PLB 712(2012)240

A light in the complexity of proton and neutron structure 10 years of Арбуз model

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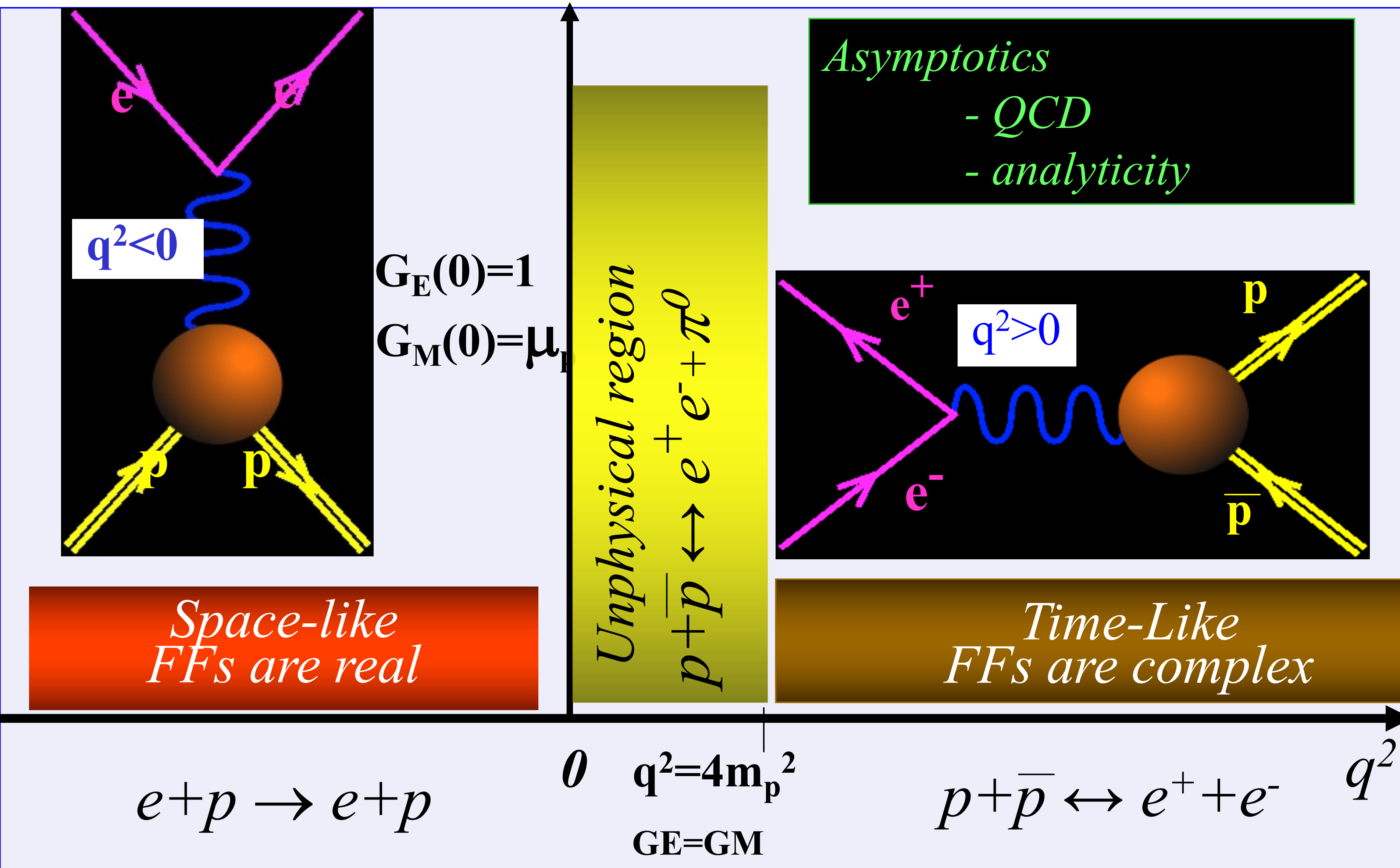
ArXiv: 2205.0917, 2204.05197

PANDA Coll. Meeting, EM Session, May 31, 2022

Nucleon Charge and Magnetic Distributions



Experimental fact

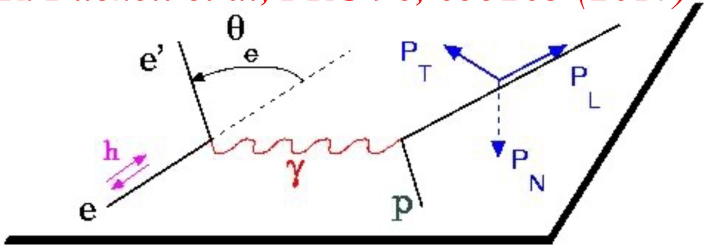
- Precise data on the proton space-like form factors by the Akhiezer-Rekalo recoil proton polarization method show that the electric and magnetic distributions in the proton are different, suggesting a steaper Q^2-decrease and eventually a zero-crossing of GE.

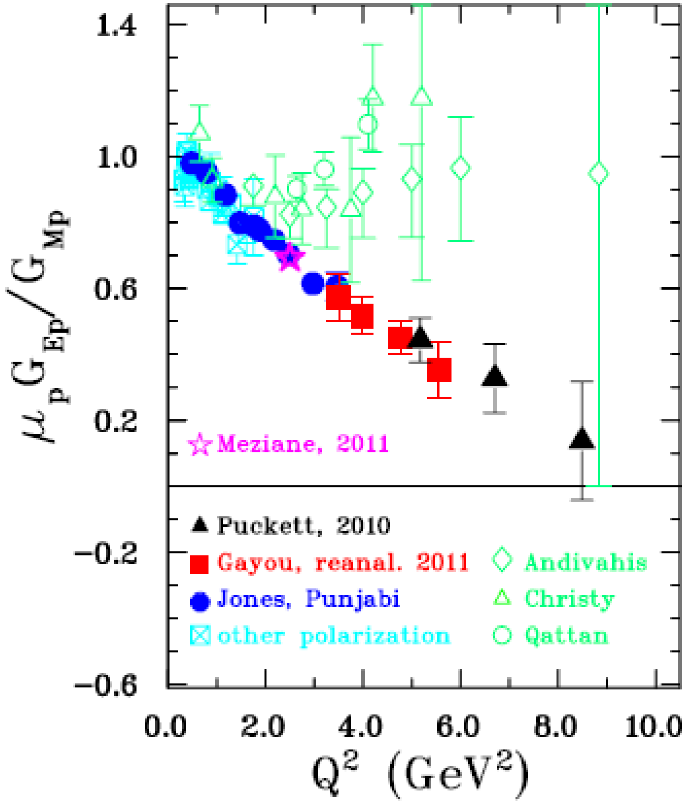
- The FF ratio decreases as a monopole

- G_M follows a dipole

- It is well accepted today that the polarization method gives THE reliable measurement of the EM FF ratio at large Q^2 (compared to the Rosenbluth method).

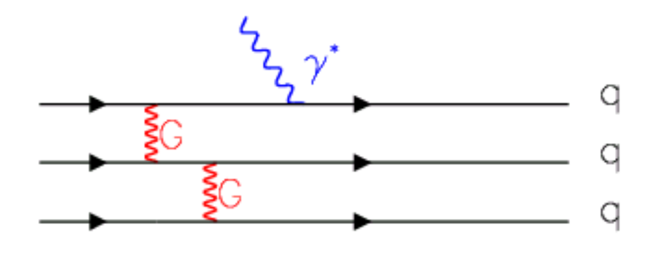
JLab-GEp Collaboration
J.R. Puckett et al, PRC 96, 055203 (2017)





