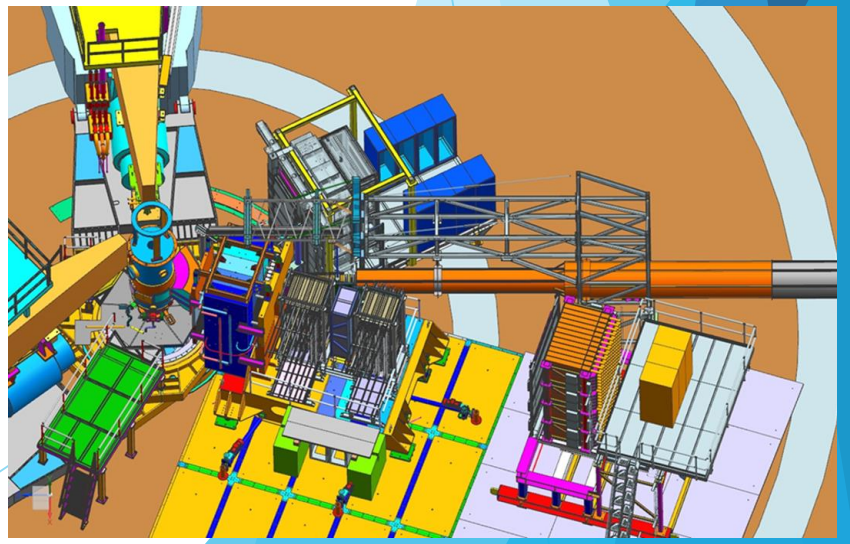
Measurement of the Proton Electric Form Factor GEp at High Momentum Transfer

Jimmy Caylor for the GE_p Collaboration

Hall A winter Meeting 2025



Jefferson Lab

GE_p Overview and Timeline

- Last of the mainline SBS experiments measuring the elastic form factors of the proton and neutron
- Will measure the electric Sachs form factor of the proton up to 12 GeV^2 with significantly increased precision at 5.5 and 8 GeV^2
- Employ the use of a new electromagnetic calorimeter and coordinate detector for the electron arm
- 16 layer GEM tracker for high efficiency tracking with high luminosity
- Installation/Testing/Commissioning into February

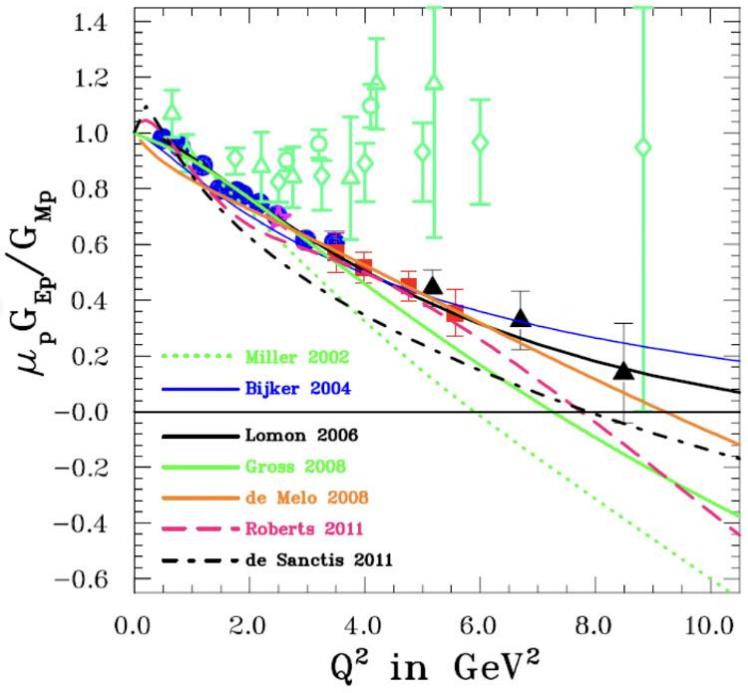
Elastic nucleon form factors

$$\mathcal{J}^{\mu}_{hadron} = ie\bar{N}(p_f)\,[\gamma^{\nu} F_1(Q^2) + \frac{i\sigma^{\mu\nu}q_{\nu}}{2M} F_2(Q^2)]N(p_i)$$

$$\frac{d\sigma}{d\Omega}(E,\theta) = \frac{\alpha^2 E'\cos^2(\frac{\theta}{2})}{4E^3\sin^4(\frac{\theta}{2})}[(F_1^2 + \kappa^2\tau F_2^2) + 2\tau(F_1 + \kappa F_2)^2\tan^2(\frac{\theta}{2})]$$

$$\frac{d\sigma}{d\Omega}(E,\theta) = \sigma_M[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2\tan^2(\frac{\theta}{2})]$$

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 F_1/F_2 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

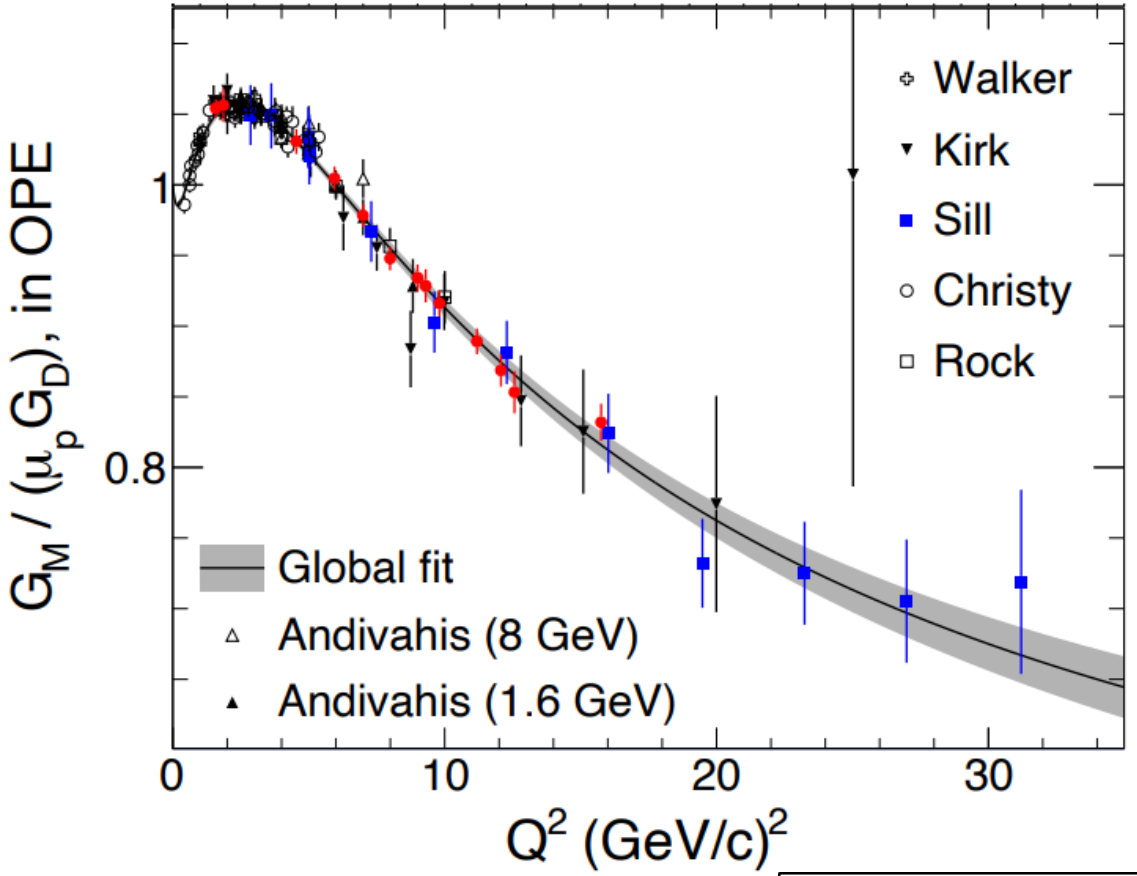
Polarization Transfer Method

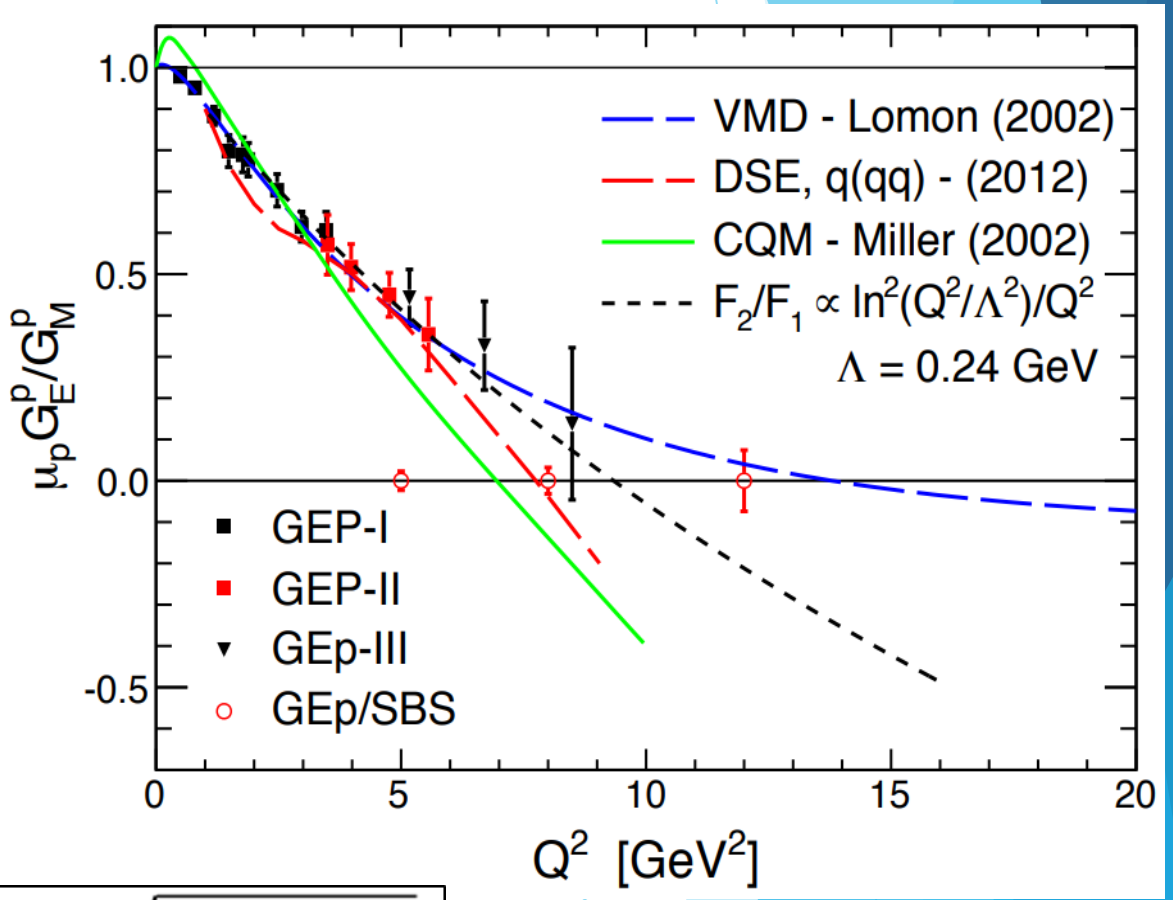
- Measures polarization transfer to hadron from polarized electron, which is sensitive to the ratio of the form factors

