Measurement of the Neutron Electromagnetic Form Factor Ratio at High Q^2 Using High Luminosity Polarized ^3He Target

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e – N Scattering & Form Factors

- To measure the neutron's electromagnetic form factor ratio, we looked at the reaction $^{3}\overrightarrow{He}(\vec{e}^{-}, e^{-}n)pp$
  - Assuming only single photon exchange.

$$j_e^{\mu} = -ie\bar{u}(s_f; k_f)\gamma^{\mu}u(s_i; k_i)$$

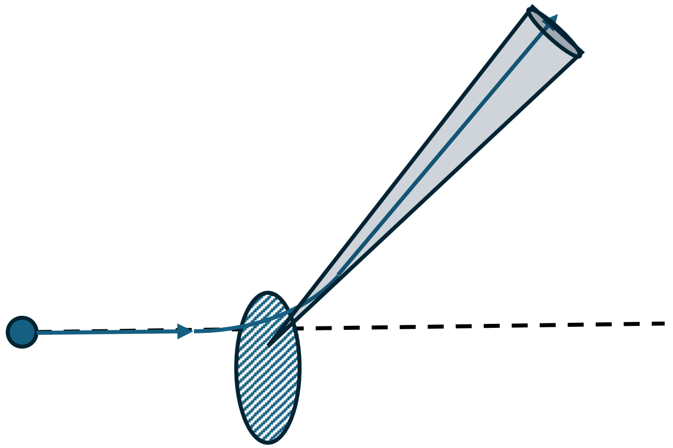
$$k_i + p_i = k_f + p_f$$
$$q = k_i - k_f = p_f - p_i$$
$$Q^2 = -q^2 = 4E_f^e E_i^e \sin^2\left(\frac{\theta}{2}\right) \leftarrow \text{Lab Frame}$$

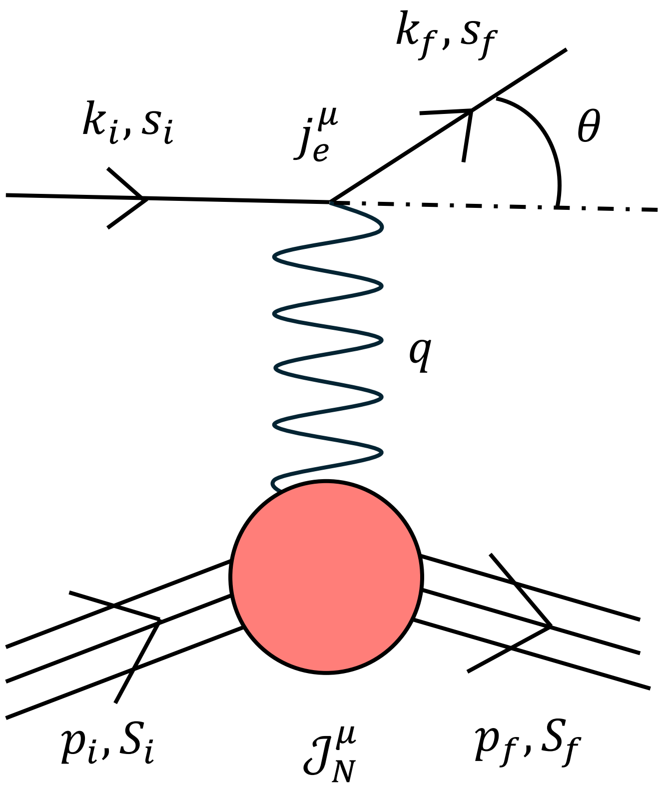
$j_e^{\mu}(s_f, s_i; k_f, k_i) \leftarrow$ Electron current
$\mathcal{J}_N^{\mu}(S_f, S_i; p_f, p_i) \leftarrow$ Nucleon current

$$\frac{d\sigma}{d\Omega} \propto \left| \mathcal{J}_N^{\mu}\left(\frac{1}{Q^2}\right) j_{\mu}^{e} \right|^2$$

$$\frac{d\sigma}{d\Omega} = \frac{d\dot{N}}{d\Omega}\frac{1}{\mathcal{L}}$$

Measure in Experiment



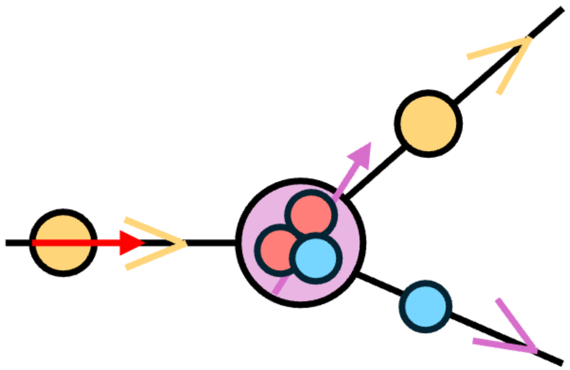


Measuring G_E^n/G_M^n

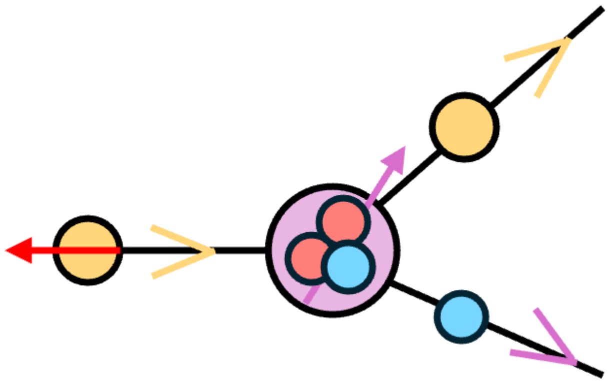
- The $\mathrm{GEn-II}$ experiment at JLab uses the double polarization method for extracting the electromagnetic form factor ratio G_E^n/G_M^n
  - This requires a polarized beam and target

$$A_{phys} = \frac{\left(\frac{d\sigma^{\rightrightarrows}}{d\Omega} - \frac{d\sigma^{\leftrightarrows}}{d\Omega}\right)}{\left(\frac{d\sigma^{\rightrightarrows}}{d\Omega} + \frac{d\sigma^{\leftrightarrows}}{d\Omega}\right)} = -\frac{1}{1+\frac{\epsilon}{\tau}\left(\frac{G_E^n}{G_M^n}\right)^2}\left[\left(\frac{G_E^n}{G_M^n}\right)\sqrt{\frac{2\epsilon(1-\epsilon)}{\tau}}P_x + \sqrt{1-\epsilon^2}P_z\right]$$

$$\frac{d\sigma^{\rightrightarrows}}{d\Omega} =$$



$$\frac{d\sigma^{\leftrightarrows}}{d\Omega} =$$



P_x – target spin component ⊥ to $\vec{q}$

P_z – target spin component ∥ to $\vec{q}$

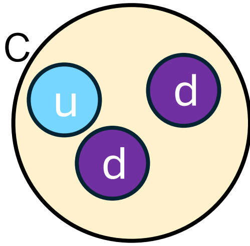
$\epsilon - (1 + 2(1+\tau)\tan^2(\theta/2))^{-1}$

$\tau - {Q^2}/{4M_N^2}$

Why Measure Form Factors?

- Sach's and others have shown the form factors are connected to the charge radius and magnetic moment of the nucleon [1].

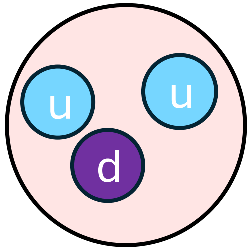
$$\langle r_{E,M}^2 \rangle = -6 \frac{dG_{E,M}}{d_Q^2}\bigg|_{Q^2=0}, |\langle \boldsymbol{M} \rangle| = \mu = G_M(0)$$



n

- Cates, et al., have shown that one can decompose the nucleon form factors into the constituent quark form factors[2].

$$F_{1,2}^u = 2F_{1,2}^p + F_{1,2}^n,$$
$$F_{1,2}^d = 2F_{1,2}^n + F_{1,2}^p$$



p

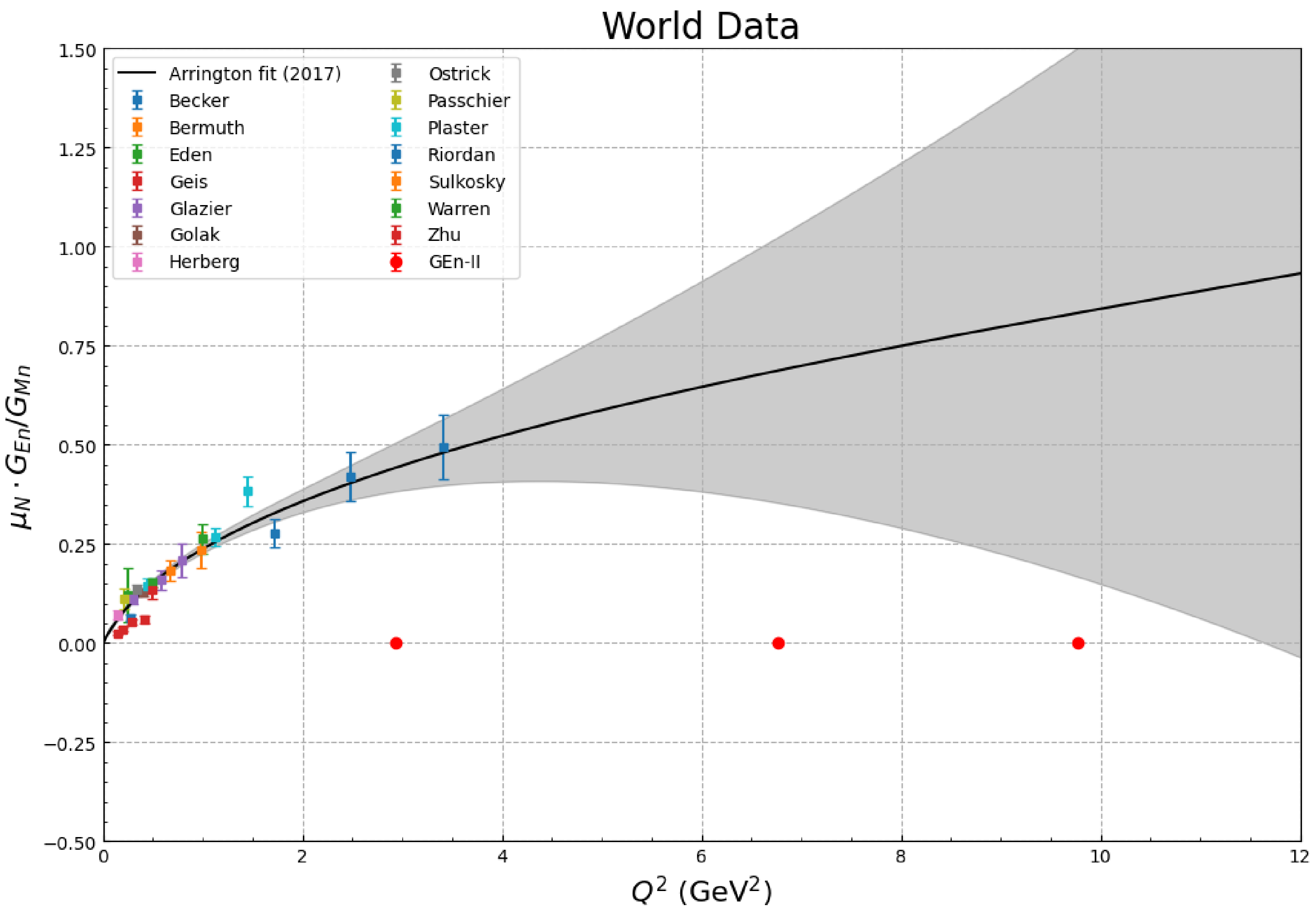
- Form factors provide constraints on the generalized parton distributions (GPDs) [3].
  - GPDs describe the non-perturbative structure of the nucleon.
    - Quark and gluon densities and their angular momentum contributions to the nucleon

