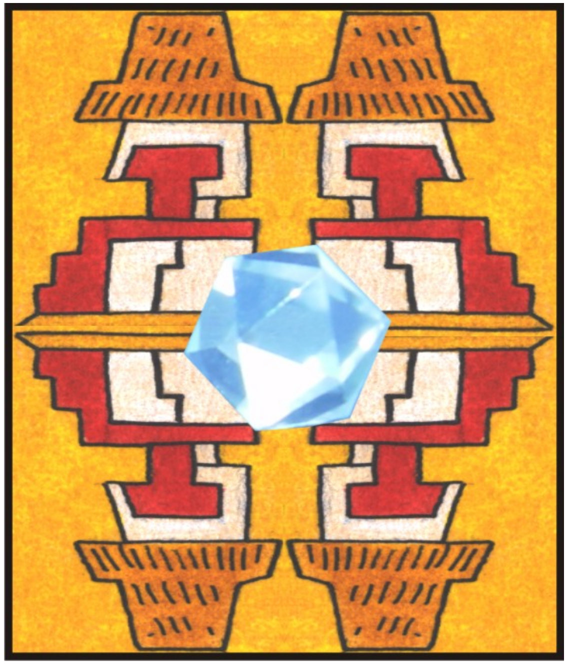
Strange Beauty of the Proton

- Introduction
- Electromagnetic and weak form factors and their flavor decomposition
- Two-component model
- Unquenched quark model
- Summary and conclusions



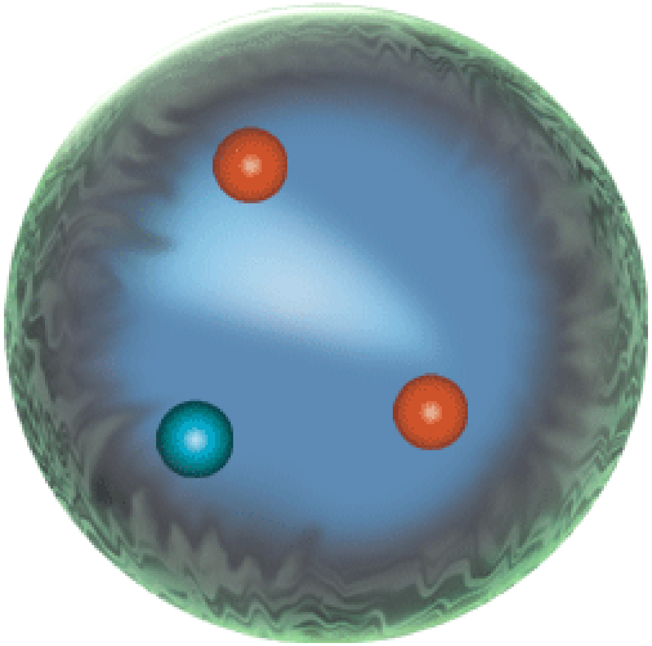
Jacopo Ferretti
Roelof Bijker (ICN-UNAM)
Elena Santopinto (Genova)

Internal Structure of the Proton

- Anomalous magnetic moment (Stern, 1930's)
- Spatial structure (Hofstadter, 1950's)
- Quark structure (Friedman, Kendall, Taylor, 1960's)
- EMC effect, spin crisis (1988)
- Flavor asymmetry (NMC, 1991)
- Form factor ratio (2000)
- Strange form factors (2000's)

Strange Protons

- The strange (anti)quarks come uniquely from the sea: there is no contamination from up or down valence quarks
- The strangeness distribution is a very sensitive probe of the nucleon's properties
- Flavor content of form factors
- New data from parity violating electron scattering SAMPLE, HAPPEX, PVA4 and G0 Collaborations



"There is no excellent beauty that hath not some strangeness in the proportion"
(Francis Bacon, 1561-1626)

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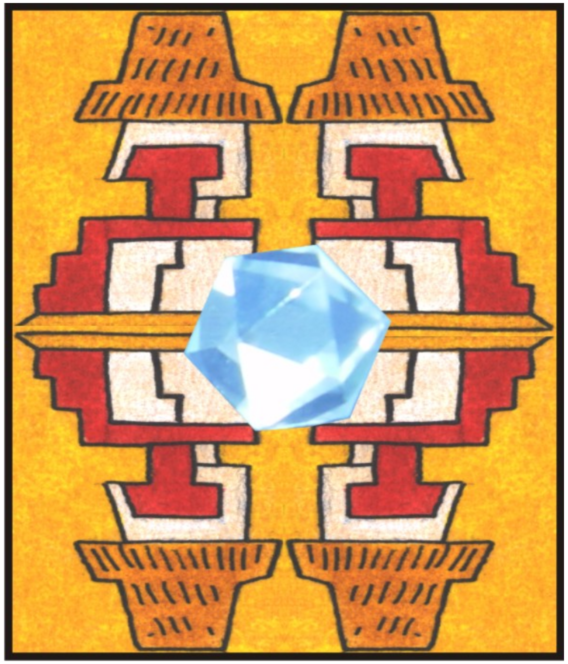
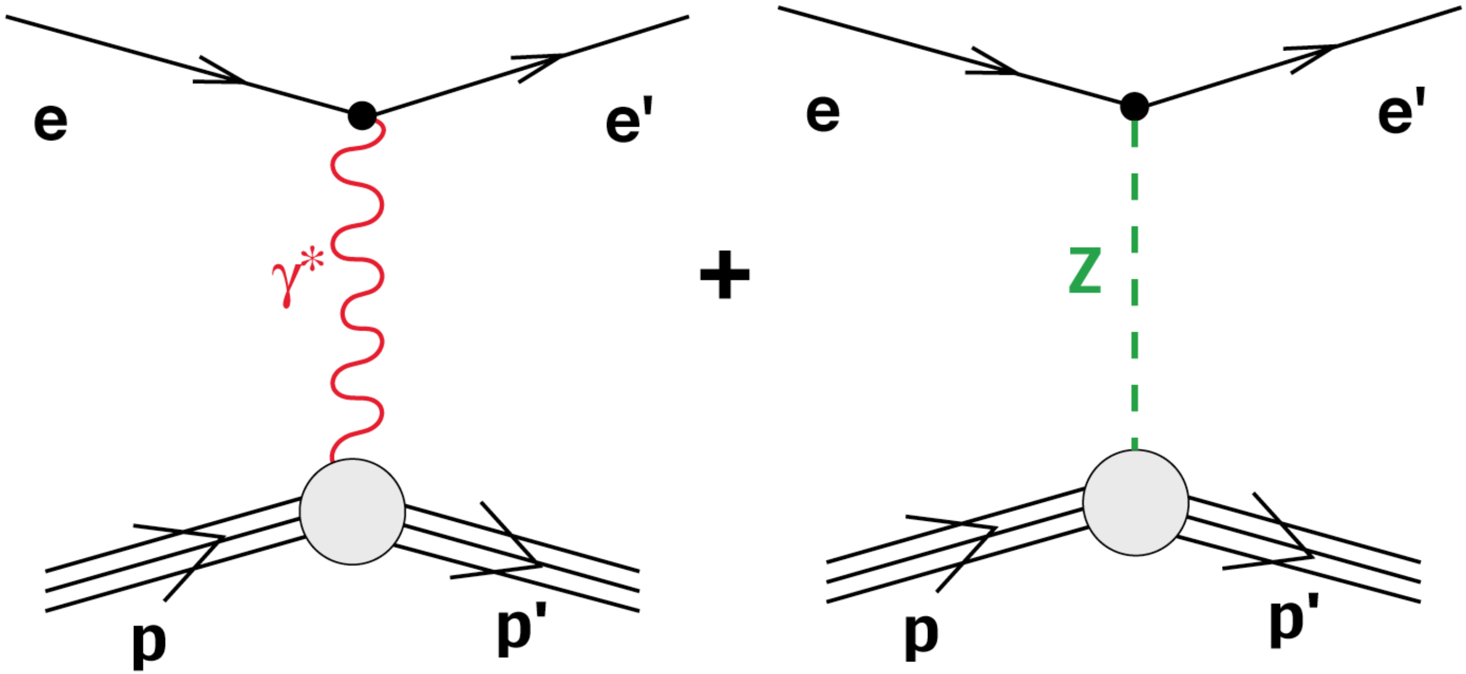