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

- Measure ratio of proton polarization along (P_l) and transverse (P_t) to momentum transfer
- Many systematics cancel in the ratio (Not directly sensitive to P_e or A_Y)
- Measurement method less dependent on two-photon contributions than the Rosenbluth separation method
- First employed at MIT-Bates and then at JLab in their subsequent GEp measurements

Existing data for proton form factors





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

Polarization Transfer Method

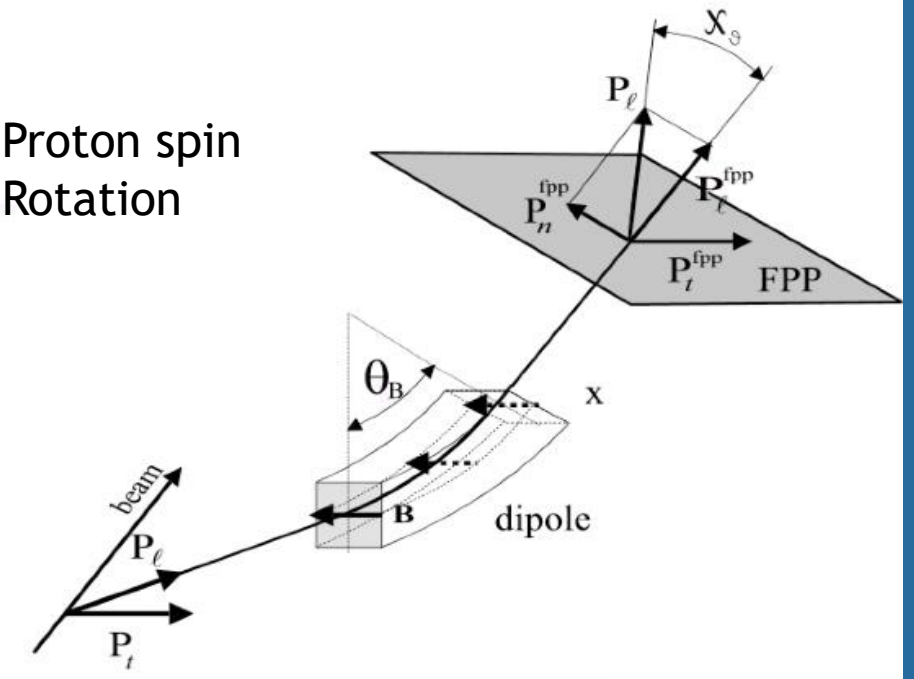
$$f^{\pm}(\vartheta,\varphi) = \frac{\epsilon(\vartheta,\varphi)}{2\pi}\left[1 \pm A_y(P_x^{fpp}\sin\varphi - P_y^{fpp}\cos\varphi)\right]$$

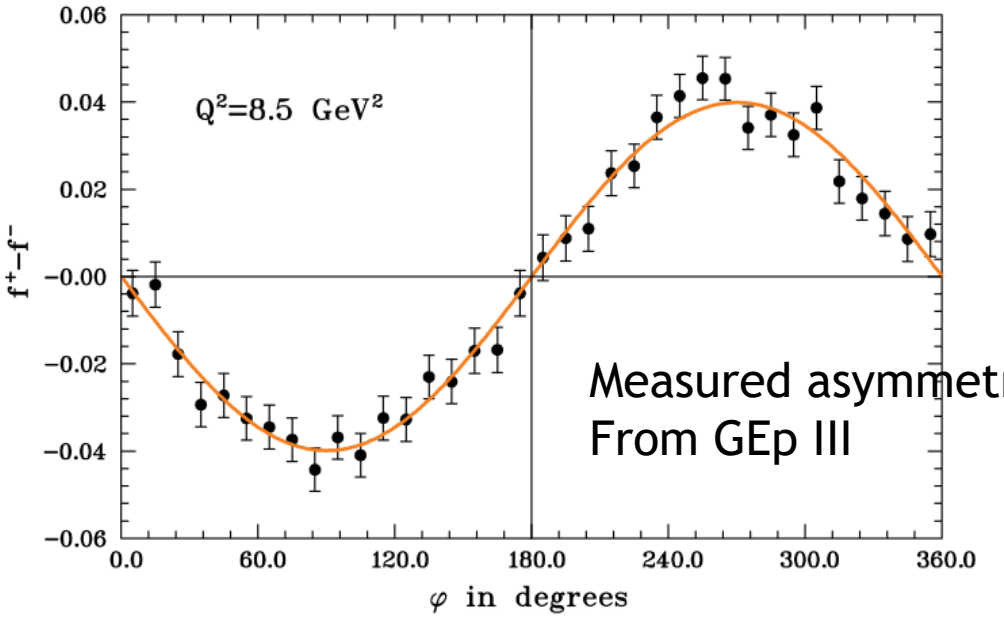
where $\pm$ refers to electron beam helicity

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

$$\frac{G_E^p}{G_M^p} = -\frac{E_e+E_{e'}}{2M}tan(\frac{\theta_e}{2})\left(\frac{P_y^{fpp}}{P_x^{fpp}}\sin\chi_e + \gamma_p(\mu_p - 1)\Delta\phi\right)$$