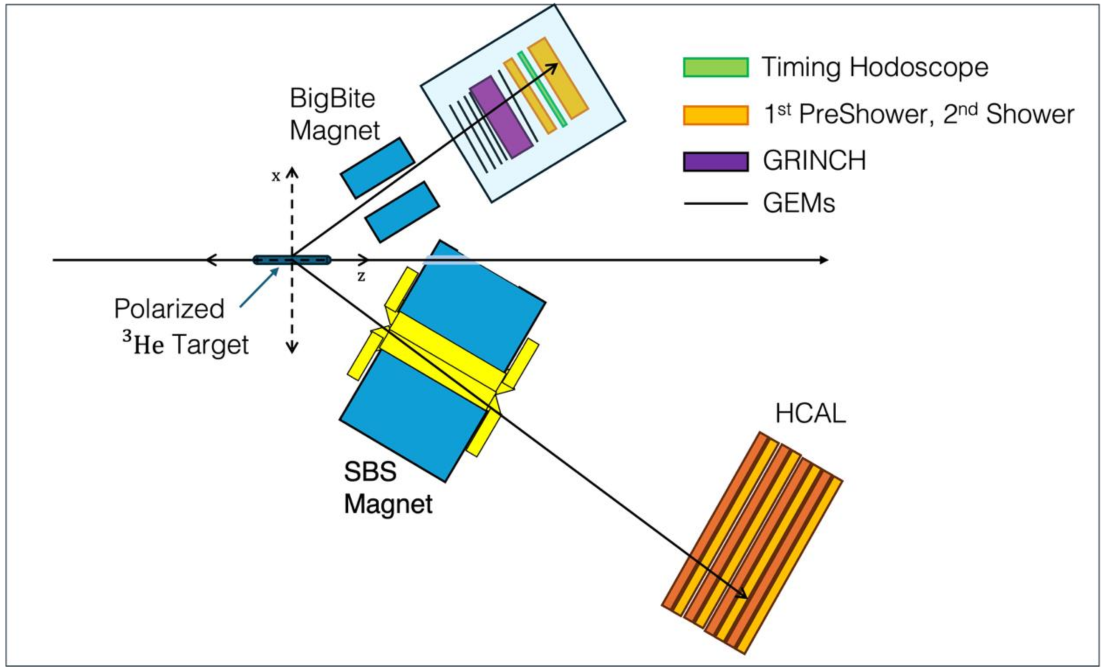
$$F_1 = \int_{-1}^{1} dx H(x, \xi, Q^2), F_2 = \int_{-1}^{1} dx E(x, \xi, Q^2)$$

$$\int_{-1}^{1} dx x [H(x, \xi, \Delta^2) + E(x, \xi, \Delta^2)] = A(\Delta^2) + B(\Delta^2) \quad J_{q,g} = \frac{1}{2}[A_{q,g}(0) + B_{q,g}(0)] \quad J_q + J_g = \frac{1}{2}$$

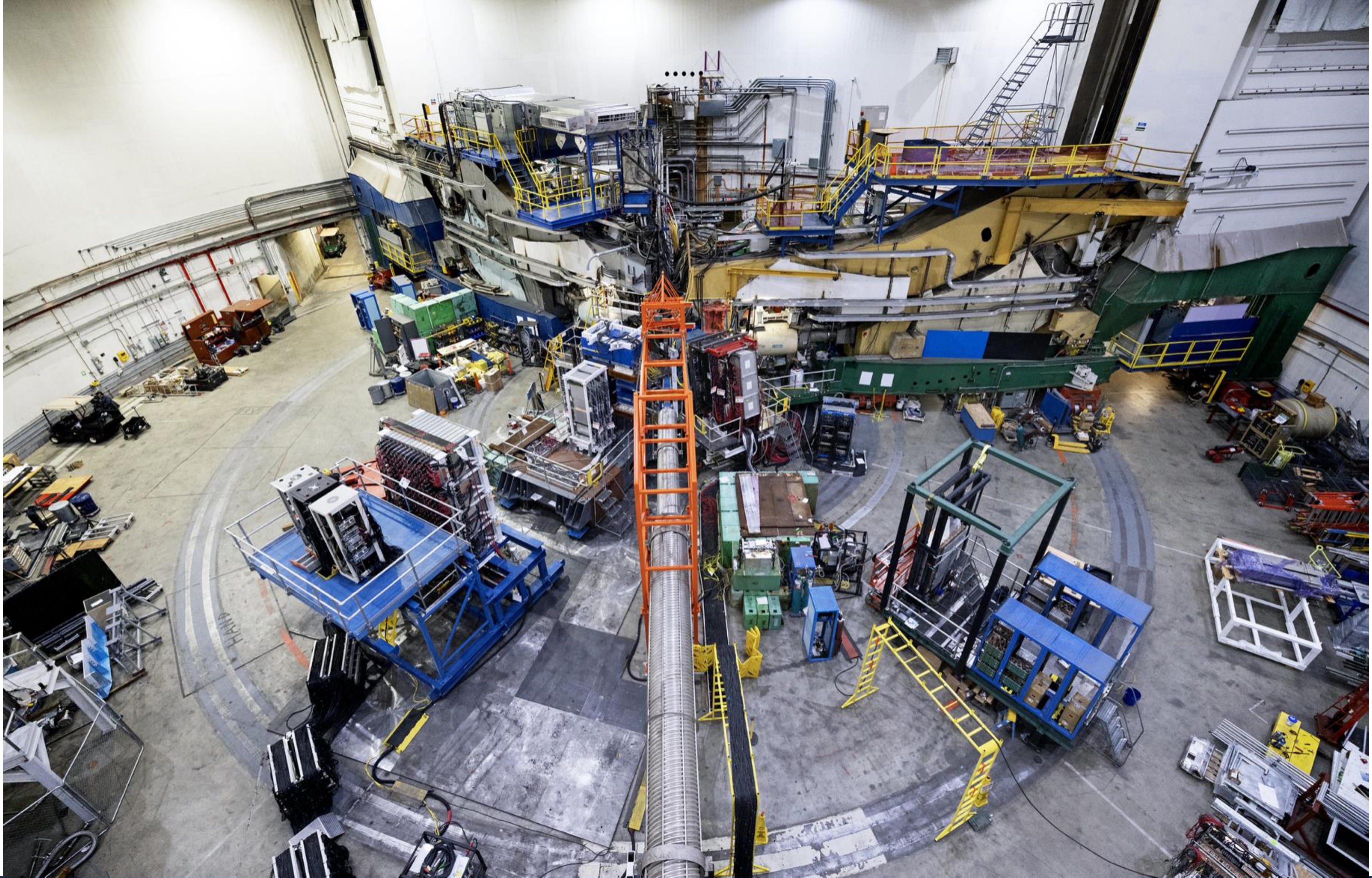
[1] F. J. Ernst, R. G. Sachs, and K. C. Wali, Phys. Rev. 119, 1105 (1960)., [2] G. D. Cates et al., Phys. Rev. Lett. 106, 252003 (2011). [3] M. Diehl, Physics Reports 388, 41 (2003).

Select Data on G_E^n/G_M^n and GEn-II Objective



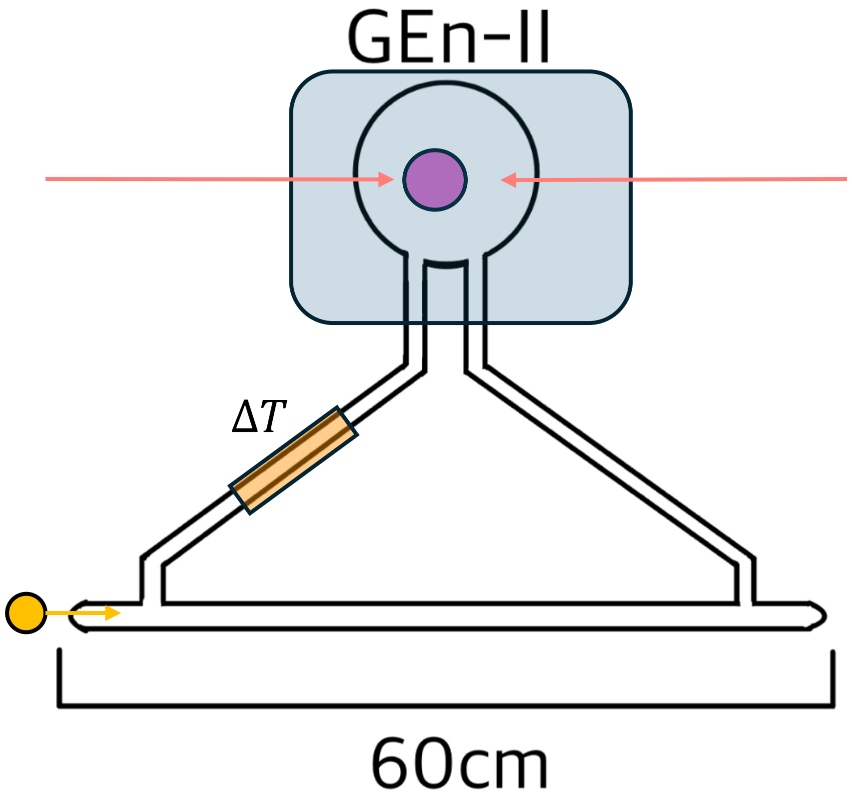


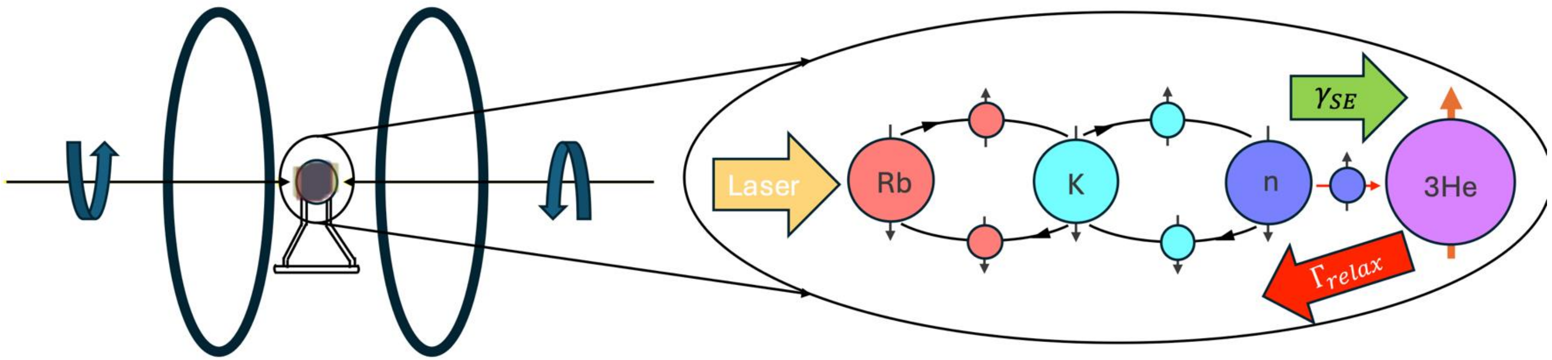
	$Q^2(GeV^2)$	$E_{beam}(GeV)$	$I_{beam}(\mu A)$	$\theta_e(deg)$
GEN2	2.93	4.29	45.0	29.5
GEN3	6.79	6.37	45.0	36.5
GEN3	9.78	8.45	45.0	35.0

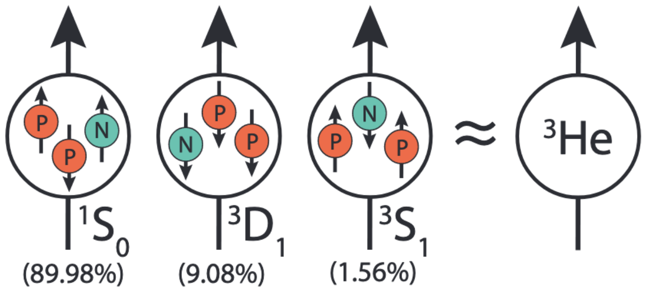


Polarized ^{3}He Target

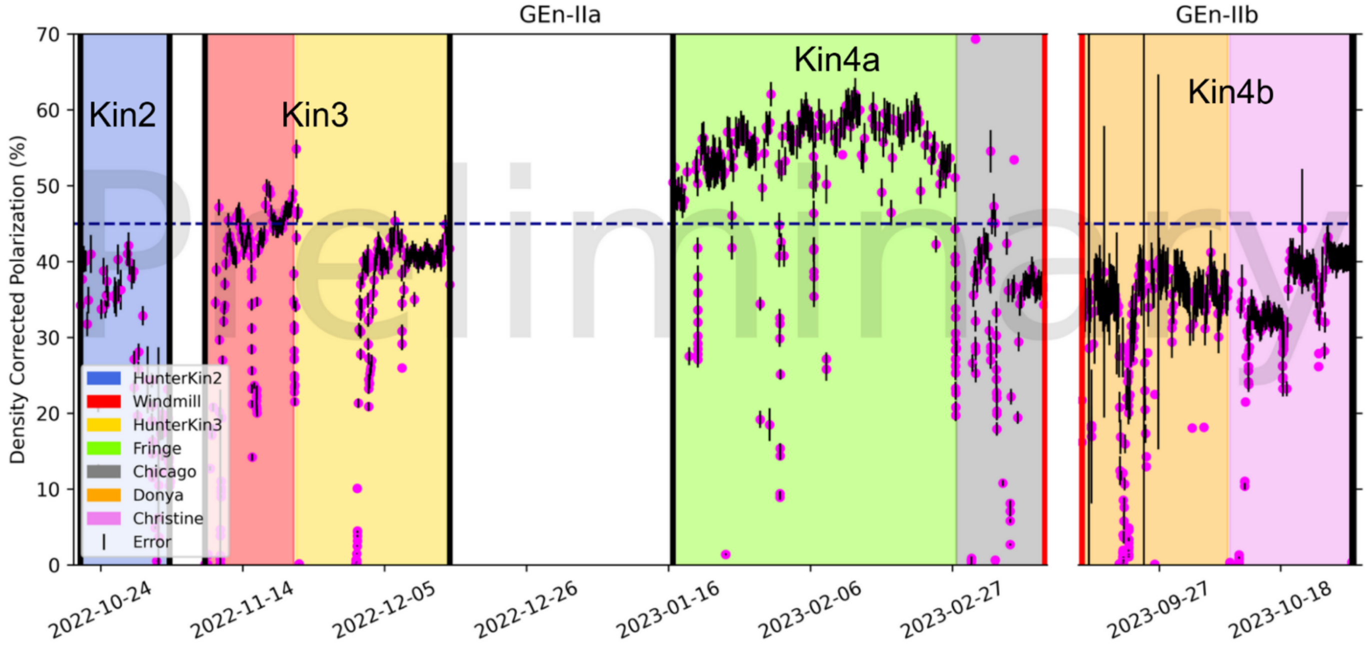
- In the PC the ^{3}He is polarized via Spin-Exchange Optical Pumping (SEOP)
  - PC is placed in an oven at temperature T~250 ℃
    - Vaporizes the alkali and provides high enough vapor pressure for optimum spin exchange.
- The neutron predominately carries the polarization of the ^{3}He nucleus.

