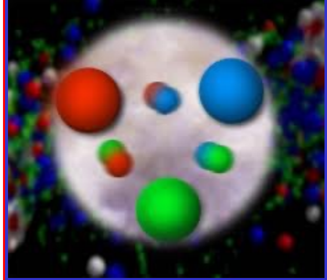
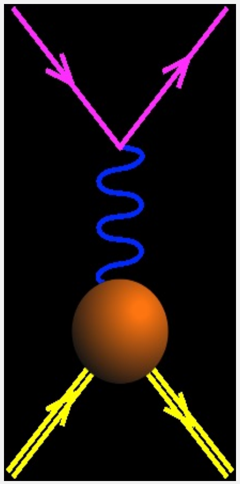


At the Heart of the Proton

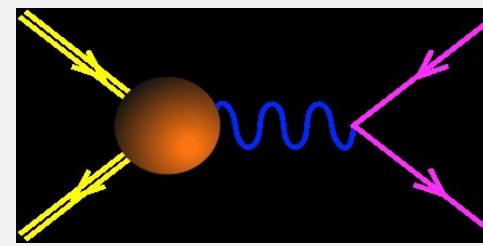


Egle Tomasi-Gustafsson

CEA, IRFU, DPhN and

Université Paris-Saclay

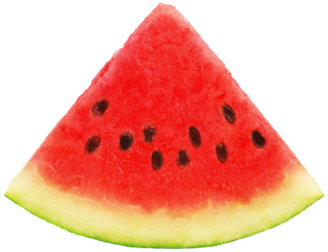
France



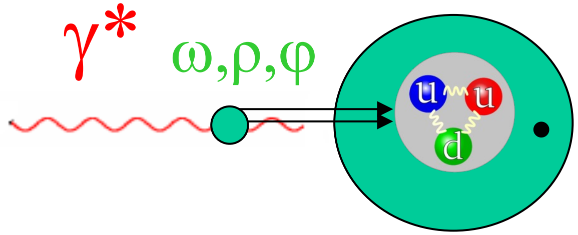
16th Varenna Conference on Nuclear Reaction Mechanisms

June 11-16, 2023

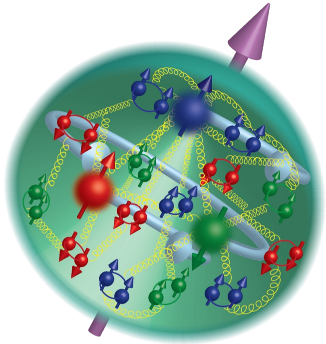
If the proton were a fruit…



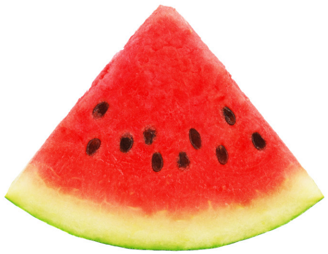
If the proton were a fruit…

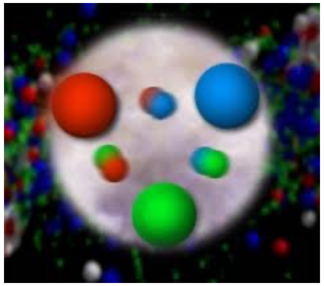


- VDM :
  vector meson dominance



- TMD,GPD…
  Parton structure functions

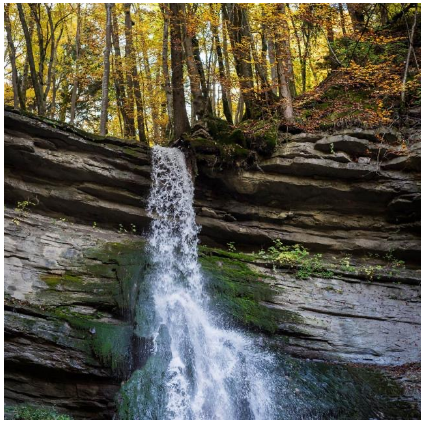




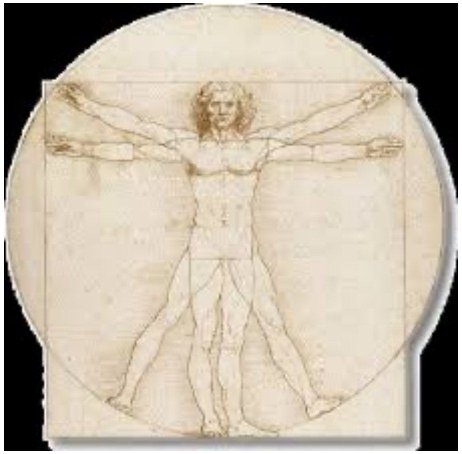
- Instantons:
  Mostly Vacuum

The proton

Proton is the the most common constituent of visible matter…



…BUT…

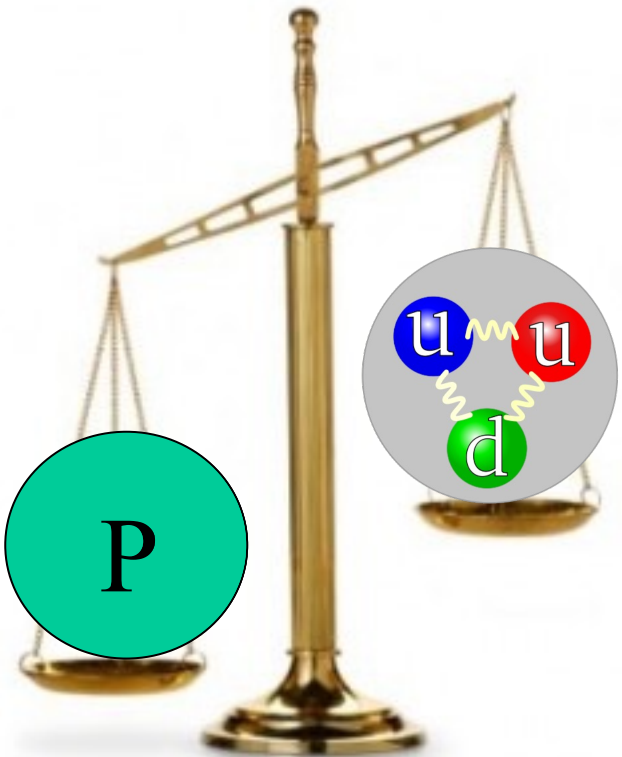


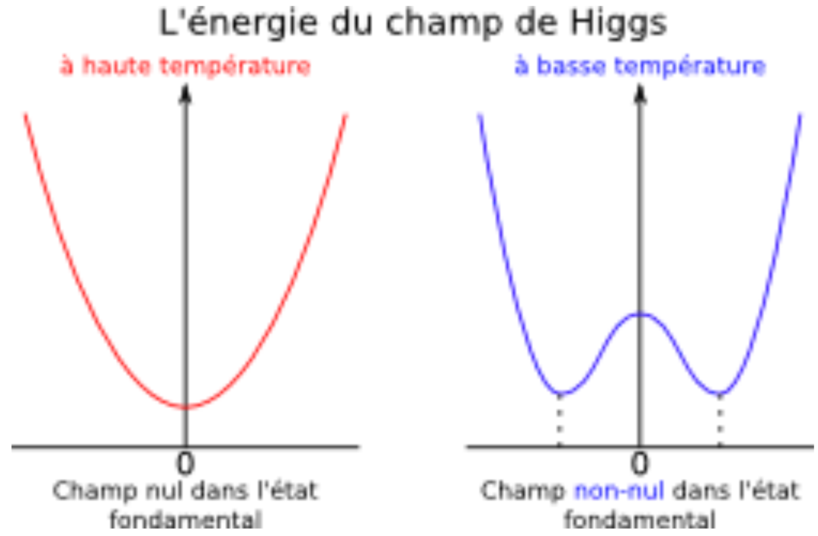
….its fundamental properties as

- Mass
- Spin
- Size

are still object of controversy

The MASS of the proton



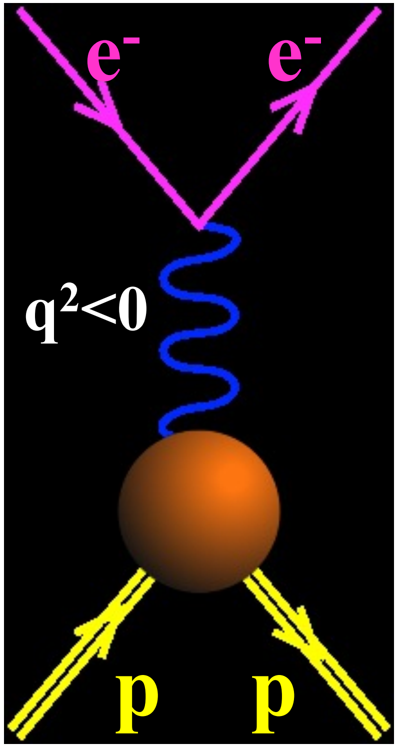


Masses
u-quark=1.5-4 MeV/c^2
d-quark=4-8 MeV/c^2

Mp=938,2720 MeV/c^2

-dynamically created by the strong interaction
-antiproton-proton collisions: gluon rich environnement

Electromagnetic Interaction



The electron vertex is known, γ_μ

The interaction is carried
by a virtual photon of 4-mom q^2

The proton vertex is parametrized
in terms of FFs: Pauli and Dirac F_1,F_2

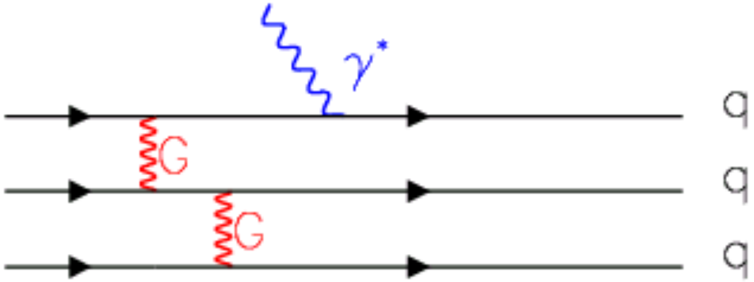
$$\Gamma_\mu = \gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2M} F_2(q^2)$$

$$q^2 = -4E_1E_2 \sin^2\theta/2$$

or in terms of Sachs FFs:
$G_E = F_1 + \tau F_2$, $G_M = F_1 + F_2$, $\tau = q^2/4M^2$
$G_E(0) = 1(e)$ $G_M(0) = \mu_N$

What about high order radiative corrections?

Dipole Approximation & pQCD



Dimensional scaling

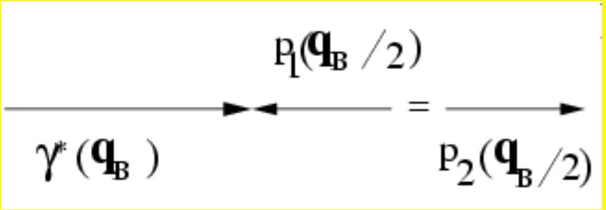
- $F_n(Q^2) = C_n\,[1/(1+Q^2/m_n)^{n-1}]$,
  - $m_n = n\beta^2$, <quark momentum squared>
  - n is the number of constituent quarks
- Setting $\beta^2 = (0.471 \pm .010)$ GeV^2 *(fitting pion data)*
  - pion: $F_\pi(Q^2) = C_\pi\,[1/(1+Q^2/0.471\ \text{GeV}^2)^1]$,
  - nucleon: $F_N(Q^2) = C_N\,[1/(1+Q^2/0.71\ \text{GeV}^2)^2]$,
  - deuteron: $F_d(Q^2) = C_d\,[1/(1+Q^2/1.41\,\text{GeV}^2)^5]$

V. A. Matveev, R. M. Muradian, and A. N. Tavkhelidze (1973), Brodsky and Farrar (1973), Politzer (1974), Chernyak & Zhitnisky (1984), Efremov & Radyuskin (1980)…

Dipole Approximation & charge density

$$G_D = (1 + Q^2 / 0.71\ \mathrm{GeV}^2)^{-2}$$

- Classical approach
  - Nucleon FF (in non relativistic approximation or in the Breit system) are Fourier transform of the charge or magnetic distribution.



