Theoretical and experimental review on Nucleon Form Factors

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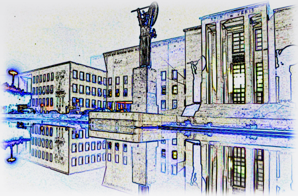

PHI PSI 13

9th - 12th September 2013
Dipartimento di Fisica
Università "La Sapienza", Roma

Agenda

- Space-like region: definitions and data
- Rosenbluth/Polarization conflict(?)
- Time-like region: definitions, data and more
- The ratio G_E^p / G_M^p
- Proton form factor at threshold

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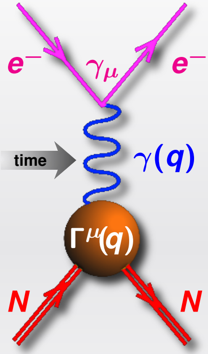
Nucleon Form Factors definition
Space-like region ($q^2 < 0$)



- **Electromagnetic current** ($q = p' - p$)

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

- **Dirac and Pauli form factors F_1 and F_2 are real**
- **In the Breit frame**

$$\begin{cases} p = (E, -\vec{q}/2) \\ p' = (E, \vec{q}/2) \\ q = (0, \vec{q}) \end{cases} \qquad \begin{cases} \rho_q = J^0 = e\left[F_1 + \frac{q^2}{4M^2}F_2\right] \\ \vec{J}_q = e\,\bar{u}(p')\vec{\gamma}u(p)\,[F_1 + F_2] \end{cases}$$

- $2M\bar{u}(p')\gamma^\mu u(p) = \bar{u}(p')[(p+p')^\mu + i\sigma^{\mu\nu}q_\nu]u(p)$
- $\bar{u}(-\vec{p})u(\vec{p}) = E/M$
- $u^\dagger(-\vec{p})u(\vec{p}) = 1$

- **Sachs form factors**

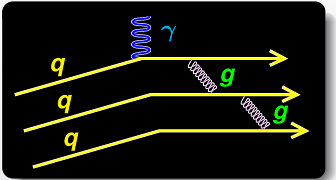
$$G_E = F_1 + \frac{q^2}{4M^2}F_2$$
$$G_M = F_1 + F_2$$

- **Normalizations**

$$F_1(0) = Q_N \qquad G_E(0) = Q_N$$
$$F_2(0) = \kappa_N \qquad G_M(0) = \mu_N$$

pQCD asymptotic behavior
Space-like region

Lett. Nuovo Cim. 7 (1973) 719
Phys. Rev. Lett. 31 (1973) 1153
JETP Lett. 96 (2012) 6-12



- **pQCD**: as $q^2 \to -\infty$, asymptotic behaviors of F_1 and F_2, and G_E and G_M must follow counting rules
- Valence quarks exchange gluons to distribute the momentum transfer q

Non-helicity-flip current $J^{\lambda,\lambda}(q^2)$

- $J^{\lambda,\lambda}(q^2) \propto G_M(q^2)$
- Two gluon propagators
- $G_M(q^2) \underset{q^2 \to -\infty}{\sim} (-q^2)^{-2}$

Helicity-flip $J^{\lambda,-\lambda}(q^2)$

- $J^{\lambda,-\lambda}(q^2) \propto G_E(q^2)/\sqrt{-q^2}$
- Two gluon propagators $/\sqrt{-q^2}$
- $G_E(q^2) \underset{q^2 \to -\infty}{\sim} (-q^2)^{-2}$

Ratio of Sachs form factors

- Ratio: $\dfrac{G_E}{G_M} \underset{q^2 \to -\infty}{\sim}$ constant

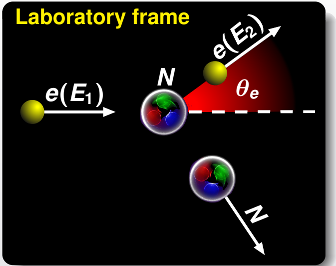
Dirac and Pauli form factors

- $F_1(q^2) \underset{q^2 \to -\infty}{\sim} (-q^2)^{-2}$
- $F_2(q^2) \underset{q^2 \to -\infty}{\sim} (-q^2)^{-3}$

Space-like data

Rosenbluth separation

Phys. Rev. 79 (1950) 615



Rosenbluth formula

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \frac{1}{1-\tau}\left[G_E^2 - \frac{\tau}{\epsilon} G_M^2\right] \qquad \tau = \frac{q^2}{4M_N^2}$$

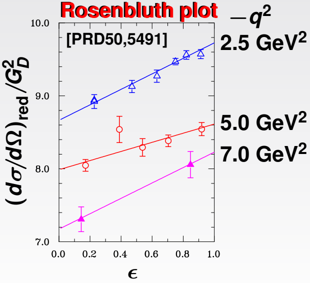
- Mott pointlike cross section

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{4\alpha^2}{(-q^2)^2}\frac{E_2^3}{E_1}\cos^2(\theta_e/2)$$

