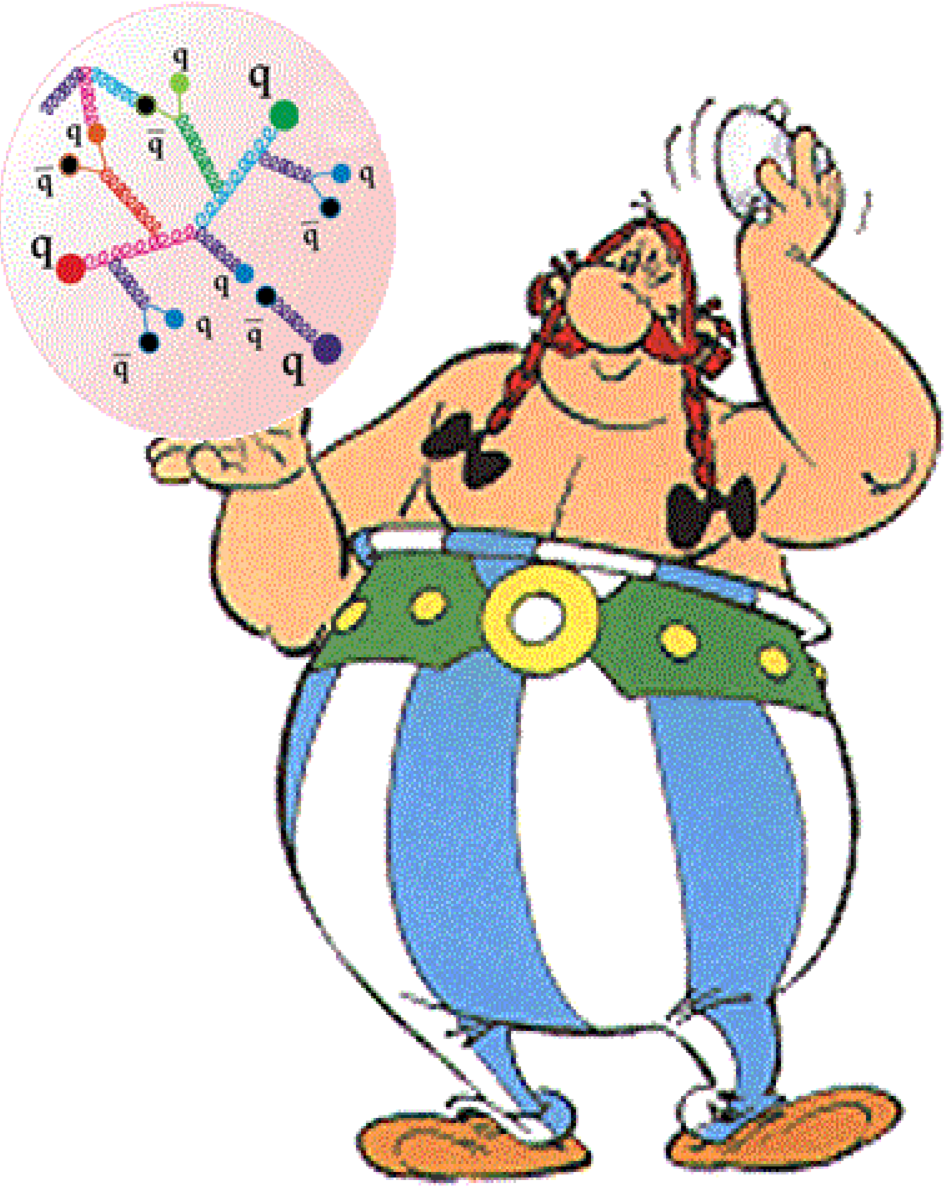
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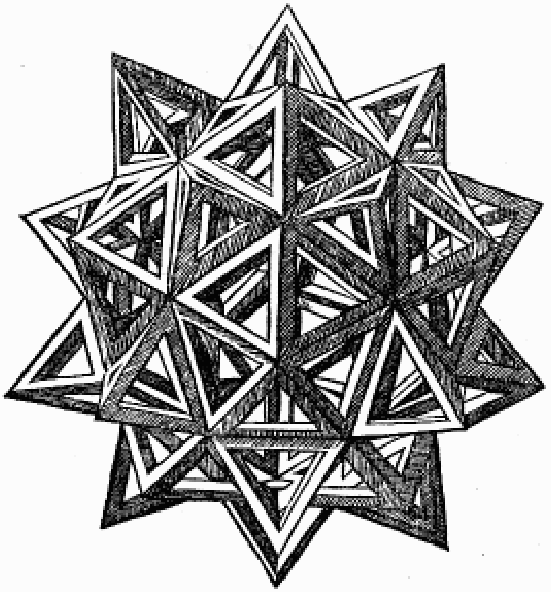
Symmetries in Nuclear and Particle Physics

- 1. Symmetries in Physics
- 2. Interacting Boson Model
- 3. Nuclear Supersymmetry
- 4. Quark Model
- 5. Unquenched Quark Model

Roelof Bijker (ICN-UNAM)
bijker@nucleares.unam.mx

Temario



- Introducción
- Modelo de quarks
- Grados de libertad exóticos
- Modelo de quarks "unquenched"
- Resultados
- Resumen y conclusiones

Structure of the Nucleon

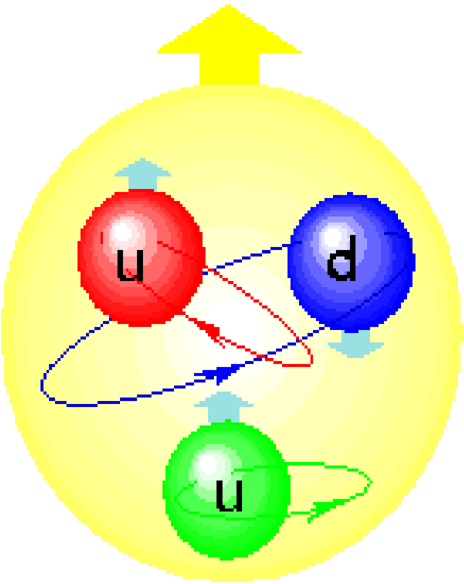
- Anomalous magnetic moment (Stern, 1930's)

