The GEp-5 Experiment

Measuring the Proton Electric Form Factor in Hall A at Jefferson Lab

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for the GEp collaboration
Hall A Summer Collaboration Meeting
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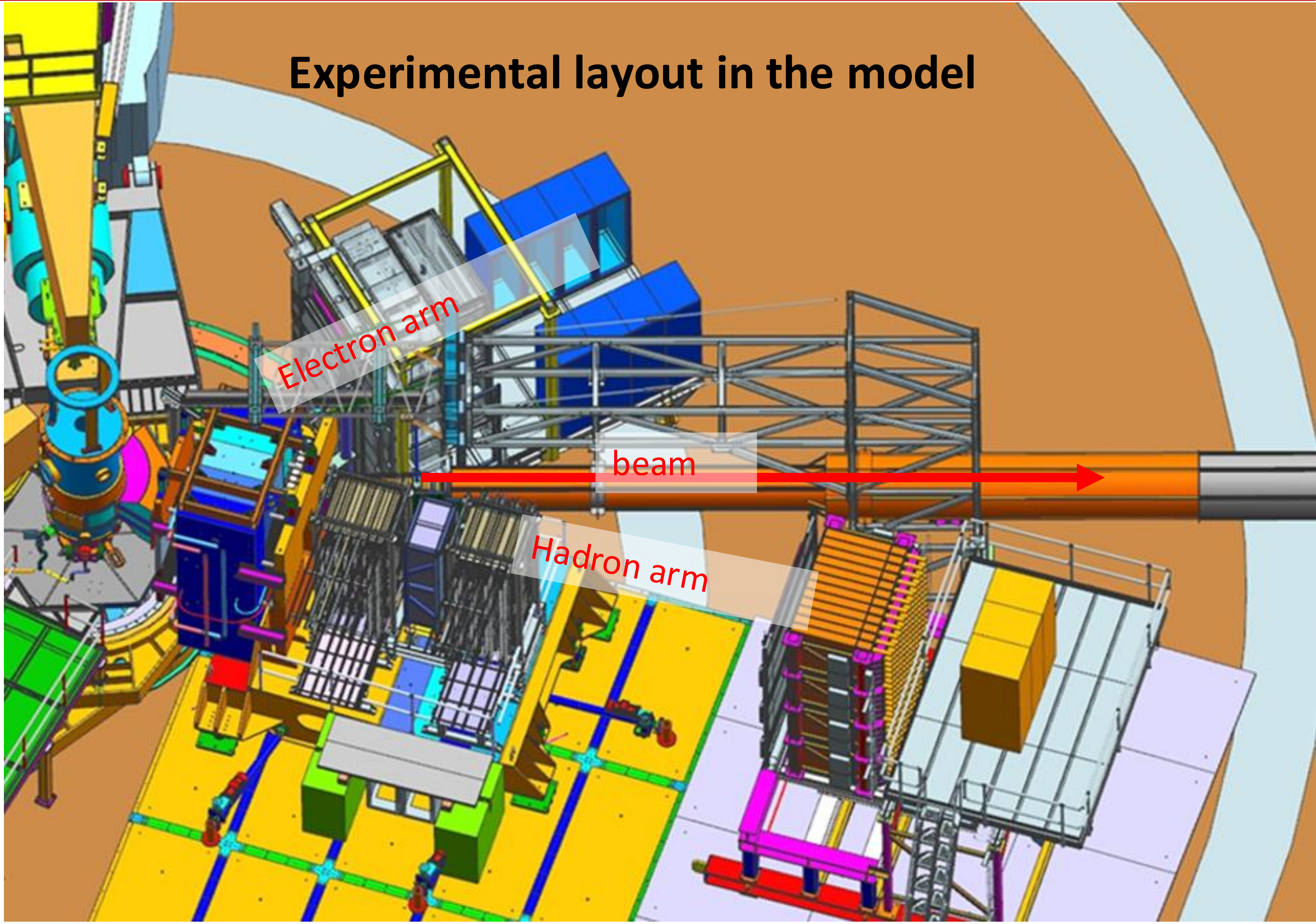
GEp-5 experiment overview

GEp Spokespersons: E.Cisbani, M.Jones, N.Liyanage, L.Pentchev, A.Puckett, B.Wojtsekhowski

- GEp currently running in Hall A until late August will measure the ratio of the proton Sachs FFs $G_E^p \ / \ G_M^p$ at high Q^2
- Designed to run at 50uA on a 30cm LH2 target
- Hadron arm includes SBS dipole magnet, proton polarimeter and HCal
- Electron arm consists of ECal and CDet

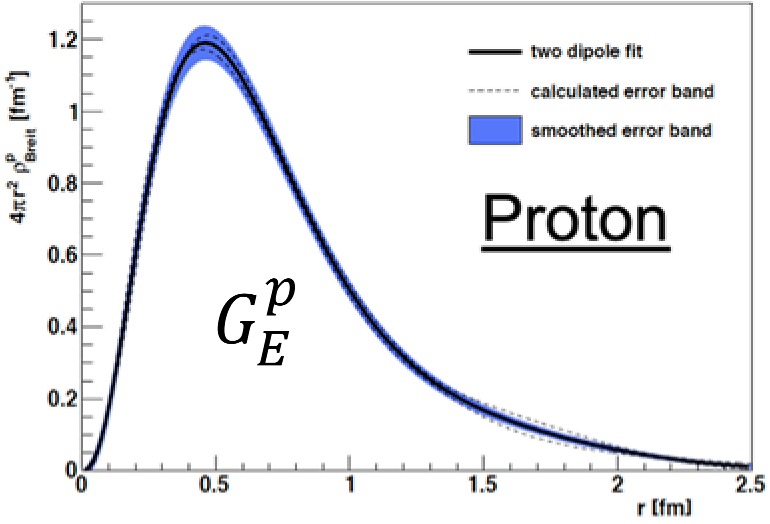


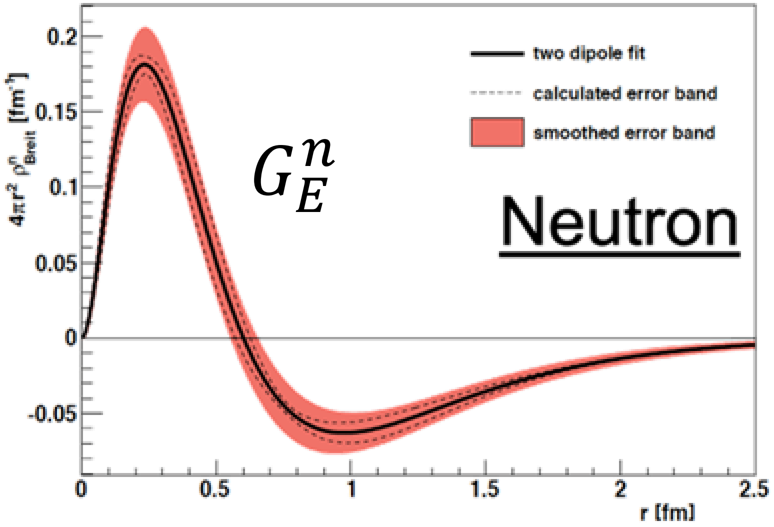
Sachs Form Factors

The nucleon's "shape" described by electric and magnetic form factors G_E^p and G_M^p (proton) and G_E^n and G_M^n(neutron)

- momentum space representations of charge and magnetization distributions in the nucleon.
- Intuitive interpretation is easiest in the Breit frame where the Fourier transforms of G_E and G_M are spatial distributions of charge and current
    - this interpretation prohibited in rest frame due to recoil

$$G_E = \int \rho(\vec{r}) e^{i\vec{q}\cdot\vec{r}} d^3\vec{r} \qquad G_M = \int \mu(\vec{r}) e^{i\vec{q}\cdot\vec{r}} d^3\vec{r}$$





C. Crawford et al. PRC 82 (2010) 045211

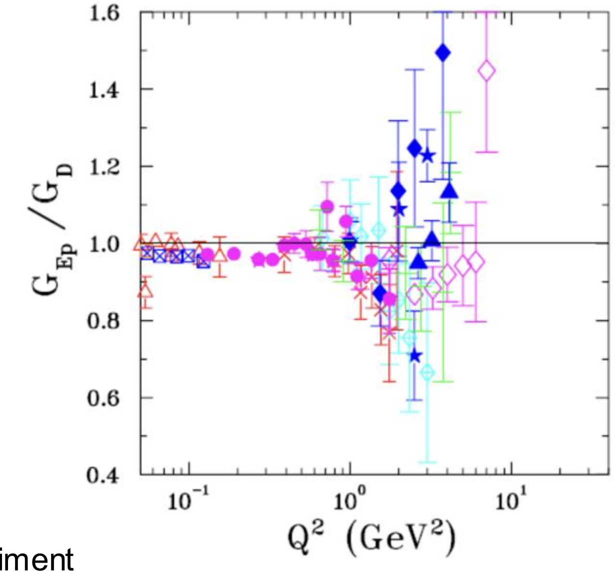
Measuring Form Factors

Rosenbluth separation

- Leverages linearity of cross section in $\varepsilon = [1 + 2(1+\tau)\tan\frac{\theta}{2}]^{-1}$

$$\sigma_R = \left(\frac{d\sigma}{d\Omega}\right)_{exp} / \left(\frac{d\sigma}{d\Omega}\right)_{M} \frac{\epsilon(1+\tau)}{\tau} = \frac{\epsilon}{\tau} G_E^2 + G_M^2$$

- Measure cross section at fixed Q^2 but varying ε (scattering angle) and G_M^2 is given by the intercept and slope provides G_E^2



Polarization transfer

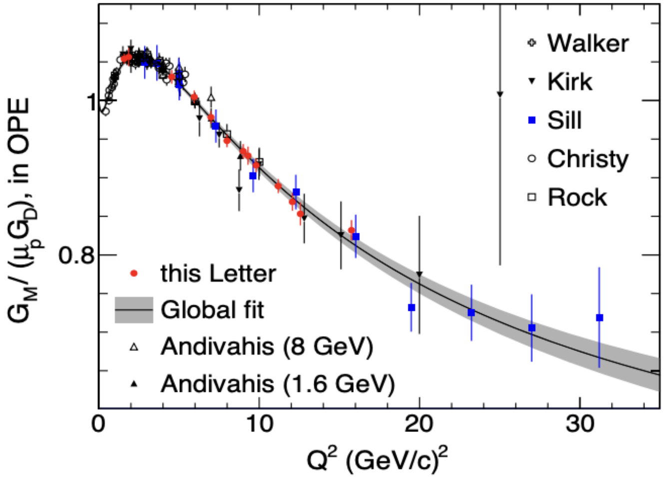
– Proposed by Akhiezer et al. in 1958, it measures polarization transferred to hadron from electron: sensitive to the ratio of the form factors

$$\frac{G_E}{G_M} = -\frac{P_t}{P_\ell}\sqrt{\frac{\tau(1+\epsilon)}{2\epsilon}}$$

– Measure ratio of hadron polarization along (Pl) and transverse (Pt) to momentum transfer

– Many systematics cancel in the ratio

– G_M^p known from prior measurements

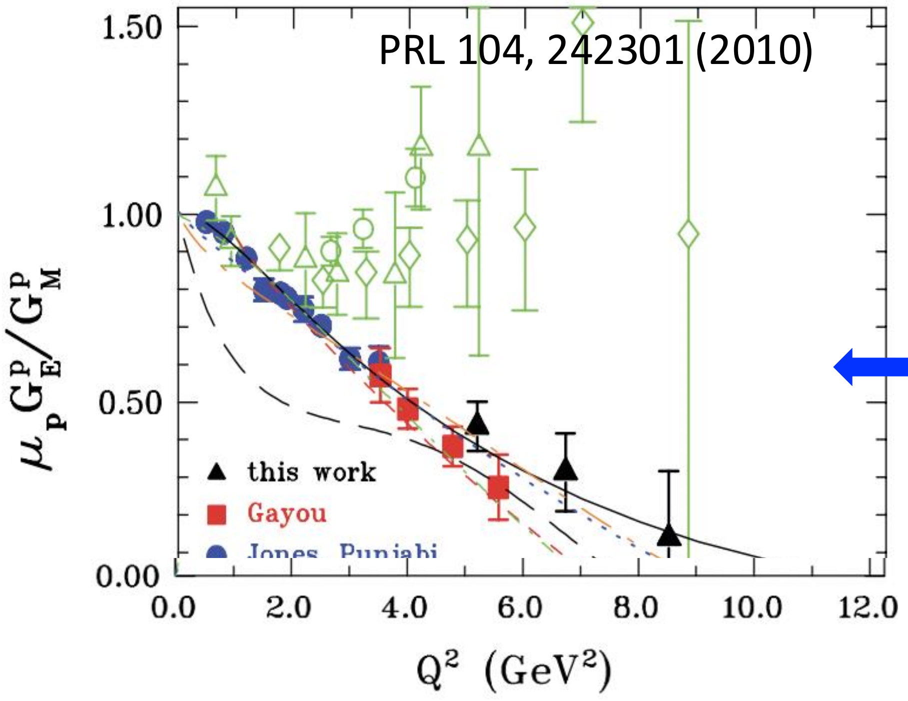


Issues with Rosenbluth Separation Technique

$$\text{Rosenbluth Formula:} \quad \frac{d\sigma}{d\Omega_e} = \left(\frac{d\sigma}{d\Omega_e}\right)_{\text{Mott}} \frac{\epsilon G_E^2 + \tau G_M^2}{\epsilon(1+\tau)}$$

$$\tau \equiv \frac{Q^2}{4M^2}$$

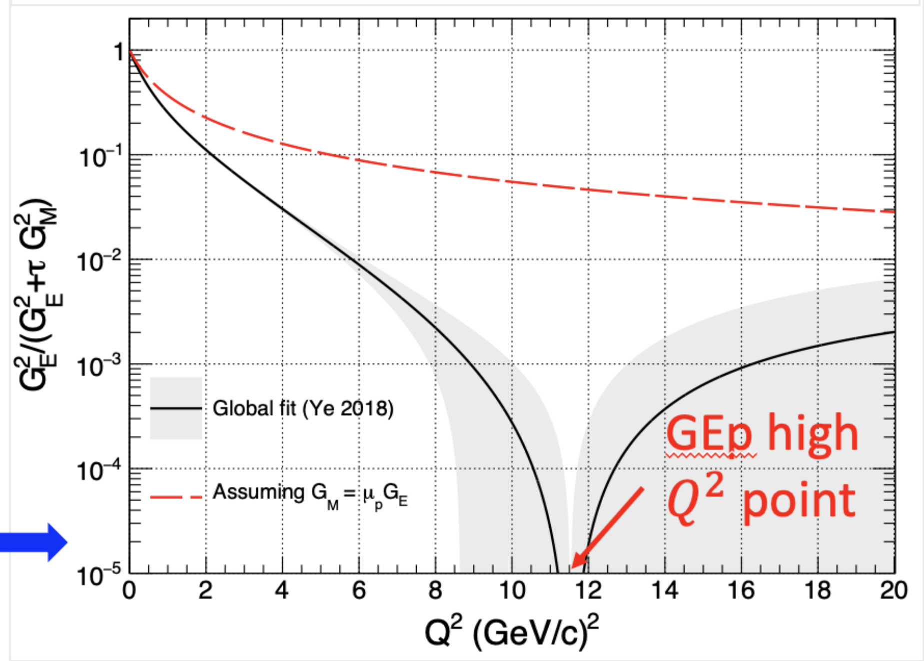
$$\epsilon \equiv \left[1 + 2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)\right]^{-1}$$



Q^2<2 GeV^2 great agreement between polarization transfer and Rosenbluth

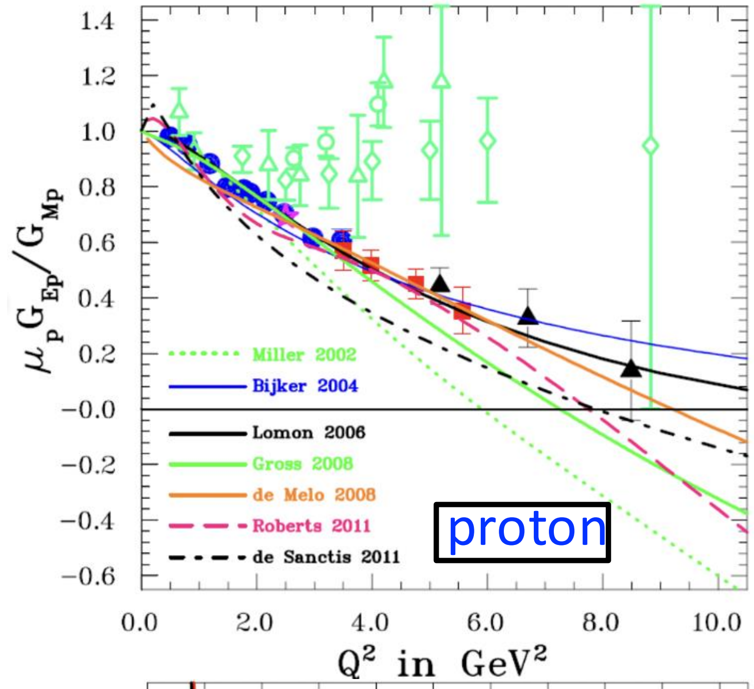
Q^2 >2 GeV^2 large disparity (TPE?)