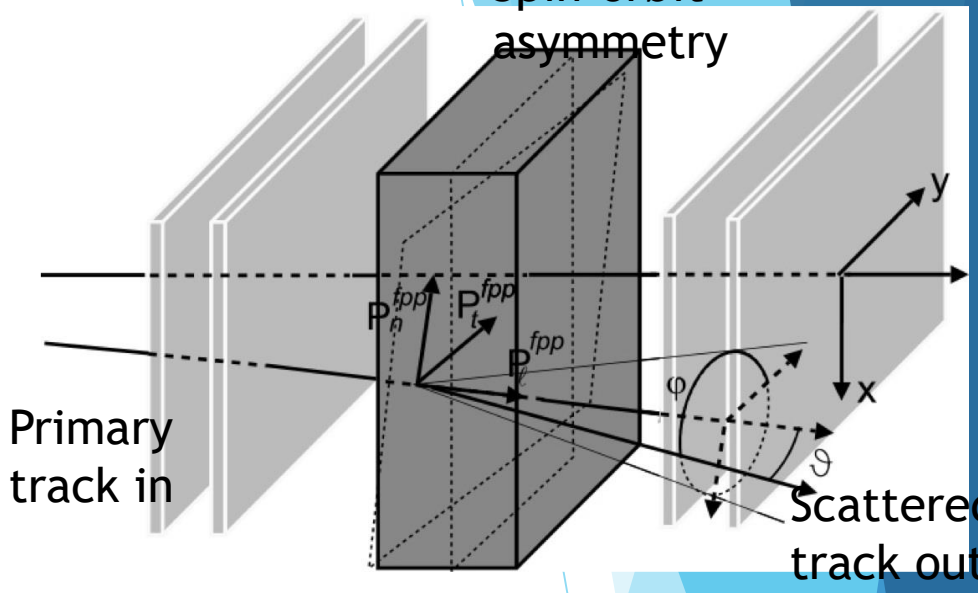
Proton spin Rotation





Measured asymmetry From GEp III

Polarization Transfer Method



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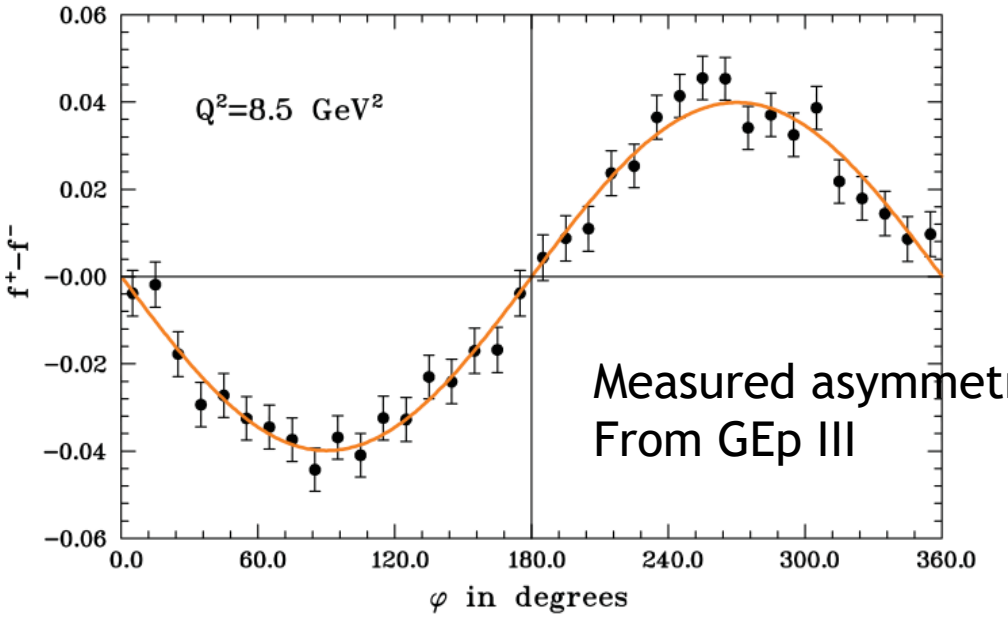
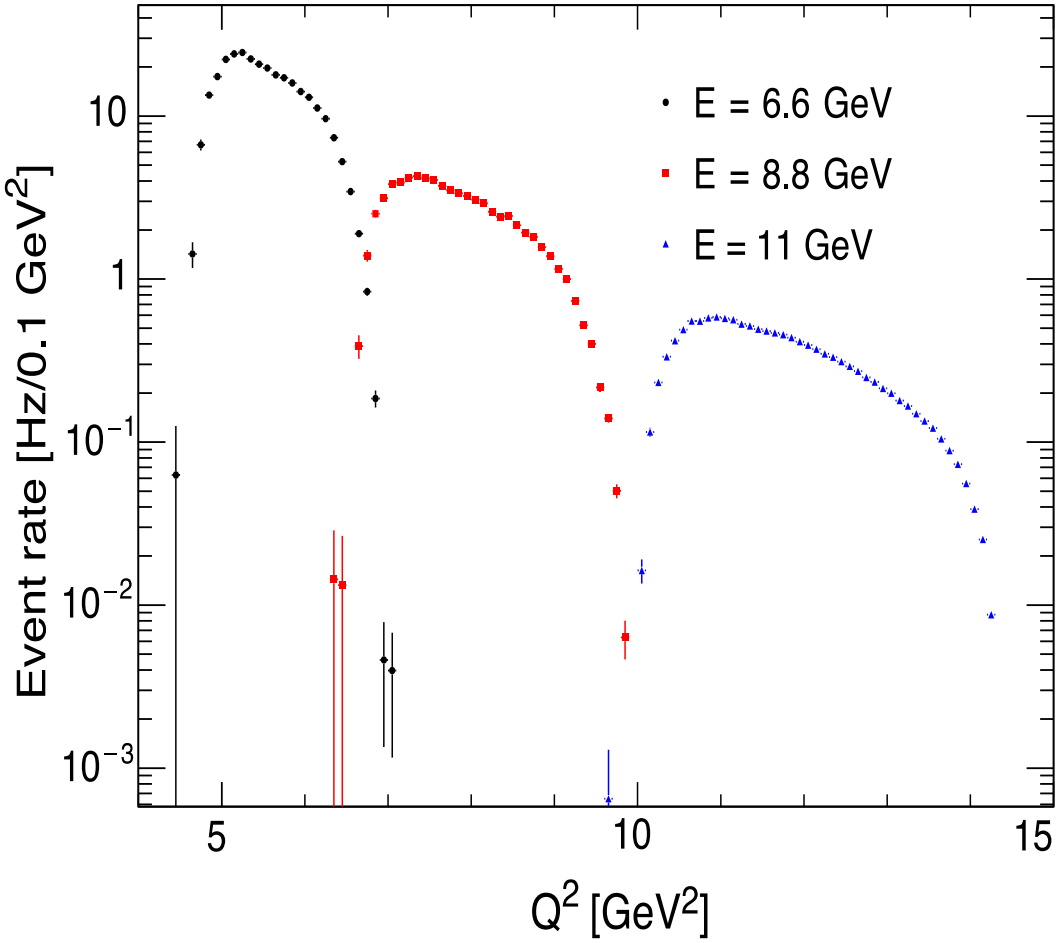


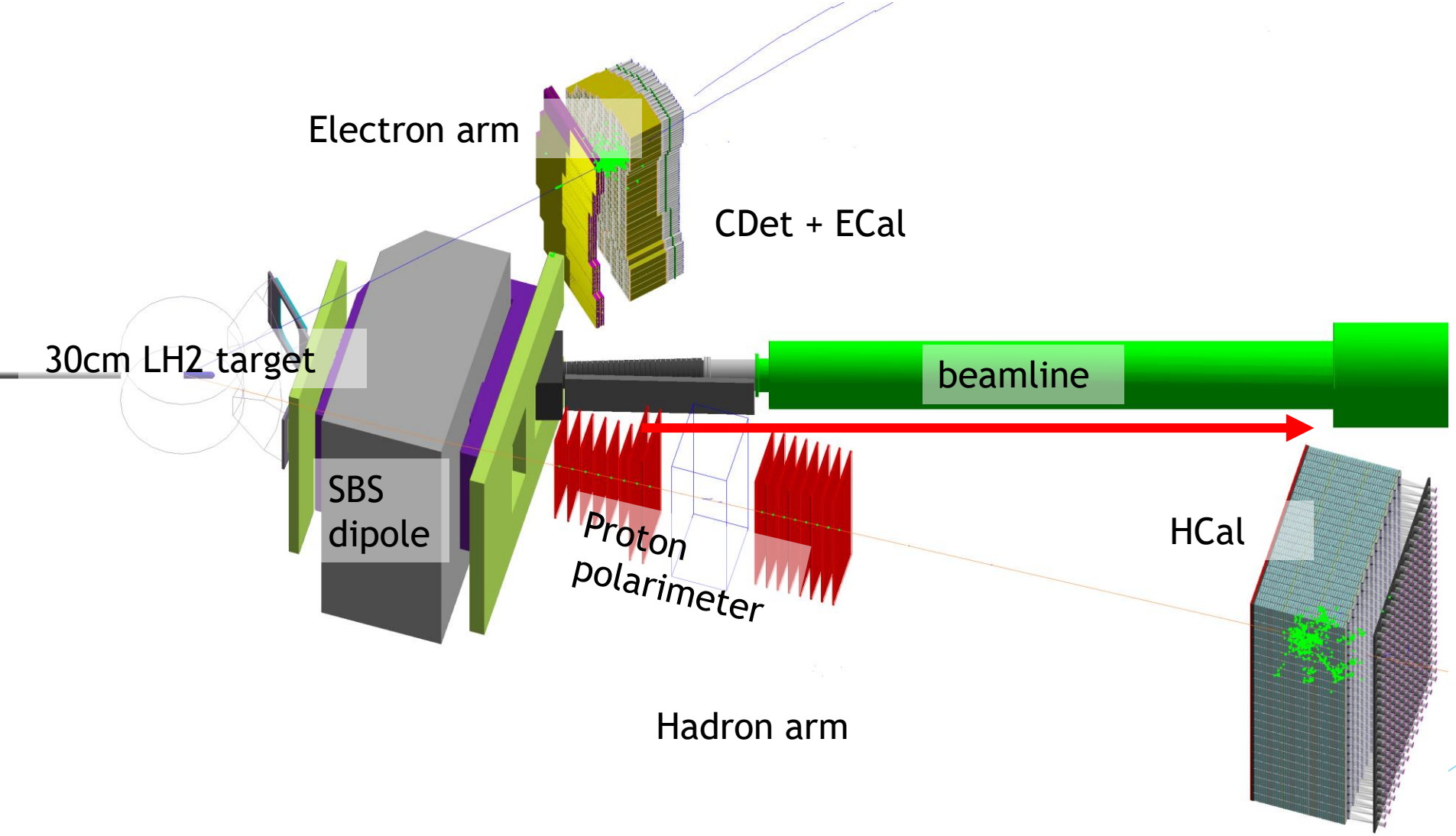
Kinematics

- Updates made to account for differences in beam energy, beam current, target, FPP, etc.
- Acceptance covers Q^2 between 4.5 – 14.5 GEV^2
- 4th kin point approved at lower Q^2 to complement future positron program



E_{beam} (GeV)	$Q^2 Range$ (GeV^2)	$\langle Q^2 \rangle$ (GeV^2)	θ_{ECal} $(degrees)$	$\langle E'_e \rangle$ (GeV)	θ_{SBS} $(degrees)$	$\langle P_p \rangle$ (GeV)	$\langle sin\chi \rangle$ $(degrees)$	PAC Days	$\Delta(\mu G_E/G_M)$
6.4	4.5-7.0	5.5	29.0	3.66	25.7	3.77	0.72	2	0.029
8.5	6.5-10.0	7.8	26.7	4.64	22.1	5.01	0.84	11	0.038
10.6	10.0-14.5	11.7	29.0	4.79	16.9	7.08	0.99	32	0.081
4.3	**3.1-4.4**	**3.7**	**35.0**	**2.35**	**28.5**	**2.73**	**0.55**	**2**	**0.011**

