Nucleon Form Factors

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Nucleon Form Factors

Introduction

- Definition
- Formalism
- Interpretation & Utility

Data

- ▷ Early Results
- ▷ Current Status

Measurements

- ▷ Techniques
- ▷ Limitations

Theory Models

Measurements at JLab

Introduction: Why Form Factors?

Mott Cross Section for spin-dependent elastic scattering of point-like particles, recoil free approximation:

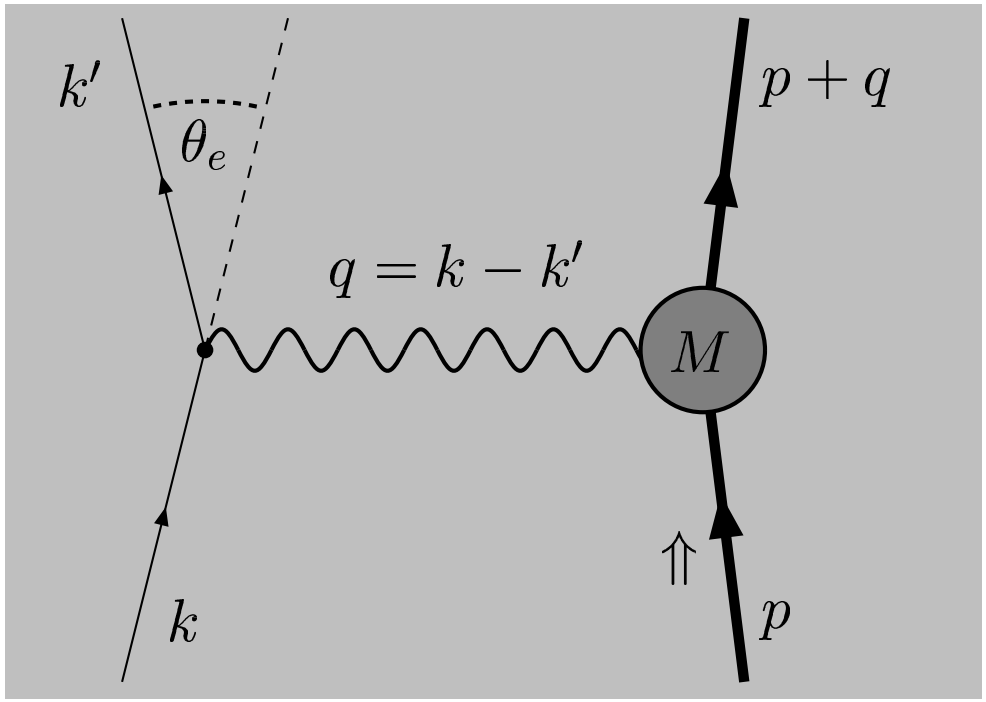
$$\left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} = \frac{4Z^2\alpha^2\,(\hbar c)^2\,E'^2}{|\vec{q}\,c|^4}\cos^2\frac{\theta}{2}$$

But: Proton, Neutron are *not* point-like!

$\Rightarrow$ Introduce phenomenological functions to describe difference between understood model and observed reality

$\Rightarrow$ Test new descriptions by matching to observed form factors or structure functions

Interjection: Scattering Kinematics



$k = (E, \vec{k})$, $k' = (E', \vec{k'})$, etc.

Momentum Transfer

("*Virtuality*")

$$Q^2 = -q^2$$

for elastically scattering m off mass M with $m \ll M$:

$$Q^2 = 2M(E - E')$$

Interjection: Scattering Kinematics

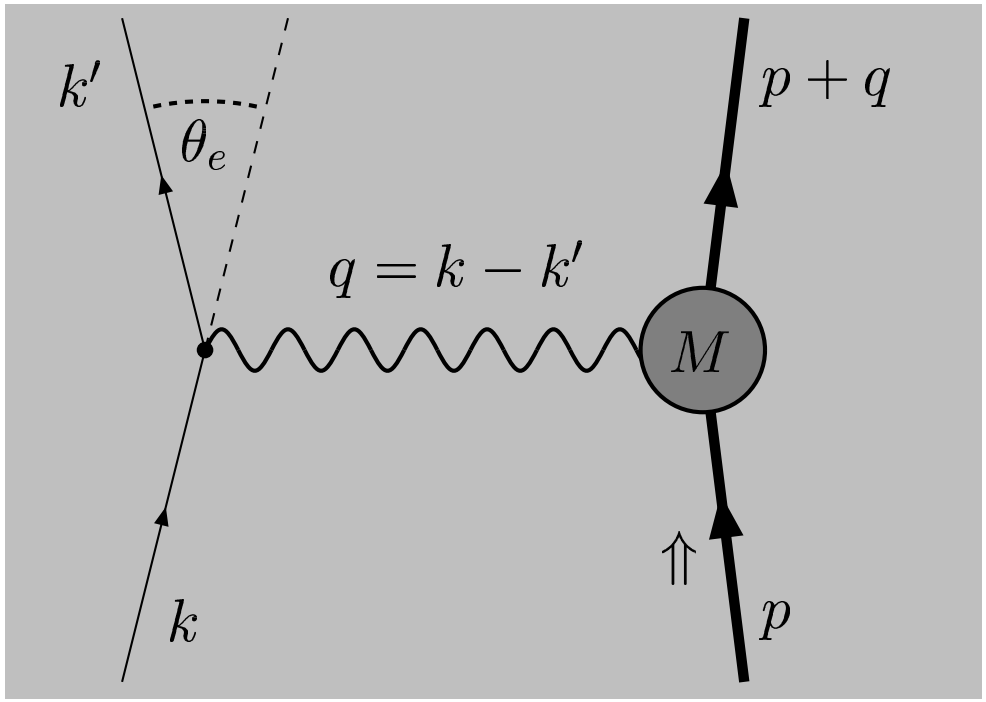
Requirement for Elastic Scattering:

relativistic mass before = relativistic mass after

$$
\begin{aligned}
(\underline{\mathbf{M}})^2 &= (\underline{\mathbf{M}} + \underline{\mathbf{q}})^2 \\
M^2 &= (\underline{\mathbf{M}} - \underline{\mathbf{Q}})^2 \\
&= M^2 + Q^2 - 2\,\underline{\mathbf{M}} \cdot \underline{\mathbf{Q}}
\end{aligned}
$$

$$
\begin{aligned}
Q^2 &= 2\,(M, 0) \cdot (E - E', \vec{k} - \vec{k}') \\
&= 2\,M(E - E')
\end{aligned}
$$

Interjection: Scattering Kinematics



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Generalization:

interpret *in*elastic scattering off nucleon as *elastic* scattering off constituent with momentum fraction x

$$Q^2 = 2\,x M(E - E') \quad \text{or} \quad x = \frac{Q^2}{2M(E-E')}$$

Introduction: Formalism

Sachs Form Factors for Elastic Scattering

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \times \left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2\frac{\theta_e}{2}\right]$$

G_E, G_M depend on Q^2 !

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

Limiting Case

point-like *probe* ($Q^2 = 0$)

Proton:	$G_E^p = 1$	$G_M^p = 2.79\ \mu_N$
Neutron:	$G_E^n = 0$	$G_M^n = -1.91\ \mu_N$
	charge	magnetic moment

Introduction: Interpretation

In Breit frame (non-relativistic limit):

Fourier Transform of Charge, Current Distribution

$$F(\vec{q}\,) = \int e^{i\,\vec{q}\,\vec{x}/\hbar}\; f(\vec{x}\,)\; d^3x$$

Momentum Space

Coordinate Space

Aside: Structure Functions

Form Factors for *Elastic* Scattering Only

More General:
Structure Functions $F_1(x, Q^2)$ and $F_2(x, Q^2)$

In the Limit of Elastic Scattering ($x \to 1$):

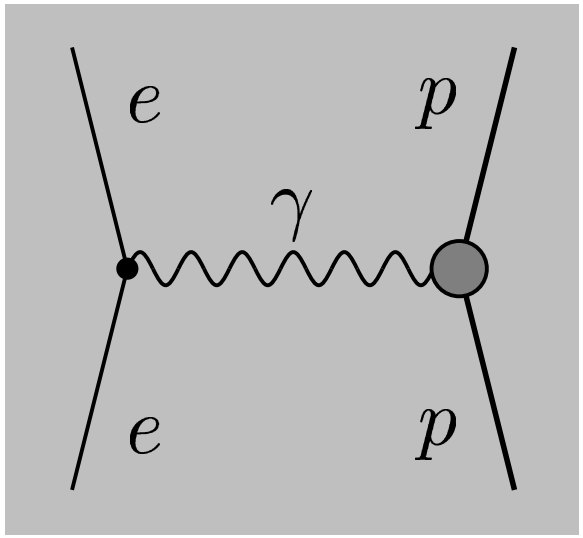
$$\begin{aligned} G_E(Q^2) &= F_1(Q^2) - \tau\mu F_2(Q^2) \\ G_M(Q^2) &= F_1(Q^2) + \mu F_2(Q^2) \end{aligned}$$

Also:
Spin Structure Functions $g_1(x, Q^2)$ and $g_2(x, Q^2)$

Aside: Weak *Form Factors*

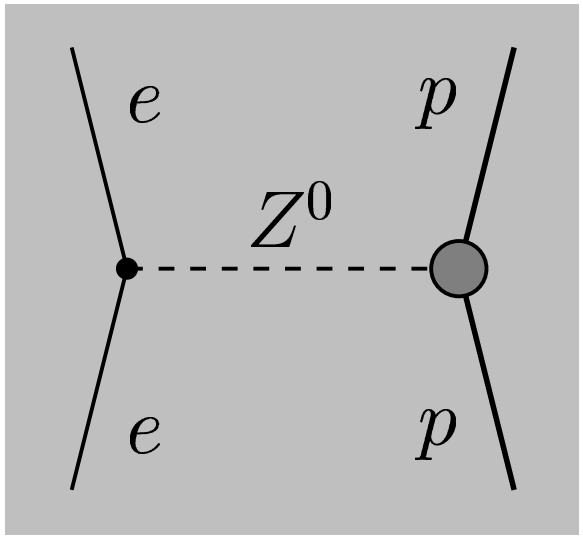
Inclusion of Weak Interaction in $e - p$ Scattering:

EM Interaction



G_E^γ, G_M^γ

Weak Interaction



$G_E^{Z^0}$, $G_M^{Z^0}$, $G_A^{Z^0}$

Cross Section $\sigma = |M_\gamma + M_{Z^0}|^2$ $\qquad \dfrac{M_\gamma \times M_Z}{M_\gamma^2} \sim 1/20\,000$

Interference Term $M_\gamma \times M_{Z^0}$ Violates Parity

Nucleon Form Factors: Introduction

Form Factors:

spacial extent of charge & current (sub-structure)

$\longrightarrow$ anomalous magnetic moment

- Fundamental Quantities
- Test of QCD
- Required for Study of Other Physics
  - *Few-Body Structure Functions*
  -

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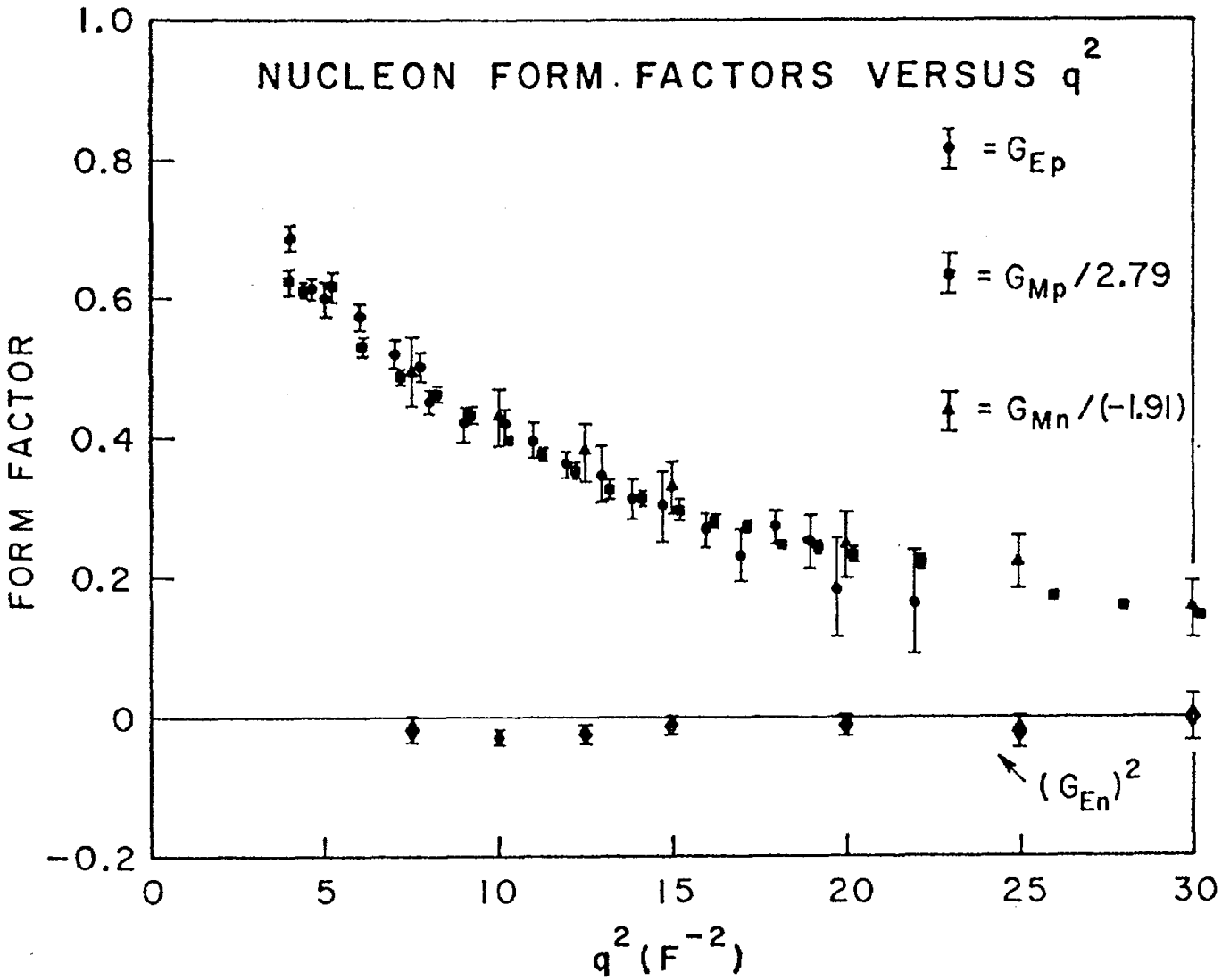
Data Surprise: Similar Q^2 Behavior



Phys. Rev. 139, B458 (1965)

$30\mathrm{fm}^{-2} \simeq 1.17\mathrm{GeV}^2$

$$G_E^p \approx G_M^p/\mu_p \approx G_M^n/\mu_n \qquad G_E^n \approx 0$$

Basic Approximation: Dipole Fit

$$G(Q^2) \approx G(Q^2=0) \times G_D(Q^2)$$

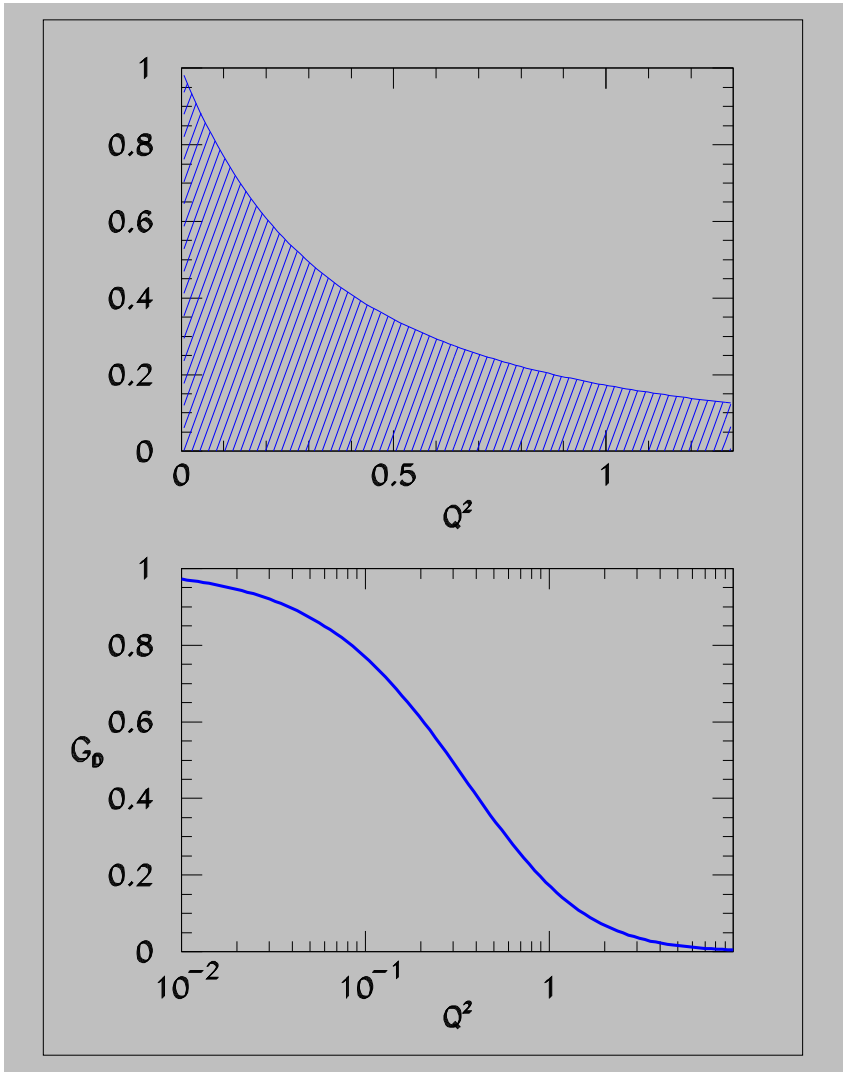
Fitted to Data:

$$G_D = \left(1 + \frac{Q^2}{0.71}\right)^{-2}$$

Based on FT of Exponential Charge Distribution

$$\sim e^{-\alpha\, r}$$

With $\alpha = 4.27\,\mathrm{fm}^{-1}$



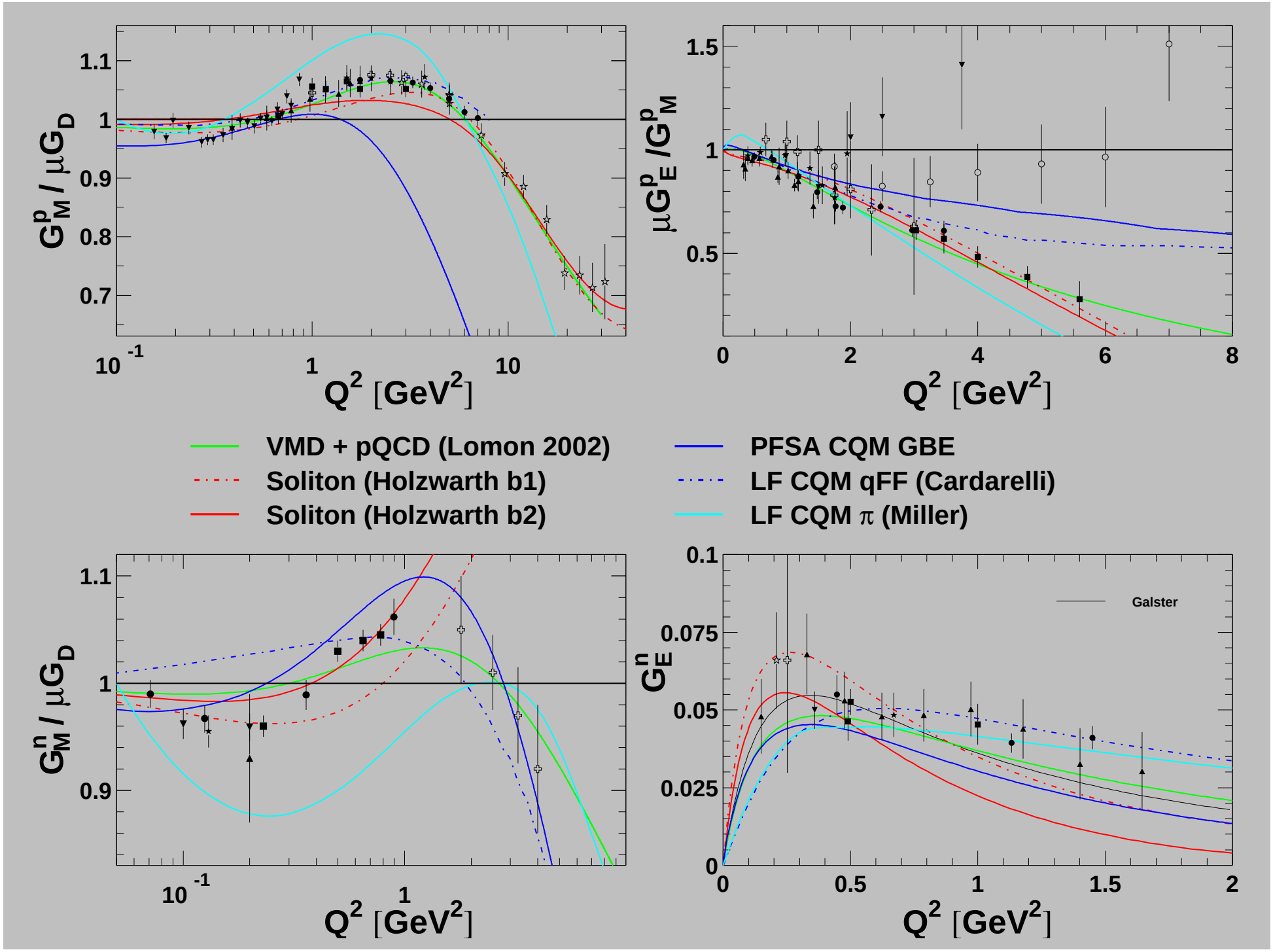
Current Status

Data:

