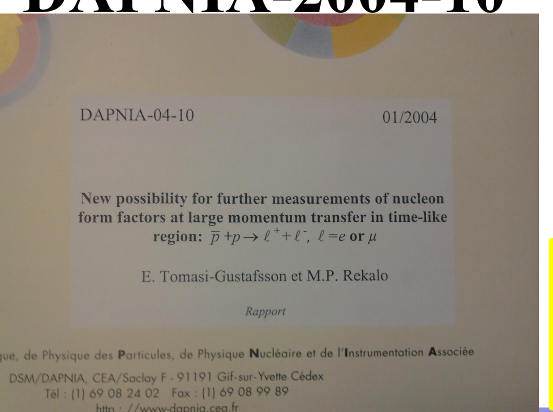
The Fourth Dimension of the Nucleon

Egle Tomasi-Gustafsson
CEA, IRFU,SPhN,
Université Paris-Saclay
France

DAPNIA-2004-10



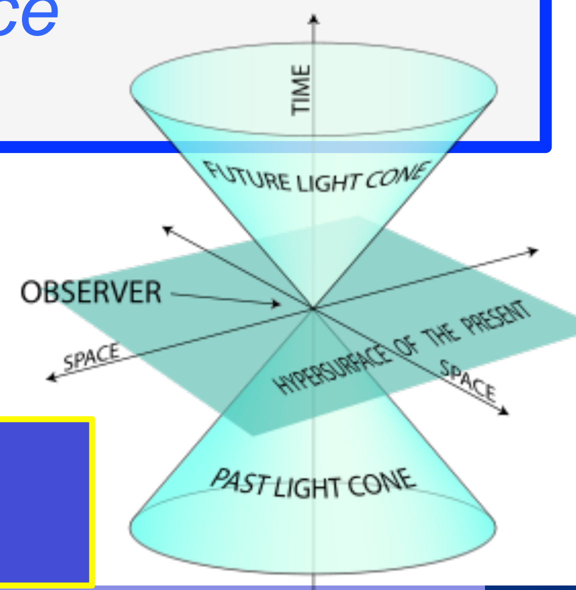
DAPNIA-04-10 01/2004

New possibility for further measurements of nucleon form factors at large momentum transfer in time-like region: $\bar{p}+p \to \ell^{+}+\ell^{-}$, $\ell = e$ or μ

E. Tomasi-Gustafsson et M.P. Rekalo

Rapport

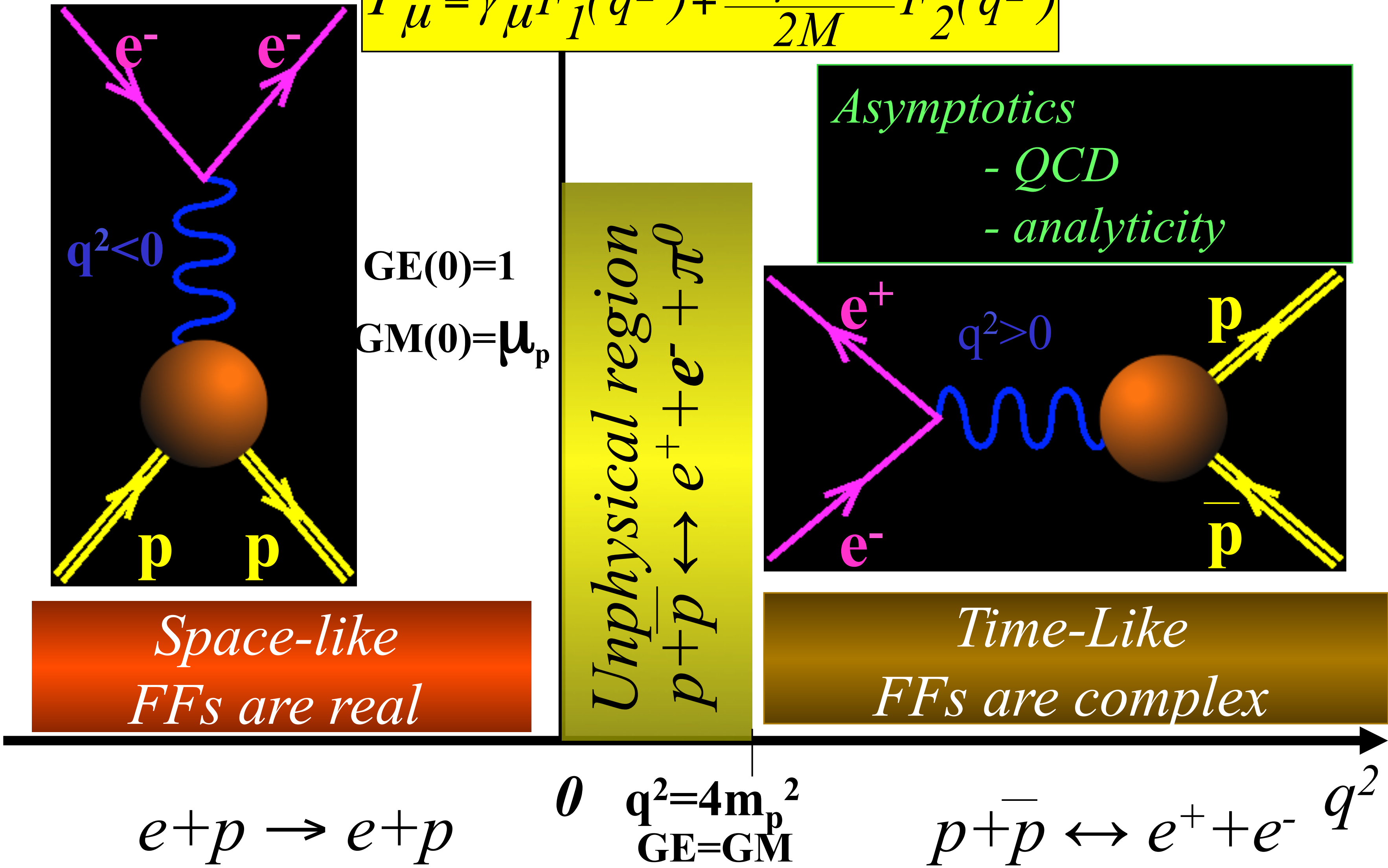
...ue, de Physique des Particules, de Physique Nucléaire et de l'Instrumentation Associée
DSM/DAPNIA, CEA/Saclay F - 91191 Gif-sur-Yvette Cédex
Tél : (1) 69 08 24 02 Fax : (1) 69 08 99 89
http : //www-dapnia.cea.fr



