Business trip short report

Hamlet Mkrtchyan

(Visit to JLab (CEBAF) from 01 March to 16 June 2020)

- Participation in A1n & d2n experiments (with polarized ^3He)
- Data Analysis (2018-2019 SIDIS + CSV + KaonLT experiments)
- Detector Calibration (Aerogel & Gas Cherenkov, Calorimeter)
- NPS work (rates, high anode current, HV divider problem)
- Participation in EIC Calorimetry group activities
- Other activities
- Future plans

ANSL Experimental Physics Division Meeting,
22 June 2020

Hall C A1n & d2n Experiments

Interest in spin structure of the nucleon become prominent in 1980's. Experiments at CERN and SLAC showed that the total spin carried by quark was very small which was in contrast to the simple relativistic quark model prediction.

Current understanding of the nucleon spin: the total spin is distributed among valence quarks, quark-antiquark sea, their orbital angular momenta, and gluons. This is called the nucleon spin sum rule:

$$S_z^N = S_z^q + L_z^q + J_z^g = \frac{1}{2}$$

where S_z^N is the nucleon spin, S_z^q and L_z^q represent respectively the quark spin and orbital angular momentum, and J_z^g is the total angular momentum of the gluons.

Only about (20-30)% of the nucleon spin is carried by spin of the quarks!

1) E12-06-110: Neutron Spin Asymmetry A1n ***(X. Zheng, G. Cates, J.-p. Chen and Z.-E. Meziani)***

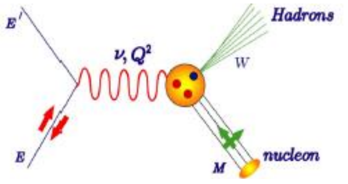
2) E12-06-121: Neutron g_2 ***and*** d_2 ***(*****B. Sawatzky, T. Averett, W. Korsch, Z.-E. Meziani)**

- Precision measurements of the neutron spin structure functions in the deep inelastic scattering in the far valence quark region $0.61 < x < 0.77$ and $3 < Q^2 < 10$ GeV^2.

- Both experiments used polarized ^{3}He target with SHMS & HMS spectrometer to study Q^2 dependence of A1n & d2n, and test predictions of various theoretical models.

Formalism of Structure Functions

Unpolarized cross section is measured structure functions F_1 and



$$\frac{d^2\sigma}{d\Omega\, dE'} = \frac{\alpha^2}{4E^2 \sin^4\frac{\theta}{2}} \left(\frac{2}{M} F_1(x, Q^2) \sin^2\frac{\theta}{2} + \frac{1}{\nu} F_2(x, Q^2) \cos^2\frac{\theta}{2} \right)$$

F_1 and F_2 contain information about the momentum structure of the nucleon

Polarized cross section is sensitive to both g_1 and g_2 structure functions :

For a longitudinally polarized target:

$$\left(\frac{d^2\sigma}{d\Omega dE'}\right)_{\|} = \sigma_{Mott} \left\{ \frac{F_1(Q^2,\nu)}{E'} \tan^2\frac{\theta}{2} + \frac{2E' F_2(Q^2,\nu)}{M\nu} \pm \frac{4}{M} \tan^2\frac{\theta}{2} \left[\frac{E + E'\cos\theta}{\nu} g_1(Q^2,\nu) - \gamma^2 g_2(Q^2,\nu) \right] \right\},$$

For a transversely polarized target:

$$\left(\frac{d^2\sigma}{d\Omega dE'}\right)_{\perp} = \sigma_{Mott} \left\{ \frac{F_1(Q^2,\nu)}{E'} \tan^2\frac{\theta}{2} + \frac{2E' F_2(Q^2,\nu)}{M\nu} \pm \frac{4}{M} \tan^2\frac{\theta}{2} E' \sin\theta \left[\frac{1}{\nu} g_1(Q^2,\nu) + \frac{2E}{\nu^2} g_2(Q^2,\nu) \right] \right\},$$

Two asymmetries are used to extract g_1 & g_2 :

$$A_{\|} \equiv \frac{\sigma^{\downarrow\Uparrow} - \sigma^{\uparrow\Uparrow}}{\sigma^{\downarrow\Uparrow} + \sigma^{\uparrow\Uparrow}} = \frac{4\tan^2\frac{\theta}{2}\left[\frac{E+E'\cos\theta}{\nu} g_1(Q^2,\nu) - \gamma^2 g_2(Q^2,\nu)\right]}{M\left[\frac{F_1(Q^2,\nu)}{E'}\tan^2\frac{\theta}{2} + \frac{2E'F_2(Q^2,\nu)}{M\nu}\right]},$$

$$A_{\perp} \equiv \frac{\sigma^{\downarrow\Rightarrow} - \sigma^{\uparrow\Rightarrow}}{\sigma^{\downarrow\Rightarrow} + \sigma^{\uparrow\Rightarrow}} = \frac{4\tan^2\frac{\theta}{2} E' \sin\theta \left[\frac{1}{\nu} g_1(Q^2,\nu) + \frac{2E}{\nu^2} g_2(Q^2,\nu)\right]}{M\left[\frac{F_1(Q^2,\nu)}{E'}\tan^2\frac{\theta}{2} + \frac{2E'F_2(Q^2,\nu)}{M\nu}\right]}.$$

d_2 is the linear combination of the g_1 and g_2

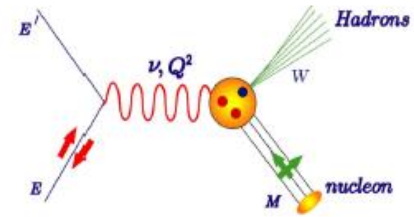
$$d_2(Q^2) = \int_0^1 x^2 2g_1(x,Q^2) + 3g_2(x,Q^2)\, dx$$

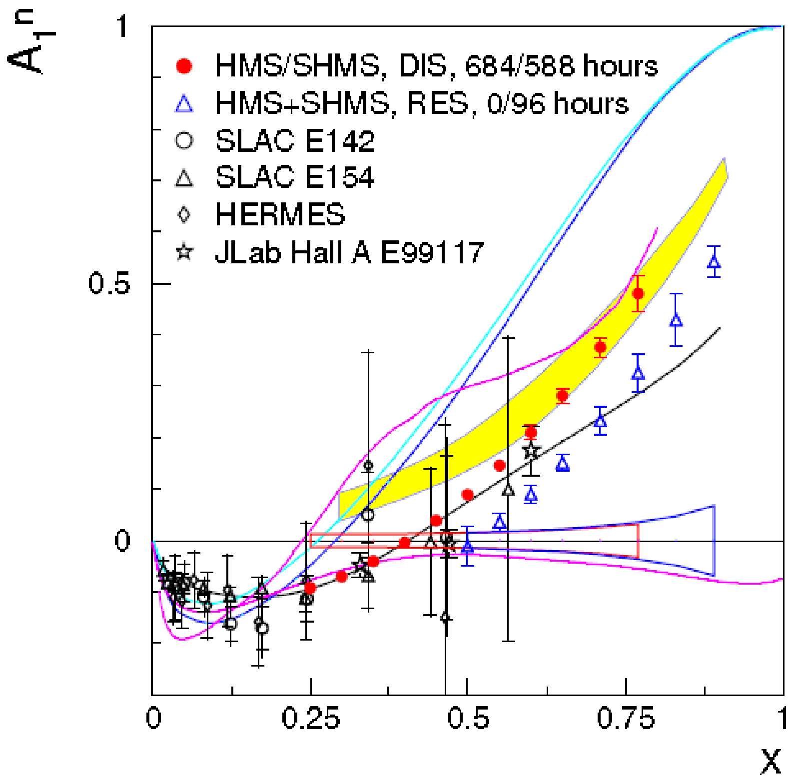
Neutron A1n and d2n current & projected data

The spin asymmetries A_1 and A_2 are related to virtual photon absorption cross sections for photon helicities +1, -1 and 0:

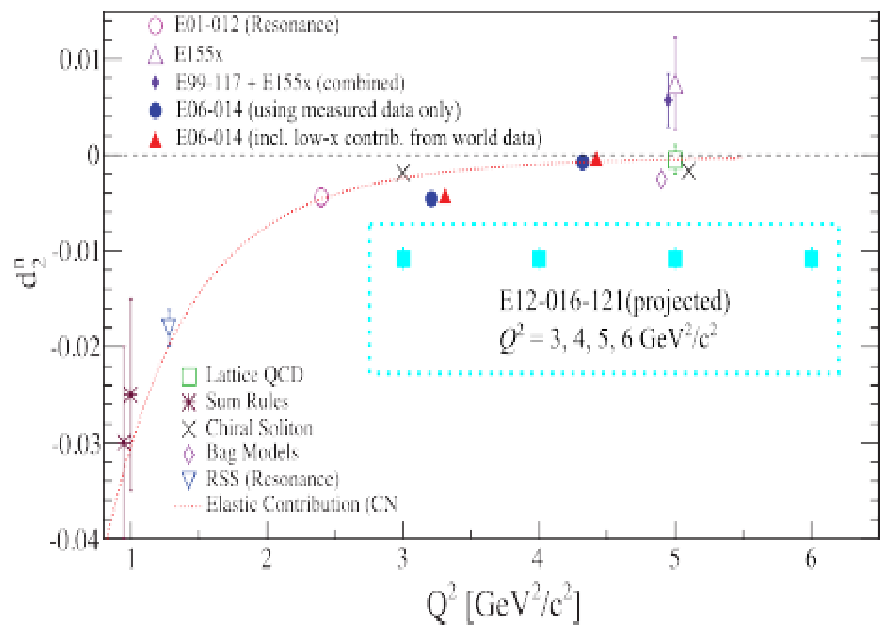
$$A_1 = \frac{\sigma^T_{1/2} - \sigma^T_{3/2}}{\sigma^T_{1/2} + \sigma^T_{3/2}} = \frac{1}{F_1}(g_1 - \gamma^2 g_2)$$

$$A_2 = \frac{2\sigma_{LT}}{\sigma^T_{1/2} + \sigma^T_{3/2}} = \frac{\gamma}{F_1}(g_1 + g_2)$$





$$d_2(Q^2)=3\int_0^1 x^2[2g_1(x,Q^2)+3g_2(x,Q^2)]dx=3\int_0^1 x^2\bar{g}_2(x,Q^2)dx$$



Due to Pauli principle, the two protons in ^{3}He are in an antisymmetric spin state. Total spin of ^{3}He is carried by the neutron. Measurement of the ^{3}He asymmetry is a measurement of the neutron asymmetry.

A1n and d2n Experimental Setup

Detectors:

- High Momentum Spectrometer (HMS)
- Super HMS (SHMS)

Electron Beam:

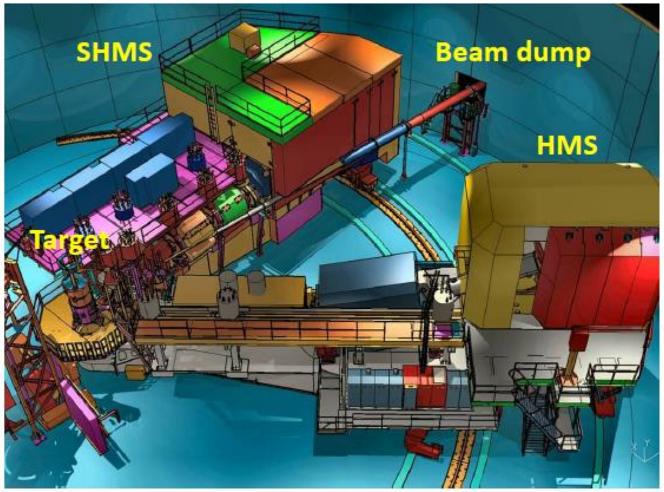
- 1-pass (elastic, Δ(1232))
- 5-pass beam (DIS, resonance)
- Beam polarization: 85%
  (2% uncertainty by Moller Polarimeter)
- Circular beam raster with 2.5mm radius
- < 50 ppm charge asymmetry (average over ~ 1–2 hr run)

Polarized ^{3}He target:

- ^{3}He production cell (40cm)
- 55–60% polarization without beam
- 30 uA beam current
  (doubles performance compare to 6 GeV era)
- 3% uncertainty for polarimetry

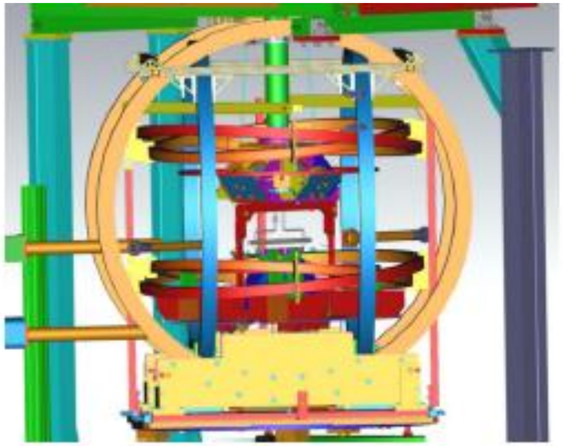
12 GeV Hall C base equipment

HMS (old) and SHMS (new) magnetic spectrometers are well suited for (e,e') coincident measurements.