- All Form Factors Measured (G_E^p, G_M^p, G_E^n, G_M^n)
- $0 \leq Q^2 < \sim 10\ GeV^2$

Models:

- Several QCD-based Models
  - *Vector Meson Dominance pQCD*
  - *light front CQM, Goldstone Boson Exchange CQM*
  - *Solitons*
- None Well Describe all Form Factors over *Entire* Measured Range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Q^2 [GeV^2]
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Form Factor Measurements

Traditional Methods:

- Cross Section Based
- Rosenbluth Separation

$$\frac{d\sigma}{d\Omega} \sim \frac{G_E^2+\tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2\frac{\theta_e}{2}$$

- Highly Sensitive to Wavefunction Models, RCs

Polarization-Based Methods:

- Polarization Observables (asymmetry, LT-ratio)
- Complex Setups
- Asymmetry Measurements Require Absolute Polarization

Rosenbluth Separation – Formalism

Recall:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \times \left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2\frac{\theta_e}{2}\right]$$

Alternatively:

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{\text{Mott}}}{\epsilon\,(1+\tau)} \times \underbrace{\left[\tau\, G_M^2(Q^2) + \epsilon\, G_E^2(Q^2)\right]}$$

depends linearly in ϵ on G_E,
but fixed contribution from G_M
$\Rightarrow$ vary ϵ but keep Q^2 fixed

Problem:
as Q^2 increases,
τG_M^2 dominates

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

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

longitudinal polarization of virtual photon

Asymmetry Measurement – Formalism

$$\left(\frac{d\sigma}{d\Omega}\right)^{pol} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \times \left[\Sigma + h\,\mathcal{P}_{\text{target}}\,\Delta\right]$$

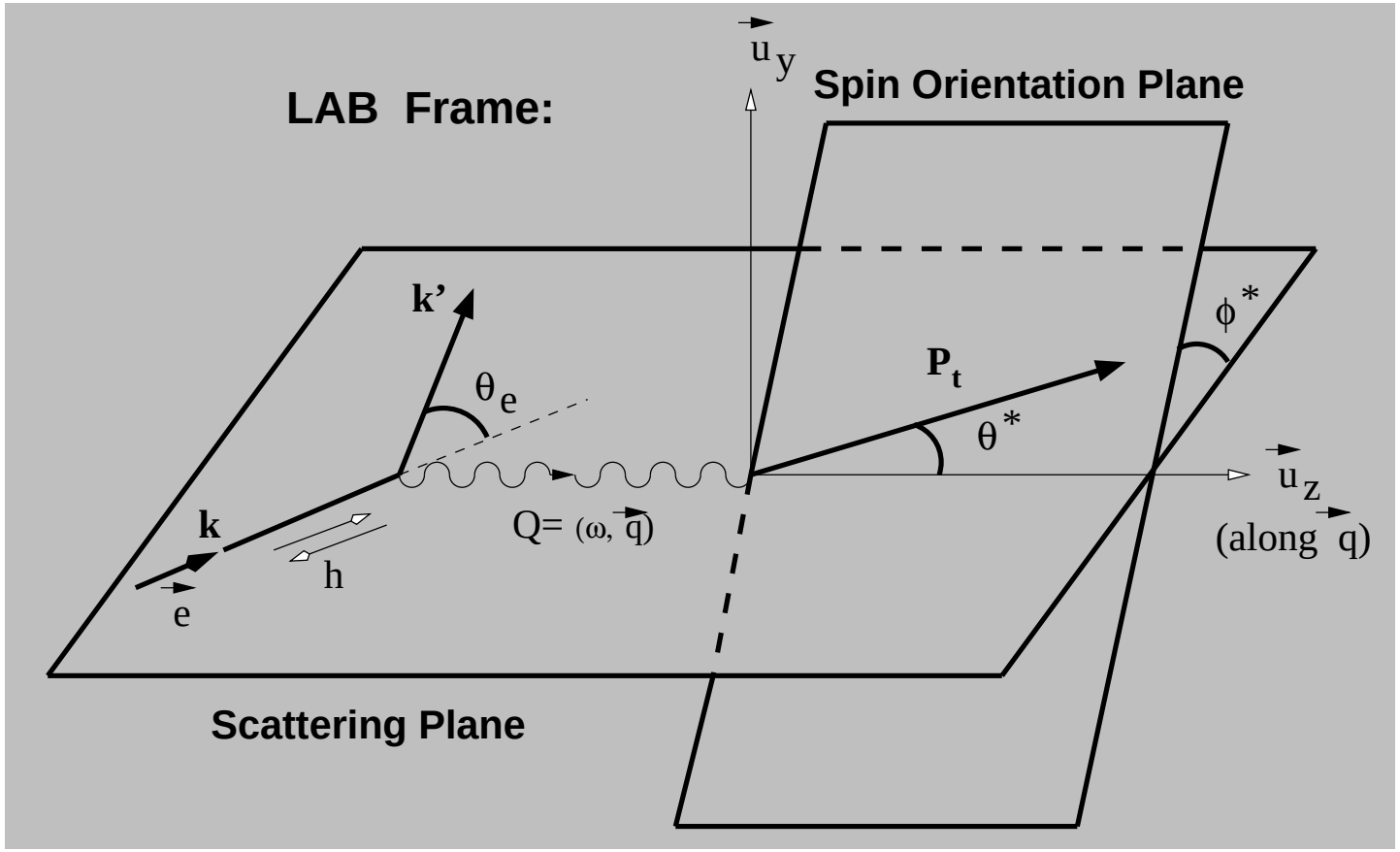
$$\Sigma = \left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2\frac{\theta_e}{2}\right]$$

$$\Delta = -2\tan\frac{\theta_e}{2}\sqrt{\frac{\tau}{1+\tau}} \times \left[\sqrt{\tau\left(1+(1+\tau)\tan^2\frac{\theta_e}{2}\right)}\,\cos\theta^*\,G_M^2 + G_E\,G_M\sin\theta^*\cos\phi^*\right]$$

Measurement via Vector Asymmetry $A^V = \frac{\Delta}{\Sigma} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$

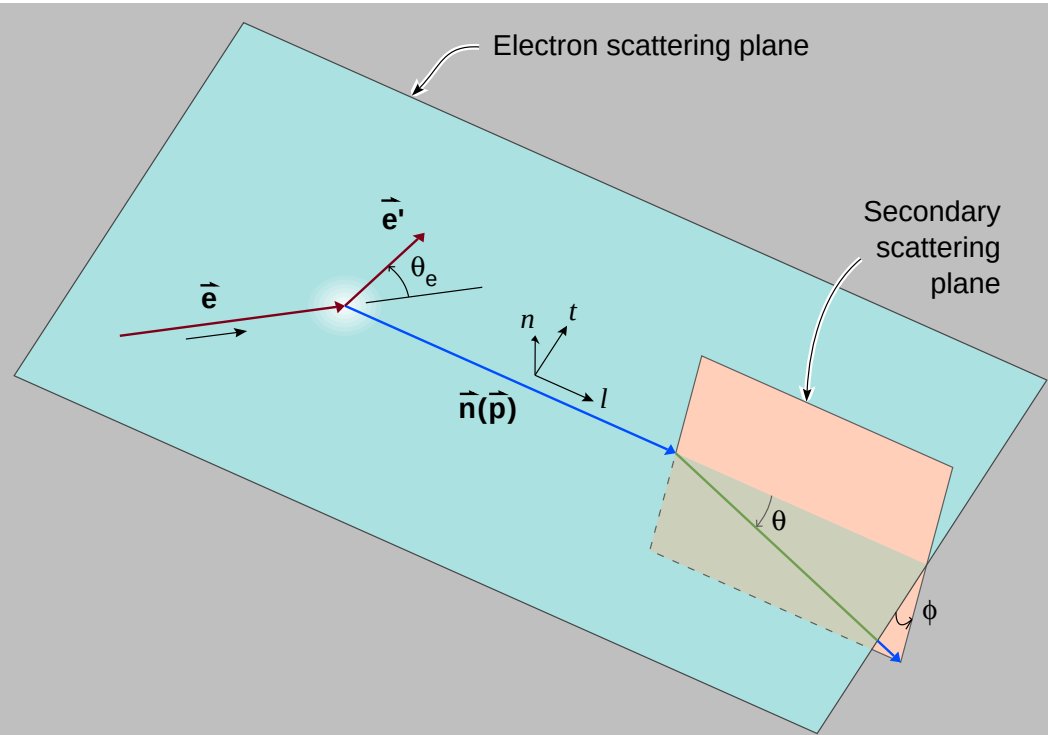
Asymmetry Measurement – Formalism

for quasi-free,
$\mathcal{P}_{\text{target}} \perp \vec{q}$
$(\theta^* = 90^o)$
and
$\mathcal{P}_{\text{target}}$ in
scattering plane
$(\phi^* = 0)$,



$$A^V = \frac{-2\sqrt{\tau(1+\tau)}\,\tan\frac{\theta_e}{2}\,G_E\,G_M}{G_E^2 + \tau[1+2(1+\tau)\tan^2\frac{\theta_e}{2}]\,G_M^2}$$

Recoil Polarimetry – Formalism



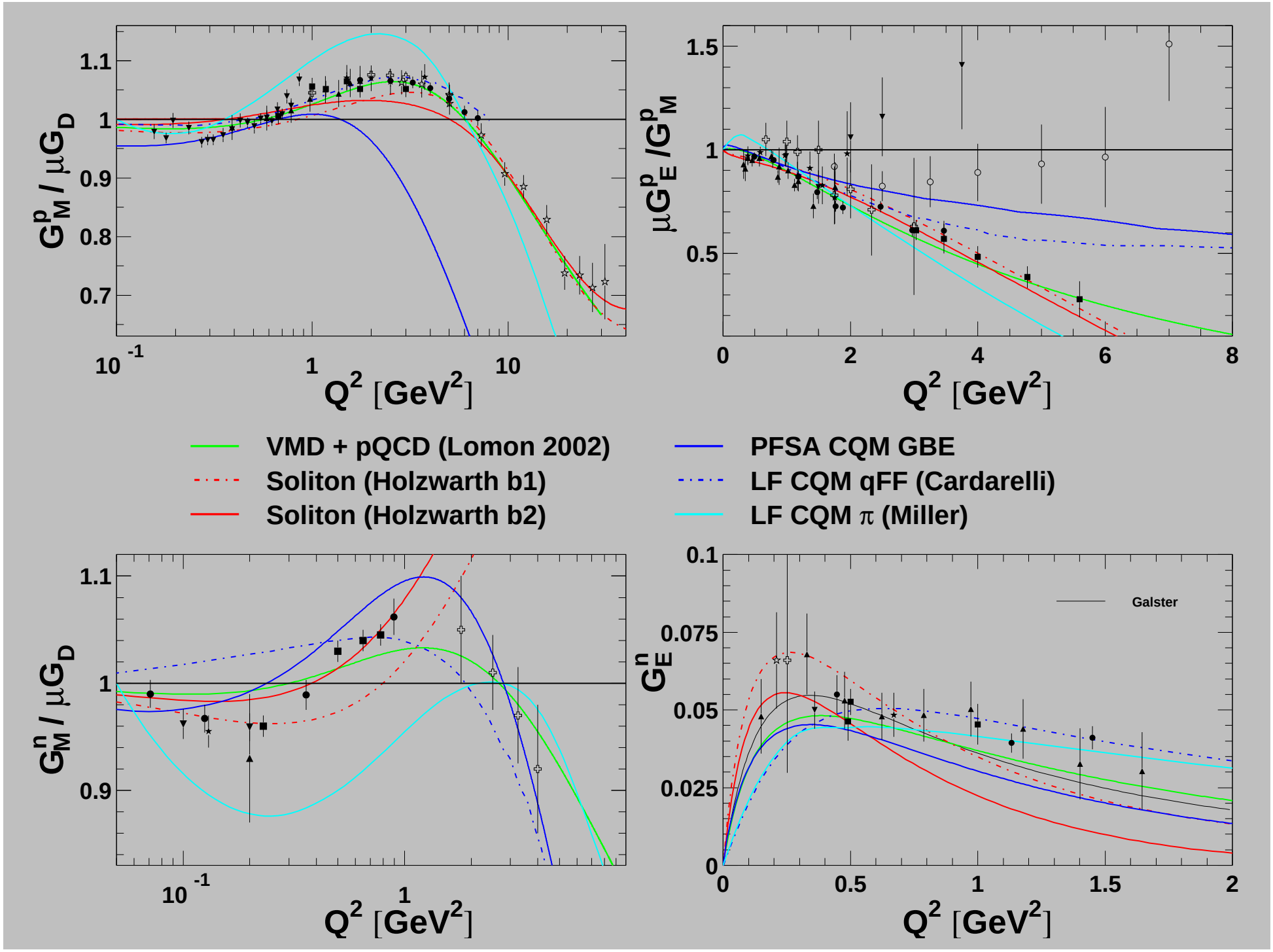
$$I_0 P_n = 0$$

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

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

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

Direct measurement of form factor ratio by measuring the ratio of the transfered polarization P_t and P_l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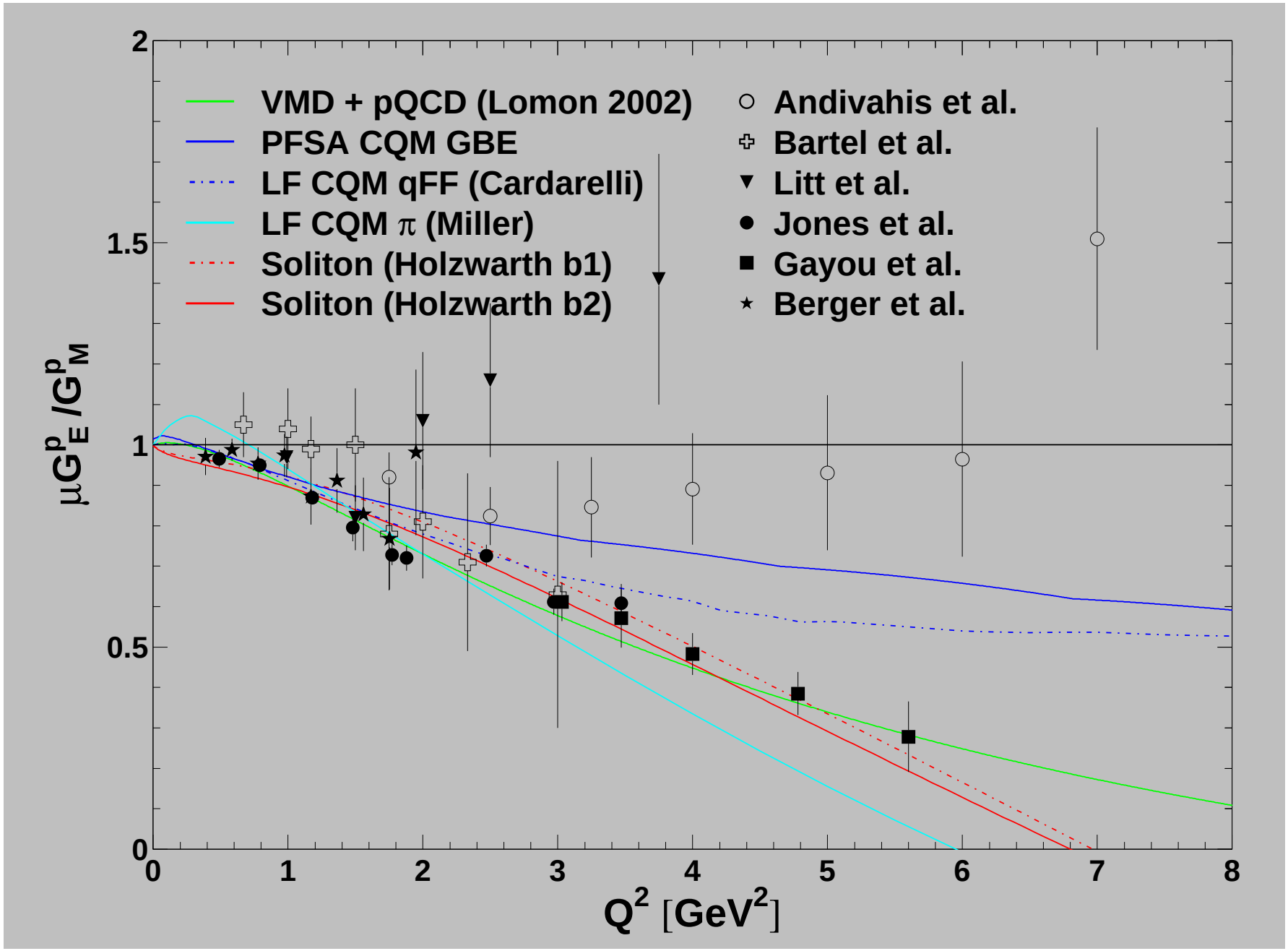
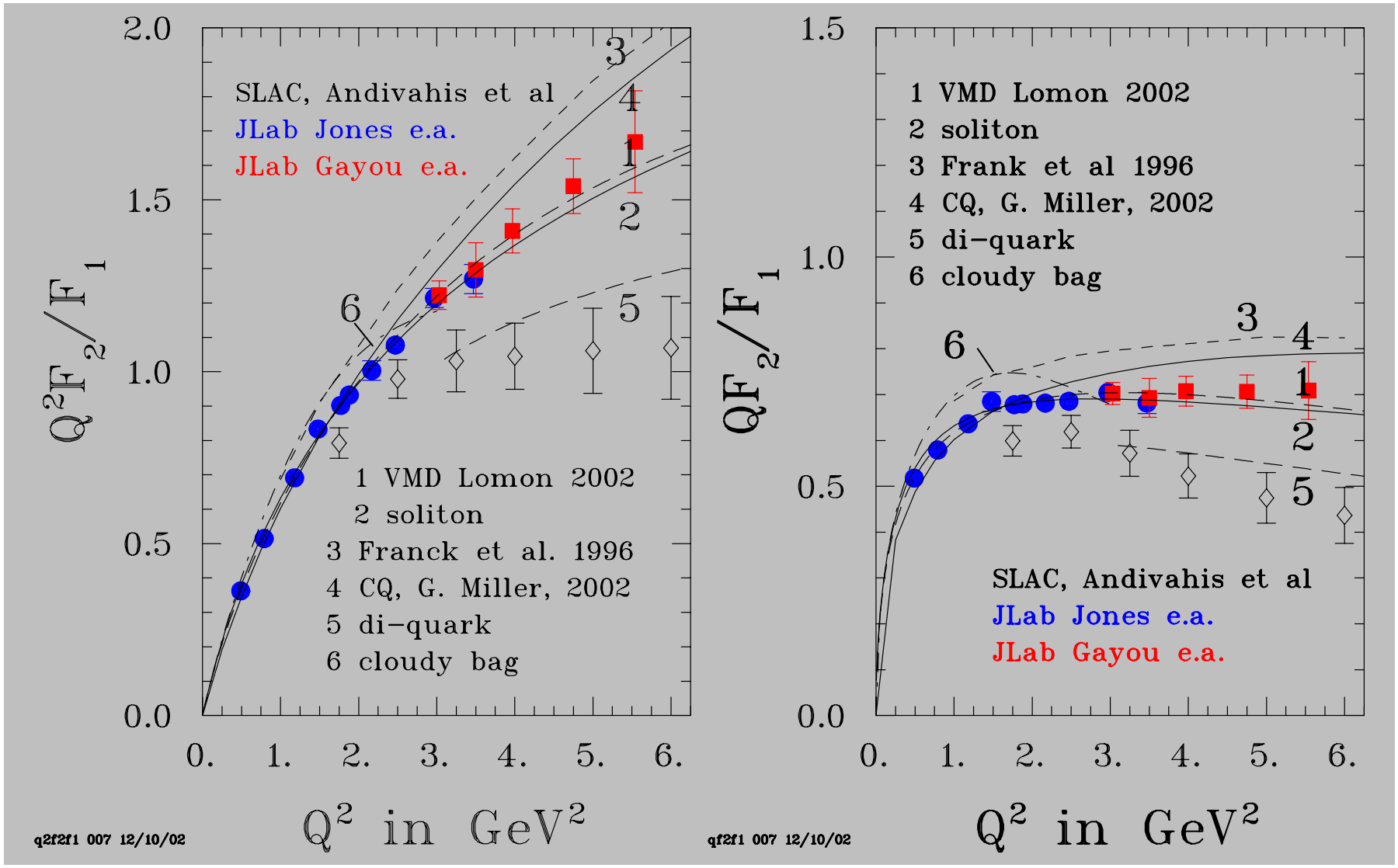
Proton Electric Form Factor



