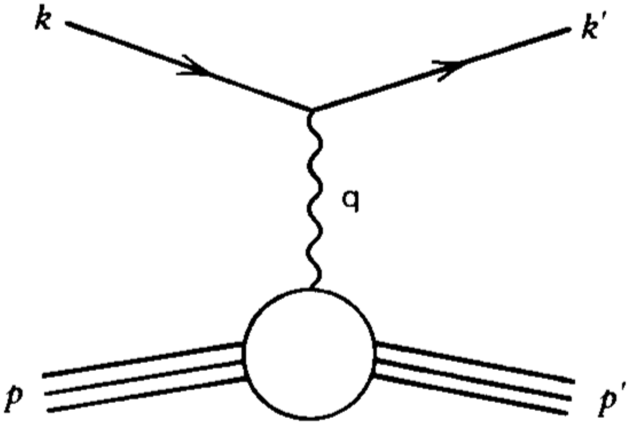
Large Acceptance Proton Form Factor Ratio Measurement at 13 and 15 GeV^2 using Recoil Polarization Method

Experiment E12-07-109

E.Cisbani, M.Jones, N.Lyanage,
L.Pentchev, A.Puckett, B.Wojtsekhowski

Electron-nucleon elastic scattering



Nucleon current, one-photon approximation,

$\alpha_{em} = 1/137$,

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

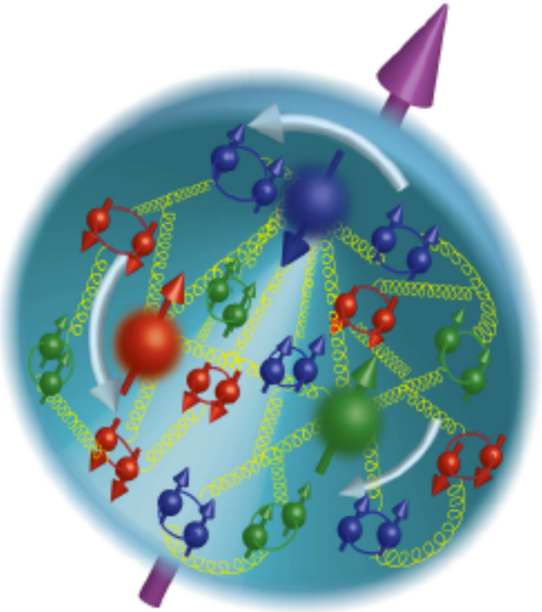
$$\boxed{\frac{d\sigma}{d\Omega}(E,\theta) = \frac{\alpha^2 E'\cos^2(\frac{\theta}{2})}{4E^3\sin^4(\frac{\theta}{2})}[(F_1^2 + \kappa^2\tau F_2^2) + 2\tau(F_1 + \kappa F_2)^2\tan^2(\frac{\theta}{2})]}$$

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

Scientific case

Nucleon Elastic Form Factors

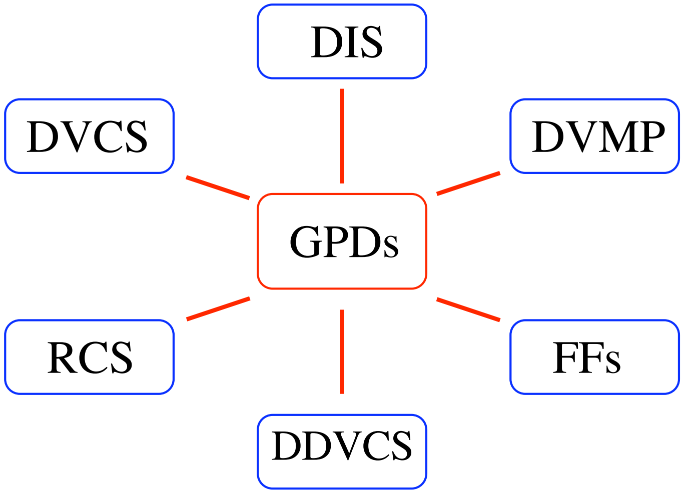
- The Form Factors (FF) are fundamental quantities which describe internal structure of the nucleons
- Related to charge and magnetization distributions of the nucleon
- Investigation of FFs provide a powerful tool toward understanding of non-perturbative QCD and confinement
- Much experimental progress in past two decades: unexpected results that is inspiring theoretical progress.



Standard Model is not complete till we figure out non-perturbative QCD and confinement.

- How does the nucleon acquire its mass: only 2% of the nucleon mass comes from Higgs.
- How does the confinement come about ?

The nucleon structure in terms of GPDs



Reduction formulas at $\xi = t = 0$ for DIS and $\xi = 0$ for FFs

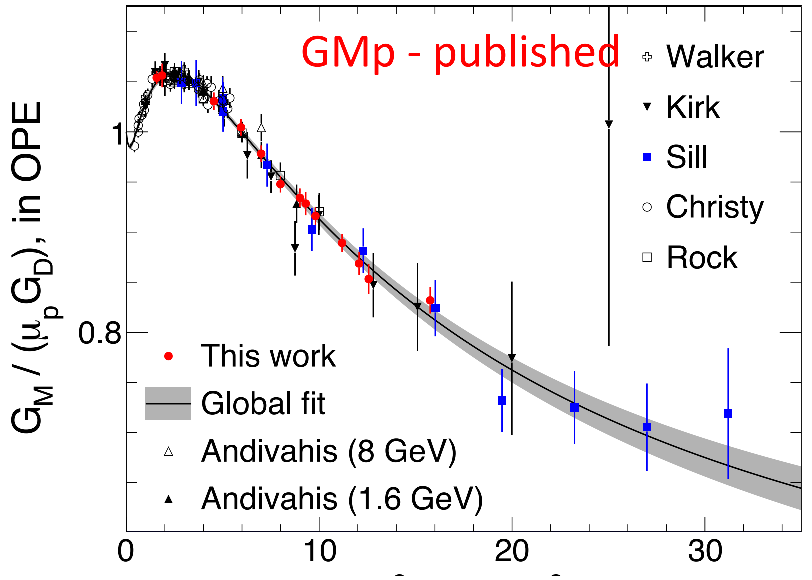
$$H^q(x, \xi = 0, t = 0) \; = \; q(x)$$

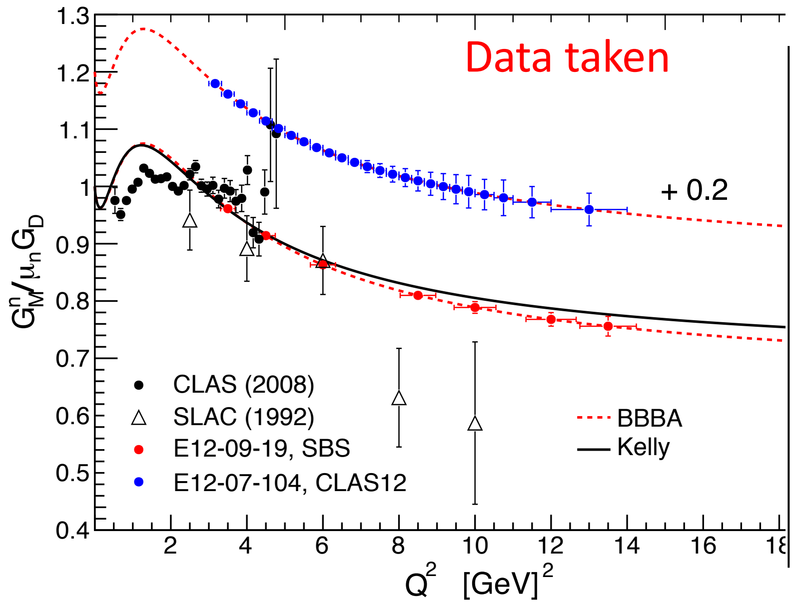
$$\tilde{H}^q(x, \xi = 0, t = 0) \; = \; \Delta q(x)$$

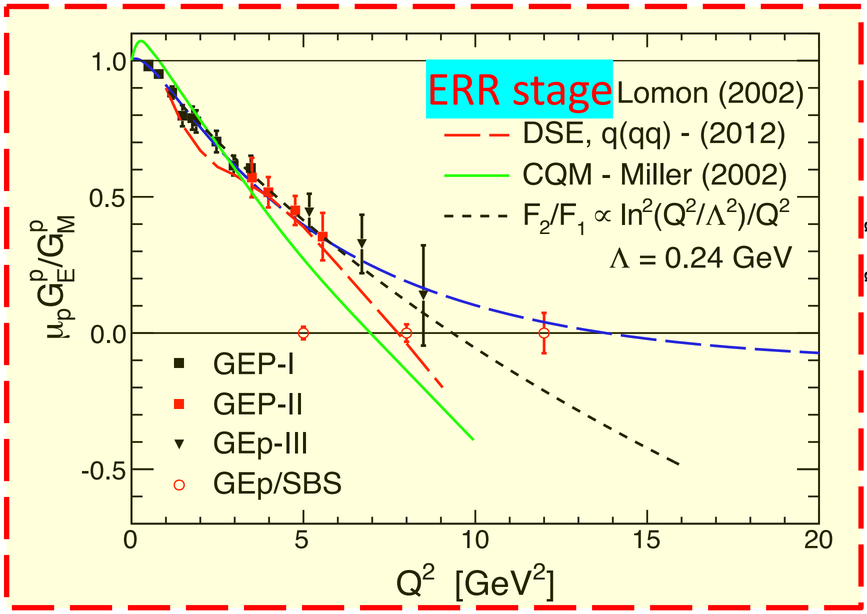
$$\int_{-1}^{+1} dx \, H^q(x, 0, Q^2) \; = \; F_1^q(Q^2)$$