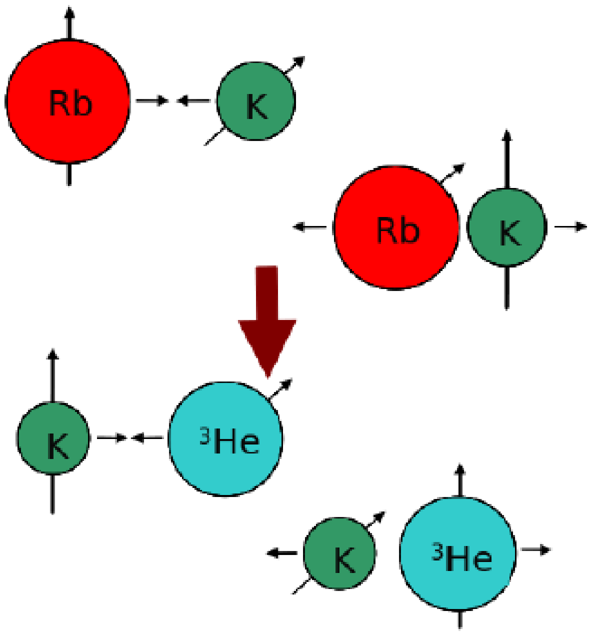
SHMS parameters:
Magnets: (HB)QQQD
P: 2 -- 11 GeV/c
ΔP: (-10% , +22%)
δP: 0.03%-0.08%
θ: 5.5 ° -- 40°
Δ Ω: 4.0 msr

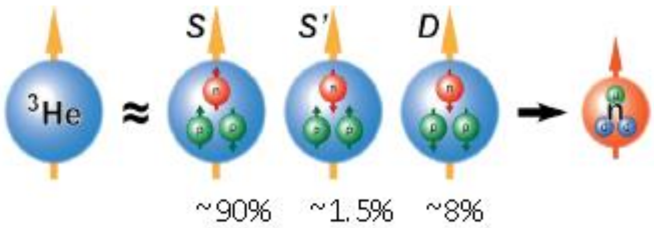
HMS parameters:
Magnets: QQQD
P: 0.5 – 7.5 GeV/c
ΔP: (-10% , +10%)
δP: 0.1%
θ: 12.5 ° -- 90°
Δ Ω: 6.0 msr
L: 10^{38} cm^{-2}s^{-1}

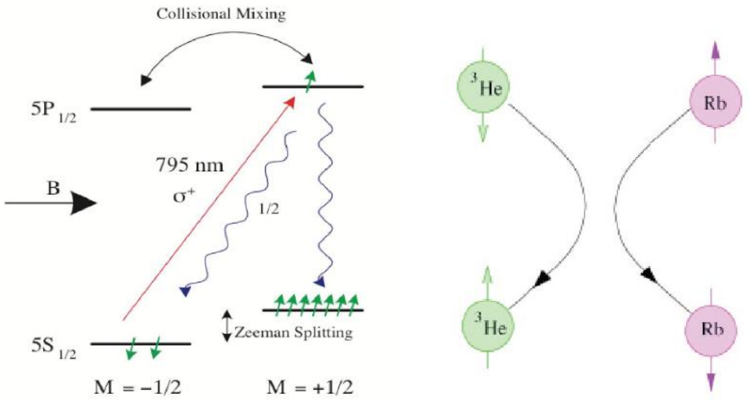


A1n and d2n Polarized 3He Target

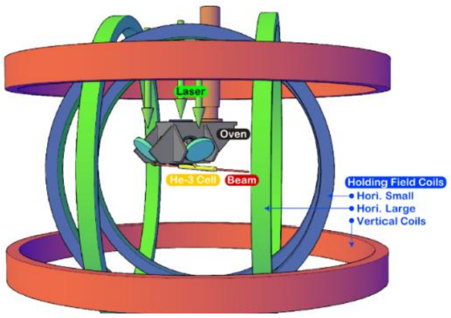
Spin-Exchange Optical Pumping (SEOP)





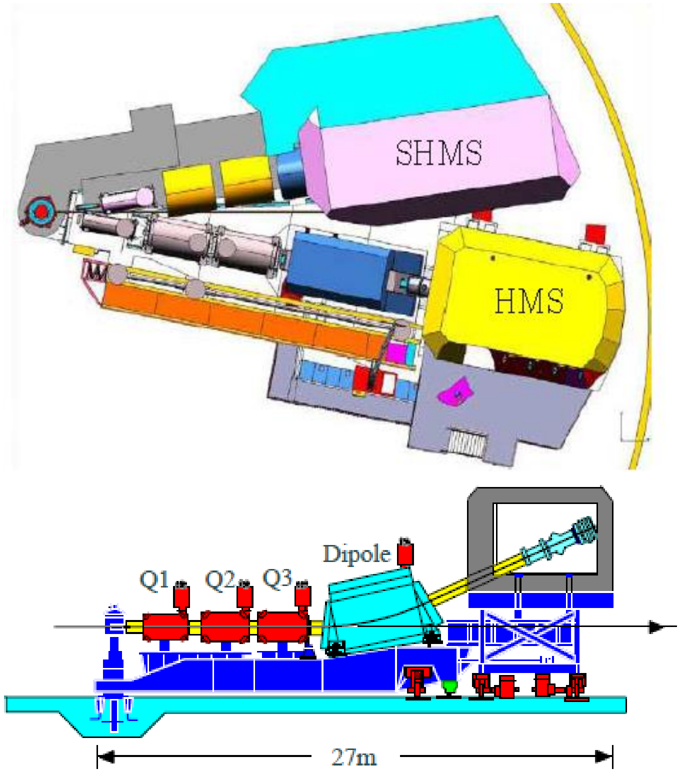


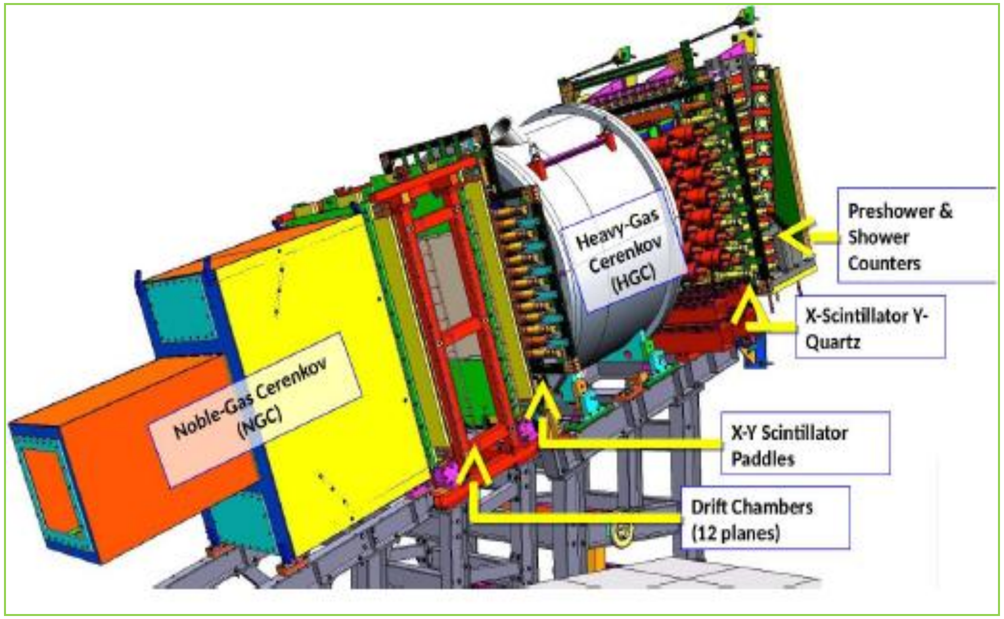
- Collision with angular momentum conservation;
- Spin exchange: Alkali atom ↔ ^{3}He nucleus;
- Rb-K mixture Alkali gas(hybrid cell);
- Higher in-beam polarization 55-60%;



Three sets of Helmholtz coils to provide polarization in 3-d

Detector Calibration and PID

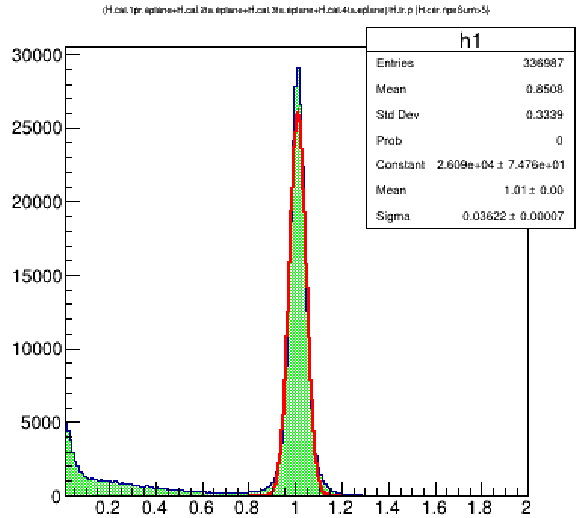


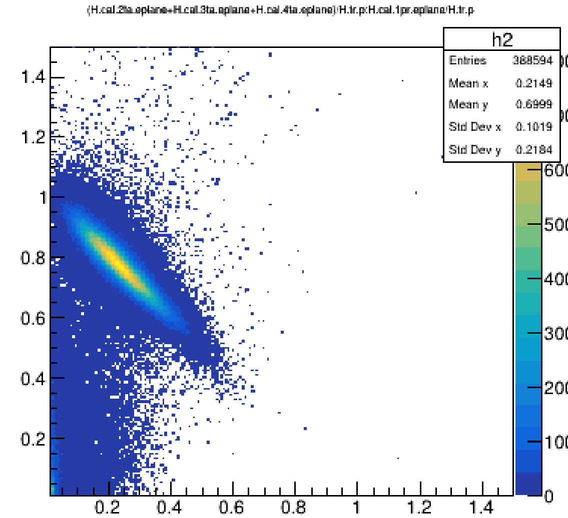


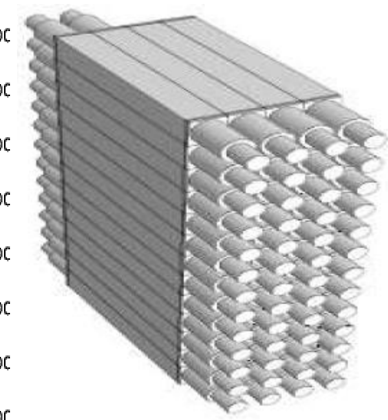
- Detector Calibration and PID
  - HMS: ECal and gas Cerenkov calibration
  - SHMS: ECal, Aerogel detector, heavy & nobel gas Cerenkov calibration
  - SHMS: Aerogel detector & heavy gas Cerenkov response to π, K and p
  - SHMS: effect of knock-electrons and scintillation on aerogel detector