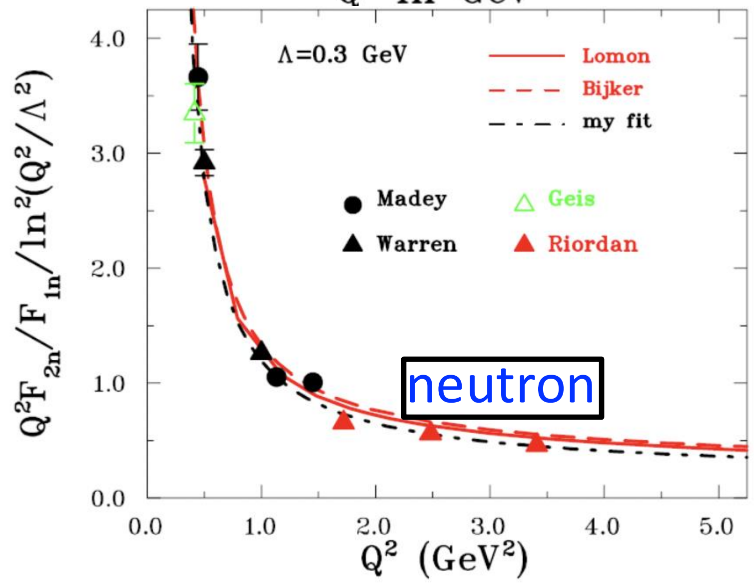
Reduced fraction of cross section carried by G_E at high Q^2



Also large ε–dependent radiative corrections required

Motivation for measuring form factors





Comparing to model predictions

- Will VMD-models (Lomon,Bjiker) describe all 4 nucleon FFs well at higher Q^2?
- Check pQCD prediction of logarithmic scaling of F1/F2 at intermediate Q^2 (Belitsky, Ji, Yuan)
- Constrain GPDs via fundamental relationship of first moments to FFs

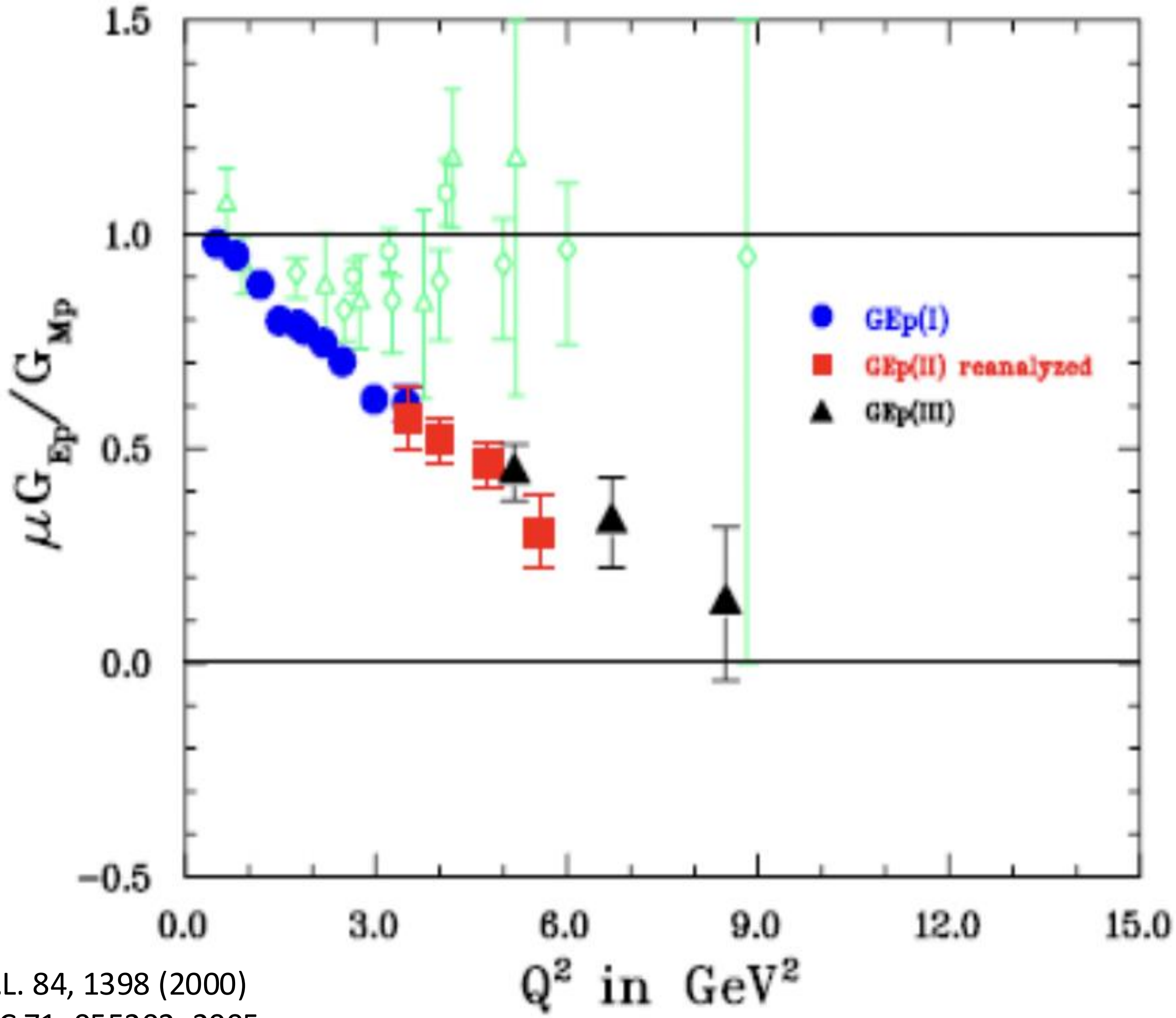
$$\int_{-1}^{+1} dx\, H^q(x,\xi,Q^2) = F_1^q(Q^2)$$

$$\int_{-1}^{+1} dx\, E^q(x,\xi,Q^2) = F_2^q(Q^2)$$

- Provide data for verifying lattice QCD predictions as they mature

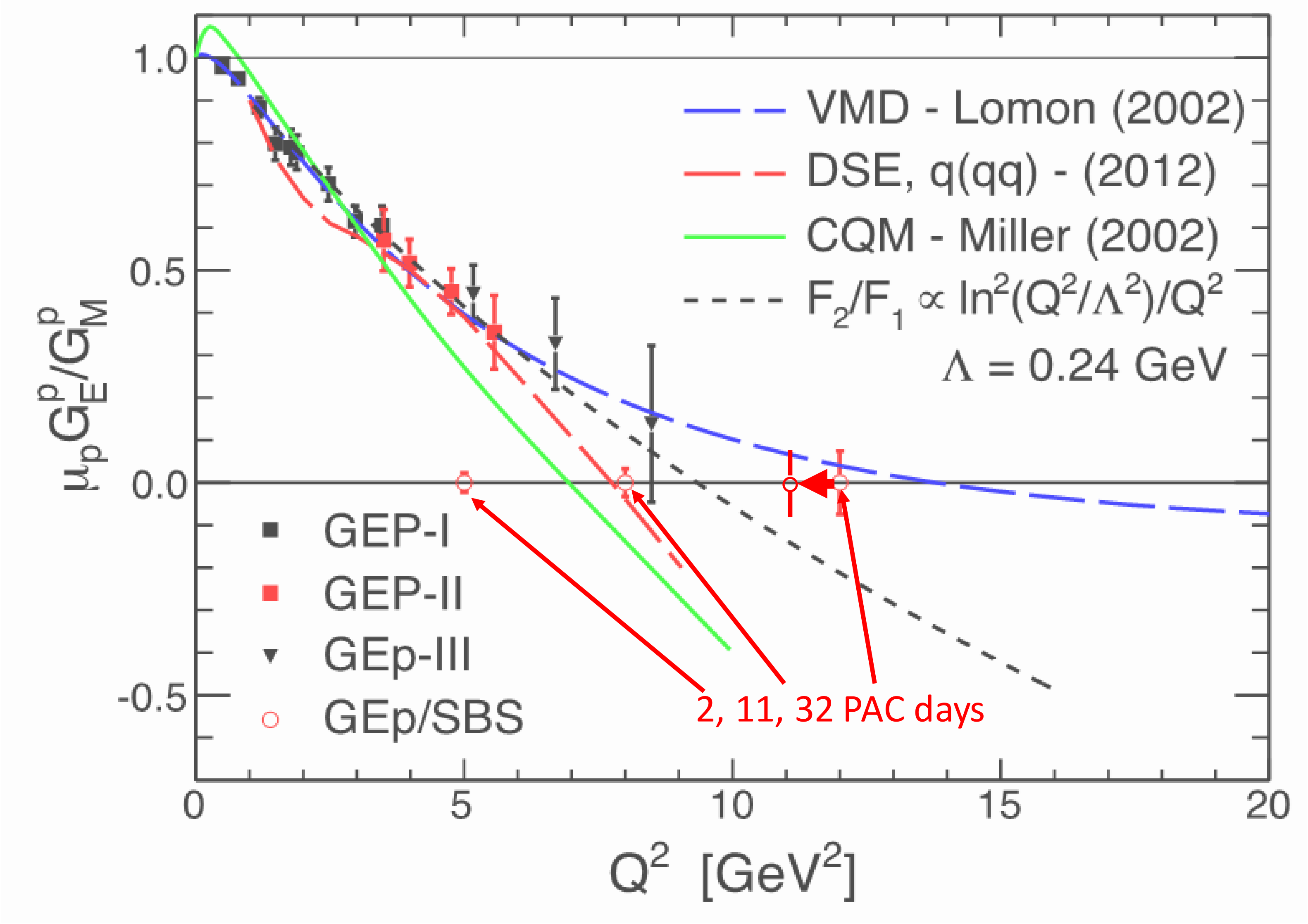
GEP historical measurements at JLab with polarization transfer

- GEP-I ran in 1998 using 2 High Resolution Spectrometers (e-p coincidence) in Hall A up to $3.5\ \mathrm{GeV}^2$ appeared to disagree with Rosenbluth results
- GEP-II ran in 2000 in Hall A with one HRS and a $3.5\ \mathrm{m}^2$ lead glass calorimeter up to $5.6\ \mathrm{GeV}^2$ further confirming the disagreement
- GEP-III ran in 2007-08 in Hall C using the HMS and a new $3.1\ \mathrm{m}^2$ lead glass calorimeter
- GEP-5 currently taking data at $\mathrm{Q}^2 = 11 \mathrm{GeV}^2$



M.K. Jones et al. P.R.L. 84, 1398 (2000)
V. Punjabi et al. P.R. C 71, 055202, 2005
O. Gayou et al., Phys.Rev. Lett., 88 (2002) 092301
A.J.R. Puckett et al. Phys. Rev. Lett. 104, 242301 (2010)

Proposed error bars



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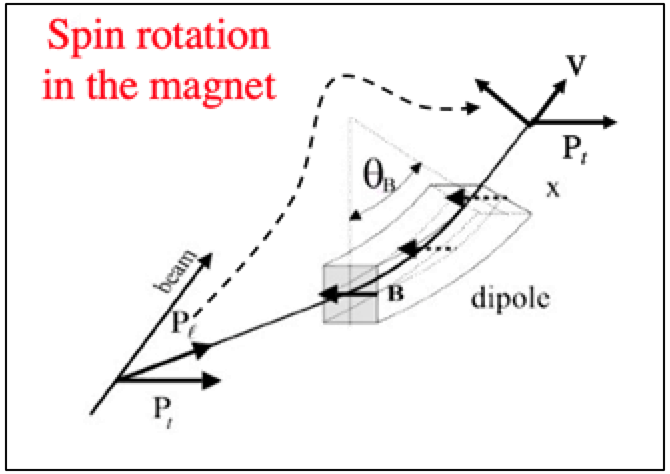
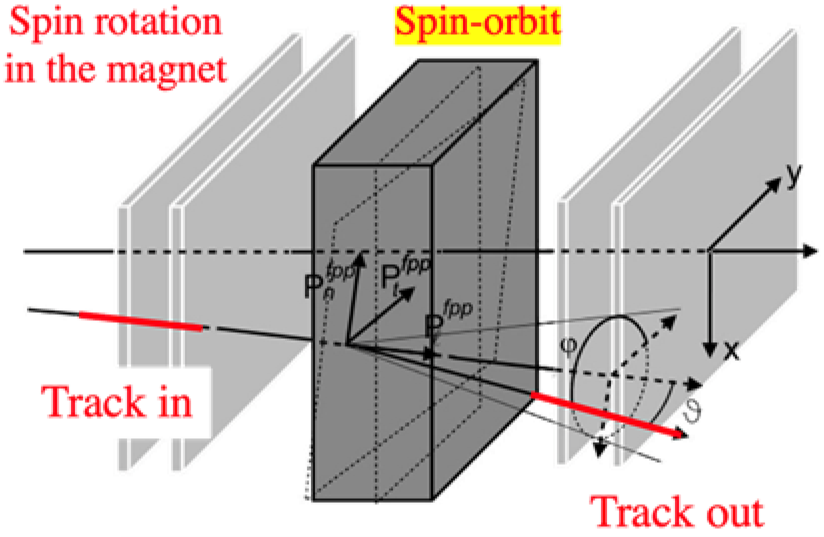
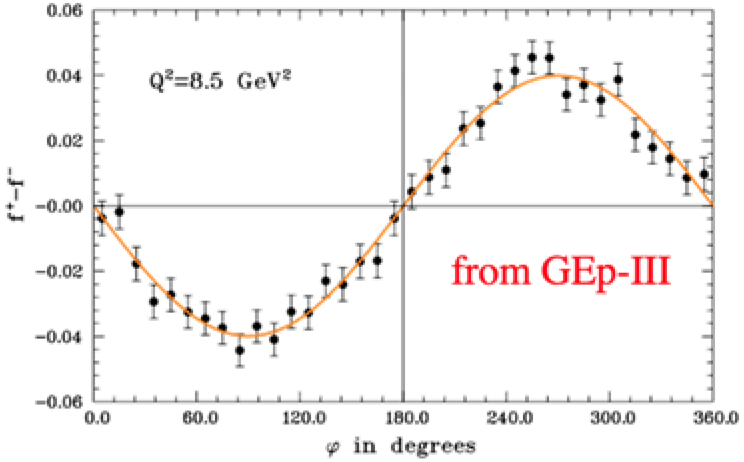
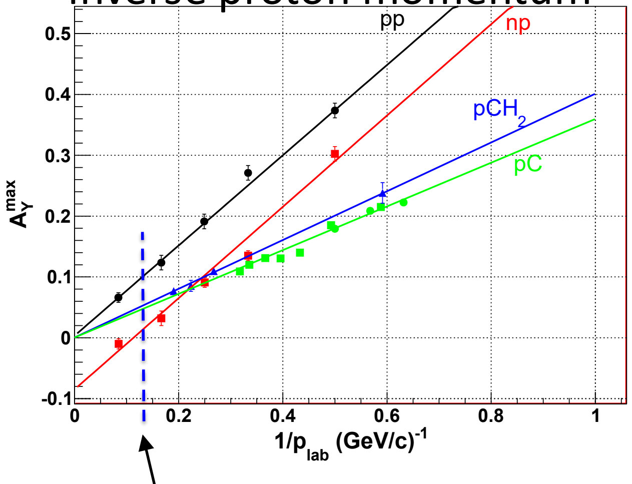
Focal Plane Polarimeter