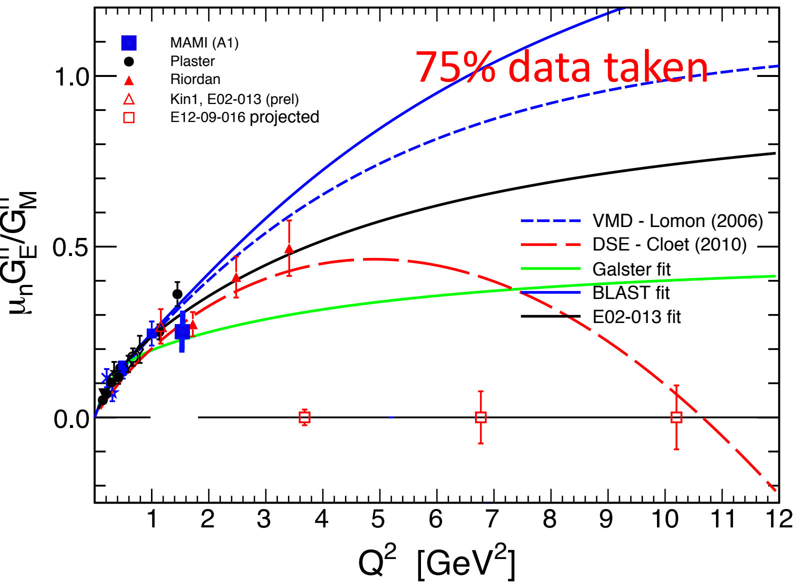
$$\int_{-1}^{+1} dx \, E^q(x, 0, Q^2) \; = \; F_2^q(Q^2)$$

The nucleon FFs

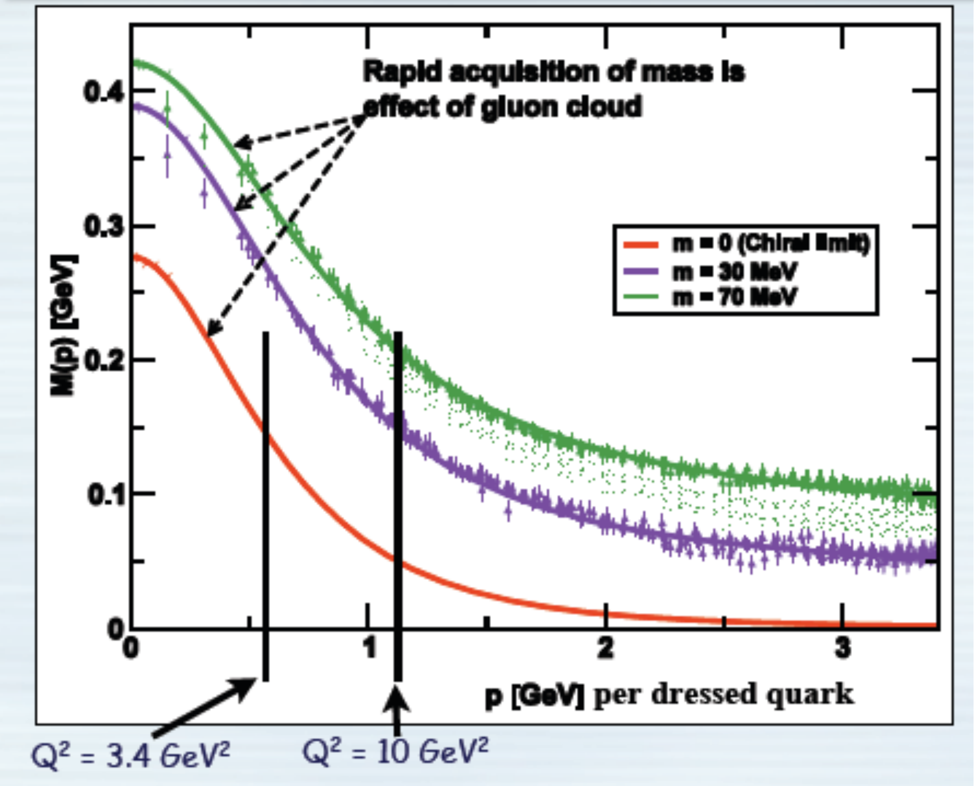




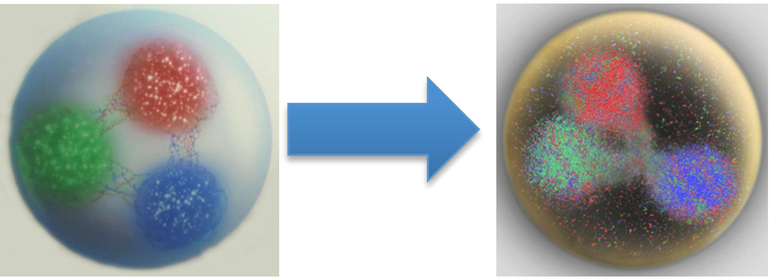




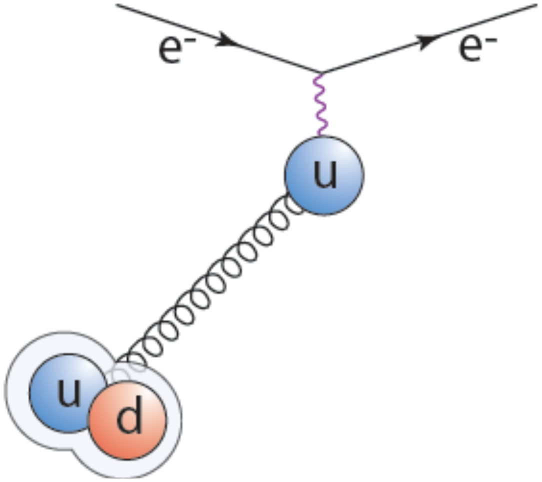
Dyson-Schwinger Equations based approach to non-perturbative QCD – Roberts et al.



Dynamic generation of mass

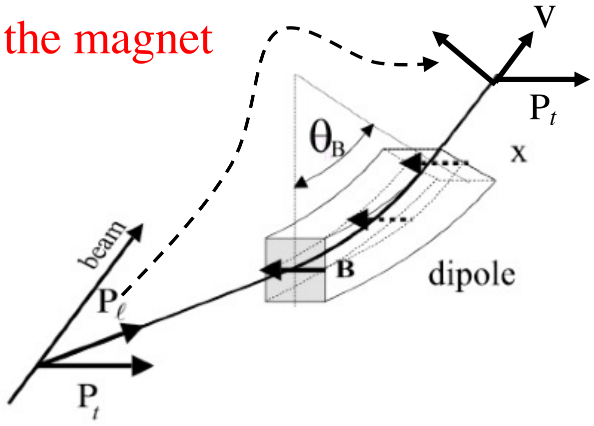


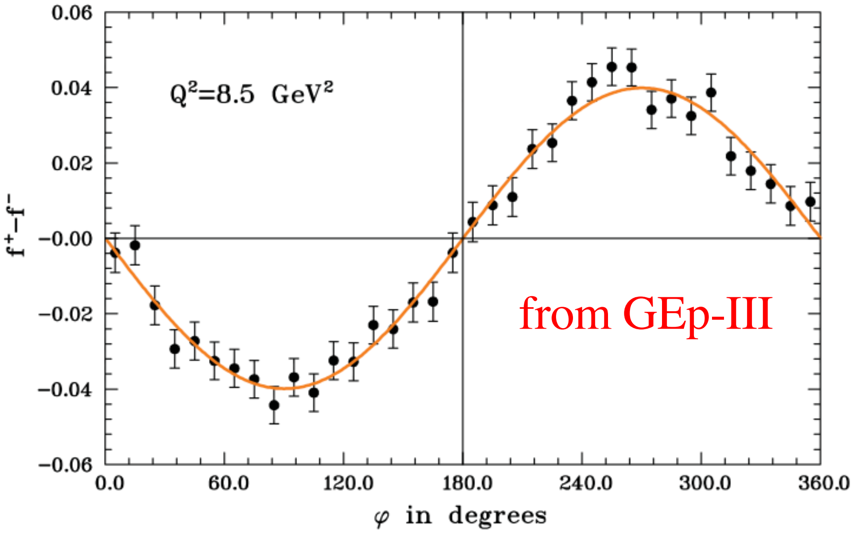
- Well suited to Relativistic Quantum Field Theory. Non Perturbative, continuum approach to QCD
- Hadrons as composites of current Quarks and Gluons
- Incorporates di-quark degrees of freedom.
- Confinement and DCSB are readily expressed
- Prediction: owing to DCSB in QCD, strong diquark correlations exist within baryons



