The space-time electromagnetic structure of hadrons

IWHSS-2022

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In collaboration with
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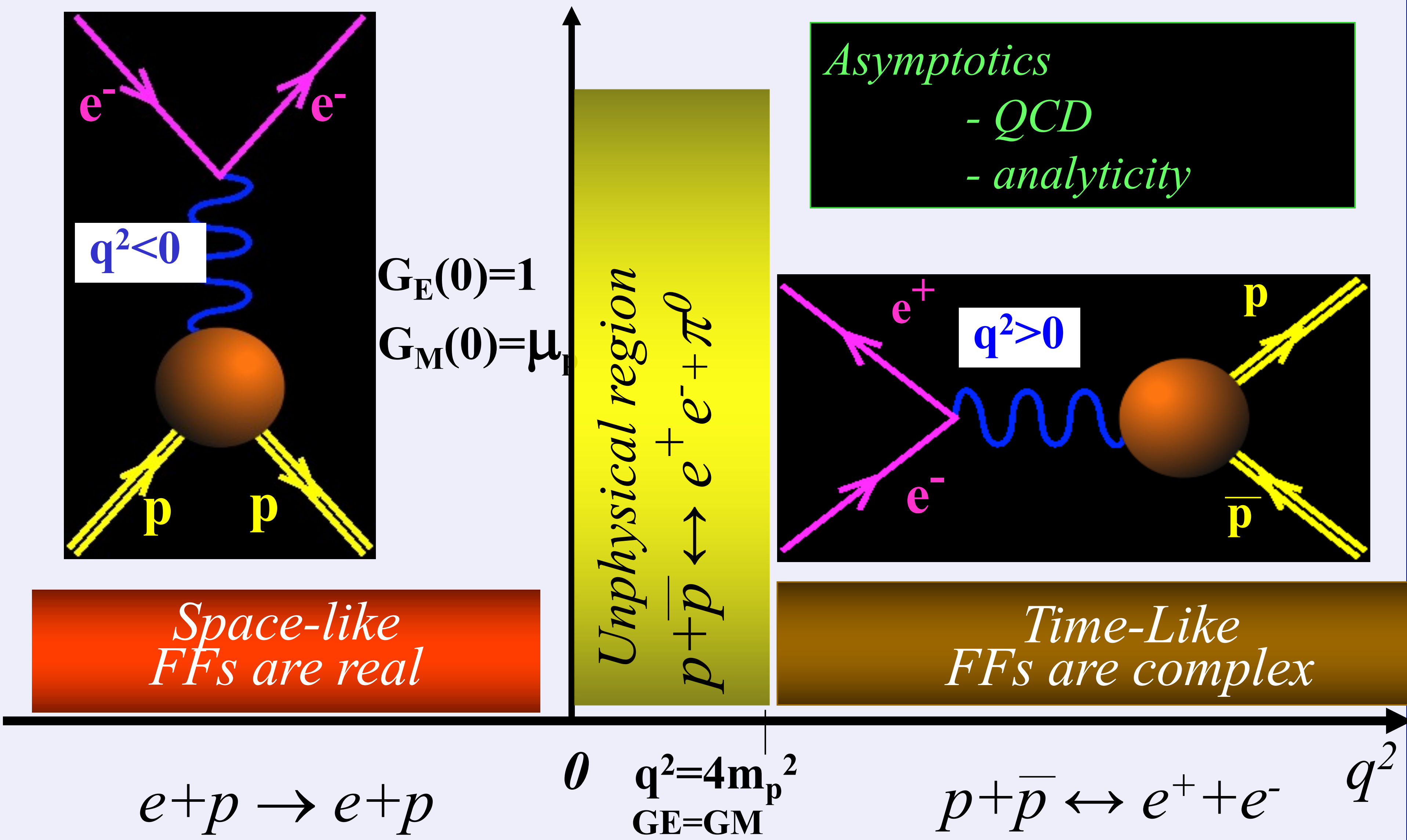
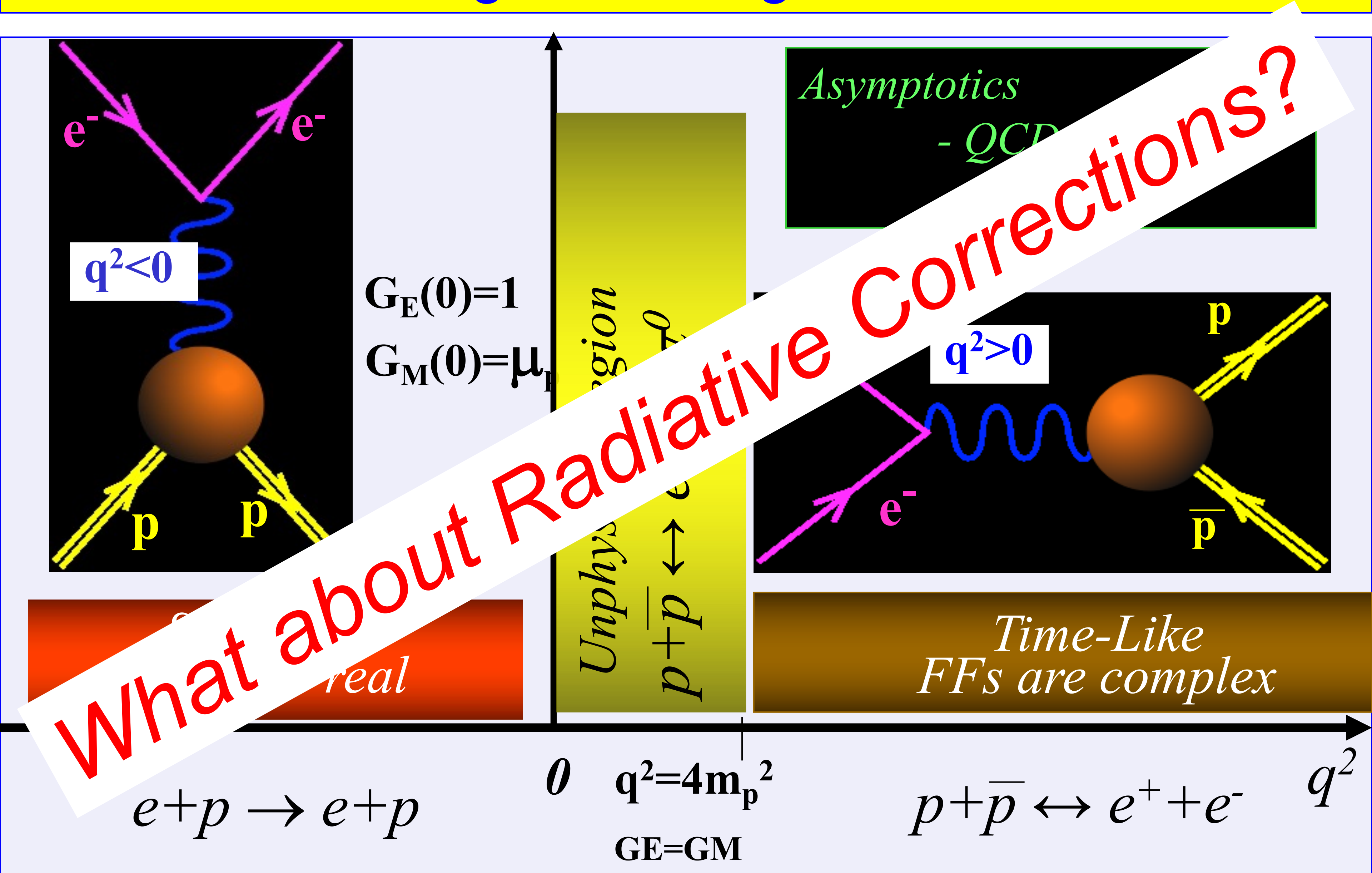
International Workshop on Hadron Structure and Spectroscopy (IWHSS-2022)
CERN, Geneva, Switzerland, August 29-31, 2022.

Nucleon Charge and Magnetic Distributions



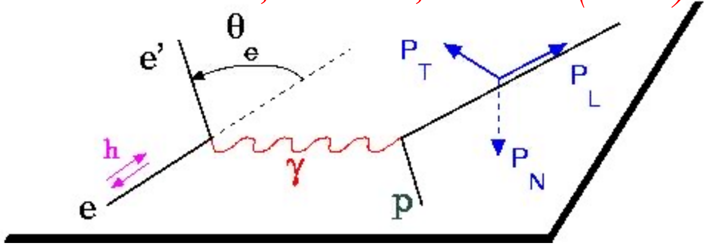
Nucleon Charge and Magnetic Distributions

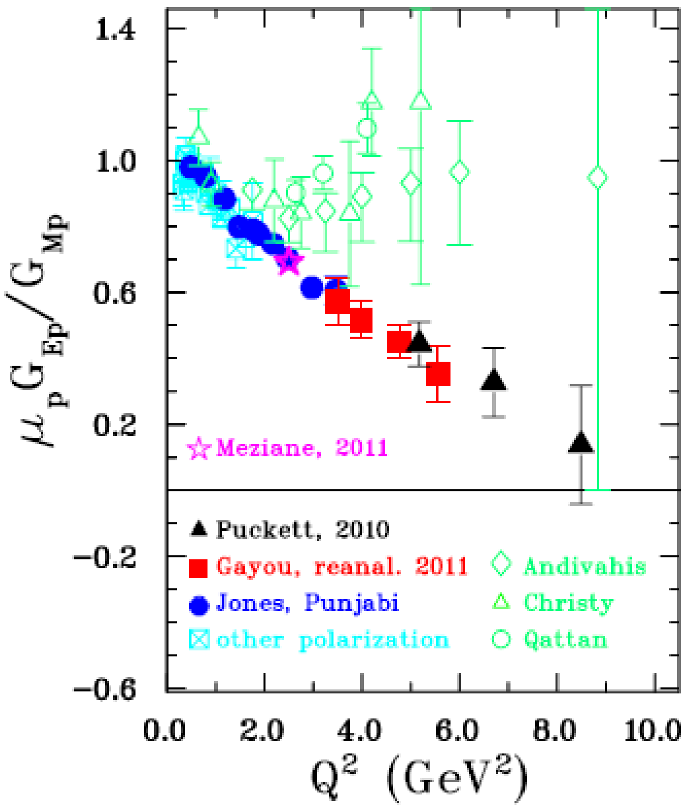


Experimental fact 1(SL): $ep \rightarrow ep$

- 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-monopole-like decrease of the ratio and eventually a zero-crossing of G_E.
- 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).
- The difference has been attributed to radiative corrections (including 2γ ?)
- Applying radiative corrections at first order in α brings a % uncertainty in cross section measurements. Not applied to the polarization ratio (cancel)