Ch. Perdrisat, V. Punjabi

The Time-like Region



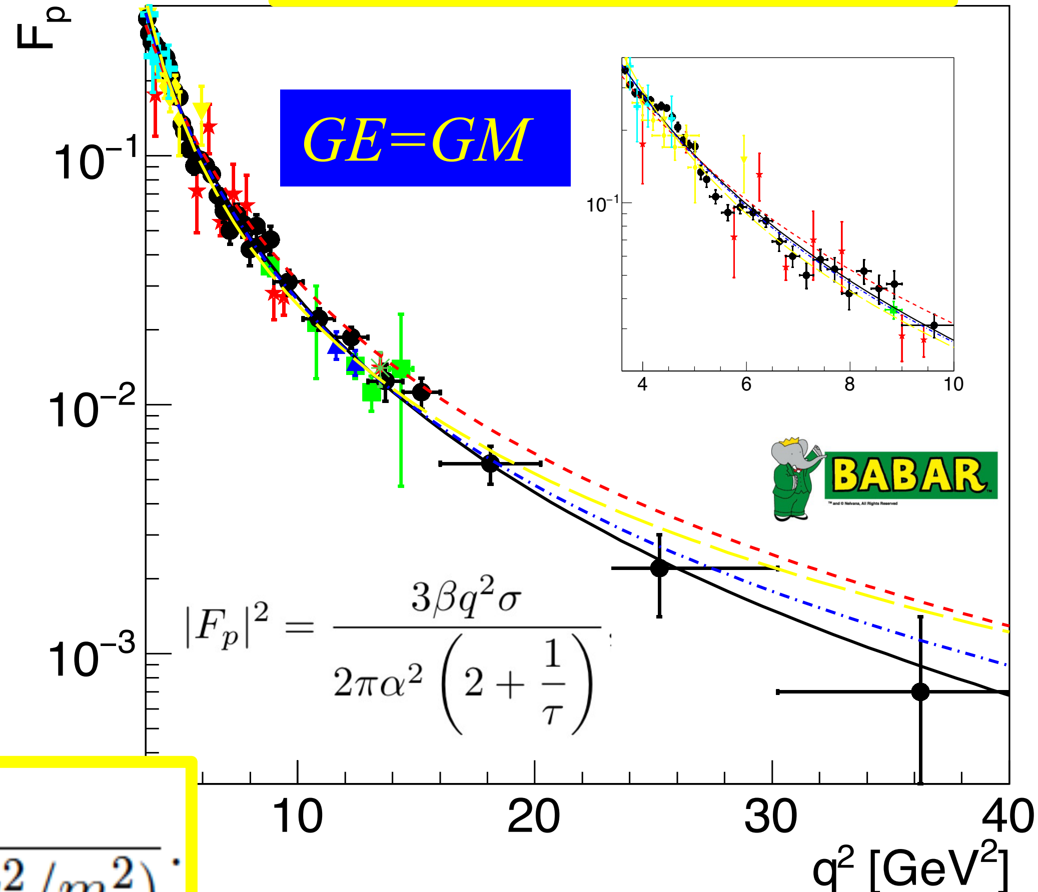
Expected QCD scaling $(q^2)^2$

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

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

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

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



$$|F_p|^2 = \frac{3\beta q^2\sigma}{2\pi\alpha^2\left(2+\frac{1}{\tau}\right)}$$

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

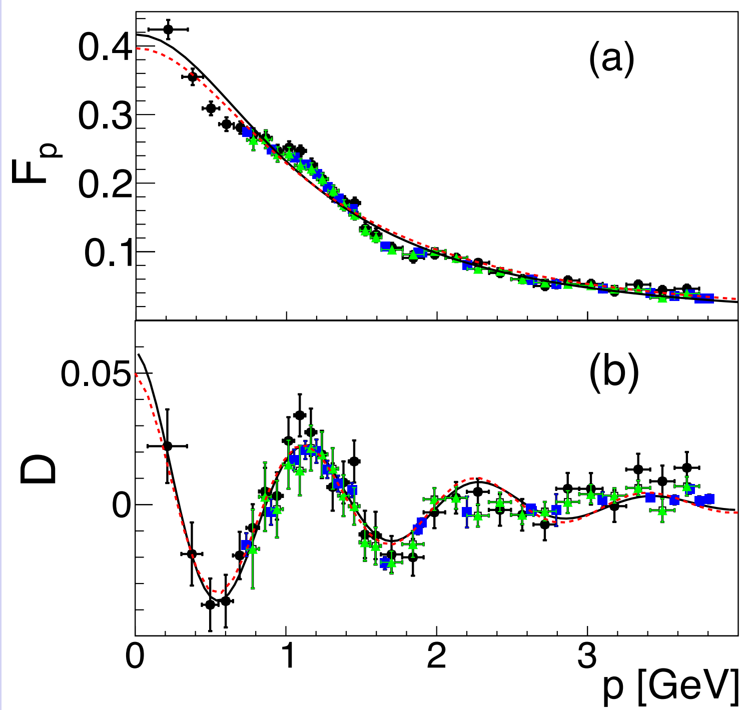
Experimental fact

- BaBar and BESIII data on the proton time-like effective form factor show a systematic sinusoidal modulation in terms od the p-$\bar{p}$ relative 3-momentum in the near-threshold region.

- ~ 10% size oscillations on the top of a regular background (dipole x monopole)

- The periodicity and the simple shape of the oscillations point to a unique interference mechanism, which occurs when the hadrons are separated by ~1 fm.

- The hadronic matter is distributed in non-trivial way.



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

$$F_{\rm 3p}(s) = \frac{F_0}{\left(1+\frac{s}{m_a^2}\right)\left(1-\frac{s}{m_0^2}\right)^2},$$

$$F_{\rm osc}(p(s)) = Ae^{-Bp}\cos(Cp+D).$$

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

Fourier Transform

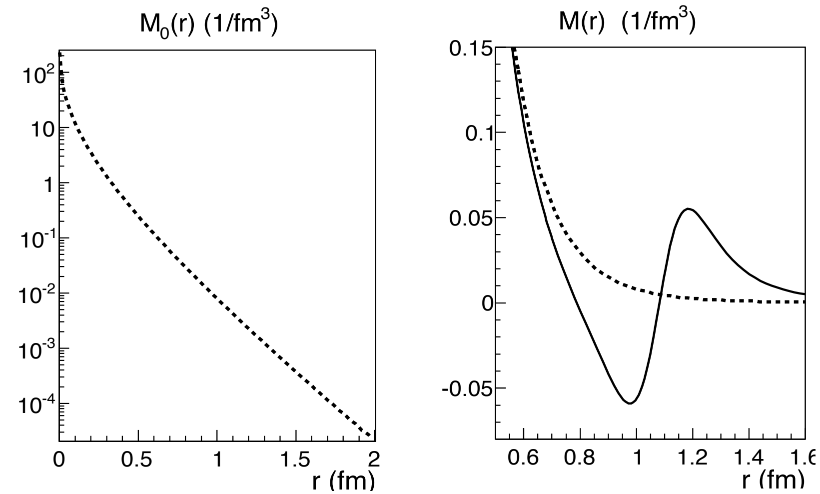
A.Bianconi, E. T-G., Phys. Rev. Lett. 114, 232301 (2015)

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

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

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

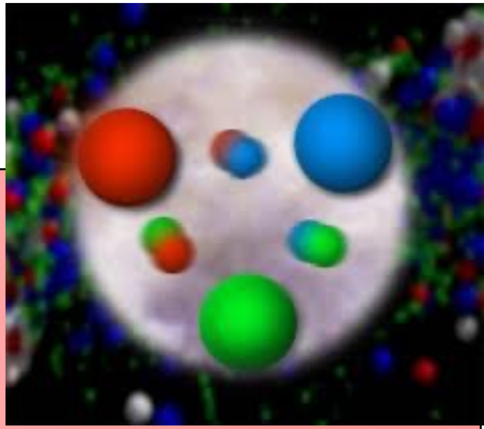
$$F_{osc}(p) \equiv A\ \exp(-Bp)\ \cos(Cp + D).$$



- *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*

The nucleon according to Арбуз

It is generally assumed that the nucleon is composed by 3 valence quarks and a neutral sea of $q\bar{q}$ pairs



Nucleon: antisymmetric state of colored quarks

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

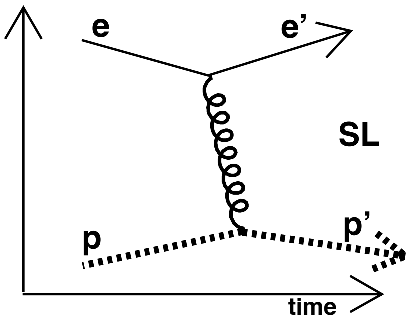
Main assumption of the Арбуз model:

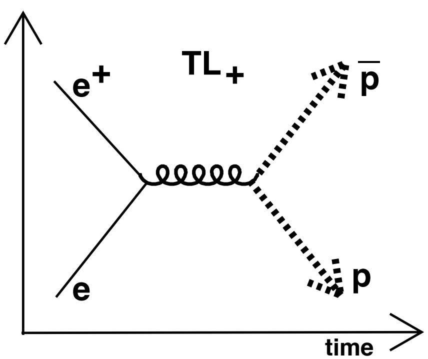
Does not hold in the spatial center of the nucleon: the center of the nucleon *is electrically neutral,* due to the strong gluonic field

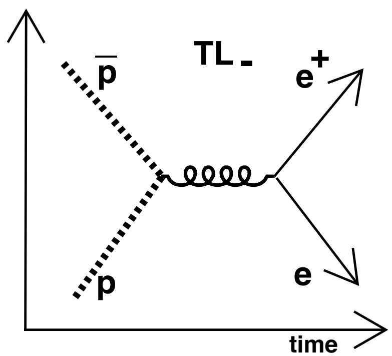
Compare the dynamical description of this model to the recent FF **data : *p, n, G_E, G_M, Geff, TL &SL***

Definition of TL-SL Form Factors

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







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

SL photon 'sees' a charge density

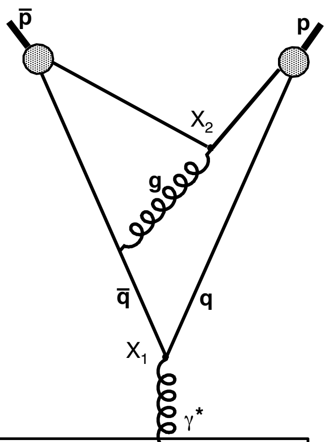
TL photon can NOT test a space distribution

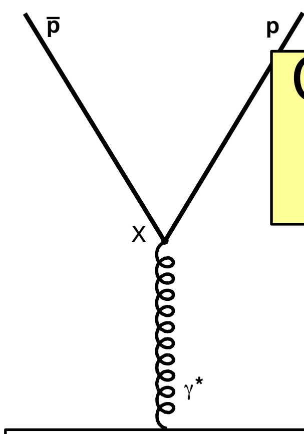
How to connect and understand the amplitudes?

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*





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

The simplest picture: qq pair + compact di-quark

Resolved *Unresolved* *representation*

The nucleon

Inner region: gluonic condensate of clusters with randomly oriented chromo-magnetic field (Vainshtein, 1982, instanton model):

Intensity of the gluon field in vacuum:

$$< 0|\alpha_s/\pi(G^a_{\mu\nu})^2|0 >\sim E^2 - B^2 \sim E^2 = 0.012\ \mathrm{GeV}^{\,4}.$$

$$G^2 \simeq 0.012\,\pi/\alpha_s GeV^4,\ \text{i.e.,}\ E \simeq\ 0.245\,GeV^2. \quad \alpha_s/\pi \sim 0.1$$

In the internal region of strong chromo-magnetic field, the color quantum number of quarks does not play any role, due to stochastic averaging

$< G|u^i u^j|G >\sim \delta_{ij}$: proton

$d^i d^j$ neutron

Colorless quarks: Pauli principle

Model

Арбуз

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

1) uu (dd) quarks are repulsed from the inner region
2) The 3rd quark is attracted by one of the identical quarks, forming a compact di-quark
3) The color state is restored

Formation of di-quark: competition between attraction force and stochastic force of the gluon field

$$\frac{Q_q^2 e^2}{r_0^2} > e|Q_q|\,E.$$

isolated quark

proton: (u) $Qq = +1/3$
neutron: (d) $Qq = -2/3$

attraction force >stochastic force of the gluon field

QCD-Counting rules

V. A. Matveev, R.M. Muradian, A.N. Tavkhelidze, Nuovo Cimento Lett. 7 (1973) 719
S.J. Brodsky, G.R. Farrar, Phys. Rev. Lett. 31 (1973) 1153.

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

Normalization: $G_E^{(p,n)}(0) = 1, 0,\ G_M^{(p,n)}(0) = \mu_{p,n}$

Quark counting rules apply to the vector part of the potential

Model

Арбуз

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

$$\Delta\phi = -4\pi e \sum Z_i n_i, \; n_i = n_{i0} exp\left[-\frac{Z_i e\phi}{kT}\right]$$

Boltzmann constant

Neutrality condition: $\sum Z_i n_{i0} = 0$

$$\Delta\phi - \chi^2\phi = 0, \; \phi = \frac{e^{-\chi r}}{r}, \; \chi^2 = \frac{4\pi e^2 Z_i^2 n_{i0}}{kT}$$

Additional suppression (Fourier transform)

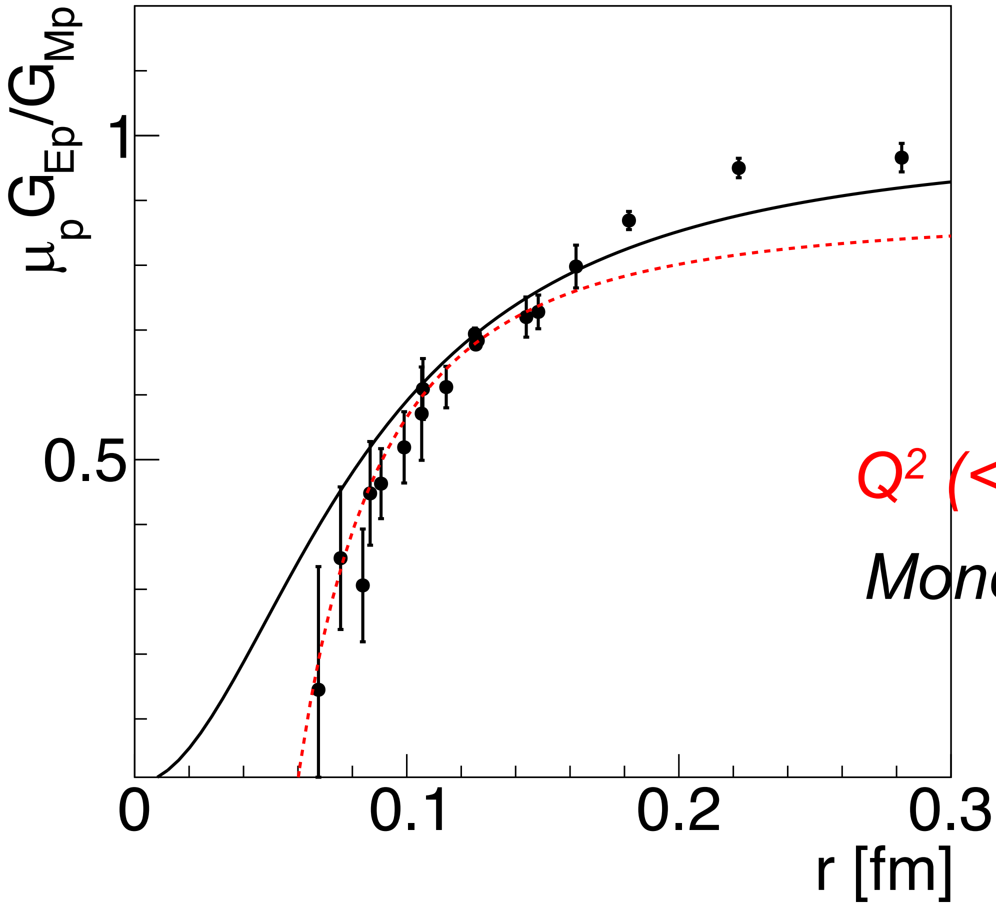
$$G_E(Q^2) = \frac{G_M(Q^2)}{\mu}\left(1 + Q^2/q_1^2\right)^{-1}$$

