Proton Form Factors

(Space-Like, EM p FF)

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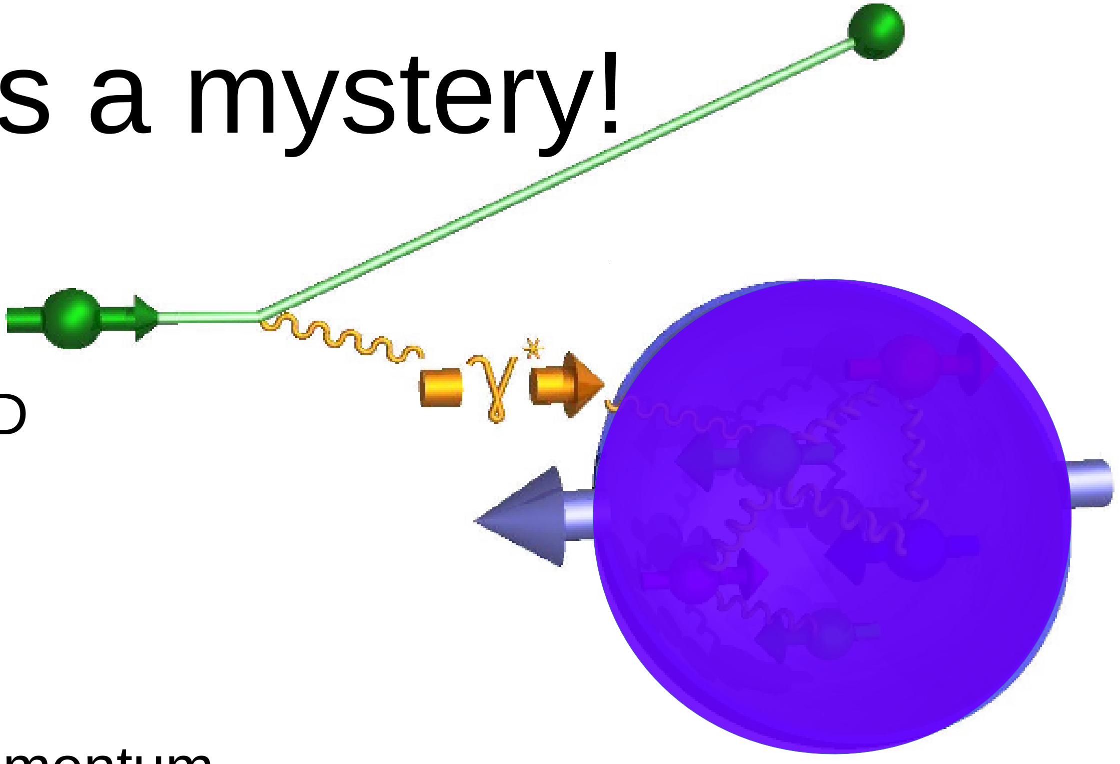
Outlook

- Short EMFF overview and p-FF status
- JLab opportunity at high Q^2
- SBS GEp experiment and expected results

Nucleon, it is a mystery!

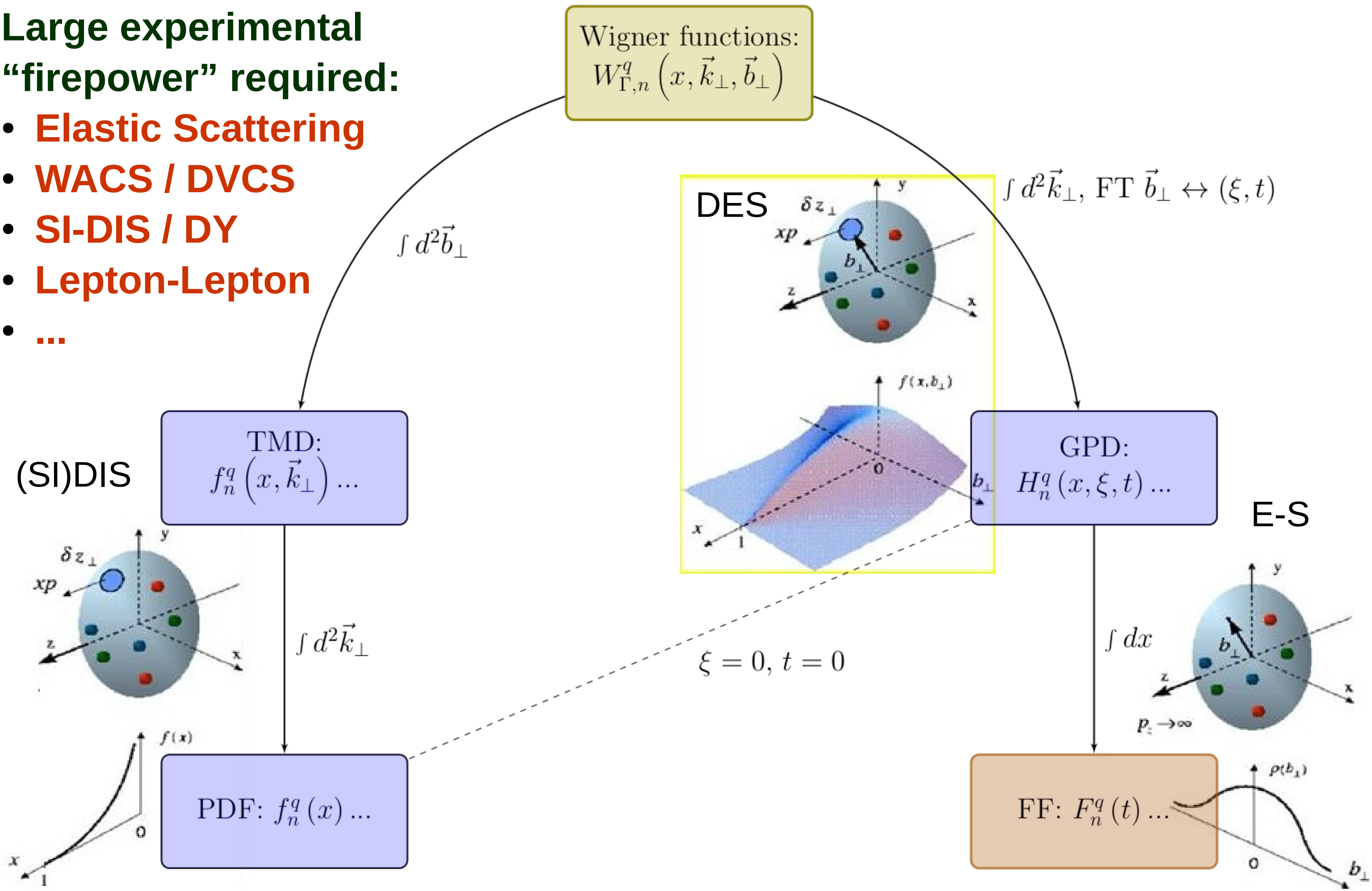


- Mass origin
  - Confinement / QCD
  - Internal dynamics
- Spin origin
  - Orbital Angular Momentum
  - Gluon Contribution
- (Proton) radius
- QED-QCD reaction mechanisms

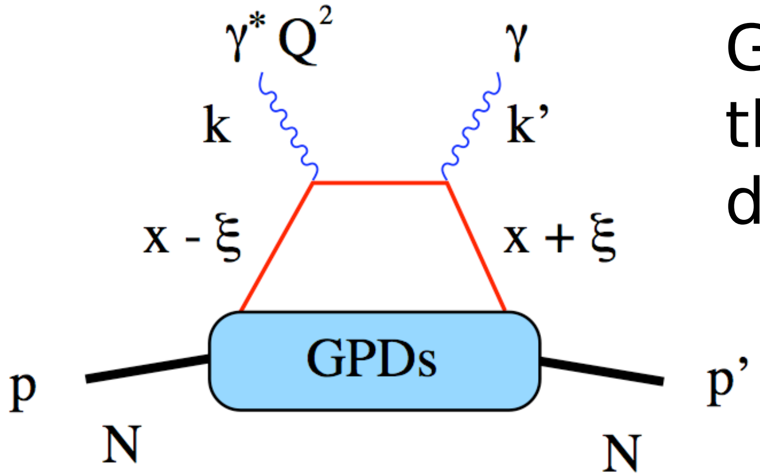
Toward a unified picture of nucleon structure

Large experimental "firepower" required:

- **Elastic Scattering**
- **WACS / DVCS**
- **SI-DIS / DY**
- **Lepton-Lepton**
- **...**



Form Factors and GPDs



GPDs provide a framework that links FF and DIS parton distributions

FF constraint 2 of the 4 GPDs through sum rules:

$$F_1^q(Q^2) = \int_{-1}^{1} dx \; H^q(x,\xi,Q^2), \quad F_2^q(Q^2) = \int_{-1}^{1} dx \; E^q(x,\xi,Q^2)$$

Strong hints for the estimation of the quark OAM (Ji PRL 78 (1997) 610-613):

$$J^q = \frac{1}{2}\int_{-1}^{1} xdx \left[H^q(x,\xi,0) - E^q(x,\xi,0)\right]$$

see M. Diehl and P. Kroll EPJ C (2013) 73:2397 model dependent attempt

*«We note that the **electromagnetic form factors** provide indirect constraints on GPDs at **high values of t**, which will conceivably never be accessible in hard exclusive scattering processes.»*

FF «traditional» extraction method

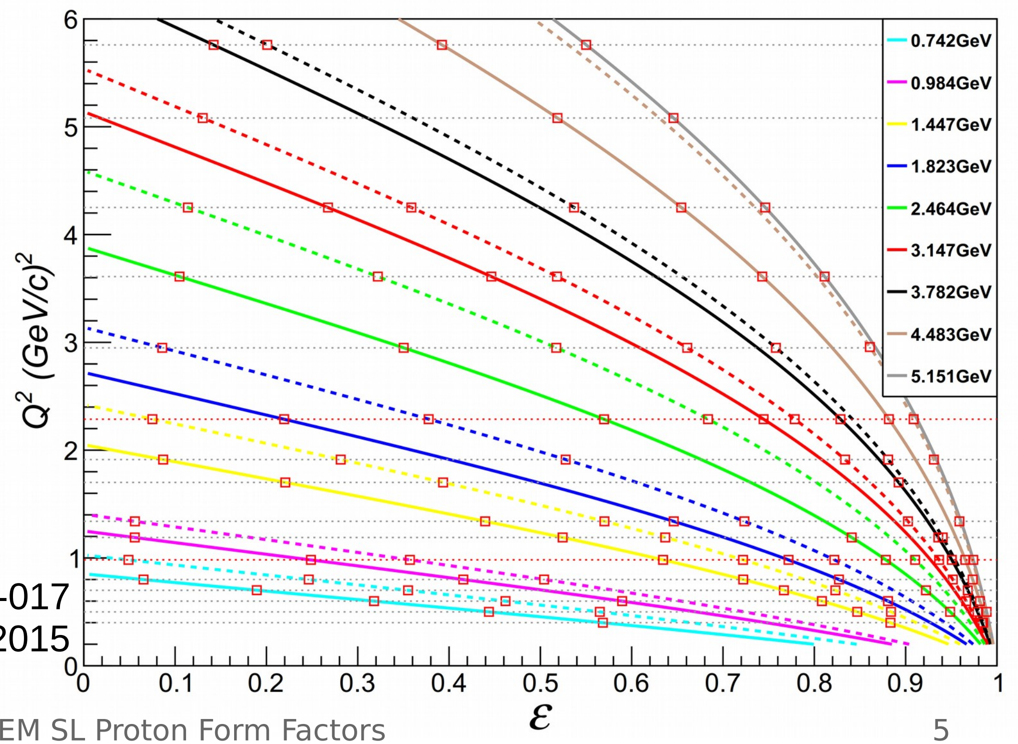
- Rosenbluth separation in Born approximation (Zα<<1)

$$\frac{d\sigma_r}{d\Omega} = \varepsilon\ G_E^2(Q^2) + \tau\ G_M^2(Q^2),$$

$$\tau = Q^2/(4M^2)$$

$$\varepsilon = \left[1 + 2(1+\tau)\tan^2(\theta_e/2)\right]^{-1}$$

- Can determine both absolute values of G_E and G_M
- τ kinematically suppress G_E at high Q^2 and G_M at low Q^2
- Measure cross sections for different ε, then make linear fits
- Different "kinematic" approaches



