New Trends in Hadronic Physics at JLab:

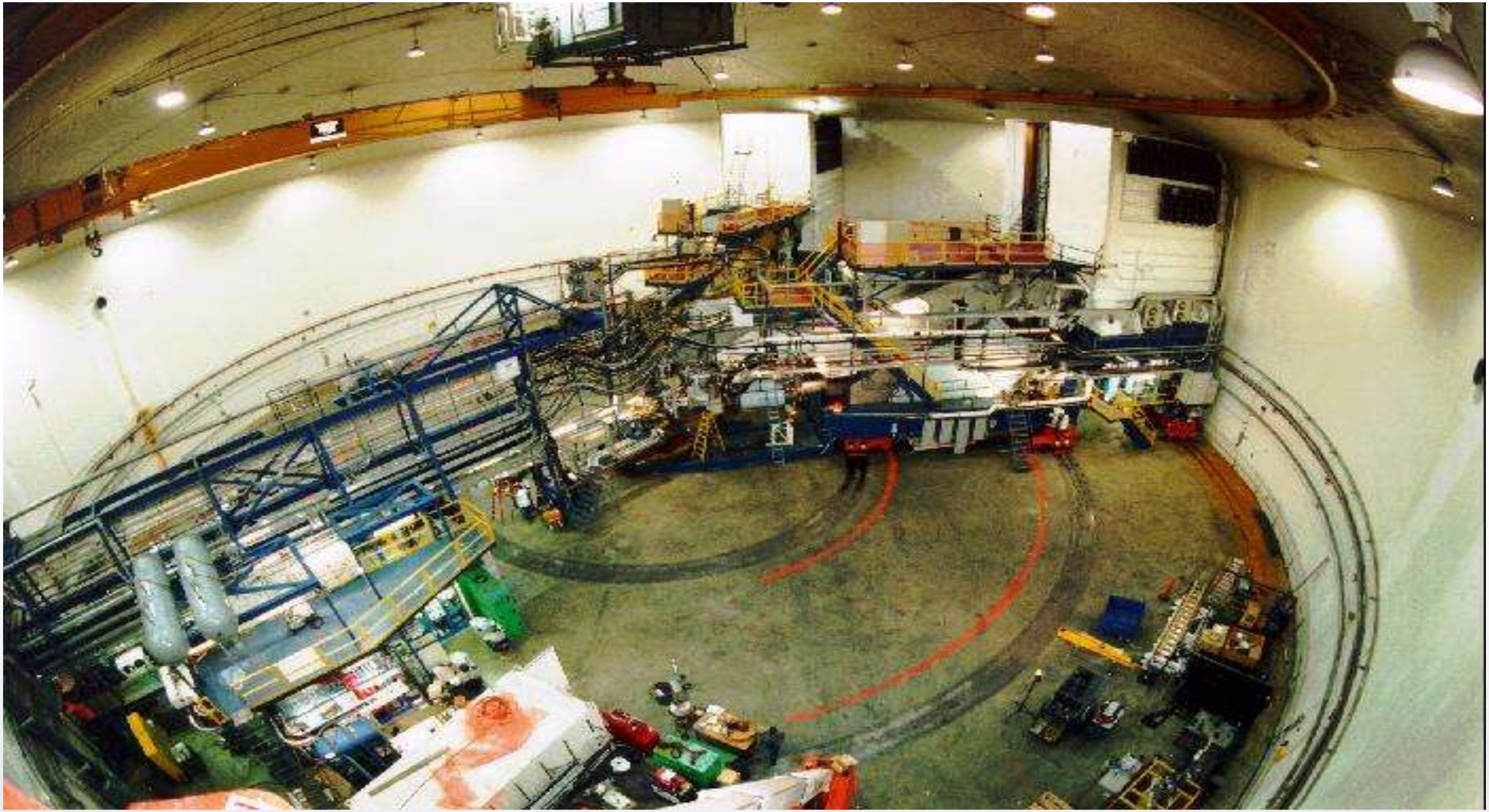
some future experiments in Hall A.

Vincenzo Bellini and INFN/CT Hall A Collaborators
Department of Physics and Astronomy, University of Catania
On behalf of the JLab Hall A Collaboration

--Content--

- Nucleon form factor studies in Hall A.
- Elastic Scattering parity-violating asymmetry in Hall A

JLab Experimental Hall A



This photo and many slides provided by R. Michaels, B. Wojtsekhowski, et al.

Nucleon Form Factor Studies in Hall A at JLab

--Outline--

- The physics of the nucleon form factors, and what is most important.
- The Super Bigbite form factor experiments.
- How the Super Bigbite project is optimized to access the highest-impact physics.

The ground-state electromagnetic form factors: an essential part of the description of the nucleon

Rosenbluth,1950 Hadron current, one-photon approximation

The hadronic current:

$$\mathcal{J}^{\mu}_{\text{hadronic}} = ie\overline{N}(p')\left[\gamma^{\mu}\underset{\substack{\uparrow\\ \text{Dirac FF}}}{F_1(Q^2)} + \frac{i\sigma^{\mu\nu}q_{\nu}}{2M}\underset{\substack{\uparrow\\ \text{Pauli FF}}}{F_2(Q^2)}\right]N(p)$$

Sachs, 1962 Does a nucleon have a core ?

The Sachs FFs:

$$G_E = F_1 - \tau F_2 \quad \text{and} \quad G_M = F_1 + F_2$$

where

$$\tau = Q^2/4M^2_{\text{nucleon}}$$

$$d\sigma = d\sigma_{NS}\,\underline{\left\{\varepsilon(G_E)^2 + \tau(G_M)^2\right\}}\cdot\left[1 + h_e A(G_E, G_M)\right]$$

$$A = A_{\perp} + A_{\parallel} = \frac{a\cdot G_E G_M \sin\theta^{\star}\cos\phi^{\star}}{G_E^2 + c\cdot G_M^2} + \frac{b\cdot G_M^2\cos\theta^{\star}}{G_E^2 + c\cdot G_M^2}$$

$\uparrow$

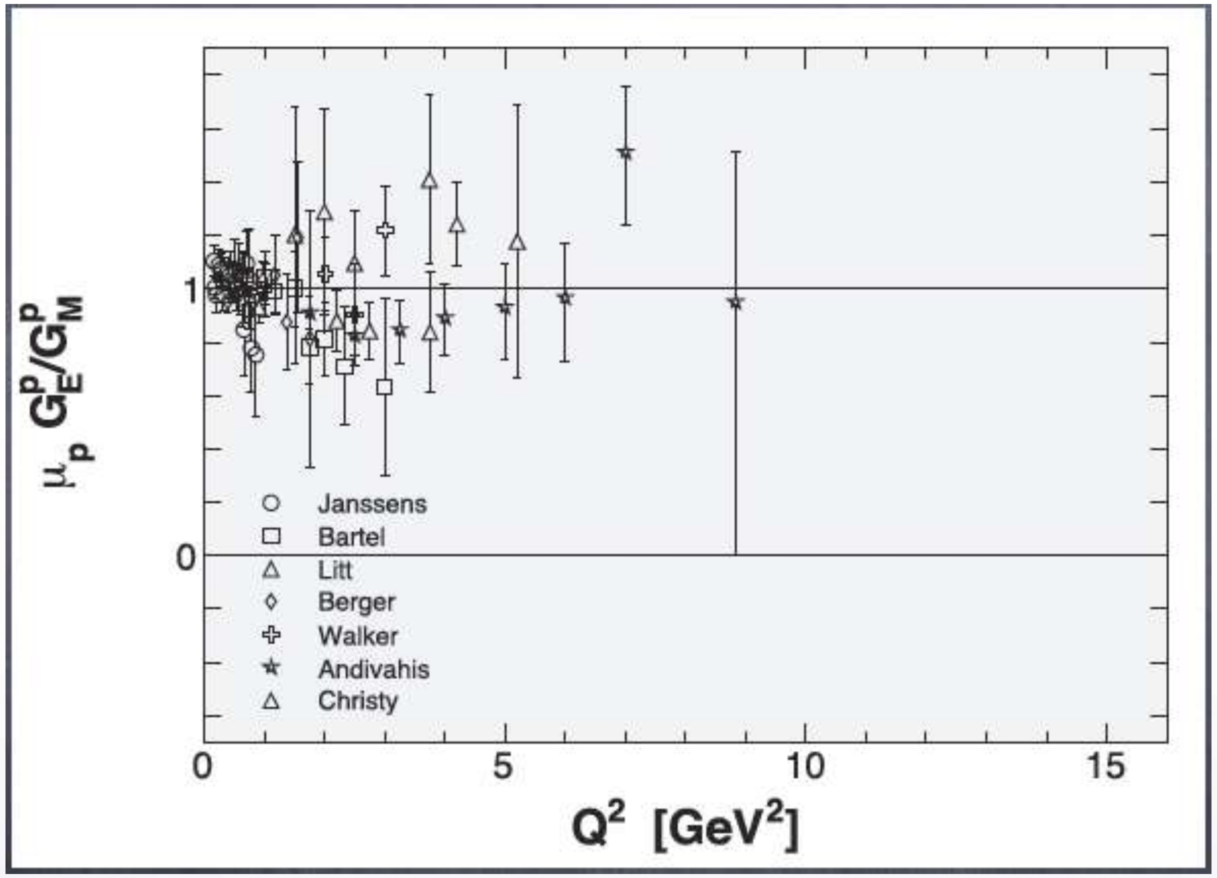
Cross section and asymmetry for electron-nucleon scattering

$$J_{fi} = 2E\cdot F(-\vec{q}^{\,2}),\quad \vec{J} = 0$$

$$\rho(r) = \frac{1}{(2\pi)^3}\int F(-\vec{q}^{\,2})e^{i\vec{q}\vec{r}}d^3\vec{q}$$

Data on G^p_E/G^p_M prior to JLab

Sachs Form Factors have been traditionally measured by Rosenbluth separation.



The expectation was that the ratio G_E^p/G_M^p would remain constant.

Rosenbluth separation data from Jlab: plot from M.E. Christy, et al., Phys. Rev. C 70, 015206 (2004);
I.A. Qattan, et al., Phys. Rev. Lett. 94, 142301 (2005).

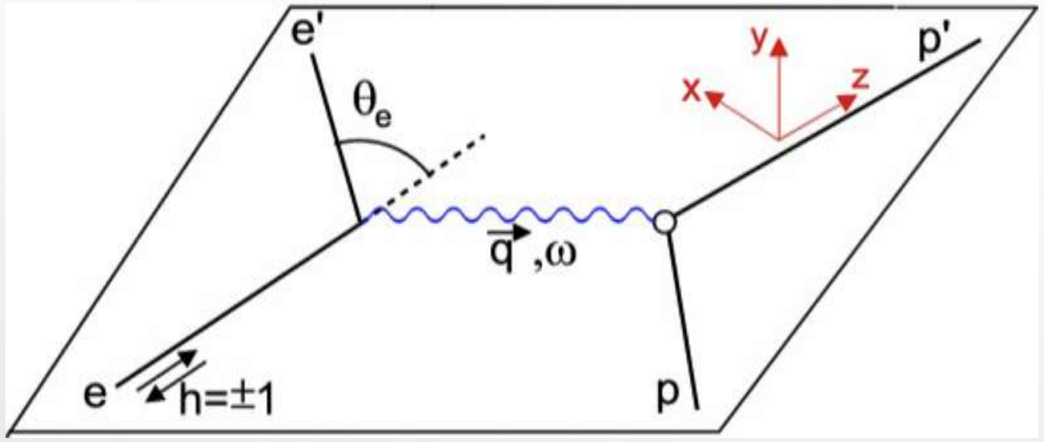
Nucleon Form Factor Studies in Hall A

Recoil Polarization method

- Longitudinally polarized electron beam on unpolarized target.
- Measurement of the scattered proton polarization components along (P_z) and perpendicular (P_x) to its direction (in the hadron plane) at a given Q^2:

$$\frac{G_E}{G_M} = -\frac{P_x}{P_z}\frac{E_e+E_{e'}}{2M}\tan\frac{\theta_e}{2}$$

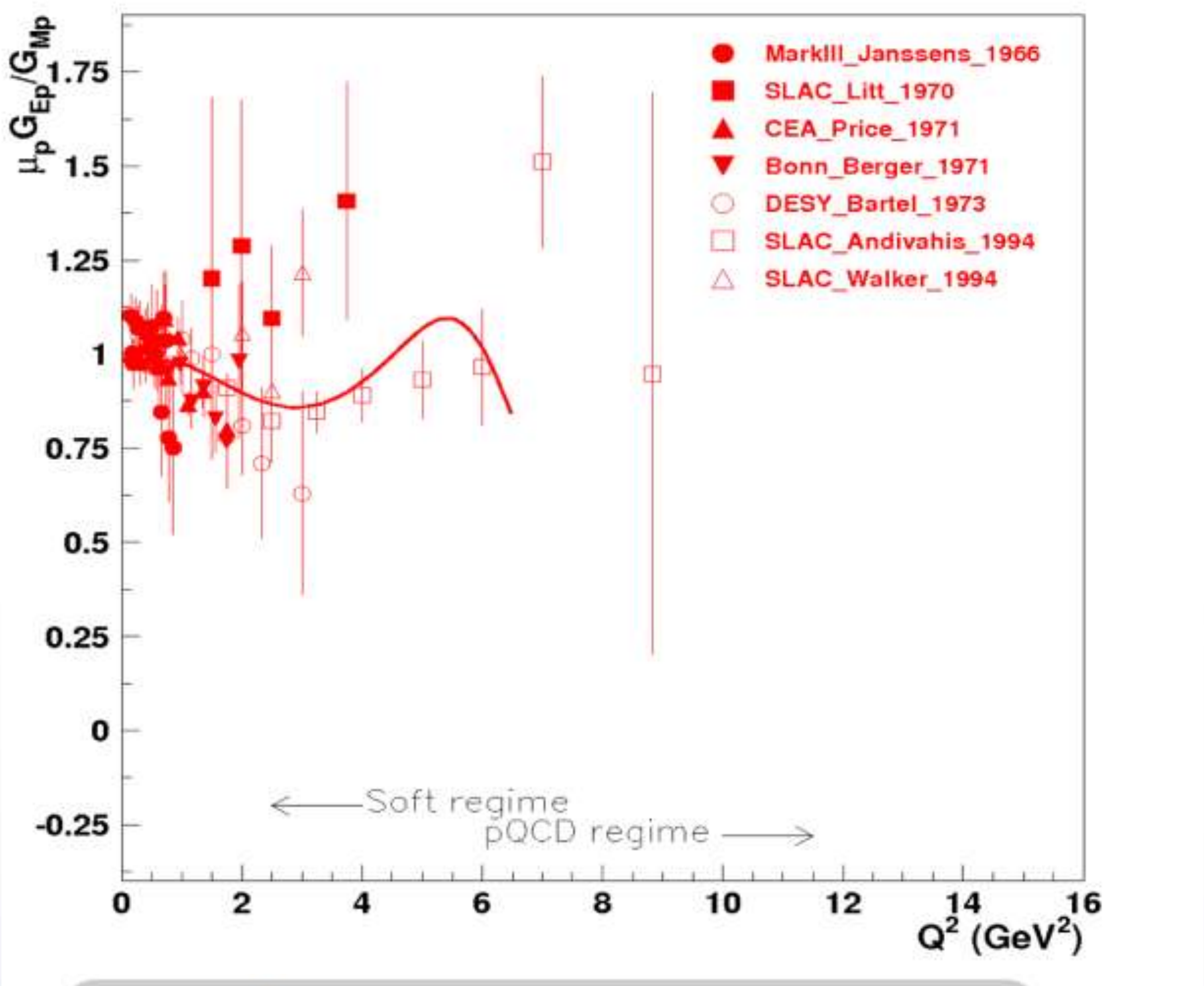
- A proton polarimeter is mandatory.



The form factor ratio can be obtained without measuring the absolute cross-sections and without changing of beam energy or detector angle, thus eliminating important sources of systematic uncertainties. Radiative corrections have been shown to be very small for polarization observables. Knowledge of analyzing power of the polarimeter and beam polarization is not a priori required (Although maximization of these quantities minimizes the time to get accurate data).