Proton Electric Form Factor



old QCD prediction

new QCD prediction

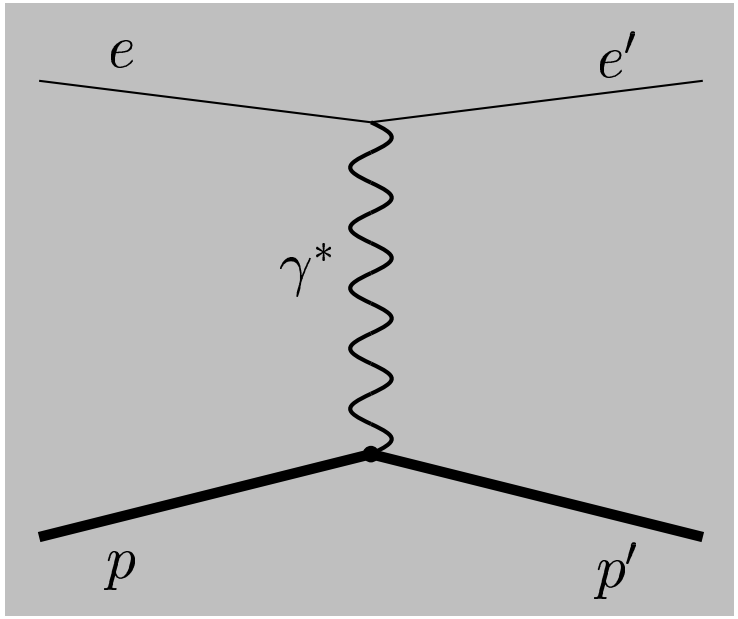
Difference: quarks carry angular momentum

Proton Electric Form Factor

$\Rightarrow$ Why did cross section data not see this trend?

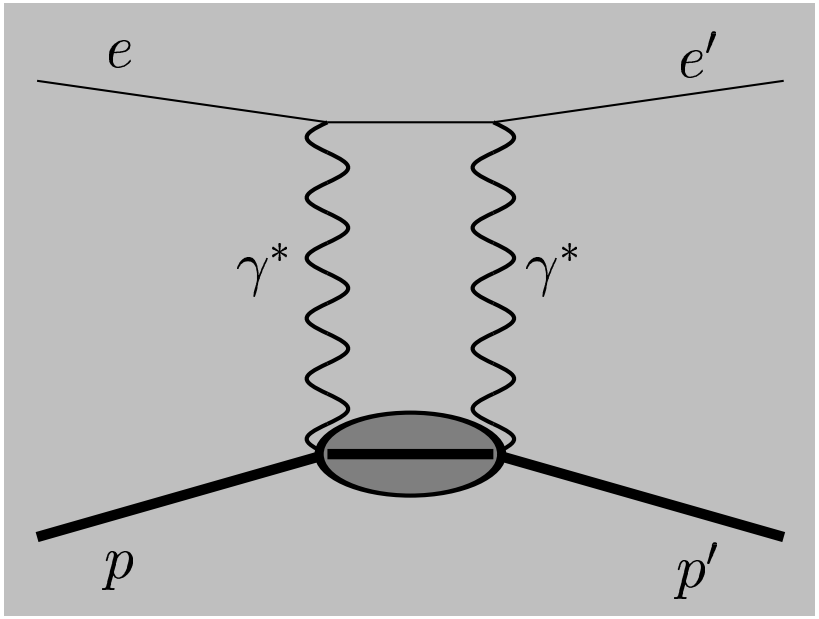
Currently Favored Theory:

1γ-Exchange



Born Approximation

2γ-Exchange



Elastic or Inelastic?

Two Photon Exchange

In general:

$$T = \frac{e^2}{Q^2}\,\overline{u}(k')\,\gamma_\mu\,u(k)\,\overline{u}(p')\left[\tilde{G}_M\,\gamma^\mu - \tilde{F}_2\,\frac{P^\mu}{M} + \tilde{F}_3\,\frac{\gamma\cdot K\,P^\mu}{M^2}\right]u(p)$$

Separating 1-photon and multi-photon contributions:

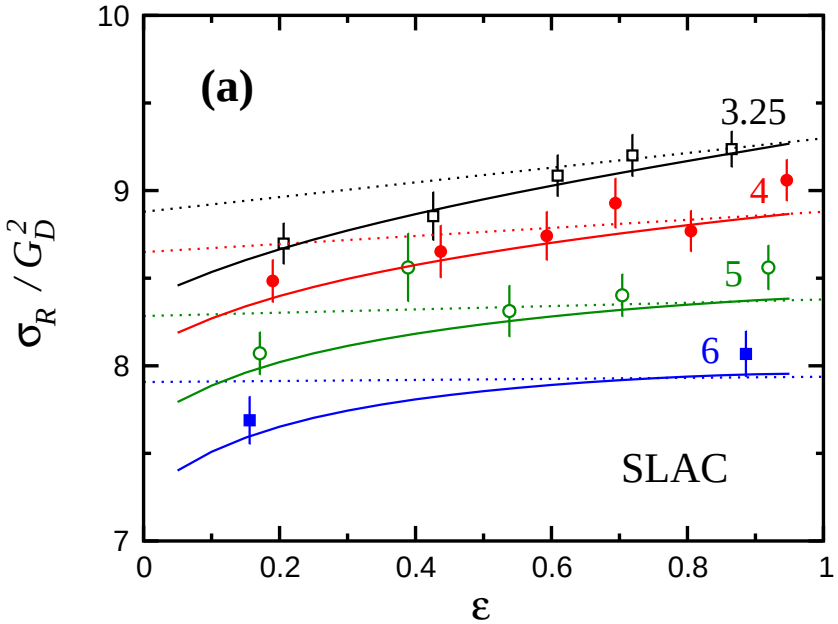
$$\begin{aligned}
\tilde{G}_M(\epsilon,Q^2) &= G_M(Q^2) + \delta\tilde{G}_M(\epsilon,Q^2)\\
\tilde{G}_E(\epsilon,Q^2) &= G_E(Q^2) + \delta\tilde{G}_E(\epsilon,Q^2)\\
\tilde{F}_3(\epsilon,Q^2) &= \delta\tilde{F}_3(\epsilon,Q^2)
\end{aligned}$$

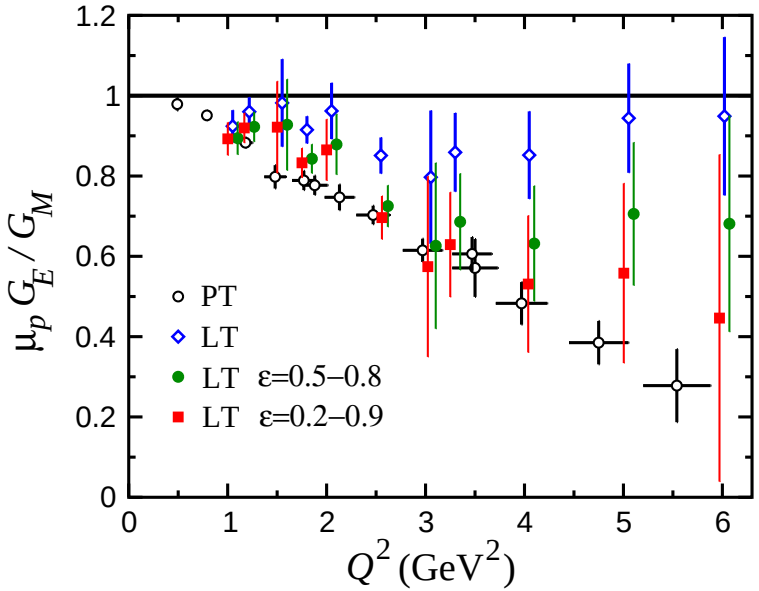
with $\tilde{G}_E = \tilde{G}_M - (1+\tau)\tilde{F}_2$ and $\dfrac{d\sigma}{d\Omega} = \sigma_{\rm Mott} \times \dfrac{\tau}{\epsilon(1+\tau)} \times \sigma_R$

we obtain for 2-photon exchange:

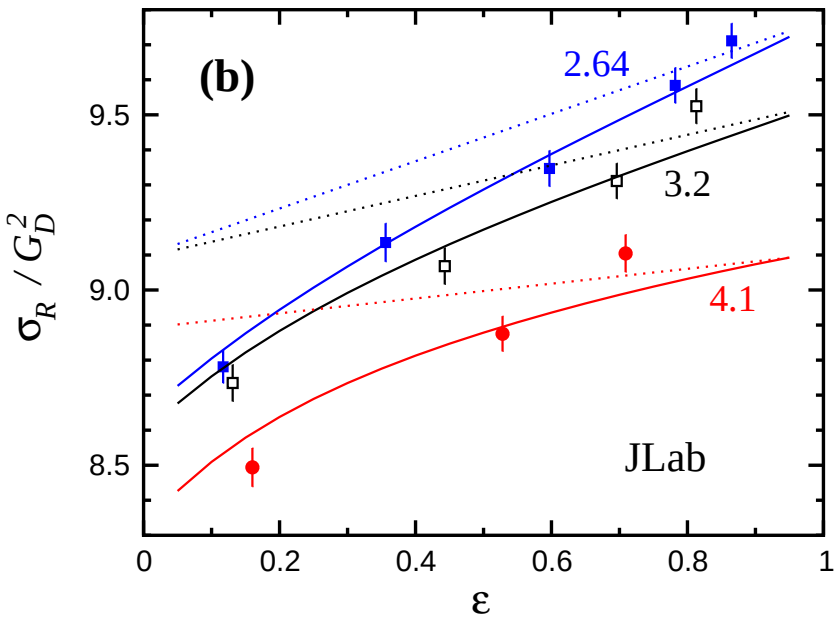
$$\sigma_R = G_M^2 + \frac{\epsilon}{\tau}\,G_E^2 + 2G_M\,\mathcal{R}(\delta\tilde{G}_M + \frac{\epsilon\nu}{M^2}\,\tilde{F}_3) + 2\frac{\epsilon}{\tau}G_E\,\mathcal{R}(\delta\tilde{G}_E + \frac{\nu}{M^2}\,\tilde{F}_3)$$

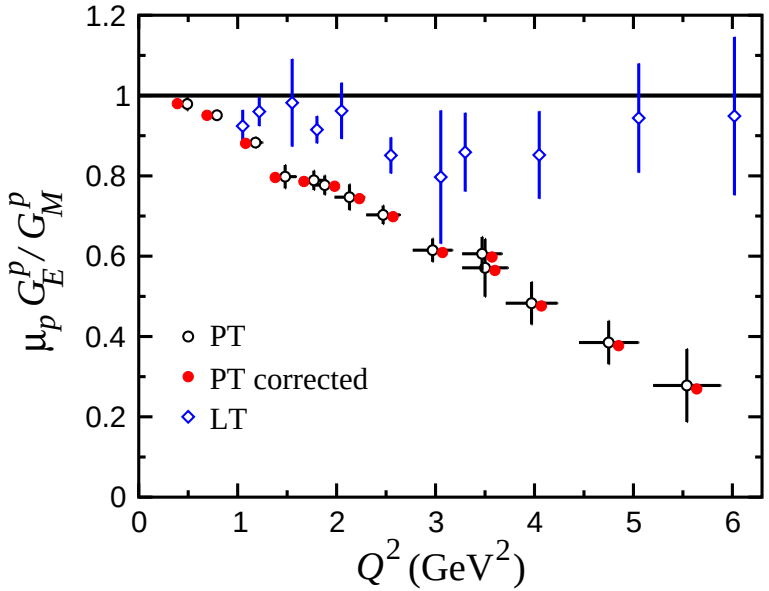
Impact of Two Photon Exchange





Phys. Rev. C **72**, 034612 (2005)





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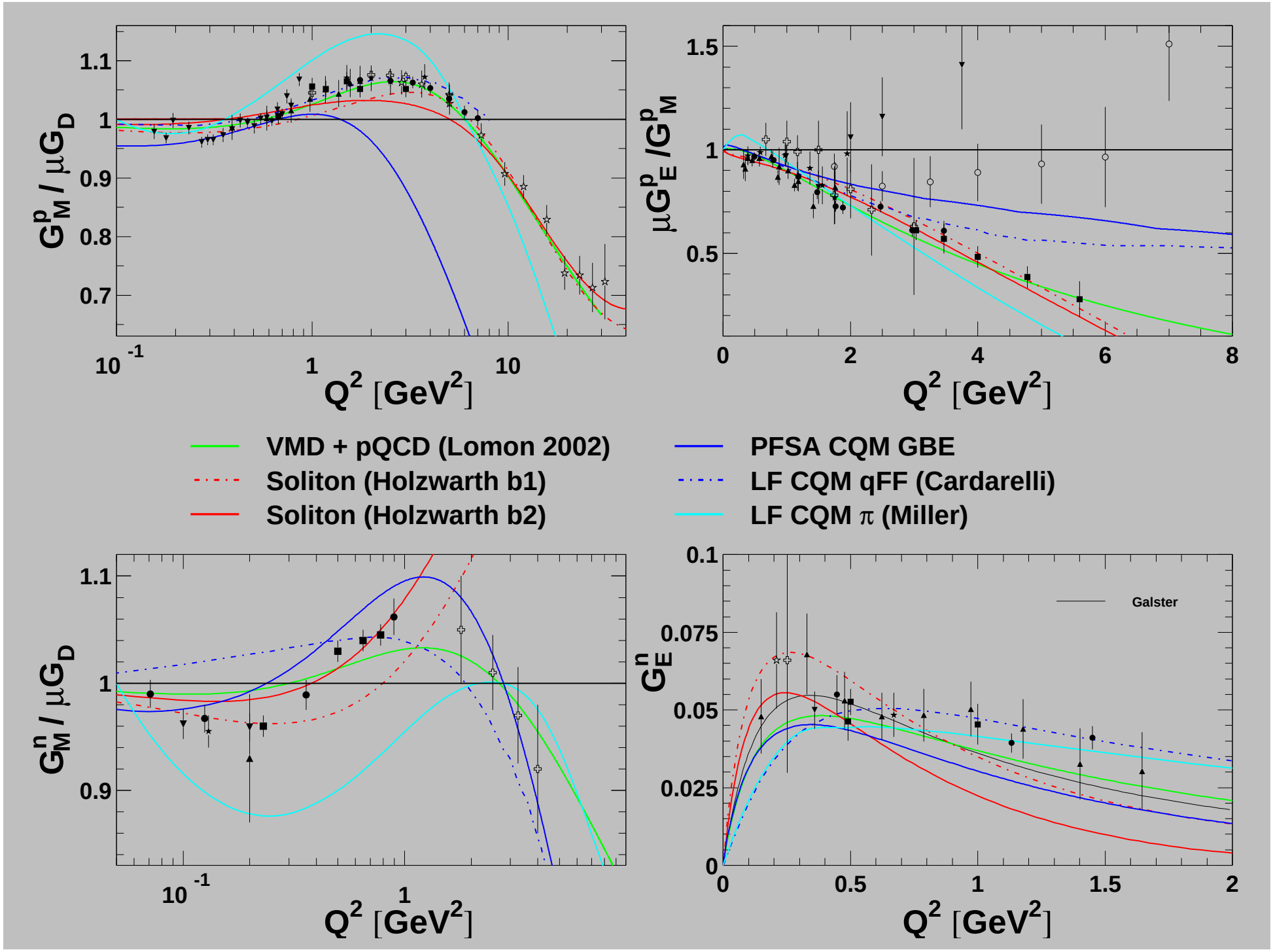
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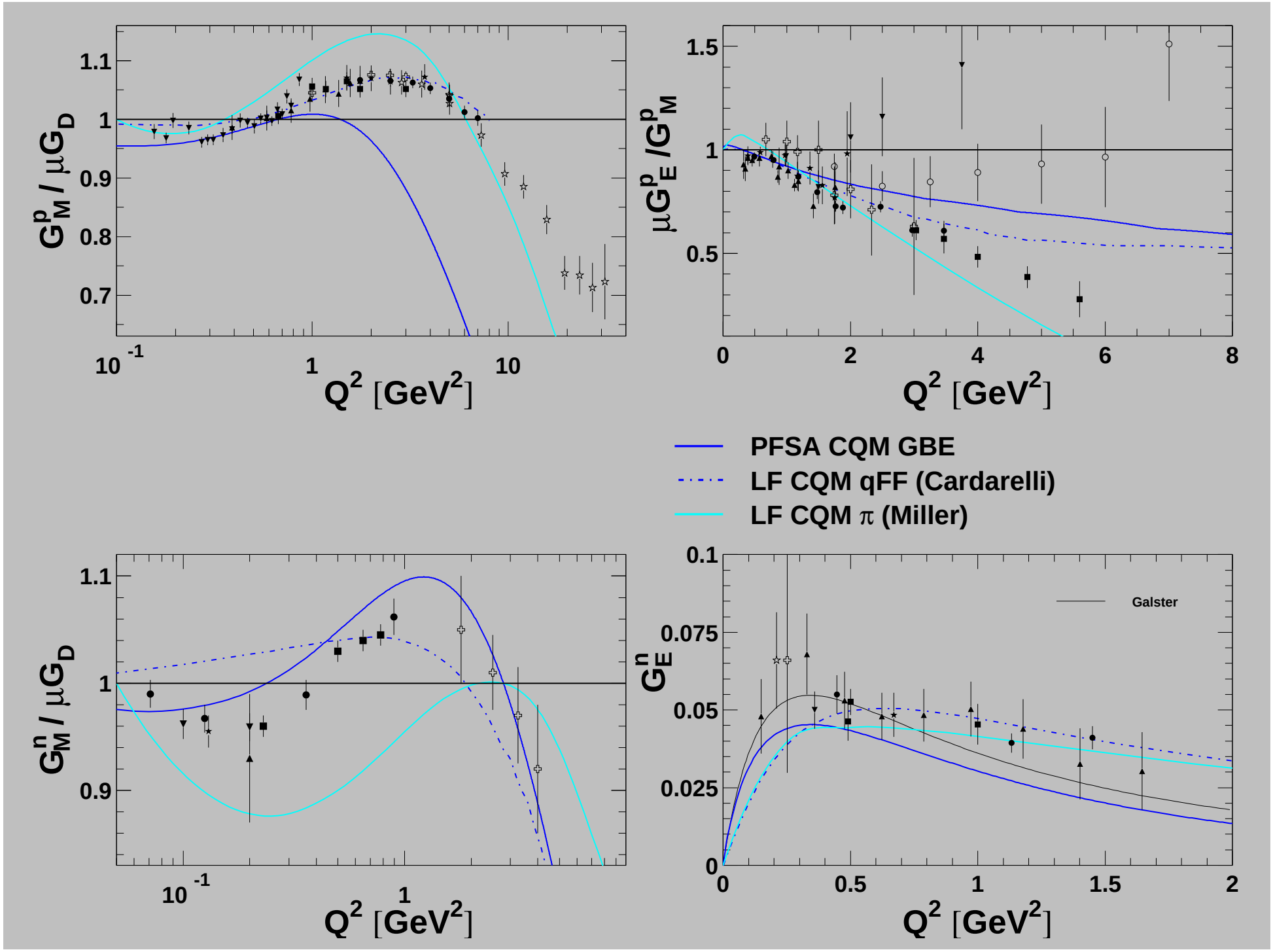
Relevant Form Factor Models