Breit system

- The dipole approximation corresponds to **an exponential density distribution.**
  - $\rho = \rho_0 \exp(-r/r_0)$,
  - $r_0^2 = (0.24\ \mathrm{fm})^2$, $\langle r^2 \rangle \sim (0.81\ \mathrm{fm})^2 \leftrightarrow m^2_D = 0.71\ \mathrm{GeV}^2$

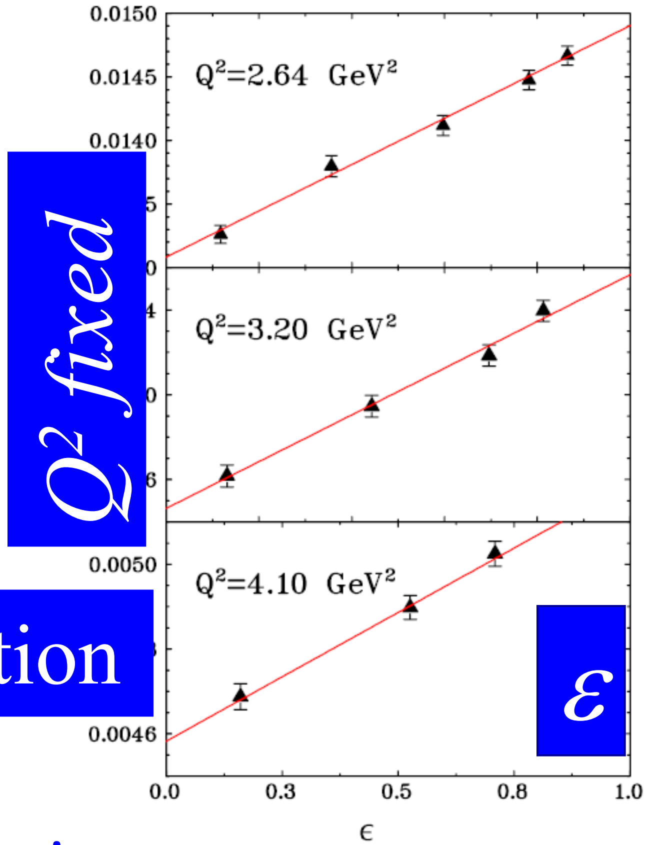
ep-elastic scattering : Rosenbluth separation

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{1}{(1+\tau)}\left(G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2)\right)$$

1950

$$\varepsilon = \left[1 + 2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)\right]^{-1}, \tau = \frac{Q^2}{4M^2}$$

$$\sigma_R = \varepsilon G_E^2 + \tau G_M^2$$



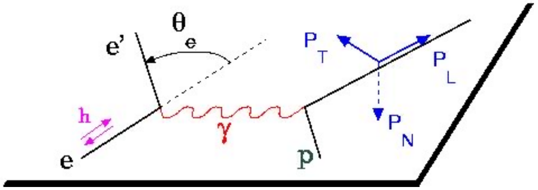
PRL 94, 142301 (2005)

Linearity of the reduced cross section

→ $\tan^2\theta_e$ dependence

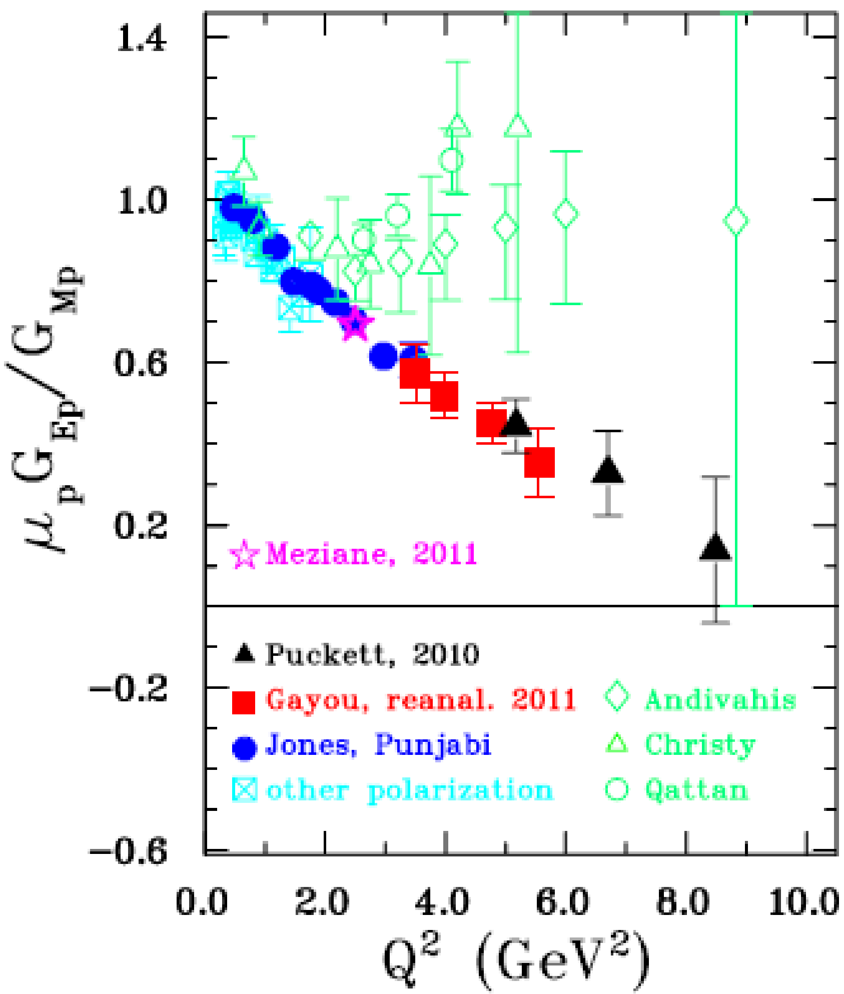
→ Holds for 1γ exchange only

The Akhiezer-Rekalo recoil proton polarizatio-Method (1967)
GEp Experiments (>2000)



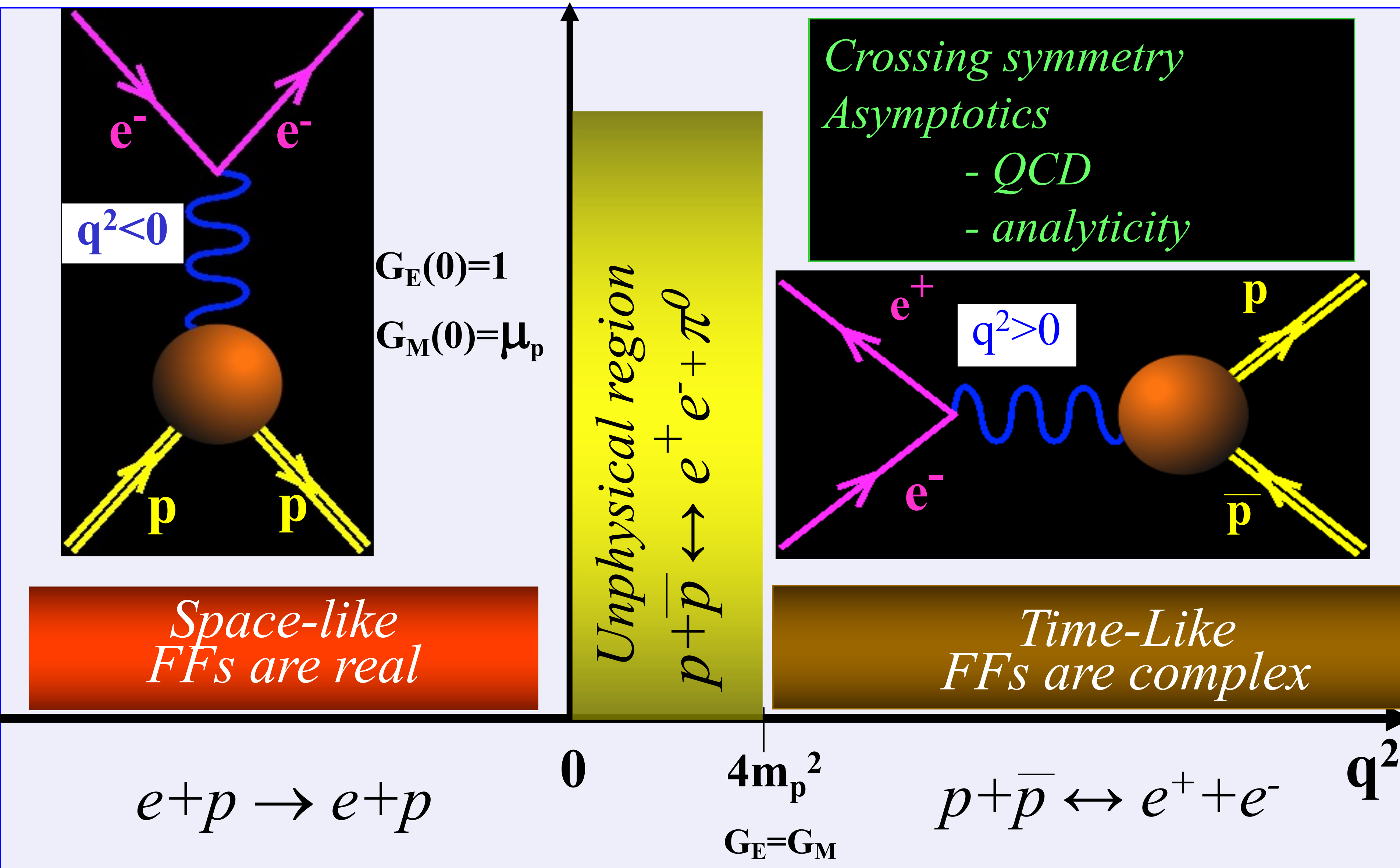
Jlab-GEp collaboration (>2000)

1) "standard" dipole function for the nucleon magnetic FFs GMp and GMn
2) linear deviation from the dipole function for the electric proton FF Gep
3) QCD scaling not reached
3) Zero crossing of Gep?
4) ***contradiction between polarized and unpolarized measurements***



A.J.R. Puckett et al, Phys. Rev. ***C96,*** *055203 (2017).*

Proton Charge and Magnetic Distributions



Time-like observables: $|G_E|^2$ and $|G_M|^2$.

-The cross section for $\bar{p} + p \to e^+ + e^-$ (1 γ-exchange):

$$\frac{d\sigma}{d(\cos\theta)} = \frac{\pi\alpha^2}{8m^2\sqrt{\tau-1}}\left[\tau|G_M|^2(1+\cos^2\theta) + |G_E|^2\sin^2\theta\right]$$

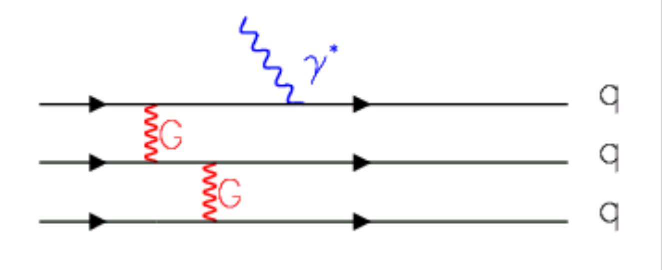
θ: angle between e^- and $\bar{p}$ in cms.

A. Zichichi, S. M. Berman, N. Cabibbo, R. Gatto, Il Nuovo Cimento XXIV, 170 (1962)
B. Bilenkii, C. Giunti, V. Wataghin, Z. Phys. C 59, 475 (1993)
G. Gakh, E.T-G., Nucl. Phys. A761,120 (2005)

As in SL region:
- Dependence on q^2 contained in FFs
- Even dependence on $\cos^2\theta$ (1γ exchange)
- No dependence on sign of FFs
- Enhancement of the magnetic term

but TL form factors are complex!

