Studies of Nucleon Form Factors with 12 GeV CEBAF and the Super Bigbite Spectrometer

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Jefferson Lab

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MIT, July 2011

Jefferson Lab
Thomas Jefferson National Accelerator Facility

CEBAF@12 GeV

Nucleon Elastic Form Factors — Formalism

Nucleon hadronic current

$$J^{\mu}_{\text{hadronic}} = e\overline{N}(p')\left[\gamma^{\mu}\, F_1(Q^2) + \frac{i\sigma^{\mu\nu}q_{\nu}}{2M}\, F_2(Q^2)\right] N(p)$$

Dirac FF

Pauli FF

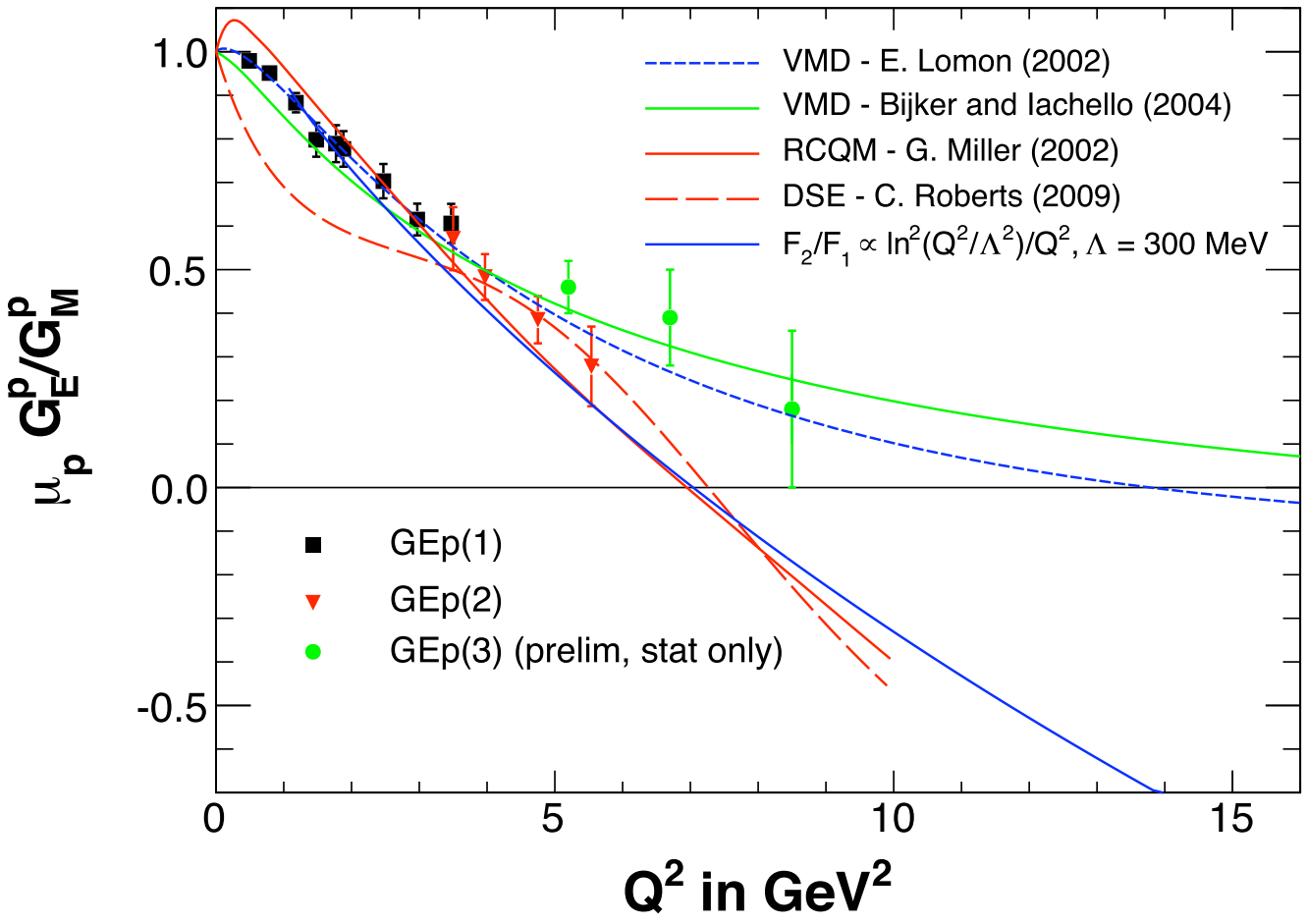
Sachs form factors

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

with

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

Second-generation data on G_E^p/G_M^p from JLab



Sharp drop completely unexpected

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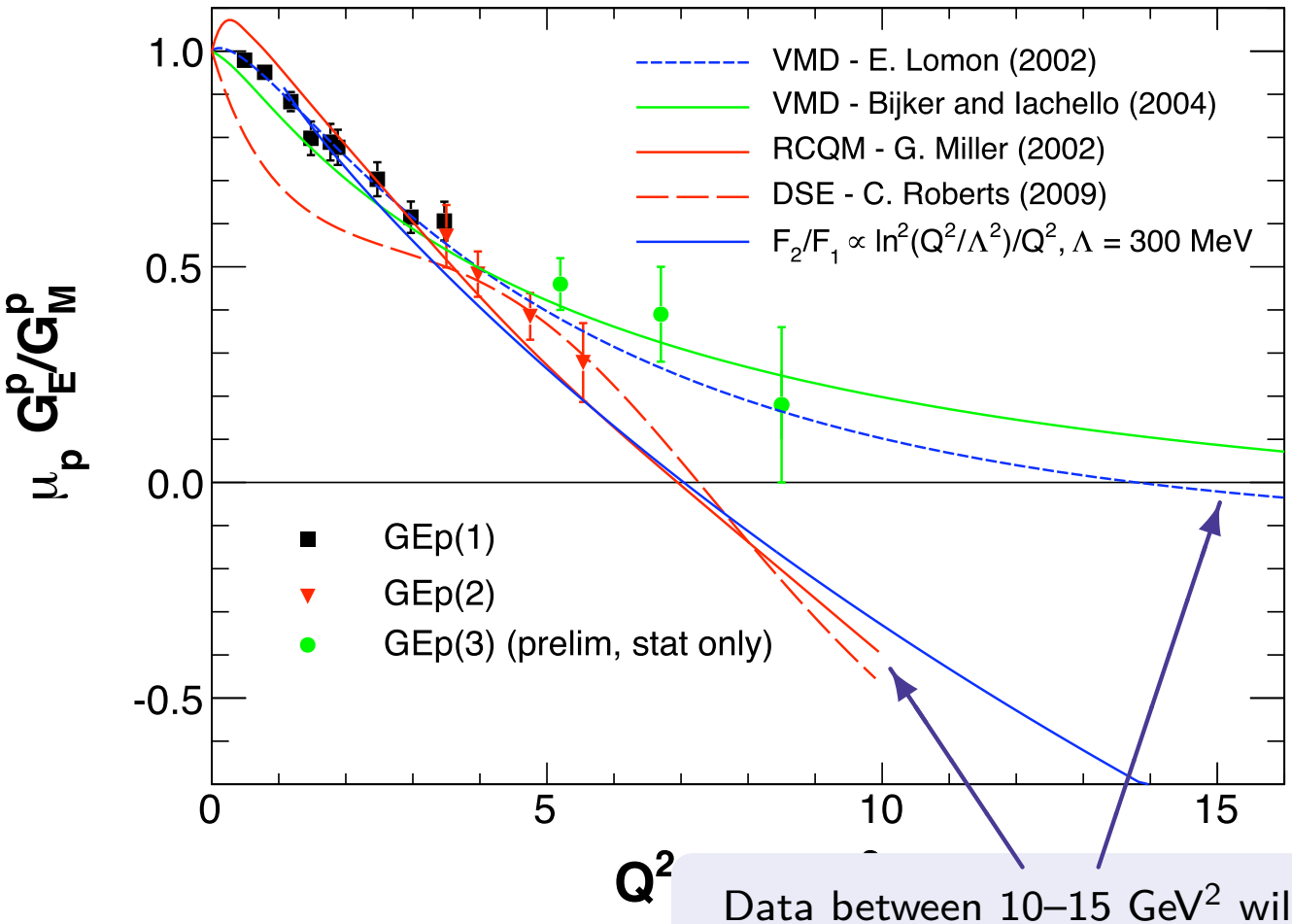
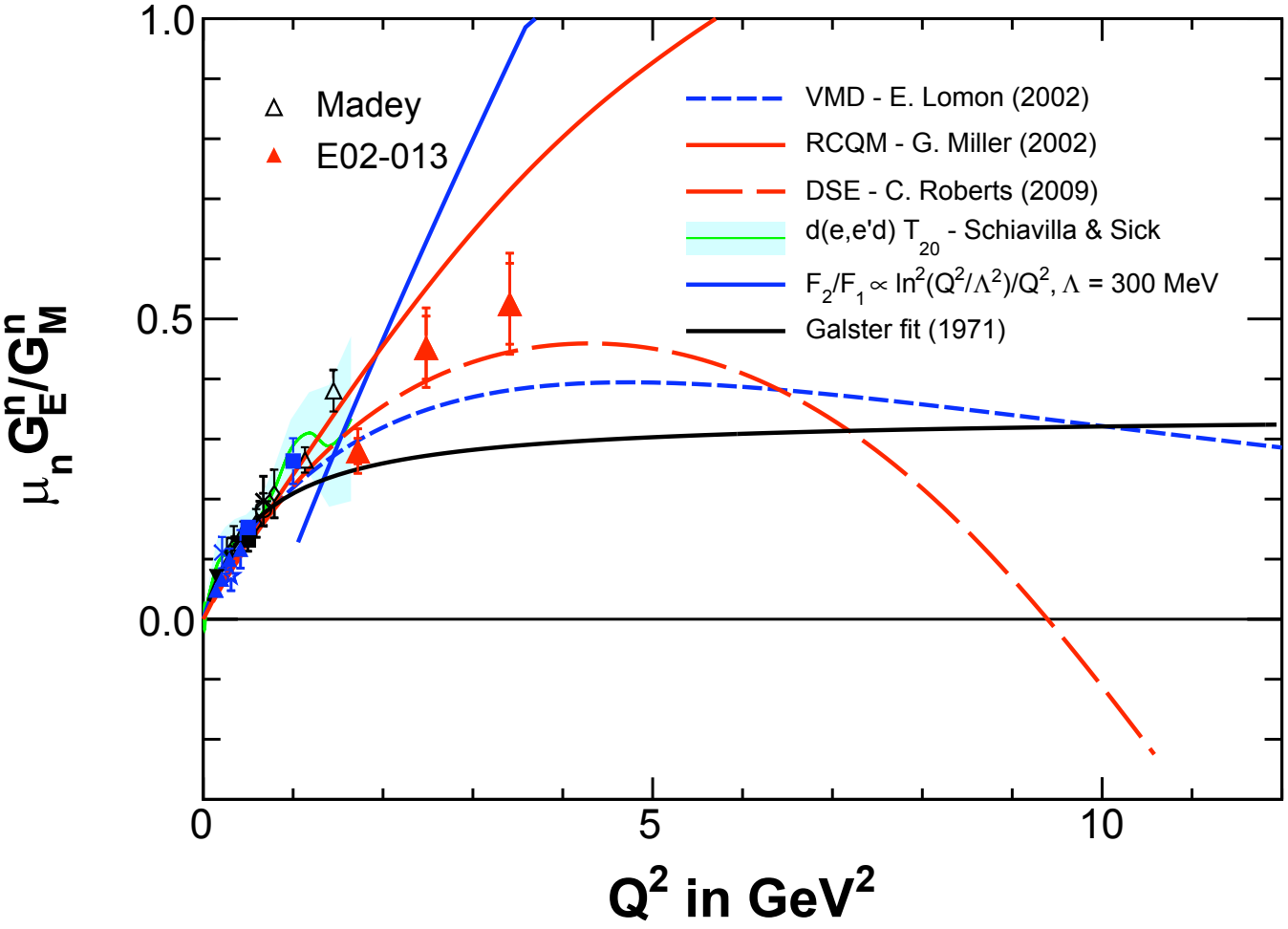