- PFSA CQM GBE — Eur. Phys. J. A **14**, 17 (2002)
  - *point-form spectator approximation*
  - *quark–quark interaction fitted to spectroscopic data*
  - *Goldstone boson exchange in impulse approximation with point-like constituent quarks*
- LF CQM qFF (Cardarelli) — Phys. Rev. C **62**, 065201 (2000)
  - *1-gluon exchange light-front calculation*
  - *quark–quark interaction fitted to spectroscopic data*
  - *constituent quark FFs fitted to data* $Q^2 < 1$
  - *accounts only for 65% of neutron charge radius*
- LF CQM π (Miller) — Phys. Rev. C **66**, 032201(R) (2002)
  - *3 point-like bound quarks surrounded by pion cloud*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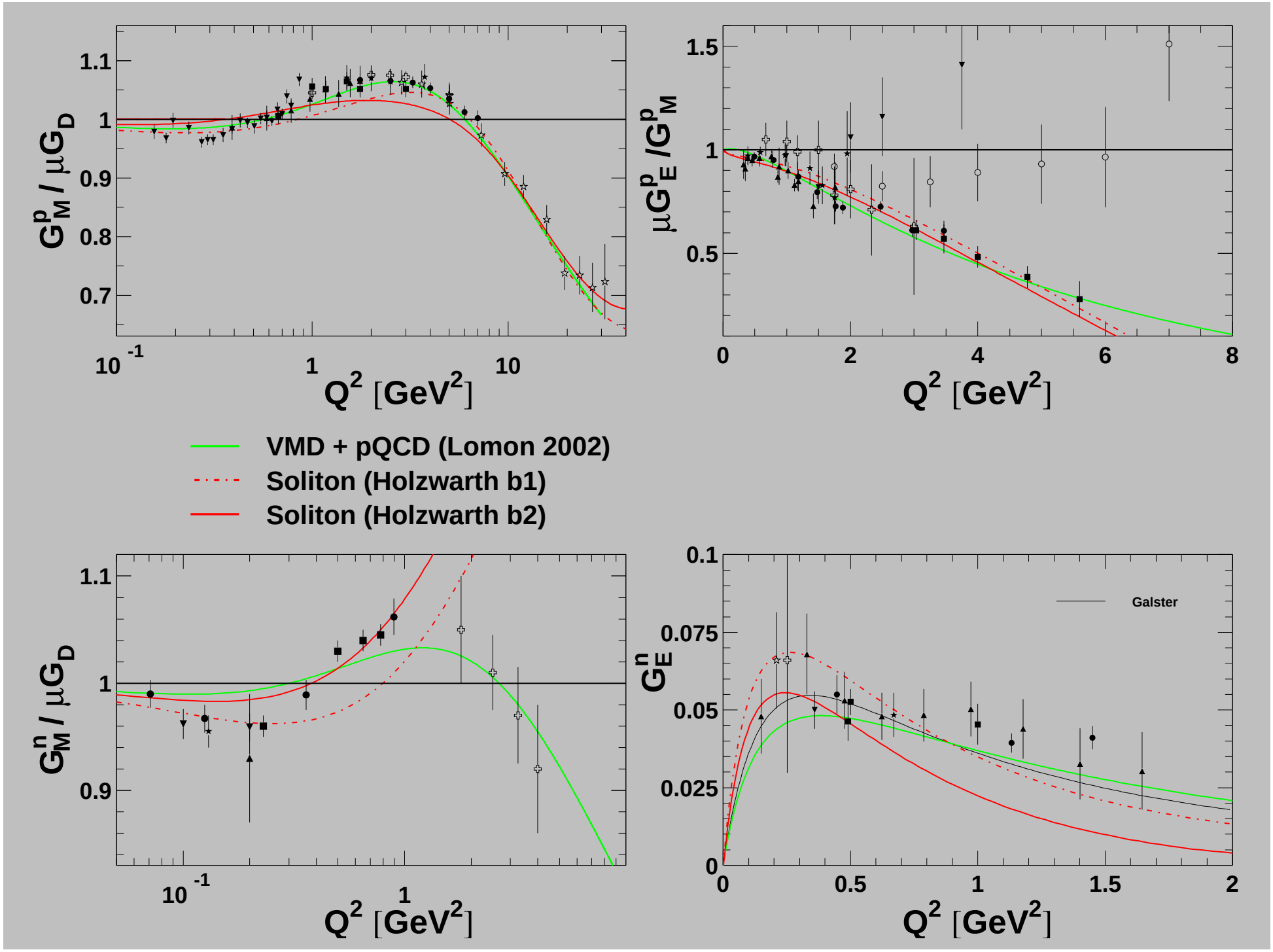
G_E^n
Galster
Q^2 [GeV^2]

Relevant Form Factor Models

- Soliton (Holzwarth) Z. Phys. A **356**, 339 (1996)
  - *chiral soliton model, extended object*
  - *partial coupling to vector mesons*
  - *relativistic recoil corrections*
- VMD + pQCD (Lomon) Phys. Rev. C **66**, 045501 (2002)
  - *interpolates low Q^2 vector-meson dominance & high Q^2 perturbative QCD*
  - *14 parameter fit*
  - *latest version of traditional meson-baryon approach*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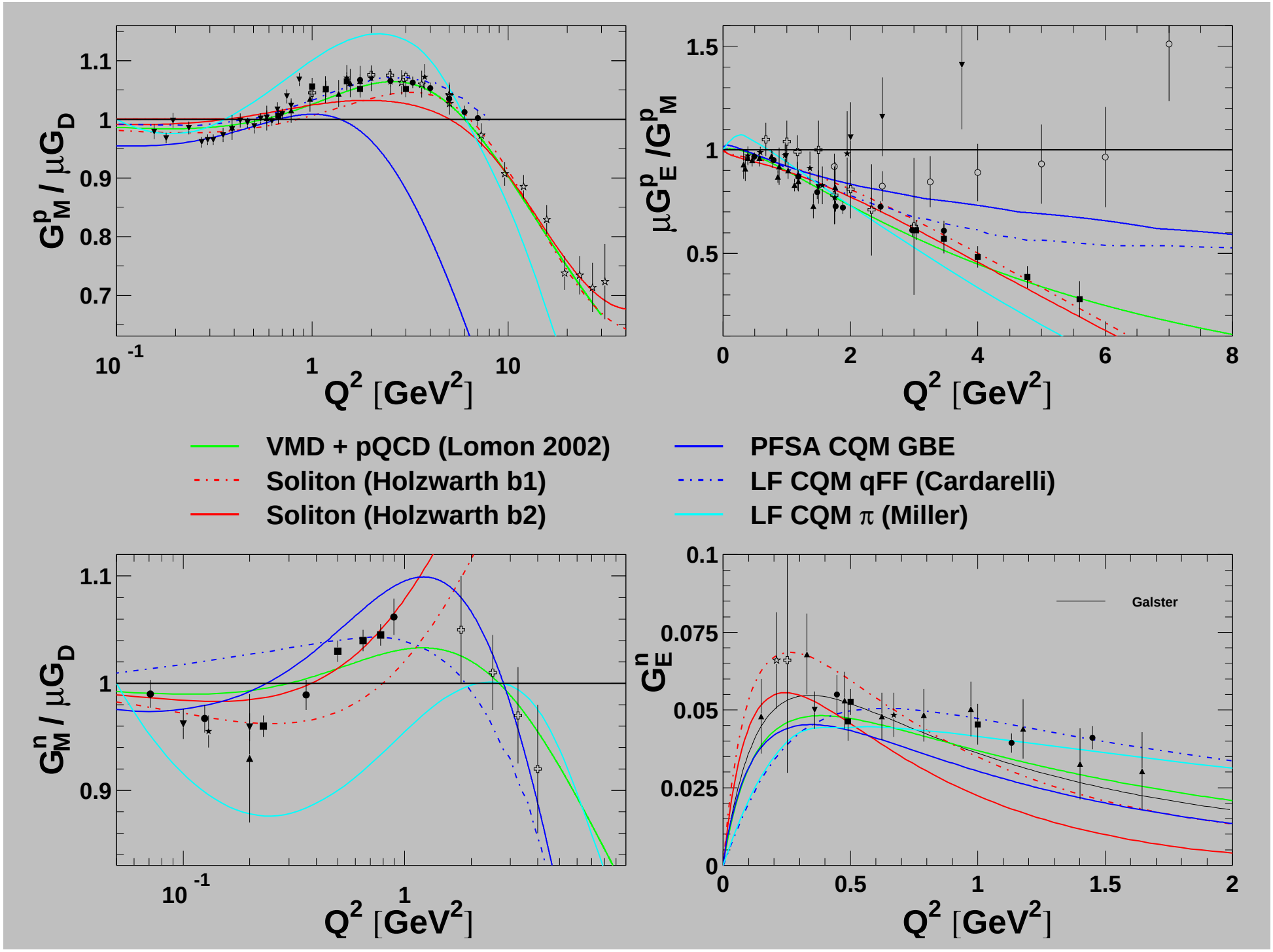
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Form Factor Measurements at JLab

Proposal, Hall		Form Factor	Technique, Reaction		Year
93-026	C	G_E^n	Asymmetry	$\overrightarrow{D}(\vec{e}, e'n)p$	1998,2001
93-027	A	G_E^p/G_M^p	Recoil	^{1}H$(\vec{e}, e'\vec{p})$	1998
93-038	C	G_E^n/G_M^n	Recoil	^{2}H$(\vec{e}, e'\vec{n})p$	2000/2001
94-017	B	G_M^n	Ratio	$\frac{d(e,e'n)p}{d(e,e'p)n}$	2000
95-001	A	G_M^n	Asymmetry	$^3\overrightarrow{\mathrm{He}}(\vec{e}, e')X$	1999
99-007	A	G_E^p/G_M^p	Recoil	^{1}H$(\vec{e}, e'\vec{p})$	2000
01-001	A	G_E^p	Rosenbluth	$^1H(e,p)$	2002
02-013	A	G_E^n	Asymmetry	$^3\overrightarrow{\mathrm{He}}(\vec{e}, e'n)$	2006
04-108	C	G_E^p/G_M^p	Recoil	^{1}H$(\vec{e}, e'\vec{p})$	2007

Form Factor Measurements in Hall A

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93-027	A	G_E^p/G_M^p	Recoil	^{1}H$(\vec{e}, e'\vec{p})$	1998
93-038	C	G_E^n/G_M^n	Recoil	^{2}H$(\vec{e}, e'\vec{n})p$	2000/2001
94-017	B	G_M^n	Ratio	$\frac{d(e,e'n)p}{d(e,e'p)n}$	2000
95-001	A	G_M^n	Asymmetry	$^3\overrightarrow{\mathrm{He}}(\vec{e}, e')X$	1999
99-007	A	G_E^p/G_M^p	Recoil	^{1}H$(\vec{e}, e'\vec{p})$	2000
01-001	A	G_E^p	Rosenbluth	$^1H(e,p)$	2002
02-013	A	G_E^n	Asymmetry	$^3\overrightarrow{\mathrm{He}}(\vec{e}, e'n)$	2006
04-108	C	G_E^p/G_M^p	Recoil	^{1}H$(\vec{e}, e'\vec{p})$	2007

Form Factor Measurements in Hall B

Proposal, Hall		Form Factor	Technique, Reaction		Year
93-026	C	G_E^n	Asymmetry	$\overrightarrow{D}(\vec{e}, e'n)p$	1998,2001
93-027	A	G_E^p/G_M^p	Recoil	^{1}H$(\vec{e}, e'\vec{p})$	1998
93-038	C	G_E^n/G_M^n	Recoil	^{2}H$(\vec{e}, e'\vec{n})p$	2000/2001
94-017	B	G_M^n	Ratio	$\frac{d(e,e'n)p}{d(e,e'p)n}$	2000
95-001	A	G_M^n	Asymmetry	$^3\overrightarrow{\mathrm{He}}(\vec{e}, e')X$	1999
99-007	A	G_E^p/G_M^p	Recoil	^{1}H$(\vec{e}, e'\vec{p})$	2000
01-001	A	G_E^p	Rosenbluth	$^1H(e,p)$	2002
02-013	A	G_E^n	Asymmetry	$^3\overrightarrow{\mathrm{He}}(\vec{e}, e'n)$	2006
04-108	C	G_E^p/G_M^p	Recoil	^{1}H$(\vec{e}, e'\vec{p})$	2007

Form Factor Measurements in Hall C

Proposal, Hall		Form Factor	Technique, Reaction		Year
93-026	C	G_E^n	Asymmetry	$\overrightarrow{D}(\vec{e}, e'n)p$	1998,2001
93-027	A	G_E^p/G_M^p	Recoil	^{1}H$(\vec{e}, e'\vec{p})$	1998
93-038	C	G_E^n/G_M^n	Recoil	^{2}H$(\vec{e}, e'\vec{n})p$	2000/2001
94-017	B	G_M^n	Ratio	$\frac{d(e,e'n)p}{d(e,e'p)n}$	2000
95-001	A	G_M^n	Asymmetry	$^3\overrightarrow{\mathrm{He}}(\vec{e}, e')X$	1999
99-007	A	G_E^p/G_M^p	Recoil	^{1}H$(\vec{e}, e'\vec{p})$	2000
01-001	A	G_E^p	Rosenbluth	$^1H(e,p)$	2002
02-013	A	G_E^n	Asymmetry	$^3\overrightarrow{\mathrm{He}}(\vec{e}, e'n)$	2006
04-108	C	G_E^p/G_M^p	Recoil	^{1}H$(\vec{e}, e'\vec{p})$	2007

Hall C Form Factor Measurements

E 93-026

- *measured G_E^n from polarization asymmetry*
- *ran 1998 and 2001*
- *1998 measurement provided highest Q^2 point at the time*

E 93-038

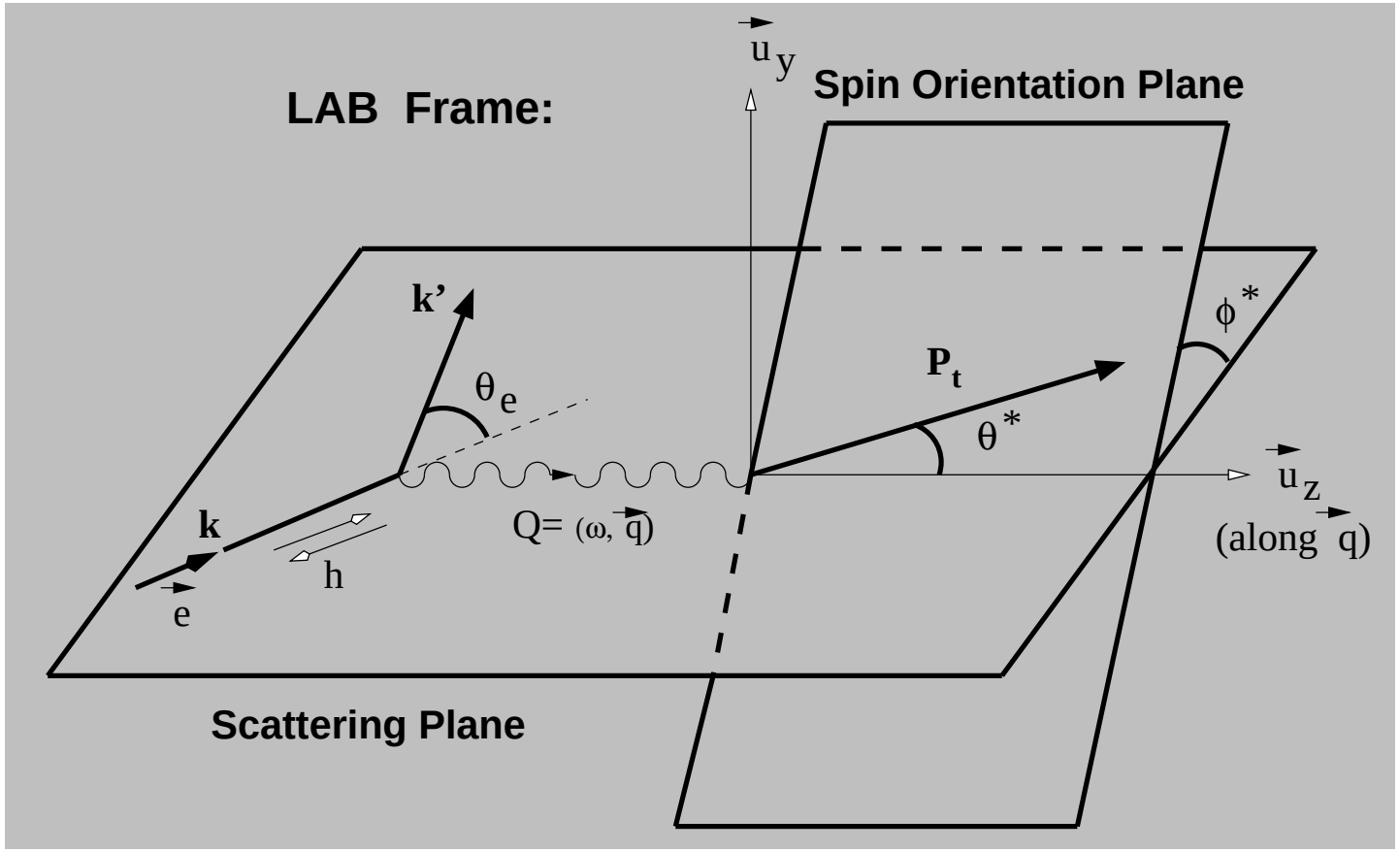
- *measured G_E^n from recoil polarization*
- *ran 2000 through 2001*
- *currently most accurate measurement at large Q^2*

E 04-108

- *scheduled to run 2007*
- *will measure G_E^p/G_M^p through recoil polarization*
- *extension of spectacular Hall A results*