Method: Focal Plane Polarimeter

Spin rotation
in the magnet





from GEp-III

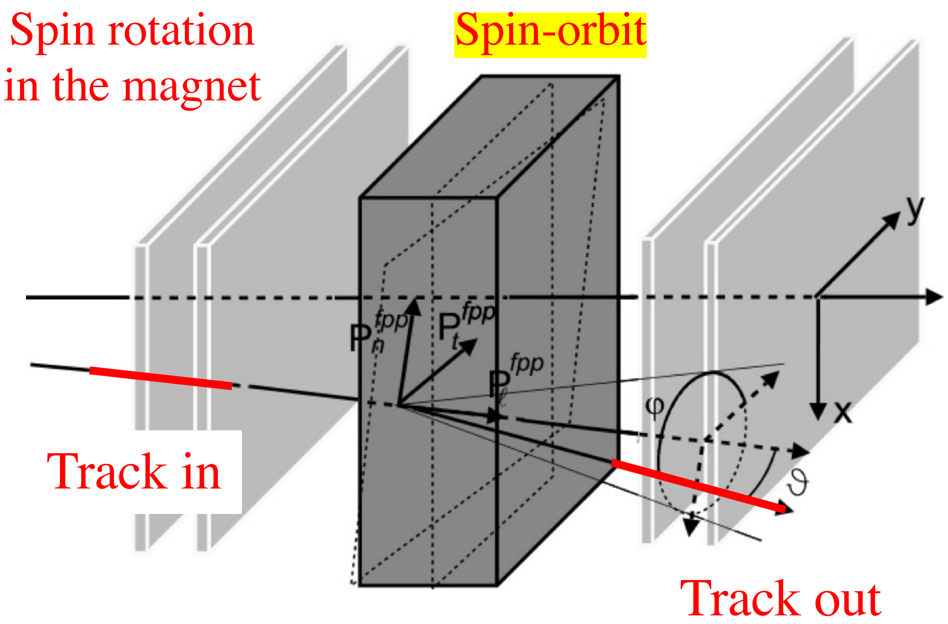
$$f^{\pm}(\vartheta,\varphi) = \frac{\epsilon(\vartheta,\varphi)}{2\pi}\left[1 \pm A_y(P_x^{fpp}\sin\varphi - P_y^{fpp}\cos\varphi)\right]$$

where ± refers to electron beam helicity

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

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

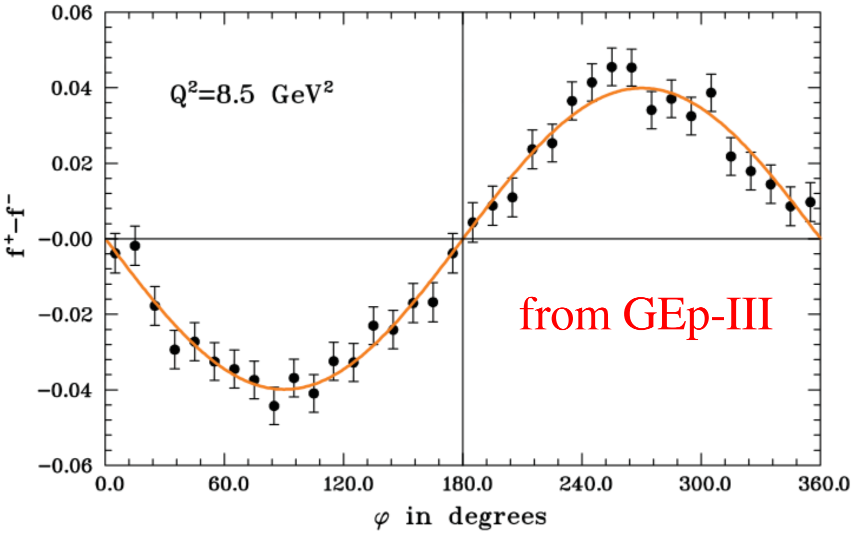
Method: Focal Plane Polarimeter


Spin rotation in the magnet

Spin-orbit

Track in

Track out


from GEp-III

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

where ± refers to electron beam helicity

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

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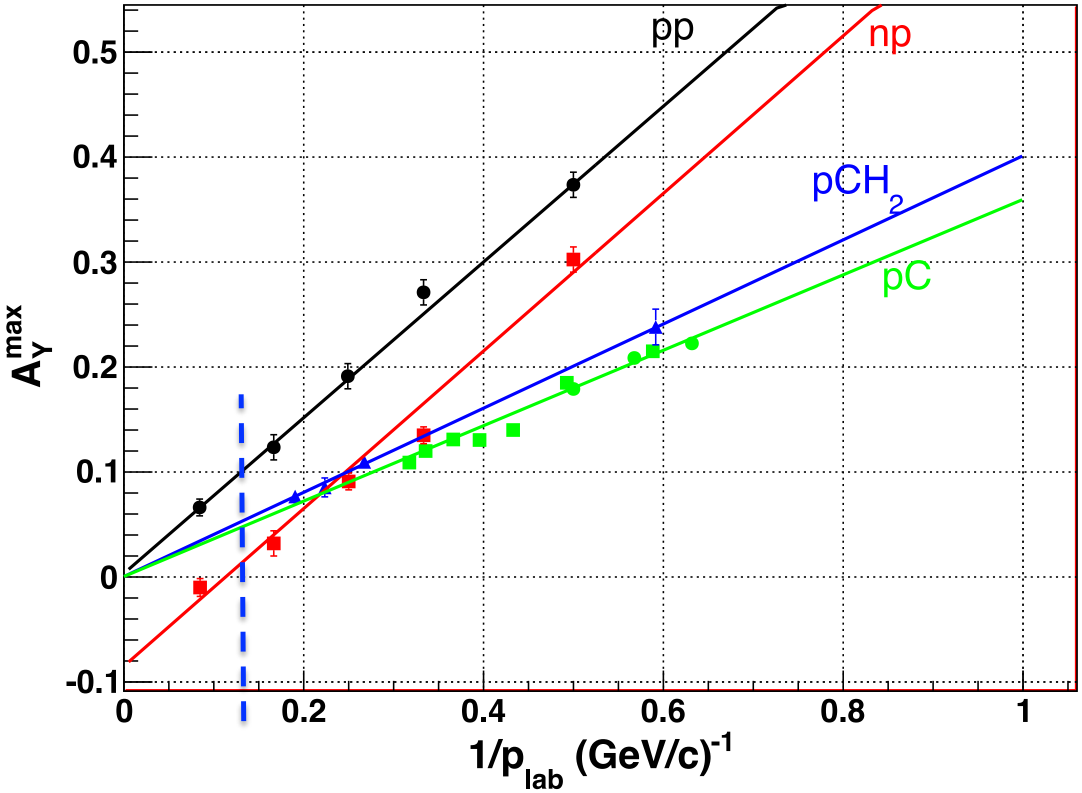
Method: Focal Plane Polarimeter

A_Y analyzing power
vs. inverse
proton momentum



proton momentum will be ~ 7.3 GeV/c

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

Challenges in this experiment

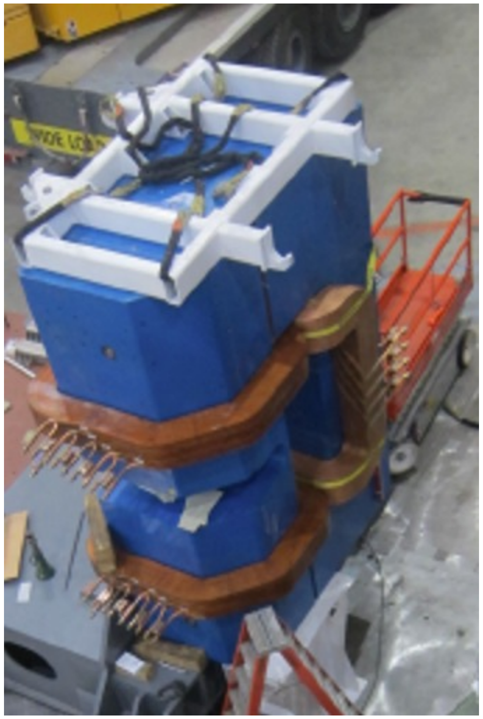
$$\text{Form factor} \propto Q^{-4}$$

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

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

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

Need large statistics => max luminosity and solid angle



Max luminosity -> large background

Large solid angle -> small bend -> huge background

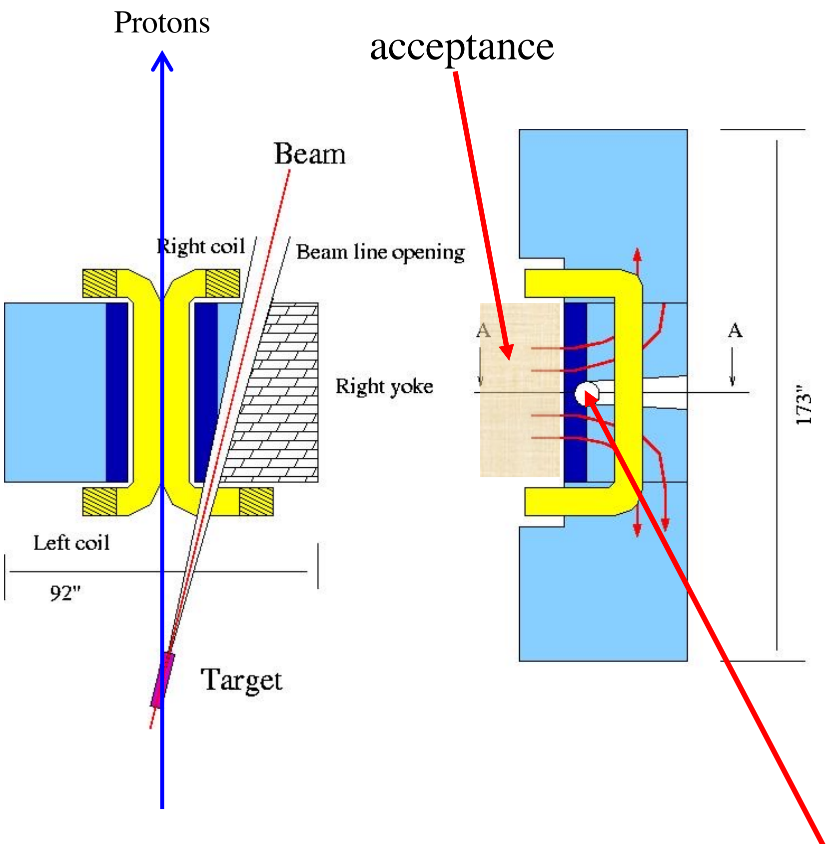
Solution is a modern tracking detector - GEM