Simulated Event with GEANT4



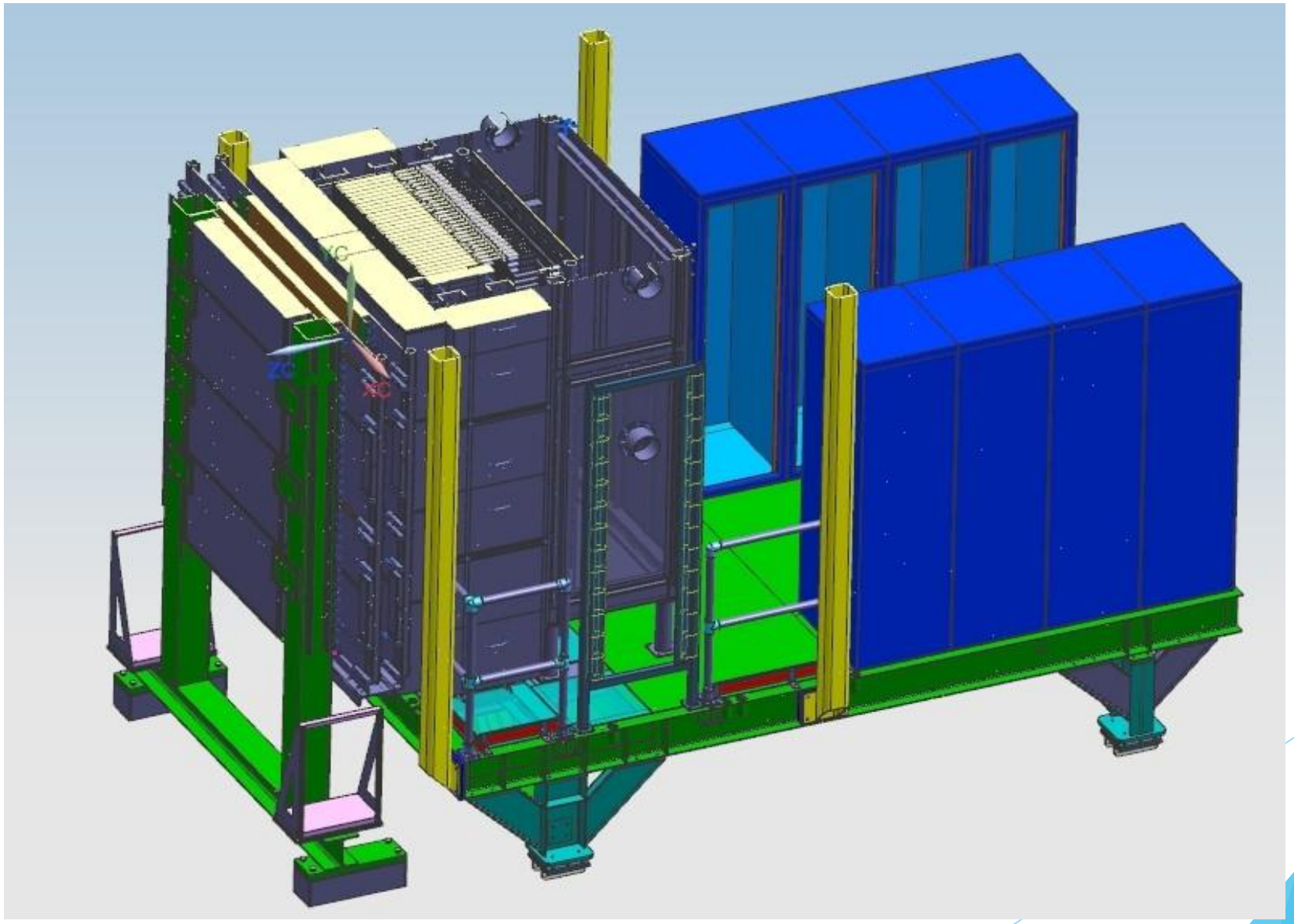
Electron Arm

- ECal
  - ~ 5% energy resolution
  - ~ 1 mrad scattering angle
- CDet
  - ~ 2 mm vertical hit location
  - ~ 1 mrad azimuthal angle

Proton Arm

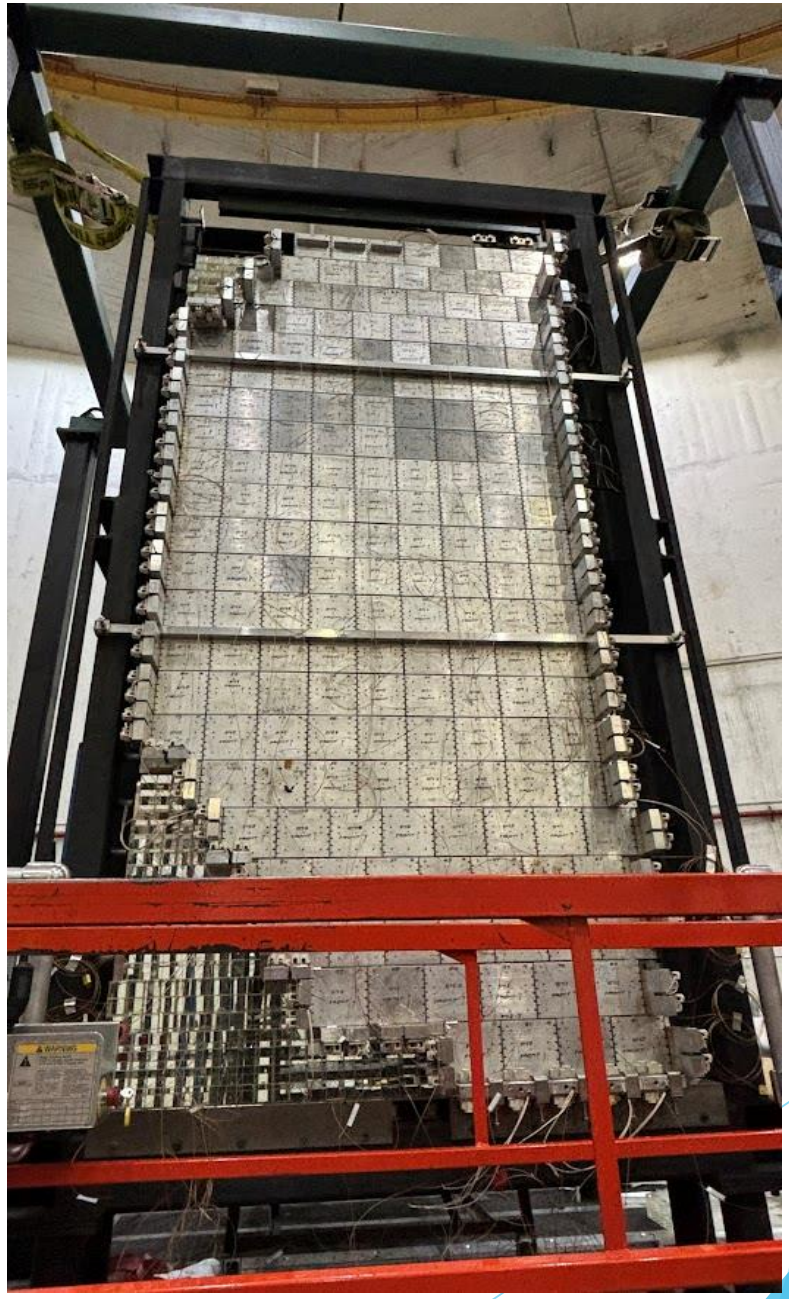
- 2.5 T-m SBS Magnet
- 16 GEM tracking layers
- CH2 passive analyzer
- ~ 1 % momentum resolution
- ~ 1 mrad angular resolution
- High efficieny HCal

Electron arm calorimeter ECal + CDet – Under Construction



ECal – Electron Arm

- 1656 lead glass crystals with individual PMTS for each cystal
- Good energy resolution (~5 %) allow for high threshold on elastic peak
  - Background reduction
- Crystals heated in situ to ~ 220 C to balance darkening from radiation load
- installation recently completed
  - All cables electronics in place
  - Recently completed light tighting
- Cosmic commissioning eminent



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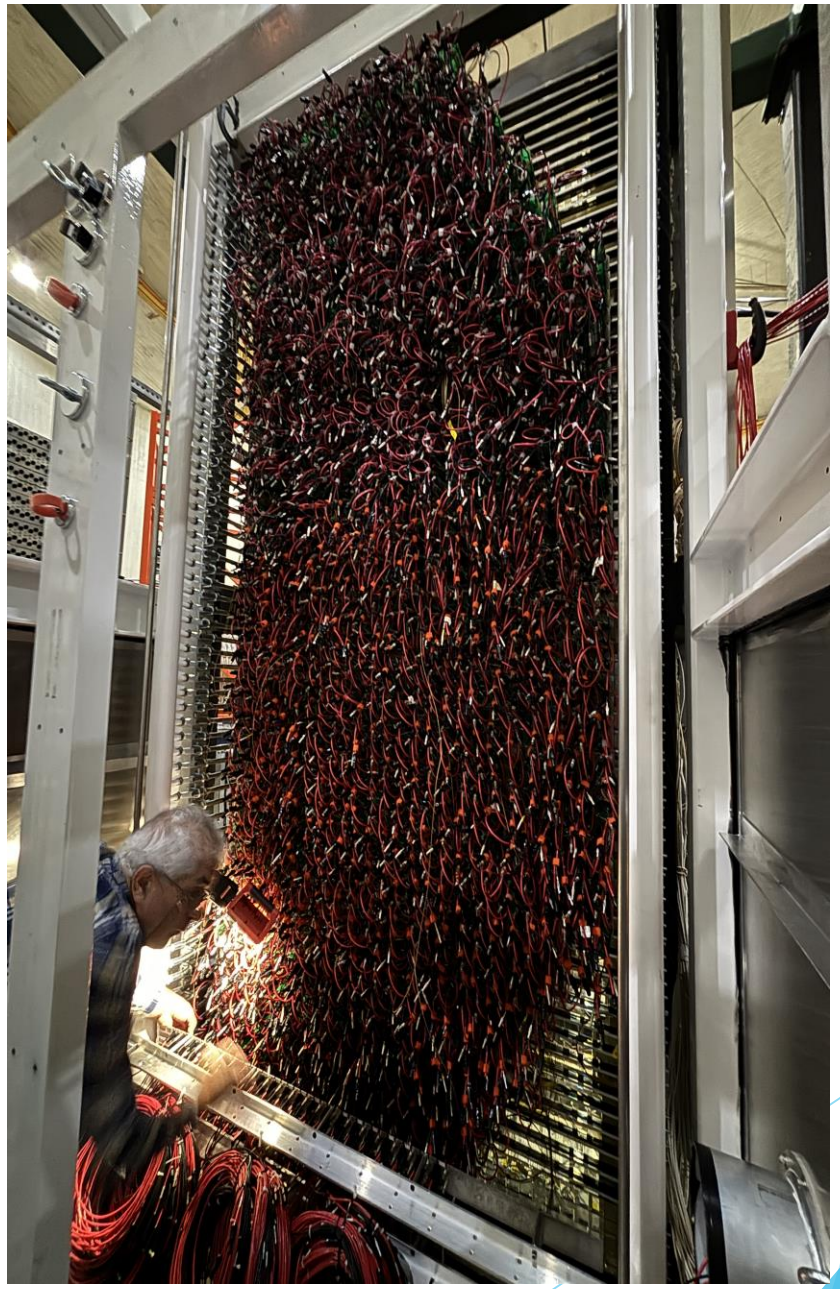

