Nucleon Form Factor Experiments: Present and Future

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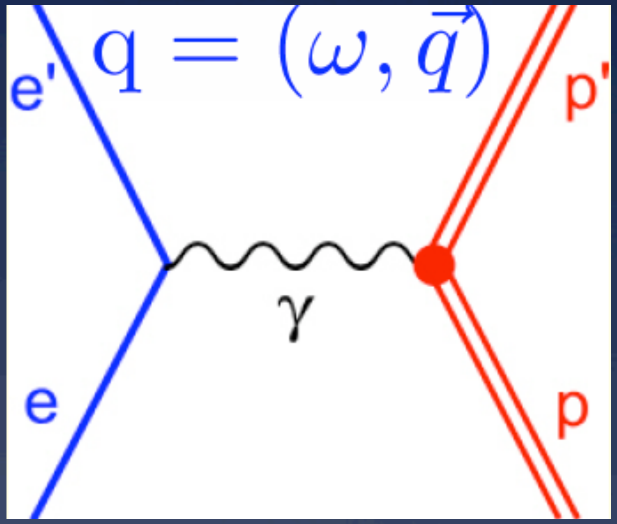
Elastic Electro-Magnetic Form Factors



The hadronic current in one photon exchange

$$J^{\mu} = e\bar{u}(p')\left[F_1(q^2)\gamma^{\nu} + i\frac{\kappa}{2M}q_{\nu}\sigma^{\mu\nu}F_2(q^2)\right]u(p)$$

F_1 , Dirac form factor; helicity conserving

F_2 , Pauli form factor; helicity non-conserving

Or in terms of Sachs form factors

$$G_E = F_1 - \kappa\tau F_2$$

$$G_M = F_1 + \kappa F_2, \tau = \frac{Q^2}{4M}$$

So the elastic cross section

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}\bigg|_{\mathrm{Mott}} \frac{E'}{E}\left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2\frac{\theta}{2}\right]$$

Elastic Electro-Magnetic Form Factors

- Elastic form factors parameterize the properties of the quark and gluon many body system of the nucleon
- They provide excellent testing ground for QCD-inspired models

In the Breit Frame, G_E and G_M are the Fourier transforms of charge and magnetization distributions of the nucleon

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_M \left\{G_E^2 + \frac{\tau}{\varepsilon} G_M^2\right\} \Big/ (1+\tau)$$

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

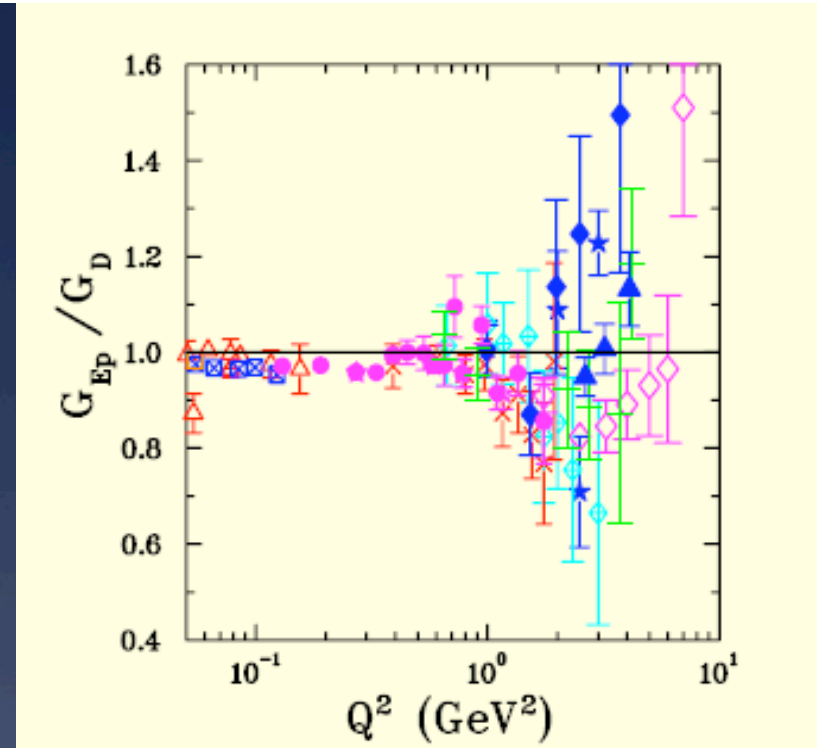
$$\epsilon = \frac{1}{1 + 2(1+\tau)\tan^2(\frac{\theta_e}{2})}$$

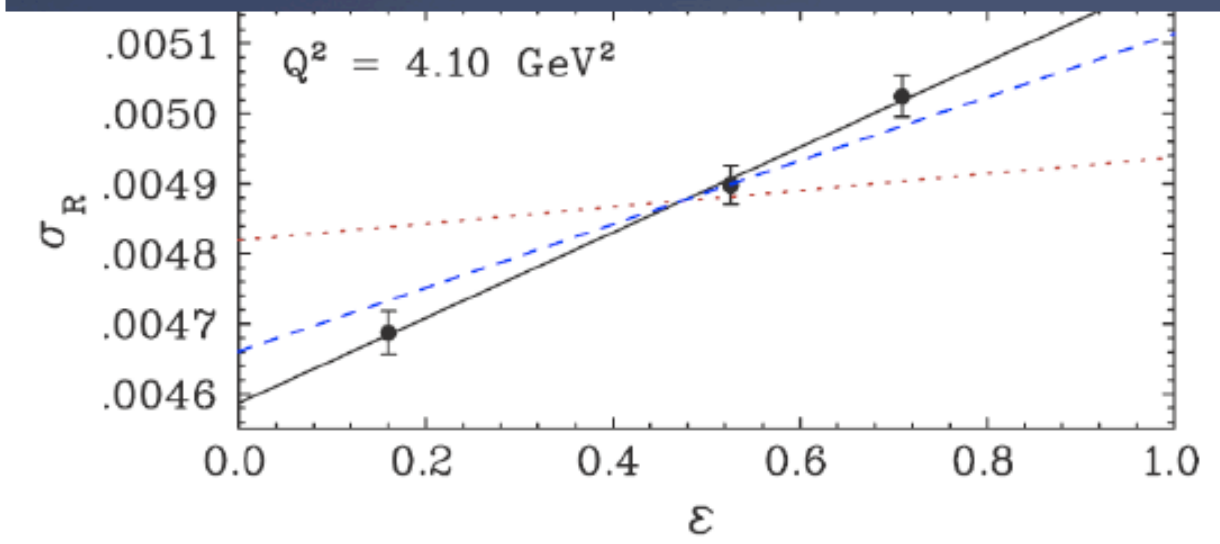
$$\sigma_R = [\varepsilon(1+\tau)/\tau][\sigma_{exp}/\sigma_{Mott}] =$$
$$= G^2_{Mp} + \varepsilon\, G^2_{Ep}/\tau$$

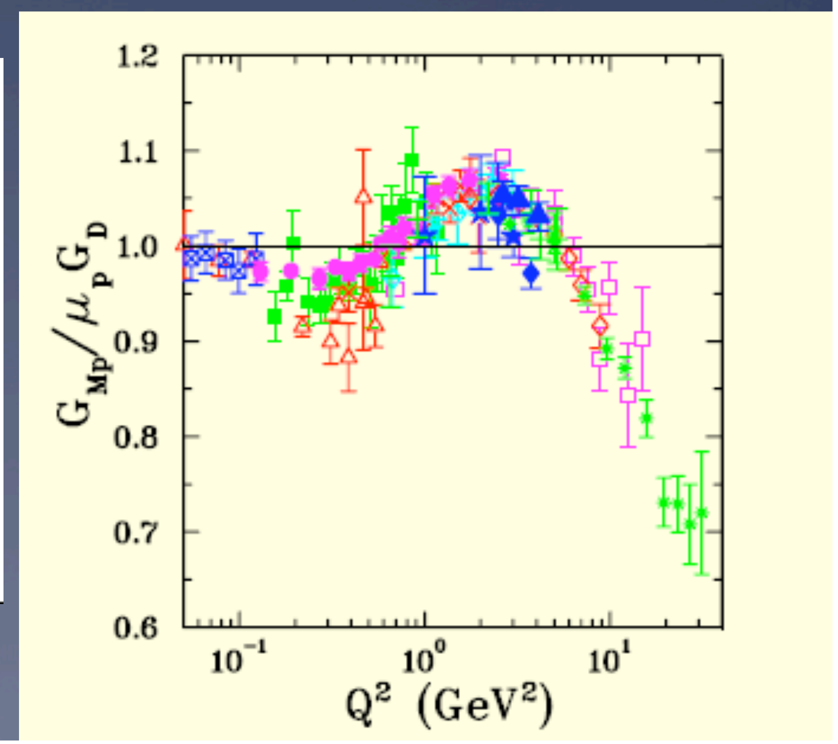
Separation of Electric and Magnetic Form Factors using cross-section data

$$\sigma_R = [\varepsilon(1+\tau)/\tau][\sigma_{exp}/\sigma_{Mott}] =$$

$$= G^2_{Mp} + \varepsilon\, G^2_{Ep}/\tau$$







Polarization method to measure GE/GM

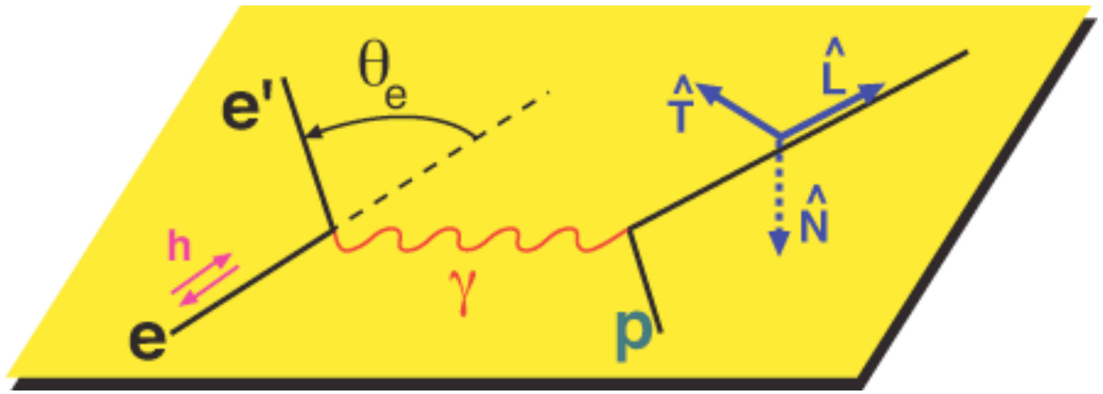
accuracy of form-factor measurements can be significantly improved by measuring the beam helicity asymmetry with a polarized target or with recoil polarimetry

Akhiezer et al., Sov. Phys. JETP 6, 588 (1958) and
Arnold, Carlson and Gross, PR C 23, 363 (1981)

Finally became possible with Jefferson lab, Mainz and Bates:

- Polarized beam with high intensity (~100 μA) and high polarization (>70 %)
- Beam polarimeters with 1-3 % absolute accuracy
- Polarized targets with a high polarization or
- Recoil polarimeters with large analyzing powers

Recoil polarization method to measure GEp/GMp



- Ratio cancels beam polarization and analyzing power
- GE/GM measured from a single measurement: no errors dues to ε dependant effects
- Not sensitive to: spectrometer solid angle, target density, trigger and detector inefficiencies, beam charge asymmetry, false asymmetries in FPP
- Main sensitivity is to spin transport

$$P_n = 0$$

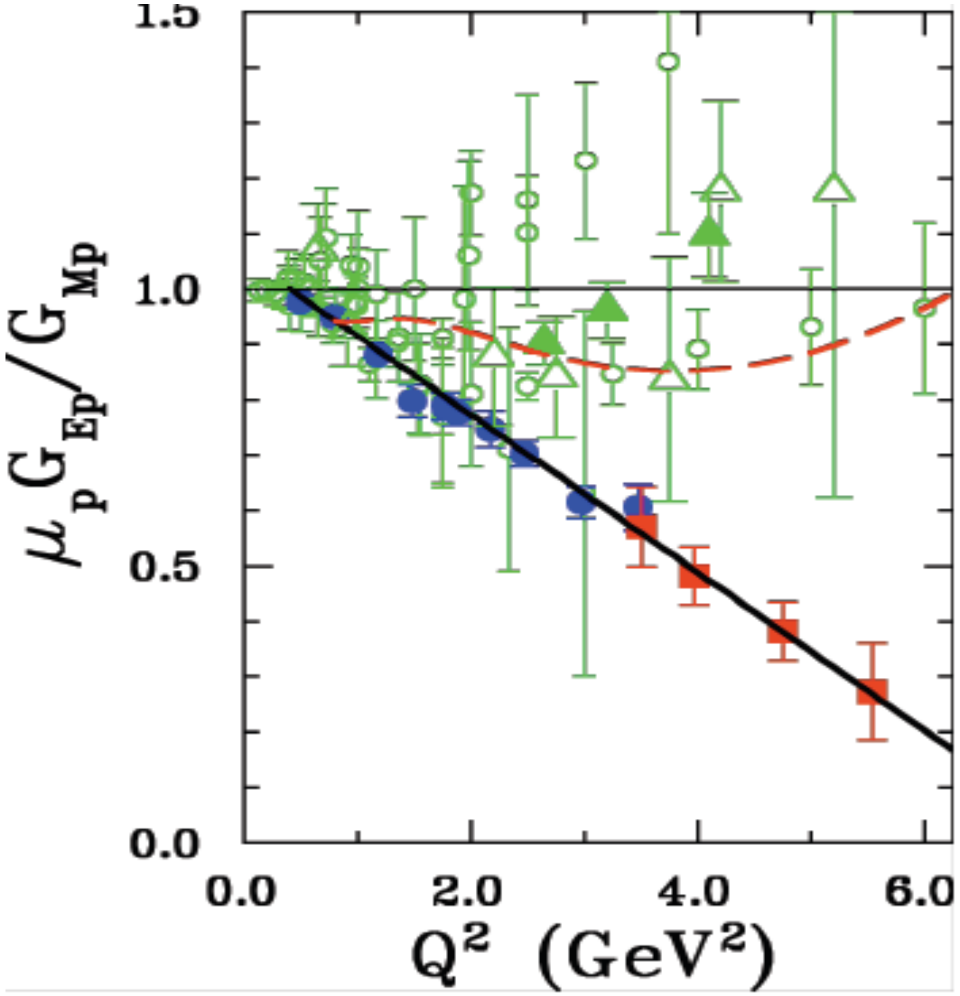
$$\pm h P_t = \mp h 2\sqrt{\tau(1+\tau)} G_E^p G_M^p \tan\left(\frac{\theta_e}{2}\right) / I_0$$

$$\pm h P_l = \pm h (E_e + E_{e'}) (G_M^p)^2 \sqrt{\tau(1+\tau)} \tan^2\left(\frac{\theta_e}{2}\right) / M / I_0$$

$$I_0 = \left\{G_E^p(Q^2)\right\}^2 + \tau\left\{G_M^p(Q^2)\right\}^2\left[1 + 2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)\right]$$

$$\frac{G_E^p}{G_M^p} = -\frac{P_t}{P_l}\frac{E_e + E_{e'}}{2M}\tan\left(\frac{\theta_e}{2}\right)$$

Hall A GEp results



- E93-027 PRL 84, 1398 (2000) Used both HRS in Hall A with FPP
- E99-007 PRL 88, 092301 (2002) used Pb-glass calorimeter for electron detection to match proton HRS acceptance

- Almost linear drop of G_{Ep}/G_{Mp} with Q2 above.
- May be an indication of the importance of quark Orbital Angular Momentum
- Recent super-Rosenbluth measurement confirmed old result: "$\mu G_{Ep}/G_{Mp}$" =1
- The difference is believed to be due to Two-photon exchange corrections.
- Several experiments to check this hypothesis.