- Photon polarization

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

Rosenbluth plot



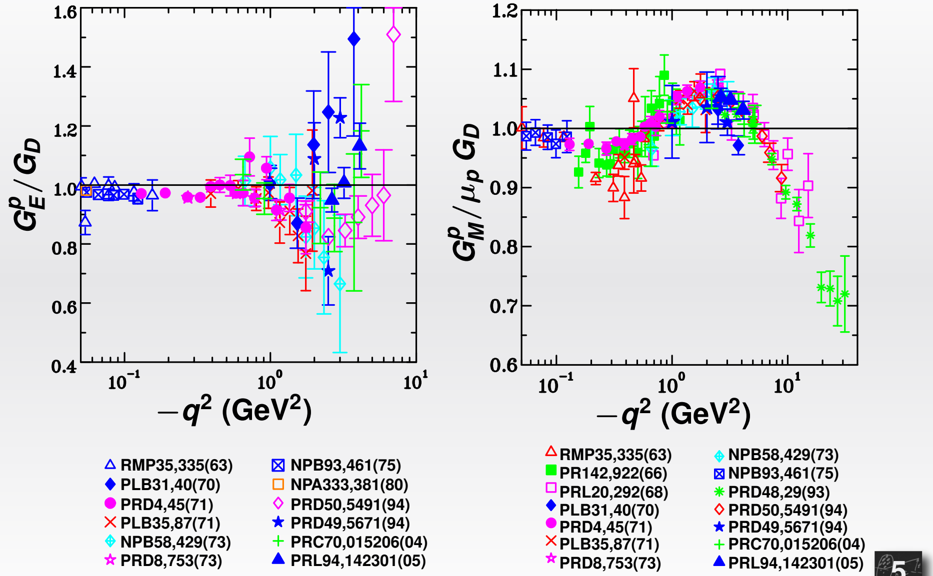
Reduced cross section

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{red}} = \frac{\epsilon(\tau-1)}{\tau}\frac{(d\sigma/d\Omega)_{\text{exp}}}{(d\sigma/d\Omega)_{\text{Mott}}} = G_M^2 - \frac{\epsilon}{\tau}G_E^2$$

- $(d\sigma/d\Omega)_{\text{red}}\,(\epsilon)$ slope $\longrightarrow G_E$
- $(d\sigma/d\Omega)_{\text{red}}\,(\epsilon)$ intercept $\longrightarrow G_M$

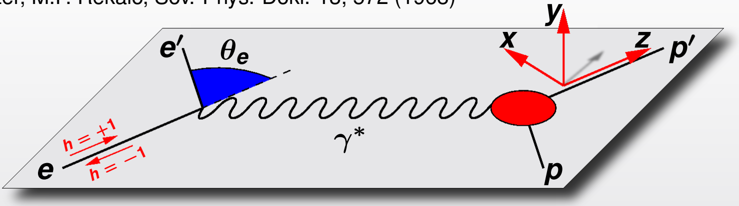
Dipole form: $G_D(q^2) = \left(1 - q^2/0.71\text{GeV}^2\right)^{-2}$

G_E^p and G_M^p with Rosenbluth separation



Polarization observables

A.I. Akhiezer, M.P. Rekalo, Sov. Phys. Dokl. 13, 572 (1968)

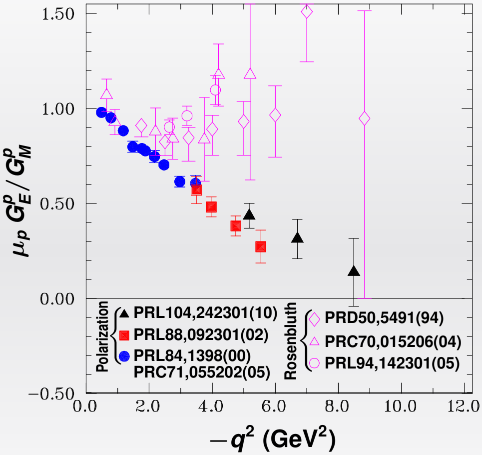


- Elastic scattering of **longitudinally polarized electrons** ($h = \pm 1$) on nucleon target
- Hadronic tensor: $W_{\mu\nu} = \underbrace{W_{\mu\nu}(0)}_{\text{no pol.}} + \underbrace{W_{\mu\nu}(\vec{P}) + W_{\mu\nu}(\vec{P}')}_{\text{ini. or fin. pol. of } N} + \underbrace{W_{\mu\nu}(\vec{P}, \vec{P}')}_{\text{ini. and fin. pol. of } N}$
- In case of **polarized electrons** ($h = \pm 1$) on **unpolarized nucleon** target:

$$P'_x = -\frac{2\sqrt{\tau(\tau-1)}}{G_E^2 - \frac{\tau}{\epsilon} G_M^2} G_E G_M \tan\left(\frac{\theta_e}{2}\right) \qquad P'_z = \frac{(E_e + E'_e)\sqrt{\tau(\tau-1)}}{M\left(G_E^2 - \frac{\tau}{\epsilon} G_M^2\right)} G_M^2 \tan^2\left(\frac{\theta_e}{2}\right)$$

$$\frac{P'_x}{P'_z} = -\frac{2M\cot(\theta_e/2)}{E_e + E'_e} \frac{G_E}{G_M}$$

G_E^p / G_M^p in polarization transfer experiments



- Polarization data do not agree with old Rosenbluth data (◊)
- New Rosenbluth data (△, ○) from JLab still do not agree with polarization data

Radiative corrections in Rosenbluth separation

Phys. Rev. D50 (1994) 5491

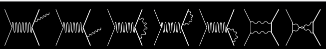
Sachs form factors G_E and G_M are extracted from Born cross sections (one-γ exchange)

The Born term is obtained from experimental cross sections correcting for radiative effects

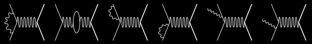
$$\frac{d\sigma^{exp}}{d\Omega} = \left[1+\delta(\epsilon)\right]\frac{d\sigma^{Born}}{d\Omega}$$

