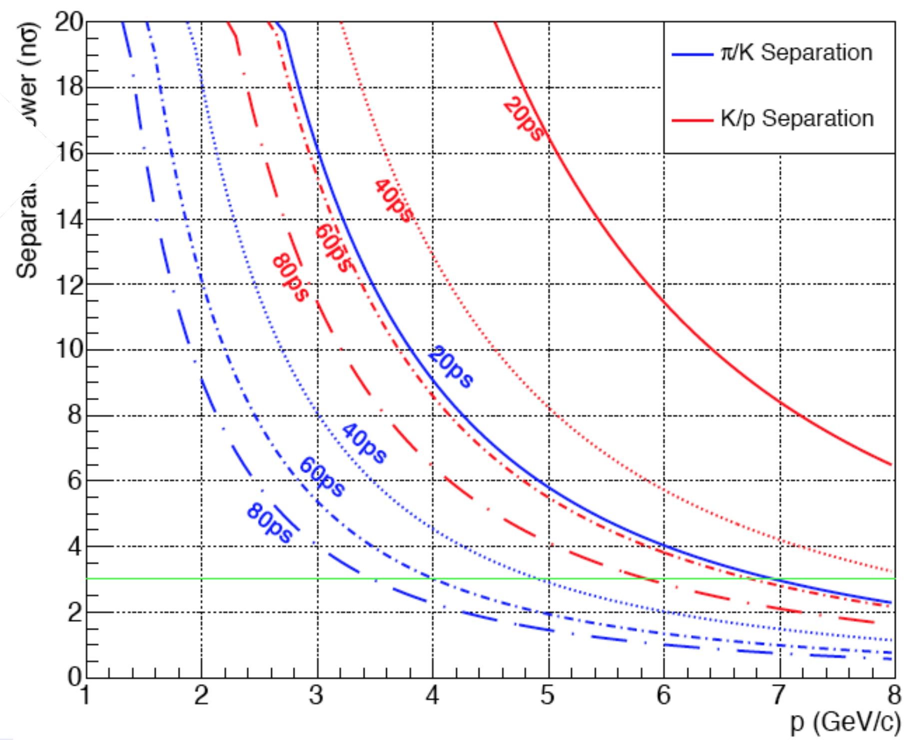
✓ Consider the pile-up effect of particles at small signals from with low-energy but high-rate

✓ Include the angle dependent background effect when determine the sizes of module segments