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

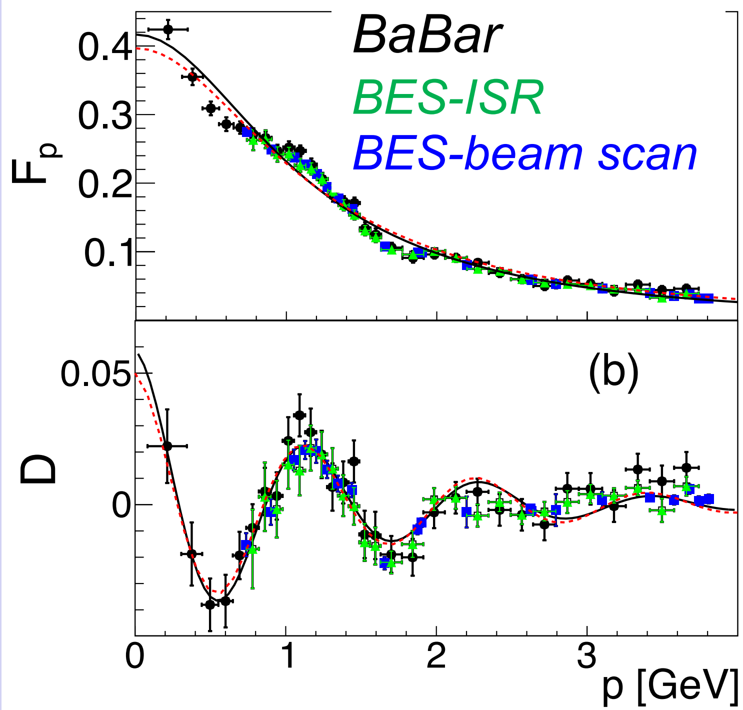




Ch. Perdrisat, V. Punjabi

Experimental fact 2 (TL): $e^+e^- \to \bar{p}p$

- BaBar and BESIII data on the proton time-like effective form factor show a systematic sinusoidal modulation in terms od the p-$\bar{\text{p}}$ 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 an interference of mechanisms of scale 0.2 and ~1 fm.
- The hadronic matter is distributed in non-trivial way.
- High order radiative corrections are applied (structure functions method)



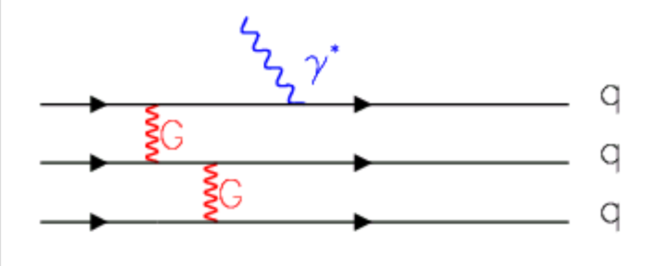
$$F_p^{\rm fit}(s) = F_{\rm 3p}(s) + F_{\rm osc}(p(s))$$

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

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

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

The Time-like Region



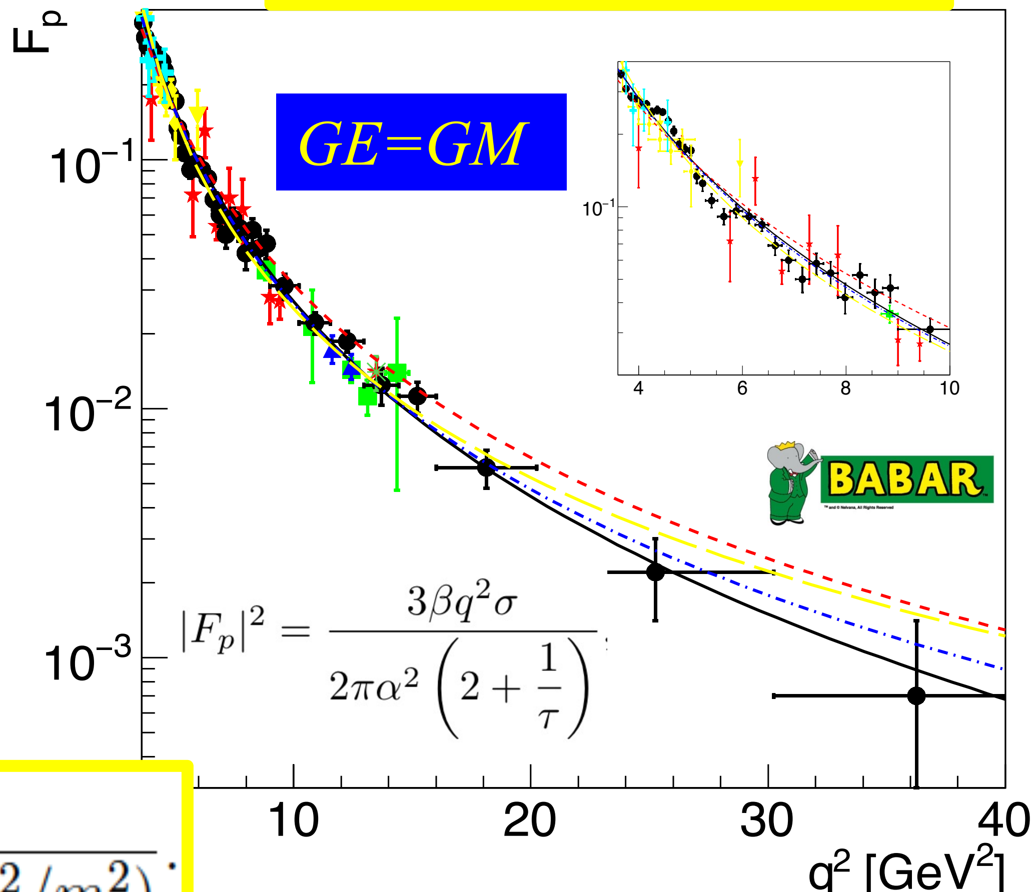
Expected QCD scaling $(q^2)^2$

$$
\begin{aligned}
e^+ + e^- &\to \bar{p} + p\,, \\
\bar{p} + p &\to e^+ + e^-
\end{aligned}
$$

$$|F_{scaling}(q^2)| = \frac{\mathcal{A}}{(q^2)^2 \log^2(q^2/\Lambda^2)}$$

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

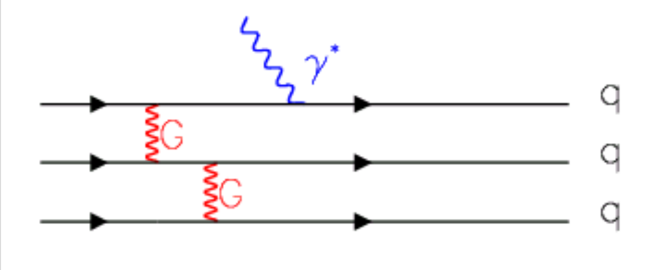
$$|F_{T3}(q^2)| \;=\; \frac{\mathcal{A}}{(1-q^2/m_1^2)(2-q^2/m_2^2)}.$$