See also talk by Battaglieri

Proton E/M Form Factors Ratio (1/2)



Rosenbluth era: before 2000

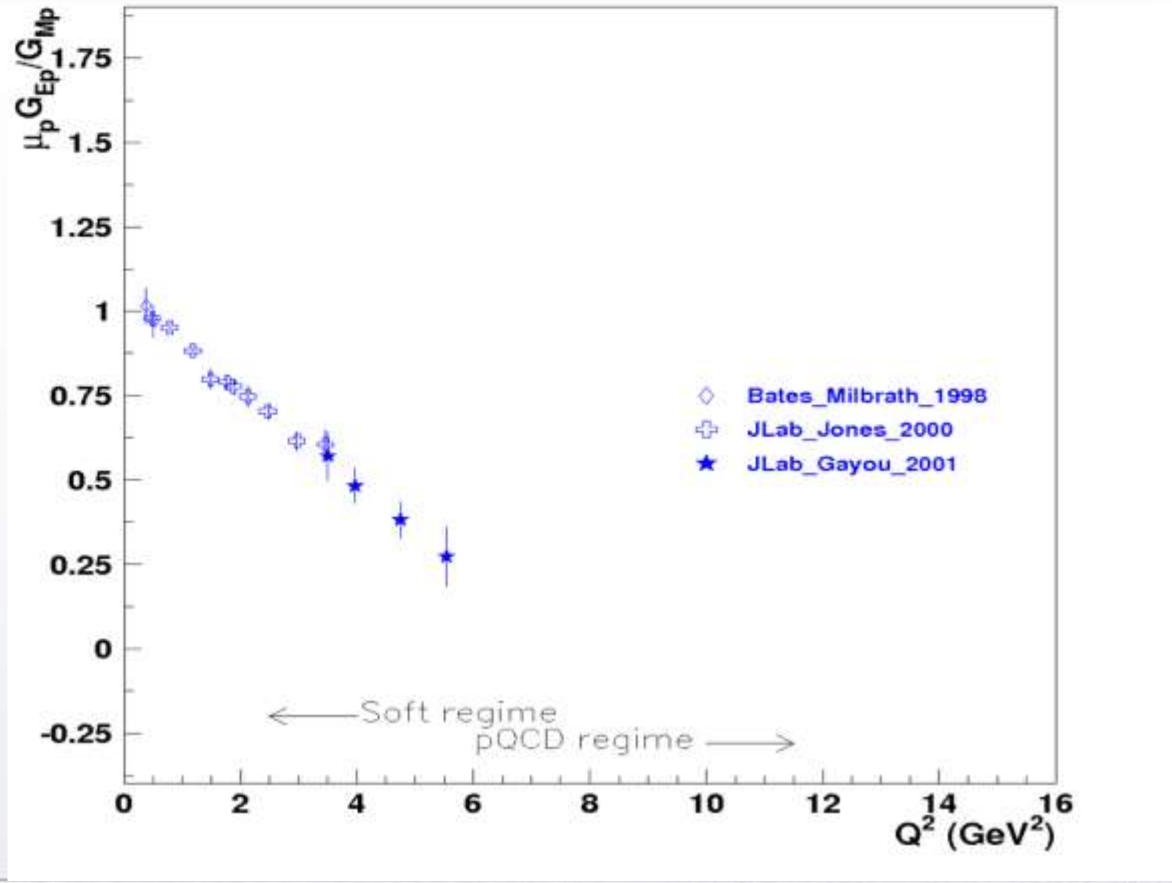
Fit of cross section vs ϵ (virtual photon polarization)
$(\frac{d\sigma}{d\Omega})_R = G_M^2 + \frac{\epsilon}{\tau} G_E^2$
(single photon approx.)
scan in angle (different Q^2)

MIT/JLab Polarization Transfer: after 2000

$$\frac{G_E}{G_M} = -\frac{P_x}{P_z}\frac{E_e+E_{e'}}{2M}\tan\frac{\theta_e}{2},$$

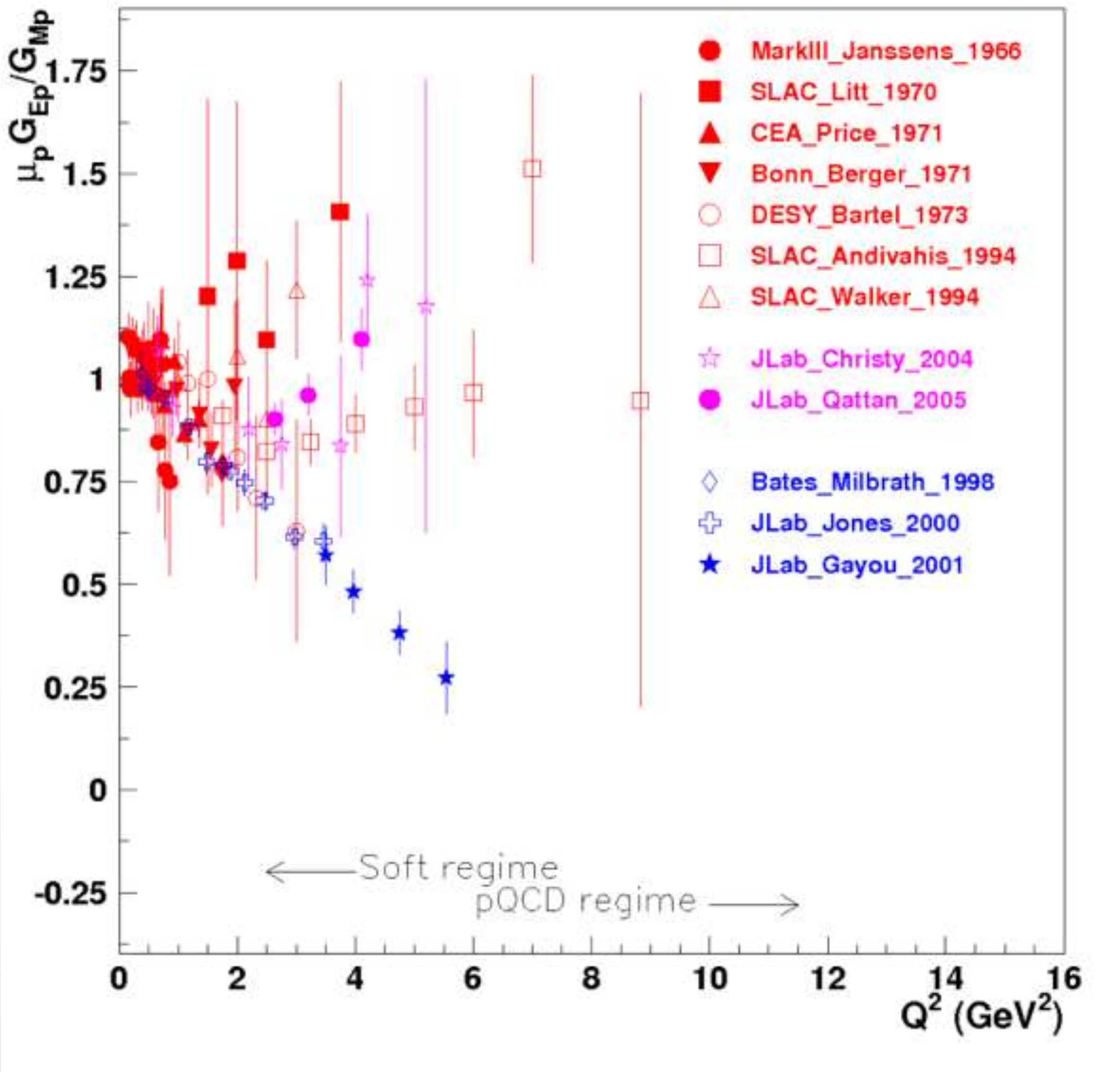
fixed angle and Q^2;
marginal systematic uncertienties

Totally unexpected, these data forced a reconsideration of nucleon structure.



Proton E/M Form Factors Ratio (2/2)

Elastic e-p scattering



All data

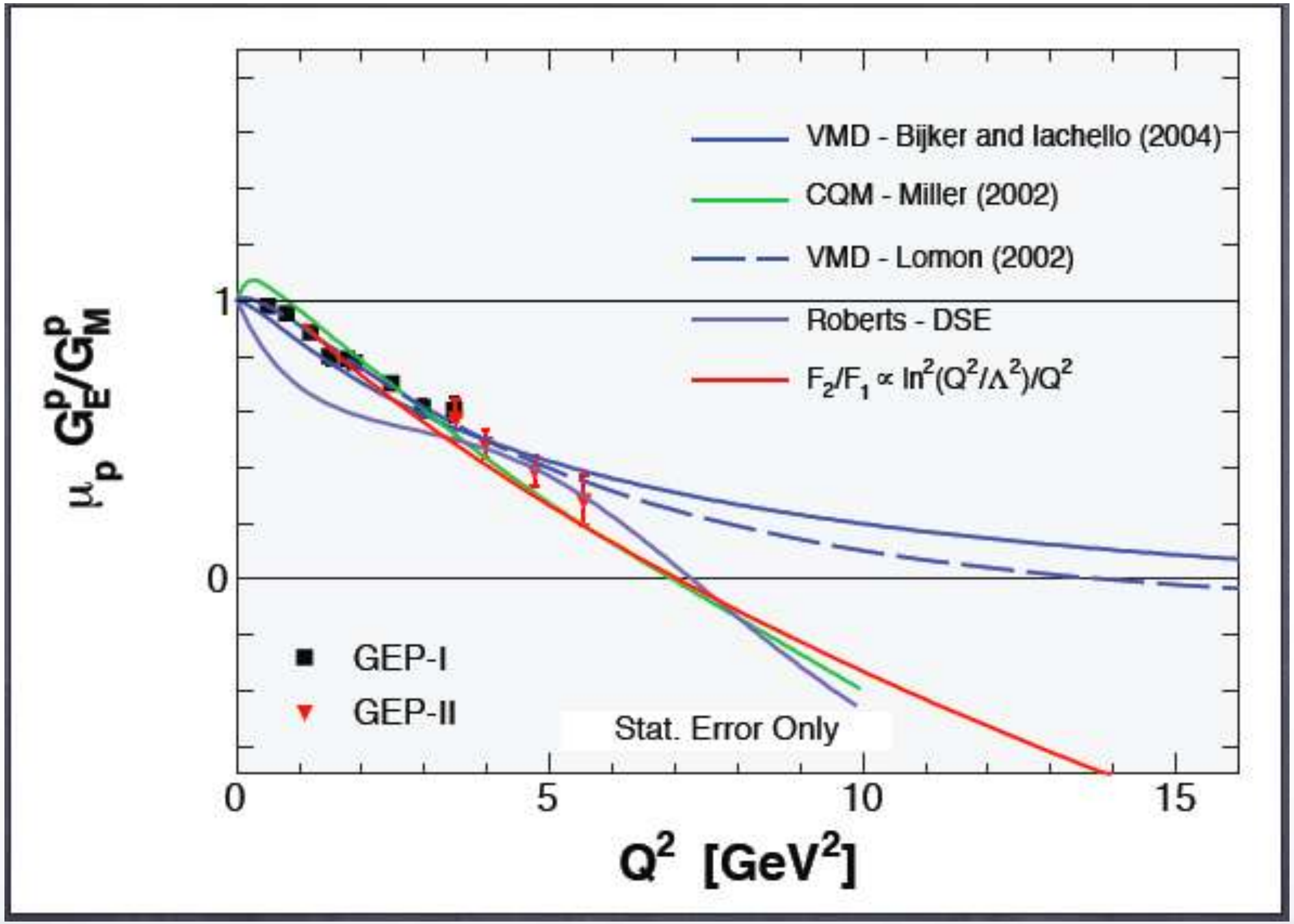
- Form Factor ratio is not constant!
- large discrepancy between the results of the two methods
- Rosenbluth affected by wrong radiative corrections and single photon approximation (?)

New experiments at larger Q^2

- explore pQCD region (and predictions: $F_2/F_1 \sim 1/Q^2$ at large Q^2)
- GEP-5 expected to measure negative Sacks FFs
- Additional info for GPD

Polarization method data and Rosenbluth separation data by JLab from O. Gayou et al., Phys.Rev. C 64, 038202 (2001); M.K. Jones, et al., Jefferson Lab Hall A Collaboration, Phys. Rev. Lett. 84, 1398 (2000); V. Punjabi et al., Phys. Rev. C 71, 0055202 (2005);V. Punjabi et al., Phys. Rev. C 71, 069902 (2005) (erratum) [Polarization data];
M.E. Christy, et al., Phys. Rev. C 70, 015206 (2004); I.A. Qattan, et al., Phys. Rev. Lett. 94, 142301 (2005) [Rosenbluth separation data].

Data on G^p_E/G^p_M at high Q^2 from JLab



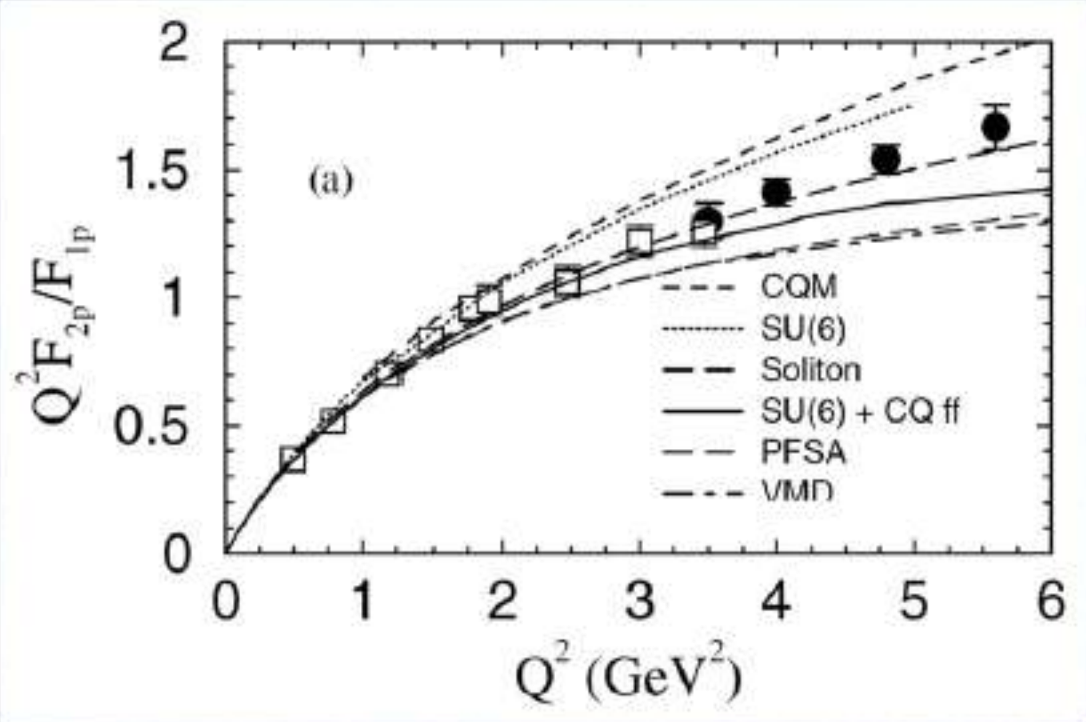
The theoretical studies that have been performed in response to the new data on G_E^p/G_M^p represent some of the most sophisticated efforts to date to understand the nucleon in terms of QCD degrees of freedom

Esperimental data from O. Gayou, et al., Phys. Rev. C 64, 038202 (2001) & Phys. Rev. Lett 88, 092301 (2002); M.K. Jones, et al., Jefferson Lab Hall A Collaboration, Phys. Rev. Lett. 84, 1398 (2000); V. Punjabi, et al., Phys. Rev. C 71, 055202 (2005); C. F. Perdrisat, Eur. Phys. J. A 17, 317-321 (2002); Ch. Perdrisat, V. Punjabi, M. Jones, E. Brash (spokespersons), Jefferson Lab experiment E09-001 (GEp(4)).

Theoretical curves from I. C. Cloet, et al., Few-Body Systems 46, 1-36 (2009); G.A. Miller, Phys. Rev. C 66, 032201 R (2002); A.V. Belitsky, X. Ji and F. Yuan, Phys. Rev. Lett. 91, 092003 (2003)

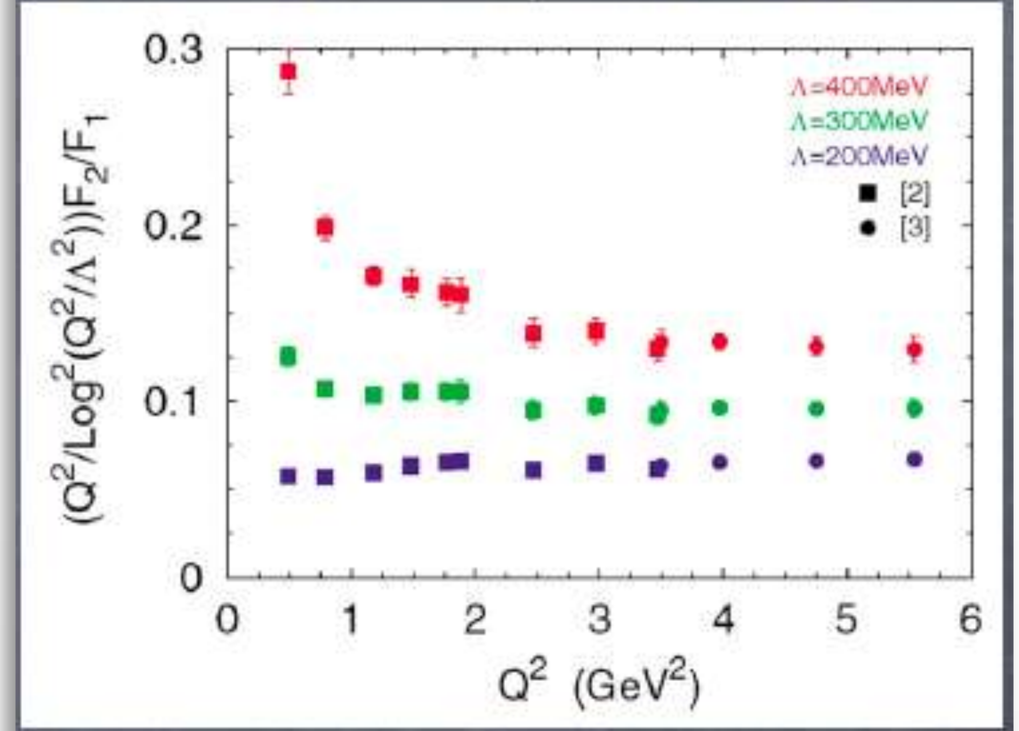
The evolution of the FFs using pQCD

Hall A results



From simple pQCD counting rules, Q^2F_{2p}/F_{1p} should become constant.