JLab exp. E05-017
from V. Punjiabi et al. 2015

The power of spin

- Akhiezer et al. Sov. Phys. JETP 6, 588 (1958), Sov. PHys. Dokl. 14 (1968), ...
  Form factor accuracy can be improved by measuring ***interference term $G_E G_M$*** *by means of beam helicity asymmetry with polarized target or recoil polarimetry*
- About 30 years to get the needed technologies:
  - Polarized e beam (high current 100 μA and polarization>70%) and beam polarimetry (~3%)
  - Highly polarized targets
  - Efficient recoil polarimeters (reasonably high analyzing power)

FF «modern» extraction methods

- Recoil polarization:

$H(\vec{e}, e', \vec{p}), {}^2H(\vec{e}, e', \vec{n})H$ $$\frac{P_t}{P_l}\tan\left(\frac{\theta}{2}\right) \propto -\frac{G_E^p}{G_M^p}$$

P_t, P_l = trans. and long. polarization of the recoil proton

- Beam-Target polarization asymmetry:

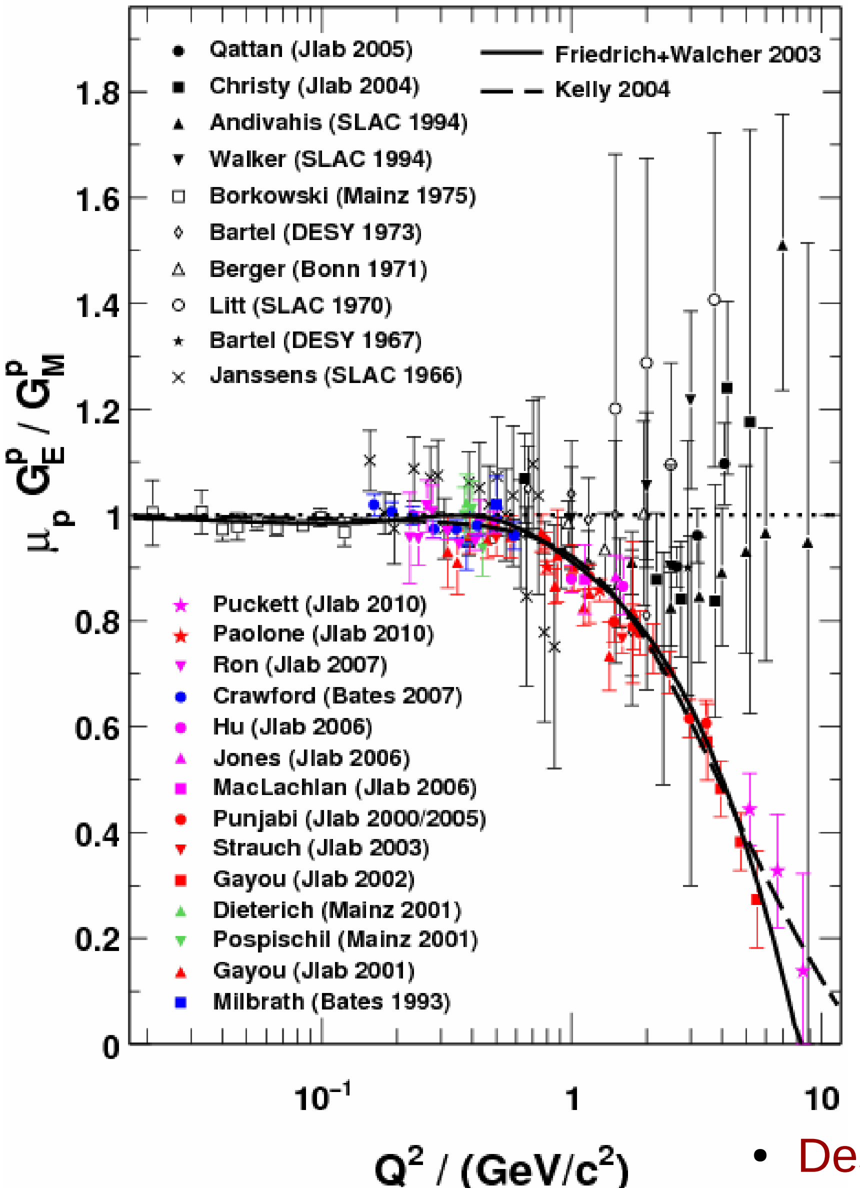
$\overrightarrow{\mathrm{H}}(\vec{e}, e'p)$

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

$$A = \frac{N^+ - N^-}{N^+ + N^-} \approx \frac{G_E}{G_M}$$

many systematics (theory and exp.) cancel in ratio

Proton G_E/G_M – an «**unexpected**» discrepancy



$$\frac{d\sigma}{d\Omega} \propto G_{Ep}^2 + \frac{\tau}{\varepsilon} G_{Mp}^2$$

Rosenbluth Separation: assume single photon approximation

Prior to JLab/2000, expectations were that proton G_E/G_M fairly constant with Q^2

$$\mu \frac{G_{Ep}}{G_{Mp}} = -\mu \frac{P_t}{P_l} \frac{(E_{beam} + E_e)}{2M_p} \tan\frac{\vartheta_e}{2}$$

Polarization transfer from the incident electron to the scattered proton

At JLab, new class of experiments show proton G_E/G_M decreasing linearly with Q^2

$$R_p = \mu_p \frac{G_E(Q^2)}{G_M(Q^2)} \approx 1 - \underbrace{0.13\,(Q^2 - 0.29)}_{Pol.\ Transfer\ Discr.}$$

- Description of the reaction mechanism is wrong (?)
- G_E and G_M do not scale the same way

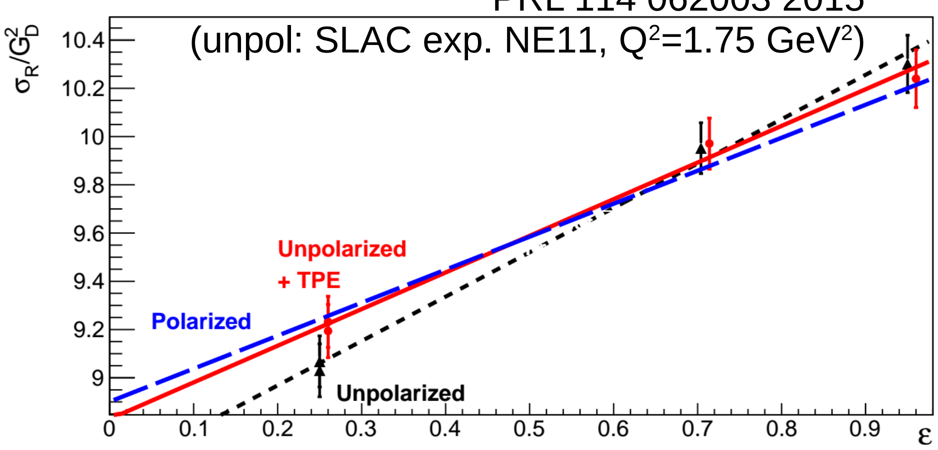
TPE makes FF extraction model dependent

Cross section up to 2γ exchange approximation (nucleon model dependent):

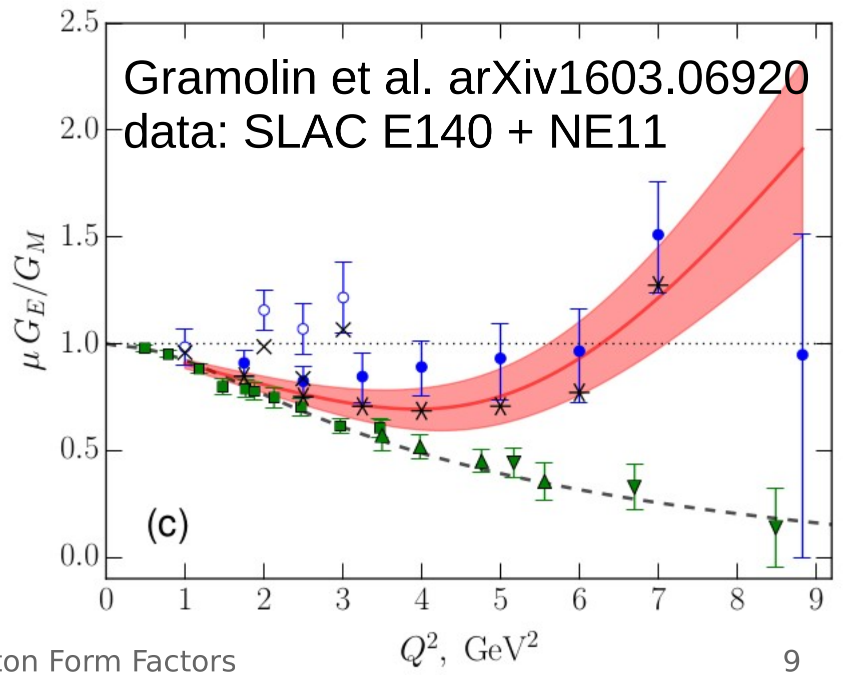
$$d\sigma_{1\gamma+2\gamma} = C\left\{\underbrace{|\tilde{G}_M|^2 + \frac{\epsilon}{\tau}\left[|\tilde{G}_E|^2}_{\text{Rosenbluth at }1\gamma\text{ approx.}} + 2|\tilde{G}_M|^2\left(\tau + \frac{|\tilde{G}_E|}{|\tilde{G}_M|}\right)Y_{2\gamma}\right]\right\}$$

$$\left(R^{exp}_{Rosenbluth}\right)^2 \doteq \frac{|\tilde{G}_E|^2}{|\tilde{G}_M|^2} + \overbrace{2\left(\tau + \frac{|\tilde{G}_E|}{|\tilde{G}_M|}\right)Y_{2\gamma}}^{\text{Not negligible at high }Q^2}$$