The Time-like Region



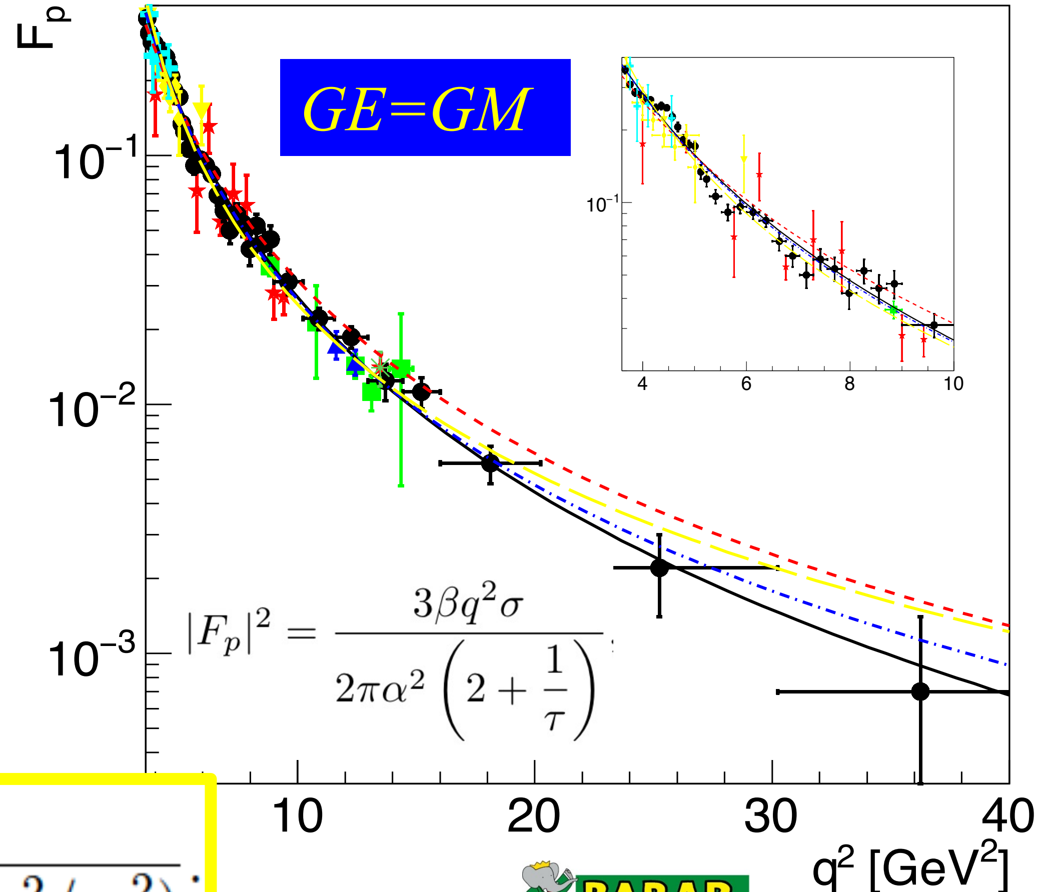
Expected QCD scaling $(q^2)^2$

$$\frac{\mathcal{A}}{(q^2)^2\left[\log^2(q^2/\Lambda^2)+\pi^2\right]}.$$

$$\frac{\mathcal{A}}{(1+q^2/m_a^2)\left[1-q^2/0.71\right]^2},$$

$$|F_{T3}(q^2)| = \frac{\mathcal{A}}{(1-q^2/m_1^2)(2-q^2/m_2^2)}.$$

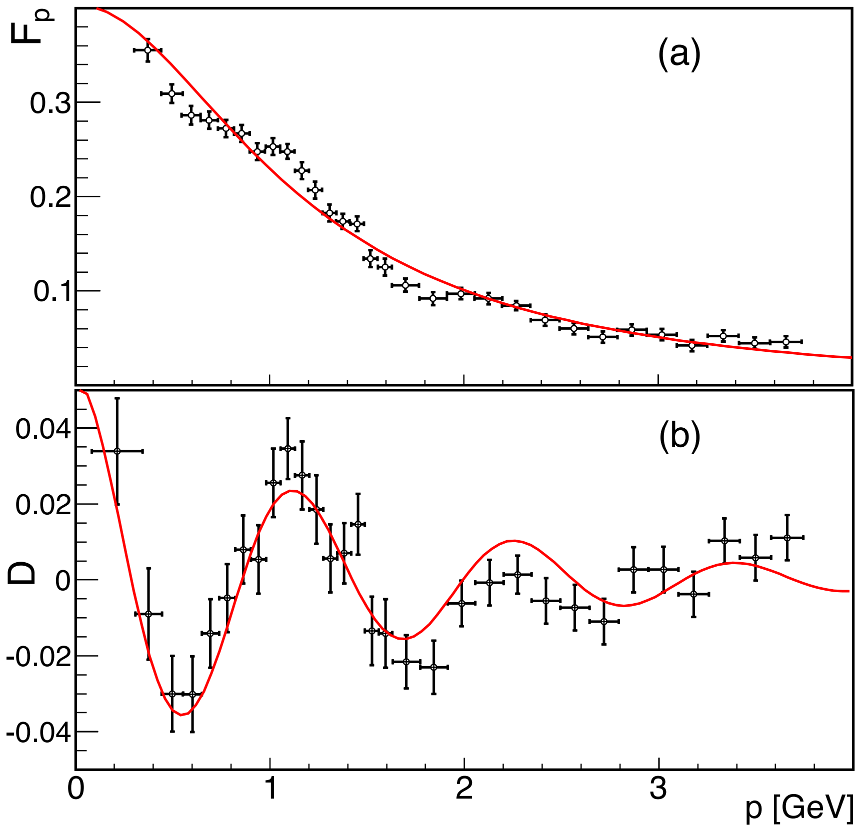
$$e^+ + e^- \to \bar{p} + p\,,$$
$$\bar{p} + p \to e^+ + e^-$$



BABAR

Oscillations : regular pattern in p_{Lab}

The relevant variable is p_{Lab} associated to the relative motion of the final hadrons



$$F_{osc}(p) \equiv A \exp(-Bp) \cos(Cp + D).$$

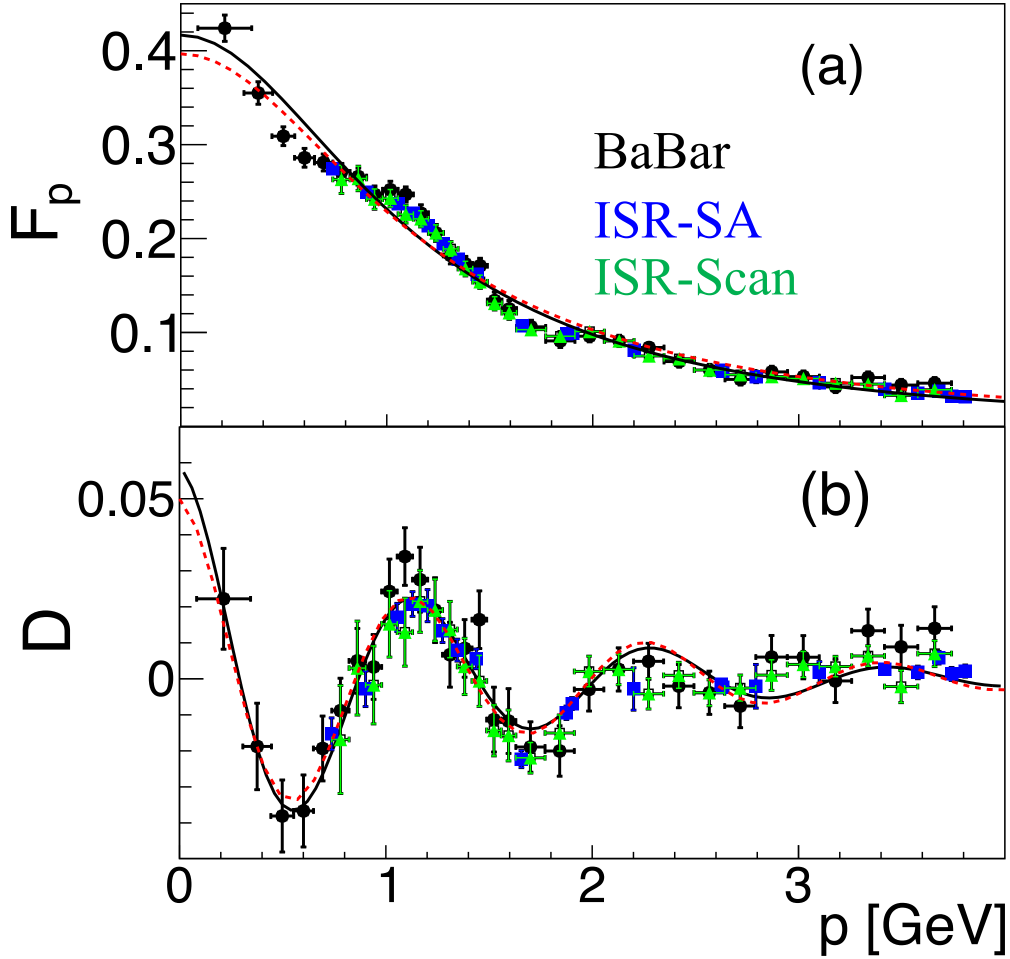
$A \pm \Delta A$	$B \pm \Delta B$ $[GeV]^{-1}$	$C \pm \Delta C$ $[GeV]^{-1}$	$D \pm \Delta D$	$\chi^2/n.d.f$
0.05 ± 0.01	0.7 ± 0.2	5.5 ± 0.2	0.03 ± 0.3	1.2

A: Small perturbation B: damping
C: r < 1fm D=0: maximum at p=0

Simple oscillatory behaviour
Small number of coherent sources

A. Bianconi, E. T-G. Phys. Rev. Lett. 114,232301 (2015)

Confirmation of regular oscillations



$$F_p^{\rm fit}(s) = F_{\rm 3p}(s) \ + \ F_{\rm osc}(p(s))$$

$$F_{\rm 3p}(s) \ = \ \frac{F_0}{\left(1+\frac{s}{m_a^2}\right)\left(1-\frac{s}{m_0^2}\right)^2},$$
$$F_{\rm osc}(p(s)) \ = \ Ae^{-Bp}\cos(Cp+D)\,.$$

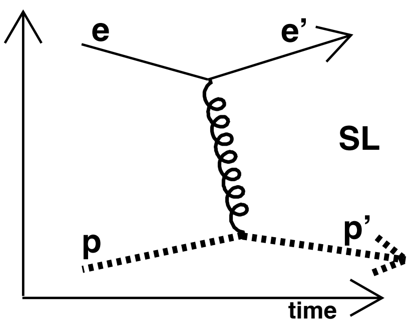
$$s \ = \ 2m_p\left(m_p+\sqrt{p^2+m_p^2}\right),$$
$$p \ = \ \sqrt{s\left(\frac{s}{4m_p^2}-1\right)}.$$

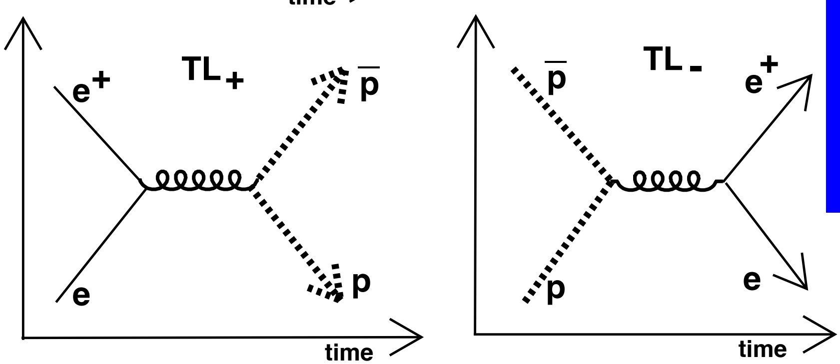
E.T.-G., A. Bianconi, S. Pacetti, Phys.Rev.C 103 (2021) 3, 035203

Time- and Space-Like Form Factors
Unified definition

$$F(q^2) = \int_{\mathcal{D}} d^4 x e^{i q_\mu x^\mu} \rho(x), \; q_\mu x^\mu = q_0 t - \vec{q} \cdot \vec{x}$$

$\rho(x) = \rho(\vec{x}, t)$ space-time distribution of the electric charge in the space-time volume $\mathcal{D}$.



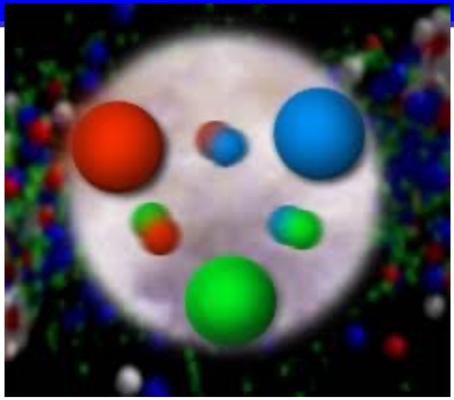


SL photon 'sees' a charge density

TL photon can not test a space distribution but sees the time evolution from the annihilation point to the formed hadron

How to connect and understand the amplitudes?

The nucleon



3 valence quarks and a neutral sea of $q\bar{q}$ pairs

Antisymmetric state of colored quarks:

$$|p> \sim \epsilon_{ijk}|u^i u^j d^k>$$
$$|n> \sim \epsilon_{ijk}|u^i d^j d^k>$$

Assumption:

Does not hold in the spatial center of the nucleon: the center of the nucleon *is electrically neutral,* due to strong gluonic field
Inner region: gluonic condensate of clusters with randomly oriented chromo-magnetic field (Vainshtein, 1982)

Charge screening as in a plasma

E.A. Kuraev, E. T-G, A. Dbeyssi, Phys.Lett. B712 (2012) 240

Predictions for SL and TL

Quark counting rules apply to the vector part of the potential

$$G_M^{(p,n)}(Q^2) = \mu G_E(Q^2);$$
$$G_E^{(p,n)}(Q^2) = G_D(Q^2) = \left[1 + Q^2/(0.71\ \mathrm{GeV}^2)\right]^{-2}$$

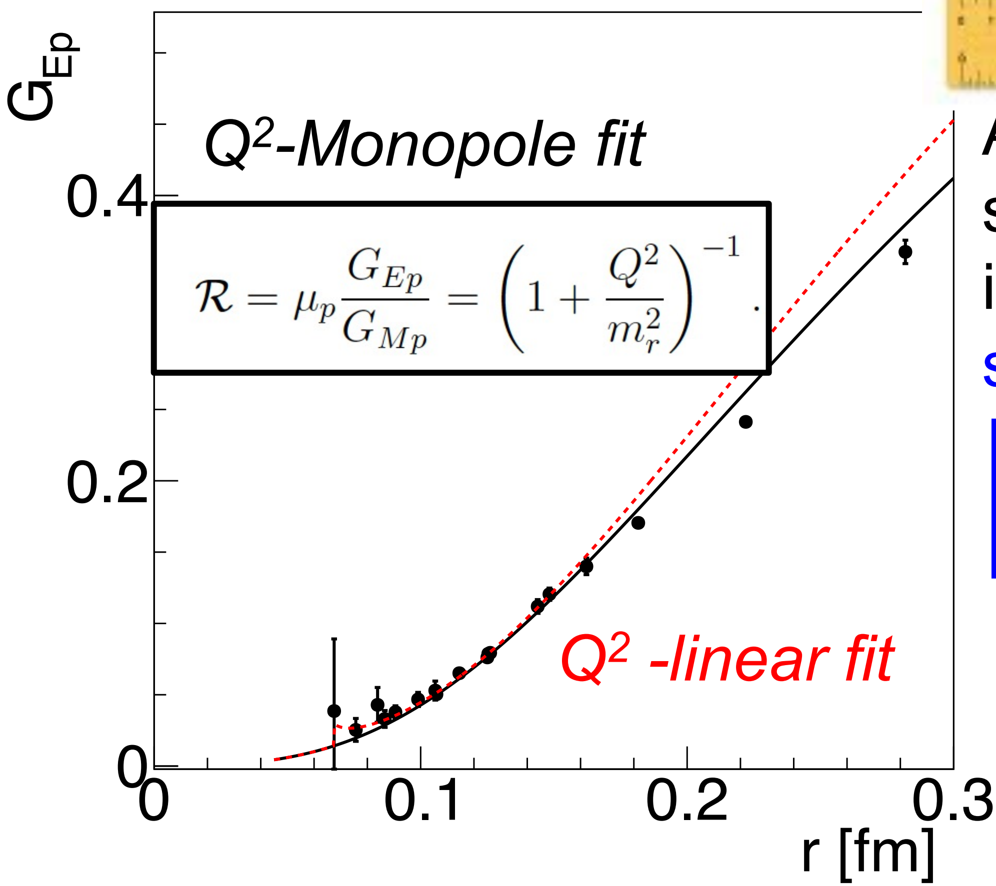
The neutral plasma acts on the distribution of the electric charge (not magnetic).

Additional suppression due to the neutral plasma

$$G_E(Q^2) = \frac{G_M(Q^2)}{\mu}\left(1 + Q^2/q_1^2\right)^{-1}$$

Similar behavior in SL and TL regions

SL- the most precise ruler



Additional suppression for the scalar part due to colorless internal region: "charge screening as in a plasma":

$$G_E(Q^2) = \frac{G_M(Q^2)}{\mu}\left(1 + Q^2/q_1^2\right)^{-1}$$

Zero crossing?