Important role of quark Orbital Angular Momentum ?

pQCD (Bjørken) scaling, taken with the assumption of Hadron Helicity Conservation predicts

$F_1 \propto 1/Q^4$; $F_2 \propto 1/Q^6$

➽ $F_2/F_1 \propto 1/Q^2$ (Brodsky & Farrar)

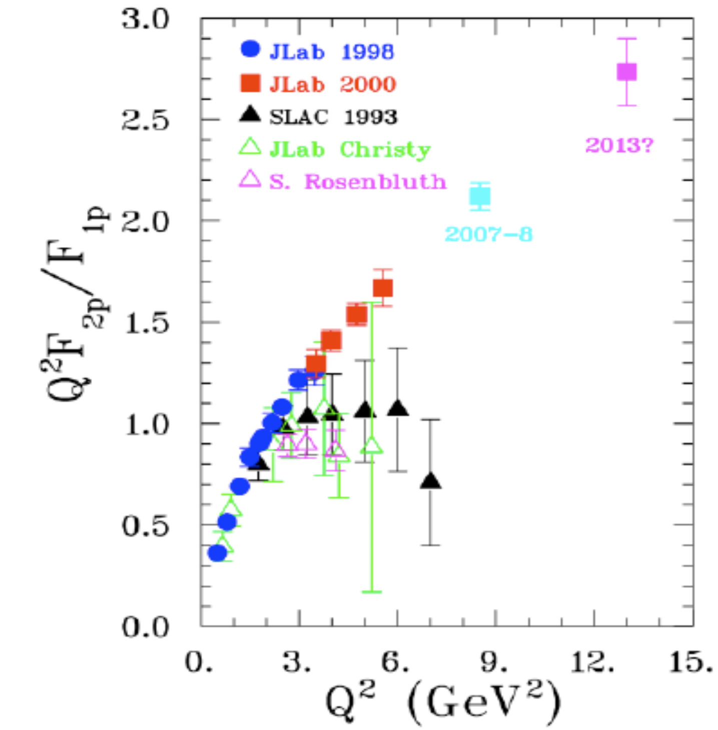
Data clearly do not follow this trend

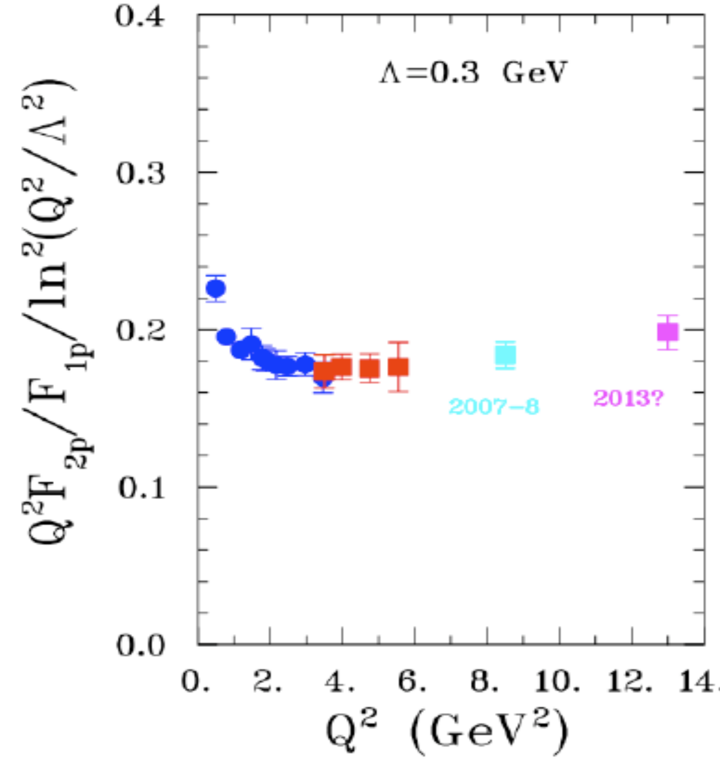
Schlumpf (1994), Miller (1996) and Ralston (2002) agree that by

- freeing the p_T=0 pQCD condition
- applying a (Melosh) transformation to a relativistic (light-front) system
- an orbital angular momentum component is introduced in the proton wf (giving up helicity conservation) and one obtains

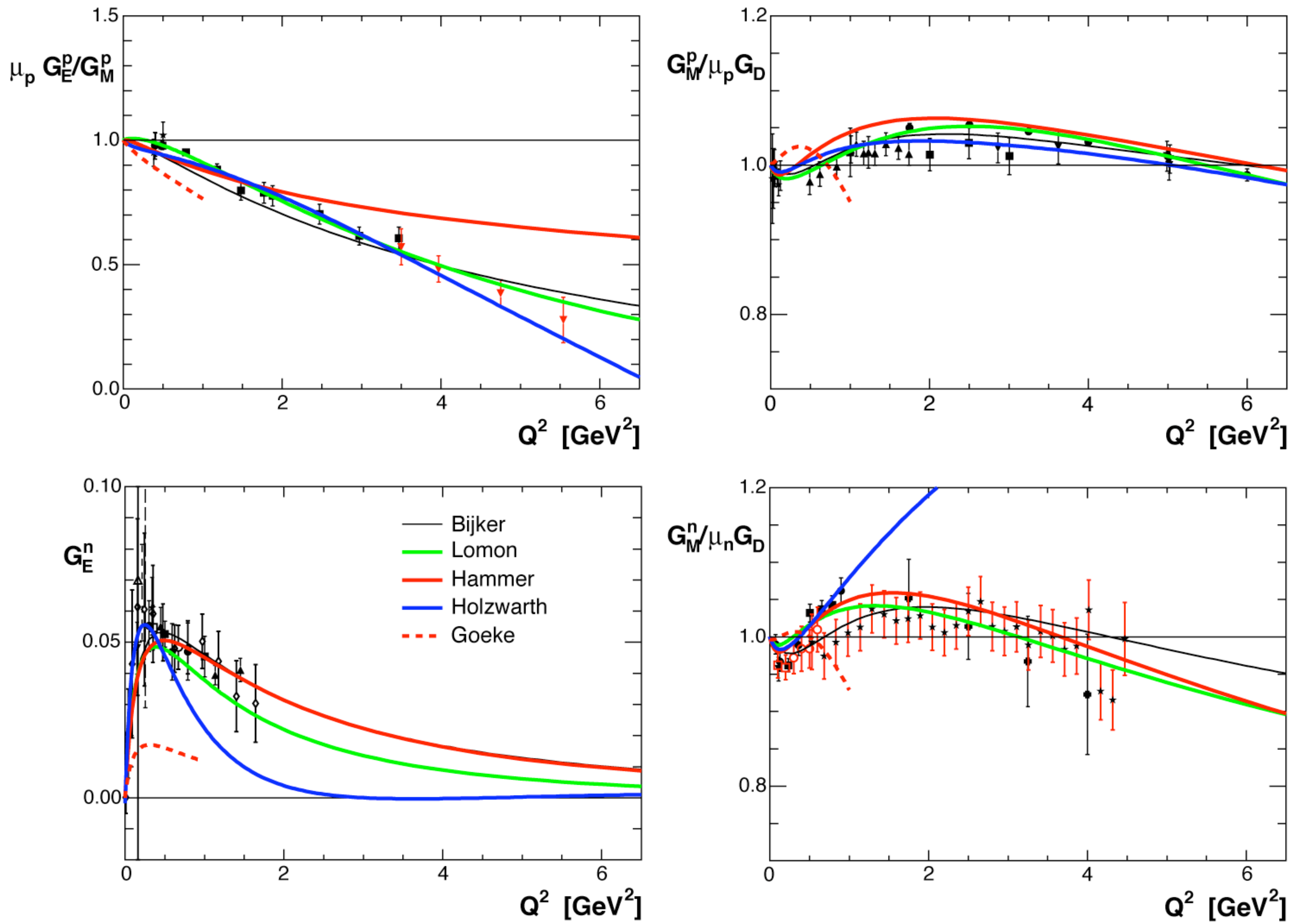
  ➽ $F_2/F_1 \propto 1/Q$
- and equivalently a linear drop off of G_E/G_M with Q^2
- Belitsky, Ji and Yuan refined the pQCD prediction by including quark OAM component l_z=1 (relax HHC) and get:

  $F_2/F_1 \propto \ln^2(Q^2/\Lambda^2)/Q^2$

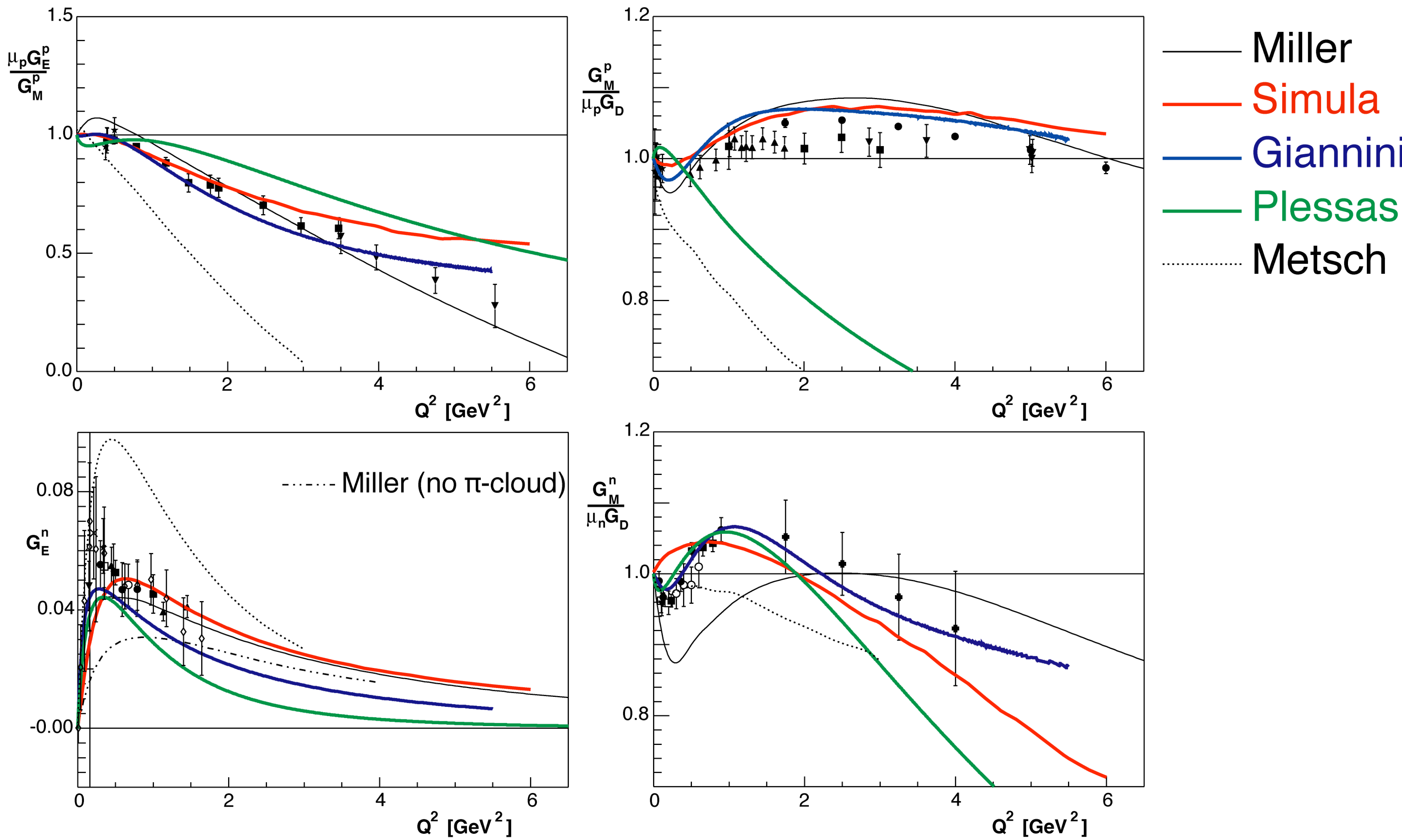




Vector-Meson Dominance models



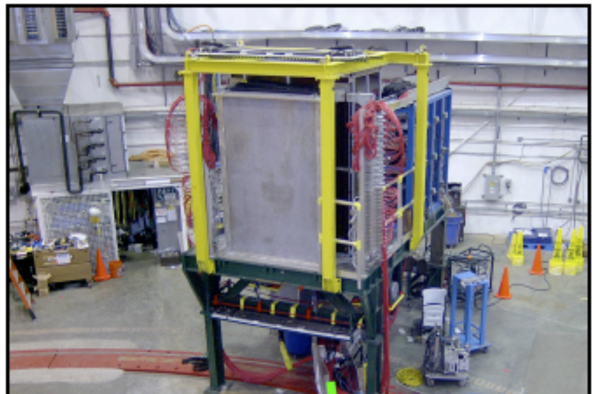
Relativistic Constituent Quark models

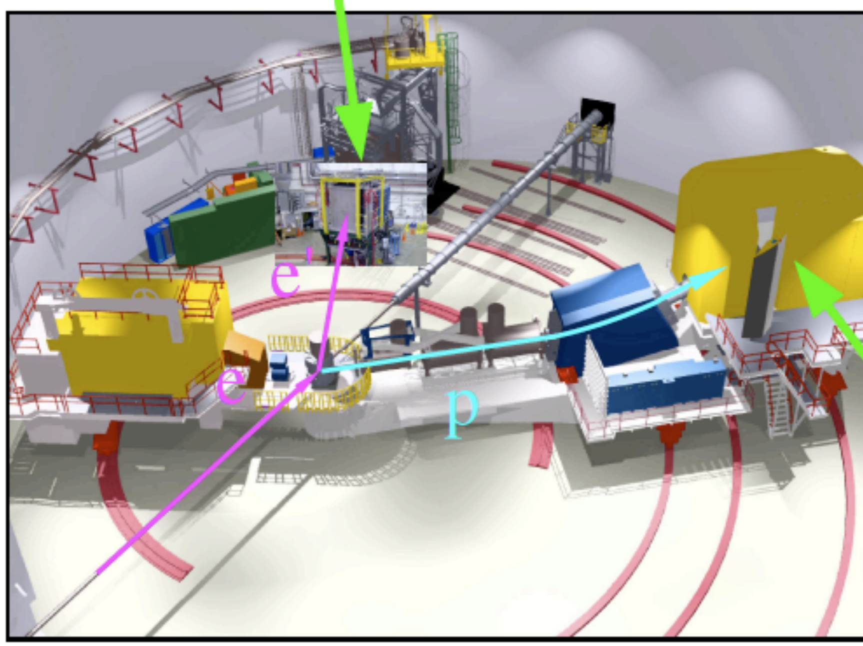


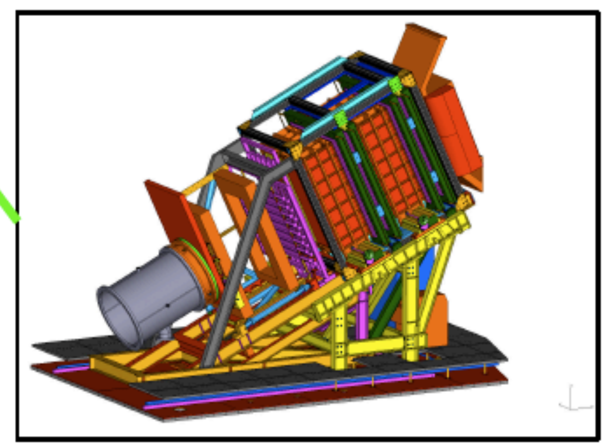
Need electric and magnetic form factor data for both neutron and proton up to high Q^2 with the highest possible precision in order to to discriminate between models and to understand underlying nucleon dynamics

Jefferson lab Hall C GEP-III experiment (E04-108)

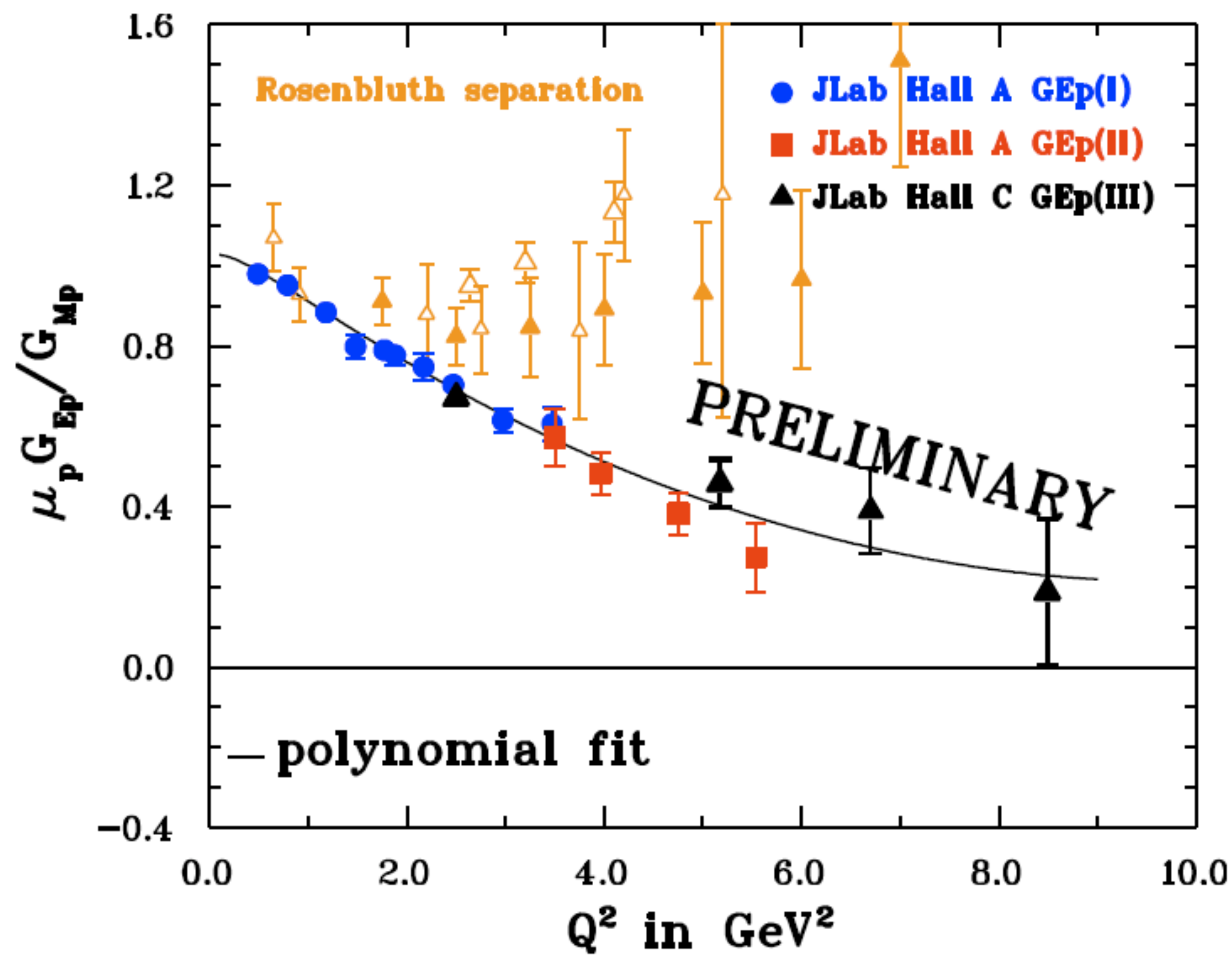
- Continuation of Hall A Gep 1+2 experiments to higher Q2: 5.2, 6.8, and 8.5 GeV2
- Elastic electron detected in large Calorimeter, BigCal
- Proton detected in HMS equipped with new FPP.
- The first high Q2 polarization transfer Gep measurement outside Hall A.