Data between 10–15 GeV^2 will cleanly distinguish some models

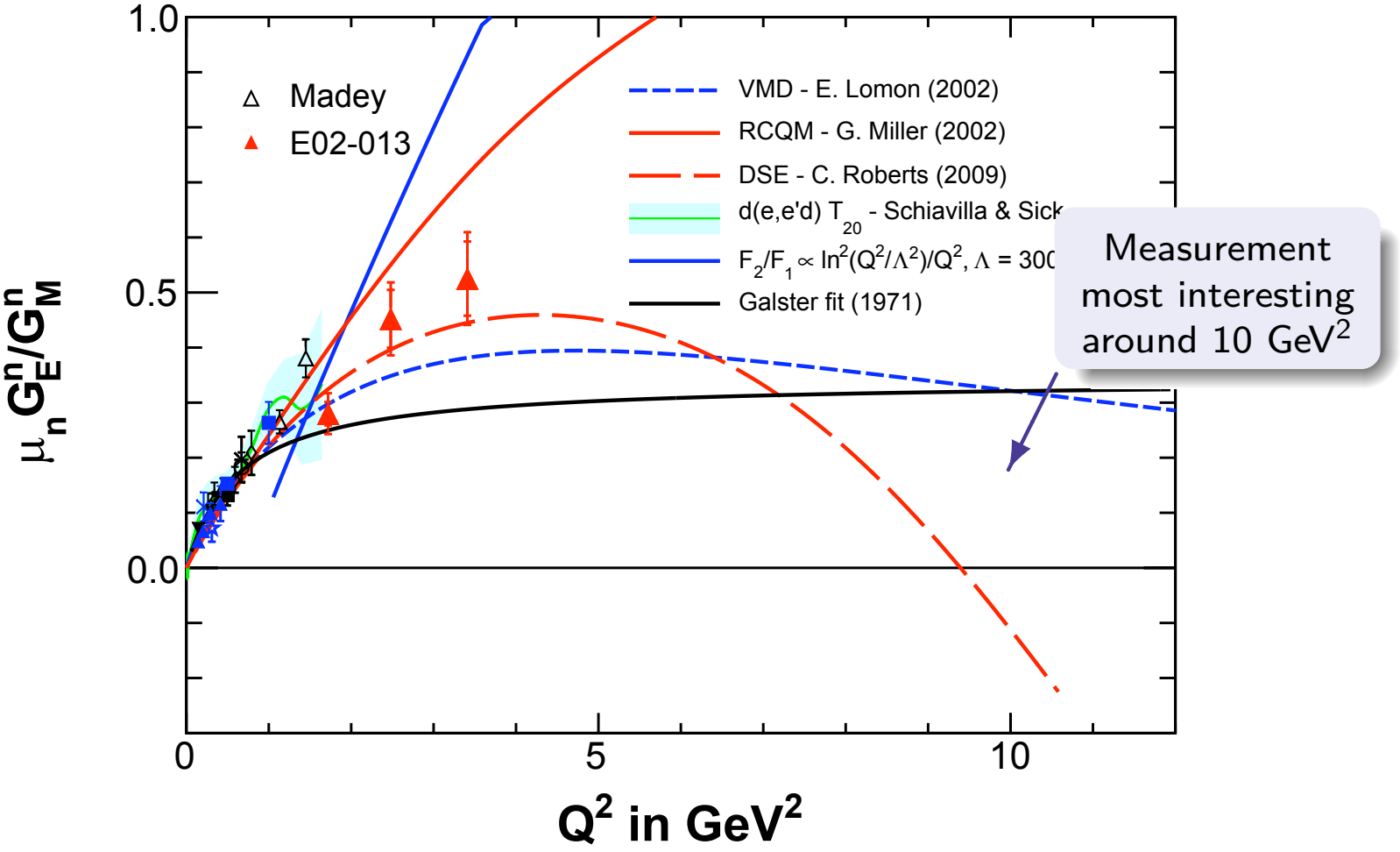
Sharp drop completely unexpected

World data on G_E^n



Difficult measurement as neutron has no electric charge

World data on G_E^n



Difficult measurement as neutron has no electric charge

Current Best Measurement Techniques

G_E^n / G_M^n

polarized target: $^3\vec{\mathrm{He}}(\vec{e}, e'n)$

$$\text{F.o.M.} \propto \sigma \cdot \Omega \cdot P_t^2 \cdot \mathcal{L} \propto \frac{E^2}{Q^{12}} \cdot \Omega \cdot P_t^2 \cdot \mathcal{L}$$

G_E^p / G_M^p

Recoil polarization asymmetry: $p(\vec{e}, e'\vec{p})$

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

(Polarized proton targets cannot tolerate high $\mathcal{L}$)

G_M^n / G_M^p

cross section ratio: $d(e, e'n) \,/\, d(e, e'p)$

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Extra factor $\mathbf{A_y^2 \propto 1/Q^4}$

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G_M^n / G_M^p

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Challenge!

G_M^n / G_M^p

cross section ratio: $d(e, e'n) \,/\, d(e, e'p)$

Current Best Measurement Techniques

G_E^n / G_M^n

polarized target: $^3\vec{\mathrm{He}}(\vec{e}, e'n)$

$$\text{F.o.M.} \propto \sigma \cdot \Omega \cdot P_t^2 \cdot \mathcal{L} \propto \frac{E^2}{Q^{12}} \cdot \Omega \cdot P_t^2 \cdot \mathcal{L}$$

G_E^p / G_M^p

Recoil polarization asymmetry: $p(\vec{e}, e'\vec{p})$

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

Need absolute measurement

(Polarized proton targets cannot tolerate high $\mathcal{L}$)