Recall: Asymmetry Measurement

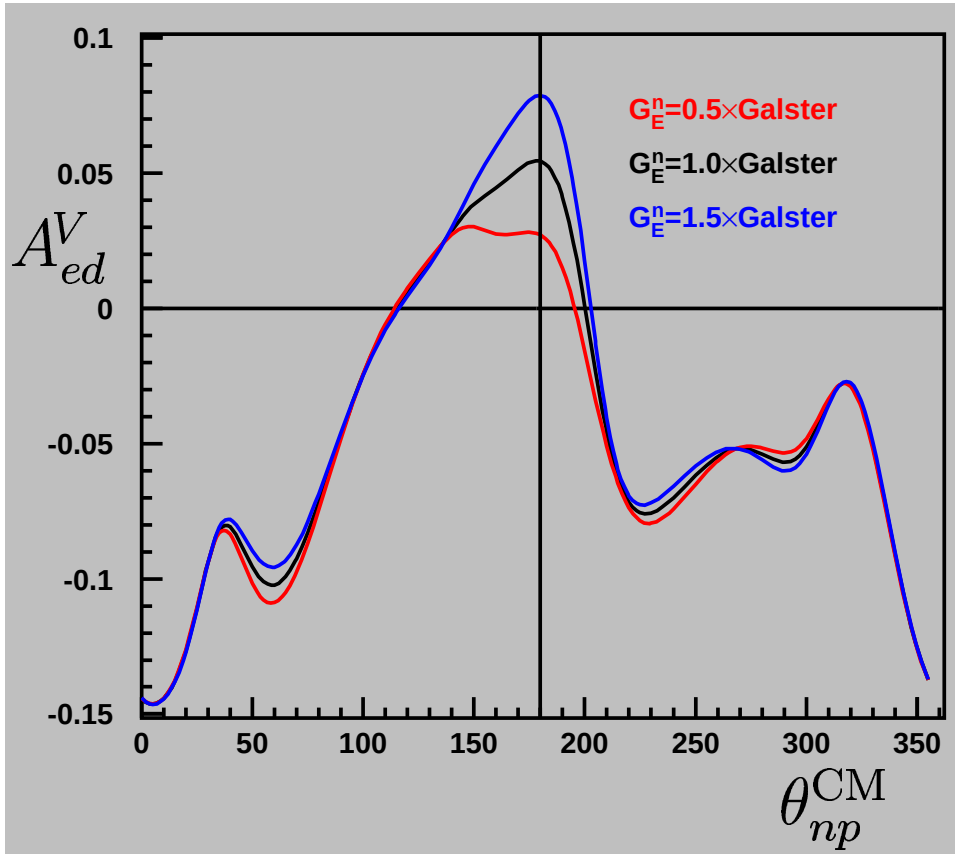
for quasi-free,
$\mathcal{P}_{\text{target}} \perp \vec{q}$
$(\theta^* = 90^o)$
and
$\mathcal{P}_{\text{target}}$ in
scattering plane
$(\phi^* = 0)$,



$$A^V = \frac{-2\sqrt{\tau(1+\tau)}\,\tan\frac{\theta_e}{2}\,G_E\,G_M}{G_E^2 + \tau[1+2(1+\tau)\tan^2\frac{\theta_e}{2}]\,G_M^2}$$

G_E^n Asymmetry – E93-026

E93-026 measured G_E^n via polarization asymmetry in quasi-elastic scattering off Deuterium



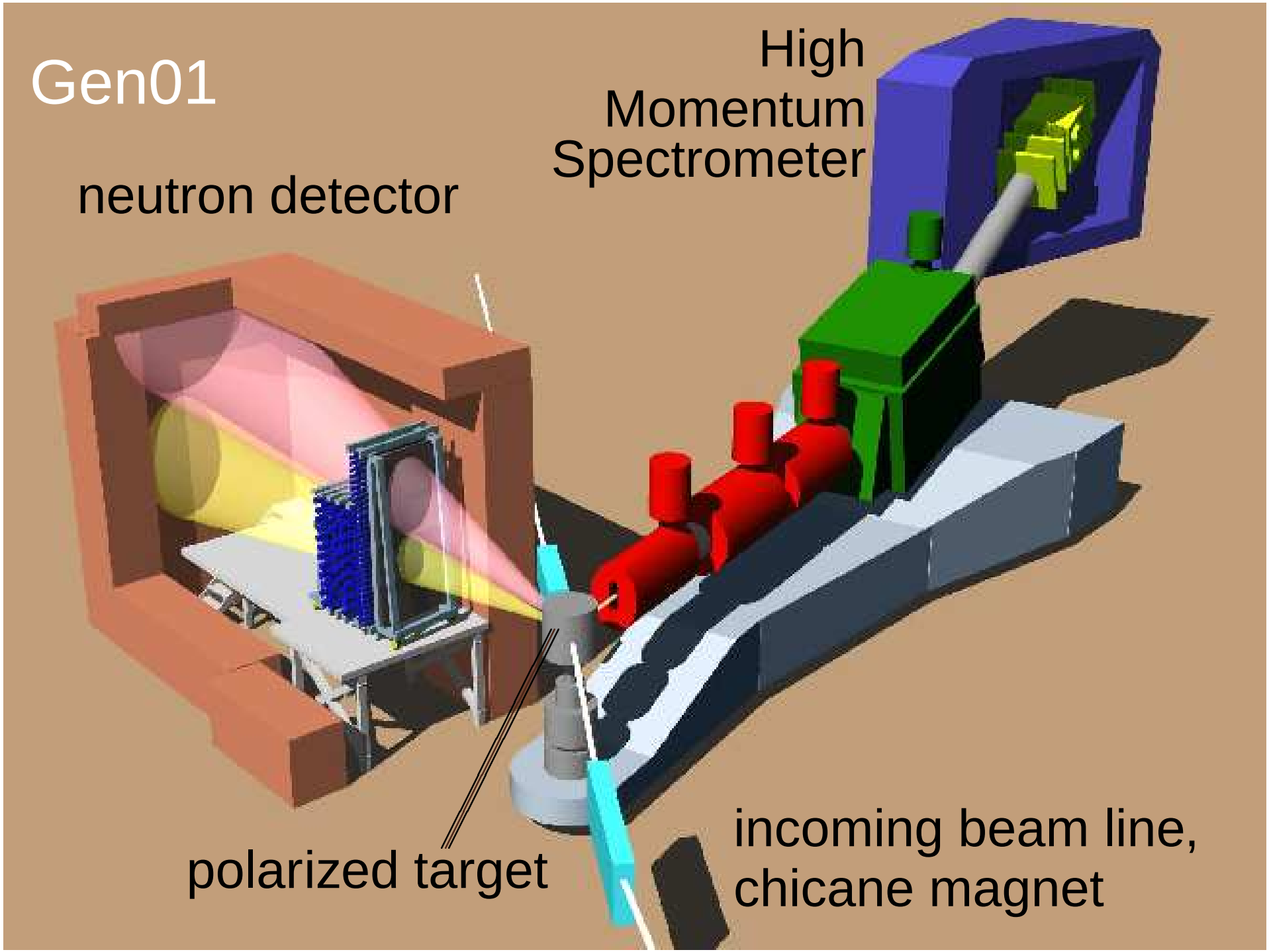
To extract measured G_E^n, compare:

measured A_{ed}^V

and

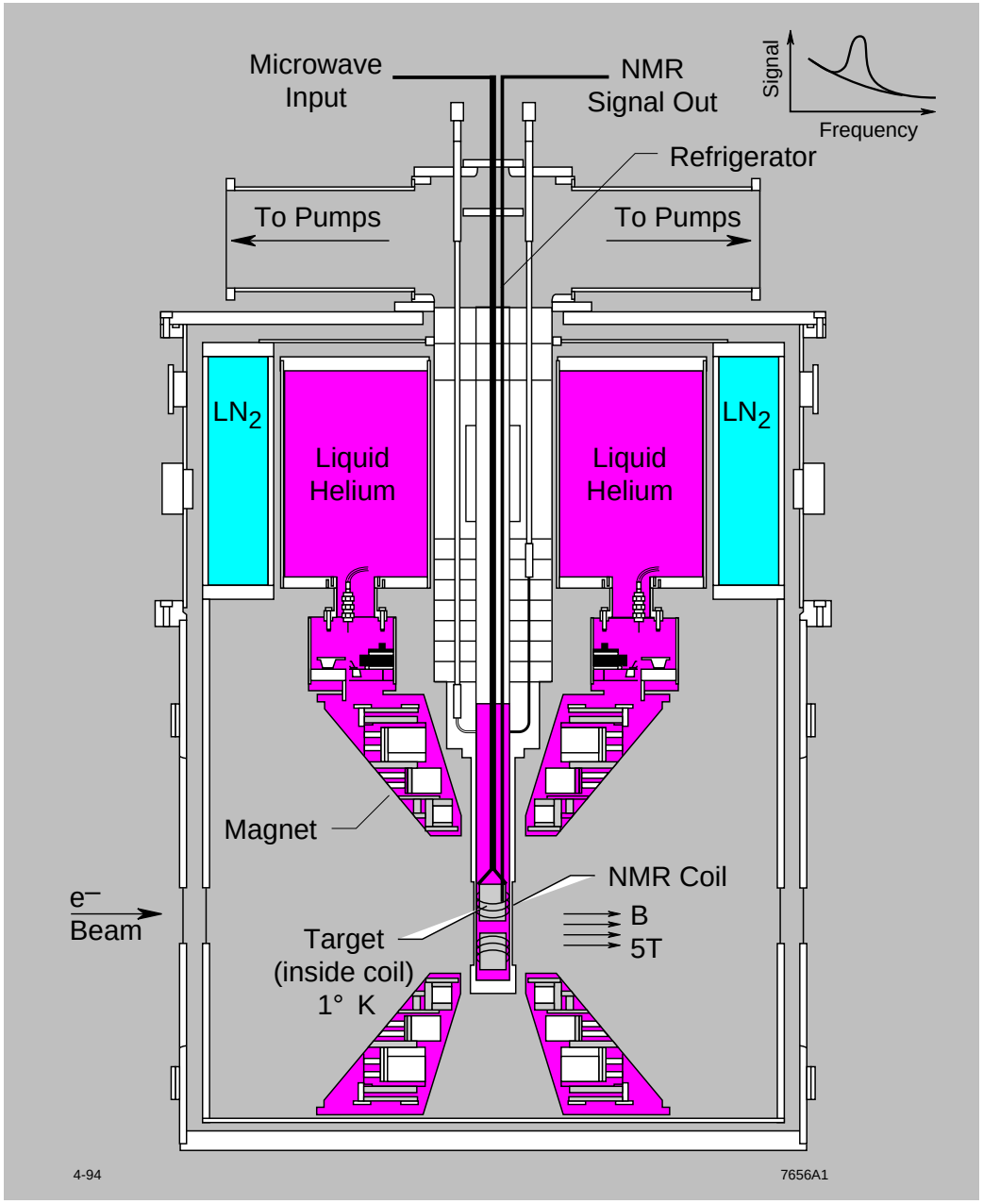
model calculations with different values of G_E^n

Quasi-Elastic kinematics: In center of mass, $\theta_{np} = 180°$


Gen01
High
Momentum
Spectrometer
neutron detector
polarized target
incoming beam line,
chicane magnet

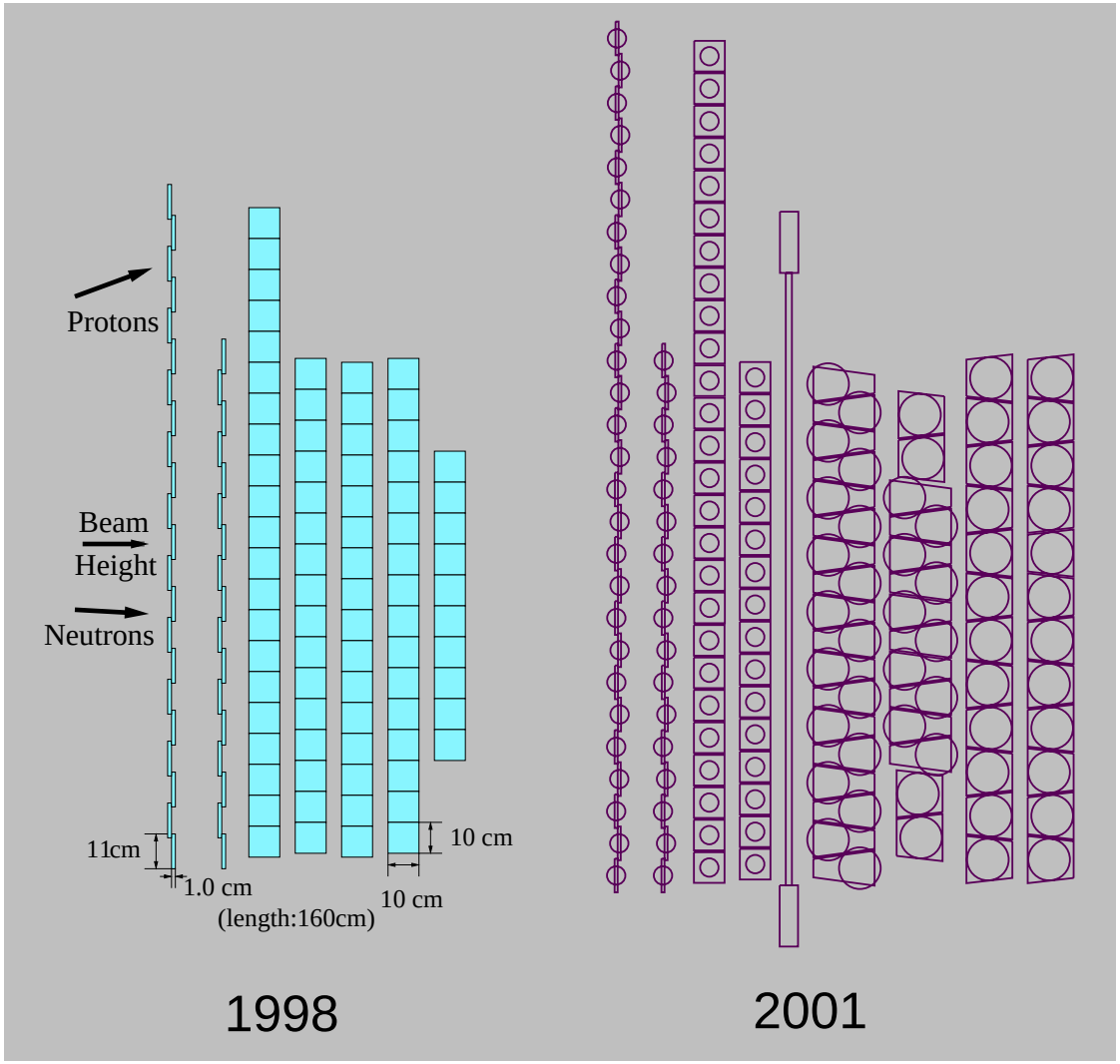
Gen01 – Polarized Target

- frozen ND_3
- ^{4}He evaporation refrigerator
- $5\ \mathrm{T}$ polarizing field
- dynamic nuclear polarization driven by microwaves
- NMR monitoring



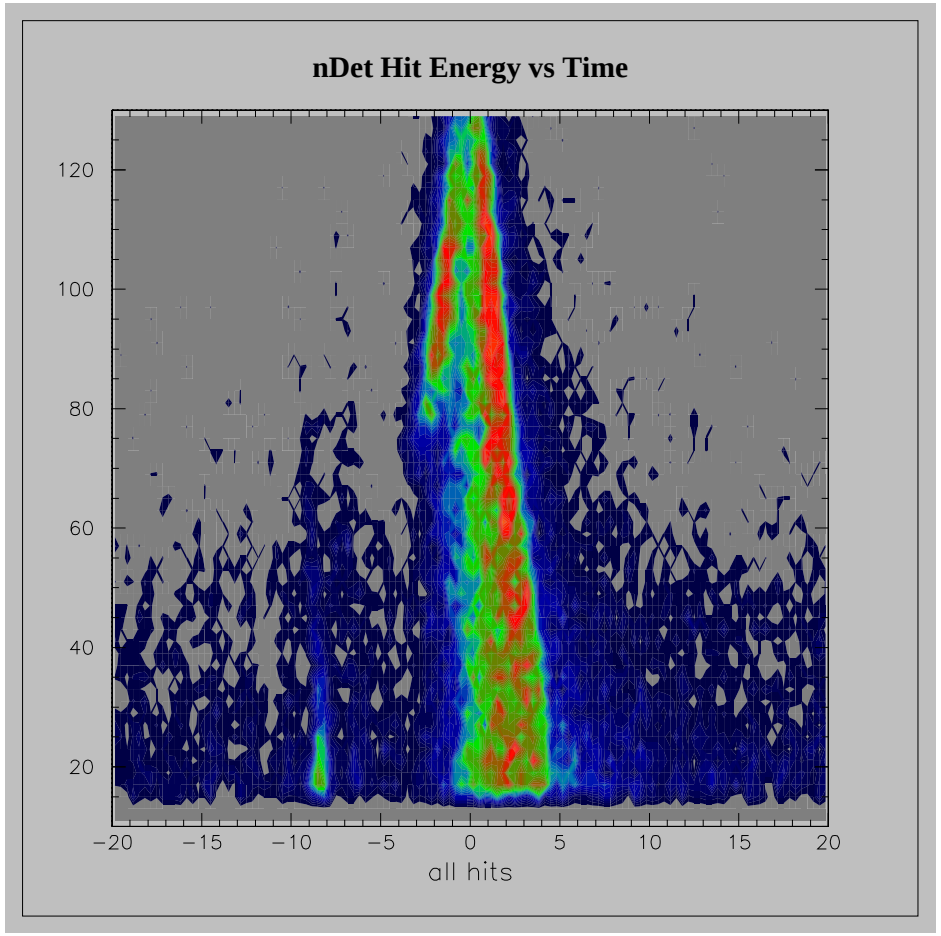
Gen01 – Neutron Detector

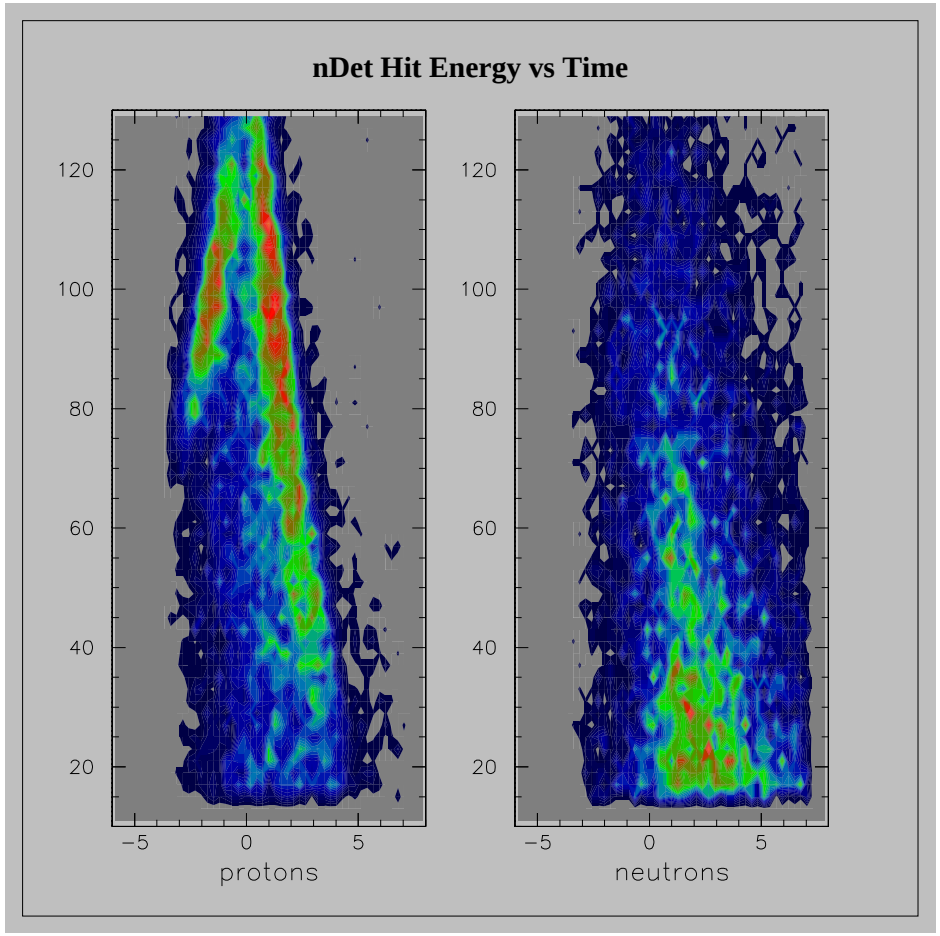
- segmented scintillator
  - *2 p^+ VETO layers*
  - *6 conversion layers*
  - *high rate: $\sim 100\,kHz$*
- vertically extended for symmetric proton acceptance
- provides 3 space coords, time & energy