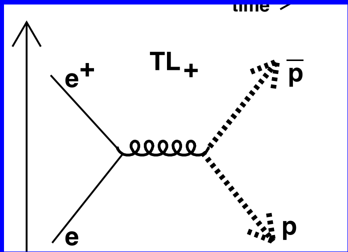
Prediction: NO

The photon 'sees' the neutral, screened region

$G_{Ep} \approx 0$ for r < 0.06 fm

$$r\ [\mathrm{fm}] = \lambda = \hbar c/\sqrt{Q^2} = 0.197\ [\mathrm{GeV\ fm}]/\sqrt{Q^2}[\mathrm{GeV}],$$

E. T-G., S. Pacetti , Phys. Rev. C 106 (2022) 3, 035203



Time-like region

Арбуз

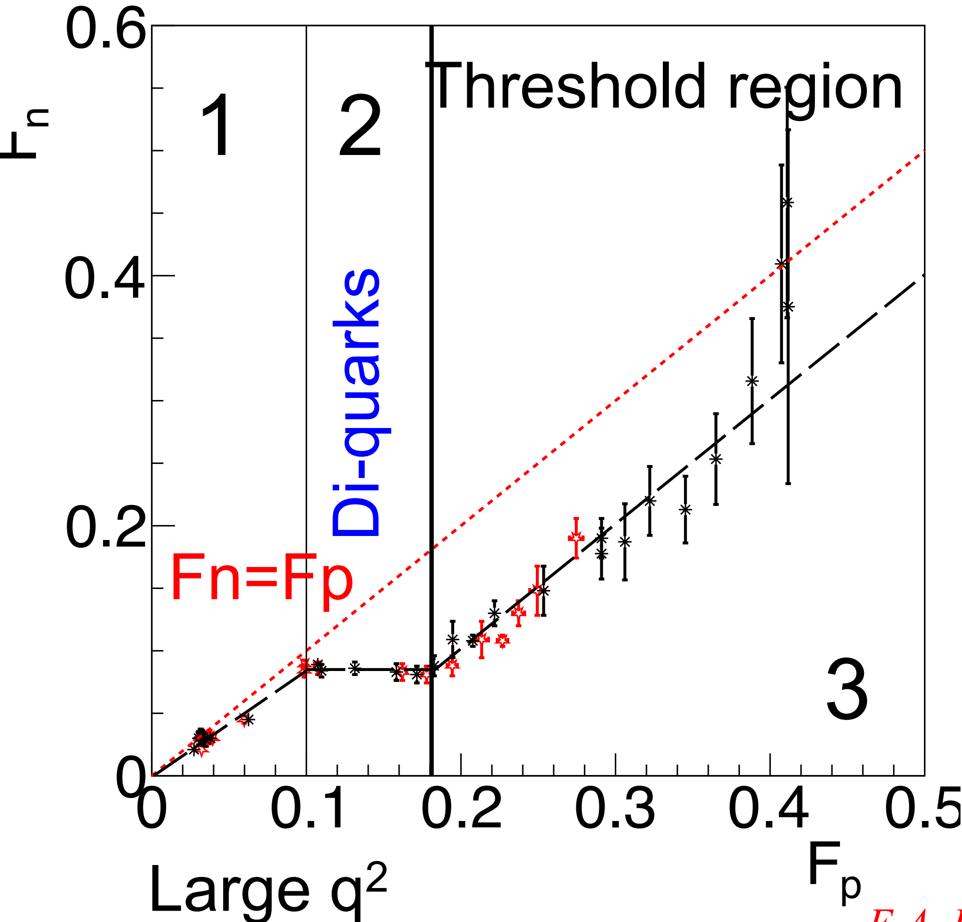
Antisymmetric state of colored quarks → *Colorless quarks: Pauli principle*

The vacuum state transfers all the released energy to a state of matter consisting at least of 6 massless valence quarks, a set of gluons, sea of $\bar{q}q$ with $q_0>2M_p$, J=1, dimensions $\hbar/(2M_p) \sim 0.1$ fm.

- uu (dd) quarks are repulsed from the inner region
- The 3rd quark *u (p)* or *d (n)* is attracted by one of the identical quarks, forming *a compact di-quark: competition between attraction force and stochastic force of the gluon field*
- The color state is restored: the 'point-like' hadron expands and cools down: *the current quarks and antiquarks absorb gluons and transform into constituent quarks*

E.A. Kuraev, A. Dbeyssi, E. T-G. Phys. Lett. 712, 240 (2012)

TL - np-correlation : 3 steps



Experimental points at the same P_L

Proton values calculated from the 6-parameter fit

1) pQCD applies

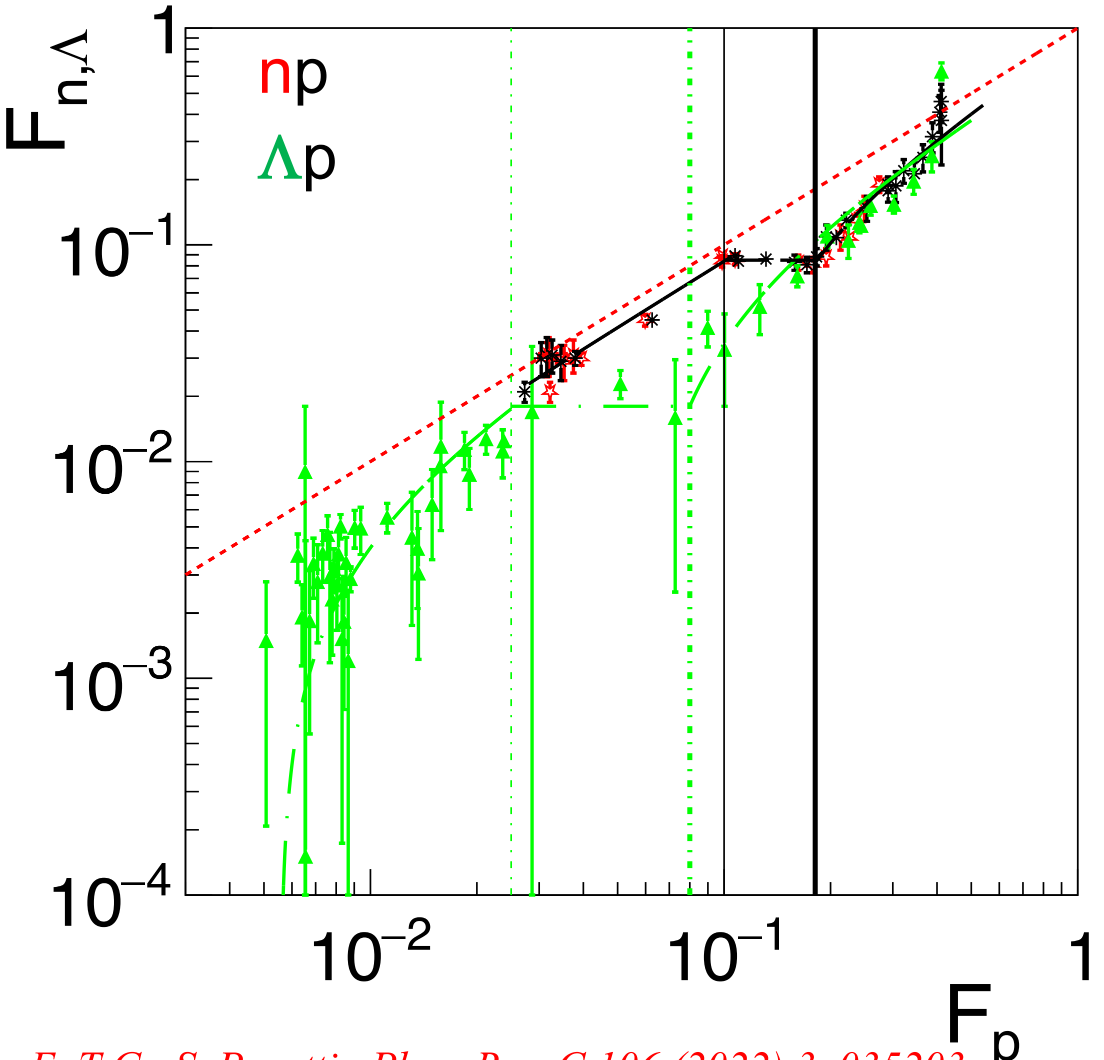
2) di-quark phase
charge redistributed

3) The hadron is formed

E.A. Kuraev, A. Dbeyssi, E. T-G. Phys. Lett. 712, 240 (2012)

E. T-G., S. Pacetti , Phys. Rev. C 106 (2022) 3, 035203

npΛ-correlation

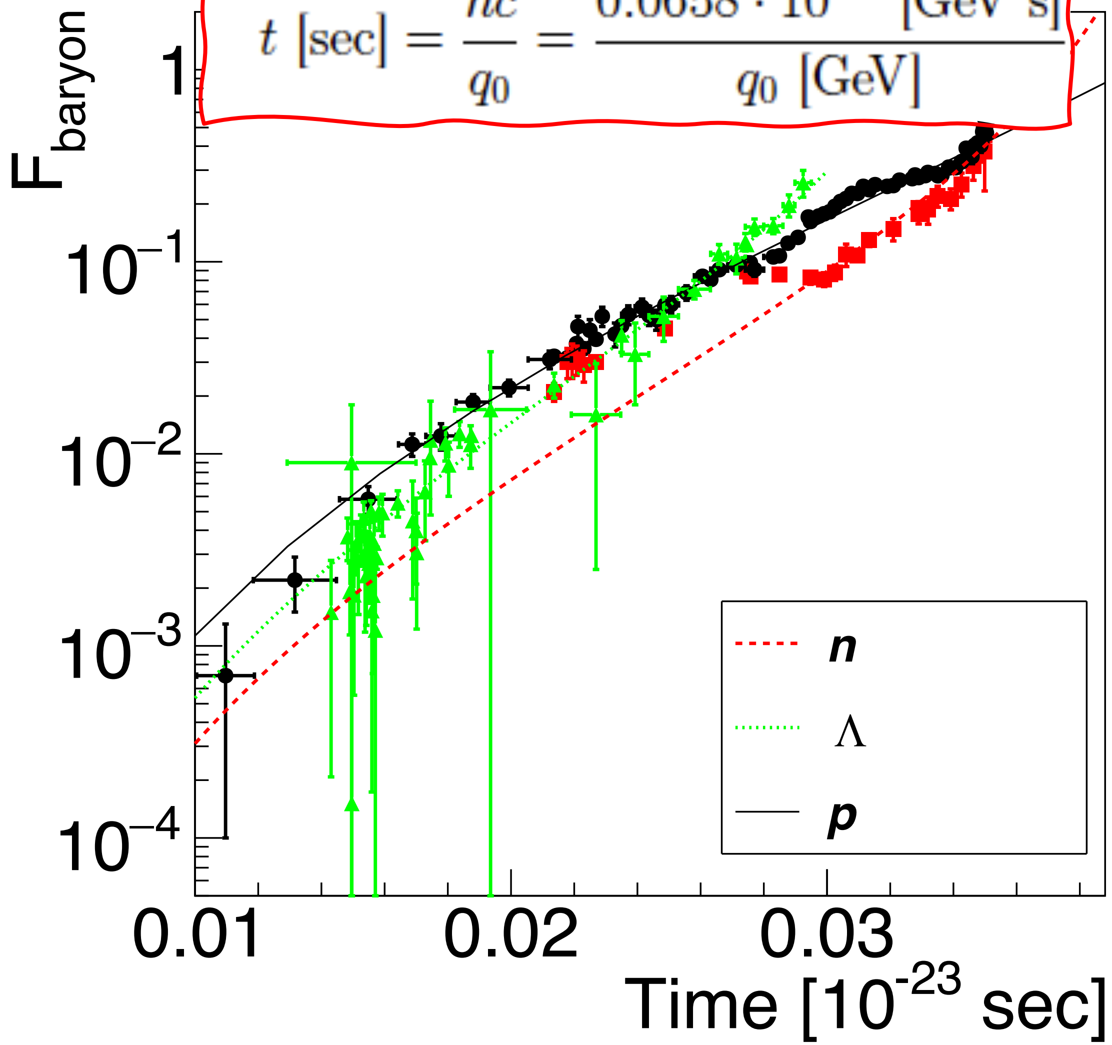


Quark pairs created by quantum vacuum fluctuations: *all quark flavors are equally probable*, but, due to Heisenberg principle, the *associated time depends on the energy (baryon mass)*

E. T-G., S. Pacetti , Phys. Rev. C 106 (2022) 3, 035203

TL- the most precise clock

$$t\ [\text{sec}] = \frac{\hbar c}{q_0} = \frac{0.0658 \cdot 10^{-23} [\text{GeV s}]}{q_0\ [\text{GeV}]}$$



10^{-23} s is the time for *light to cross a proton*

Di-quark phase dominant at *t*~ 0.02-0.03 [10^{-23} s]

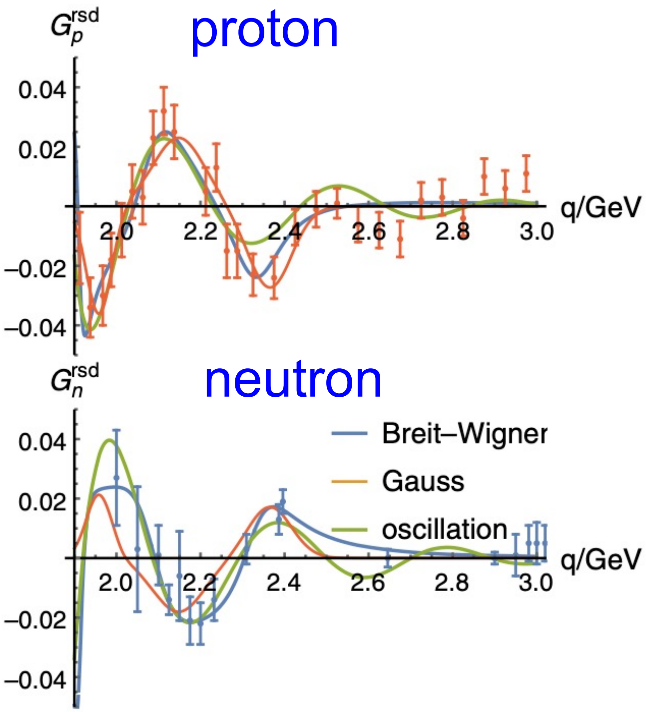
E. T-G., S. Pacetti , Phys. Rev. C 106 (2022) 3, 035203