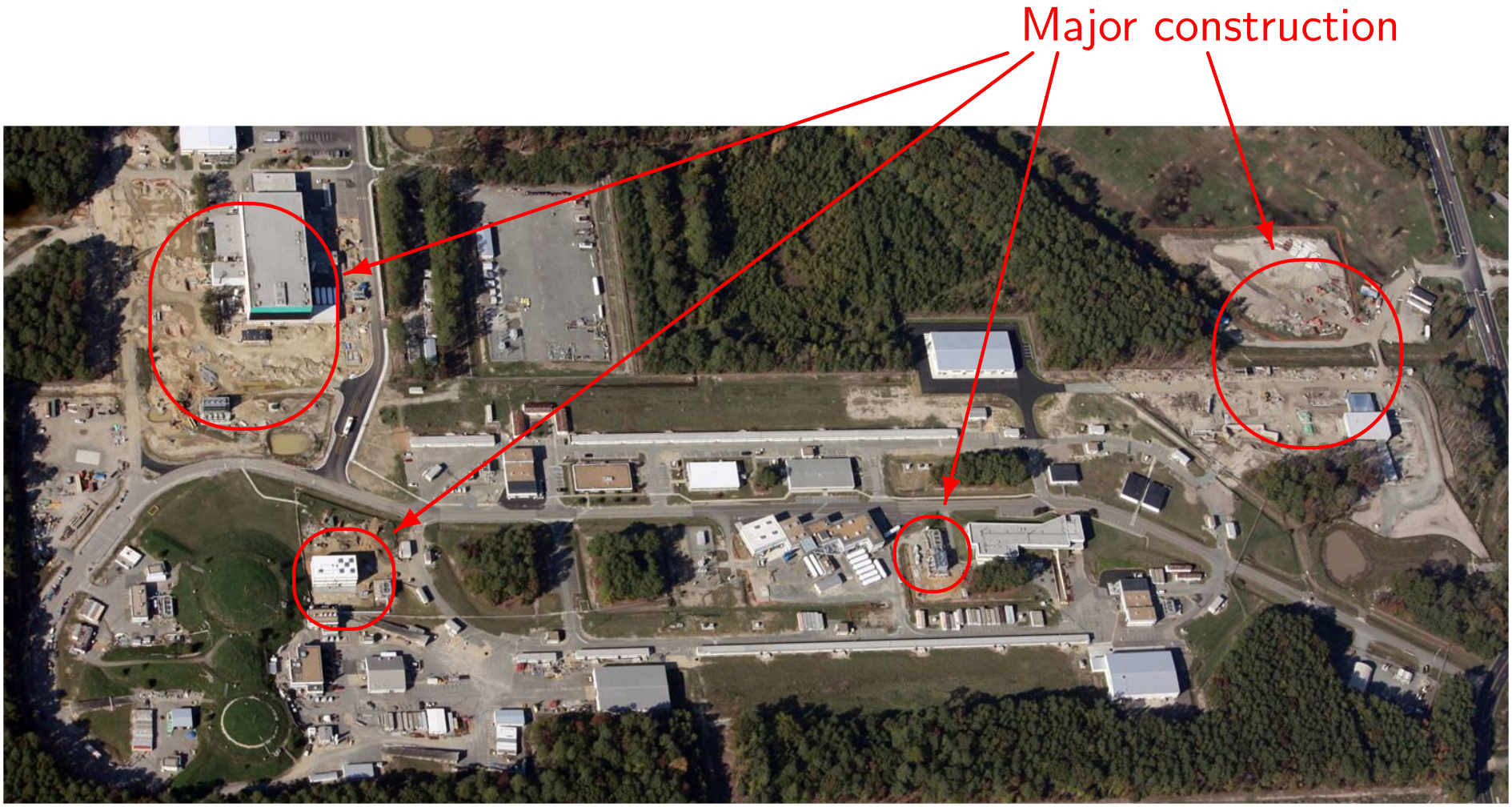
G_M^n / G_M^p

cross section ratio: $d(e, e'n) \,/\, d(e, e'p)$

Jefferson Lab

6 GeV electron accelerator, $I_{max} \approx 200\ \mu A$, $P_{beam} = 85\%$

Jefferson Lab



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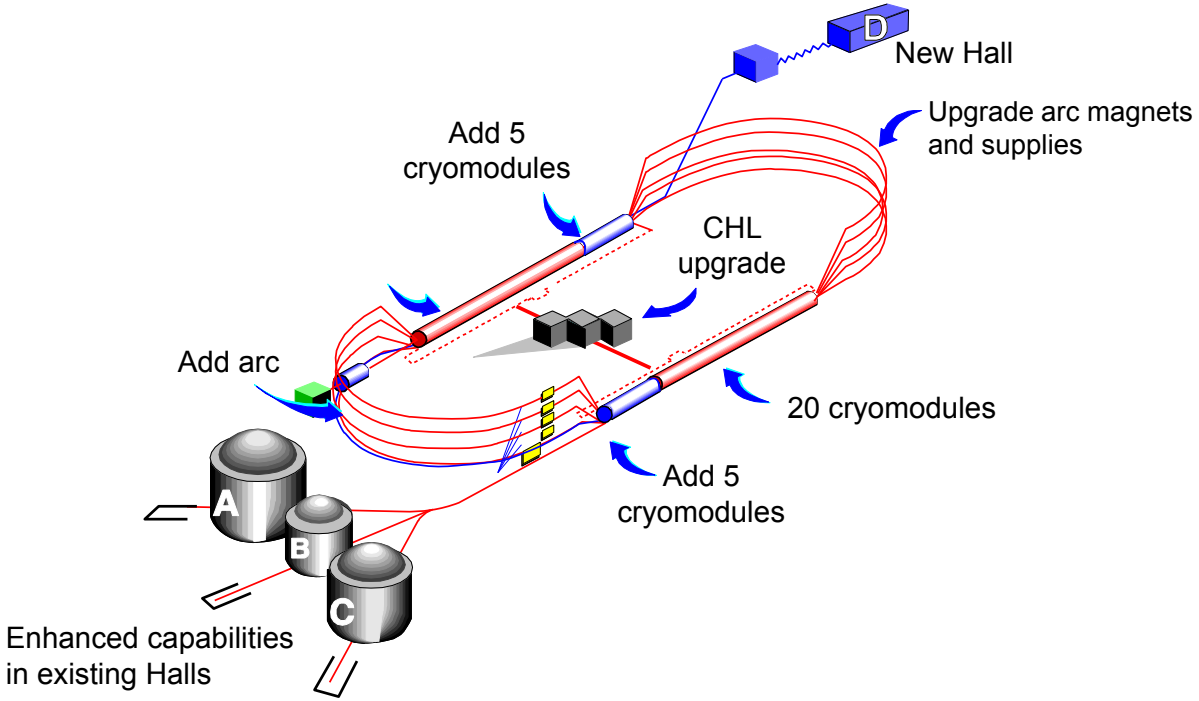
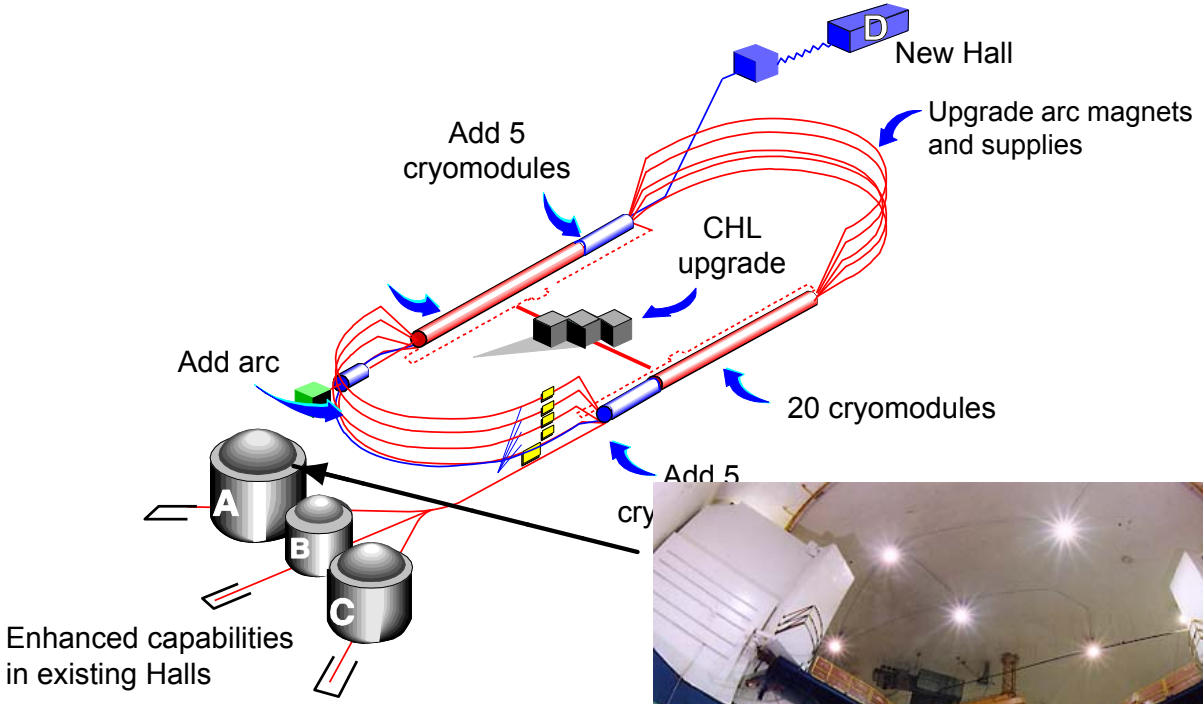
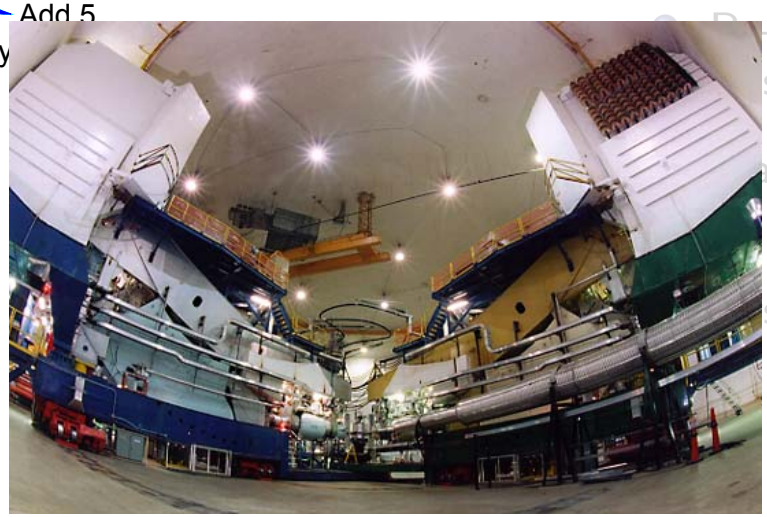
JLab 12 GeV Upgrade



- Double beam energy ($6 \rightarrow 12$ GeV)
- 11 GeV max to Halls A, B, C
  12 GeV to new Hall D
- Maintain ability to deliver lower-pass energies to Halls (1.1, 2.2, ... GeV)
- Re-use vast majority of existing equipment
- Major upgrades to existing Halls
- First physics in 2014