D. Adikaram et al. (CLAS12 TPE)
PRL 114 062003 2015
(unpol: SLAC exp. NE11, Q^2=1.75 GeV^2)



Gramolin et al. arXiv1603.06920
data: SLAC E140 + NE11



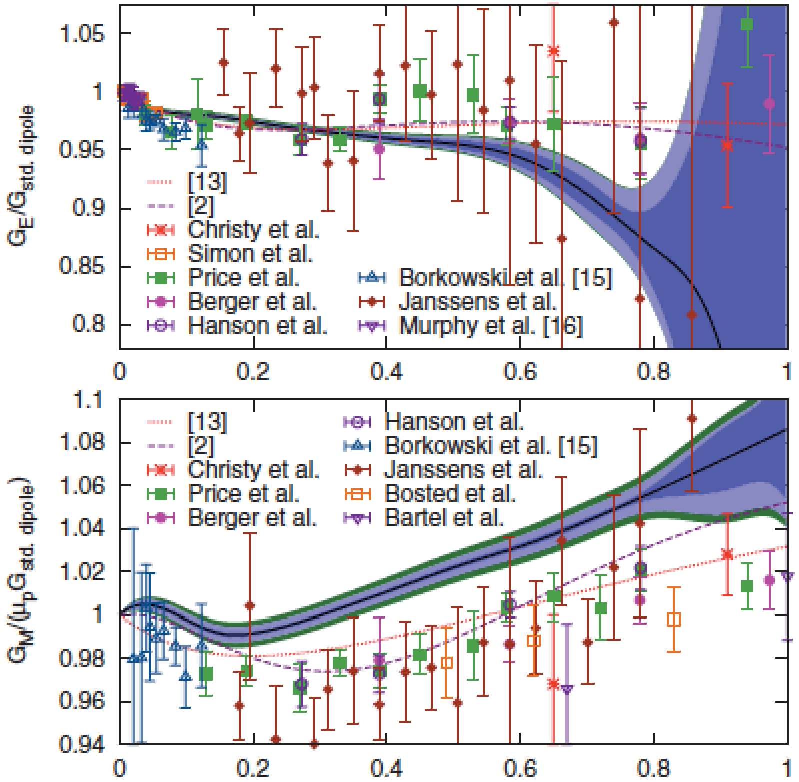
FF at small Q^2: the nucleon E,M radius

Nucleon size (radius) derived from Form Factors (at low Q^2)

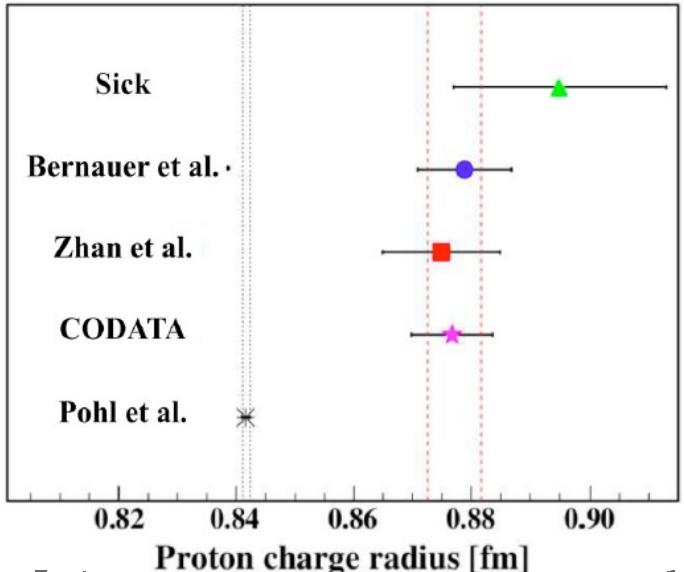
$$G_E^{p,n}(Q^2) = G_E^{p,n}(0) - \frac{1}{6}Q^2\langle r^2\rangle_E^{p,n} + \cdots \Rightarrow \langle r^2\rangle_E^{p,n} = -6\left.\frac{dG_E^{p,n}(Q^2)}{dQ^2}\right|_{Q^2=0}$$

$$G_M^{p,n}(Q^2)/\mu = 1 - \frac{1}{6}Q^2\langle r^2\rangle_M^{p,n} + \cdots$$

(similar for the magnetic radius)



2010 (Pohl et al.): <u>Large disagreement</u> between the proton charge radius from ep scattering/spectroscopy and μp Lamb shift

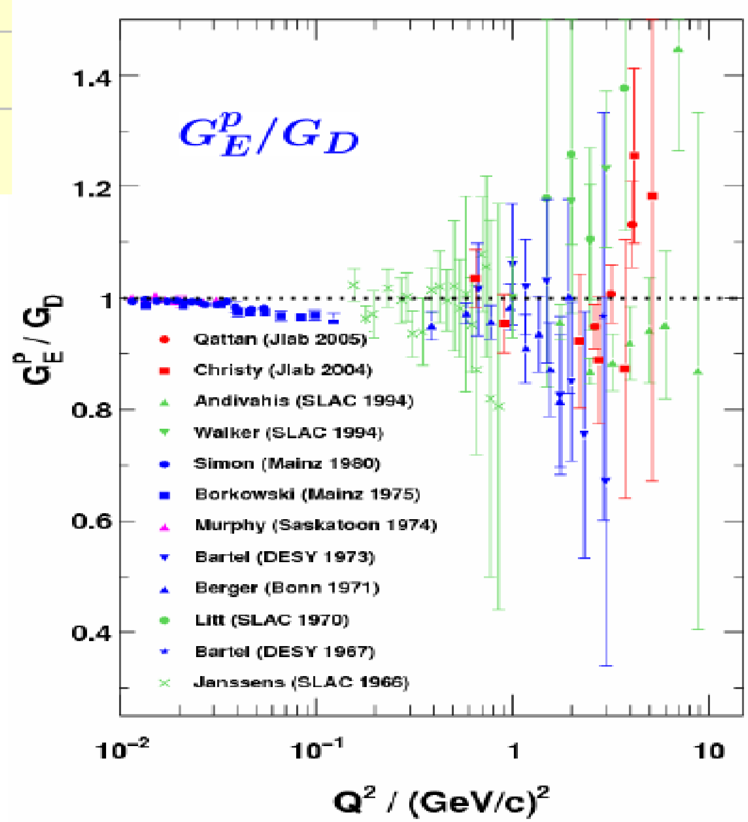


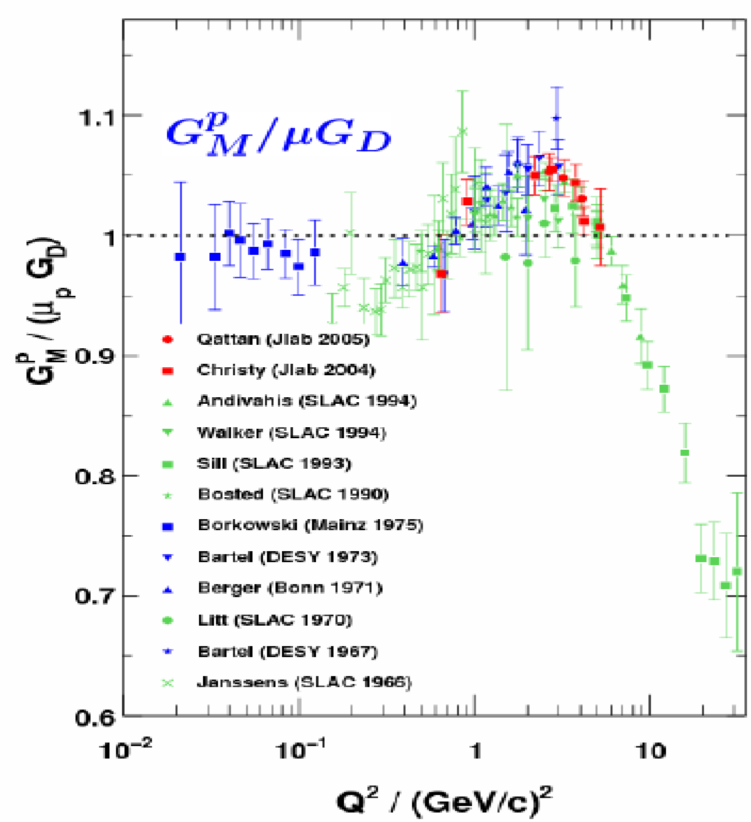
Form Factor Dipole Scaling

«standard» dipole approx. $G_E^p \sim \frac{G_M^p}{|\mu_p|} \sim \frac{G_M^n}{|\mu_n|} \sim G_D(Q^2)$

$Q^2 \to 0$		
G	p	n
E	**1**	**0**
M	μ_p	μ_n

$$G_D(Q^2) = \left[1 + \frac{Q^2}{0.71}\right]^{-2} \qquad G_E^n \sim -\mu_N \frac{a\tau}{1+b\tau} G_D(Q^2)$$