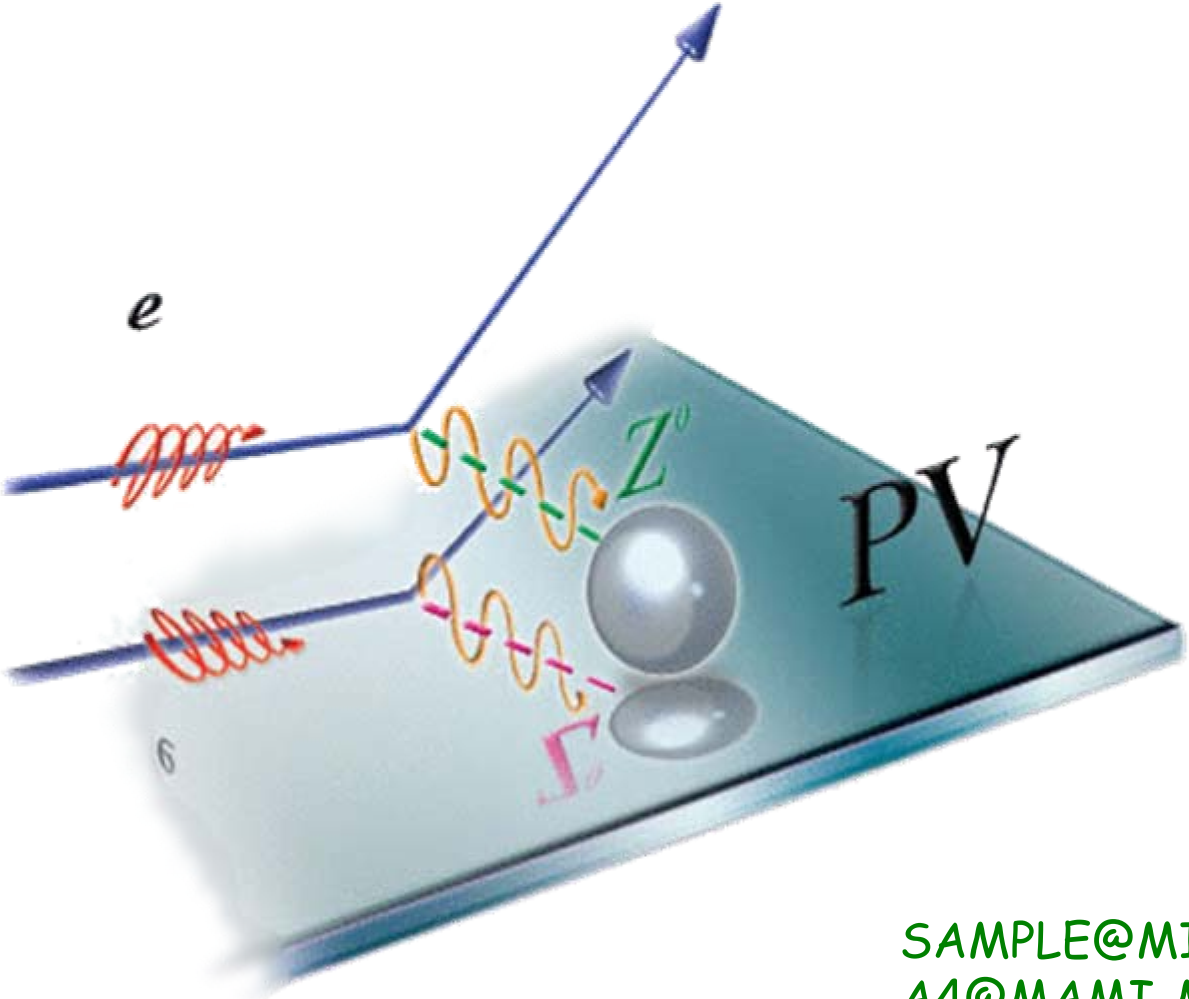


Parity conserving

$G^{\gamma}(Q^2)$

Parity violating

$G^{Z}(Q^2)$



SAMPLE@MIT-BATES
A4@MAMI-Mainz
HAPPEX@Jlab
G0@JLab

EM and Weak Vector Currents

Dirac and Pauli form factors

$$\langle N|V_\mu|N\rangle = \bar{u}_N \left[F_1(Q^2)\gamma_\mu + \frac{1}{2M}F_2(Q^2)i\sigma_{\mu\nu}q^\nu\right] u_N$$