δ contributions

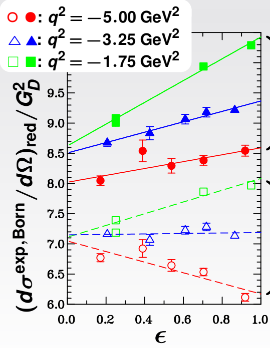
- proton side

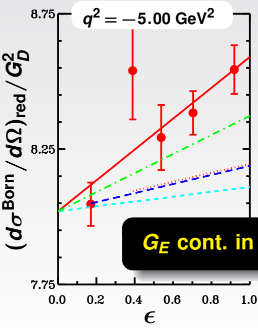


- Apparatus corrections
- electron side



An example

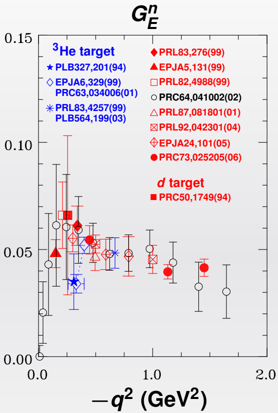


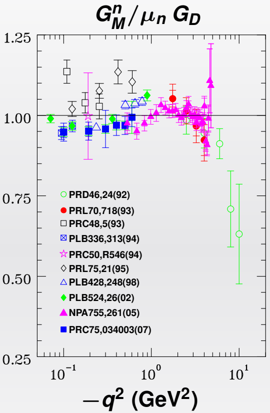


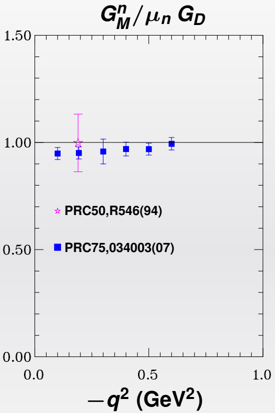
- Virtual Compton Scattering PRC62,025501(00)
- Two-photon with GPD PRD72,013008(05)
- Structure functions RC PRC75,015207(07)
- Polarization data

G_E cont. in $\left(\frac{d\sigma^{Born}}{d\Omega}\right)_{red} < 1\%$

G_E^n and G_M^n with different techniques





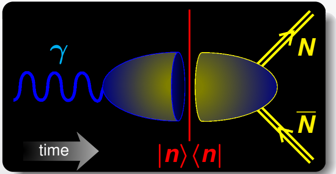


- Elastic *e-d* cross section
- Polarization observables in electron scattering with ^{2}H and ^{3}He targets

- Quasi-elastic *e-d* / elastic *e-p* cross sections
- Polarization observables in electron scattering on a polarized $^3\vec{\text{He}}$ target

Time-like region

Nucleon form factors
Time-like region ($q^2 > 0$)



- **Crossing symmetry**:

$$\langle N(p')|j^\mu|N(p)\rangle \to \langle \overline{N}(p')N(p)|j^\mu|0\rangle$$

- **Form factors are complex functions of q^2**

Optical theorem

$$\mathrm{Im}\langle \overline{N}(p')N(p)|j^\mu|0\rangle \sim \sum_n \langle \overline{N}(p')N(p)|j^\mu|n\rangle\langle n|j^\mu|0\rangle \implies \left\{ \begin{array}{l} \mathrm{Im}F_{1,2} \neq 0 \\ \text{for } q^2 > 4M_\pi^2 \end{array} \right.$$

$|n\rangle$ are on-shell intermediate states: 2π, 3π, 4π, ...

Time-like asymptotic behavior

Phragmèn Lindelöf theorem: If $f(z) \to a$ as $z \to \infty$ along a straight line, and $f(z) \to b$ as $z \to \infty$ along another straight line, and $f(z)$ is regular and bounded in the angle between, then $a = b$ and $f(z) \to a$ **uniformly in this angle**.

- $$\underbrace{\lim_{q^2 \to -\infty} G_{E,M}(q^2)}_{\text{space-like}} = \underbrace{\lim_{q^2 \to +\infty} G_{E,M}(q^2)}_{\text{time-like}}$$

- $$G_{E,M} \underset{q^2 \to +\infty}{\sim} (q^2)^{-2}$$ **real**

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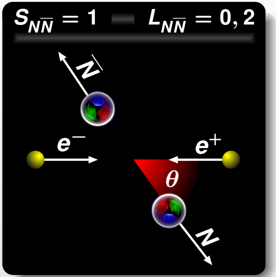
Cross section and analyticity

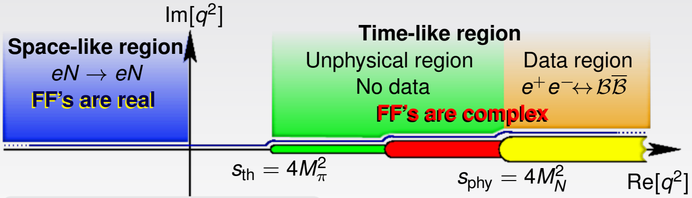


Annihilation cross section formula

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta \mathcal{C}}{4q^2} \left[(1+\cos^2\theta)|G_M|^2 + \frac{1}{\tau}\sin^2\theta |G_E|^2 \right]$$

- Outgoing nucleon velocity: $\beta = \sqrt{1 - 1/\tau}$
- Coulomb correction: $\mathcal{C} = \dfrac{\pi\alpha/\beta}{1 - \exp(-\pi\alpha/\beta)}$

q^2-complex plane

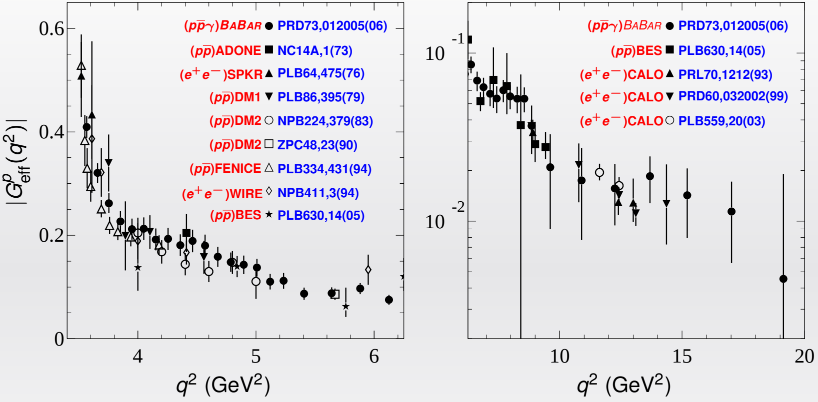


Hadronic helicity $= \begin{cases} 1 \Rightarrow G_E \\ 0 \Rightarrow G_M \end{cases}$

