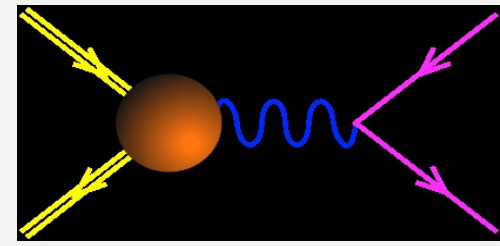
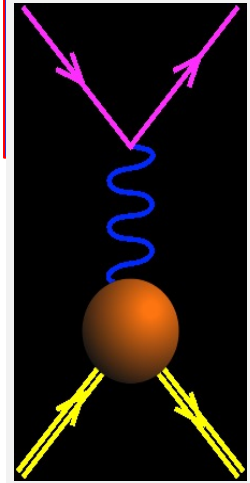


Nel Cuore della Materia

Egle Tomasi-Gustafsson

*CEA, IRFU, DPhN and
Université Paris-Saclay
France*



Università degli Studi di Perugia



A.D. 1308
unipg

UNIVERSITÀ DEGLI STUDI
DI PERUGIA

19 Ottobre 2023



Il protone

Il protone è l'elemento più diffuso nella materia visibile ...

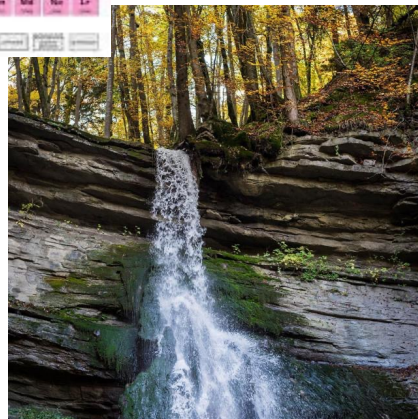
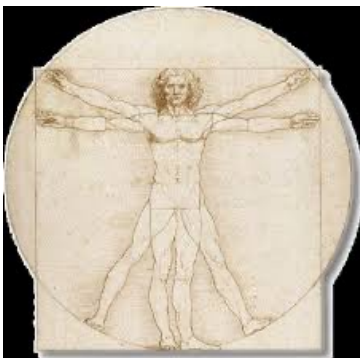
A periodic table of chemical elements, titled "Tableau périodique des éléments chimiques". The table is color-coded by groups and includes element symbols, atomic numbers, and names in French. It also features a legend at the bottom for element categories.



...Ma...

....le sue proprietà fondamentali come

- Massa
- Spin
- Raggio

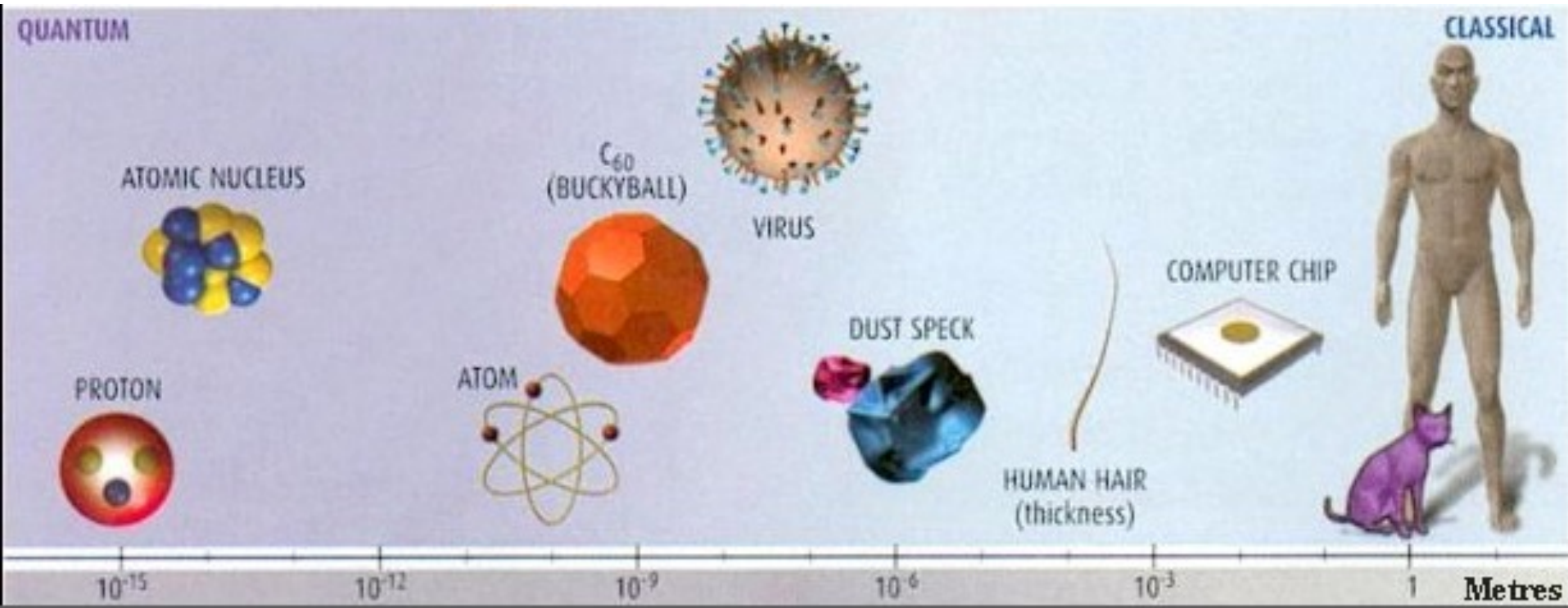


Riservano ancora dei misteri



Ordini di grandezza

...0.000001 m=1/1000000 0.001 m=1/1000 1 m



10^{-15} m

10^{-12} m

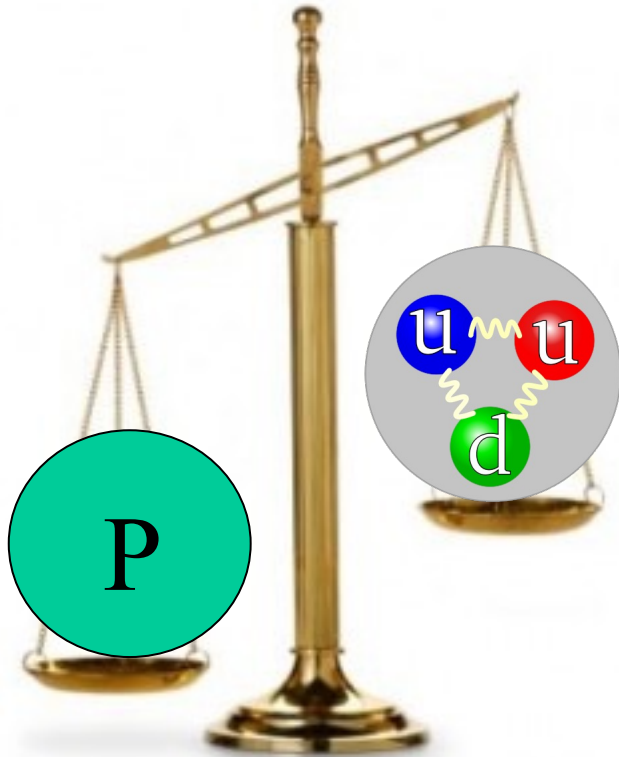
10^{-9} m

10^{-6} m

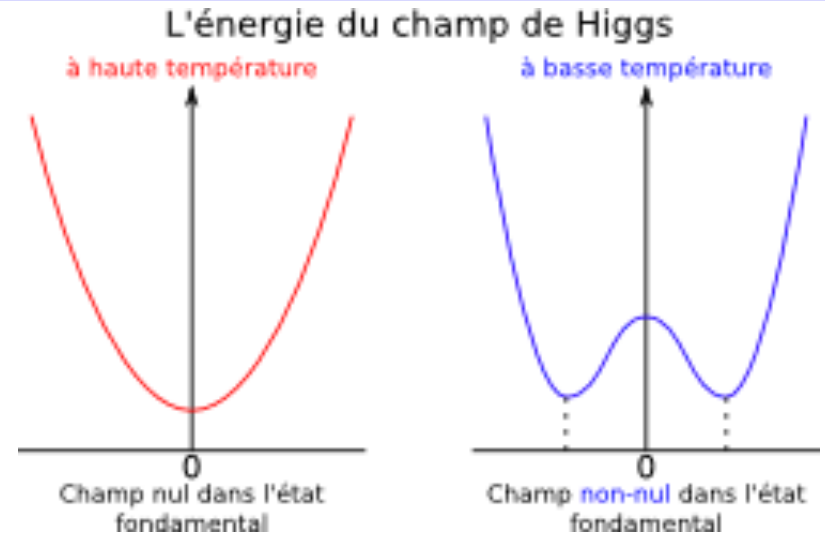
10^{-3} m

1 m

La MASSA del protone



$$M_p = 938,2720 \text{ MeV}/c^2$$



Masse

$$u\text{-quark} = 1.5\text{-}4 \text{ MeV}/c^2$$

$$d\text{-quark} = 4\text{-}8 \text{ MeV}/c^2$$

- creata **dinamicamente** dall'interazione forte



Quarks, Leptoni e Interazioni Fondamentali

Particelle

Bosoni: mediatori

4 interazioni

mass →	≈2.3 MeV/c ²	≈1.275 GeV/c ²	≈173.07 GeV/c ²	0	≈126 GeV/c ²
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	u up	c charm	t top	g gluon	H Higgs boson
	d down	s strange	b bottom	γ photon	
	e electron	μ muon	τ tau	Z Z boson	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

QUARKS

LEPTONS

GAUGE BOSONS



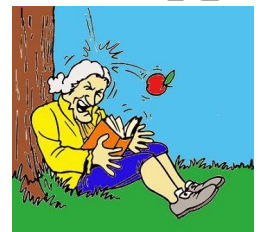
Forte
(energia nucleare)



Elettromagnetica
(elettromagnetismo)



Debole
(radioattività)

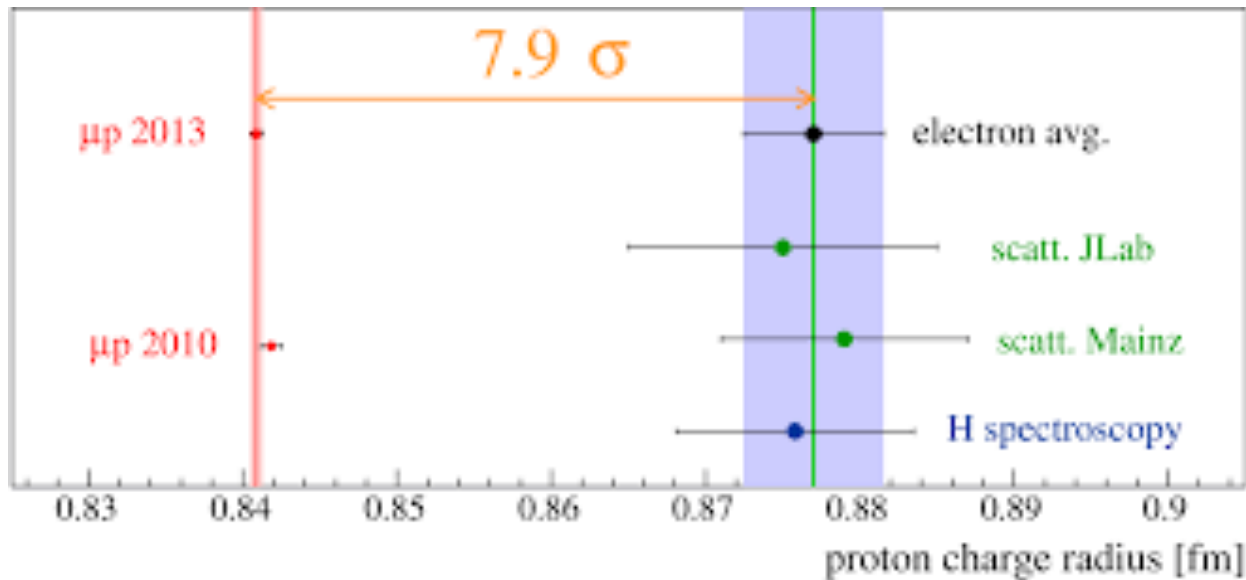


Gravitazionale
(stelle, pianeti)

raggio d'azione, intensità, SIMMETRIE..