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

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

The Time-like Region



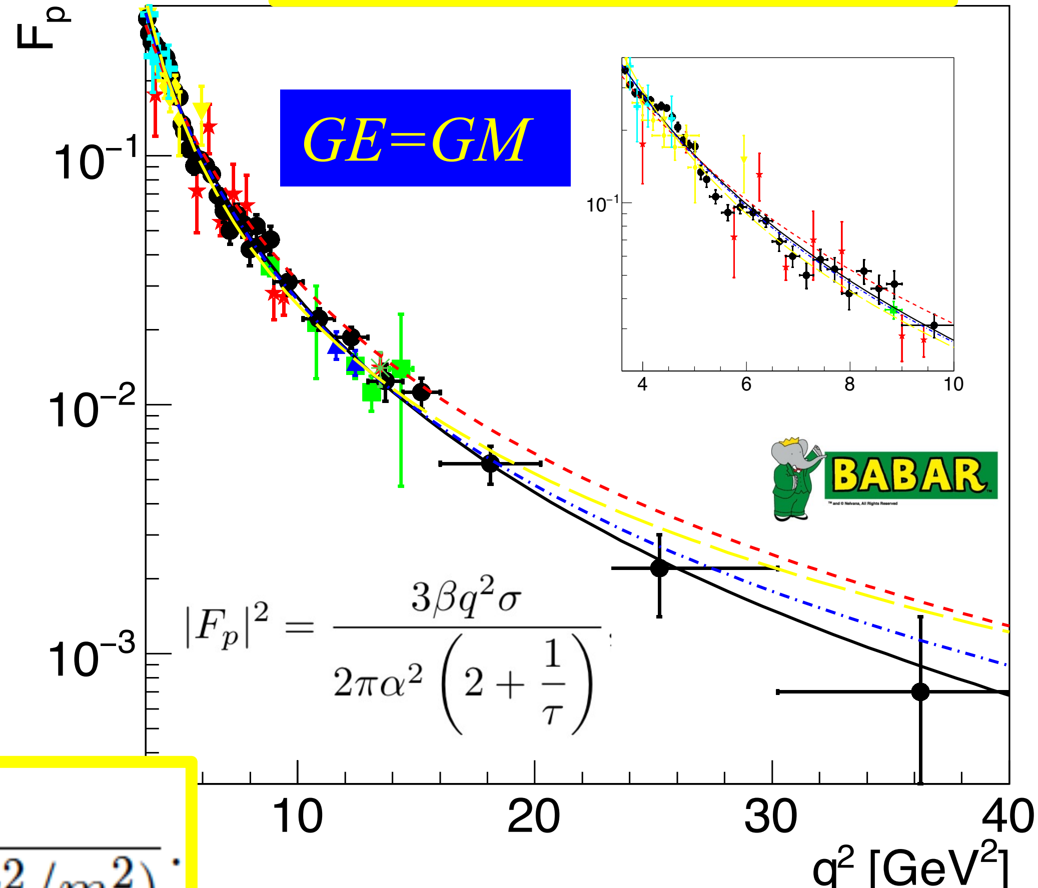
Expected QCD scaling $(q^2)^2$

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

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

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

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

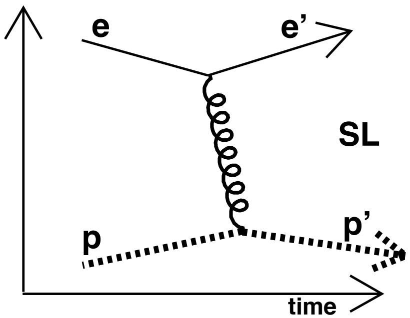


A.Bianconi, E. T-G. Phys. Rev. Lett. 114,232301 (2015)

Арбуз Model of proton PLB712(2012)240

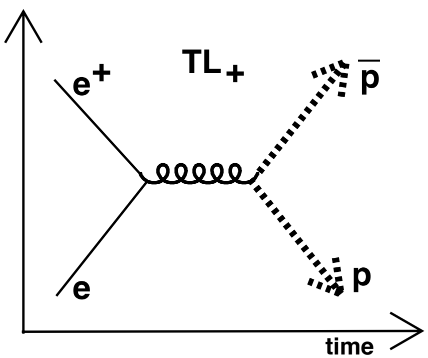
10 years ago a generalization of FFs in SL and TL was proposed

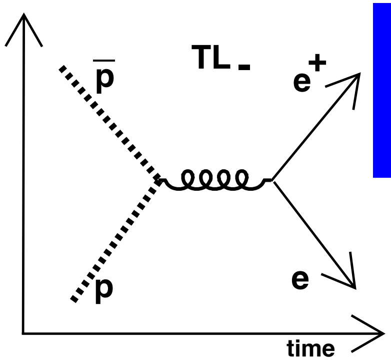
$$F(q^2) = \int_{\mathcal{D}} d^4x e^{iq_\mu x^\mu} \rho(x), \; q_\mu x^\mu = q_0 t - \vec{q} \cdot \vec{x}$$



$\rho(x) = \rho(\vec{x}, t)$ 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

How to connect and understand the amplitudes?

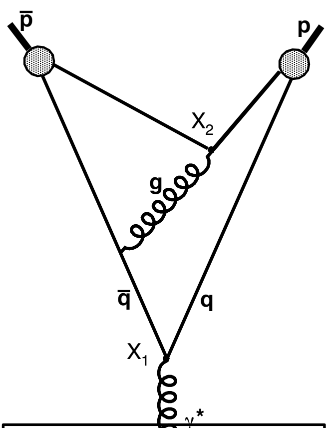
E.A. Kuraev, A. Dbeyssi, E. T-G. Phys. Lett. 712, 240 (2012)
A.Bianconi, E. T-G. Phys. Rev. Lett. 114,232301 (2015)

Photon-Charge coupling

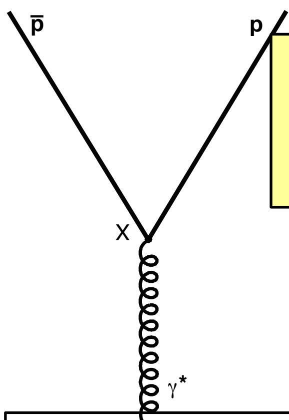
…access projections of $F(q^2)$

$\rho(\vec{x})$ **SL**: Fourier transform of a stationary charge and current distribution *(Breit frame)*

$R(t)$ **TL**: Amplitude for creating *charge-anticharge pairs* at time *t* *(CMS frame)*



Resolved



Unresolved

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

The simplest picture: $q\bar{q}$ pair + compact di-quark

representation

Fourier Transform

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

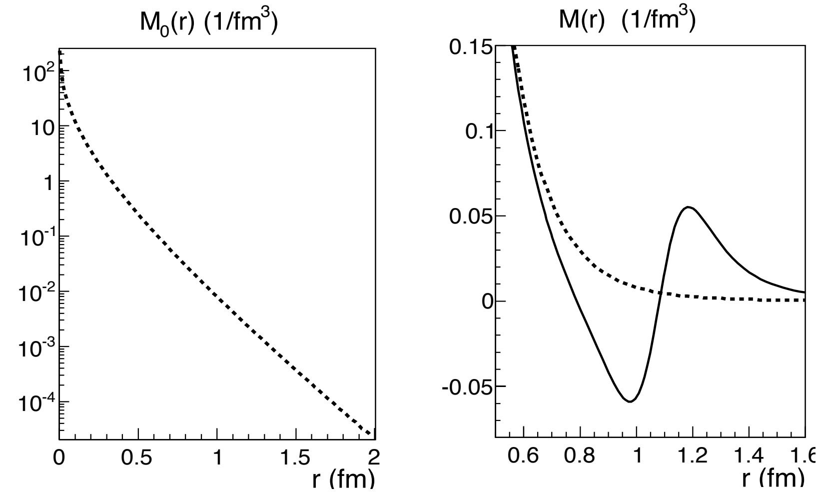
p: relative momentum
r: distance between the center of the forming hadrons
(p,r) conjugate variables, r $\leftrightarrow$ *t*

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

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

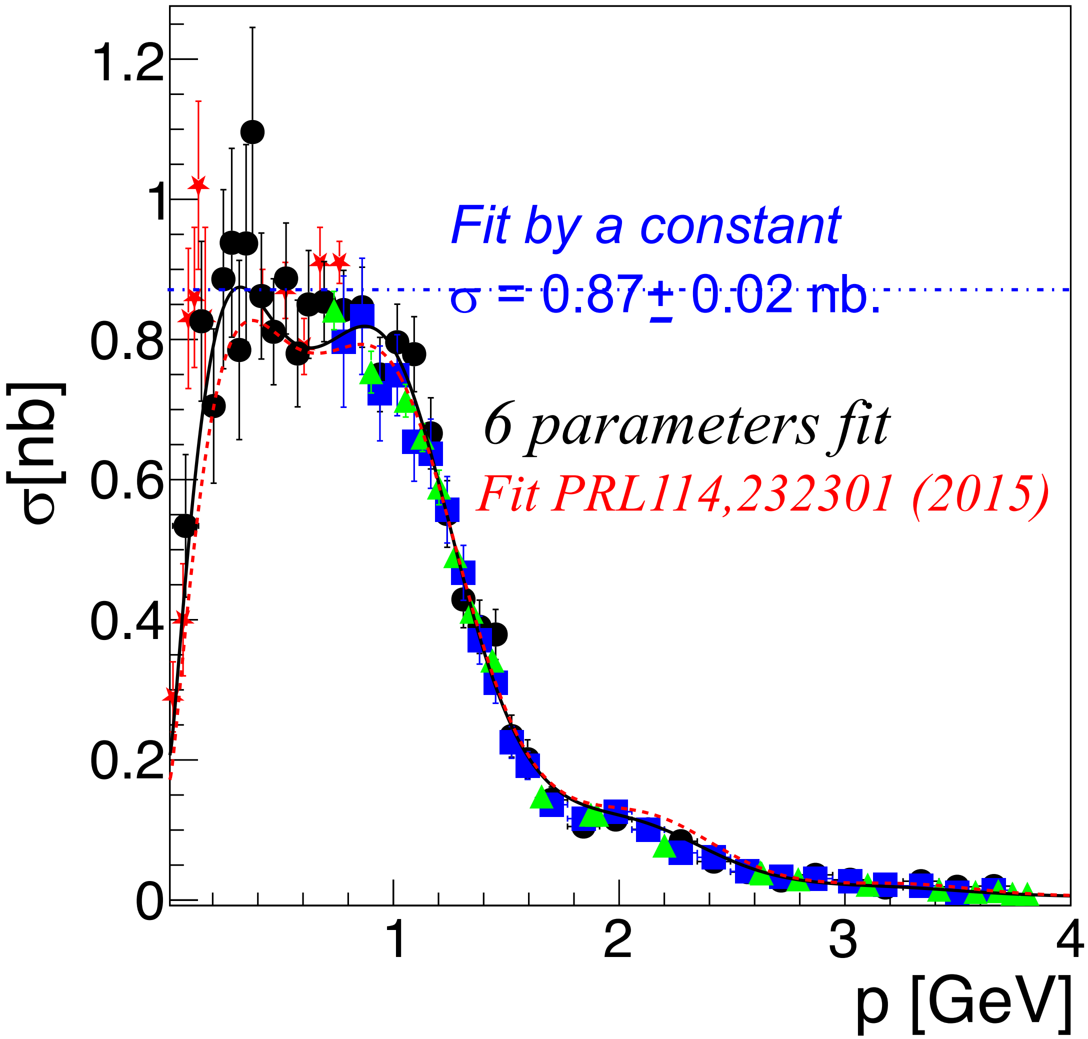
$$F_0 = \frac{\mathcal{A}}{(1 + q^2/m_a^2)\,[1 - q^2/0.71]^2},$$

