SBS program and instrumentation

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01/31/2020

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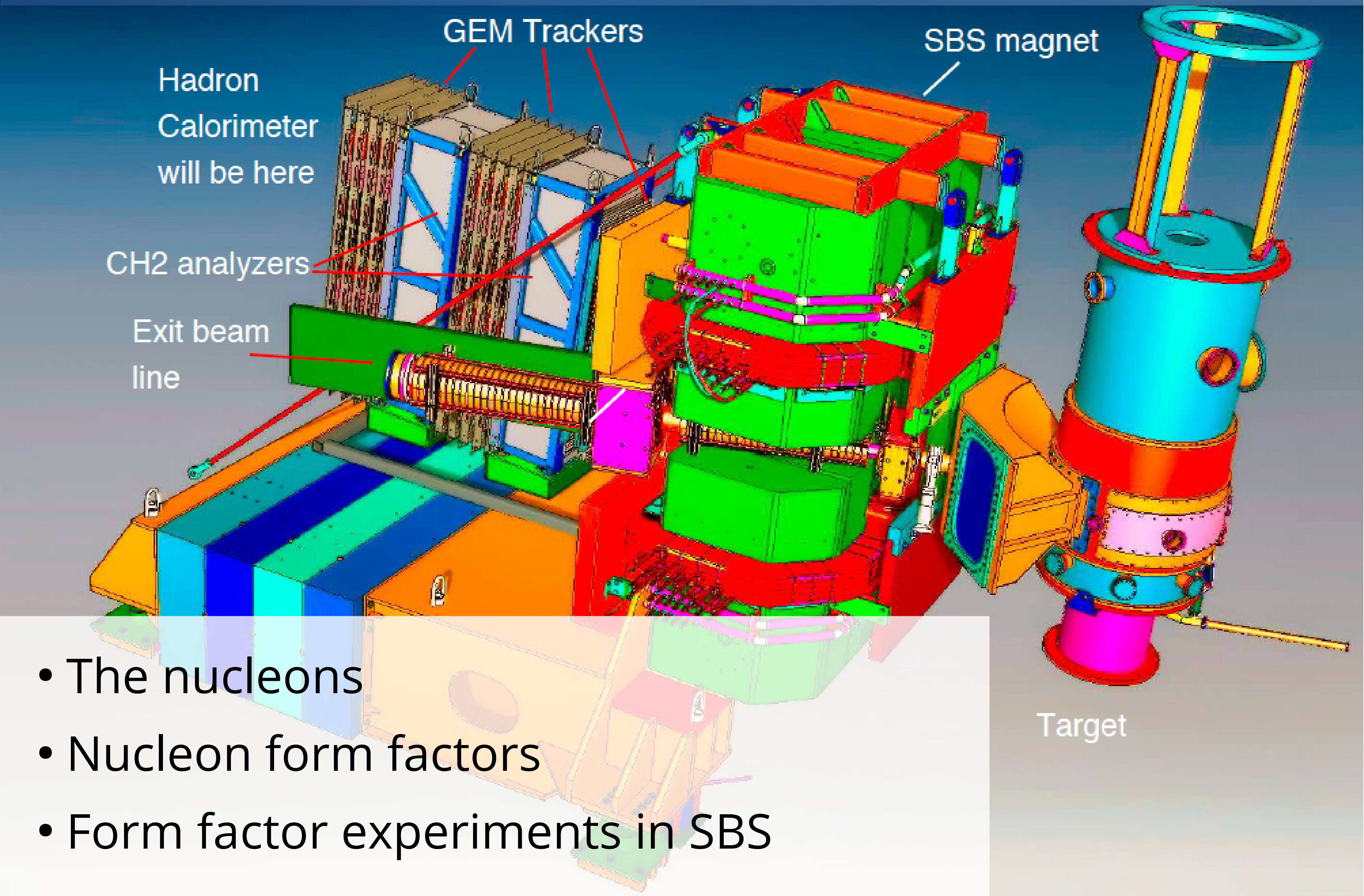
Jefferson Lab
Thomas Jefferson National Accelerator Facility

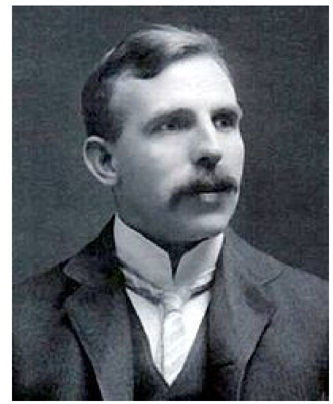
Outline



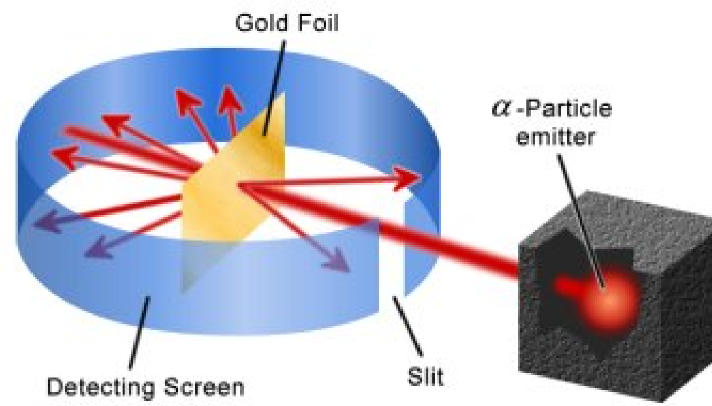
- The nucleons
- Nucleon form factors
- Form factor experiments in SBS

Proton is the most studied sub-atomic particle.

- Discovered by Rutherford in 1911 in the “gold foil” experiment.

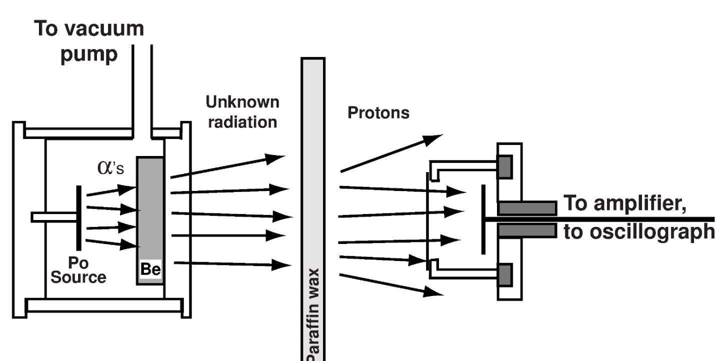


Ernest Rutherford



Neutron is the electric neutral counterpart of the proton.

- It was discovered by Chadwick in 1932.



James Chadwick

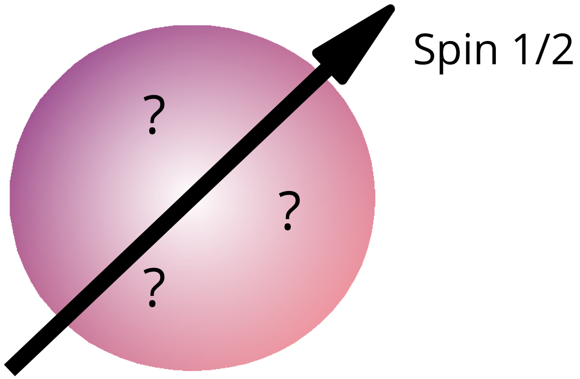
Story of the Nucleons

- In 1933, Stern measured the anomalous magnetic moment of the proton, which indicated that proton is NOT an elementary point like particle.

Otto Stern

$$\mu_p = 2.79\ \mu_N \neq 1\ \mu_N$$

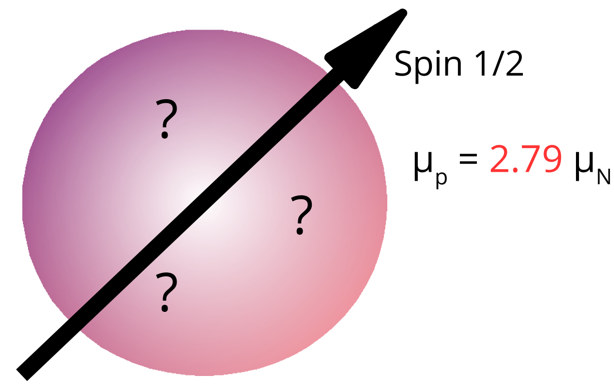
$$\mu_n = -1.91\ \mu_N \neq 0$$



Nucleon has substructure?

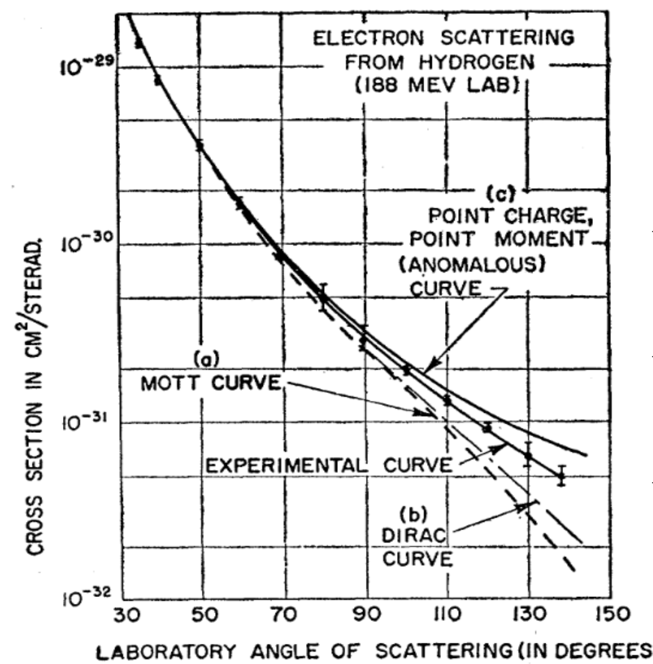
Story of the Nucleons

- In 1956, Hofstadter confirmed with electron elastic scattering experiment that the proton has substructure



Proton has substructure?

R. Hofstadter



(a) Mott curve
- Point like, no spin

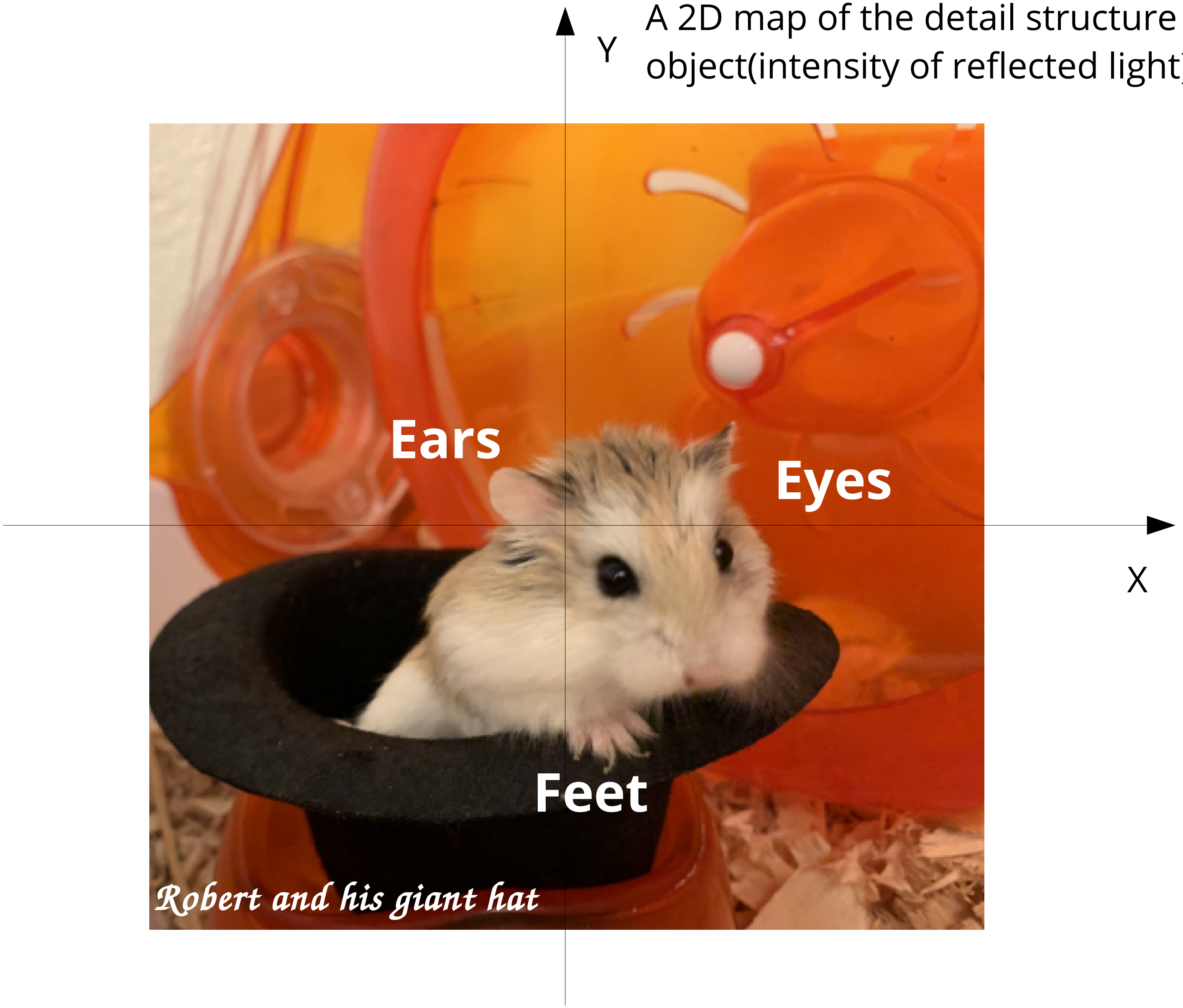
(b) Dirac curve
- Point like, ½ spin

(c) Anomalous curve
- Point like, with anomalous magnetic moment

Electron scattering cross section from the proton at an incident energy of 188 MeV. R. Hofstadter, 1956

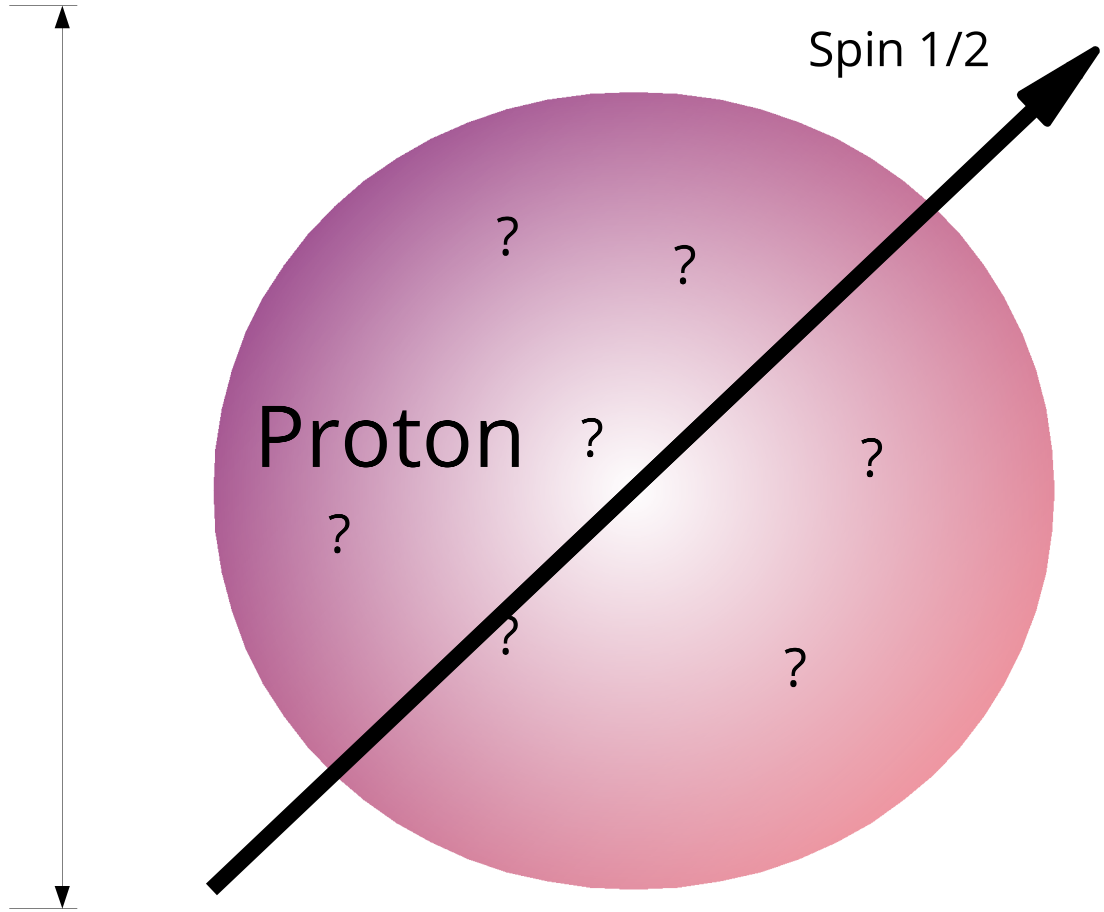
Photograph!

A 2D map of the detail structure of an object(intensity of reflected light)



Photograph proton?

10^{-15} m



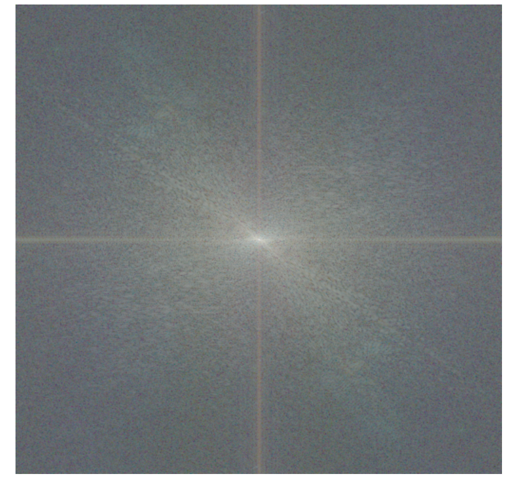
Charge distribution?