JLab 12 GeV Upgrade





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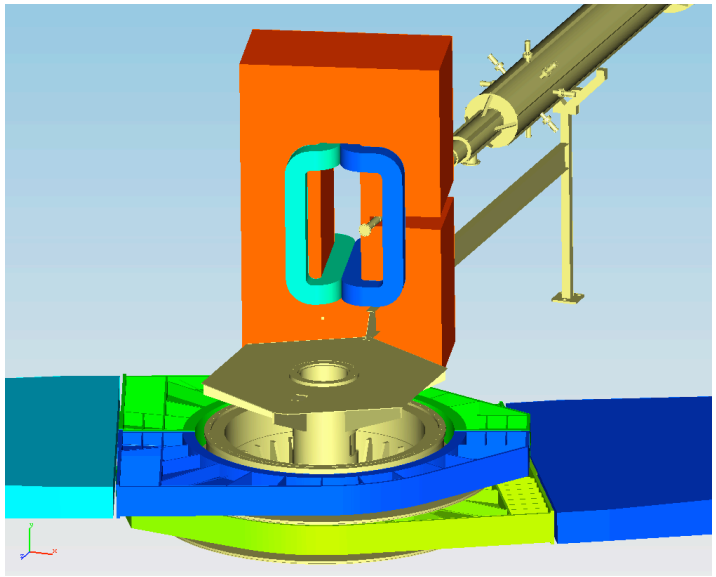
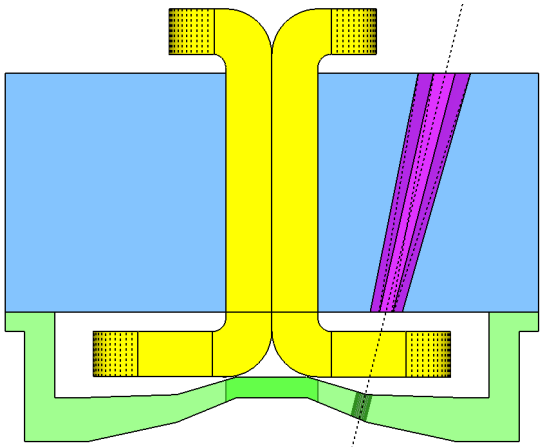
Super BigBite

- New equipment in Hall A, to be constructed
- Set of components for flexible spectrometer configuration
  - Dipole magnet
  - GEM trackers
  - Calorimeter
  - CH_2 analyzers (for p polarimeter)
  - Dual-radiator RICH (for SIDIS program)
- Use in combination with existing apparatuses, *e.g.* BigBite

SBS Magnet





- Simple dipole, vertical bending
- 46 cm gap, 2.5 T-m
- Provides **large acceptance**

θ_{centr} (deg)	D (m)	$\Delta\phi$(hor) (deg)	$\Delta\theta$(vert) (deg)	Ω (msr)
3.5	9.5	± 1.3	± 3.3	5
5.0	5.8	± 1.9	± 4.9	12
7.5	3.2	± 3.0	± 8.0	30
15	1.6	± 4.8	± 12.2	72
30	1.5	± 4.9	± 12.5	76

- Momentum resolution

$$\frac{\Delta p}{p} = (0.03p[\text{GeV}] + 0.29)[\%]$$

- Angular resolution $\approx$ 0.3 mrad
- Vertex resolution $\approx 1 \ldots 2$ mm

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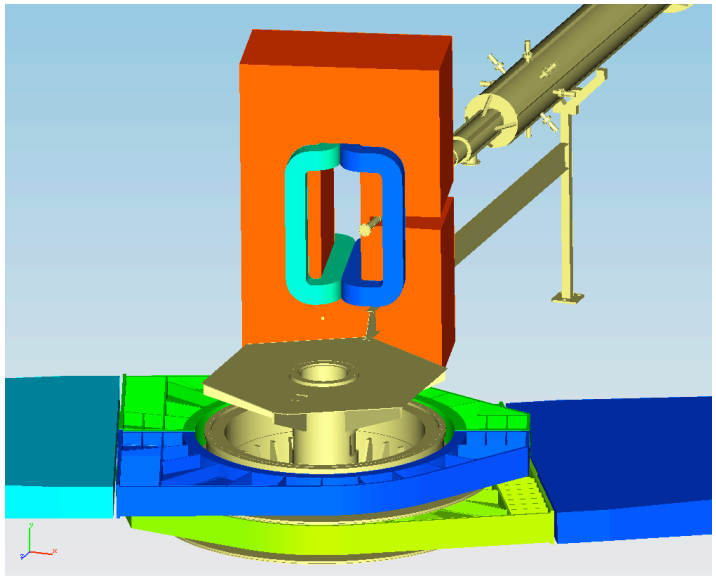

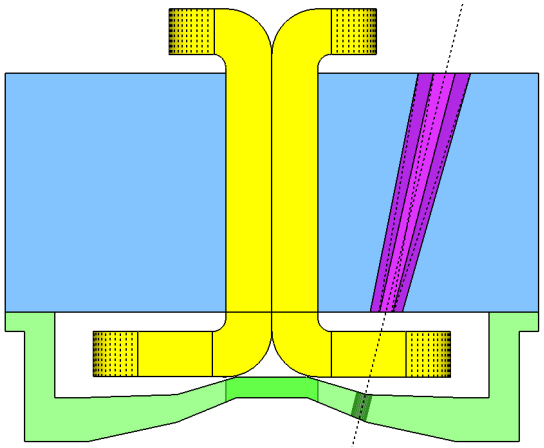

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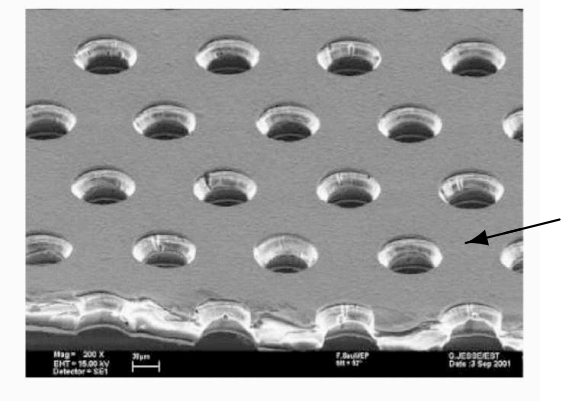
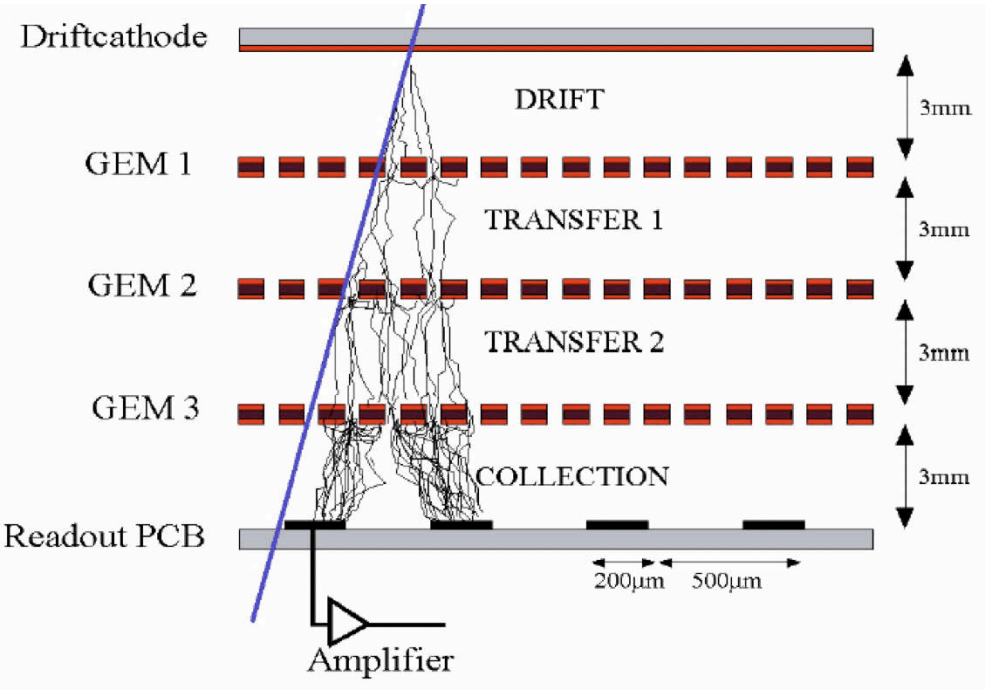
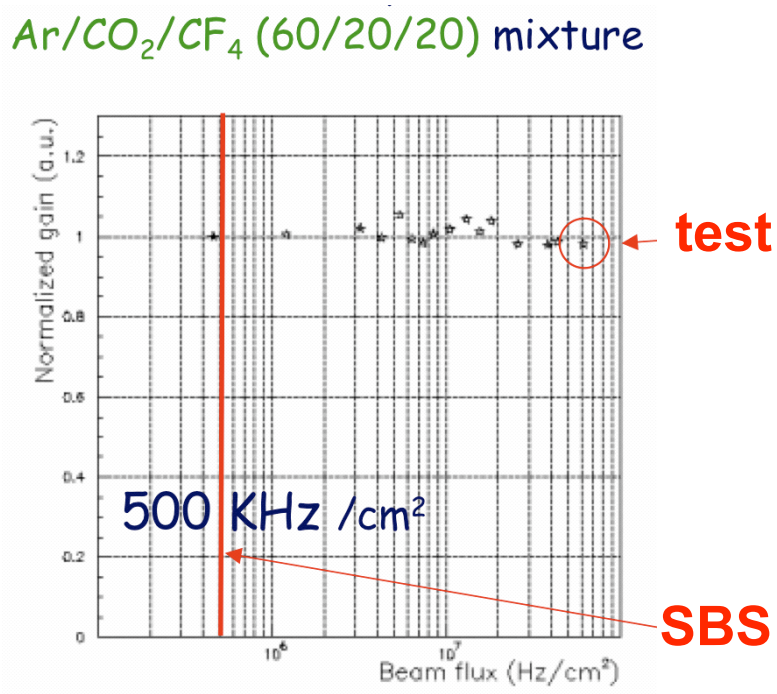
Gas Electron Multiplier (GEM) Trackers