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



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



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

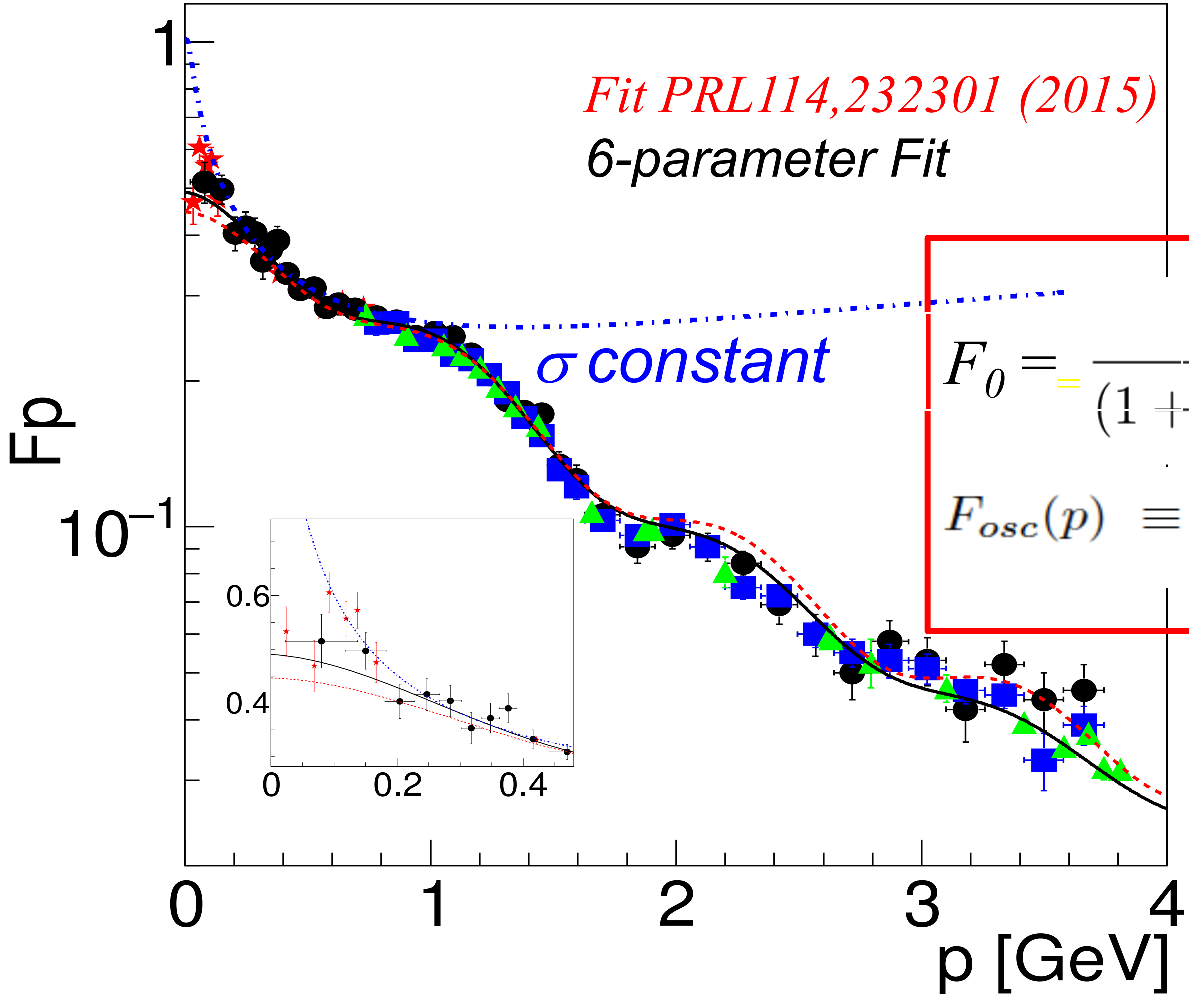
BaBar 85pt
1.9<2E<4.5
PRD87,092005 (2013)

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

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

Generalized Form Factor

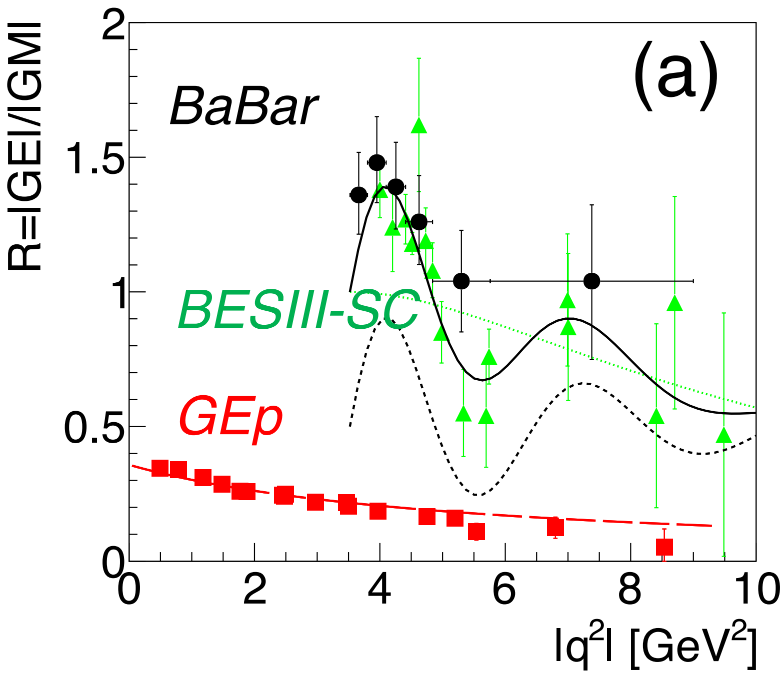
$$F_p(s)^2 = \frac{2\tau|G_M(s)|^2 + |G_E(s)|^2}{2\tau + 1}$$



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

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

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

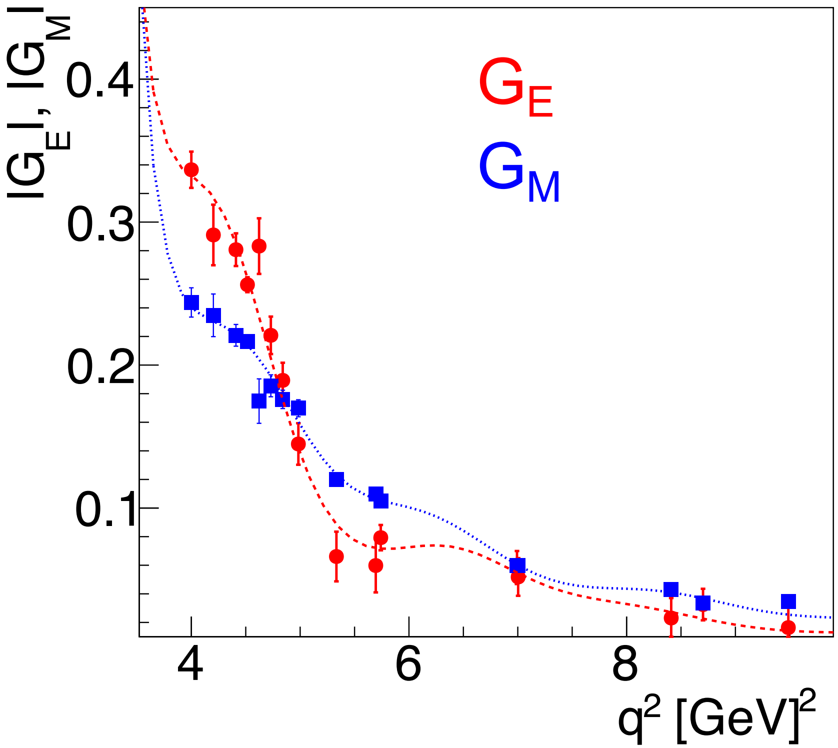


- Precise data from BESIII
- Dip at $|q^2|$~5.8 GeV^2
- Comparison with SL (Jlab-GEp data) – *fitted by a monopole*
- Oscillations on top of a monopole: from GE or GM?