B. Wojtsekhowski

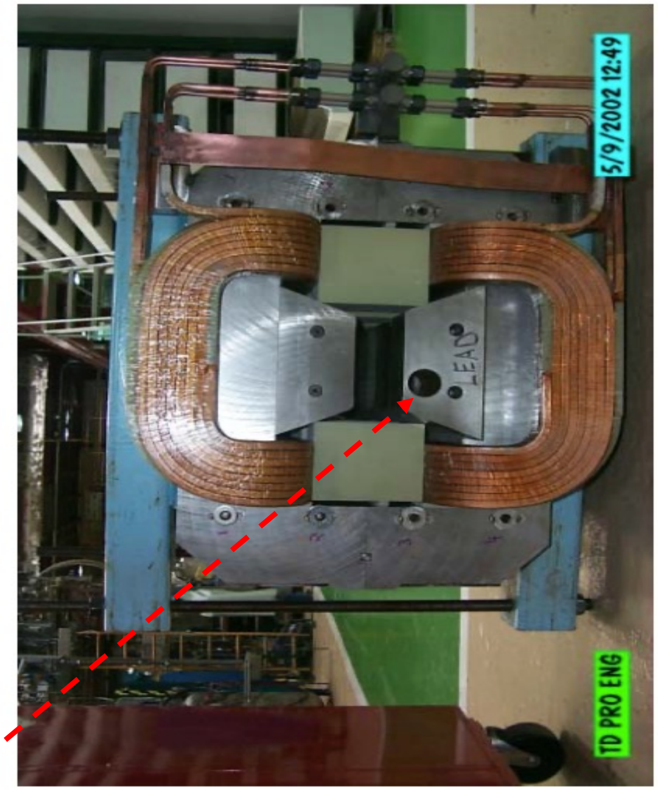
McLaughlin Run Activity Center, Upper St. Clair township, just south of Pittsburgh, PA

Concept of a large solid angle proton arm

acceptance



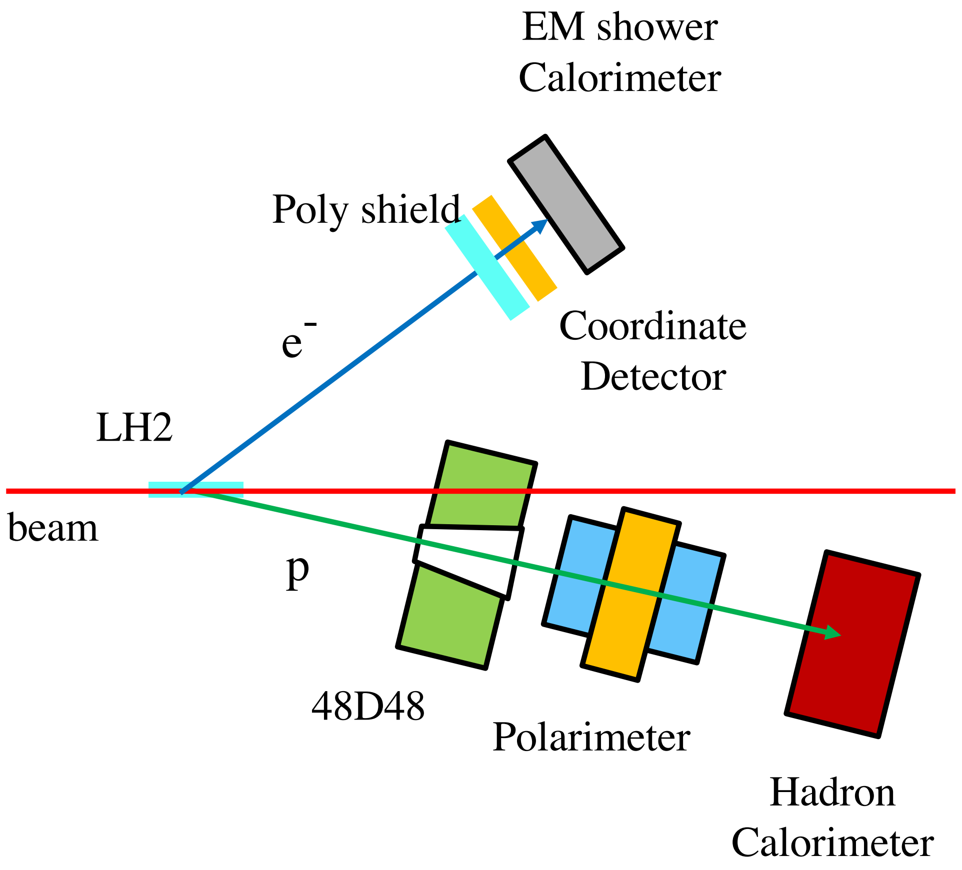
Lambertson magnet in accelerator field



beam

Magnet: 48D48 - 46 cm gap, 2-3 Tesla*m
Solid angle is 70 msr at angle 15 deg.
GEM chambers with 70 μm resolution
momentum resolution is 0.5% for 5 GeV/c
angular resolution is 0.5 mr

Scheme of the elastic scattering experiment

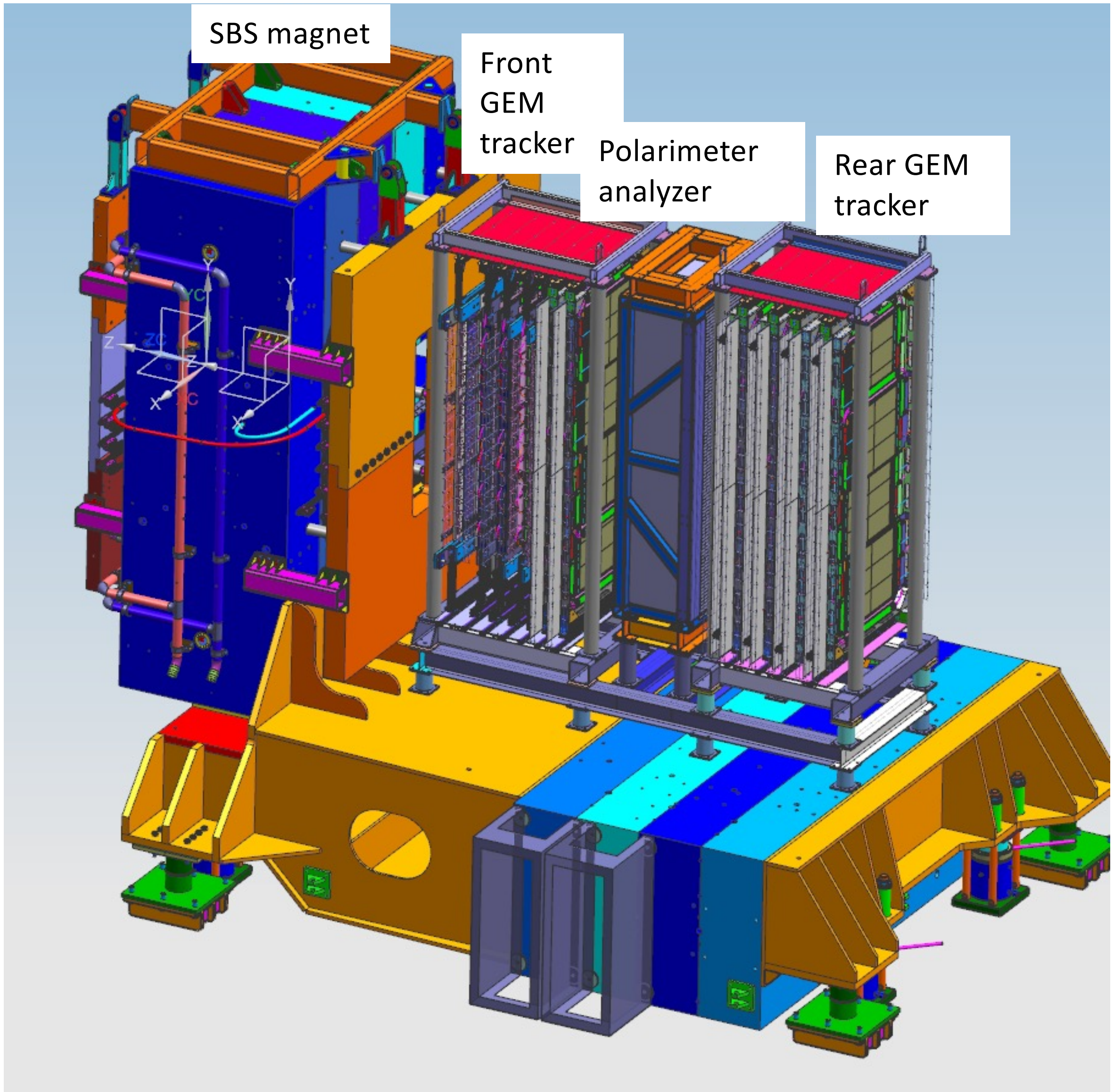


Electron arm

Calorimeter energy resolution ~5%
Hit location resolution ~5 mm
scattering angle ~1 mrad
CDET - vertical hit location ~2 mm
azimuthal angle ~1 mrad

Proton arm

SBS magnet - 2.5 T-m
GEM based trackers
CH2 analyzer
Momentum resolution ~1%
Angular resolution ~1 mrad