HMS Calorimeter Calibration

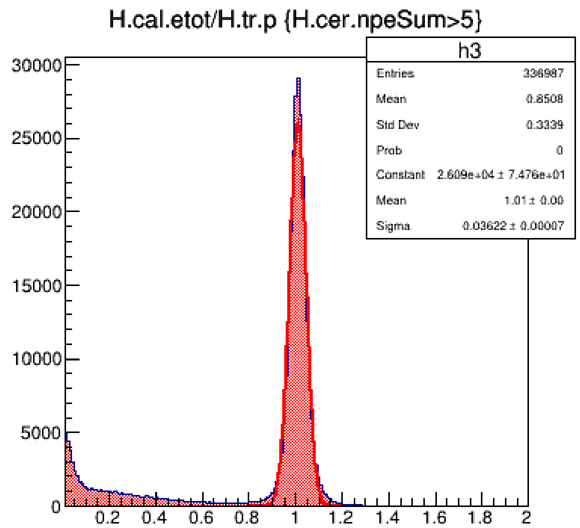
Spring 2019 data

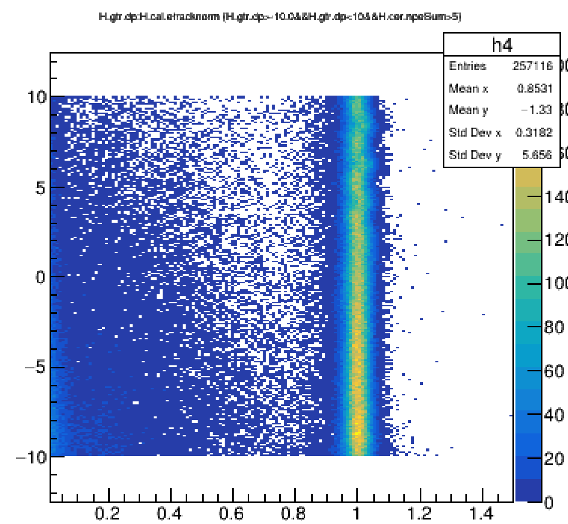






A sketch of the HMS calorimeter



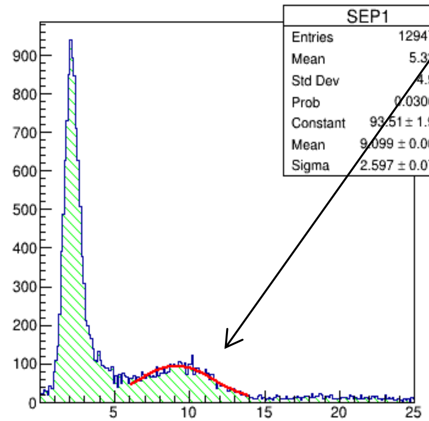


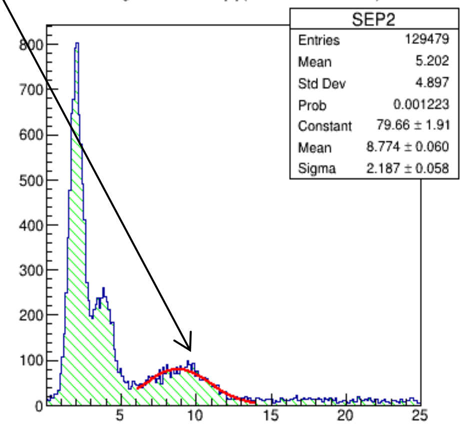
Calorimeter analysis and Calibration codes have been developed by V. Tadevosyan

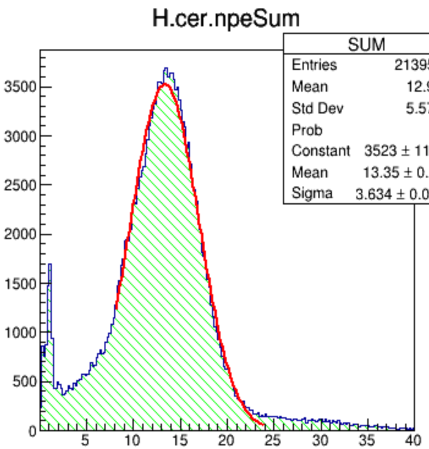
HMS Gas Cerenkov Detector Calibration

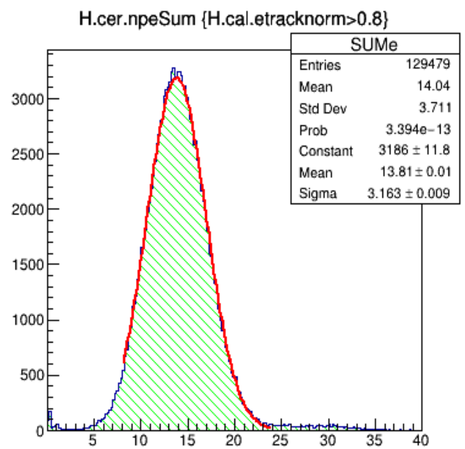
Cerenkov radiation threshold for particles (1-β) < (n-1)

PMTs Pulse Integral distributions from fADC have been used to localize SEP







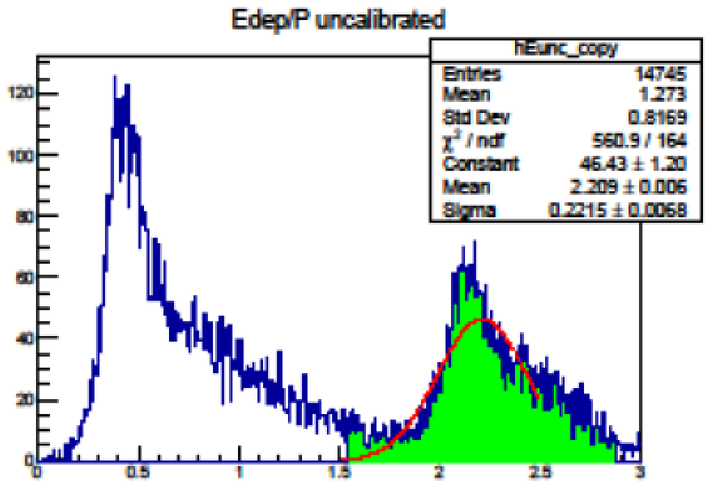


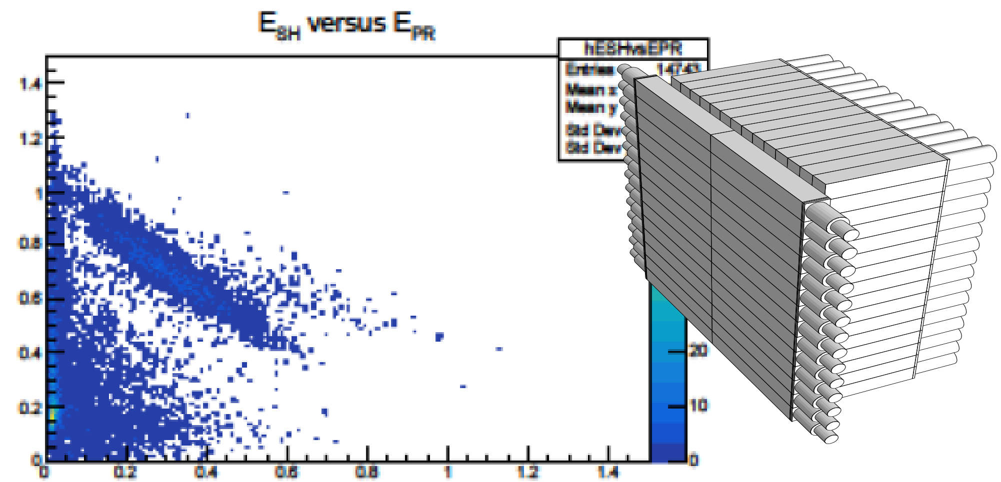
HMS Cerenkov: 2R = 150 cm, L=165cm

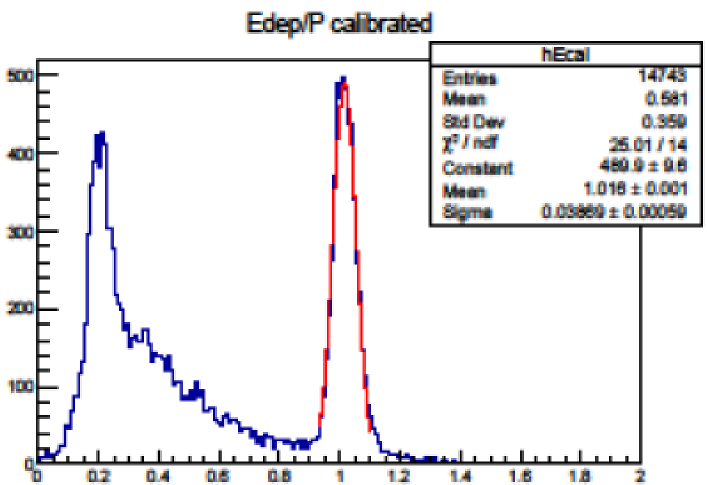
- Filled C_4F_8O (octafluorotetrahydrofuran) at 0.42 atm, n=1.0006, (n=1.0014 at 1 atm)
- Pion threshold momentum ~4.0 GeV/c
- 2 mirrors and 2 PMTs (5” Burle 8854 coated with WLS to improve efficiency

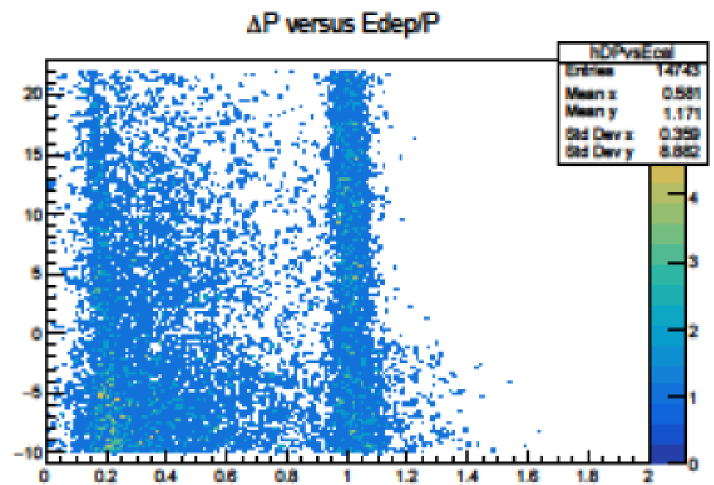
Sum of Photoelectrons before and after PID cut

SHMS Calorimeter Calibration





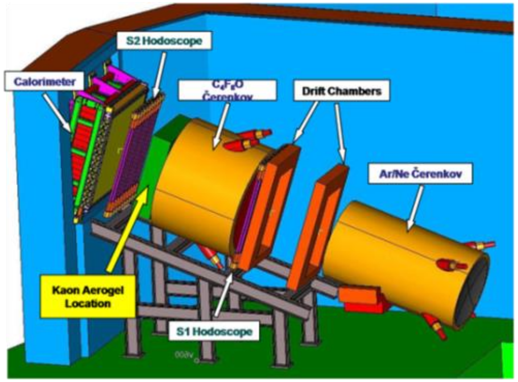




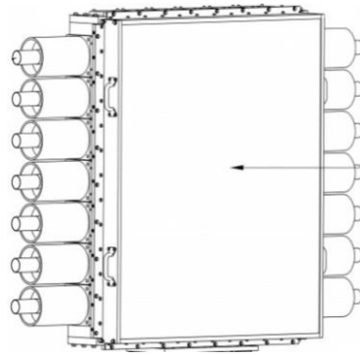
Note, SHMS Calorimeter have been designed and build by YerPhI group