Il RAGGIO del protone



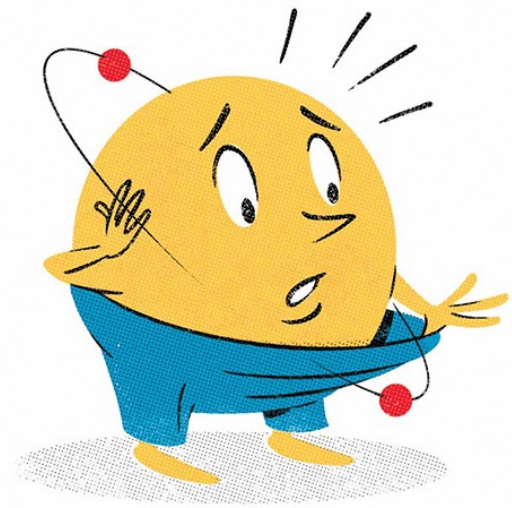
$$R_p = 0.879(18) \text{ fm}$$

$$R_p = 0.8768(69) \text{ fm}$$



$$R_p = 0.84184(67) \text{ fm (muonic H)}$$

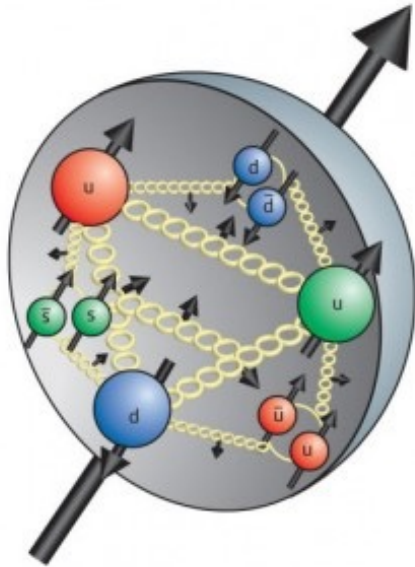
$$R_p = 0.8335(95) \text{ fm (new H)}$$



The New York Times



Lo SPIN del protone



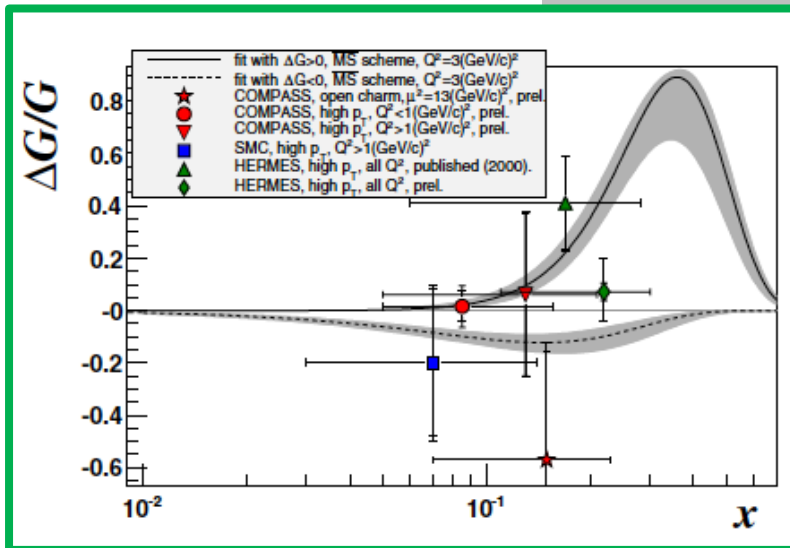
$$S = 1/2$$

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

Quarks

gluoni

momento angolare orbitale

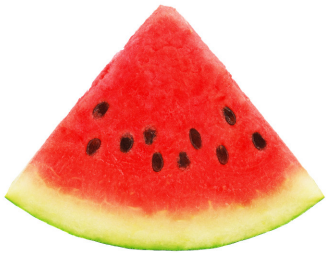


Misurato: $\sim 1/4$

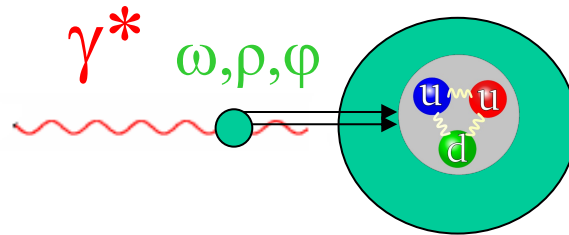
L:
TMD's, PDF's...



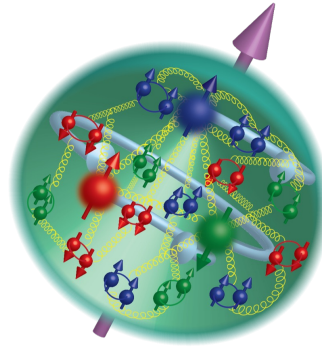
Se il protone fosse un frutto...



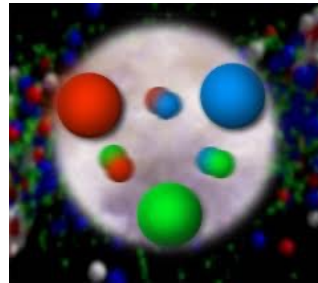
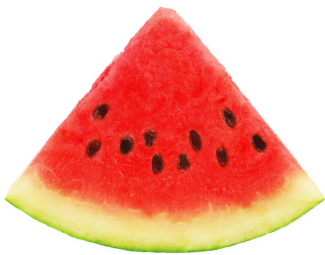
Se il protone fosse un frutto...



- VDM :
vector meson dominance



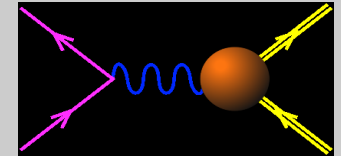
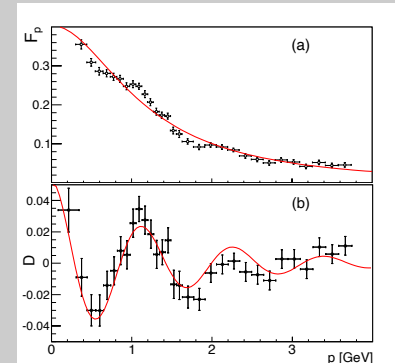
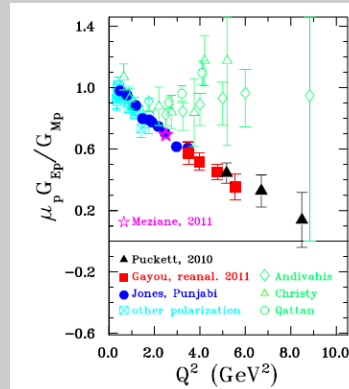
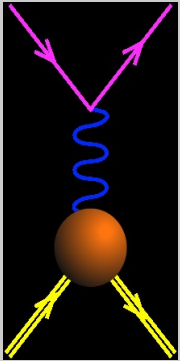
- TMD, GPD...
Parton structure functions



- Instantons:
Mostly Vacuum



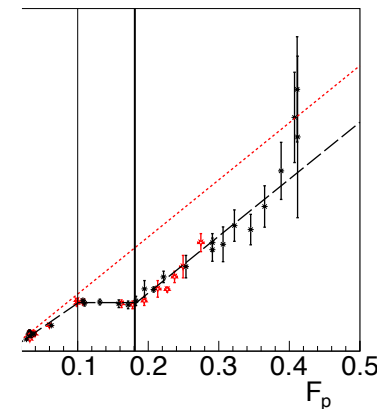
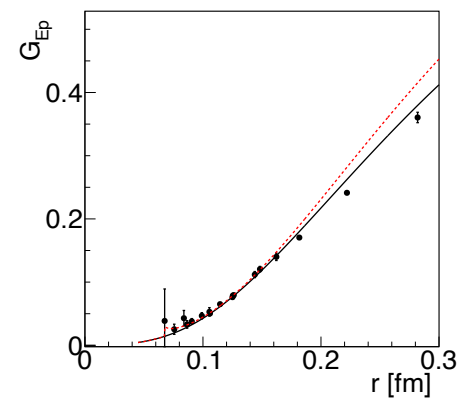
Due scoperte recenti



*Diffusione elastica
elettrone-protone*

*Annichilazione
elettrone-positrone*

- *Quadro globale*
- *Dati e modelli*



Fisica delle Particelle, Nucleare, Adronica



Scale in m:

10^{-10} m

atom

Scale in 10^{-18} m:

100,000,000

10^{-14} m

nucleus

10,000

1 fm

10^{-15} m

proton

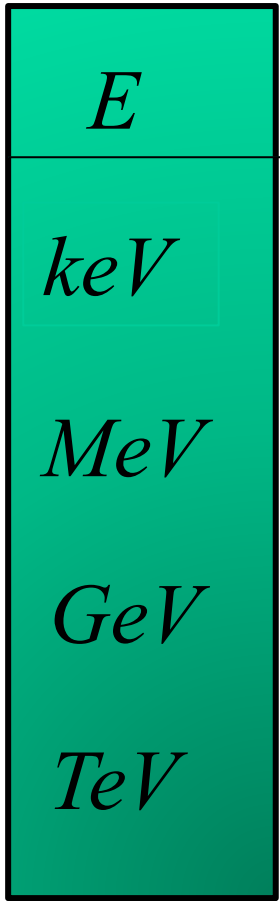
1,000

$\leq 10^{-18}$ m

quark

electron

≤ 1



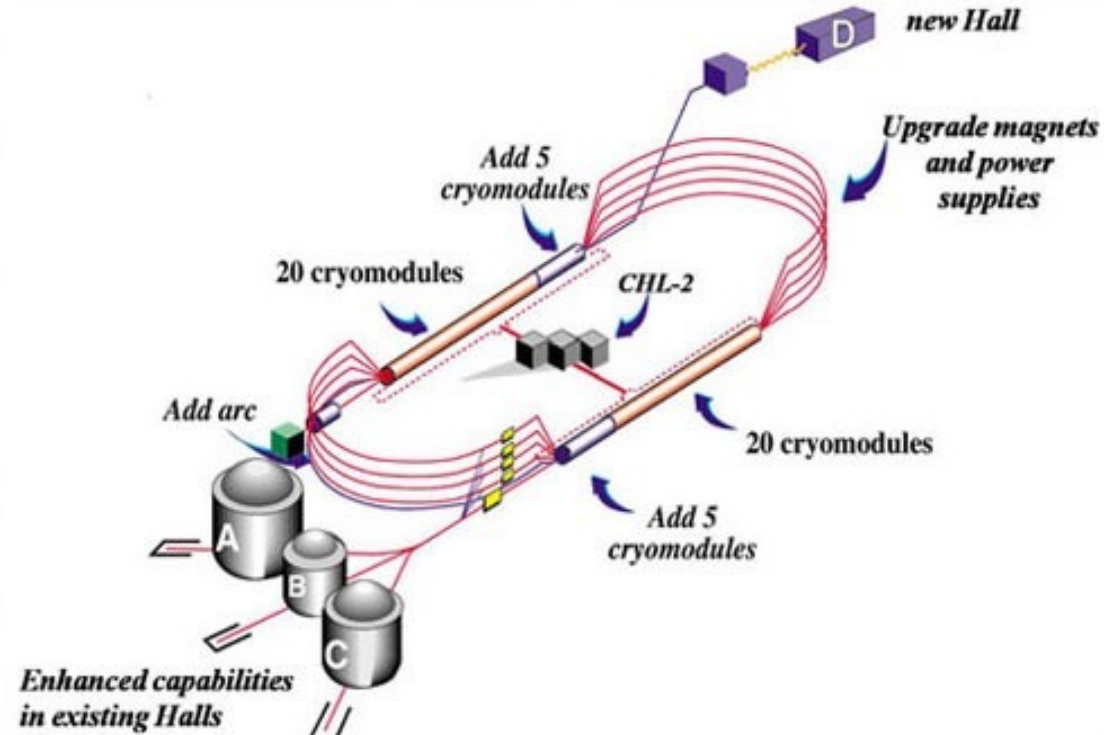
Qual è il microscopio?