$q_1 (\equiv \chi)$

fitting parameter

SL Form Factors Ratio

Large Q^2-> Small r



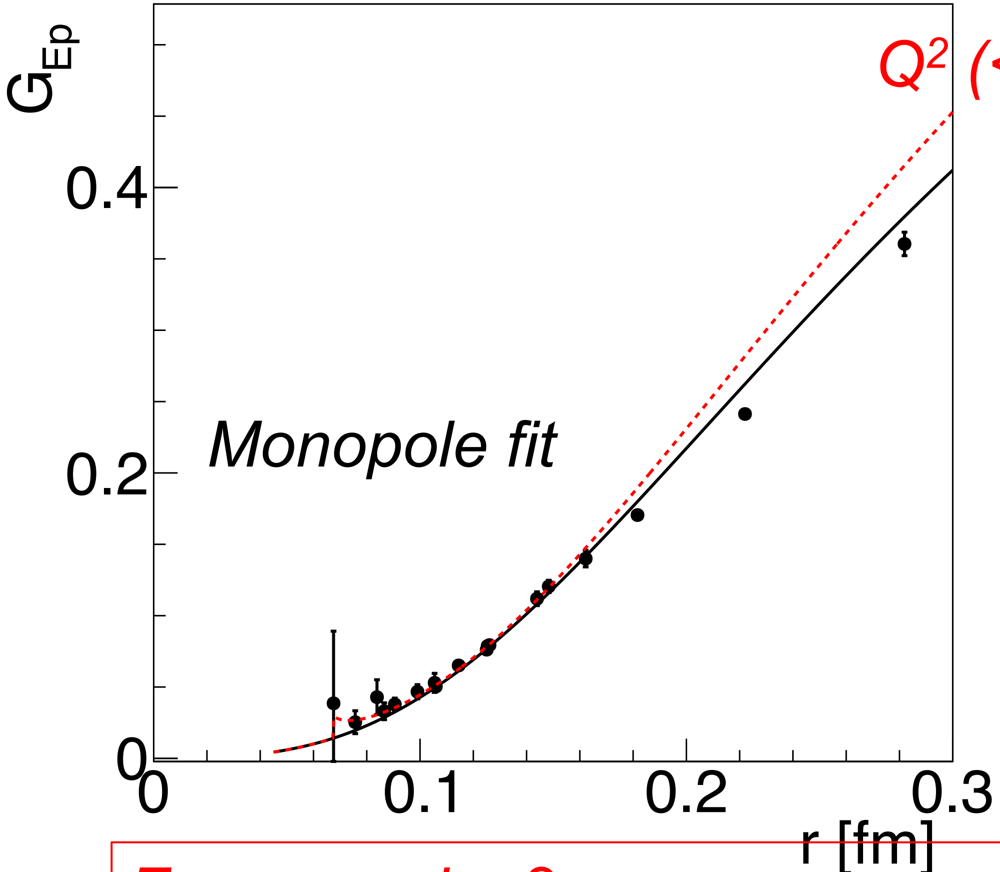
$$\mathcal{R} = \mu_p \frac{G_{Ep}}{G_{Mp}} = \left(1 + \frac{Q^2}{m_r^2}\right)^{-1}.$$

Q^2 (<0.15 GeV^2) – linear fit

Monopole fit

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

SL- the most precise ruler

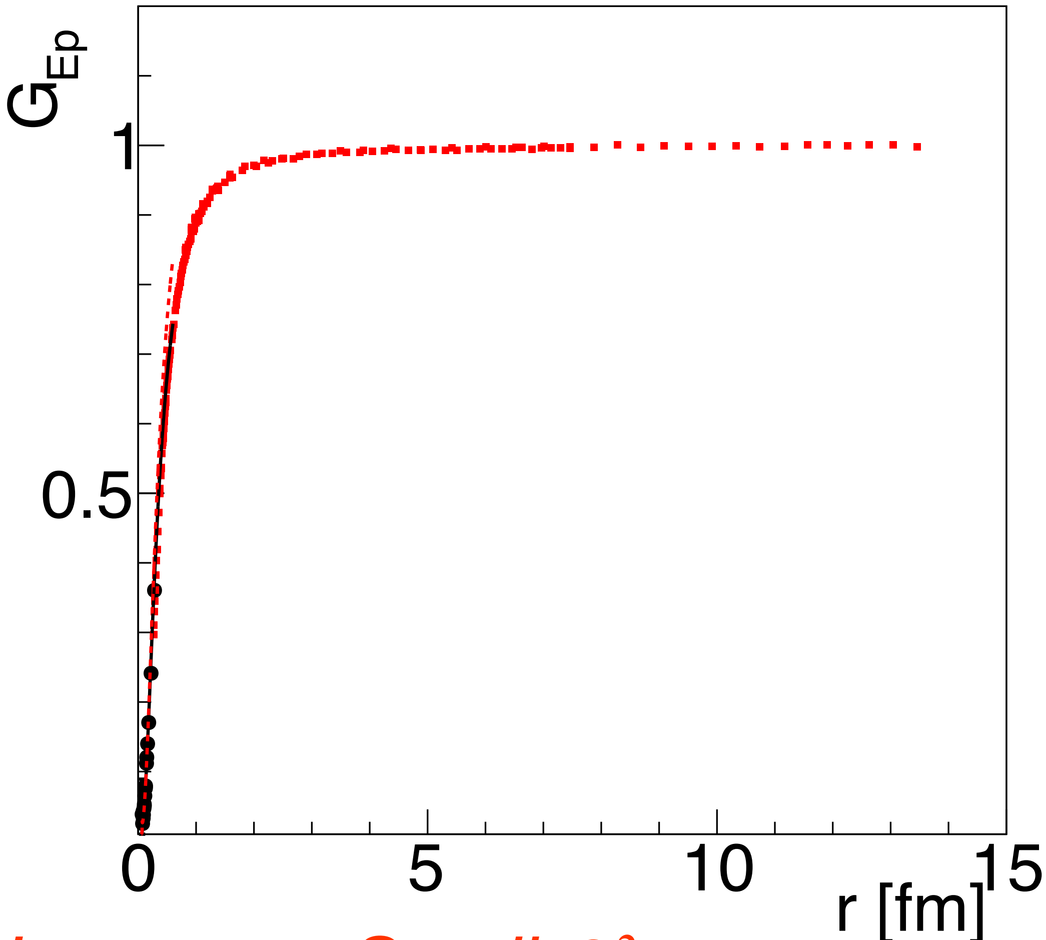


Zero crossing?

The photon 'sees' the neutral, screened, small region

Proton radius

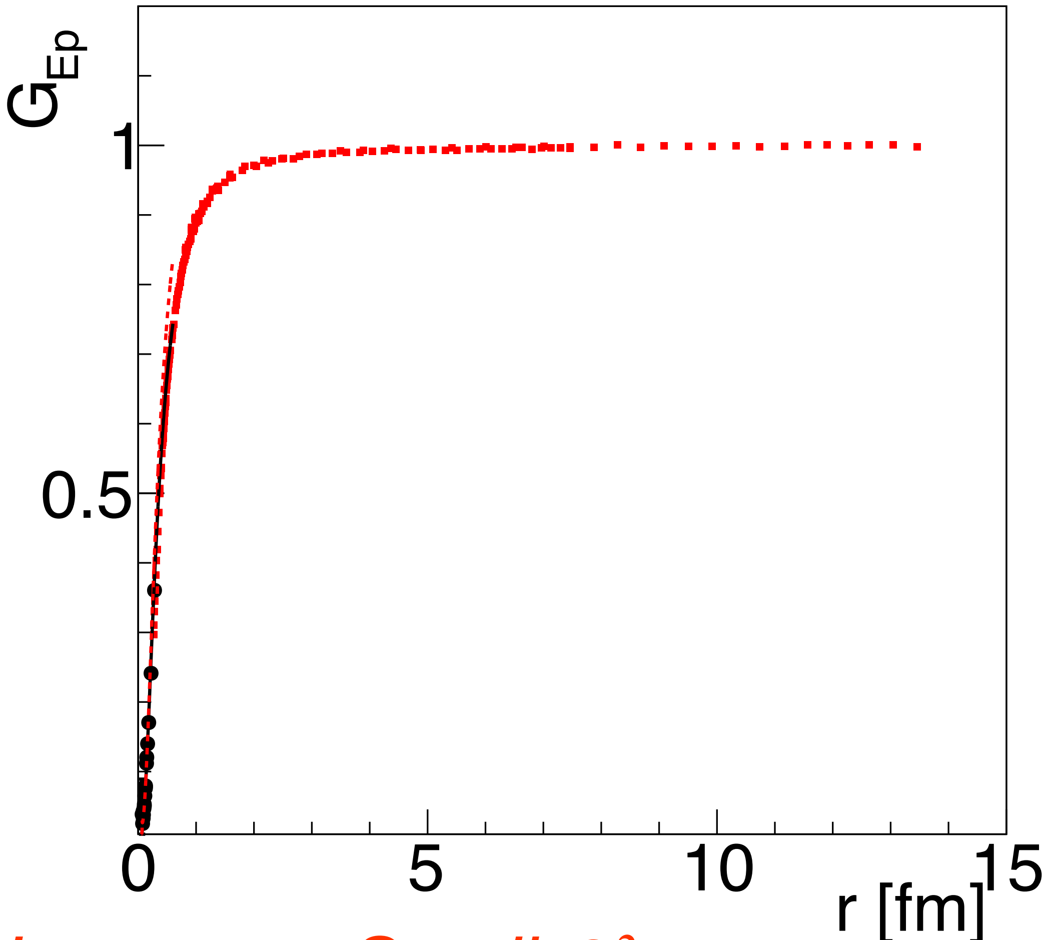
Data from Mainz,
PRC 90, 015206 (2014)



Large r -> Small Q^2

Proton radius

Data from Mainz, CLAS…



How can a photon with wavelength ~ 15 fm distinguish between a proton size of 0.84 or 0.87 fm?