Sachs form factors

$$G_M = F_1 + F_2$$

$$G_E = F_1 - \tau F_2 \qquad \tau = \frac{Q^2}{4M^2}$$

Flavor Decomposition

Charge symmetry

Electromagnetic current

$$V_\mu^{\gamma,p} = \frac{2}{3}\bar{u}\gamma_\mu u - \frac{1}{3}\left(\bar{d}\gamma_\mu d + \bar{s}\gamma_\mu s\right)$$

$$V_\mu^{\gamma,n} = \frac{2}{3}\bar{d}\gamma_\mu d - \frac{1}{3}\left(\bar{u}\gamma_\mu u + \bar{s}\gamma_\mu s\right)$$

Neutral weak vector current

$$\begin{aligned} V_\mu^{Z,p} \;&=\; \left(1 - \frac{8}{3}\sin^2\Theta_W\right)\bar{u}\gamma_\mu u \\ &\quad + \left(-1 + \frac{4}{3}\sin^2\Theta_W\right)\left(\bar{d}\gamma_\mu d + \bar{s}\gamma_\mu s\right) \end{aligned}$$

EM and Weak Form Factors

- Nucleon electromagnetic form factors

$$
\begin{aligned}
G^{\gamma,p} &= \frac{2}{3}G^u - \frac{1}{3}(G^d + G^s) \\
G^{\gamma,n} &= \frac{2}{3}G^d - \frac{1}{3}(G^u + G^s)
\end{aligned}
$$

- Proton weak form factor

$$
\begin{aligned}
G^{Z,p} &= \left(1 - \frac{8}{3}\sin^2\Theta_W\right) G^u \\
&\quad + \left(-1 + \frac{4}{3}\sin^2\Theta_W\right)\left(G^d + G^s\right)
\end{aligned}
$$

Quark Form Factors

- Charge symmetry

$$G^{u,p} = G^{d,n} \equiv G^{u}$$
$$G^{d,p} = G^{u,n} \equiv G^{d}$$
$$G^{s,p} = G^{s,n} \equiv G^{s}$$

- Quark form factors

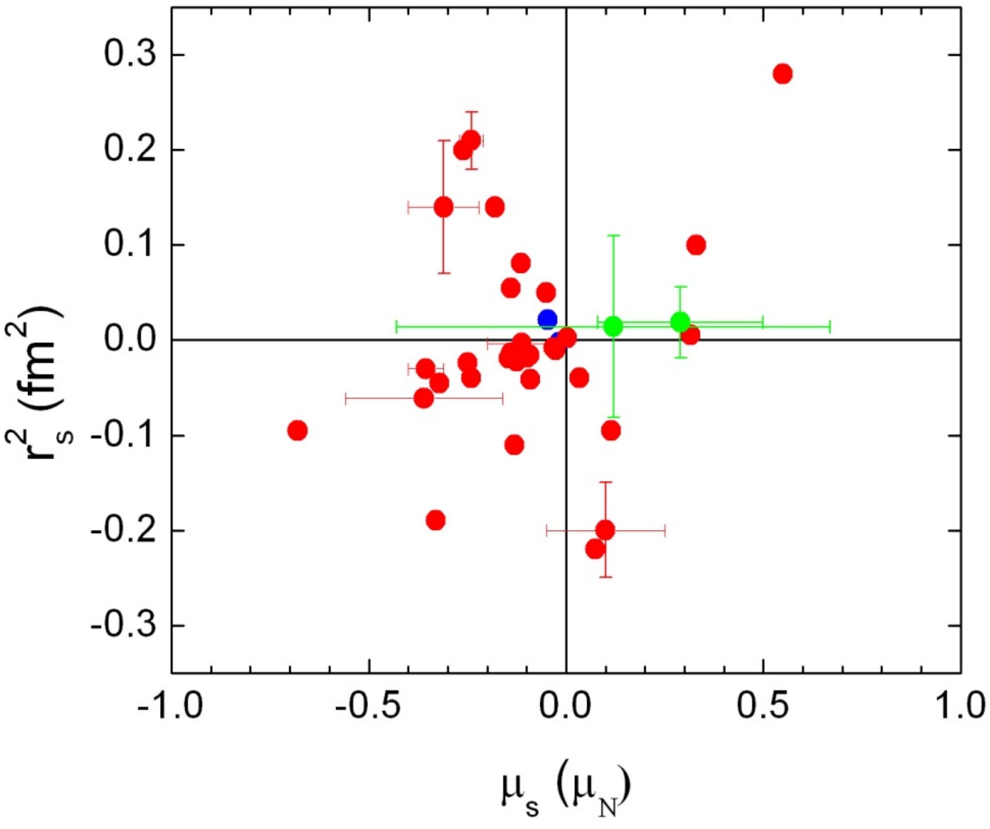
$$G^{u} = \left(3 - 4\sin^2\Theta_W\right) G^{\gamma,p} - G^{Z,p}$$
$$G^{d} = \left(2 - 4\sin^2\Theta_W\right) G^{\gamma,p} + G^{\gamma,n} - G^{Z,p}$$
$$G^{s} = \left(1 - 4\sin^2\Theta_W\right) G^{\gamma,p} - G^{\gamma,n} - G^{Z,p}$$

McKeown, PLB 219, 140 (1989)
Beck, PRD 39, 3248 (1989)
Beck & McKeown, Annu. Rev. Nucl. Part. Sci. 51, 189 (2001)