Preliminary results of GEp(III)

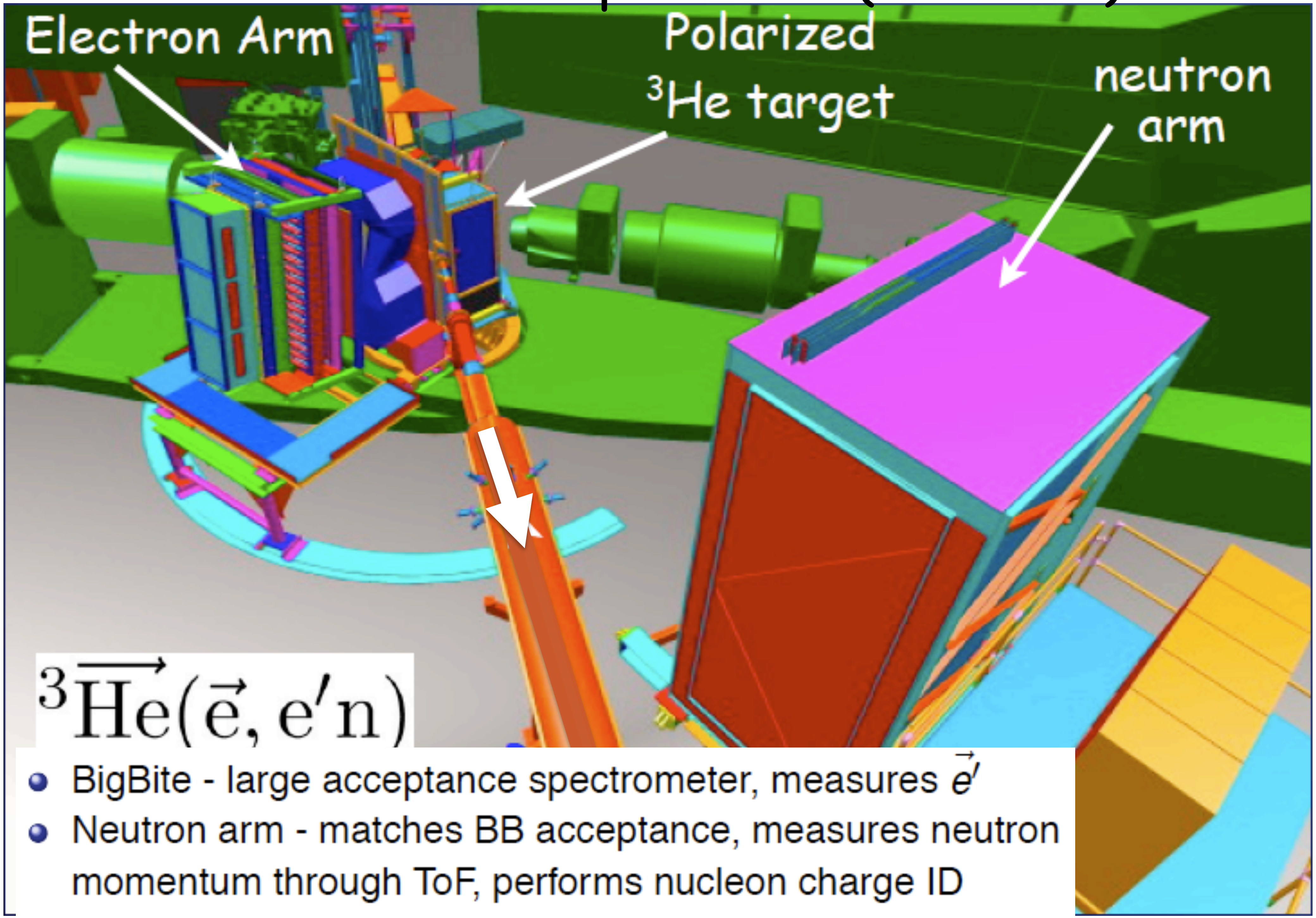


Double Polarization method to measure Gen

- Use (e,e'n) reaction off deuterium with polarized target (like ND_3) or with recoil polarimetry.
    - Problems
        - Low deuteron polarization (~ 25%)
        - Low beam on target (< 100 nA)
        - Low FOM for neutron polarimeters.
- Use (e,e'n) off polarized 3He target
    - Recent advances make this method very attractive
        - > 50% target polarization with over 12 μA of beam
        - Above Q2 ~ 1-2 GeV^2 Glauber method provides sufficiently accurate nuclear corrections.

Polarized 3He target combined with a large acceptance electron spectrometer and a large neutron detector allows Gen to be measured to high Q2.

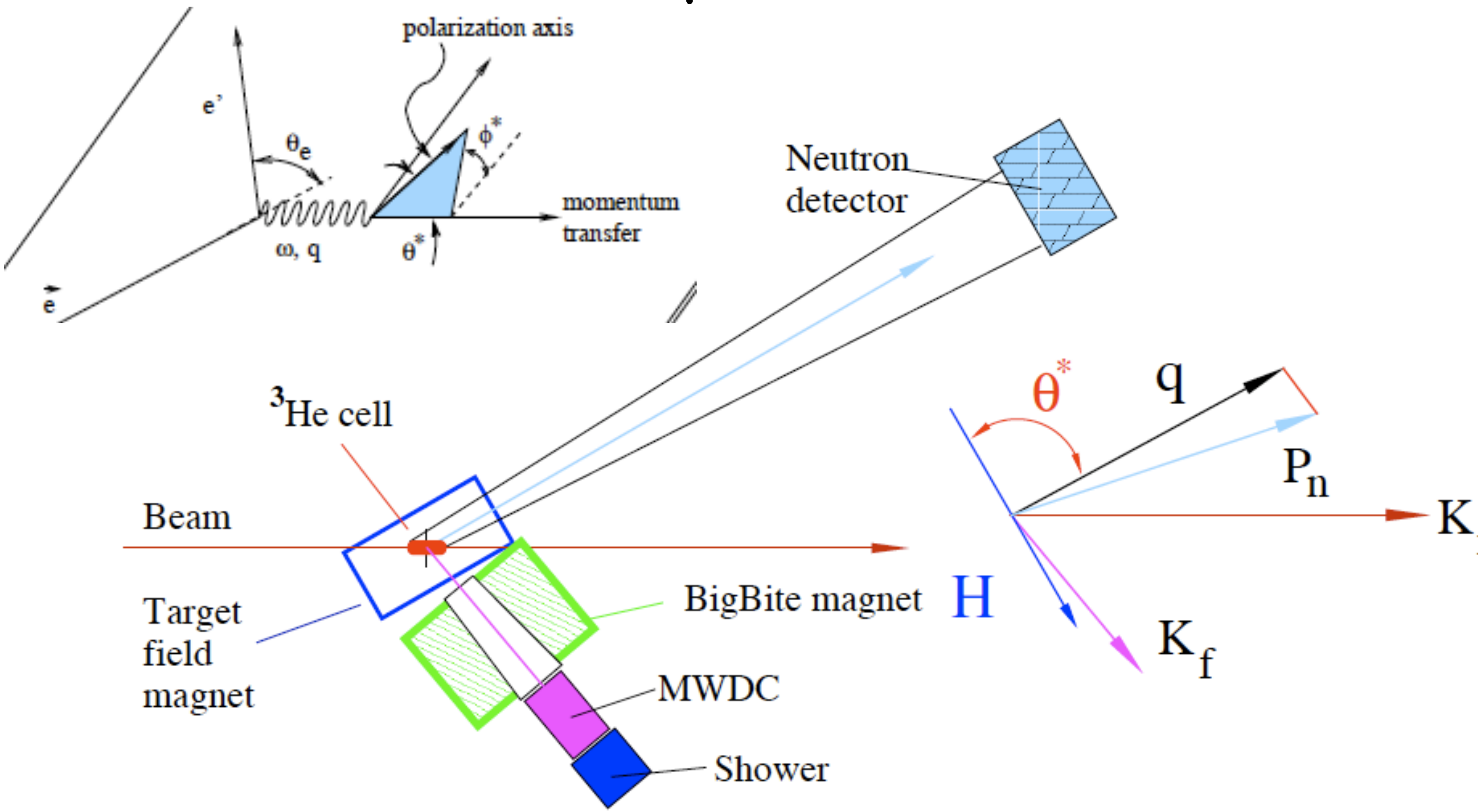
Hall A GEn experiment (E02-103)



$$^3\overrightarrow{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{n})$$

- BigBite - large acceptance spectrometer, measures $\vec{e}'$
- Neutron arm - matches BB acceptance, measures neutron momentum through ToF, performs nucleon charge ID

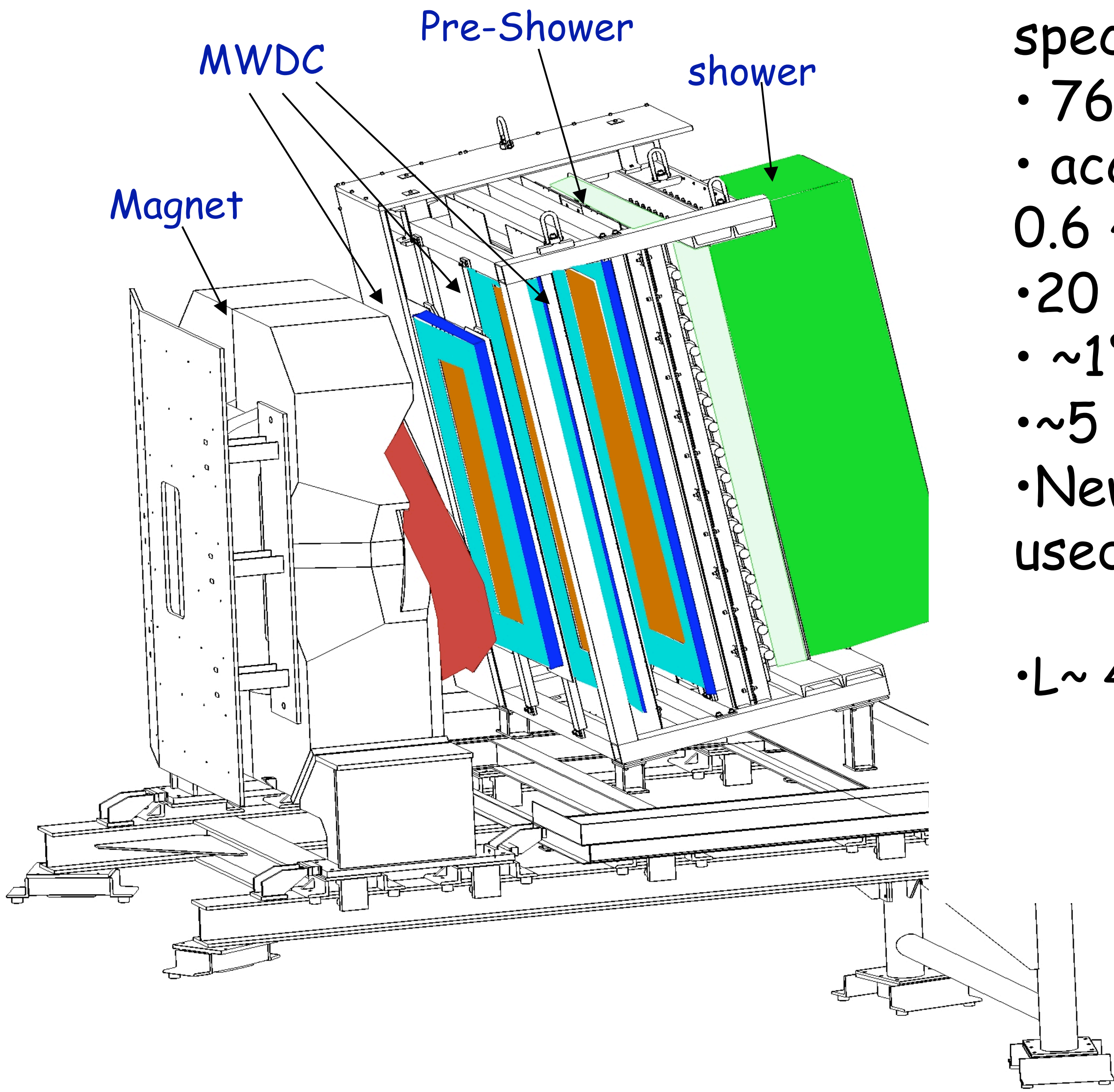
Hall A GEn experiment (E02-103)



$$A_{phys} = A_{\perp} + A_{\parallel} = \frac{a \cdot (G_E/G_M) \sin\theta^* \cos\phi^*}{(G_E/G_M)^2 + c} + \frac{b \cdot \cos\theta^*}{(G_E/G_M)^2 + c}$$

Here a, b and c are solely functions of kinematic factors (and not θ^* or Φ^*)

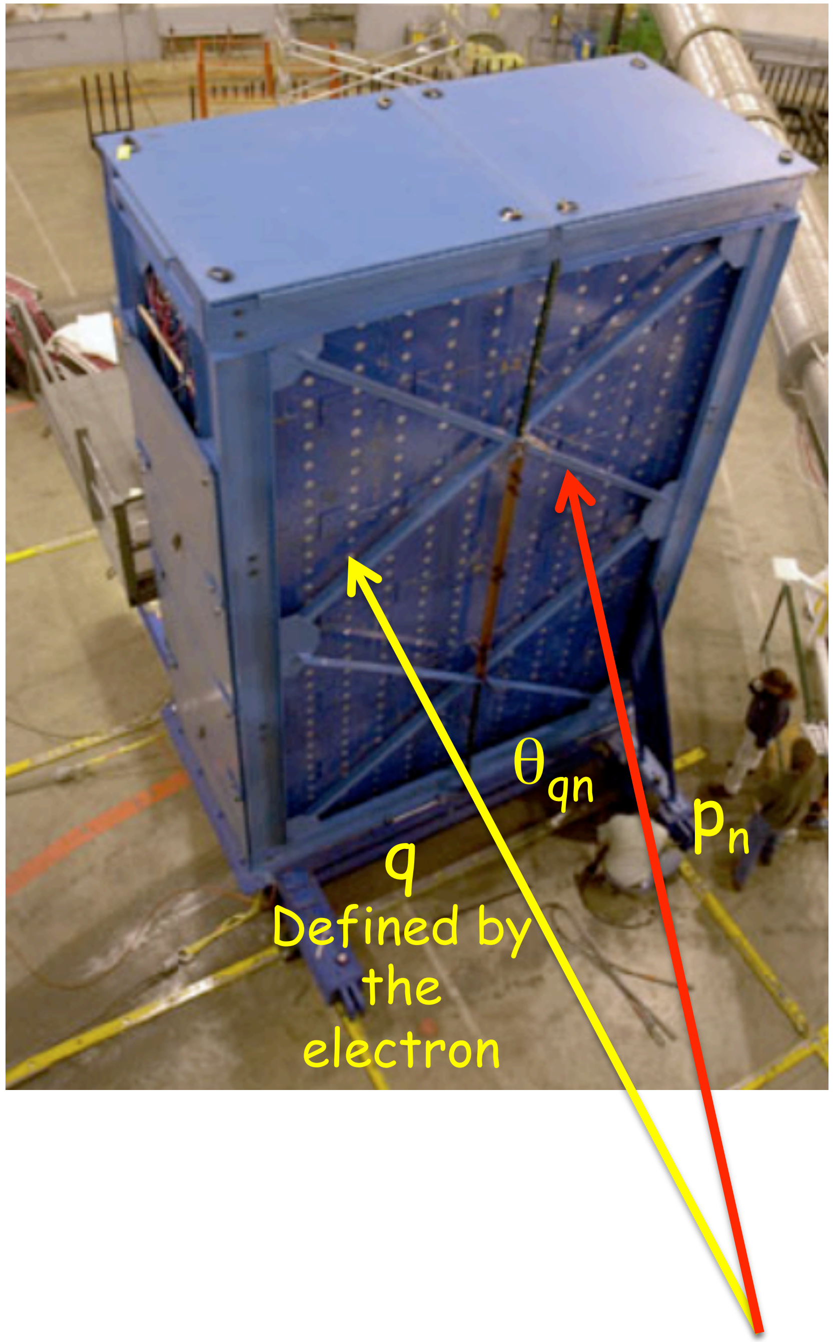
Bigbite Spectrometer



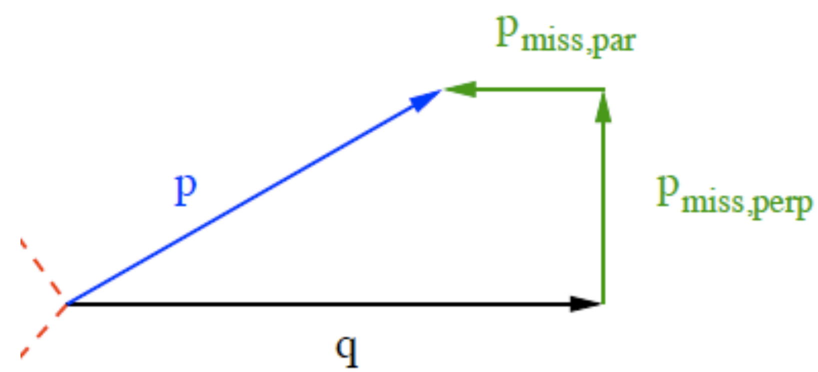
- Non-focusing large angular and momentum acceptance spectrometer
- 76 msr over 40 cm of target.
- accepting electrons between 0.6 ~ 1.6 GeV
- 20 MHz/plane on MWDC.
- ~1% momentum resolution
- ~5 mm y_tg resolution
- New detector package, first used for Gen