Journées FAIR-FRANCE
IPNO, 17-18/II/2017

Scattering and Annihilation

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



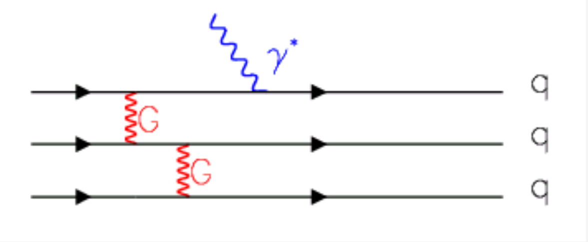
Dipole Approximation $G_D=(1+Q^2 / 0.71\ GeV^2)^{-2}$

- Classical approach
  - Nucleon FF (in non relativistic approximation or in the Breit system) are Fourier transform of the charge or magnetic distribution.
- **Dipole approximation => exponential density distribution.**
  - $\rho = \rho_0 \exp(-r/r_0)$,
  - $r_0^2= (0.24\ fm)^2$, $<r^2> \sim(0.81\ fm)^2 \leftrightarrow m^2_D =0.71\ GeV^2$

- Dimensional scaling in QCD $F_n(Q^2)= C_n [1/(1+Q^2/m_n)^{n-1}]$,
  - $m_n=n\beta^2$, *<quark momentum squared>*
  - *n is the number of constituent quarks*
- Setting $\beta^2 =(0.471\pm.010)\ GeV^2$ *(pion data)*

  pion: $F_\pi(Q^2)= C_\pi [1/(1+Q^2/0.471\ GeV^2)^1]$

  nucleon: $F_N(Q^2)= C_N [1/(1+Q^2/0.71\ GeV^2)^2]$

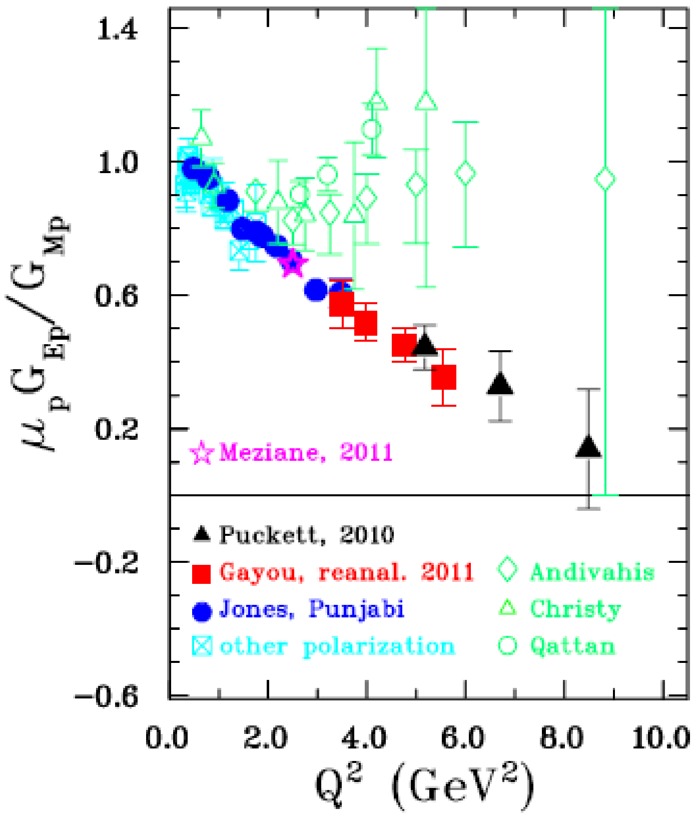


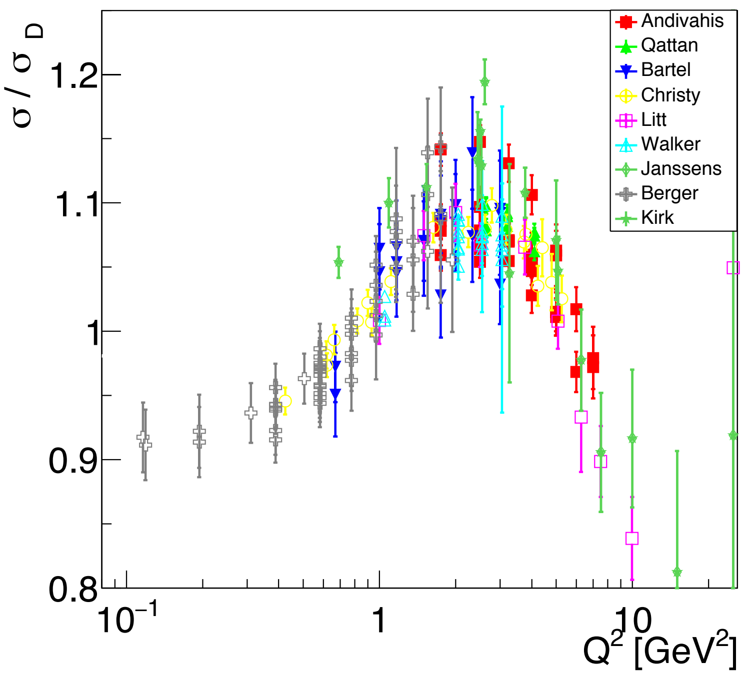
Dipole Approximation

Does not hold in SL region:

neither for GE

nor for GM





...and in TL ?