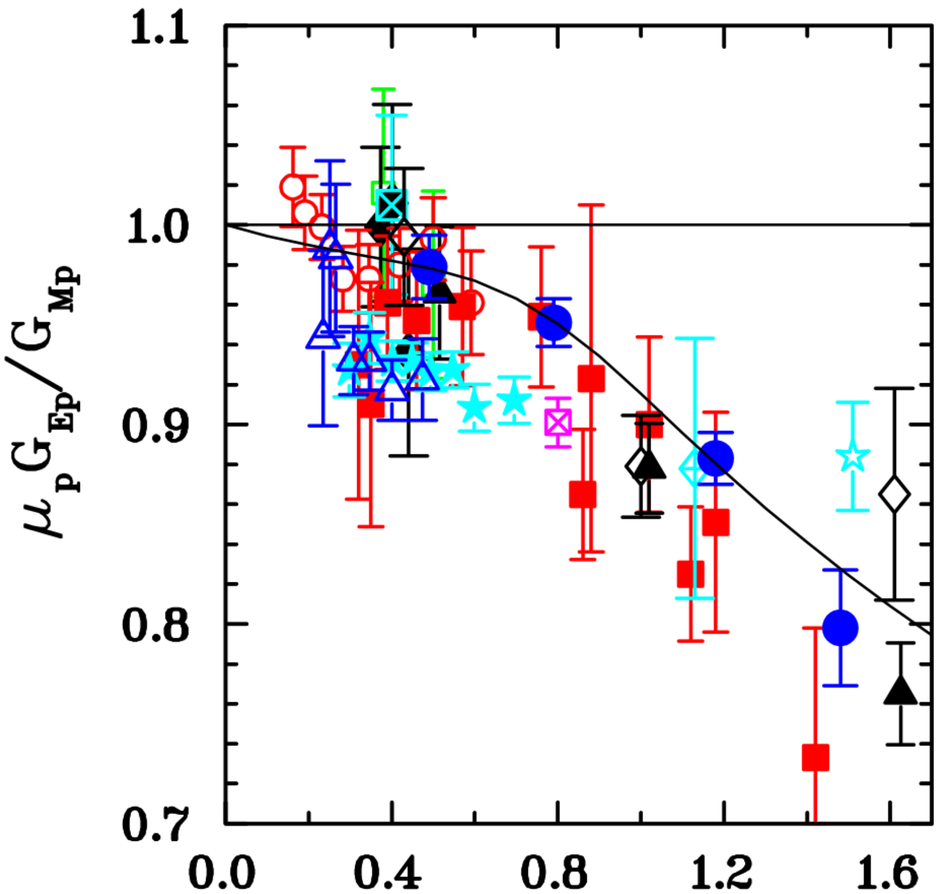


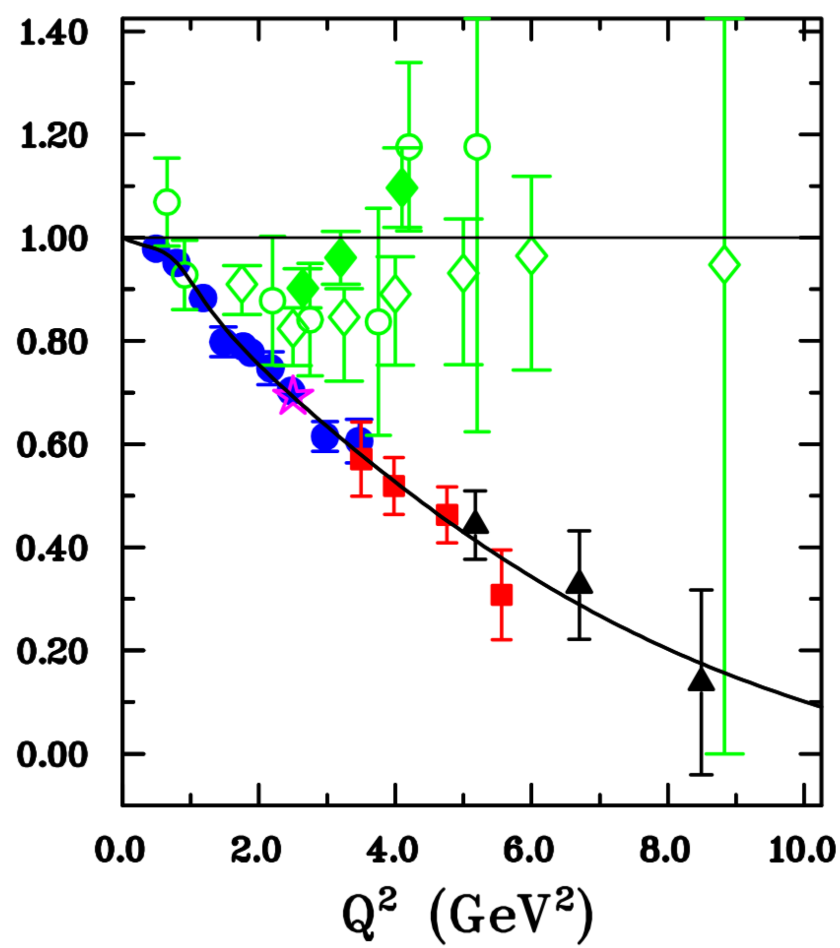


Different variations of the Rosenbluth approach give consistent results

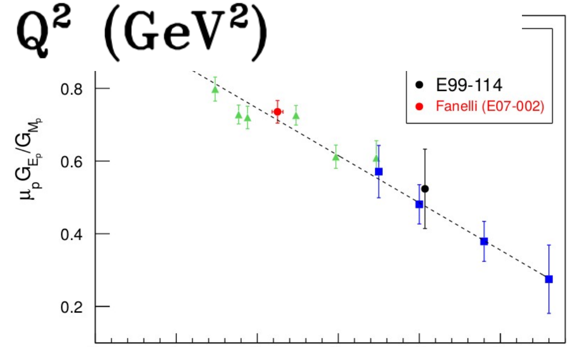
→ exp. systematic under control

“Non Rosenbluth” measurements





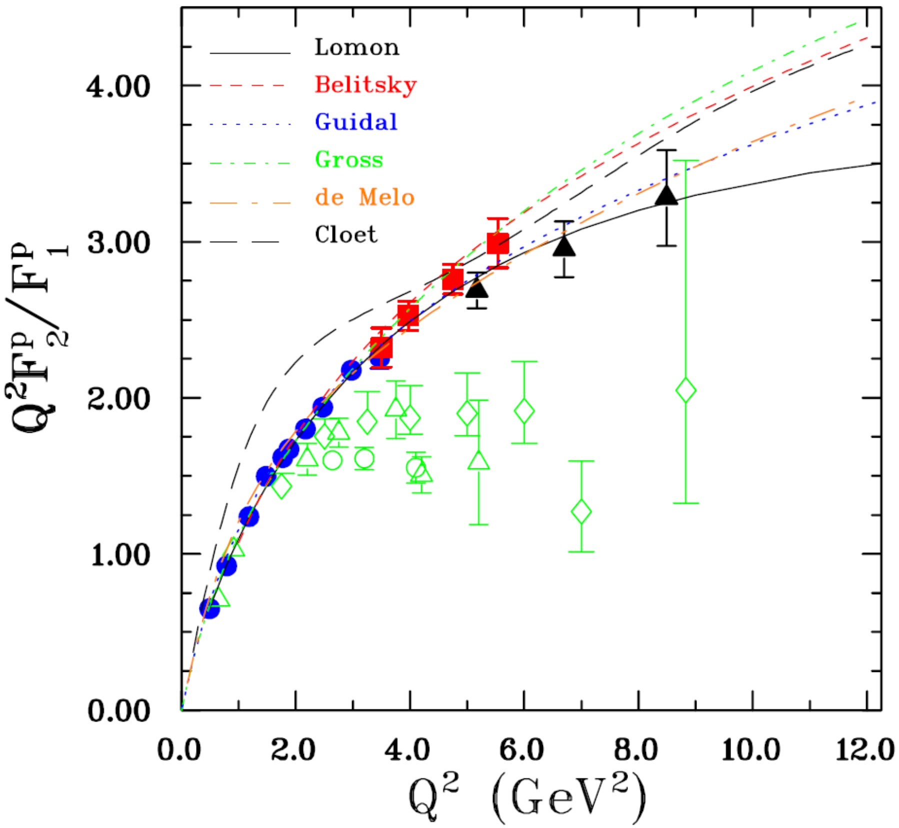
From Punjabi et al (2015) Q^2 (GeV^2)



Red open circle and Cyan open star: beam target asymmetry
Green; Rosenbluth separation data
Magenda Star: GEp(2γ) coll.
Line: poly/poly 7-param. fit

General good agreement between different experiments

Proton F_2/F_1 scaling – pQCD prediction



$$F2/F1 \sim \underbrace{\ln^2(Q^2/\Lambda^2)}_{quark-OAM}/Q^2$$

- Quark Helicity conservation
- Counting rules:
  - $1/Q^2$ for gluon line
  - $1/Q^2$ for helicity flip
- Photon absorbed by one «collinear» quark which interacts with the other two quarks by 2×gluon exchange

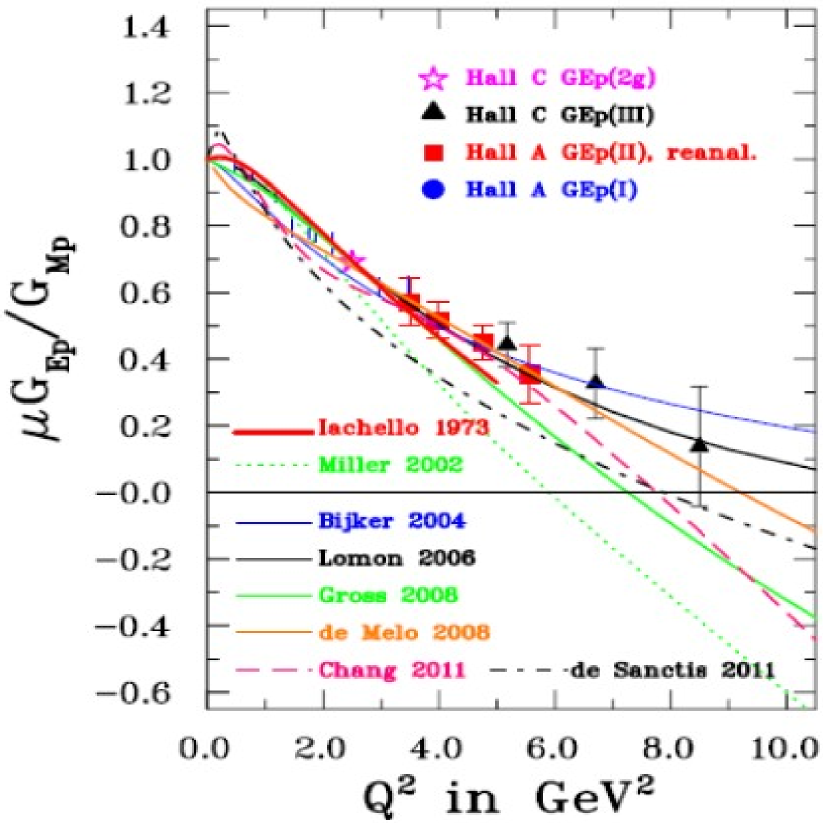
→ $F_1 \sim 1/Q^4$, $F_2 \sim 1/Q^6$

Modified pQCD: Belitsky et al. & other models include quark orbital angular momentum and gluon polarization effects to explain F_2/F_1 at large Q^2

Naive Summary - Why and where are FFs interesting

- Fundamental properties of the nucleon
- Many fundamental models able to calculate them
- Large Q^2:
  - Distinguish important models for GE/GM
  - Scaling behavior (flavor form factors components)
  - Constrain GPD at high x (valence quark dominate)
  - Smaller effective mass of the quarks
  - Toward pQCD dominated regime
- Very Low Q^2:
  - Pion cluod effects
  - Precise nucleon size estimation