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

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

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



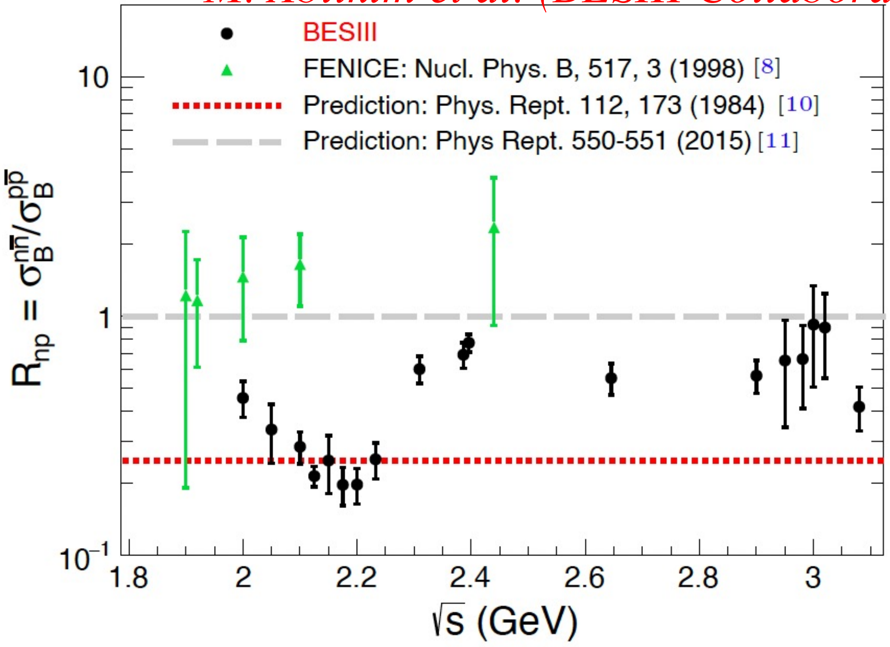
$$|G_E(s)| = F_p(s)\sqrt{\frac{1+2\tau}{R^2(s)+2\tau/R^2(s)}}$$

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

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

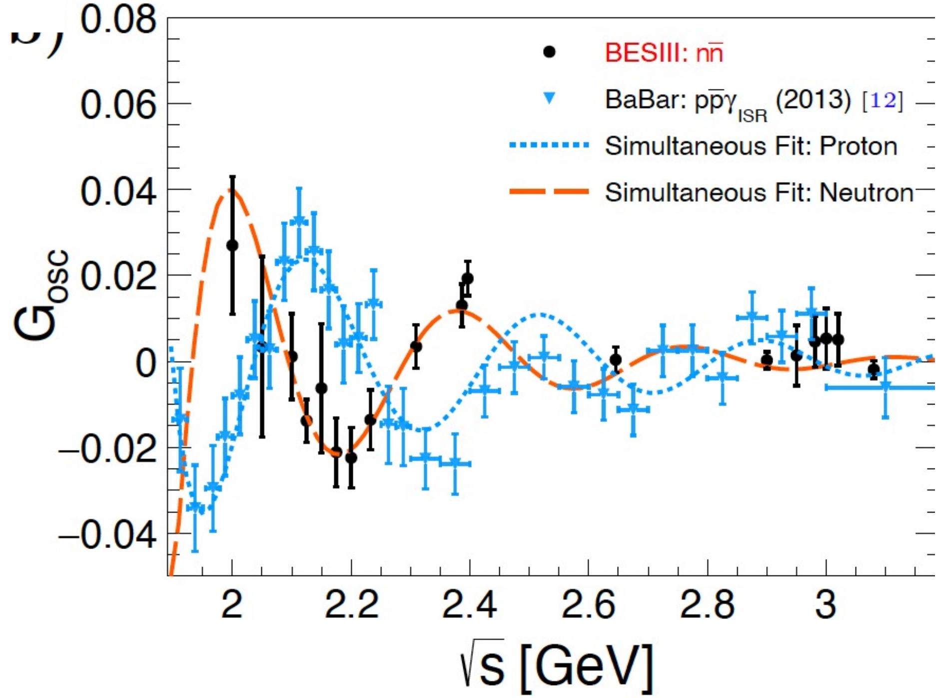
Neutron time-like form factor

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



R (*n/p*) <1

Same 6 parameter fit
Simultaneous fit *p* & *n*
Same parameters but
$\Delta\phi = 125° \pm 12°$



- Interfering amplitudes?

A. Bianconi, E.T-G., PRL 114,232301 (2015)

- I=0,1 channel mixing?

X. Cao, J.-P. Dai, and H. Lenske PRD 105 (2022) L071503

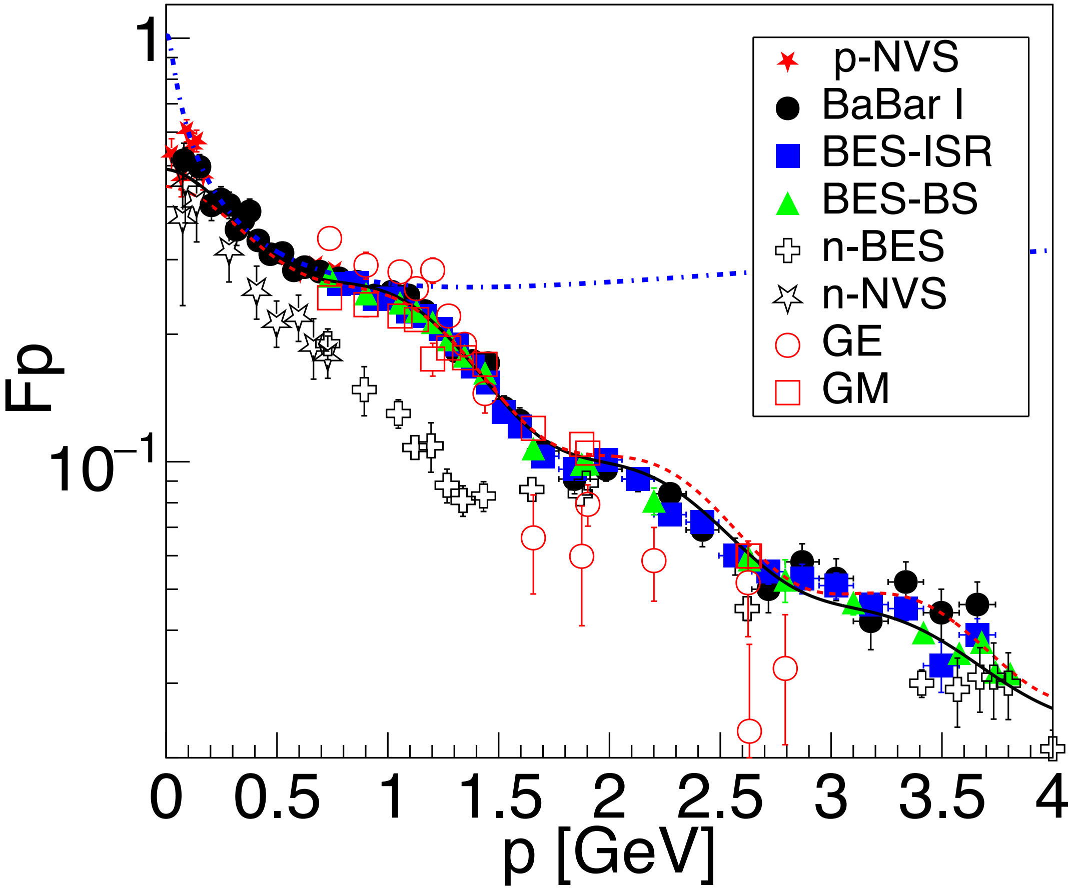
- Resonances?

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

Proton & Neutron

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

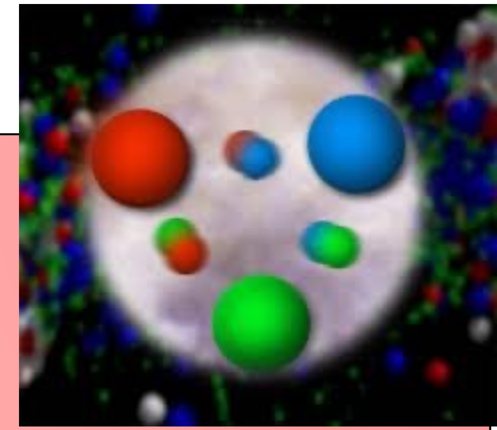
M. Ablikim et al. (BESIII Collaboration), Nature Phys. 17, 1200 (2021)



- Depends on background
- Gap between the points
- n-fit without Novosibirsk data

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

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

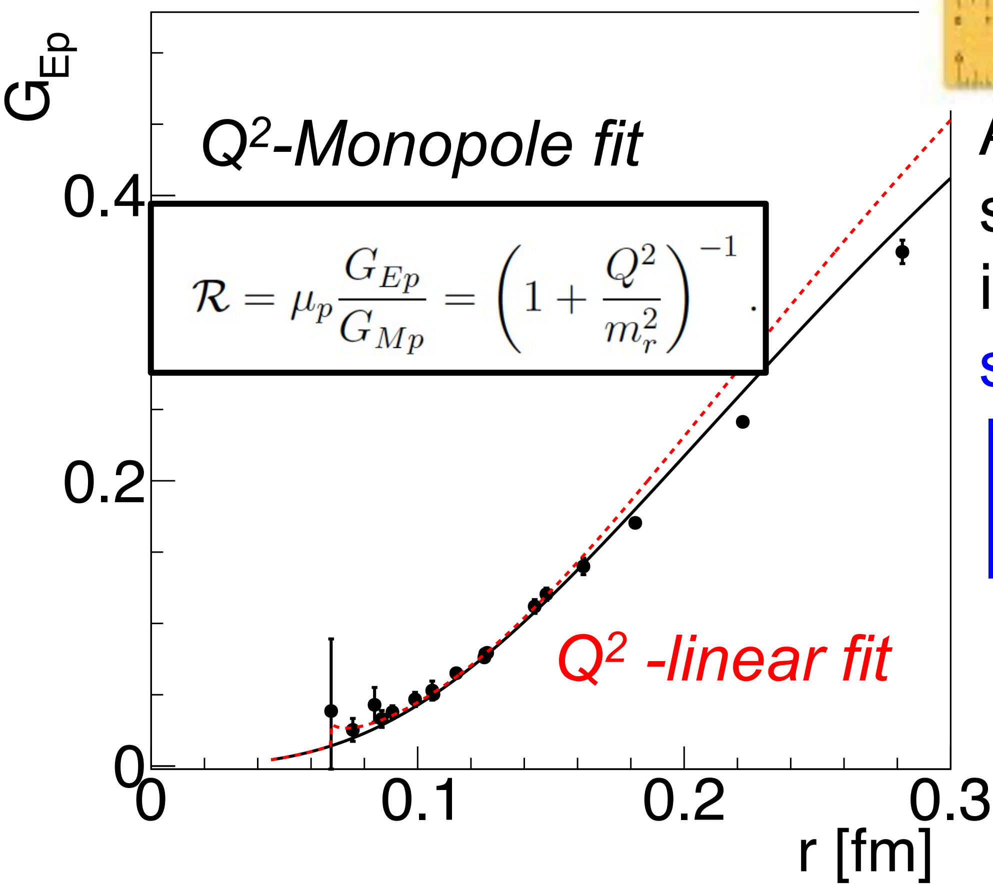
Main assumption of the Арбуз model:

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

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

The color quantum number of quarks does not play any role, due to stochastic averaging. Pauli principle applies.