- L~ 4.5 x 10^{36} $cm^{-2}s^{-1}$

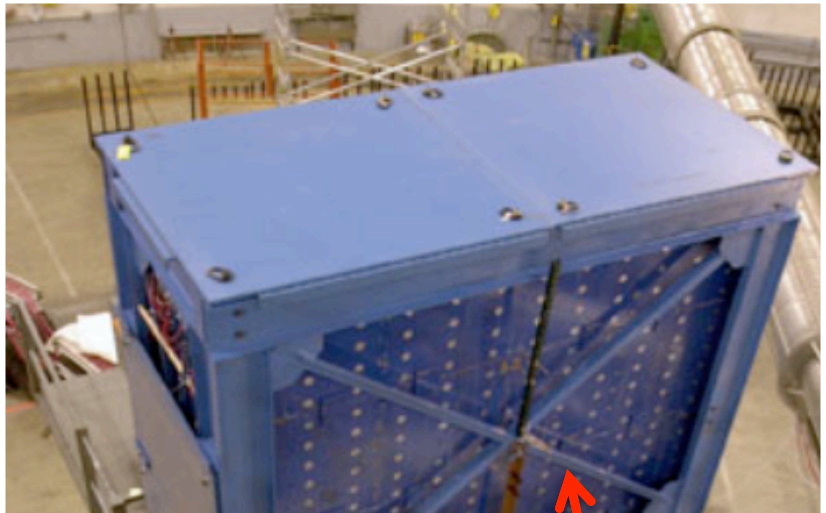
Neutron Detector -BigHAND



- Match BigBite solid angle in QE kinematics.
- Flight-path ~ 10 m
- 1.6 x 5 m2 active area.
- 7 layers of sintilator bars + 2 layers of veto bars.
- time resolution ~ 0.3 ns.
- θ_{qh} is very effective in suppressing background:



Neutron Detector -BigHAND



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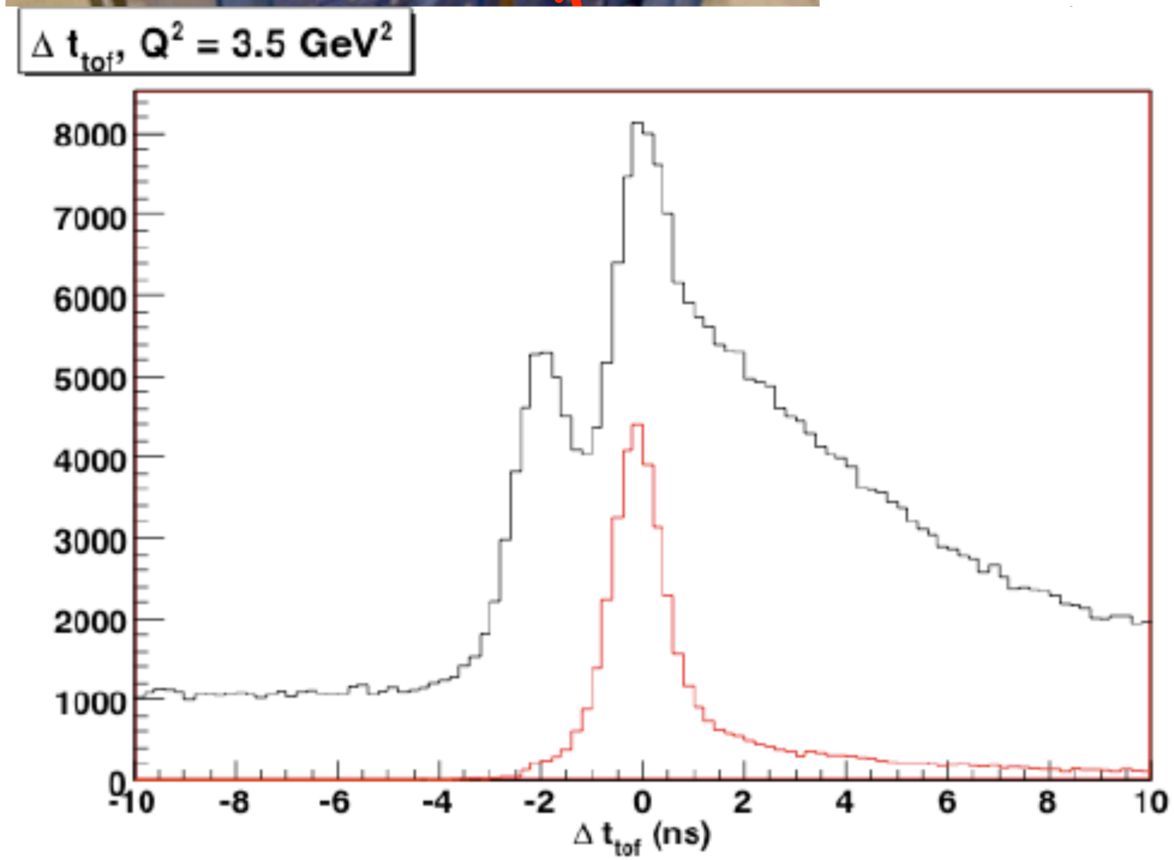
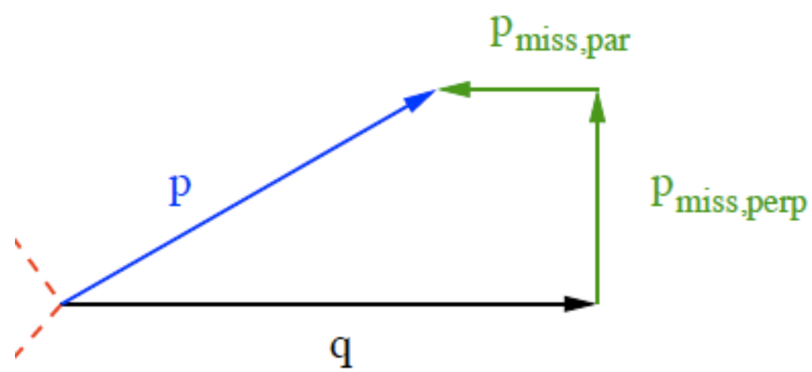
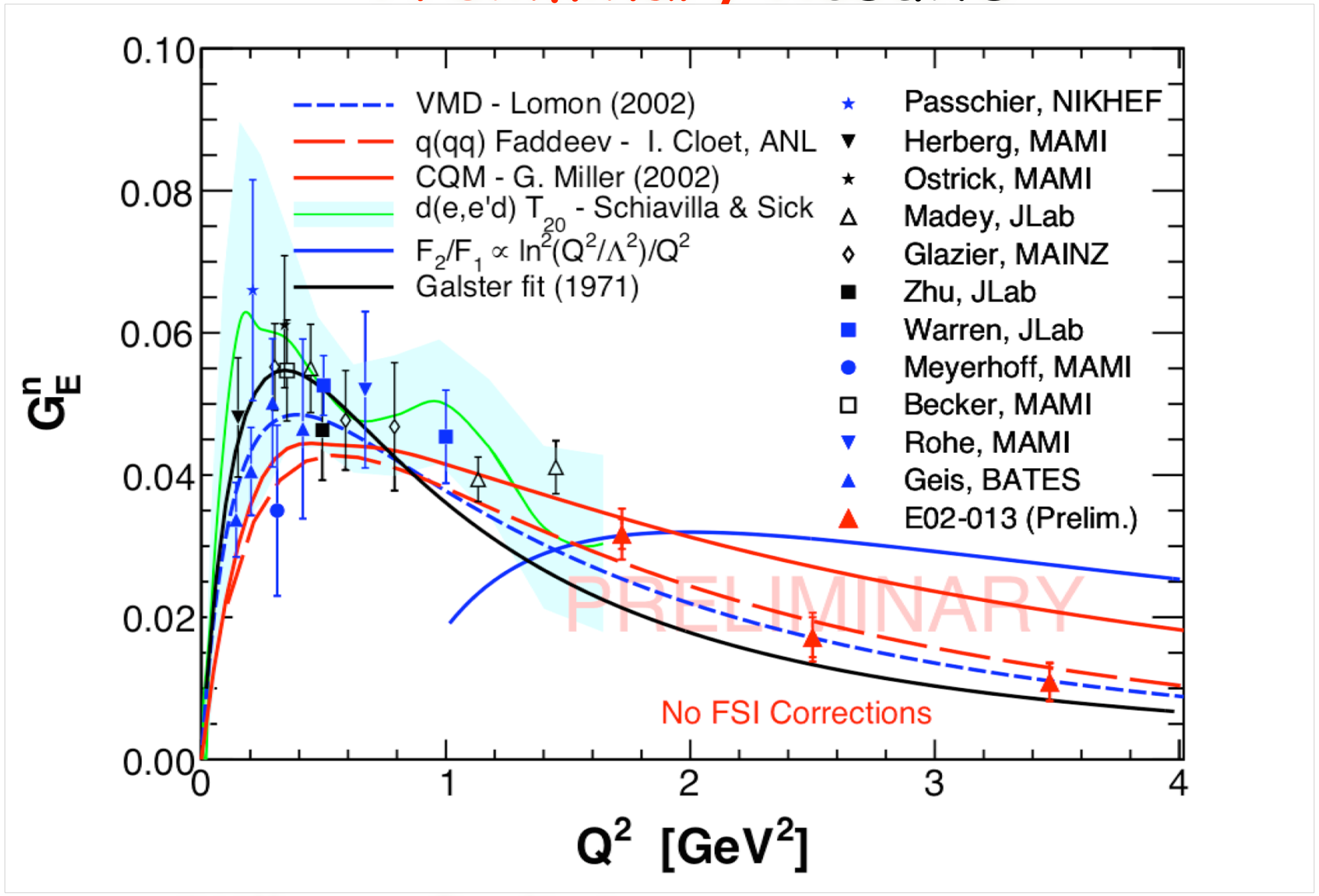




Preliminary Results



Still very Preliminary:

still to be done:

- Neutron detector simulation need to be finalized: will select final cuts based on this
- Nuclear corrections – neutron polarization and FSI

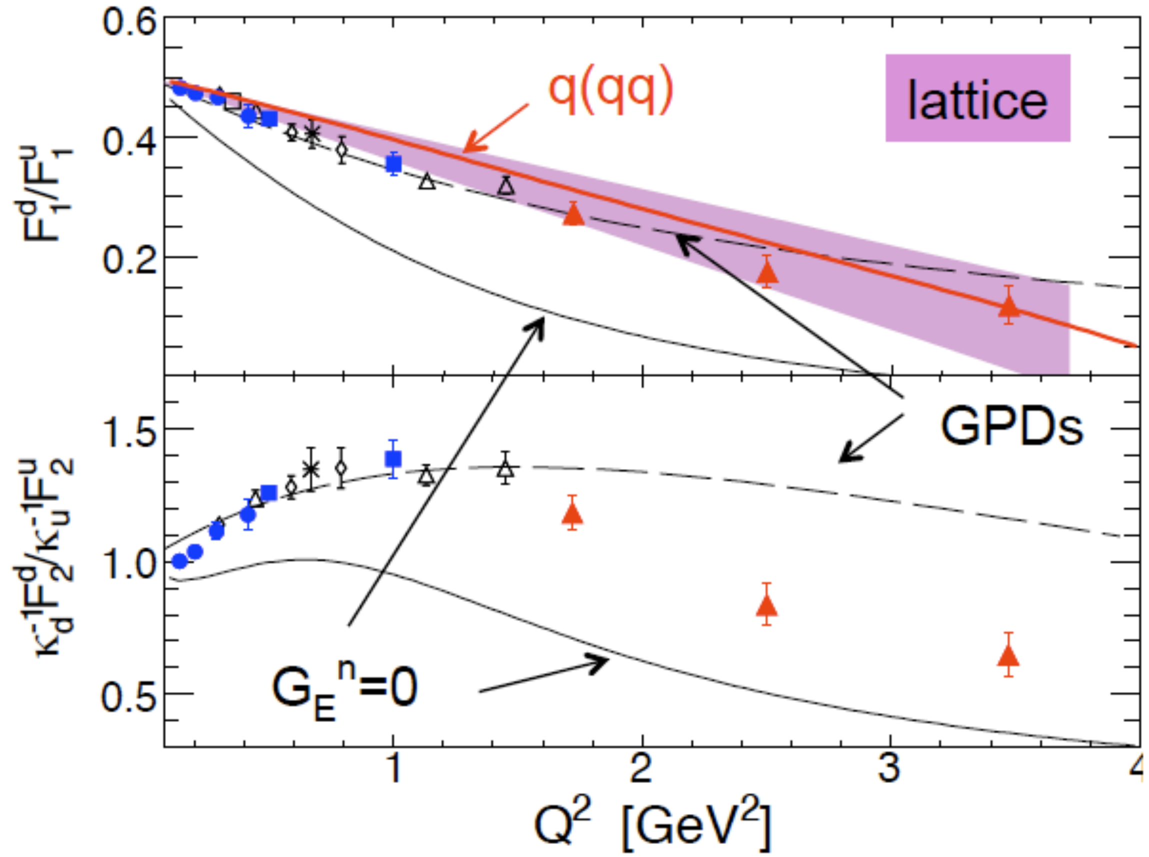
$F_1^d{}_{(2)}/F_1^u{}_{(2)}$ with proton and neutron FFs

$$F_1 = \frac{G_E + \tau G_M}{1+\tau}$$

$$F_2 = -\frac{G_E - G_M}{1+\tau}$$

$$F_1^u = 2\,F_{1p} + F_{1n}$$

$$F_1^d = 2\,F_{1n} + F_{1p}$$

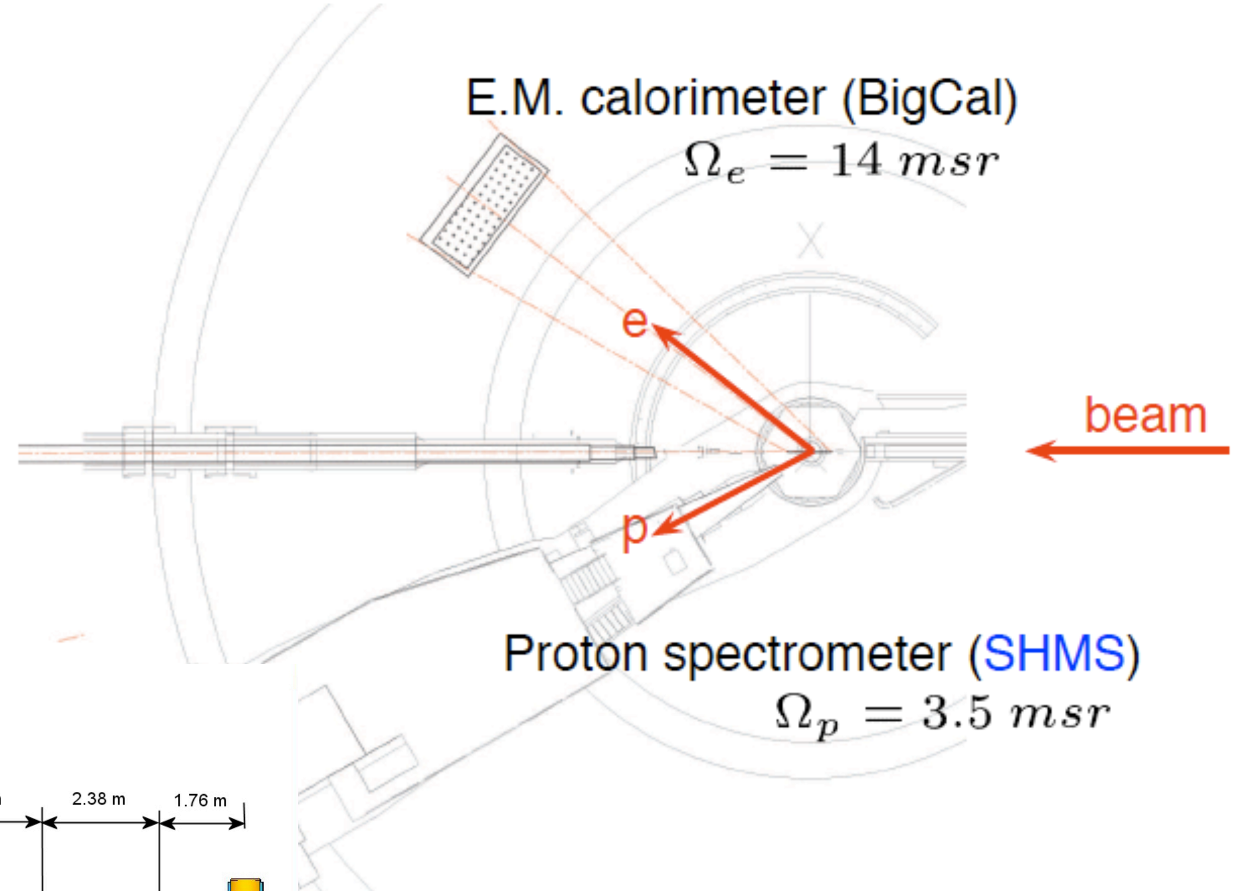


still to be done:

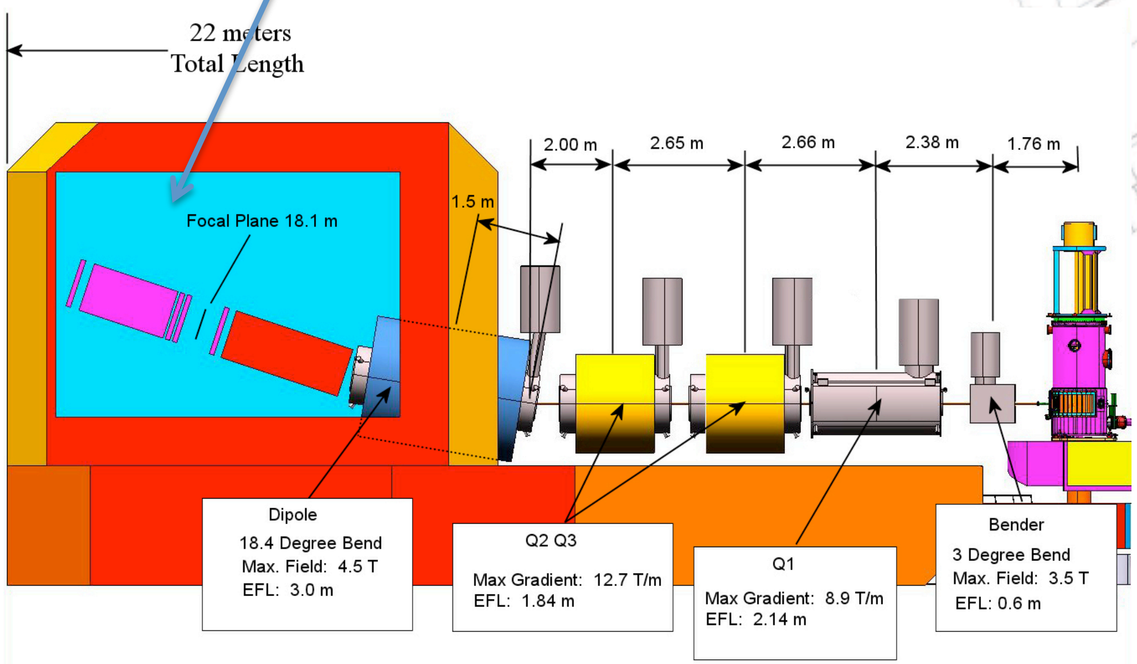
- Neutron detector simulation need to be finalized: will select final cuts based on this
- Nuclear corrections – neutron polarization and FSI

High Q^2 form factor measurements with CEBAF 12 GeV beam

GEp/GMp up to Q2 = 13 GeV2 SHMS - Gep-IV

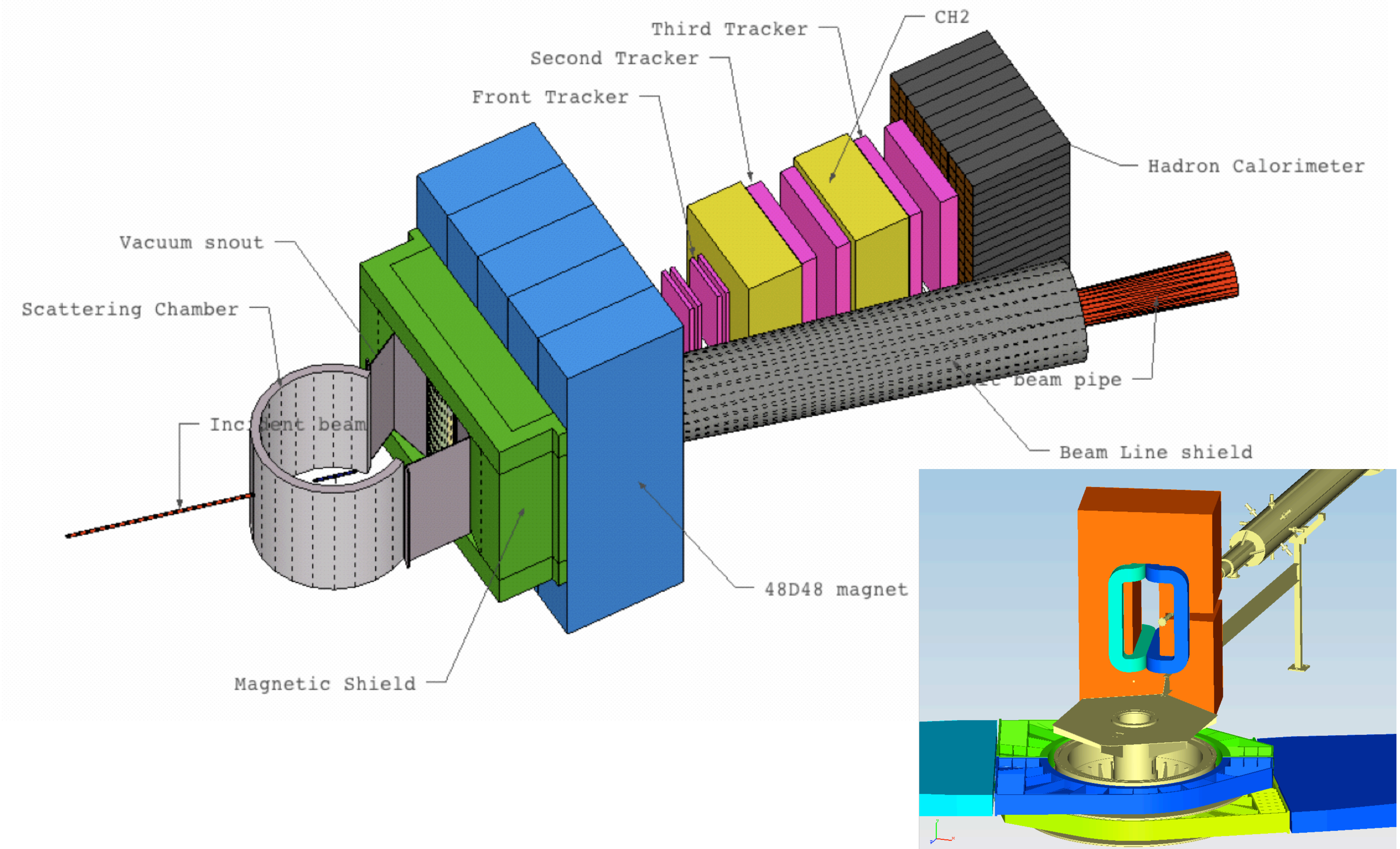


Install a double FPP (replacing the gas cerenkov)

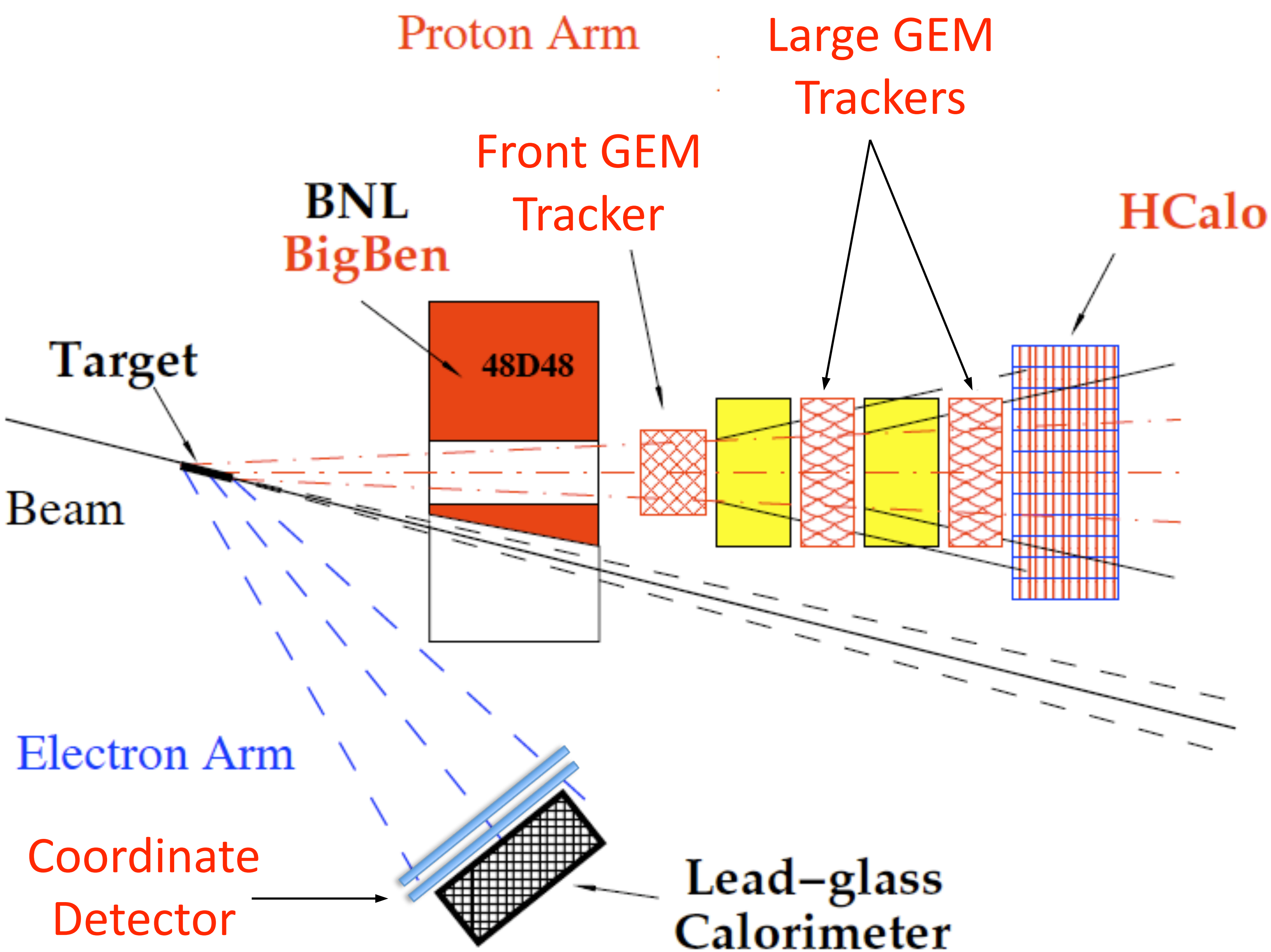


- Proven polarization transfer measurement – similar to Gep I-III
- Focusing spectrometer: cleanly identifies elastic protons, low rates at FPP
- Very small acceptance: not possible to go to higher Q2

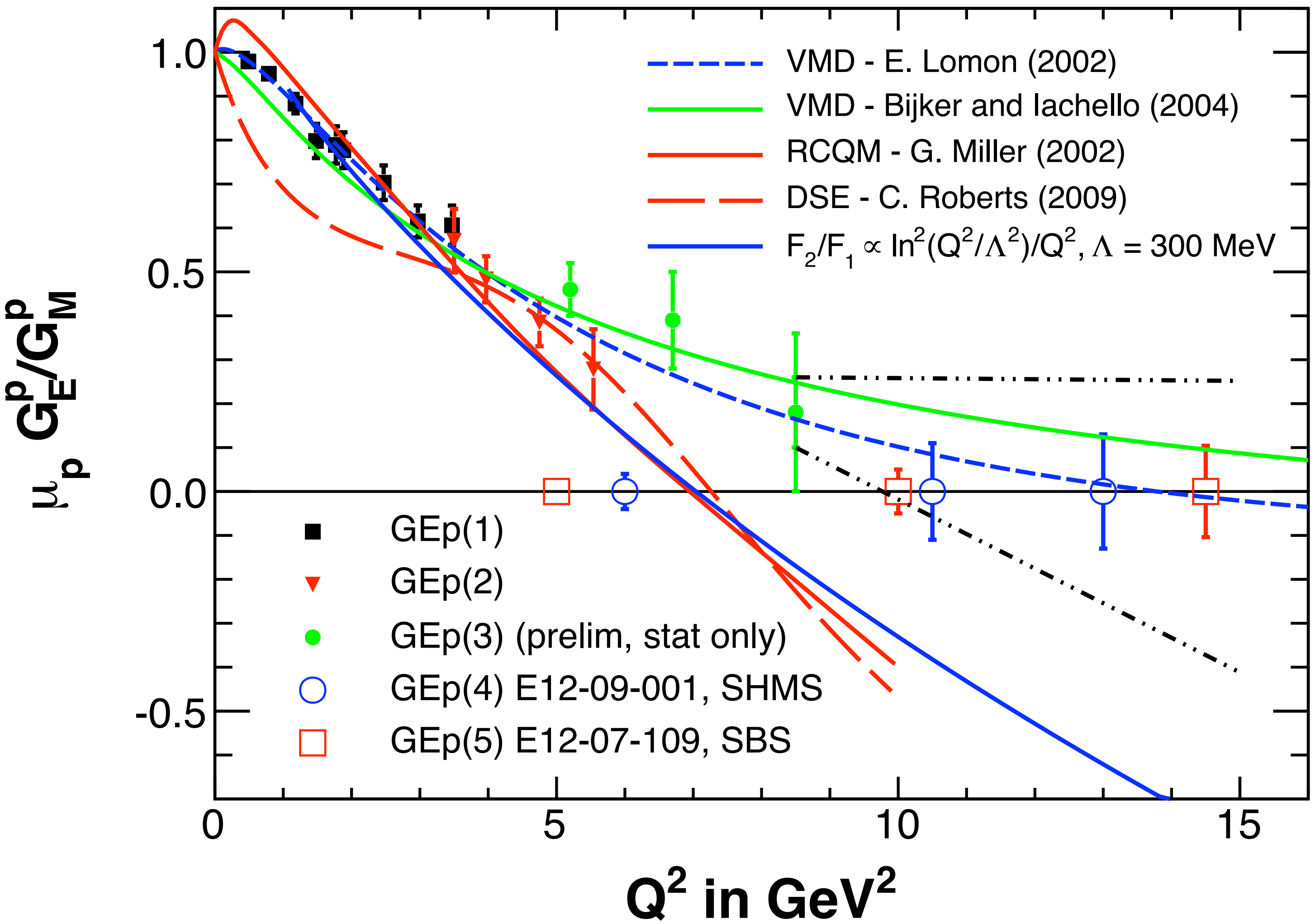
GEp, GEn and GMp measurements with Super-Bigbite spectrometer in Hall A