Only S-wave at threshold

$G_E(4M_N^2) = G_M(4M_N^2)$

Time-like magnetic proton form factor



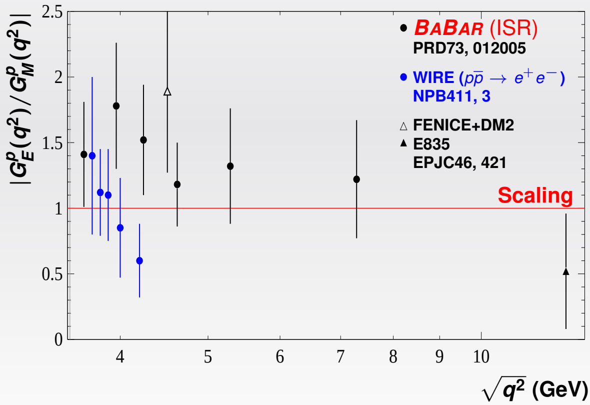
Data obtained with $|G^p_M| = |G^p_E| \equiv |G^p_{\rm eff}|$ (assumed true only at threshold)

$$|G^p_{\rm eff}|^2 = \frac{\sigma_{p\bar{p}}(q^2)}{\frac{16\pi\alpha^2\mathcal{C}}{3}\,\frac{\sqrt{1-1/\tau}}{4q^2}\left(1+\frac{1}{2\tau}\right)}$$

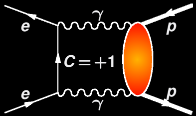
Time-like $|G_E^p/G_M^p|$ measurements

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2\beta C}{2q^2}|G_M^p|^2\left[(1+\cos^2\theta)+\frac{4M_p^2}{q^2\mu_p^2}\sin^2\theta|R|^2\right]$$

$$R(q^2) = \mu_p \frac{G_E^p(q^2)}{G_M^p(q^2)}$$



$\gamma\gamma$ exchange

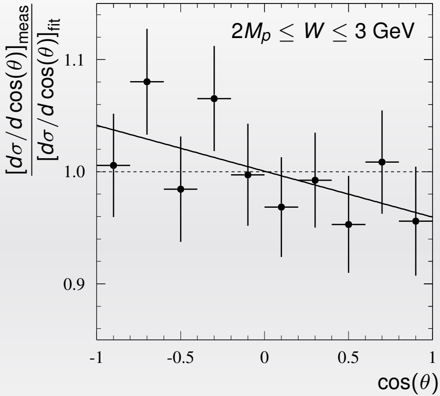


$\gamma\gamma$ exchange interferes with the Born term

Asymmetry in angular distributions
[E. Tomasi-Gustafsson, M.P. Rekalo, PLB504,291(01)]

$\gamma\gamma$ exchange from $e^+e^- \to p\bar{p}\gamma$ BABAR 2013 data

Phys. Lett. B659 (2008) 197
arXiv:1302.0055



Integrated over the $p\bar{p}$-CM energy from threshold up to 3 GeV

The MC-fit assumes **one-photon exchange**

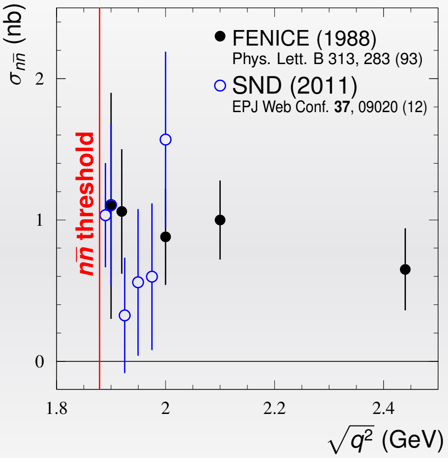
Slope = $-0.041 \pm 0.026 \pm 0.005$

Integral asymmetry

$$\langle \mathcal{A} \rangle_{\cos\theta_p} = \frac{\sigma(\cos\theta_p > 0) - \sigma(\cos\theta_p < 0)}{\sigma(\cos\theta_p > 0) + \sigma(\cos\theta_p < 0)} = -0.025 \pm 0.014 \pm 0.003$$

$\sigma(\cos\theta_p \gtrless 0)$ is the cross section integrated with $W \leq 3$ GeV and $\cos\theta_p \gtrless 0$

$e^+e^- \to n\bar{n}$



A very large cross section also at threshold

Still room for β like rising

	$\lvert G_M^n / G_M^p \rvert$
Data	$\sim$ **1.5**
Naively	$\sim \lvert Q_d / Q_u \rvert$
pQCD	$<$ 1
Soliton models	$\sim$ 1
VMD (Dubnicka)	$\gg$ 1

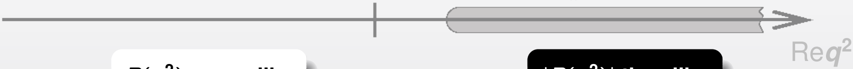
The ratio $R = \mu_p G_E^p / G_M^p$

- Dispersion relation for the imaginary part
  - Model-independent approach
    - First time-like $|G_E| - |G_M|$ separation

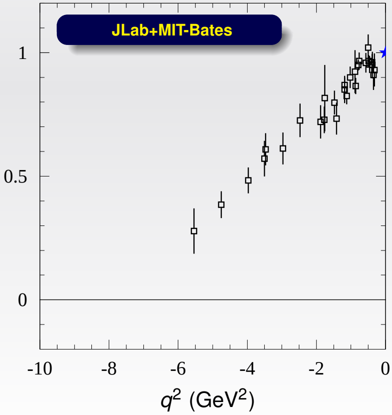
$\Longrightarrow$ Ratio in the whole q^2 complex plane