A_Y analyzing power vs. inverse proton momentum



p will be ~7 GeV/c

$$f^{\pm}(\vartheta,\varphi) = \frac{\epsilon(\vartheta,\varphi)}{2\pi}\left[1 \pm A_y(P_x^{fpp}\sin\varphi - P_y^{fpp}\cos\varphi)\right]$$

where $\pm$ refers to electron beam helicity

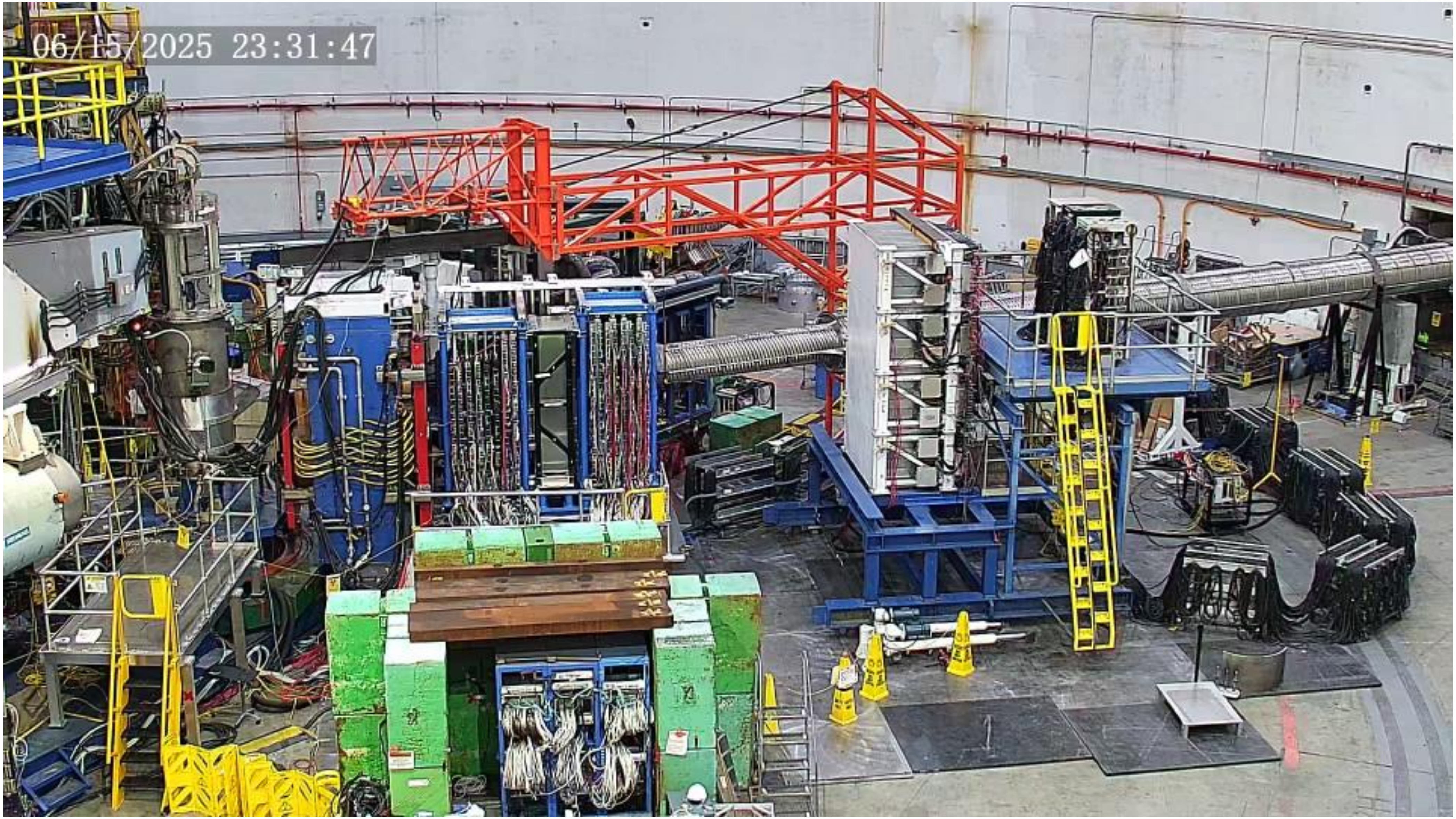
$$A = \frac{f^+ - f^-}{f^+ + f^-} = A_y\left(P_x^{fpp}\sin\varphi - P_y^{fpp}\cos\varphi\right)$$

$$\mu_p\frac{G_E^p}{G_M^p} = -\mu_p\frac{E_e+E'_e}{2M_p}\tan\frac{\theta_e}{2}\left(\frac{P_x^{fpp}}{P_y^{fpp}}\sin\chi_\theta + \gamma_p(\mu_p-1)\Delta\phi\right)$$

precession angle

fringe field correction

Camera image of GEP in Hall A beam right



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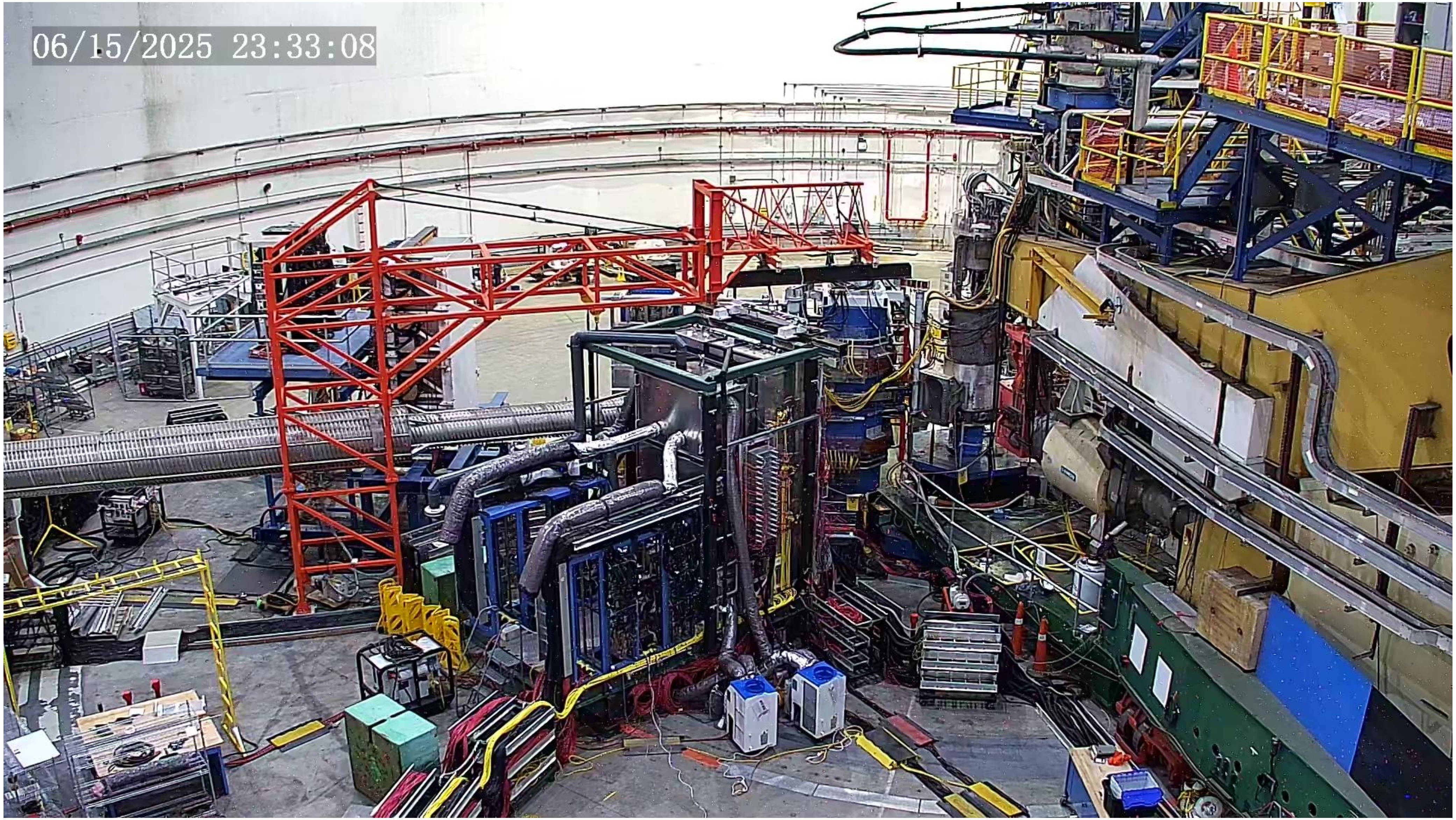
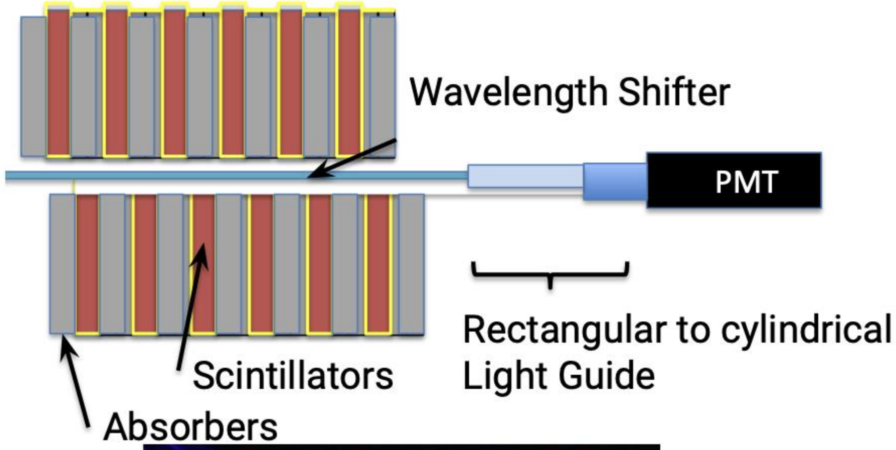
Camera image of GEP in Hall A beam left

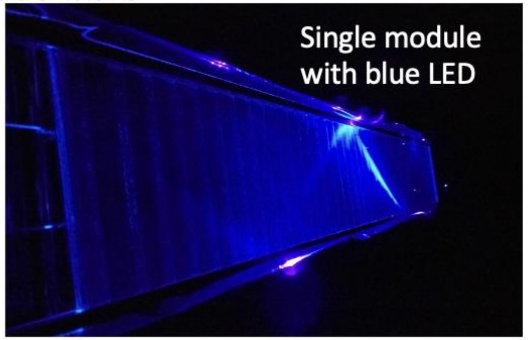


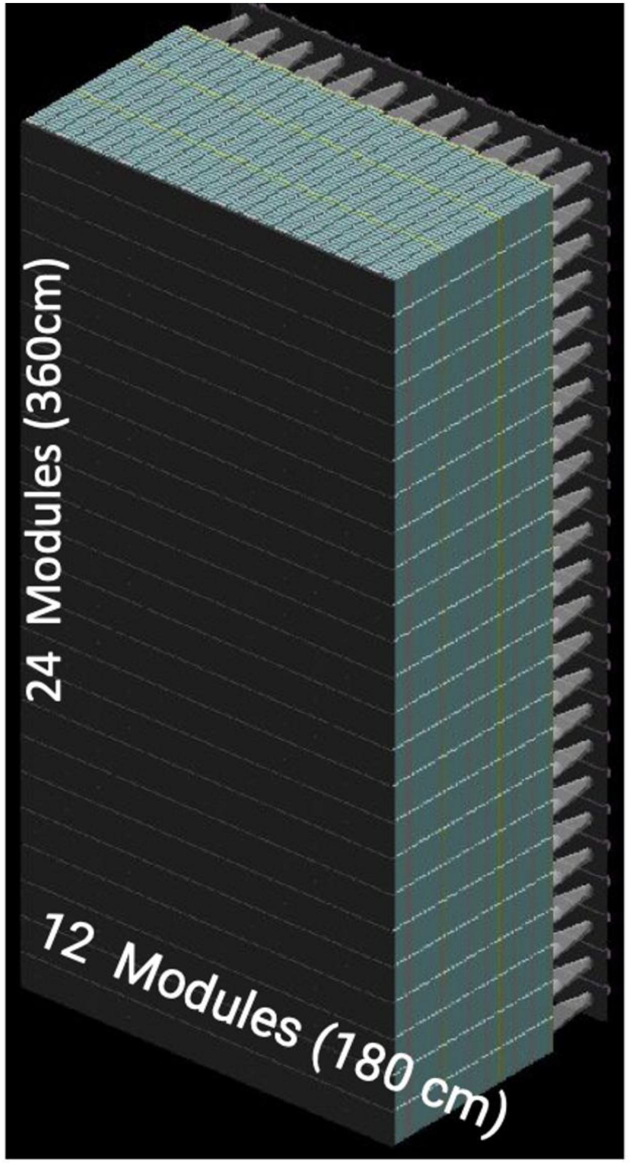
HCAL design

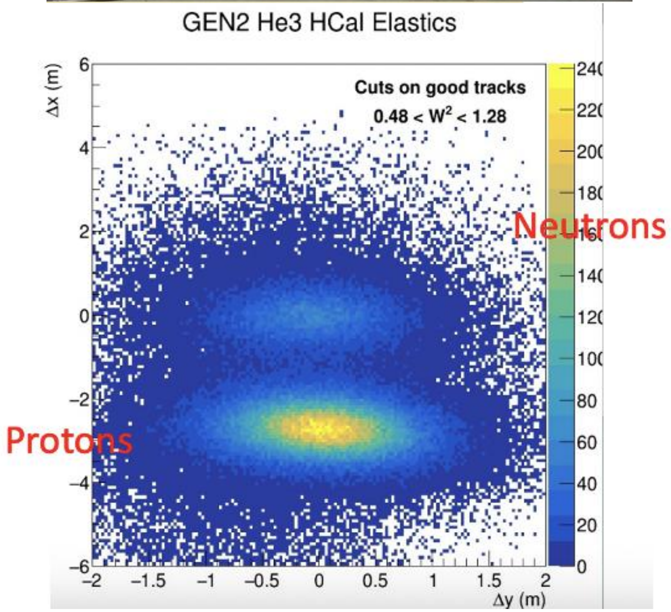
Each module is 15 cm x 15 cm x ~1 m
- Plus light guide and PMT at end