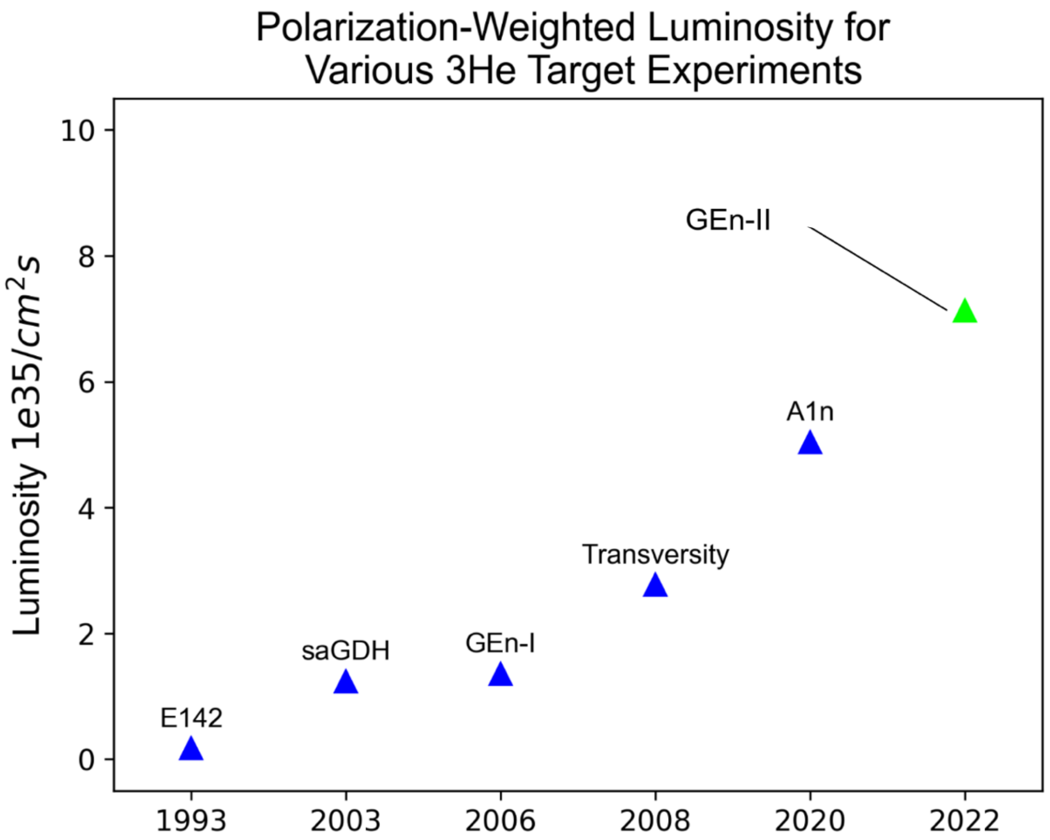




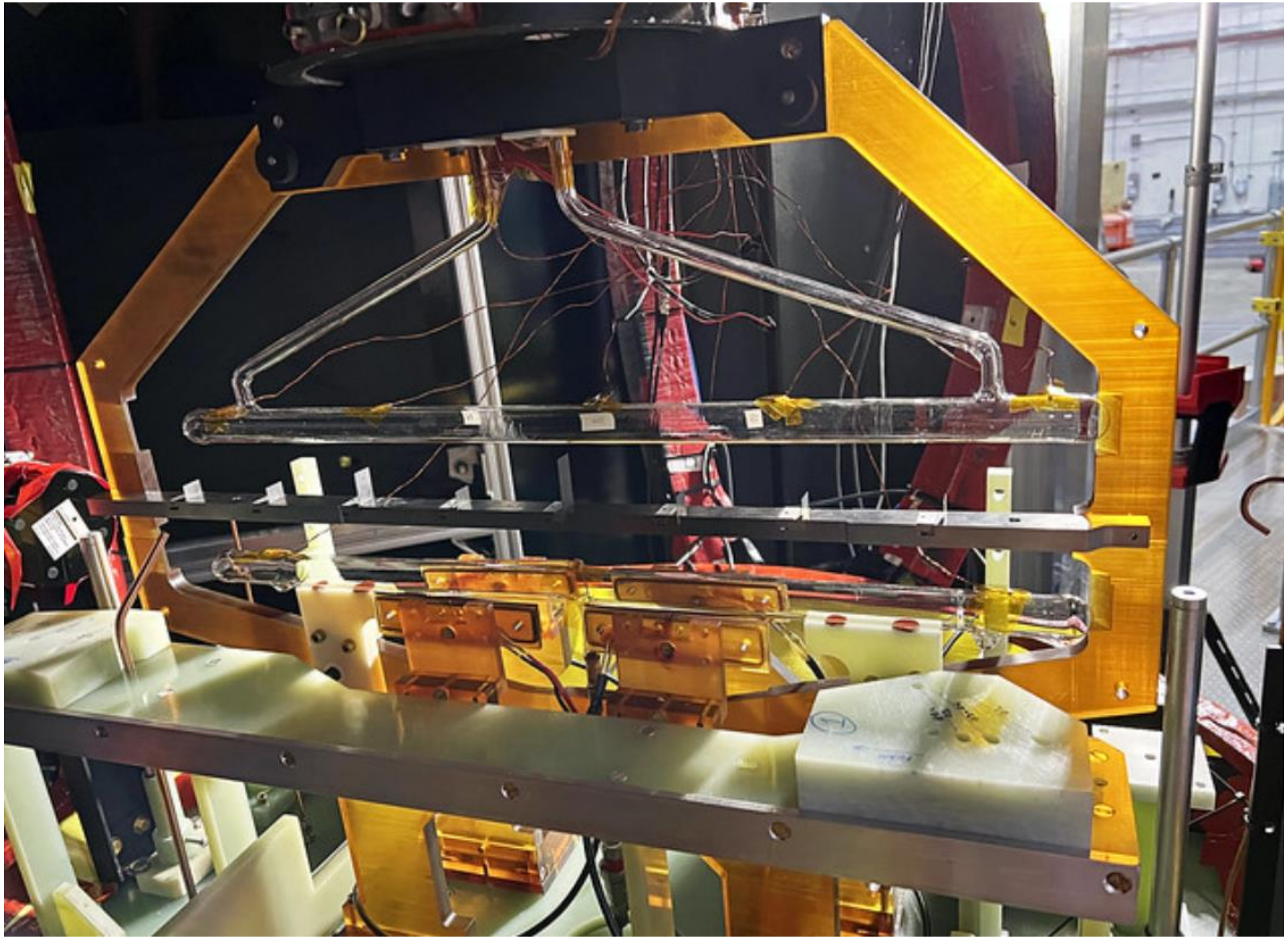


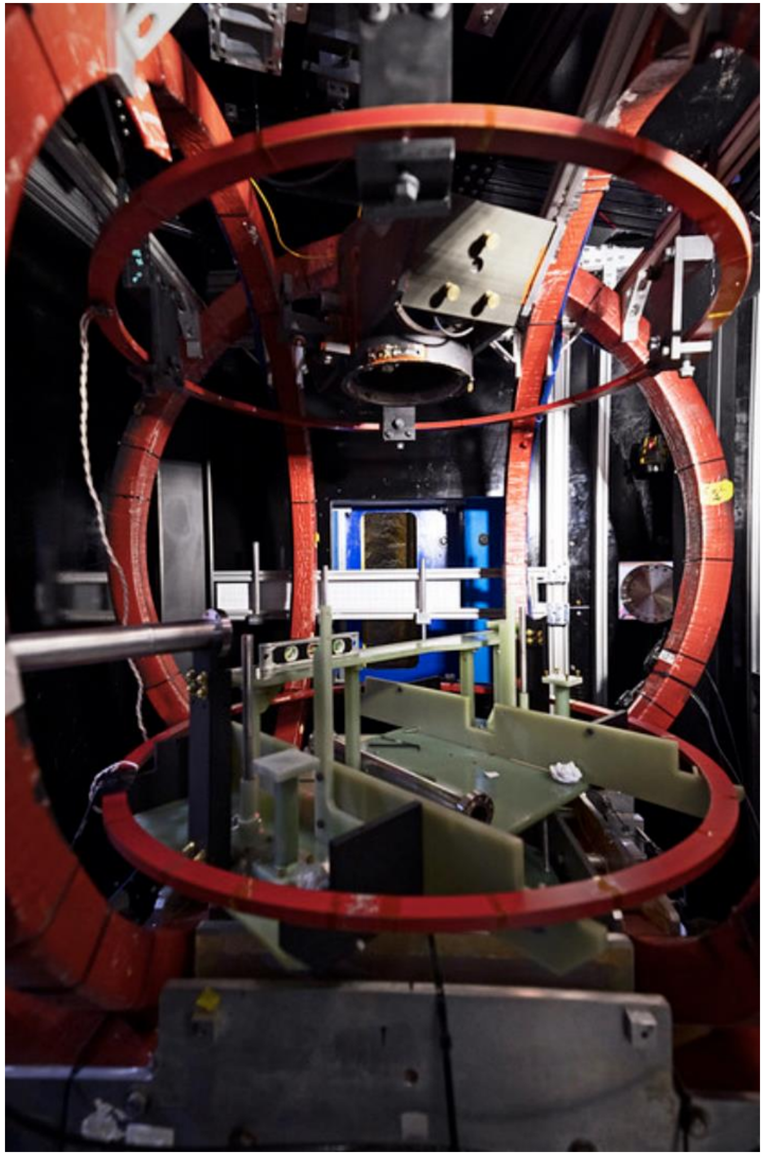
Polarized ^{3}He Target





^{3}He Target Pictures





Questions?

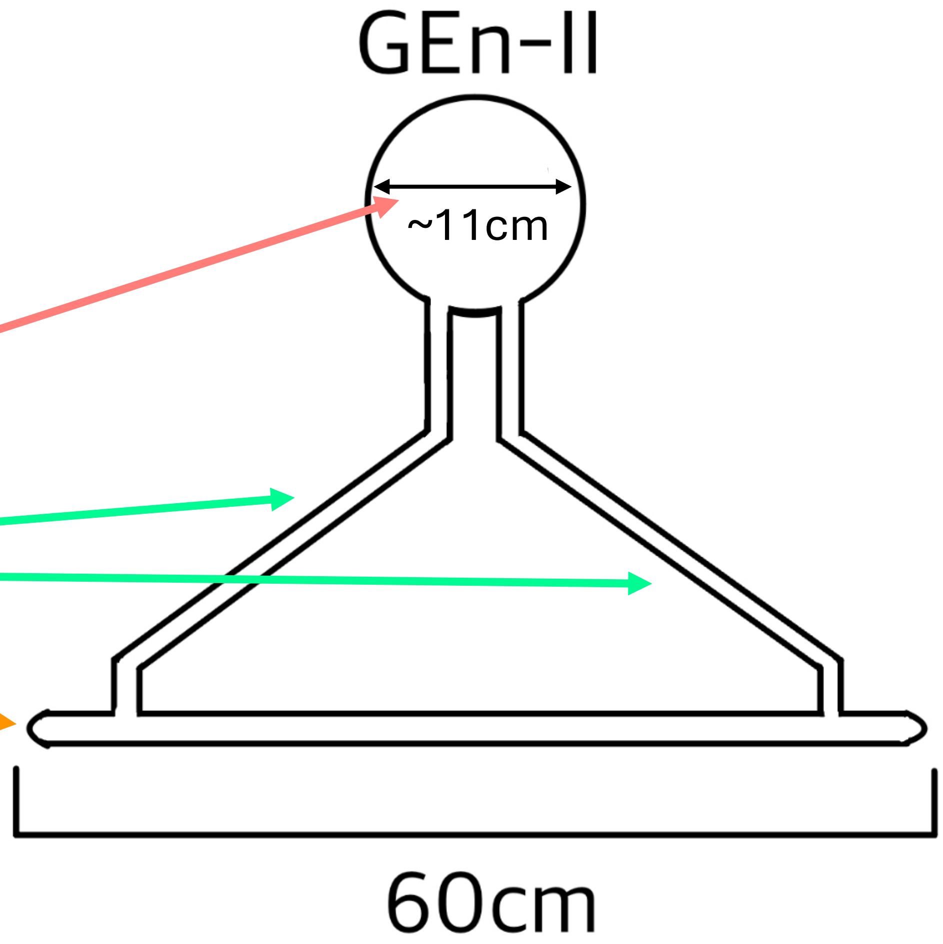
Backup Slides

Polarized ^3He Target

- The target is filled with:
  - 6-8 amg of ^3He
  - 0.1 amg of N_2
  - ~1e-5 amg of Rb (@ 250 ℃)
  - ~1e-5 amg of K (@ 250 ℃)