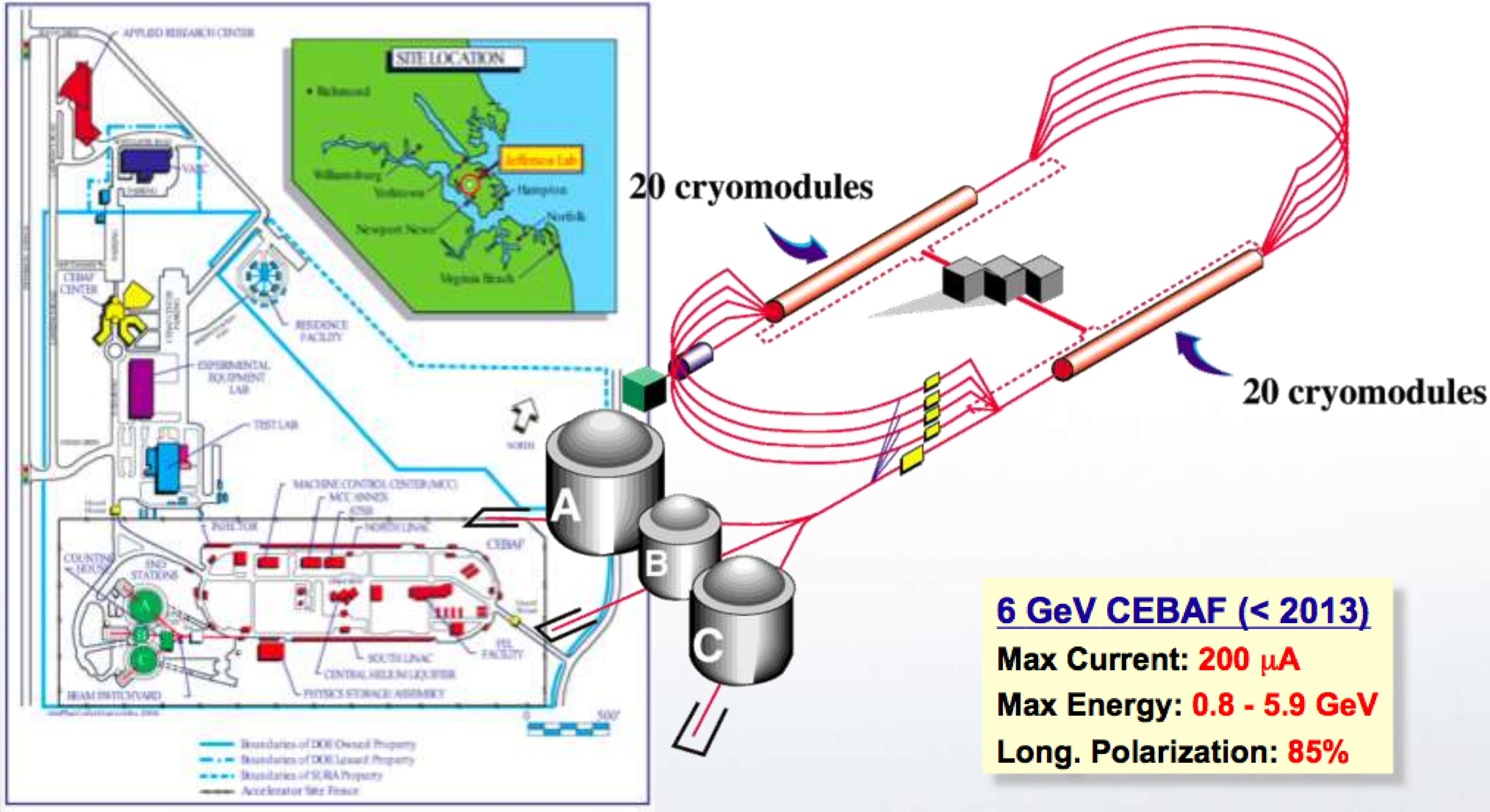
From Belitski, Ji and Yuan



With logarithmic corrections, scaling appears to be restored.

The corrections result from including in the light-cone quark wave function components with L≠0, indicating the dynamic importance of quark orbital angular momentum.

Nucleon Form Factor Studies at JLab



6 GeV CEBAF (< 2013)

Max Current: 200 μA

Max Energy: 0.8 - 5.9 GeV

Long. Polarization: 85%

JLab CEBAF electron beam in 2014

Beam energy	11/12 Ge
Beam power	1 MW
Beam current (Hall A/D)	85/5 μA
Beam polarization	85%
Emittance @ 12 GeV	10 nm-rad
Energy spread @ 12 GeV	0.02%
Beam spot	~ 0.1mm
Simultaneous beam delivery	Up to 3 halls

Hall A will be the first hall to get the beam

Challenges at high Q^2

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

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

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

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

A **figure of merit** *is a quantity used to characterize the performance of a device, system or method, relative to its alternatives.*

For a double-polarization experiment with a recoil polarimeter

Need large statistics → max luminosity and solid angle

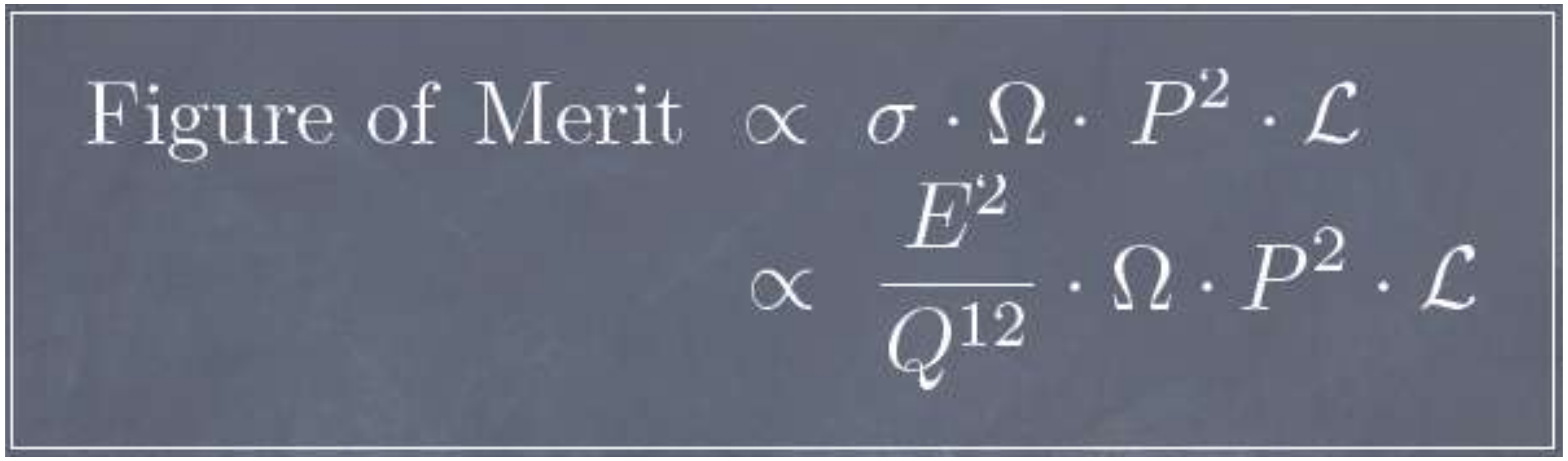
Max luminosity → large background

Large solid angle → small bend → huge background

Solution is a modern tracking detector based on Gas Electron Multiplier (F.Sauli, 1997)

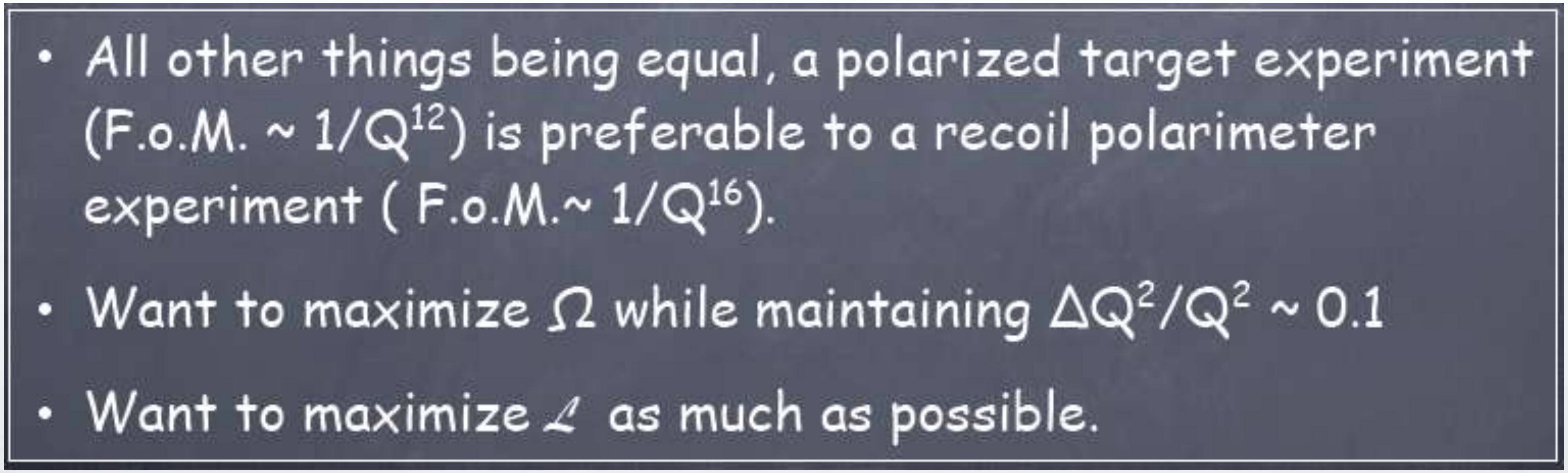
Optimizing Form Factor Experiments

For a double-polarization experiment with a polarized target:



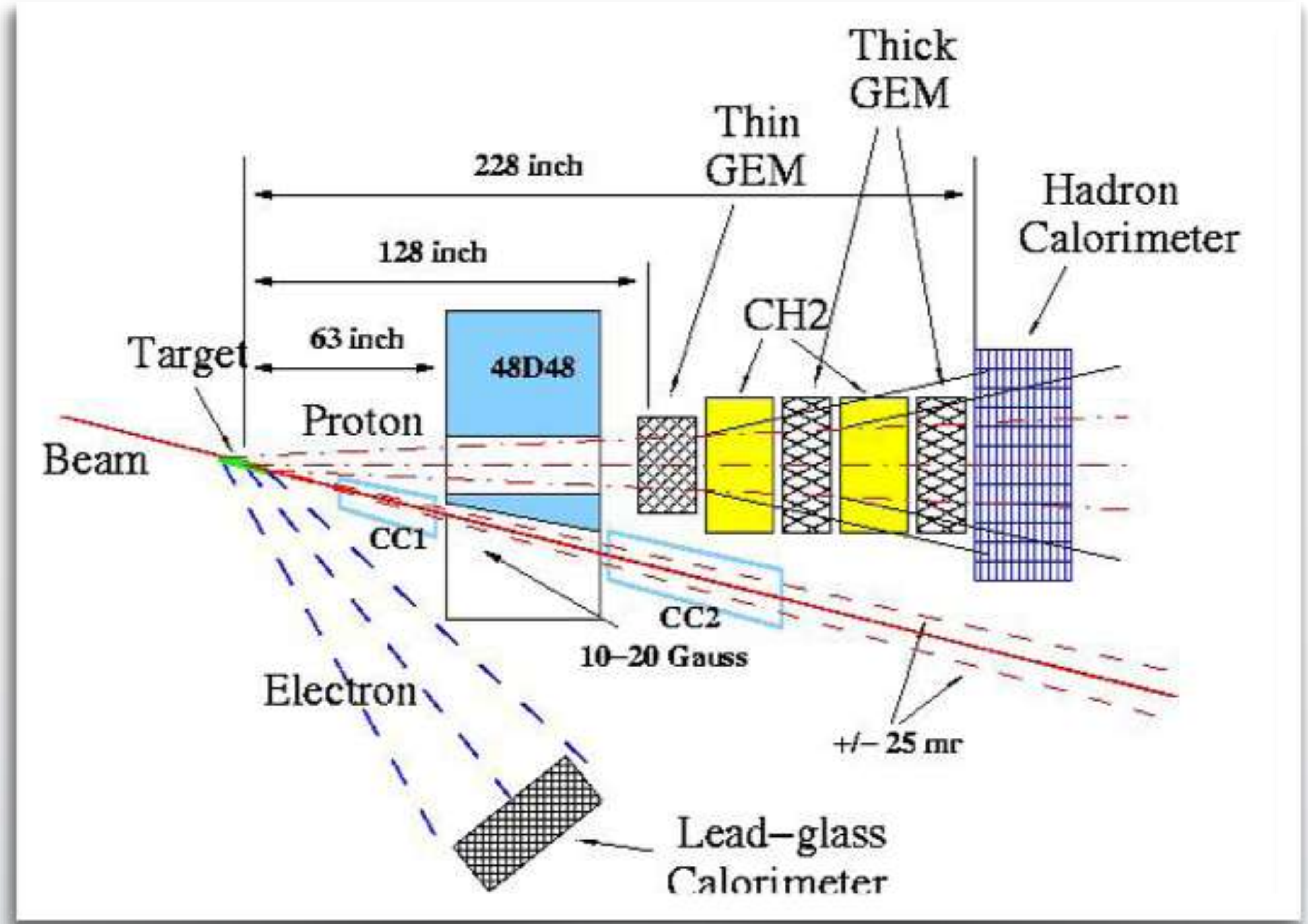
$$\text{Figure of Merit} \propto \sigma \cdot \Omega \cdot P^2 \cdot \mathcal{L} \propto \frac{E^2}{Q^{12}} \cdot \Omega \cdot P^2 \cdot \mathcal{L}$$

From all this, we gather the following:



- All other things being equal, a polarized target experiment (F.o.M. ~ $1/Q^{12}$) is preferable to a recoil polarimeter experiment (F.o.M.~ $1/Q^{16}$).
- Want to maximize Ω while maintaining $\Delta Q^2/Q^2 \sim 0.1$
- Want to maximize $\mathcal{L}$ as much as possible.

Hall A 2014 Experimental Setup



e^- Beam

11 GeV, 75 μA, 85% pol.

Target

Liquid H_2, 40 cm

Electron → BigCal

$\theta = 37^o, \Omega = 180$ msr

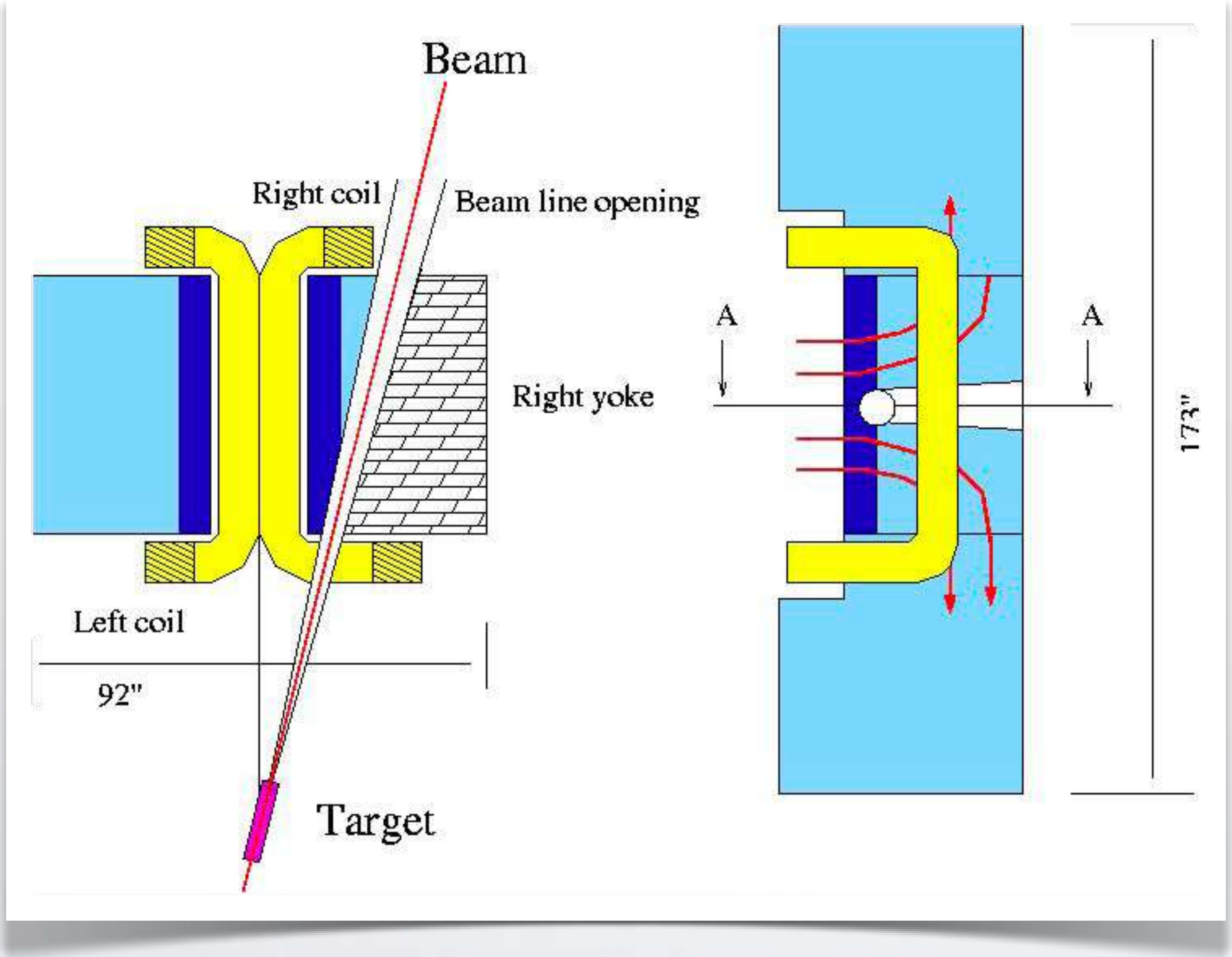
Proton → New Spec.