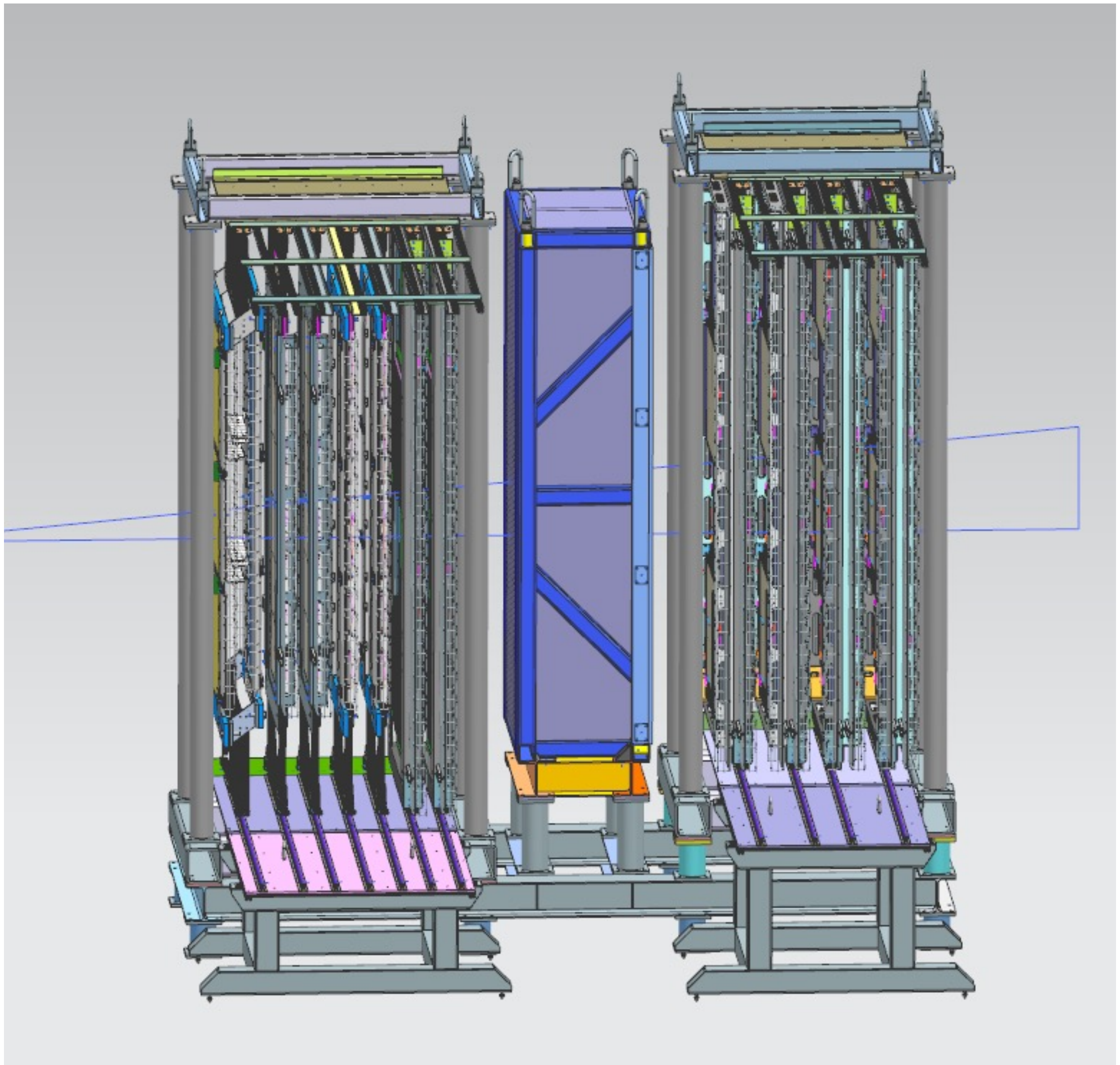


SBS magnet

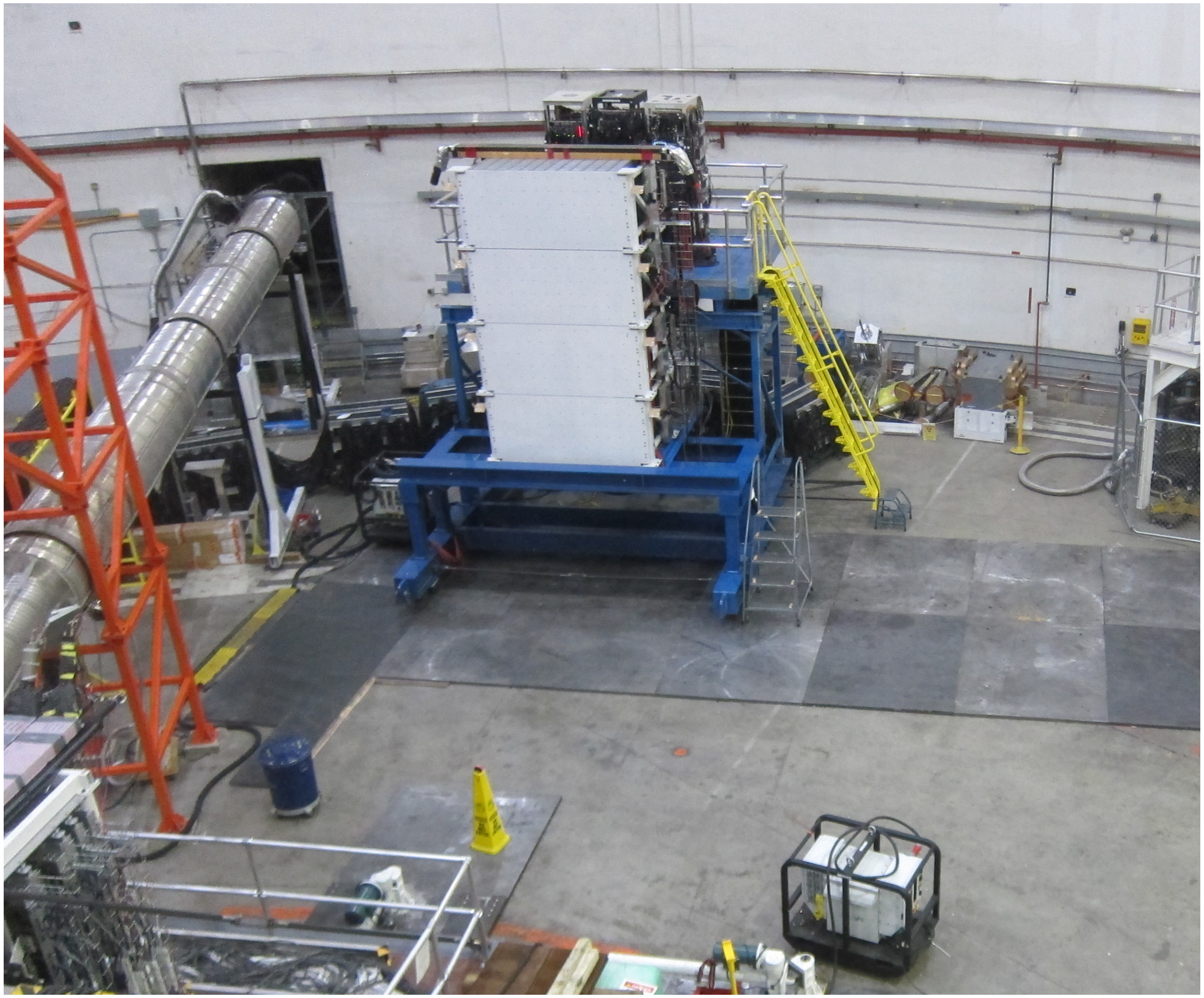
Front GEM tracker

Polarimeter analyzer

Rear GEM tracker

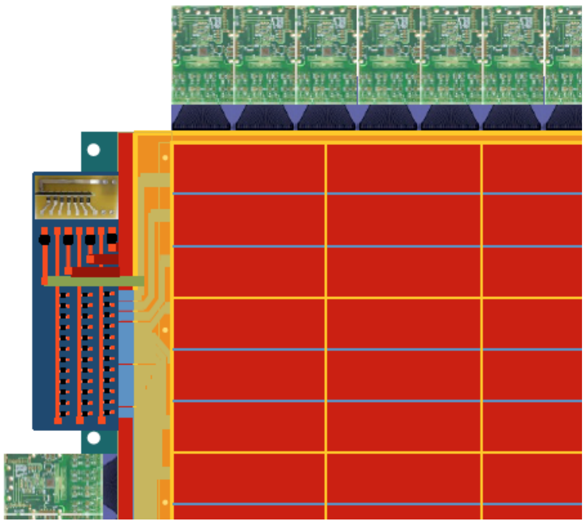


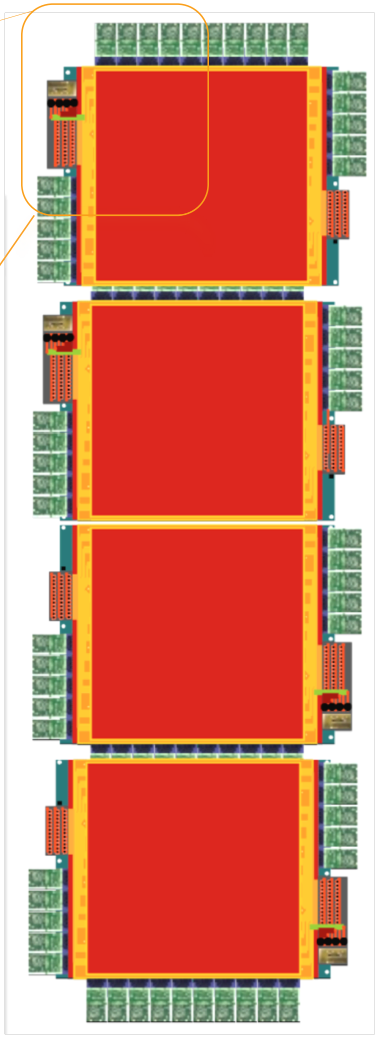
Proton arm: calorimeter



HCAL parameters confirmed in GMn and GEn runs

SBS trackers in the polarimeter

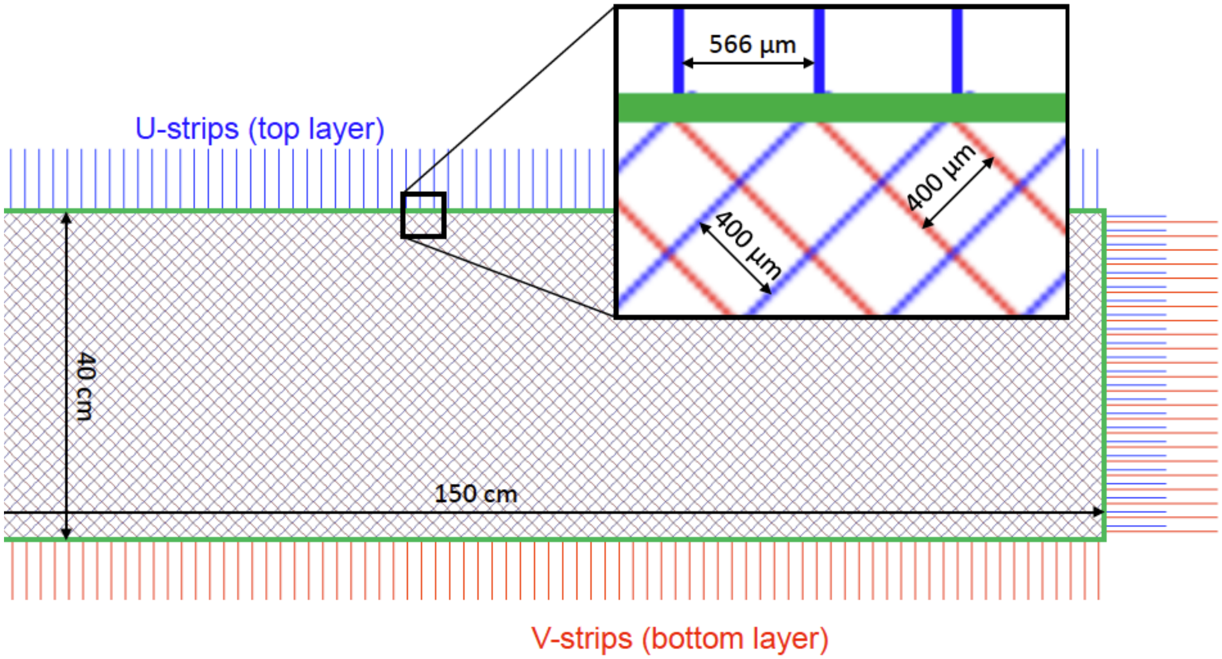




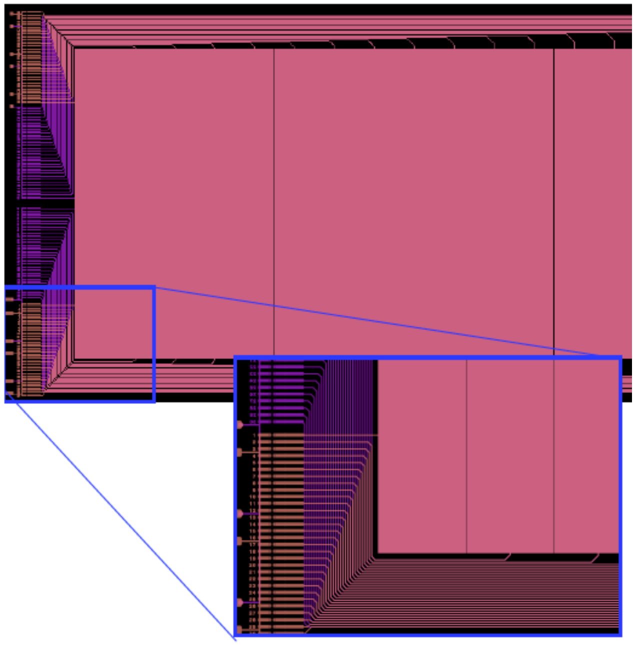
- Protection resistors are outside the chamber: reliable, easy access.
- Large alignment pins, away from the active area
- Wide frames on the two sides not in active area: better mechanical rigidity and more room for gas inlets, HV traces etc.
- Electronics arranged to minimize the material within active area.

U-V and XW readout large GEM modules for SBS Front Tracker (FT)

- 30° UV strip readout (4 modules), and 0° X/45° W in XW strip readout (2 modules),
- Complement the X-Y Cartesian strip readout
- Combination of U-V, XW and X-Y strips improves tracking in high rate environment
- Each U-V (XW) GEM layer is one single large GEM (no dead area)
  - Unlike XY SBS GEM layers made of several modules: new GEM foil technology allows building single module instead: No dead area for frames or electronics.
  - The GEM layer's active area is 150 cm × 40 cm
- Produced by the UVa group: All 4 UV modules used in Gen-II; the two XW under construction