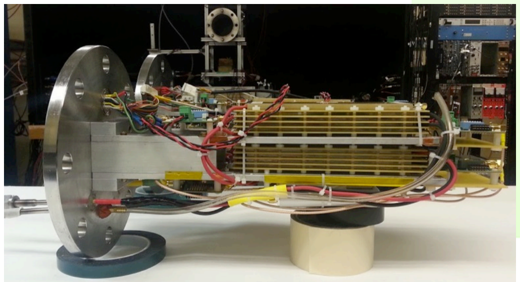


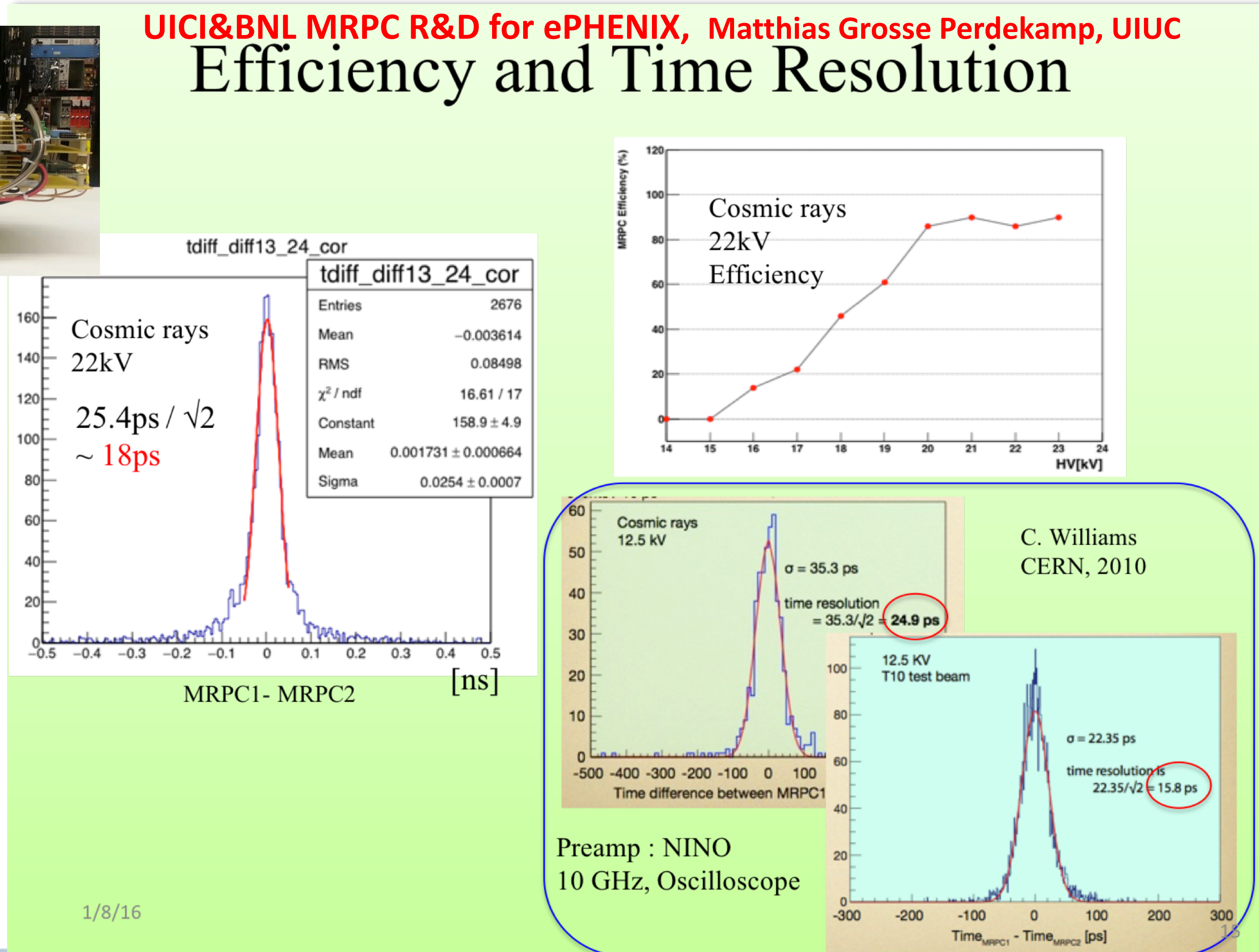


Kaon Detection on SoLID

- New MRPC R&D Progresses:

Several MRPC collaborations in US and Europe all aim for sub-ps MRPC time resolution via their R&D work:

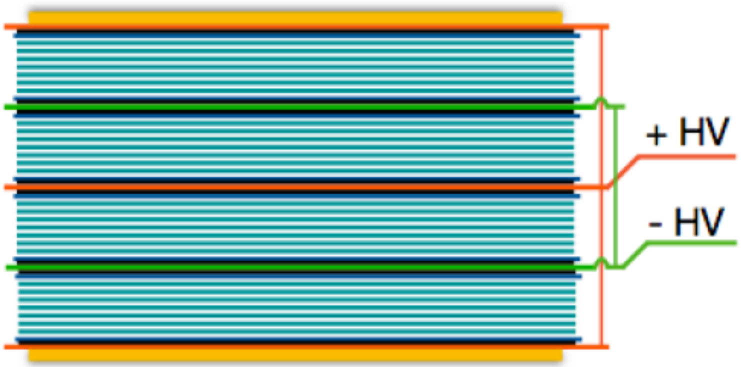




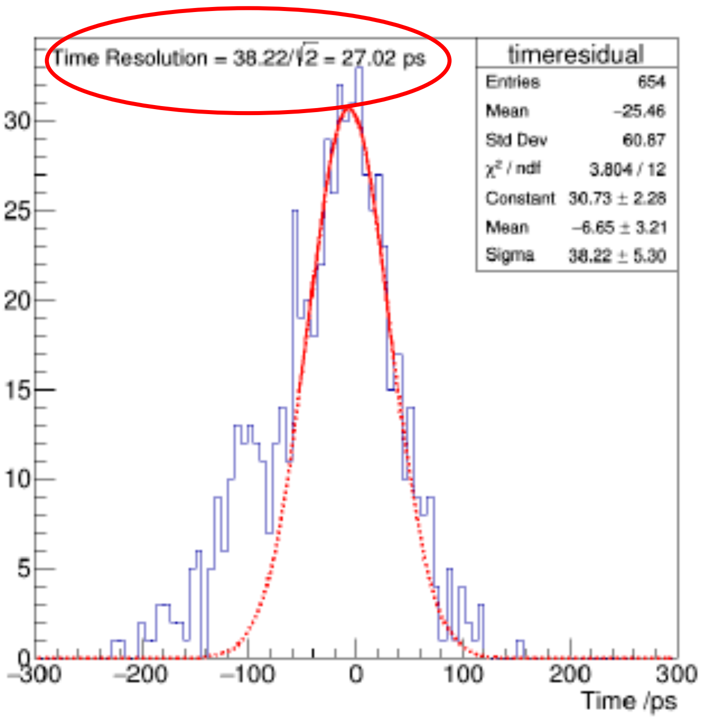
Kaon Detection on SoLID

➢ New MRPC R&D Progresses:

Tsinghua University (Y. Wang, spokesperson) are building MRPC for SoLID, improving the design (27 ps now)

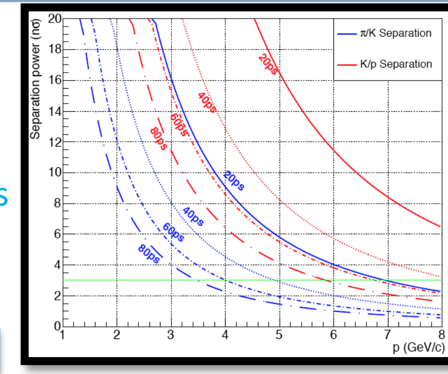


- Thinner gas gaps (0.25mm --> 0.104mm) with 8 gaps per stack (4 stacks)
- Faster Front-End Electronics to minimize time-jetter and reduce noise.
- Using Neural-Network Machine-Learning algorithms for Time-Reconstruction (learn the full signal wave-form patterns from simulation data, and estimate the particle arrival time).



- A 27 ps resolution was obtained using Cosmic Ray tests;
- Plan to perform test in a high rate experimental environment at Jefferson Lab

Kaon Detection on SoLID



- Combination of HGC and MRPC:

MRPC-TOF performs better $\pi^{\pm}/\ K^{\pm}$ separation at lower momenta

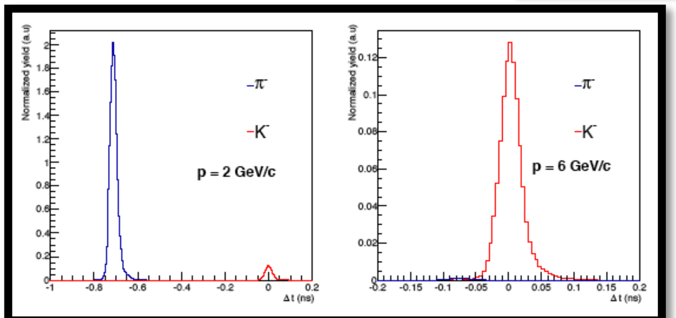
Time Resolution

40 ps

20 ps

1.0 GeV/c 2.2 GeV/c 5.0 GeV/c 7.0 GeV/c

Hadron Momentum



$\pi^{\pm}/K^{\pm}$ ratio

HGC performs better $\pi^{\pm}/\ K^{\pm}$ separation at higher momenta

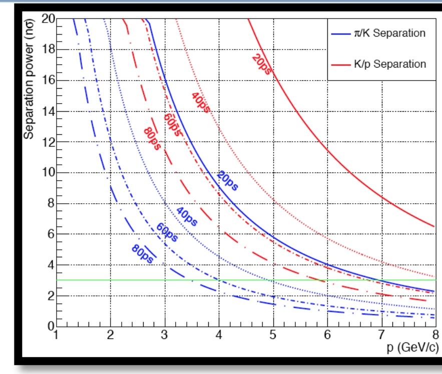
Conclusion:

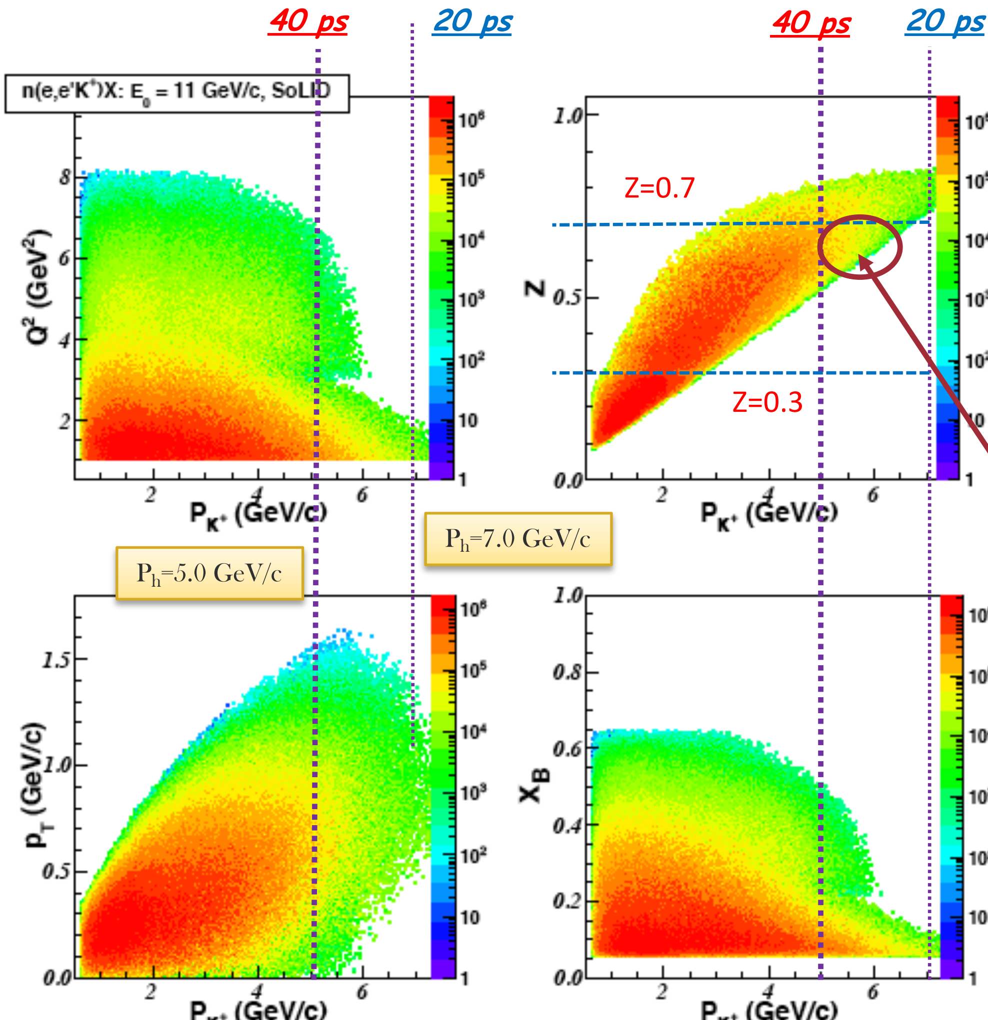
- ✓ The veto-signal of the HGC can largely isolate kaons and suppress pions at large momenta;
- ✓ MRPC can easily separate kaons from pions at low momentum using Time-Of-Flight info
- ✓ Combination of HGC veto-signals and MRPC TOF can effective identify kaons
- ✓ Existing MRPC R&D projects have reached a 20 ps time-resolution or better on MRPC;
- ✓ Even a 40 ps time resolution is acceptable considering the high-rate environment.