PHYSICAL REVIEW D **105**, L071503 (2022)

Letter

Timelike nucleon electromagnetic form factors: All about interference of isospin amplitudes

Xu Cao,[1,2,*] Jian-Ping Dai,[3,†] and Horst Lenske[4,‡]

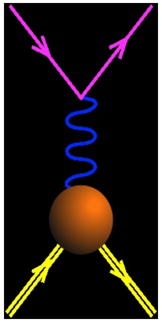


- No multimeson rescattering processes
- Competing isospin-clean vector meson intermediate states
  $\phi(2170)$ $(I=0)$ and $\rho(2150)$ $(I=1)$
- Sinusoidal modulation
- Energy dependent relative phase
- Related to the imaginary part of FFs

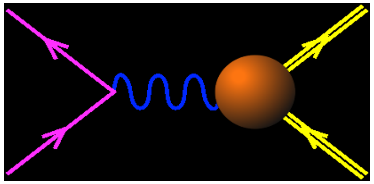
$$\frac{|I_1^{\rm rsd}+I_0^{\rm rsd}|}{|I_1^{\rm rsd}-I_0^{\rm rsd}|}=\frac{A_p}{A_n}=0.88\pm0.35$$

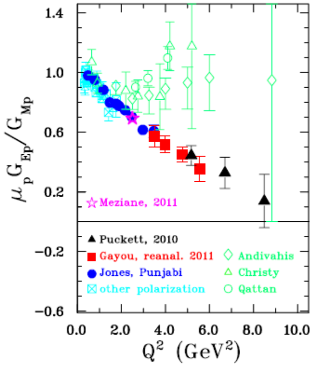
Balanced isospin content
Not depending on energy
Limited range for the fit

Conclusions

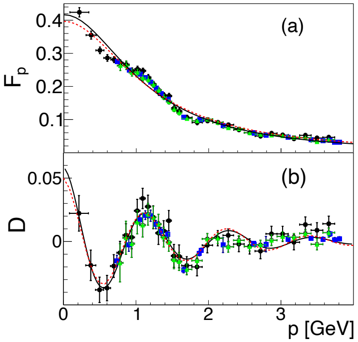


- Disentangle *structure* and *reaction* mechanism:
  1γ exchange mechanism

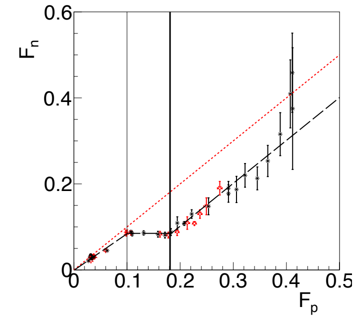




- Global understanding of scattering and annihilation reactions



- Dynamical structure in *four* dimensions: space and time



Hadron Electromagnetic Form factors

The Nobel Prize in Physics 1961

"for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the stucture of the nucleons"

Robert Hofstadter

1/2 of the prize

USA

Stanford University
Stanford, CA, USA

Characterize the internal structure of a particle (≠ point-like)

Elastic form factors contain information on the hadron ground state.

In a P- and T-invariant theory, the EM structure of a particle of spin S is defined by 2S+1 form factors.

Neutron and proton form factors are different (G_E,G_M)

Playground for theory and experiment

at low q^2 probe the size of the nucleus,
at high q^2 test QCD scaling

Assumption: dipole for GEp,GMp and GMn while GEn=0.

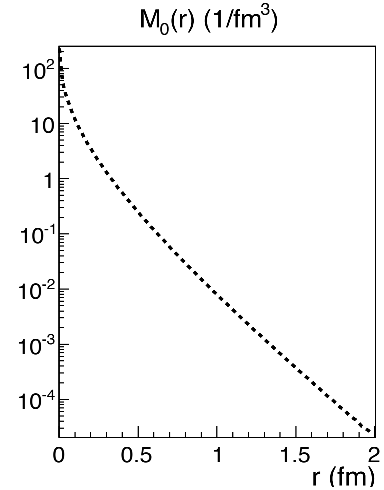
Fourier Transform

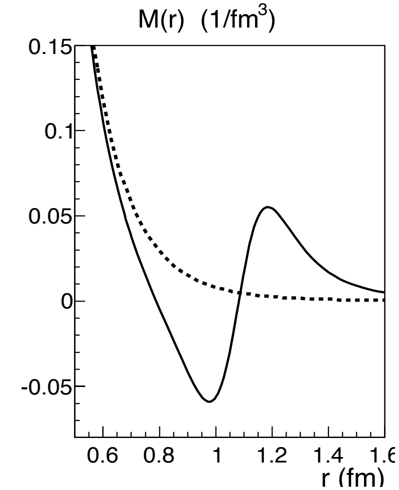
A.Bianconi, E. T-G., Phys. Rev. Lett. 114, 232301 (2015)

p: relative momentum
r: distance between the center of the forming hadrons
(p,r) conjugate variables, r $\leftrightarrow$ *t*

$$F_0(p) \equiv \int d^3\vec{r}\ exp(i\vec{p}\cdot\vec{r})\ M_0(r)$$

$$F(p) = F_0(p) + F_{osc}(p) \equiv \int d^3\vec{r}\ exp(i\vec{p}\cdot\vec{r}) M(r).$$



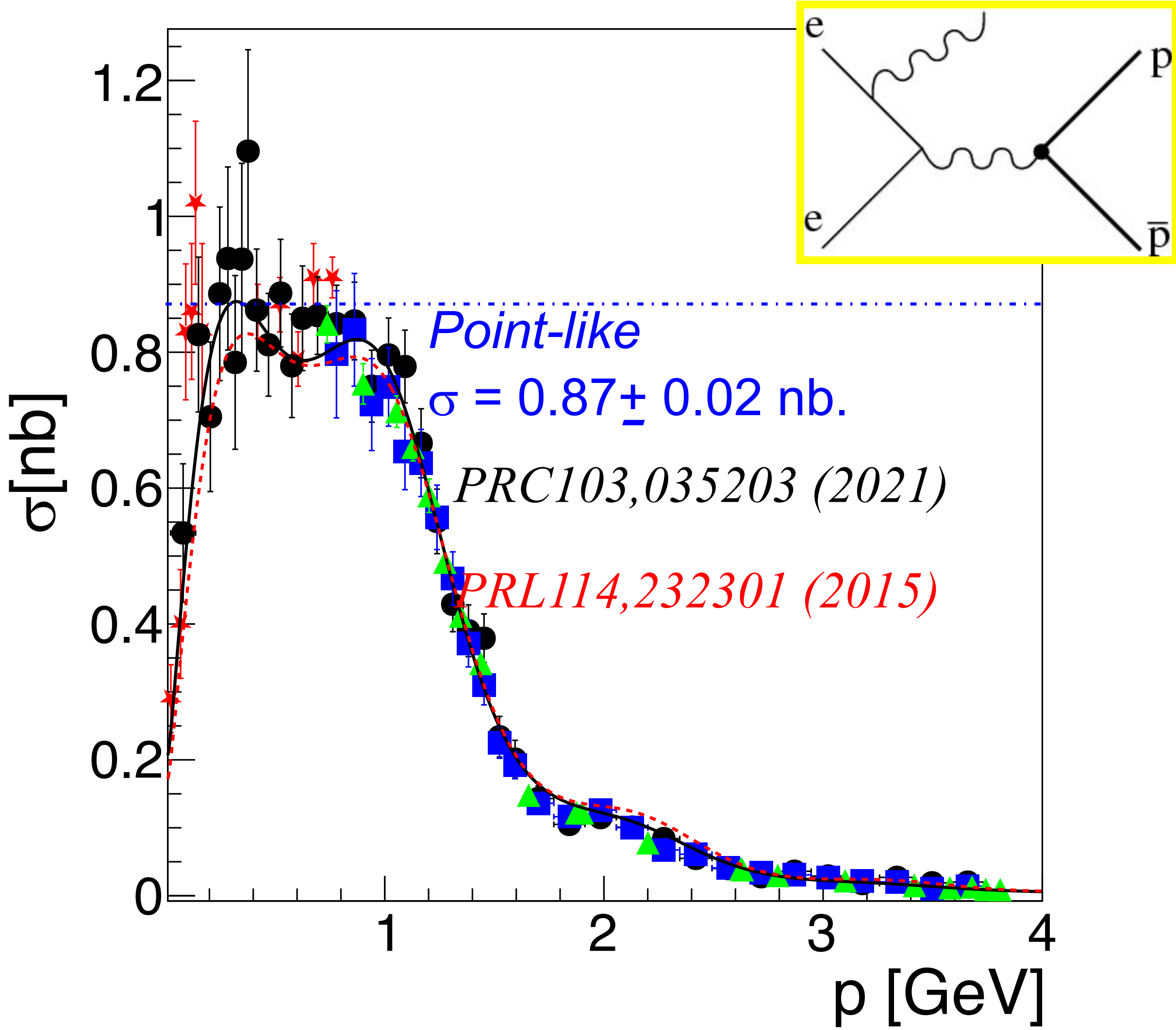


$$F_0 = \frac{\mathcal{A}}{(1+q^2/m_a^2)\,[1-q^2/0.71]^2},$$

$$F_{osc}(p)\ \equiv\ A\ \exp(-Bp)\ \cos(Cp\ +\ D).$$

- *Rescattering processes*
- *Large imaginary part*
- *Related to the time evolution of the charge density?*
  (E.A. Kuraev, E. T.-G., A. Dbeyssi, PLB712 (2012) 240)
- *Consequences for the SL region?*
- *Data from BESIII, expected from PANDA*

Cross section from $e^+e^- \to p\bar{p}\ (\gamma)$



Novosibirsk 38pt
1.9<2E<4.5
PLB794,64 (2019)

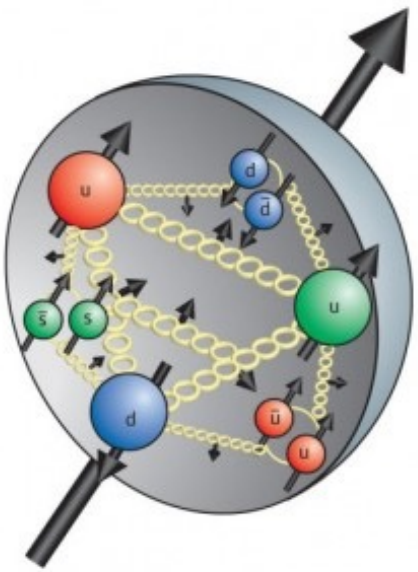
BaBar 85pt
1.9<2E<4.5
PRD87,092005 (2013)

ISR-ISR-SA 30pt
2<2E<3.6
PRD99,092002 (2019)

ISR-Scan 22pt
2<2E<3.1
PRL124,042001 (2020)

E.T.-G., A. Bianconi, S. Pacetti, Phys.Rev.C 103 (2021) 3, 035203

The SPIN of the proton



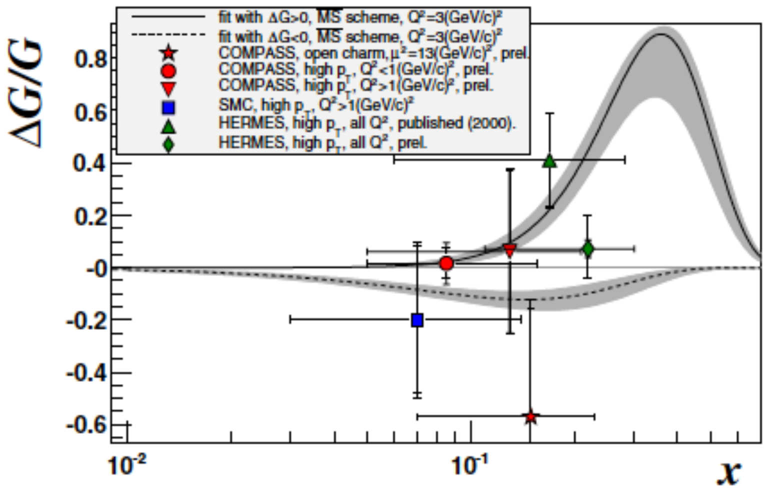
$S = 1/2$

$\Delta\Sigma + \Delta G + L$

Quarks

gluons

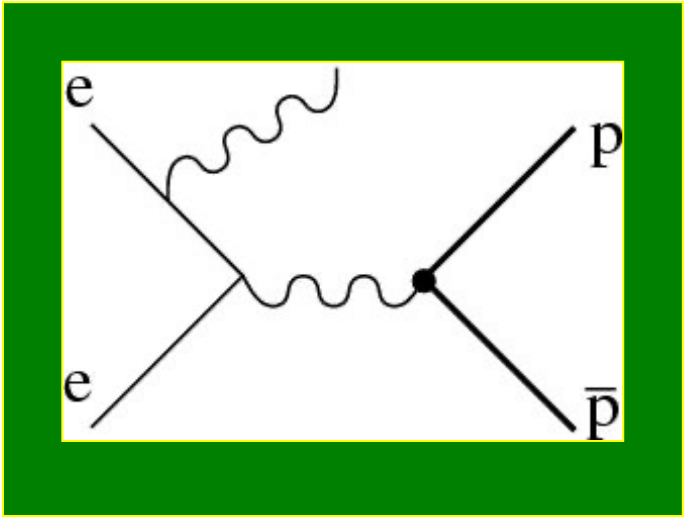
orbital momentum



Measured: ~ 1/4

L: spin-orbital correlations
TMD's, PDF's…

Radiative return (ISR)



$$e^+ + e^- \to p + \overline{p} + \gamma$$

$$\frac{d\sigma(e^+e^- \to p\bar{p}\gamma)}{dm\, d\cos\theta} = \frac{2m}{s} W(s,x,\theta)\sigma(e^+e^- \to p\bar{p})(m), \quad x = \frac{2E_\gamma}{\sqrt{s}} = 1 - \frac{m^2}{s},$$