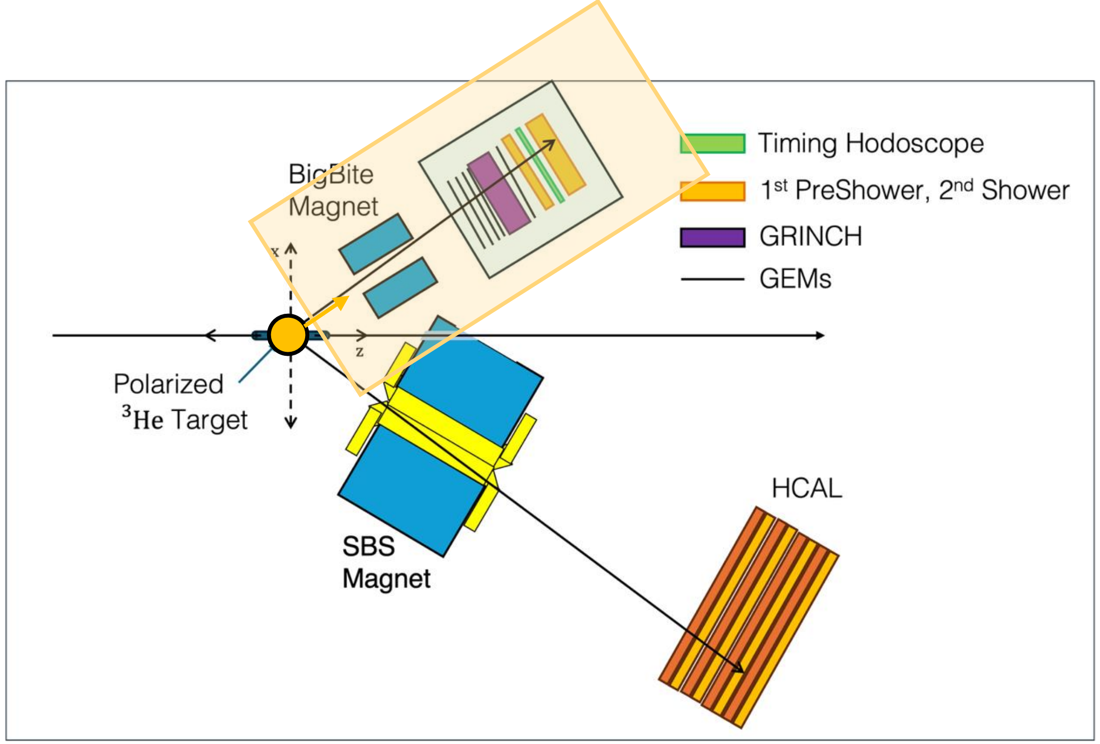
  ~6:1 (K:RB)

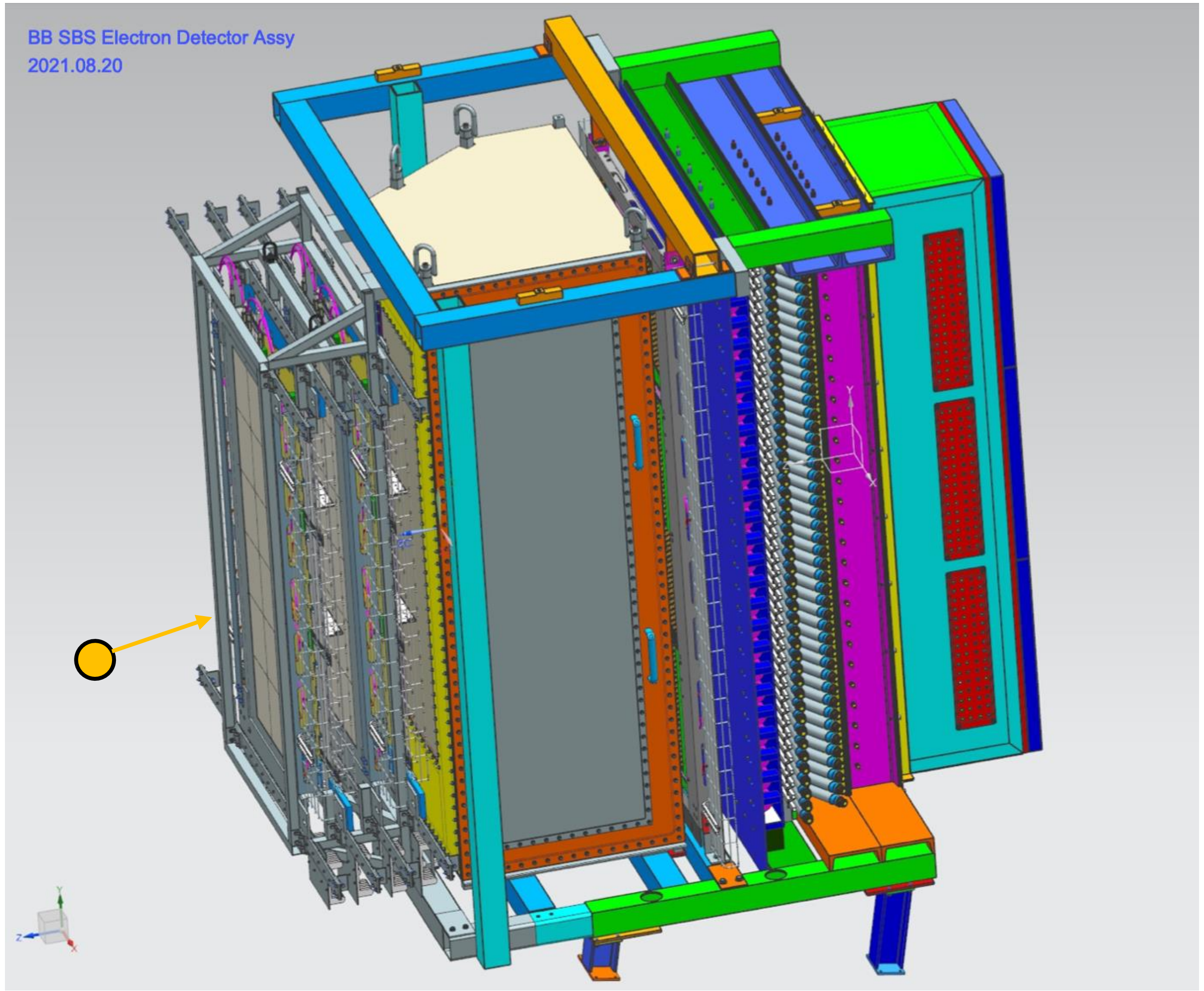
- The target cell is segmented into 3 parts:
  - The Pumping Chamber
  - The Transfer Tubes
  - The Target Chamber




SAFEAIRE VAV
STOR-ALL

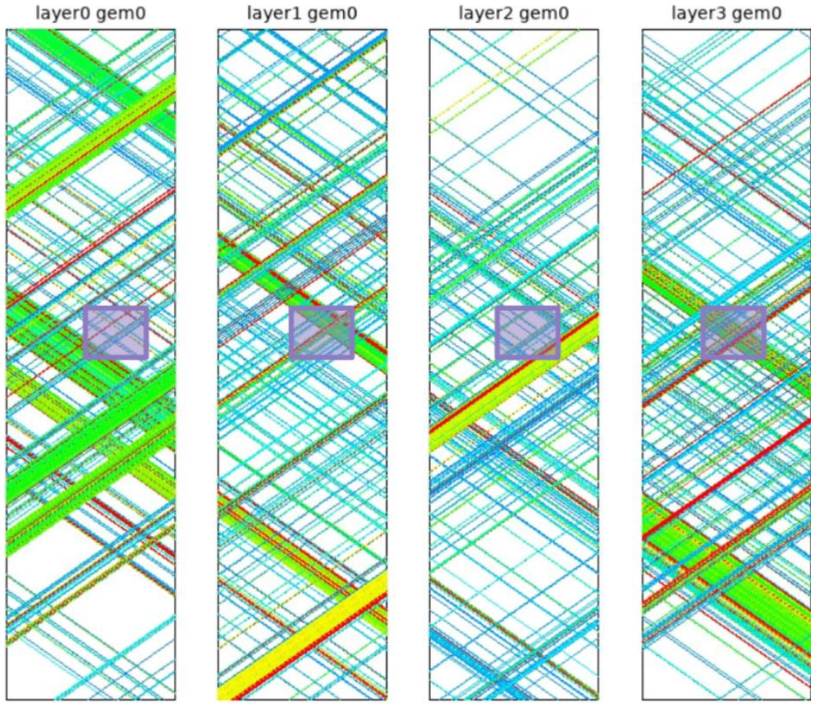
Electron Arm

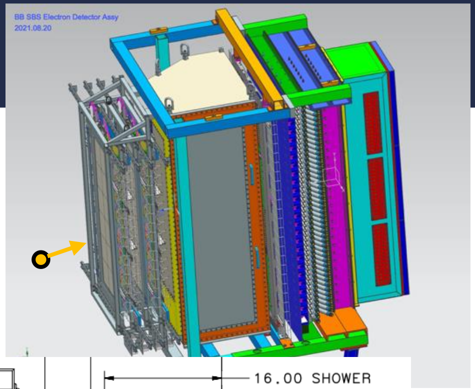


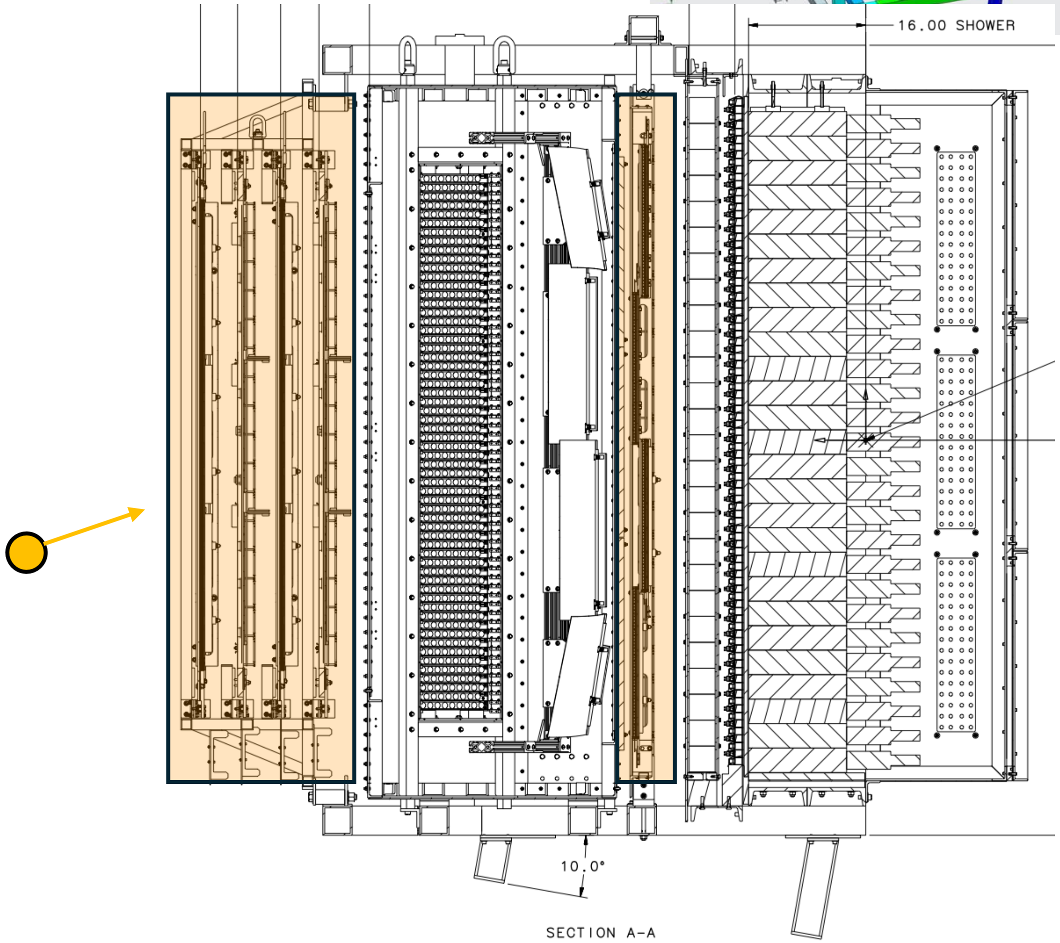


Electron Arm – GEMs

- Gas Electron Multiplier (GEM)
  - 5 foil layers used for precise tracking
    - Precise target vertex reconstruction
      - resolution $\sim 0.1mm$
    - Momentum reconstruction