40 layers scintillators + iron per module
- Staggered to increase light output



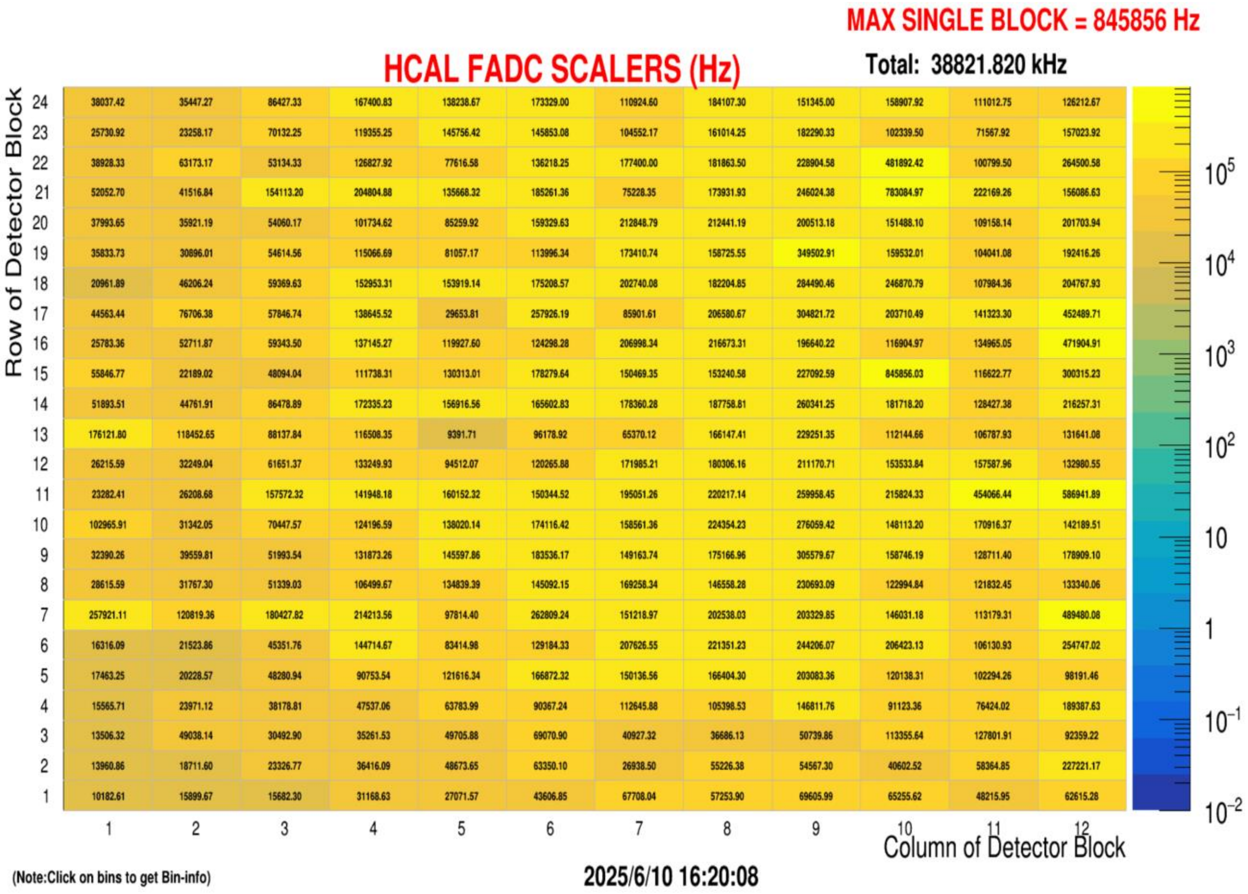


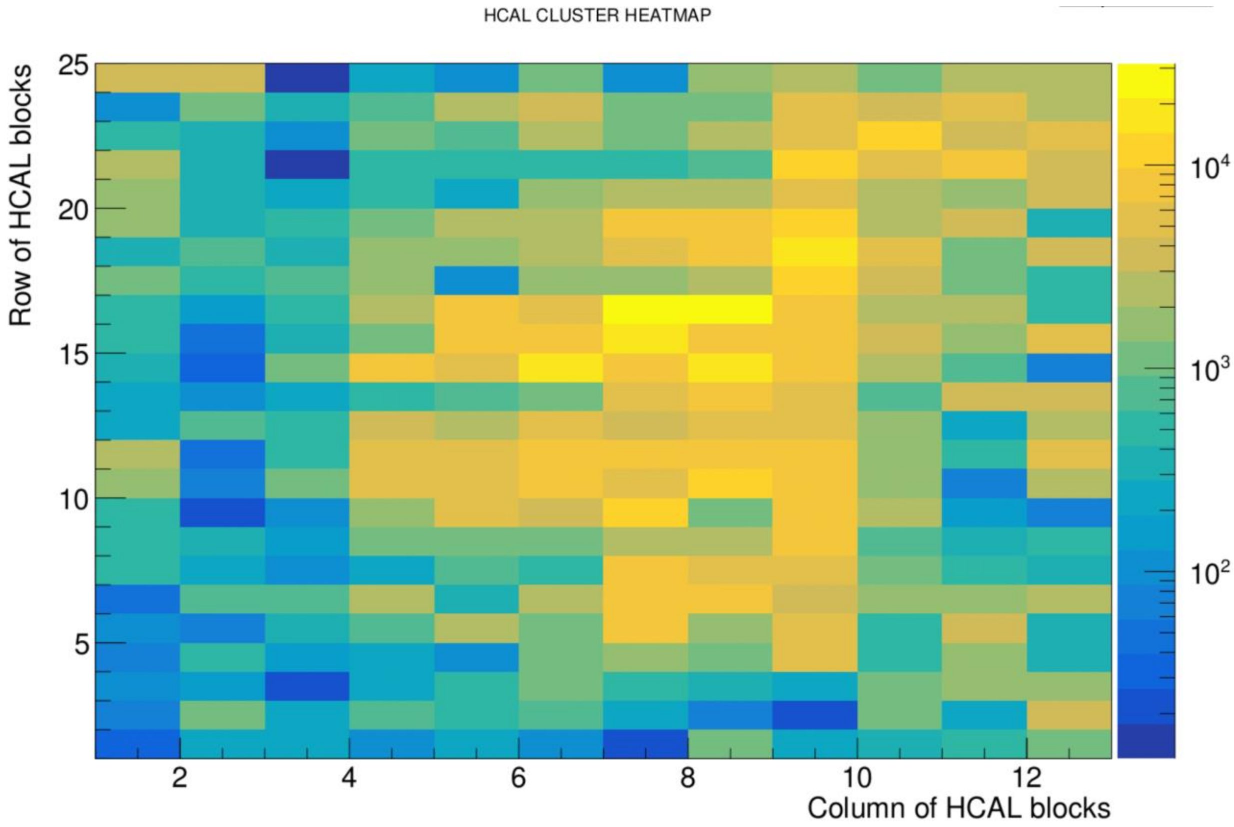




HCAL during GEp

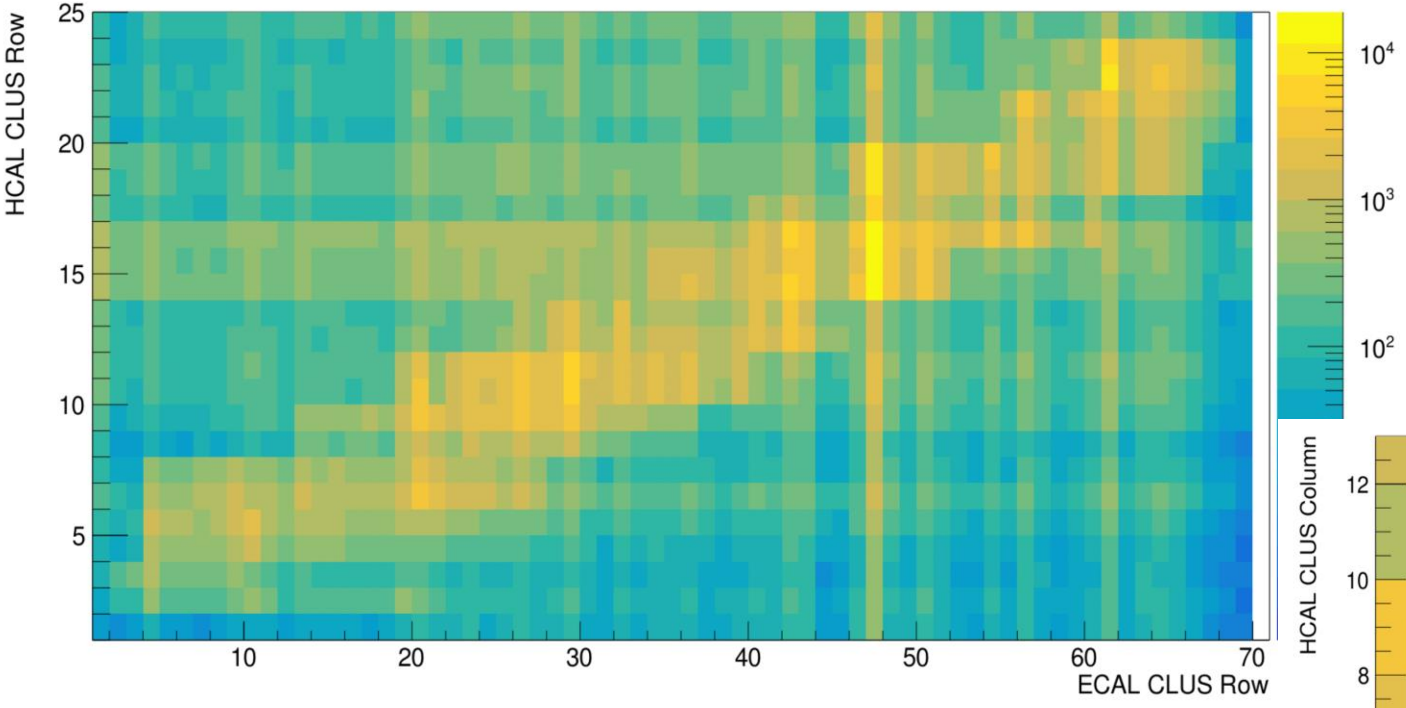
- Plots from highest kinematics runs (5th pass beam) showing fADC scalers and CLUSTER heatmap

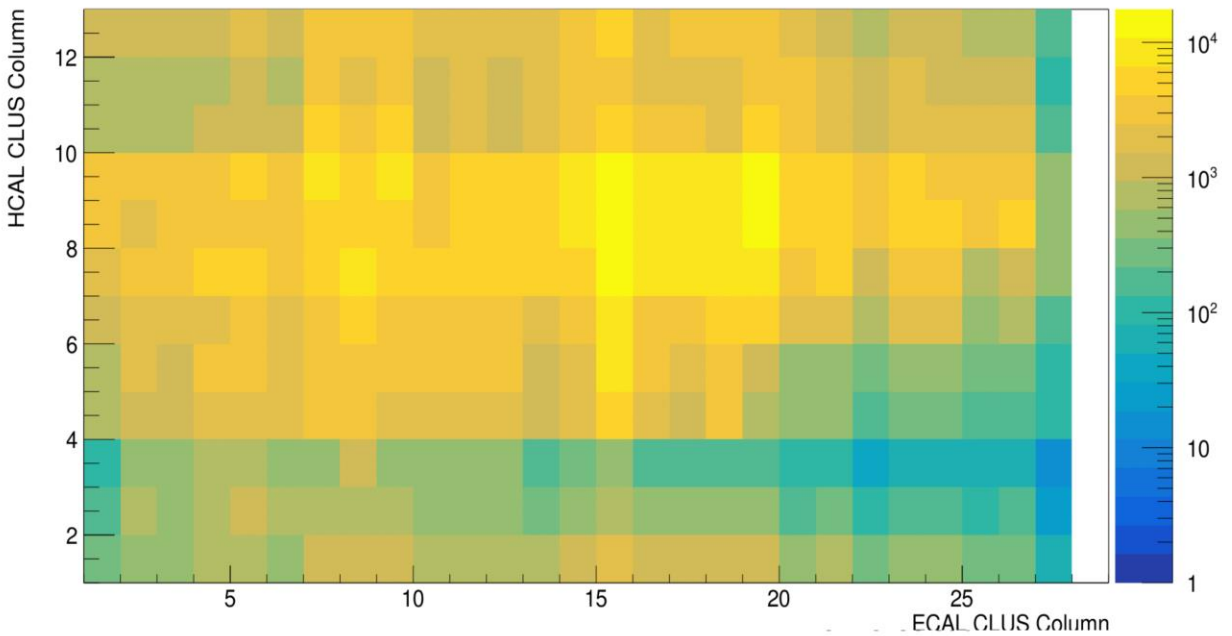




HCAL during GEp

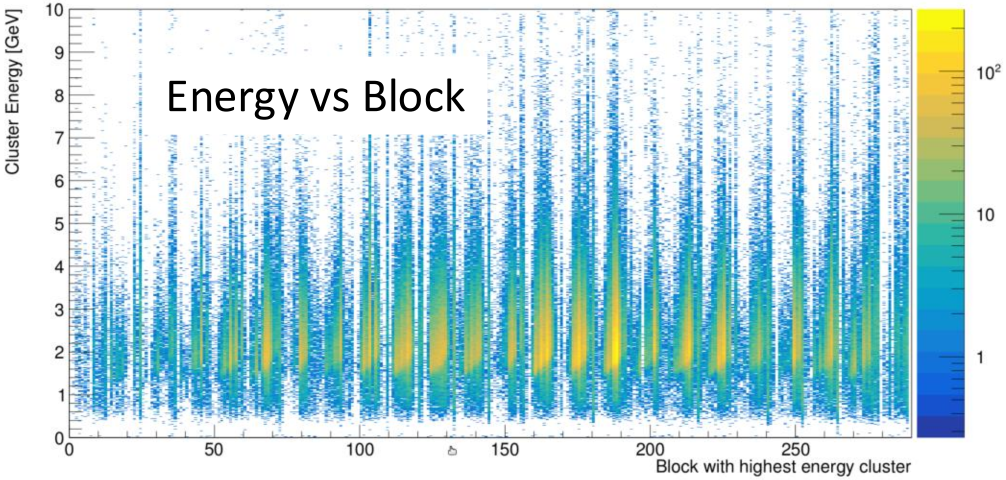
- Cluster position correlation between ECAL and HCAL

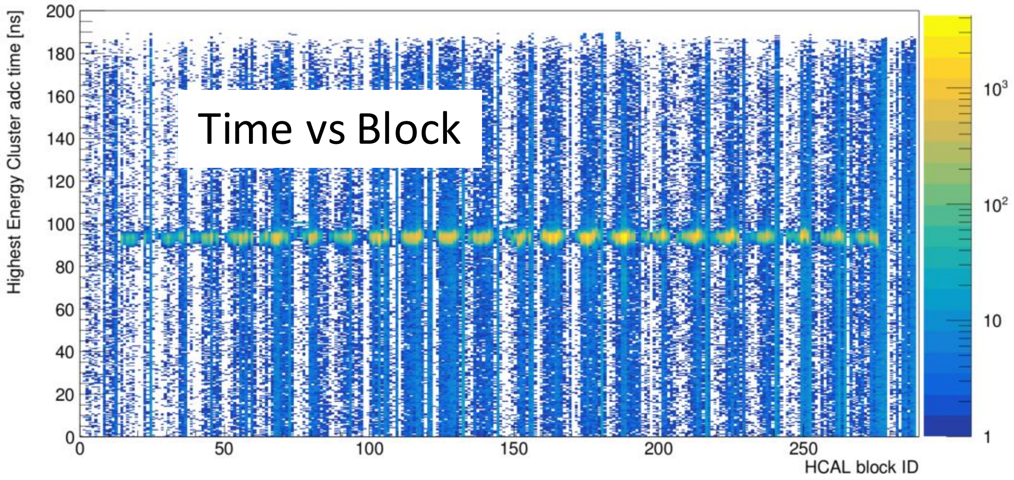




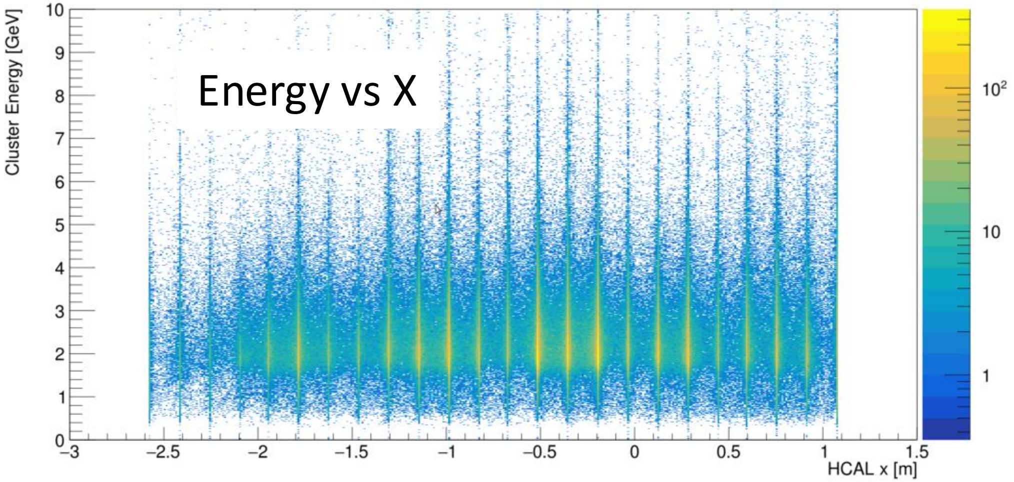
HCAL during GEp

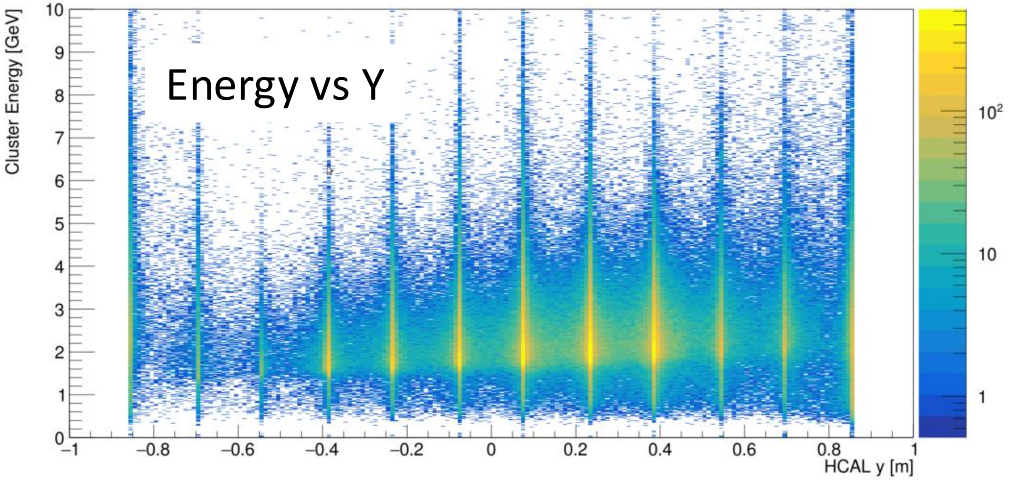
Cluster Energy and timing for HCAL blocks





Cluster Energy and positions in HCAL (x: vertical, y: horizontal distance)