50 μm Cu-kapton foil

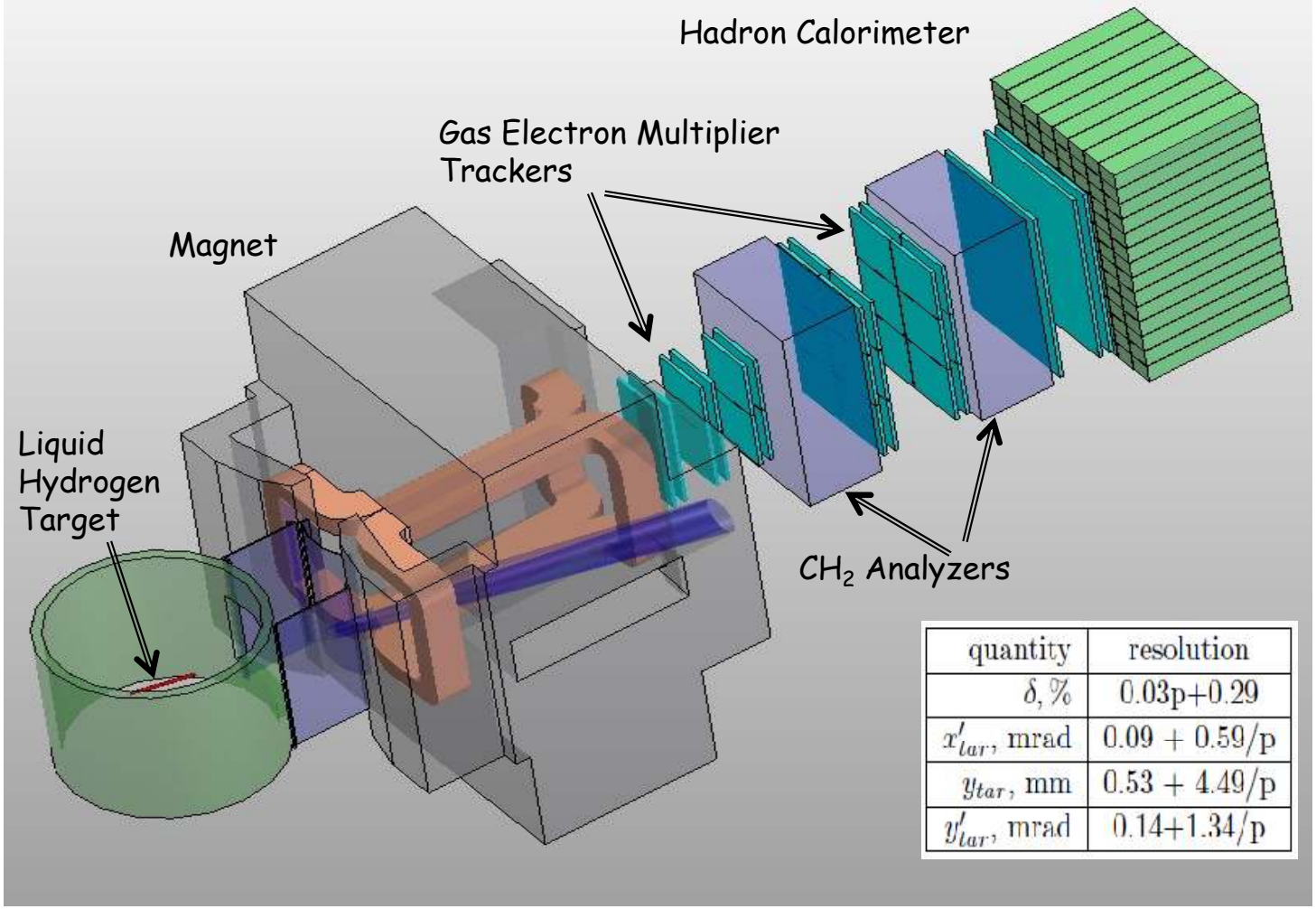
- F. Sauli, NIM A386, 531 (1997)
- **Very high rate capability**
- Successfully used in COMPASS
- Gain $\mathcal{O}(10^4)$
- $\leq 70\mu$m position resolution
- 40×50 cm^2 prototype sections being tested





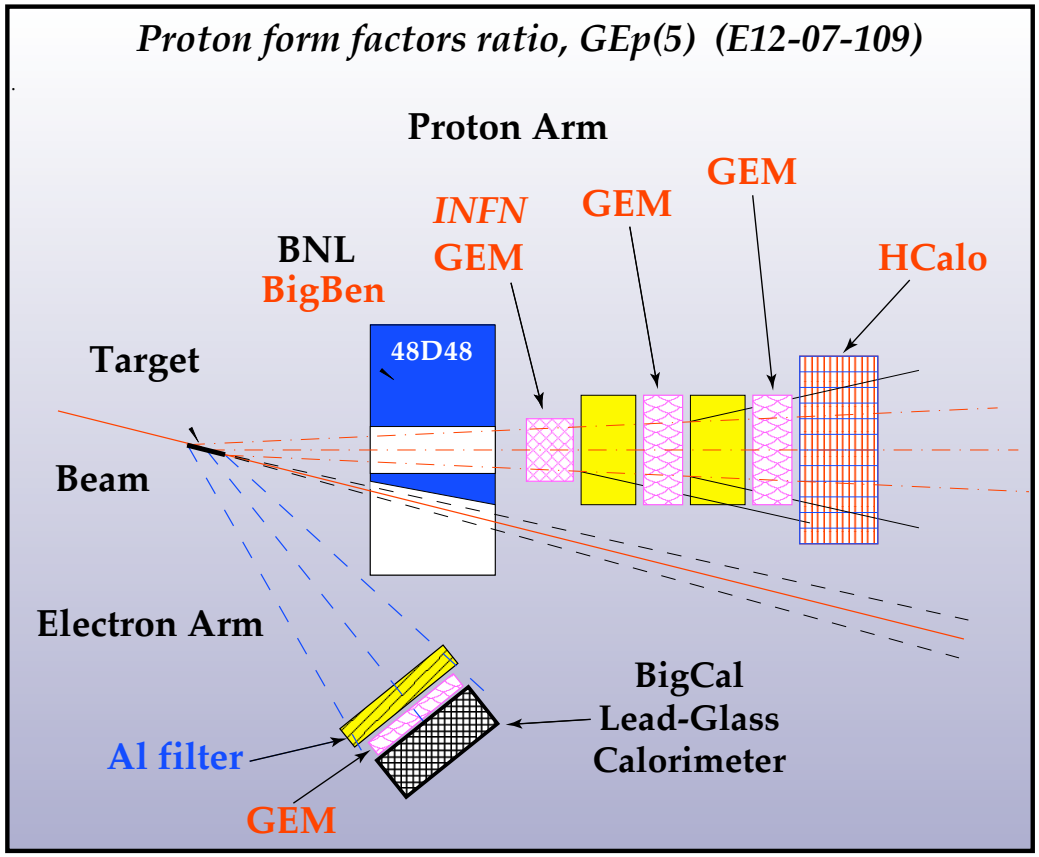
Gain vs. rate

SBS for Gep5



quantity	resolution
δ, %	0.03p+0.29
x'_{tar}, mrad	0.09 + 0.59/p
y_{tar}, mm	0.53 + 4.49/p
y'_{tar}, mrad	0.14+1.34/p

GEp(5) experiment



Reaction

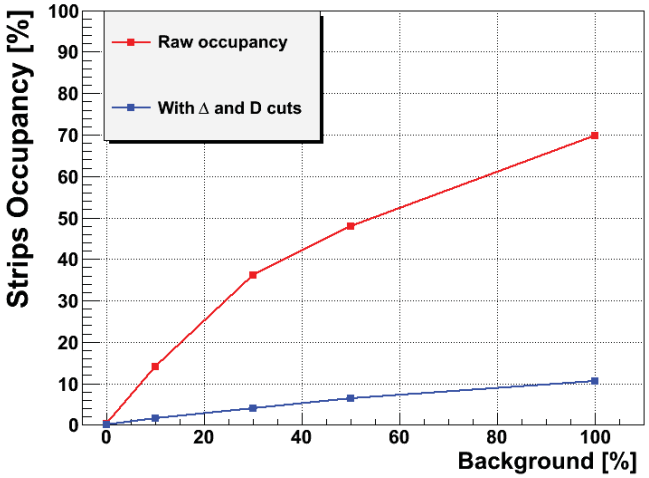
$$p(\vec{e}, e'\vec{p})$$

- 40 cm LH2 target
- $\mathcal{L} = 8 \cdot 10^{38} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- High calorimeter thresholds to reject background
- Coincidence rate $\leq$ 5 kHz
- 45 days of beam approved