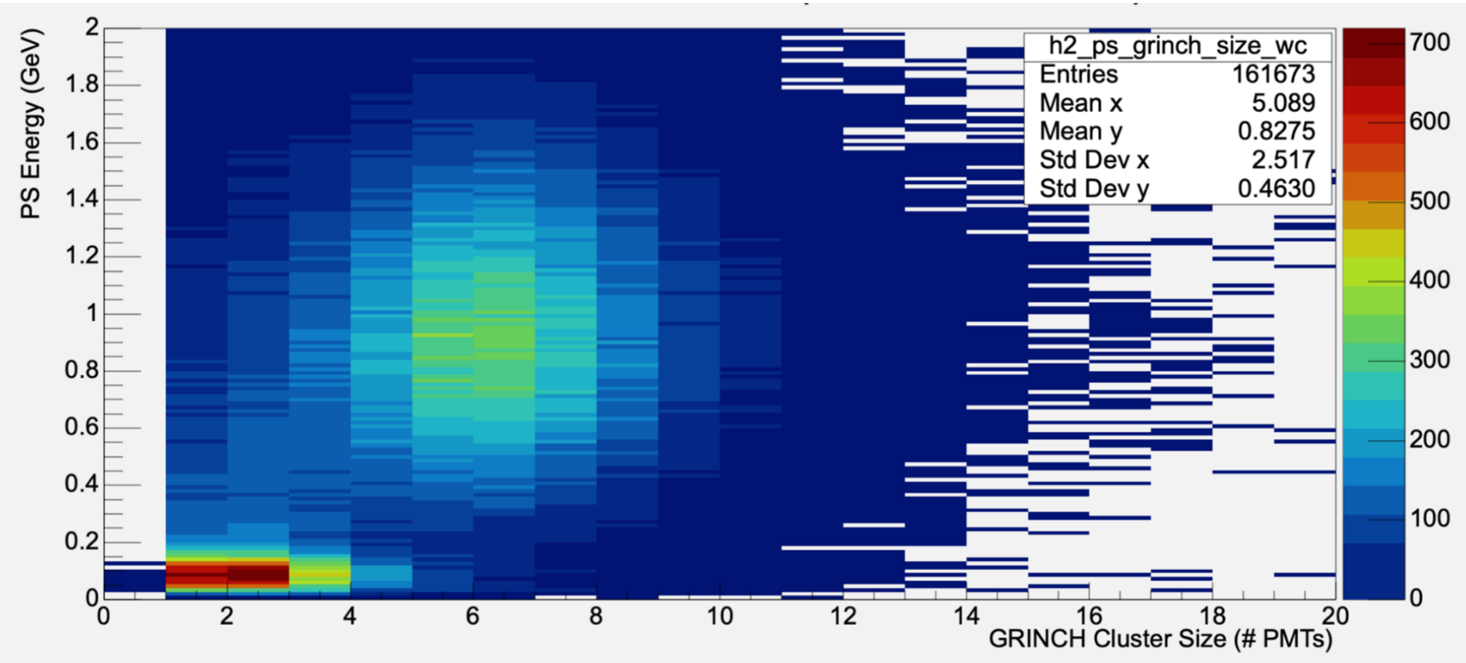


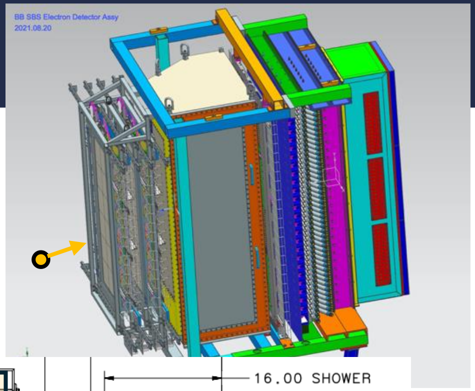


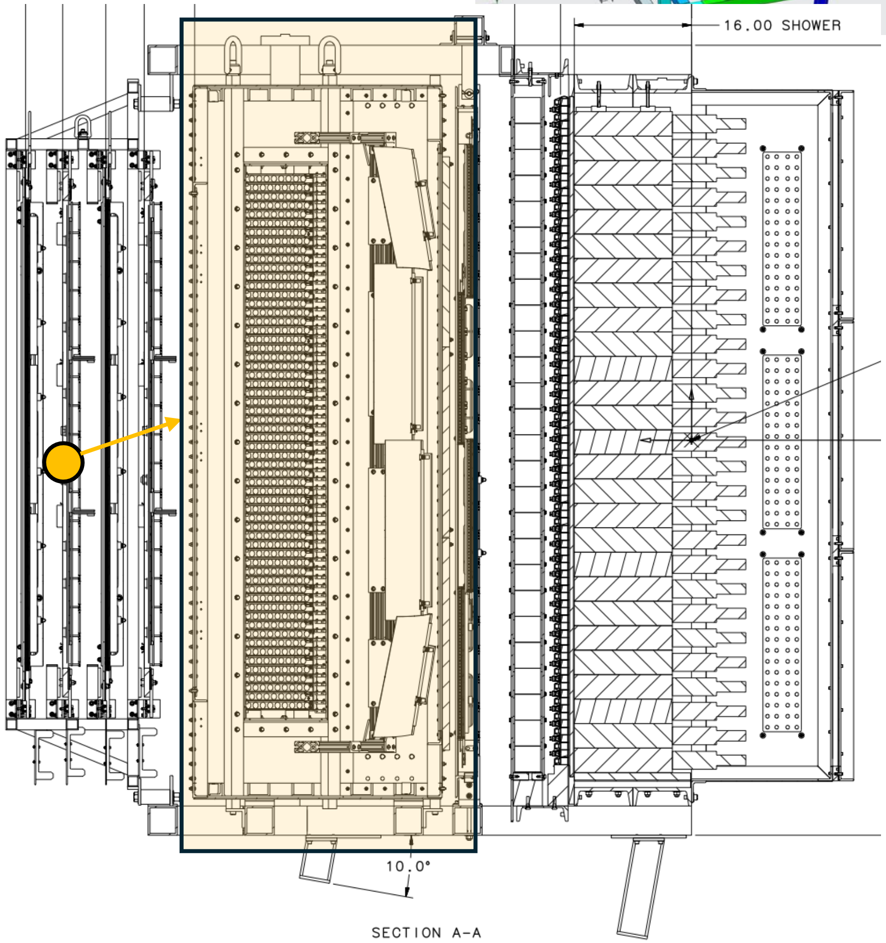


Electron Arm – GRINCH

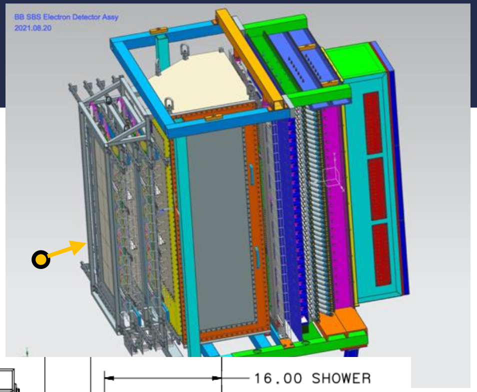
- Gas Ring Imaging Cherenkov (GRINCH)
  - Provides particle identification
    - Distinguishing charged pions from electrons



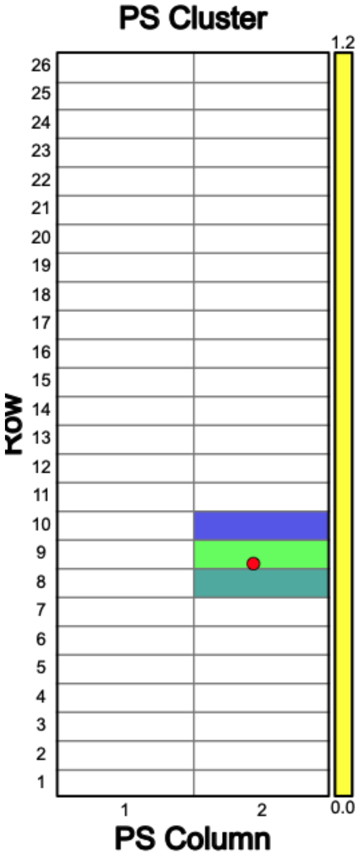


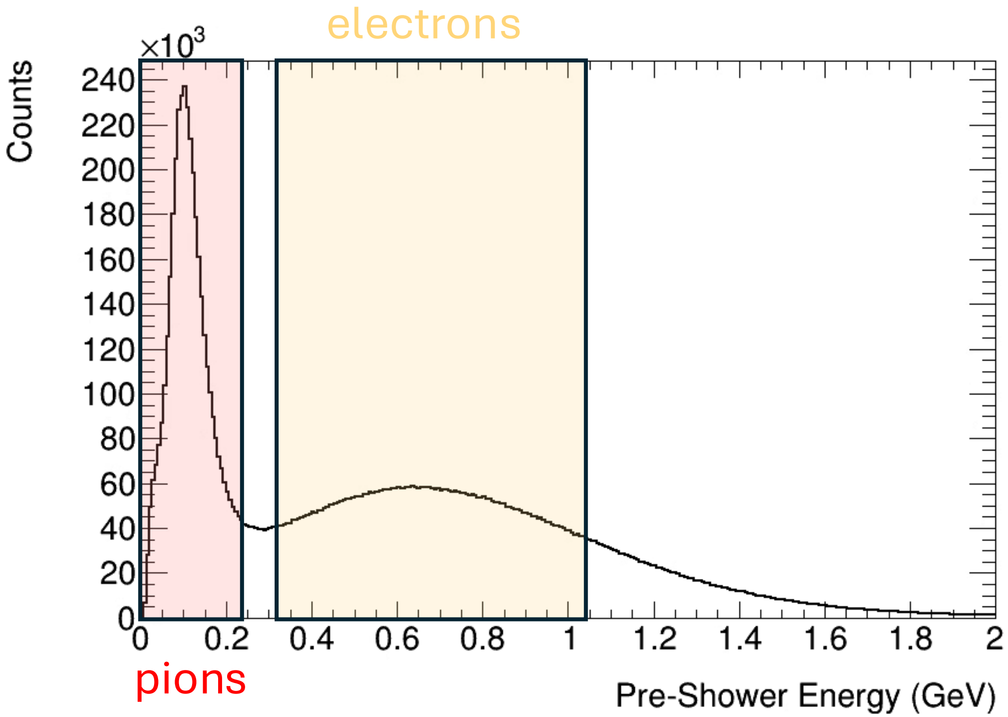


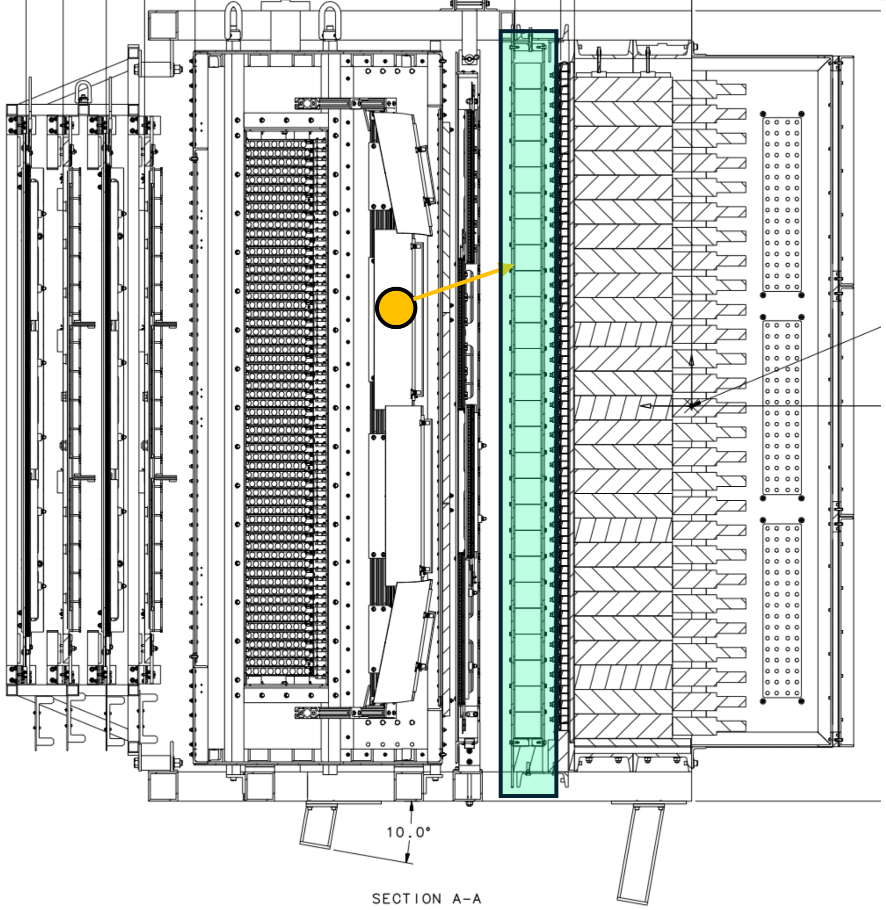
Electron Arm – Calorimeter (pre-shower)



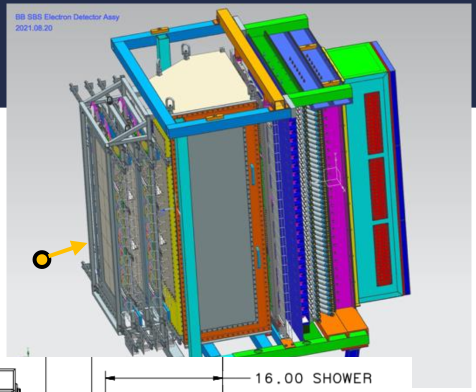
- Pre-Shower calorimeter
  - Isolates MIPs and electron by energy deposition
  - ADC timing and energy information.