$$\mu_p = 2.793\ \mu_N \ , \qquad \mu_n = -1.913\ \mu_N$$

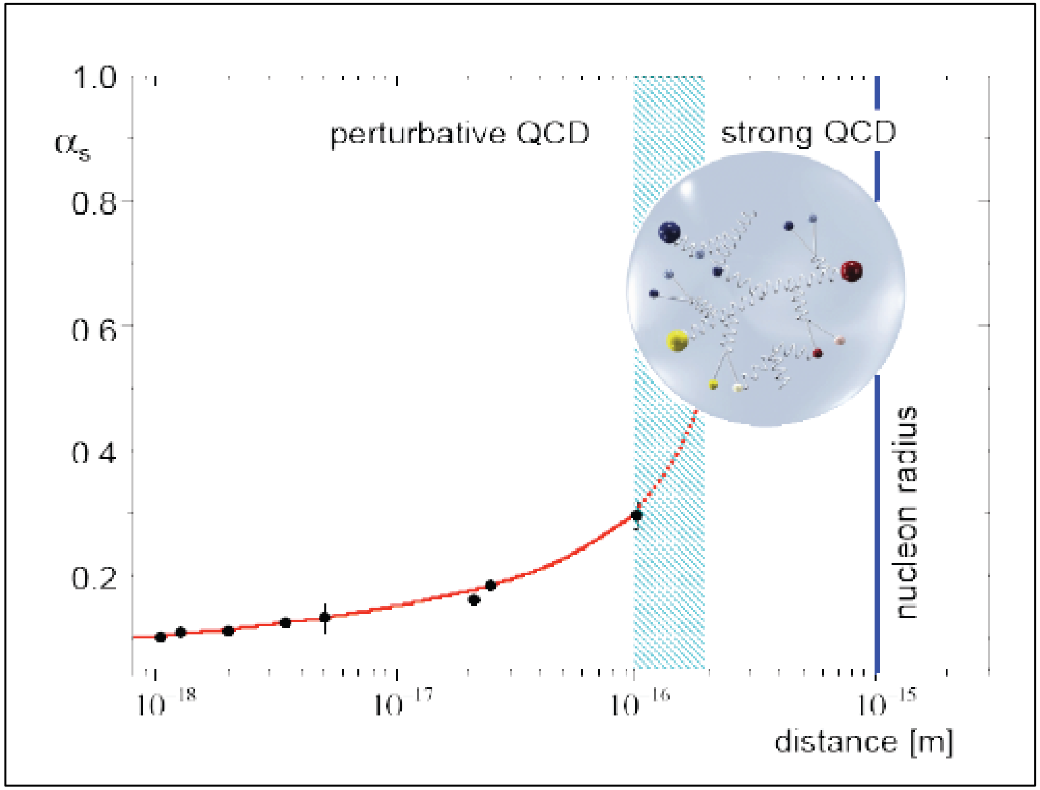
- Radius (Hofstadter, 1950's)

$$r_p = 0.862 \text{ fm}$$

- Quark structure of the proton (Friedman, Kendall, Taylor, 1968)
- Spin crisis (EMC, 1988)
- Flavor asymmetry (NMC, 1991)
- Form factor ratio G_E/G_M (2000's)
- Strangeness (2000's)

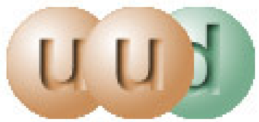


Baryons: Strong QCD



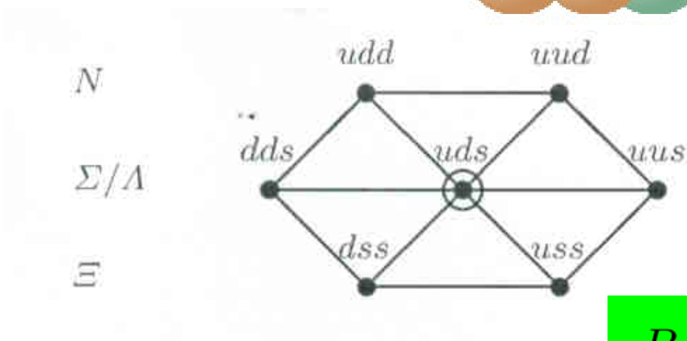
- Lattice QCD
- Chiral PT as EFT of QCD
- Effective degrees of freedom
- Quark models

Constituent Quark Model



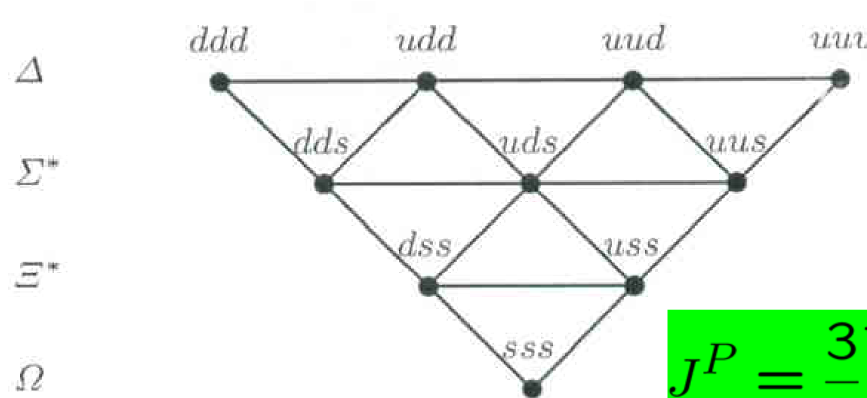
- Octet baryons (qqq)
- Decuplet baryons (qqq)
- Magnetic moments

$$\frac{\mu_p}{\mu_n} = -\frac{3}{2} \qquad -1.46 \text{ exp}$$



$$J^P = \frac{1}{2}^+$$

- Photocouplings, helicity amplitudes, form factors, strong decays, …



$$J^P = \frac{3}{2}^+$$

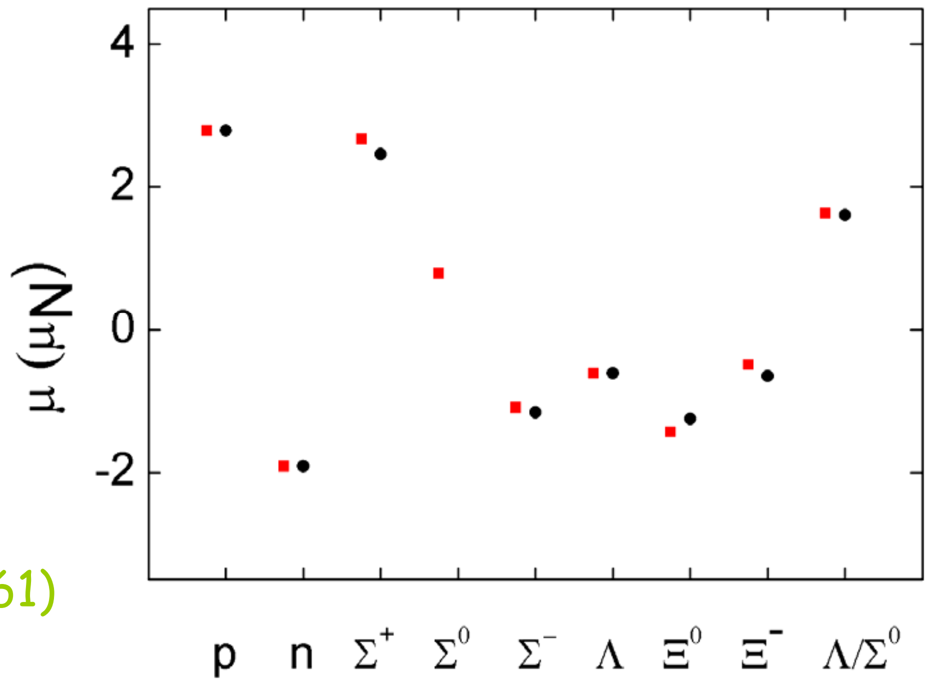
Gell-Mann, Ne'eman, Zweig 1961-1964

Magnetic Moments

$$\begin{aligned}
\mu_p &= (4\mu_u - \mu_d)/3 \\
\mu_n &= (4\mu_d - \mu_u)/3 \\
\mu_\Lambda &= \mu_s \\
\mu_{\Sigma^+} &= (4\mu_u - \mu_s)/3 \\
\mu_{\Sigma^0} &= (2\mu_u + 2\mu_d - \mu_s)/3 \\
\mu_{\Sigma^-} &= (4\mu_d - \mu_s)/3 \\
\mu_{\Xi^0} &= (4\mu_s - \mu_u)/3 \\
\mu_{\Xi^-} &= (4\mu_s - \mu_d)/3 \\
\mu_{\Sigma^0\Lambda} &= (\mu_u - \mu_d)/\sqrt{3}
\end{aligned}$$

$$\begin{aligned}
\mu_u &= 1.852\ \mu_N \\
\mu_d &= -0.972\ \mu_N \\
\mu_s &= -0.613\ \mu_N
\end{aligned}$$