Large r -> Small Q^2

The annihilation channel: $e^+ + e^- \to \gamma^*(q) \to p + \bar{p}$.

1) Creation of a $p\bar{p}$ state through ${}^3S_1 = < 0|J^\mu|p\bar{p} >$ intermediate state with $q = (\sqrt{q^2}, 0, 0, 0)$.

2) The vacuum state transfers all the released energy to a state of matter consisting of:

- 6 massless valence quarks
- Set of gluons
- Sea of current $q\bar{q}$ pairs of quarks with energy $q_0 > 2M_p$, J=1, dimensions $\hbar/(2M_p) \sim 0.1$ fm.

3) Pair of p and $\bar{p}$ formed by three bare quarks:

•Structureless

•Colorless → pointlike FFs !!!

The annihilation channel: $e^+ + e^- \to \gamma^*(q) \to p + \bar{p}$.

- The point-like hadron pair expands and cools down: the current quarks and antiquarks absorb gluon and transform into constituent quarks

- The residual energy turns into kinetic energy of the motion with relative velocity $2\beta = 2\sqrt{1 - 4M_p^2/q_0^2}$.

- The strong chromo-EM field leads to an effective loss of color. Fermi statistics: identical quarks are repulsed. The remaining quark of different flavor is attracted to one of the identical quarks, creating a compact diquark (*du*-state)

The annihilation channel: $e^+ + e^- \to \gamma^*(q) \to p + \bar{p}$.

Арбуз

The repulsion of p and $\bar{p}$ with kinetic energy

$$T = \sqrt{q^2} - 2M_p c^2$$

is balanced by the confinement potential

$$q_0 - 2M_p c^2 = (k/2)R^2$$

- The long range color forces create a stable colorless state of proton and antiproton
- The initial energy is dissipated from current to constituent quarks originating on shell $\bar{p}p$ separated by R.

The annihilation channel: $e^+ + e^- \to \gamma^*(q) \to p + \bar{p}$

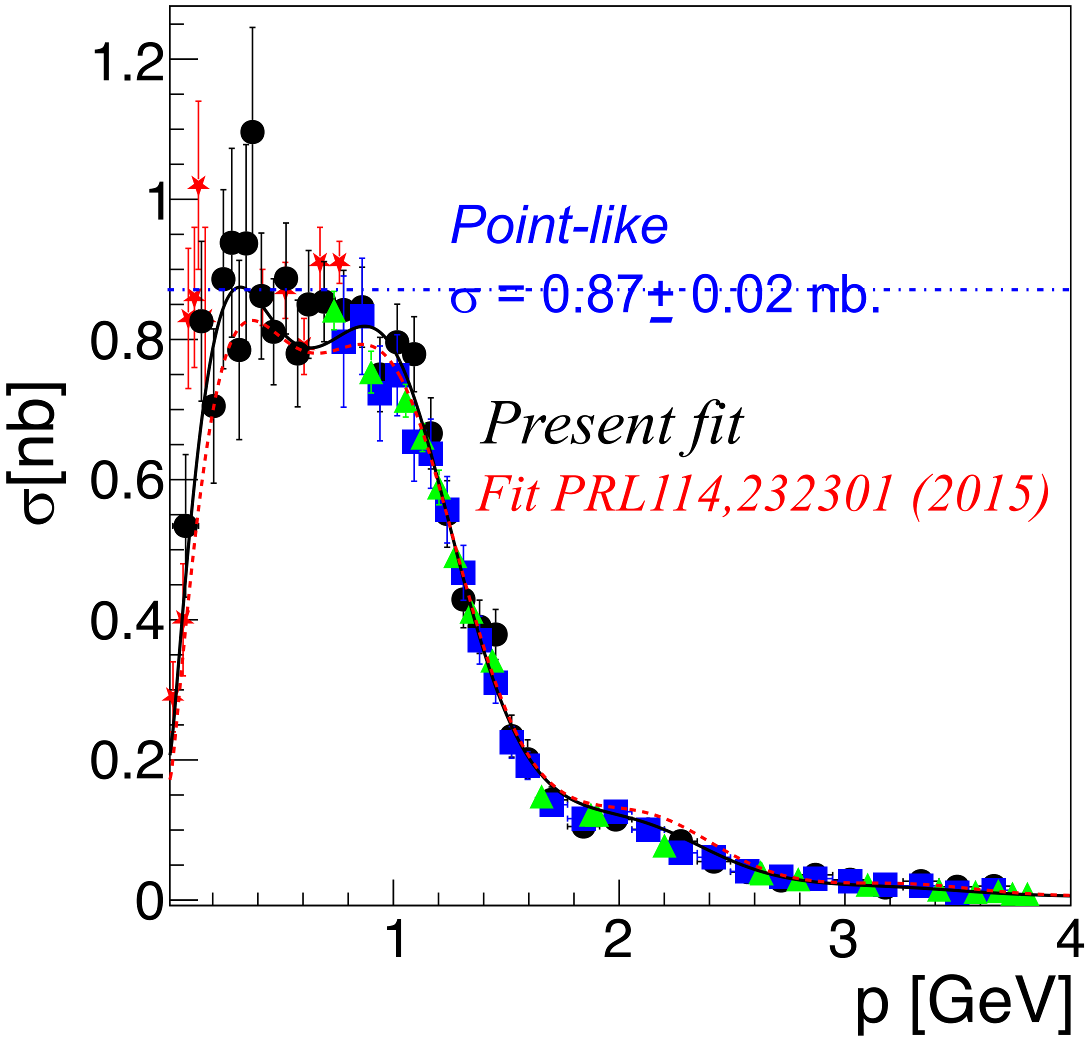
Арбуз

At larger distances, the inertial force exceeds the confinement force: p and $\bar{p}$ start to move apart with relative velocity β

p and $\bar{p}$ leave the interaction region: at larger distances the integral of Q(t) must vanish.

For very small values of the velocity $\alpha\pi/\beta \simeq 1$ *FSI lead to the creation of a bound $\bar{N}N$ system .*