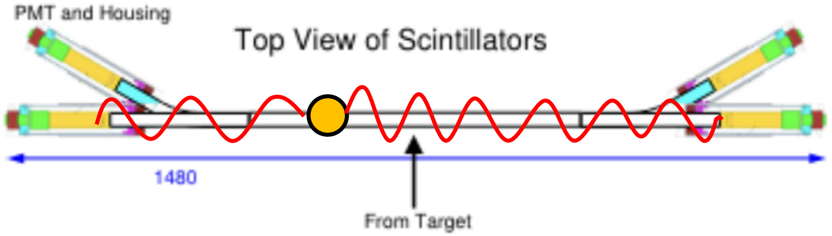


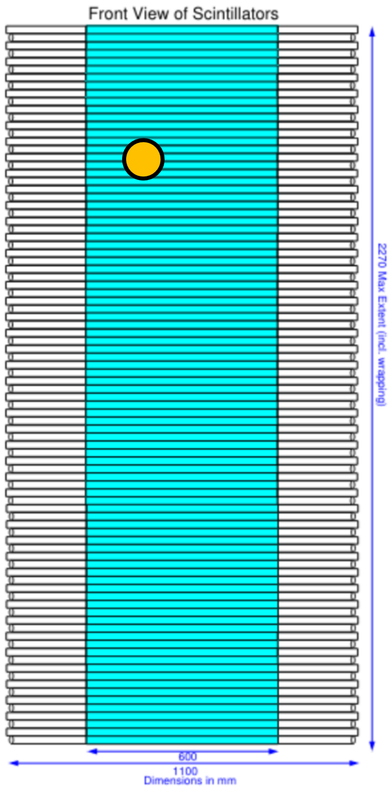


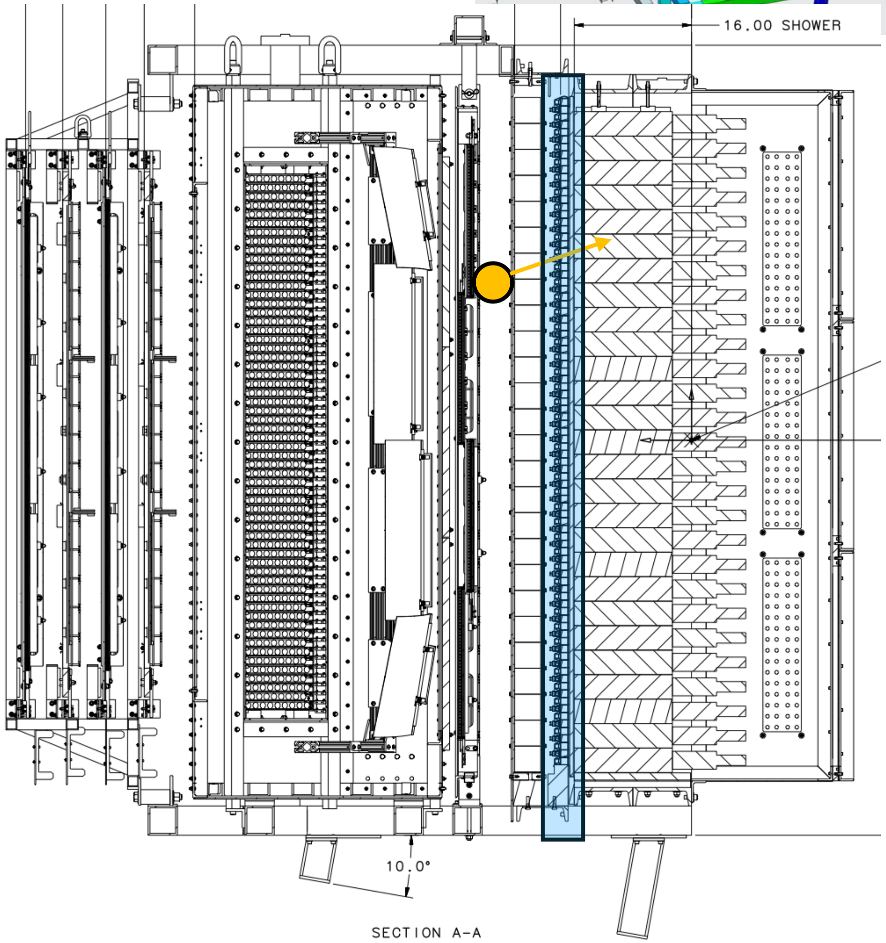
Electron Arm – Timing Hodoscope



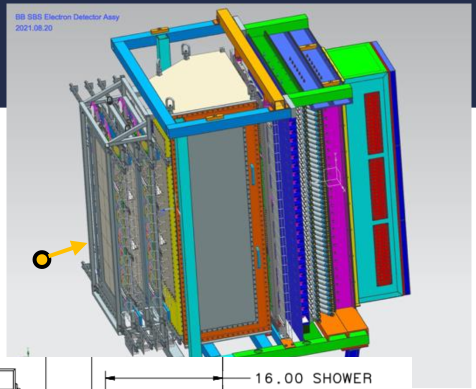
- Timing Hodoscope
  - High resolution timing via Time-to-Digital Converters (TDC)
    - TDC clock resolution is ~60ps
      - Currently seeing timing resolution of 300ps







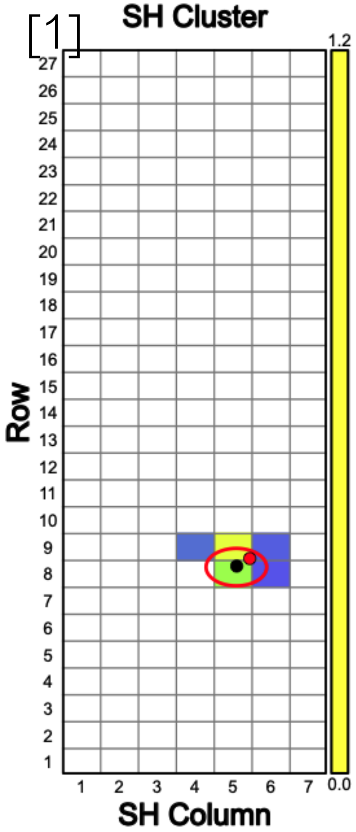
Electron Arm – Calorimeter (shower)

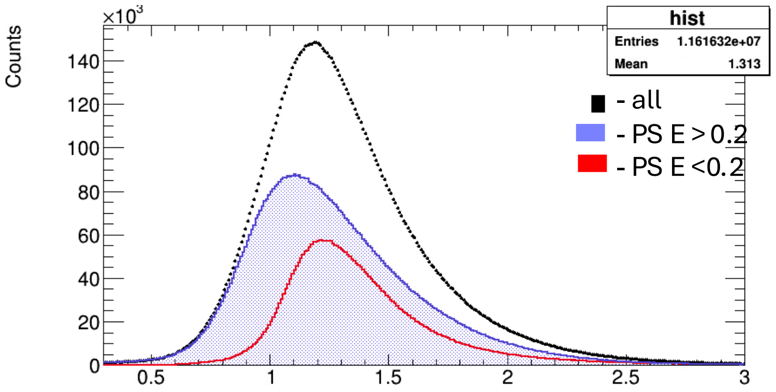


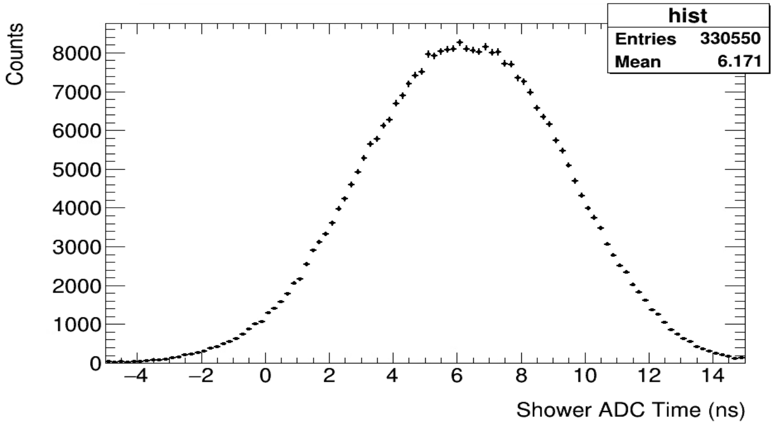
Shower calorimeter

- Absorbs all remaining electron energy.
- Constrains track reconstruction.
- ADC timing and energy information.

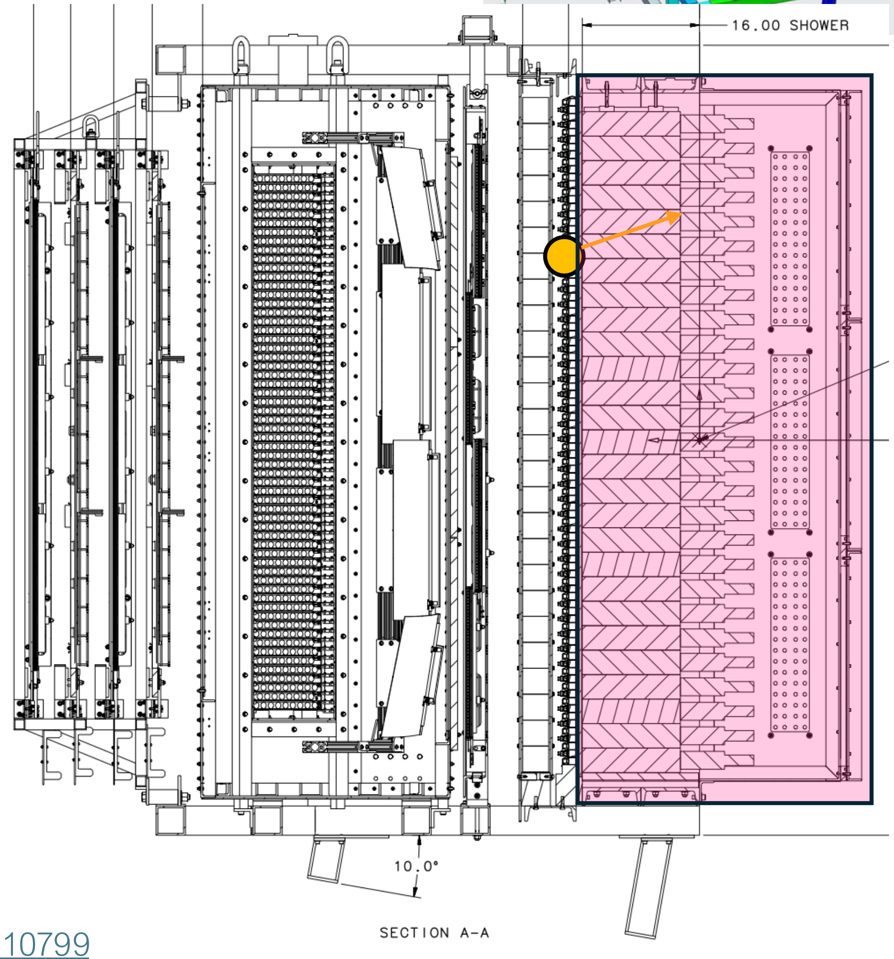
[1]