IL NUOVO CIMENTO Vol. XXIV, N. 1 1° Aprile 1962

Proton-Antiproton Annihilation into Electrons, Muons and Vector Bosons.

A. Zichichi and S. M. Berman (*)

CERN - Geneva

N. Cabibbo and R. Gatto

Università degli Studi - Roma e Cagliari
Laboratori Nazionali di Frascati del CNEN - Roma

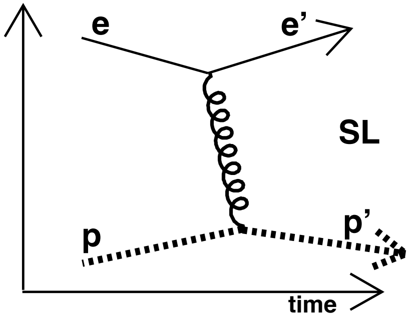
Whereas in the spacelike experiments the form factors are given the physical interpretation *of the Fourier transforms of the spacial charge and magnetic structure* of the proton,

the timelike momentum transfers yield information about the frequency structure of the protons.

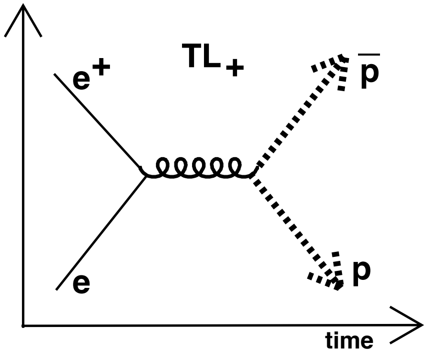
TL-SL Generalization of Form Factors

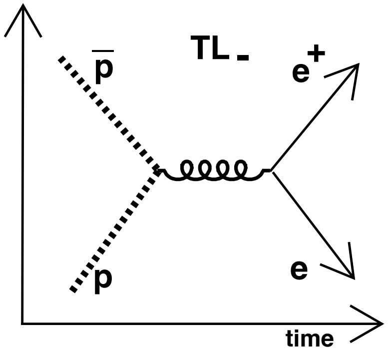
E.A. Kuraev, E. T-G, A. Dbeyssi, Phys.Lett. B712 (2012) 240
A. Bianconi, E. T-G., PRC 95, 015204 (2017)

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



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

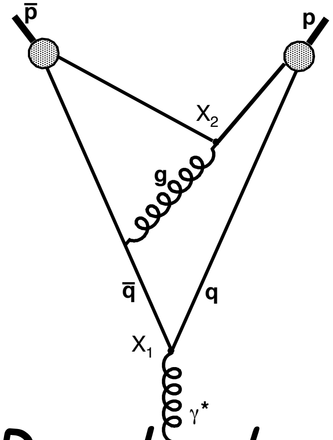
How to connect and understand the amplitudes?

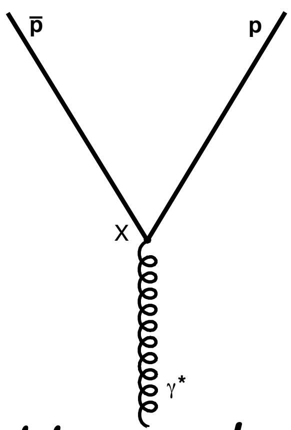
Photon-Charge coupling

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

$\rho(\vec{x})$ 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 $\gamma^* \rightarrow charge - anticharge$ vertexes





The simplest picture:
qq pair + compact di-quark

Resolved or *Unresolved* *Representation of the photon*

Time-like FFs

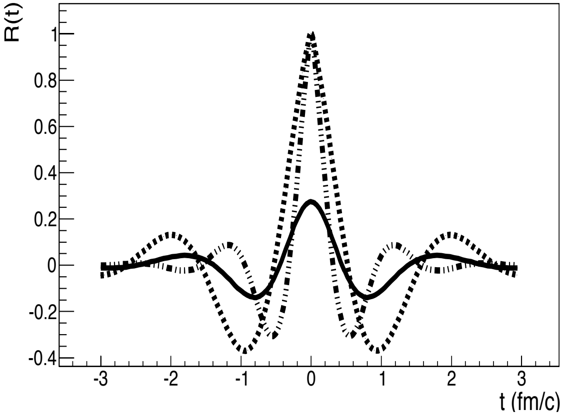
- New understanding of Form Factors in the Time-like region: time distribution of quark-antiquark pair creation vertices

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

- The distributions tested by the virtual photon are projections in orthogonal 1 and 3-dim spaces of the function

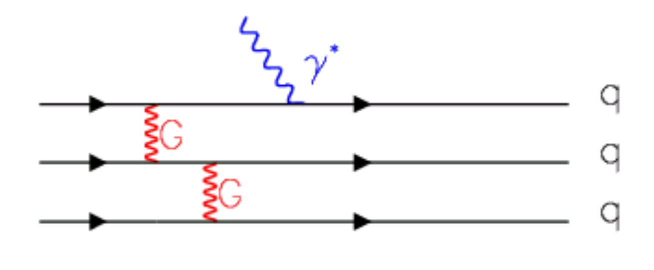
- $\rho(x) = \rho(\vec{x}, t)$ $R(t)$ and $\rho(\vec{x})$