SBS original motivations (2007) - Proton G_E/G_M

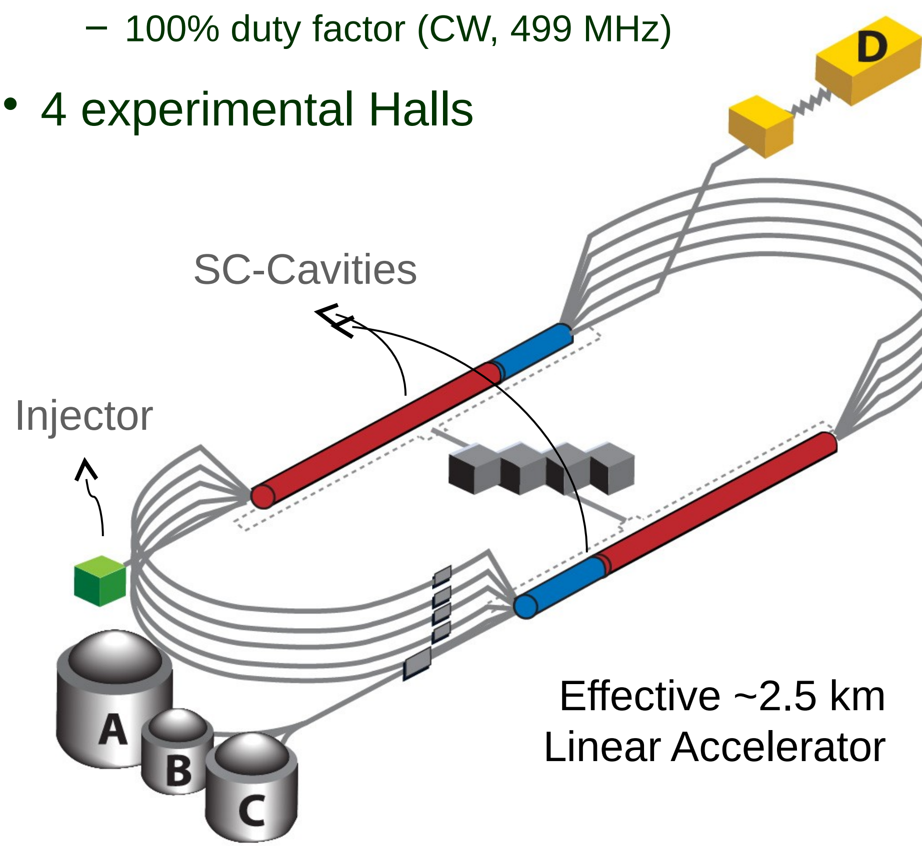


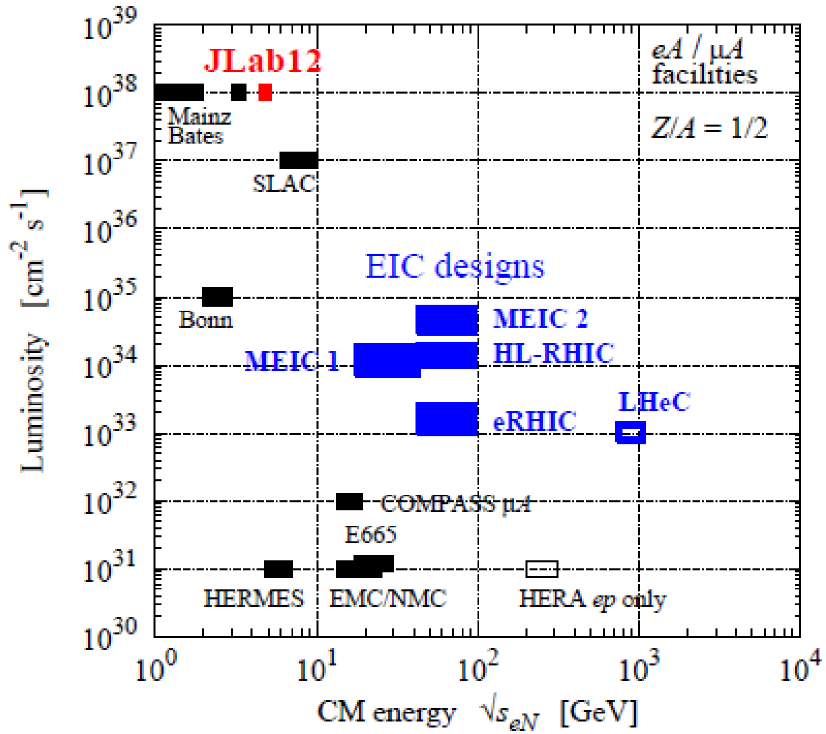
- VMD (Iachello, Lomon, Bijker), generally good description of all FFs
- Relativistic CQM (Miller, Gross, ...) spin dependent quark density
- Lattice QCD, starts to give prediction
- Dyson-Schwinger, dressed quarks, diquark correlation, ...
  - pQCD-based:
    $G_E/G_M \rightarrow \text{const}, Q^2 \rightarrow \infty$
- GPD-based: direct connection to quark OAM, FF's constraint GPD's

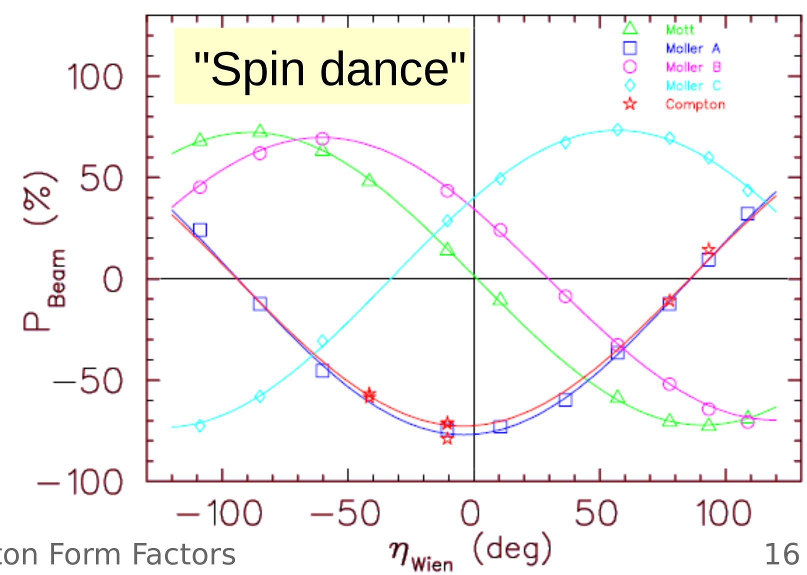
Most of them agree with current data but diverge at higher, unexplored, Q^2

JLab 12 GeV - CEBAF

- Energy up to 12 GeV with $\delta E/E \sim 10^{-4}$
- *Excellent emittance:* ~ few nm-rad
- Long. Polarized Beam ~ 85%
  - (1kHz helicity flip)
- Current up to 100 μA
  - 100% duty factor (CW, 499 MHz)
- 4 experimental Halls

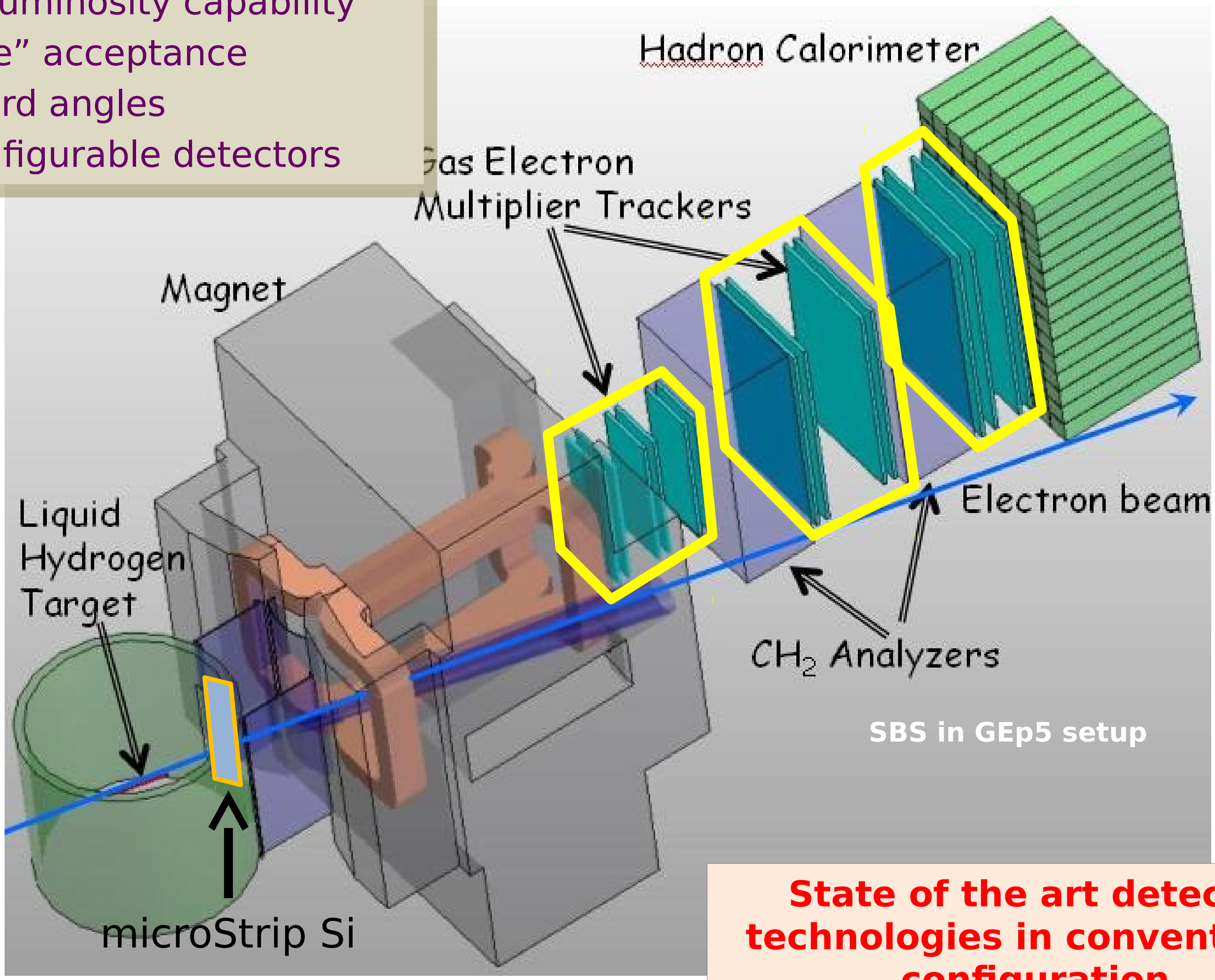






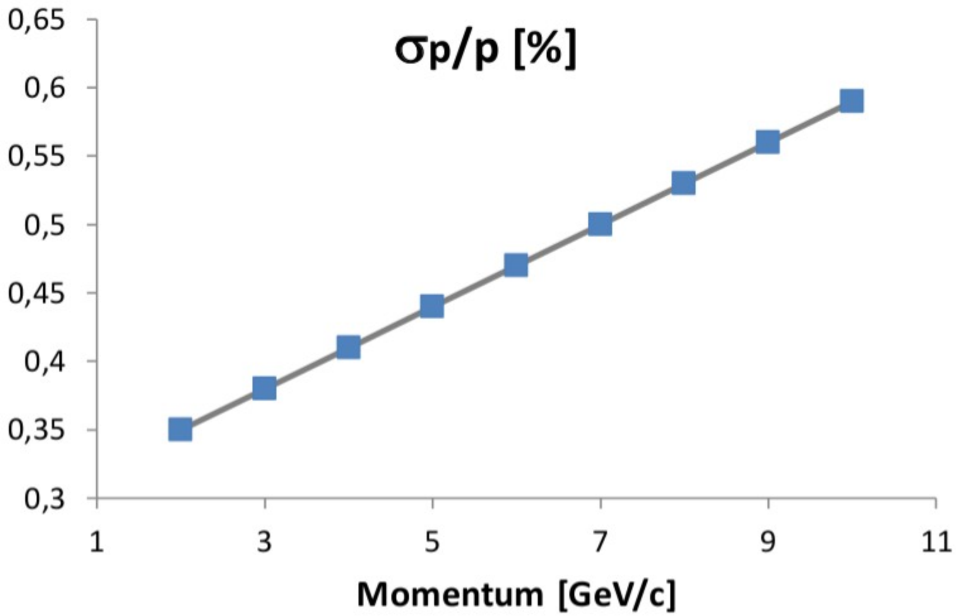
New SuperBigbite Spectrometer (SBS) in Hall A