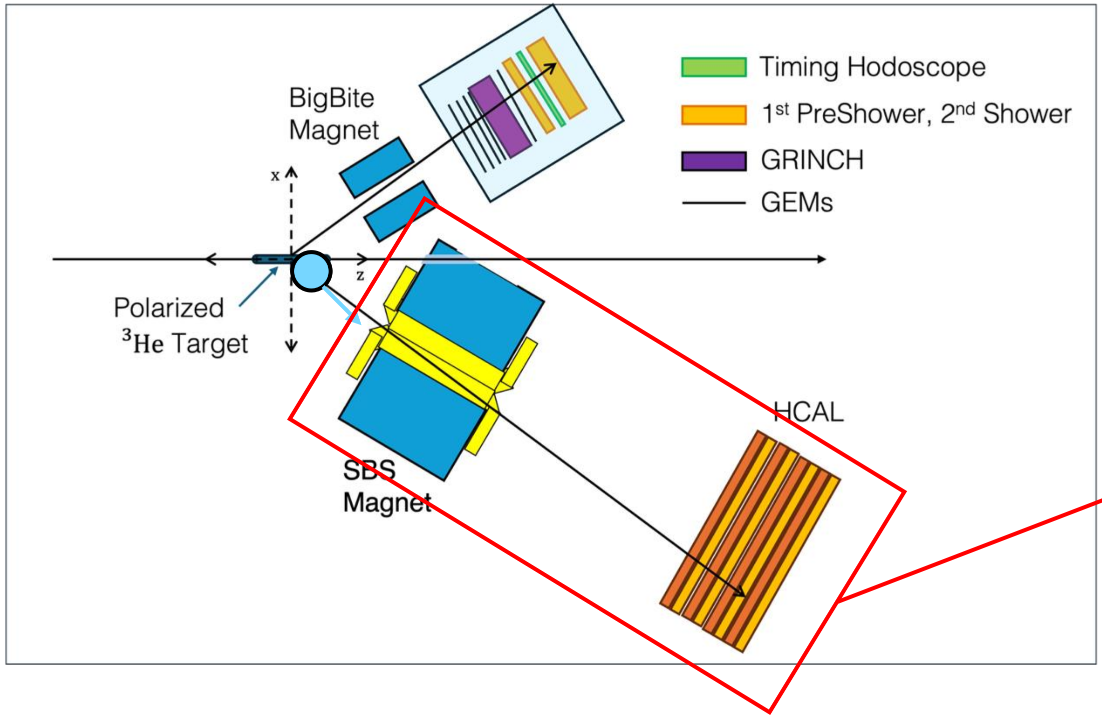


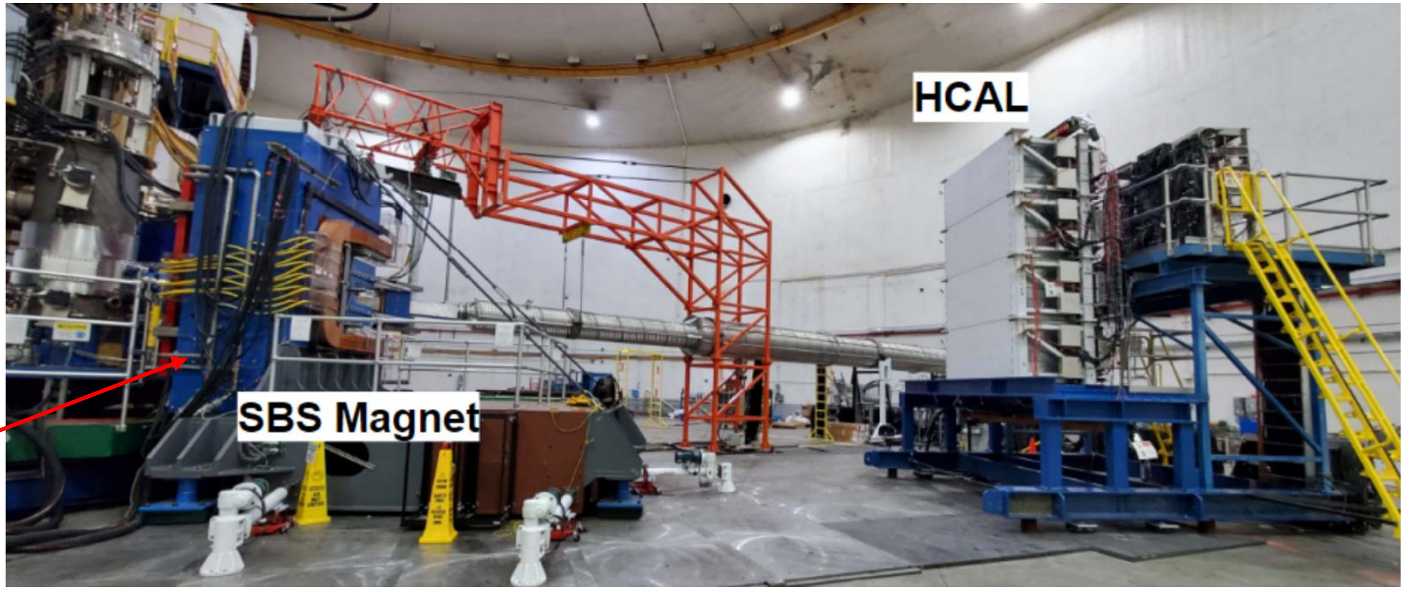
Calorimeter Performance:
$\delta_E/E \sim 0.062$
$\delta_t \sim 500ps$
$\delta_x \sim 1.2cm$



[1] Datta, et al. arXiv:2601.10799

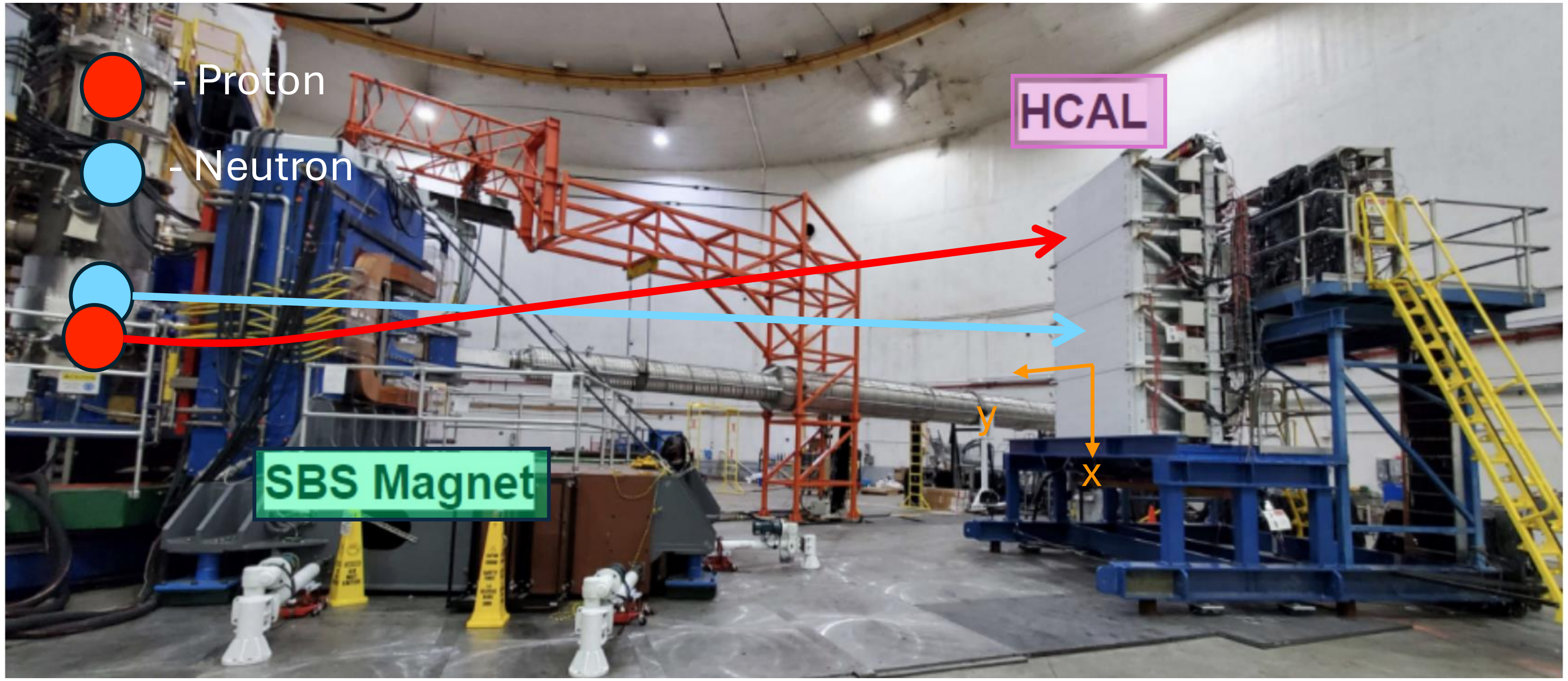
Hadron Arm

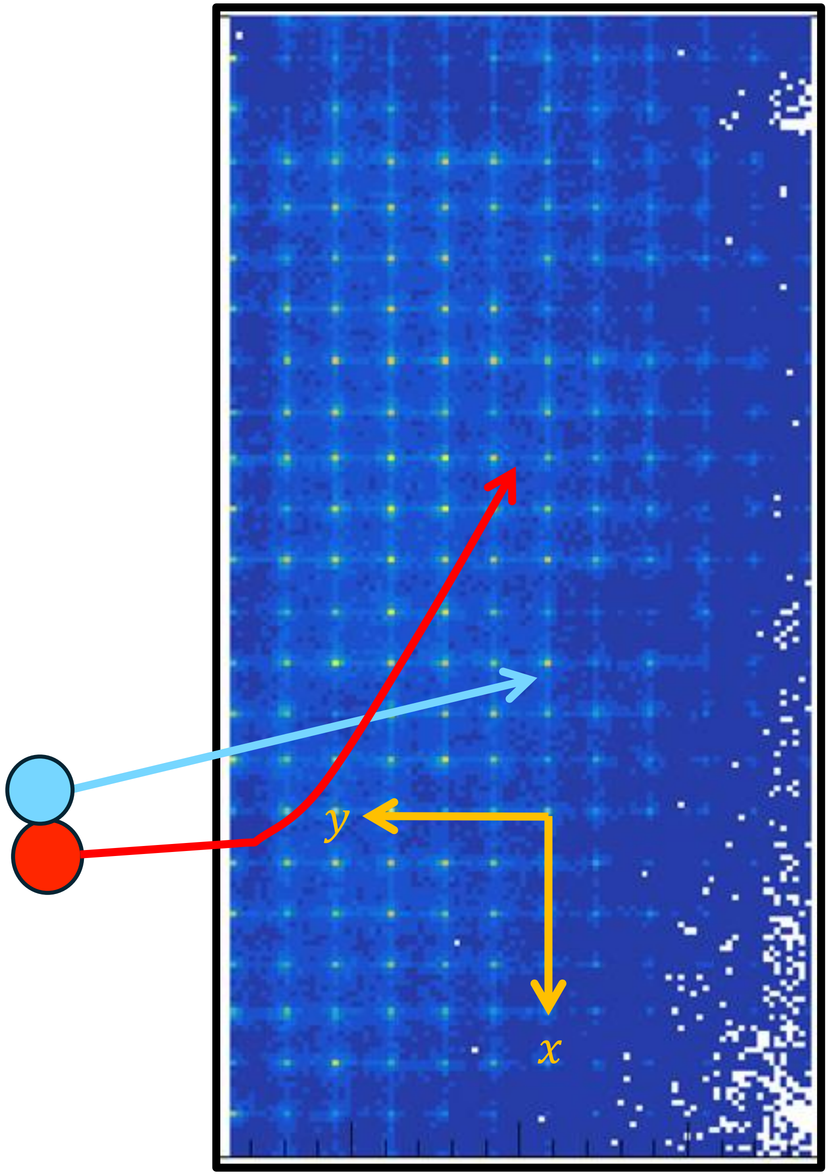

BigBite
Magnet
Timing Hodoscope
1st PreShower, 2nd Shower
GRINCH
GEMs
x
z
Polarized
3He Target
SBS
Magnet
HCAL


HCAL
SBS Magnet

Hadron Arm – Detector Package

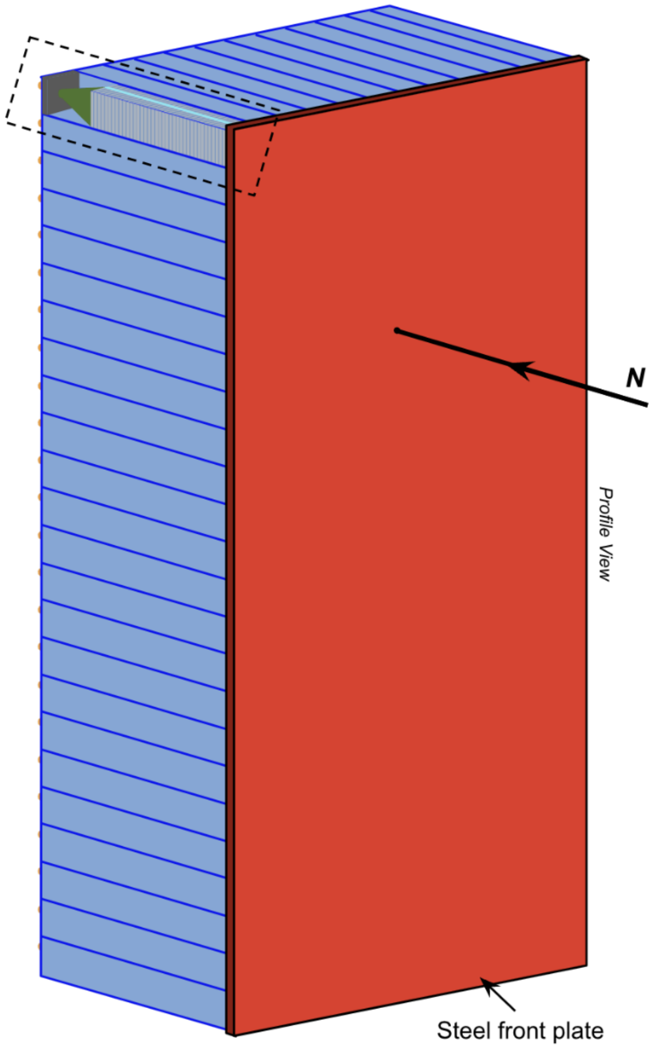
- The SBS Magnet deflects protons, and neutrons remain undeflected
- The Hadronic Calorimeter (HCAL).