Kaon Detection on SoLID

- Physics Phase-Space Cut-Off due to TOF Resolution:

Correlations of maximum Kaon momenta and important physics quantities are not strong at >6GeV/c





- w/ *20 ps* resolution

  separate $\pi^{\pm}/K^{\pm}$ at P_h<7.0 GeV/c

- w/ *40 ps* resolution,

  separate $\pi^{\pm}/K^{\pm}$ at P_h<5.0 GeV/c

- w/ 60 ps resolution,

  easily separate $K^{\pm}$/p at P_h<7.0 GeV/c

The good physics events locate at 0.3<Z<0.7, hence only lose a small portion of physics events w/ 40ps resolution

Conclusion

- SoLID is the next generation detector system in experimental nuclear physics to detect high energy electrons and pions w/ high rate (100KHz) under strong magnetic fields.
- Kaons Detection can double the physics topics to study how the proton is composed by valance quarks (by measuring pions) and also sea quarks (by measuring kaons).
- In our newly approved proposal, we used the Geant4 simulation to demonstrate the capability of detecting kaons by requires 20~40ps time resolution of MRPC w/ helps from HGC. No extra configuration-change or significant-cost needed.
- Recent MRPC R&D showed that <20 ps is achievable, but needed to verify in high rate experiments.

46th PROGRAM ADVISORY COMMITTEE (PAC46)

July 16, 2018 Jefferson Lab

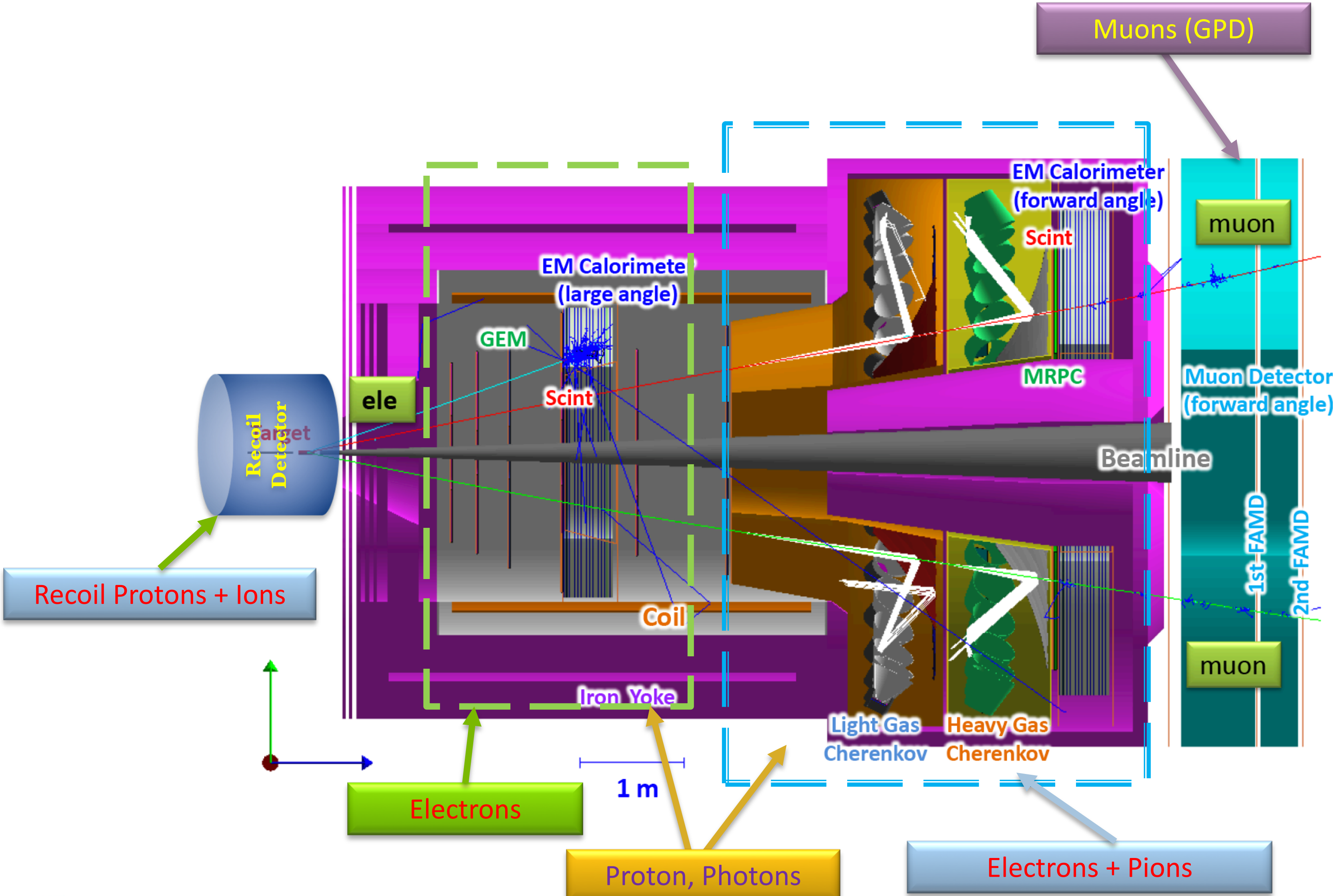
The PAC also encourages the collaboration to explore whether a broader program with kaon measurements could be established in SoLID, once the detection technique has been demonstrated to be viable.