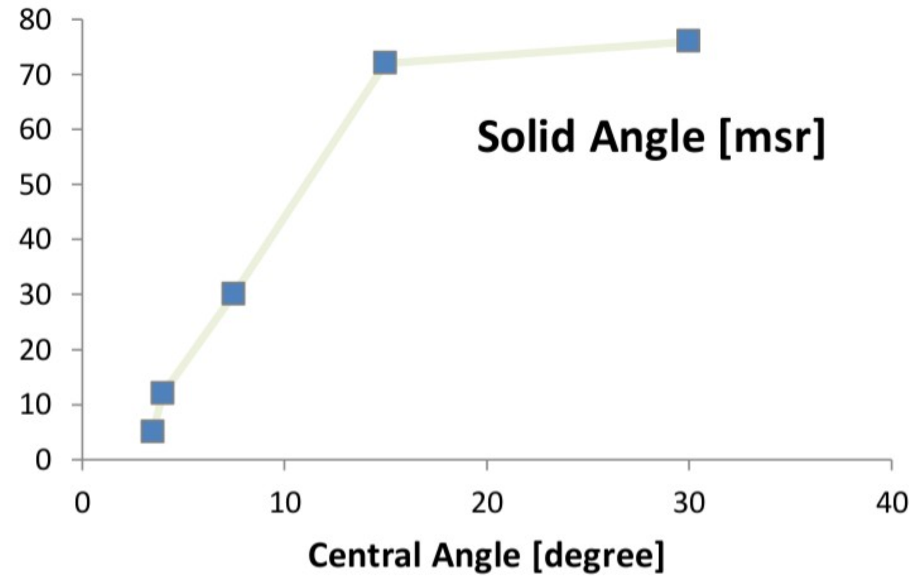
- High luminosity capability
- “Large” acceptance
- Forward angles
- Reconfigurable detectors

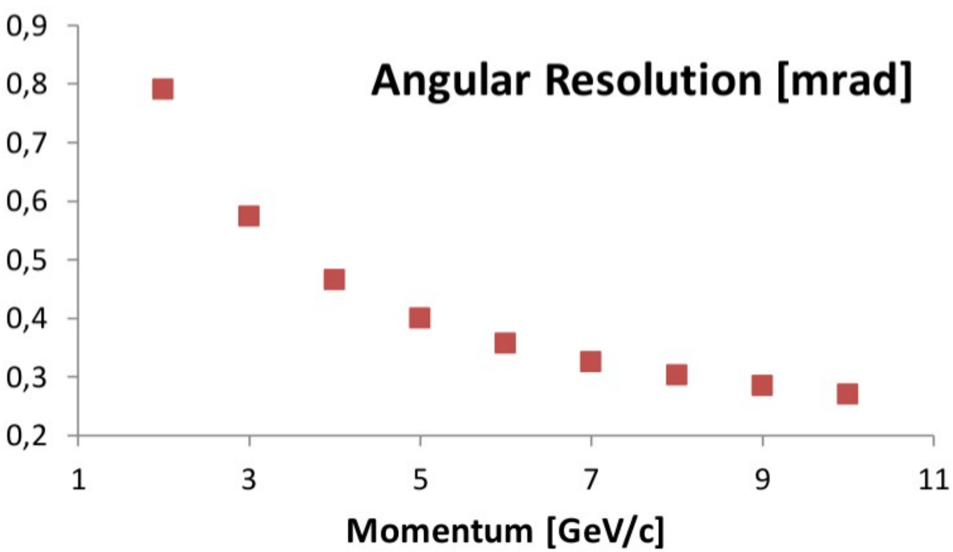


State of the art detector technologies in conventional configuration

SBS specifications (fully configured)







Momentum Acceptance optimized in 2-10 GeV/c

Vertex resolution: <2 mm

EMFF measurements at high Q^2 by pol. methods

Method:	Polarization Transfer: $p(\vec{e}, e'\vec{p})$	Target Perp. Polarization: $p^{\uparrow}(\vec{e}, e'p)$
Measure (one photon approx.)	$$\frac{P_t}{P_l}\tan\left(\frac{\theta}{2}\right) \propto \frac{G_E^p}{G_M^p}$$ P_t, P_l : trans. and long. polarization of the recoil proton	$$A = \frac{N^+ - N^-}{N^+ + N^-} \sim \frac{G_E^p}{G_M^p}$$ N^+ and N^- : events with opposite transverse target polarization
Many systematics effects (theory and exp.) cancel in ratio		
Figure of Merit (stat.) Ω: acceptace L: Luminosity σ: elastic xsec $\sim E^2/Q^{12}$ Pb: beam polarization	$$\Omega\, L\, \sigma\, P_b^2\, \epsilon\, A_y^2$$ $$\sim \frac{\boldsymbol{\Omega\, L\, \epsilon}}{\mathbf{Q^{16}}}$$ A_y: polarimeter analyzing power ϵ: polarimeter efficiency	$$\Omega\, L\, \sigma\, P_b^2\, P_T^2$$ $$\sim \frac{\boldsymbol{\Omega\, L}}{\mathbf{Q^{12}}}\mathbf{P_T^2}$$ P_T : Target polarization
At $Q^2 \sim 10$ GeV^2 expected: $\text{FoM}_{pol\_trans} \sim 10 \times \text{FoM}_{targ\_pol}$ (target polarization cannot tolerate large L)		

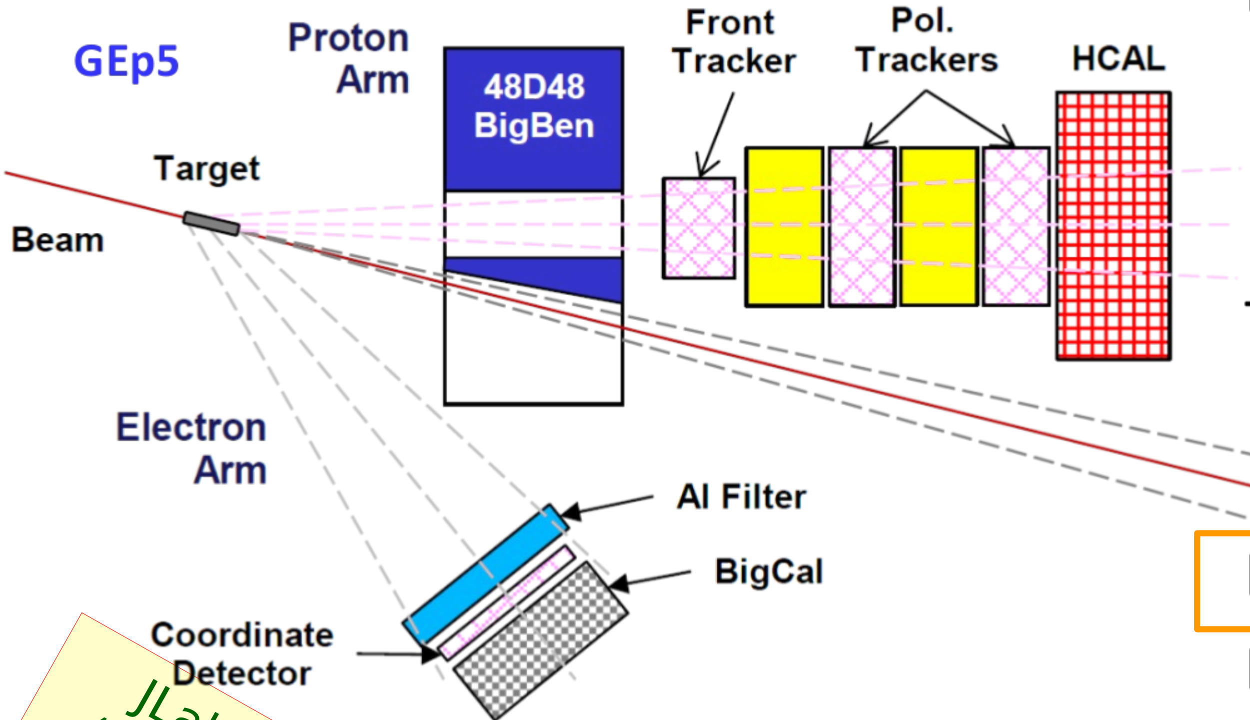
Challenges at high Q^2: need to maximize

- **(coincidence) acceptance (solid angle)**
- **luminosity**
- polarimetry efficiency
- beam polarization

(... having the needed beam energy)

... keeping costs at «affordable» level

Proton G_E/G_M at large Q^2 by polarization transfer



JLab/PAC41: "High Impact" Experiment

Beam:

- **Current= 75 mA,**
- **Polarization= 85% long.**
- **Energy= 6, 8 and 11 GeV**

Target:

- **H_2 Liquid**
- **Length= 40 cm**

Luminosity = $8 \cdot 10^{38}$

Detectors:

- **P-arm: SBS + Polarimeter**
- **E-arm: BigCal + Coordinate**

GOAL: Extend the measurement of the proton form factor ratio G_E/G_M to the maximum Q^2 that is possible with 11 GeV beam with constraints:

Absolute error < 0.1 Beam time = 60 days

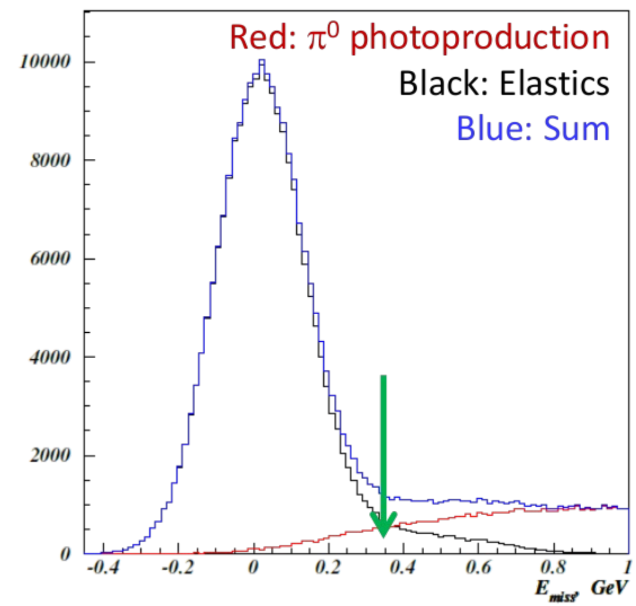
Large Luminosity ⇨ Large Background

Tracker	Area of interest for tracking, cm^2	Hit Rate, kHz/cm^2
First	0.20 x 18	400
Second	$2\pi\ 0.35^2$	130
Third	$\pi\ 4.8^2$	64
BigCal	$\pi\ 1.2^2$	173