$\theta = -14^o$, $\Omega = 35$ msr

Kinematic Region

$Q^2 = 6, 12.5, 15$ GeV^2

Hall A 2014 Experimental Setup

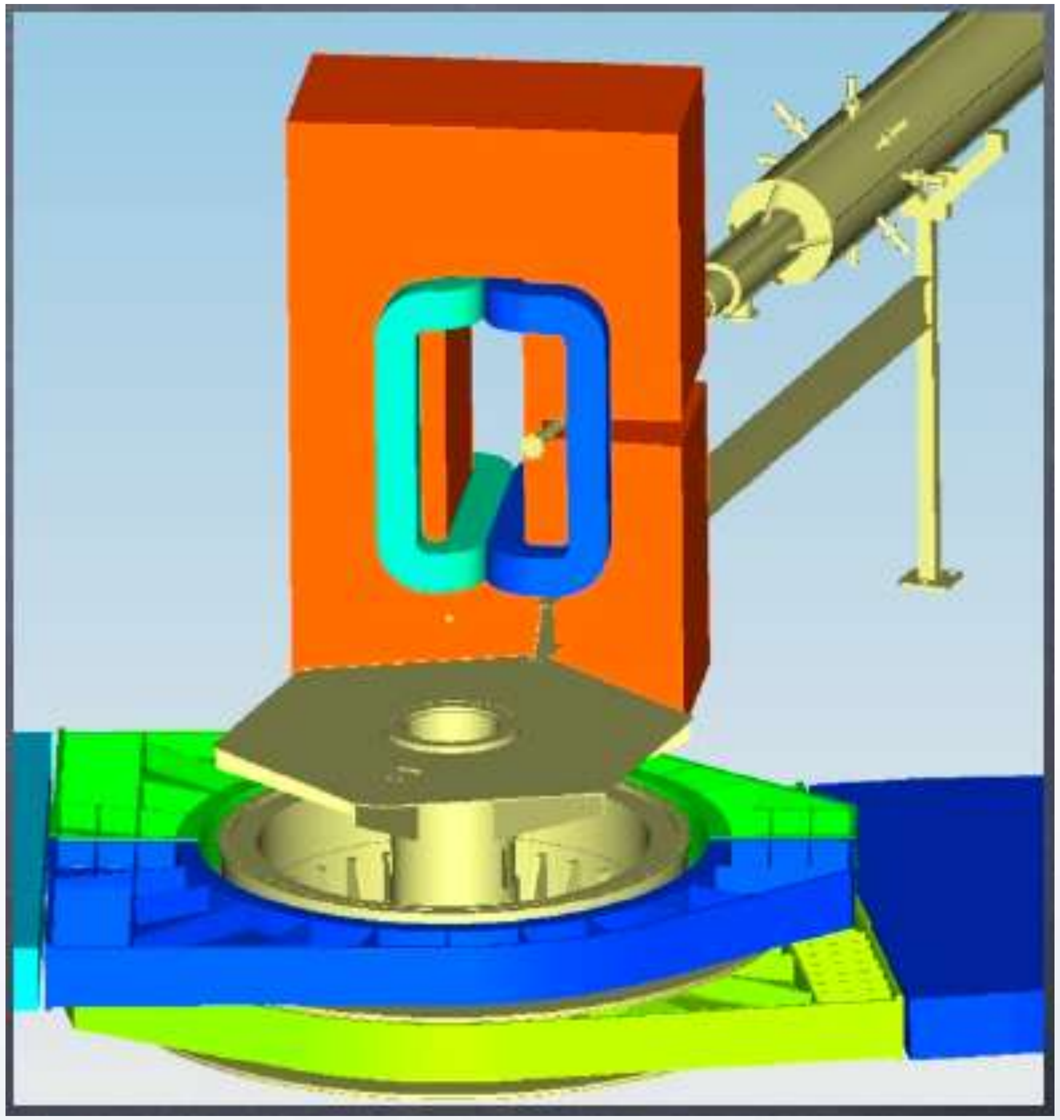


- 48D48 – 46 cm gap, 2.5 Tesla*m
- Solid angle is 70 msr at angle 15°
- GEM chambers with 70 μm resolution
- momentum resolution is 0.5% for 5 GeV/c
- angular resolution is 0.3 mrad

Optimizing acceptance and rates

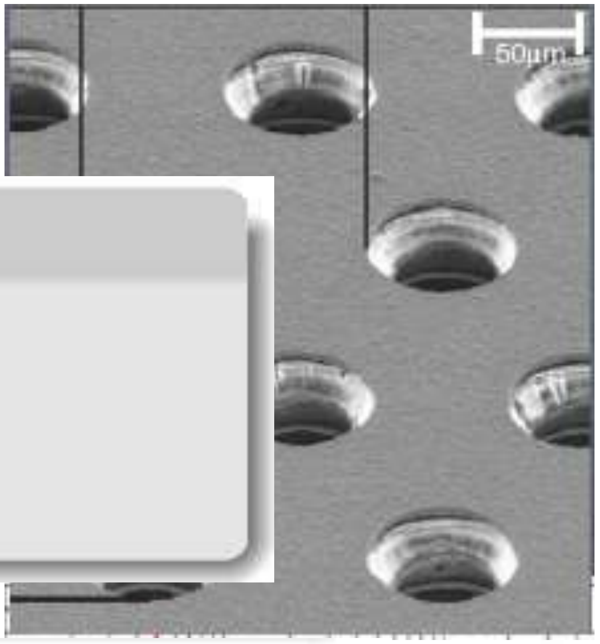
The Super Bigbite magnet is optimized for FF measurements.

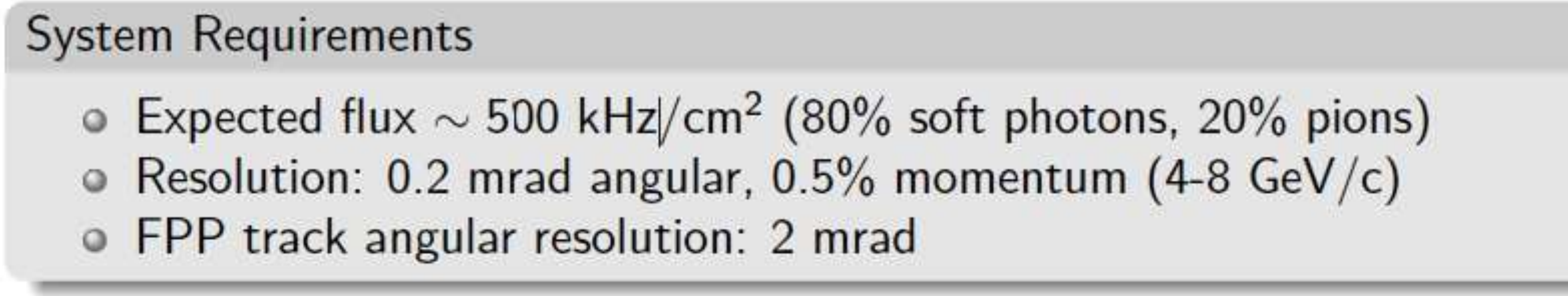
- Single dipole provides adequate momentum resolution (~1%) and large solid angle (~70 msr) acceptance. (Also true of original BigBite magnet).
- Vertical aperture well matched to electron arm while still appropriate for $\Delta Q^2/Q^2 \sim 0.1$.
- Cut in yoke permits operating at small angles where the recoil is going.



Optimizing detectors for luminosity

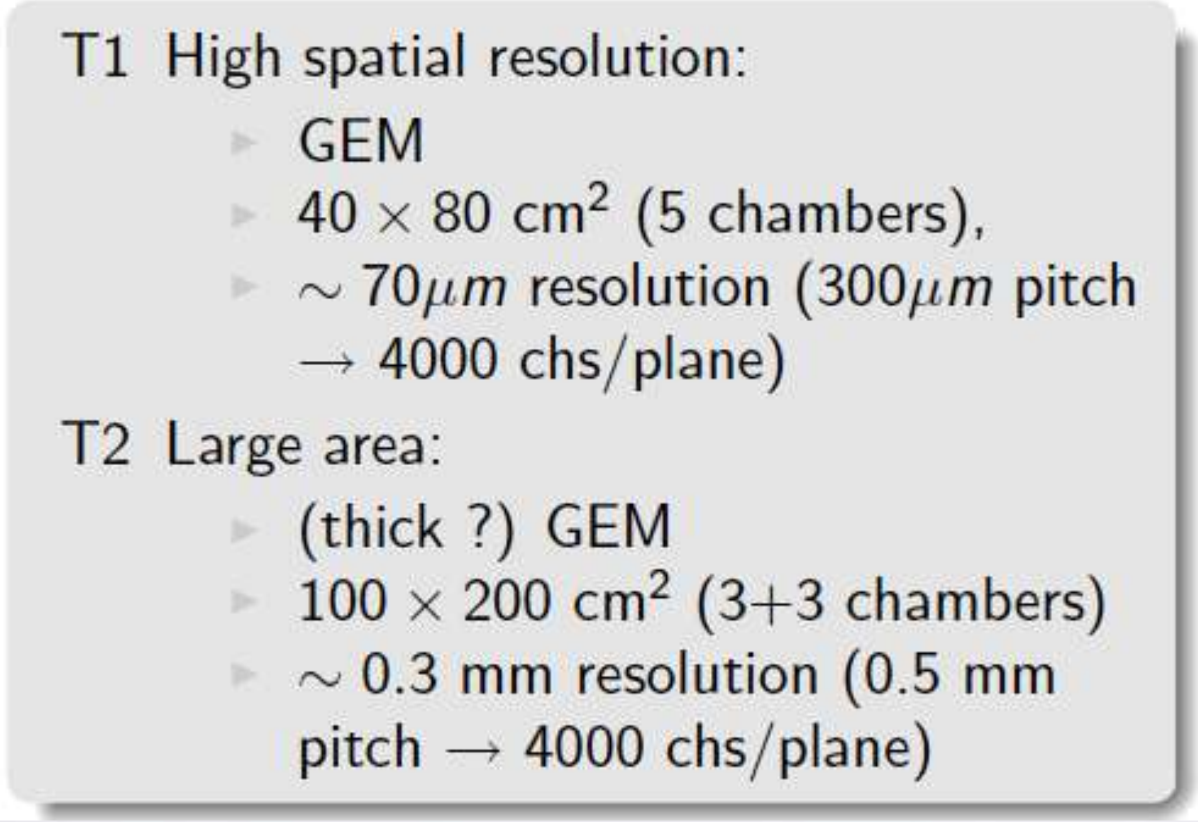
Gas Electron Multiplier (GEM) technology for tracking ensures the ability to handle very high luminosity.





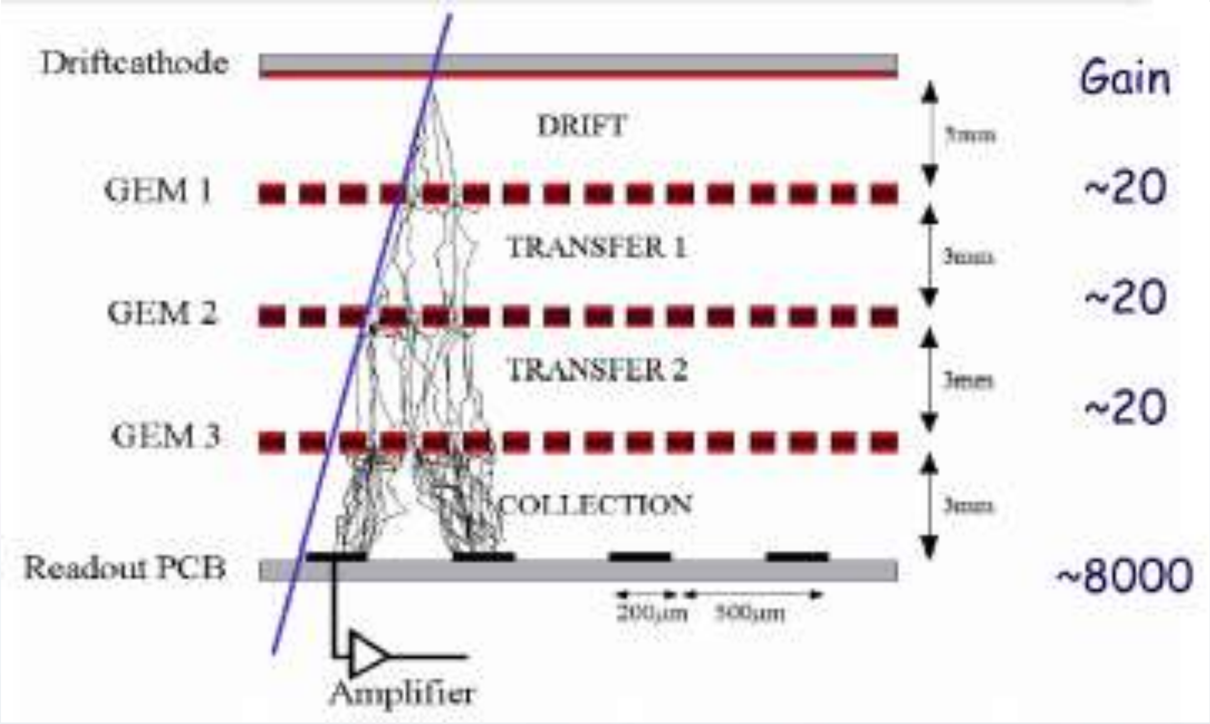
System Requirements

- Expected flux ~ 500 kHz/cm^2 (80% soft photons, 20% pions)
- Resolution: 0.2 mrad angular, 0.5% momentum (4-8 GeV/c)
- FPP track angular resolution: 2 mrad

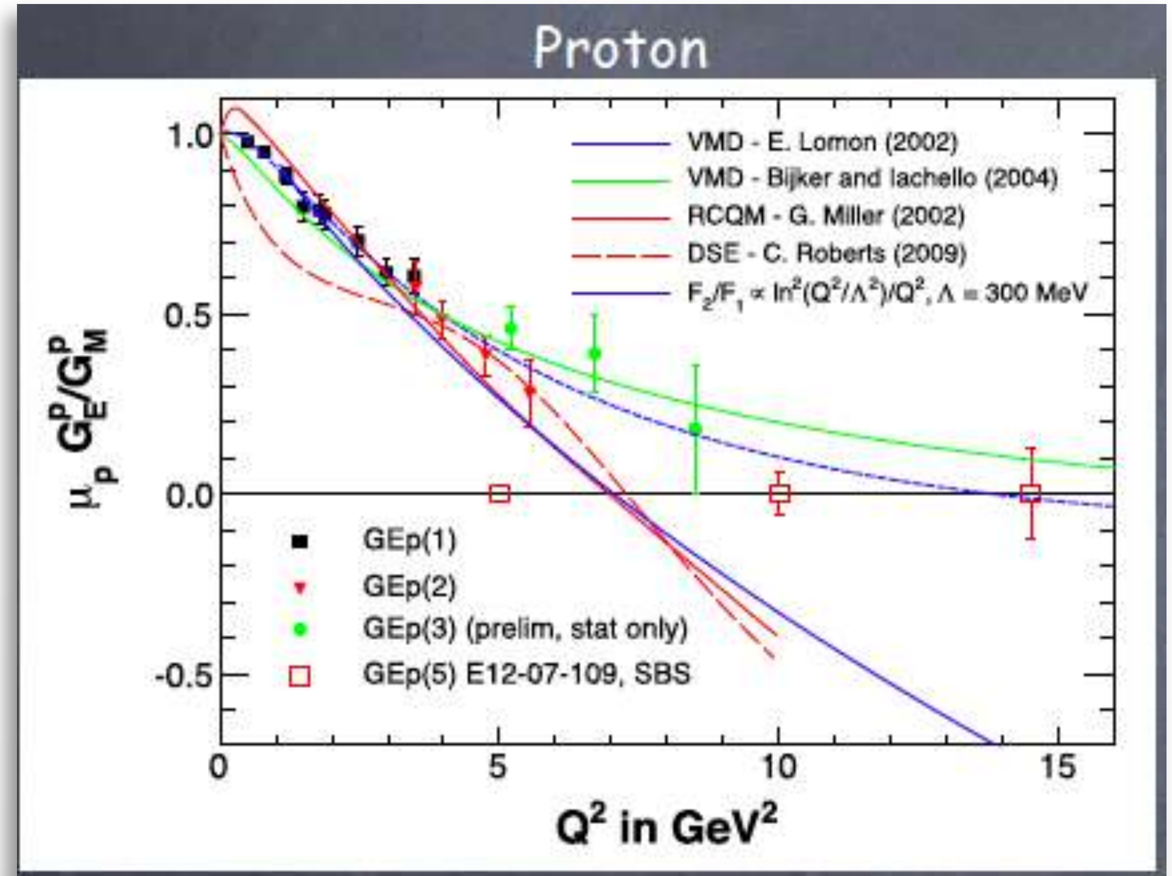


T1 High spatial resolution:
  - GEM
  - 40 × 80 cm^2 (5 chambers),
  - ~ 70μm resolution (300μm pitch → 4000 chs/plane)