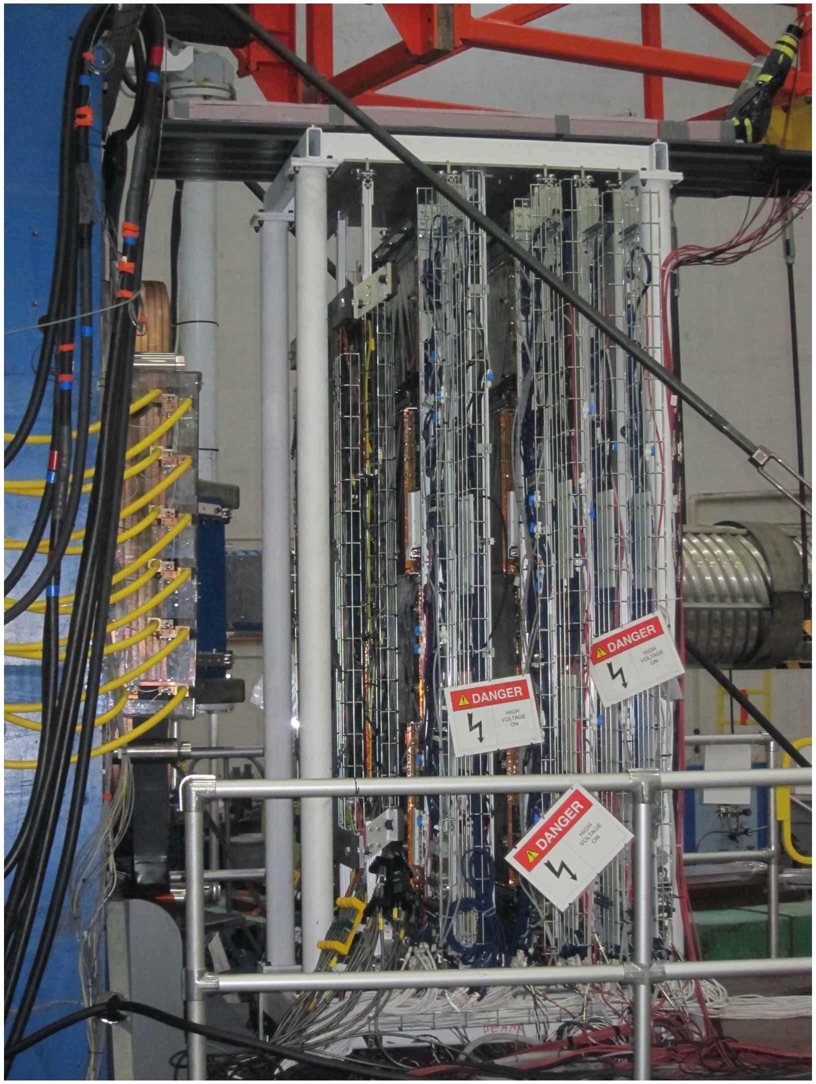


readout layer arrangement schematic

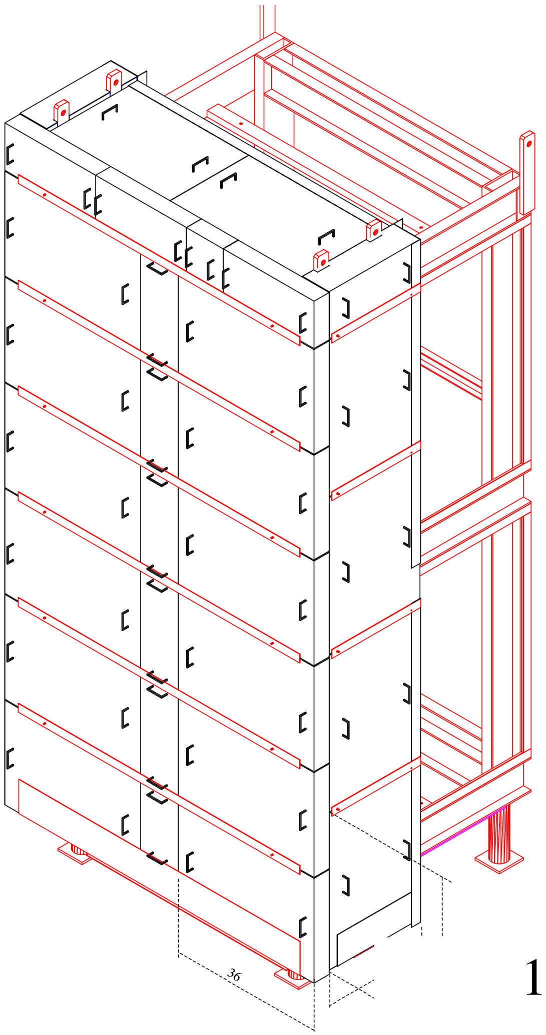


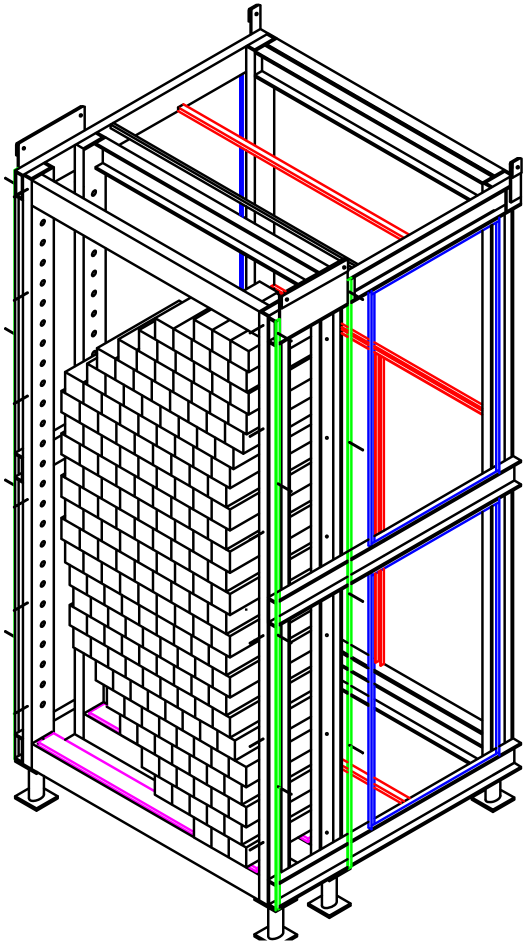
Completed GEM foil design

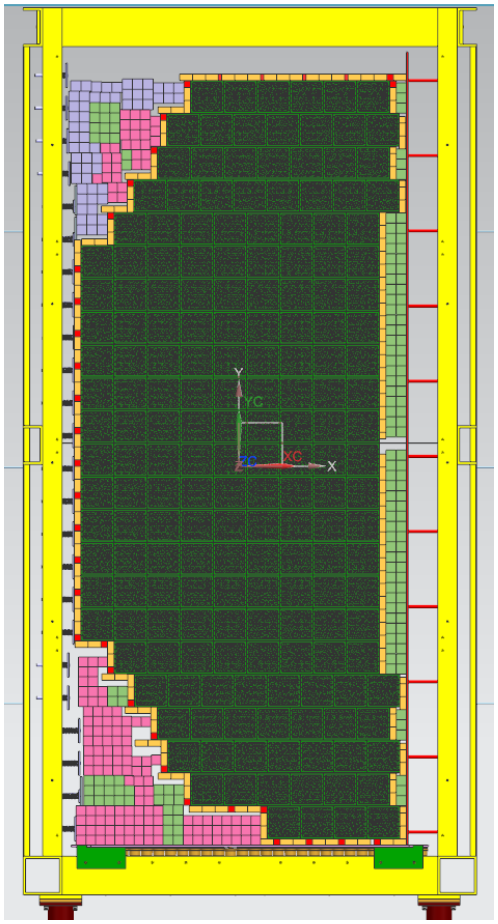
SBS trackers under test during GEn run



Electron arm: calorimeter CAD model

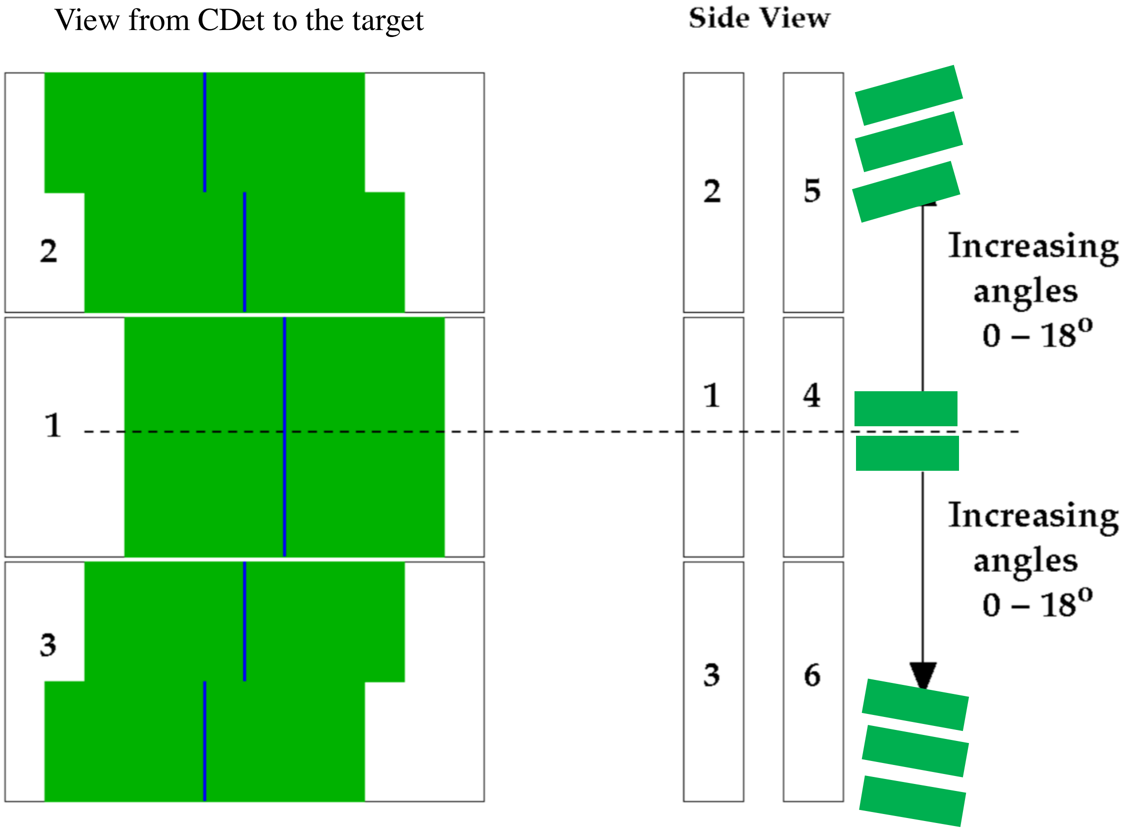






184 SMs (each is a 3x3 group of lead-glass modules),
Elevated temperature of the glass (225-185 C)
provides continuous annealing of radiation damage
(confirmed with actual beam test of the 4x4 prototype)

Electron arm: Coordinate detector

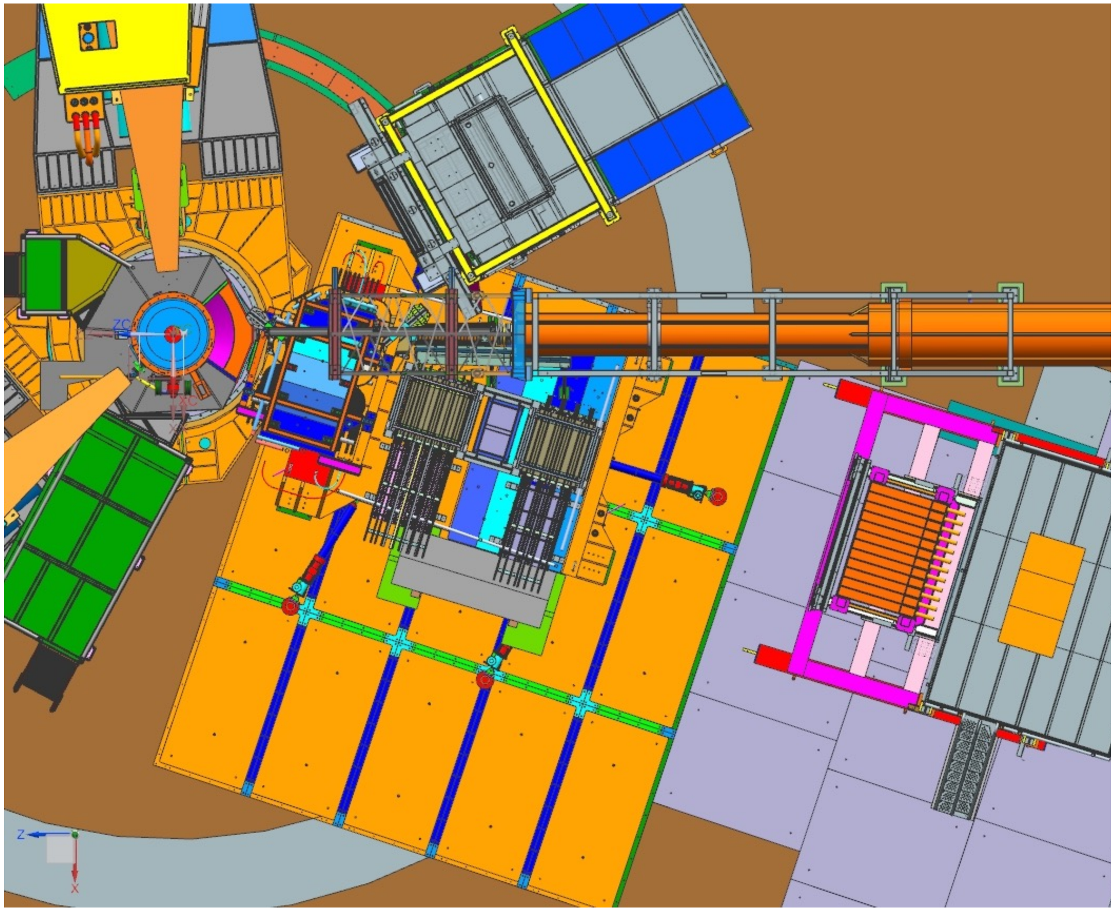


Two layers: 6 modules (each has 16 x 14 x 2 counters)