$L \sim 10^{39}\ /cm^2/s$

- Must be supported by the detectors ⇨ GEM technology
- Must be handled by the trigger:
  - spatial and time correlation between electron and proton elastically scattered
  - «high» energy threshold in segmented CALO's

Good tracking resolution needed
- momentum resolution: 1 %
- angular resolution: 1 mrad
- vertex reconstruction: 5 mm



For E_{miss}<0.35 GeV, remaining π^0 background: ≤10%

Adequate proton polarization precession reconstruction (next slide)

GEp5: Proton Polarimeter (PP)

$$\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{E+E'}{2M}\tan\frac{\theta}{2}\left[1+(\text{few }\%)_{2\gamma}\right]$$

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

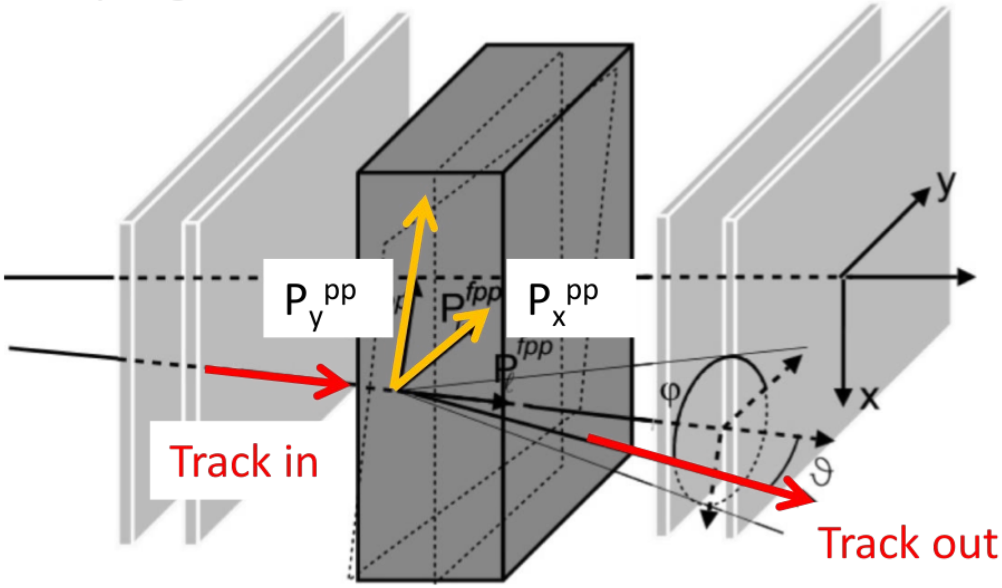
Number of scattered protons:

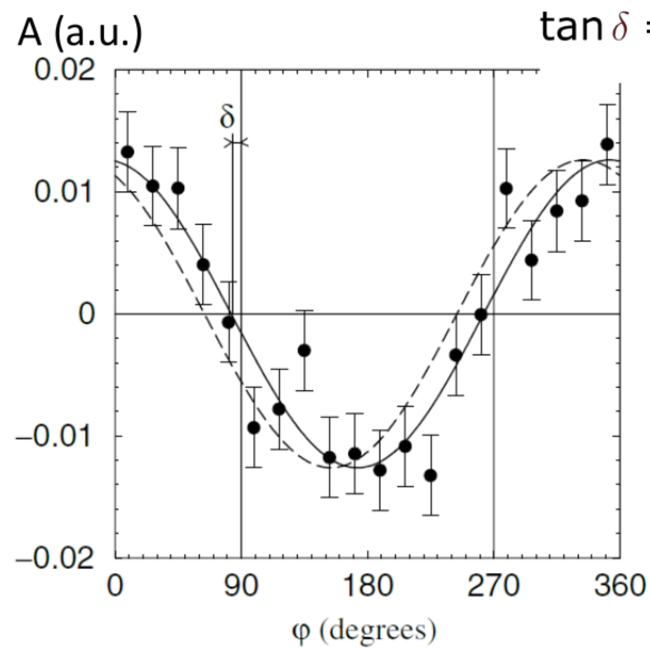
$$f^{\pm}(\vartheta,\varphi) = \frac{\epsilon^{pp}(\vartheta,\varphi)}{2\pi}\left[1 \pm A_y\left(P_x^{pp}\sin\varphi + P_y^{pp}\cos\varphi\right)\right]$$

where $\pm$ refers to electron beam helicity

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

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





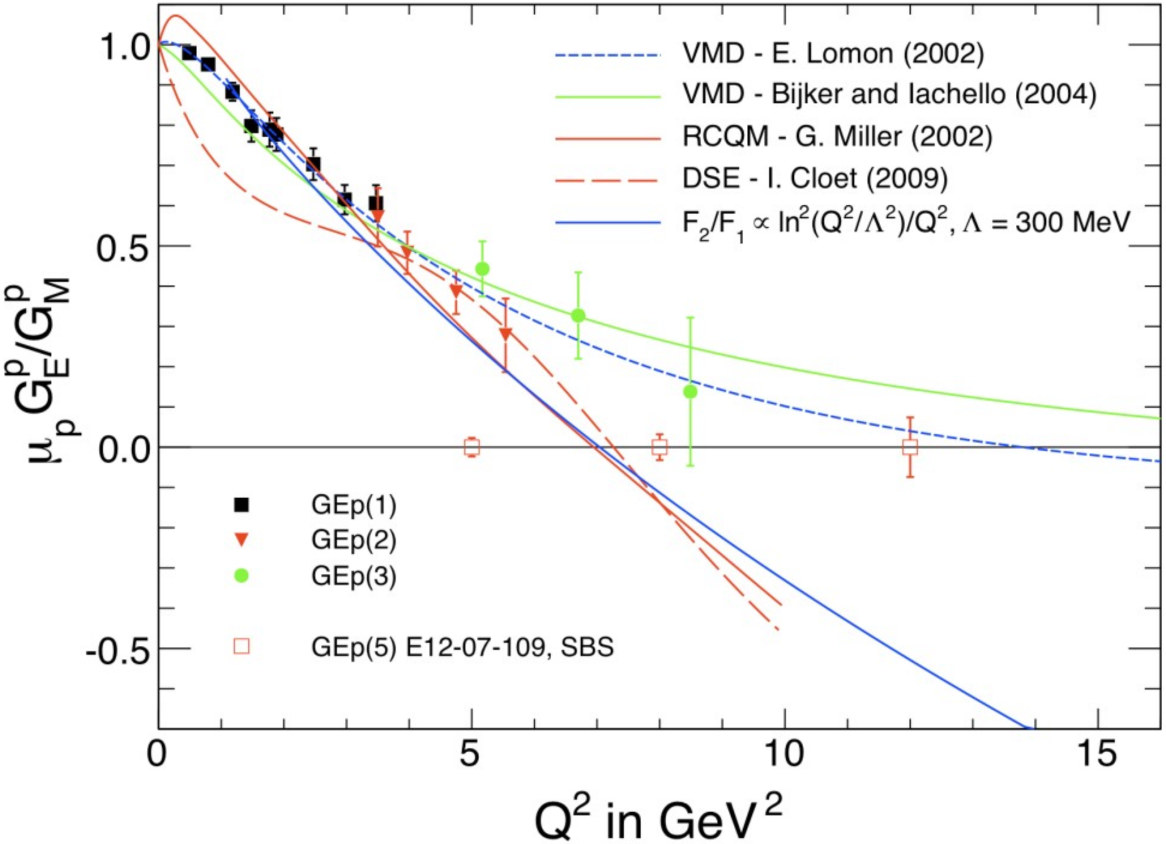
Polarimeter only measures components of proton spin that are **transverse** to the proton's momentum direction

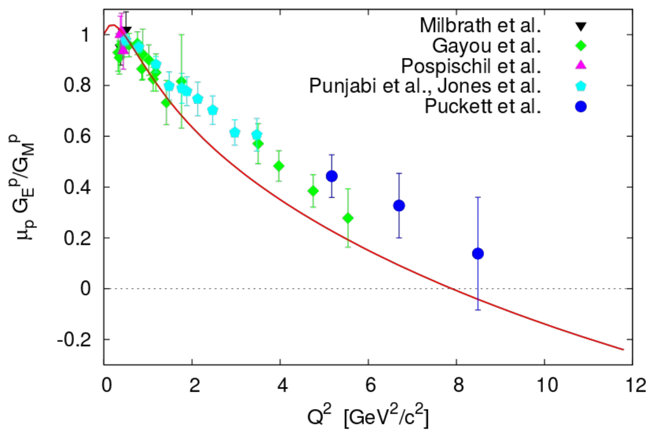
$\sigma_{P^{pp}_{x,y}} \sim \sqrt{2}/(A\cdot P_e\cdot\sqrt{N})$ ➡ Maximize P_e

N=number of scattered proton, P_e beam polarization

➡ Require: Dipole magnet to precess P_l at target to P_y^{pp}

GEp5 Projected results





red curve: M. De Sanctis, et al. Phys. Rev. C84(2011) 055201 (quark-diquark - RCQM)

Kinematics and expected accuracy			
E (GeV)	Q^2 (GeV^2)	Days	$\Delta\mu G_E/G_M$
6.6	5.0	1	0.023
8.8	8.0	10	0.032
11.0	12.0	30	0.074

Significant discovery potential:

- Settle the question of a zero crossing of GEp/GMp
- Constrain GPDs at high x, large t

New software tools may improve analysis

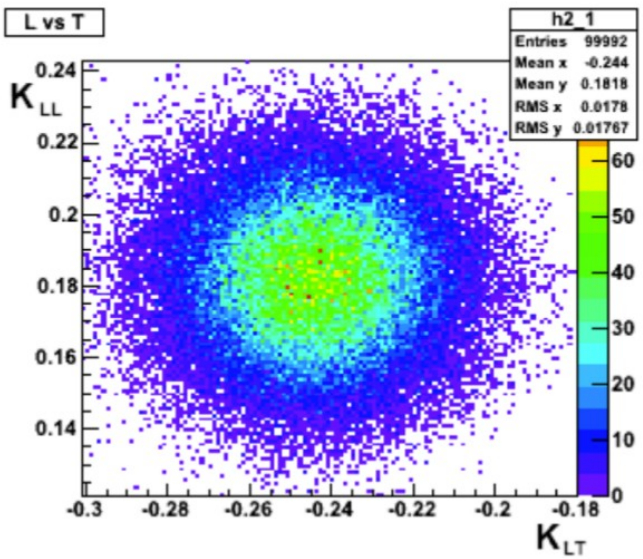
from C. Fanelli (ECT* 2015)