SL- the most precise ruler



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

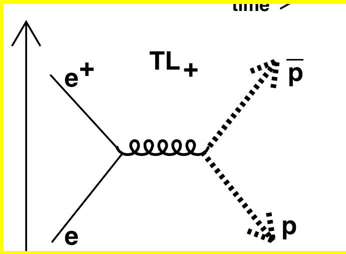
$$G_E(Q^2) = \frac{G_M(Q^2)}{\mu}\left(1 + Q^2/q_1^2\right)^{-1}$$

Zero crossing?

Prediction: NO

The photon 'sees' the neutral, screened region $G_{Ep} \approx 0$ for $r < 0.06$ fm

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



Time-like region

Арбуз

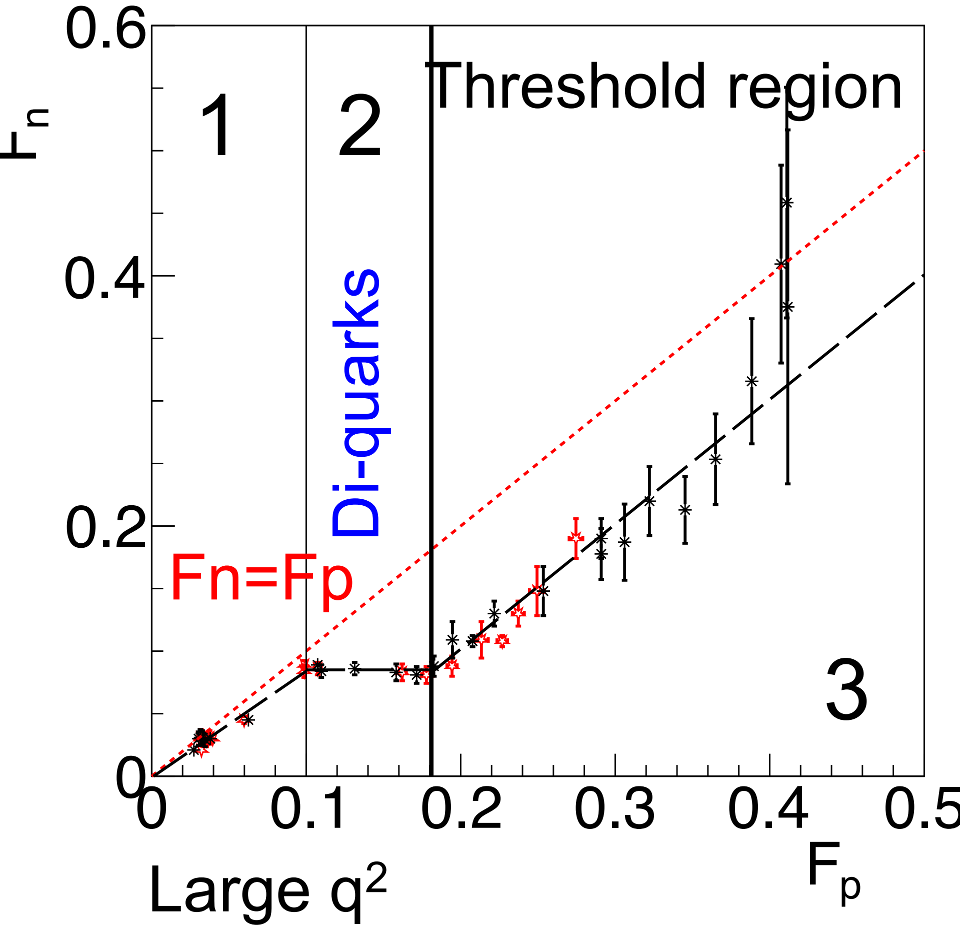
Antisymmetric state of colored quarks → *Colorless quarks: Pauli principle*

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 $q\bar{q}$ 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