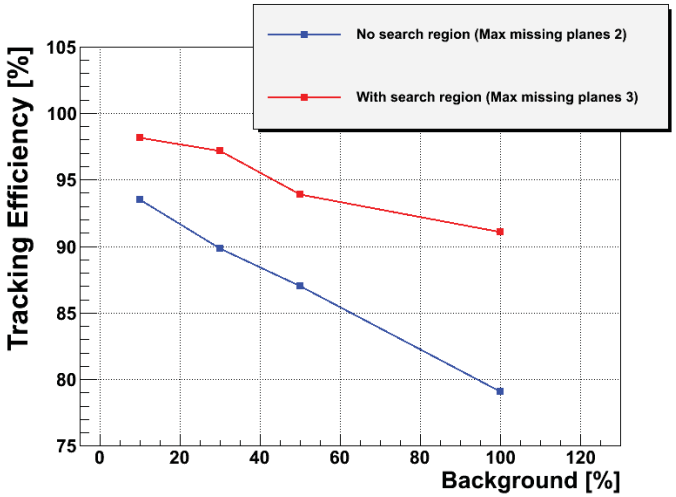
Q^2 (GeV)	E_{beam} (GeV)	p_p (GeV)	θ_{SBS} (deg)	E' (GeV)	θ_{BigCal} (deg)	$\Delta[G_E/G_M]$ (%)
5.0	6.6	3.5	28.0	3.94	26.3	2.3
10.0	8.8	6.2	16.7	3.47	35.3	6.5
12	11	7.4	16.9	4.45	29	13.5

GEp(5) Tracking Monte Carlo

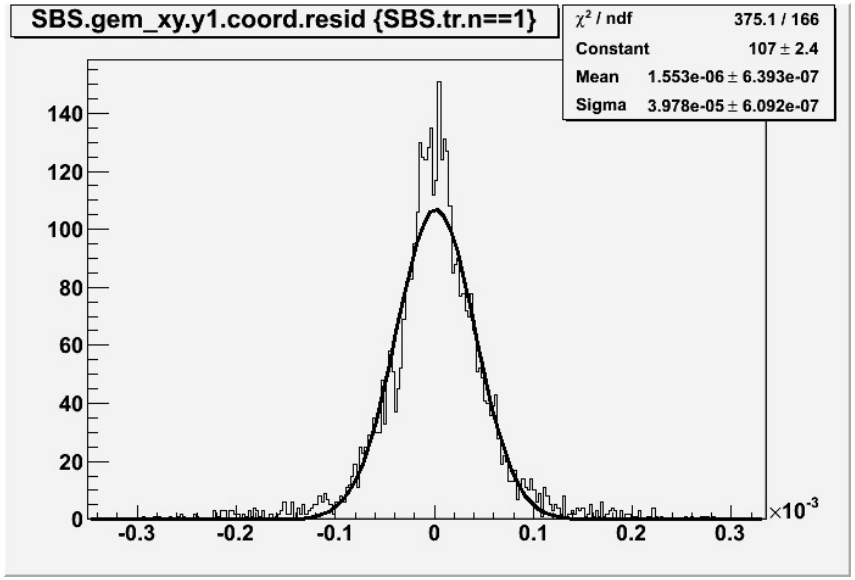
Front tracker GEM strip occupancy



Tracking Efficiency

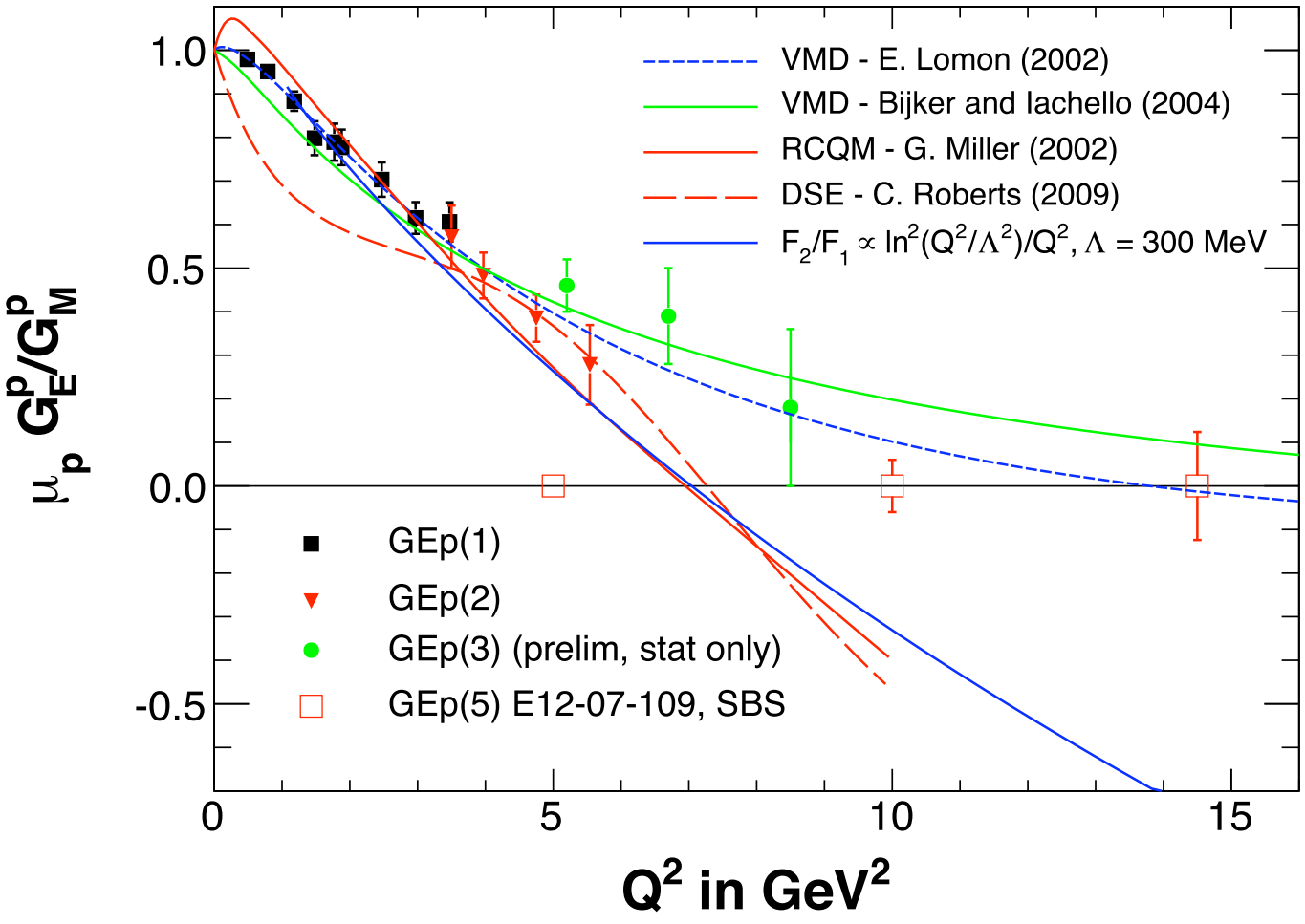


Track reconstruction accuracy

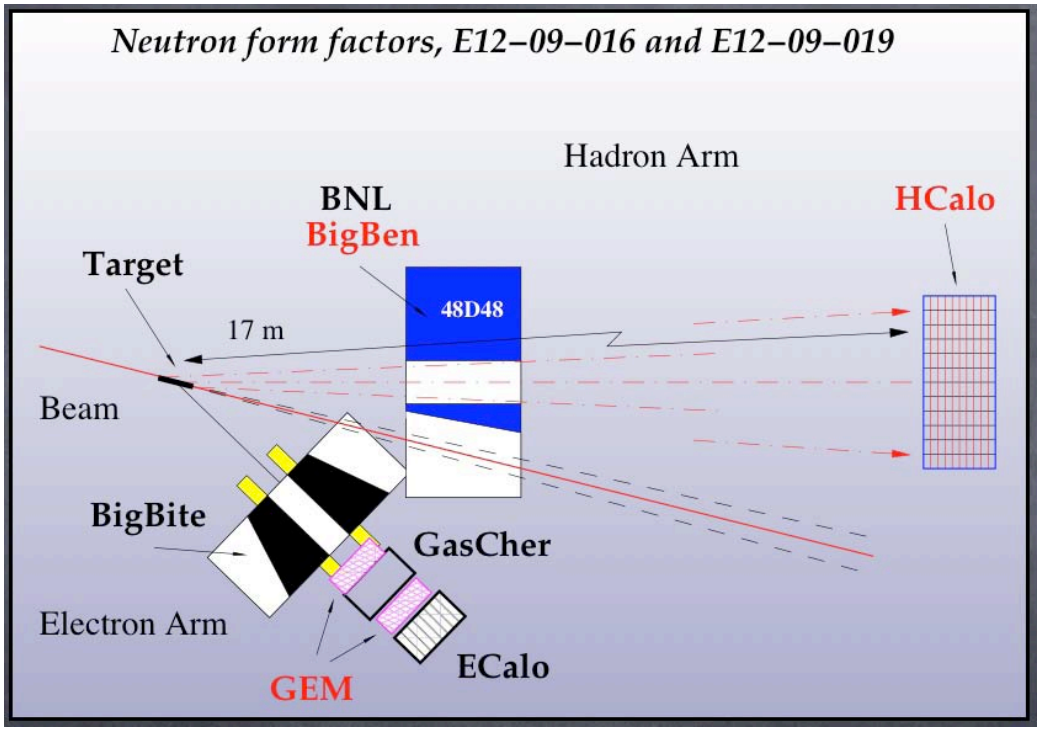


- Realistic digitization of GEM & electronics response
- Huge photon background rate, $\mathcal{O}(100)$ MHz
- $> 90\%$ tracking efficiency despite $> 70\%$ raw occupancy!
- $\approx 40\ \mu$m reconstruction accuracy