Static Properties

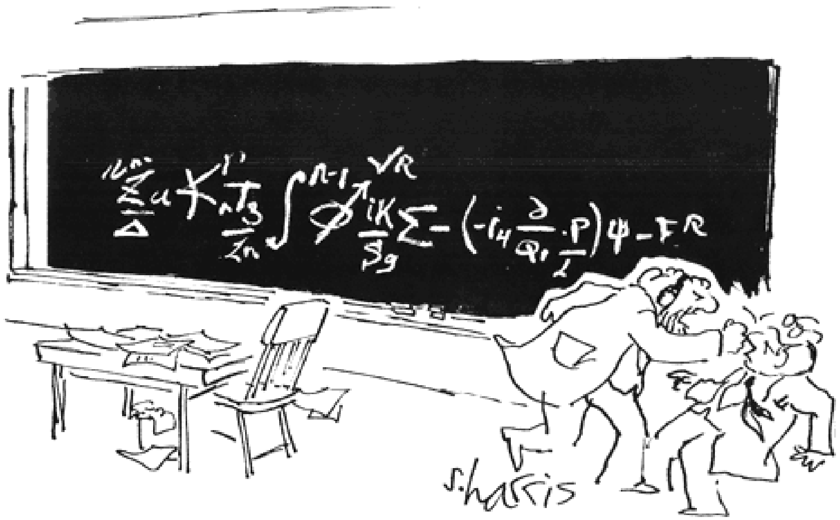
$G_E(0) = e$	Electric charge
$G_M(0) = \mu$	Magnetic moment
$\left\langle r^2 \right\rangle_E = -6 \left. \frac{dG_E}{dQ^2} \right\|_{Q^2=0}$	Charge radius
$\left\langle r^2 \right\rangle_M = -\frac{6}{\mu} \left. \frac{dG_M}{dQ^2} \right\|_{Q^2=0}$	Magnetic radius

Strangeness radius and strange magnetic moment



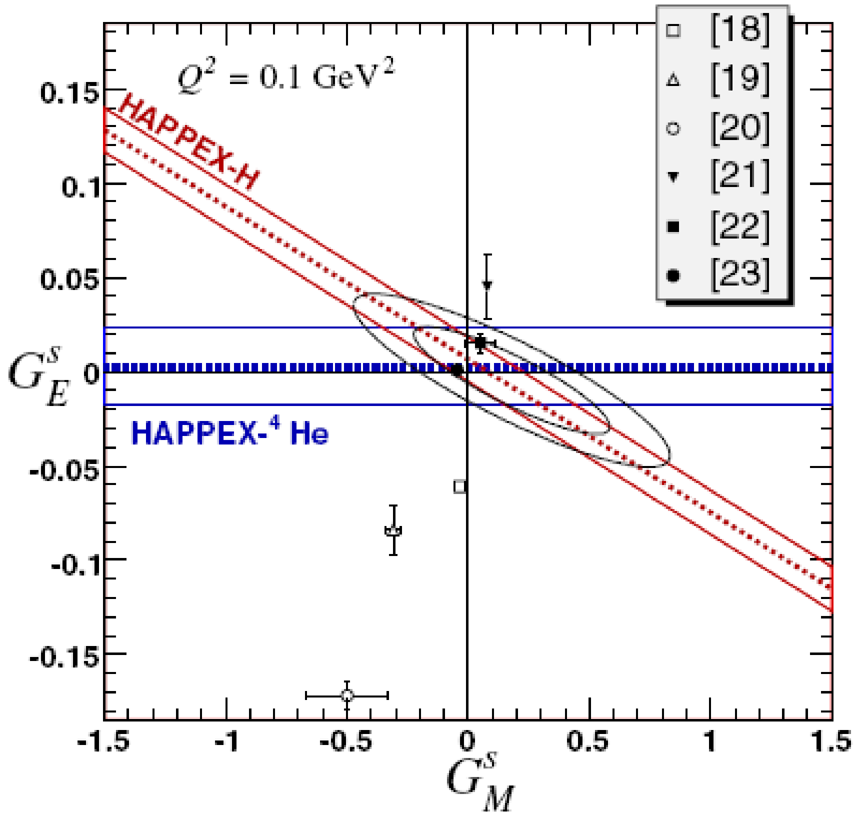
Theory

- Lattice QCD
- Chiral perturbation theory
- Dispersion relations
- Chiral quark-soliton model
- Kaon loops
- Quark models
- Chiral bag models
- Skyrme model
- Vector Meson Dominance
- Unquenched quark model
- ...



"You want proof? I'll give you proof!"

Strange Form Factors



Acha et al, PRL 98, 032301 (2007)

$$G_E^s = -0.005 \pm 0.019$$
$$G_M^s = 0.18 \pm 0.27$$
$$@ \quad Q^2 = 0.10 \text{ GeV}^2$$

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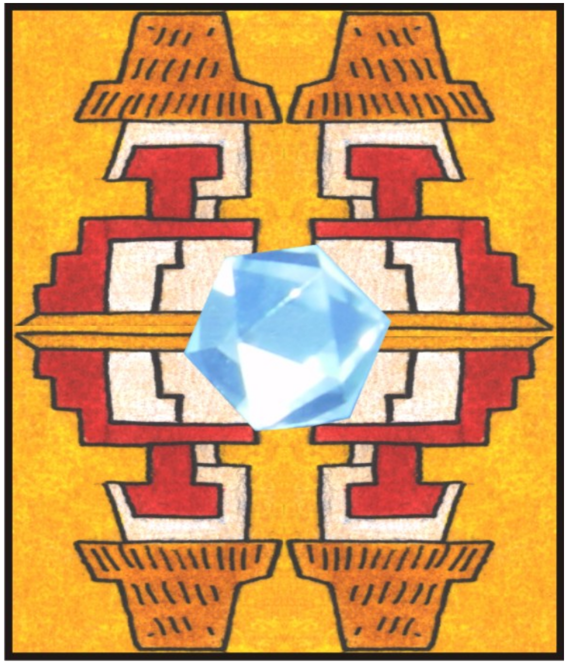