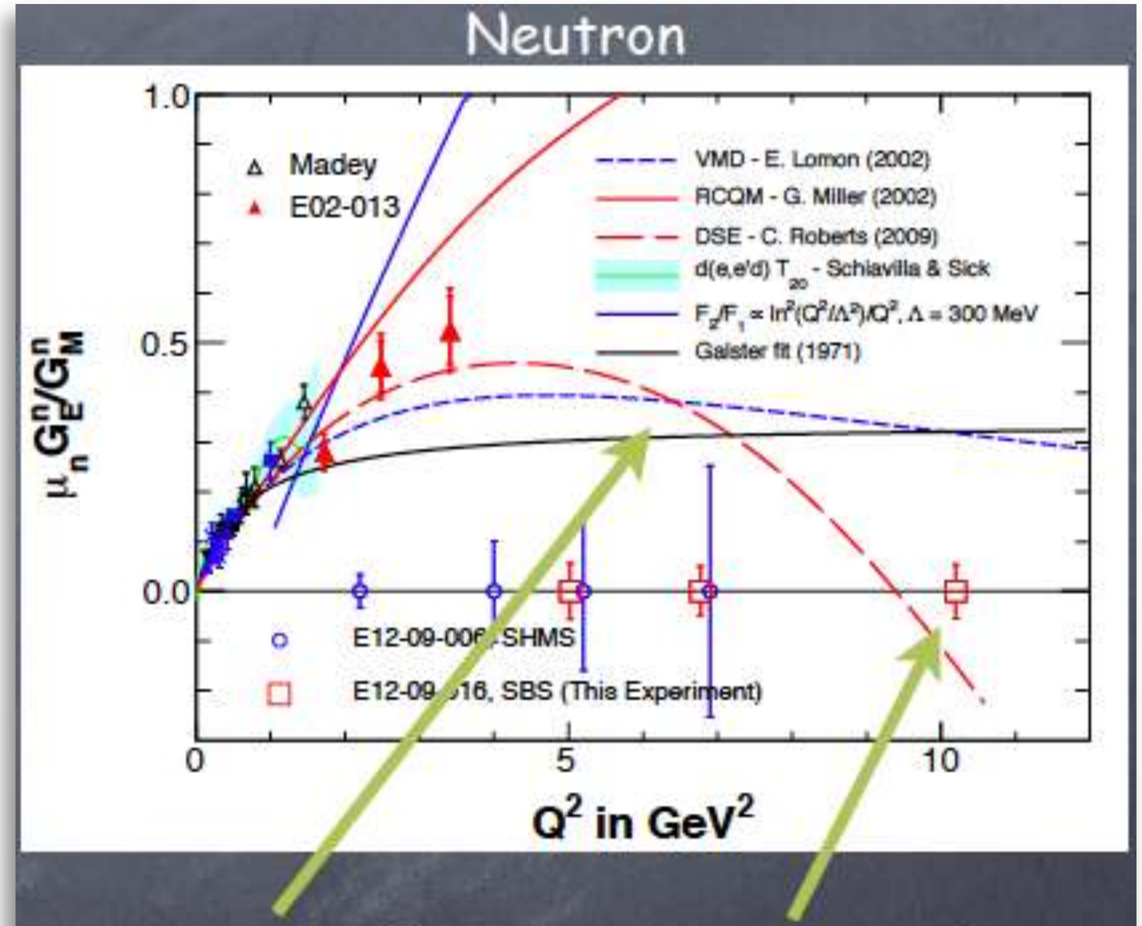
T2 Large area:
  - (thick ?) GEM
  - 100 × 200 cm^2 (3+3 chambers)
  - ~ 0.3 mm resolution (0.5 mm pitch → 4000 chs/plane)



12 GeV approved Form Factor experiments



Data between 10-15 GeV^2 will cleanly distinguish between some of the models.

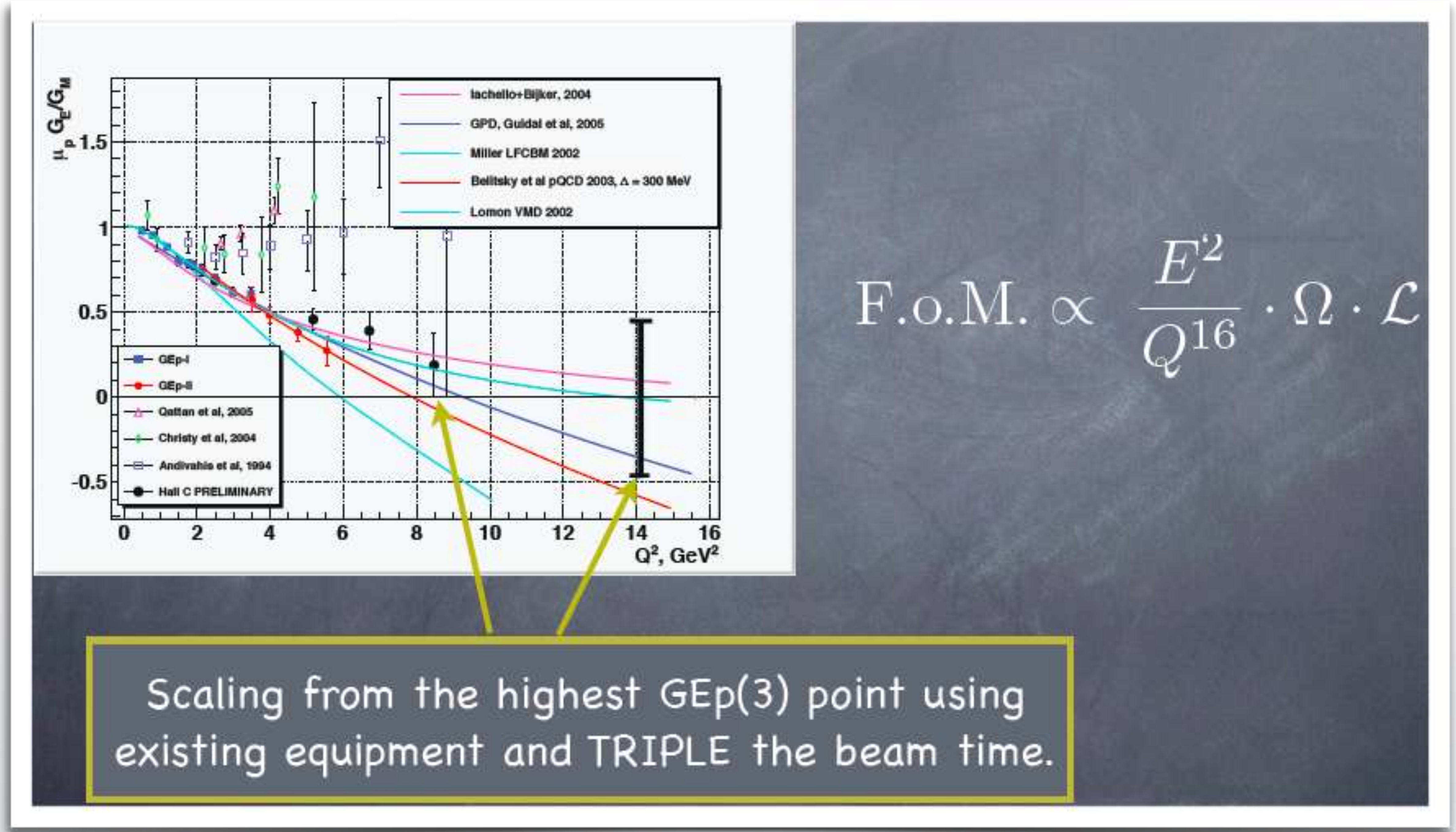


At 7 GeV^2 some models are still close to one another.

By 10 GeV^2, it is possible to discriminate between all the best models.

Nucleon Form Factor Studies in Hall A

A challenge of measuring G^p_E/G^p_M at high Q^2 with existing equipment

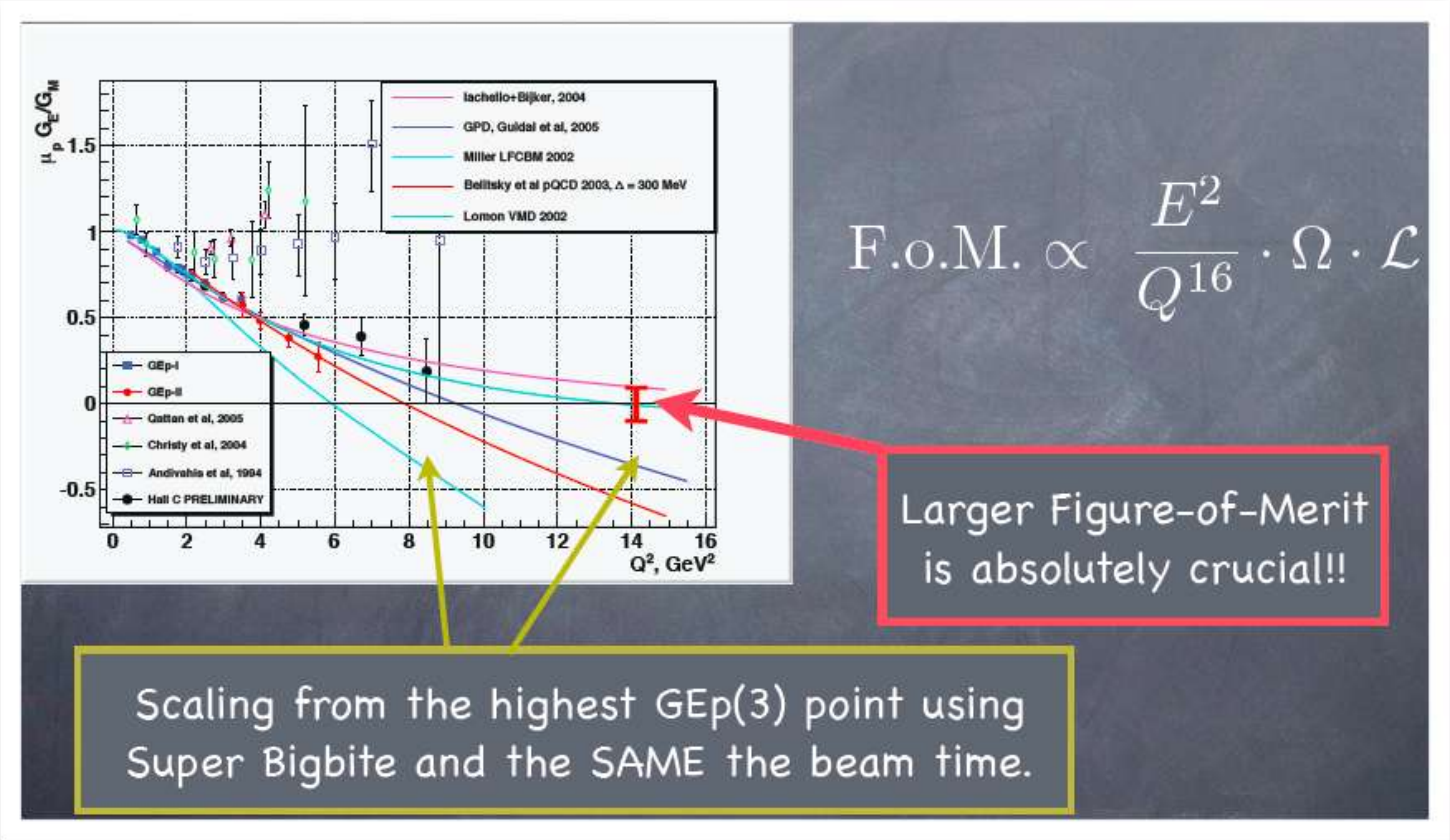


$$\text{F.o.M.} \propto \frac{E^2}{Q^{16}} \cdot \Omega \cdot \mathcal{L}$$

Scaling from the highest GEp(3) point using existing equipment and TRIPLE the beam time.

Nucleon Form Factor Studies in Hall A

Super BigBite allows to achieve a higher Figure of Merit.

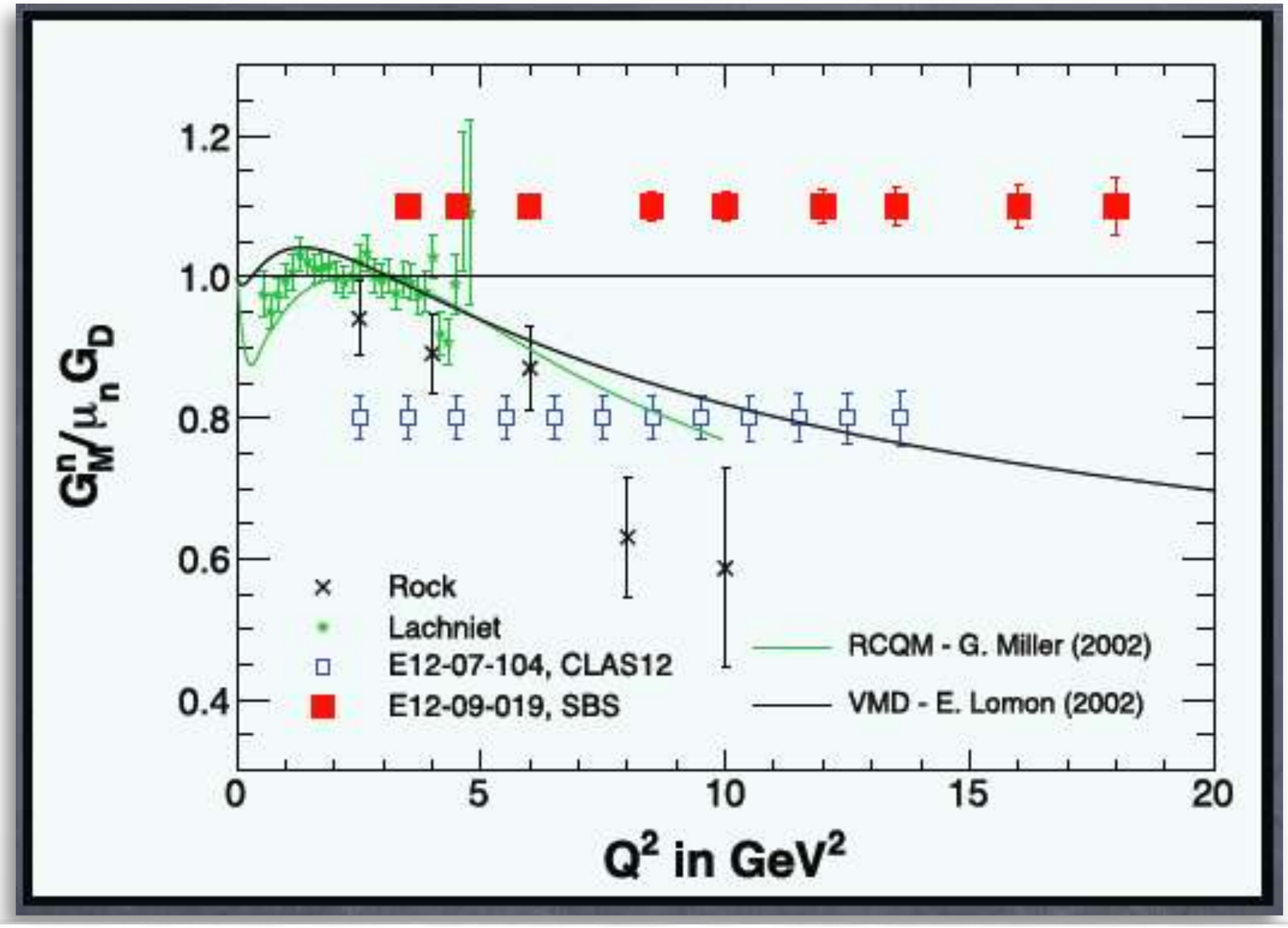


$$\text{F.o.M.} \propto \frac{E^2}{Q^{16}} \cdot \Omega \cdot \mathcal{L}$$

Larger Figure-of-Merit is absolutely crucial!!

Scaling from the highest GEp(3) point using Super Bigbite and the SAME the beam time.

12 GeV Hall A measurement of G^n_M/G^p_M



Will represent the most accurate measurement to date of G^n_M at high Q^2.

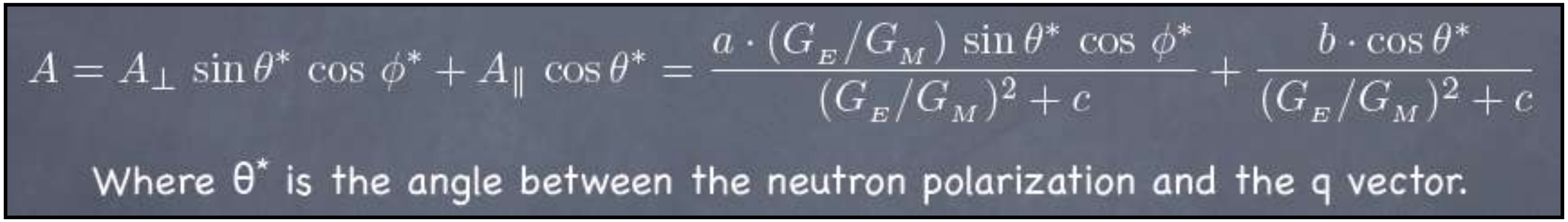
Will test model predictions as well as pQCD scaling.