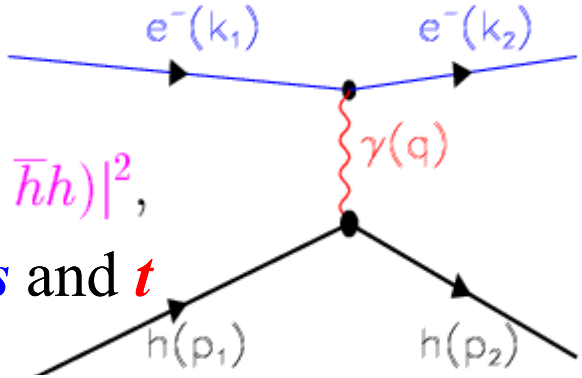
$$W(s,x,\theta) = \frac{\alpha}{\pi x}\left(\frac{2-2x+x^2}{\sin^2\theta} - \frac{x^2}{2}\right), \quad \theta >> \frac{m_e}{\sqrt{s}}.$$

*B. Aubert (BABAR Collaboration) Phys Rev. **D73**, 012005 (2006)*

Crossing symmetry

Scattering and annihilation channels:

$e^- + h \to e^- + h$



- Described by the same amplitude :

$$|\overline{\mathcal{M}}(e^{\pm}h \to e^{\pm}h)|^2 = f(s,t) = |\overline{\mathcal{M}}(e^+e^- \to \overline{h}h)|^2,$$

- function of two kinematical variables, s and t

$$s = (k_1 + p_1)^2$$
$$t = (k_1 - k_2)^2$$

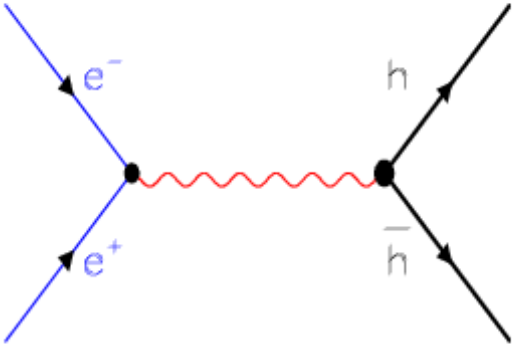
$e^- + e^+ \to \overline{h} + h$

- which scan different kinematical regions

$$k_2 \longrightarrow -k_2$$

$$p_2 \longrightarrow -p_2$$

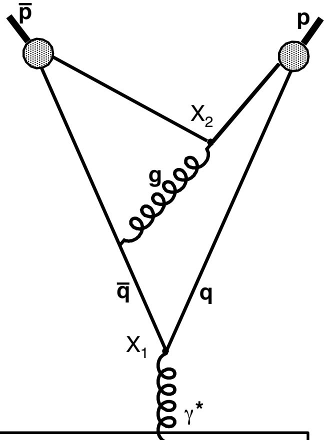
$$cos^2\tilde{\theta} = 1 + \frac{st + (s - M^2)^2}{t(\frac{t}{4} - M^2)} \to 1 + \frac{ctg^2\frac{\theta}{2}}{1+\tau}$$



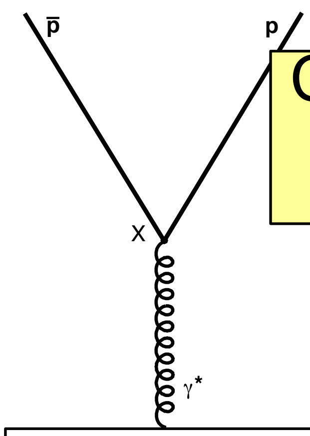
Photon-Charge coupling

$\rho(\vec{x})$ Fourier transform of a stationary charge and current distribution

$R(t)$ Amplitude for creating *charge-anticharge pairs* at time *t*



Resolved



Unresolved

Charge distribution: distribution in time of $\gamma^* \longrightarrow$ *charge-anticharge vertices*

The simplest picture: qq pair + compact di-quark

representation

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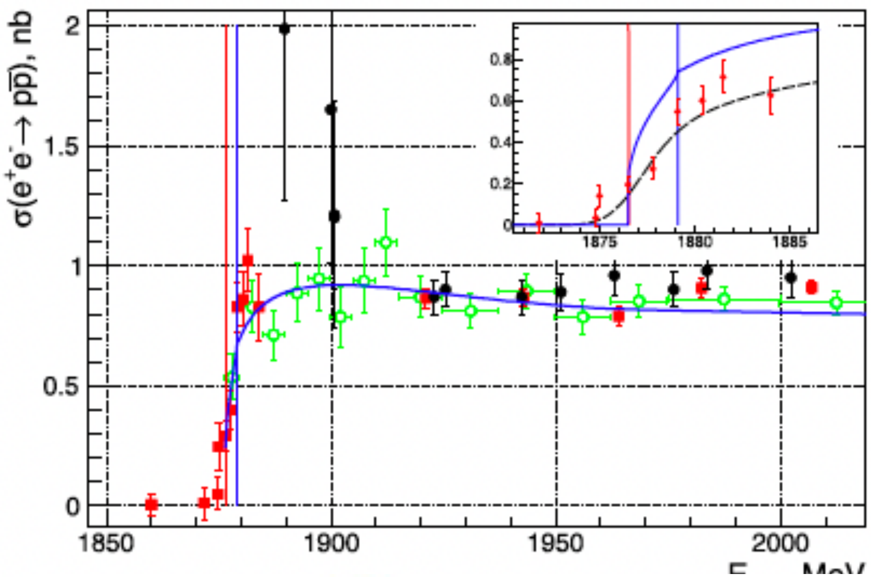
R.R. Akhmetshin et al. / Physics Letters B 794 (2019) 64–68



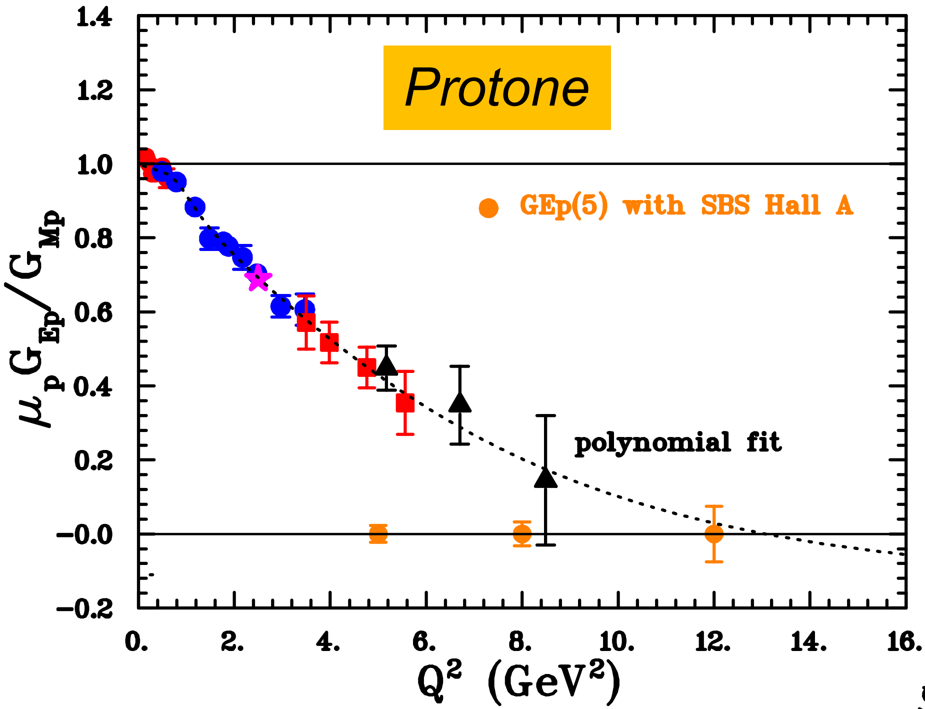
Convolution of the radiative cross section with the cm spread energy function (ΔE~0.95 MeV)

$$\sigma_{\mathrm{vis}}(E_{\mathrm{c.m.}}) = \frac{1}{\sqrt{2\pi}\,\sigma_{E_{\mathrm{c.m.}}}} \int dE'_{\mathrm{c.m.}}\,\sigma_{f\gamma}(E'_{\mathrm{c.m.}}) \cdot \exp\left(-\frac{(E_{\mathrm{c.m.}} - E'_{\mathrm{c.m.}})^2}{2\sigma^2_{E_{\mathrm{c.m.}}}}\right),$$

$$\sigma_{f\gamma}(E_{\mathrm{c.m.}}) = \int_0^{E_\gamma^{\max}} dE_\gamma \cdot \sigma_{\mathrm{Born}}\left(E_{\mathrm{c.m.}}\sqrt{1 - E_\gamma/E_{\mathrm{c.m.}}}\right) \cdot F\left(E_{\mathrm{c.m.}}, E_\gamma\right),$$

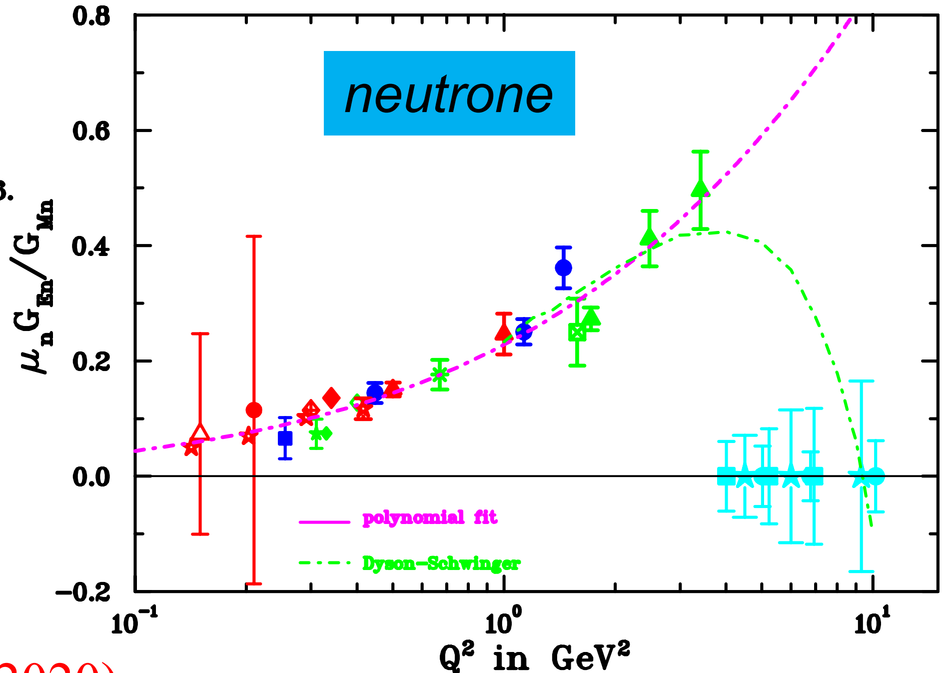
$$\sigma_{\mathrm{Born}}(E_{\mathrm{c.m.}}) = A + B\left[1 - \exp\left(-\frac{(E_{\mathrm{c.m.}} - E_{\mathrm{thr}})}{\sigma_{\mathrm{thr}}}\right)\right],$$

...and future plans



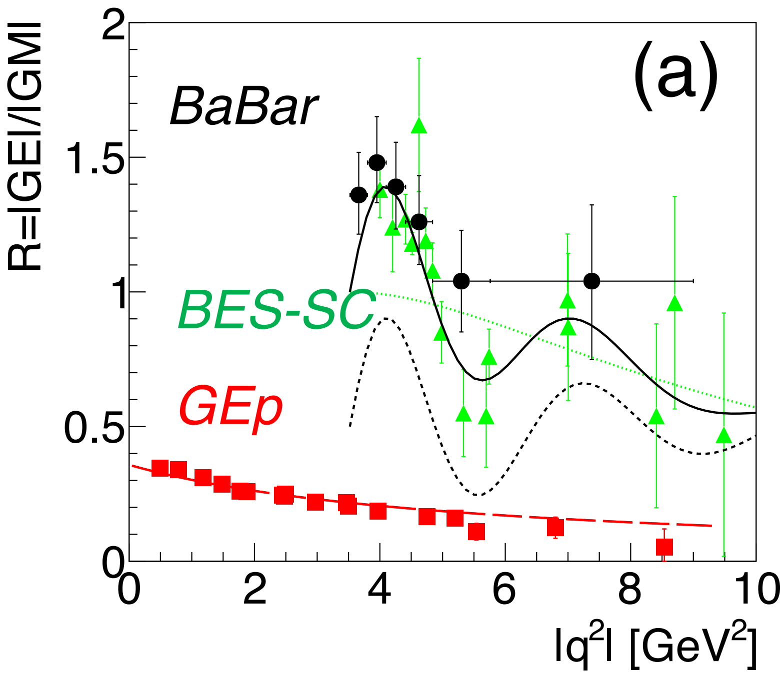
Ch. Perdrisat, Jlab PR12-07-109

J. Anderson Jlab PR12-09-009
J. Annand Jlab PR12-09-019



S.N. Basilev et al, Eur.Phys.J.A 56 (2020)