CQM
Experiment

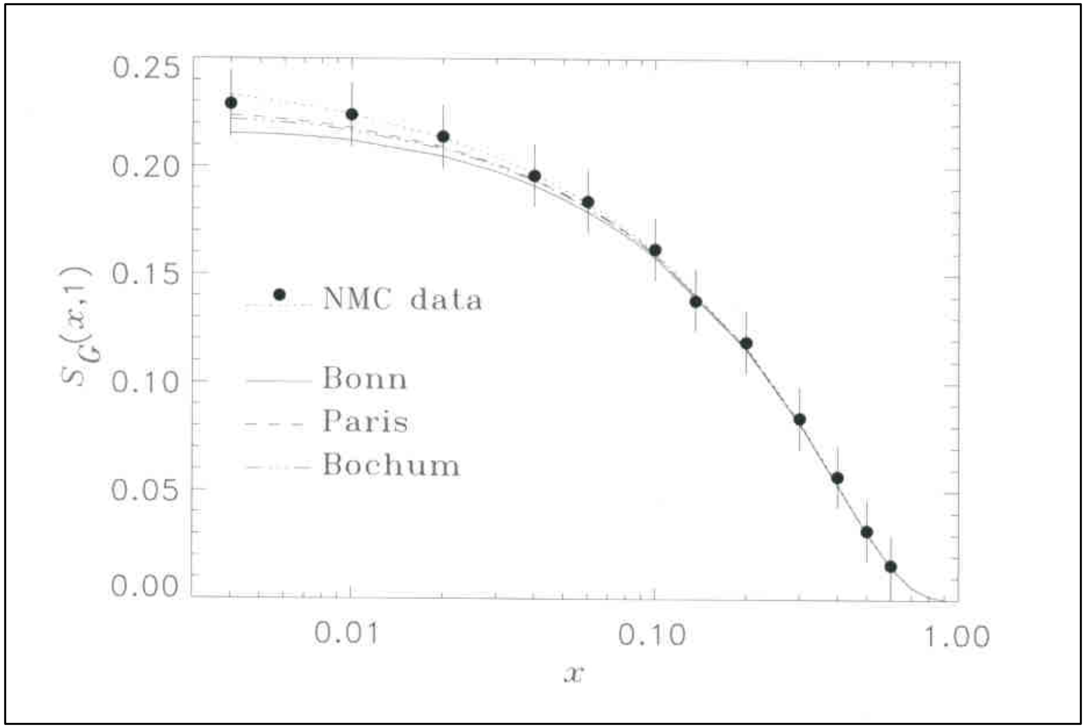


Coleman & Glashow, PRL 6, 423 (1961)
Beg, Lee & Pais, PRL 13, 514 (1964)

Problem 1: Flavor asymmetry

- Gottfried sum rule

$$S_G = \int_0^1 dx \frac{F_{2p}(x) - F_{2n}(x)}{x} = \frac{1}{3} - \frac{2}{3}\int_0^1 dx \left[\bar{d}(x) - \bar{u}(x)\right]$$



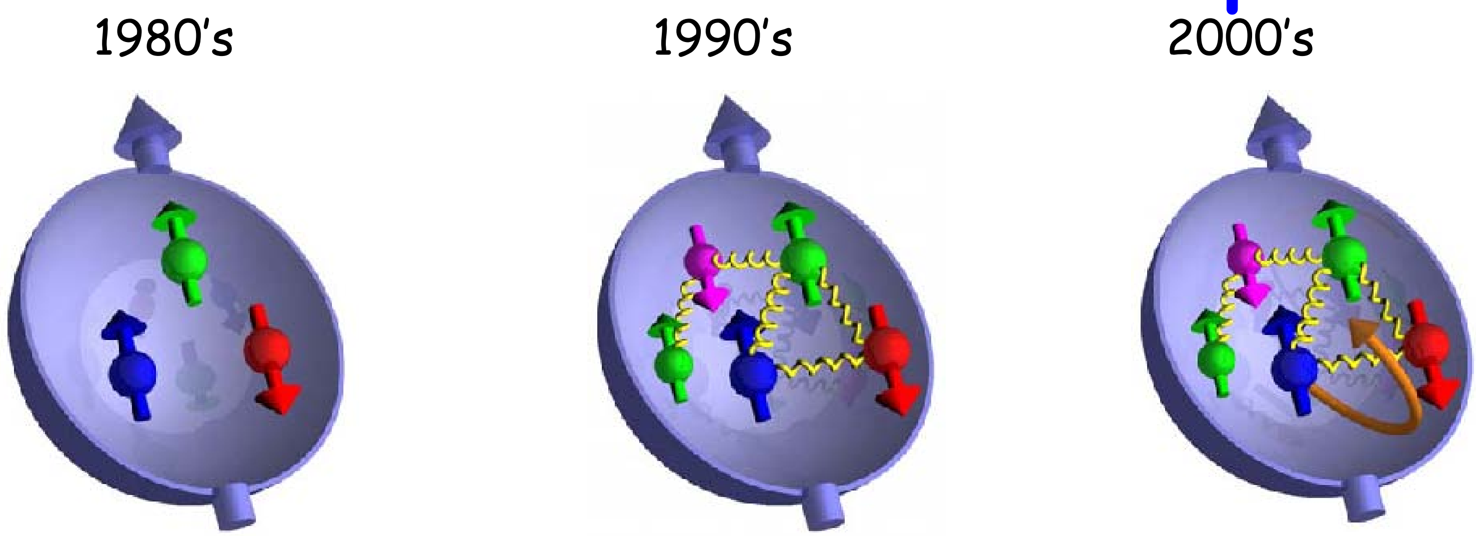
$$S_G(x,1) = \int_x^1 dx' \frac{F_{2p}(x') - F_{2n}(x')}{x'}$$

$$S_G = 0.2281 \pm 0.0065$$

$$\mathcal{A}(p) = \int_0^1 dx \left[\bar{d}(x) - \bar{u}(x)\right] = 0.16 \pm 0.01$$