Analytic $R(q^2)$

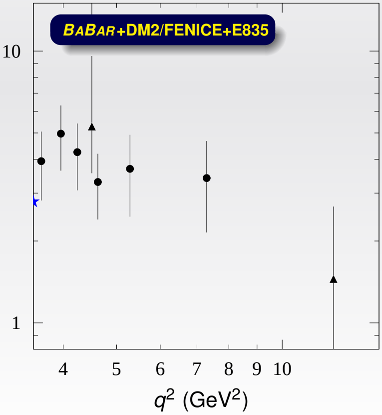
$$R(q^2) = R(0) + \frac{q^2}{\pi}\int_{4M_\pi^2}^{\infty} \frac{\mathrm{Im}R(s)}{s(s-q^2)}ds$$



$R(q^2)$ space-like



$|R(q^2)|$ time-like



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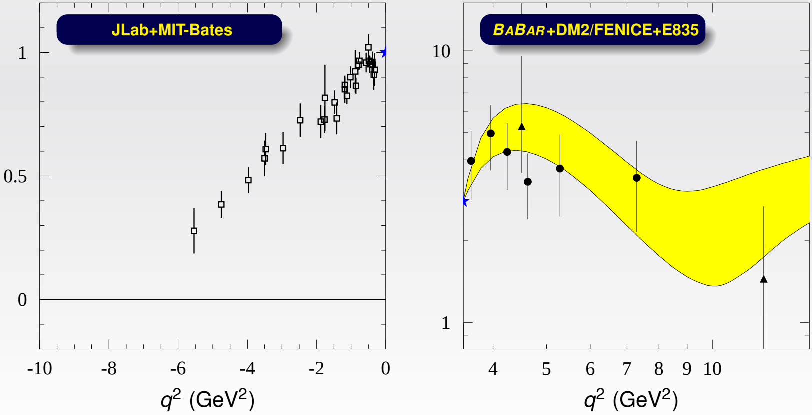
Req^2

$R(q^2)$ space-like

$|R(q^2)|$ time-like



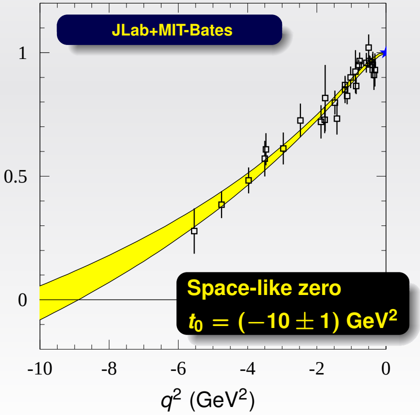
Analytic $R(q^2)$

Eur. Phys. J. A32 (2007) 421

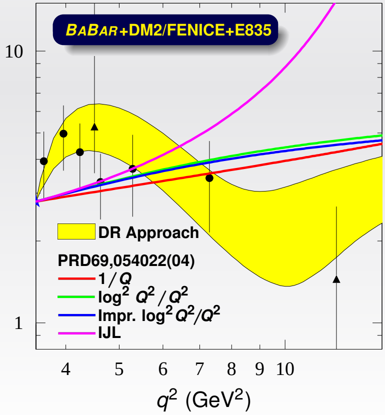
$$R(q^2) = R(0) + \frac{q^2}{\pi}\int_{4M_\pi^2}^{\infty}\frac{\mathrm{Im}R(s)}{s(s-q^2)}ds$$

Req^2

$R(q^2)$ space-like



$|R(q^2)|$ time-like



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Eur. Phys. J. A32 (2007) 421

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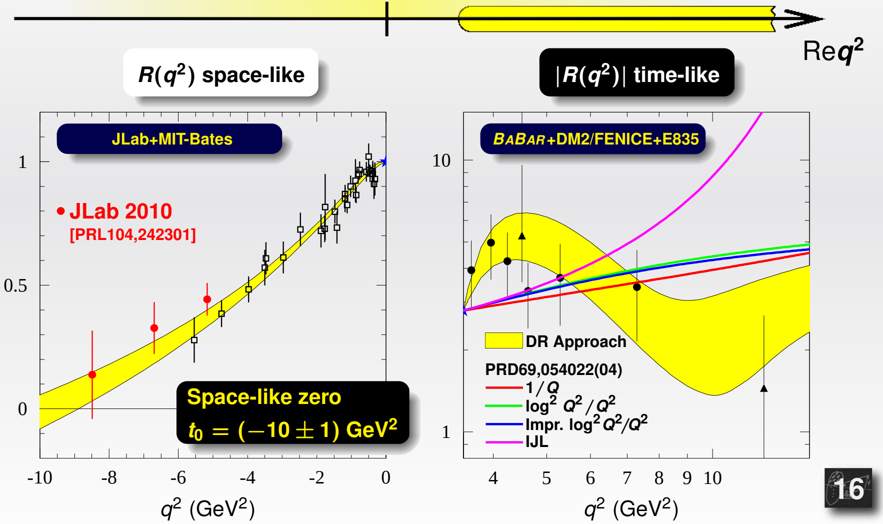
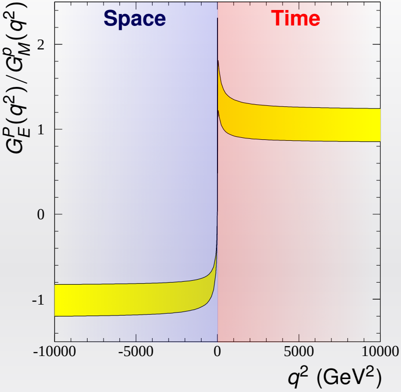
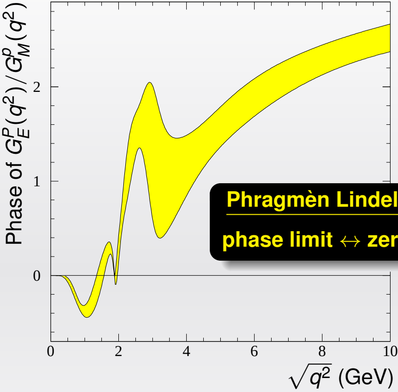