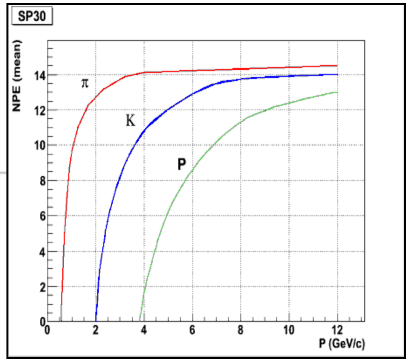
SHMS Aerogel Cerenkov PMTs Calibration

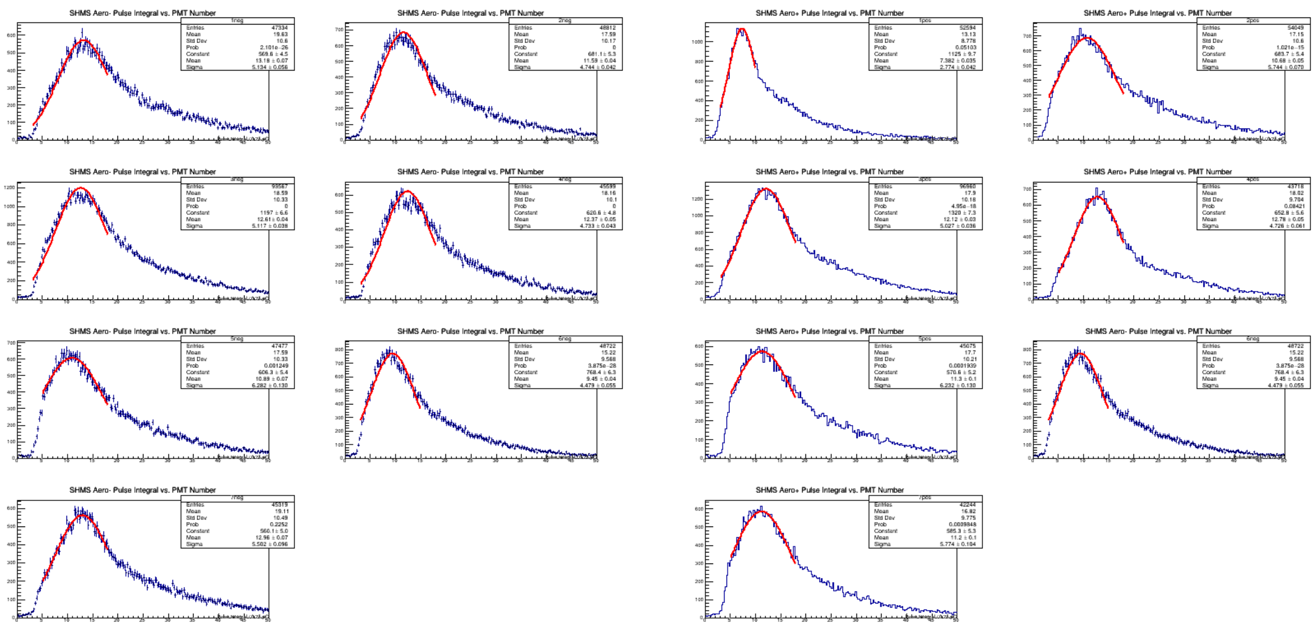
Cerenkov radiation threshold for particles $(1-\beta) < (n-1)$



14 PMTs, 5” XP4572
4 exchangeable tray:
n=1.030, n=1.020
n=1.015 and n=1.011



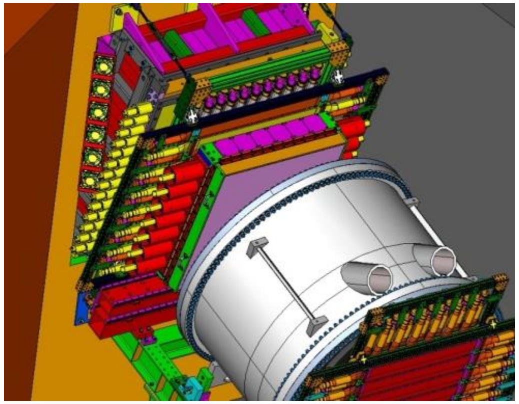




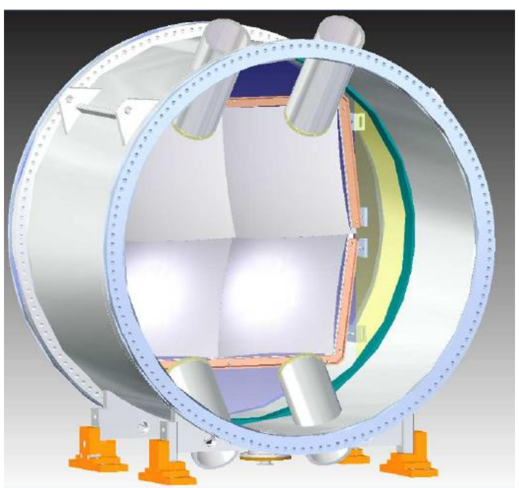
SHMS Aerogel detector PMTs SEP distributions.

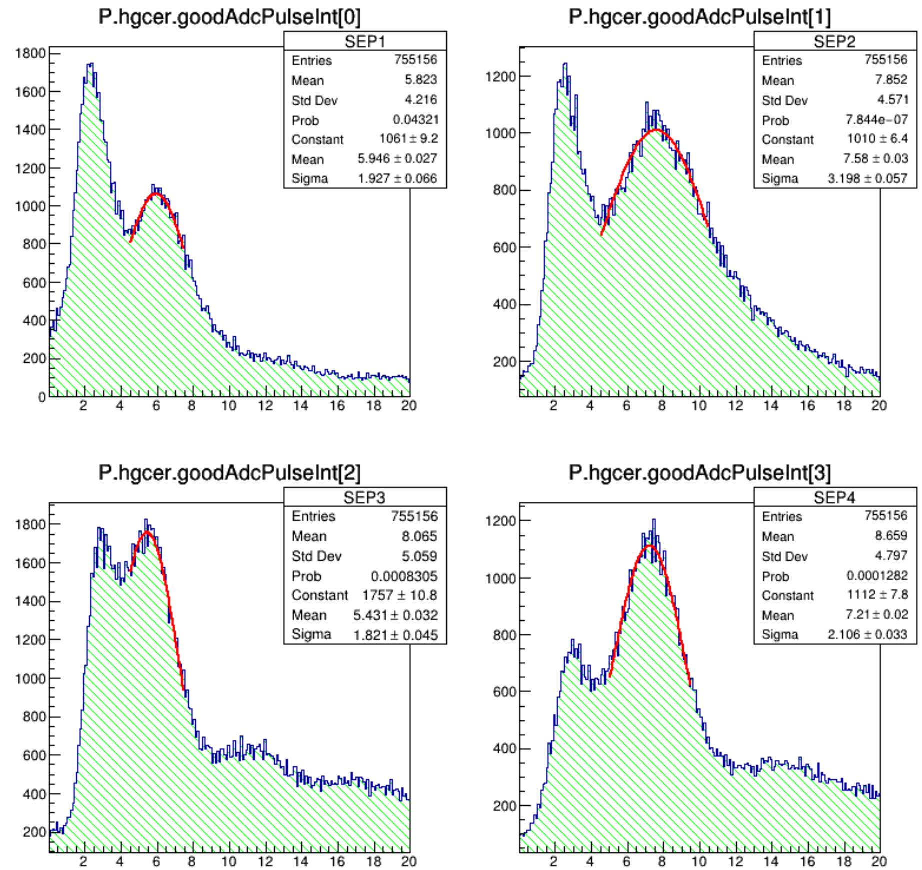
SHMS HG Cerenkov Calibration

Cerenkov radiation threshold for particles (1-β) < (n-1)



- Filled with C_4F_8O (octafluorotetra-hydrofuran) n=1.0014 at 1 atm
- 4 mirrors and 4 PMTs (Hamamatsu)

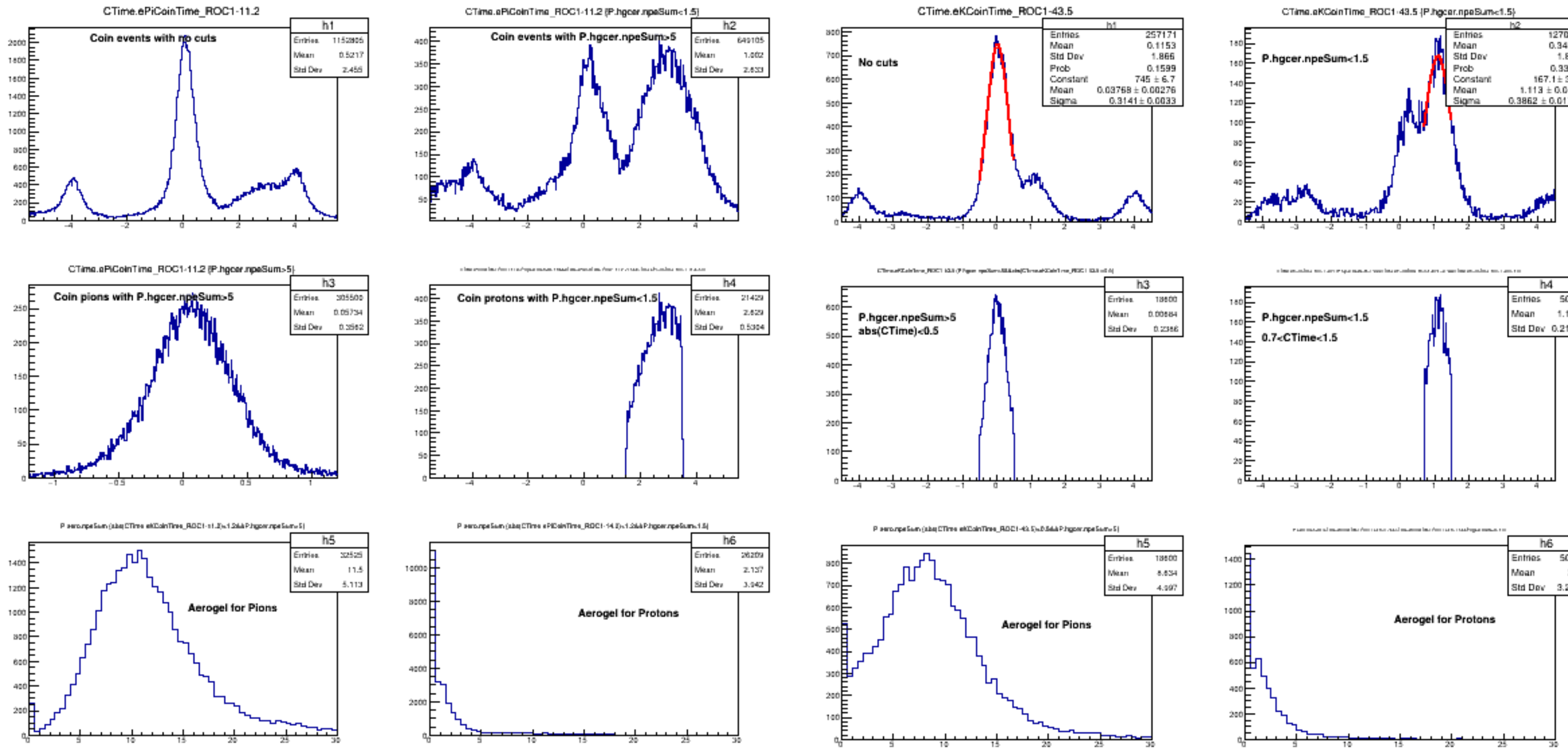




- HG Cerenkov PMTs SEP positions from run-to-run are stable.
- In some cases the 2 electron peak also can be seen.

Aerogel detector response to π (K) & protons

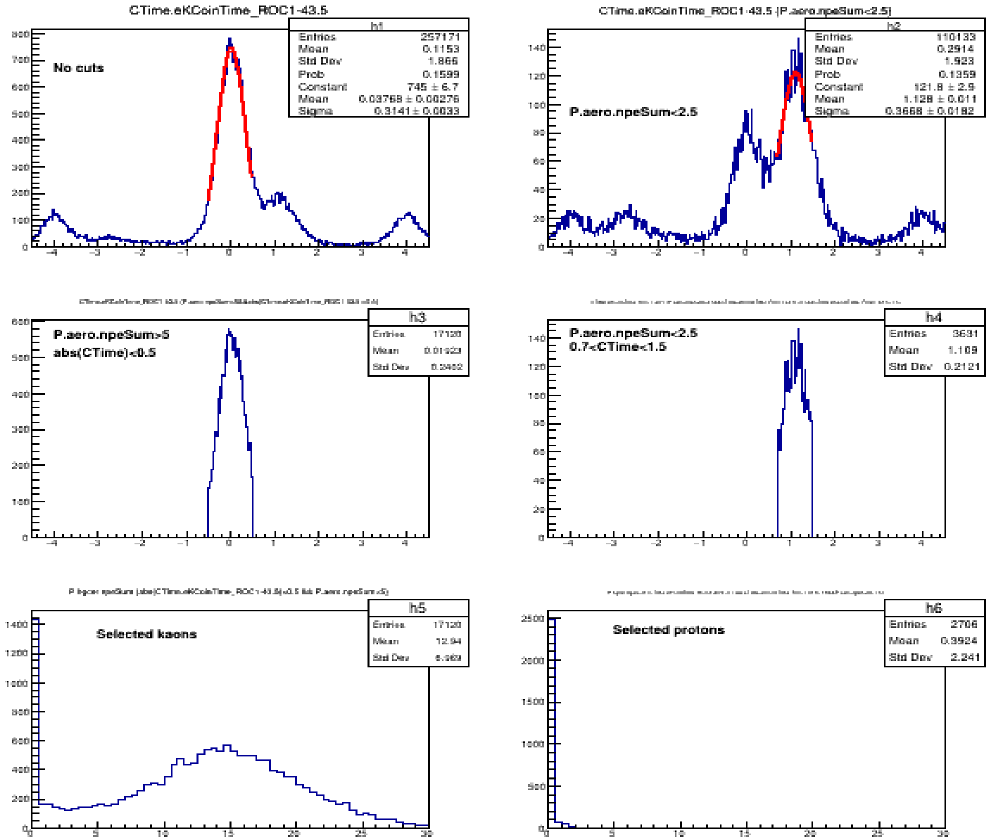
P =3.319 GeV/c | P =5.389 GeV/c



SP15 (n = 1.015) | SP11 (n = 1.011)

- At P=3.319 & 5.389 GeV there are 1-3 nsec differences between coincidence times eπ and ep.
- Coincidence time and heavy gas Cerenkov npe cuts were used to select proton-reach and kaon-reach (+pion-reach) events and look aerogel detector response to these two groups of particles.
- Results show that aerogel responses will allow to separate "pions+kaons" and "protons"
- SP15 and SP11 Aerogels have similar responses to under-threshold protons.