Vector Meson Dominance

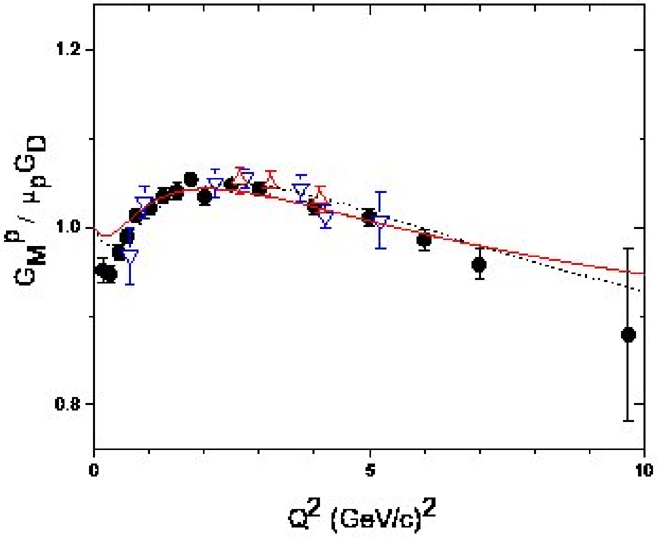
Photon couples to nucleon via vector meson (ρ,ω,ϕ)
Adjust high Q^2 behaviour to pQCD scaling
Include the finite width of ρ meson

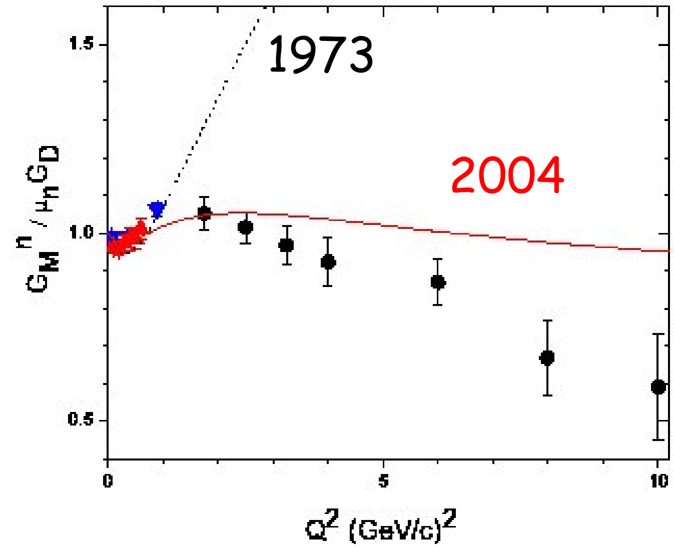
Two-component model:

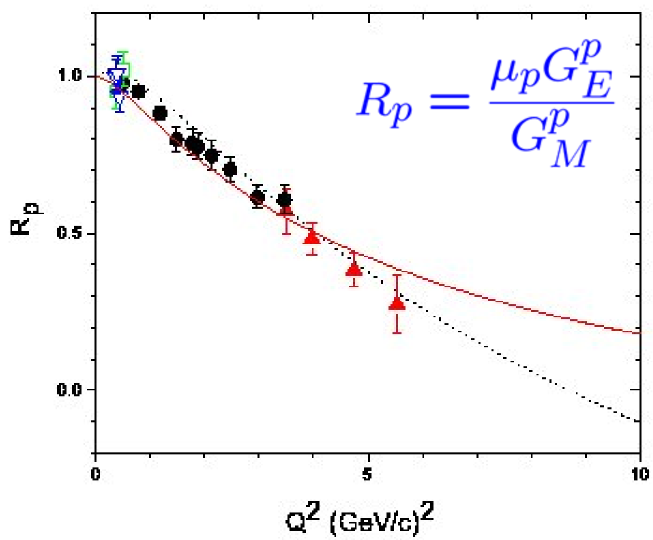
Intrinsic structure (valence quarks)
Meson cloud (quark-antiquark pairs)

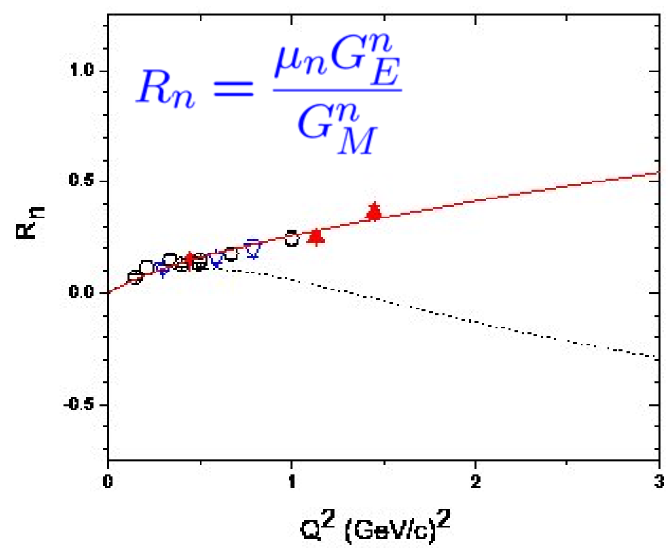
Iachello, Jackson & Lande, PLB 43, 191 (1973)
Bijker & Iachello, PRC 69, 068201 (2004)