GEp(5) Expected Precision



Neutron FF Experiments



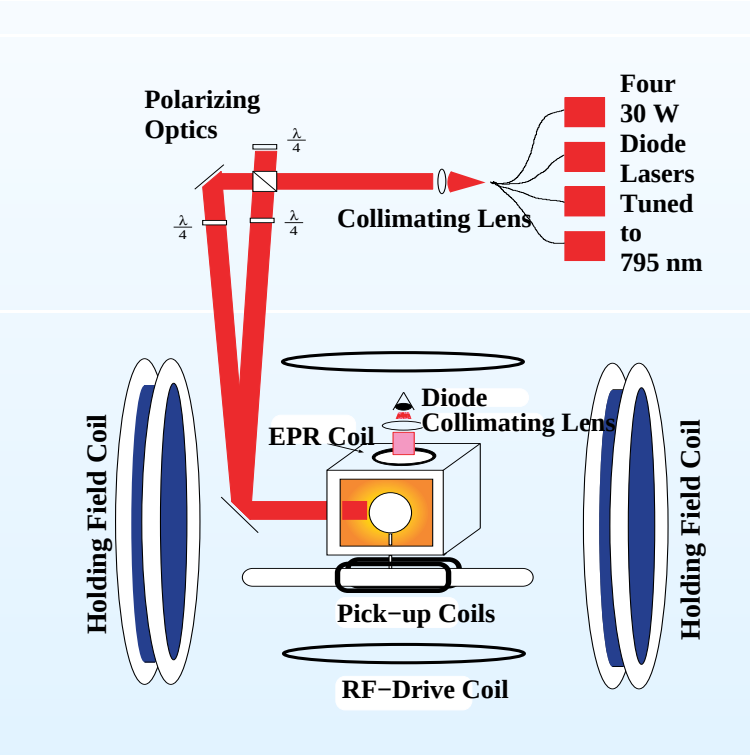
G_E^n measurement

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

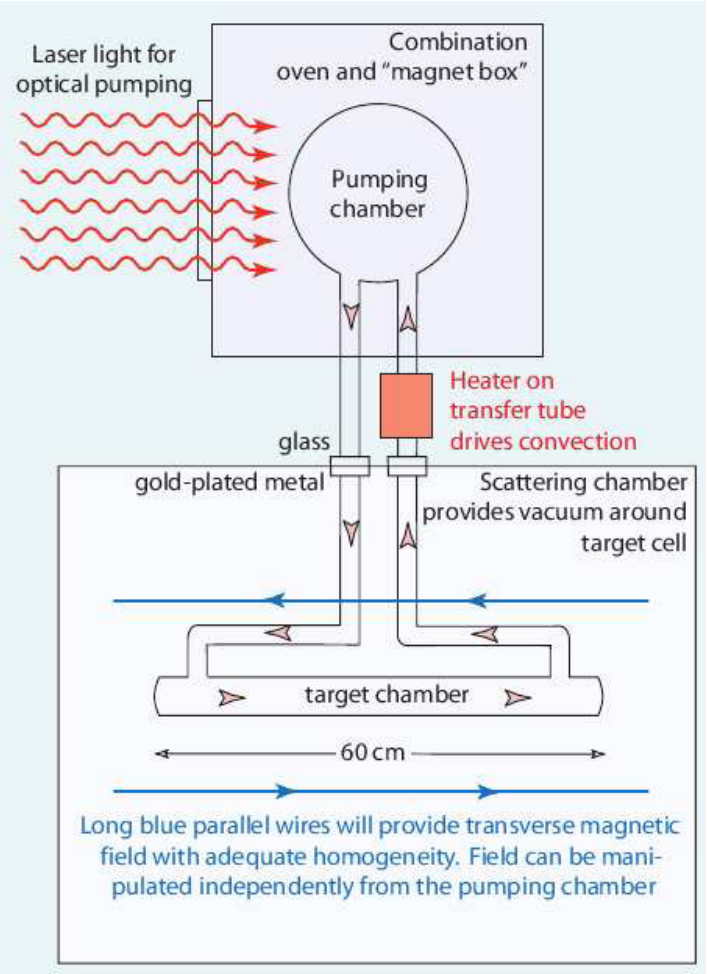
$$A \propto \frac{G_E^n G_M^n \sin\theta^* \cos\phi^*}{a(G_M^n)^2} + b$$

- 60 cm high-pressure $^3\vec{\mathrm{He}}$ target (effective polarized neutron)
- $P_t \geq 65\%$ at I $= 40\ \mu$A
- $\mathcal{L} = 6 \cdot 10^{36}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- BigBite with GEM trackers for precise electron kinematics
- SBS magnet deflects protons
- 50 days of beam approved

Polarized ^{3}He Target

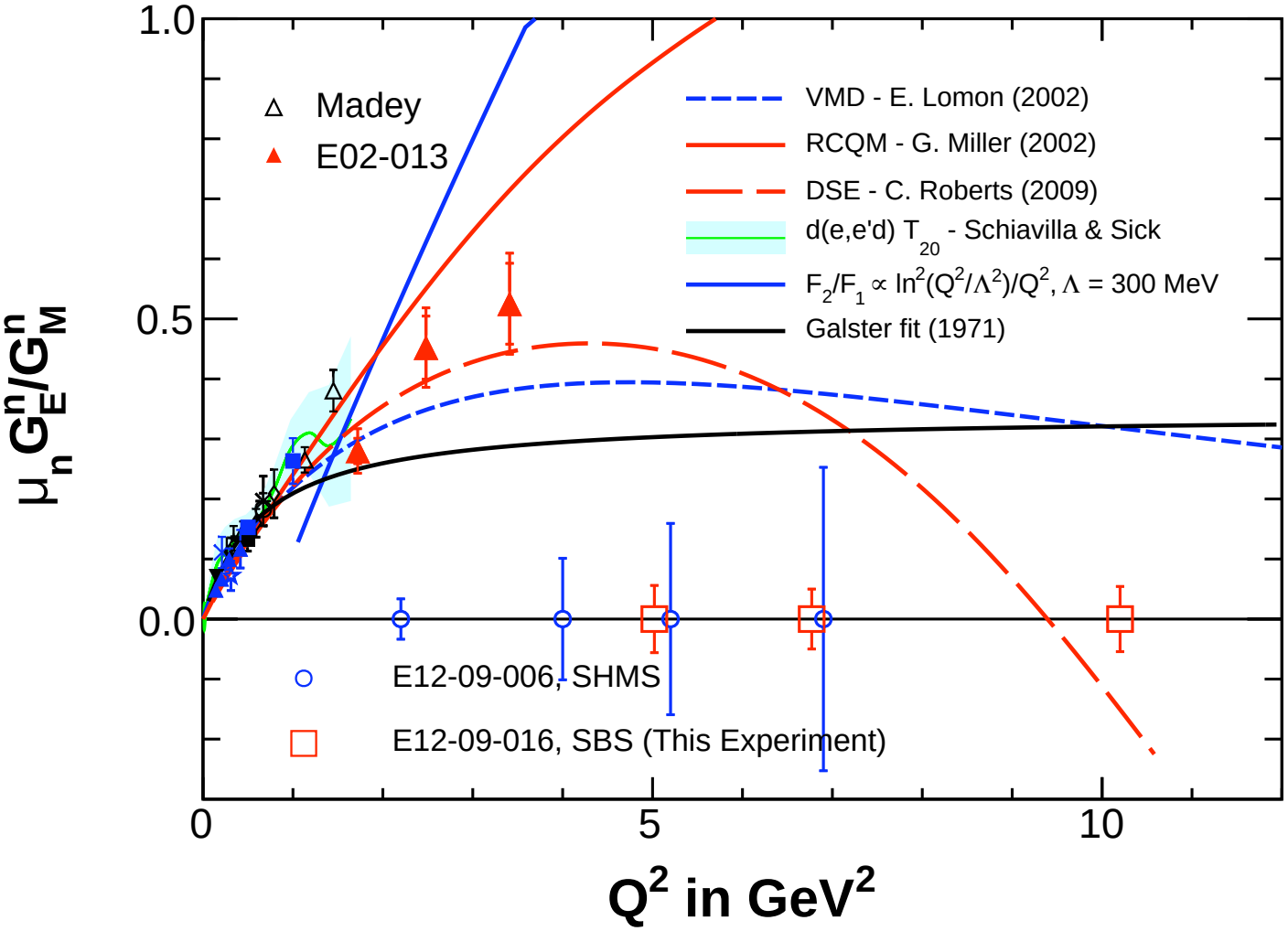


New target cell design gains $\times 15$ in luminosity

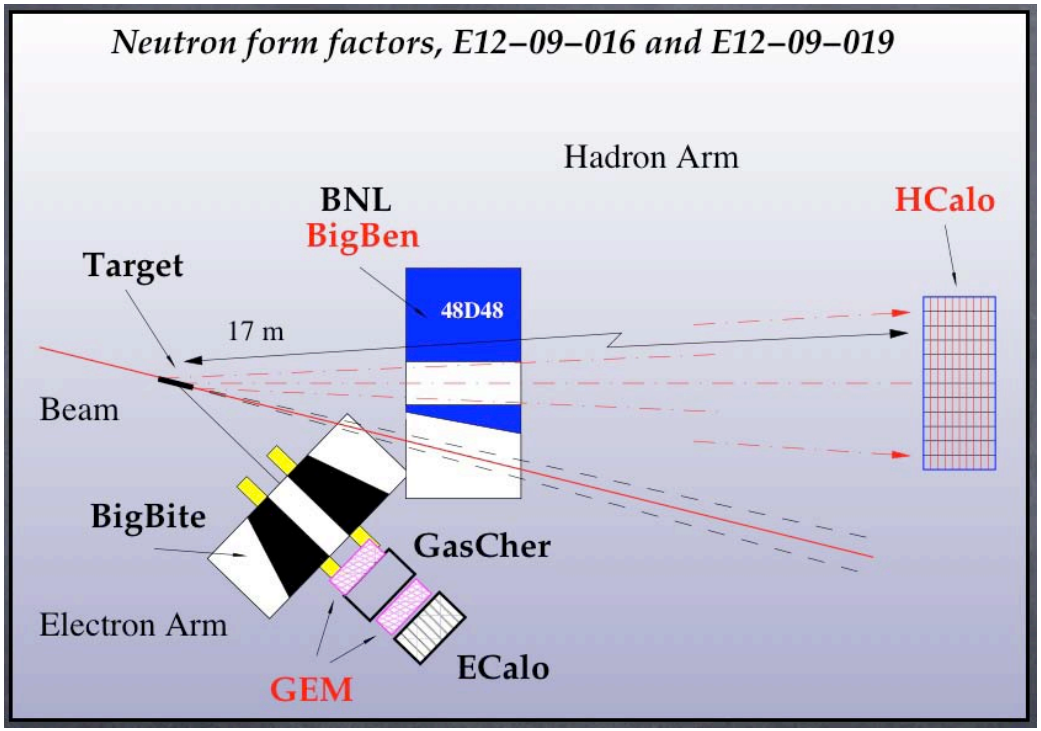


- Optically-pumped spin-exchange target
- Extensive R&D over last decade (UVa)
- New convection method very promising
- $P \geq 65\%$
- Fast spin rotation (seconds)