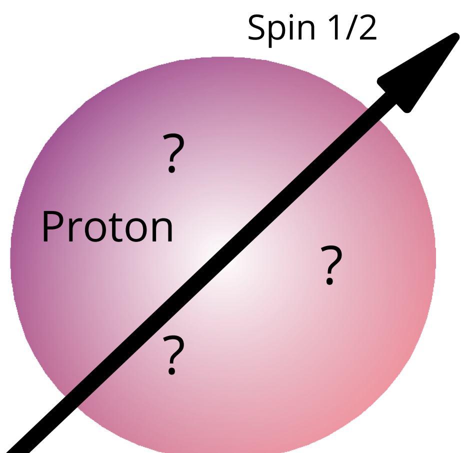
Imaging the Nucleons

Coordinate space

Momentum space

Fourier transform

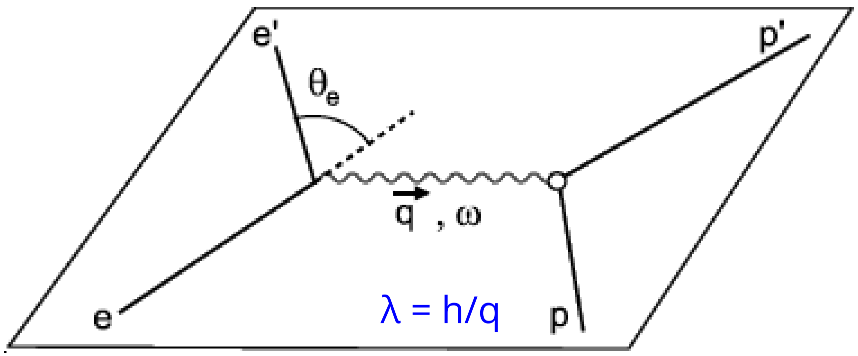


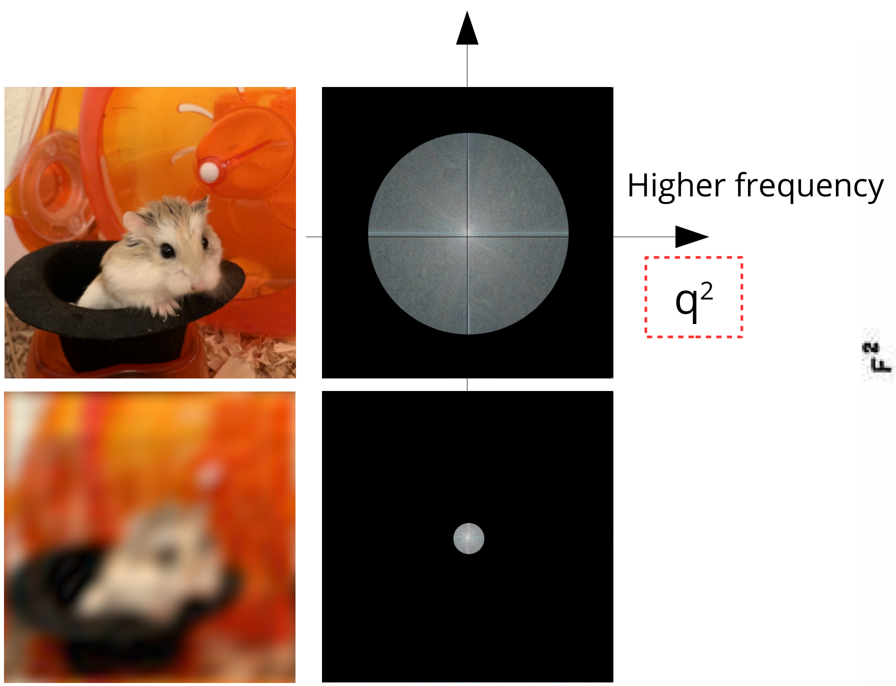


Imaging the Nucleons—Scattering experiment

"Camera" for nucleon

Electron elastic scattering





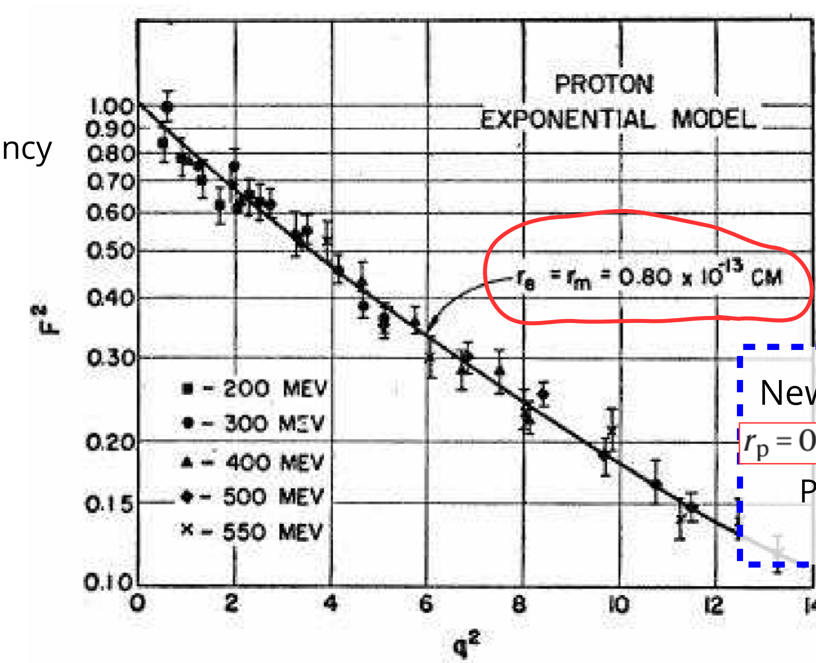
$\rho(\vec{r})$ $\quad$ $F(q)$

Fourier transform of the **charge density** in coordinate space to **form factor** in momentum space

$$F(q) = \int_{volume} \rho(\vec{r}) e^{i\vec{q}\cdot\vec{r}} d^3 r$$

Elastic cross section(classic)

$$\sigma(\theta_e) = \sigma_{Mott} |F(q)|^2$$



Hofstadter

0.8 fm

New result on Nature!

$r_p = 0.831 \pm 0.007_{stat} \pm 0.012_{syst}$

PRad collaboration

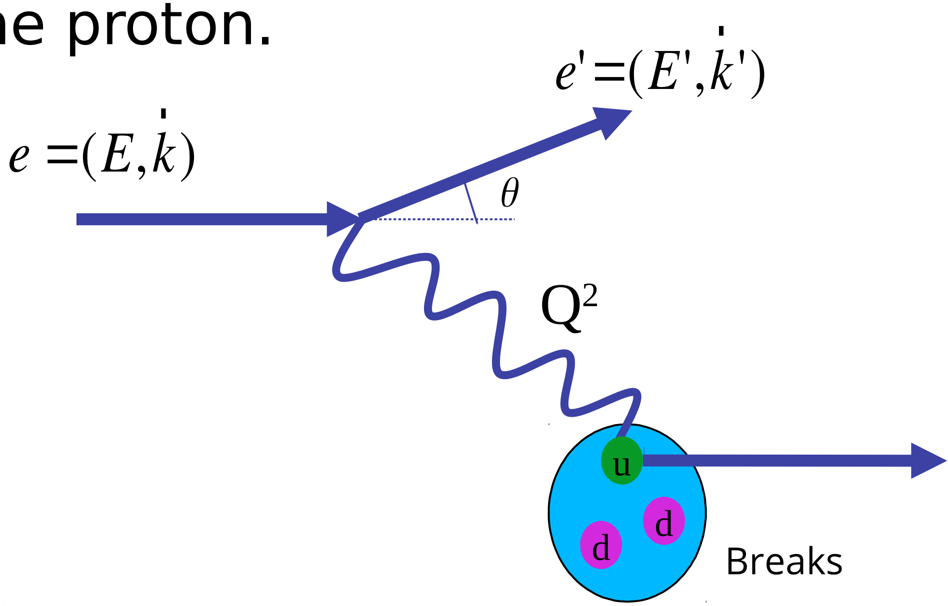
Xinzhan

Hofstadter measured the radius of the proton in 1958

Probing the Nucleons – Going Higher Q^2

MIT-SLAC experiments 1967: Deep Inelastic electron Scattering off protons to confirm the quarks inside the proton.

Kendall, Friedman and Taylor et al.



Form factor independent of Q^2! Point like particle!

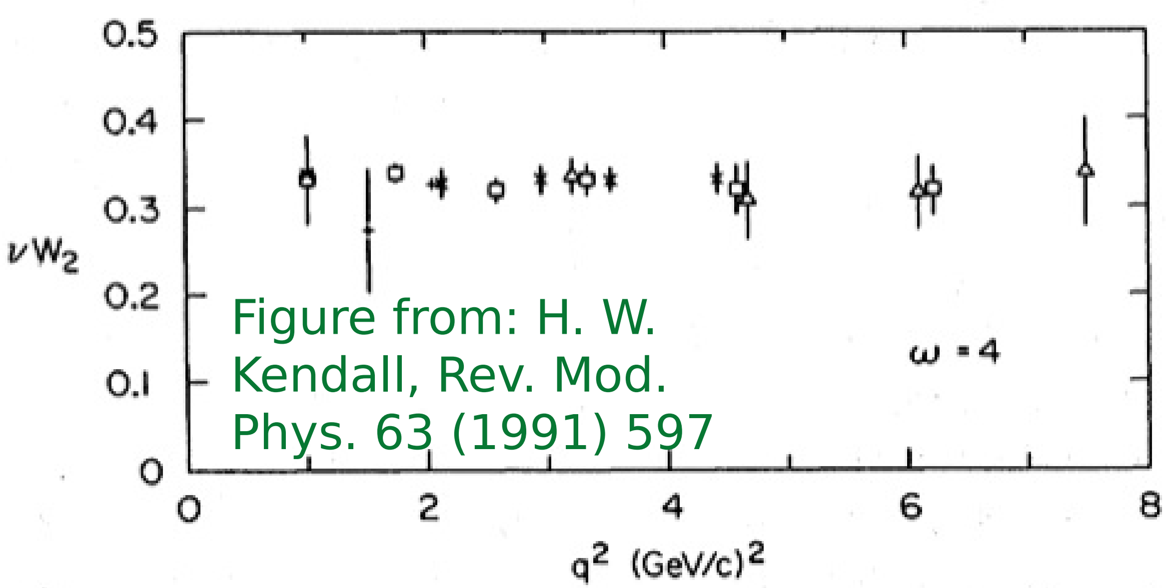


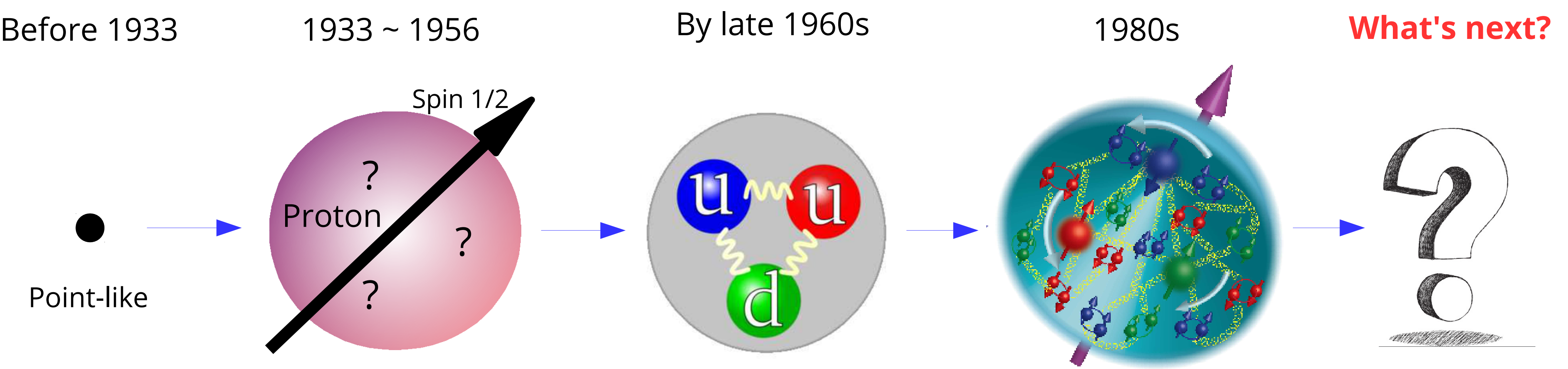
Figure from: H. W. Kendall, Rev. Mod. Phys. 63 (1991) 597

Death star destruction(Star Wars)

Probing the Nucleons

1970's: Quantum Chromo Dynamics (QCD): theoretical framework for strong interaction between quarks medicated by gluons.

1980's – Today: Looking deep inside the nucleon

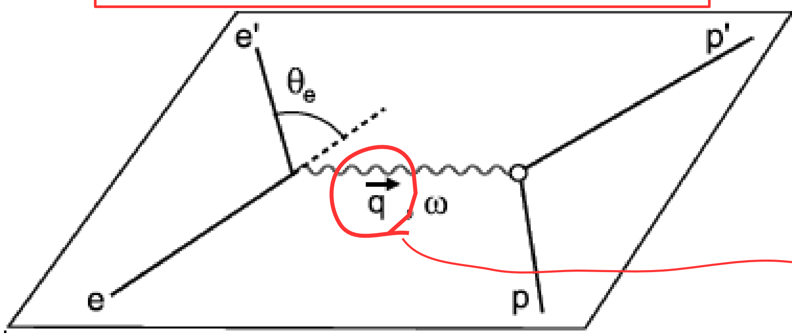


Many deep questions to answer

- How does nucleons acquire its mass: only ~1% from valence quarks
- What are the different contributions to nucleon spin?
- How does the confinement come about?
- What role does the gluon play in all these?

Seeking finer detail of the nucleon

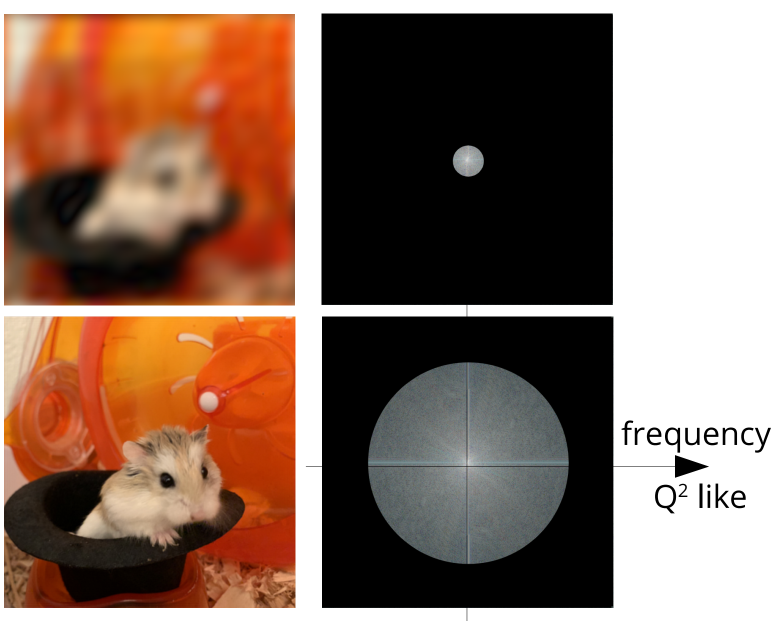
Electron elastic scattering



Our "**camera**" for "photographing" ground state nucleon structure

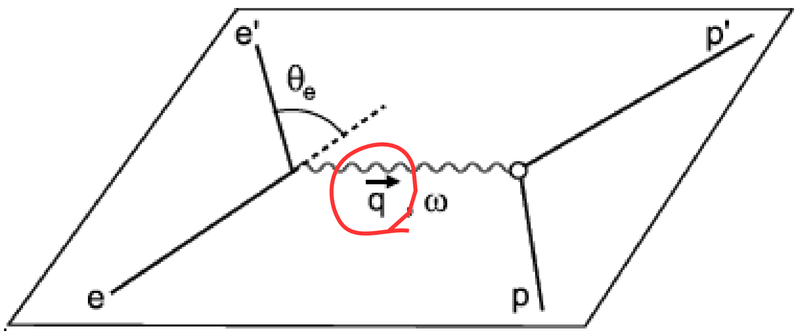
"**Resolution**" of the "camera"

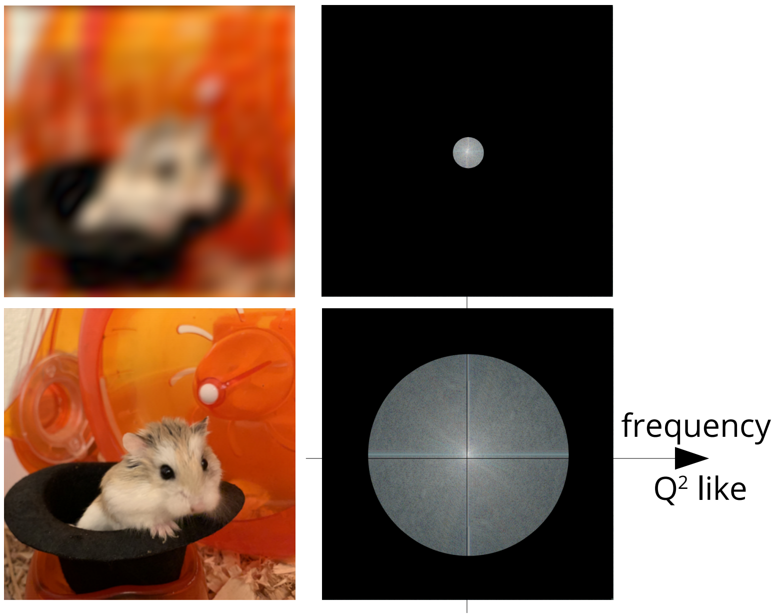
- Increase Q^2, to see details of the nucleon structure.
- Keep our nucleon "safe" to see its ground state.



Finer picture of the nucleon at Jefferson Lab!