- Simple functions R(t) can explain the origin of oscillatory phenomena



A. Bianconi, E. T-G., PRC 95, 015204 (2017)

The Time-like Region



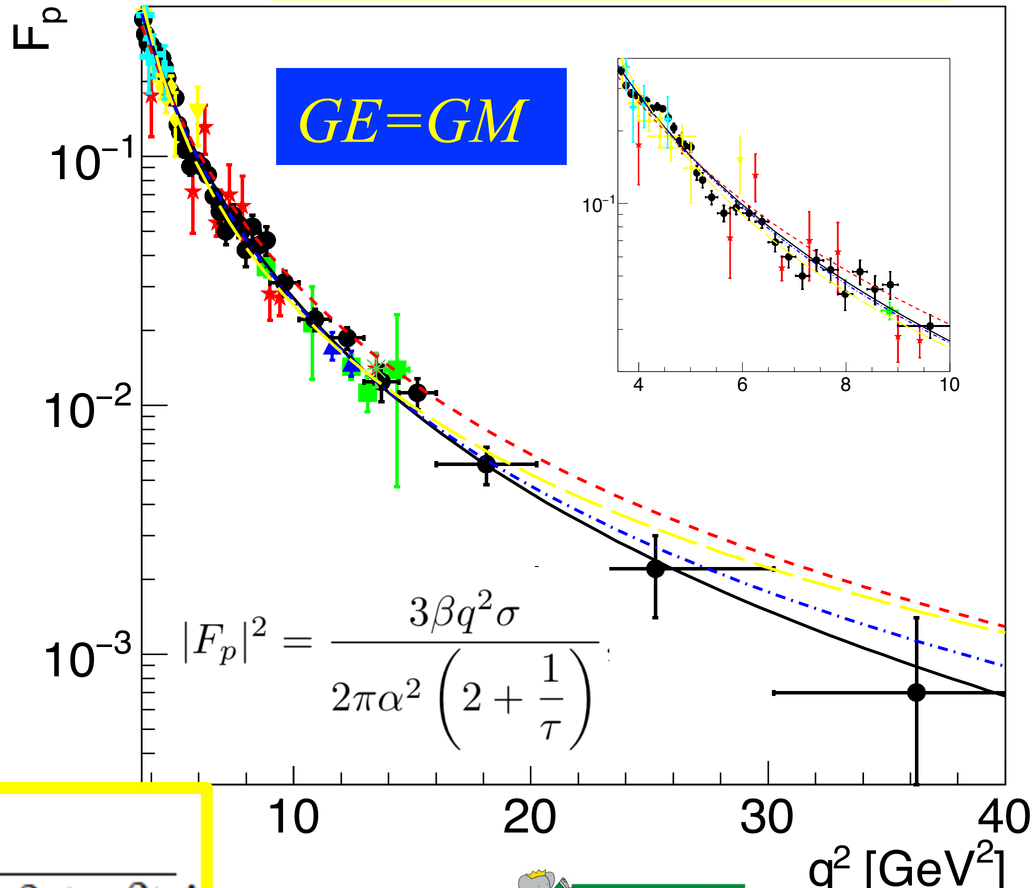
Expected QCD scaling $(q^2)^2$

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

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

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

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

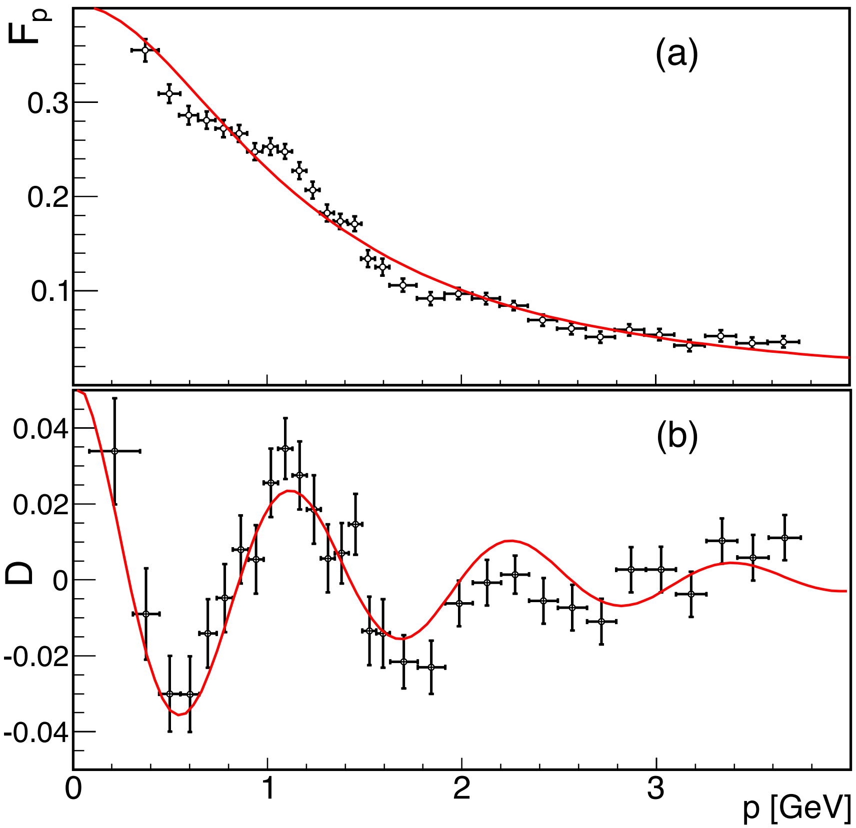


BABAR

Oscillations : regular pattern in P_{Lab}

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

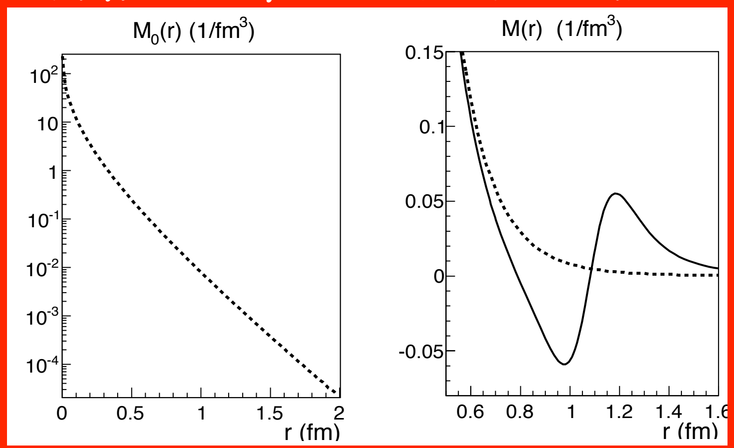
$$F_{osc}(p) \equiv A \exp(-Bp) \cos(Cp + D).$$