Form Factor Ratio R=|GE|/|GM|

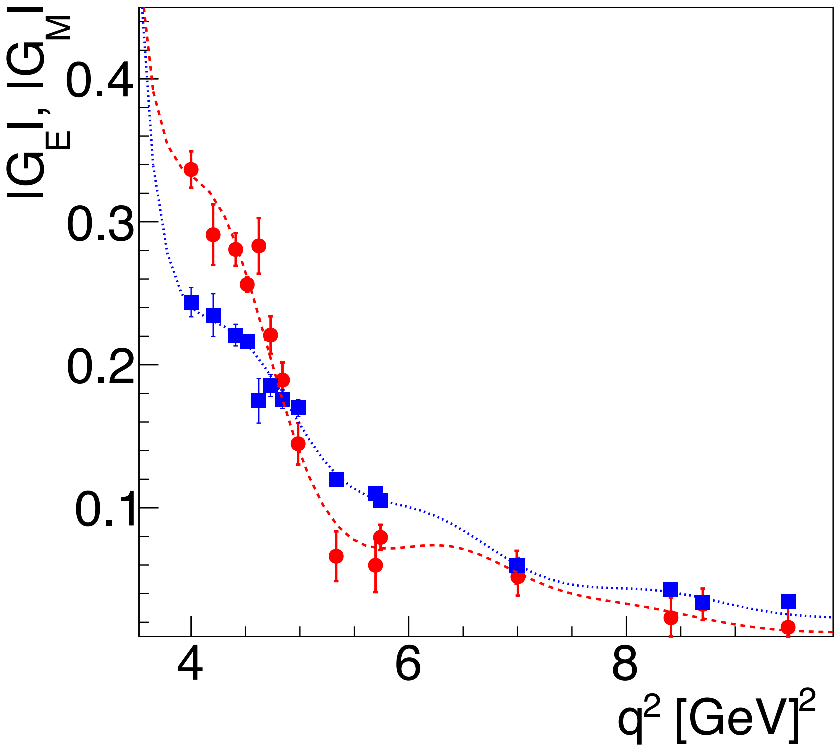


- Precise data from BESIII
- Dip at $|q^2|$~5.8 GeV^2
- Comparison with SL (Jlab-GEp data)
- Oscillations on top of a monopole: from GE or GM?

$$F_R(\omega(s)) = \frac{1}{1+\omega^2/r_0}\left[1 + r_1 e^{-r_2\omega}\sin(r_3\omega)\right],\ \omega = \sqrt{s} - 2m_p\,,$$

Sachs form factors: $|G_E|$, $|G_M|$

From the fit on Fp and the fit on R,
the Sachs FFs (moduli) can be reconstructed



$$|G_E(s)| = F_p(s)\sqrt{\frac{1+2\tau}{R^2(s)+2\tau/R^2(s)}}$$

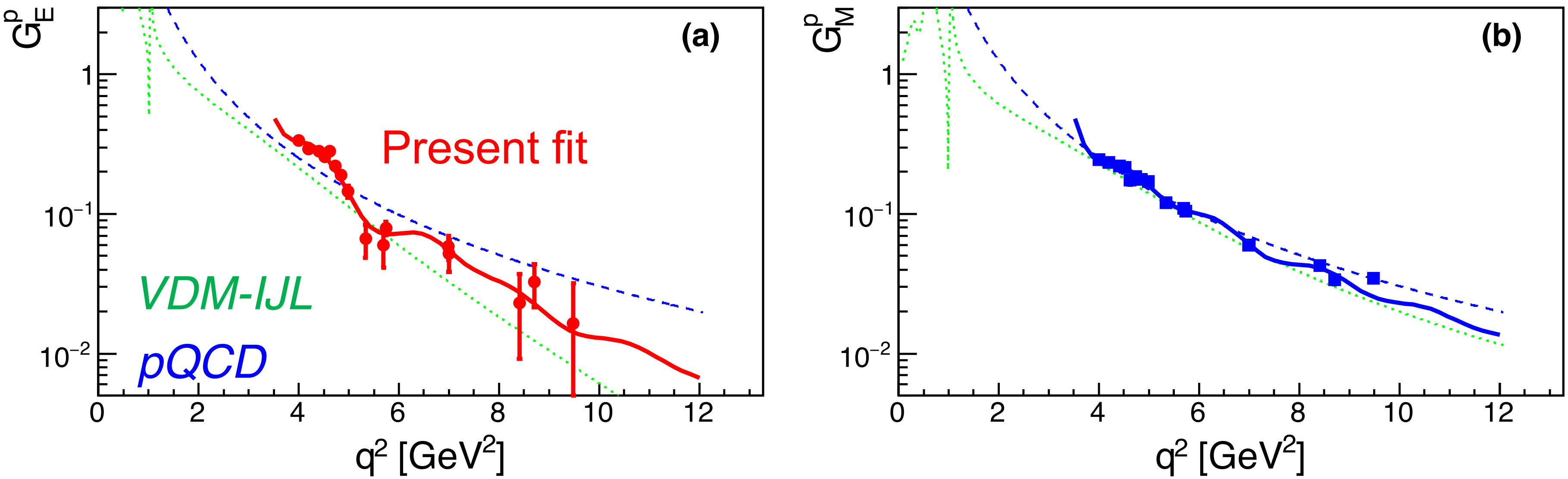
$$|G_M(s)| = F_p(s)\sqrt{\frac{1+2\tau}{R^2(s)+2\tau}}.$$

Threshold constrain R=1 for $\tau=1$
The fit gives :
$|G_E| = |G_M| = 0.48$

E.T.-G., A. Bianconi, S. Pacetti, Phys.Rev.C 103 (2021) 3, 035203

Models

Parametrizations have been determined by fitting Fp & R



|GE|: more pronounced oscillations
faster q^2-decrease

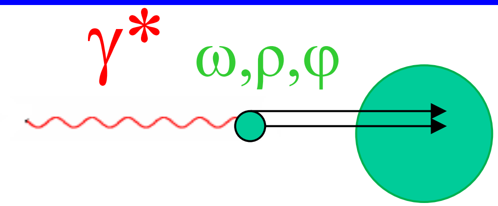
Threshold constrain R=1 for $\tau=1$

The fit gives : pQCD : 0.34

$|G_E| = |G_M| = 0.48$ VDM-IJL : 0.29

E.T.-G., A. Bianconi, S. Pacetti, Phys.Rev.C 103 (2021) 3, 035203

VMD: Iachello, Jakson and Landé (1973)



Isoscalar and isovector FFs

$$F_1^s(Q^2) = \frac{g(Q^2)}{2}\left[(1-\beta_\omega-\beta_\phi)+\beta_\omega\frac{\mu_\omega^2}{\mu_\omega^2+Q^2}+\beta_\phi\frac{\mu_\phi^2}{\mu_\phi^2+Q^2}\right],$$

$$F_1^v(Q^2) = \frac{g(Q^2)}{2}\left[(1-\beta_\rho)+\beta_\rho\frac{\mu_\rho^2+8\Gamma_\rho\mu_\pi/\pi}{(\mu_\rho^2+Q^2)+(4\mu_\pi^2+Q^2)\Gamma_\rho\alpha(Q^2)/\mu_\pi}\right],$$

$$F_2^s(Q^2) = \frac{g(Q^2)}{2}\left[(\mu_p+\mu_n-1-\alpha_\phi)\frac{\mu_\omega^2}{\mu_\omega^2+Q^2}+\alpha_\phi\frac{\mu_\phi^2}{\mu_\phi^2+Q^2}\right],$$

$$F_2^v(Q^2) = \frac{g(Q^2)}{2}\left[(\mu_p-\mu_n-1)\frac{\mu_\rho^2+8\Gamma_\rho\mu_\pi/\pi}{(\mu_\rho^2+Q^2)+(4\mu_\pi^2+Q^2)\Gamma_\rho\alpha(Q^2)/\mu_\pi}\right],$$

$$g(Q^2) = \frac{1}{(1+\gamma e^{i\theta}Q^2)^2}$$

Intrinsic factor

Meson Cloud

$$2F_i^p = F_i^s + F_i^v,$$
$$2F_i^n = F_i^s - F_i^v.$$

Few # parameters, with physical meaning

Naturally arising TL imaginary part

$$\alpha(Q^2) = \frac{2}{\pi}\sqrt{\frac{Q^2+4\mu_\pi^2}{Q^2}}\, ln\left[\frac{\sqrt{(Q^2+4\mu_\pi^2)}+\sqrt{Q^2}}{2\mu_\pi}\right]$$

Total Cross Section from $e^+e^- \to p\bar{p}$

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

- Effective FF: $\sigma_{Tot} \sim F_p^2$

$$F_p(s)^2 = \frac{2\tau|G_M(s)|^2 + |G_E(s)|^2}{2\tau+1}$$

- Equivalent to:

$$|G_E(s)| = |G_M(s)| \equiv F_p(s)$$

Strictly valid at threshold, where only one amplitude is present

Focus to threshold

• Large activity at all world facilities both in Space and Time-like regions

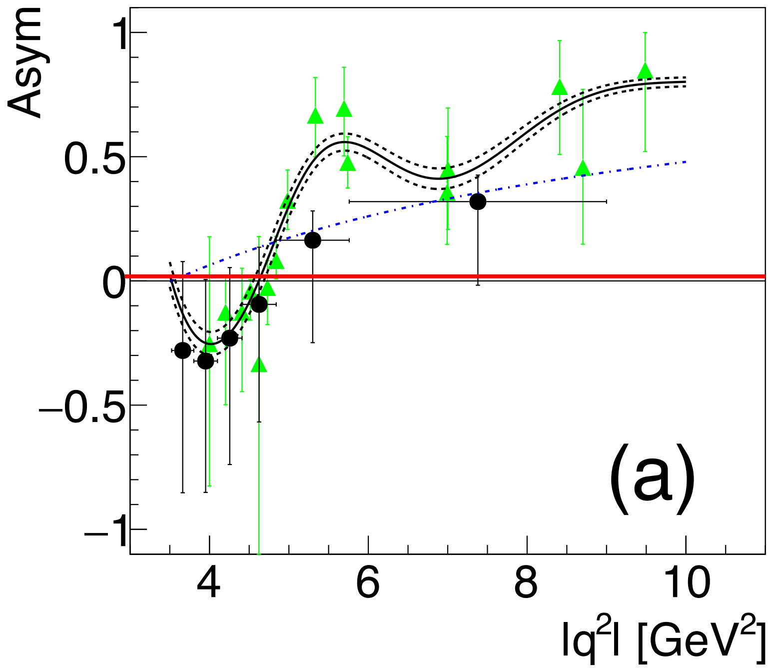
• Theory: unified models in SL and TL regions:
- *describe all 4 FFs:*
  proton and neutron, electric and magnetic

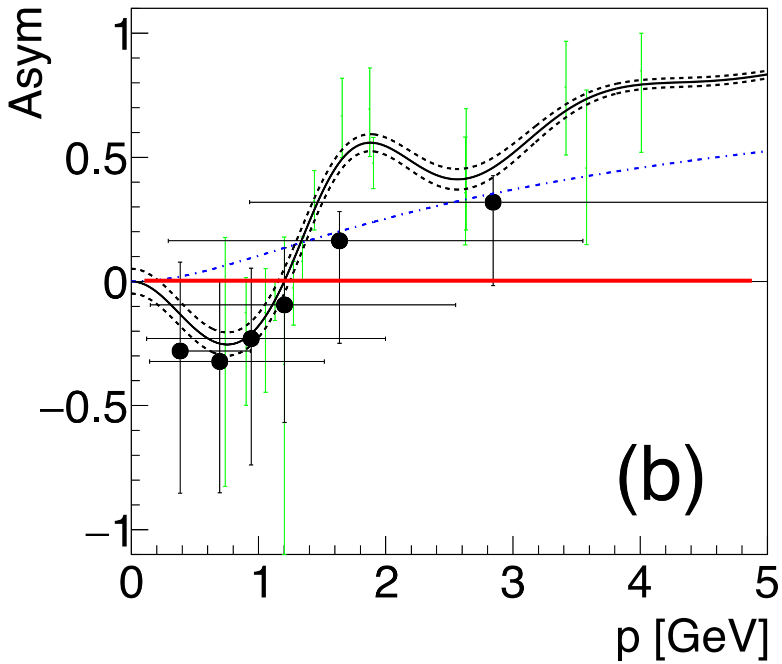
• Features in SL and TL regions explained by an inner vacuum:
- monopole decrease of R in n&p, SL &TL, diquark phase
  prediction of non-zero crossing of SL ratio

• $p\bar{p}$ annihilation at threshold : pointlike?:
- R=1 : but what is the value of FFs? test of models
- Are the e+e- ↔ pp really equivalent? related by time reversal, but … FSI, Coulomb interaction, radiative corrections…

Time structure of the nucleon: enter the 4th dimension !