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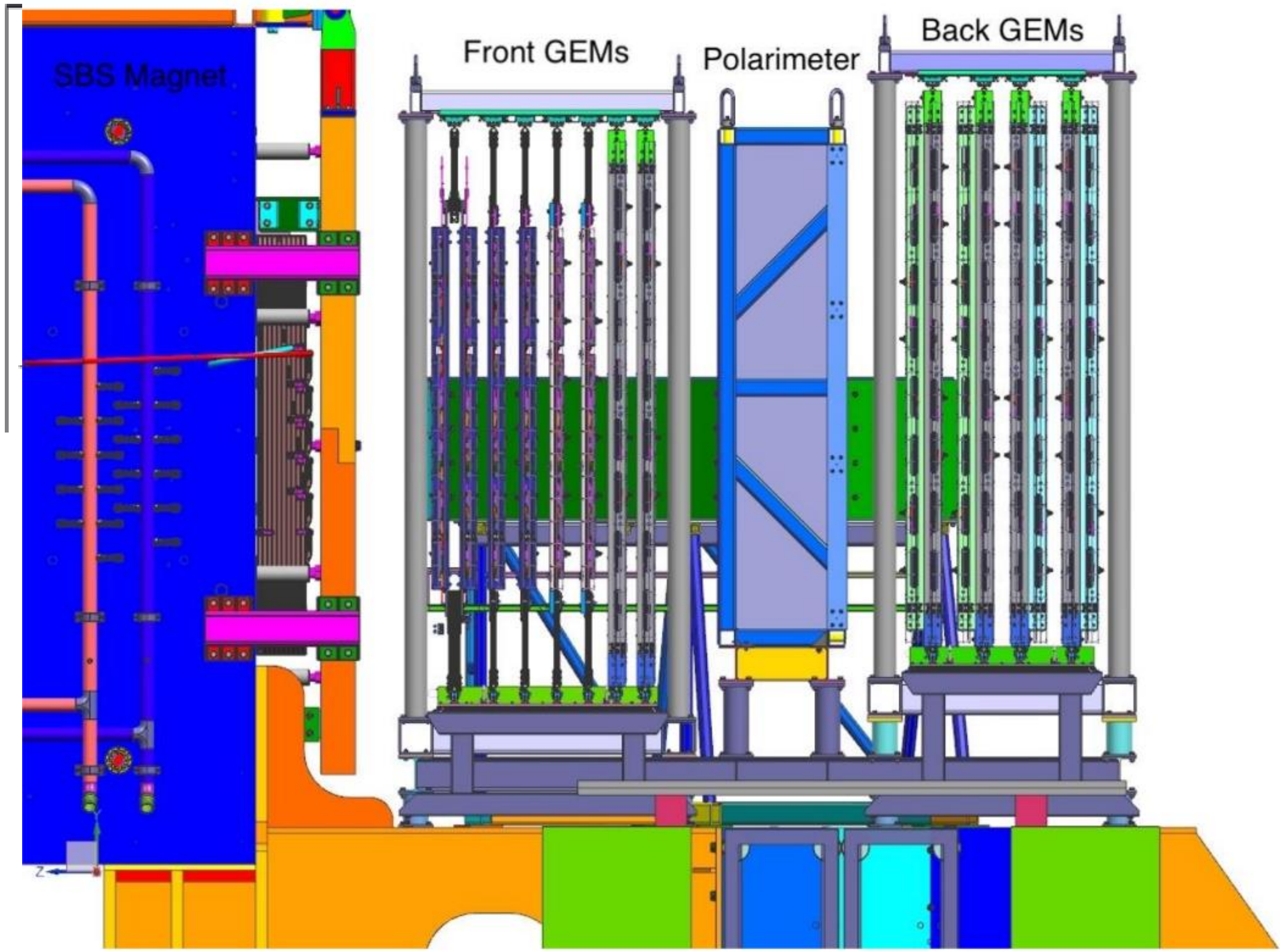
GEM tracker status

Overall performance of SBS Front & Back Trackers

- The SBS GEM tracking system includes:
  - Forty-six (46) GEM modules
  - Front trackers: 6 GEM layers of 40 x 150 cm and 2 GEM layers of 60 x 240 cm
  - Back trackers: 8 GEM layers of 60 X 200 cm



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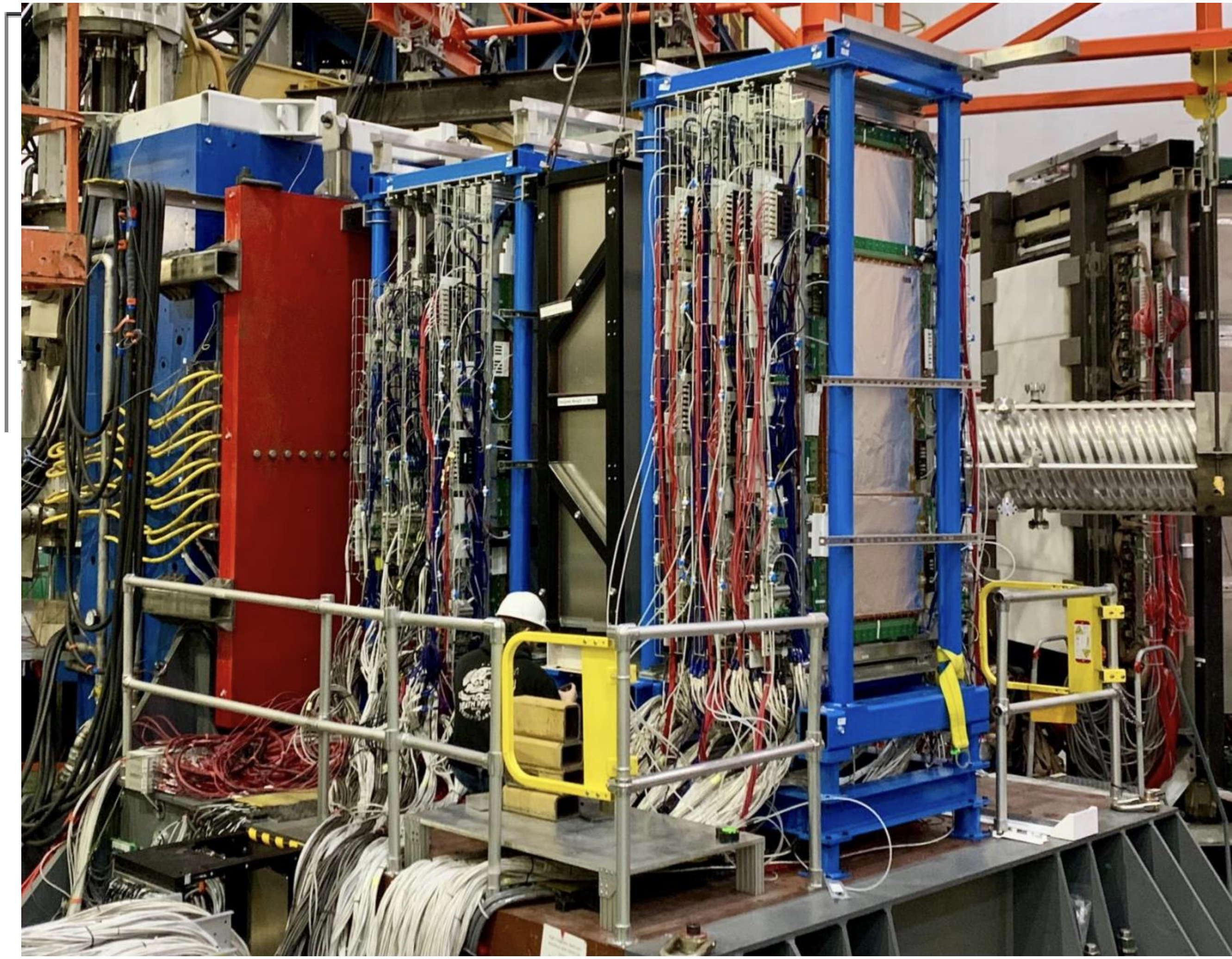

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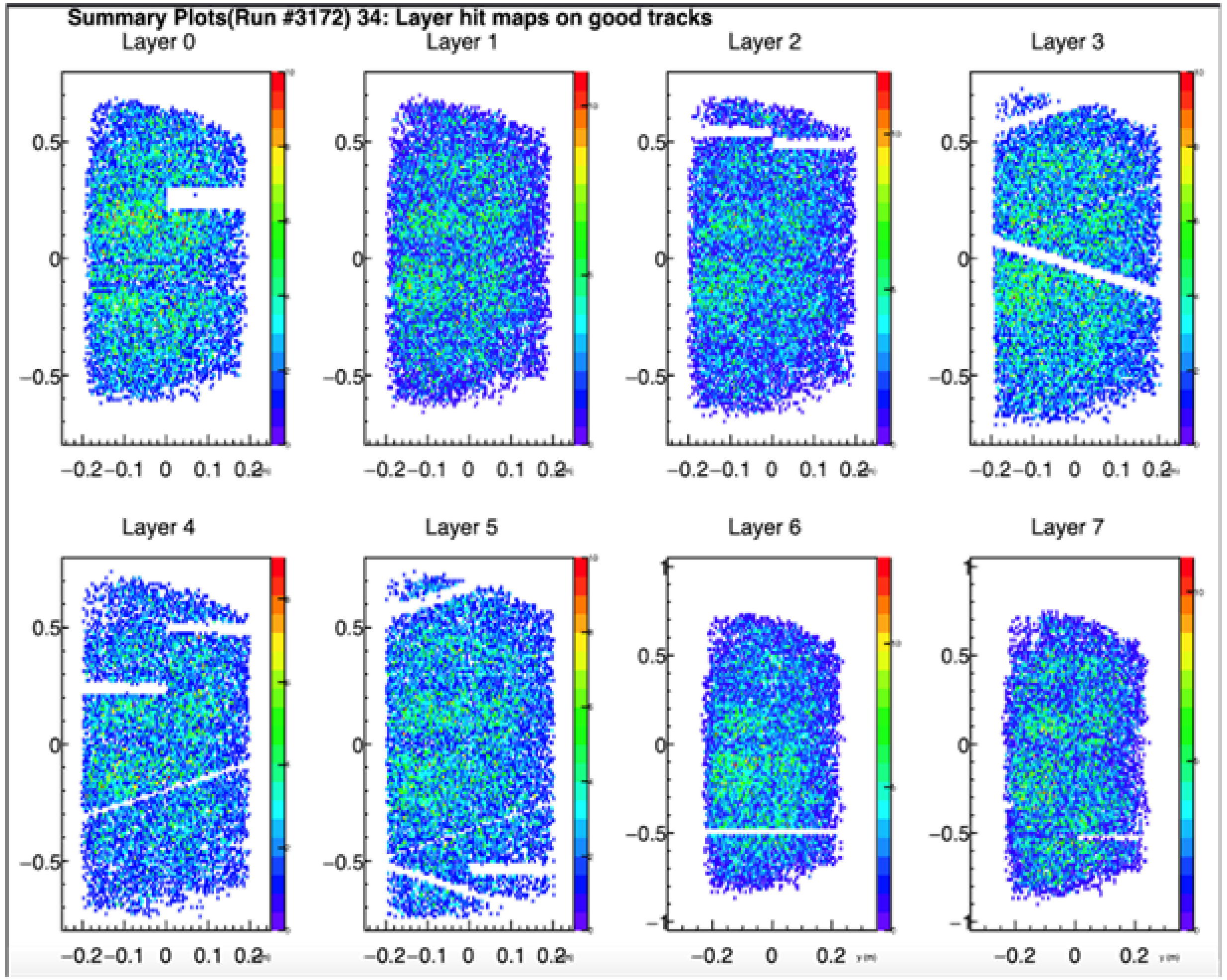
  - Forty-six (46) GEM modules
  - Front trackers: 6 GEM layers of 40 x 150 cm and 2 GEM layers of 60 x 240 cm
  - Back trackers: 8 GEM layers of 60 X 200 cm
- The SBS GEMs are operating at rate much higher than any other experiments
  - Both front and back trackers are performing well
  - A few dead areas caused by dead high voltage sectors and faulty electronics
  - Since the beginning of the GEp, only about 7 sectors out of 1560 sectors were lost



Hit map on 8 GEM layers of the front tracker

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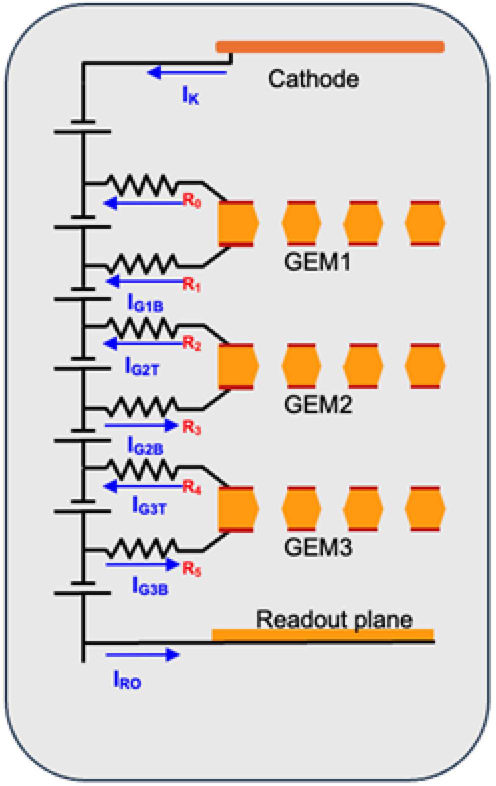
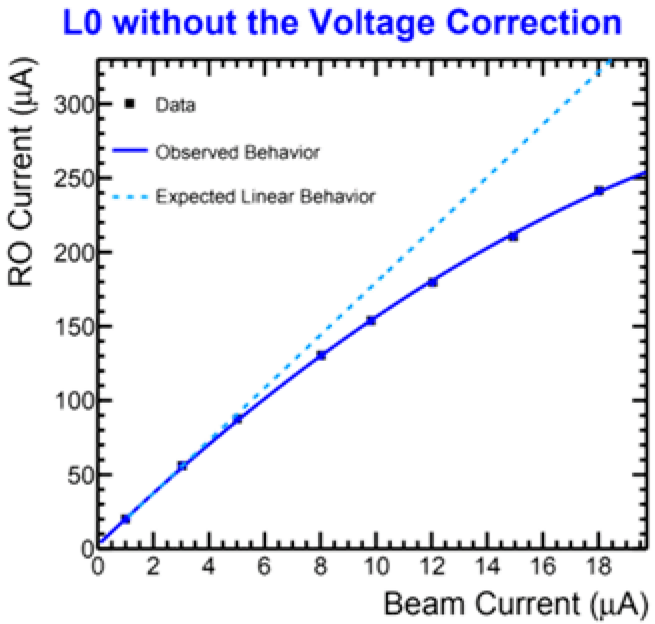
GEM performance

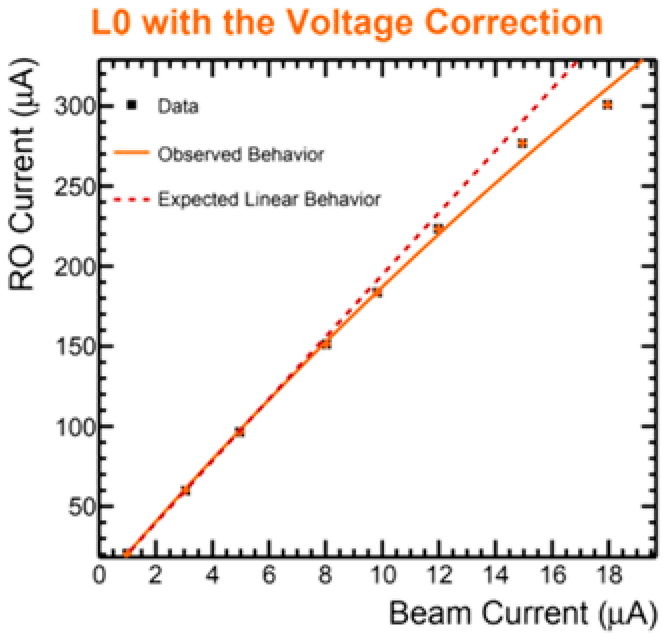
Operating GEMs in High Rate Environment

- High rate conditions lead to the drop voltage on GEM protective resistors
  →Lower the field strength in GEM holes
  →Lower GEM gain
- Solution: Applied HV correction to compensate the voltage drop on protective resistors →Restore the field strength in GEM holes →restore detector gain
- With HV corrections, the RO current is near linear to the beam current
  →indicating no loss in GEM gain



The slope of the plot is proportional to the gain

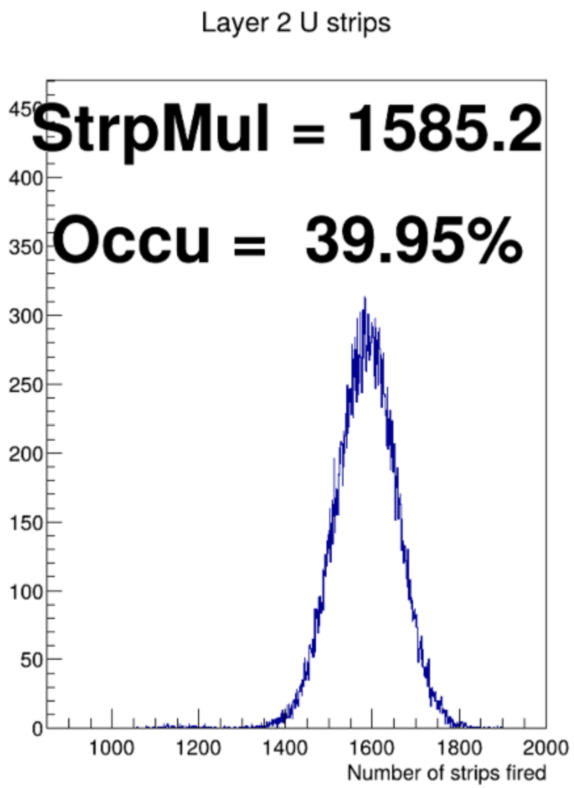


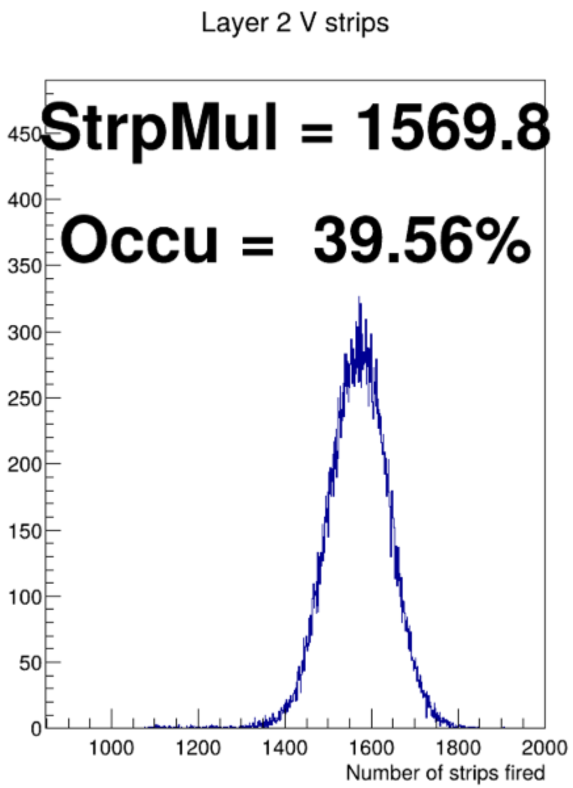


GEM performance

Detector Occupancy in High Rate Environment

- GEM modules with shorter readout strips and improved robustness are used in the front tracker
- At 15uA, the raw occupancy on the front tracker reaches between 30 to 50%
- This high occupancy imposes challenge to the tracking analysis
    - High detector occupancy → Large number of 2D hit combinations →Increase difficulty in track finding