Gen01 – Particle Identification

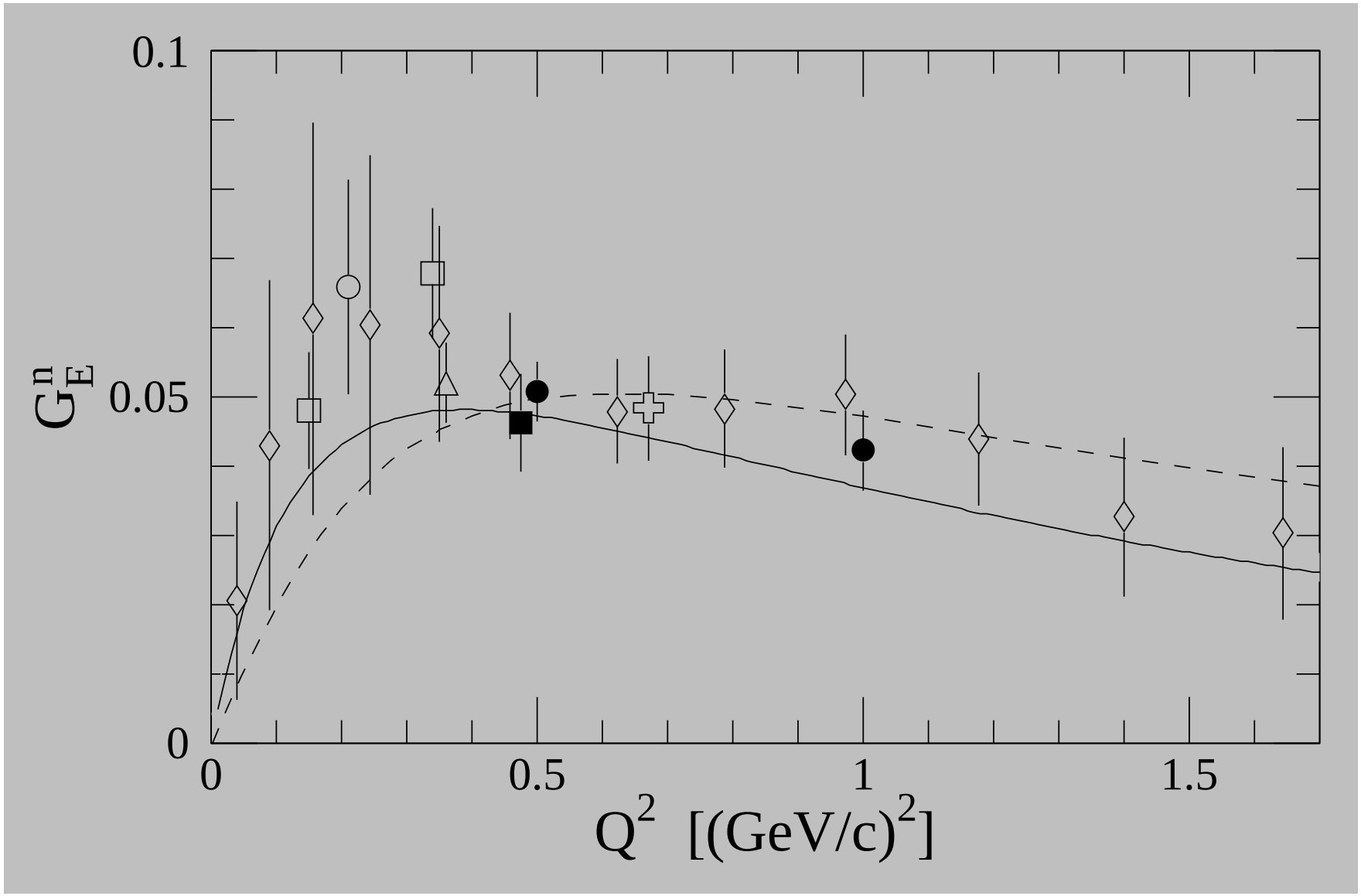
Particle Energy plotted against Detection Time





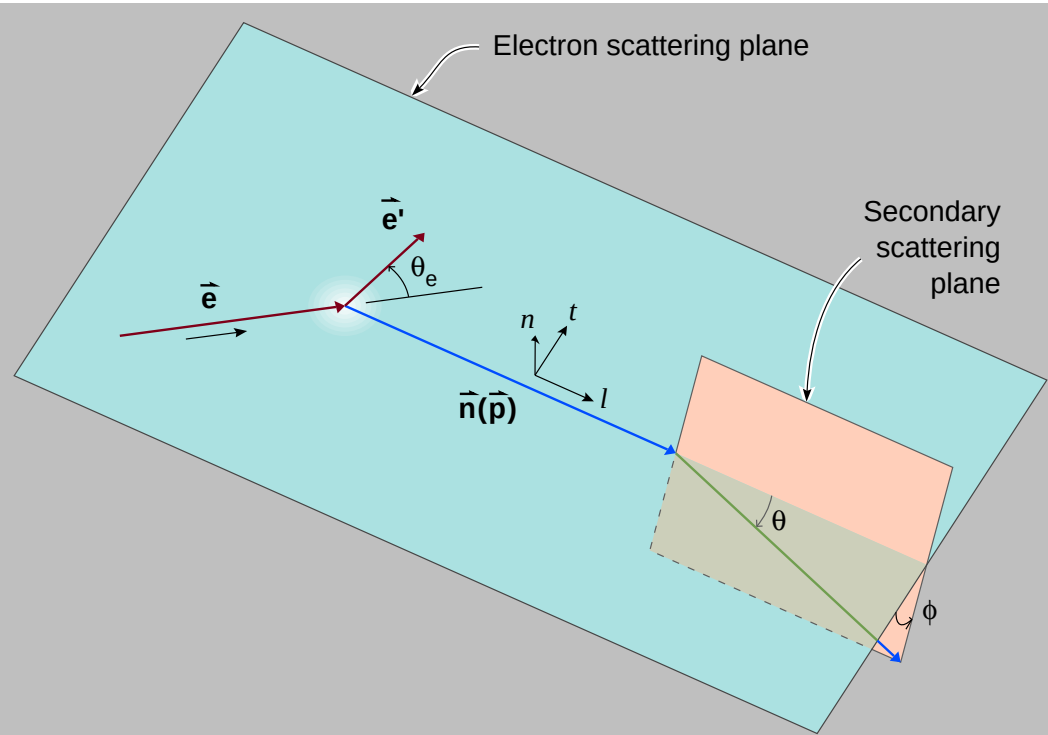
arbitrary offset; only hit times and VETO matches were considered

Gen01 – Results



nucl-ex/0308021

Recall: Recoil Polarimetry



$$I_0 P_n = 0$$

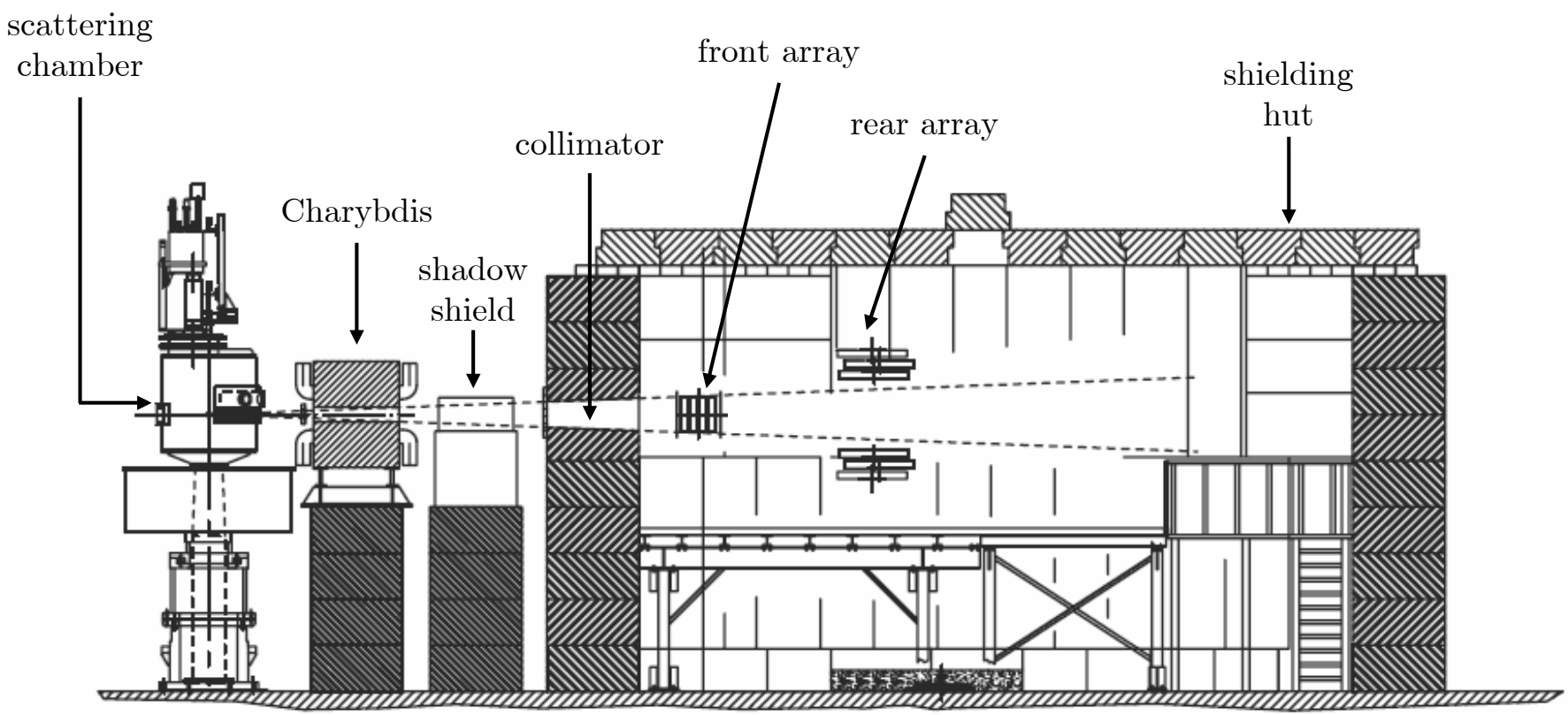
$$I_0 P_t = -2\sqrt{\tau(1+\tau)}\, G_E G_M \tan(\theta_e/2)$$

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

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

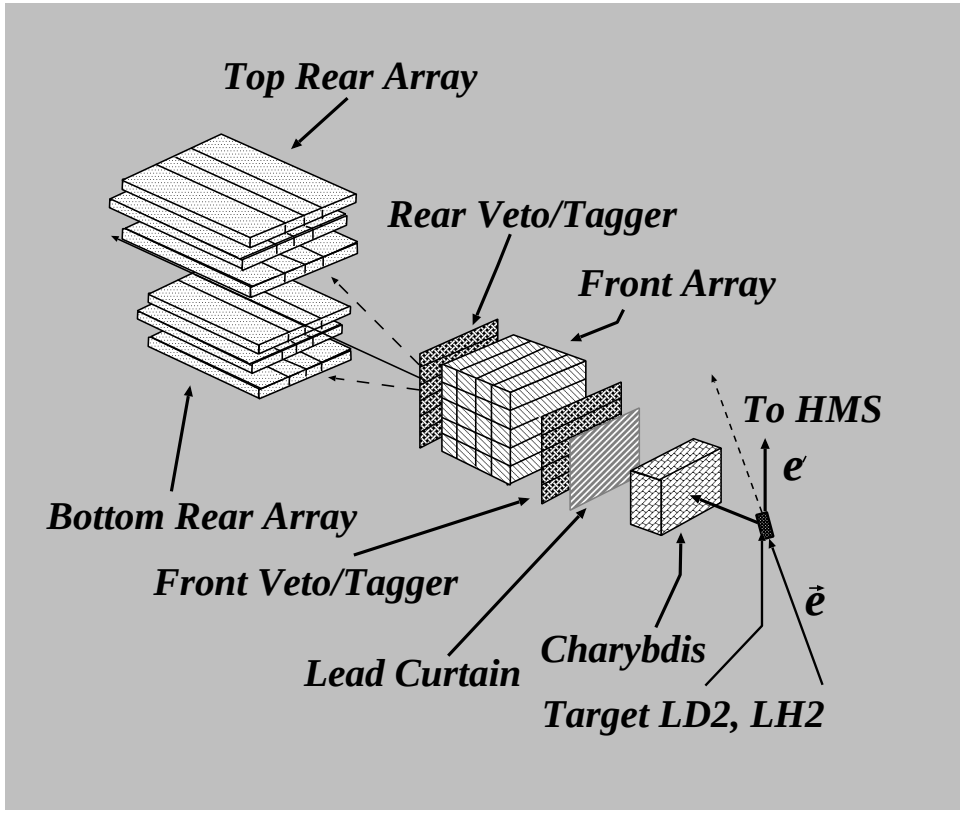
Direct measurement of form factor ratio by measuring the ratio of the transfered polarization P_t and P_l

G_E^n Recoil Polarimetry – E93-038



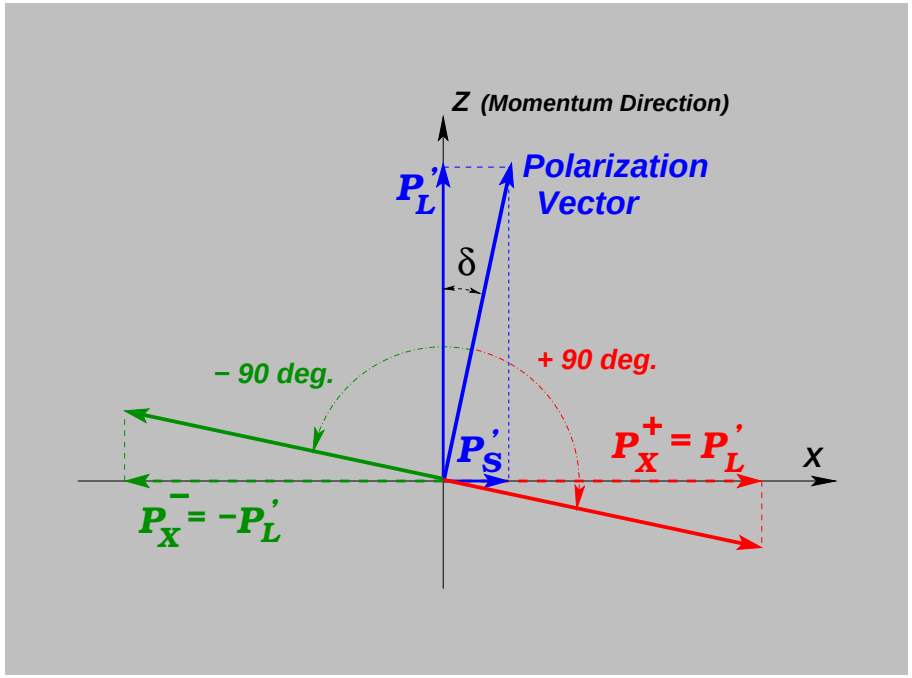
E93-038 measured G_E^n via recoil polarization in quasi-elastic scattering off Deuterium at $Q^2 = 0.45$, 1.13, and $1.45\,(\mathrm{GeV}/c)^2$ using the HMS in ^{2}H$(\vec{e}, e'\vec{n})^1$H scattering

E93-038 – Method



want to determine P_l and P_t at target

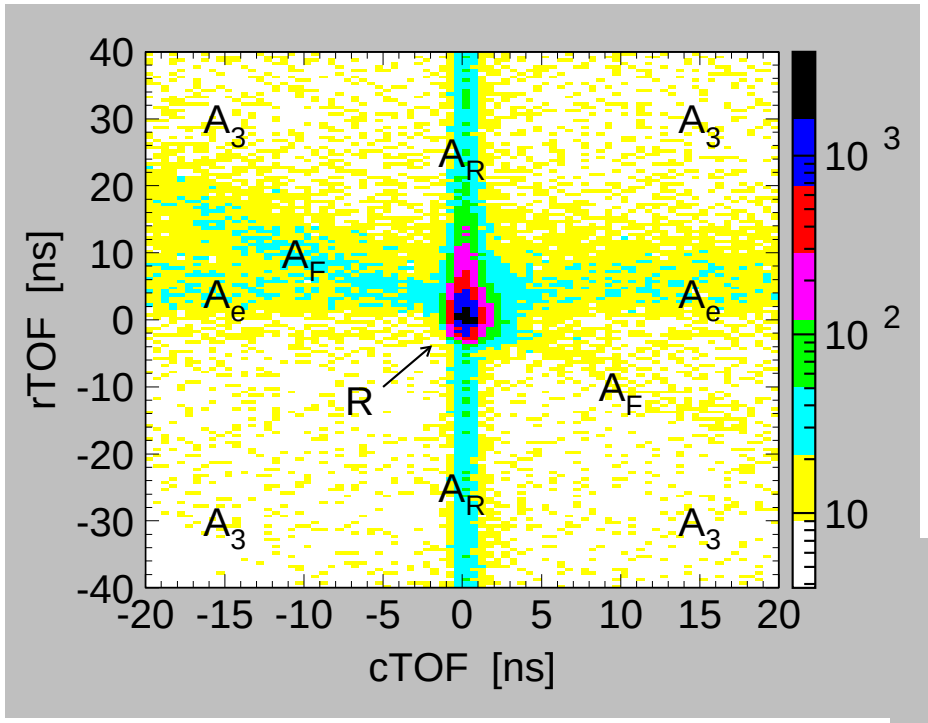
polarimeter sensitive to transverse pol only



$\rightarrow$ rotate longitudinal pol with *Charybdis* magnet

$$P_t^{\mathrm{pol}} = P_l \sin\chi + P_t \cos\chi$$

E93-038 – Data



Coincidence VS Front-Rear TOF

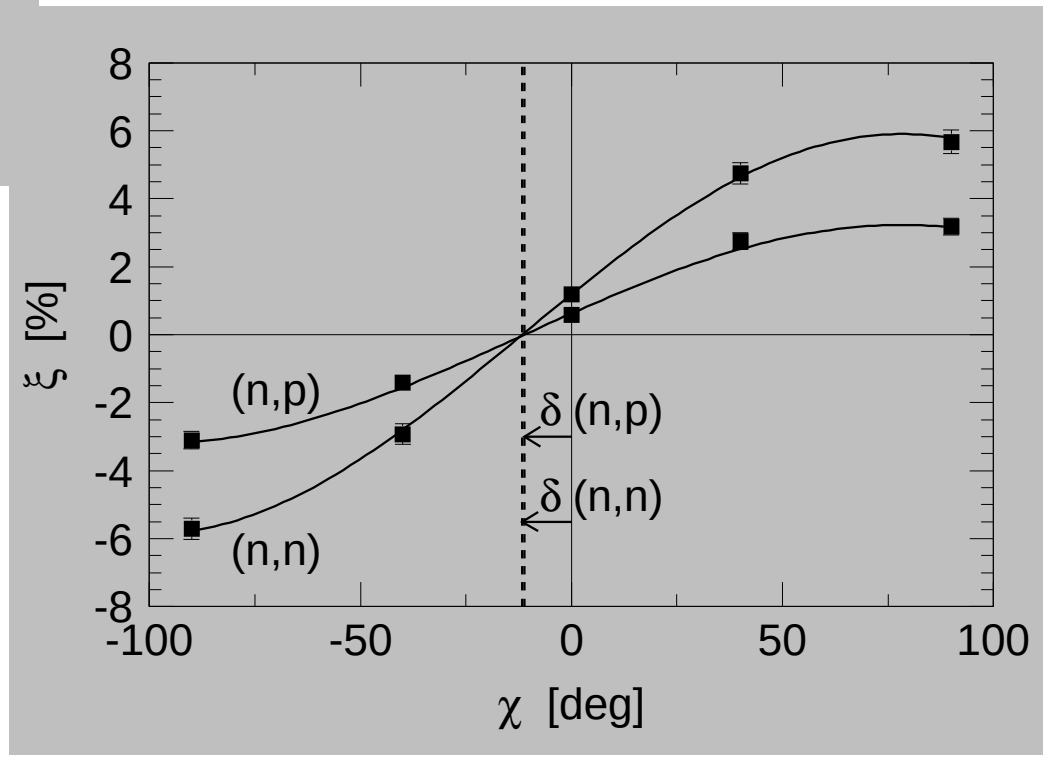
5 Distinct regions:

$\mathbf{A}_3$ triple accidental,

$\mathbf{A}_e$ accidental e,

$\mathbf{A}_F/\mathbf{A}_R$ accidental front/rear,

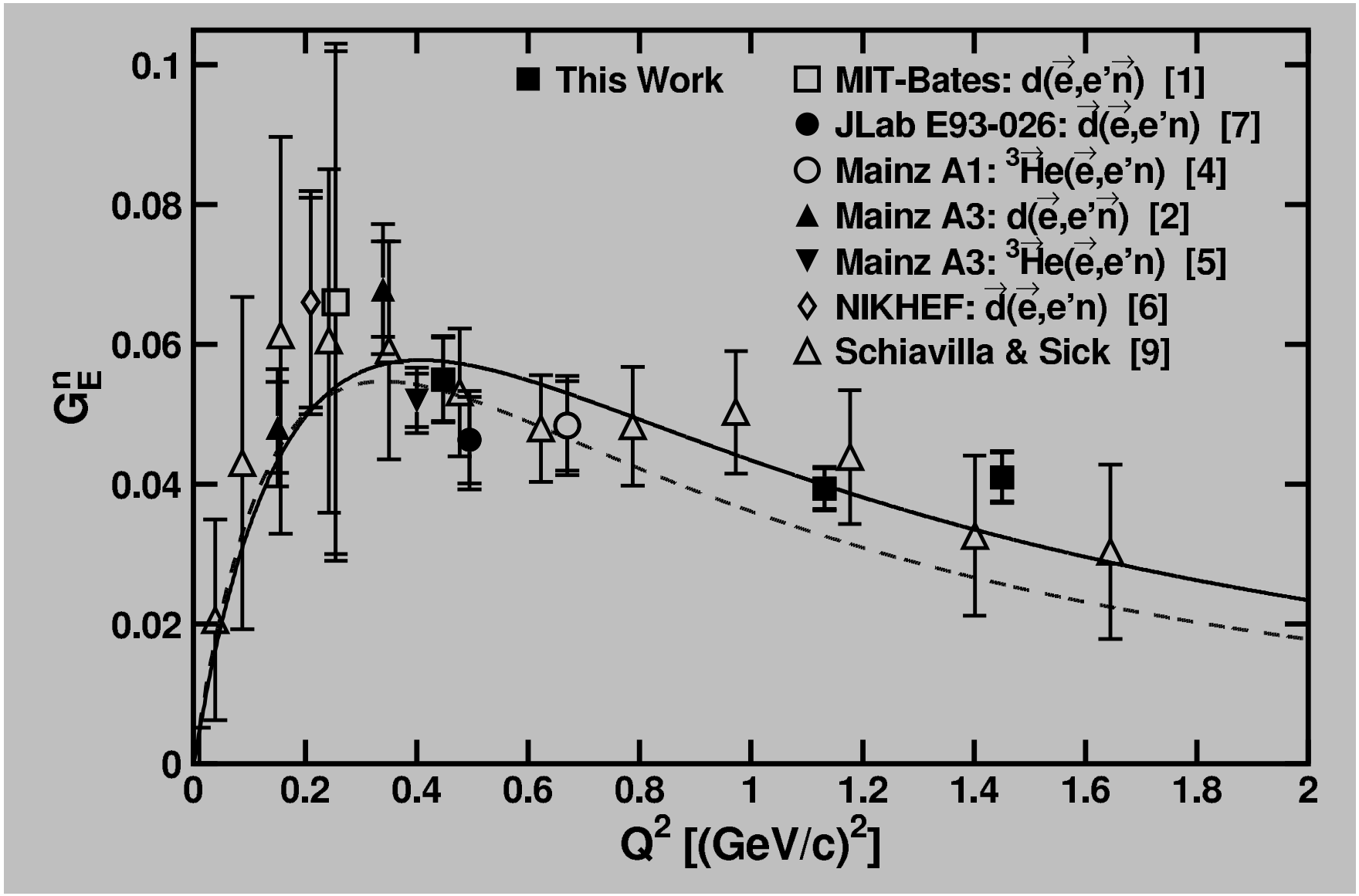
R triple coincidence



Measured Asymmetry VS Precession Angle

phase δ correlates to G_E^n

E93-038 – Results



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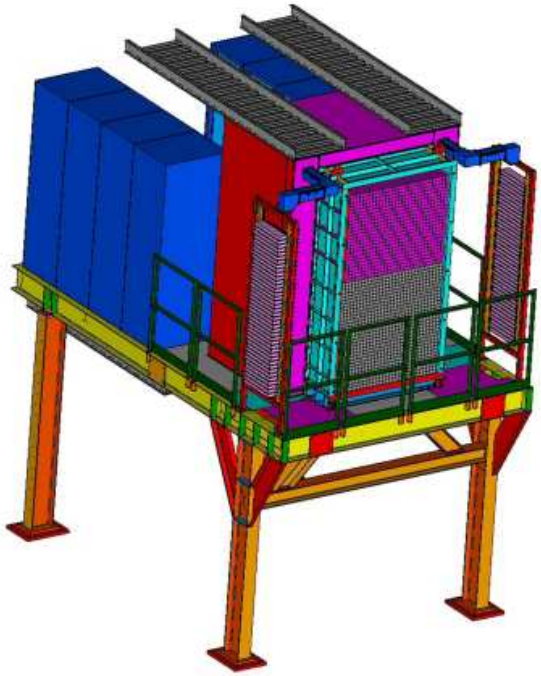
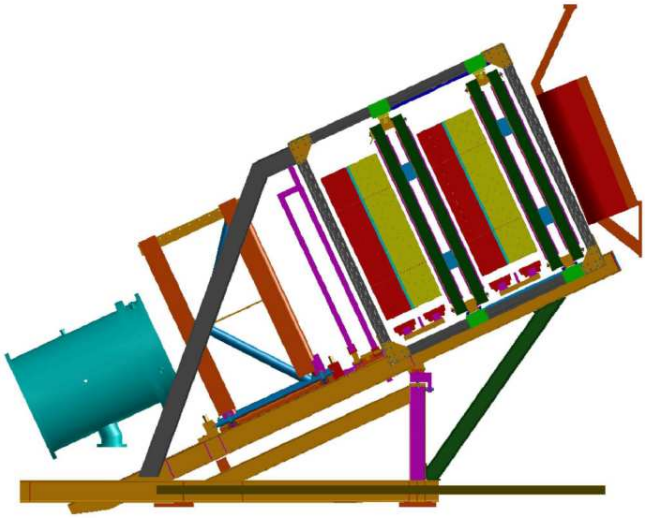
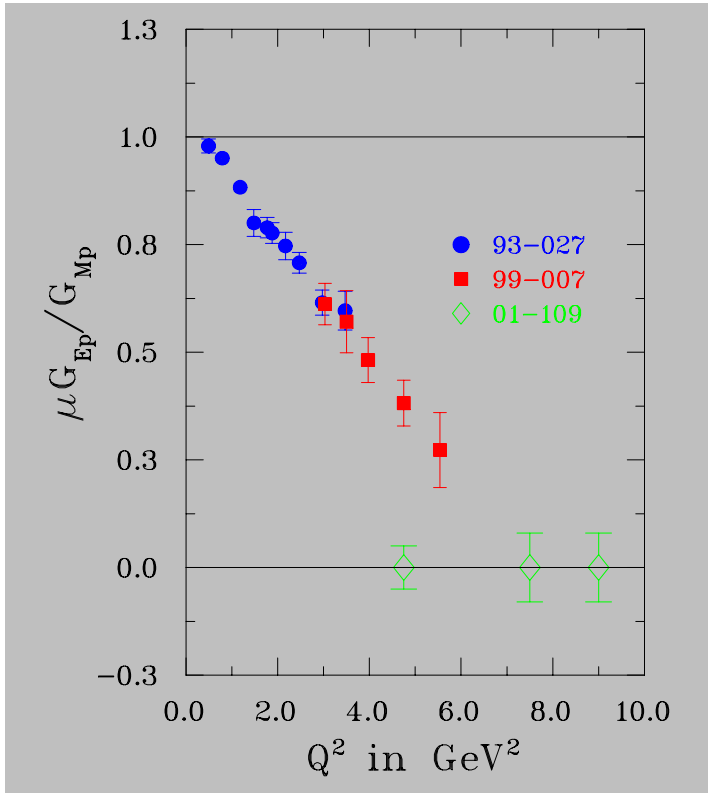
G_E^p Recoil Polarimetry – E04-108





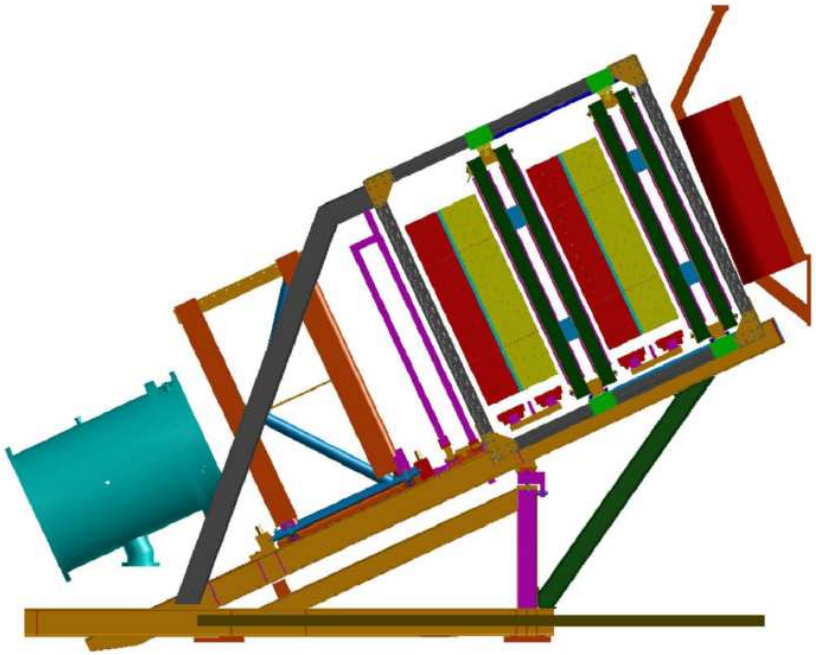
E04-108 will measure G_E^p/G_M^p at highest Q^2 yet, using *new* calorimeter and polarimeter

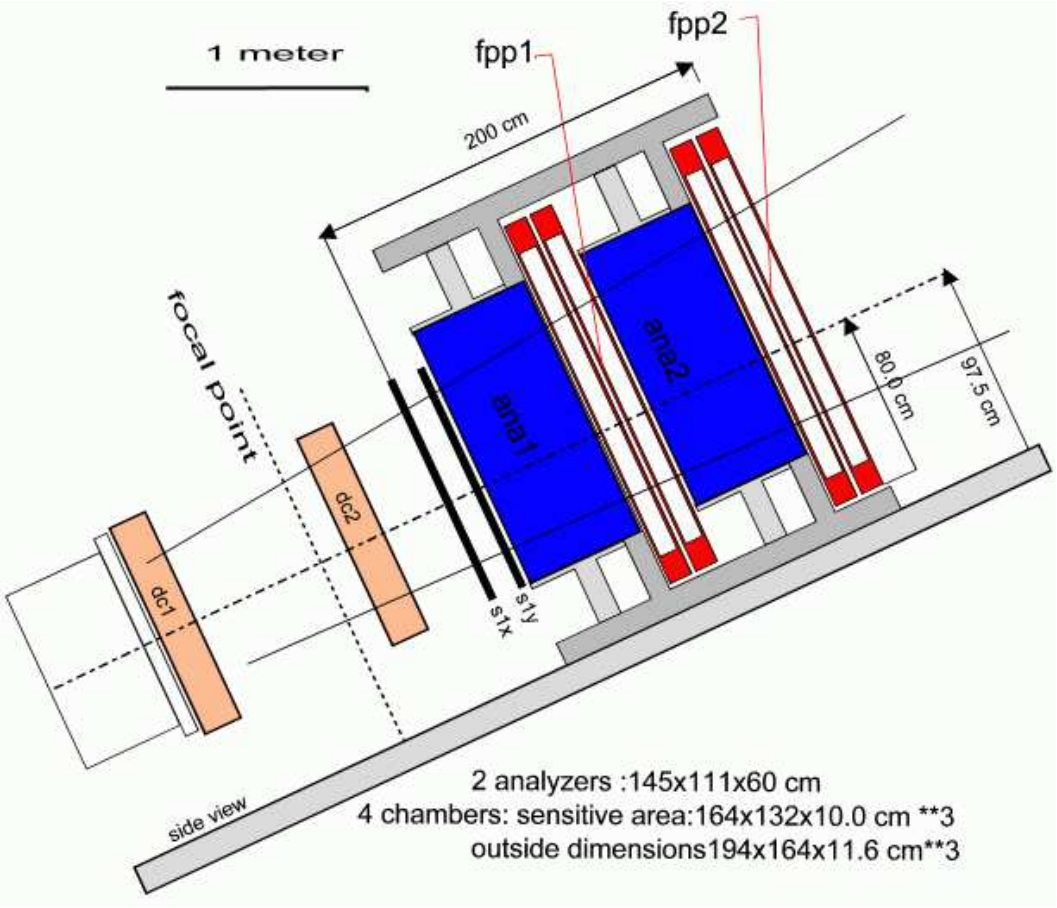


E04-108 – BigCal

E04-108 – FPP

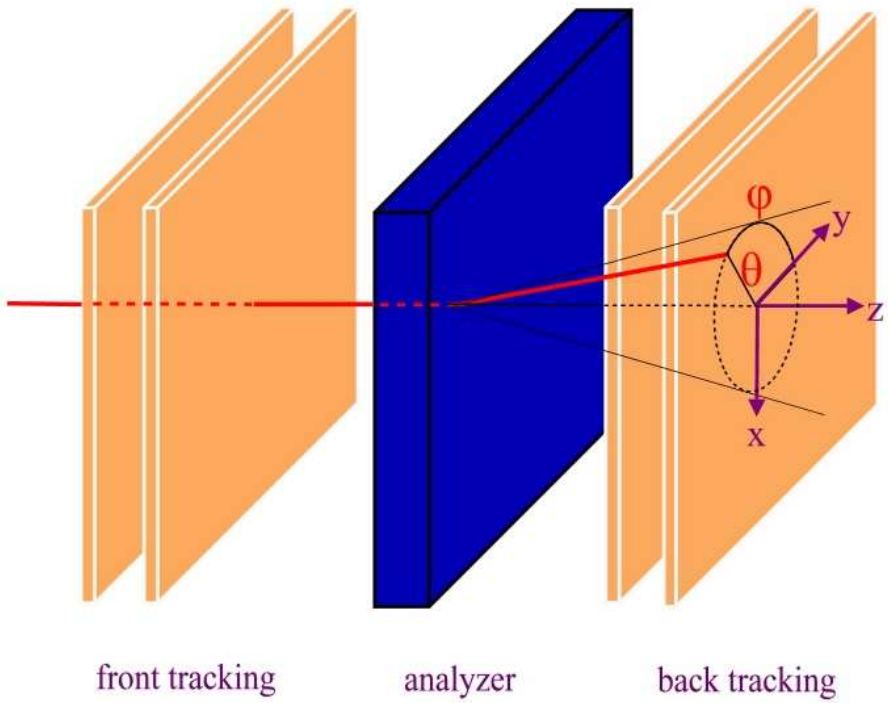
Newly constructed Focal Plane Polarimeter installed into HMS





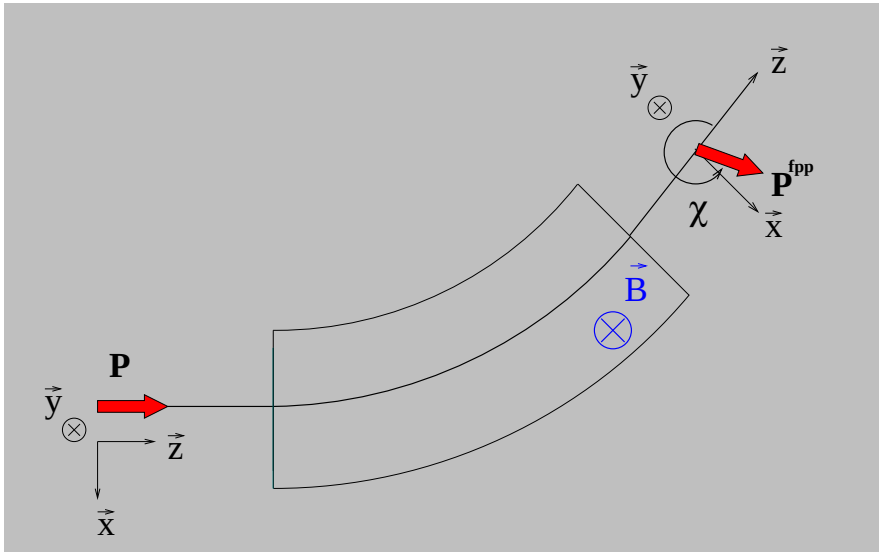
2 polarimeters in succession enhance efficiency

E04-108 – Polarimetry

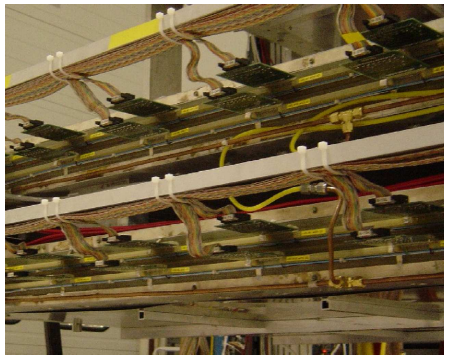


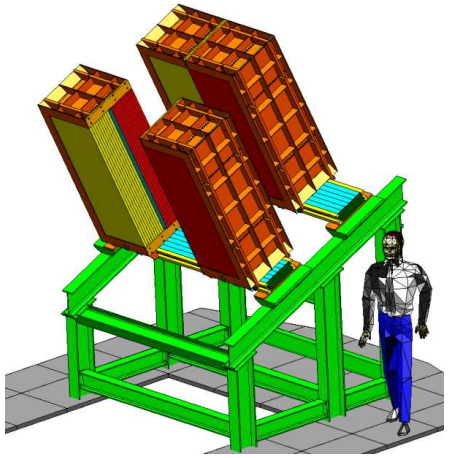
Polarimeter measures polarization dependent re-scattering