$A \pm \Delta A$	$B \pm \Delta B$ $[GeV]^{-1}$	$C \pm \Delta C$ $[GeV]^{-1}$	$D \pm \Delta D$	$\chi^2/n.d.f$
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

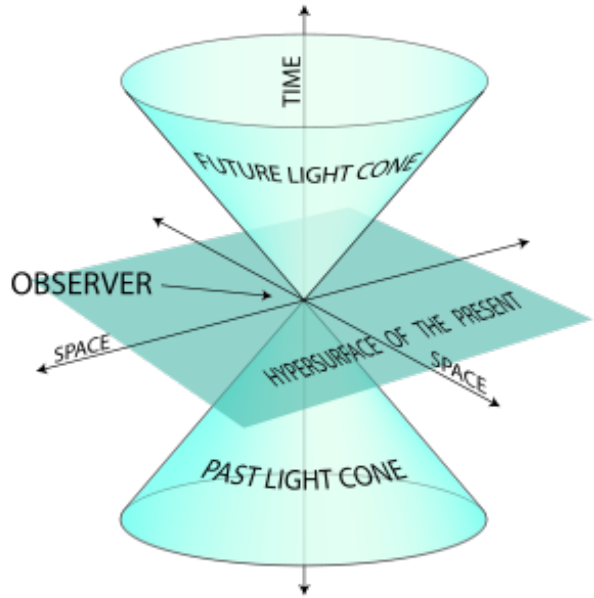
Simple oscillatory behaviour
Small number of coherent sources



A. Bianconi, E. T-G.
P.R.L.114,232301 (2015)

Examples: Monopole-like shape

- F(x) ≠ 0 in past and future LC.
- Annihilation and creation processes:
  - -time symmetric.
  - -differ by a phase.
- Summing two terms with the same phase: when t>> 1/a



$$R(t) = \theta(t)e^{-at} + \theta(-t)e^{at} = e^{-a|t|},$$

- Either the second pair is formed within 1/a or the system evolves differently.

$$F(q)/\pi = \frac{1}{a-iq} + \frac{1}{a+iq} = \frac{2a}{a^2+q^2}.$$

1/a: formation time

=> zero mass resonance of width a

Examples: Breit-Wigner

A Breit-Wigner probability contains all four poles:

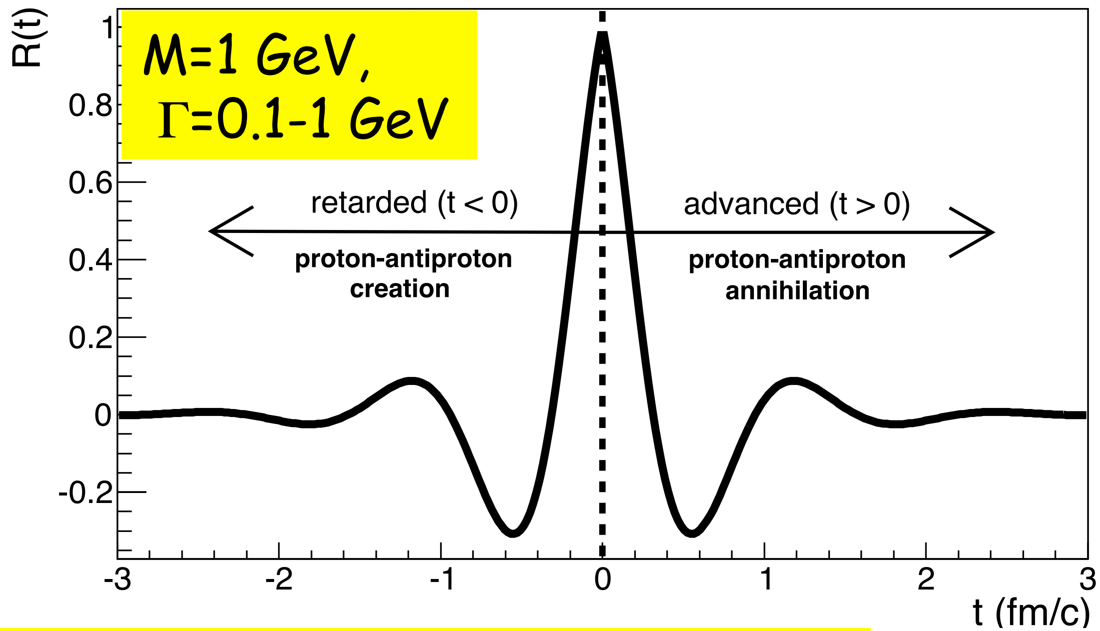
$$F_{\pm}(q) \propto \frac{1}{(q^2 - M^2) \pm iMa},$$