Jefferson Lab

Virginia, Newport News, Norfolk
 Lunghezza: 1.5 km
 Fascio: elettroni
 Dimensione fascio : 0.1 mm
 Energia: 11 GeV



Acceleratori di particelle: LHC

Protone-protone

100 m di profondità

27 km circonferenza

9593 magneti

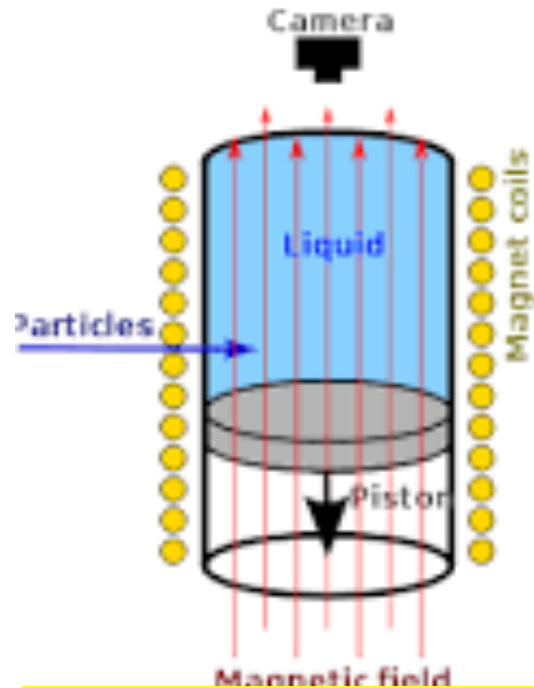
1 miliardo di collisioni/secondo

11245 giri/secondo



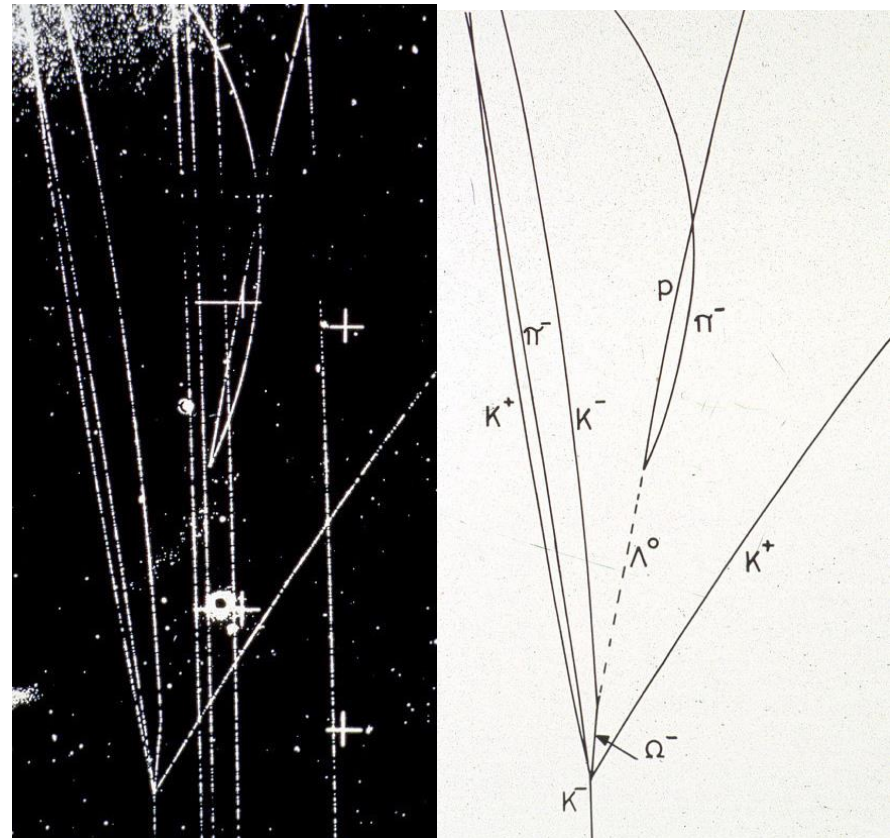
Rivelatori: camere a bolle, a nebbia, emulsioni

Le particelle cariche interagiscono, lasciano energia, ionizzano il liquido, appaiono delle bolle: tracce osservabili!



Contiene un liquido al punto di ebollizione

Rivelatori ottimi ma lenti



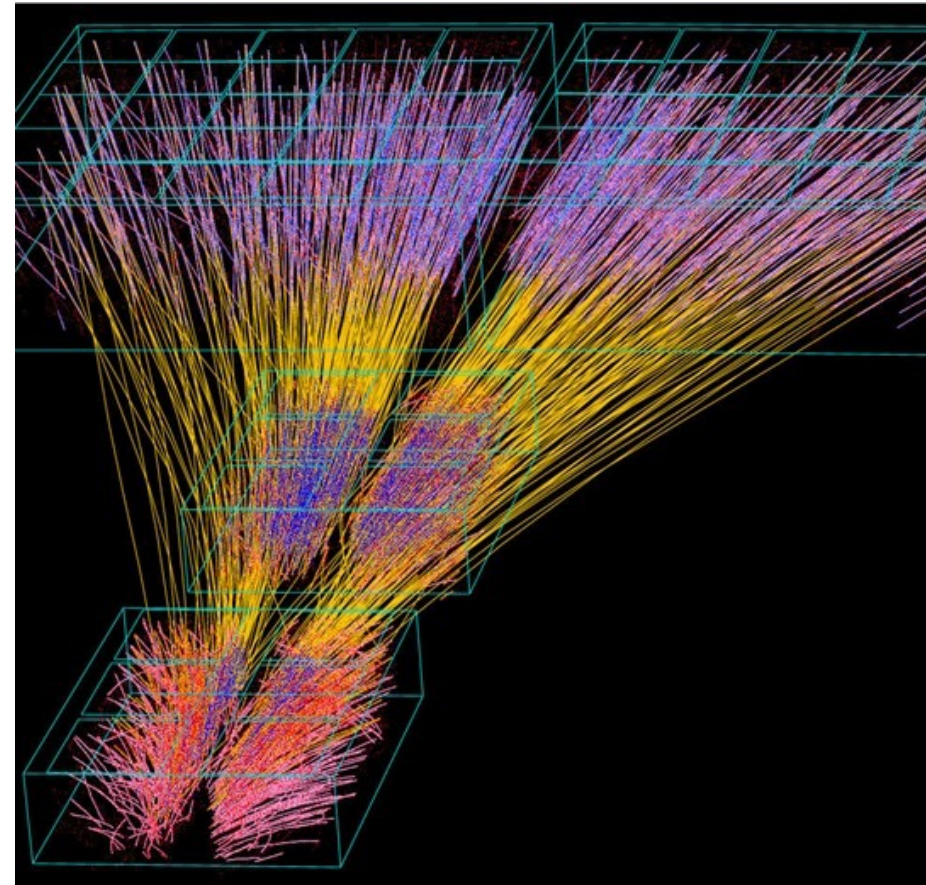
Rivelatori

Ad alta energia la molteplicità delle particelle è troppo grande:
rivelatori elettronici

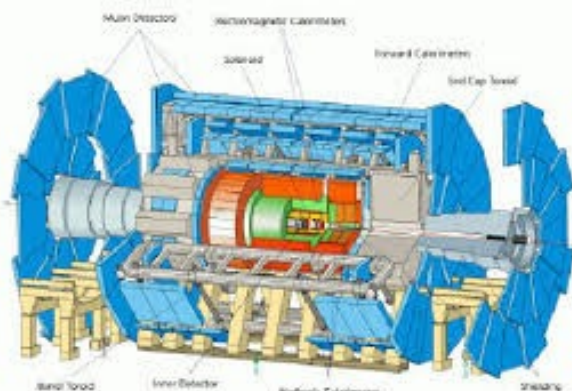


ATLAS
CMS
STAR

.....

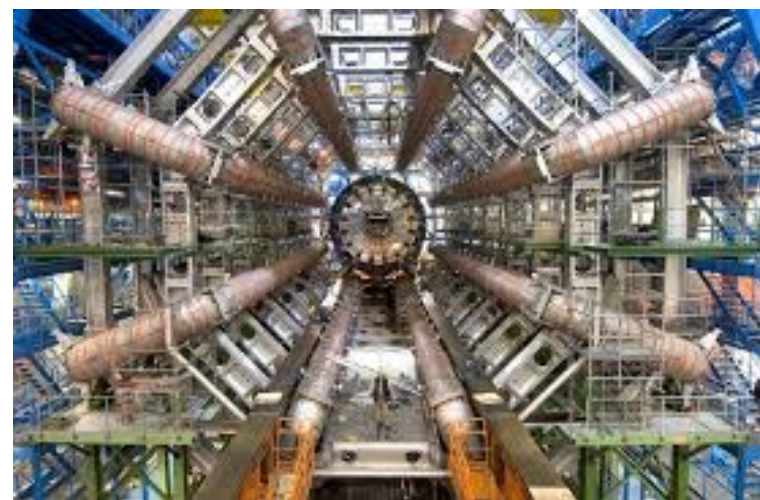
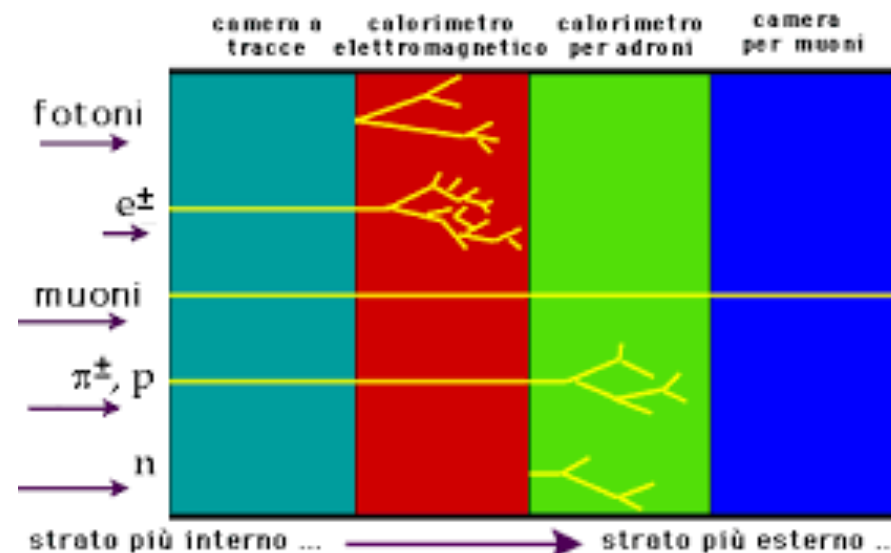
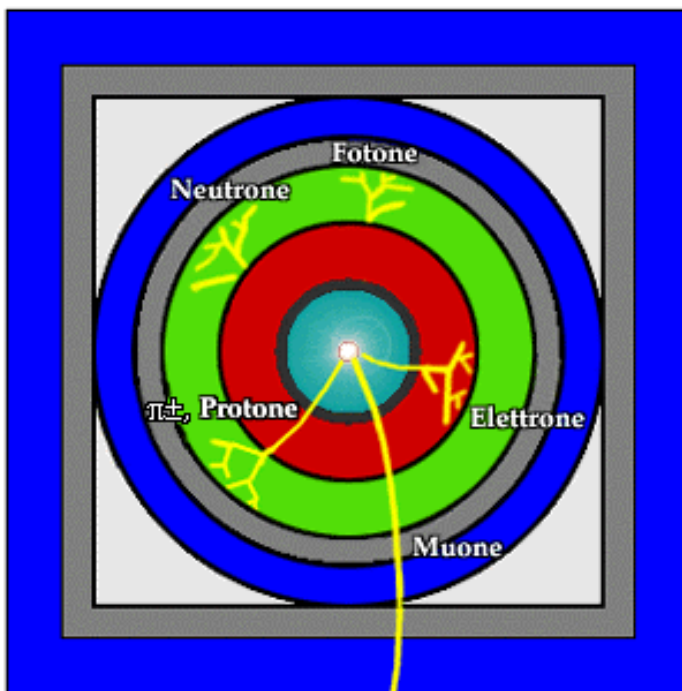


Rivelatori di Particelle

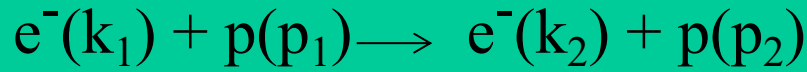


Sezione di un rivelatore, con indicate tracce di particelle

- Fascio (al centro)
- Camera a tracce
- Bobina del magnete
- Calorimetro E-M
- Calorimetro per adroni
- Acciaio magnetizzato
- Camere per muoni