Needed to extract G^n_E from measurements of G^n_E/G^n_M .

Needed to perform flavor separations of all FFs.

Measuring G^n_E/G^n_M

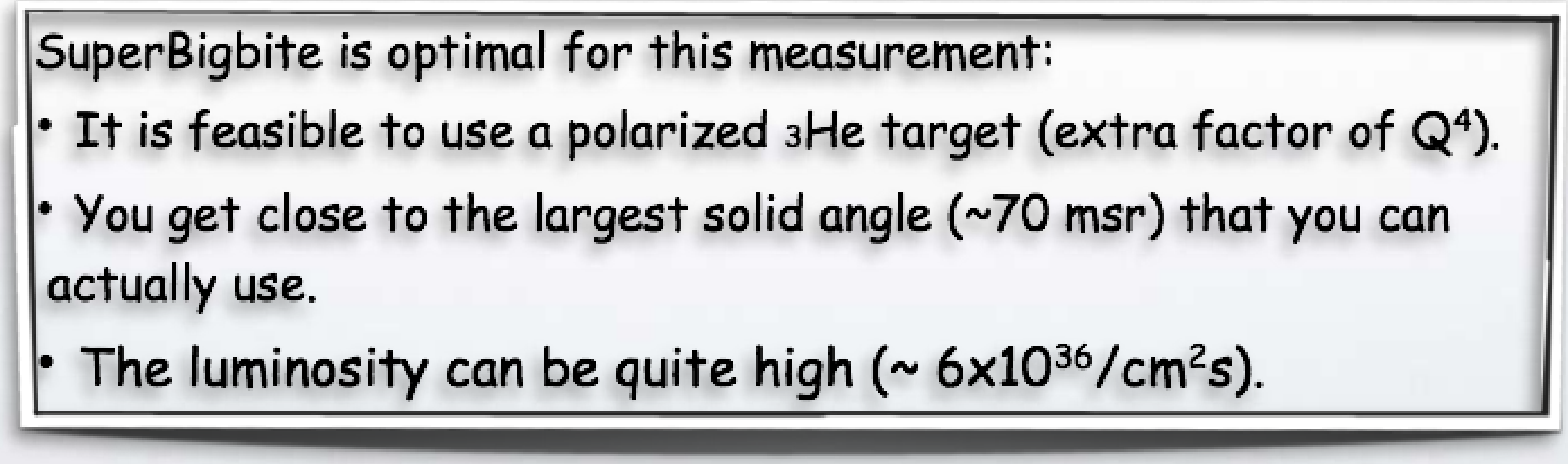
In this case, it is feasible to use a polarized ^{3}He target (gaining a factor of Q^4 over a recoil polarimeter). The measured asymmetry has the form:



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

Where θ^* is the angle between the neutron polarization and the q vector.

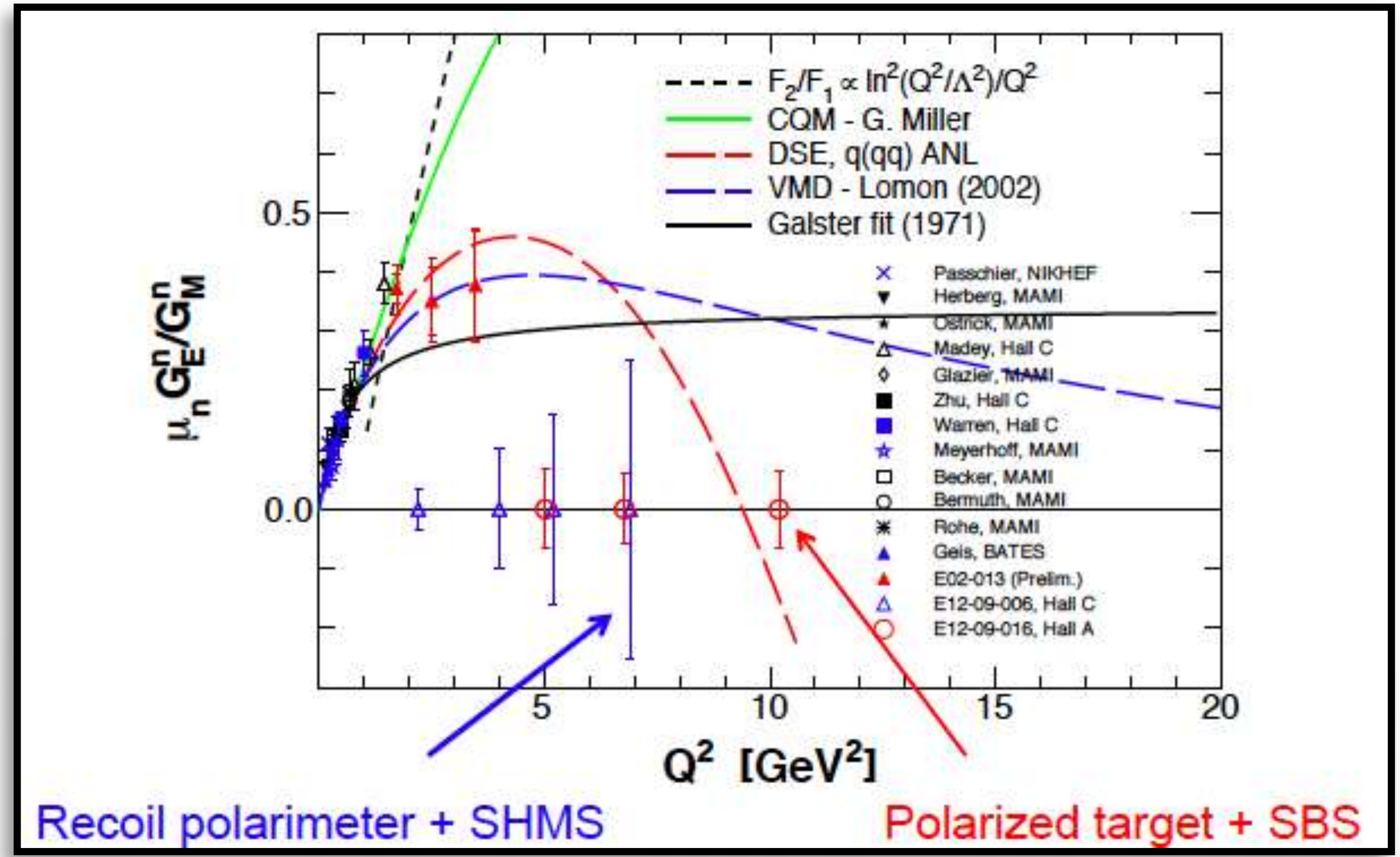
From the form of the asymmetry given above, the neutron detector needs to be at roughly 90° to the polarization. This limits the region over which detection is optimal. It precludes, for instance, trying to achieve 2π azimuthal coverage.



SuperBigbite is optimal for this measurement:

- It is feasible to use a polarized ^{3}He target (extra factor of Q^4).
- You get close to the largest solid angle (~70 msr) that you can actually use.
- The luminosity can be quite high (~ $6\times10^{36}/\mathrm{cm}^2\mathrm{s}$).

12 GeV Hall A measurement of $G^n_{E/}G^n_M$



Recoil polarimeter + SHMS

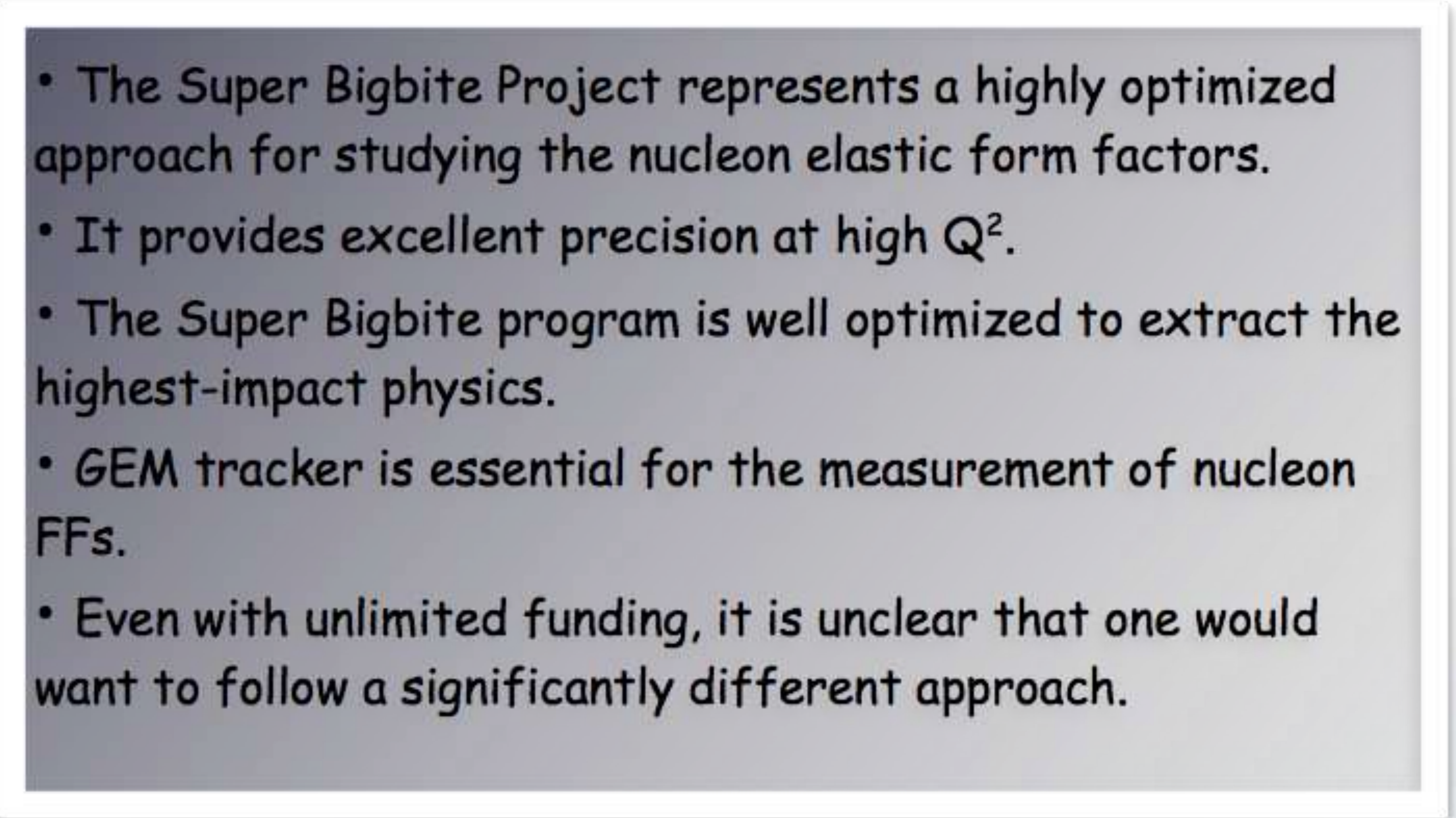
Polarized target + SBS

Why to study the neutron Charge Form Factor?

- ☒ Test of the QCD motivated FF models is a powerful approach to the understanding of confinement
- ☒ Charge density is a fundamental property of the neutron
- ☒ Flavor separated FFs are a productive test of lattice QCD
- ☒ Unique constraint on the model of GPDs E_u and E_d
- ☒ Dirac/Pauli density for up and down quarks and its connection to the Siver's effect
- ☒ Applications e.g. for the neutrino-nuclei cross section

Existing neutron data from K. de Jager, Int. J. Mod. Phys E 19, 844-855 (2010); B. Plaster, et al., Phys. Rev. Lett. 91, 122002 (2003);
Preliminary results for GEn(1) (E02-013) from G. Cates, N. Liyanage and B. Wojtsekhowski (spokespersons), Jefferson Lab experiment E02-013, http://hallaweb.jlab.org/experiment/E02013/ *with several predictions*;
Projected errors for GEn(2) (E12-09-016) from K. de Jager, Int. J. Mod. Phys E 19, 844-855 (2010); G. Cates, S. Riordan and B. Wojtsekhowski (spokespersons), Jefferson Lab experiment E12-09-016.

Form Factors- Summary

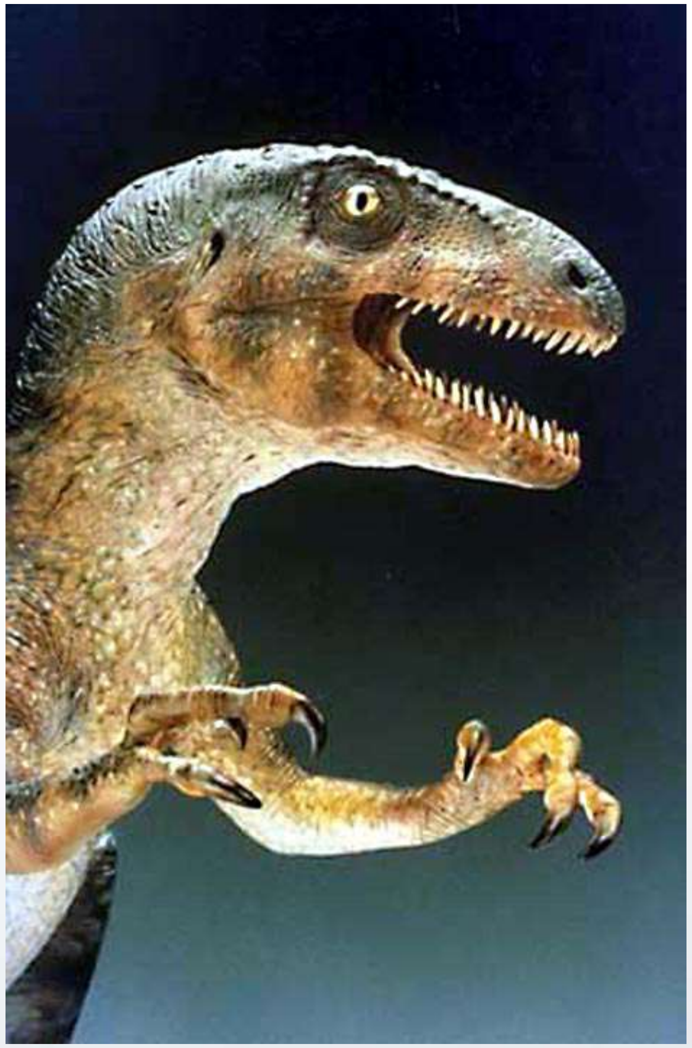


- The Super Bigbite Project represents a highly optimized approach for studying the nucleon elastic form factors.
- It provides excellent precision at high Q^2.
- The Super Bigbite program is well optimized to extract the highest-impact physics.
- GEM tracker is essential for the measurement of nucleon FFs.
- Even with unlimited funding, it is unclear that one would want to follow a significantly different approach.