The combination:

$$F(q) \propto F_{+}(q) + F_{-}(q)$$

corresponds to

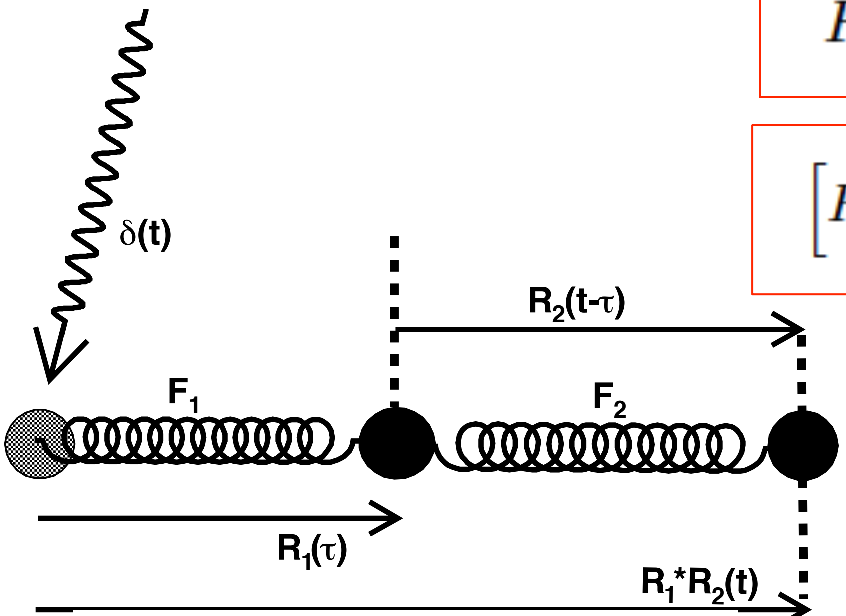
$$R(t) \propto cos(Mt)\, e^{-a|t|},$$



Retarded response of a classical bound and damped oscillator to a $\delta(t)$ external perturbation

$$R(t) \equiv R_{creation}(t)\theta(-t) + R_{ann}(t)\theta(t).$$

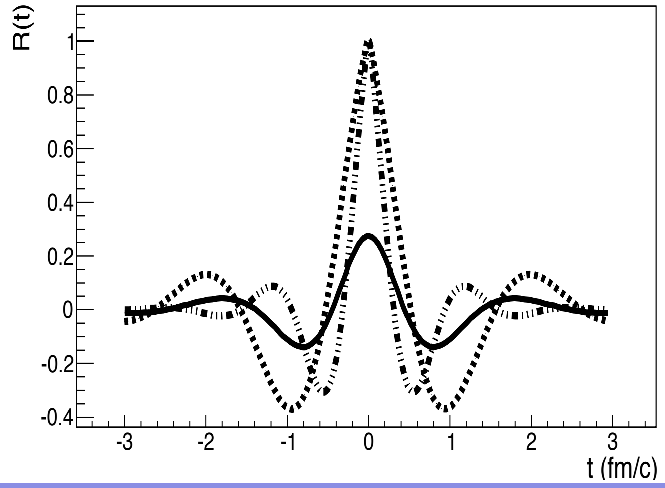
Several spectators: dipole and asymptotics



$$F_1(q)F_2(q) = F.T.\Big[R_1(t) * R_2(t)\Big],$$

$$\Big[R_1(t) * R_2(t)\Big] \equiv \int d\tau R_1(\tau) R_2(t-\tau).$$

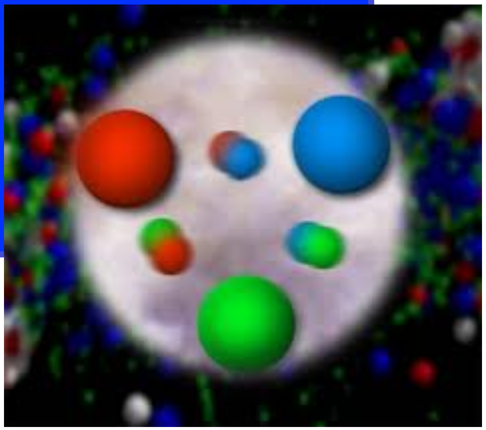
Use FT properties of convolutions
Chain of two oscillators,
one directly connected to the photon
The second is a decaying correlation
between active quark and spectator



$$R(t) = \int d\tau\, e^{-a|t-\tau|}\, e^{-b|\tau|}.$$

$$F(q) \propto \frac{1}{(a^2+q^2)(b^2+q^2)},$$

The nucleon



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

antisymmetric state of colored quarks

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

Main assumption

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

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

Thank you for attention

More complicated examples

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

Three quark-antiquarks pair in the intermediate state.