Reazioni elementari



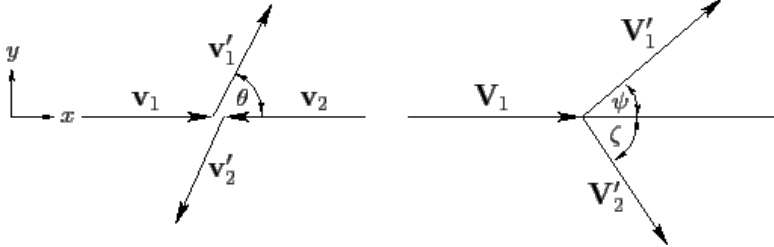
4-vector

$$k_1 = (\epsilon_1, \vec{k}_1)$$

$$k_1^2 = \epsilon_1^2 - \vec{k}_1^2 = m^2$$

center of mass frame

laboratory frame



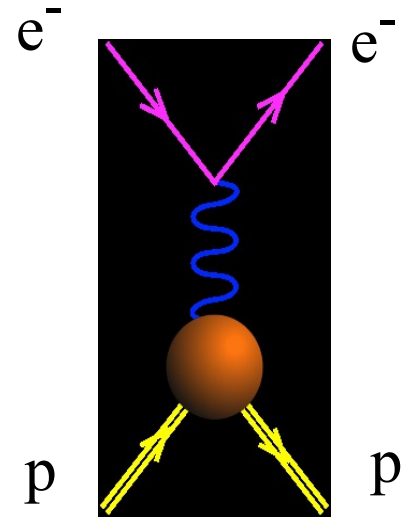
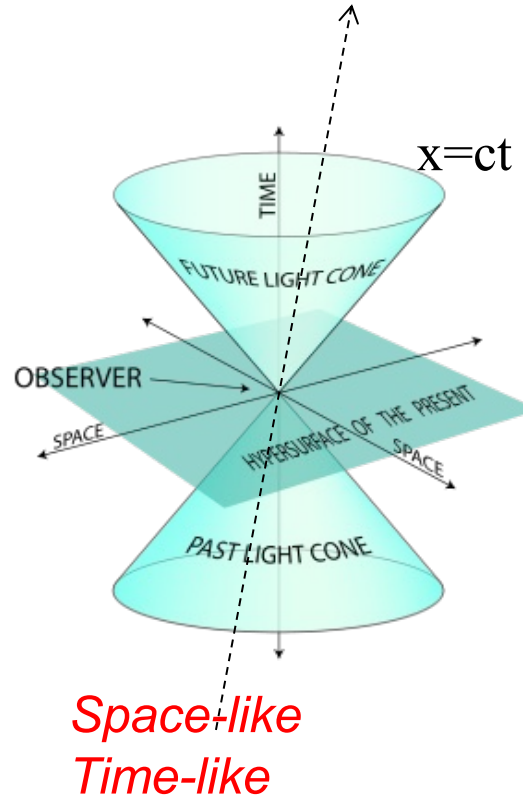
4-momentum conservation

$$k_1 + p_1 = k_2 + p_2$$

$$q^2 = (k_1 - k_2)^2 = -4E_1 E_2 \sin^2 \theta / 2 < 0 \text{ SL}$$

$$q^2 = (p_2 - p_1)^2 = 2mT = 2M(E_2 - M)$$

$$P = (t \text{ or } E, \vec{x} \text{ or } \vec{p})$$

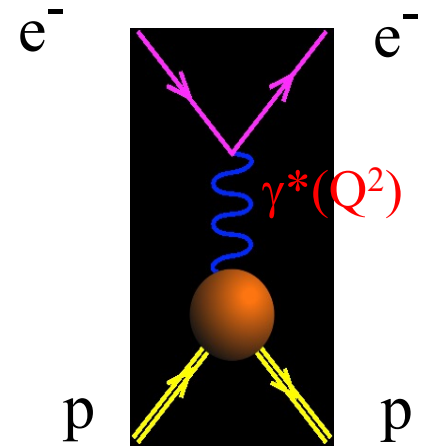


R. Feynman
(1918-1988)



Reazioni elementari

$e^-(k_1) + p(p_1) \rightarrow e^-(k_2) + p(p_2)$	<i>Diffusione</i>
$p(p_1) + \bar{p}(-p_2) \rightarrow e^-(k_2) + e^+(-k_1)$	<i>Annichilazione</i>
$e^-(k_1) + e^+(-k_2) \rightarrow \bar{p}(-p_1) + p(p_2)$	

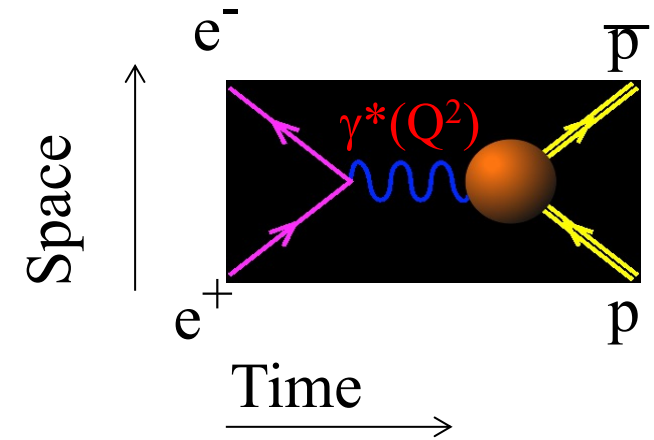


L'interazione avviene tramite lo scambio di un fotone virtuale di 'massa' Q^2

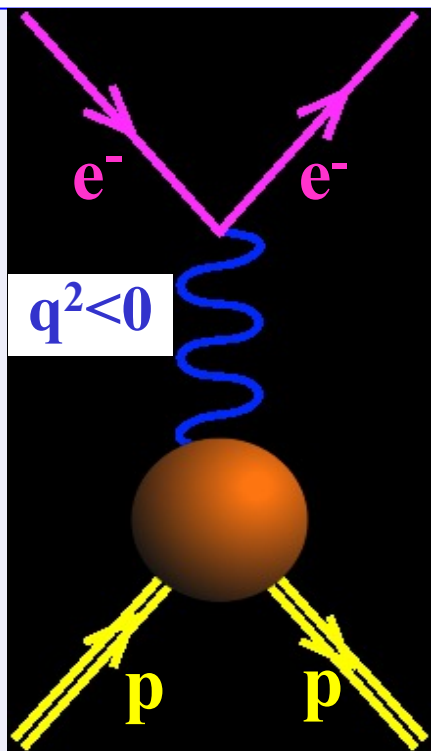
$-Q^2 = t = (k_1 - k_2)^2$: *t-channel*
 $Q^2 = s = (k_1 + p_1)^2$: *s-channel*

Canali 'incrociati':

- Descritti dalla stessa ampiezza $f(s,t)$
- Una particella diventa antiparticella
- I quadrimomenti cambiano segno
- Esplorano diverse regioni cinematiche



Distribuzione di carica elettrica e magnetica



$$G_E(0) = 1$$

$$G_M(0) = \mu_p$$

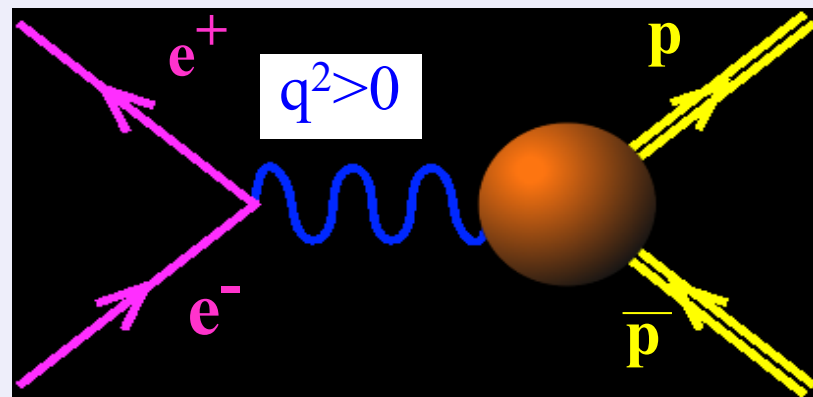
*Space-like
FFs are real*

$$e + p \rightarrow e + p$$

Unphysical region
 $p + \bar{p} \leftrightarrow e^+ e^- + \pi^0$

*Crossing symmetry
Asymptotics*

- QCD
- analyticity



*Time-Like
FFs are complex*

$$p + \bar{p} \leftrightarrow e^+ + e^-$$

0

$4m_p^2$

$G_E = G_M$

q^2



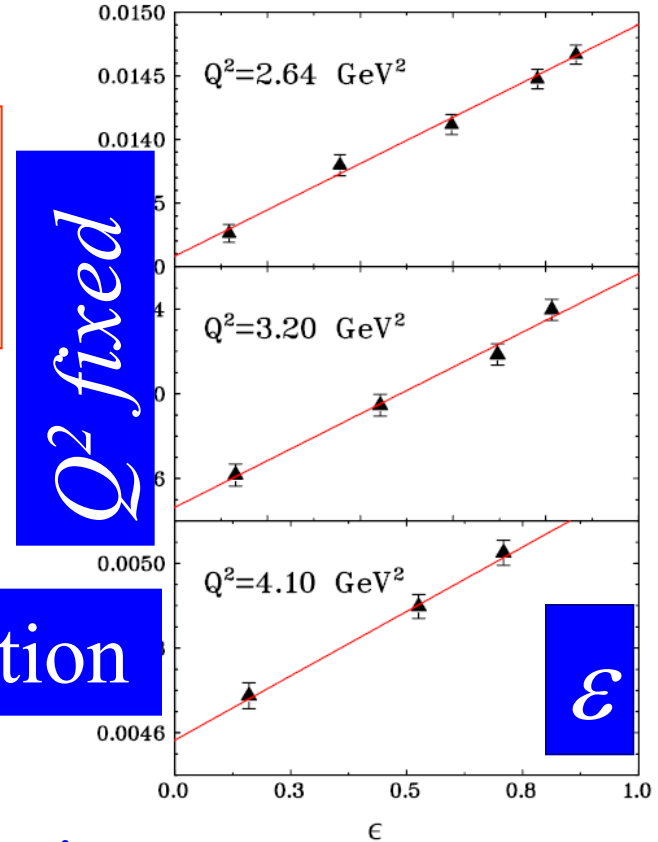
ep-elastic scattering : Rosenbluth separation

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

1950

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

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



Linearity of the reduced cross section

→ $\tan^2 \theta_e$ dependence

→ Holds for 1γ exchange only

PRL 94, 142301 (2005)



ep-elastic scattering : The Akhiezer-Rekalo method

PHYSICS

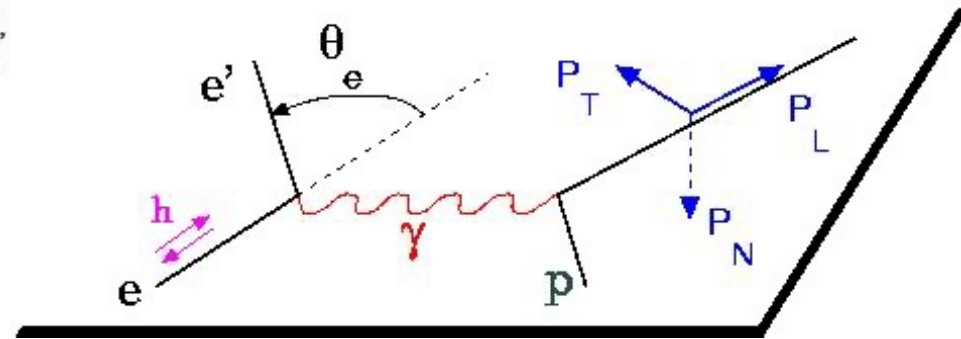
1967

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,

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



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

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



MAGNETIC DISCUSSION

Ben Stenlund

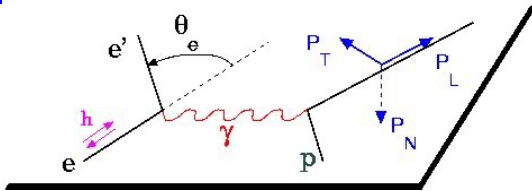
$$\Rightarrow \frac{G_E^p}{G_M^p} = -\frac{P_t}{P_l} \frac{E_e + E_{e'}}{2M} \tan\left(\frac{\theta_e}{2}\right)$$

The simultaneous measurement of P_t and P_l reduces the systematic errors



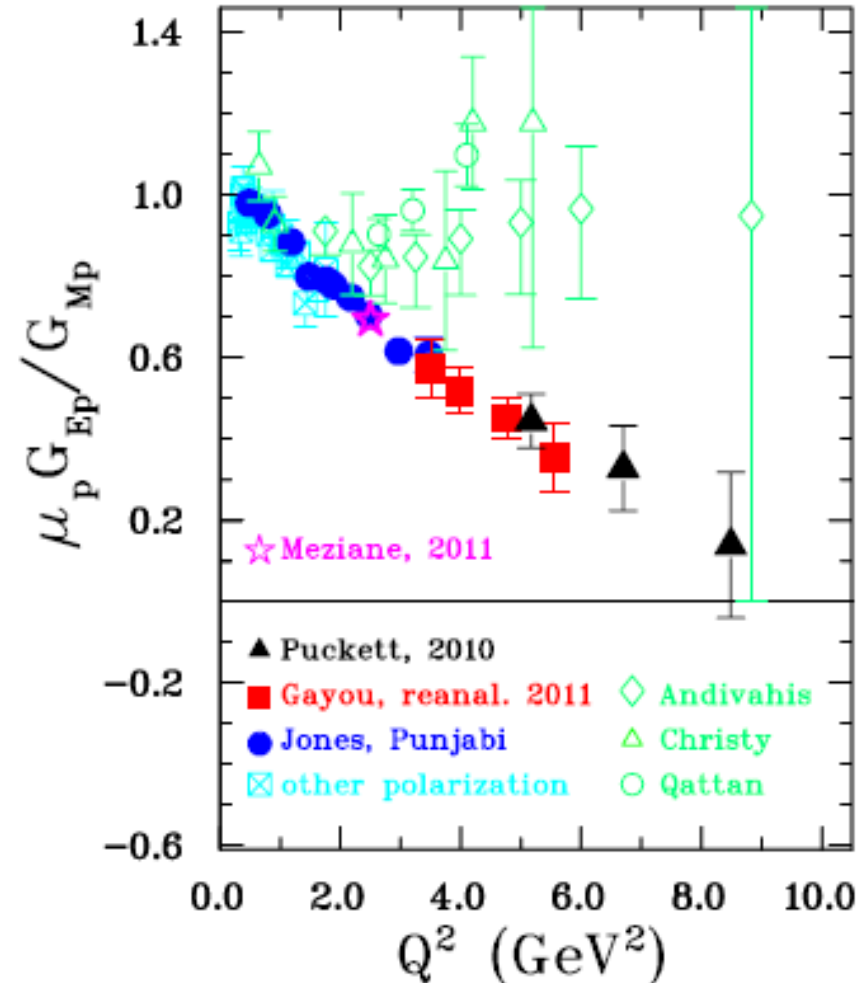
The Akhiezer-Rekalo recoil proton polarization method (1967)