Excess: $\bar{d} > \bar{u}$

Problem 2: Proton Spin



Naive quark model
3 valence quarks

QCD: contributions from
sea quarks and gluons

.. and orbital angular
momentum

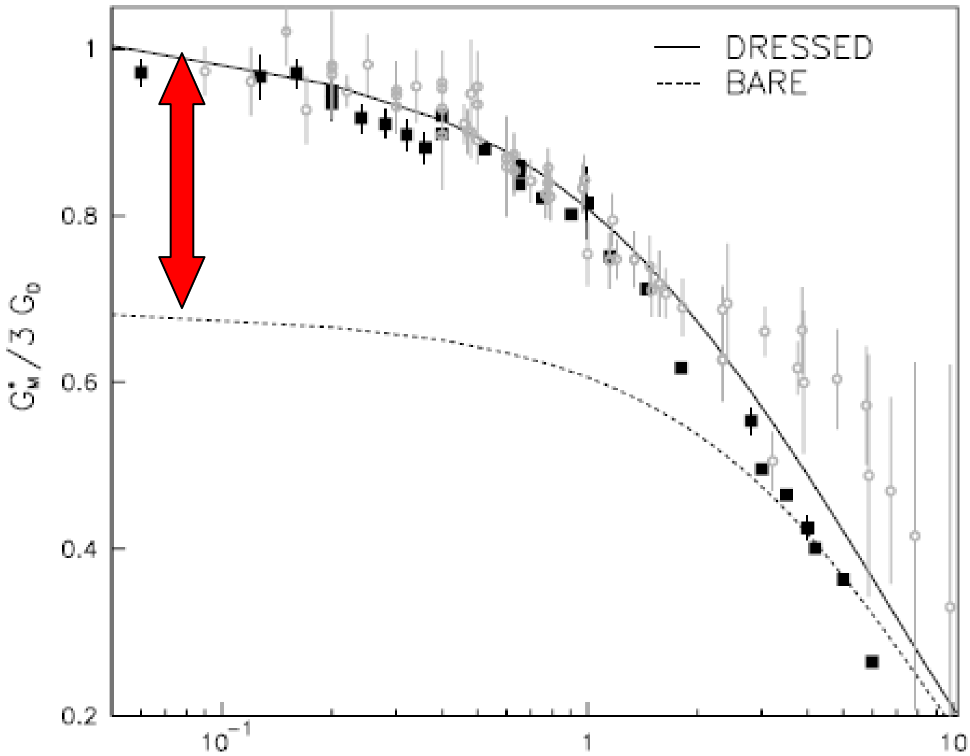
$$\frac{1}{2} = \frac{1}{2}(\Delta u + \Delta d)$$

$$\frac{1}{2} = \frac{1}{2}\underbrace{(\Delta u + \Delta d + \Delta s)}_{\Delta\Sigma} + \Delta G + \Delta L$$

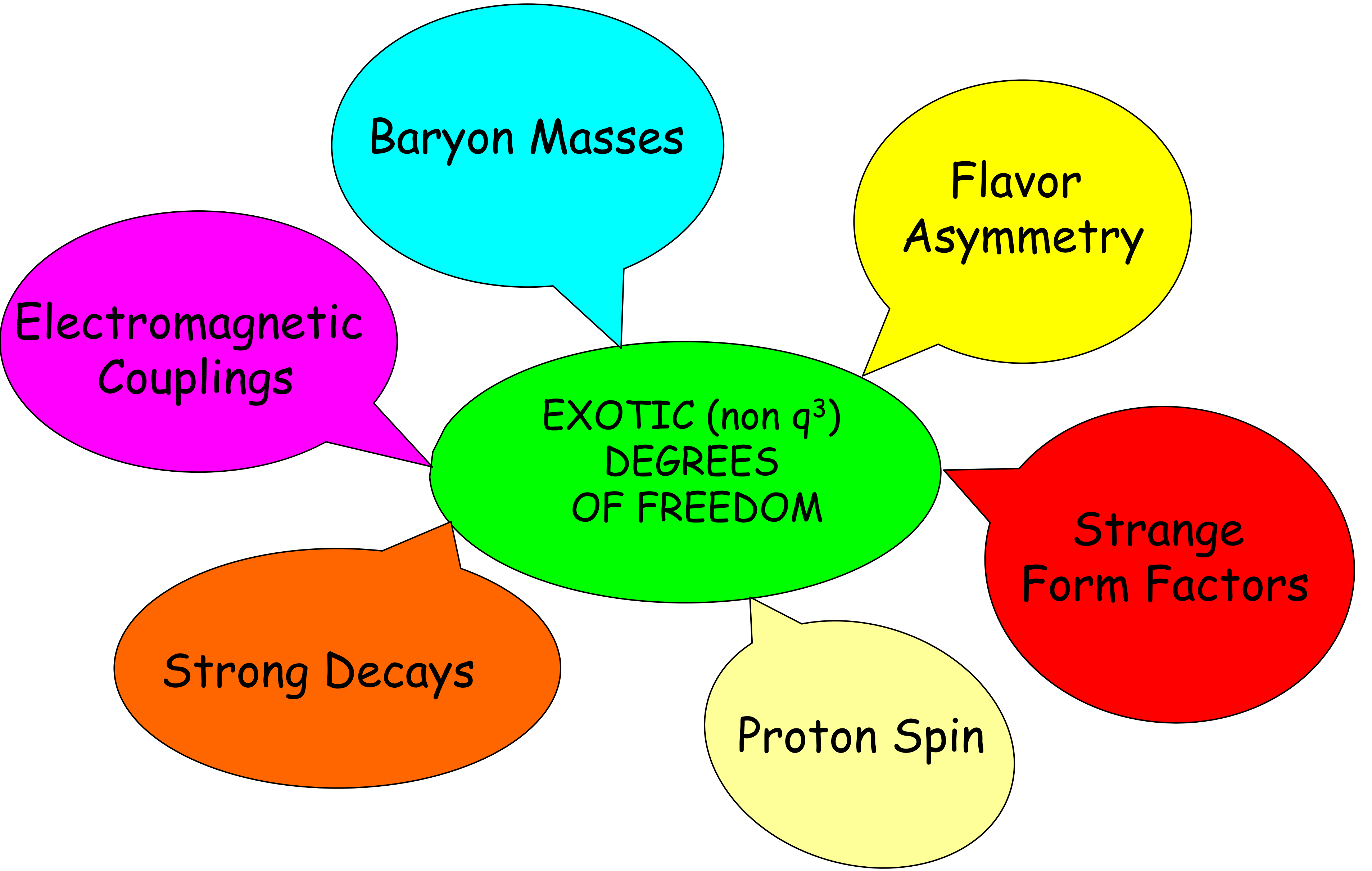
$$\left.\begin{array}{rr} \Delta u = & 0.842 \\ \Delta d = & -0.427 \\ \Delta s = & -0.085 \end{array}\right\} \Delta\Sigma = 0.330 \pm 0.039$$

HERMES, PRD 75, 012007 (2007)
COMPASS, PLB 647, 8 (2007)

Problem 3: Delta(1232)

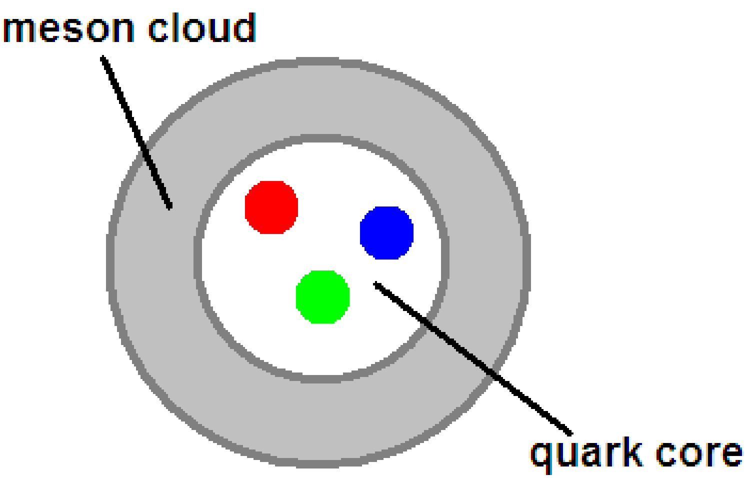


Julia-Diaz et al, PRC 75, 015205 (2007)