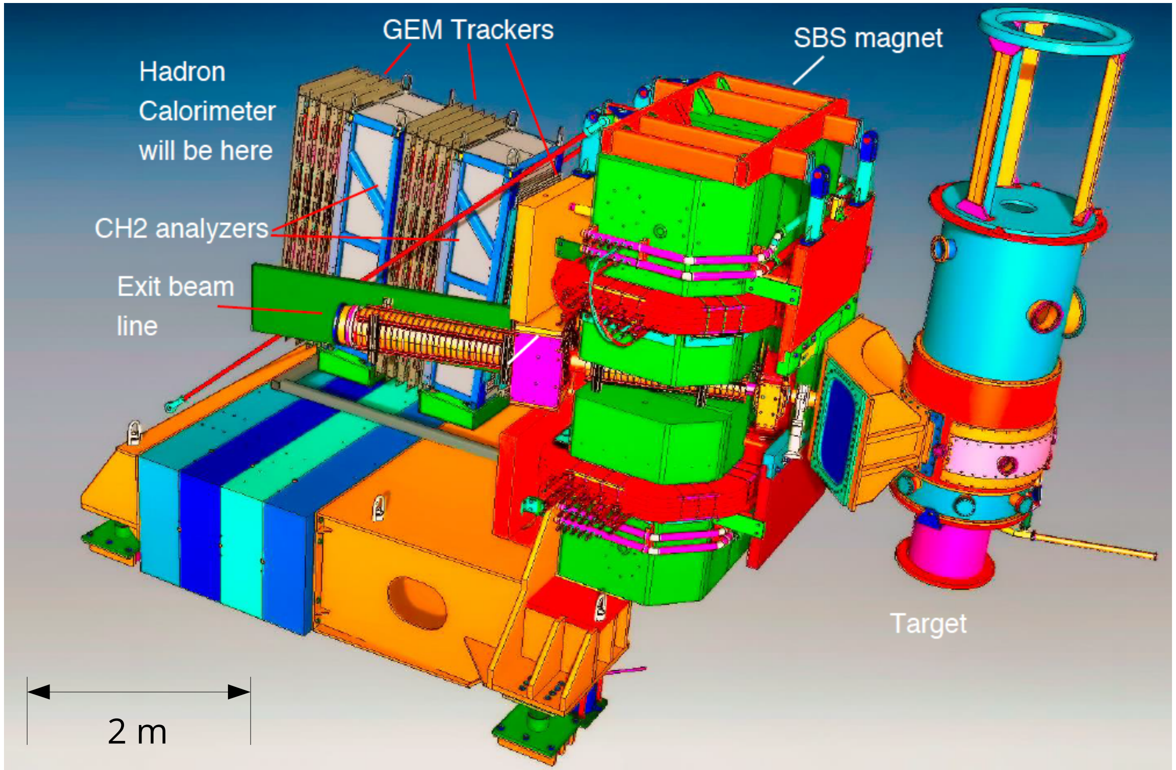
Electron elastic scattering





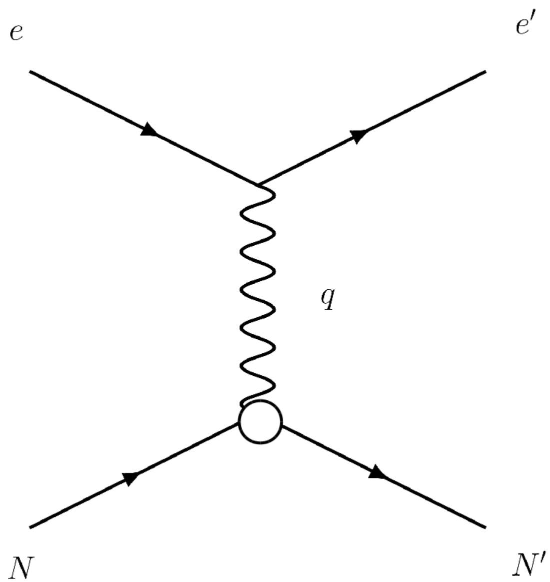
A New “gentle high-resolution camera” !

Super BigBite Spectrometer(SBS) at JLab



Allow <u>ground state</u> nucleon form factor measurements at high Q^2 !!!

Elastic electron scattering off nucleon



Leading order Feynman diagram of elastic scattering

$$\sigma(\theta_e) = \sigma_{Mott}|F(q)|^2$$ (at low Q², classic)

$$\left(\frac{d\sigma}{d\Omega}\right)_N = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{1}{1+\tau}\left(G_E^2 + \frac{\tau}{\epsilon}G_M^2\right)$$ (QED)

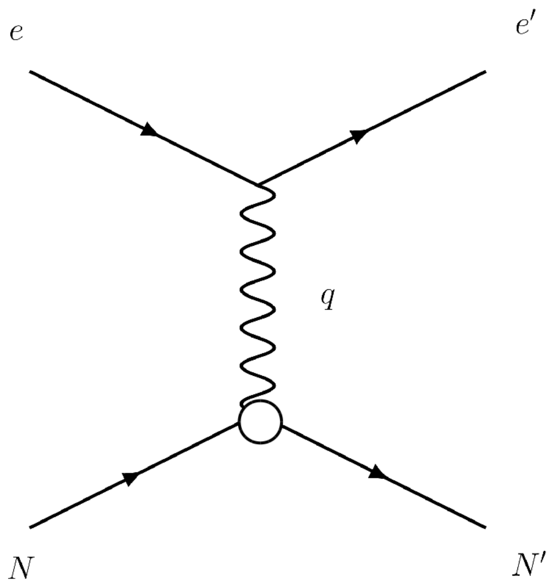
$$\tau = \frac{Q^2}{4m^2}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{\alpha^2 cos^2\frac{\theta}{2}}{4E_e^2 sin^4\frac{\theta}{2}}$$

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

- G_E and G_M are functions of Q^2 and respectively the electric and magnetic form factors(Sachs form factor). They parameterize the detailed structure of the nucleon.
- In Breit frame where there is no energy transfer, the G_E and G_M can be interpreted as the Fourier transforms of electric and magnetic distributions.
- In the limit of $Q^2 \rightarrow 0$, G_E approaches 1(0) for proton(neutron) and G_M approaches anomalous magnetic moment. The cross section reduces to classic form.

Elastic electron scattering off nucleon



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How are G_E and G_M measured in SBS program?

	Proton	Neutron
Electric	SBS	SBS
Magnetic	GMp	SBS

Rosenbluth Separation

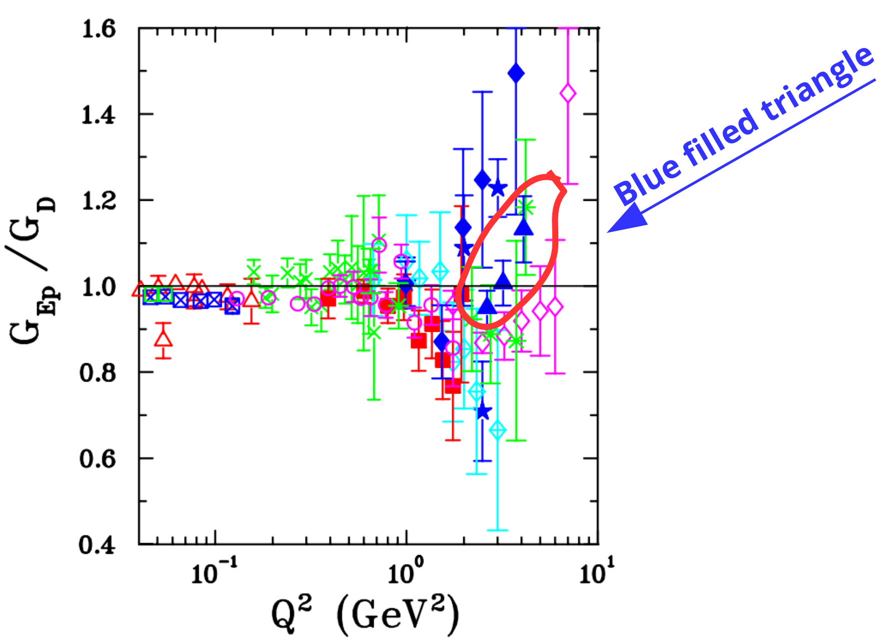
- The technique measures the σ_{red} at different beam energy and scattering angle to vary ε while holding Q^2 constant.
- Suffers from large uncertainty in G_E at large Q^2 since $G_E^2/\tau << G_M^2$.

$$\sigma_{red} \equiv \frac{\epsilon(1+\tau)}{\tau} \cdot \left(\frac{d\sigma}{d\Omega}\right)_N / \left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{\epsilon}{\tau} G_E^2 + G_M^2$$

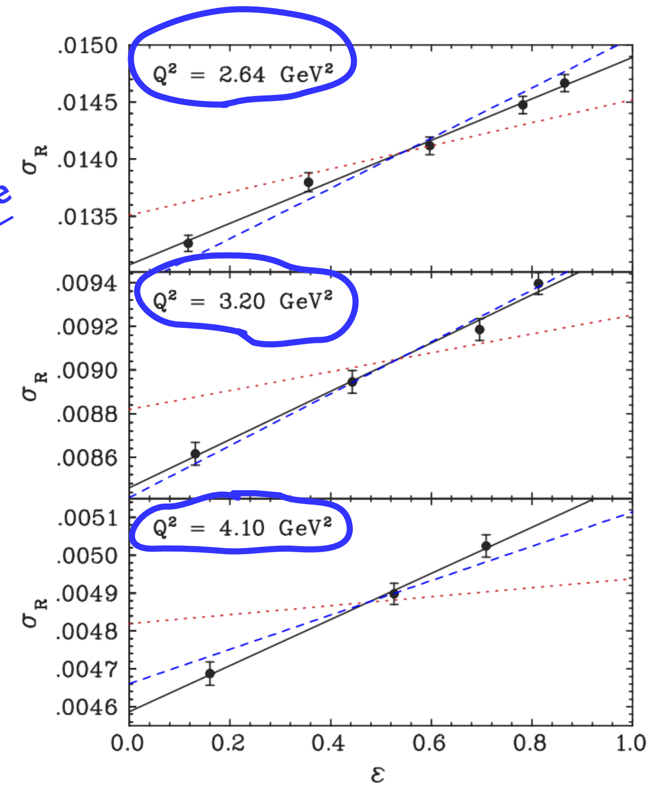
$$\tau = \frac{Q^2}{4m^2} \qquad \epsilon = \left[1 + 2(1+\tau)tan^2\frac{\theta}{2}\right]^{-1}$$

Slope

Intercept



Proton electric form factor data using Rosenbluth separation method

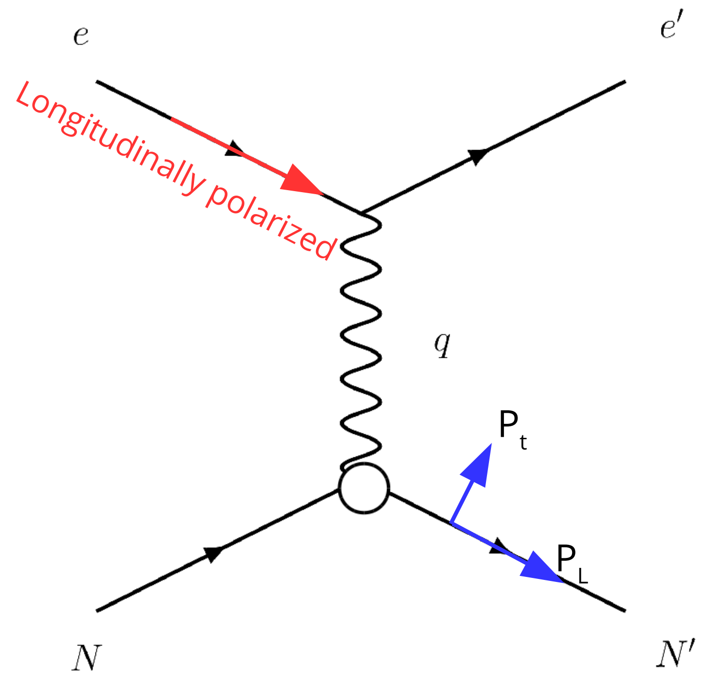


Qattan et al., Phys. Rev. Lett. 94, 142301 (2005)

- Black solid: fit to data
- Blue dashed: prediction from $\mu G_E/G_M$ = 1
- Red dashed line: prediction from result of polarization method

Polarization Transfer in Elastic eN scattering

- Use longitudinally polarized electron beam and unpolarized target.
- Much more sensitive to G_E at large Q^2 than "reduce" cross section Rosenbluth separation method because the ratio of transferred polarization components is directly proportional to G_E/G_M.
- Showed clear decrease of the ratio of G_E/G_M, contradicting to previous belief of $\mu G_E/G_M = 1$.



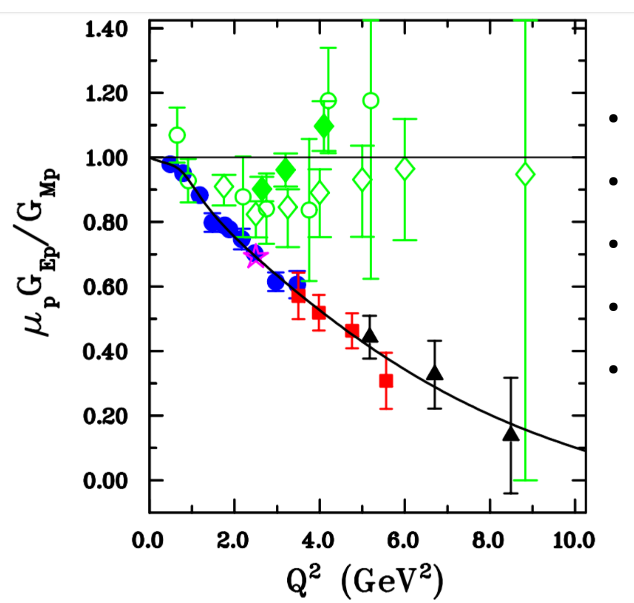
$$I_0 P_l = h\sqrt{\tau(1+\tau)}tan^2\frac{\theta_e}{2}\frac{E_e+E'_e}{M}G_M^2$$

$$I_0 P_t = -2h\sqrt{\tau(1+\tau)}tan\frac{\theta_e}{2}G_E G_M$$

$$I_0 P_n = 0$$

$$I_0 = G_E^2 + \frac{\tau}{\epsilon}G_M^2$$

$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{E_e+E'_e}{2m_p}tan\frac{\theta_e}{2}$$



- Blue circle: GEp-I
- Red square: GEp-II
- Black triangle: GEp-III
- Magenta star: GEp-2γ
- Green: experiments using Rosenbluth separation method

Proton electric form factor data from JLab experiments using polarization transfer method

Polarized beam-target asymmetry

- Use longitudinally polarized electron beam and polarized target.
- The target polarization is best to be set perpendicular with respect to the momentum transfer vector of the virtual photon and within the scatter plane($\theta^* = 90^\circ$, $\psi^* = 0^\circ$ or 180°).
- For quasi-elastic electron scattering, nuclear effects corrections are necessary.

Cross section: $\sigma_h = \Sigma + h\Delta$

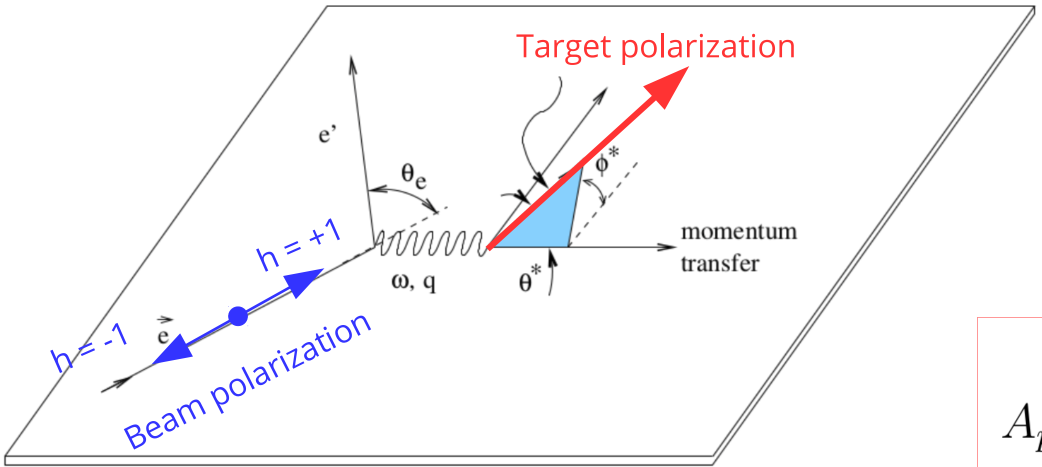
Asymmetry: $A_{phys} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{\Delta}{\Sigma}$

$$\Delta = -2\frac{d\sigma}{d\Omega}\Big|_{Mott}\frac{E_f}{E_i}\sqrt{\frac{\tau}{1+\tau}}tan\frac{\theta}{2}$$
$$\left[\sqrt{\tau(1+(1+\tau)tan^2(\frac{\theta}{2}))}cos\theta^* G_M^2 + sin\theta^* cos\phi^* G_M G_E\right]$$

$$A_{phys} = A_\perp sin\theta^* cos\phi^* + A_\parallel cos\theta^*$$

$$A_\perp = -\frac{2\sqrt{\tau(\tau+1)}tan\frac{\theta}{2}\frac{G_E^n}{G_M^n}}{\frac{G_E^n}{G_M^n}^2 + (\tau + 2\tau(1+\tau)tan^2\frac{\theta}{2})}$$

$$A_\parallel = -\frac{2\tau\sqrt{1+\tau+(1+\tau)^2 tan^2\frac{\theta}{2}}tan\frac{\theta}{2}}{\frac{G_E^n}{G_M^n}^2 + (\tau + 2\tau(1+\tau)tan^2\frac{\theta}{2})}$$



$$A_{phys} = -\frac{2\sqrt{\tau(\tau+1)}tan\frac{\theta}{2}\frac{G_E^n}{G_M^n}}{\frac{G_E^n}{G_M^n}^2 + (\tau + 2\tau(1+\tau)tan^2\frac{\theta}{2})}$$

The SBS form factor experiments

–--Our new “gentle high resolution camera”