GEp Experiments (>2000)



Jlab-GEp collaboration (>2000)

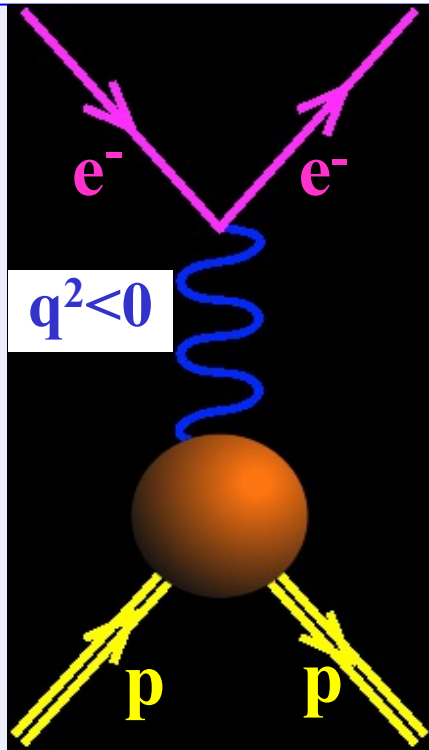
- 1) "standard" **dipole function** for the nucleon magnetic FFs **GMp** and **GMn**
- 2) **linear deviation** from the dipole function for the electric proton FF **GEp**
- 3) **QCD scaling** not reached
- 3) **Zero crossing** of G_{ep} ?
- 4) **contradiction between polarized and unpolarized measurements**



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



Distribuzione di carica elettrica e magnetica



$$G_E(0) = 1$$

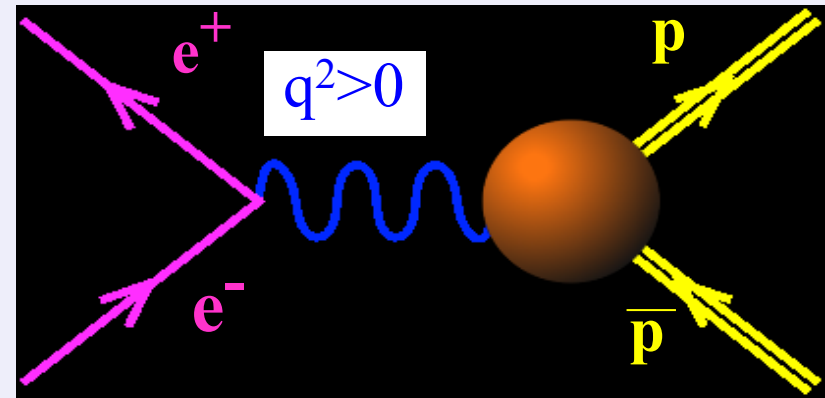
$$G_M(0) = \mu_p$$

*Space-like
FFs are real*

$$e + p \rightarrow e + p$$

Unphysical region
 $p + \bar{p} \leftrightarrow e^+ e^- + \pi^0$

Crossing symmetry
Asymptotics
 - QCD
 - analyticity



*Time-Like
FFs are complex*

$$p + \bar{p} \leftrightarrow e^+ + e^-$$

0

$4m_p^2$
 $G_E = G_M$

q^2



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

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

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

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

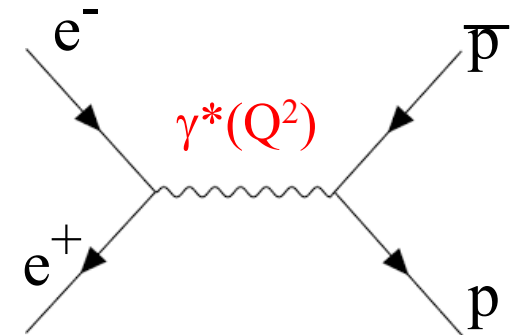
A. Zichichi, S. M. Berman, N. Cabibbo, R. Gatto, Il Nuovo Cimento XXIV, 170 (1962)

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:

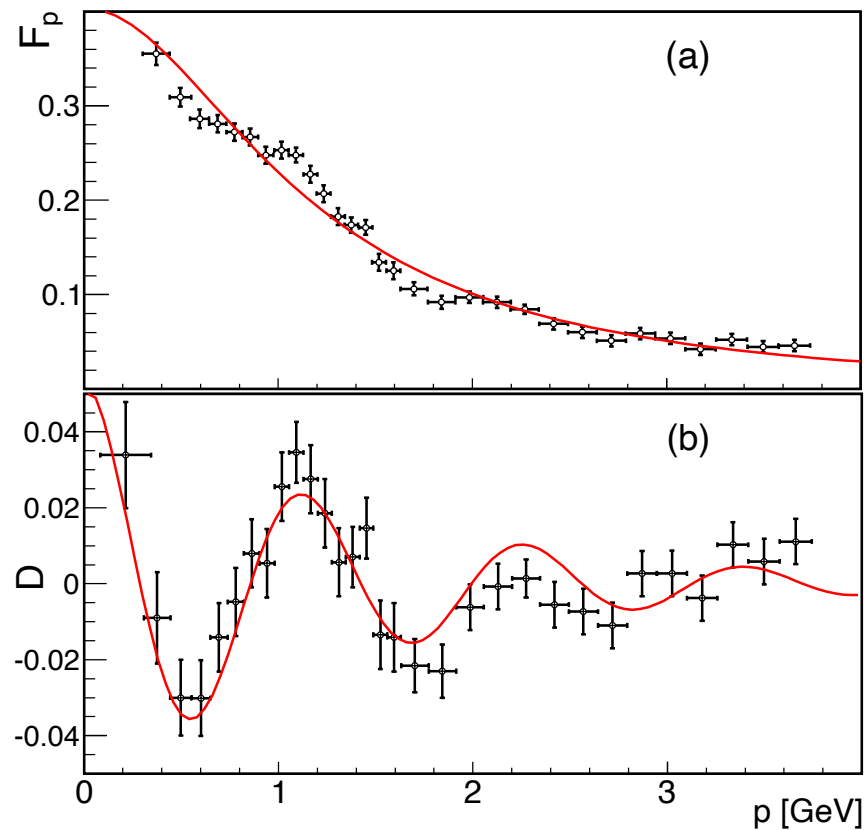
- Dependence on q^2 contained in FFs
- Even dependence on $\cos^2\theta$ (1 γ exchange)
- No dependence on sign of FFs
- Enhancement of the magnetic term



but TL form factors are complex!

Oscillazioni smorzate e regolari in p_{Lab}

La variabile interessante è p_{Lab} associata al moto relativo delle particelle nello stato finale



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

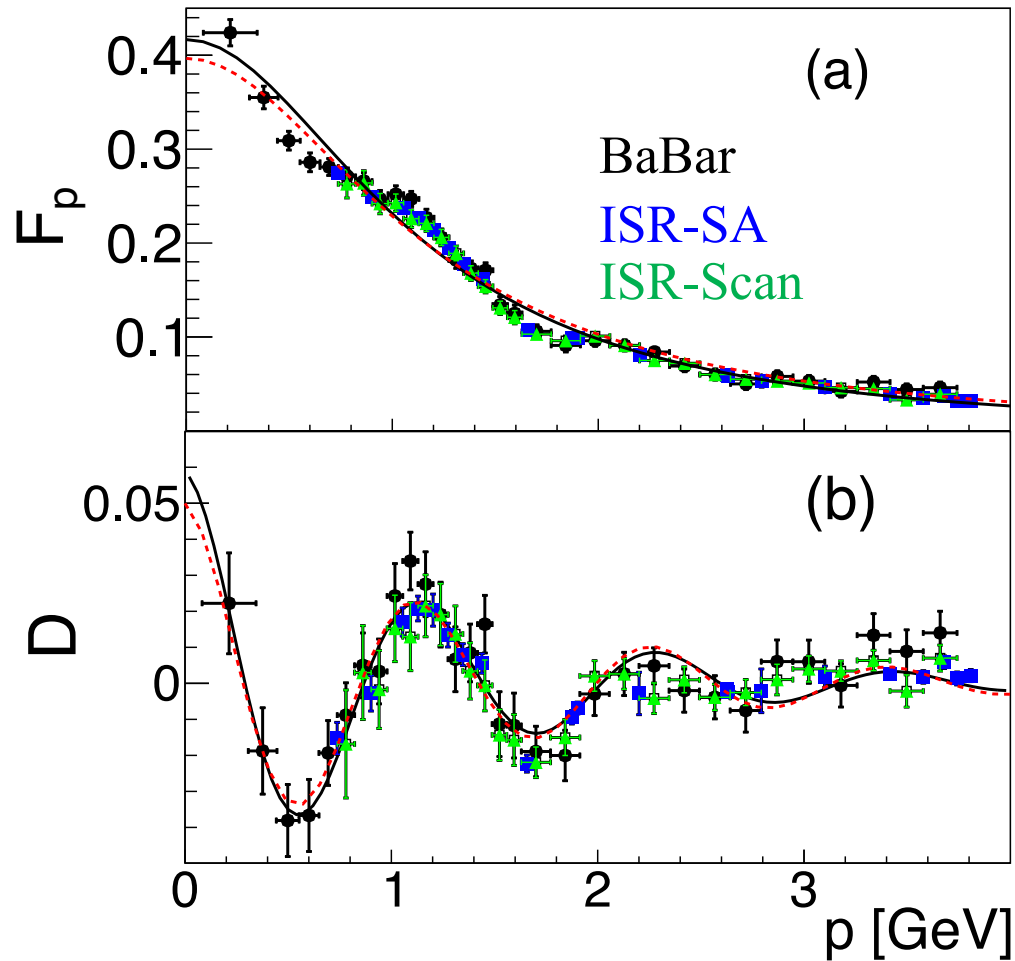
$A \pm \Delta A$	$B \pm \Delta B$	$C \pm \Delta C$	$D \pm \Delta D$	$\chi^2/n.d.f$
	$[GeV]^{-1}$	$[GeV]^{-1}$		
0.05 ± 0.01	0.7 ± 0.2	5.5 ± 0.2	0.03 ± 0.3	1.2

A: Piccola perturbazione B: smorzamento
C: $r < 1\text{fm}$ D=0: massimo a $p=0$

Semplici oscillazioni: interferenza di un piccolo numero di sorgenti coerenti

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

Confirmation of regular oscillations



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

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

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

$$s = 2m_p \left(m_p + \sqrt{p^2 + m_p^2} \right),$$

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

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

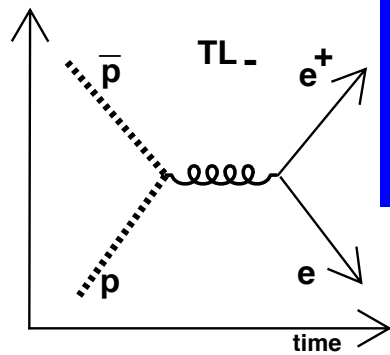
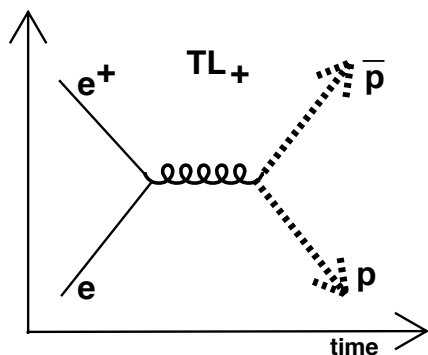
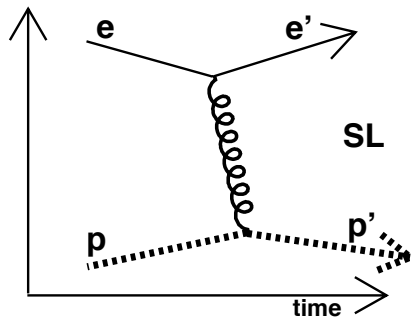


Time- and Space-Like Form Factors

Unified definition

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

$\rho(x) = \rho(\vec{x}, t)$ 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 but sees the time evolution from the annihilation point to the formed hadron

How to connect and understand the amplitudes?