Asymptotic $G_E^P(q^2)/G_M^p(q^2)$ and phase





Phragmèn Lindelöf

phase limit $\leftrightarrow$ zeros

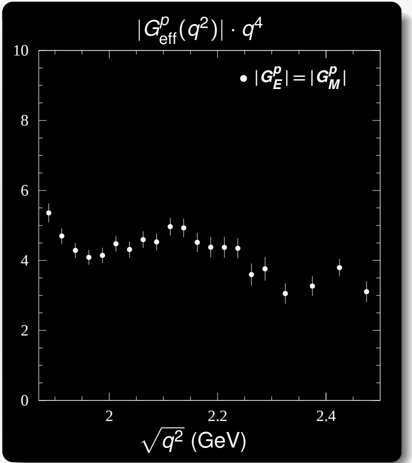
pQCD prediction

$$\frac{G_E^p(q^2)}{G_M^p(q^2)} \underset{|q^2|\to\infty}{\longrightarrow} -1$$

Phase from DR

$$\phi(q^2) = -\frac{\sqrt{q^2 - s_{th}}}{\pi} \text{Pr} \int_{s_{th}}^{\infty} \frac{\ln|R(s)|ds}{\sqrt{s - s_{th}}(s - q^2)}$$

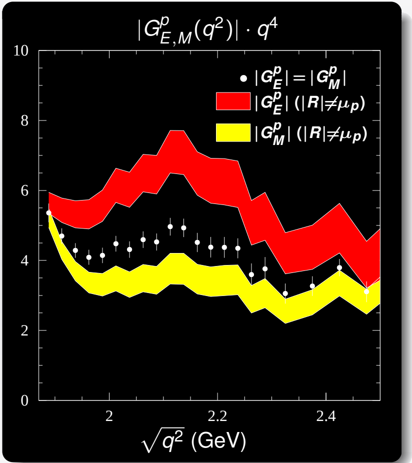
$|G_E^p(q^2)|$ and $|G_M^p(q^2)|$ from $\sigma_{p\bar{p}}$ and DR



$$|G^p_{\rm eff}(q^2)|^2 = \frac{\sigma_{p\bar{p}}(q^2)}{\frac{4\pi\alpha^2\beta\mathcal{C}}{3s}}\left(1+\frac{1}{2\tau}\right)^{-1}$$

- **Usually what is extracted from the cross section $\sigma(e^+e^- \to p\bar{p})$ is the effective time-like form factor $|G^p_{\rm eff}|$ obtained assuming $|G_E^p| = |G_M^p|$ i.e. $|R| = \mu_p$**
- **Using our parametrization for R and the BaBar data on $\sigma(e^+e^- \to p\bar{p})$, $|G_E^p|$ and $|G_M^p|$ may be disentangled**

$|G_E^p(q^2)|$ and $|G_M^p(q^2)|$ from $\sigma_{p\bar{p}}$ and DR

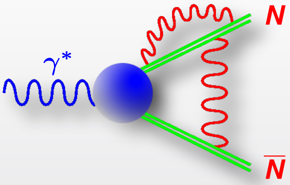


$$|G_M^p(q^2)|^2 = \frac{\sigma_{p\bar{p}}(q^2)}{\frac{4\pi\alpha^2\beta\mathcal{C}}{3s}}\left(1 + \frac{|R(q^2)|}{2\mu_p\tau}\right)^{-1}$$

- **Usually what is extracted from the cross section $\sigma(e^+e^- \to p\bar{p})$ is the effective time-like form factor $|G^p_{\rm eff}|$ obtained assuming $|G_E^p| = |G_M^p|$ i.e. $|R| = \mu_p$**
- **Using our parametrization for R and the BABAR data on $\sigma(e^+e^- \to p\bar{p})$, $|G_E^p|$ and $|G_M^p|$ may be disentangled**

Sommerfeld resummation factor needed?

The Coulomb Factor



$$\sigma_{p\bar{p}} = \frac{4\pi\alpha^2\beta\,\mathcal{C}}{3q^2}\left[|G_M^p(q^2)|^2 + \frac{2M_p^2}{q^2}|G_E^p(q^2)|^2\right]$$

$\mathcal{C}$ describes the $p\bar{p}$ Coulomb interaction as FSI

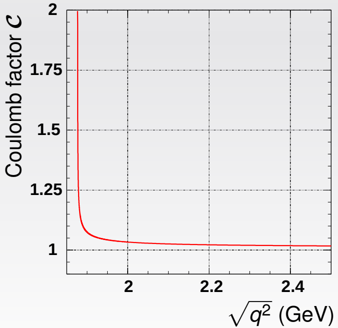
[Sommerfeld, Sakharov, Schwinger, Fadin, Khoze]

Distorted wave approximation

$$\mathcal{C} = |\Psi_{\text{Coul}}(0)|^2$$

- **S-wave:** $\mathcal{C} = \dfrac{\frac{\pi\alpha}{\beta}}{1-\exp\left(-\frac{\pi\alpha}{\beta}\right)} \xrightarrow[\beta\to 0]{} \dfrac{\pi\alpha}{\beta}$
- **Rel. corr.:** $\beta \to \tilde{\beta} = \dfrac{\beta}{1-\beta}$ [hep-ph/05090089]
- **D-wave:** $\mathcal{C} = 1$

No Coulomb factor for boson pairs (P-wave)