Lead (^{208}Pb) Radius Experiment : **PREX**

Elastic Scattering Parity Violating Asymmetry

$\theta = 5^{0}$ E = 1 GeV, electrons on lead



--Outline--

- **PREX-I Results 2010 Run**
- **Future : PREX-N ? (N = II,III, IV, V ...)**

Spokespersons

Kent Paschke, Paul Souder, Krishna Kumar, Guido Maria Urciuoli, Robert Michaels

PREX Slides contributed by R. Michaels (PAVI – 11 Conference)

PREX

Z^0 of weak interaction : sees the neutrons

	proton	neutron
Electric charge	1	0
Weak charge	0.08	1

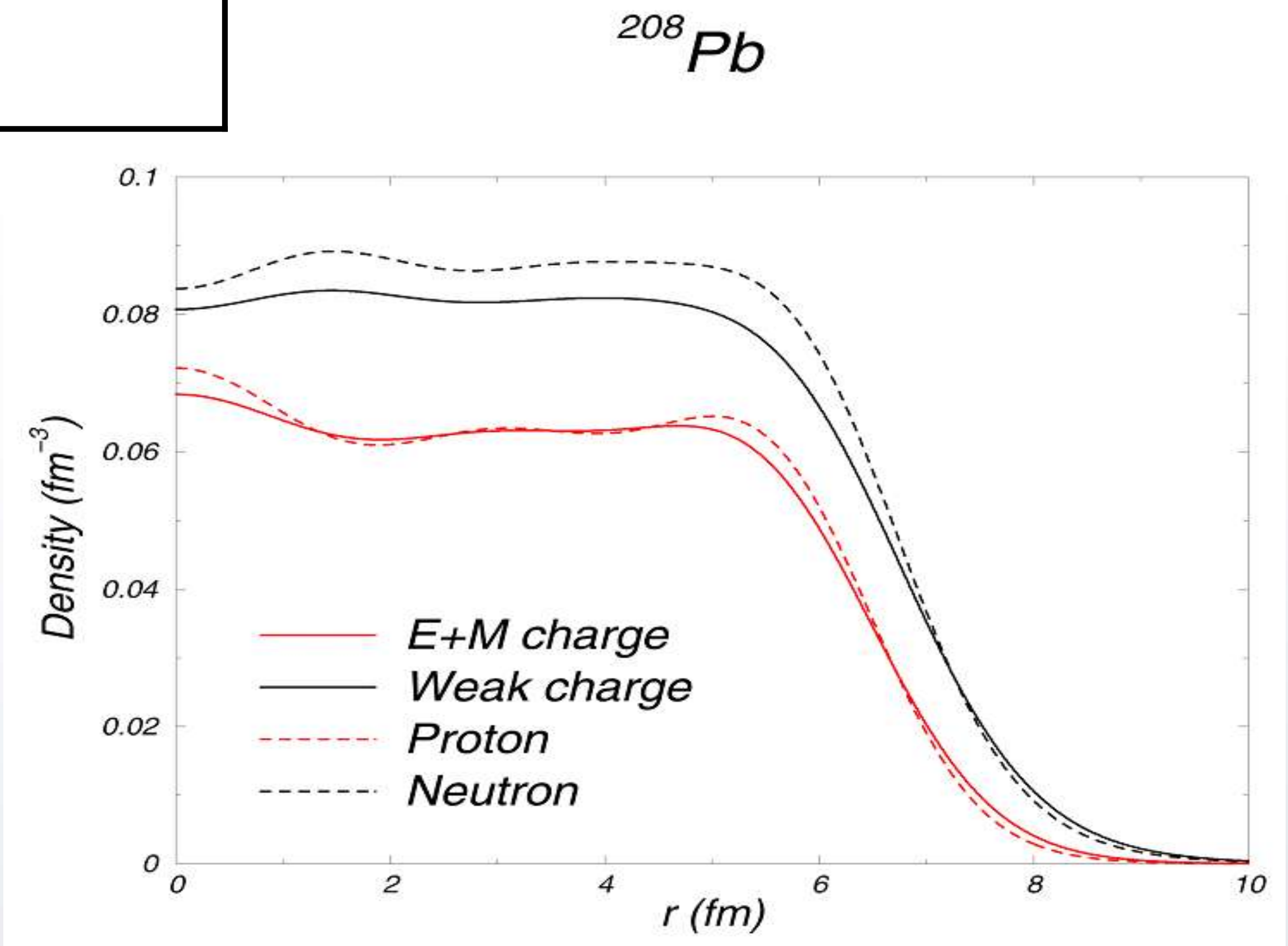
T.W. Donnelly, J. Dubach, I. Sick
Nucl. Phys. A 503, 589, 1989
C. J. Horowitz, S. J. Pollock,
P. A. Souder, R. Michaels
Phys. Rev. C 63, 025501, 2001

Neutron form factor

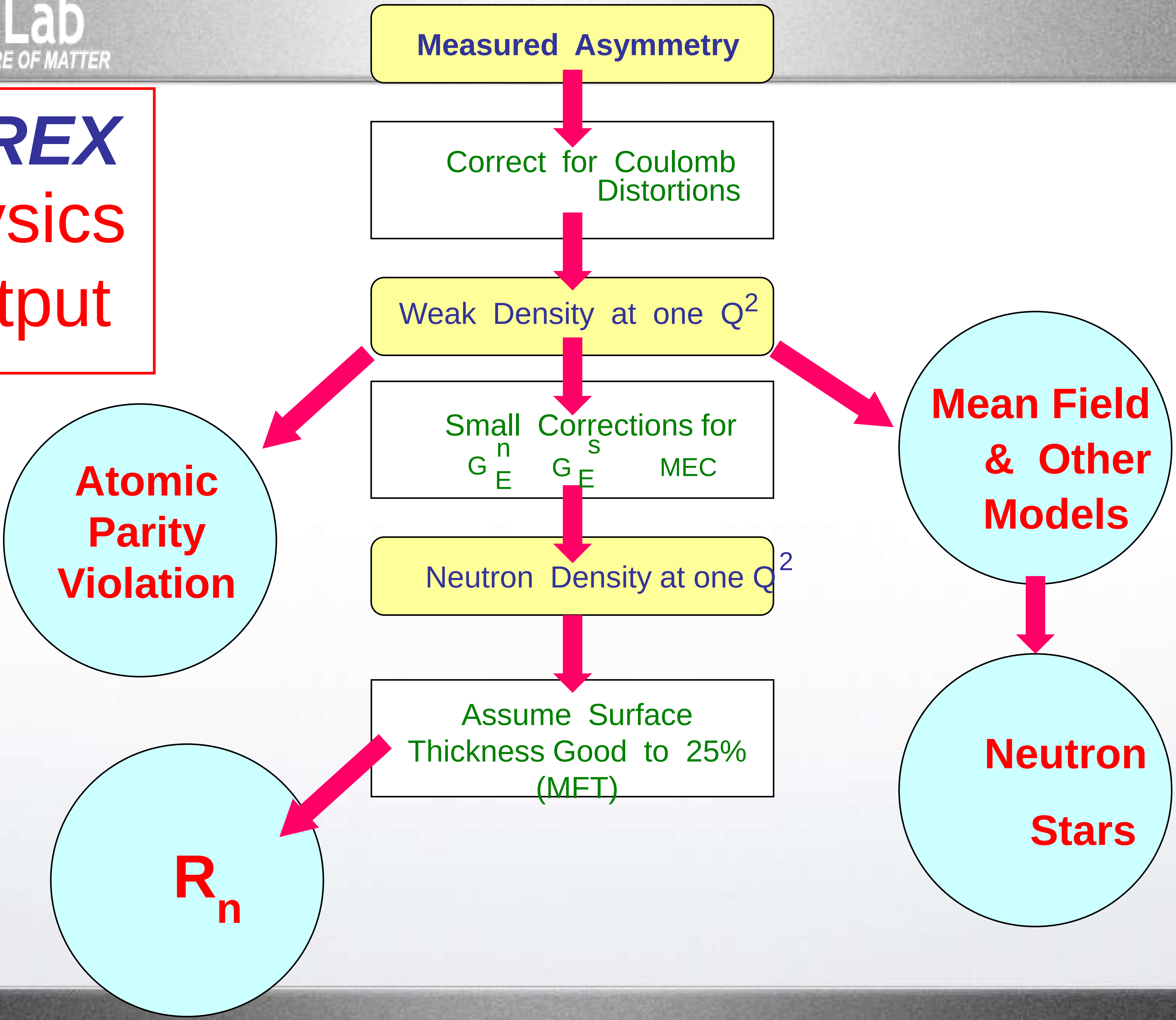
$$F_N(Q^2) = \frac{1}{4\pi}\int d^3r\ j_0(qr)\ \rho_N(r)$$

Parity Violating Asymmetry

$$A = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}\left[\underbrace{1-4\sin^2\theta_W}_{\approx 0} - \frac{F_N(Q^2)}{F_P(Q^2)}\right]$$



PREX Physics Output



Measured Asymmetry

Correct for Coulomb Distortions

Weak Density at one Q^2

Small Corrections for G_E^n G_E^s MEC

Neutron Density at one Q^2

Assume Surface Thickness Good to 25% (MFT)

Atomic Parity Violation

Mean Field & Other Models

Neutron Stars

R_n

PREX

Slide adapted from J. Piekarewicz

Nuclear Structure: *Neutron density is a fundamental observable that remains elusive.*

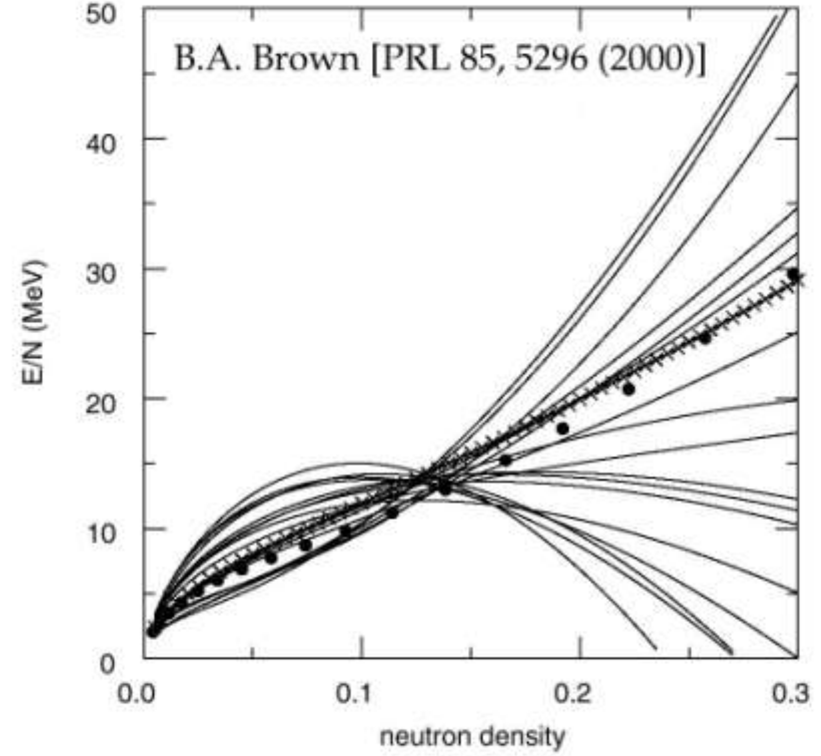


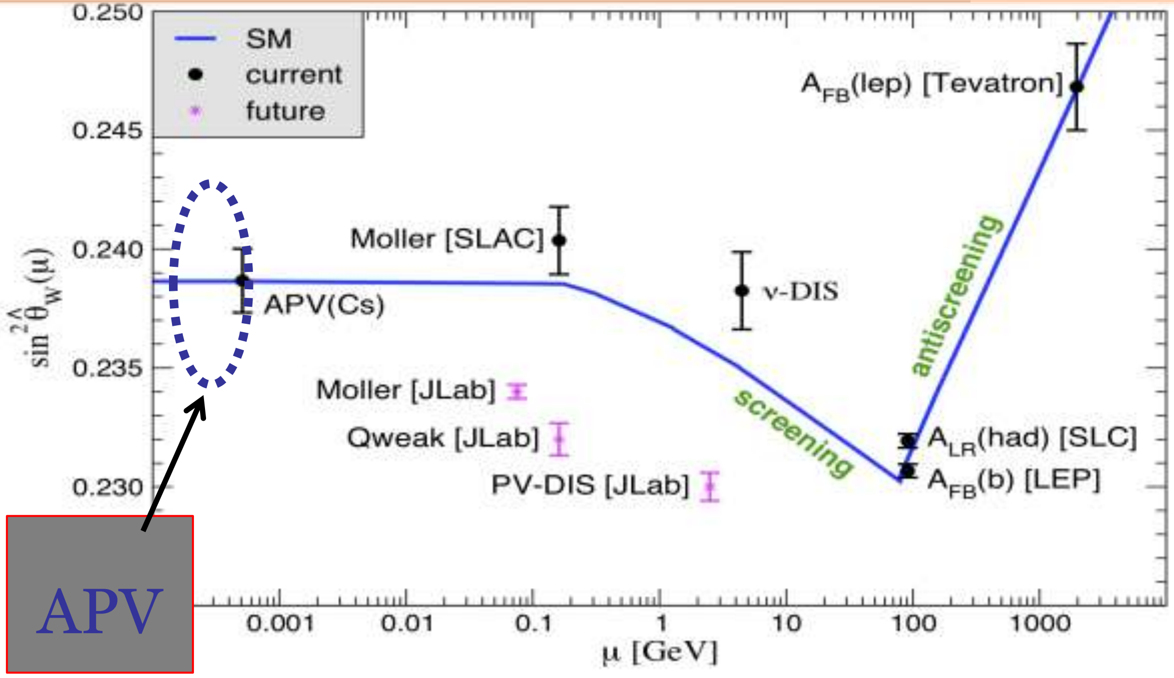
FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/fm^3.

Reflects poor understanding of symmetry energy of nuclear matter = the energy cost of $N \neq Z$

$$E(n,x) = E(n,x=1/2) + S_\upsilon(n)(1-2x^2)$$

$n =$ n.m. density $x =$ ratio proton/neutrons

- Slope unconstrained by data
- Adding R_N from Pb^{208} will eliminate the dispersion in plot.



Application: **Atomic Parity Violation**

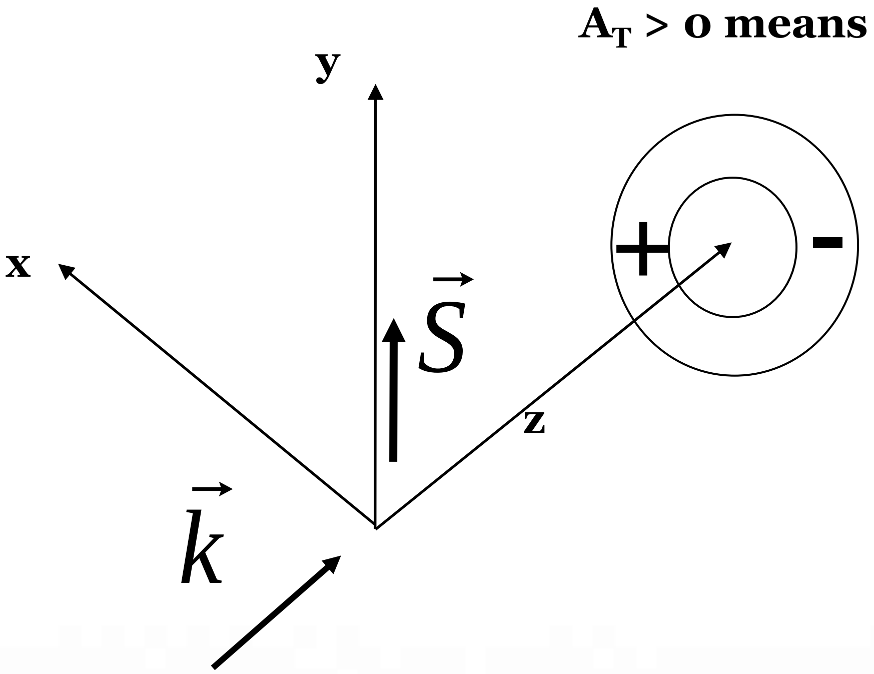
- Low Q^2 test of Standard Model
- Needs R_N (or APV measures R_N)

$$H_{PNC} \approx \frac{G_F}{2\sqrt{2}} \int \left[-N\ \rho_N(\vec{r}) + Z(1-4\sin^2\theta_W)\rho_P(\vec{r}) \right] \psi_e^{\prime}\, \gamma^5 \psi_e\, d^3r$$

Beam-Normal Asymmetry in elastic electron scattering

$$A_T \equiv \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \propto \vec{S}_e \bullet (\vec{k}_e \times \vec{k}'_e)$$

Possible systematic if small transverse spin component



New results PREX

Preliminary !