Quarks, Leptoni e Interazioni Fondamentali

Particelle

Bosoni: mediatori

4 interazioni

mass →	≈2.3 MeV/c ²	≈1.275 GeV/c ²	≈173.07 GeV/c ²	0	≈126 GeV/c ²
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	u up	c charm	t top	g gluon	H Higgs boson
	d down	s strange	b bottom	γ photon	
	e electron	μ muon	τ tau	Z Z boson	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

QUARKS

LEPTONS

GAUGE BOSONS



Forte
(energia nucleare)

Elettromagnetica
(elettromagnetismo)



Debole
(radioattività)

Gravitazionale
(stelle, pianeti)

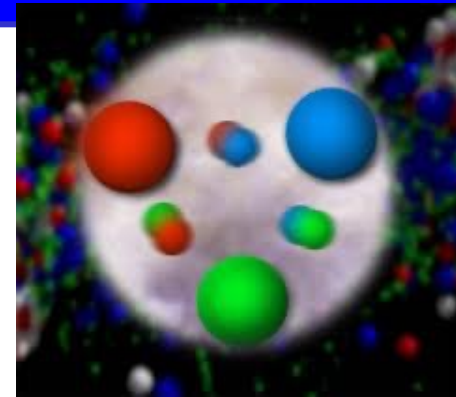


raggio d'azione, intensità, SIMMETRIE..



Il nucleone (protone e neutrone)

3 quarks di valenza
e un 'mare' neutro di coppie $q\bar{q}$



Stato antisimmetrico di quarks con 'colore'

$$\begin{aligned} |p\rangle &\sim \epsilon_{ijk} |u^i u^j d^k\rangle \\ |n\rangle &\sim \epsilon_{ijk} |u^i d^j d^k\rangle \end{aligned}$$

Immaginiamo che nel centro ci sia una regione elettricamente neutra : *condensato di clusters di gluoni* con forte campo cromomagnetico orientati casualmente

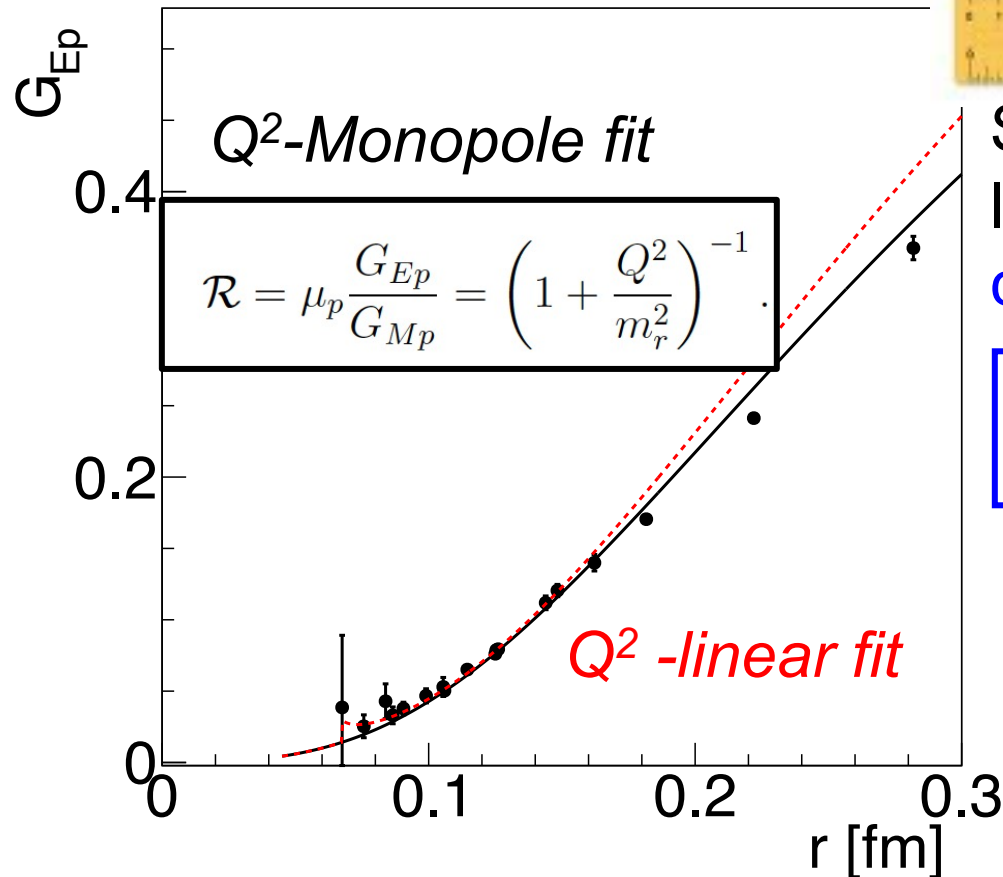
Il campo elettrico risulta schermato, come in un plasma.

Si puo dimostrare che il fattore di forma elettrico è soppresso di un fattore q^2 rispetto al magnetico.

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



SL- il righello piu preciso



Soppressione addizionale per la carica : **screening della carica come in un plasma:**

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

Zero crossing?

Predizione: NO

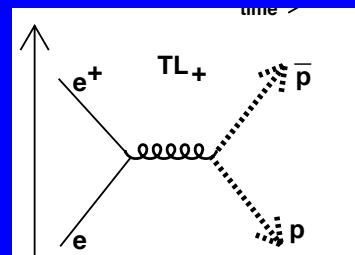
Il fotone 'vede' la regione neutra, schermata

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

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

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





Regione Tempo

Stato antisimmetrico di quark di colore



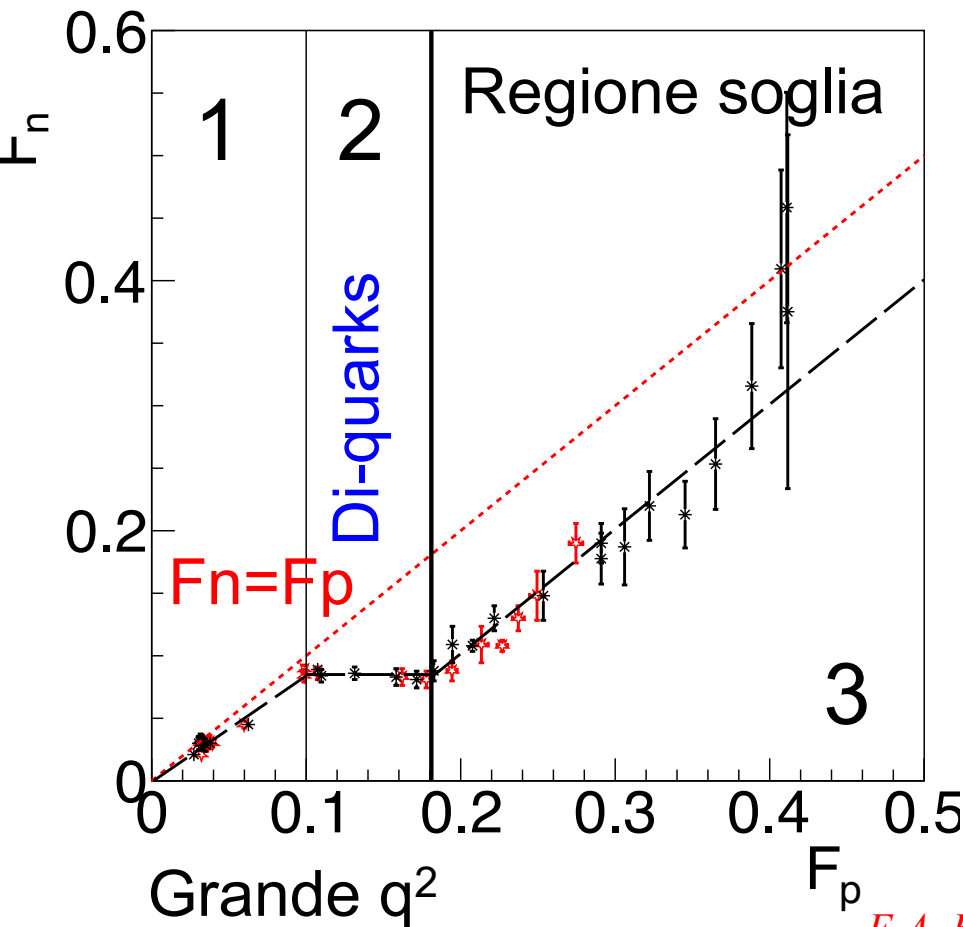
*Il colore sparisce:
Principio di Pauli*

Lo stato di vuoto trasferisce tutta l'energia in uno stato di materia che consiste almeno di 6 quark di valenza, senza massa, un set di gluoni un mare di $\bar{q}q$, con $q_0 > 2M_p$, dimensione $\hbar/(2M_p) \sim 0.1 \text{ fm}$.

- I quarks uu (dd) sono spinti fuori dalla regione interna
- Il terzo quark u (p) o d (n) è attratto da uno dei quark identici, di segno opposto e forma un di-quark compatto : *il destino del sistema è deciso dal bilancio della forza di attrazione e la forza stocastica del campo gluonico*
- Il colore è restaurato, l'adrone puntiforme si espande, e 'si raffredda': i quark assorbono gluoni e diventano quark costituenti con massa, momento magnetico, dimensione...



Correlazione np (TL) : 3 regimi



Punti allo stesso P_L

Altrimenti i valori del protone sono calcolati dal fit a 6 parametri

- 1) Si applica pQCD
- 2) Fase di quark: la carica si riorganizza
- 3) L'adrone è formato

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



MQ ... trasgressiva

Leggi di conservazione: energia, momento angolare, carica, parità....

Conservazione dell'energia:

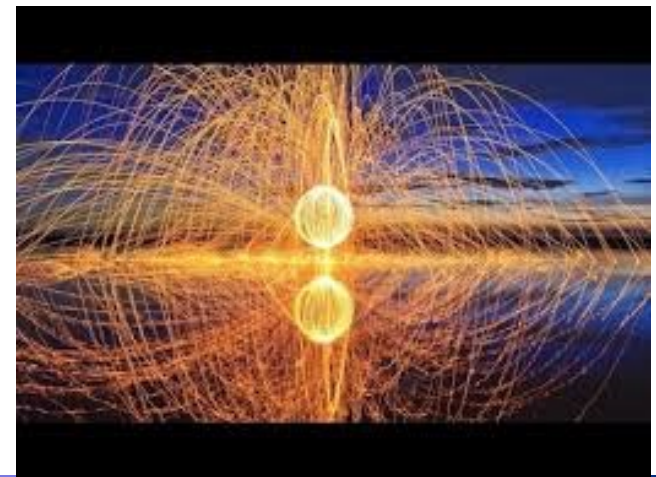
ma...in un tempo abbastanza corto si possono creare '**particelle virtuali**' di qualsiasi massa

$$\Delta E \Delta t \geq \frac{\hbar}{4\pi}$$

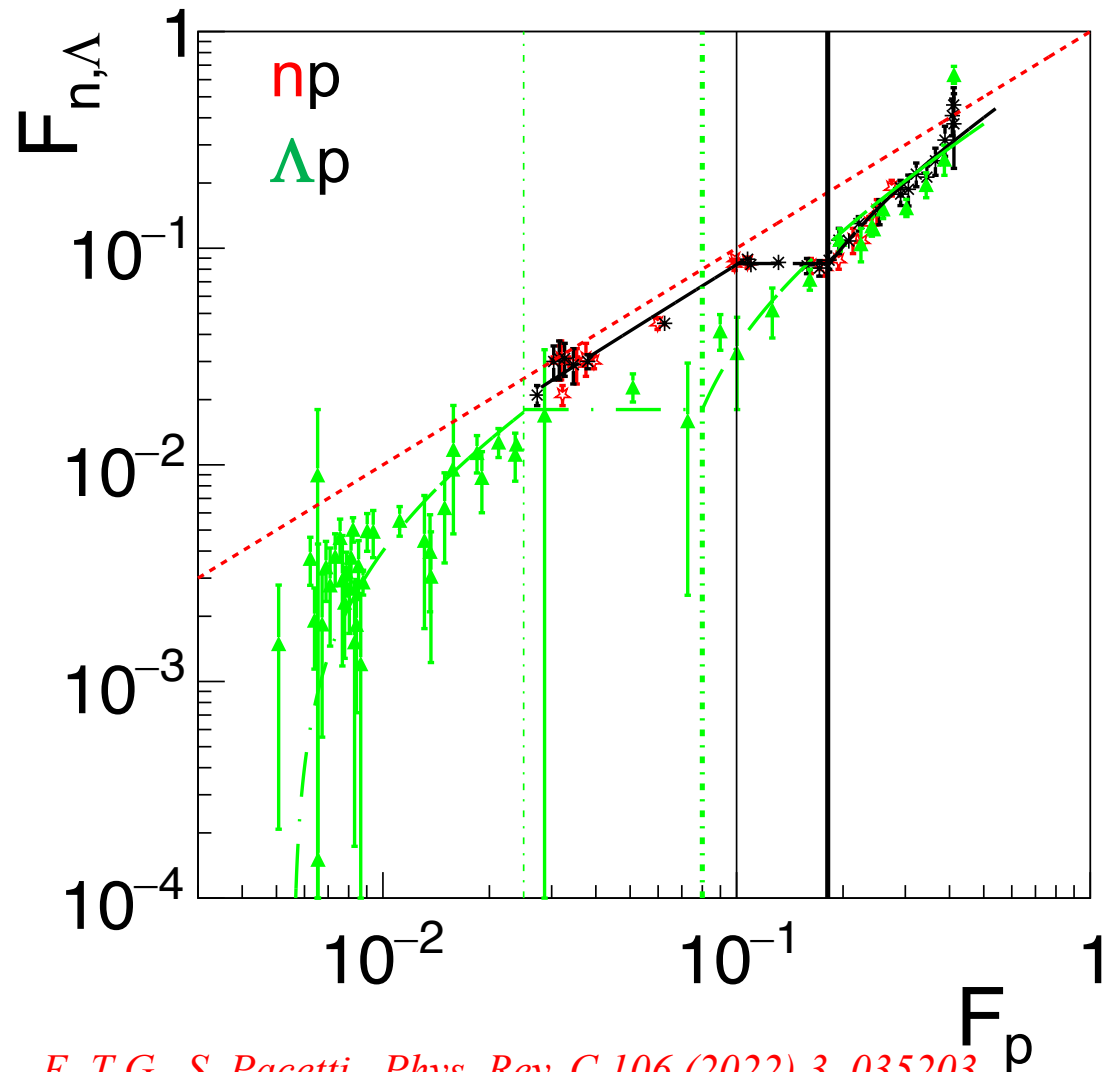
Il vuoto quantistico pullula di particelle!