GEp/GMp up to Q2 = 15 GeV2 with SBS

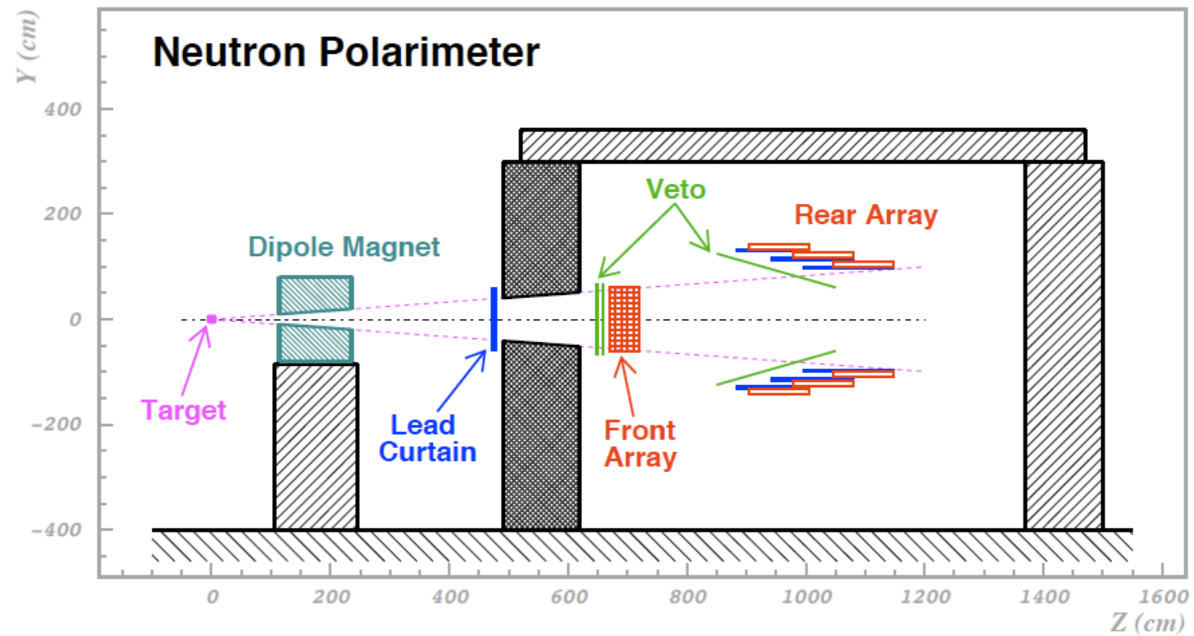


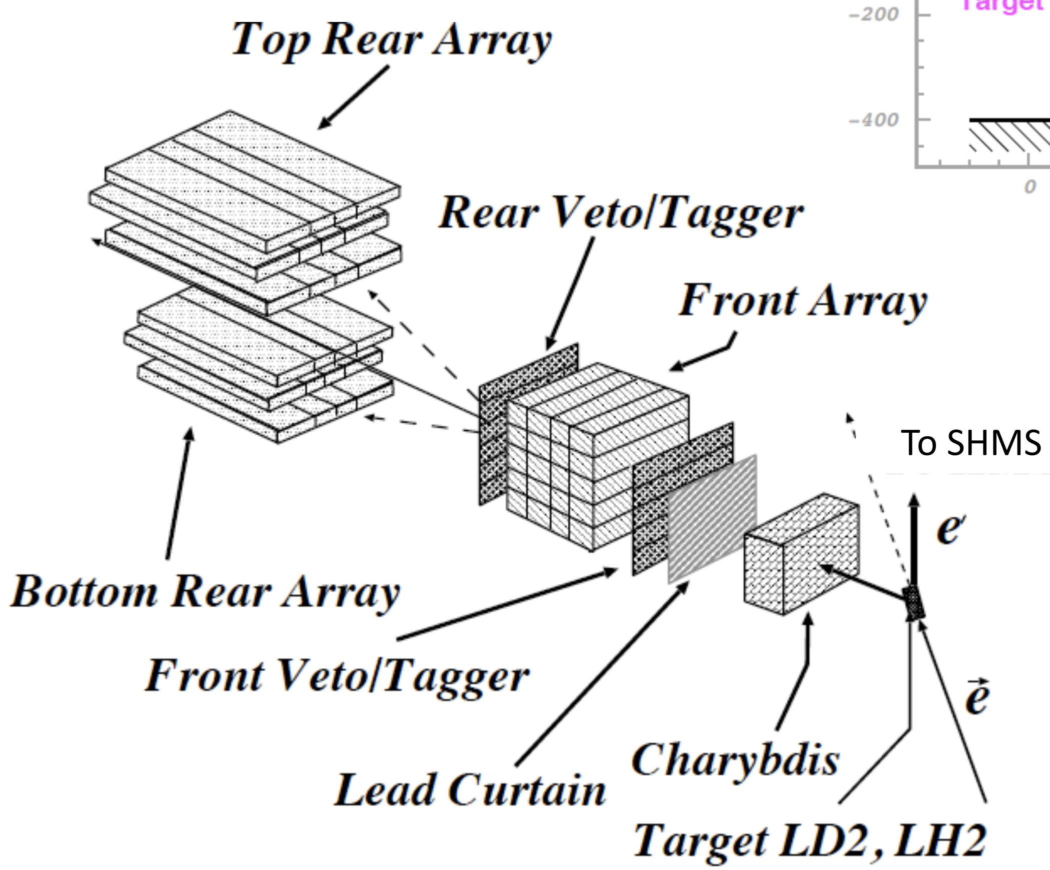
GEp/GMp up to Q^2 = 15 GeV^2 with SBS



High Q2 GEn Measurements with 12 GeV beam

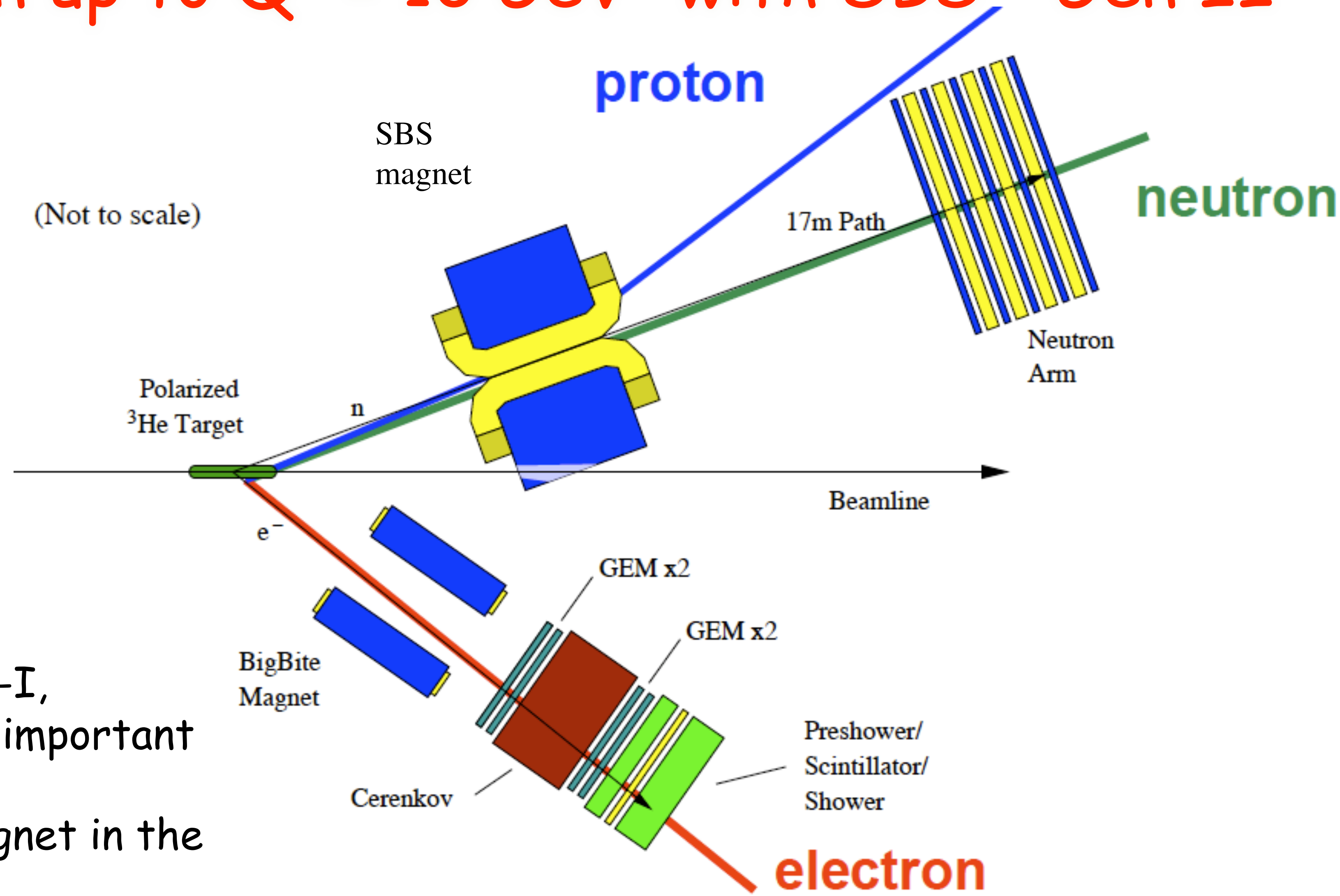
E12-09-006: GEn up to Q2= 7 GeV^2 using recoil polarimetry (similar to E93-038)





Once again, statistics severely limited due to Very small acceptance of HSMS; not possible to go to higher Q2

GEn/GMn up to Q^2 = 10 GeV^2 with SBS - Gen II



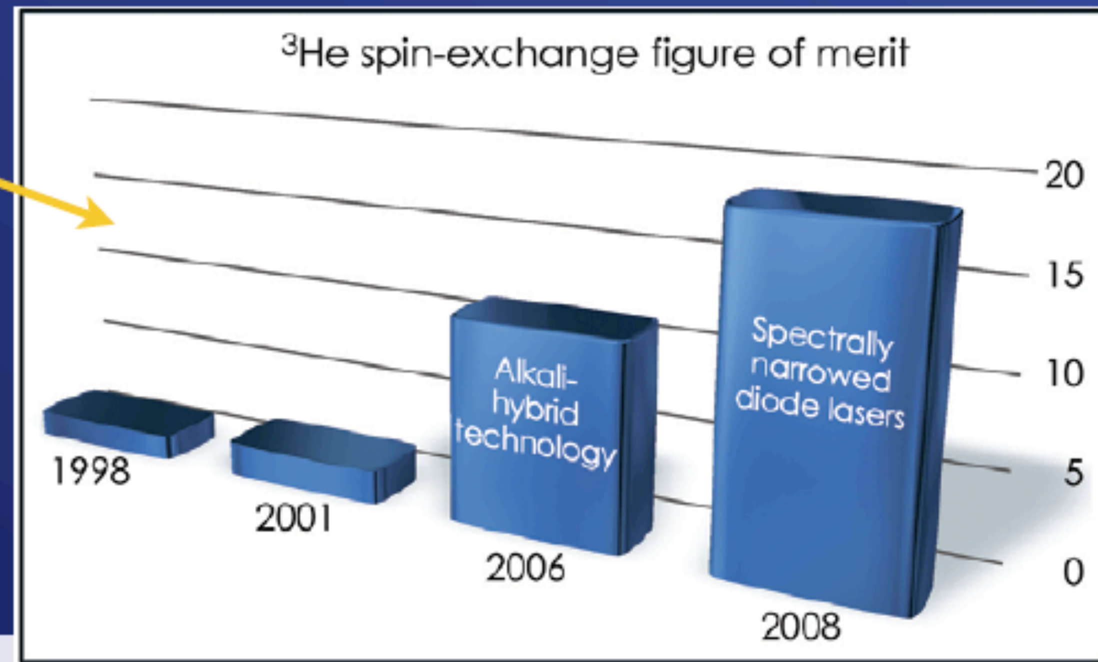
Similar to GEn-I,
But with some important changes:

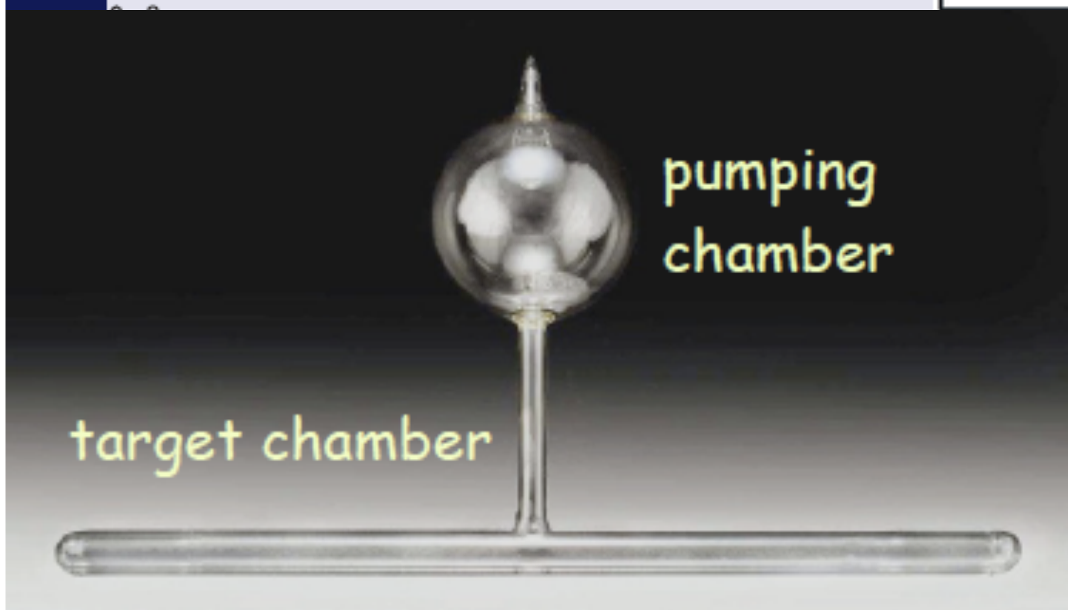
- Sweeping magnet in the Neutron arm
- Very high rate capable GEM-based Electron tracker + Cerenkov
- High-Luminosity pol. 3He target: projected 60% polarization with 60 μA beam

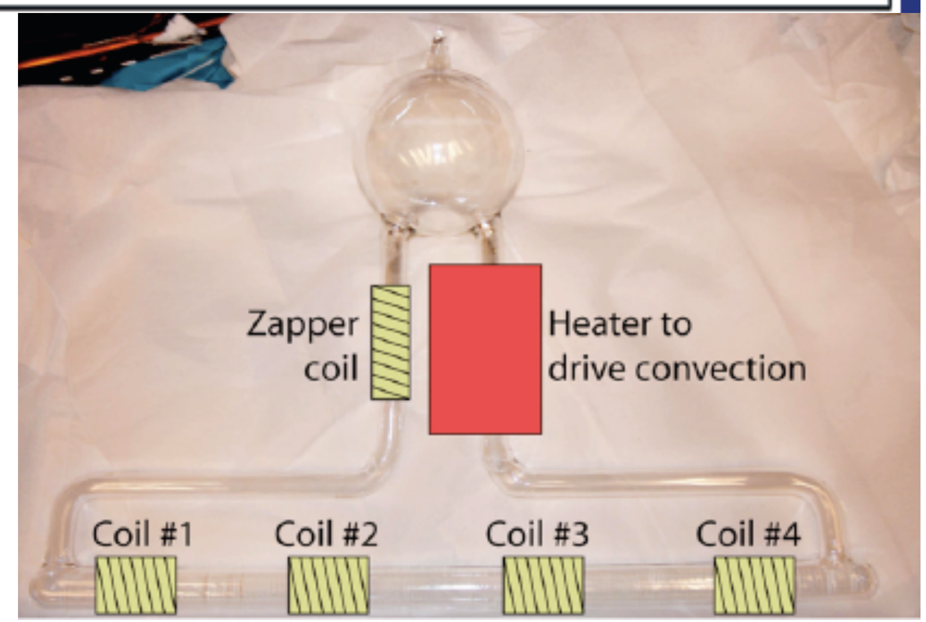
Spin-exchange target will take advantage of huge improvements in F.O.M.

Target evolution at JLab

Shown is the F.O.M. defined as spins polarized per second weighted by polarization^2

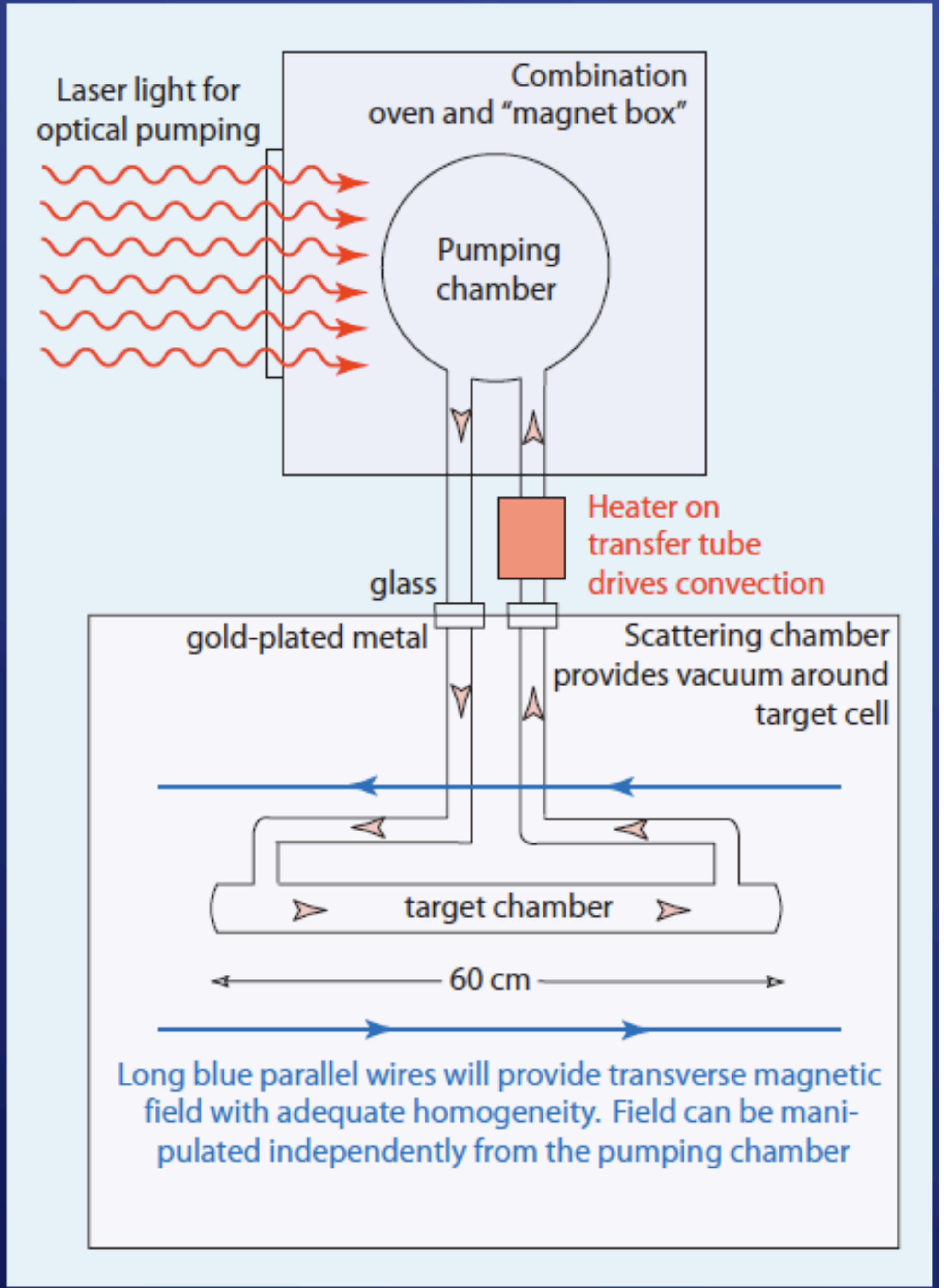




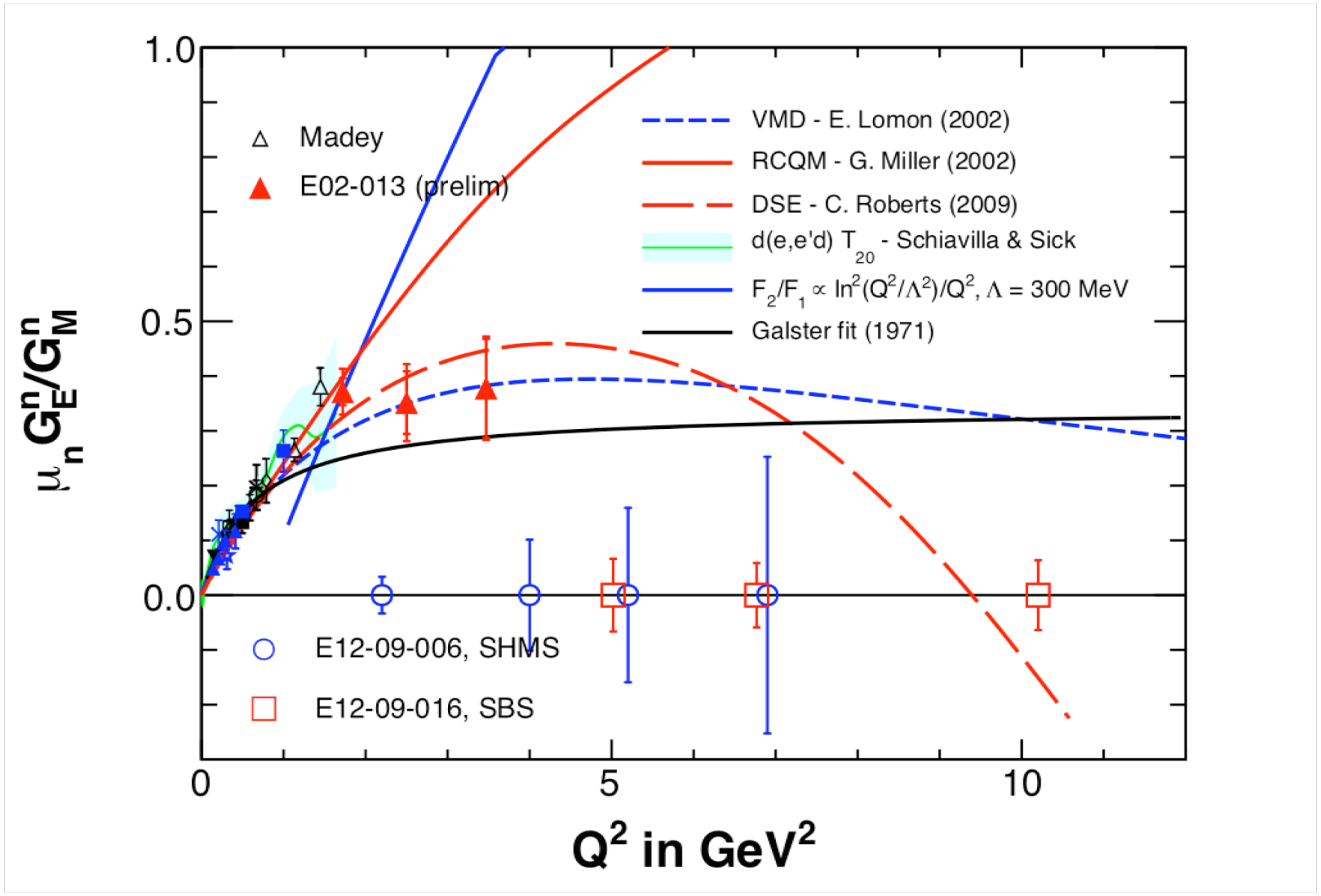


Very-high-luminosity polarized ^{3}He target

- Large pumping chamber provides ample reservoir of polarized spins to replenish the effects of intense electron beam.
- Convection-driven gas flow insures mixing times of minutes or less.
- Metal target cell (gold coated) ensures the target can physically tolerate the beam.
- Keeping the target cell in vacuum ensures the detectors see a manageable overall luminosity.
- Separating the pumping chamber and the target chamber by arbitrary distances greatly simplifies the magnetic field.