Publication in preparation

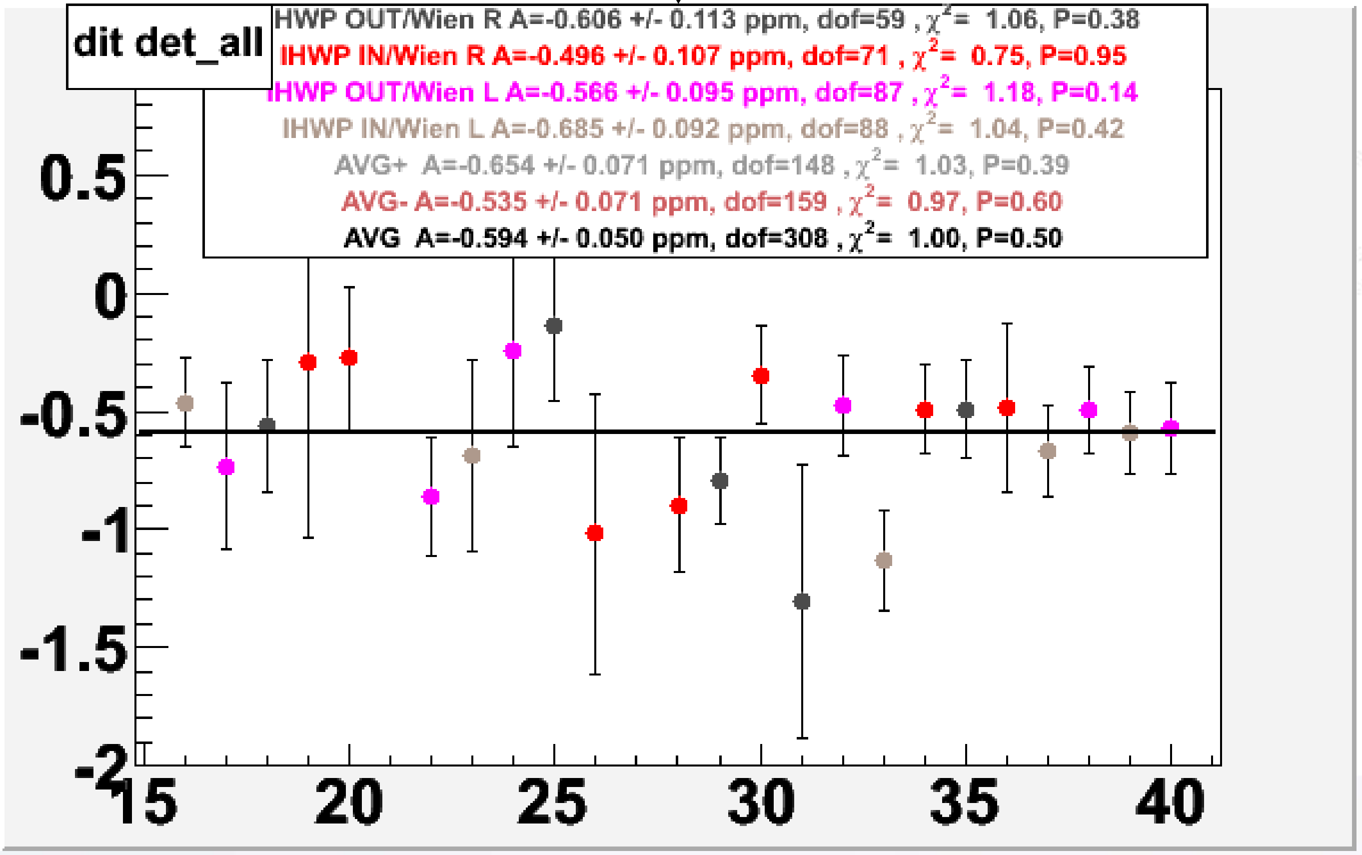
$$^{208}Pb: \quad A_T = +0.13 \pm 0.19 \pm 0.36 \ ppm$$

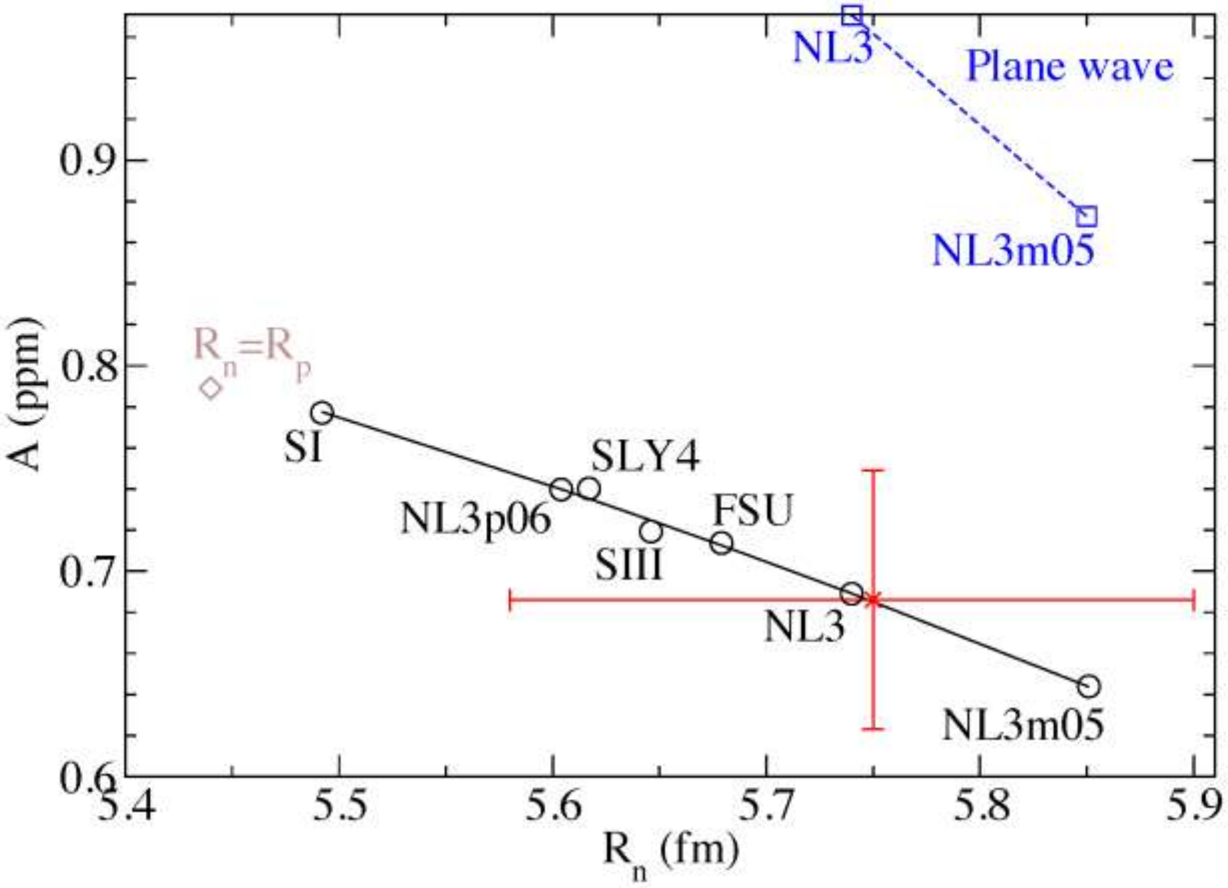
$$^{12}C: \quad A_T = -6.52 \pm 0.36 \pm 0.35 \ ppm$$

- Small A_T for ^{208}Pb is a big (but pleasant) surprise.
- A_T for ^{12}C qualitatively consistent with ^{4}He and available calculations.

PREX-I

PREX Asymmetry (P_e x A)

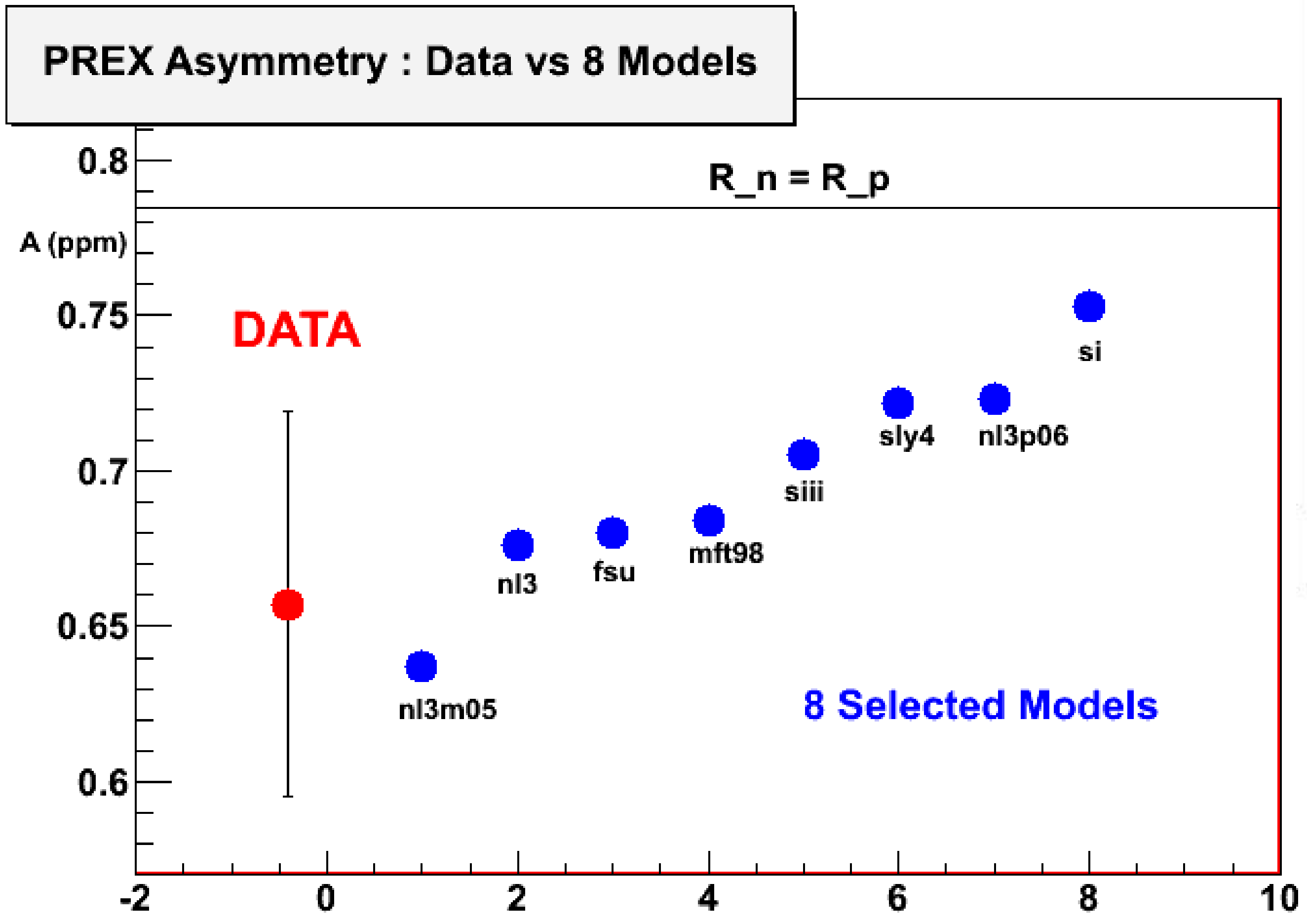


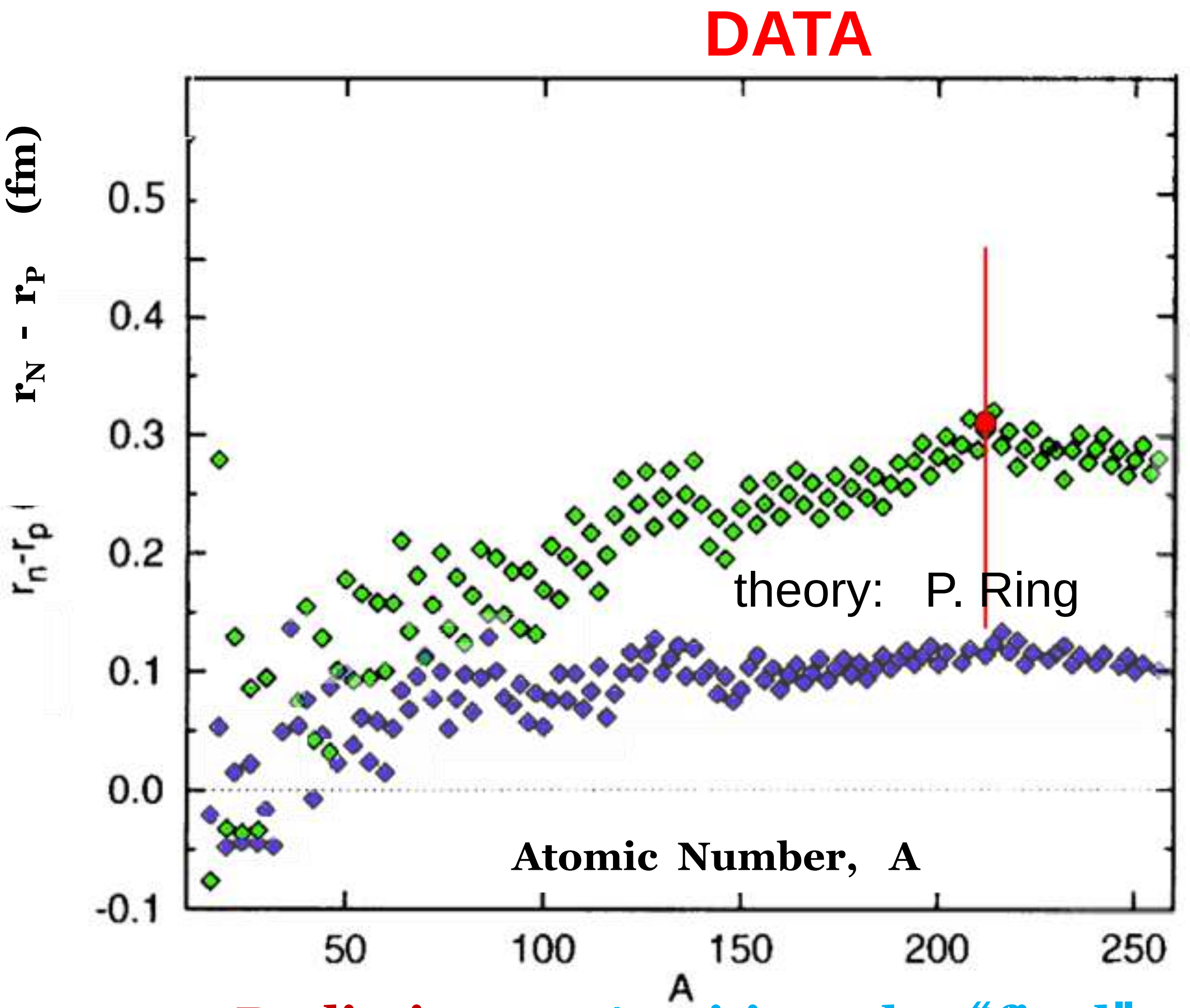


Asymmetry leads to R_N

PREX-I Results

$$A = 0.6571\ ppm \pm 0.0604(stat) \pm 0.0130(syst)$$


PREX Asymmetry : Data vs 8 Models

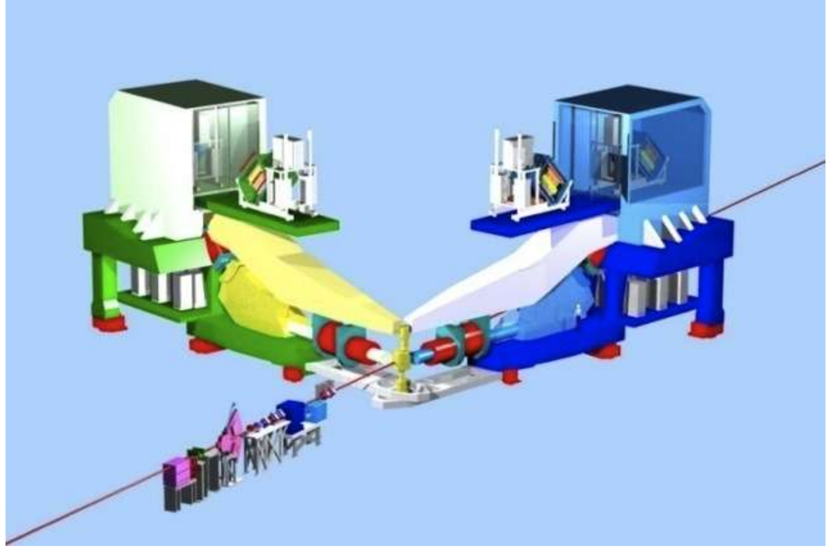


Preliminary: **Awaiting the "final" acceptance function**

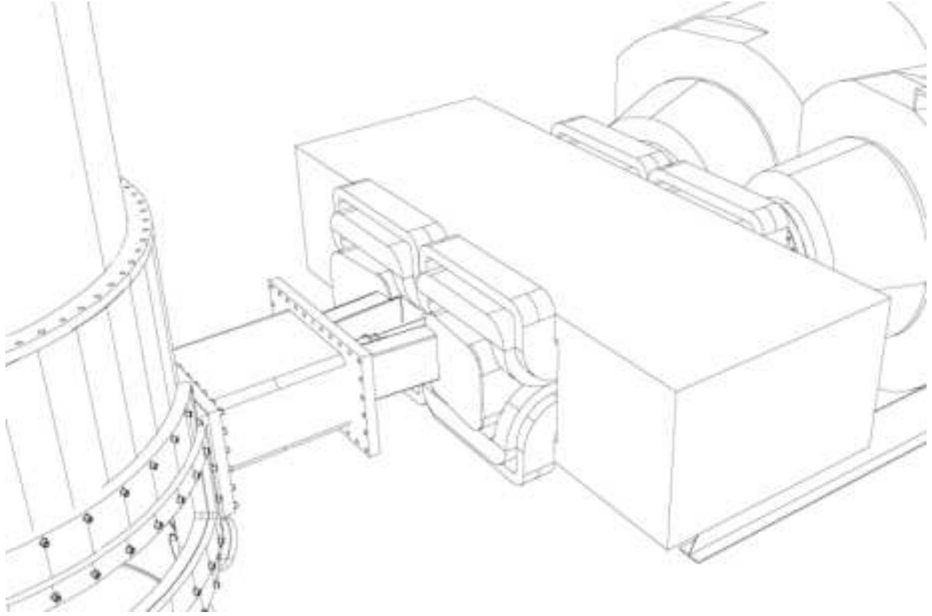
Neutron Skin = $R_N - R_P = 0.31 + 0.15 - 0.17$ fm

A physics letter is in preparation for publication.

PREX-N



Possible Future PREX Program ?



Each point 30 days stat. error only

Not yet proposed. Just a “what if ?”

^{208}Pb	1	1 %	**PREX-II** (approved)
^{48}Ca	2.2 (1-pass)	0.4 %	natural 12 GeV exp’t
^{48}Ca	2.6	2 %	surface thickness
^{40}Ca	2.2 (1-pass)	0.6 %	basic check of theory
tin isotope	1.8	0.6 %	apply to heavy ion
tin isotope	2.6	1.6 %	surface thickness

Shufang Ban, C.J. Horowitz, R. Michaels *arXiv:1010.3246 [nucl-th]*

PREX : Summary

- PREX-I achieved a 9% stat. error in Asymmetry
  (original goal : 3 %)
- Systematic Error Goals Achieved
- PREX-II approved (runs in 2013 or 2014)

New Trends in Hadronic Physics at JLab

Conclusions

It will be very exciting for me to cooperate with other physicists at Hall A using the CEBAF @12 GeV electron beam, on both topics that I discussed, and also on other nice experiments already approved by PACS and that will use the GEM Tracker set up by INFN.