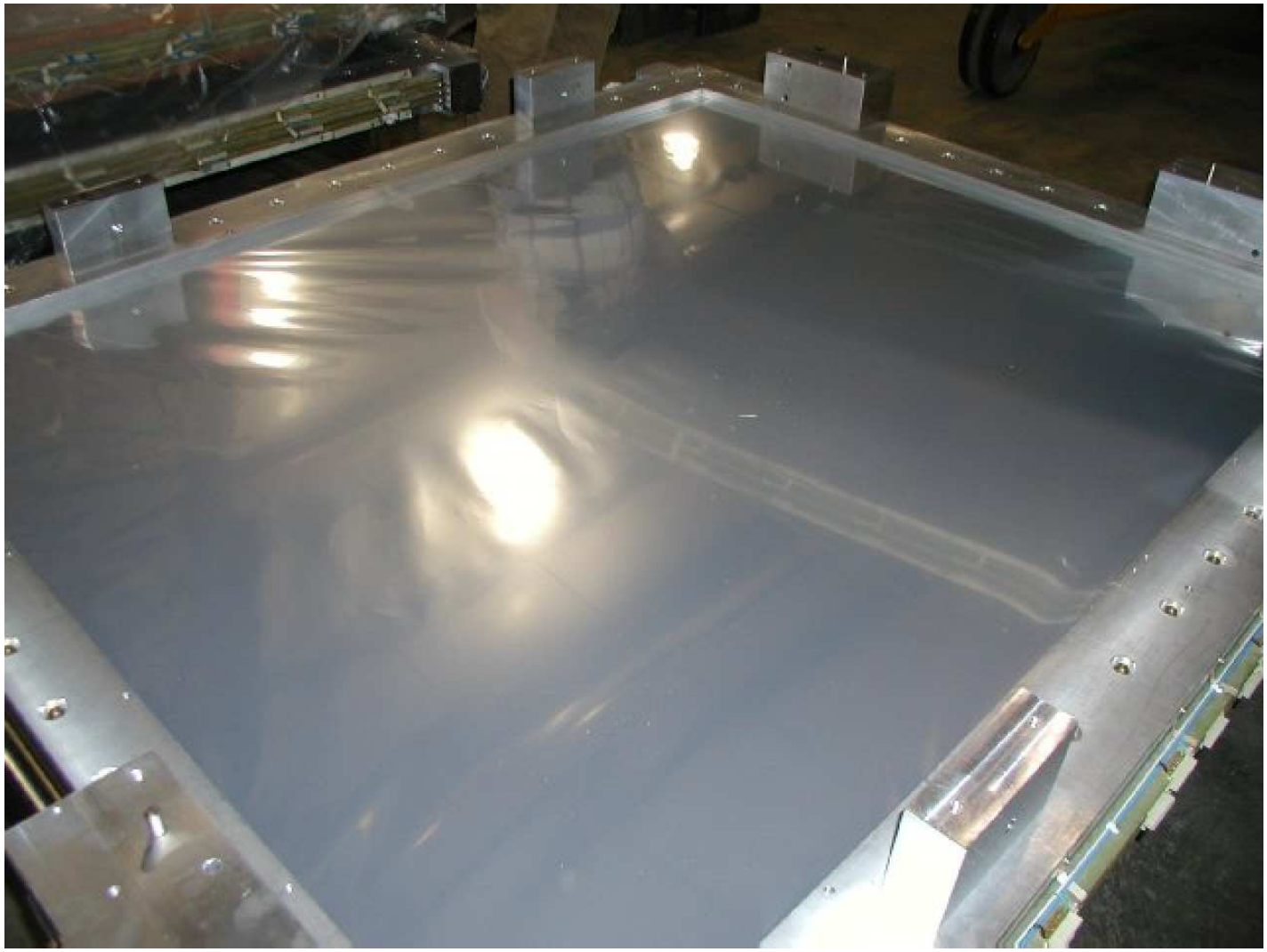
Polarization vector precesses in magnetic dipole and quadrupole fields



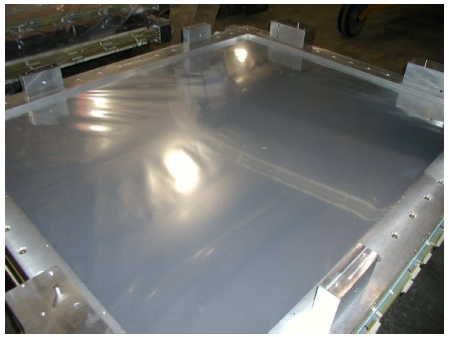
E04-108 – FPP

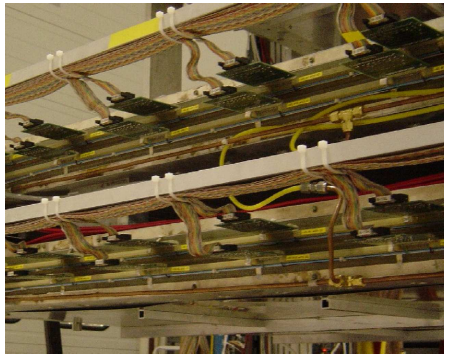


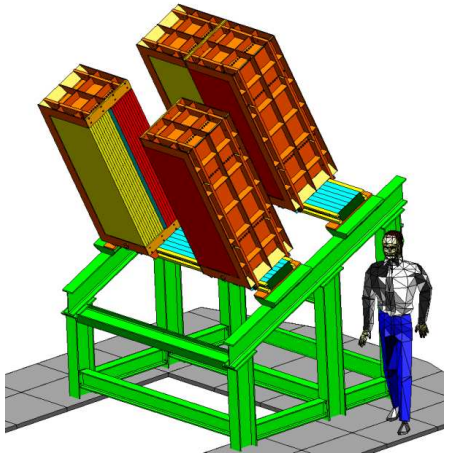




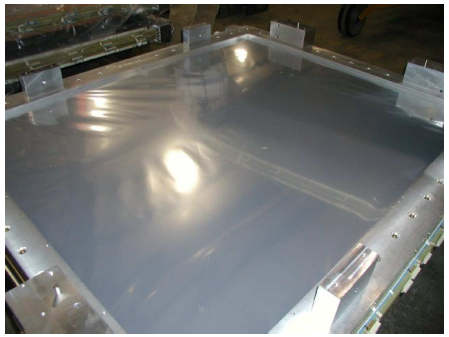
E04-108 – FPP

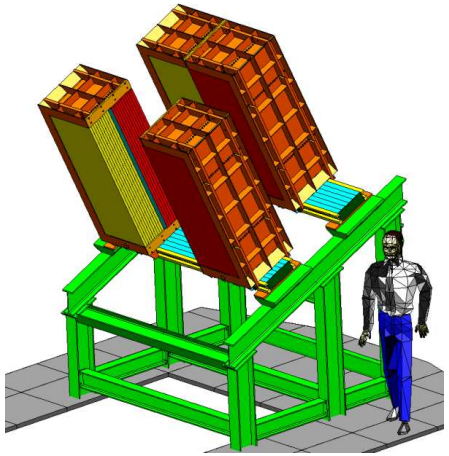


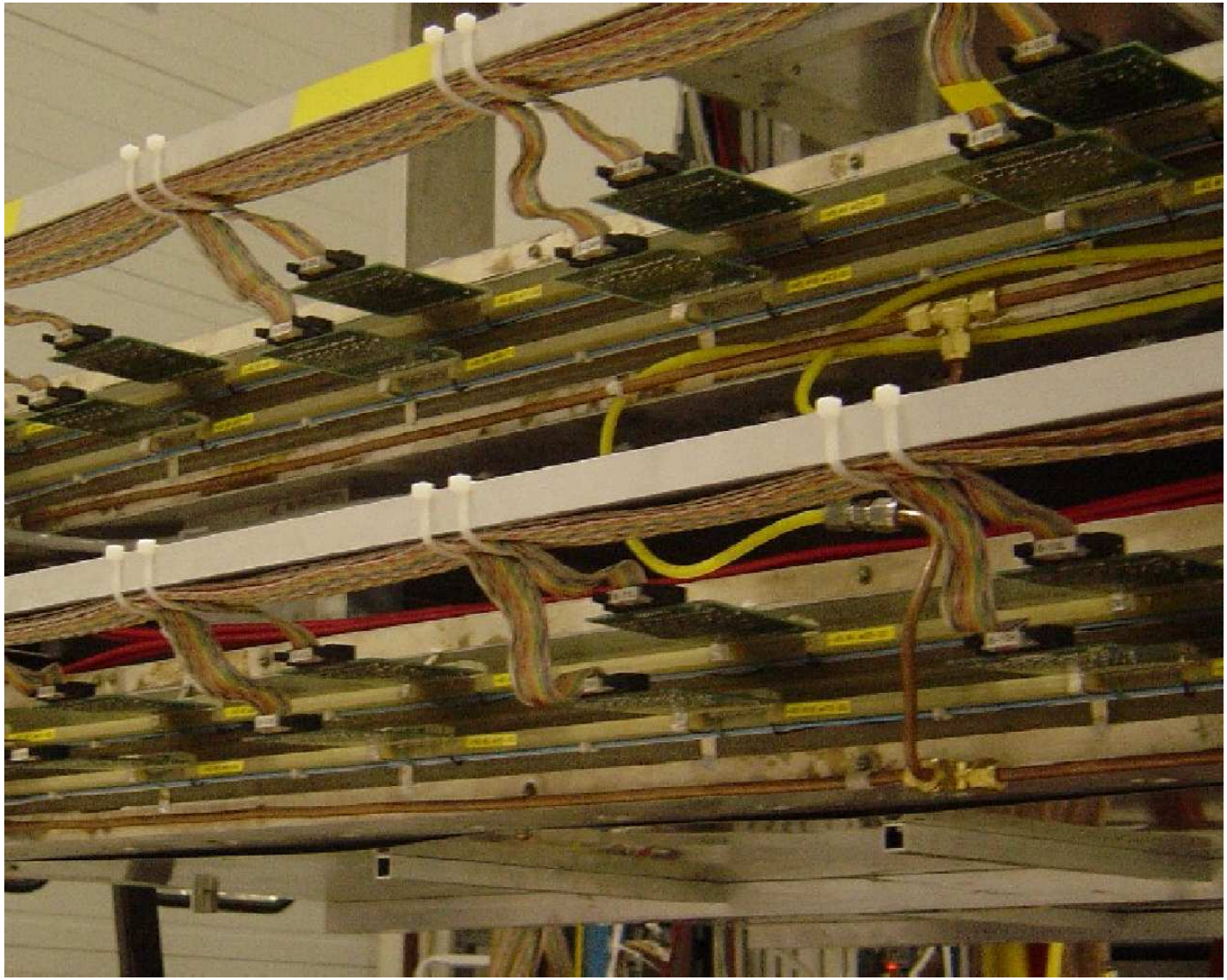




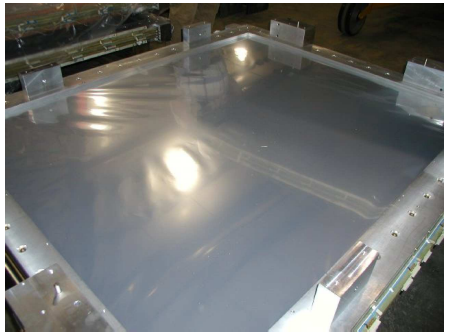
E04-108 – FPP

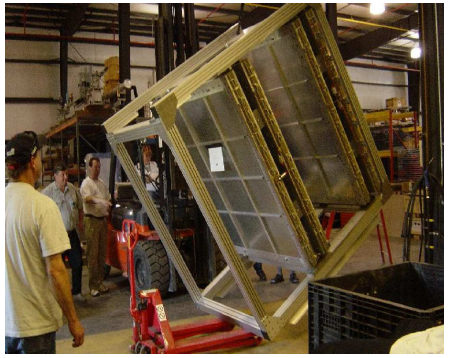


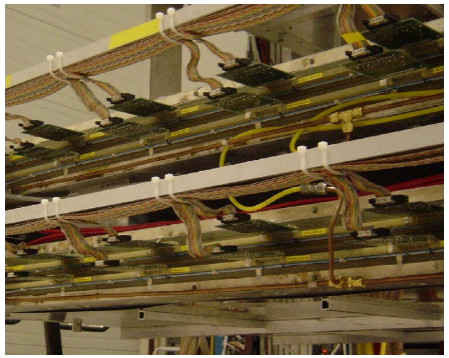


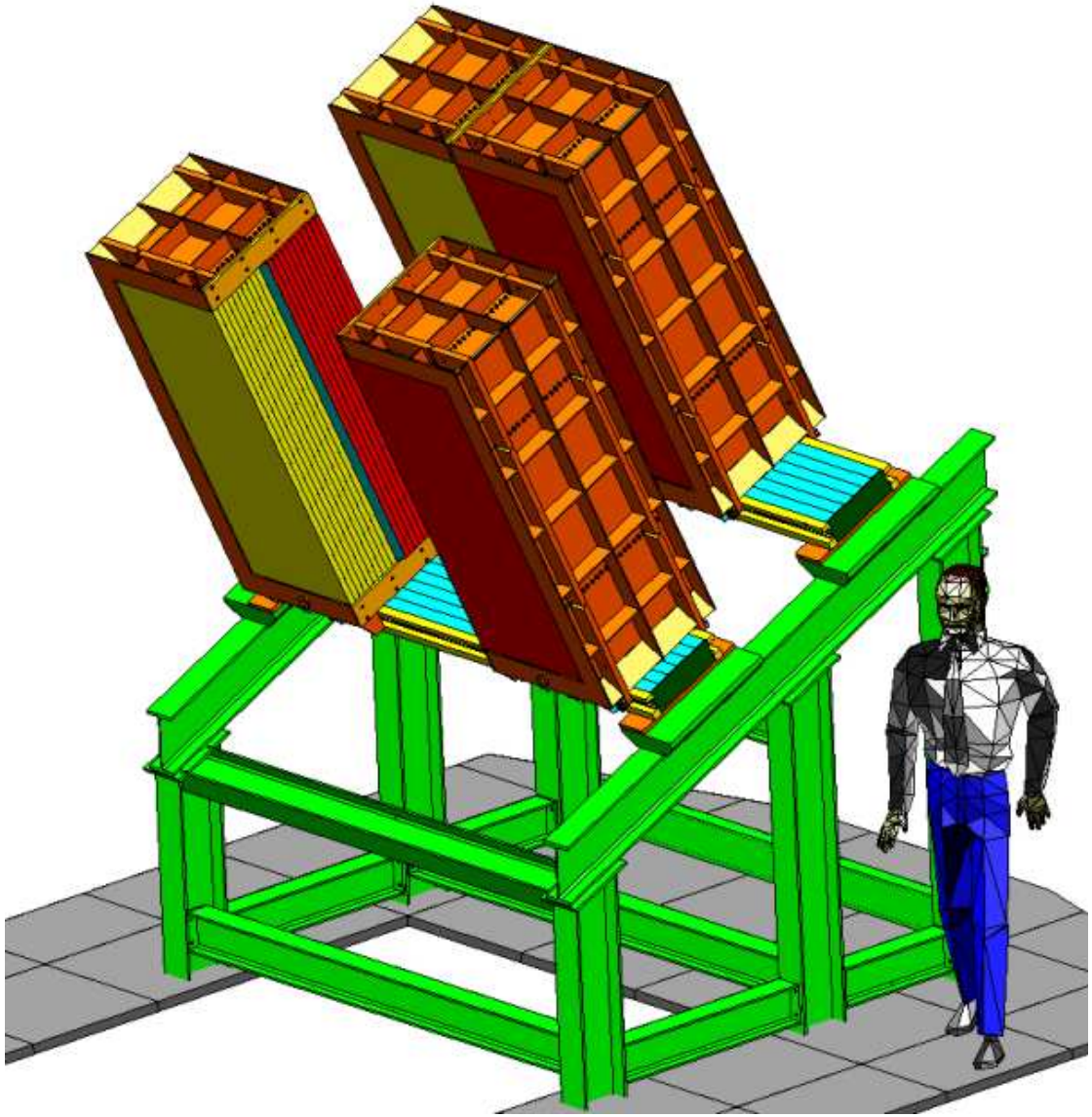


E04-108 – FPP

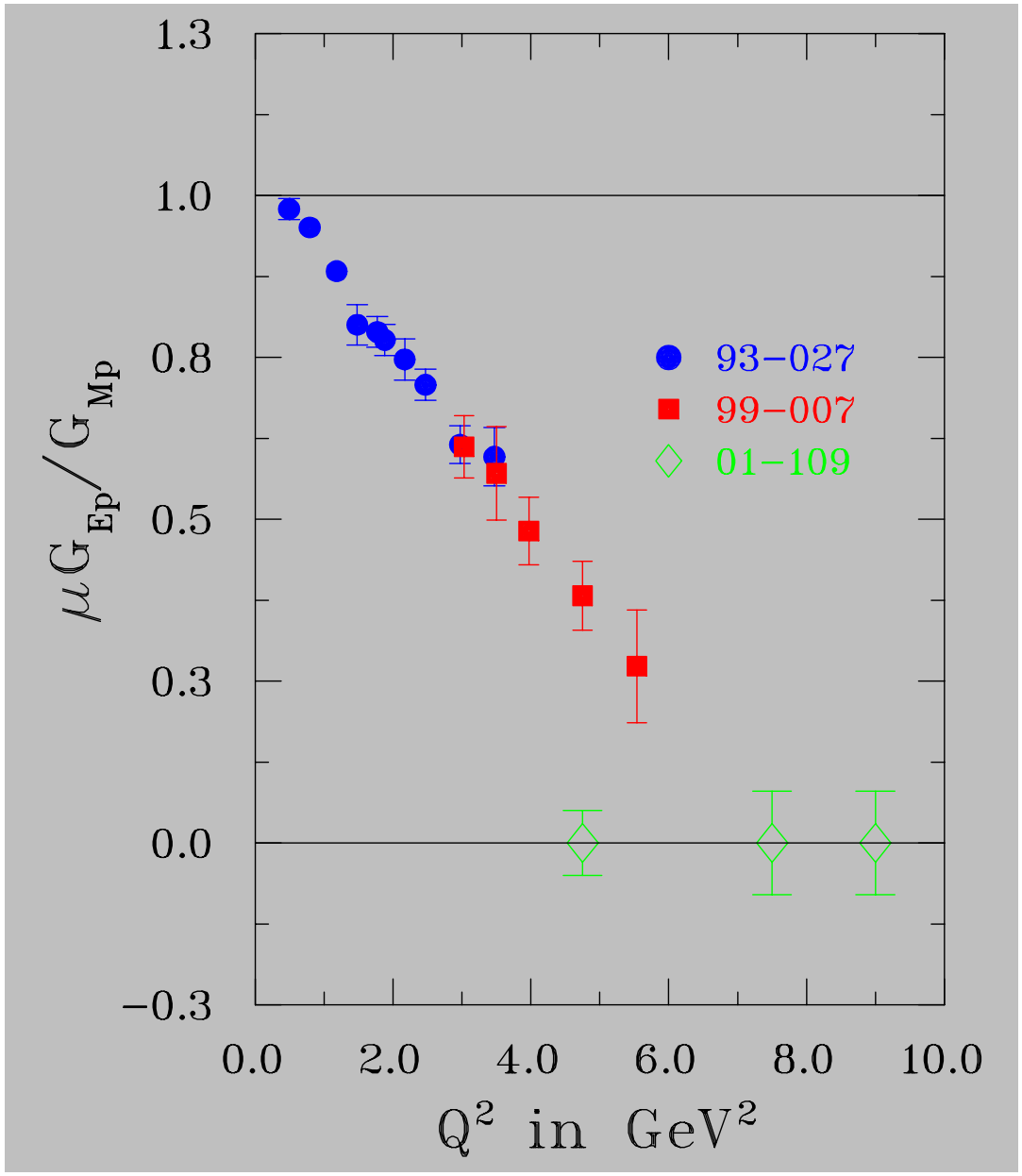








E04-108 – Expected Results



- Expands upon spectacular Hall A results
- Sister experiment: dedicated 2γ measurement
- scheduled for 2007/2008

Summary

- Form Factors are Vital to Our Understanding of Nature
- Many Experiments have Already been Undertaken
  - *limited kinematic range*
- Comprehensive theory model lacking
  - *higher Q^2 data?*
- Significant Contribution from Jefferson Lab
  - *recent G_E^n measurement in Hall A*
  - *upcoming G_E^p/G_M^pin Hall C*
  - *extensive weak FF program (G^0, Q_{weak})*