Enhancement and Resummation Factors

Coulomb factor $\mathcal{C}$ for S-wave only

- **Partial wave FF** .... $G_S = (2G_M\sqrt{\tau} + G_E)/3\,, \qquad G_D = (G_M\sqrt{\tau} - G_E)/3$
- **Cross section** .... $\sigma(q^2) = 2\pi\alpha^2 \dfrac{\beta}{\tau\, q^2}\left[\mathcal{C}\,|G_S(q^2)|^2 + 2|G_D(q^2)|^2\right]$
- **$\mathcal{E}$nhancement and $\mathcal{R}$esummation factors** .... $\mathcal{C} = \mathcal{E} \times \mathcal{R}$

Enhancement factor

$$\mathcal{E} = \frac{\pi\alpha}{\beta}$$

- It is responsible for the **one-photon exchange $p\bar{p}$ FSI**
- dominates close to threshold: $\mathcal{C} \underset{\beta\sim 0}{\simeq} \mathcal{E}$
- cancels the phase-space factor $\Rightarrow$ stepwise cross section at threshold

$$\sigma_{p\bar{p}}(4M_p^2) = \frac{\pi^2\alpha^3}{2M_p^2}\frac{\not\beta}{\not\beta}|G_S^p(4M_p^2)|^2 = 0.85\,|G_S^p(4M_p^2)|^2 \text{ nb}$$

Resummation factor

$$\mathcal{R} = \frac{1}{1 - e^{-\frac{\pi\alpha}{\beta}}}$$

- It is responsible for the **multi-photon exchange $p\bar{p}$ FSI**
- becomes ineffective few MeV above threshold: $\mathcal{R} \underset{\beta > 0}{\simeq} 1$
- must account also for gluon exchange

$$\mathcal{R} \to \mathcal{R}_s = \left[1 - \exp\left(-\pi\alpha_s/\tilde{\beta}\right)\right]^{-1}$$

$\alpha_s \simeq 0.5$

$\tilde{\beta} = \beta/(1-\beta)$

Step and plateau in *BABAR* data
. . . another possibility (Vladimir F. Dmitriev)

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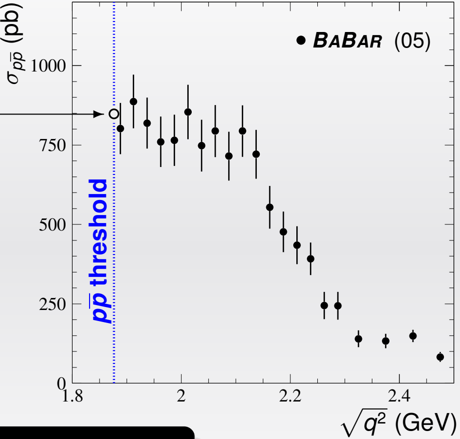
Expected cross section with

$|G_S^p(4M_p^2)| = 1$



At threshold

$$\sigma_{p\bar{p}}(4M_p^2) = \frac{\pi^2\alpha^3}{2M_p^2}\frac{\beta_p}{\beta_p}|G_S^p(4M_p^2)|^2$$

$$\sigma_{p\bar{p}}(4M_p^2) = 0.85\,|G_S^p(4M_p^2)|^2 \text{ nb}$$

$\Longrightarrow$

$|G_S^p(4M_p^2)| \equiv 1$

as pointlike fermion pairs!

Step and plateau in *BaBar* data
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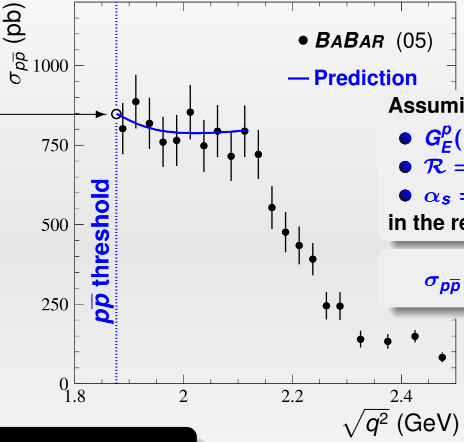

Assuming:

- $G_E^p(q^2) = G_M^p(q^2) = 1$
- $\mathcal{R} = \mathcal{R}_s$
- $\alpha_s = 0.5$

in the region $q^2 \leq (2.1\text{GeV})^2$

$$\sigma_{p\bar{p}} = (850\,\text{pb})\,\frac{1}{\tau}\,\mathcal{R}_s$$

At threshold

$$\sigma_{p\bar{p}}(4M_p^2) = \frac{\pi^2\alpha^3}{2M_p^2}\,\frac{\not{\beta}_p}{\not{\beta}_p}\,|G_S^p(4M_p^2)|^2$$

$$\sigma_{p\bar{p}}(4M_p^2) = 0.85\,|G_S^p(4M_p^2)|^2\ \text{nb}$$

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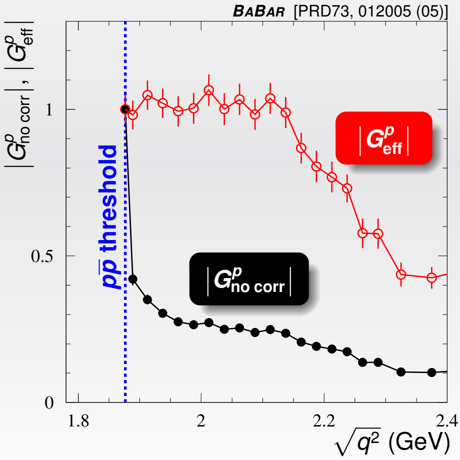
BABAR: $G_{\rm eff}^p$ including threshold effects

$$\left|G^p_{\rm no\ corr}(q^2)\right|^2 = \frac{\sigma_{p\bar p}(q^2)}{\mathcal{E}\mathcal{R}\,\frac{16\pi\alpha^2}{3}\,\frac{\beta}{4q^2}\left(1+\frac{1}{2\tau}\right)}$$

$$\left|G^p_{\rm eff}(q^2)\right|^2 = \frac{\sigma_{p\bar p}(q^2)}{\mathcal{E}\mathcal{R}_s\,\frac{16\pi\alpha^2}{3}\,\frac{\beta}{4q^2}\left(1+\frac{1}{2\tau}\right)}$$