$$R(t) = \left[[R_1(t) * R_2(t)] * R_3(t)\right],$$

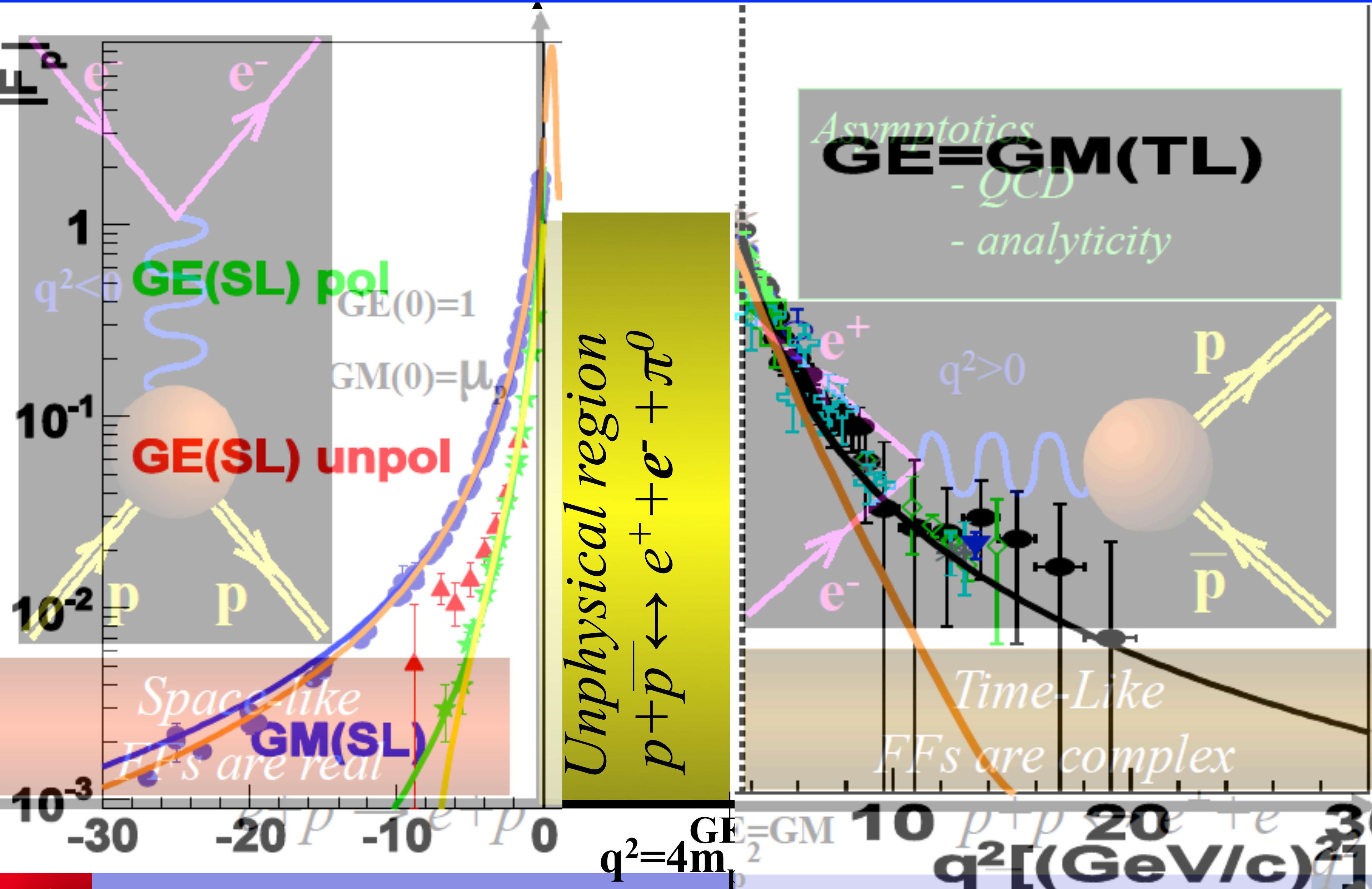
$$F(q) \propto \frac{1}{(q^2 \pm a^2)(q^2 \pm b^2)(q^2 \pm c^2)},$$

Sum of two contributions of equal shape:

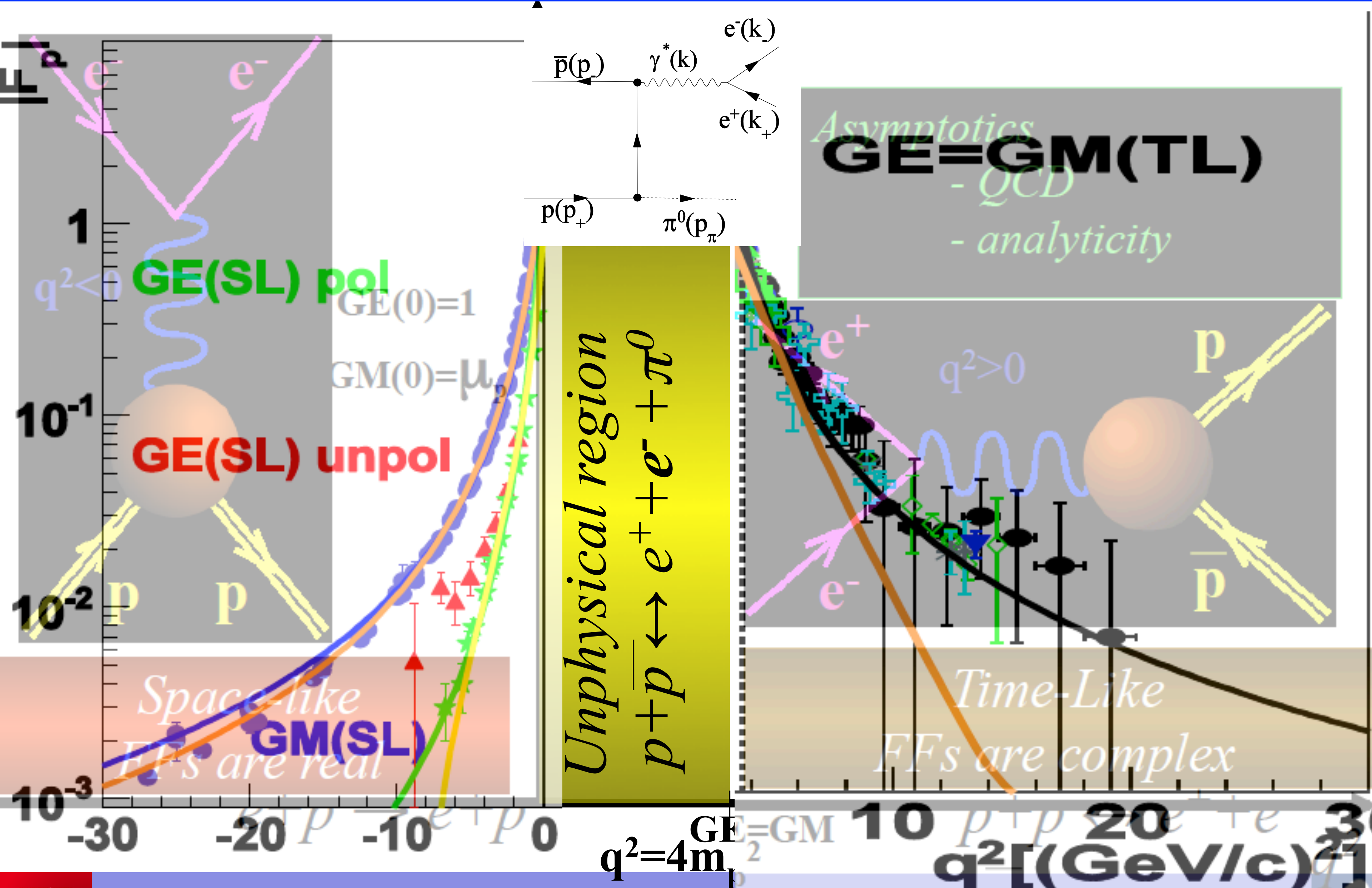
$$\begin{aligned} R(t) &= R_0(t) + aR_0(t-b), \; a \ll 1, \\ F(q) &= F_0(q)[1 + ae^{ibq}], \end{aligned}$$