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

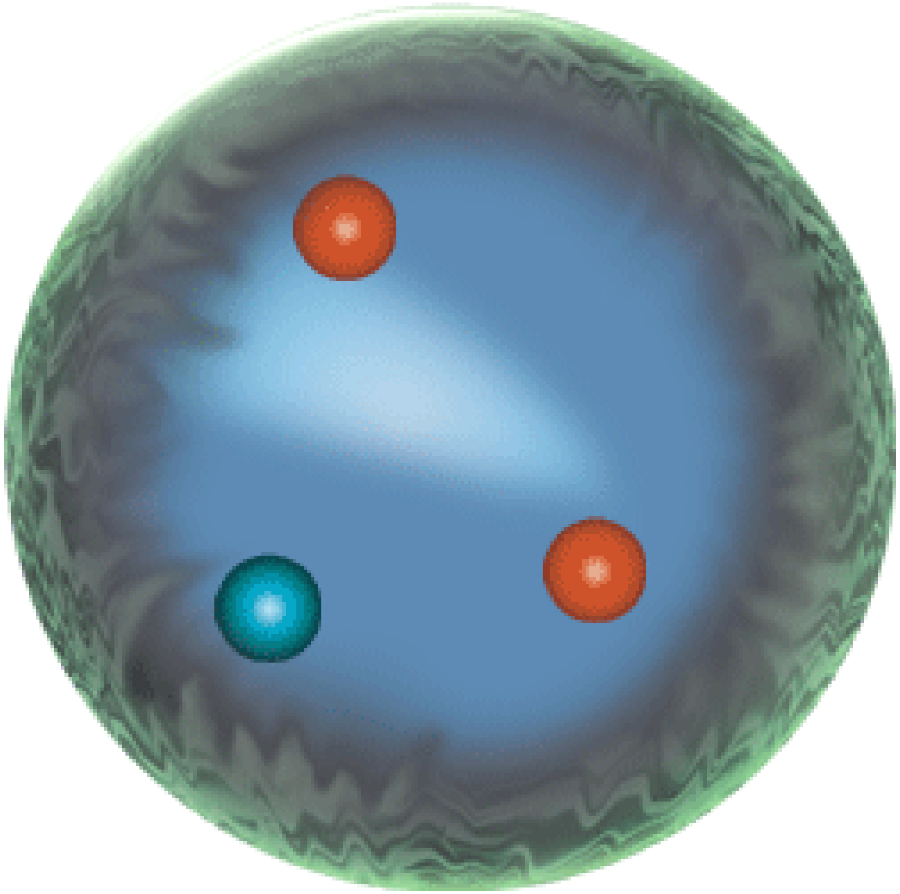
Exotic Degrees of Freedom

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

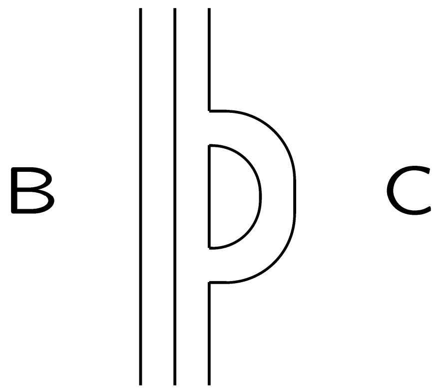


$$\psi = \mathcal{N}\left[\psi(q^3) + \alpha\,\psi(q^3 - q\bar{q})\right]$$

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



Unquenched Quark Model



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 successes of CQM

Geiger & Isgur, PRD 55, 299 (1997)

> It would be desirable to devise tests of the mechanisms underlying the delicate cancellations which conspire to hide the effects of the sea in the picture presented here. It also seems very worthwhile to extend this calculation to $u\bar{u}$ and $d\bar{d}$ loops. Such an extension could reveal the origin of the observed violations [38] of the Gottfried sum rule [39] and also complete our understanding of the origin of the spin crisis. From our previous calculations [4], the effects of "un-

Extensions

Bijker & Santopinto, PRC 80, 065210 (2009)

- Any initial baryon or baryon resonance
- Any flavor of the quark-antiquark pair
- Any model of baryons and mesons

Formalism

$$| \psi_A\rangle = \mathcal{N} \left\{ | A\rangle + \sum_{BClJ} \int d\vec{K} k^2 dk \mid BC, l, J; \vec{K}, k\rangle \frac{\langle BC, l, J; \vec{K}, k \mid T^\dagger \mid A\rangle}{M_A - E_B - E_C} \right\}$$

Three-quark configuration
SU(3) flavor symmetry

Five-quark component
Isospin symmetry

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

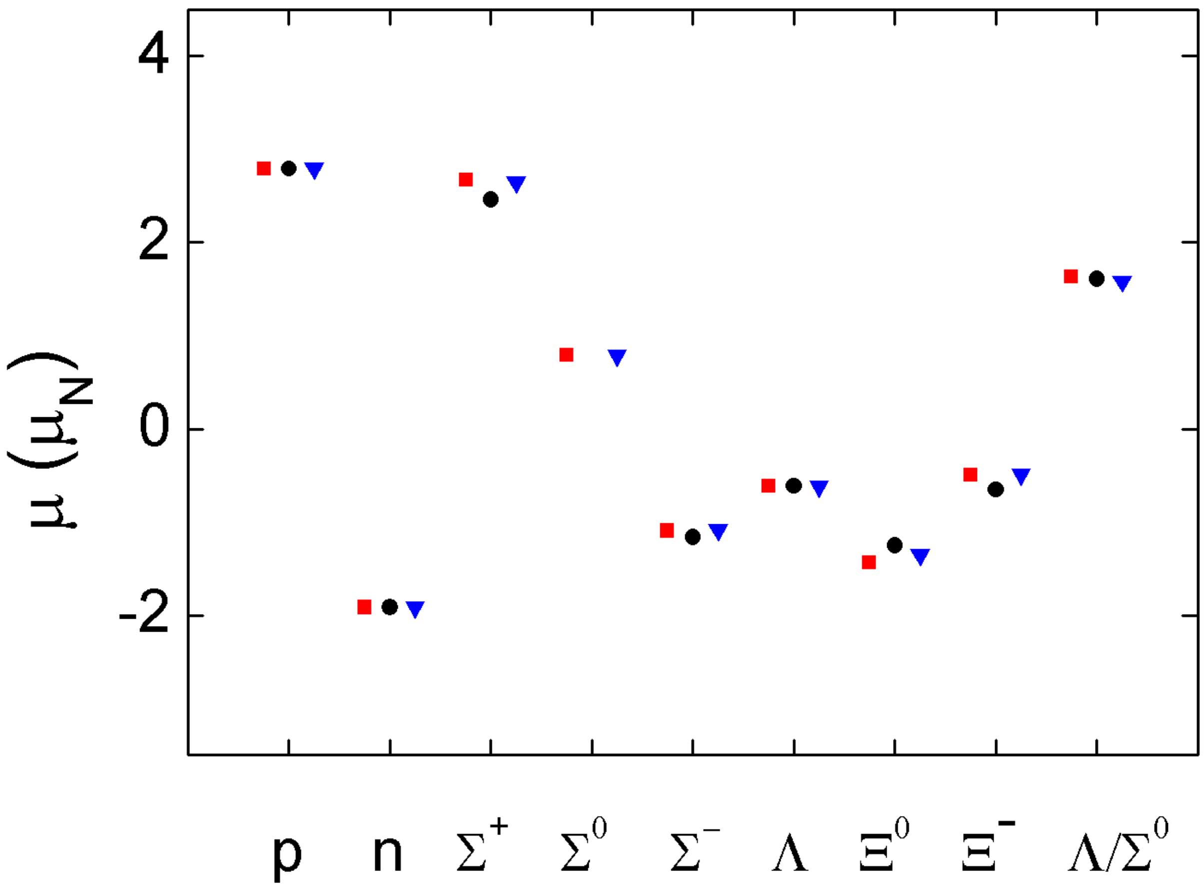
L=S=1, J=0, color singlet, flavor singlet