Fluttuazioni del vuoto:
Particelle-antiparticelle....
Creazione dell'Universo...

...perché solo materia?



Correlazione $np\Delta$

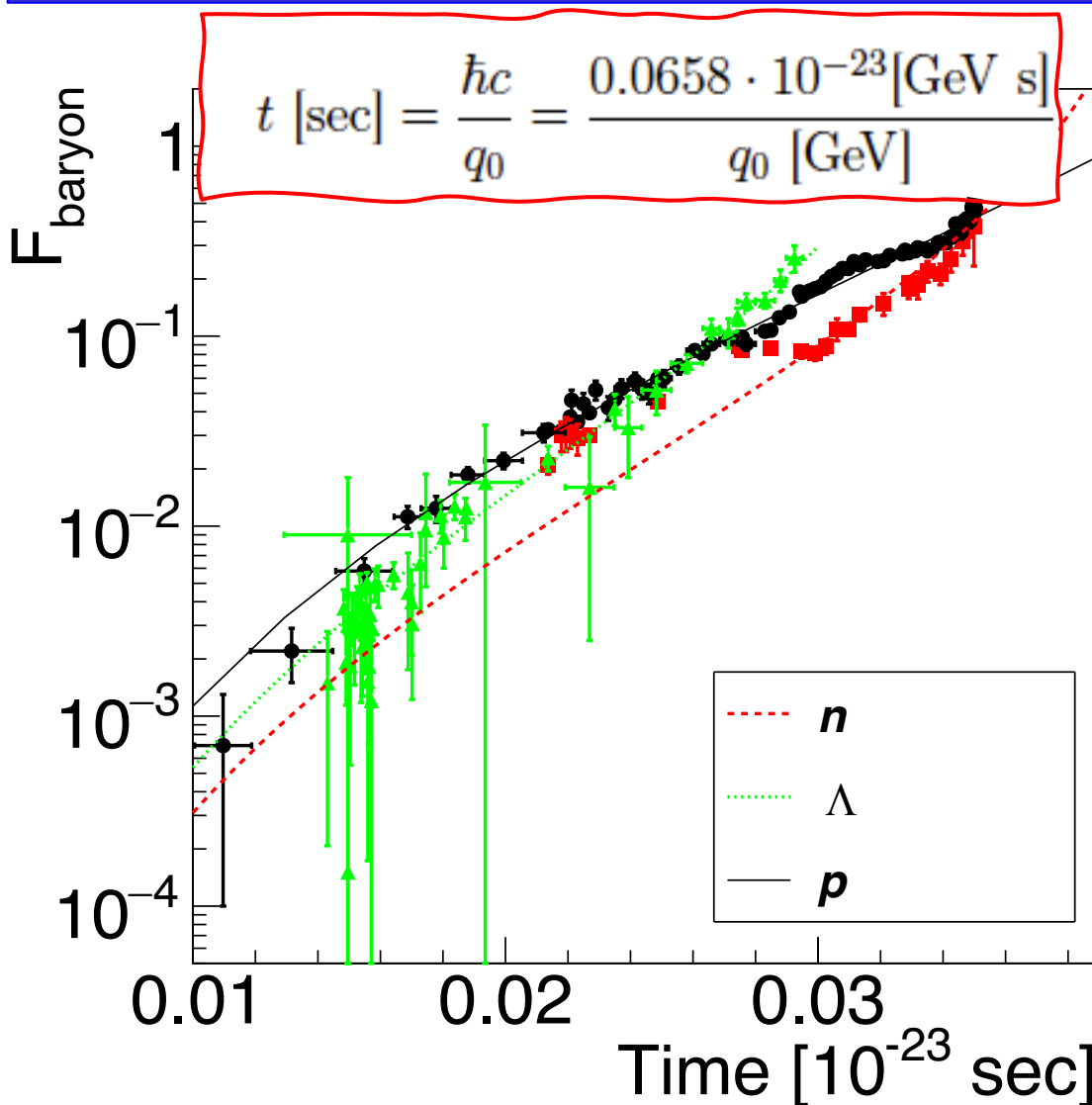


Le coppie di quark sono create dalle fluttuazioni del vuoto: tutti i quark sono equi-probabili, ma-per il principio di Heisenberg- Il tempo associato dipende dall'energia (la massa).

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



TL- l'orologio piu preciso



10^{-23} : tempo
 impiegato dalla luce
 per attraversare il protone

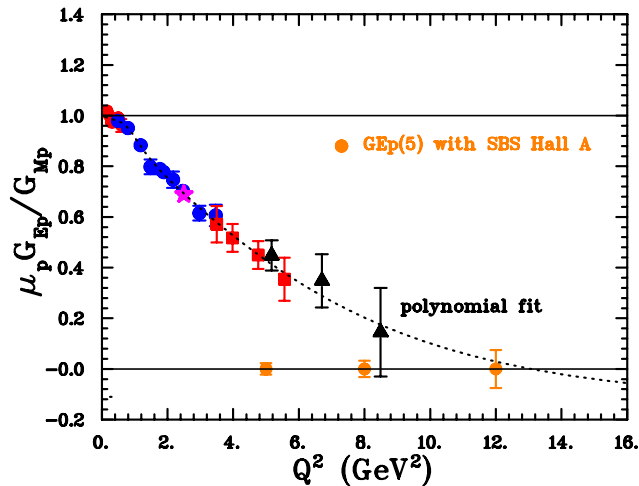
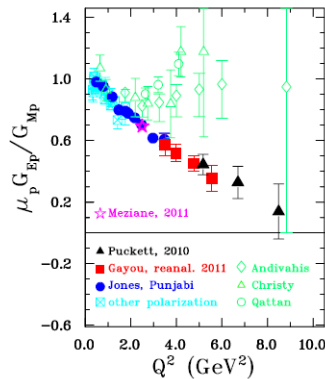
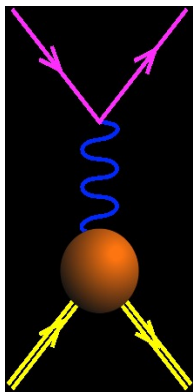
La fase di-quark domina
 a $t \sim 0.02-0.03$ [10^{-23} s]

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

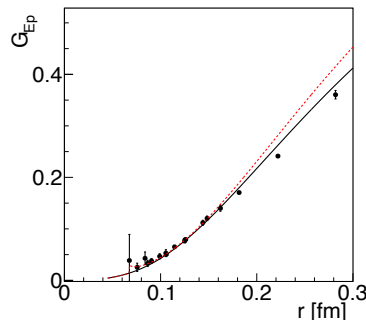
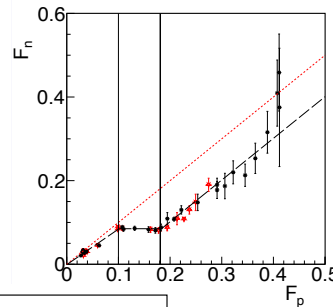
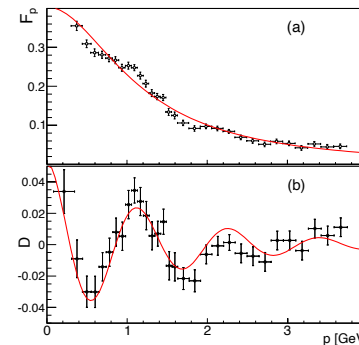
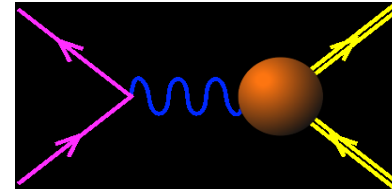
Conclusione

Due scoperte recenti, risultati, predizioni

Diffusione elastica ep



Annichilazione e+e-



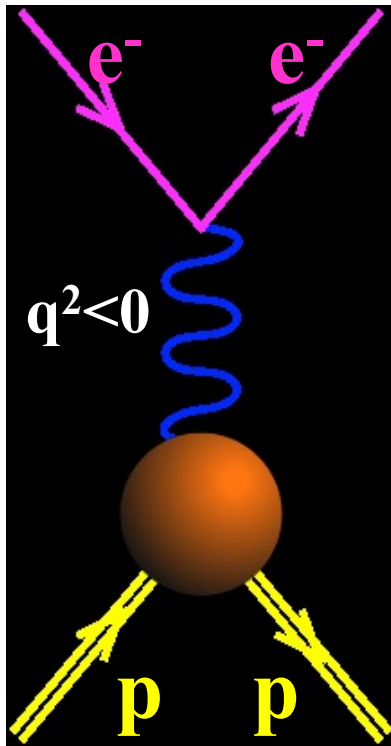
- *Vuoto Q. all'interno*
- *La struttura del protone è 'dinamica': l'immagine cambia secondo la distanza*
- *coesistenza di stati*
- *accesso alla quarta dimensione: il tempo*





Grazie per l'Attenzione!
egle.tomasi@cea.fr

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

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

$$q^2 = -4E_1 E_2 \sin^2 \theta/2$$

or in terms of Sachs FFs:

$$G_E = F_1 + \tau F_2, \quad G_M = F_1 + F_2, \quad \tau = q^2/4M^2$$

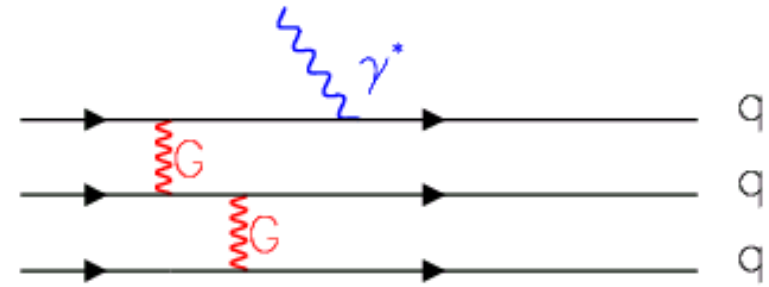
$$G_E(0) = 1(e) \quad G_M(0) = \mu_N$$

What about high order radiative corrections?



Dipole Approximation & pQCD

Dimensional scaling



- $F_n(Q^2) = C_n [1/(1+Q^2/m_n^2)]^{n-1}$,
 - $m_n = n\beta^2$, <quark momentum squared>
 - n is the number of constituent quarks
- Setting $m_\pi = (0.471 \pm 0.010) \text{ GeV}^2$ (fitting pion data)
 - pion: $F_\pi(Q^2) = C_\pi / (1+Q^2/0.471 \text{ GeV}^2)^1$,
 - nucleon: $F_N(Q^2) = C_N / (1+Q^2/0.71 \text{ GeV}^2)^2$,
 - deuteron: $F_d(Q^2) = C_d / (1+Q^2/1.41 \text{ GeV}^2)^5$

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

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

- Classical approach

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

The diagram shows a horizontal line with three arrows. The leftmost arrow points to the right and is labeled $\gamma^*(\mathbf{q}_B)$. The middle arrow points to the left and is labeled $P_1(\mathbf{q}_B/2)$. The rightmost arrow points to the right and is labeled $P_2(\mathbf{q}_B/2)$. An equals sign is placed between the middle and right arrows, indicating that $P_1(\mathbf{q}_B/2) = P_2(\mathbf{q}_B/2)$.