GMn → GEn-RP → GEn-II → GEp-V

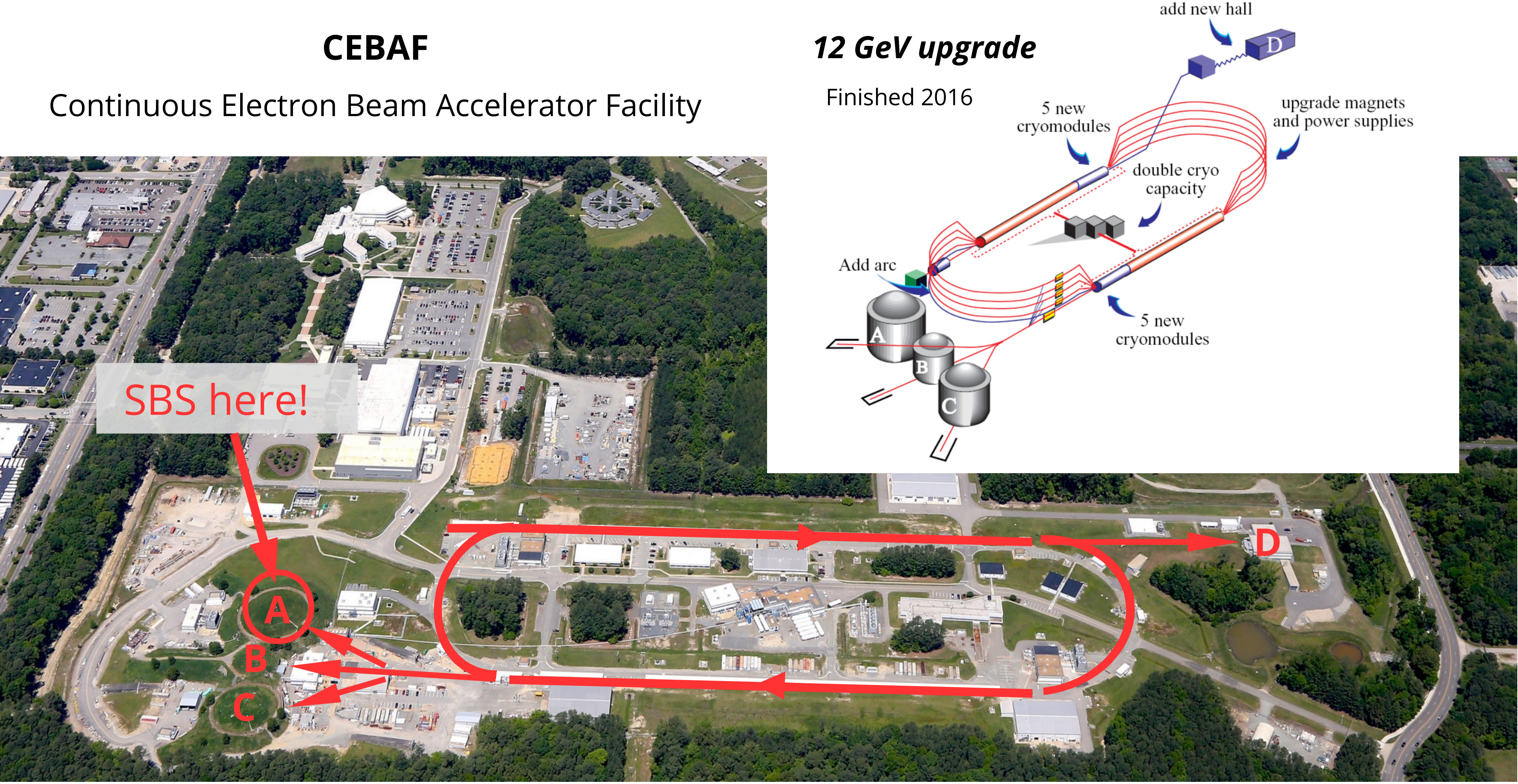
CEBAF at Jefferson Lab

CEBAF

Continuous Electron Beam Accelerator Facility

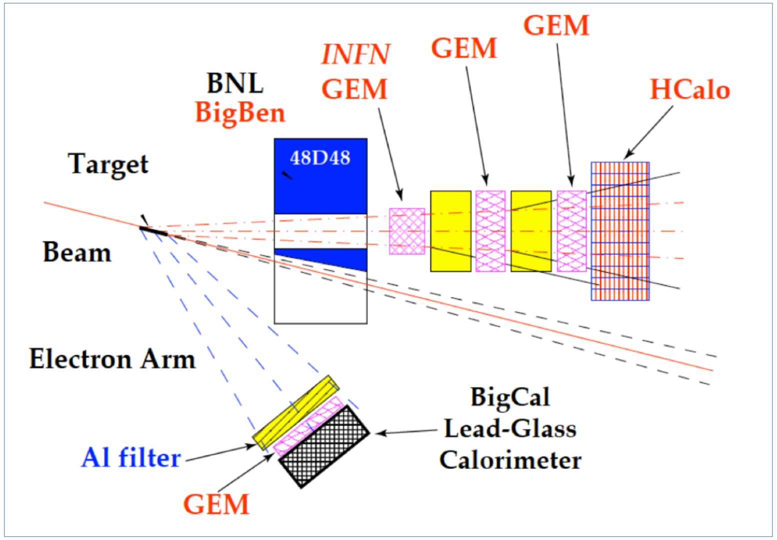
12 GeV upgrade

Finished 2016

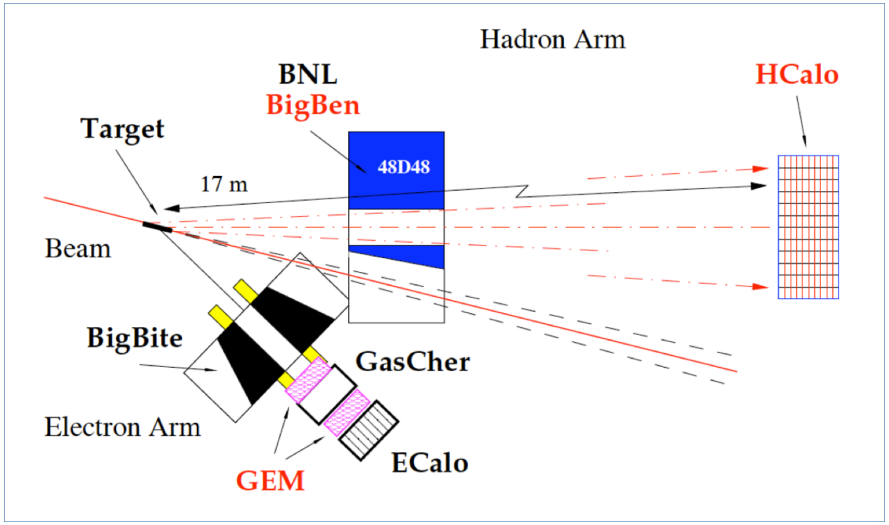


Super BigBite spectrometer in Hall A at JLab

- **SBS**: A 2.5 T*m dipole magnet and set of modular configurable detectors.
- ***Aim to reach high Q^2***
  - Designed to operate at ***high luminosity***(up to 10^{39} Hz*cm^{-2}) with moderate solid angle at forward angles
  - Elastic ep cross section scales as $\sigma \approx E^2 / Q^{12}$
  - Analyzing power of polarimeter scales as $1/Q^2$
  - The figure-of-merit(FOM) scales as: E^2 / Q^{16}
  - 12 Gev beam upgrade at CEBAF increases luminosity by factor of 2.
  - The way to go: ***Increase solid angle.*** Doubling target thickness and solid angle from 6 to 35 msr leads to ~30X gain in figure-of-merit.
  - Large gap SBS dipole magnet placed ***at forward angle*** close to target to achieve large acceptance. Detectors have a clear line-of-sight view of the target and a portion of the beam-line. Large background rate.



Proton form factor experiment configuration: Gep-V

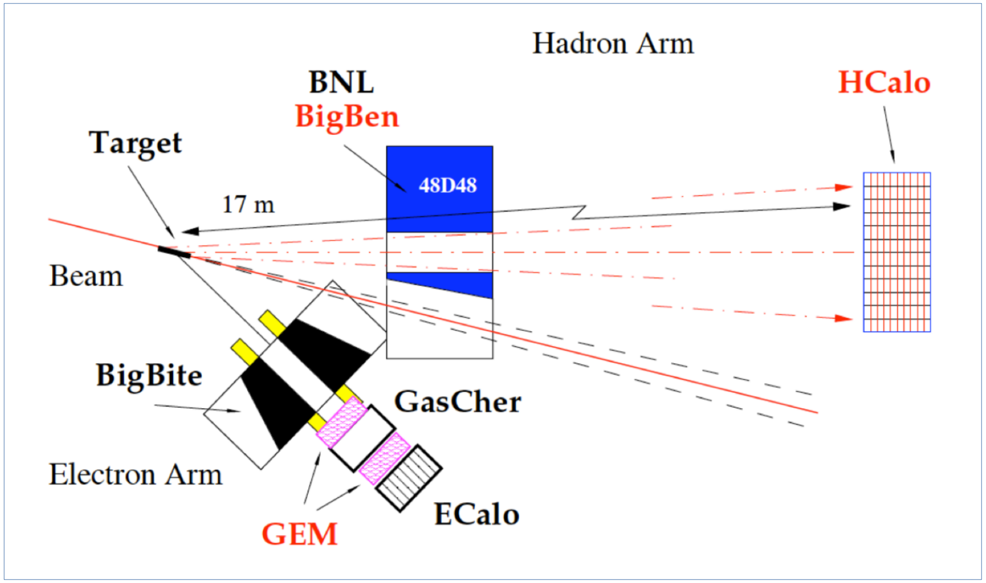


Neutron form factor experiments configuration: GMn, GEn-II, and GEn-RP.

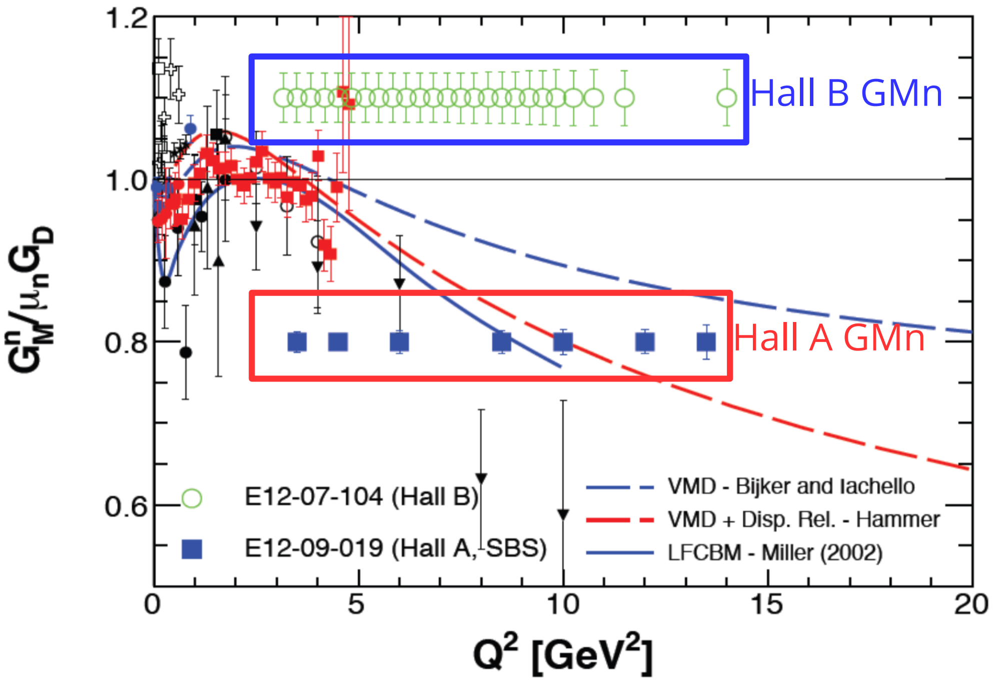
GMn experiment: neutron magnetic form factor at high Q^2

"Neutron picture" – magnetic

- The first experiment in SBS experiments(2020).
- 10-cm liquid deuterium/hydrogen target (luminosity~2×10^{38} Hz*cm^{-2}).
- The scattered electron track is measured by the upgraded BigBite spectrometer.
- Nucleon momentum is measured using time-of-flight method to separate quasi-elastic/inelastic channels.

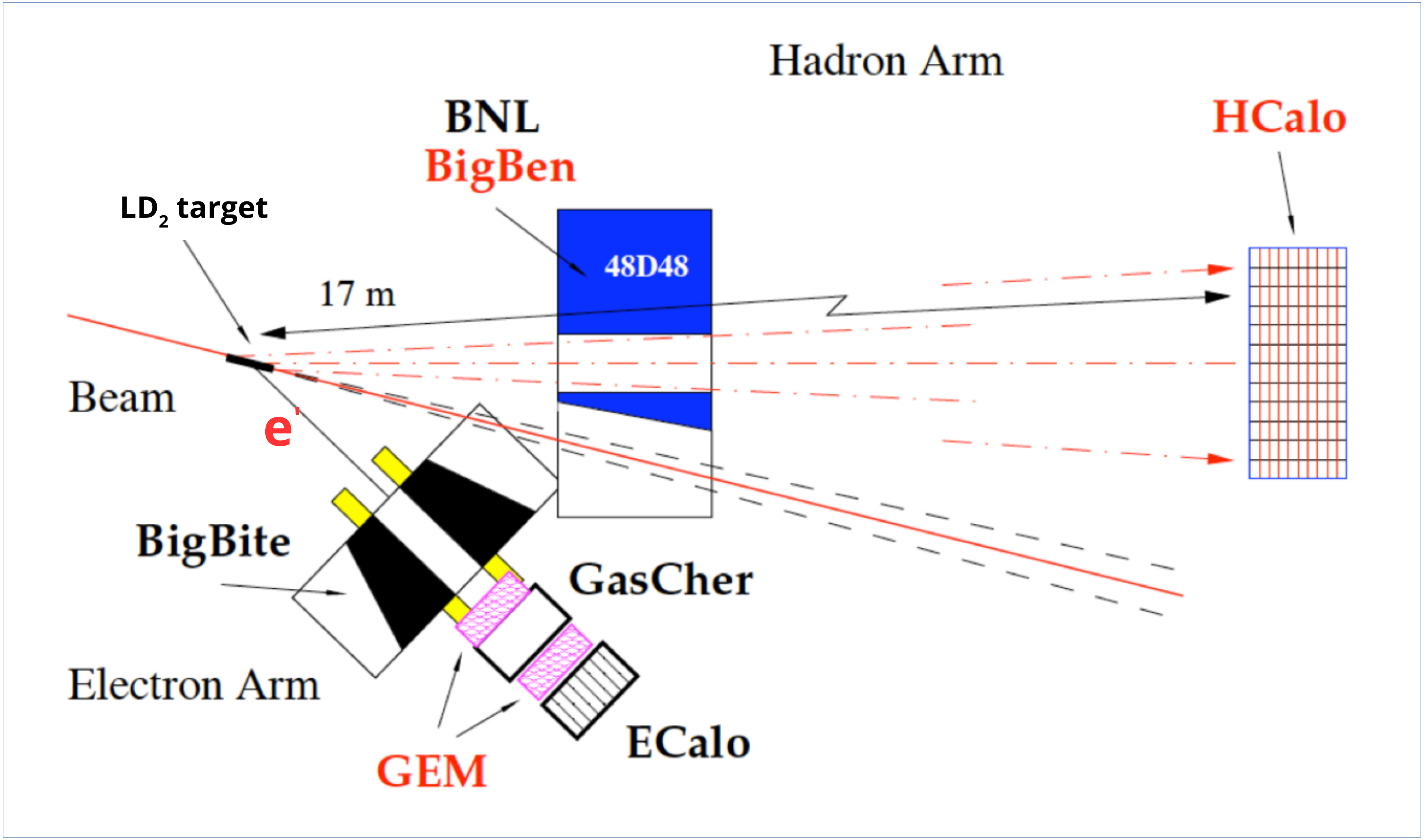


GMn projected result

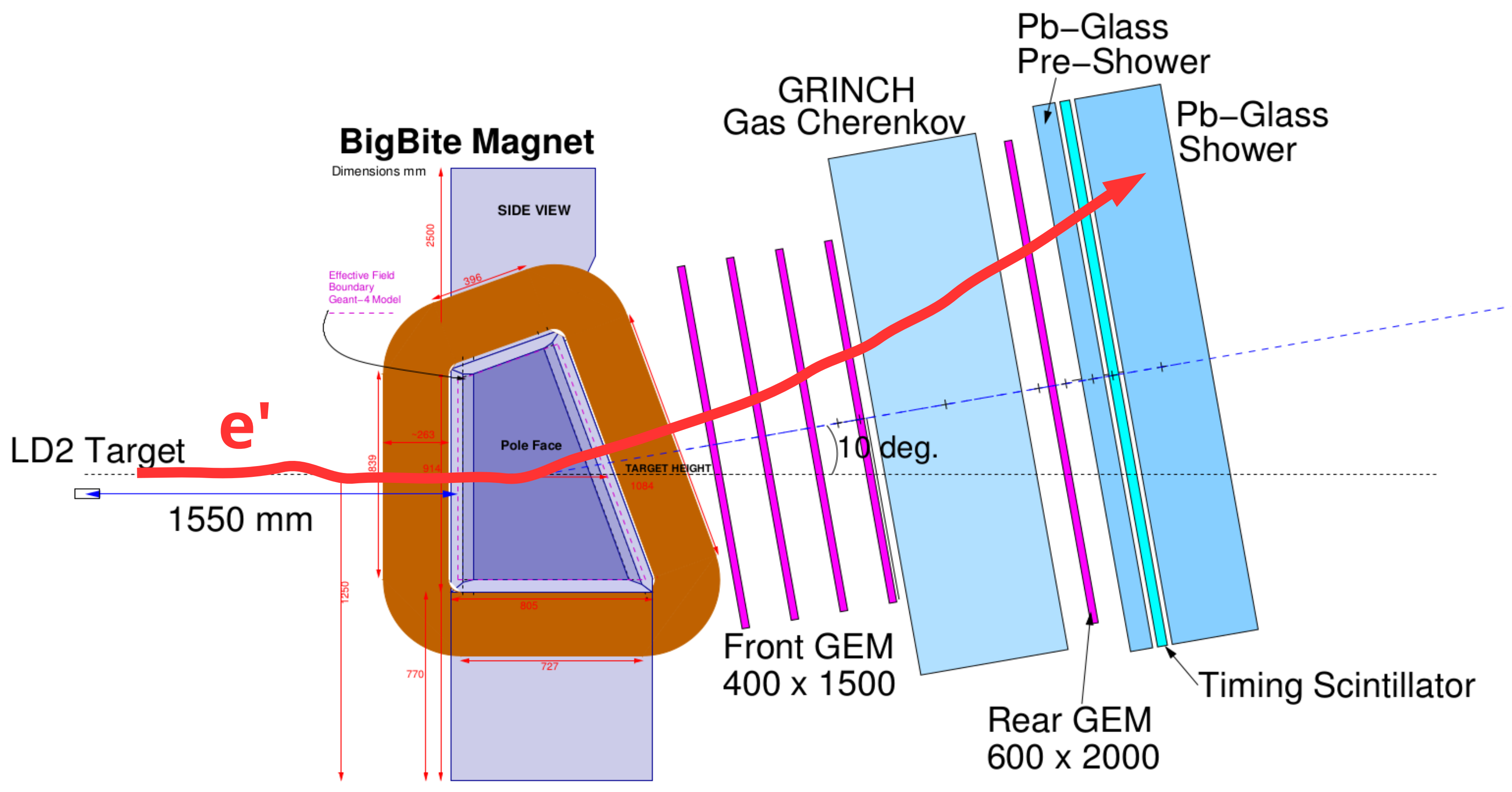


- GMn measures the ratio of the quasi-elastic d(e,e'n)p cross section over the quasi-elastic d(e,e'p)n cross section. Precise elastic ep cross section is needed to extract the neutron magnetic form factor.
- Provides GMn data to extract GEn.
- Discrete data points with generally smaller error bar compared to Hall B GMn experiment. Complementary to each other.