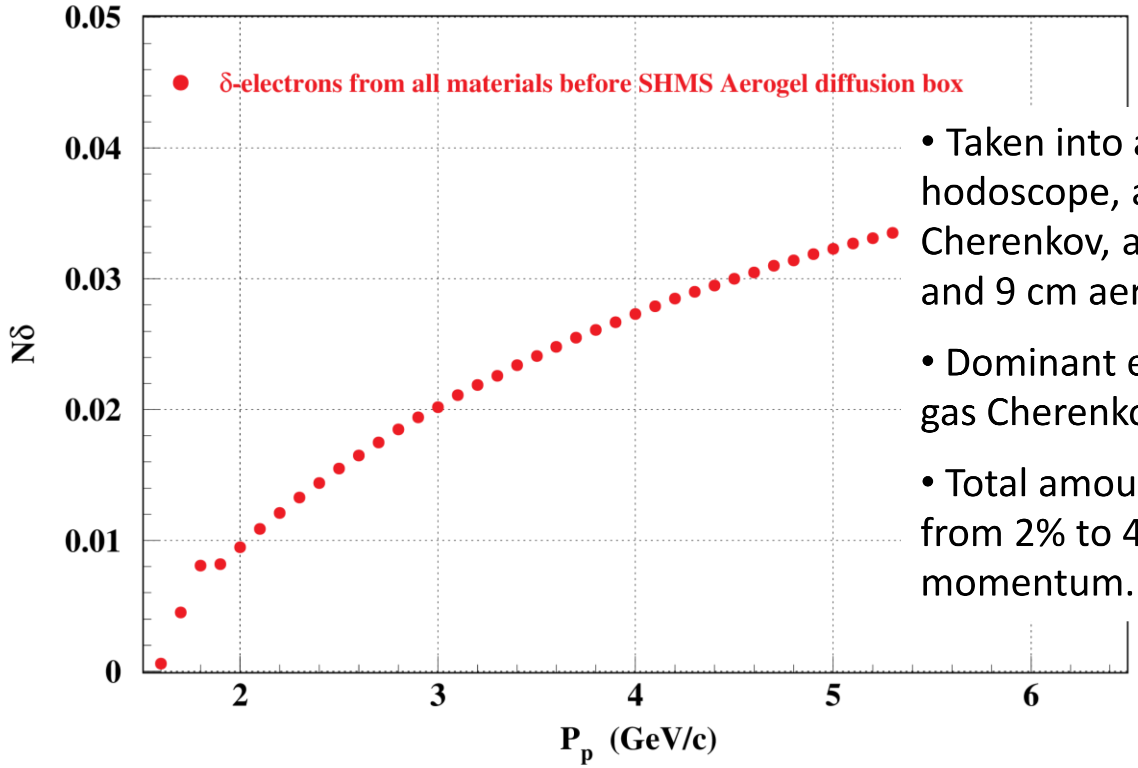
Heavy gas Cherenkov Response to Kaons & Protons



- Kaons at P= 5.389 GeV/c was selected using Coincidence Time and Aerogel Npe (number of photoelectrons0 cuts (|CoinTime|<0.5 && P.aero.npeSum >5).
- At P= 5.389 GeV/c there is ~ 3 nsec difference between coincidence timing eπ and ep. Protons was selected using cuts|CoinTime+3|<0.5 && P.aero.npeSum <1.5.
- Heavy gas Cherenkov response to kaons and protons (Npe distributions) show that it can provide high rejection factor for protons at high detection efficiency for K.

δ-electrons & scintillation effect on SHMS Aero

Knock-out electrons from all detectors located before the SHMS aerogel



- Taken into account first two layers of hodoscope, air gaps, drift chambers, gas Cherenkov, aerogel detector front window and 9 cm aerogel.
- Dominant effect coms from the heavy gas Cherenkov and aerogel front window.
- Total amount of knock electrons varies from 2% to 4% depending on protons momentum.

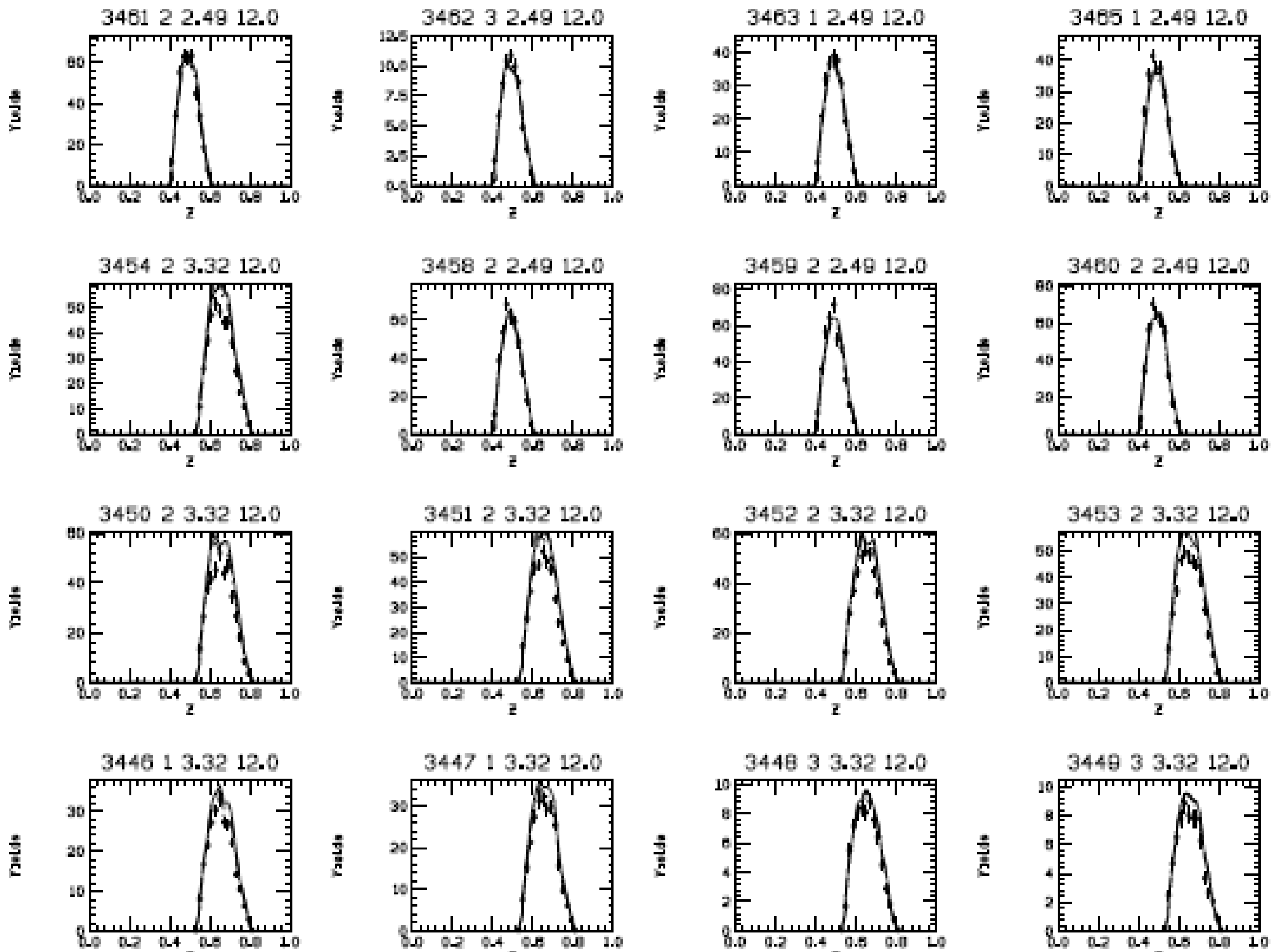
- The total effect from scintillation in aerogel + air + reflectors inside of aerogel detector box was estimated with cosmic μ-rays passing through detector with empty box, and found to be 1-2 pe
- This also was estimated using SIDIS experimental data for protons with momentum P< 3 GeV/c
- Cosmic and SIDIS data are in agreement within statistical accuracy

Experimental Data analysis

Experimental data taken in 2018-2019

- E12-09-011: The L-T Separated Kaon Electroproduction Cross section (Kaon L/T)
- E12-09-017 : Transverse momentum dependence of SI π-Production (Pt-SIDIS)
- E12-09-002: Charge Symmetry Violating Quark Distributions (SIDIS CSV)

Pion and Kaon normalized yields



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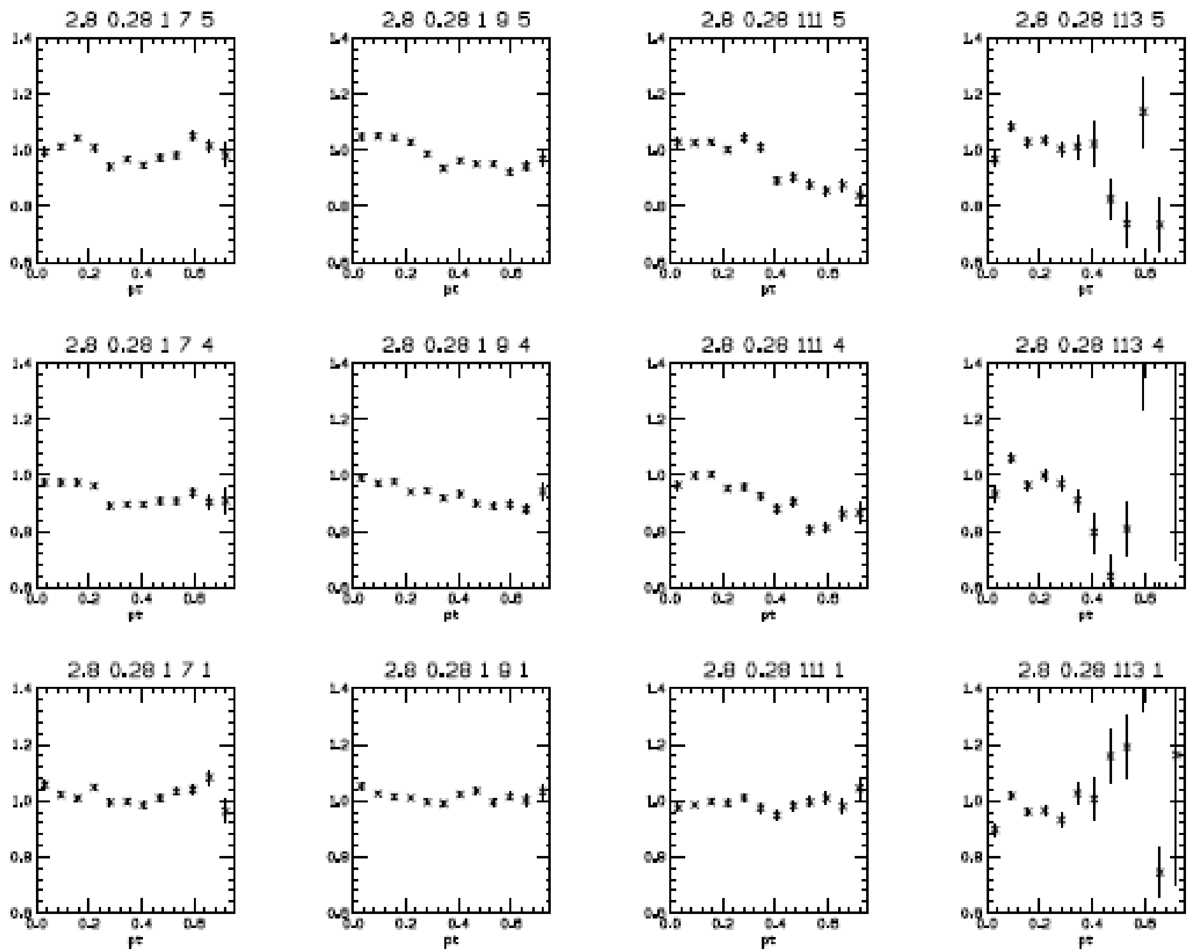
The ratios $\pi+/\pi-$ and Al/D