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



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

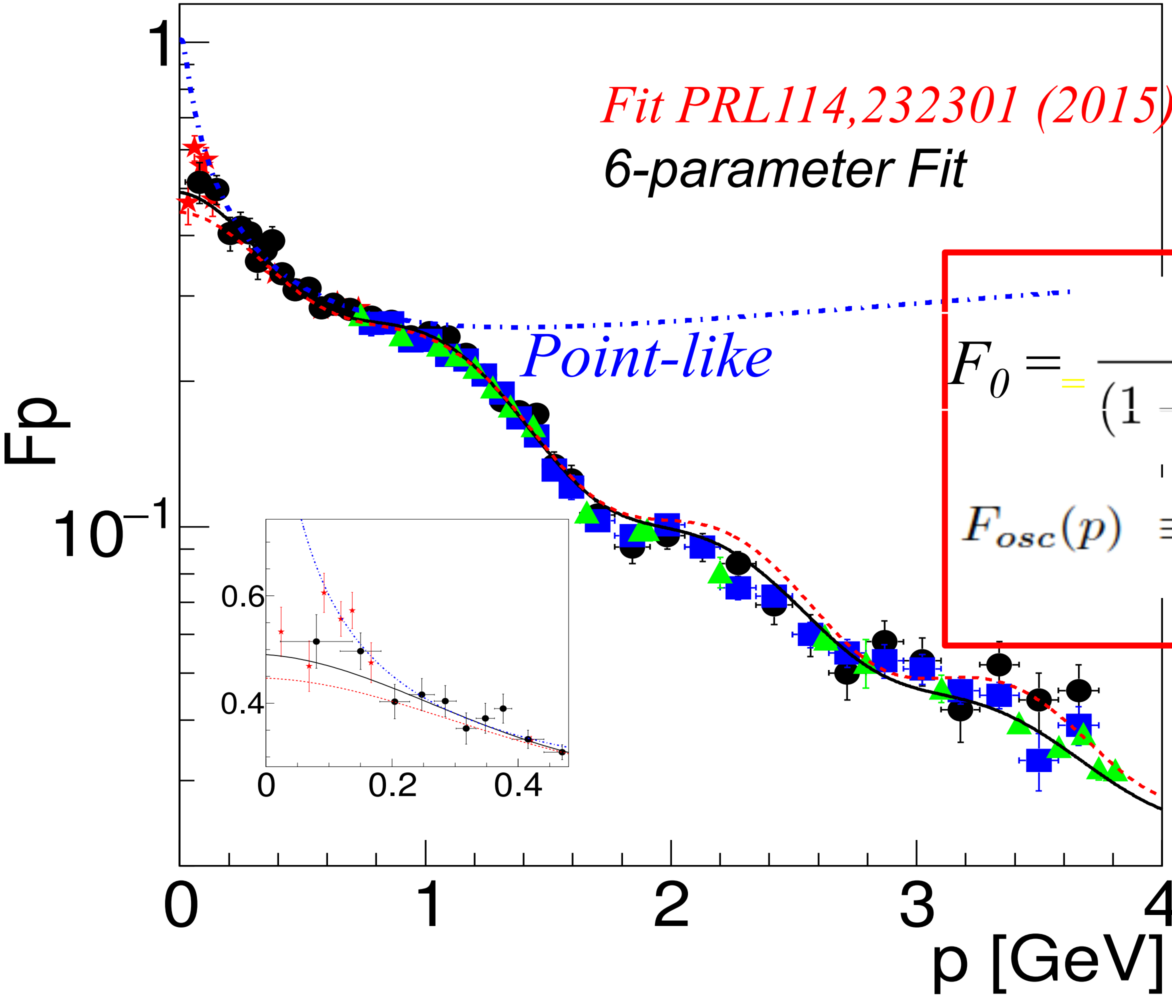
BaBar 85pt
1.9<2E<4.5
PRD87,092005 (2013)

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

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

Generalized Form Factor

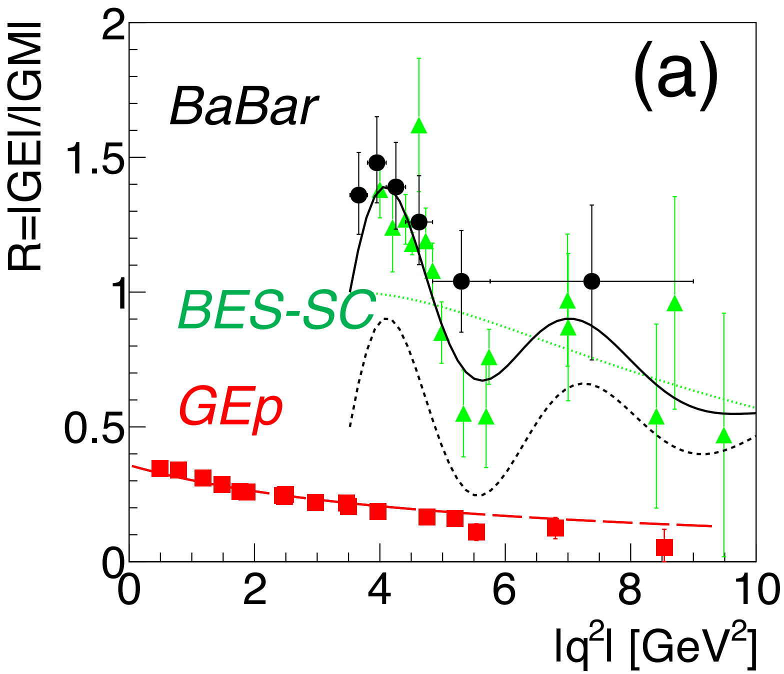
$$F_p(s)^2 = \frac{2\tau|G_M(s)|^2 + |G_E(s)|^2}{2\tau + 1}$$



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

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

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

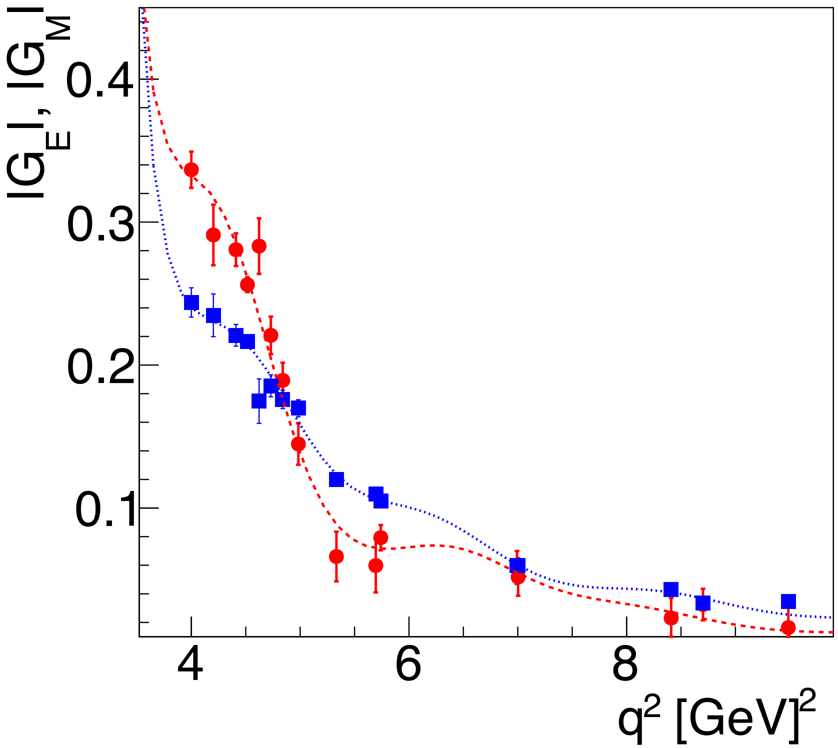


- Precise data from BESIII
- Dip at $|q^2|$~5.8 GeV^2
- Comparison with SL (Jlab-GEp data)
- Oscillations on top of a monopole: from GE or GM?

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

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

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



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

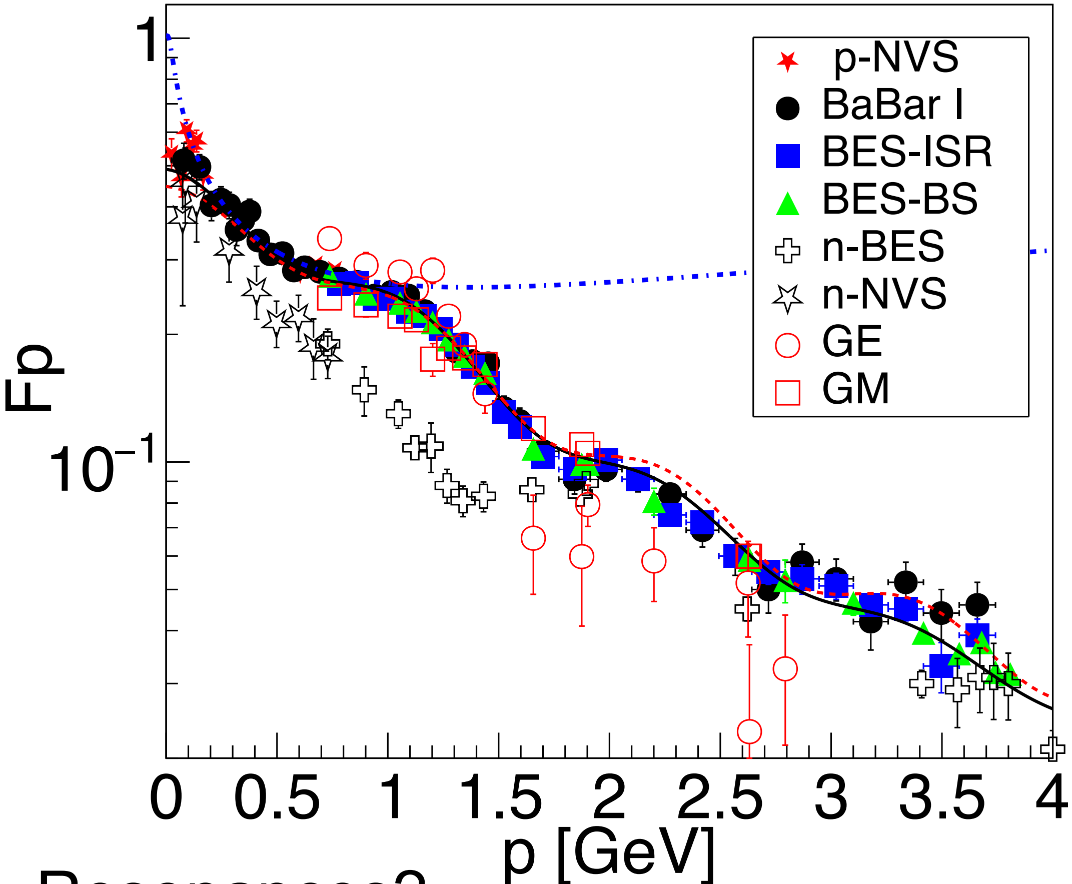
$$|G_M(s)| = F_p(s)\sqrt{\frac{1+2\tau}{R^2(s)+2\tau}}.$$