GMn: $\frac{\text{Neutron event}}{\text{Proton event}}$ → Cross section ratios → GMn

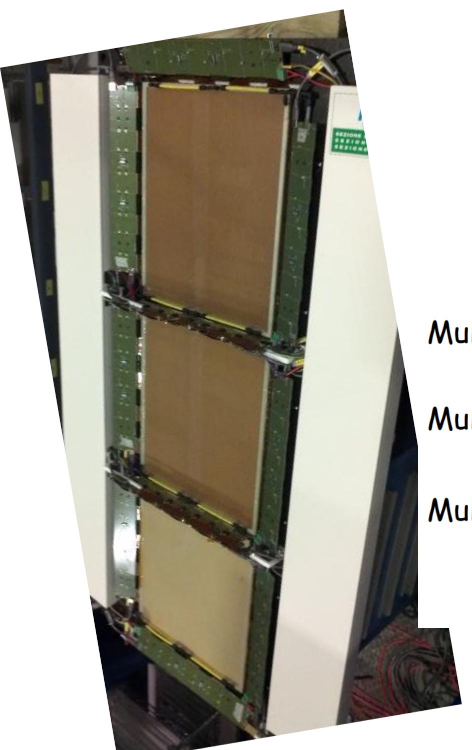


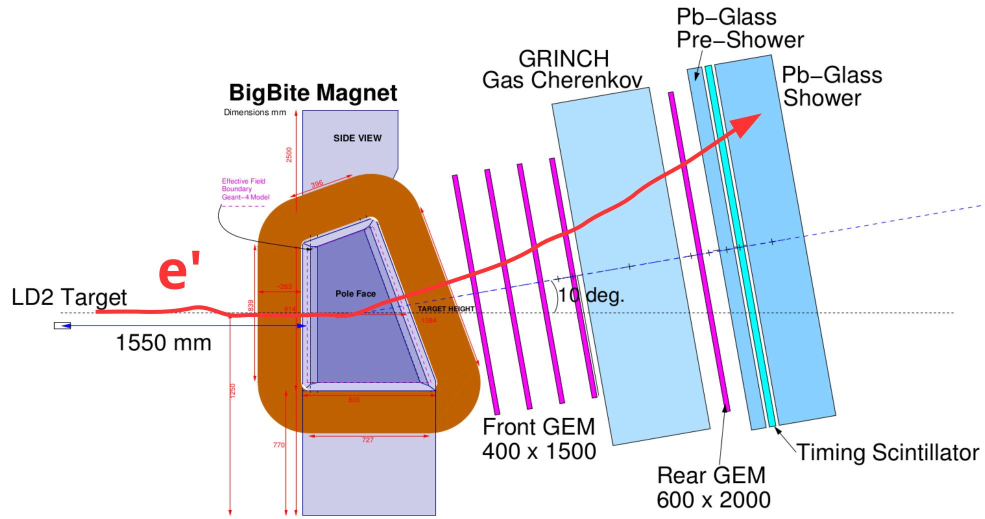
Upgraded **BigBite**: Identify and measure elastic electron



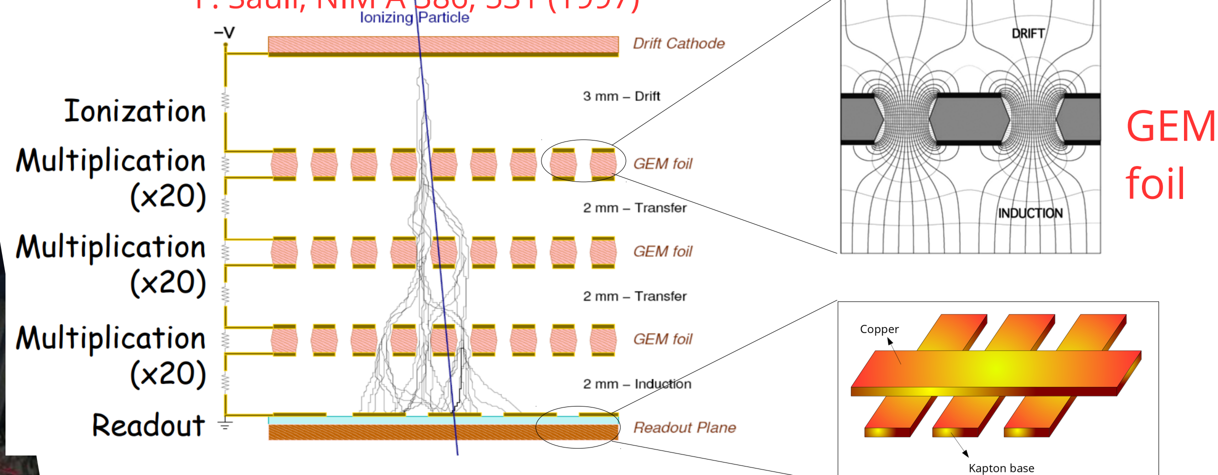
GEMs: tracking

INFN GEM

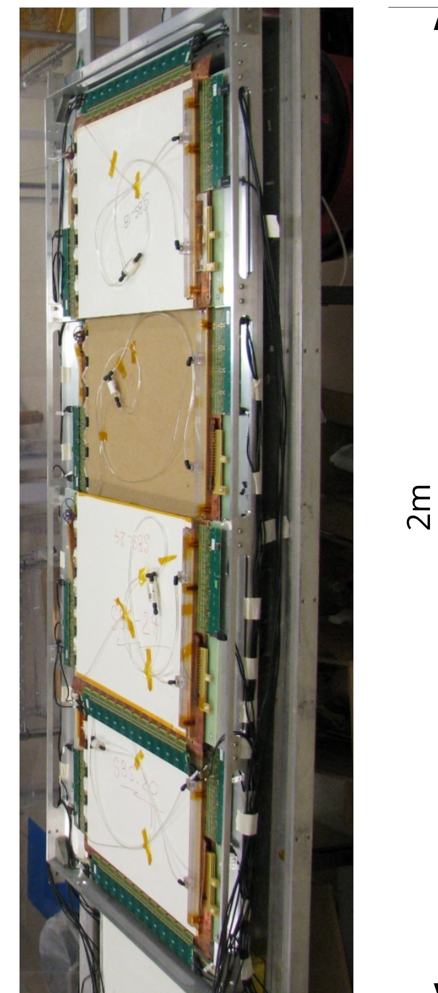




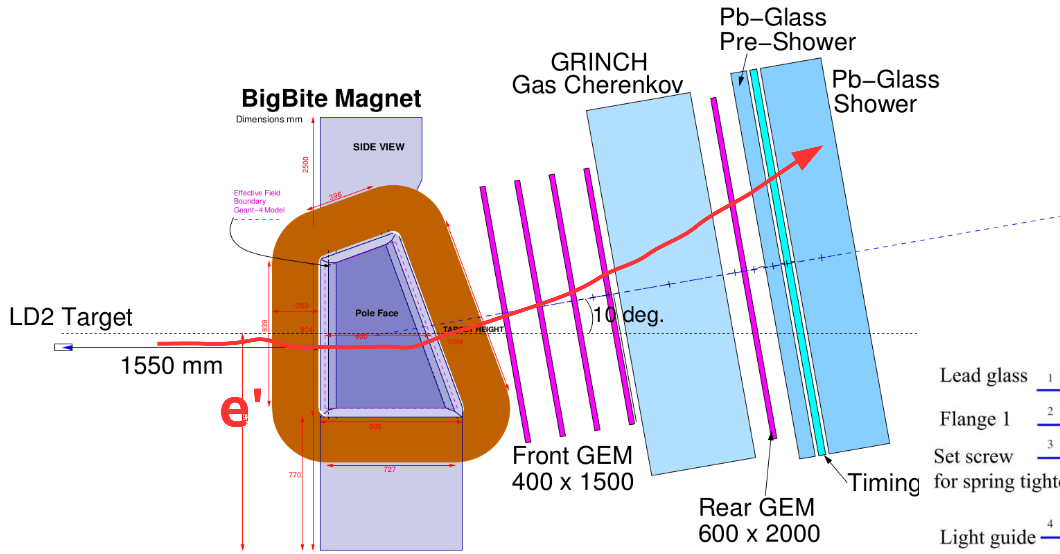
F. Sauli, NIM A 386, 531 (1997)

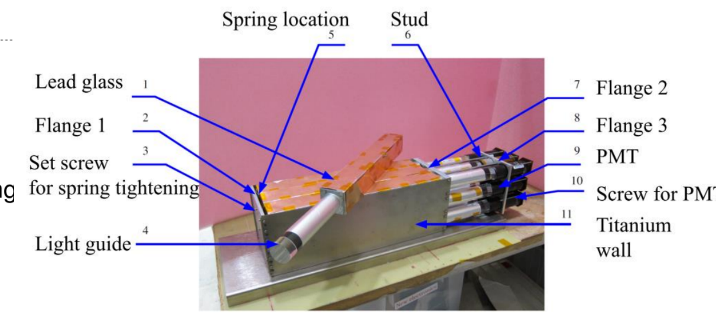


UVa GEM

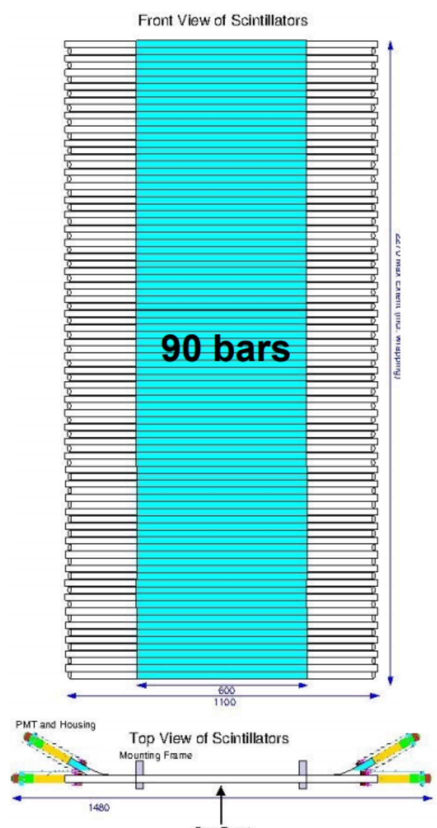


High rate, high relosution





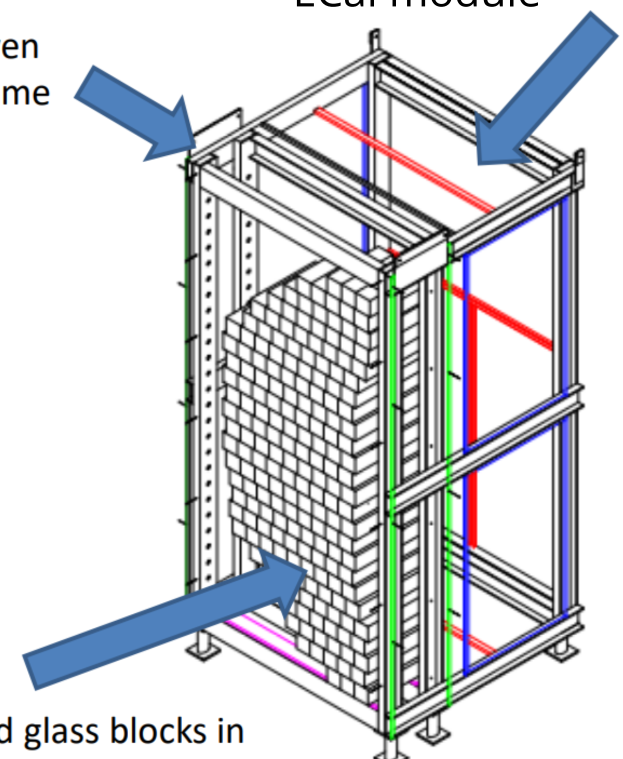
GRINCH(picture from Todd)



Timing hodoscope
(picture from Montgomery)

ECal module

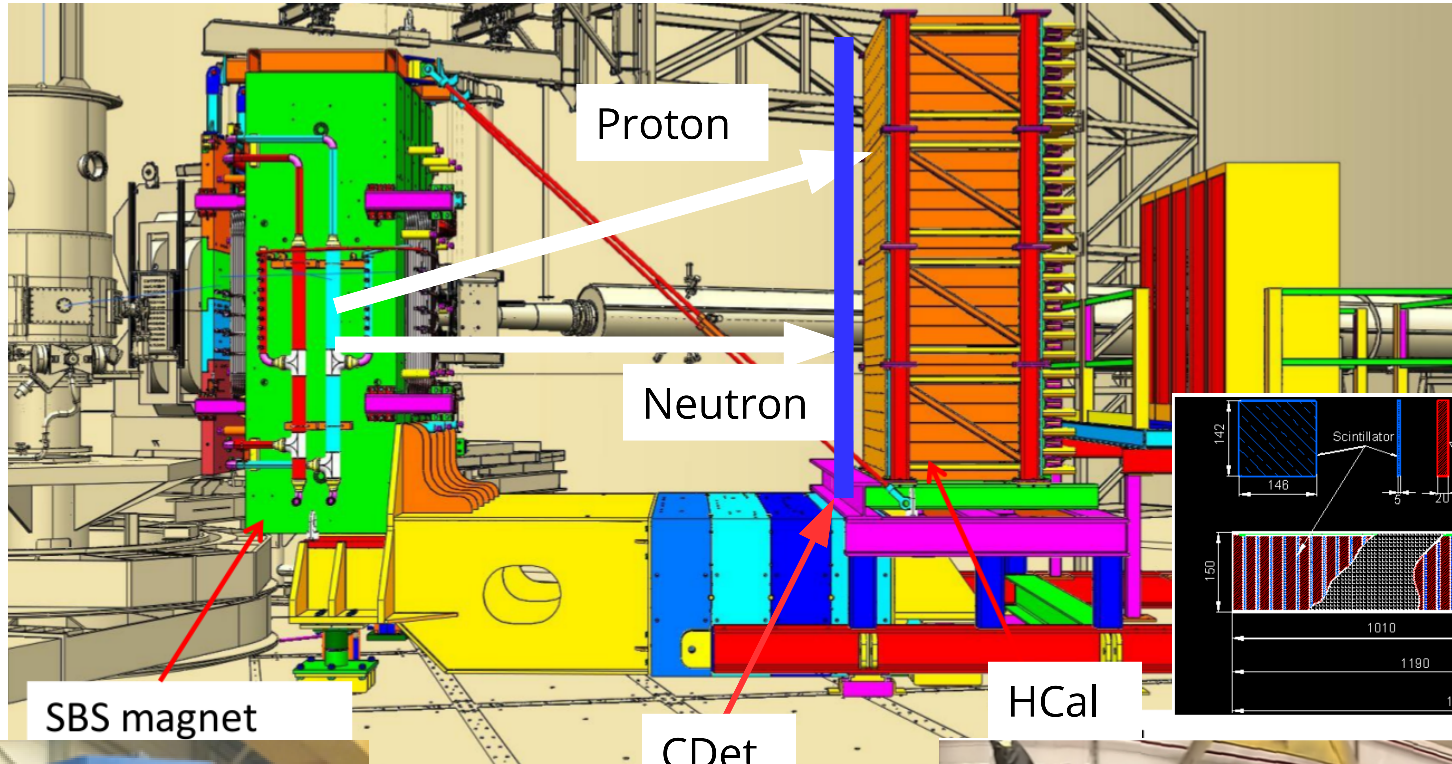
Oven
frame

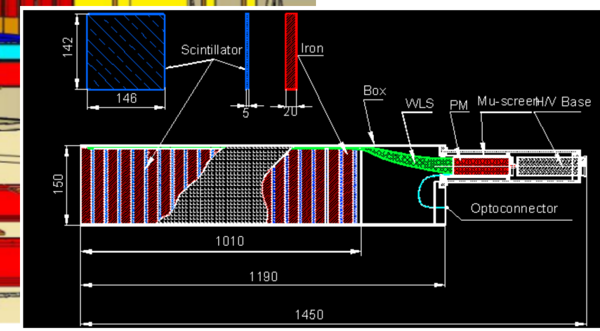


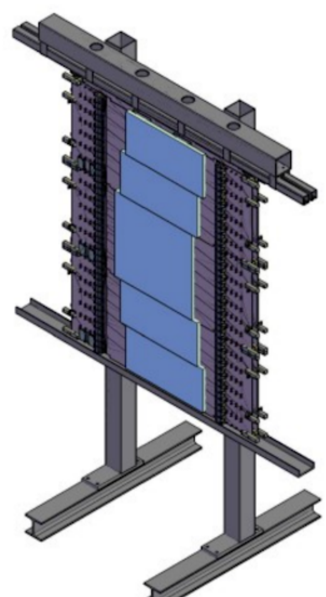
1719 lead glass blocks in
191 supermodules

ECal(Pictures from Mark)