Unquenched Quark Model

- Harmonic oscillator quark model
- Sum over intermediate meson-baryon states includes for each oscillator shell all possible spin-flavor states
- Number of oscillator shells $N_B, N_C \leq 5$
- Oscillator size parameters taken for baryons and mesons taken from literature (Capstick, Isgur, Karl)
- Smearing of the pair-creation vertex (Geiger, Isgur)
- Strength of $^3P_0$ coupling taken from literature on strong decays of baryons (Capstick, Roberts)

- No attempt to optimize the parameters

1. Magnetic Moments



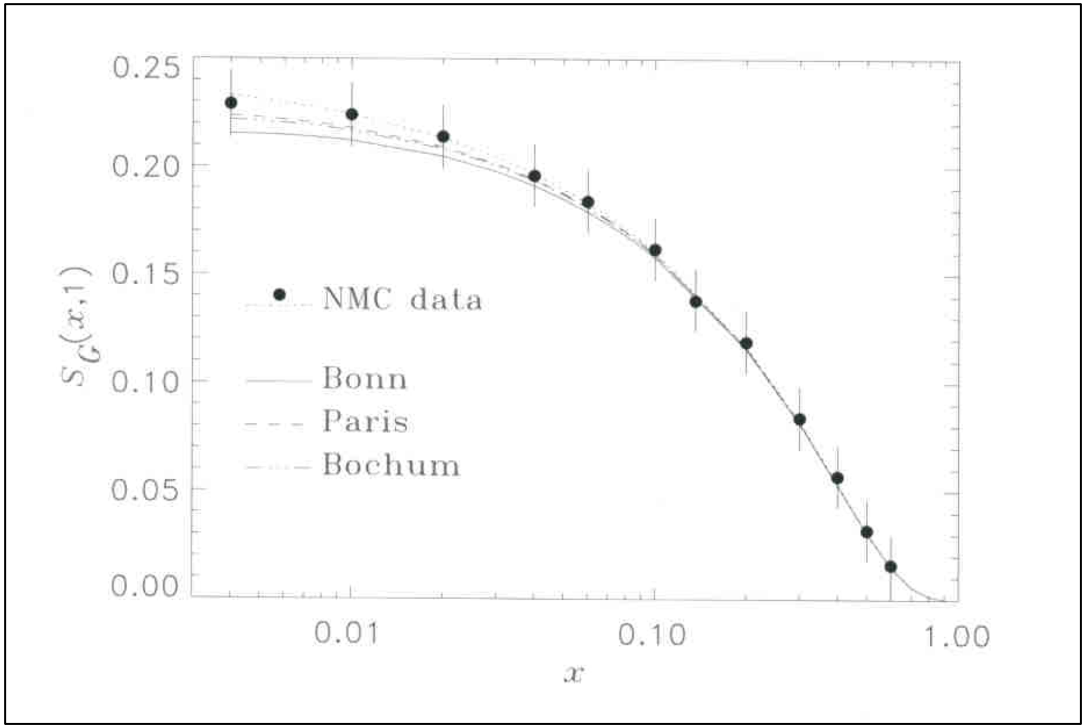
CQM
Experiment
Unquenched QM

	CQM	UQM
μ_u	1.852	2.044
μ_d	-0.972	-0.959
μ_s	-0.613	-0.567

2. Flavor asymmetry

- Gottfried sum rule

$$S_G = \int_0^1 dx \frac{F_{2p}(x) - F_{2n}(x)}{x} = \frac{1}{3} - \frac{2}{3} \int_0^1 dx \left[\bar{d}(x) - \bar{u}(x) \right]$$



$$S_G(x,1) = \int_x^1 dx' \frac{F_{2p}(x') - F_{2n}(x')}{x'}$$

$$S_G = 0.2281 \pm 0.0065$$

$$\mathcal{A}(p) = \int_0^1 dx \left[\bar{d}(x) - \bar{u}(x) \right] = 0.16 \pm 0.01$$

Excess: $\bar{d} > \bar{u}$

Proton Sea

	$\mathcal{A}(p)$
E866 2001	0.118 ± 0.012
NMC 1994	0.147 ± 0.039
NMC 1997	0.1578 ± 0.0097
HERMES 1998	0.16 ± 0.03
Unquenched QM	0.151

Flavor asymmetry: nonperturbative QCD
Pauli blocking (Field & Feynman, 1977) too small
Pion dressing of the nucleon (n-π^+ channel)
(Thomas et al., 1983, Henley & Miller, 1990)

Other Models

- Baryon asymmetry

Model	$\mathcal{A}(\Sigma^+)/\mathcal{A}(p)$	$\mathcal{A}(\Xi^0)/\mathcal{A}(p)$
Unquenched QM	0.833	−0.005
Octet couplings	0.353	−0.647
Chiral QM	2	1
Balance Model	3.083	2.075

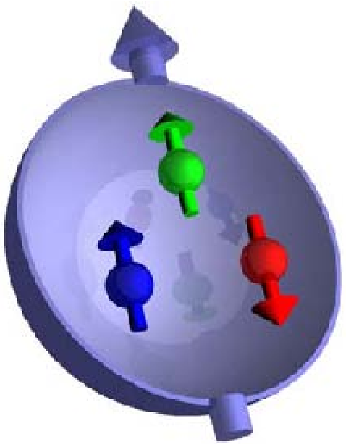
- Flavor asymmetry of Σ hyperons can be measured using the Drell-Yan process in hyperon-induced dilepton production with Σ-hyperon beams on protons

$$\Sigma^{\pm} + p \rightarrow \ell^+ + \ell^- + X$$

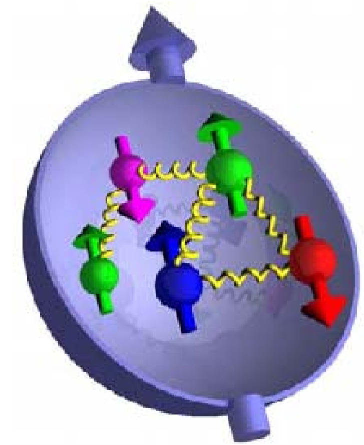
Alberg et al., PLB 389, 367 (1996)
NPA 644, 93 (1998)

3. Proton Spin Crisis

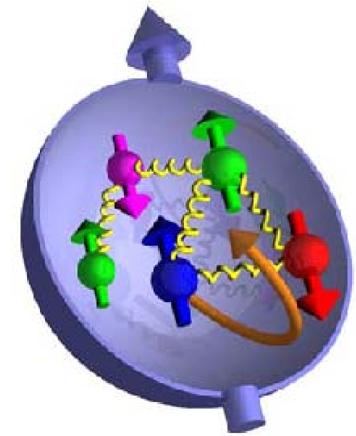
1980's



1990's



2000's



Naive parton model
3 valence quarks

$$\frac{1}{2} = \frac{1}{2}(\Delta u + \Delta d)$$

QCD: contributions from
sea quarks and gluons

.. and orbital angular
momentum

$$\frac{1}{2} = \frac{1}{2}\underbrace{(\Delta u + \Delta d + \Delta s)}_{\Delta\Sigma} + \Delta G + \Delta L$$

$$\left.\begin{aligned} \Delta u &= 0.842 \\ \Delta d &= -0.427 \\ \Delta s &= -0.085 \end{aligned}\right\} \Delta\Sigma = 0.330 \pm 0.039$$