Hadronic Calorimeter

- This is a sampling calorimeter.
  - Only measures a portion of the nucleon's kinetic energy.
    - For GEn-II, it has a sampling fraction ~ 8%.
- The ADC's provide the nucleon timing information.
- The small block segmentation provides nucleon position information.



Acknowledgements

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    - Vimukthi Gamage – University of Virginia
    - Jack Jackson – William & Mary
    - Jacob Koenemann – University of Virginia
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  - Graduated
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    - Hunter Presley – University of Virginia; June 2025
- Special Thanks
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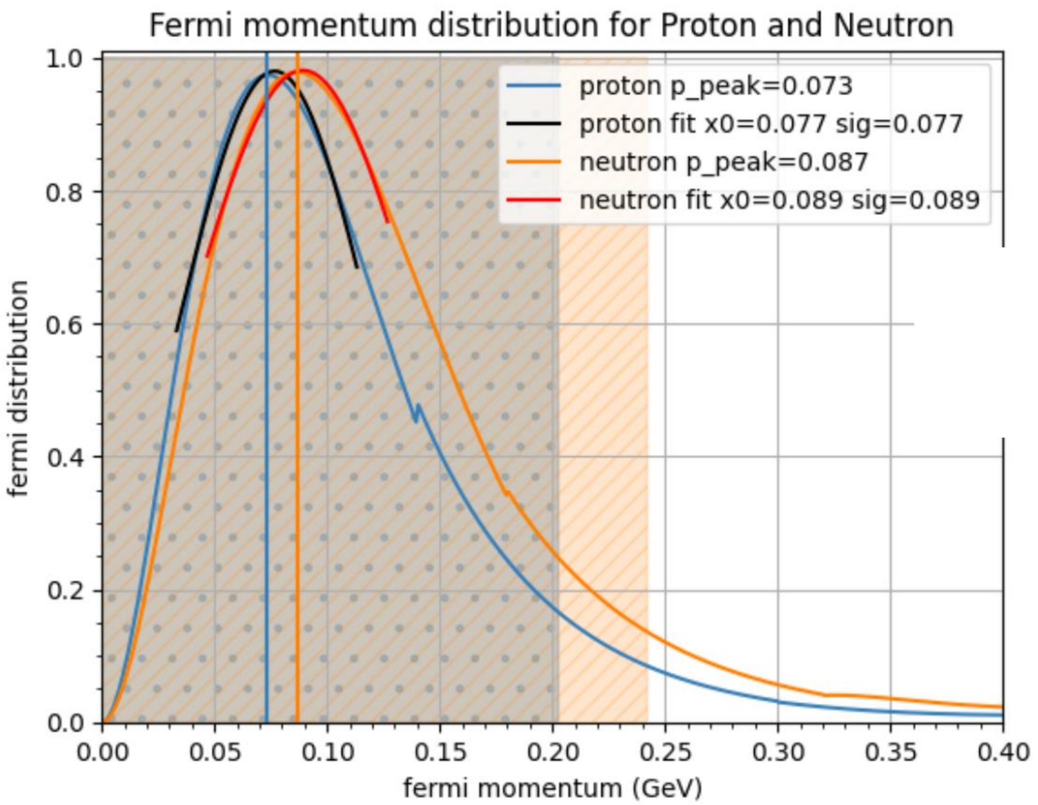
  - Arun Tadepalli – Jefferson Lab

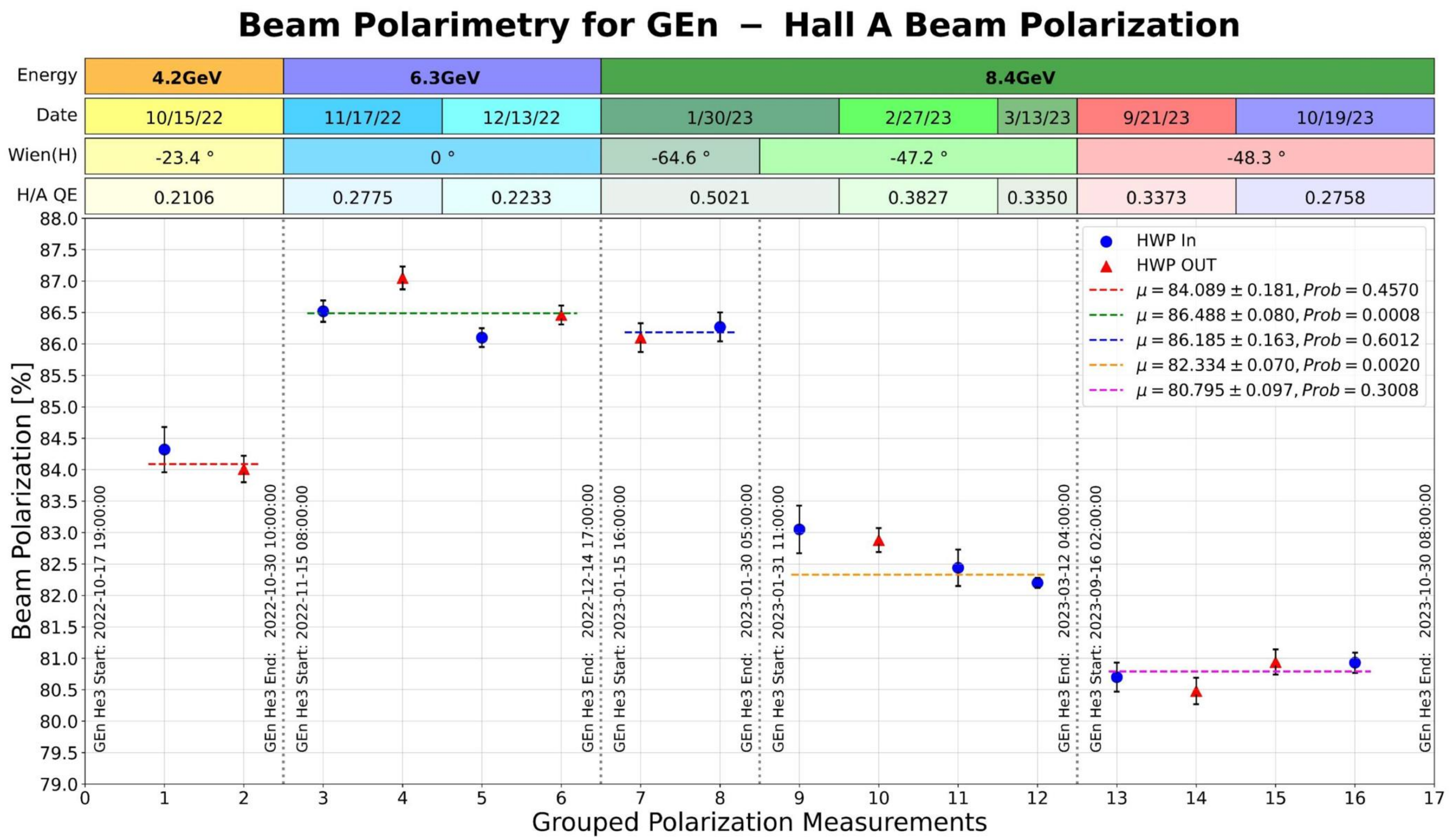
Luminosity Peformance

	Cell Name	Max Polarization	Average Polarization	Average Luminosity 1e35/cm^2s	Duration Installed
Kinematic 2	Hunter	42.22%	35.54%	**4.97**	20 days
Kinematic 3	Windmill	48.61%	43.74%	**8.34**	14 days
	Hunter	44.16%	39.32	**5.82**	24 days
Kinematic 4	Fringe	61.59%	55.14%	**10.26**	60 days
	Chicago	41.18%	38.92%	**4.72**	12 days
	Donya	45.56%	35.21%	**4.21**	31 days
	Christin	51.20%	36.70%	**5.40**	20 days

$$\langle \mathcal{L}_{exp} \rangle = \frac{\sum_{i=0}^{N} \mathcal{L}_i * T_i}{\sum_{i=0}^{N} T_i}$$

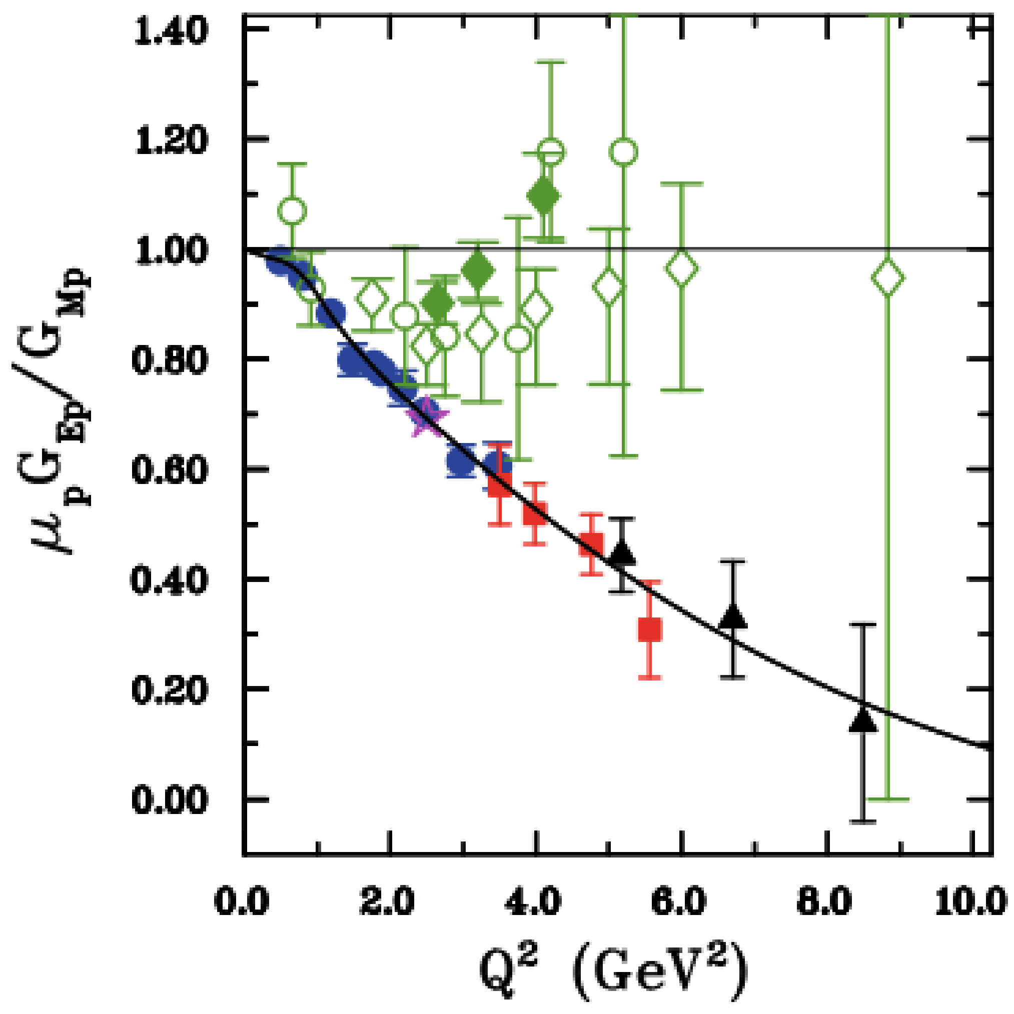
He3 Nucleon Distribution Function





Beam Polarimetry for GEn − Hall A Beam Polarization
Energy
4.2GeV
6.3GeV
8.4GeV
Date
10/15/22
11/17/22
12/13/22
1/30/23
2/27/23
3/13/23
9/21/23
10/19/23
Wien(H)
-23.4 °
0 °
-64.6 °
-47.2 °
-48.3 °
H/A QE
0.2106
0.2775
0.2233
0.5021
0.3827
0.3350
0.3373
0.2758
HWP In
HWP OUT
$\mu = 84.089 \pm 0.181, Prob = 0.4570$
$\mu = 86.488 \pm 0.080, Prob = 0.0008$
$\mu = 86.185 \pm 0.163, Prob = 0.6012$
$\mu = 82.334 \pm 0.070, Prob = 0.0020$
$\mu = 80.795 \pm 0.097, Prob = 0.3008$
GEn He3 Start: 2022-10-17 19:00:00
GEn He3 End: 2022-10-30 10:00:00
GEn He3 Start: 2022-11-15 08:00:00
GEn He3 End: 2022-12-14 17:00:00
GEn He3 Start: 2023-01-15 16:00:00
GEn He3 End: 2023-01-30 05:00:00
GEn He3 Start: 2023-01-31 11:00:00
GEn He3 End: 2023-03-12 04:00:00
GEn He3 Start: 2023-09-16 02:00:00
GEn He3 End: 2023-10-30 08:00:00
Beam Polarization [%]
Grouped Polarization Measurements

The G_E^p/G_M^p Problem



[1] V. Punjabi et al., Eur. Phys. J. A 51, 79 (2015).