Electromagnetic Form Factors

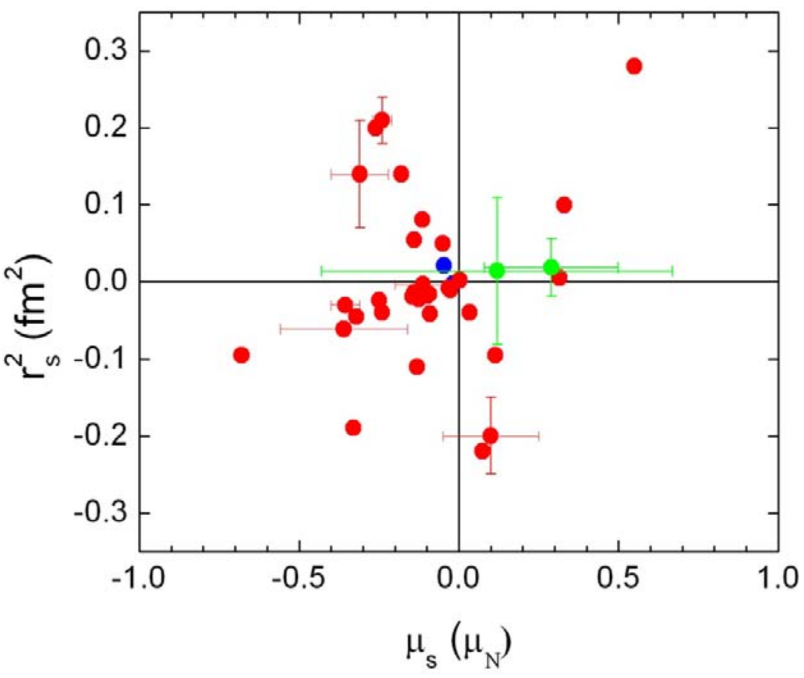


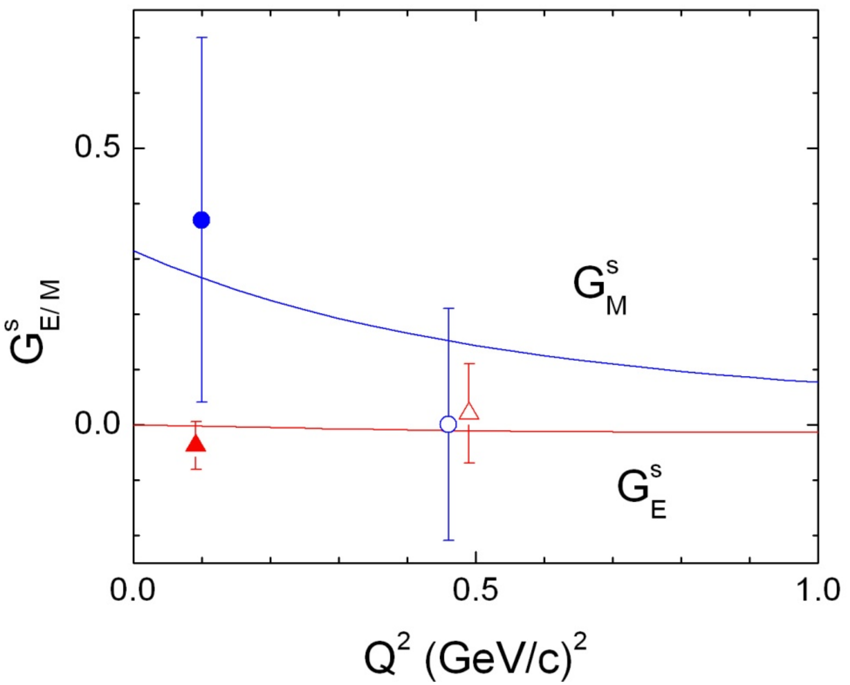






Strangeness content





Bijker, JPG 32, L49 (2006)

SAMPLE – PLB 583, 79 (2004)
HAPPEX – arXiv:nucl-ex/0506010
Pate – PRL 92, 082002 (2004)
HAPPEX + E734 (Brookhaven)

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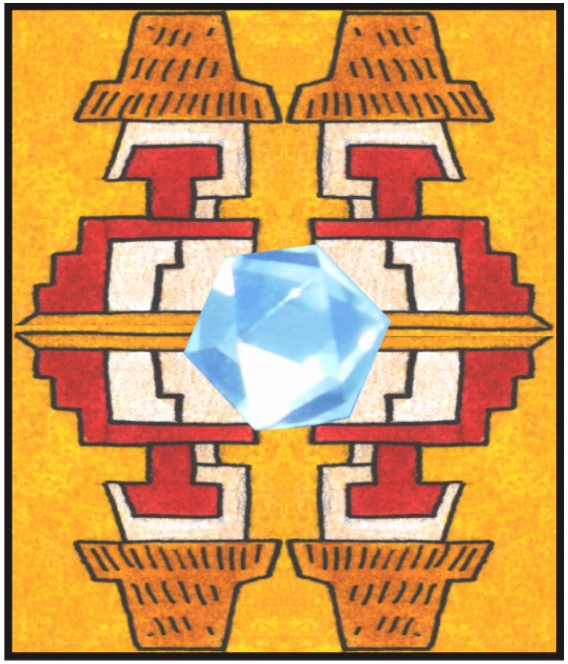
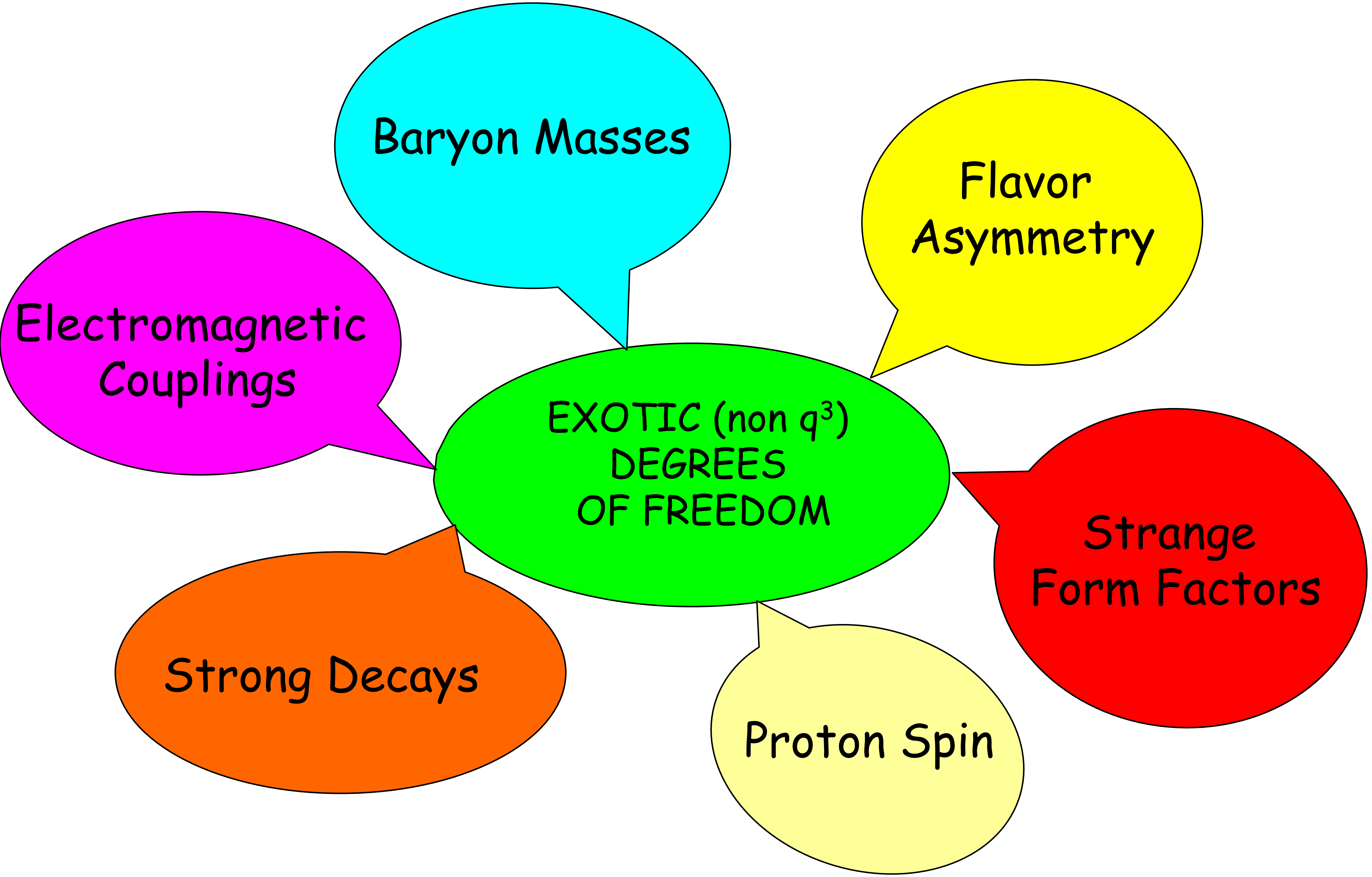