Hadron Arm





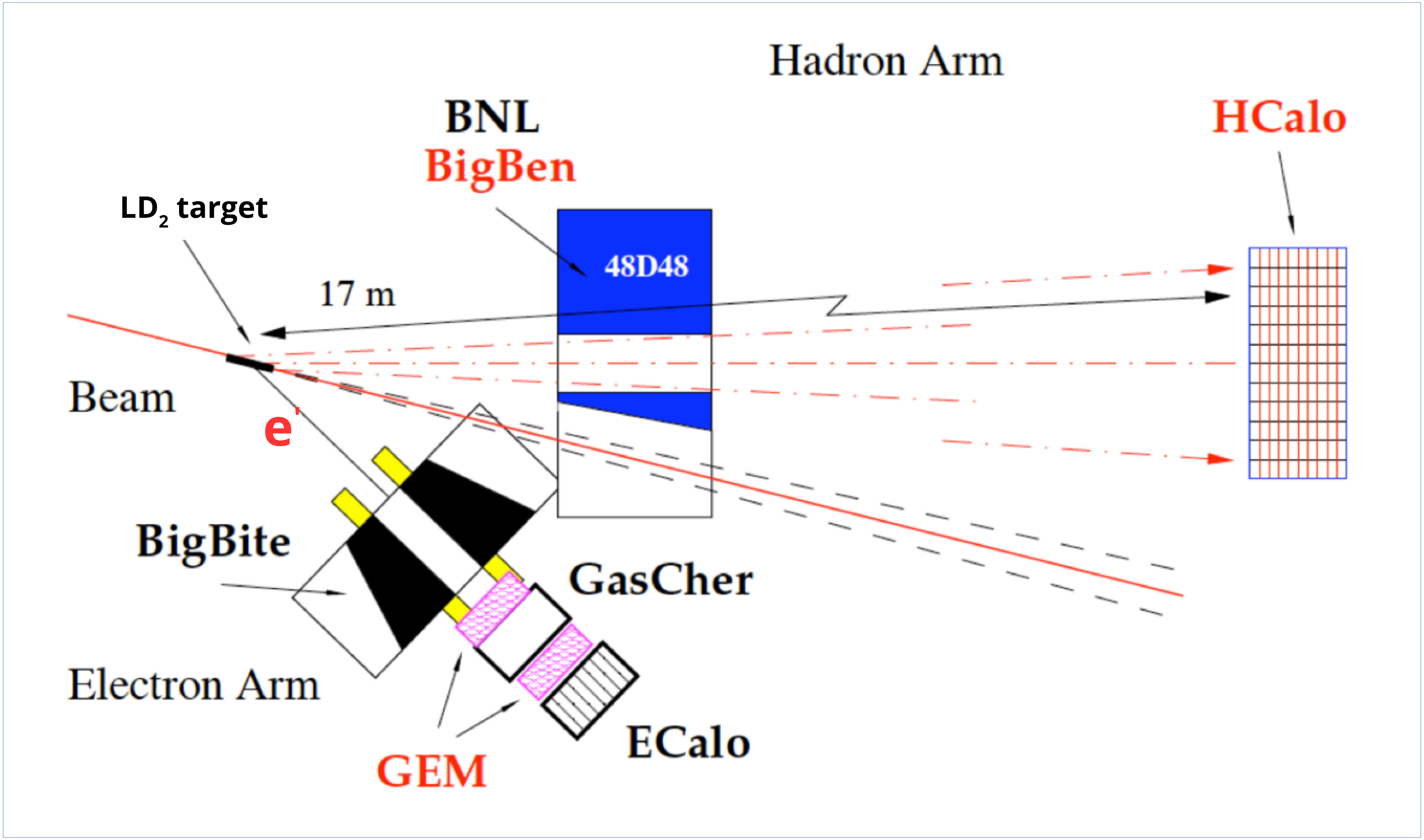


(Pictures from Bogdan)

HCal

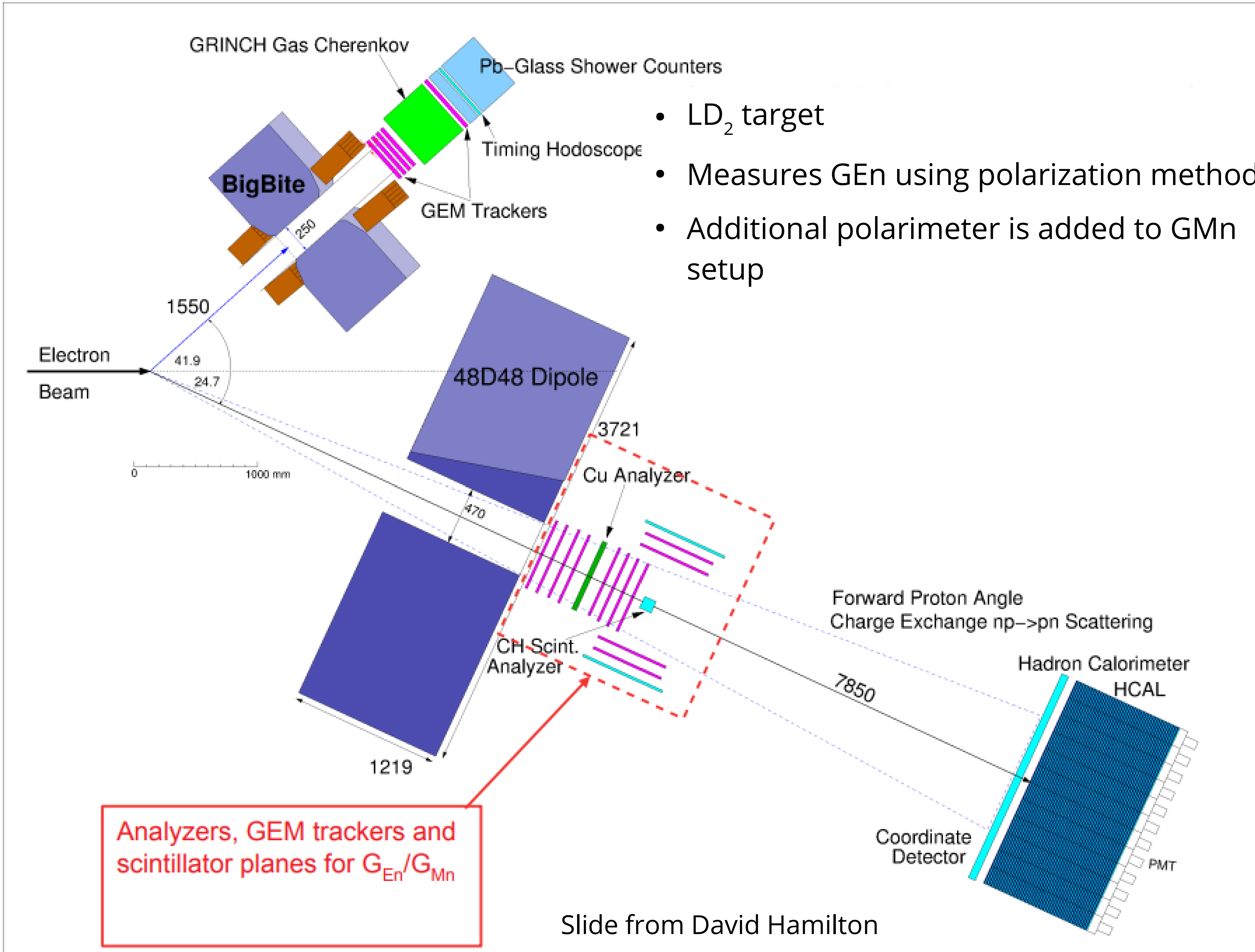
GMn:

$$\frac{\text{Neutron event}}{\text{Proton event}} \longrightarrow \text{Cross section ratios} \longrightarrow \text{GMn}$$



GEn-RP

- LD_2 target
- Measures GEn using polarization method.
- Additional polarimeter is added to GMn setup

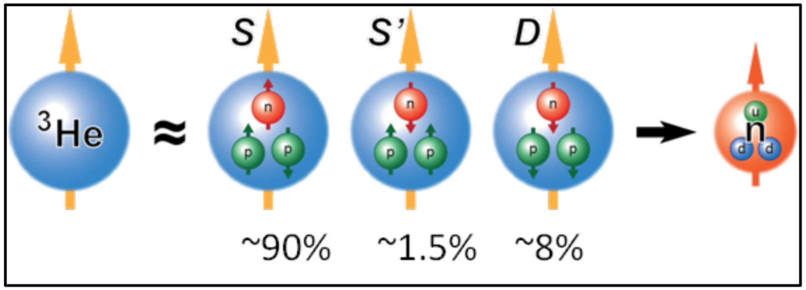


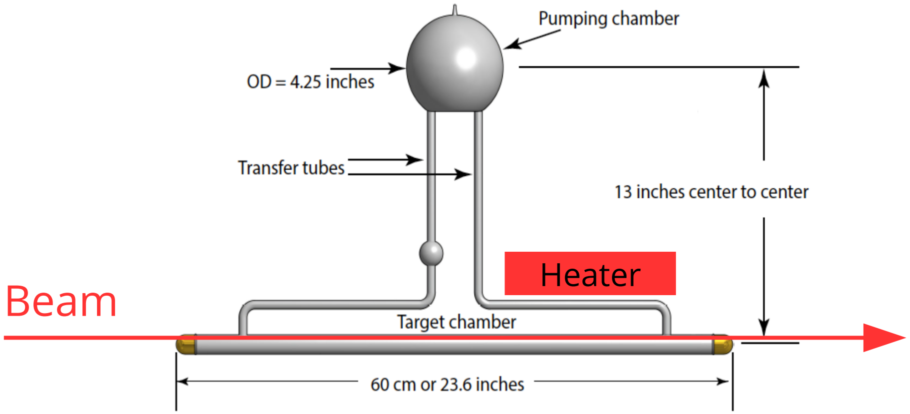
Slide from David Hamilton

GEn-II experiment: neutron form factor ratio at high Q^2

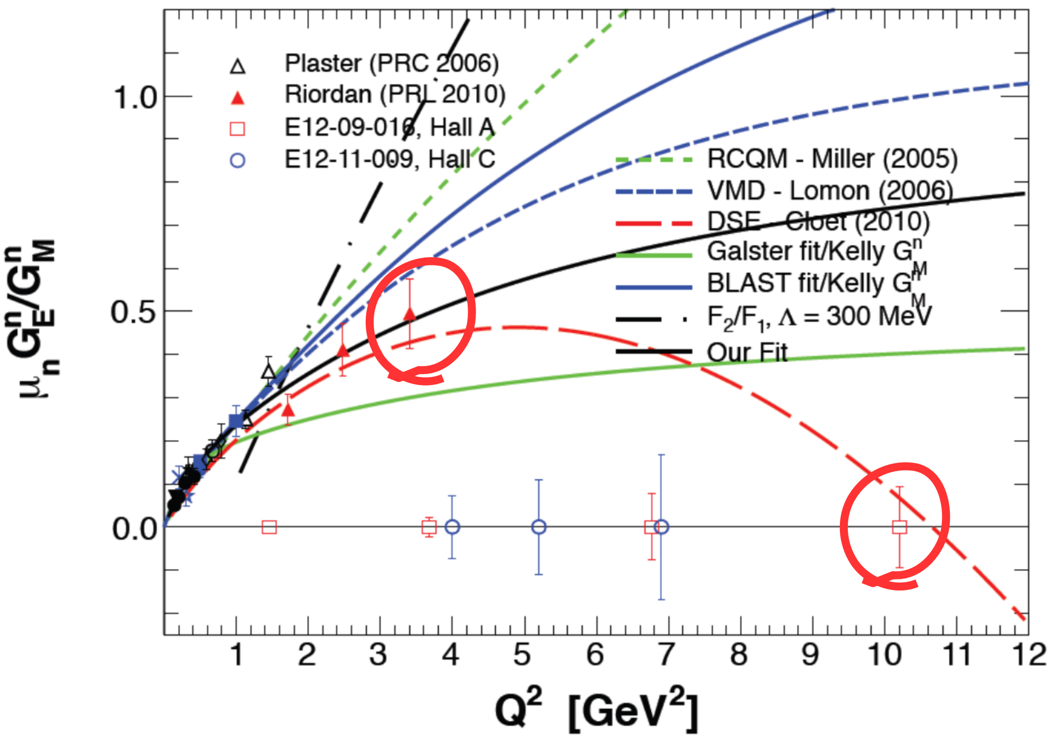
"Neutron picture" – electric

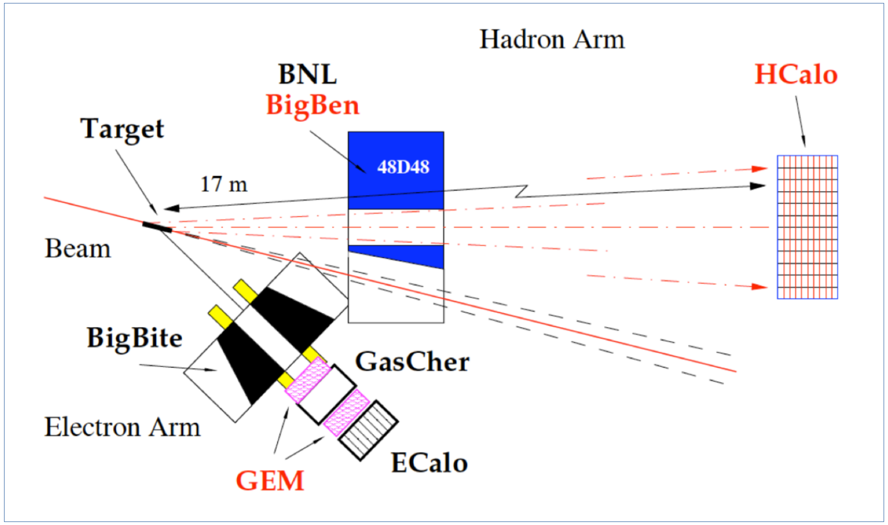
- Same detector setup as GMn experiment.
- Use polarized electron beam and polarized ^{3}He target.(beam target asymmetry method)
- Triple the range of Q^2 of existing data. Potentially providing the most powerful discrimination between different models.





GEn projected result





GEn-II experiment: neutron form factor ratio at high Q^2

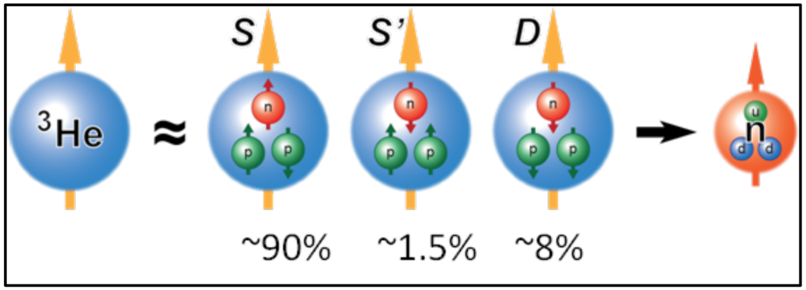
"Neutron picture" – electric

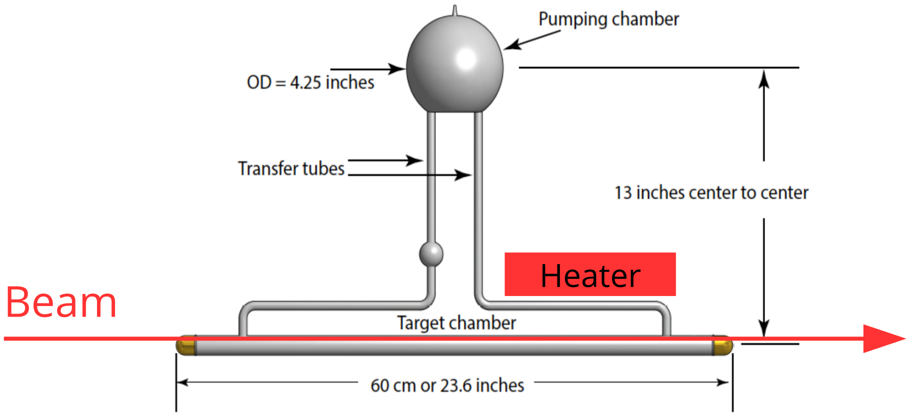
- Same detector setup as GMn experiment.
- Use polarized electron beam and polarized ^3He target.(beam target asymmetry method)

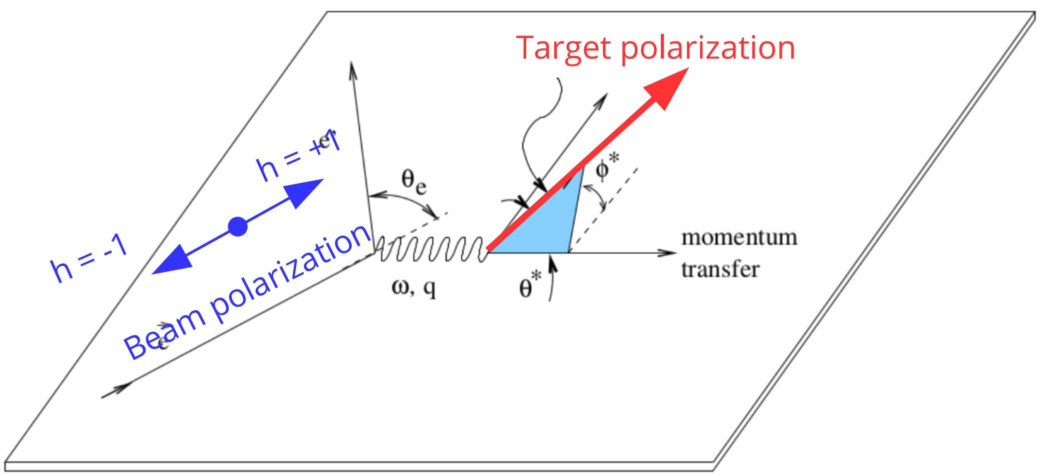
Cross section: $\sigma_h = \Sigma + h\Delta$

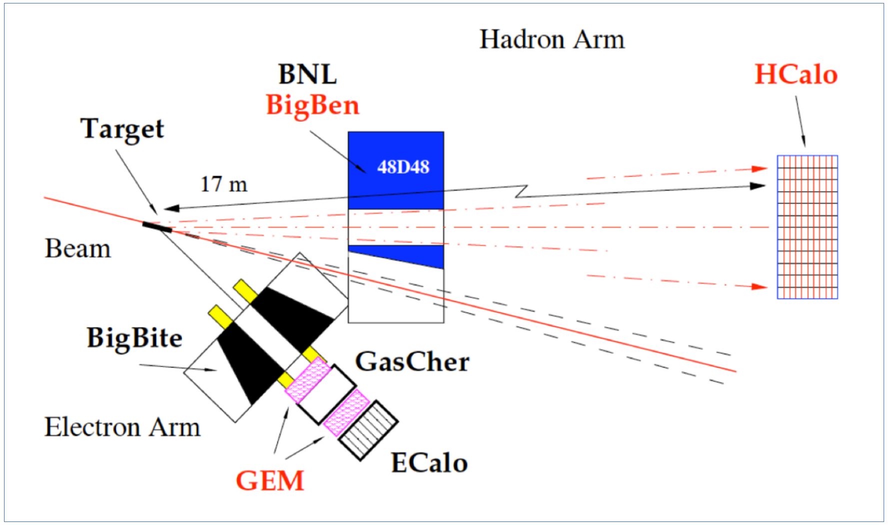
Asymmetry: $A_{phys} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{\Delta}{\Sigma}$

$$A_{phys} = -\frac{2\sqrt{\tau(\tau+1)}tan\frac{\theta}{2}\frac{G_E^n}{G_M^n}}{\frac{G_E^n}{G_M^n}^2 + (\tau + 2\tau(1+\tau)tan^2\frac{\theta}{2})}$$