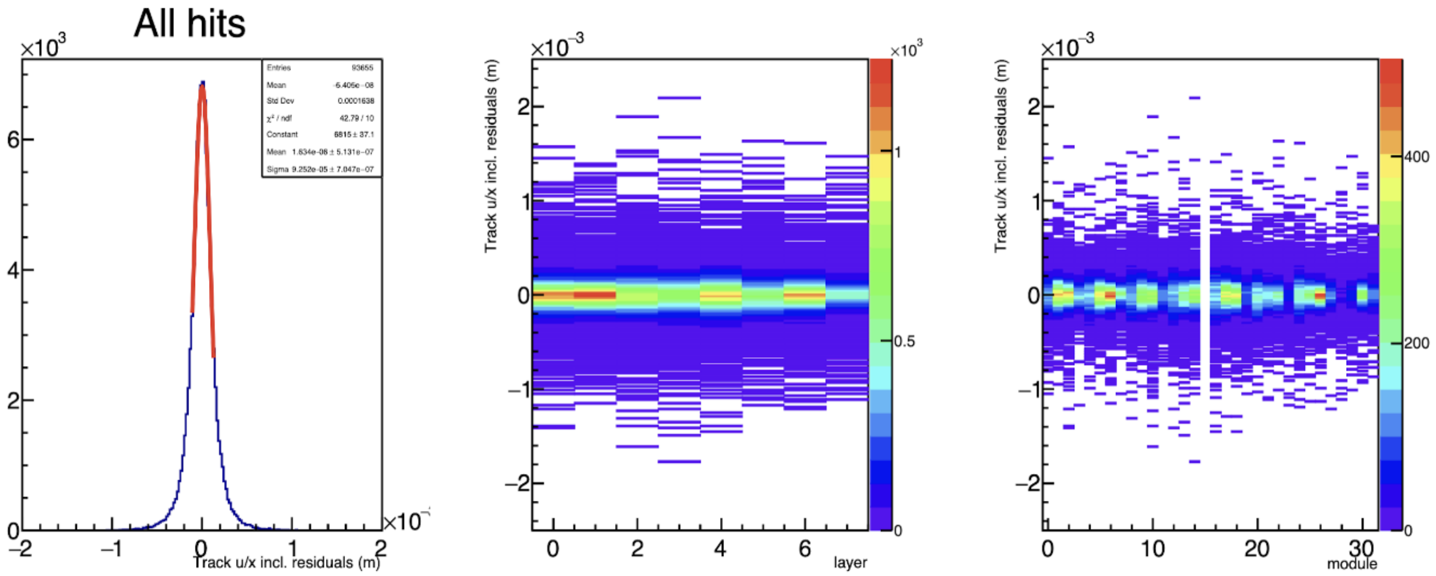




•The GEMs are handling unprecedented rates very well.
•The total integrated rates and occupancies are an order of magnitude than in any other experiment ever in the world

Alignment of GEM Trackers

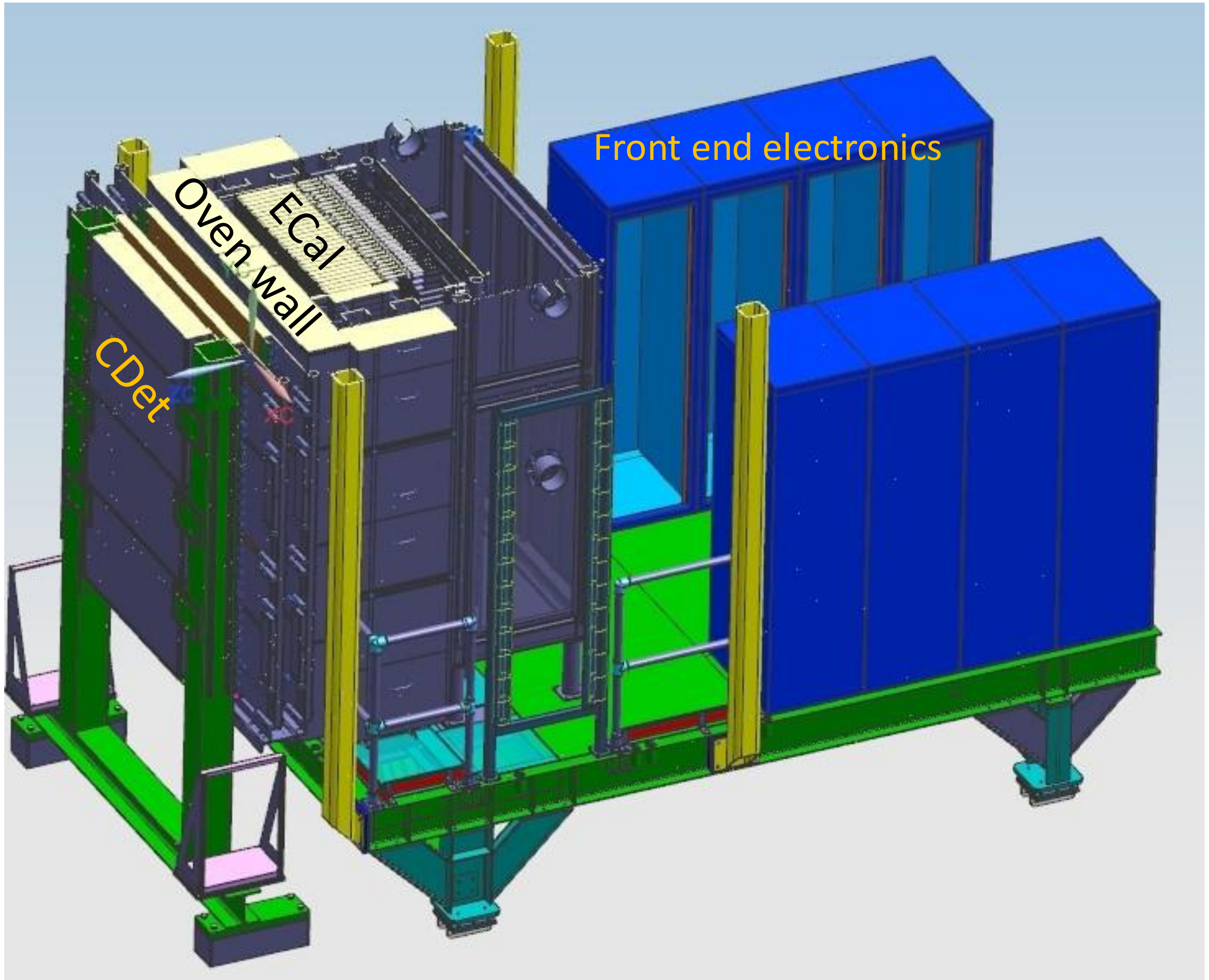
- Because of the high occupancy, the alignment has been very challenging
- During the early stage of the experiment, several repairs required sliding out some layers in the back tracker so alignment must be redone



- Despite all the challenges, Andrew and Anu were able to align both trackers
- Tracking results from the 1uA data during Kin1 suggest the spatial resolution is ~ 90 µm

ECal design

- 1656 lead glass crystals
- Crystals heated to continuously anneal from radiation damage:
  - 210 ℃ (front) to 180℃ (back)
  - Controls and monitoring software developed by DSG require little oversight: alarms monitor temperatures and hardware/software activity while process controllers turn off heaters if unsafe conditions detected



ECal design

- 1656 lead glass crystals
- Purpose of ECal is to reduce trigger rate with tight conditions based on position and energy
- Crystals heated to continuously anneal from radiation damage:
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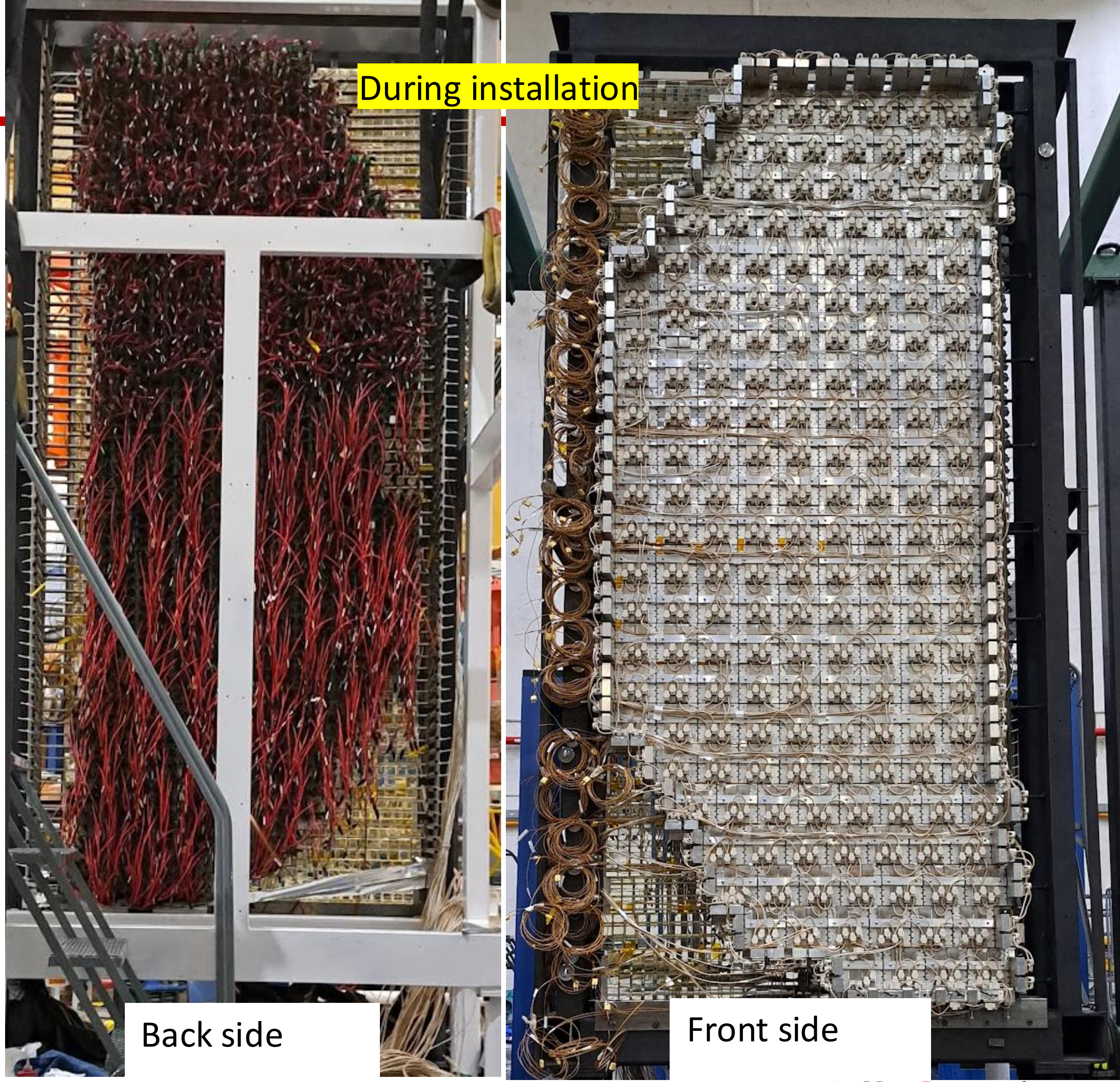

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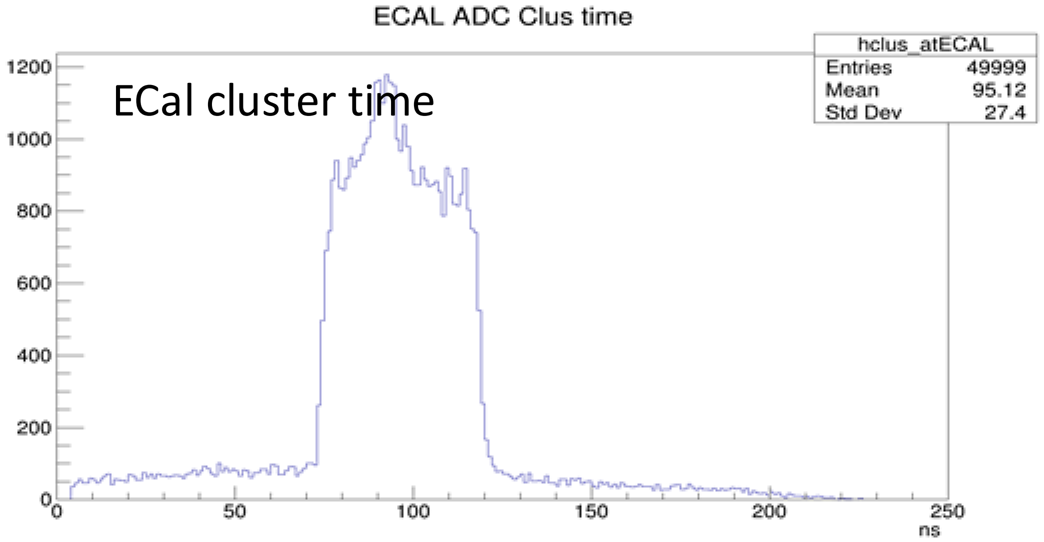
- Rear enclosure cooled with 3 16000BTU air conditioners to keep it below 50 ℃

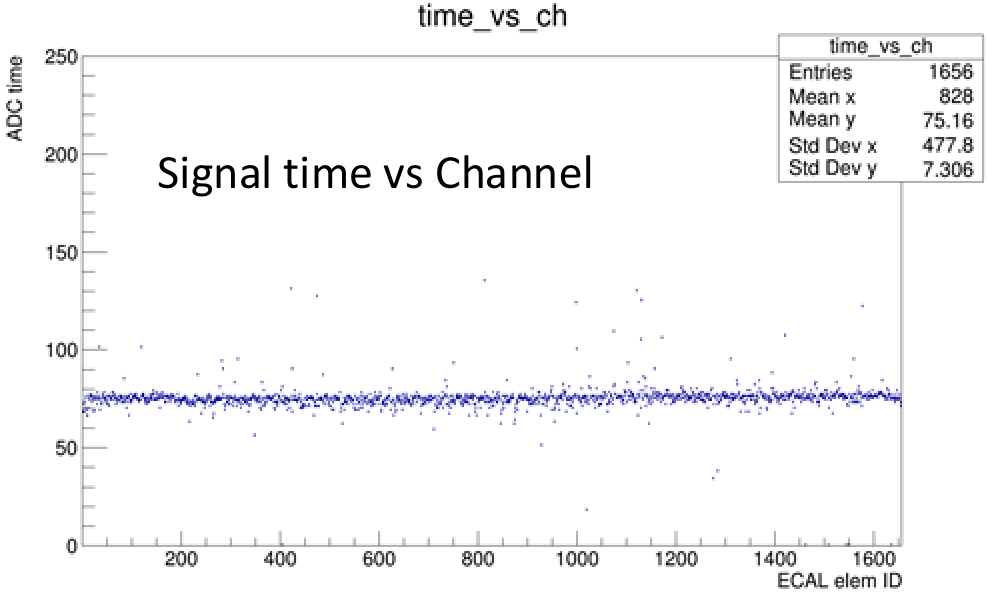
ECal timing

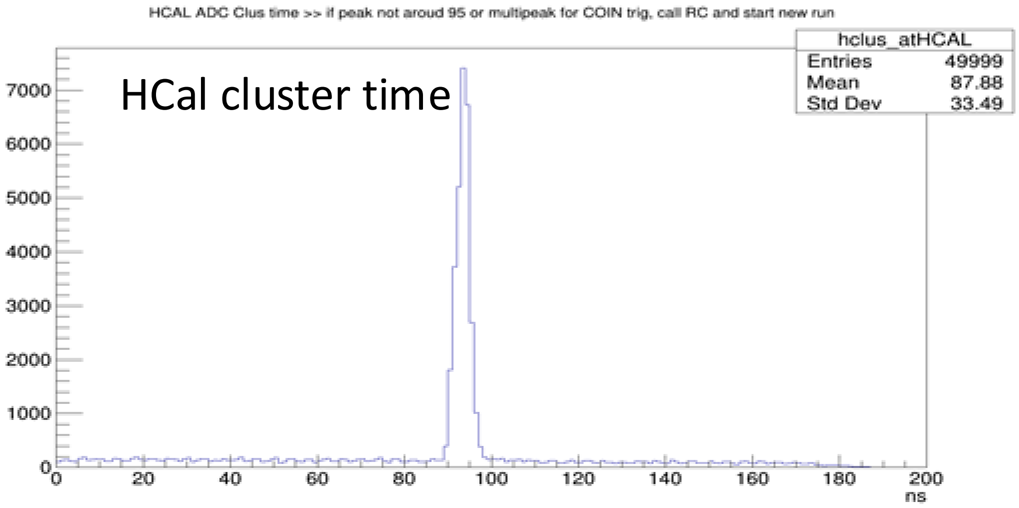
Started with the relative time difference among all the ECal channels with cosmic data, and then improved it with beam data.