HERMES, PRD 75, 012007 (2007)
COMPASS, PLB 647, 8 (2007)

Proton Spin

- COMPASS@CERN: ΔG is small
- Unquenched quark model

Ageev et al., PLB 633, 25 (2006)
Platchkov, NPA 790, 58 (2007)

		CQM	Unquenched QM		
			Valence	Sea	Total
p	$\Delta\Sigma$	1	0.38	0.30	0.68
	$2\Delta L$	0	0.00	0.32	0.32
	$2\Delta J$	1	0.38	0.62	1.00

- More than half of the proton spin from the sea!
- Orbital angular momentum related to flavor asymmetry

$$|\psi_N\rangle = \frac{1}{\sqrt{1+a^2+b^2}}\left[|N\rangle + a|N\pi\rangle + b|\Delta\pi\rangle\right]$$

$$\Delta L = \mathcal{A}(p) = \frac{2a^2-b^2}{3(1+a^2+b^2)}$$

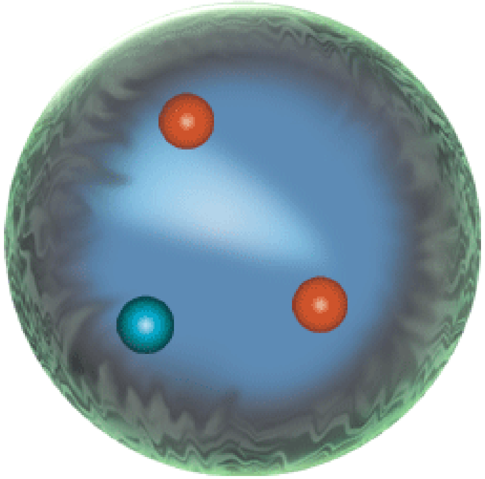
Garvey, PRC 81, 055212 (2010)

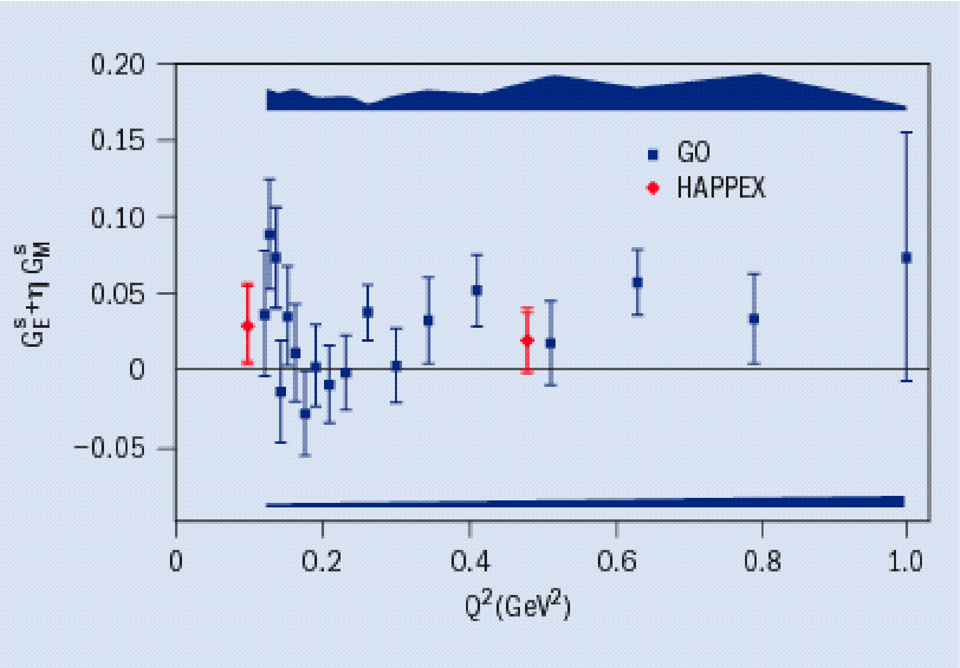
- Importance of orbital angular momentum

Myhrer & Thomas, 2008

4. Strangeness in the Proton

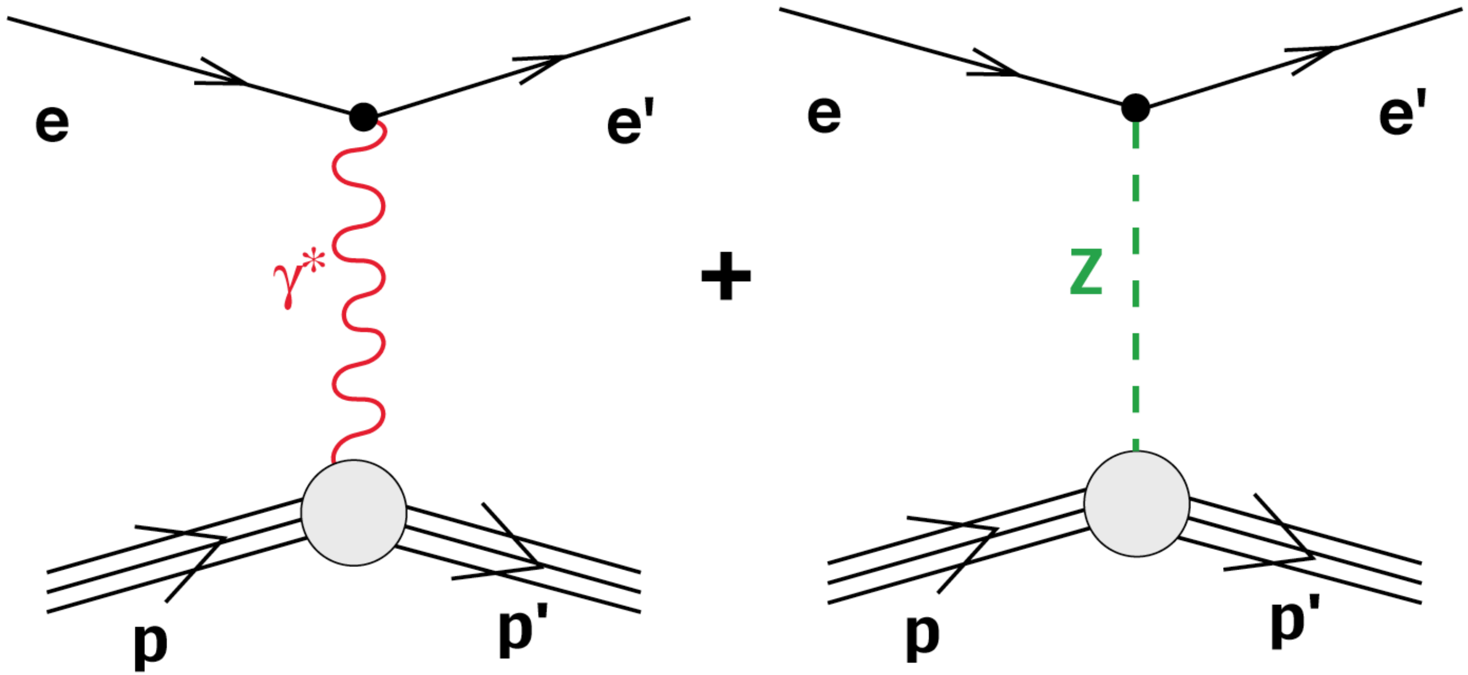
New data from parity violating electron scattering





The strange (anti)quarks come uniquely from the sea: there is no contamination from up or down valence quarks