Baryon Masses
Flavor Asymmetry
Electromagnetic Couplings
EXOTIC (non q^3) DEGREES OF FREEDOM
Strange Form Factors
Strong Decays
Proton Spin

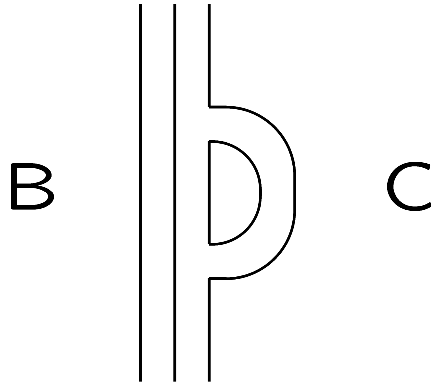
Exotic Degrees of Freedom

- Quark-antiquark pairs: pentaquarks, meson cloud models (Thomas, Speth, Kaiser, Weise, Oset, Brodsky, Ma, Geiger & Isgur, …)
- Higher-Fock components (Riska, Zou, …)

$$\psi = \psi(q^3) + \alpha\,\psi(q^3 - q\bar{q})$$

Extend the CQM to include
the effects of quark-antiquark pairs
in a general and consistent way

Quark-Antiquark Pairs



Strange quark-antiquark pairs in the proton with h.o. wave functions

Tornqvist & Zenczykowski (1984)
Geiger & Isgur, PRD 55, 299 (1997)
Isgur, NPA 623, 37 (1997)

- Pair-creation operator with $^3P_0$ quantum numbers of vacuum
- Important: sum over a large tower of intermediate states to preserve the phenomenological success of CQM

Unquenched Quark Model

$$| \psi_A \rangle = \mathcal{N} \left\{ | A \rangle + \sum_{BClJ} \int d\vec{k} \; | BC\vec{k}\, l J \rangle \frac{\langle BC\vec{k}\, lJ \mid T^{\dagger} \mid A \rangle}{M_A - E_B - E_C} \right\}$$

Three-quark configuration
SU(3) flavor symmetry

Five-quark component
Isospin symmetry

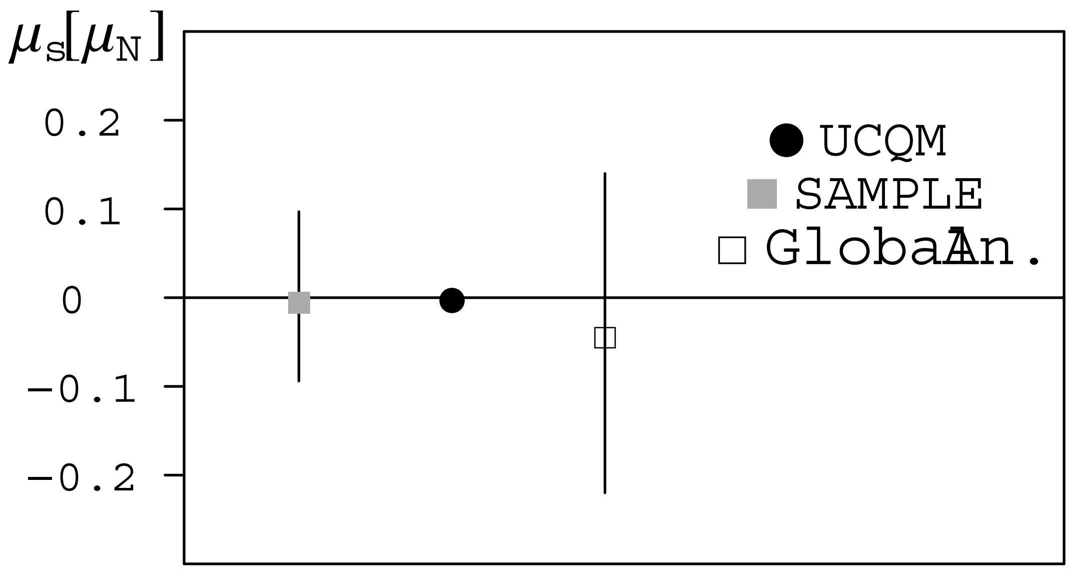
Pair-creation operator: $T^{\dagger} = T^{\dagger}(^3P_0)$

L=S=1, J=0, color singlet, flavor singlet

Bijker & Santopinto, PRC 80, 065210 (2009)
PRC 82, 062202 (2010)