G_E^n Expected Precision



G_M^n Ratio Method Measurement

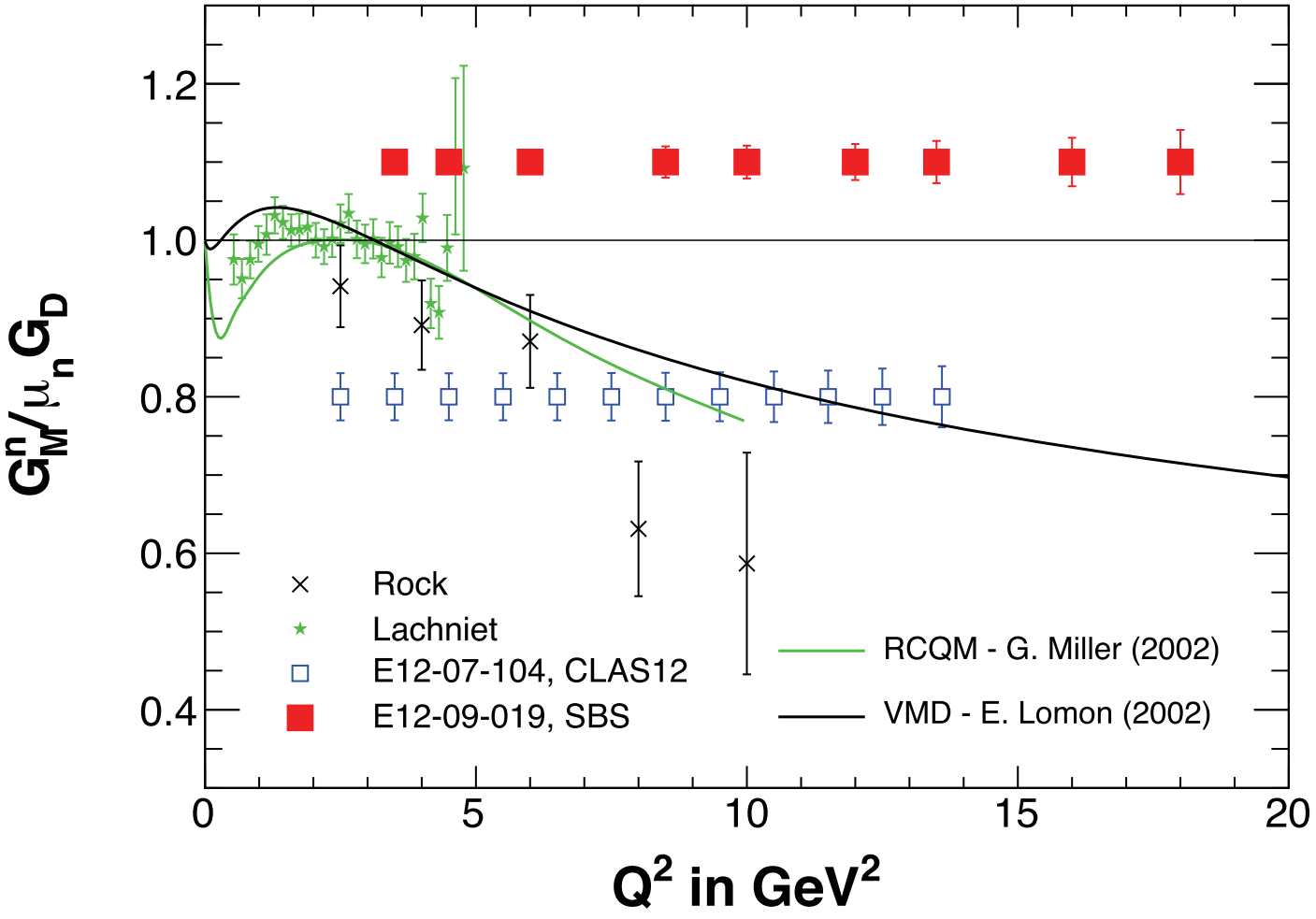


G_M^n measurement

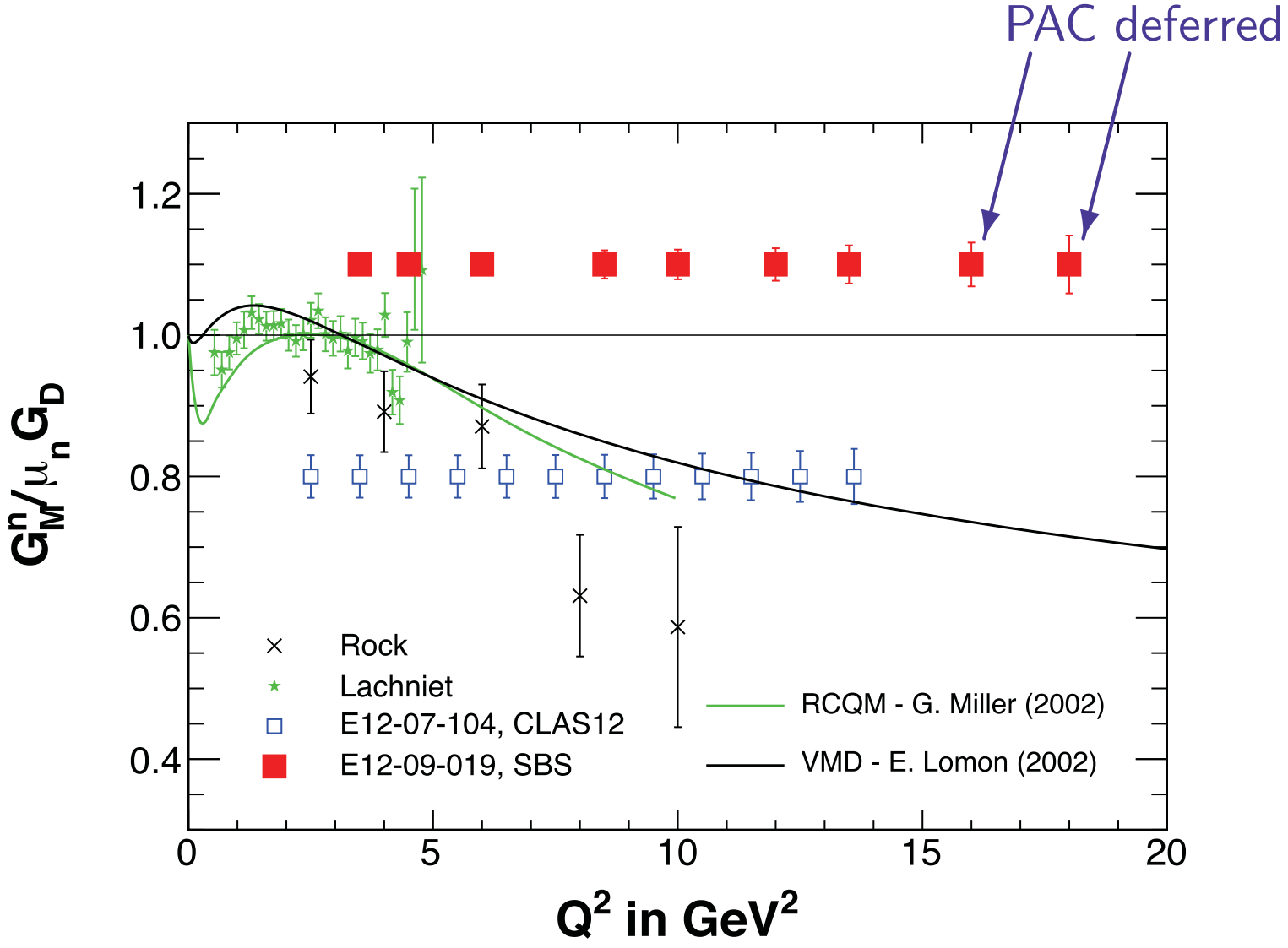
$$d(e, e'n) \,/\, d(e, e'p)$$

- 10 cm LD2 target
- $\mathcal{L} = 3 \cdot 10^{37} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Magnet separates QE protons and neutrons
- 25 days of beam approved

G_M^n Expected Precision



G_M^n Expected Precision



Summary

- The Super BigBite program in JLab's Hall A will measure the nucleon elastic form factors at the highest Q^2 to date.
- The measurements represent the current state of the art, offering the highest figure of merit in each case.
- Results will provide crucial input for theory in a previously-unexplored kinematical regime.