Angular Asymmetry





$$\frac{d\sigma_{e^+e^-\to\bar{p}p}}{d\Omega}(s,\theta) = \sigma_0(s)\left[1+\mathcal{A}(s)\cos^2(\theta)\right]$$

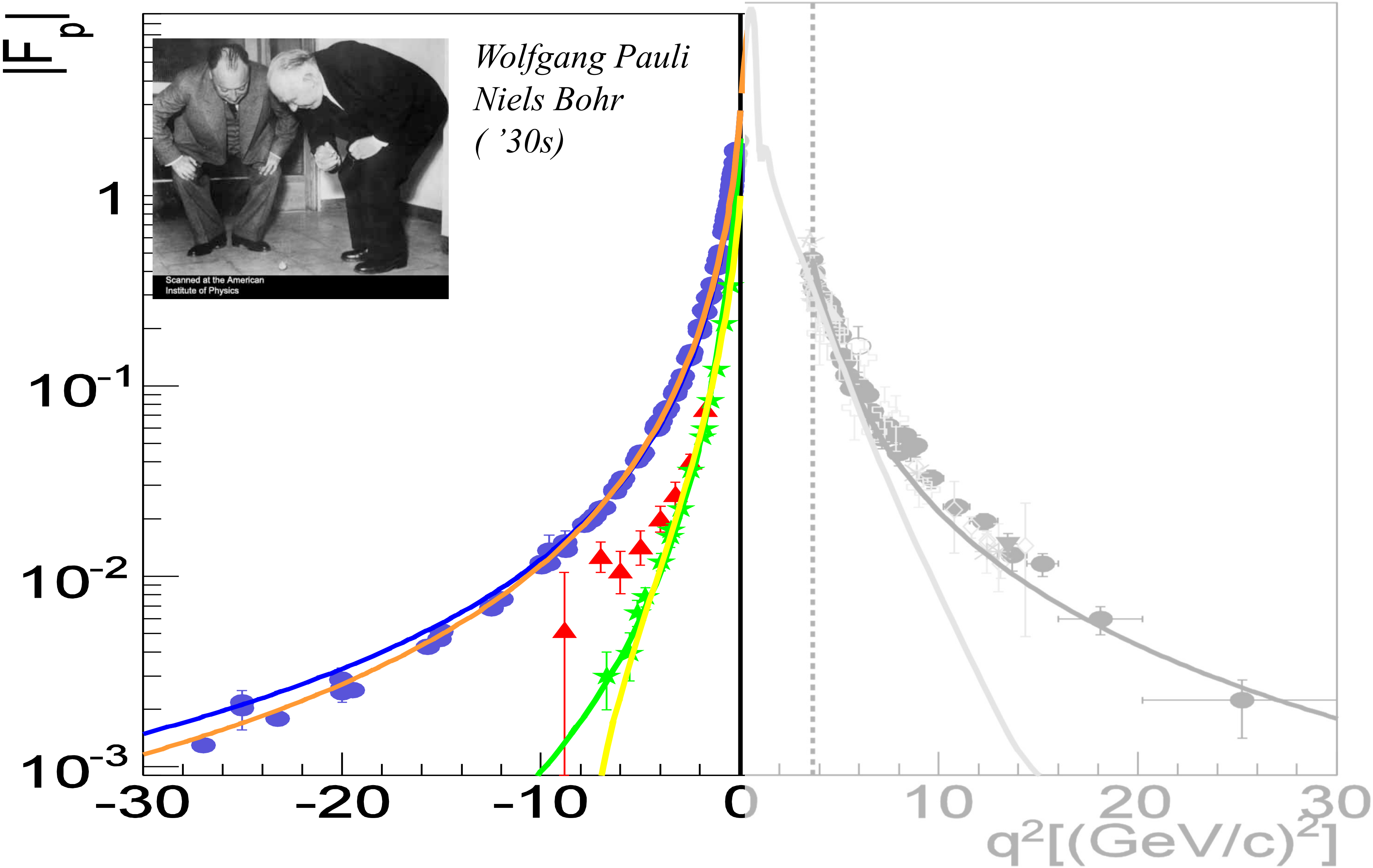
$$\sigma_0(s) = \frac{\alpha^2\beta\,\mathcal{C}(\beta)}{4s}\left(|G_M(s)|^2+\frac{1}{\tau}|G_E(s)|^2\right)$$

$$\mathcal{A}(s) = \frac{\tau|G_M(s)|^2-|G_E(s)|^2}{\tau|G_M(s)|^2+|G_E(s)|^2} = \frac{\tau-R(s)^2}{\tau+R(s)^2}$$

q^2 =(4.60 ± 0.07) GeV^2
p =(1.20 ± 0.04) GeV

Zero of the angular asymmetry

The Space-Like region

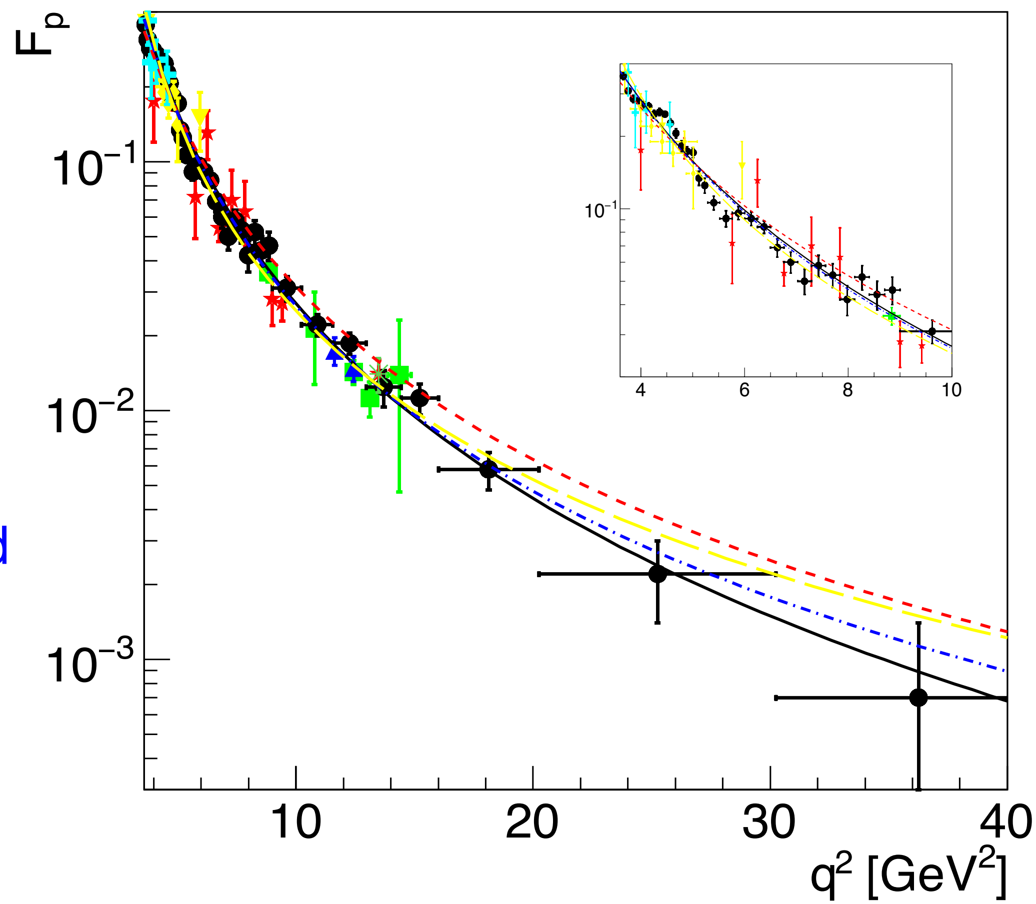


The Time-like Region

$G_E = G_M$

The Experimental Status

- Individual determination of GE and GM : only recently!
- TL proton FFs twice larger than in SL at the same Q^2
- Steep behaviour at threshold
- BaBAR:Structures?
  Resonances?



Confirmed by BES

S. Pacetti, R. Baldini-Ferroli, E.T-G , Physics Reports, 514 (2014) 1

Panda contribution: *M.P. Rekalo, E.T-G , DAPNIA-04-01, ArXiv:0810.4245.*

ep-elastic scattering :
The Akhiezer-Rekalo method

PHYSICS

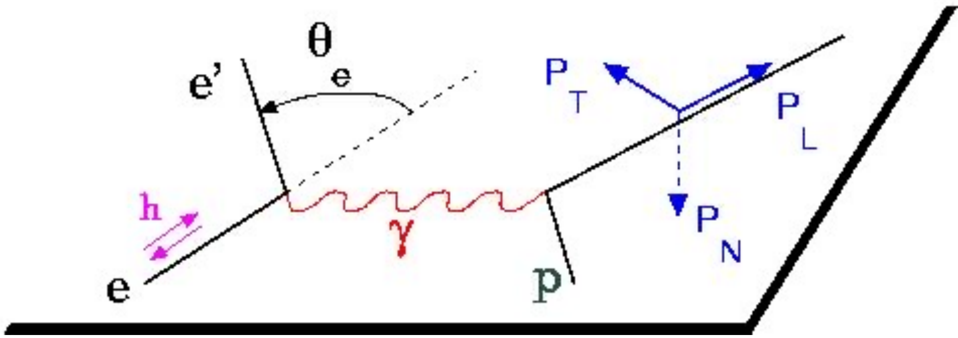
1967

POLARIZATION PHENOMENA IN ELECTRON SCATTERING BY PROTONS IN THE HIGH-ENERGY REGION

Academician A. I. Akhiezer* and M. P. Rekalo

Physicotechnical Institute, Academy of Sciences of the Ukrainian SSR
Translated from Doklady Akademii Nauk SSSR, Vol. 180, No. 5, pp. 1081-1083, June, 1968
Original article submitted February 26,

$$s_2 \frac{d\sigma}{d\Omega_R} = 4p_2 \frac{(s\cdot q)}{1+\tau} \Gamma(\theta, \varepsilon_1) \left[\tau G_M (G_M + G_E) - \frac{1}{4\varepsilon_1} G_M (G_E - \tau G_M)\right],$$



The polarization induces a term in the cross section proportional to $G_E\, G_M$

Polarized beam and target or

polarized beam and recoil proton polarization

The polarization method (exp: 2000)

Transferred polarization is:

C. Perdrisat, V. Punjabi, et al., JLab-GEp collaboration

$$P_n = 0$$

$$\pm h P_t = \mp h\, 2\sqrt{\tau(1+\tau)} G_E^p G_M^p \tan\left(\frac{\theta_e}{2}\right) / I_0$$

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

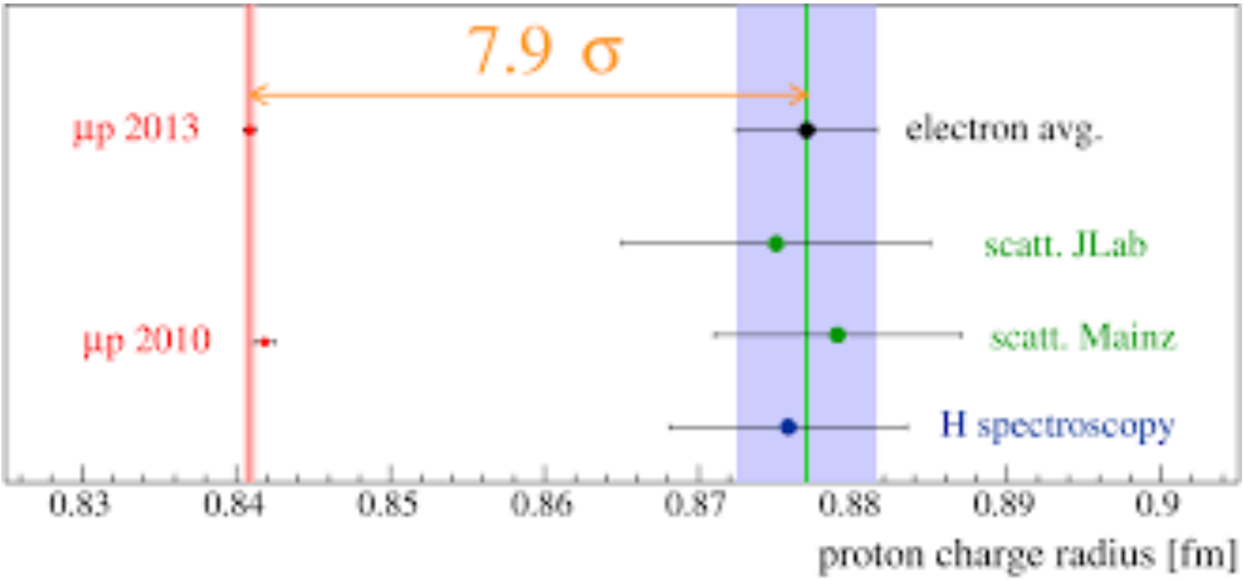
Where, $h = |h|$ is the beam helicity

$$I_0 = (G_E^p(Q^2))^2 + \frac{\tau}{\epsilon}(G_M^p(Q^2))^2$$

$$\Longrightarrow \frac{G_E^p}{G_M^p} = -\frac{P_t}{P_l}\frac{E_e + E_{e'}}{2M}\tan\left(\frac{\theta_e}{2}\right)$$

The simultaneous measurement of P_t and P_l reduces the systematic errors

The SIZE of the proton

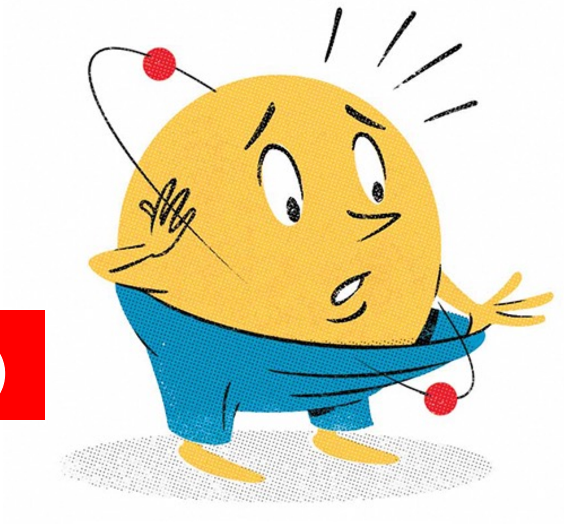


Rp=0.879(18) fm

Rp=0.8768(69) fm

Rp=0.84184(67) fm (muonic H)

Rp=0.8335(95) fm (new H)



The New York Times