Summary: The PAC is excited at the prospect of kaon measurements in SoLID. It endorses the effort to reach suitable time resolution of the MRPC and, if this can be realized, supports the run group addition.

The new experiment was approved!

Backup

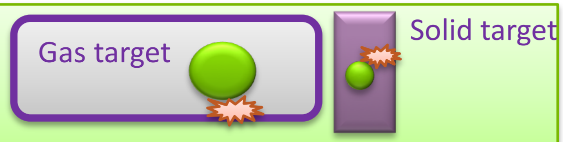
All Possible Upgrades on SoLID

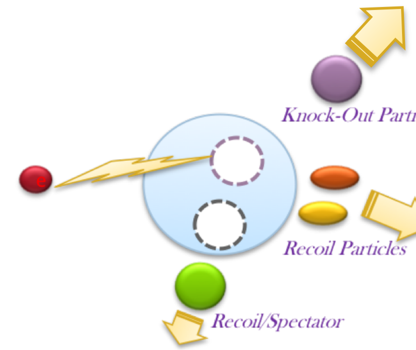


General Purpose 4π Detector Systems - SoLID

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

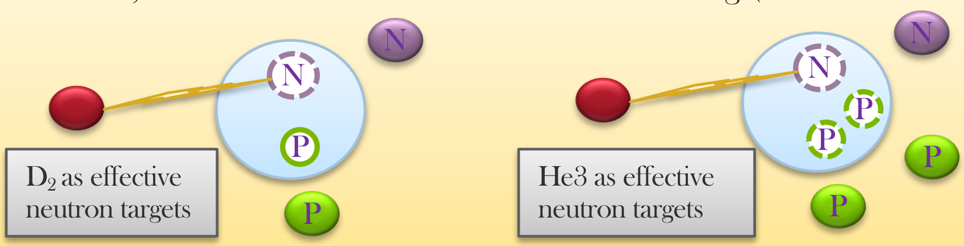
❖ Low energy knock-out particles can not get out from thick targets



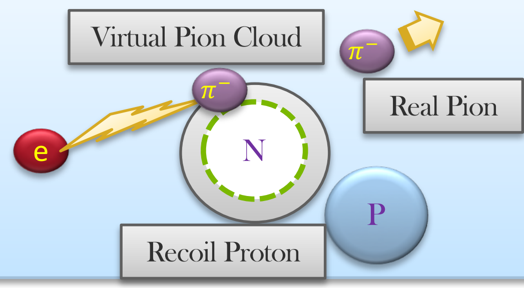


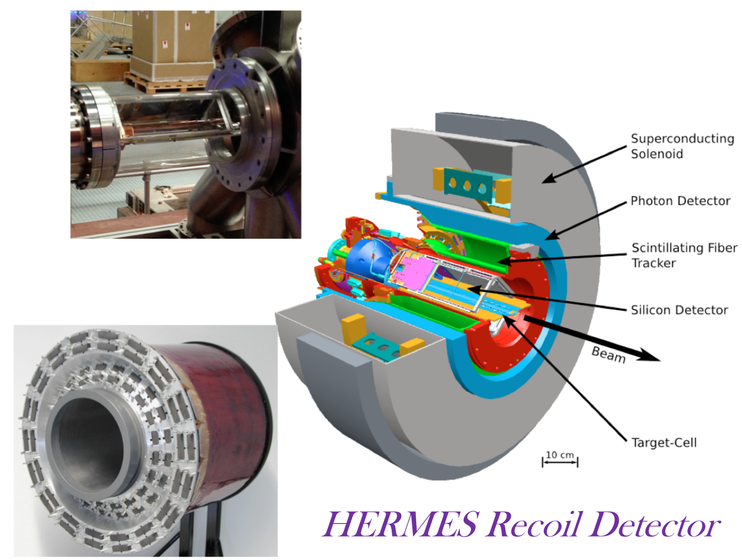
Spectator Nucleons move with Fermi-Momentum (<200 MeV/c)