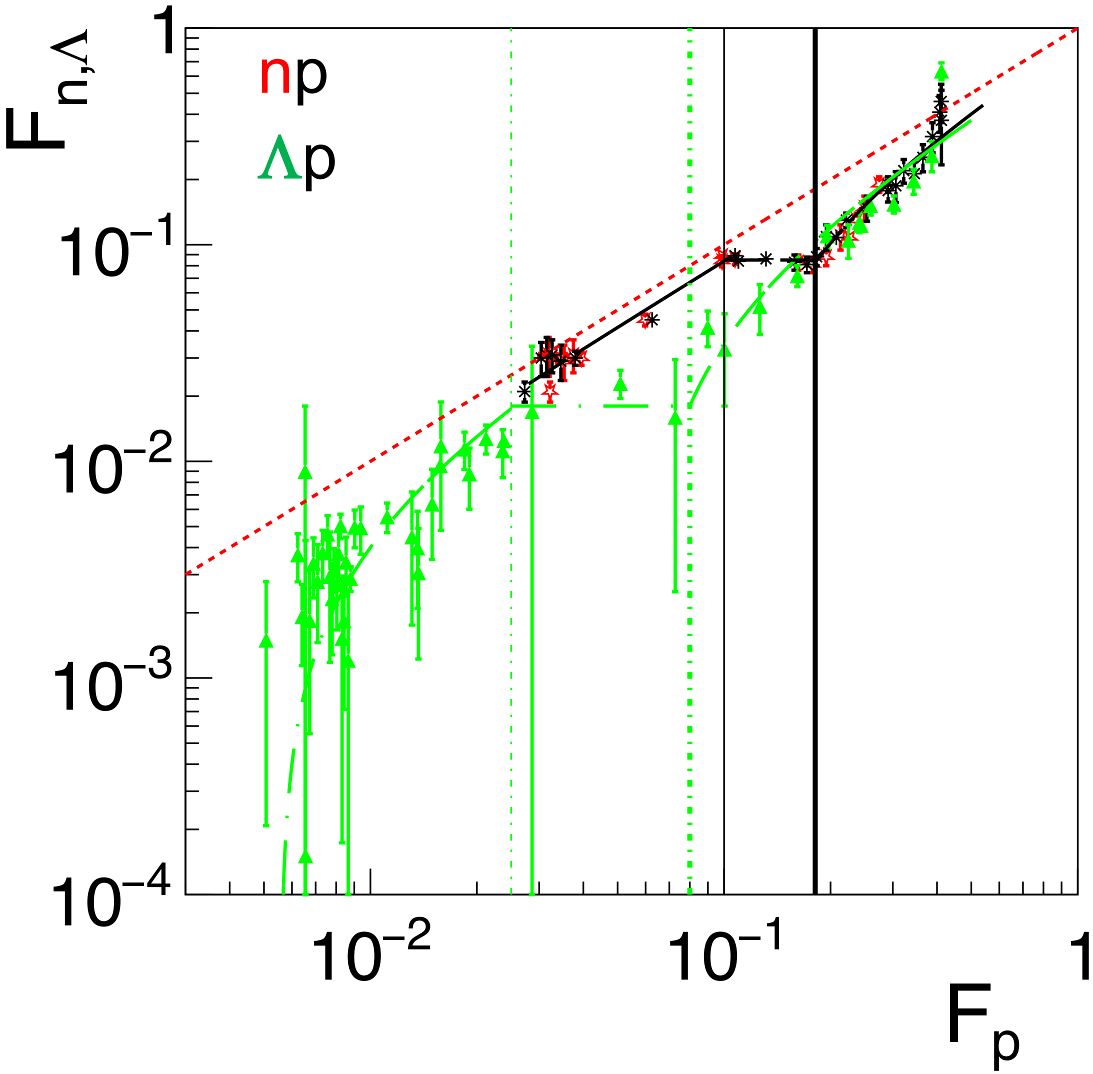
1) pQCD applies

2) di-quark phase
   charge redistributed

3) The hadron is formed

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

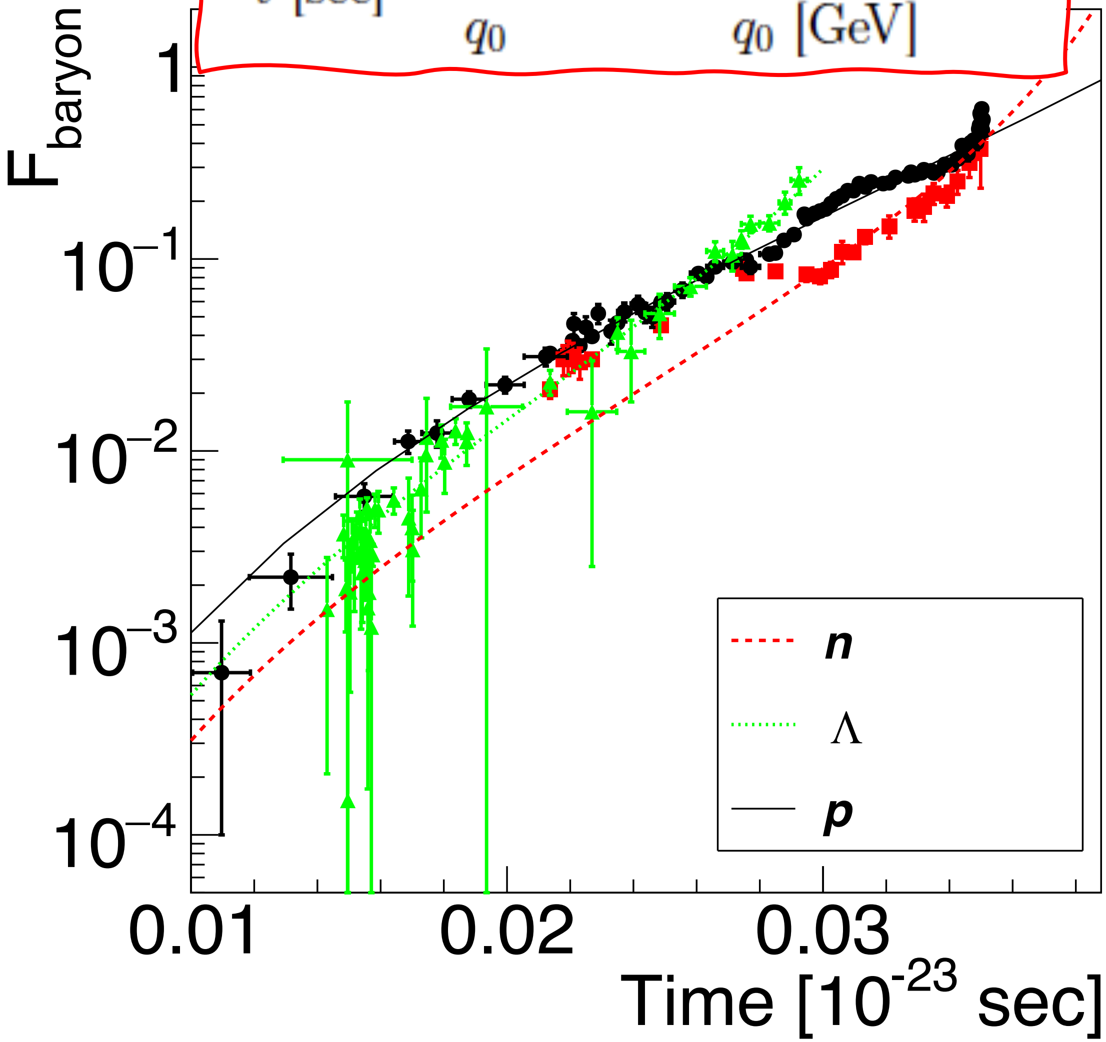
npΛ-correlation



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)*

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]

Summary & Conclusions

- BESIII new data on TL *n* & *p* FFs, their ratio and *first determination of individual proton TL 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 *np*Λ FFs correlation
- Predicts
  - similarities between n&p, SL & TL, non zero crossing in SL

Deepen quantitative aspects!

Thank you for your attention

Decreasing of the ratio G_E/G_M Арбуз

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

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

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

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

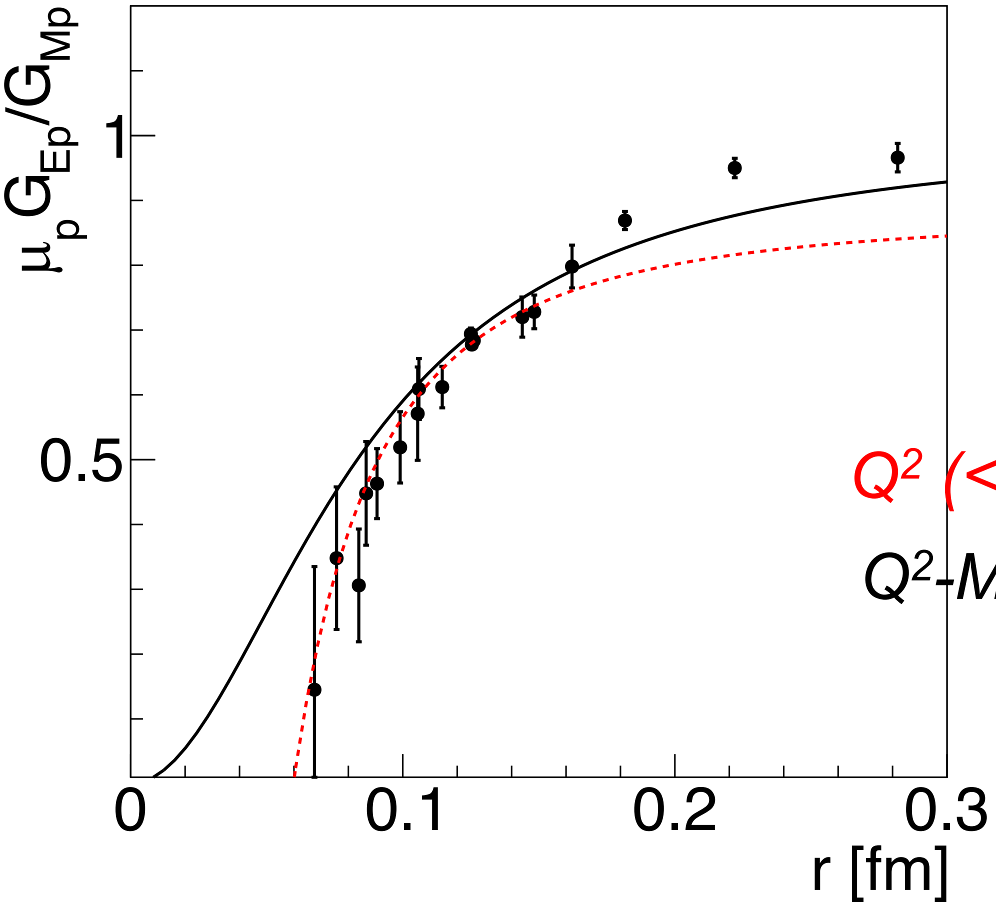
Additional suppression (Fourier transform)

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

$q_1 (\equiv \chi)$ 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

Q^2-Monopole fit

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

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:

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

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

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.

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

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

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: $e^+ + e^- \rightarrow \gamma^*(q) \rightarrow p + \bar{p}$.

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

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

Арбуз

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

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 $\bar{p}p$ separed by a distance R.

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

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

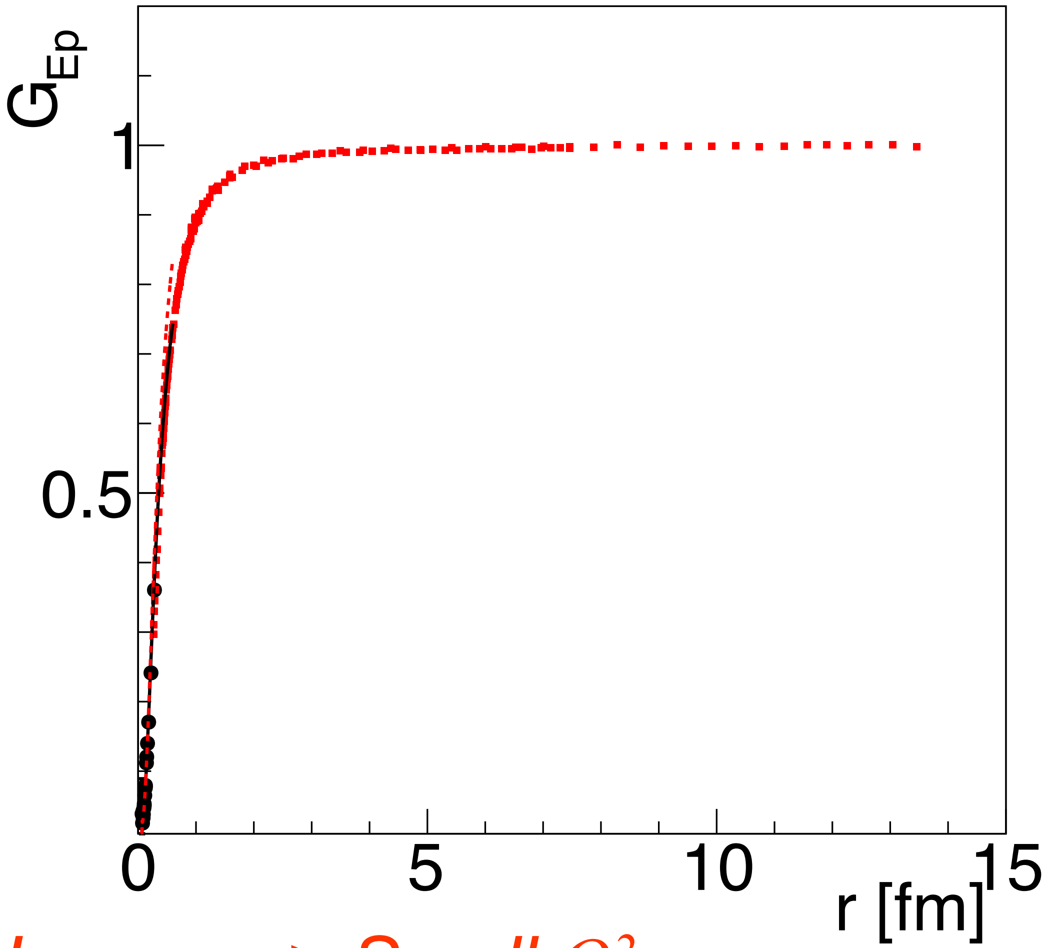
p and $\bar{p}$ leave the interaction region: at larger distances the integral of Q(t) must vanish