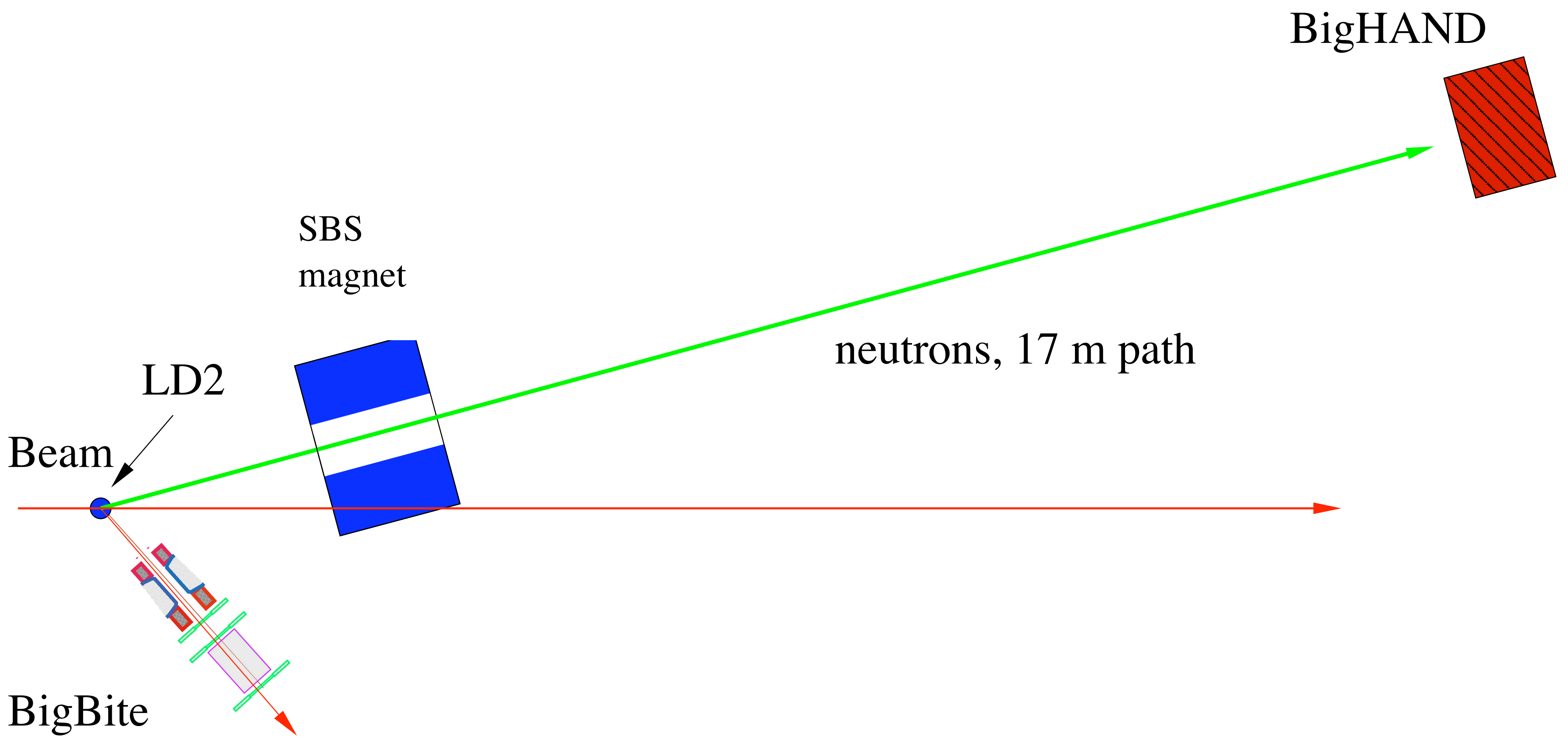


GEn/GMn up to Q^2 = 10 GeV^2 with SBS - Gen II



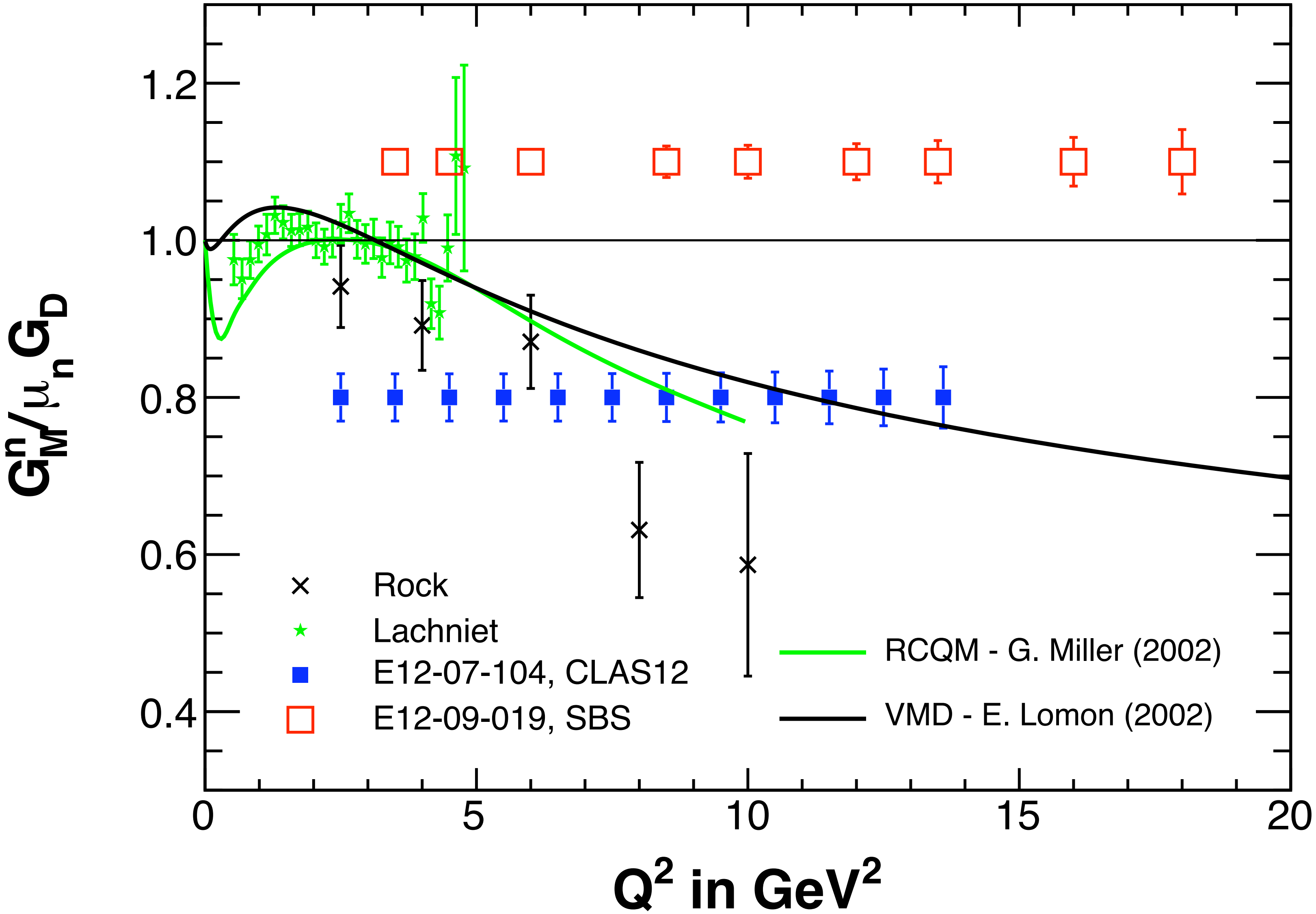
The SBS Gen experiment will provide clear discrimination between models (all of which seem to do an OK job fitting to high Q^2 GEp data)

GMn up to Q^2 = 18 GeV^2 with SBS - Gen II



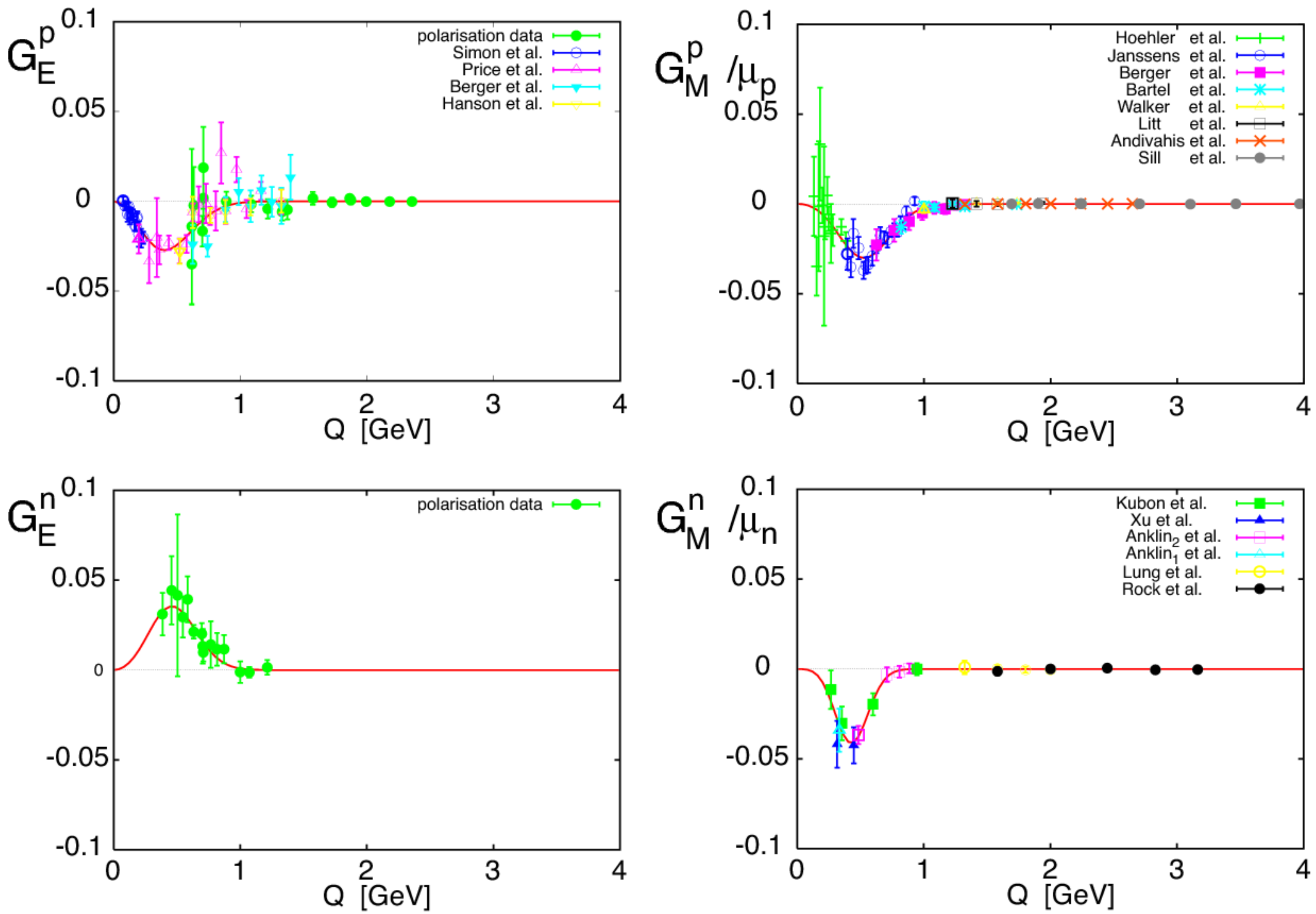
- Use the ratio method:
D(ee'n)/D(ee'p)
- Use SBS magnet to kick the QE protons up; so they can be clearly separated from QE neutrons
- Both QE protons and neutrons are detected; for a given q-vector, the expected location of neutron is different from that of the proton
- Also has a veto-plane to assist with n/p identification

GMn up to Q^2 = 18 GeV^2 with SBS - Gen II



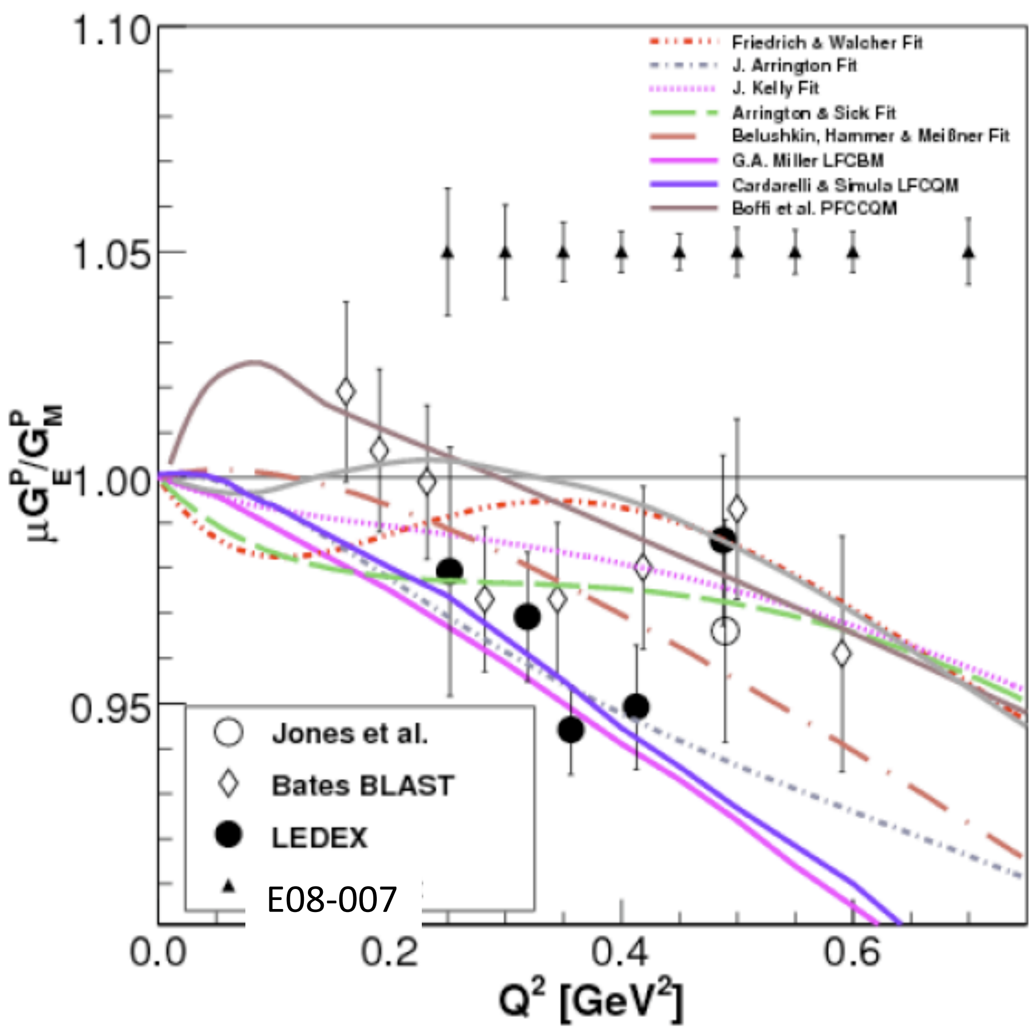
High precision proton form factor data at low Q^2

- 2003 – Fit by Friedrich & Walcher Eur. Phys. J. A17, 607 (2003):
- Smooth dipole form + "bump & dip" around Q2 ~ 0.1 GeV^2
- All four FFs exhibit similar structure at small momentum transfer.
- Proposed interpretation: effect of pion cloud peaked around ~ 0.9 fm