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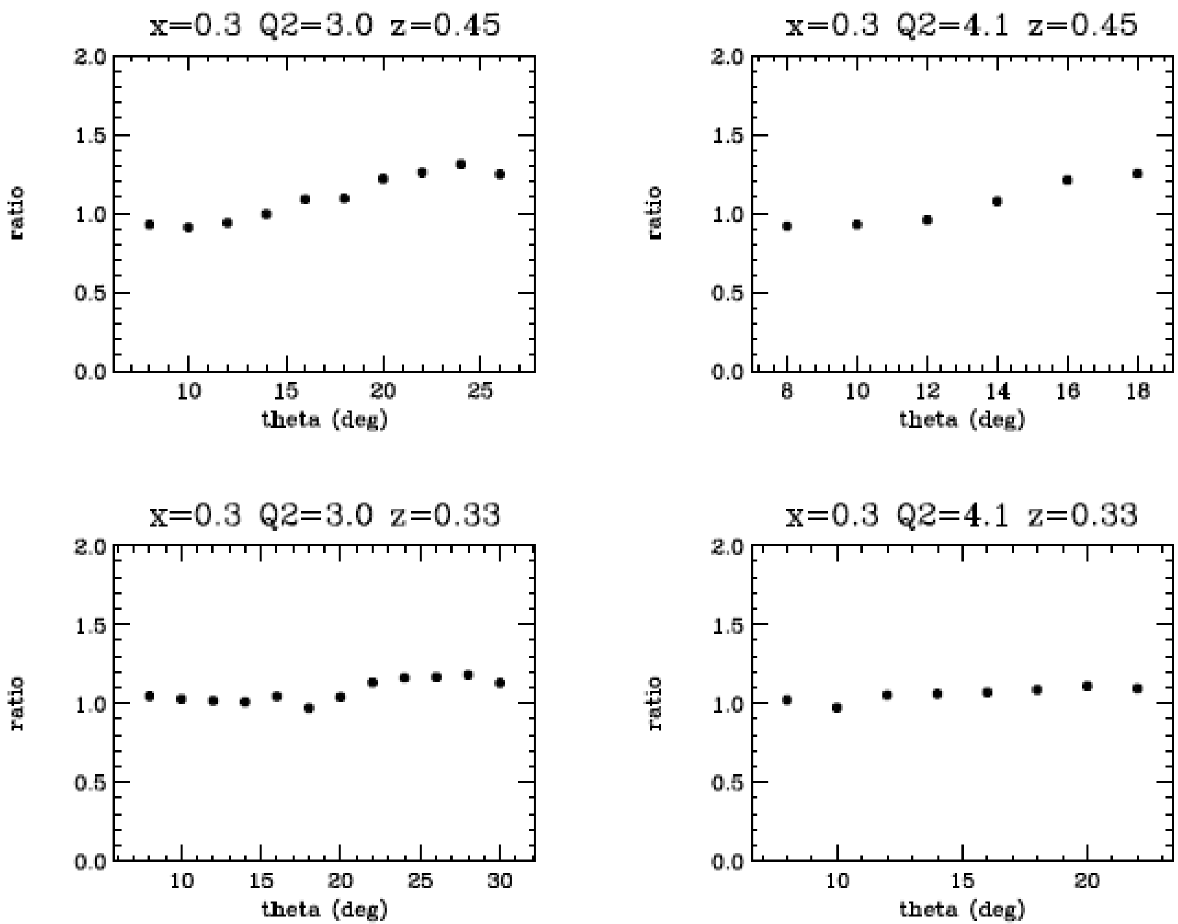
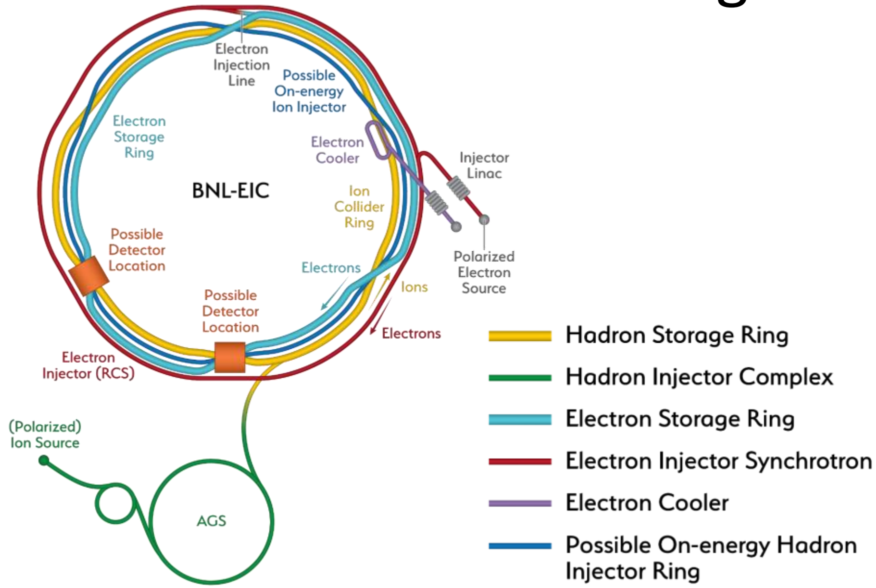
Data and MC rations



EIC Basic Parameters

- Center of Mass Energies 20 GeV – 141 GeV
- Maximum Luminosity 10^{34} $cm^{-2}s^{-1}$
- Hadron Beam Polarization 80%
- Electron Beam Polarization 80%
- Ion Species Range p to Uranium
- Number of interaction regions up to two



EIC Working Groups

Theory Working Groups (not full list)

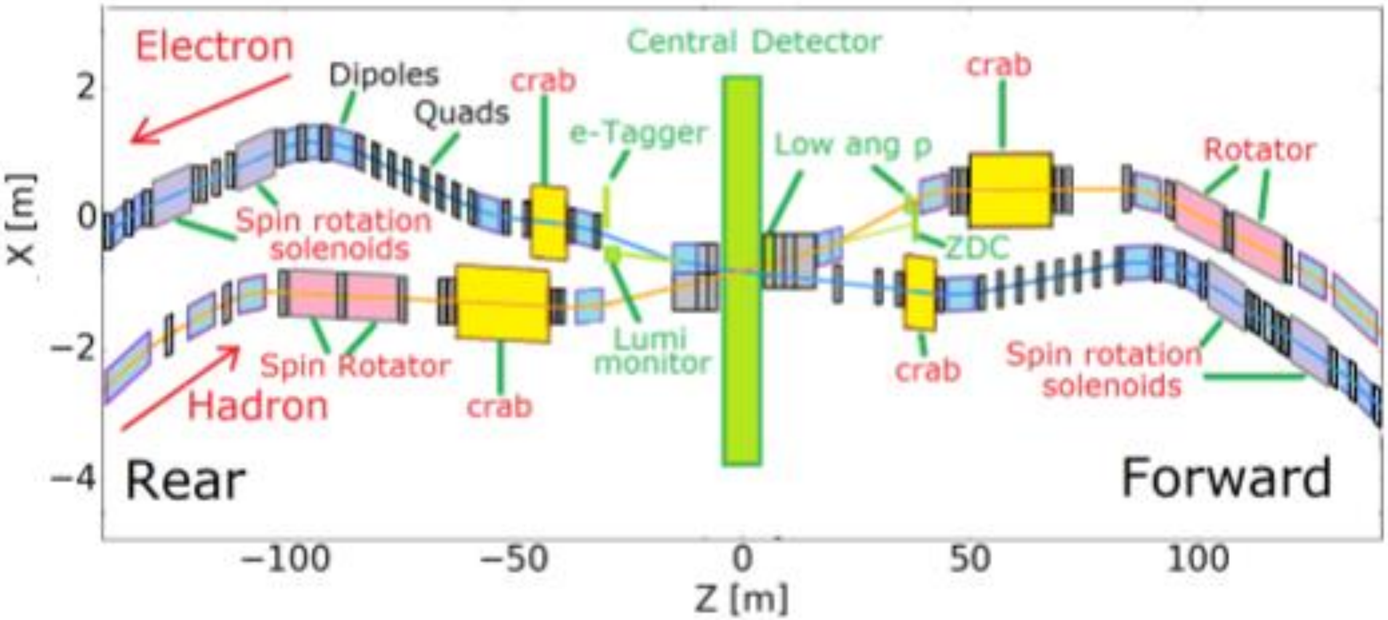
- Jet substructure and 3D imaging studies for the EIC, J. Osborn, M. Arrata
- Heavy meson production at the EIC, I. Vitev
- Charm and Bottom at EIC, M. Kelsey
- Neutral and Charged Current in unpolarized ep collisions, Xi. Chu, M. Posik,
- J/Psi studies S. Joosten
- Parton Distribution Functions (PDF) studies, T. Hobbs
- .DVCS and deep exclusive $\pi 0$, M. Defurne
- SIDIS, R. Seidl, J. Stevens, A. Vladimirov, L. Zheng et al.
- SRC measurements at EIC, F. Hauenstein + CLAS Collaboration
- Pion and Kaon Structure at the EIC, R. Trotta, T. Horn.

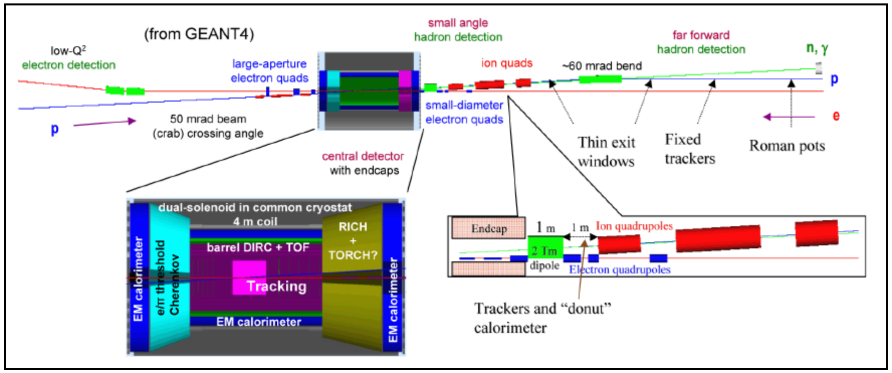
Hardware and DAQ/Electronics

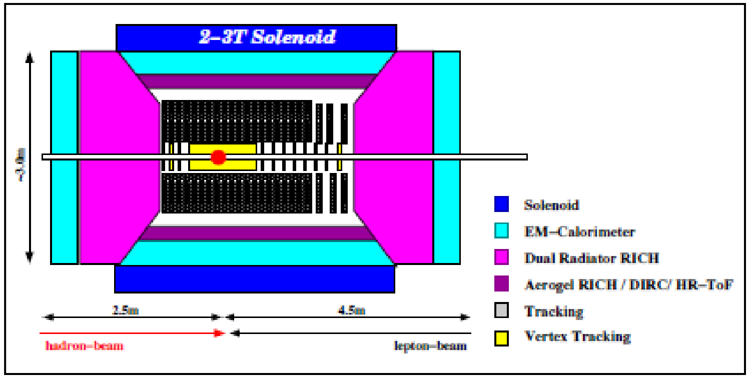
- Tracking WG: D. Elia, K. Gnanvo, L. Greiner et al.
- Particle ID WG: P. Rossi, T. K. Hemmick et al.
- Calorimetry WG: E. Chudakov, V. Berdnikov, T. Horn et al.
- Forward Detector WG: A. Jentsch, J. Furletova, M. Murray et al.
- Polarimetry WG: E. Aschenauer, D. Gaskell et al.
- DAQ/Electronics WG: A. Celentano, J. Huang, M. Diefenthaler et al.
- Central Detector WG: A. Kiselev et al.