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

Арбуз

Proton radius

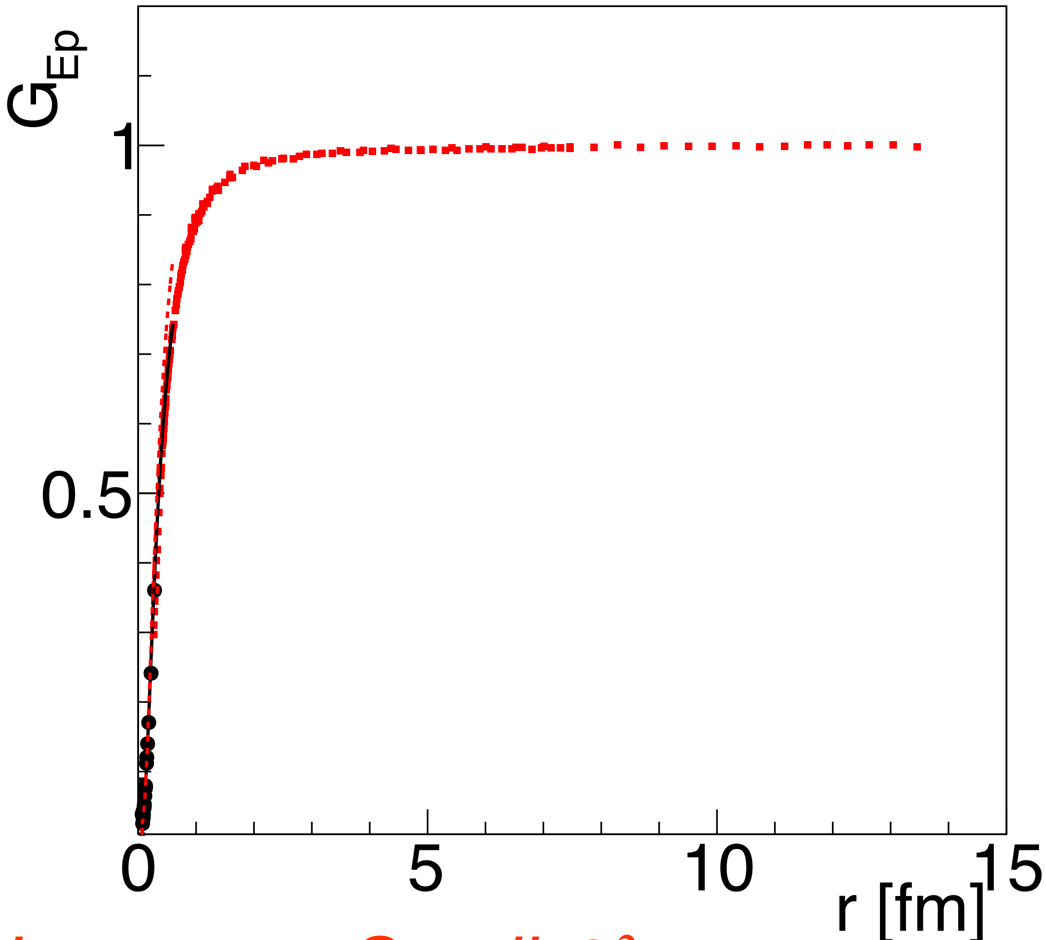
Data from Mainz,
PRC 90, 015206 (2014)



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

Plan

- *Definition of form factors in space and time-like regions*

- new data in SL and TL

- Nucleon Structure
- Time Evolution of hadron formation
- proton, neutron and hyperon FF correlation

What can we learn from time-like processes?

Symmetry Relations(annihilation)

- Differential cross section at complementary angles:

The SUM cancels the 2γ contribution:

$$\frac{d\sigma_+}{d\Omega}(\theta) = \frac{d\sigma}{d\Omega}(\theta) + \frac{d\sigma}{d\Omega}(\pi - \theta) = 2\frac{d\sigma^{Born}}{d\Omega}(\theta)$$

The DIFFERENCE enhances the 2γ contribution:

$$\frac{d\sigma_-}{d\Omega}(\theta) = \frac{d\sigma}{d\Omega}(\theta) - \frac{d\sigma}{d\Omega}(\pi - \theta) = 4N\Big[(1+x^2)ReG_M\Delta G_M^* + \\ + \frac{1-x^2}{\tau}ReG_E\Delta G_E^* + \sqrt{\tau(\tau-1)}x(1-x^2)Re(\frac{1}{\tau}G_E - G_M)F_3^*\Big]$$

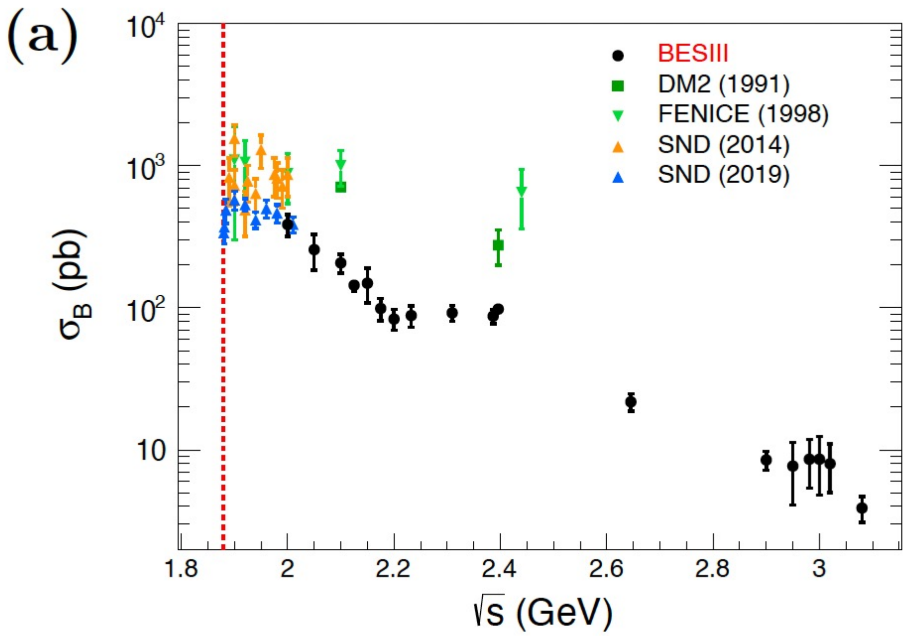
$$\tau = \frac{q^2}{4m^2}, \quad x = cos\theta$$

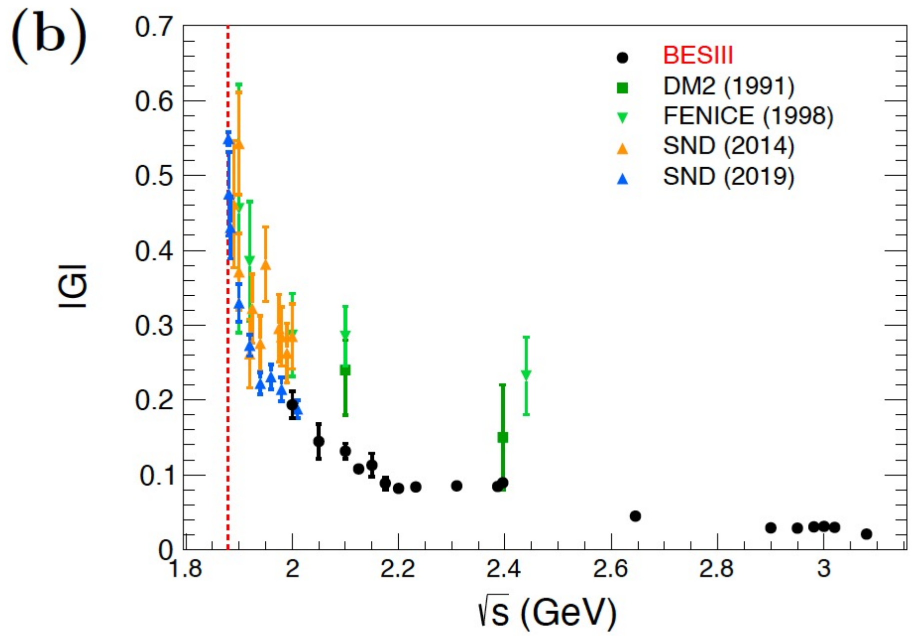
Neutron time-like form factor

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

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

Form factor





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 magnetic term

but TL form factors are complex!

Conclusions

- *High order radiative corrections* are mandatory to claim a percent precision on the observables

- Effects as correlations and normalizations should be carefully scrutinized
  see GEp as a parameter
  ε-derivative of the reduced elastic cross section

- Two photon exchange as *K*-factor

Radiative corrections modify not only the absolute values but also the dependence of the observables on the relevant kinematical variables

Unpolarized cross section

-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.

Two Photon Exchange:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4q^2}\sqrt{\frac{\tau}{\tau-1}}D,$$

- Induces four new terms
- Odd function of θ:
- Does not contribute at θ=90°

$$D = (1+\cos^2\theta)(|G_M|^2 + 2ReG_M\Delta G_M^*) + \frac{1}{\tau}\sin^2\theta(|G_E|^2 + 2ReG_E\Delta G_E^*) +$$
$$2\sqrt{\tau(\tau-1)}\cos\theta\sin^2\theta Re(\frac{1}{\tau}G_E - G_M)F_3^*.$$

M.P. Rekalo and E. T.-G., EPJA 22, 331 (2004)
G.I. Gakh and E. T.-G., NPA761, 120 (2005)