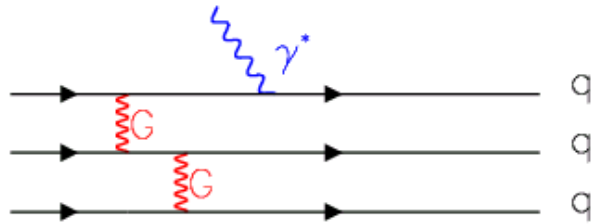
Breit system

- The dipole approximation corresponds to an exponential density distribution.

- $\rho = \rho_0 \exp(-r/r_0)$,
- $r_0^2 = (0.24 \text{ fm})^2$, $\langle r^2 \rangle \sim (0.81 \text{ fm})^2 \leftrightarrow m_D^2 = 0.71 \text{ GeV}^2$



The Time-like Region

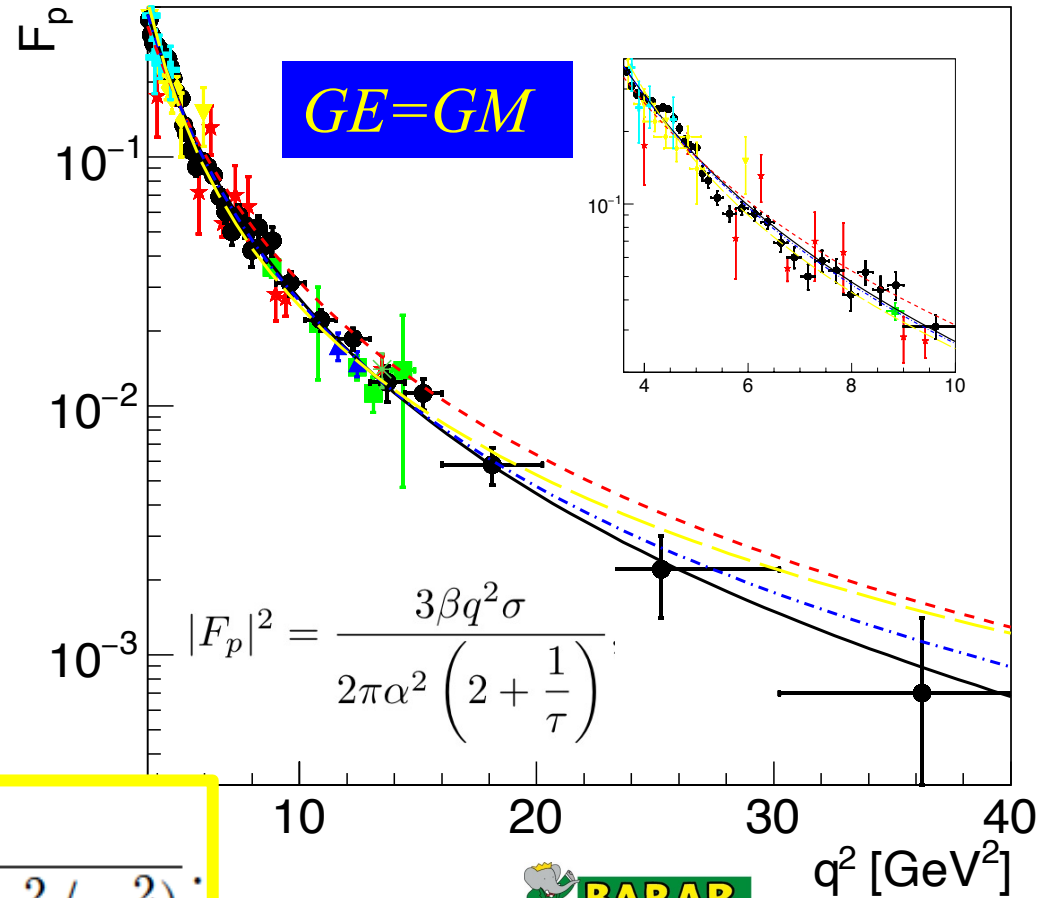
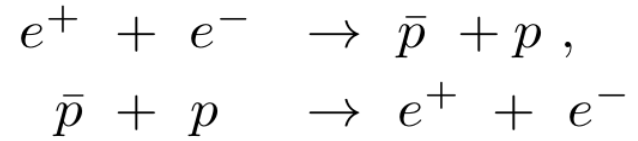


Expected QCD scaling $(q^2)^2$

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

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

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



Predictions for SL and TL

Quark counting rules apply to the vector part of the potential

$$G_M^{(p,n)}(Q^2) = \mu G_E(Q^2);$$

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

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



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 structure of the nucleons"



Robert Hofstadter

🕒 1/2 of the prize

USA

Stanford University
Stanford, CA, USA

Characterize the internal structure of a **particle** (\neq 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 G_E^p, G_M^p and **$G_M^n=0$** .



Fourier Transform

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

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

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

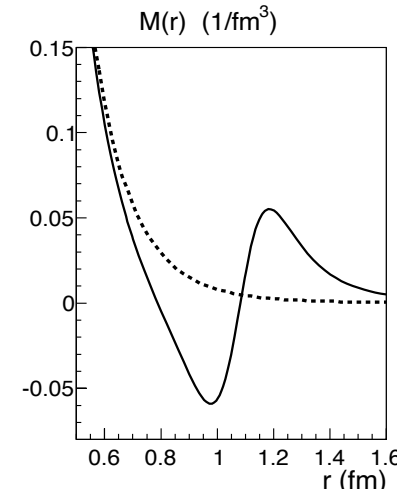
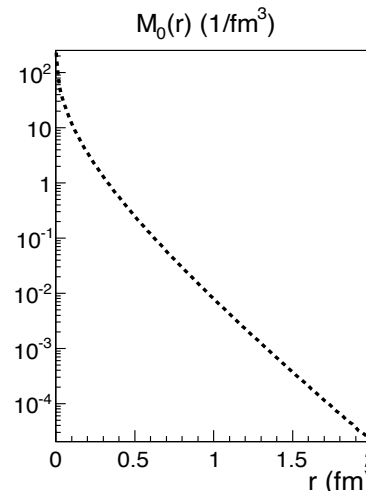
p : relative momentum

r : distance between the center of the forming hadrons

(p, r) conjugate variables, $r \leftrightarrow t$

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

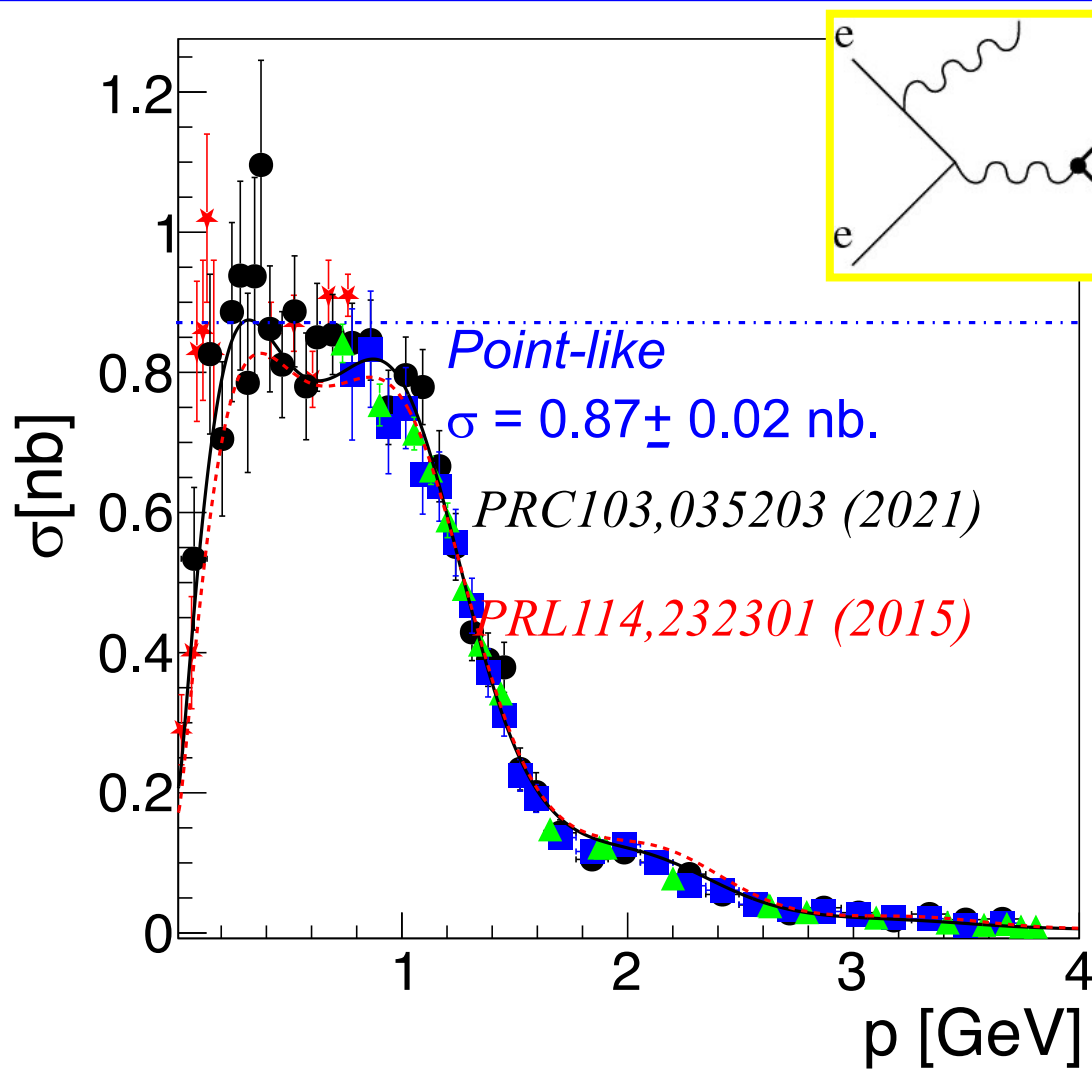
$$F_{osc}(p) \equiv A \exp(-Bp) \cos(Cp + D).$$



- 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 $e^+e^- \rightarrow p\bar{p} (\gamma)$



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)

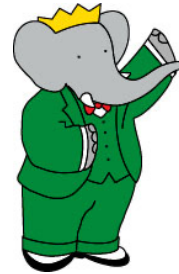
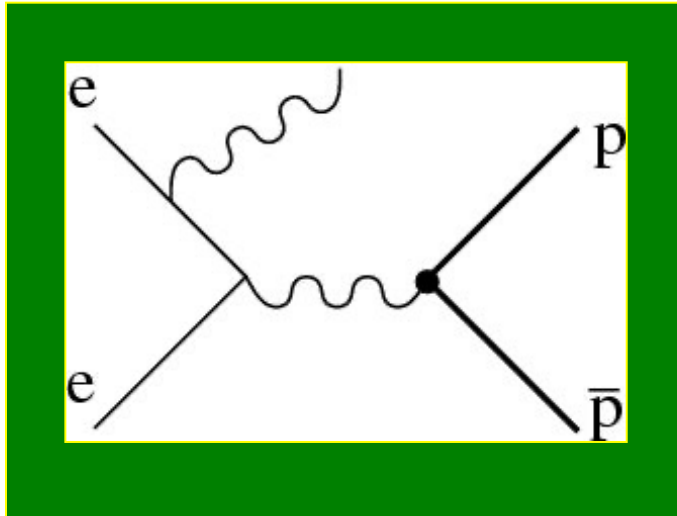
ISR-Scan 22pt

$2 < 2E < 3.1$

PRL124,042001 (2020)

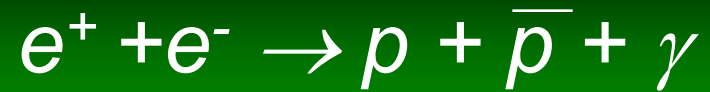
E.T.-G., A. Bianconi, S. Pacetti, Phys.Rev.C 103 (2021) 3, 035203

Radiative return (ISR)



BABARTM

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

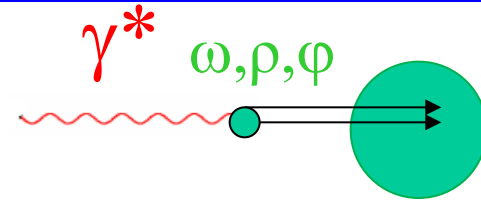
$$W(s, x, \theta) = \frac{\alpha}{\pi x} \left(\frac{2 - 2x + x^2}{\sin^2 \theta} - \frac{x^2}{2} \right), \quad \theta \gg \frac{m_e}{\sqrt{s}}.$$

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



VMD: Iachello, Jackson 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

$$2F_i^p = F_i^s + F_i^v,$$

$$2F_i^n = F_i^s - F_i^v.$$

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

Few # parameters, with physical meaning
Naturally arising TL imaginary part