Accommodate for the time difference between ECal and HCal in order to line up their timing windows for coincidence.

Coincidence matching is now implemented between ECal and HCal to reduce trigger rate.







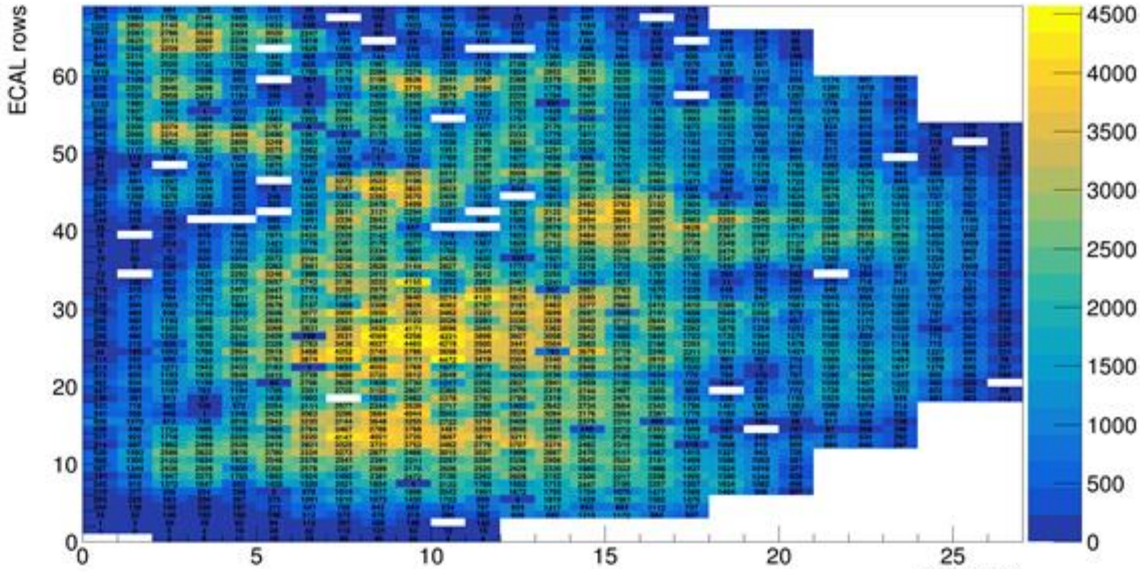
ECal gain matching

Starting estimate for gain matching used endpoint of ep inelastic spectrum to find approximate HV settings

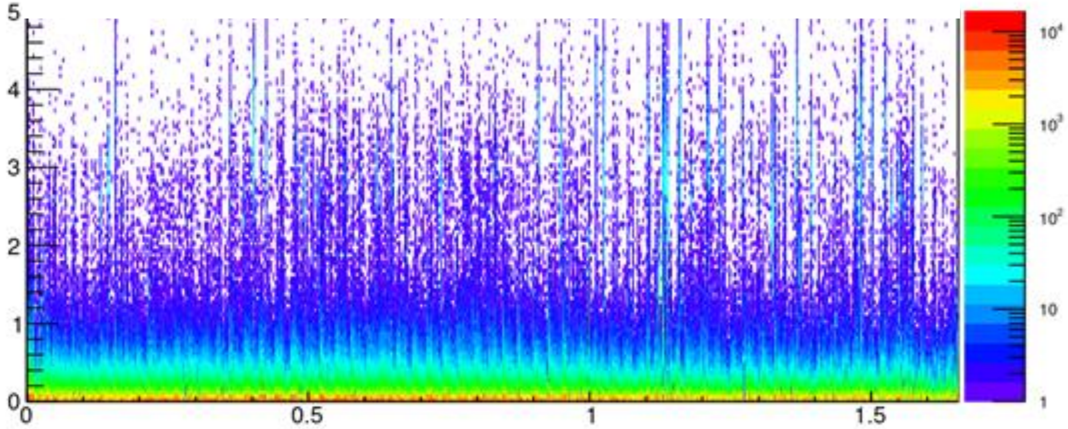
After collecting enough elastic events, re-calibrated ECal and obtain more accurate gain factors.

Several rounds of elastic calibrations have allowed for us to iterate upon the calibration in attempt to maximize the trigger efficiency.

Number of Good Events per block for ep calibration

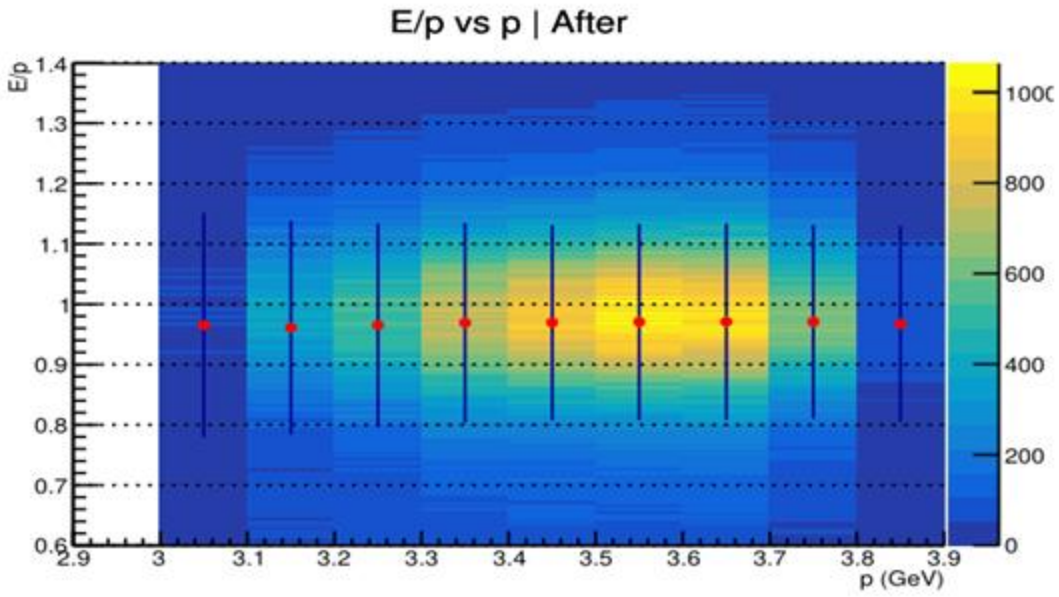


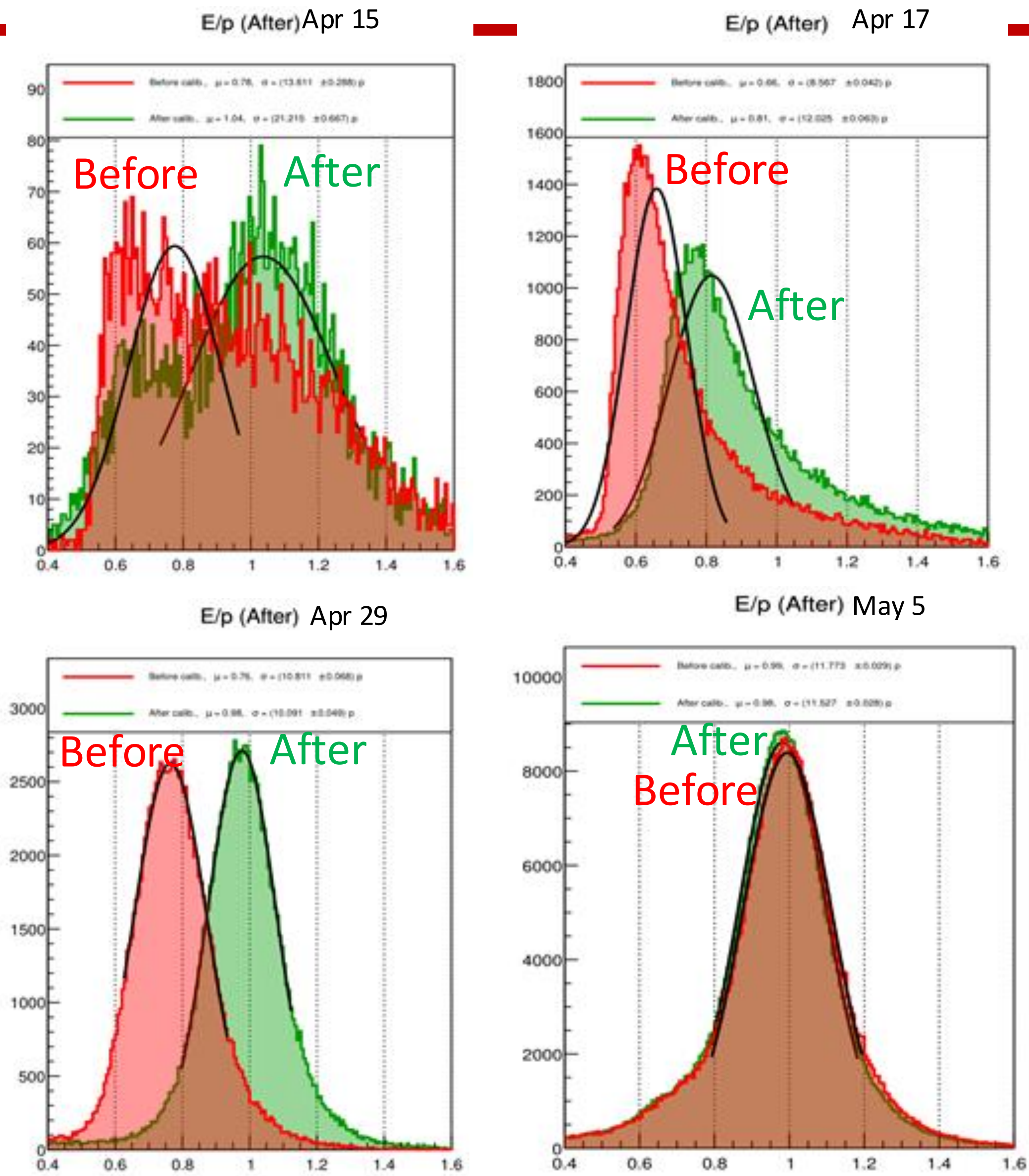
Energy spectrum (GeV) vs ECal blocks.



ECal elastic ep calibration

Calibration with electron E/p from elastic events in Kin 1 (3 pass) , we currently achieve an energy resolution of ~11.5%, we hope to get closer to the expected ~5-6% resolution with further iterations of elastic calibration





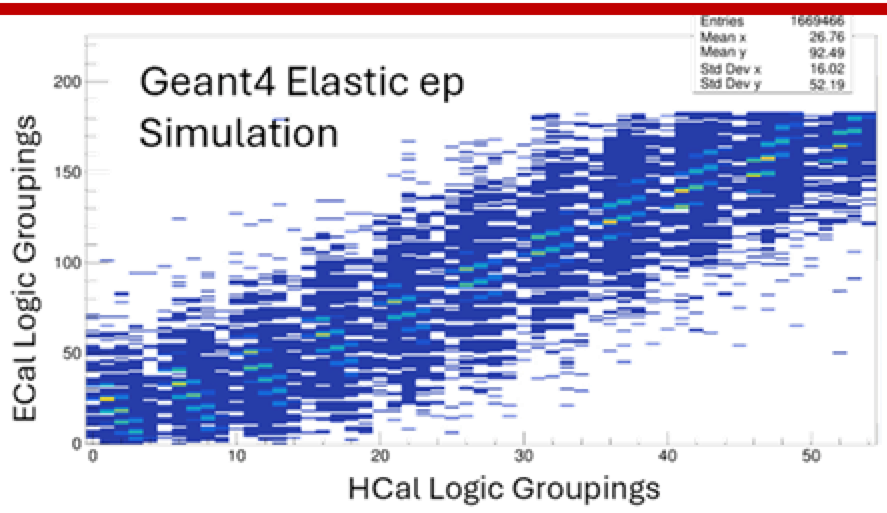
ECal-HCal coincidence trigger

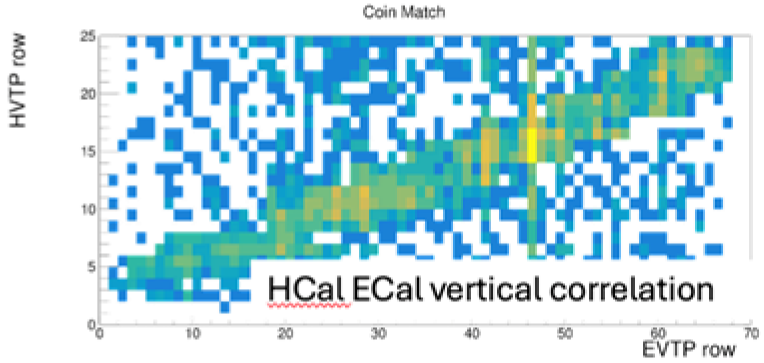
Geant4 simulations of elastic ep scattering determines correlation between logic groups of the electron and hadron calorimeters.

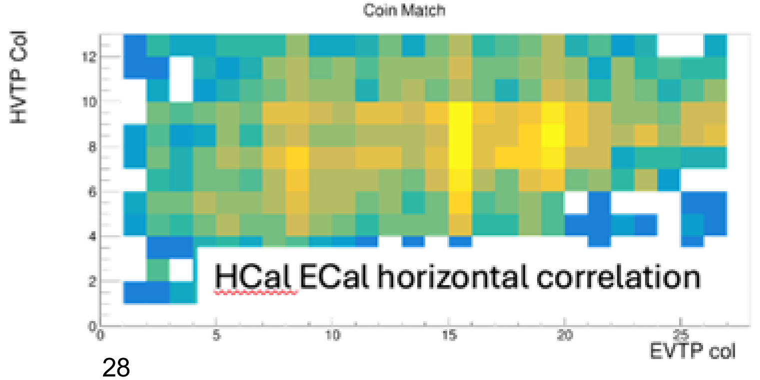
Insert lookup table from simulation into the trigger logic between the calorimeters to determine when a good trigger is formed, which we refer to as the coincidence matching trigger.

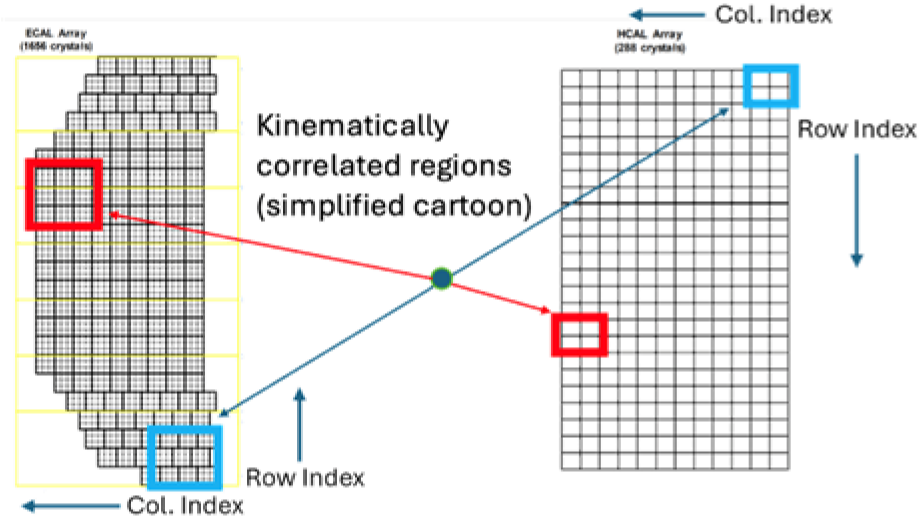
Coinc trigger reduces rate by ~10x relative to HCal **AND** ECal

At cluster energy thresholds of HCal = 20% and ECal=65% of the expected elastic energy, trigger rates ~2kHz and DAQ livetime is consistently around 100%, although we have yet exceeded 22uA.