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

Proton & Neutron

Similar 6-parameter fit for p & n with a different phase

M. Ablikim et al. (BESIII Collaboration), Nature Phys. 17, 1200 (2021)

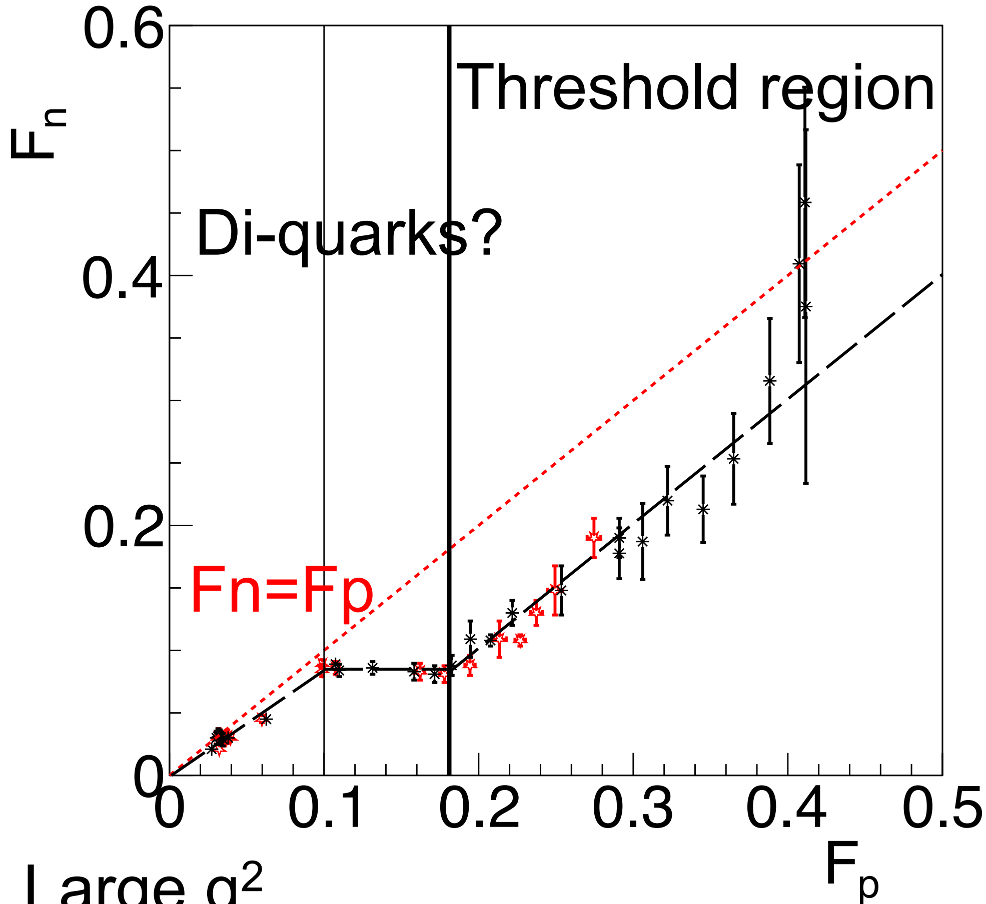


- Depends on background
- n-fit without Novosibirsk data

Resonances?

H. Lin, H.-W. Hammer, and U.-G. Meissner, P.R.L. 128, 052002 (2022)

np-correlation : 3 steps?



Large q^2

Experimental points at the same P_L

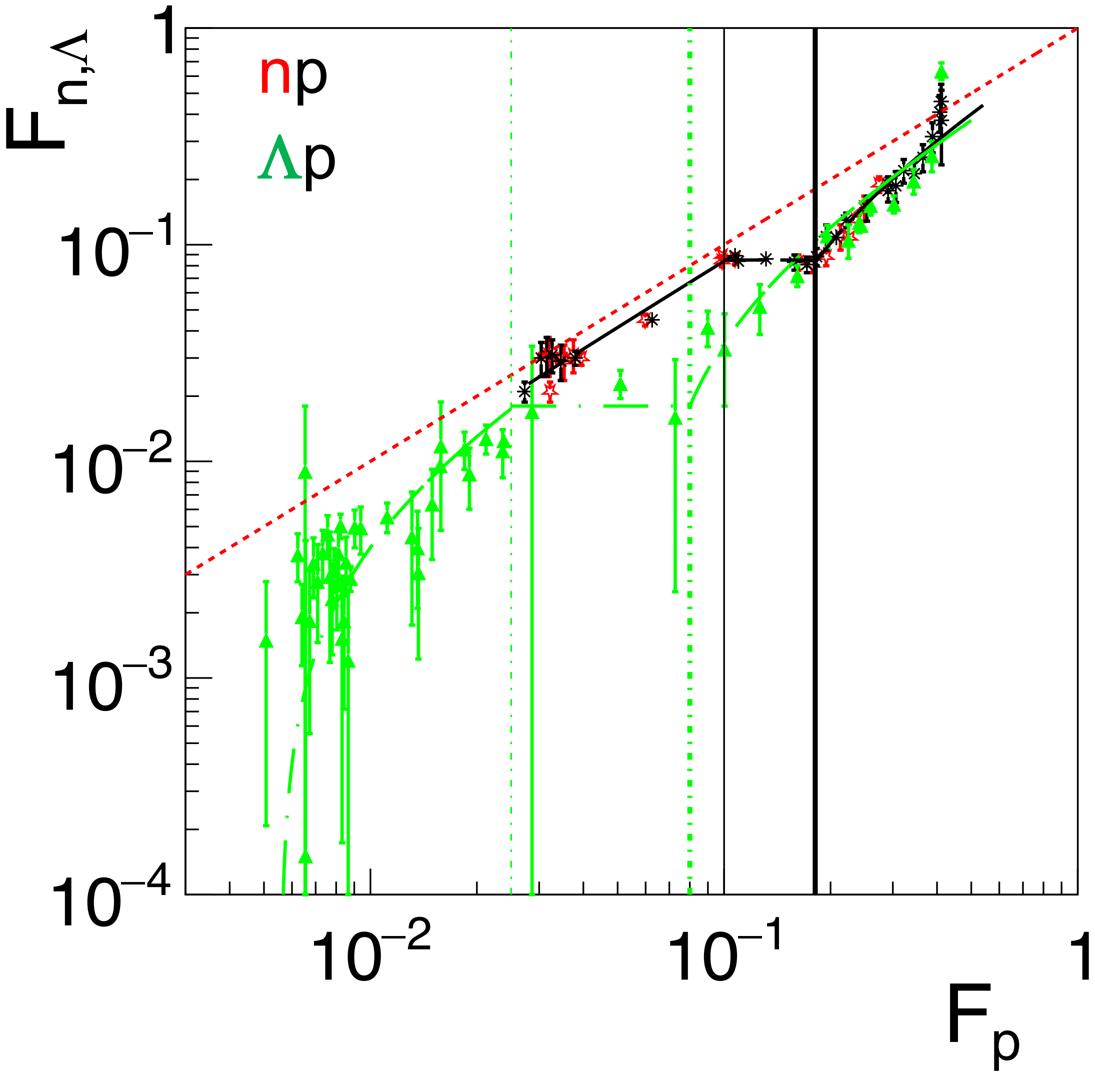
Proton values calculated from the 6-parameter fit