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



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

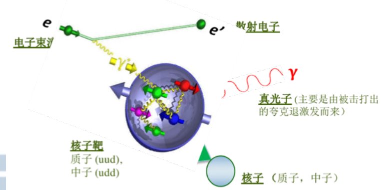




HERMES Recoil Detector

❖ 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

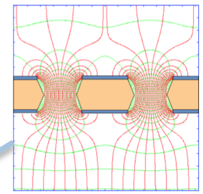
$$e + \vec{n} \rightarrow e' + n + \gamma$$

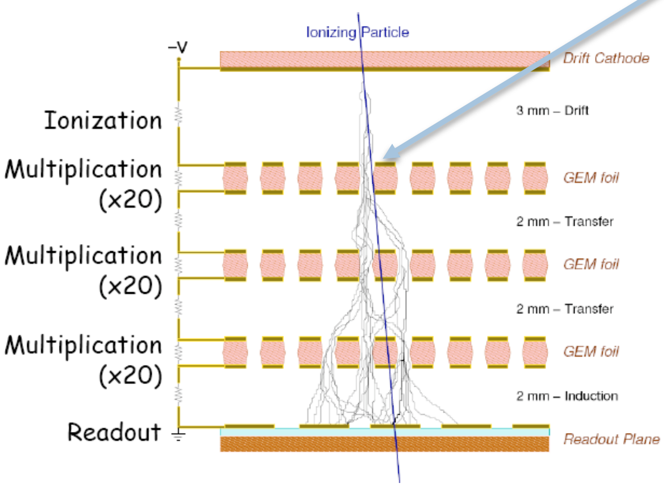


General Purpose 4π Detector Systems - SoLID

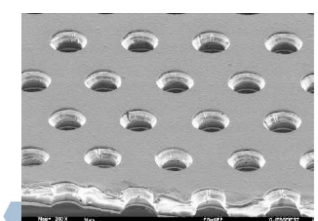
- Gas Electric Multiplier (GEM):
  - ✓ Can handle very high rate (50MHz per mm^2)
  - ✓ Can also work in a high magnetic field

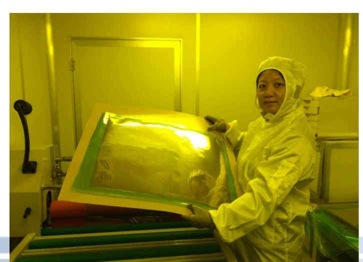
- ❖ Strong electric field inside the holes
- ❖ Charged particles ionize atoms
- ❖ Drifting electrons are amplified during cascade
- ❖ Signals are read out in the back panel



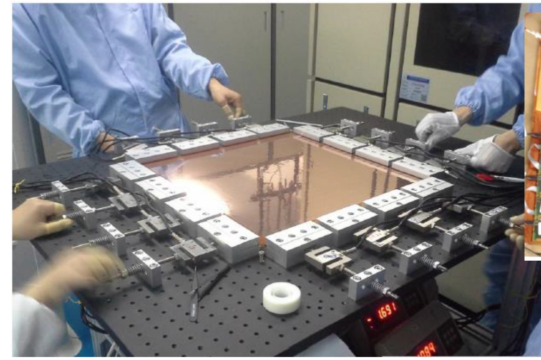


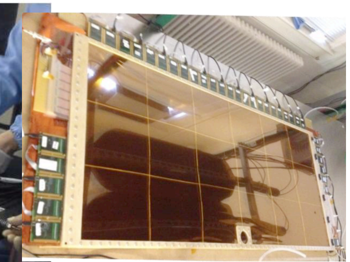
- ❖ GEM foil: 50 mm Kapton + few mm copper on both sides with 70 mm holes, 140 mm pitch