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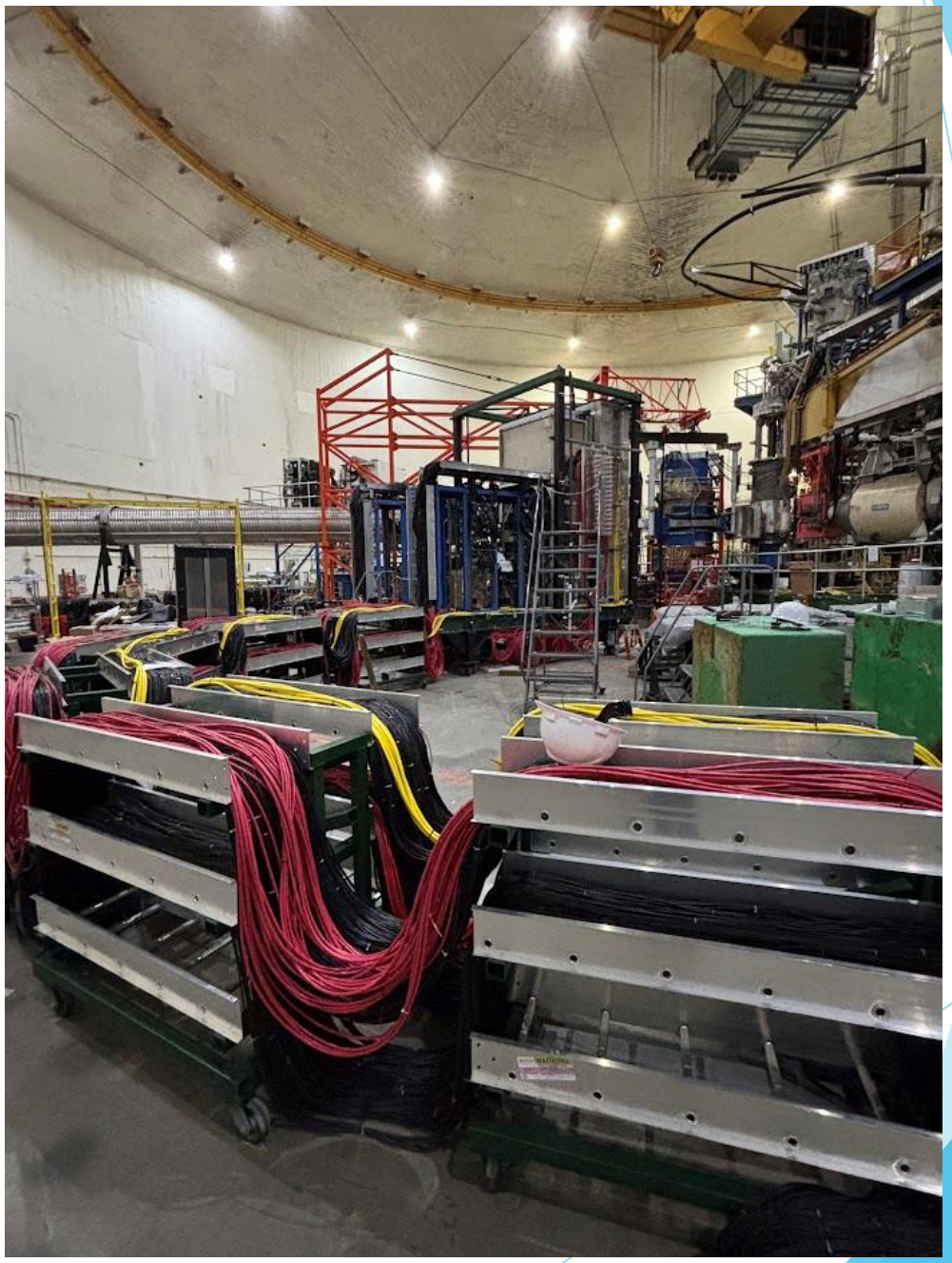
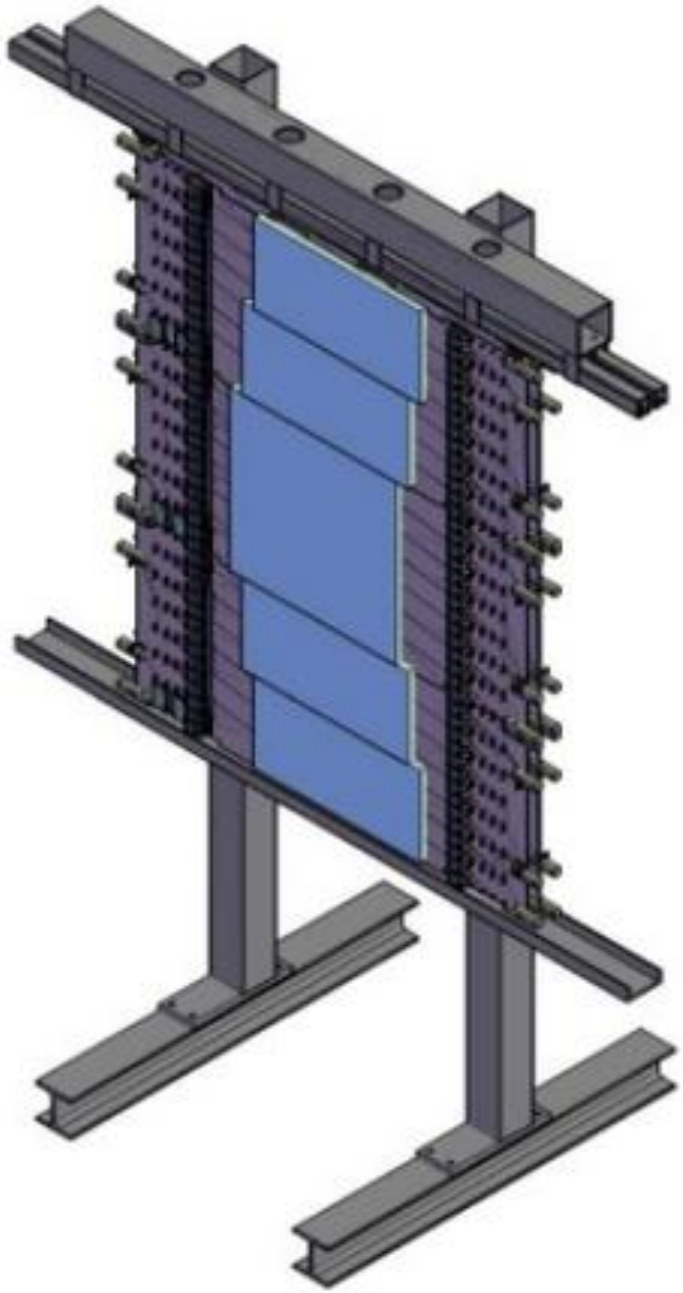


CDet – Electron Arm

- Positioned direction in front of ECal
- Provides better vertical position resolution that ECal alone → azimuthal angle constraint
- 2352 scintillator bars instrumented with 168 maPMTS
- Modules have been light tight tested and will soon be installed onto the mounting frame
- Likely to test and commission with cosmics with modules laying flat before mounting on frame



Ack R. Marinaro

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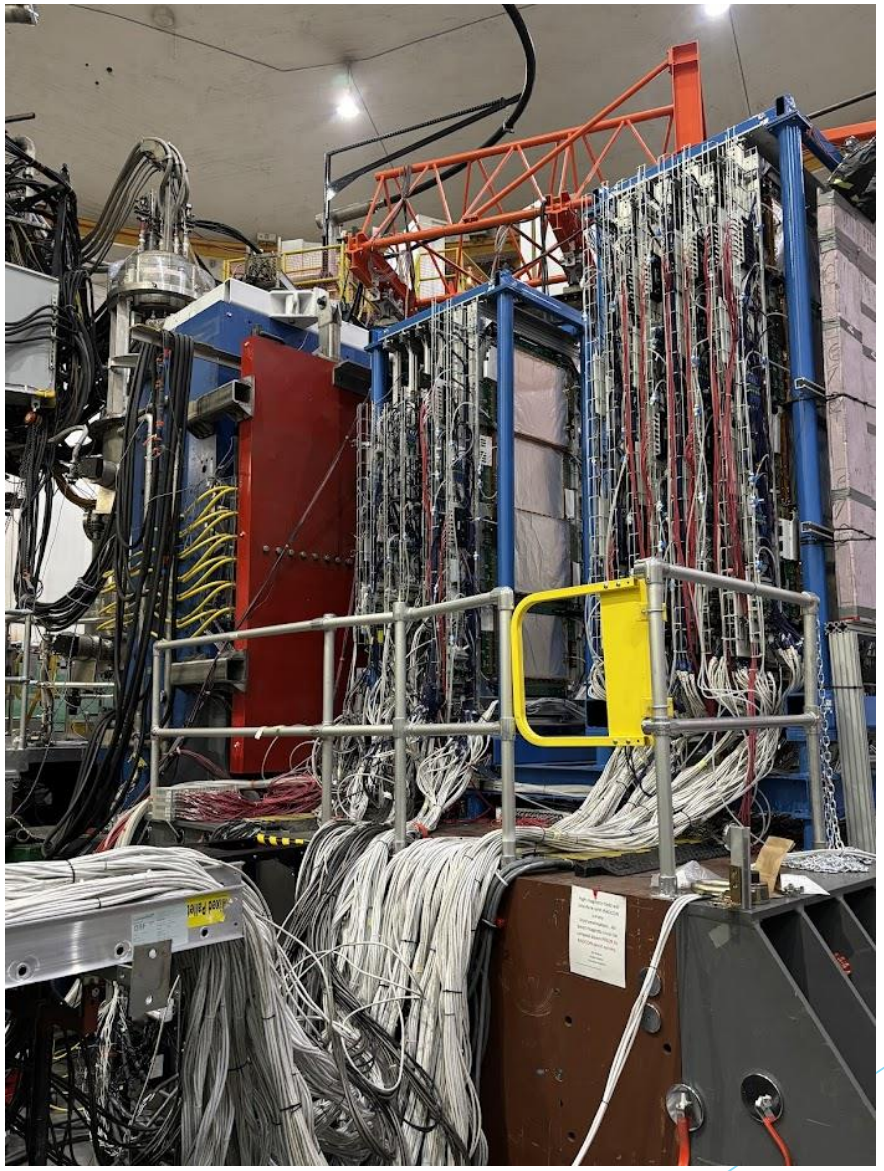
GEMs – Proton Arm

- 16 total GEM layers
- 8 in the front tracker before the analyzer
- 8 in the back tracker after the analyzer
- BigBite GEMs + 1 new layer all moved to SBS platform
- More layers in each tracker than previous experiments keeps the tracking efficiency high even with decreased layer efficiency due to increased luminosity
- All layers instrumented and cosmic data taking is underway
- New electronics bunker under construction
- Lead wall needs installed on the beamline side
    - Awaiting fulfillment from vender