1) pQCD applies

2) n-p independent
 (di-quark
 charge redistributed)

3) The hadron is formed

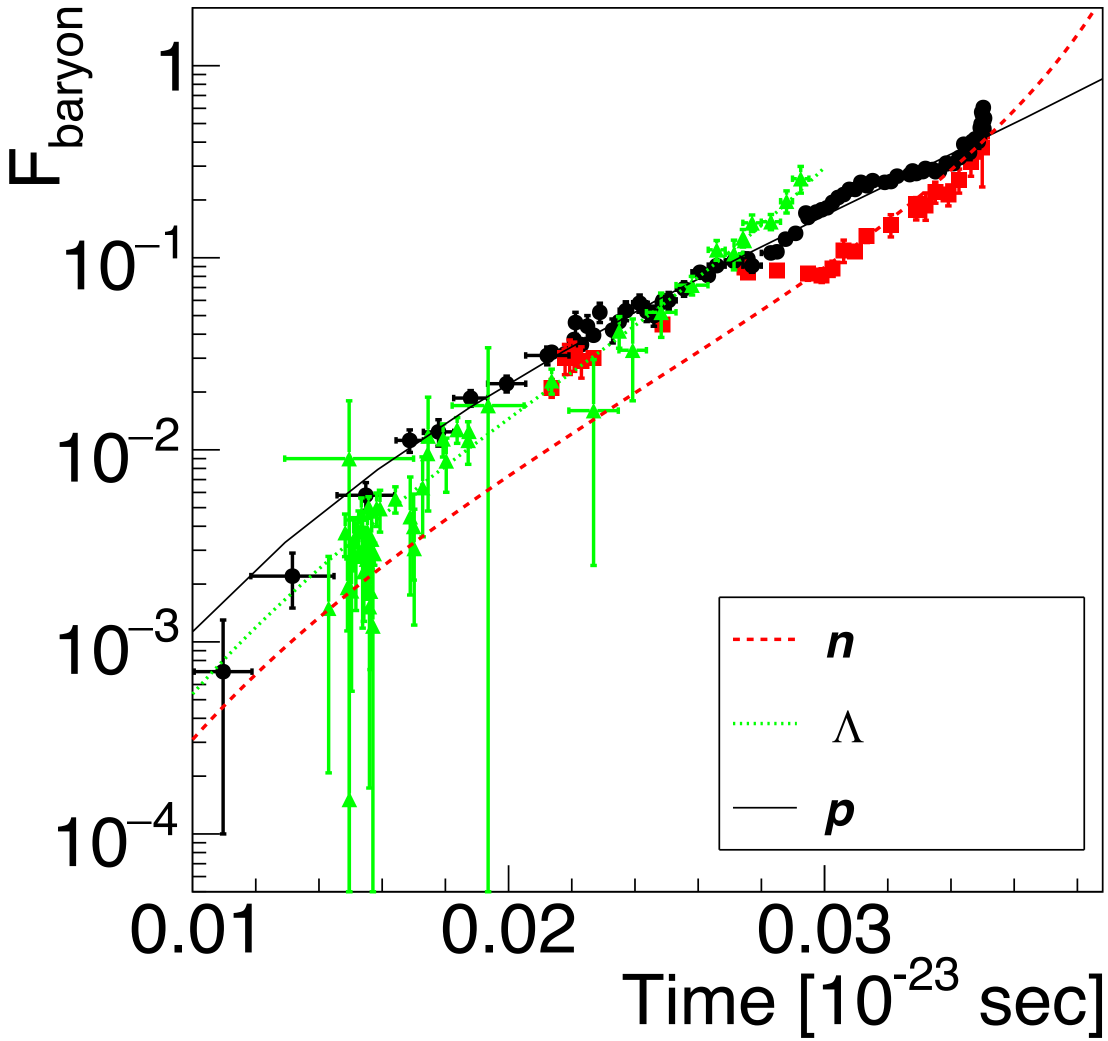
npΛ-correlation



3 steps:

The quantum vacuum is '<u>democratic</u>': *all quark flavors are equally probable,* but, due to Heisenberg principle, the *time associated to the vacuum fluctuations depends on the energy (mass)*

TL- the most precise clock



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

Conclusions

- BESIII precise data on time-like n & p form factors, their ratio and *first determination of individual FFs ($|G_E|$ and $|G_M|$)*
- *FFs ratio:* damped oscillations around a monopole decrease
- Oscillations more pronounced in $|G_E|$
- Origin of oscillatory phenomena :
  Di-quark as a necessary step towards hadron creation?
- *Main features of the SL and TL FFs data qualitatively explained by the* Арбуз model:
  - ➢ The monopole-like decrease of the FF ratio
  - ➢ The formation of a di-quark component in the nucleon
  - ➢ The npΛ correlation
- Predicts
  - similarities between n&p, SL & TL, non zero crossing in SL

Deepen the connections with instantons.

Thank you for your attention

Model

$$\frac{Q_q^2 e^2}{r_0^2} > e|Q_q|\, E.$$

attraction force >
stochastic force of the gluon field

Proton: r_0=0.18 fm, p_0 = 0.86 GeV

Neutron: r_0=0.33 fm, p_0 = 0.61 GeV

Applies to the scalar part of the potential

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

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

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

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

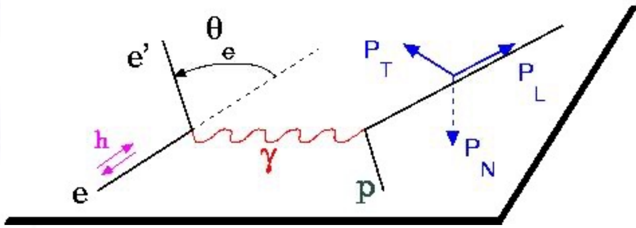
- Equivalent to:

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

Strictly valid at threshold, where only one amplitude is present

SOVIET PHYSICS – DOKLADY VOL. 13, NO. 6 DECEMBER, 1968

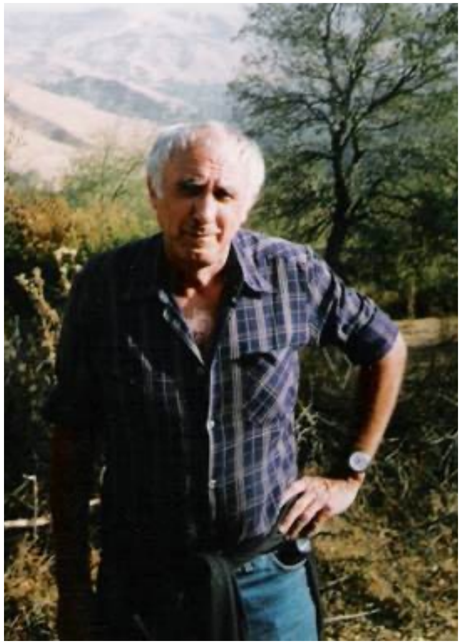
PHYSICS



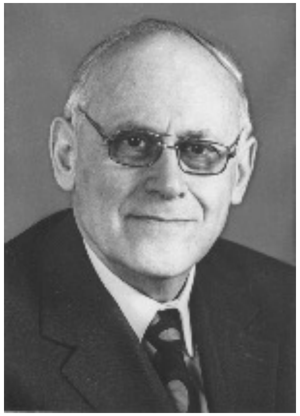
POLARIZATION PHENOMENA IN ELECTRON SCATTERING BY PROTONS IN THE HIGH-ENERGY REGION

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, 1967



M.P. Rekalo
(1938-2004)



A.I. Akhiezer
(1911-2000)

$$S_2 \frac{d\sigma}{d\Omega_R} = 4p_2 \frac{(s\cdot q)}{1+\tau}\Gamma(\theta,\ \varepsilon_1)\Big[\tau G_M (G_M + G_E) - \frac{1}{4\varepsilon_1} G_M (G_E - \tau G_M)\Big],$$

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