periodic modulation

Hadron Electromagnetic Form factors

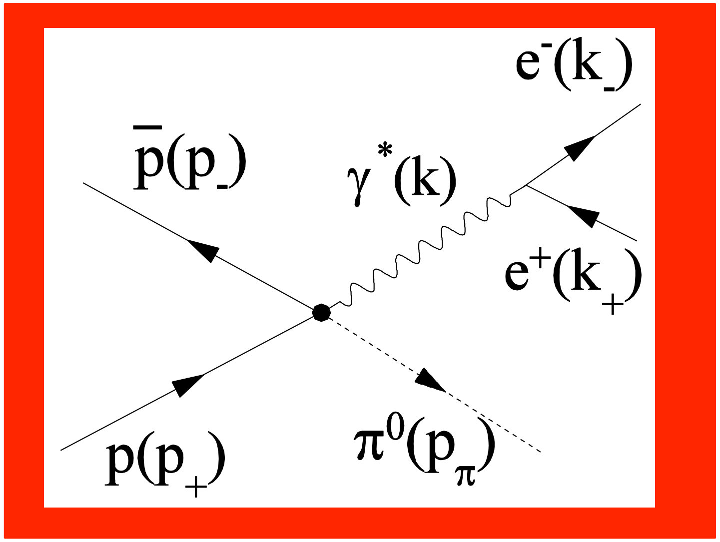


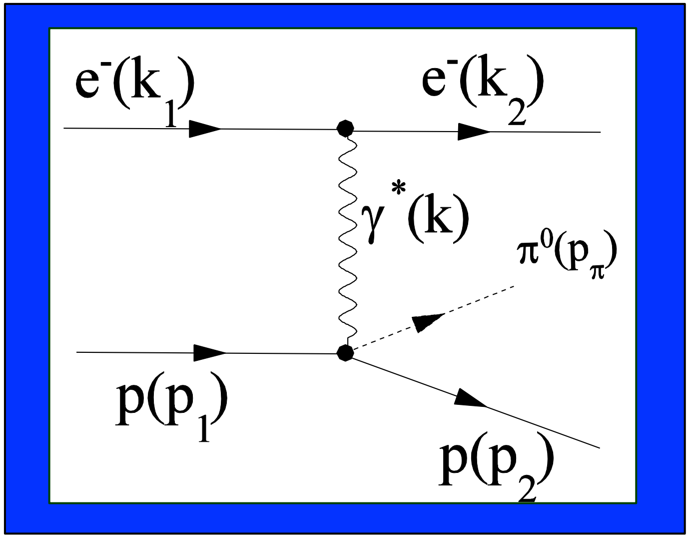
Hadron Electromagnetic Form factors



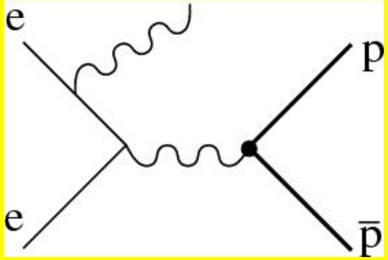
$p + \bar{p} \to e^+ + e^- + \pi^0$ and $e^- + p \to e^- + p + \pi^0$

M. P. Rekalo, 1967





- *Described in general by 6 amplitudes which depend on three kinematical variables*
- *'ISR' for strong interaction*
- *Gives access to EM FF in unphysical region*
- *To TL axial FF (with a deuteron target)*



C. Adamuscin et al, P.R.C. 75, 045205 (2007).
E.A. Kuraev, et al., J.Exp.Theor.Phys.115(2012)93
G.I. Gakh, J. Boucher, E.T-G., P.R.C83 (2011)

Definition of TL-SL Form Factors

$$F(q) = \int d^4x e^{iqx} F(x).$$

$$F_{SL,Breit}(q) = \int d^3\vec{x}\, e^{-i\vec{q}\cdot\vec{x}} \int dt F(t,\vec{x}) \equiv \int d^3\vec{x}\, e^{-i\vec{q}\cdot\vec{x}} \rho(|\vec{x}|),$$

$$\rho(|\vec{x}|) = \int dt F(t,\vec{x}).$$

$$F_{TL,CM}(q) = \int dt\, e^{iqt} \int d^3\vec{x} F(t,\vec{x}) \equiv \int dt\, e^{iqt} R(t),$$

$$R(t) = \int d^3\vec{x} F(t,\vec{x}).$$

$\rho(\vec{x})$ and $R(t)$, represent projections of the same distribution in orthogonal subspaces

Conclusion

•Large activity in Space and Time-like regions for FFs meausurements:

- To increase precision
- To extend q^2 range

Jefferson Lab

VEPP-3 Novosibirsk

BES IHEP

BABAR

panda

PANDA will:

- *Measure electric and magnetic FF with e, muons (simulations by Mainz group): time evolution of quantum vacuum*
- *Explore the unphysical region*
- *Investigate the creation of lepton and hadron pairs (scaling laws, asymptotics)*
- *Impulse theoretical developments towards unified models in TL and SL regions*

Optical model analysis

The excited vacuum created by e+e- annihilation decays in multi-quark states: pbar-p is one of them

- feeding at small r by decay of higher mass states in pbar-p
- depletion at large r from pbar-p annihilation into mesons

From the pbar-p point of view, the coupling with the other channels transforms into an imaginary potential that

- destroys flux (absorption – negative potential)
- generates flux (creation – positive potential)

Optical model :

2 component imaginary potential:
absorbing outside,
regenerating inside,
with steep change of sign.