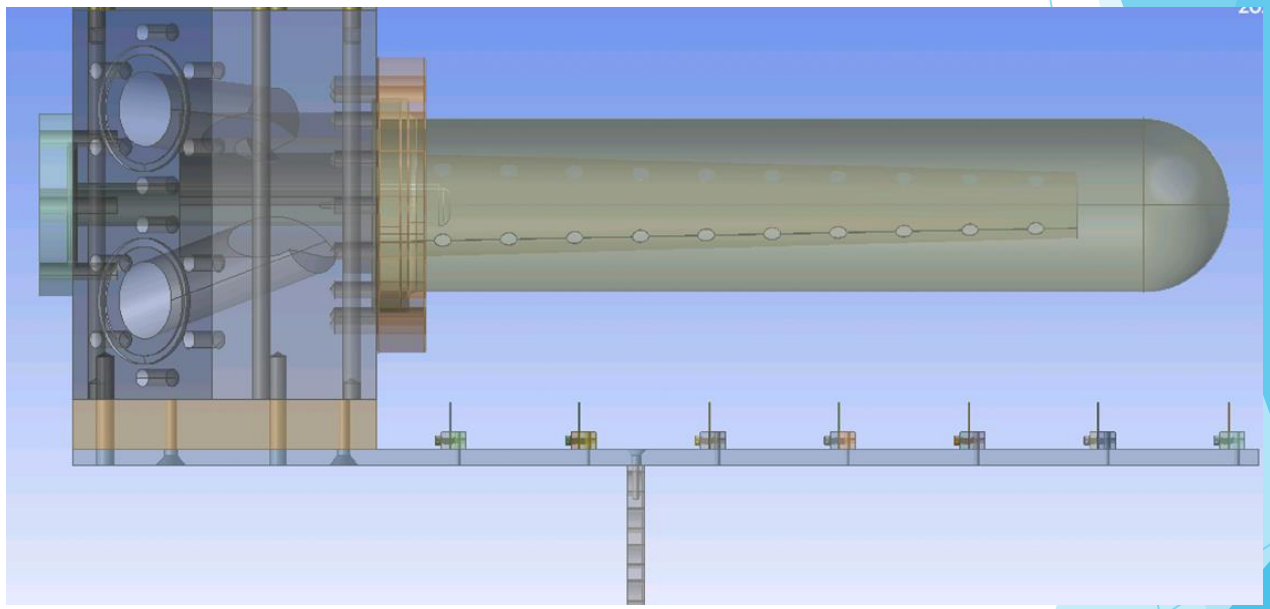
HCal – Proton Arm

- 288 iron/scintillator sandwich modules
- Detector was previously used in GMN and GEN experiments
- No significant detector hardware work done to get ready for GEP
- Implemented digital trigger with FADCs/VTP
- Signal cables need to be re-routed and attached the SBS platform to allow for CDET/ECAL to move into place for kin3
- 2 PMTs and 1 HV card replaced

Ack J. Poudel

Target

- New 30 cm LH2 target cell designed and installed
- Expected to run at 50 uA with a 2x2 raster
- New beam exit snout installed
- Target work required the SBS magnet to be moved downstream out of the way
- SBS Magnet now in production location
- Final alignment needs to be done before beam



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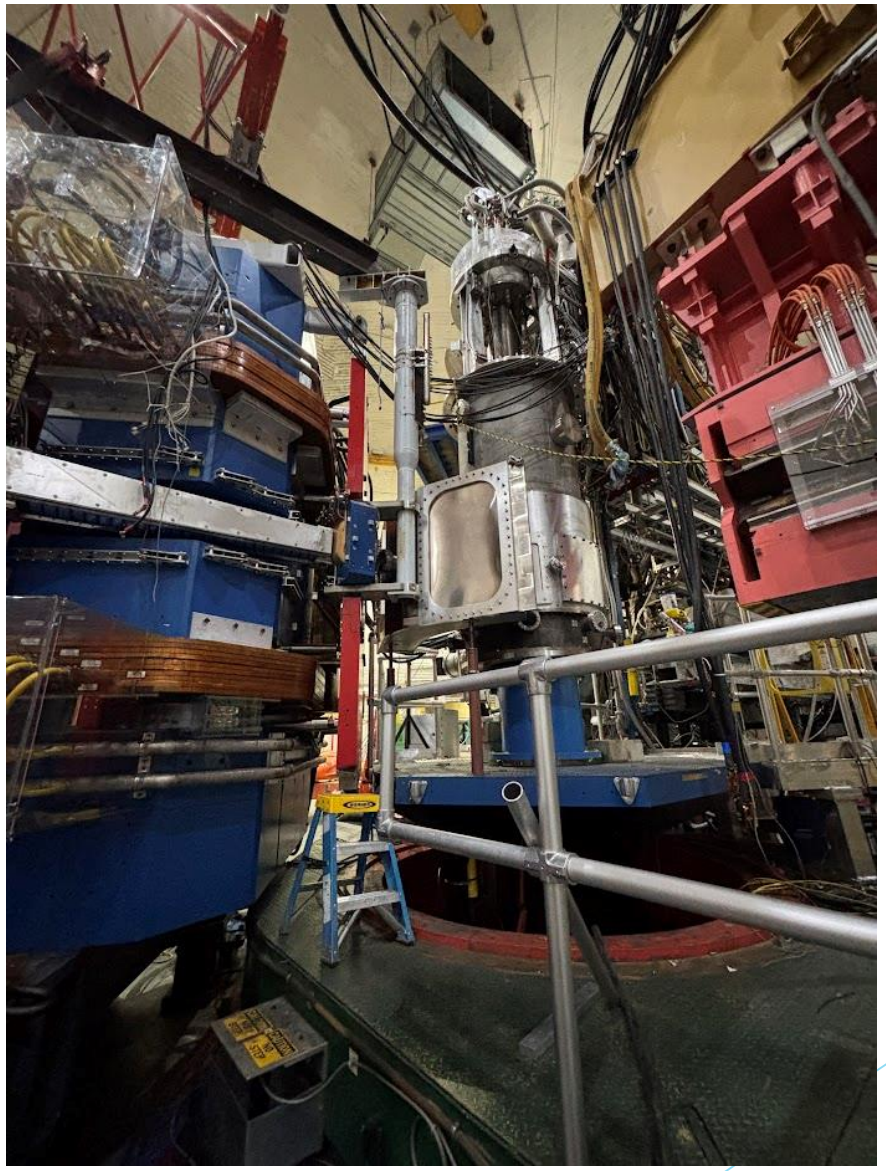


Ack S. Dusa

Software/DAQ/Polarimetry

- Software
  - Finalized geometry in G4SBS included updated shielding placement and realistic placement of ECal supermodules
  - Simulated background rates in GEMS
  - Simulation signal rates using realistic beam energy and target placement
  - Coincidence formation between electron clusters in ECal and proton tracks
- DAQ
  - CDet needs to be added to DAQ when signals are connected
  - Lessons learned from Gen-RP → better shielding for GEM MPDs hopefully mean more stable running, also added easier diagnostics
- Polarimetry
  - Current dipole magnet power supply was not capable of current needed for 5 pass
  - Power Supply was recently replaced by DC power – Needs to be tested at high current

Ack K. Hunt

Work Force

- Ph.D. students
  - Kip Hunt – UConn
  - Mahmoud Gomina – VT
  - Ben Spaude – W&M
  - Jhih-Ying Su – UMass
  - Jacob Mcmurtry – UVa
  - New UVa student joining soon
- Postdocs
  - ~10 postdocs spending at least part of their time

Shift Schedule

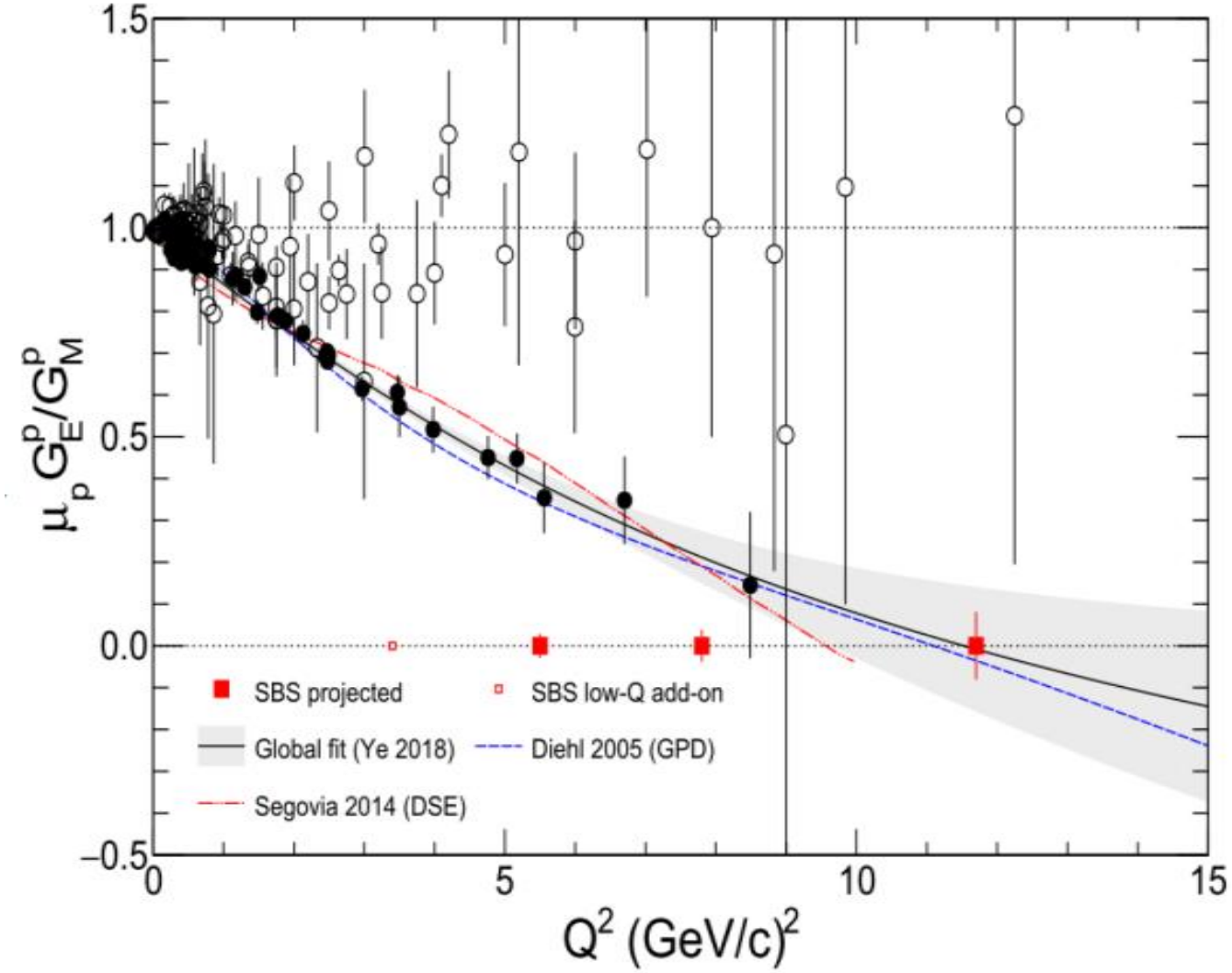
- Currently have shift schedule posted from the end of February until the beginning on July
- 15 shifts required for inclusion on future GEp papers
- Will need cryo target training if not previously trained on Gen-RP (Hall C training counts as well)
- Roughly 800 shifts needed for the experiment
  - We need your help