BaBar: G^p_{eff} including threshold effects

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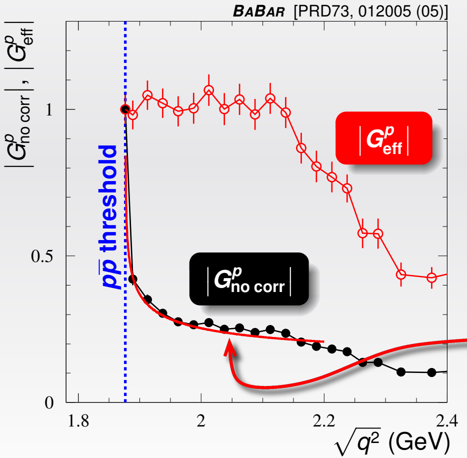
$$\left|G^p_{\text{eff}}(q^2)\right|^2 = \frac{\sigma_{p\bar{p}}(q^2)}{\mathcal{E}\mathcal{R}_s\,\frac{16\pi\alpha^2}{3}\,\frac{\beta}{4q^2}\left(1+\frac{1}{2\tau}\right)}$$



$$\frac{1}{\sqrt{\mathcal{R}}} = \sqrt{1 - e^{-\frac{\pi\alpha}{\beta}}}$$

Experiments: now and future

Space-like region

A1 — Mainz

- G_E^n at $-q^2 = 1.5$ GeV^2 (Pol. ^{3}He)
- G_E^p and G_M^p for $-q^2 \leq 2.0$ GeV^2

Jefferson Lab

- [Hall A] G_E^p/G_M^p up to 14 GeV^2
- [Hall A] G_M^n (ratio) up to 18 GeV^2
- [Hall A] G_E^n/G_M^n up to 10.2 GeV^2
- [Hall B] G_M^n (deuterium) up to 14 GeV^2
- [Hall C] G_E^n up to 7 GeV^2

Time-like region

SND, CMD — at VEPP-2000 e^+e^- collider

$|G_{\rm eff}^p|$, $|G_{\rm eff}^n|$ (scan)
$q^2 \leq (4\ {\rm GeV})^2$

BESIII — at BEPCII e^+e^- collider

$|G_E^p|$, $|G_M^p|$, $|G_{\rm eff}^n|$ (scan and ISR)
$q^2 \leq (3.5\ {\rm GeV})^2$

panda — at FAIR $p\bar{p}$ collider

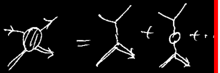
$|G_E^p|$, $|G_M^p|$, G_E^p/G_M^p phase ($\bar{p}$ polarization)
$(2.4\ {\rm GeV})^2 \leq q^2 \leq (3.7\ {\rm GeV})^2$

Belle II ? — at SuperKEKB e^+e^- collider

$|G_E^p|$, $|G_M^p|$, (ISR)
$q^2 \leq (4.5\ {\rm GeV})^2$

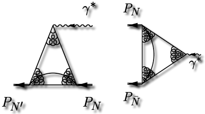
Radiative corrections

- Values of G_E^p / G_M^p from **Rosenbluth** and **polarization transfer** techniques, that have different radiative corrections, **do not agree**.
- Form factor values are obtained from cross section at **first order** (Born approx.). G_E and G_M appear in the Born amplitude with **different kinematical factors**.
- Radiative corrections depending on **relevant kinematical variables** must be applied.

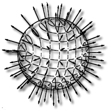


Models that reproduce **proton** and **neutron**, **electric** and **magnetic** form factors in **space-like** and **time-like** regions

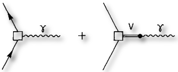
- **Light-front constituent quark model** [G. Salmè *et al.*]
  Space-like and time-like nucleon form factors are determined in the framework of a relativistic quark model based on Bethe-Salpeter amplitudes and vector meson dominance.



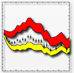
- **Skyrme model with vector mesons** [U.-G. Meissner *et al.*]
  Space-like form factors, obtained as Fourier transforms of charge and magnetic moment distributions, can be analytically continued in the time-like region. Desired time-like imaginary parts are obtained even though they appear quite "unstable". [See **Simone Moretti** poster].



- **VMD based models** [Gari, Krümpelmann, Iachello, Jackson, Landé,. . .]
  Nucleon form factors are parametrized using a mixture of VMD and pQCD.
  At low energy the coupling to the photons is described through VM exchange.
  At high energy "hadron/quark" form factors drive the transition to pQCD.

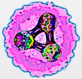


"To do" list



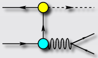
Time-like $|G_E|$-$|G_M|$ separation:

DR and data

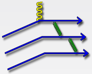


Understanding threshold effect(s):

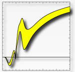
Dispersive analyses: integral equation, sum rule,. . .



Experimental observation in $p\bar{p} \to \pi^0 l^+ l^-$
[PRC75,045205(07)]



Asymptotic behavior: DR and data for the phase



Zeros $\leftrightarrow$ phases: DR and data

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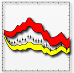

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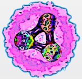
BESIII | panda | CMD SND



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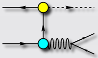

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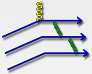
panda



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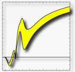
panda



Zeros $\leftrightarrow$ phases: DR and data

panda | Jefferson Lab