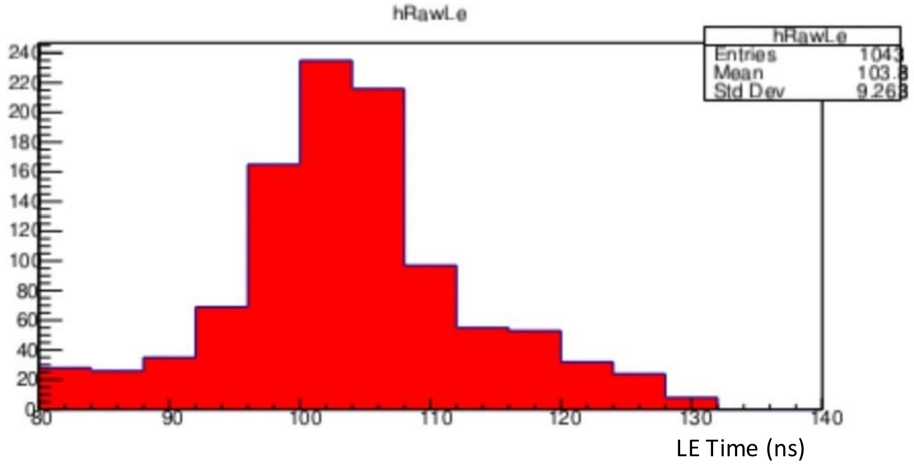




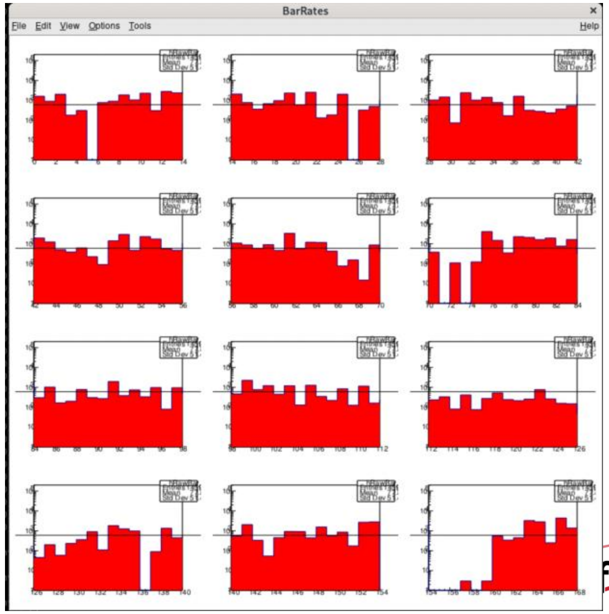
HCal vs ECal trigger hit plots from real data shows the expected positive linear correlation between hits in the two calorimeters, with the vertical correlation being much stronger than the horizontal

CDet Readout/Detector Performance

- Latency = 3216 ns, Window = 52 ns
- Clear peak in timing spectra – established at low current running
- Using trigger reference signal in additional vfTDC module – reasonable vtTDC timing calibration achieved; resolution ~10’s of ps (still work in progress)
- Updated vfTDC firmware to use block readout to solve deadtime/livetime issues
- Reasonable HV/threshold values determined with HV scan at lower currents (still a few ”missing” bars at upper edge of second layer of CDet, as well as a few “hot” bars that have HV disabled)

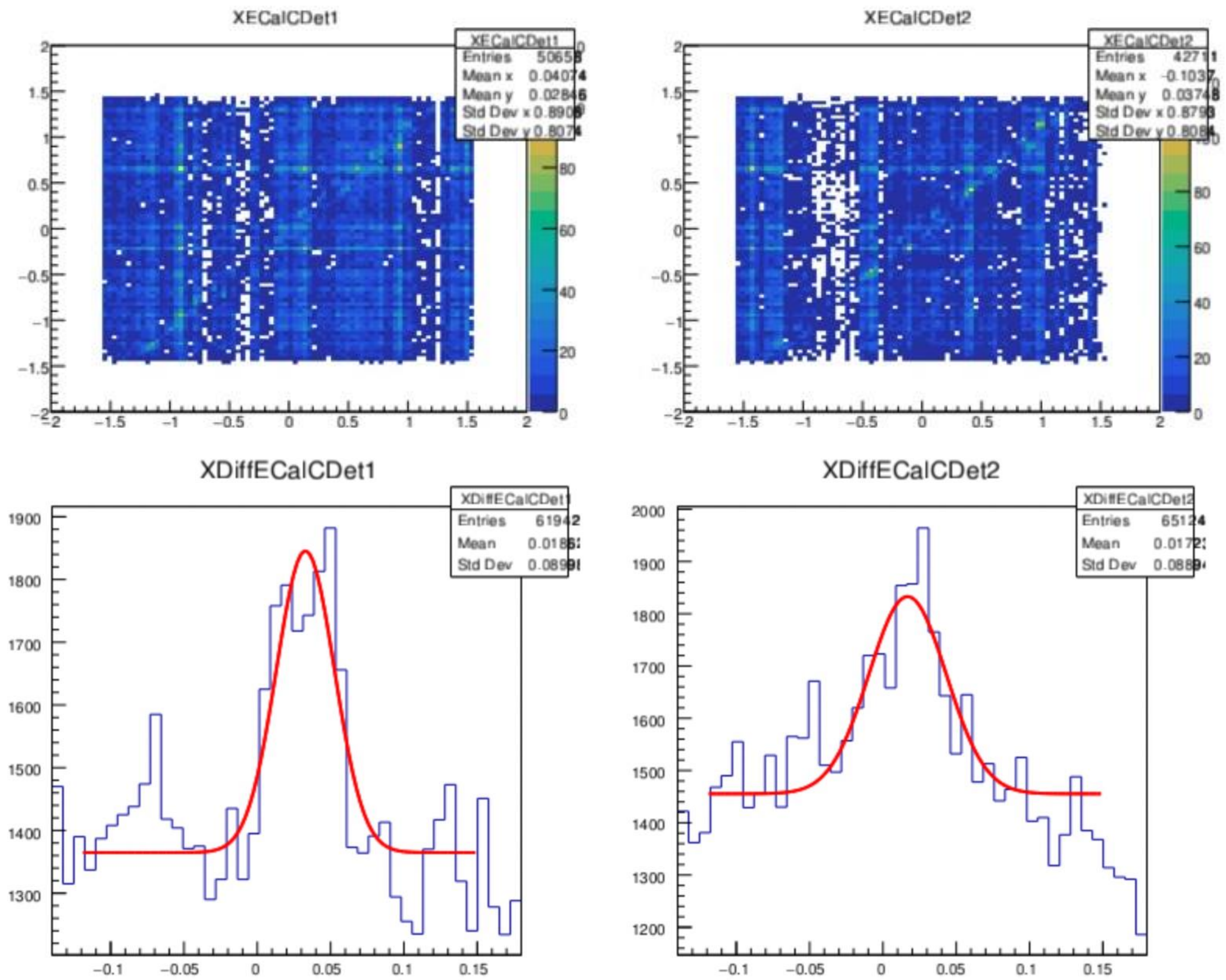


Hit Rates for All CDet Bars



ECal Position Correlations

- Observe clear correlation between CDet X-position of hit paddle and determined ECal X-position of best cluster
- Signal-to-noise ratio ~0.15 per layer after all timing and multiplicity cuts applied
- At 20uA on LH2, approximately 800 raw CDet TDC hits per event; filtering implemented in SBSCDet class to use LE timing and Time-Over-Threshold cuts -> reduction to ~30 TDC hits per event.
- Working in progress -> identify CDet “clusters” based on hits in adjacent paddles.



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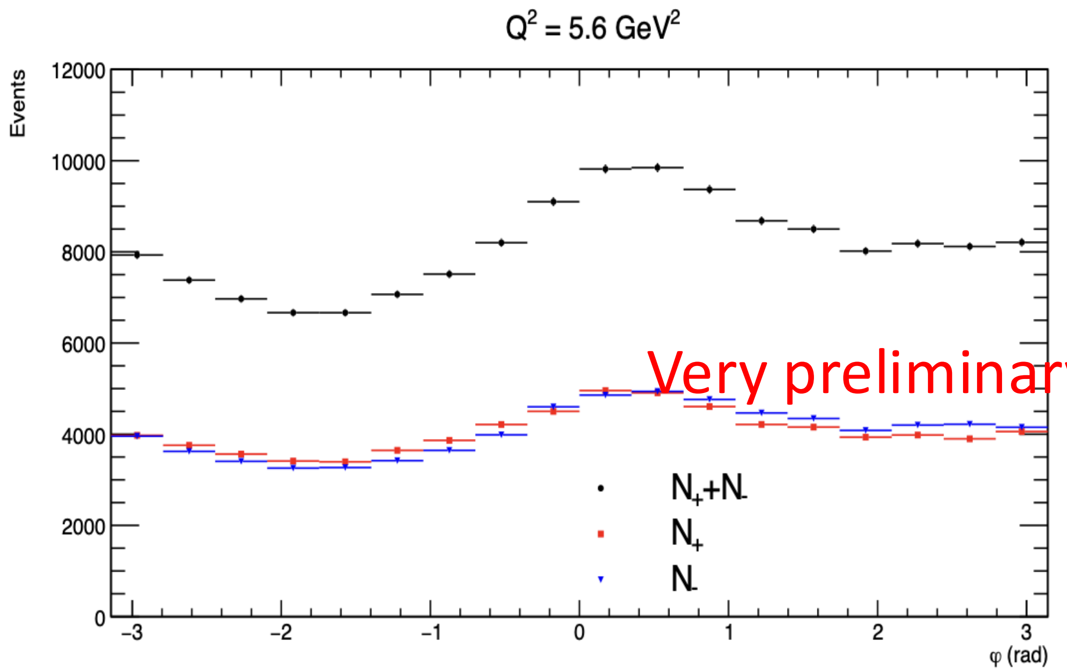
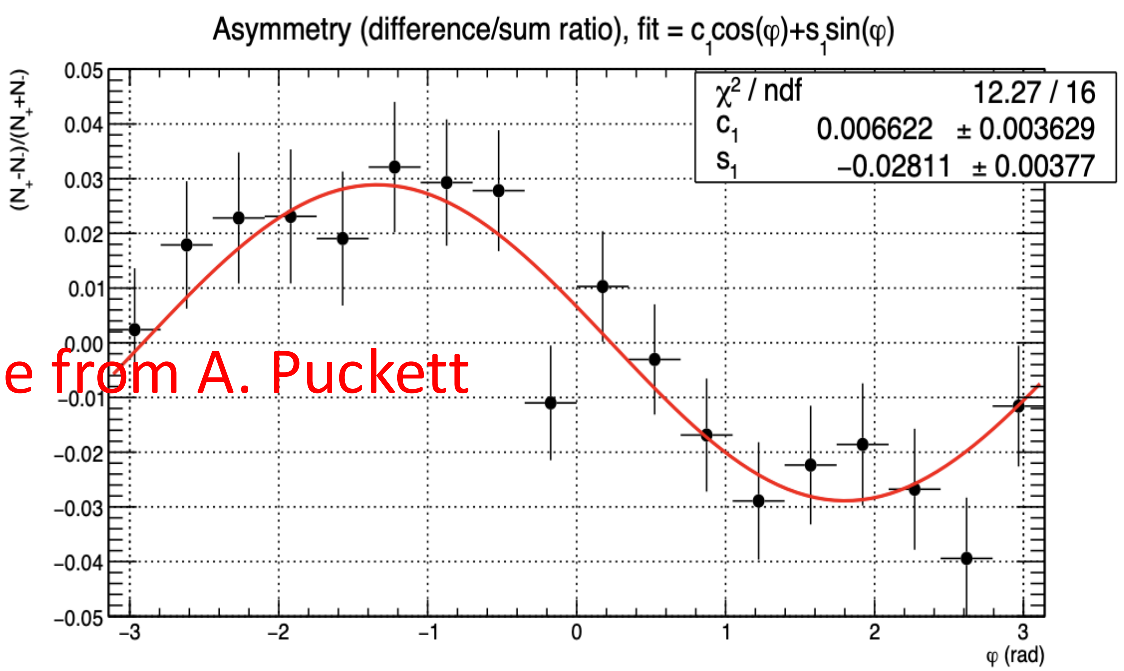
GEp is at the frontier on several fronts

We are running in a new regime

- GEMs have not been run at these levels before
- For a short period the experiment was generating 2.4GB/s at 22uA:
  - 2x what we proposed
  - Temporarily had to pause data taking and then revert to 15uA because Computing couldn’t write it to tape fast enough
  - With higher trigger thresholds and improved GEM parameters we were able to reduce this by 2x.
  - Firmware upgrade being developed for GEM region of interest readout which is expected to further reduce data generation by 3x
- Recall that we want to get to 50uA but that depends on well calibrated detectors with tight trigger conditions…
- But to get calibration data (very rare ep elastic events) you need fairly well calibrated detectors or very loose cuts and lots of computing power
- 10 seconds of data (20 GB file) takes the farm almost 24 hours to analyze/decode. Fortunately, you can do thousands in parallel.
- We are generating data locally so fast that we cannot complete track analysis before the local copies disappear forcing all tracking analysis to be on the batch farm.

Are we measuring polarization yet?





Very preliminary slide from A. Puckett

- Left: FPP azimuthal angle distribution passing all exclusivity and other cuts; for helicity sum and individual helicity states—large instrumental asymmetry due to nonuniform acceptance/efficiency
- Right: Helicity asymmetry: difference/sum ratio
- Asymmetry amplitude and relative sign/magnitude of sine and cosine asymmetries are consistent with expectations

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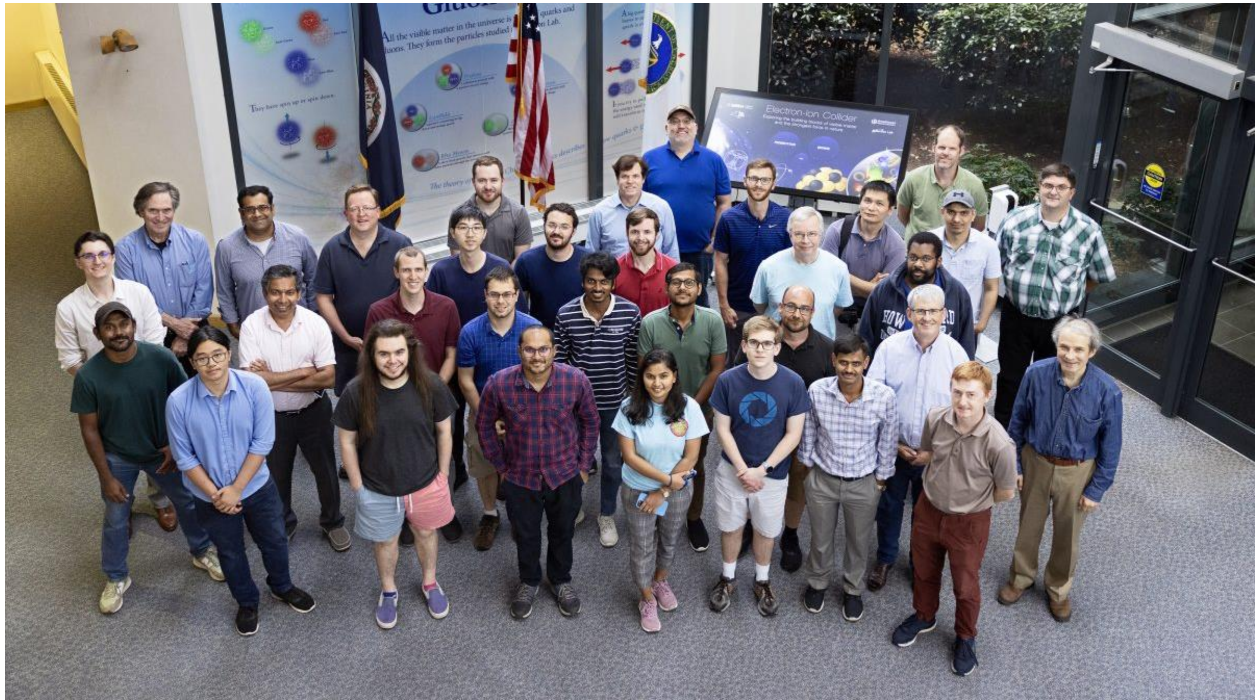
Conclusion

- The GEp experiment is currently running in Hall A under challenging conditions that push the boundaries on several fronts.
- We are currently taking data at our highest Q-squared point at Q^2=11.1GeV^2
- The successes and challenges of this experiment will inform future experiments especially those with high rate tracking requirements.
- This has been a huge effort with so many individuals and institutions involved. I would like to acknowledge this great group!

THANK YOU



Increasing difficulty with each iteration

$$\text{Form factor} \propto Q^{-4}$$

$$\text{Cross section} \propto E^2/Q^4 \times Q^{-8}$$

$$\text{Figure-of-Merit } \epsilon A_Y^2 \times \sigma \times \Omega$$

$$\propto E^2/Q^{16}$$

Need large statistics, max luminosity and solid angle

Max luminosity -> large background
Large solid angle -> small bend -> huge background

Critical to this experiment is the maturing technology of high rate tracking with GEMS

Q^2 increases from 8.5 to 11.1 GeV^2 but higher beam energy 10.7 vs. 6 GeV => a factor of 5-6 of the FOM loss, but the SBS larger solid angle helps.