- https://misportal.jlab.org/mis/physics/shiftSchedule/?experimentRunId=GEp-V

March/April APS Meeting Mini-Symposium

- **Joint March Meeting and April Meeting: Global Physics Summit 2025**
  - March 16th-21st 2025
  - Anaheim, CA
- 3 session mini-symposium on Tuesday and Wednesday
  - 2 invited talks
  - Total of 23 abstracts accepted covering past, present and future SBS program
- Field at large is interested in the SBS program and are looking forward to results coming soon(ish) from the first experiments

Estimated Uncertainties



From PR-12-24-010

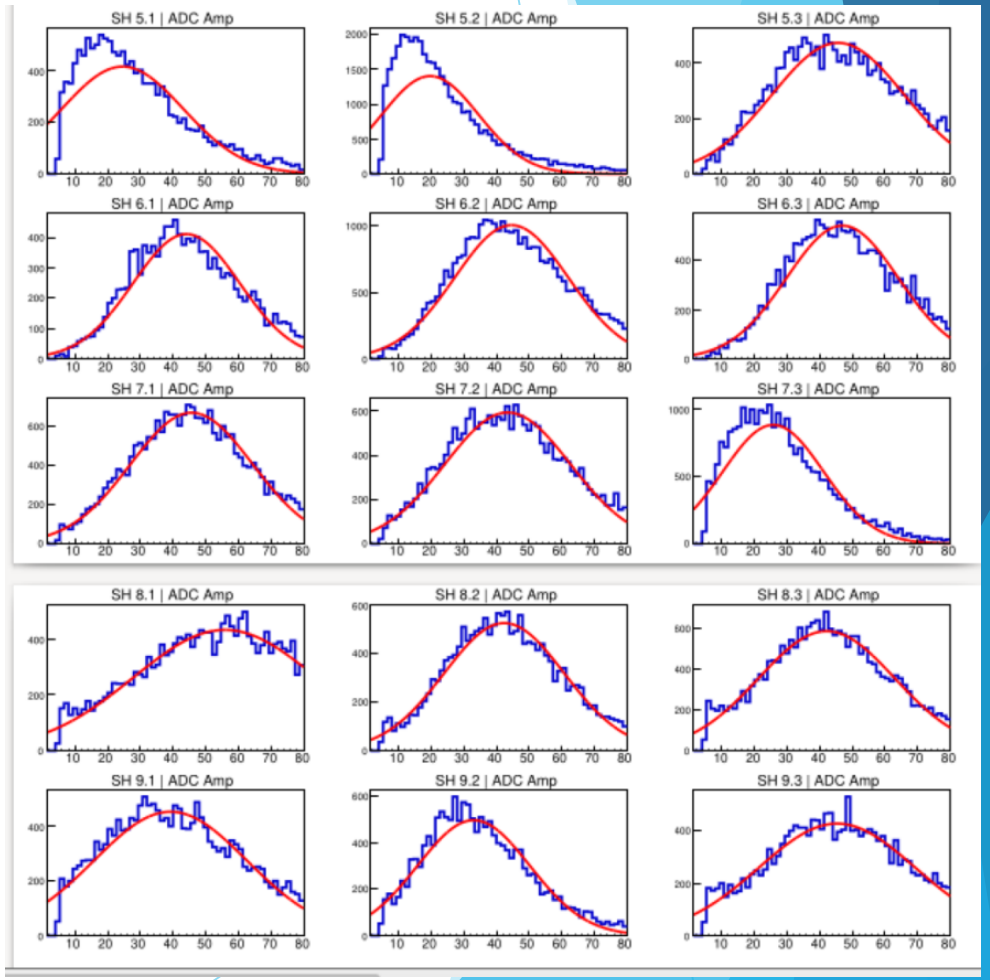
Summary

- GE_p set to start running soon (Whenever beam is ready)
  - Using the recoil polarization method to measure the elastic form factor ratio of the proton out to Q^2 = 12 GeV^2
  - Theoretical models differ significantly at Q^2 greater than 5 GeV^2
- New detector systems and target developed and installed
- Detector systems starting to take cosmic data
- Still Lots of work to be done to make beam commissioning go smoothly
  - Looking for new collaborators/shift takers

Backup Slides

Parasitic cosmic data taking during previous experiment

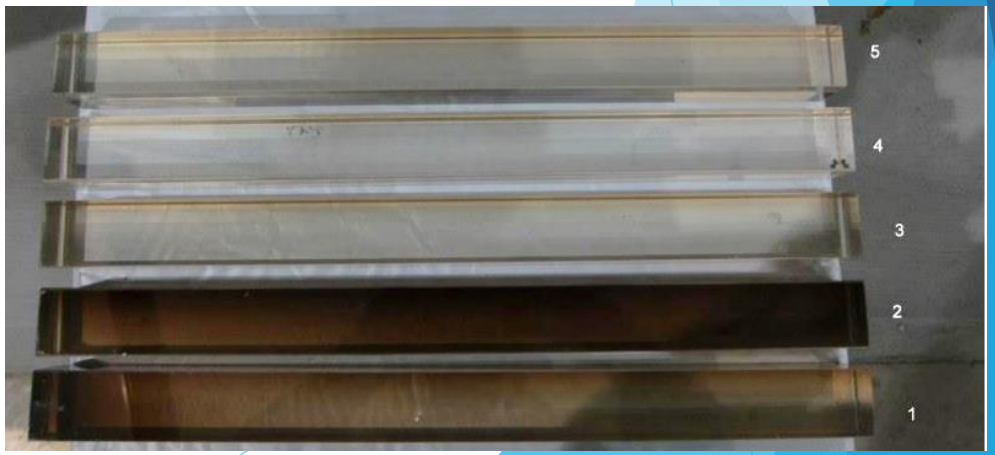
- 27 channels fully instrumented during previous experiment
- Cosmic ray data was taken opportunistically when beam was not available
- Data taking with and without amplifiers to check noise pickup
- Energy resolution ≅ 10 % /√GeV -> Consistent with Elastic Test from 2015 (10.4 % / √GeV)



Example energy spectra from FADC with fits

Continuous Thermal Annealing of Crystals

- Each of the 1656 shower blocks are continuously heated to ~220 C to insure optical transparency under intense radiation load
  - ~5 % energy resolution, ~7 mm spatial resolution
  - Tests are well underway with the fully developed heating system
  - Tests ongoing for the cooling system for the lightguides and the PMTs
- Previously completed test showed ~85-90% transparency in equilibrium and an energy resolution of ~8 % at 1.5 GeV



Increasing difficulty with each iteration

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

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

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

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

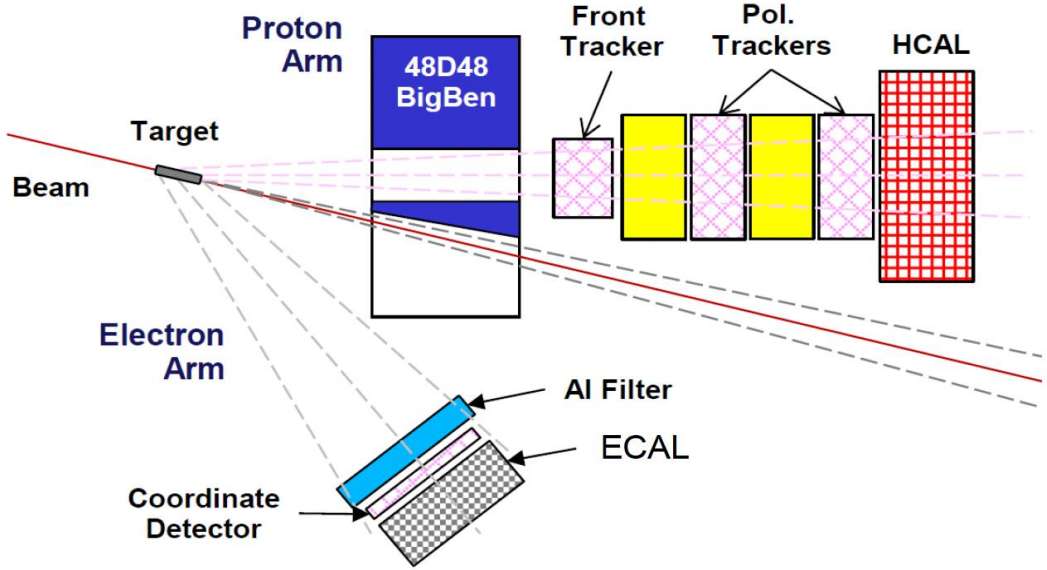
Need large statistics, max luminosity and solid angle

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

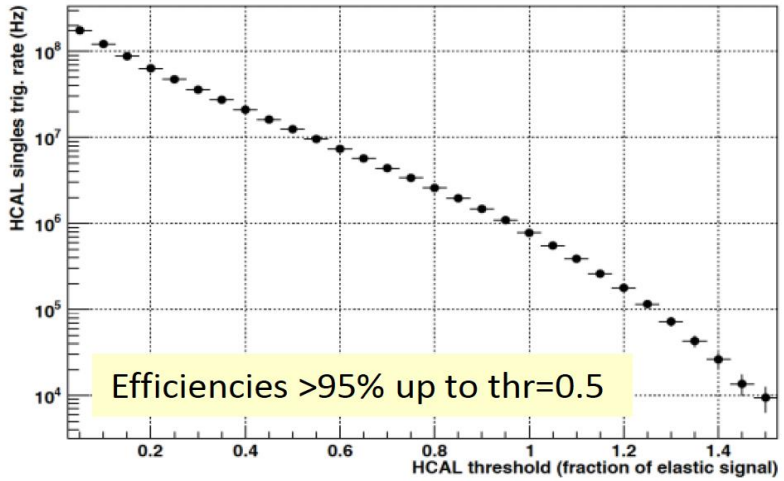
Critical to this experiment is the maturing technology of high rate tracking with GEMS

Q^2 increases from 8.5 to 12.0 GeV^2 but higher beam energy 10.5 vs. 6 GeV => a factor of 5-6 of the FOM loss, but the SBS larger solid angle helps.