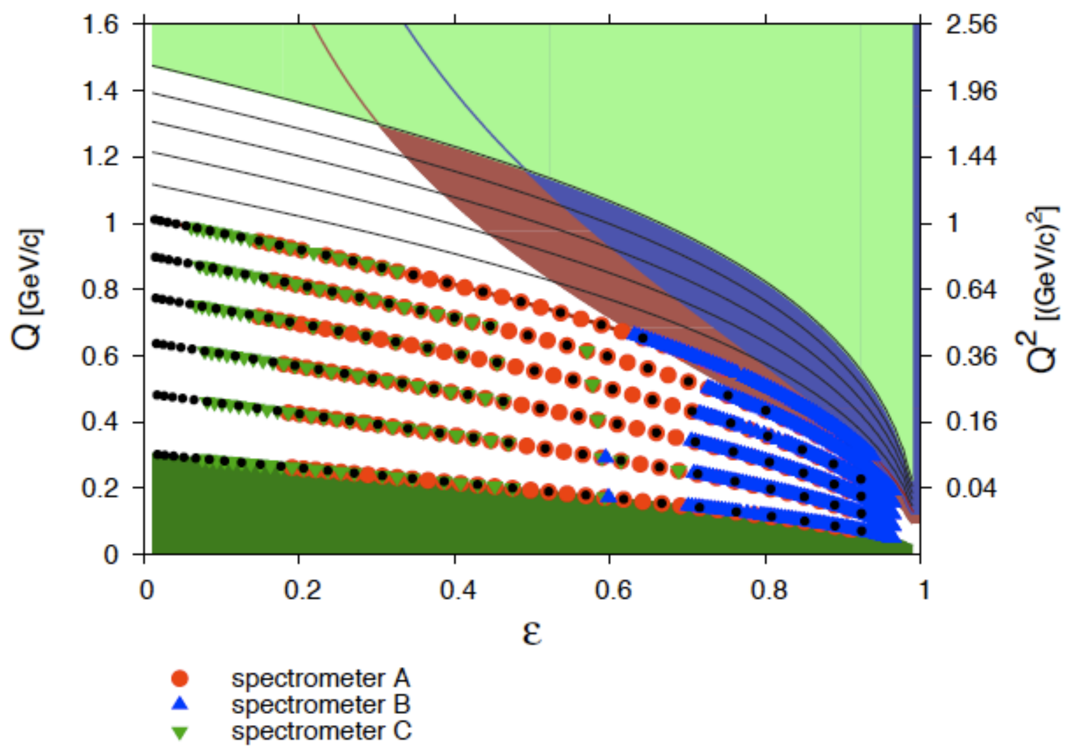
High precision proton form factor data at low Q^2

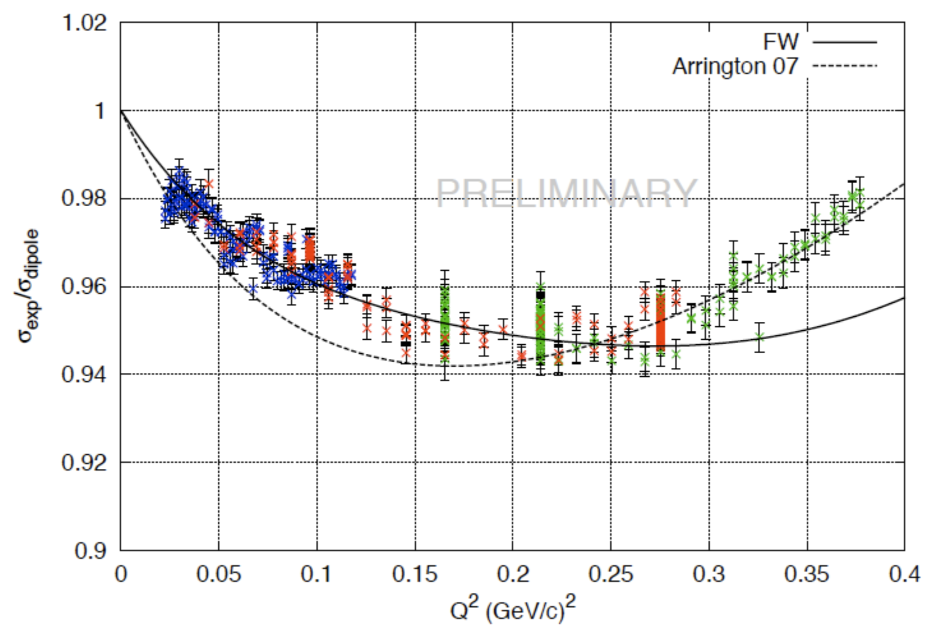
- BLAST and Hall A LEDEX result clearly show $\mu GEp/GMp < 1$ for Q2 ~ 0.3-0.4 GeV^2.
- But these does now support F&W analysis; different structure.
- New high precision experiment E08-007 in Hall A: results expected soon.



Mainz A1 high precision proton form factor experiment at low Q^2

- High precision Rosenbluth separation.
- ~ 1000 settings





Summary

• Exciting and very active hadron form factor program thanks to high quality polarized beams, high-power polarized targets, large neutron detectors and high efficiency polarimeters.

• Electro-Magnetic form factors: high Q2 precision data available

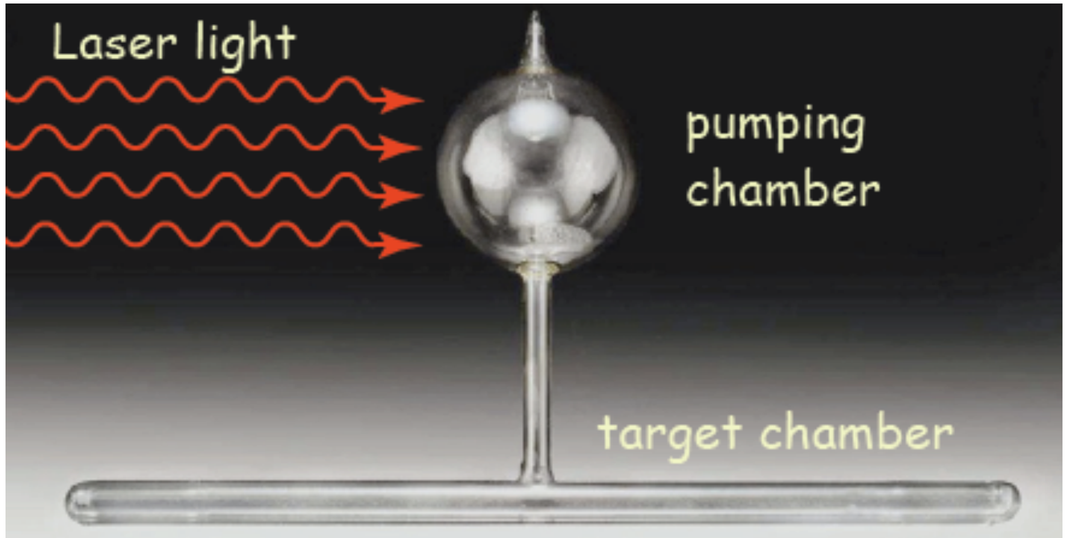
  • GEp: up to 8.5 GeV2; discrepancy between polarization and Rosenbluth data may be due to 2-photon exchange.
  • GEn: up to 3.5 GeV2
  • GMn: up to 5 GeV2

• With 12 GeV upgrade these ranges can be extended to 15, 10 and 18 GeV2.

• Stringent tests on theoretical models.

• New high precision low Q^2 data: insight on Pion cloud ?

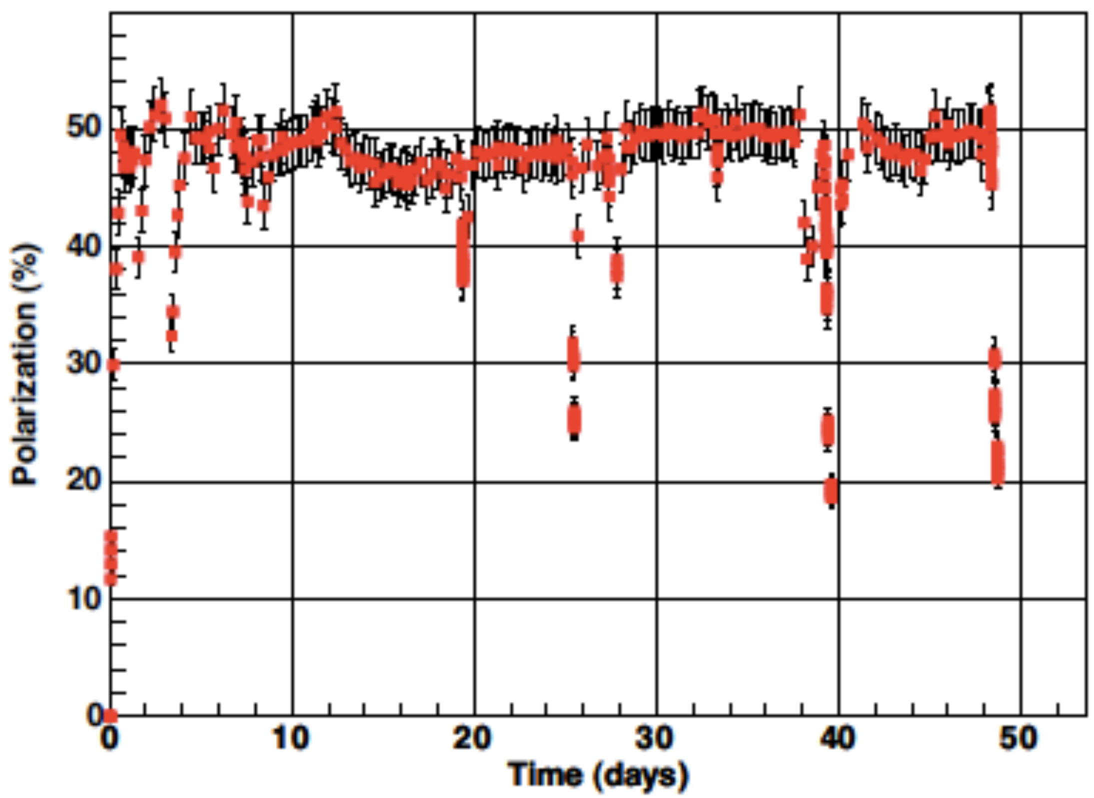
• Also a very active program measuring strange form-factors.



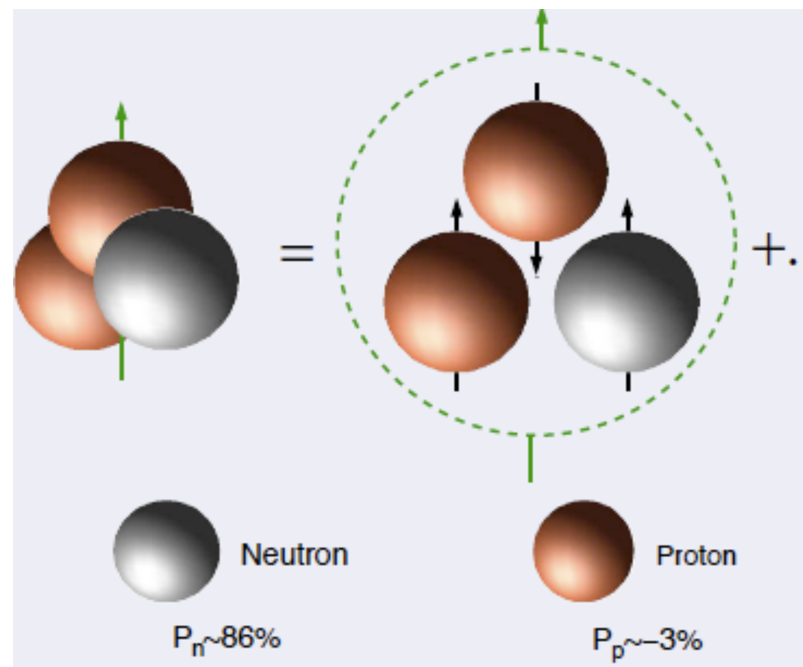
Polarized 3He target

- based on spin exchange optical pumping
- Use of new Rb+K hybrid mixture to achieve higher spin exchange efficiency

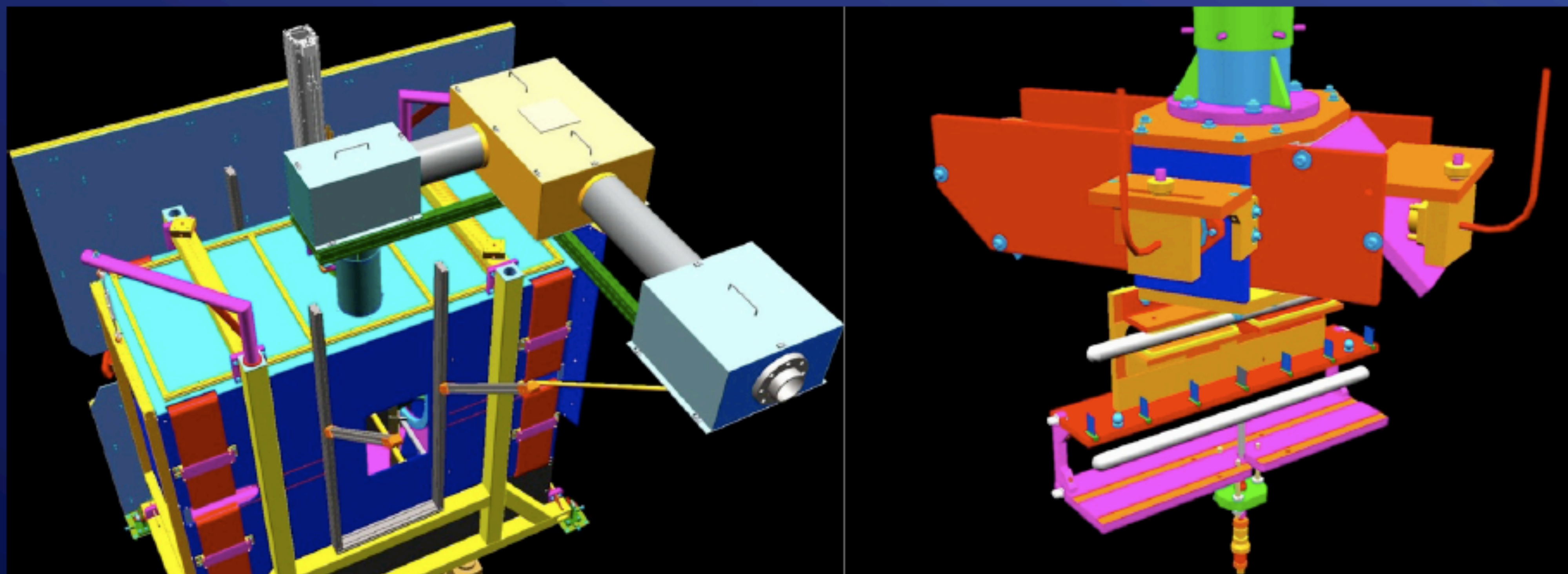
$$\vec{\gamma} \rightarrow \mathrm{Rb} \rightarrow \mathrm{K} \rightarrow {}^{3}\mathrm{He}$$



- ~ 50% polarization achieved for most of running

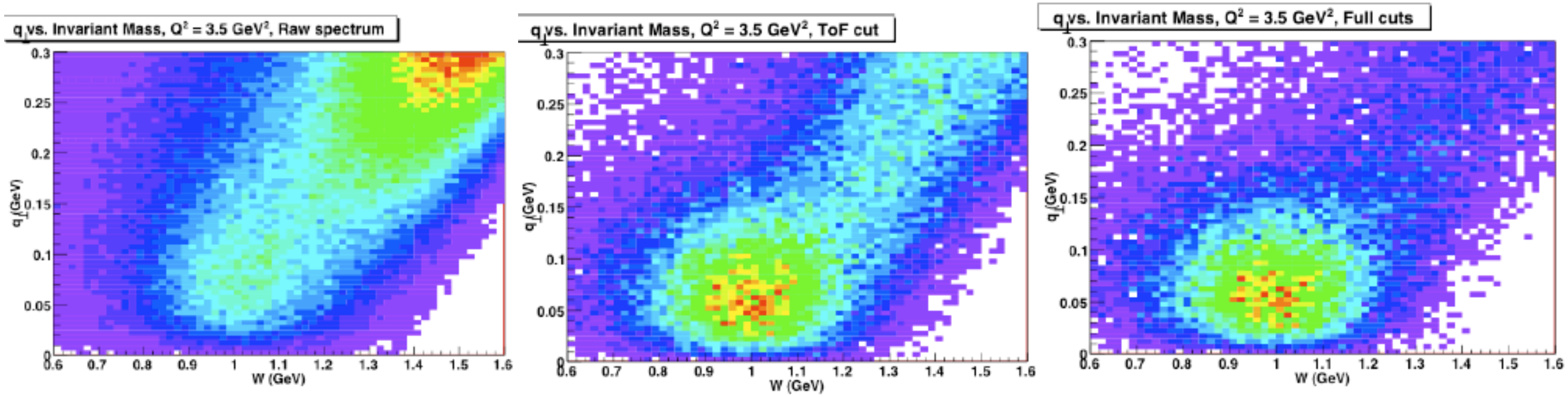


GEN required a novel implementation of ^{3}He spin-exchange technology



- Needed to be extremely close to the open-geometry BigBite magnet.
- Needed magnetic field inhomogeneities no worse than around 10 mG/cm
- "Iron Box" magnet design permitted target/BigBite distance of ~ 1m.
- Fiber-optic based laser/optics design greatly reduced space requirements.

Analysis



- Also a cut on missing mass of 3He(e,e',n)X
- Use a MC simulation to evaluate inelastic contribution: very small
- Asymmetry corrected for:
  - p->n conversion in shielding
  - Accidental events
  - A_par contribution and A_proton
  - Target and beam polarization
  - FSI for 3He(e,e',n) – not done yet.