EIC Proposed IR (Interaction Region)

- The facility must be able to accommodate 2 detectors at 2 interaction points
- Current detector is designed to provide full acceptance to all fragments produced in collisions.
- The central detector is based on a 5 m long solenoid offset by 50 cm from the Interaction point

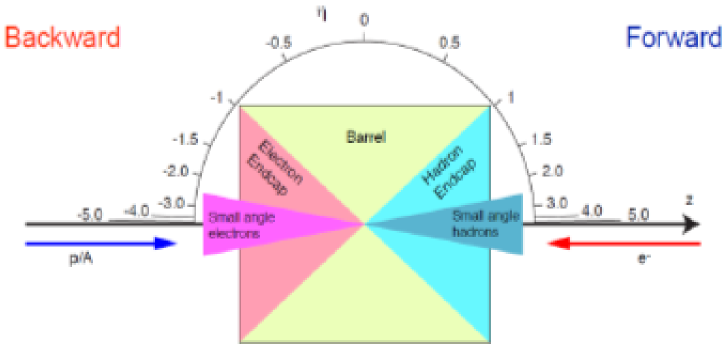




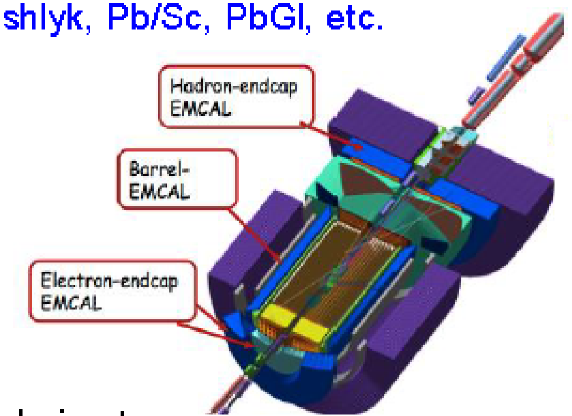


EIC Calorimetry group

EIC Calorimetry overview



Several options including crystals, glass, W/SciFi, Shashlyk, Pb/Sc, PbGl, etc.



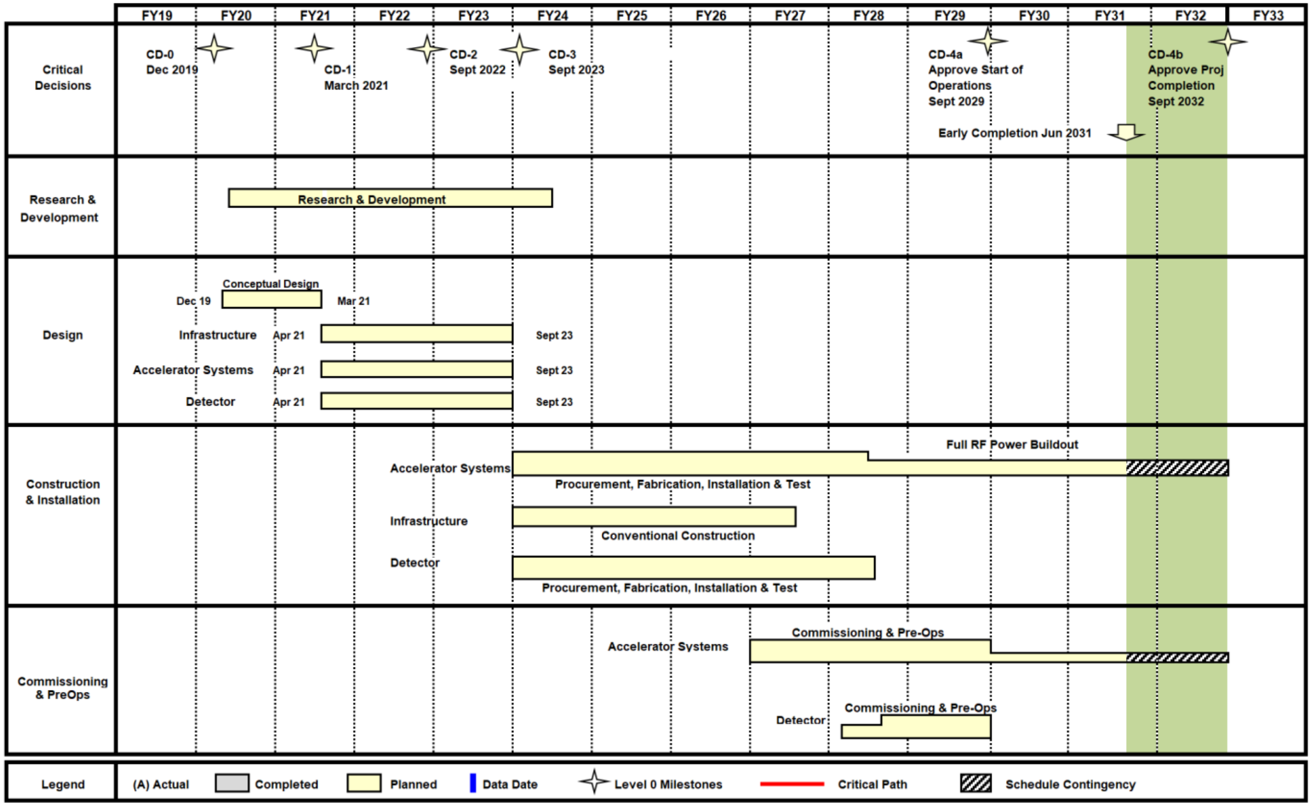
Detector Matrix for the calorimeters

η	Nomenclature	EmCal						HCal			
		Energy resolution %	Spatial resolution mm	Granularity cm^2	Min photon energy MeV	PID e/π πsuppression	Technology examples*	Energy resolution %	Spatial resolution mm	Granularity cm^2	Technology solution
-3.5 : -2	backward	2/√E ⊕ 1	3/√E ⊕ 1	2x2	50	100	$PbWO_4$	50/√E⊕10	50/√E ⊕30	10x10	Fe/Sc
-2 : -1	backward	7/√E ⊕ 1.5	3(6)/√E ⊕1	2.5x2.5 (4x4)	100	100	DSB:Ce glass; Shashlik; Lead glass	50/√E⊕10	50/√E ⊕30	10x10	Fe/Sc
-1 : 1	barrel	(10-12)/√E ⊕2	3/√E ⊕1	2.5x2.5	100	100	W/ScFi	100/√E⊕ 10	50/√E ⊕30	10x10	Fe/Sc
1 : 3.5	forward	(10-12)/√E ⊕2	3/√E ⊕1	2.5x2.5 (4x4)	100	100	W/ScFi Shashlyk, glass	50/√E⊕ 10	50/√E ⊕30	10x10	Fe/Sc

***Technology selection depends on the space available**
Several other technologies are under consideration

e/π: pion suppression depends on the energy, and the energy and momentum resolutions

Timeline for earliest realization of the EIC



- EIC will be ready before 2033 (not in 2030 as proposed)
- CD1 scheduled to have before March 2021
- CD2 and CD3 before 2024
- Two or three more years would be needed to finalize and choose option for EIC
- Construction accelerator systems and Detectors could start in 2024 ?
- EIC Commissioning may start in 2026-2027 and may take 3-5 years

Summary and Outlook

Collaboration with JLab Hall C started in early 90's. Its effective and productive

In CEBAF 6 GeV era YerPhI group main contributions are:

- ✓ Design and construction LG calorimeters for HMS and SOS spectrometers
- ✓ Design construction of Aerogel detector for HMS spectrometer
- ✓ Participation in ~50 experiments installation, data taking and analysis
- ✓ Participation in development of physics program at 6 GeV
- ✓ YerPhI group first proposed and lead first SIDIS experiment at JLab

In CEBAF 12 GeV era YerPhI group main contributions are:

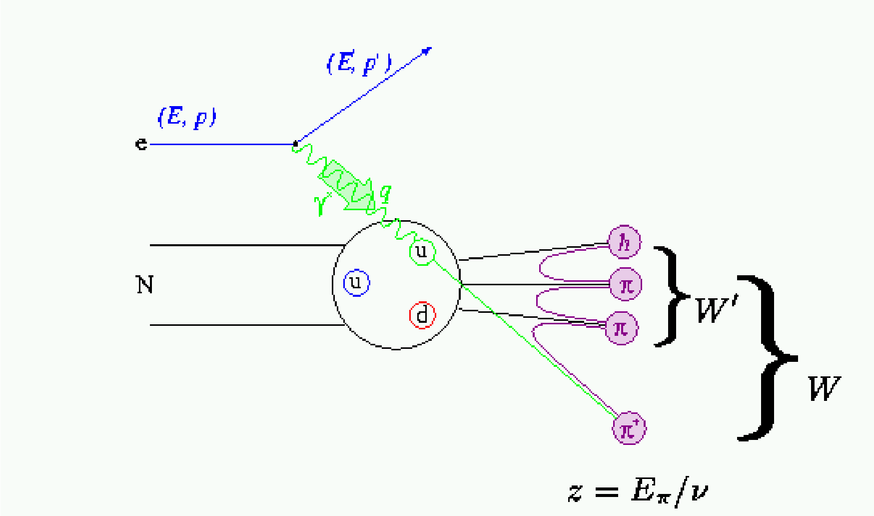
- ➢ Design and construction Shower and Preshower Calorimeter for SHMS
- ➢ Design and construction Aerogel detector for SHMS (in collaboration with CUA)
- ➢ Development 3 physics proposals related to SIDIS at 12 GeV energy
- ➢ Development Neutral Particle Spectrometer (NPS) program and PbWO crystal based multichannel calorimeter for upcoming approved experiments
- ➢ Development of TCS project (currently under preparation)

- ❖ **Future effective continuation required support from AANSL and SC**
- ❖ **Need students & PhD to cover all our responsibilities and program**

Backup slides

Meson electro-production in SIDIS

$$l + N \rightarrow l' + h + X$$



$$\sigma \sim f(x,Q^2) \cdot D(z)$$

$$\sigma_{SIDIS} = \sigma_{DIS} \cdot \sum e_i^2 [q_i(x,Q^2) D_i(z)] \cdot b e^{-b p_T^2}$$

$$z = \frac{E_h}{\nu} \qquad x = \frac{Q^2}{2m\nu} \qquad \nu = E - E'$$

$$W^2 = m_p^2 + Q^2 \cdot \left(\frac{1}{x} - 1 \right)$$

$$W'^2 = m_p^2 + Q^2 \cdot (1-z) \cdot \left(\frac{1}{x} - 1 \right)$$

- At high energies SIDIS has been shown to factorize into lepton-quark scattering followed by quark hadronization. $\sigma \sim f(x,Q^2) \cdot D(z)$
- At low energies, this factorization ansatz is expected to brake down, due to effects of FSI, resonant nucleon excitations and high twist.

E12-09-002: Charge Symmetry Violating (CSV) Quark Distribution via $\pi^{\pm}$ Ratios in SIDIS

What is charge symmetry (CS) ?

CS is a specific case of isospin symmetry (IS) that involves a rotation of 180° in isospin space

Low energy CS in Nuclei

- pp and nn scattering length are nearly the same
- $M_p \approx M_n$ (to 1%)
- $B(^3H) \approx B(^3He)$
- Energy levels in mirror nuclei are equal (t0 1%)

After electromagnetic corrections
CS respected down to ~ 1%

Equality of cross sections for mirror reactions

$$\sigma(n, {}^3He) = \sigma(p, {}^3H)$$

Equality of masses for mirror nuclei

$$m({}^3He) = m({}^3H)$$

QCD CS in quark distributions

- $u^p(x, Q^2) = d^n(x, Q^2)$
- $d^p(x, Q^2) = u^n(x, Q^2)$

Origin of CS violations:

- Electromagnetic interaction
- $\delta m = m_d - m_u$

Naively one would expect that CSV would be of the order of $(m_d - m_u)/M$, where M ~ 0.5-1 GeV

So, CSV effect ➔ ~ 1%

E12-09-002: CSV Tests in SIDIS

CS in parton distributions almost universally assumed for the past 40 years !