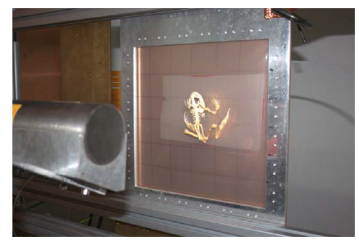


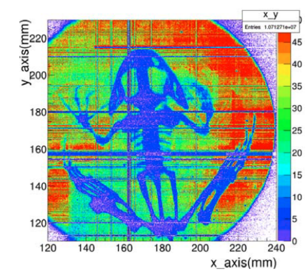
- ❖ Easily built into different shapes based detector geometry





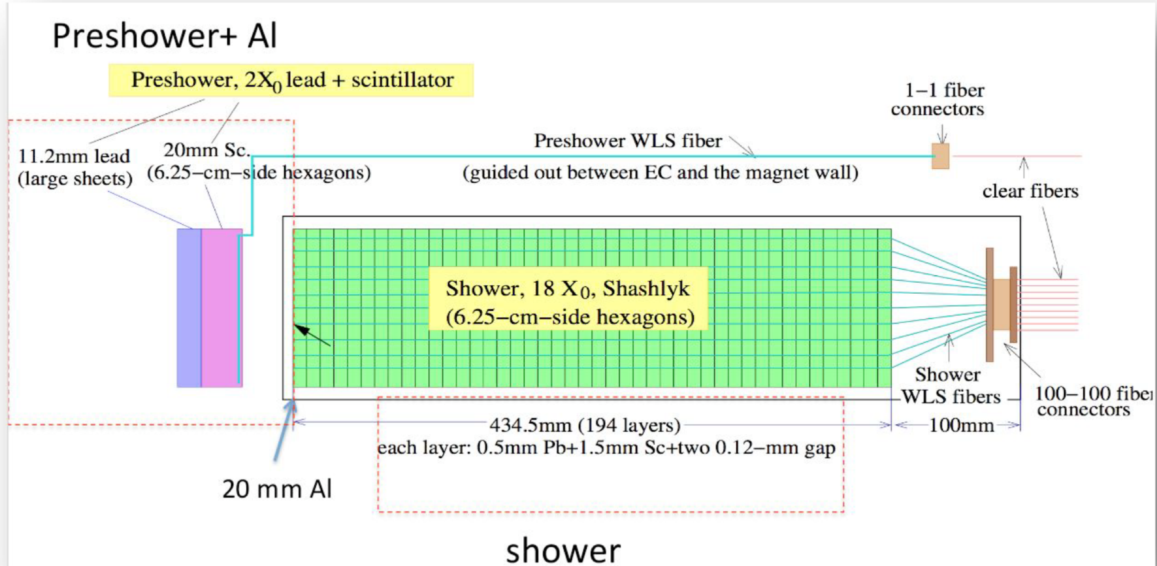
- ❖ Provide good position resolution (80um)





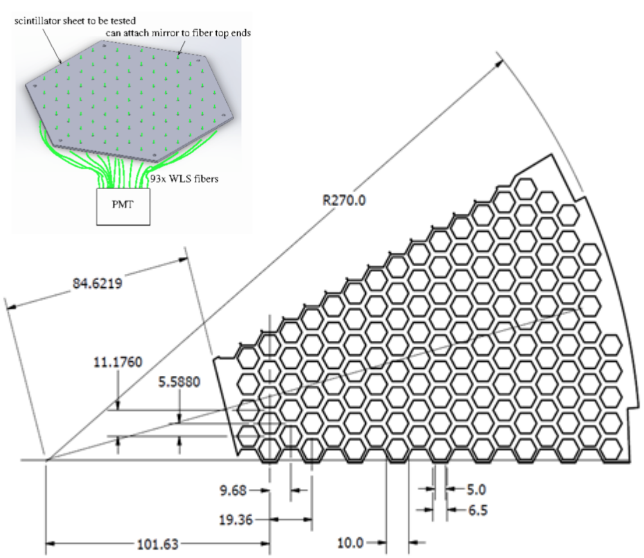
General Purpose 4π Detector Systems - SoLID

- 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