Strange Magnetic Moment

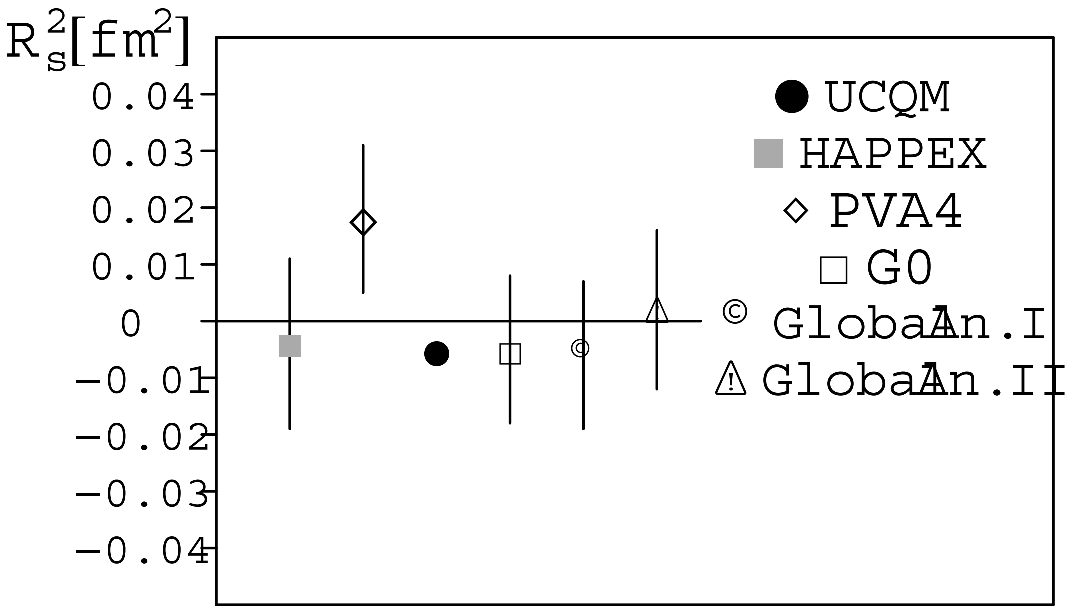
$$\vec{\mu}_s = \sum_i \mu_{i,s} \left[2\vec{s}(q_i) + \vec{\ell}(q_i) - 2\vec{s}(\bar{q}_i) - \vec{\ell}(\bar{q}_i) \right]$$



Ferretti, Ph.D. Thesis, 2011
Bijker, Ferretti & Santopinto, PRC 85, 035204 (2012)

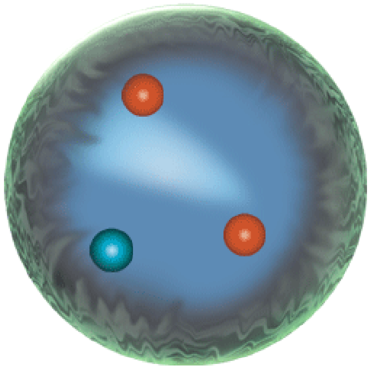
Strange Radius

$$R_s^2 = \sum_{i=1}^{5} e_{i,s} \left(\vec{r}_i - \vec{R}_{CM}\right)^2$$



Ferretti, Ph.D. Thesis, 2011
Bijker, Ferretti & Santopinto, PRC 85, 035204 (2012)

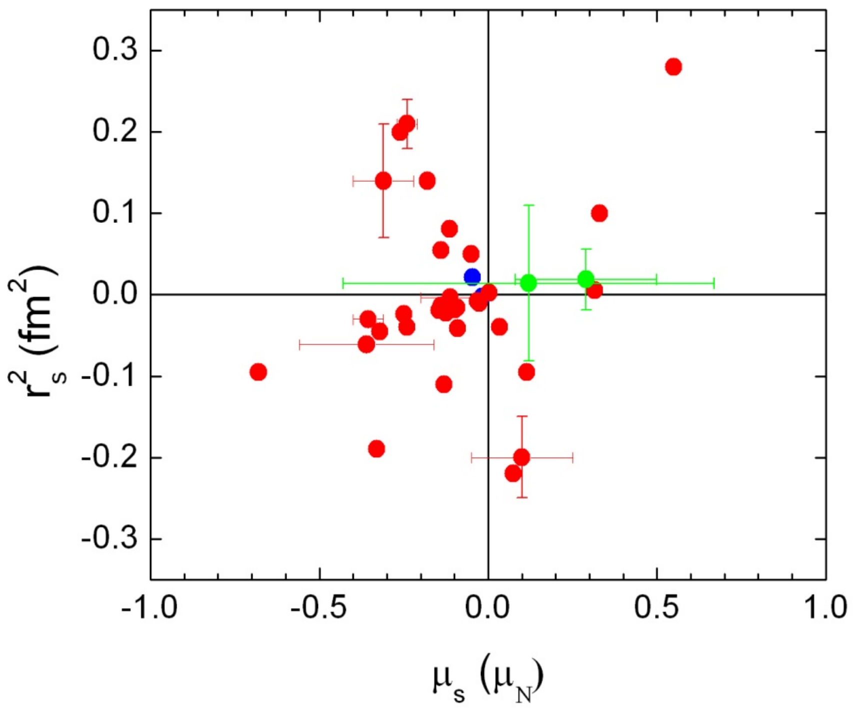
Strangeness



- Strange radius and magnetic moment of the proton
- Theory
- Lattice QCD
- Global analysis PVES
- Unquenched QM

$$\mu_s = -6 \cdot 10^{-4}\,(\mu_N)$$
$$\langle r^2 \rangle_s = -4 \cdot 10^{-3}\,(\text{fm}^2)$$

Jacopo Ferretti,
Ph.D. Thesis, 2011



Summary and Conclusions

- First explicit calculations of the proton strange radius and magnetic moments in an unquenched quark model
- Agreement with experimental values from PVES and lattice QCD results

- Other applications of the unquenched quark model
- Magnetic moments of octet baryons
- Flavor asymmetry of sea quarks
- Quark spins and orbital angular momenta
- Correspondence with MCM and Chiral QM

- First results are very promising, and indicate that the unquenched quark model may provide an important improvement of the CQM and enhance its range of applicability

Outlook

- Relativistic quark model
- Electromagnetic couplings
  (Hugo García Tecocoatzi)
- Relation with Chiral QM and MCM
  (Miguel Ángel López Ruiz & Silvia Díaz Gómez)
- Strong couplings, axial form factors
  (Giuseppe Galata, Jacopo Ferretti)
- ...