A Markov chain Monte Carlo has been used to extract the polarization transfers from the Likelihood:

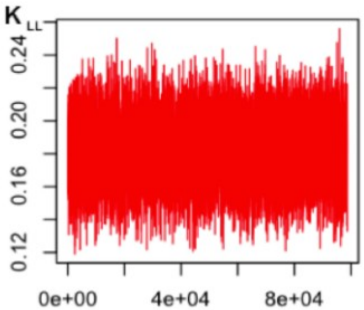
$$\mathcal{L}(\mathbf{P}) = \prod_{i=1}^{N_{evt}} \frac{1}{2\pi}[1 + (a_1 + h\epsilon^{(i)} A_y^{(i)} \sum_{j=x,z} S_{yj}^{(i)} P_j + A_y^{(i)} S_{yy}^{(i)} P_y) \cos\varphi^{(i)} +$$

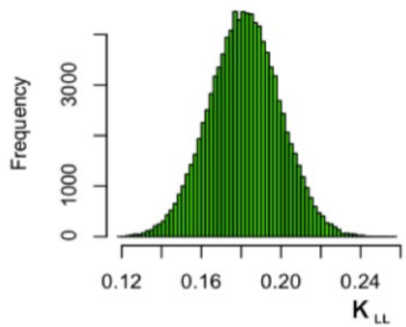
$$+(b_1 - h\epsilon^{(i)} A_y^{(i)} \sum_{j=x,z} S_{xj}^{(i)} P_j - A_y^{(i)} S_{xy}^{(i)} P_y) \sin\varphi^{(i)} +$$

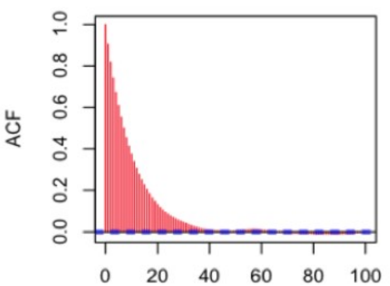
$$+a_2 \cos 2\varphi^{(i)} + b_2 \sin 2\varphi^{(i)} + \cdots]$$



$P_z(= K_{LL})$ vs $P_x(= K_{LT})$







New software tools may improve analysis

- Likelihood function from azimuthal asymmetry, event by event observed quantities
- Bayesian MCMC (uniform priors distribution)
- Estimate posterior distribution functions of polarization transfer
- Pro's
  - global picture
  - search max. no approximation
  - ad hoc priors could improve uncertainties

Similar approaches in:
N. Sato/ECT* 2016 for PDFs extraction
Super Rosenbluth Separation - J. C. Bernauer 2010

GMp in JLab/HallA (E12-07-108) at high momentum transfer

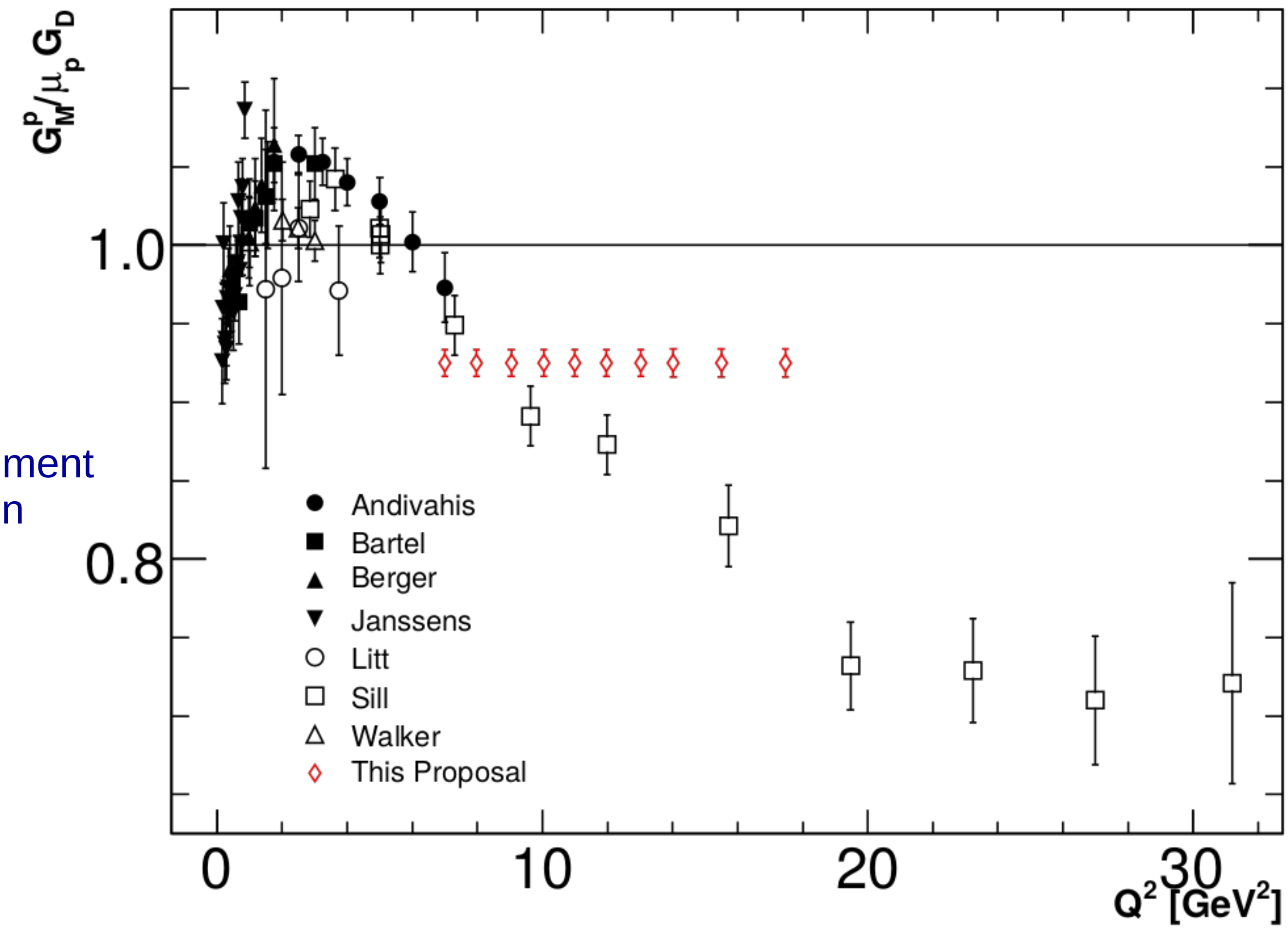
Measure proton elastic cross section at $Q^2 \sim 7 - 17.5\ GeV^2$ with high statistical precision

Keep systematics under control (beam energy, target density, scattering angle)

Use standard HRS spectrometers in JLab HallA:

- "commissioning" experiment for the 12 GeV transition

status: running



Kinematics at smaller ε respect to existing SLAC data: GEp contributions smaller

TPE still affecting the GMp extraction, but not the elastic cross section measurements

Lepton – Nucleon Scattering

as a probe of QCD

$\sigma \sim$ QED $\otimes$ QCD

Asymptotic Freedom

Confinement

Small Distance
High Energy

“Large” Distance
Low Energy

← JLab →

Perturbative QCD
DIS Scattering
Parton models

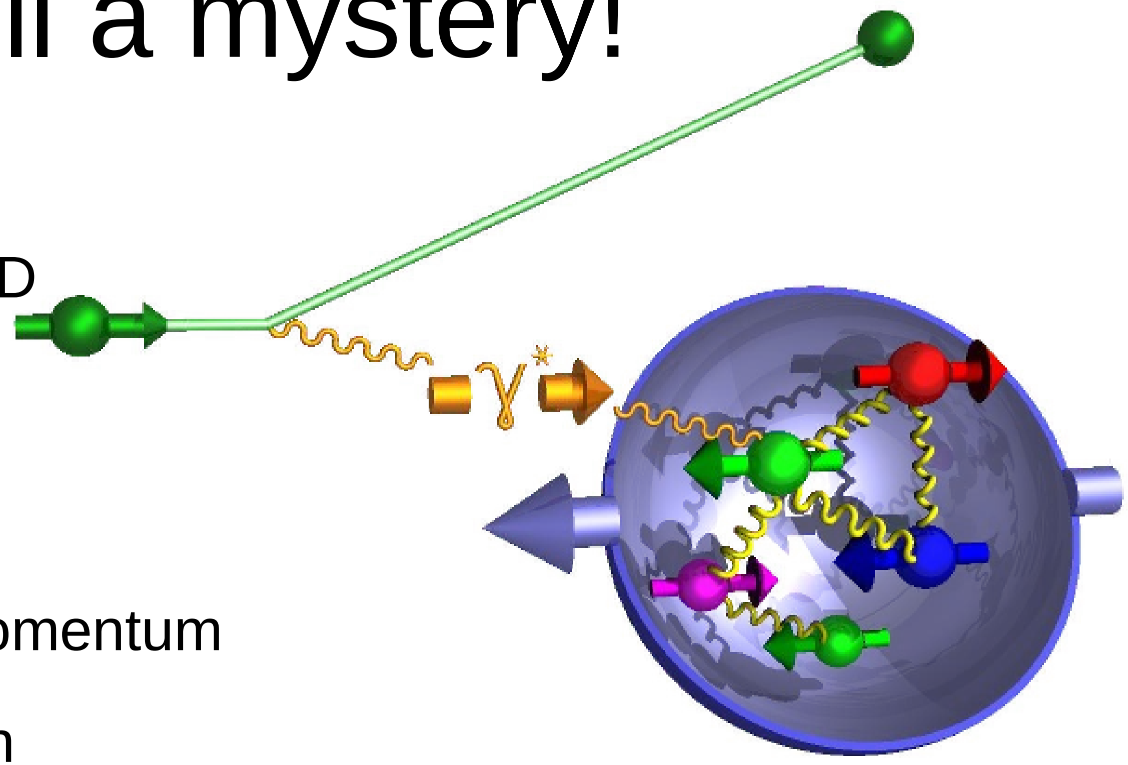
Strong QCD
Spectroscopy
Phenomenological Models

… but higher QED corrections are coupled to nucleon internal structure:

the probe gets correlated to the investigated sample!

Nucleon, still a mystery!

- Mass origin
  - Confinement / QCD
  - Internal dynamics
- Spin origin
  - Orbital Angular Momentum
  - Gluon Contribution
- (Proton) radius
- QED-QCD reaction mechanisms



sample image show
(actual product may vary)

Current experimental programs on FF, GPD, TMD, QCD spectroscopy … (thanks to technological progresses in Lumi, Polarization, Coherent Light production …) & theoretical developments

are going to offer real chance to shed light on this mystery