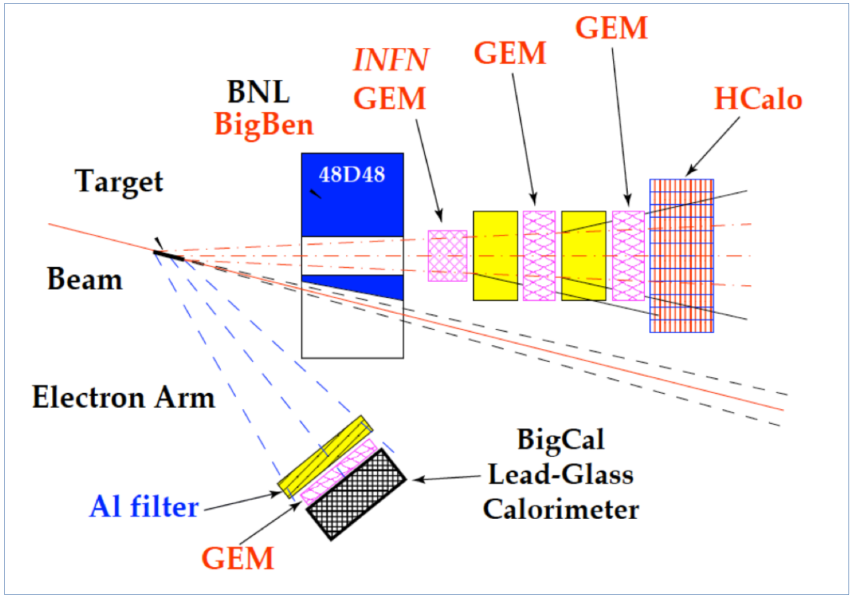




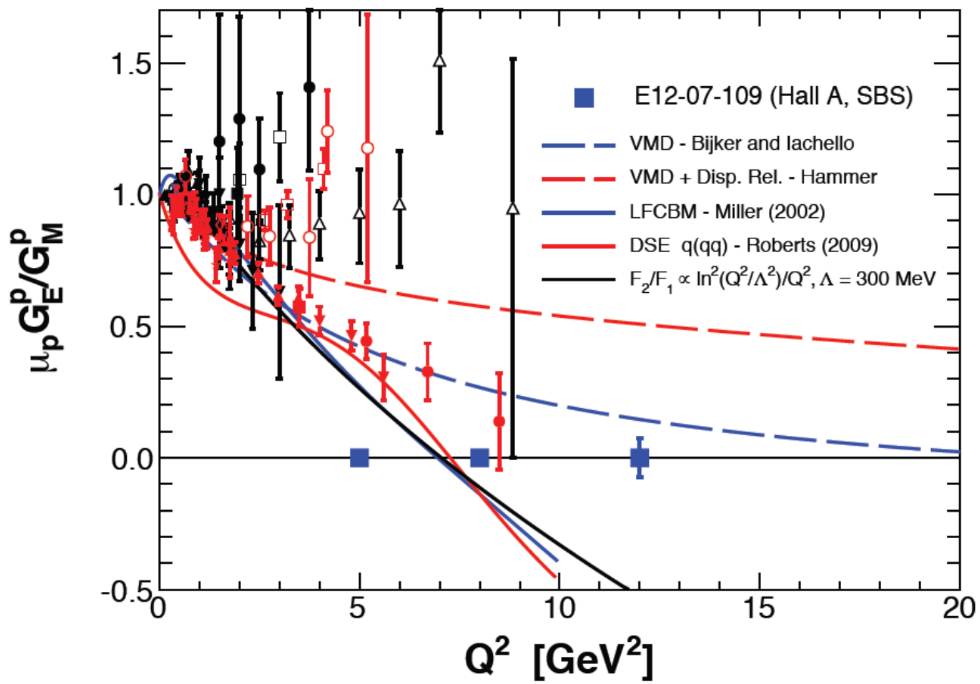
GEp-V experiment: proton form factor ratio at high Q^2

"Proton picture" – electric

- Original motivation for SBS project.
- 40-cm liquid hydrogen target(Luminosity ~ 8×10^{38} Hz*cm^{-2}).
- Proton and electron is detected in coincidence. Kinematic correlations can be used to help tracking in high-rate environment, rejecting inelastic or random backgrounds.



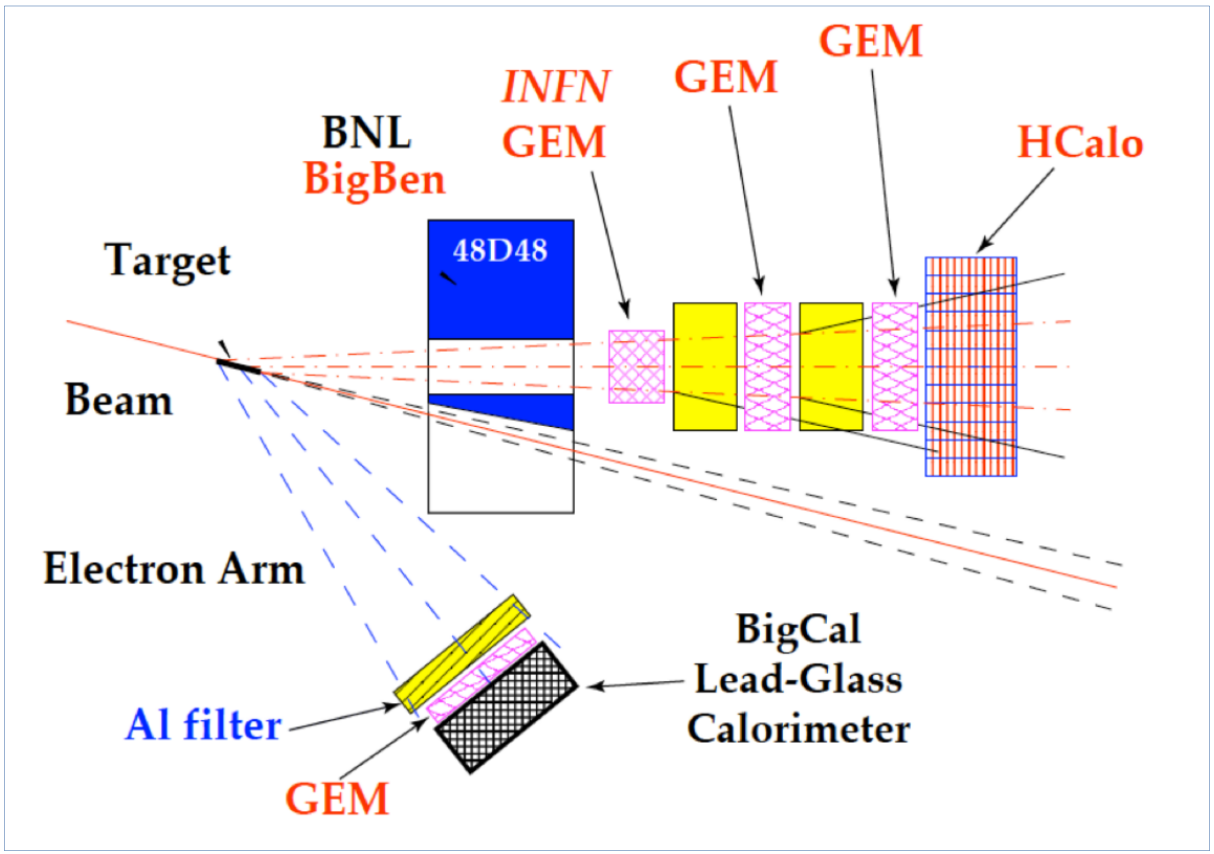
GEp-V projected result

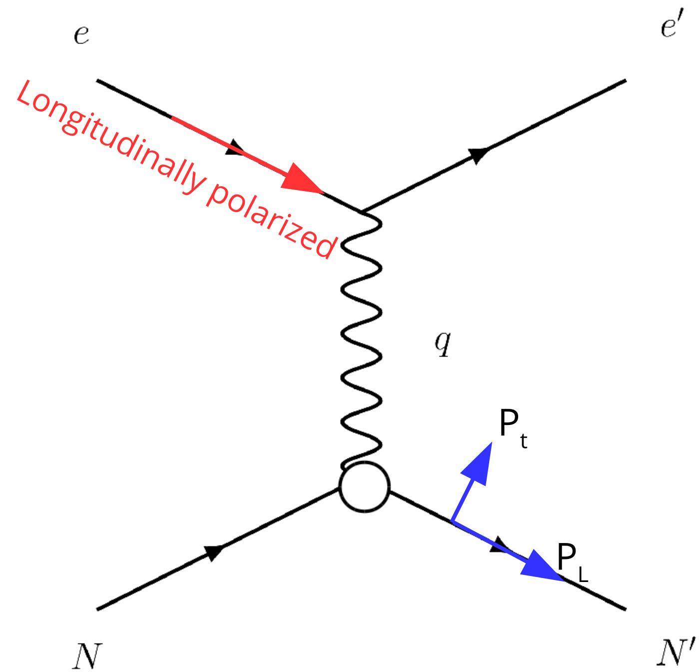


- Measures the proton form factor ratio G_{Ep}/G_{Mp} at Q^2 = 5, 8, and 12 GeV^2.
- Provides much better precision at overlapping Q^2 range with GEp-II and GEp-III experiments.
- Provides data at Q^2 = 12 GeV^2 with similar prevision compared to previous data around Q^2 = 5 GeV^2.

GEp-V:

- Elastic ep scattering
- Form factor from measuring polarization transfer





$$I_0 P_l = h\sqrt{\tau(1+\tau)}tan^2\frac{\theta_e}{2}\frac{E_e+E'_e}{M}G_M^2$$

$$I_0 P_t = -2h\sqrt{\tau(1+\tau)}tan\frac{\theta_e}{2}G_E G_M$$

$$I_0 P_n = 0$$

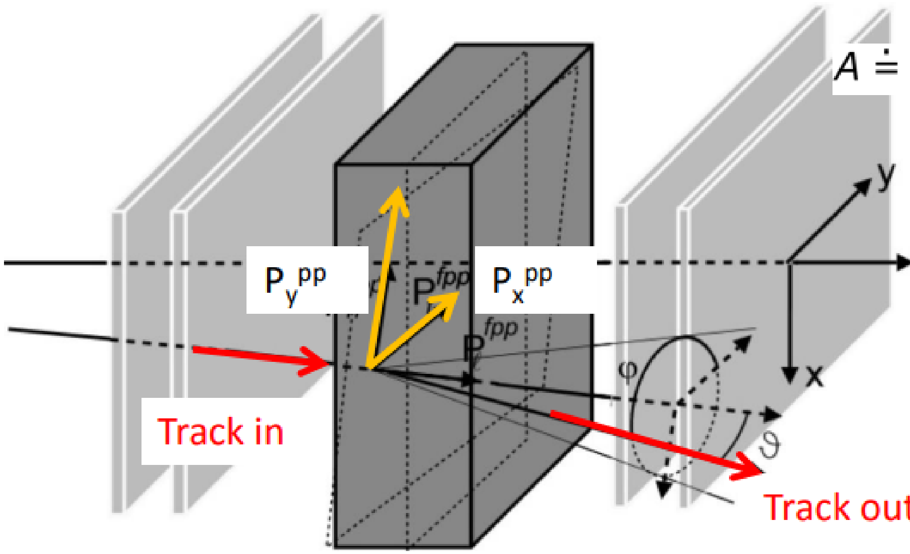
$$I_0 = G_E^2 + \frac{\tau}{\epsilon}G_M^2$$

$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{E_e+E'_e}{2m_p}tan\frac{\theta_e}{2}$$

Proton polarimeter in GEp

Slide from Evaristo

Use azimuthal asymmetry of the proton scattering off matter induced by spin-orbit coupling



Polarimeter only measures components of proton spin that are **transverse** to the proton's momentum direction

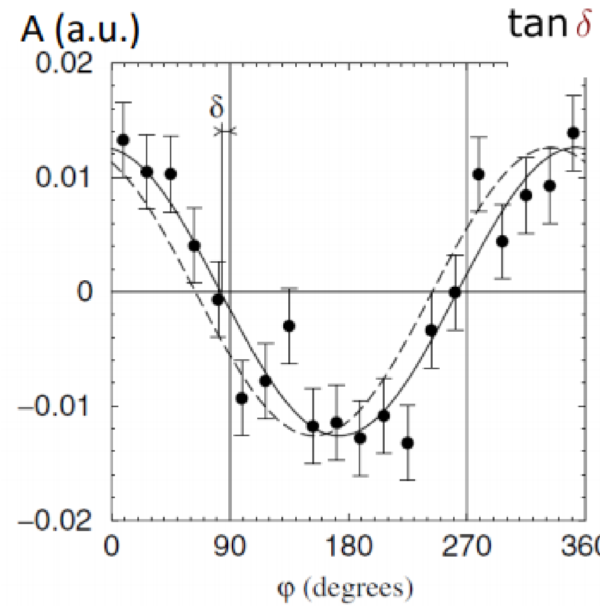
Number of scattered protons:

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

where ± refers to electron beam helicity

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

$$\tan\delta \doteq \frac{P_x^{pp}}{P_y^{pp}}$$

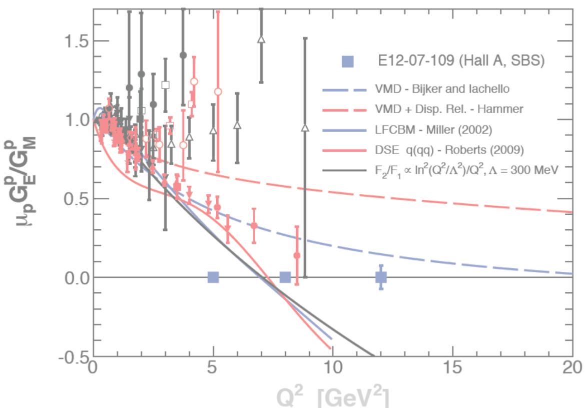


$$\sigma_{P_{x,y}^{pp}} \sim \sqrt{2}/(A \cdot P_e \cdot \sqrt{N})$$ ⇨ Maximize P_e

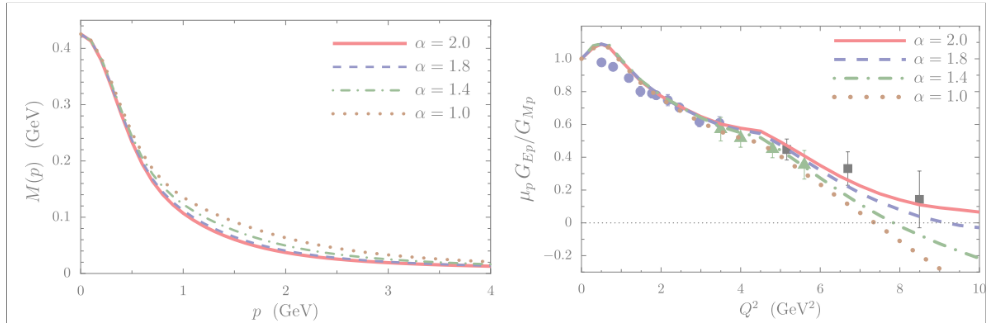
N=number of scattered proton, P_e beam polarization

Rich physics from SBS programs

Proton electric FF, Q^2 8.5 –> 12 GeV^2



Potentially settle the question of the zero crossing behavior of G_{Ep}.



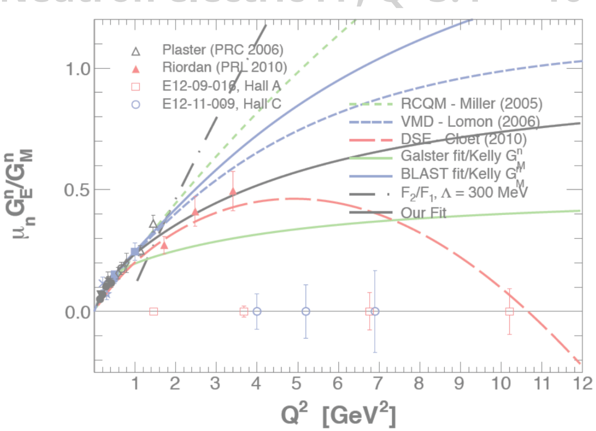
Cloet, Roberts, Thomas, PRL 111, 101803 (2013)

Zero crossing of G_{Ep} provides valuable inputs to the mass function of dressed quark

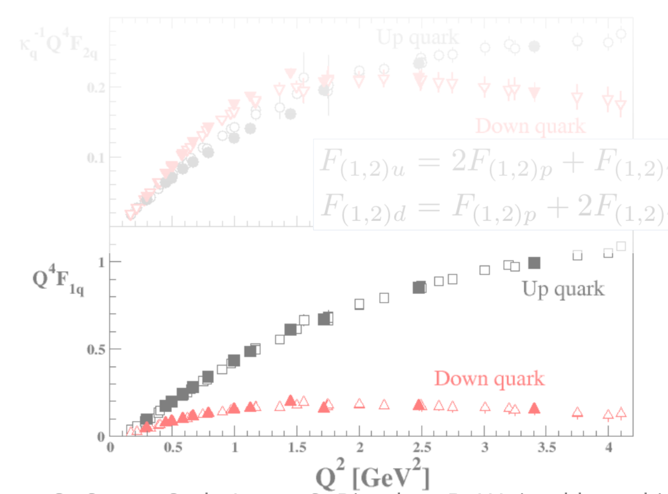
Neutron magnetic FF, Q^2 5 –> 13.5 GeV^2

The nucleon form factors is a well-defined measurable dynamical properties of the nucleon. It can be ... theoretical ... at high Q^2

Neutron electric FF, Q^2 3.4 –> 10 GeV^2



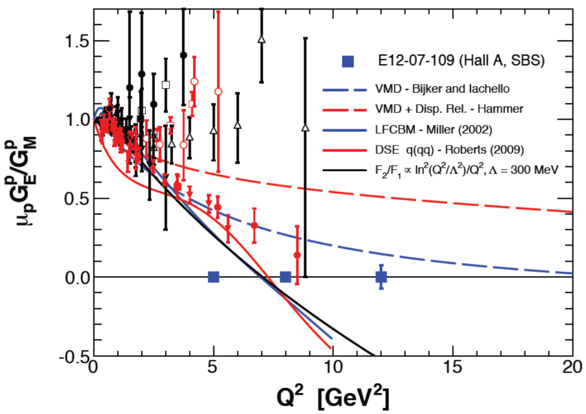
Potentially provide strong support to the DSE model of the nucleon if a bend-over is seen around Q^2 = 10 GeV^2.