Experiment: Layout and Parameters

$$H(\vec{e},e'\vec{p})$$

High Q^2 kinematics

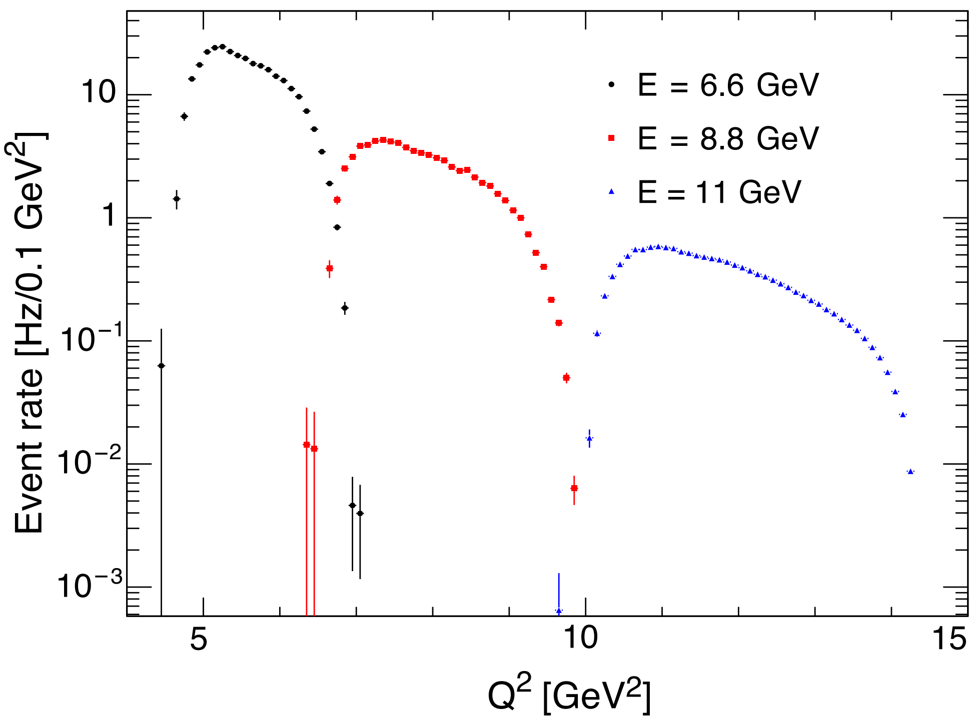


Beam: 75 μA, 85% polarization
Target: 30 cm liquid H_2
Electron arm at 30^o, covers
Q^2 range from 11-13 GeV^2
Proton arm at angle 17^o, $\Omega \sim$
0.3 of electron one, => 35 msr,
Spin precession angle is ~ 80^o

Total 45 PAC days of production time resulting accuracy close to

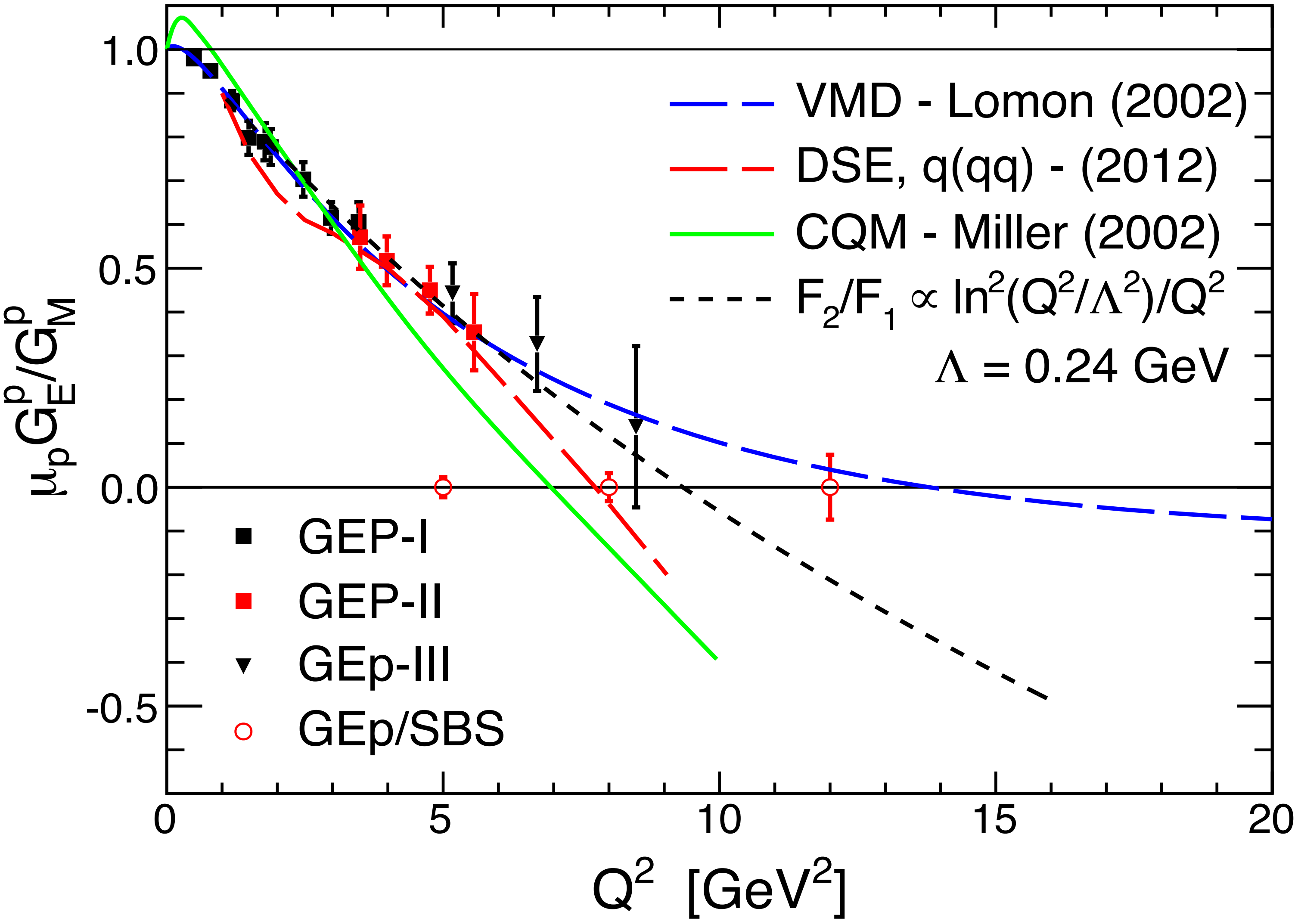
$$\Delta(\mu G_E^p/G_M^p) = \pm 0.10$$

GEp/SBS Q^2 acceptance and projected accuracy



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	$\langle\sin\chi\rangle$	Event rate Hz	Days	$\Delta\,(\mu G_E/G_M)$
6.6	4.5-7.0	5.5	29.0	3.66	25.7	3.77	0.72	291	2	0.029
8.8	6.5-10.0	7.8	26.7	4.64	22.1	5.01	0.84	72	11	0.038
11.0	10.0-14.5	11.7	29.0	4.79	16.9	7.08	0.99	13	32	0.081

The proton GEp form factor



B. Wojtsekhowski

ERR held in April

Updated Hall A schedule

Date	Activity
March 20th – May 29th 2023	SAD work in the Hall A
May 29th – July 21 2023	Hall A Crane repair
July 21- Aug 10 2023	Hall A prepare for beam
Aug 10 – Oct 2 2023	Run 3He GEn and A_LL
Oct 3 2023 – Jan 30 2024	Deinstall polarized 3He target, modify beam line and install cryotarget
Jan 31 – Feb 26 2024	Run GEn-RP and K_LL
Feb 27 2024	Start Deinstall GEn-RP and installing GEp
~~Aug 26 2024~~ ~ Oct 2024	Start running GEp

The experiment will be schedule to run at a maximum of 50uA beam current since it will run with experiments in Hall C that need high current. The floor time will be increased to compensate for dropping the current from 70uA in the proposal.

Summary

After years of development the GEP experiment is on track to be ready for installation in spring 2024

Prof. Charles Perdrisat, 2017 Tom W. Bonner Prize in Nuclear Physics Recipient

Former post-docs

- Mark Jones (W&M): now Hall A/C leader
- Lubomir Pentchev (W&M): Now staff scientist Hall D

Former Students

- Olivier Gayou (W&M): Senior Director, Physics Commissioning Varian Medical Systems
- Krishni Wijesooriya (W&M): Professor of Radiation Oncology physics, University of Virginia
- Sonja Dieterich (Rutgers): Professor of Radiation Oncology, University of California, Davis.
- Andrew Puckett (UVa and MIT): Associate Professor of Physics, University of Connecticut