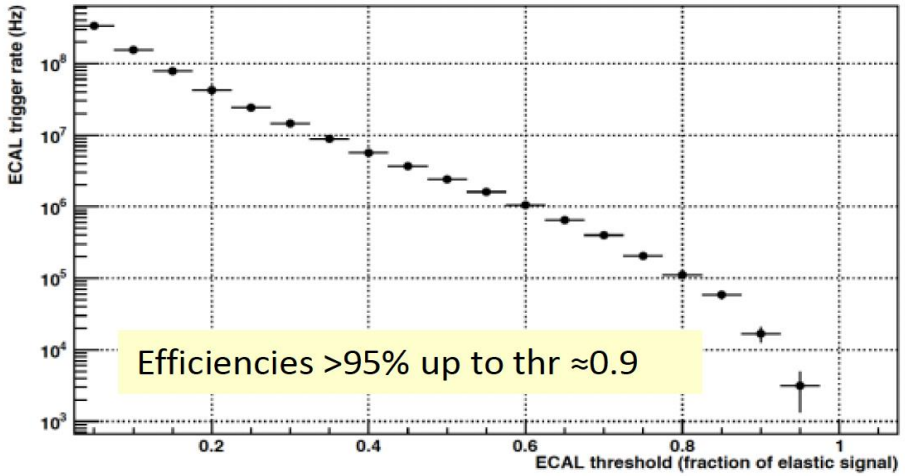
GEp - Most Demanding DAQ Rate



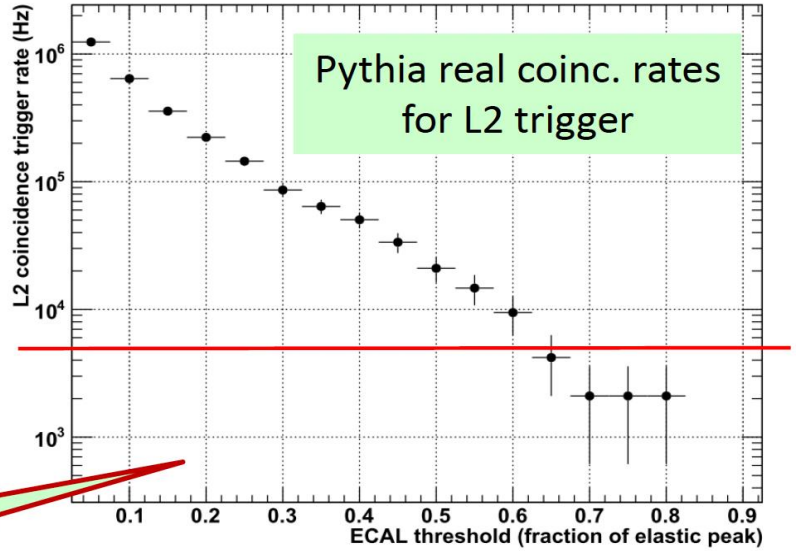
HCAL Singles: SLAC+DESY data in Wiser Code



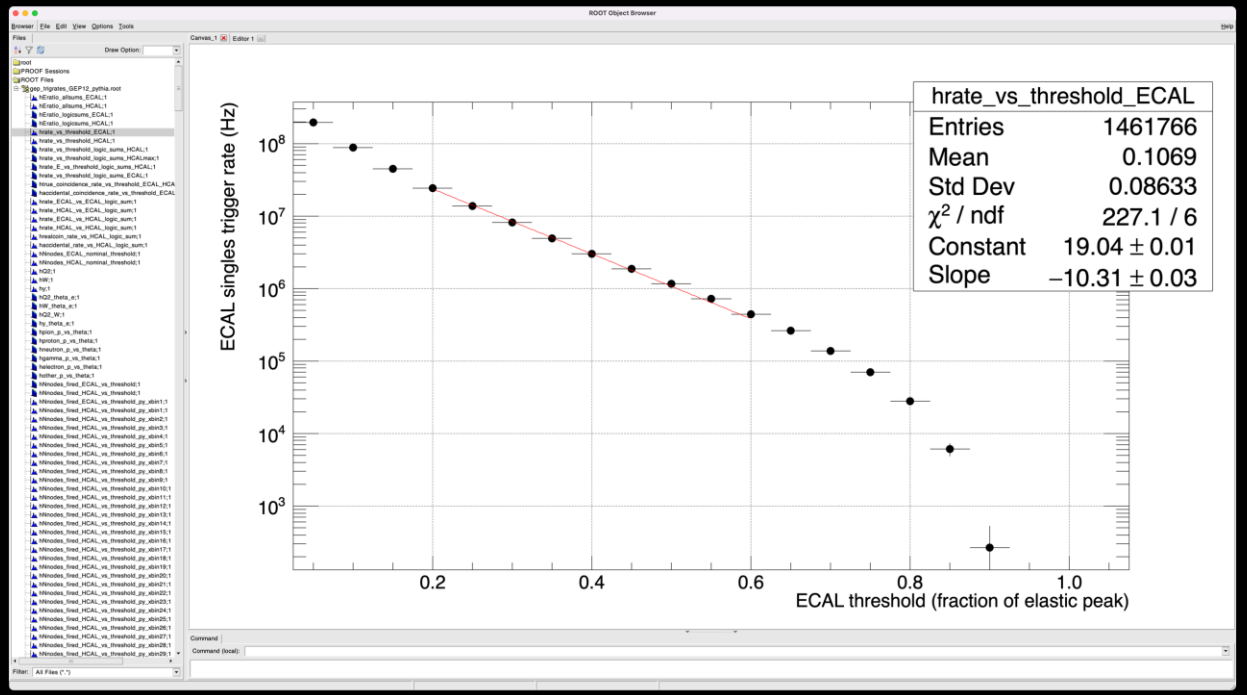
ECAL Singles: from tuned GEANT4

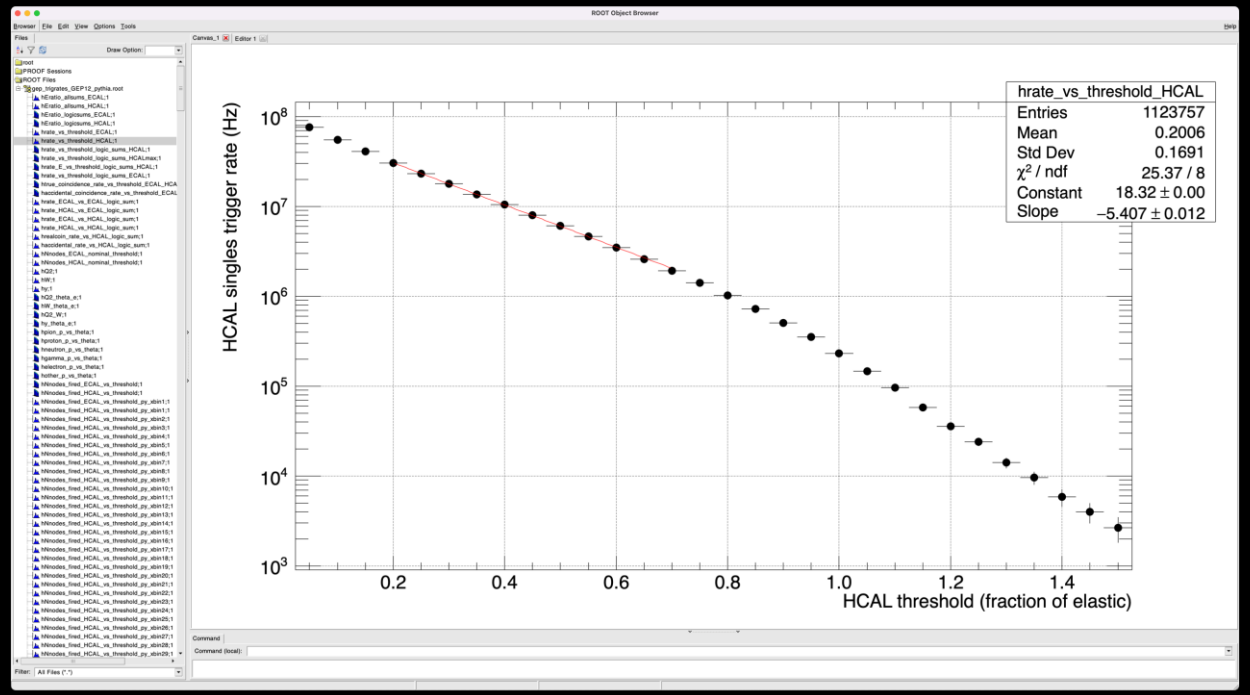


HCAL threshold = 50% of elastic peak



Expected Coincidence Rate (L2) up to **5 kHz** (including accidentals)





Global OR of all ECAL sums gives ~30-50 kHz trigger rate at ~80% threshold

- Global OR of all HCAL sums gives ~4-7 MHz trigger rate at ~50-60% threshold → Too high, need kinematic correlation in the trigger!
- (NOTE: all rate estimates were done assuming 70 uA beam current and old analog logic for ECAL)

Courtesy A. Puckett

ECal cooling system