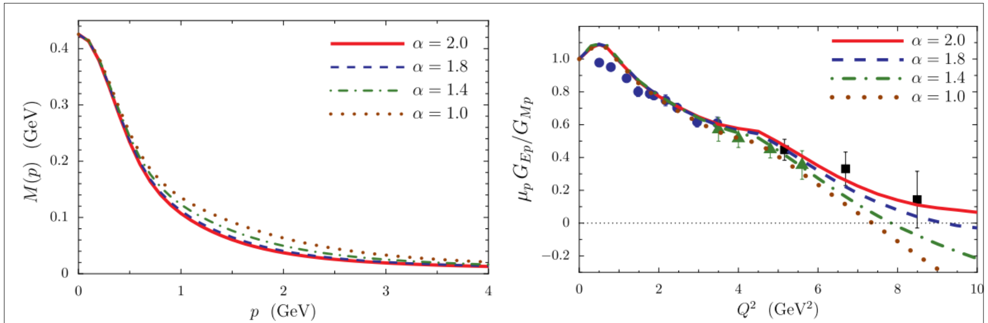
G. Cates, C. de Jager, S. Riordan, B. Wojtsekhowski, Phys. Rev. Lett. 106, 252003 (2011)

Combined with proton magnetic FF, these measurements allow extraction of the dressed quark FF.

Proton electric FF, Q^2 8.5 –> 12 GeV^2



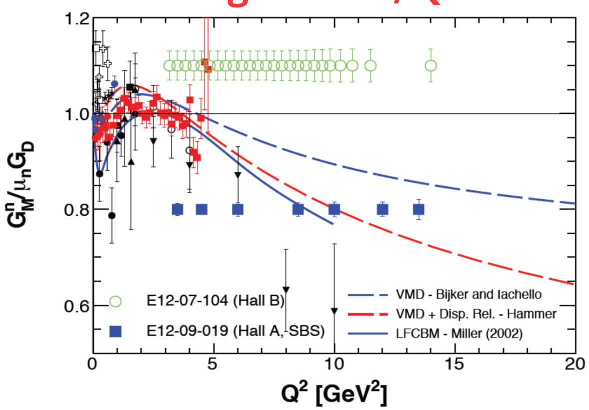
Potentially settle the question of the zero crossing behavior of G_{Ep}.



Cloet, Roberts, Thomas, PRL 111, 101803 (2013)

Zero crossing of G_{Ep} provides valuable inputs to the mass function of dressed quark

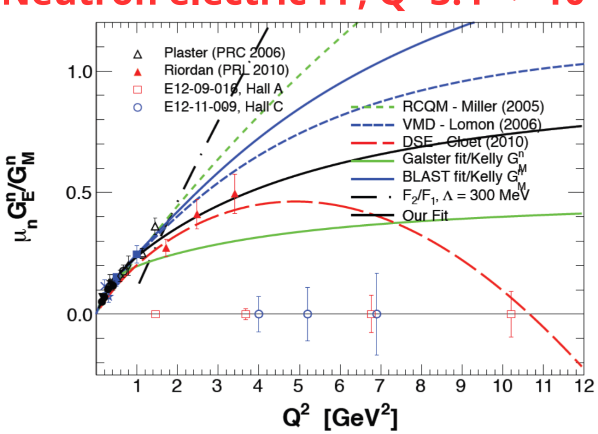
Neutron magnetic FF, Q^2 5 –> 13.5 GeV^2



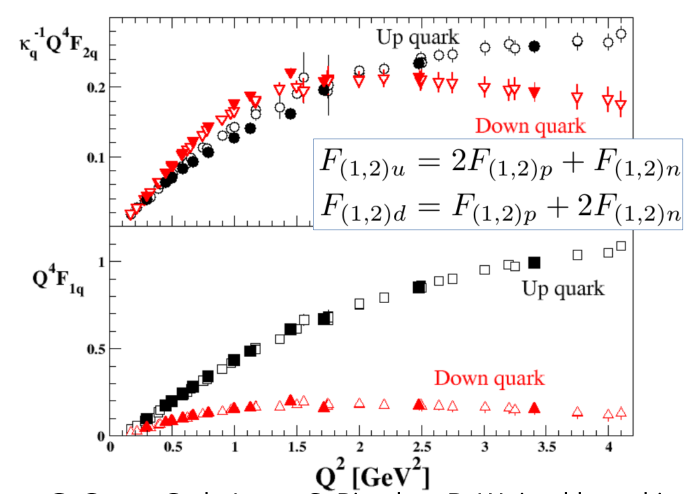
Nucleon form factors at high Q^2

The nucleon form factors is a well-defined measurable dynamical properties of the nucleon. It can be used as a benchmark for all theoretical predictions of nucleon structure

Neutron electric FF, Q^2 3.4 –> 10 GeV^2



Potentially provide strong support to the DSE model of the nucleon if a bend-over is seen around Q^2 = 10 GeV^2.

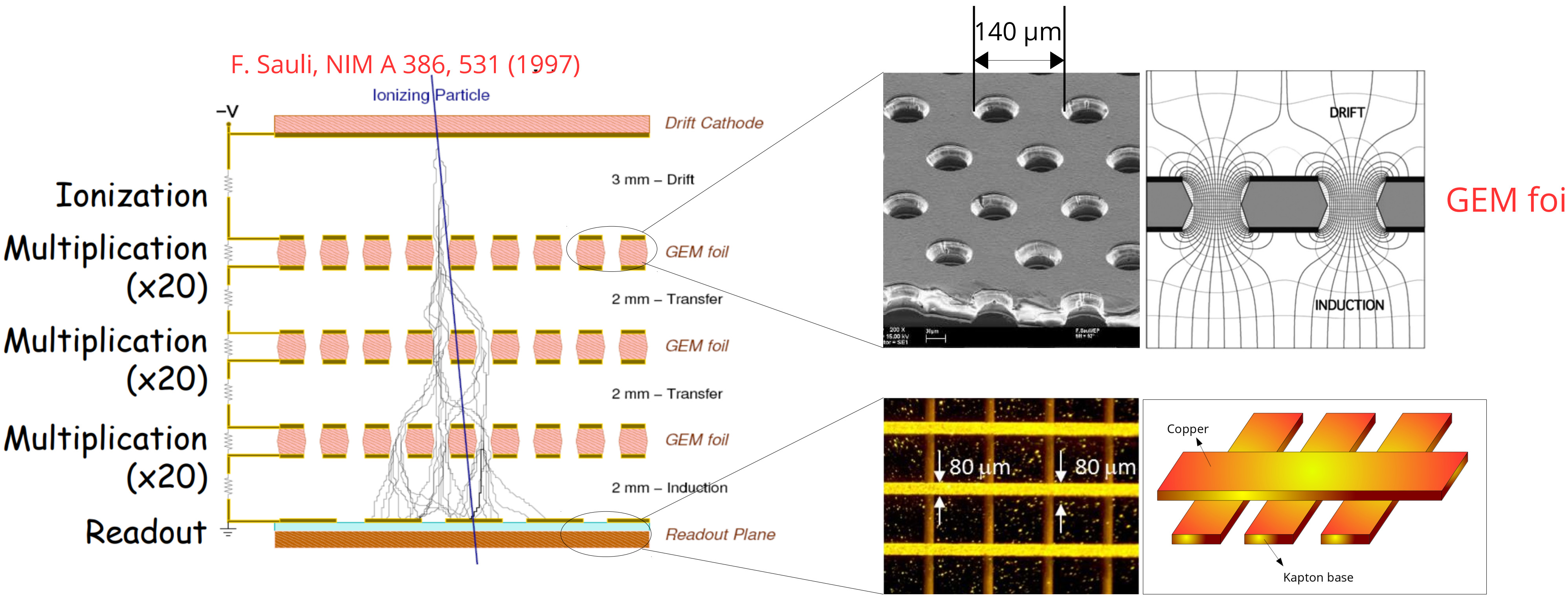


G. Cates, C. de Jager, S. Riordan, B. Wojtsekhowski, Phys. Rev. Lett. 106, 252003 (2011)

Combined with proton magnetic FF, these measurements allow extraction of the dressed quark FF.


Thanks for attention!

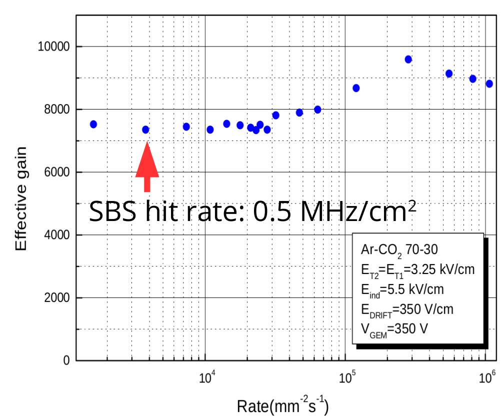
Gas Electron Multiplier(GEM) – novel tracking detector

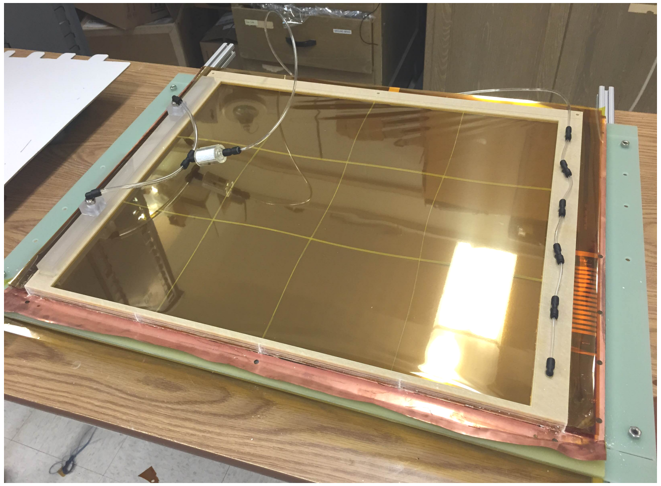


Enables the SBS program!

- Invented in 1997 by Fabio Sauli.
- High rate tolerance: up to 1 MHz/mm².
- High spacial resolution: ~70 µm.
- Stackable: multiple GEM foils operated at low gain to achieve high total gain while keeping chance of discharge low.
- Good timing resolution: ~10 ns

GEM rate capability

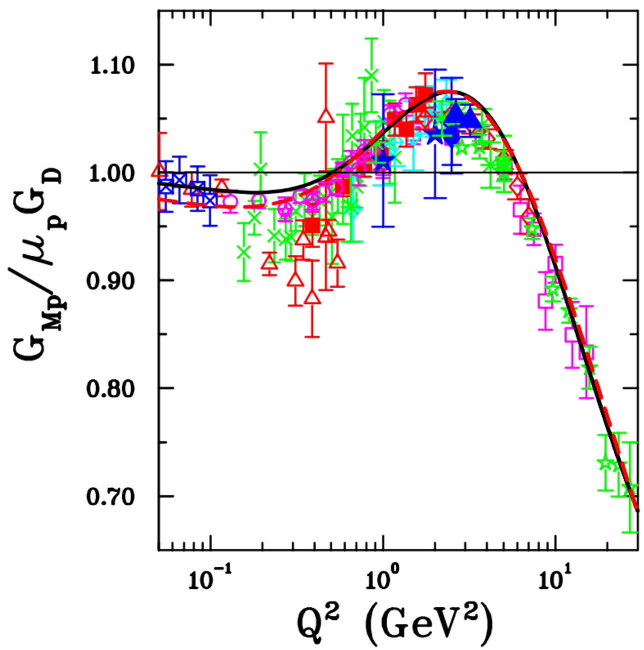




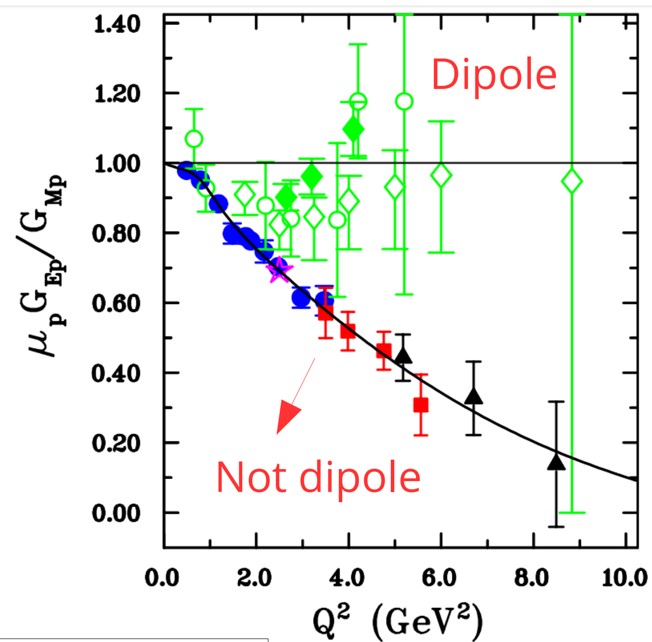
SBS GEM detector built at UVa

Existing proton form factors data

Proton magnetic FF G_{Mp}



Proton electric FF G_{Ep}



- Blue circle: GEp-I
- Red square: GEp-II
- Black triangle: GEp-III
- Magenta star: GEp-2γ
- Green: experiments using Rosenbluth separation method

- G_{Mp} is extracted from cross section using Rosenbluth separation method.
- High Q^2 data is extracted assuming $\mu G_E/G_M = 1$ because the dominance of G_M term in cross section.
- Black line is a parametrization $G(Q^2) \propto \dfrac{\sum_{k=0}^{n} a_k \tau^k}{1 + \sum_{k=1}^{n+2} b_k \tau^k}$

J. J. Kelly, Phys. Rev. C 70, 068202 (2004)

Dipole form factor

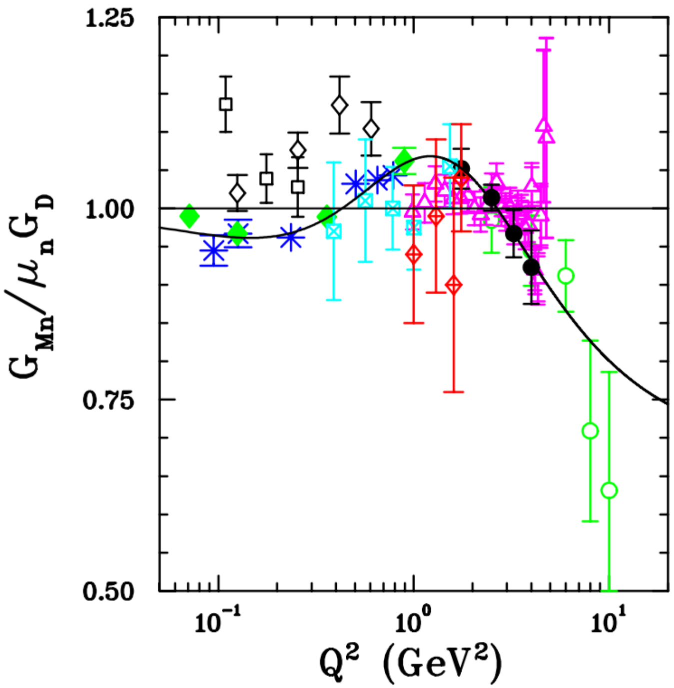
$$G_D = \left(1 + \frac{Q^2}{\Lambda^2}\right)^{-2}$$

$$\Lambda^2 = 0.71\ \text{GeV}^2$$

- Rosenbluth separation experiments has scaling $\mu G_E/G_M = 1$.
- Polarization transfer experiments has obvious decline in the ratio $\mu G_E/G_M$.
- The discrepancy not fully understood

Existing neutron form factors data

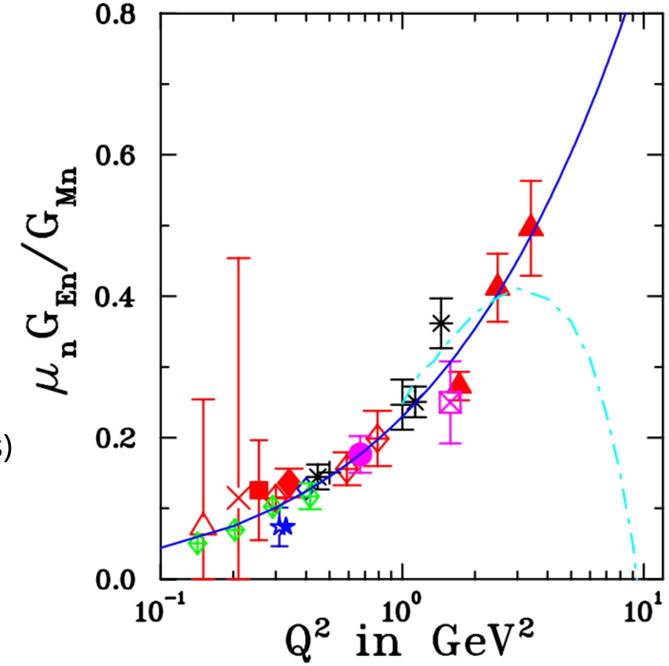
Neutron magnetic FF G_{Mp}



- Magenta triangle: JLab Hall B experiment(2009)
- Green circle: SLAC ed cross sections experiment(1980s)

- G_{Mn} is measured by three main method:
  - "Ratio" method
  - Absolute d(e,e'n)p quasi-elastic cross section measurement
- The experiment at JLab in Hall B using CLAS measured G_{Mn} in fine Q^2 bins from 1.0 to 4.8 GeV^2(open triangles). Consistent with "dipole" model

Neutron electric FF G_{Ep}



- Red filled triangle: JLab Gen-I(up to Q^2 = 3.4 GeV^2)
- Cyan dashed line: prediction of DSE model by **Ian C. Cloët** (2009)

- G_{En} is the least known form factor and most difficult to measure:
  - G_{En} is 0 at low Q^2.
  - G_{En} contribution to cross section is small at large Q^2.
- Methods:
  - Polarized beam-polarized target asymmetry using ^{3}**He**(e,e'n)pp or ^{2}**H**(e,e'n)p
  - Polarization transfer using d(e,e'n)p