But experimentally never tested !

$$u^p(x,Q^2) \stackrel{?}{=} d^n(x,Q^2) \qquad \delta u(x) = u^p(x) - d^n(x)$$

$$d^p(x,Q^2) \stackrel{?}{=} u^n(x,Q^2) \qquad \delta d(x) = d^p(x) - u^n(x)$$

Theoretical predictions

- δd ~2-3% and δu~1% ➔ Sather, PLB 274 (1992) 4333
- δd could reach up to 10% at high x ➔ Thomas et al., Mod. PLA (1994) 1799

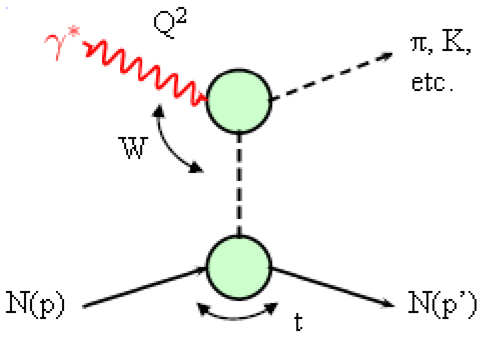
$$R^D_{\text{Meas}}(x,z) = \frac{4N^{D\pi^-}(x,z) - N^{D\pi^+}(x,z)}{N^{D\pi^+}(x,z) - N^{D\pi^-}(x,z)} \qquad R(x,z) = \frac{5}{2} + R^D_{\text{Meas}}$$

$$D(z)\,R(x,z) + A(x)C(x) = B(x,z)$$

$A(x)$ and $B(x,z)$ are known

$$C(x) = \delta d(x) - \delta u(x)$$

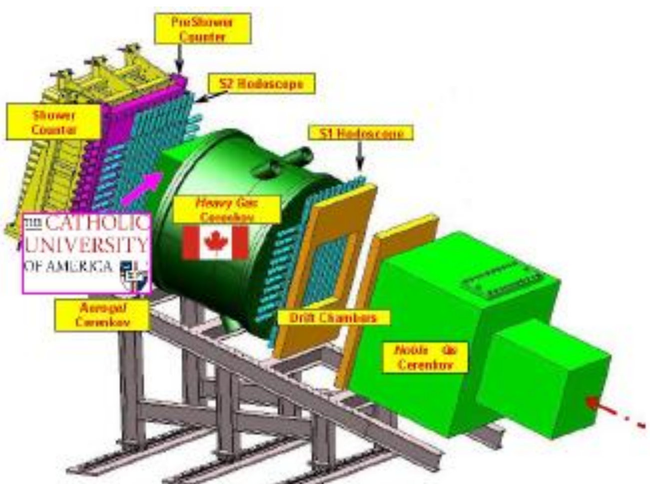
E12-09-011: L-T Separated Kaon Electro-production

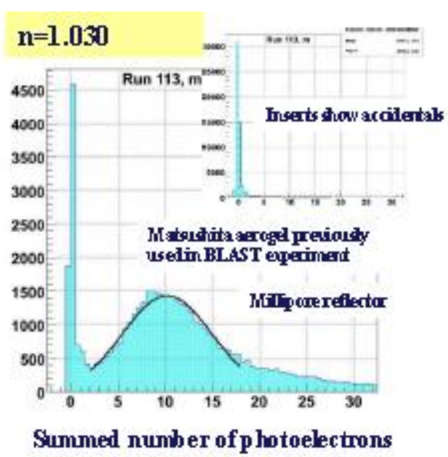


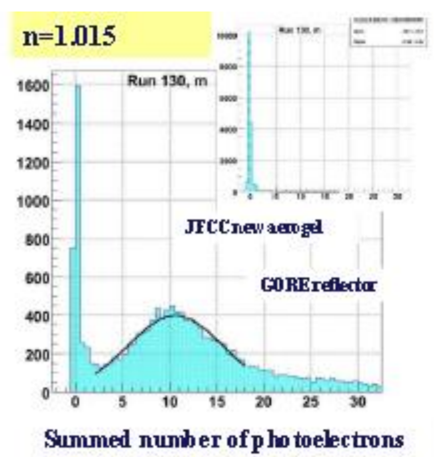
t-channel process

- In the limit of small $-t$, meson production can be described by the t-channel meson exchange (pole term)
  - Spatial distribution described by form factor

$$2\pi\frac{d^2\sigma}{dt\,d\phi}=\varepsilon\frac{d\sigma_L}{dt}+\frac{d\sigma_T}{dt}+\sqrt{2\varepsilon(\varepsilon+1)}\,\frac{d\sigma_{LT}}{dt}\cos\phi+\varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

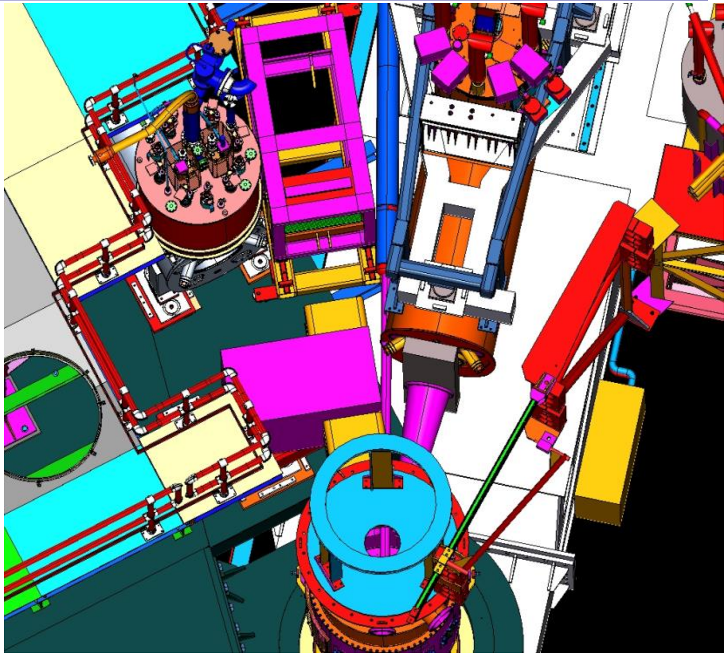






Neutral Particle Spectrometer (NPS)

A Neutral Particle Spectrometer (NPS) is required to carry out the JLab 12 GeV Hall C program of precision cross section measurements and L/T separations, extending the charged-particle (p, $\pi^{+/-}$, $K^{+/-}$) measurements to neutral particles (γ and π^0). It will open new opportunities in Hall C, utilizing the well-understood HMS and the new SHMS infrastructure.



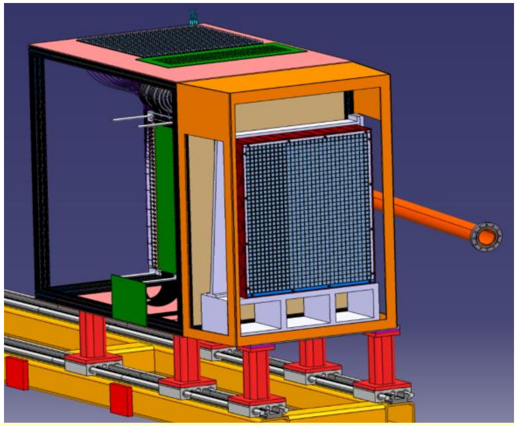
Proposals benefitting from the NPS facility, so far:

- E12-13-007, Measurement of Semi-Inclusive π^0 Production as Validation of Factorization. (25 days, PAC40 approved, A- rating, running with E12-13-010).
- E12-13-010, Exclusive Deeply Virtual Compton and Neutral Pion Cross-Section Measurements in Hall C. (53 days, PAC40 approved, A rating).
- E12-14-003, Wide-angle Compton scattering at 8 and 10 GeV photon energies. (18 days, PAC42 approved, A rating).
- E12-14-005, Wide Angle, Exclusive Photoproduction of π^0 Mesons. (18 days, PAC42 approved, B rating).

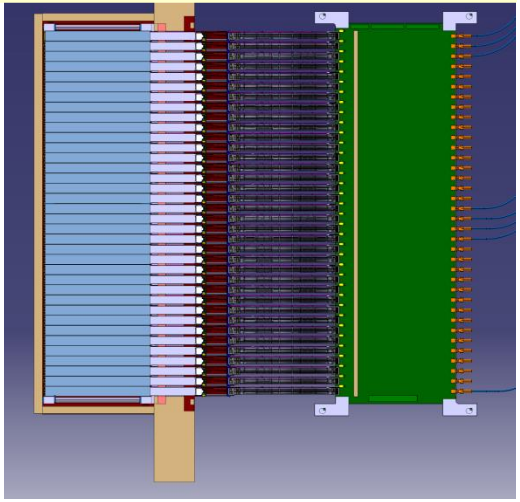
Neutral Particle Spectrometer (NPS)

NPS ERR (Experiment Readiness Review) – 15 May 2019

- Magnet assembled and tested with software control
- Hall-probe mapper were used to measure three-axis field in 1 cm intervals
- 560 Crystals onsite (460 from SICCAS+100 from Crytur)
- Calorimeter frame design completed
- Full assembling scheduled – Fall 2020
- First experiment WACS preliminary scheduled -2021



PbWO Crystal Calorimeter



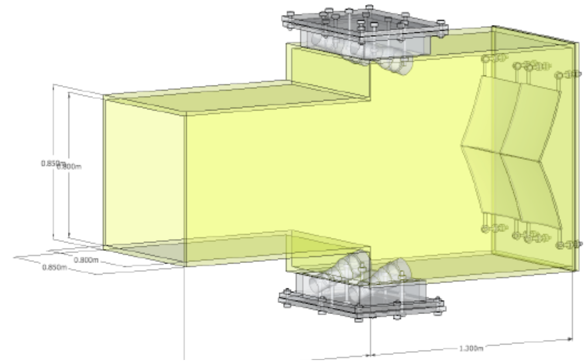
Vendor	Samples	Delivered
SICCAS	460	FY 2017
CRYTUR	100	FY 2018

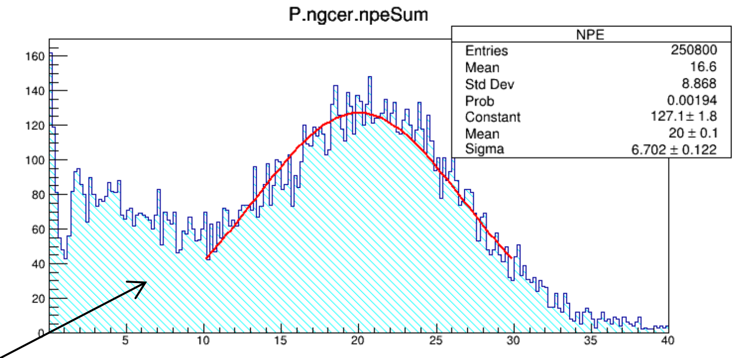
Sweep magnet

SHMS NG Cerenkov Calibration

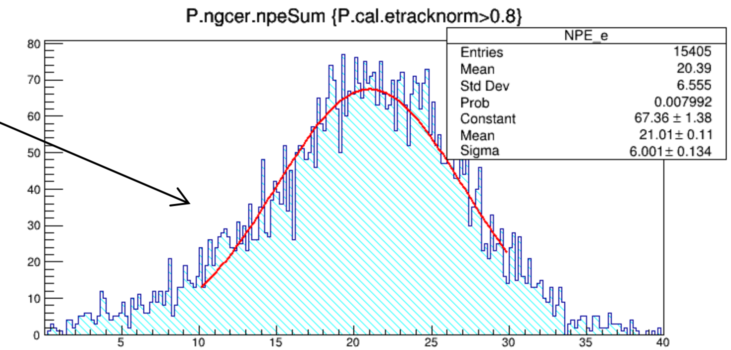
Cerenkov radiation threshold for particles $(1-\beta) < (n-1)$

- Filled with Ar or Ne (at 1 atm)
- n =1.001233 for Ar
- n = 1.001205 for Ne
- 4 mirrors and 4 PMTs (5” Hamamatsu R1584, coated with WLS to improve QE)





Number of photoelectrons without and with electron-PID requirement



- For electrons we expect npeSum ~20.