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

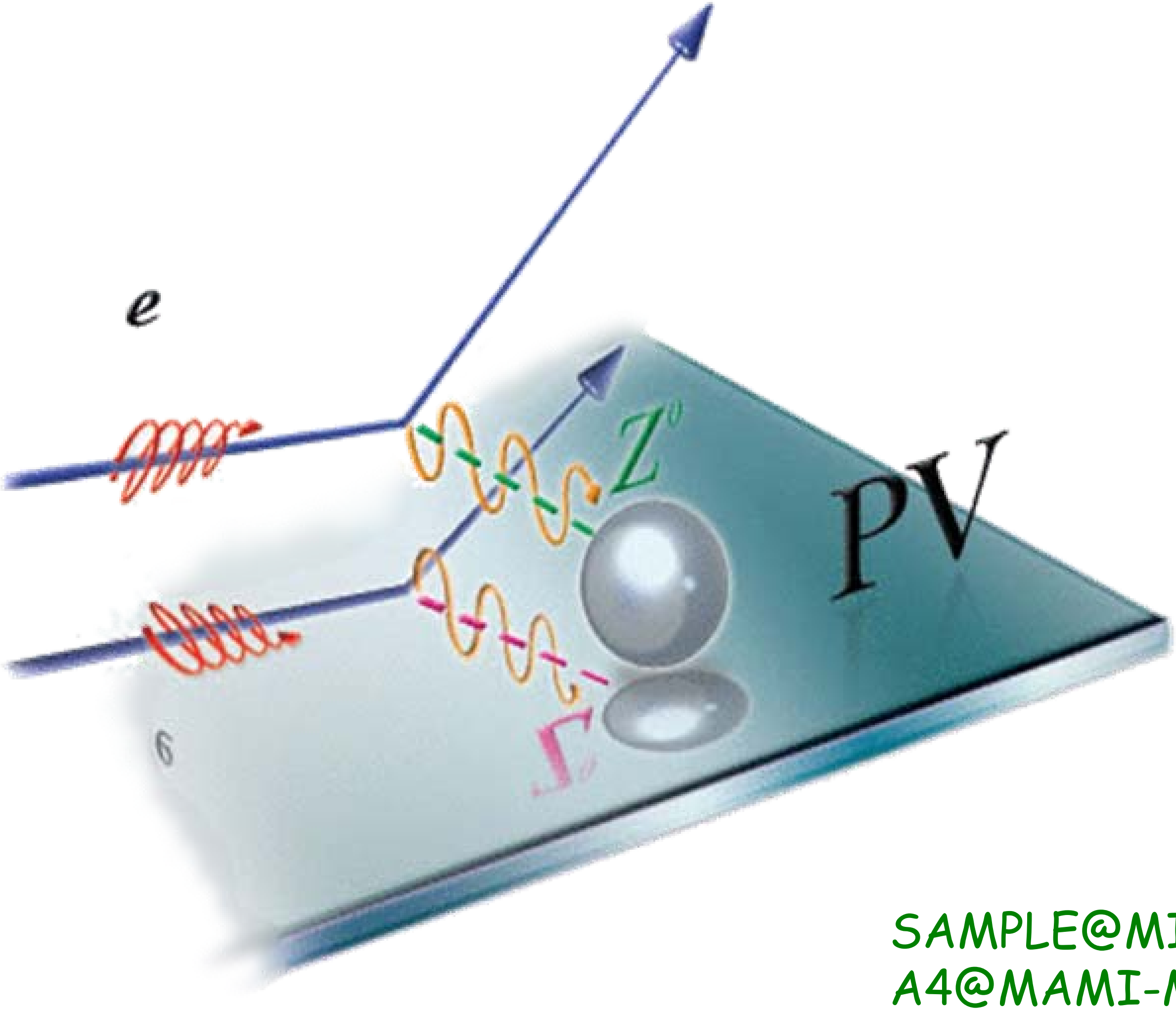


Parity conserving

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

Parity violating

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



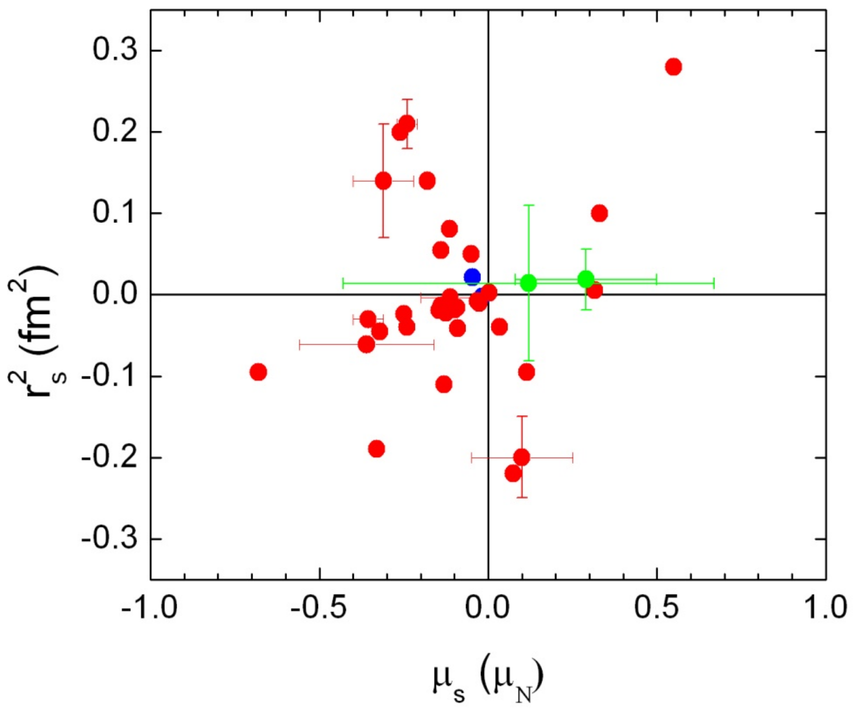
SAMPLE@MIT-BATES
A4@MAMI-Mainz
HAPPEX@Jlab
G0@JLab

Strange Proton

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

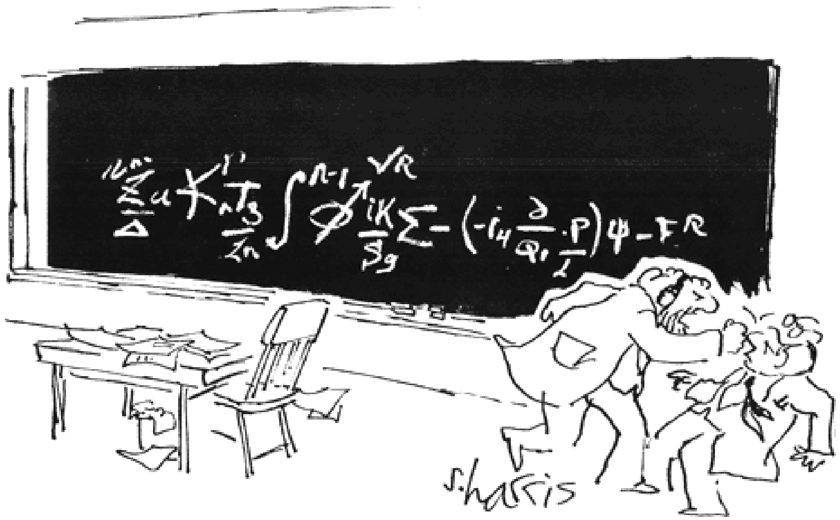
$$\begin{aligned}\mu_s &= 0.0018\,(\mu_N)\\ \langle r^2\rangle_s &= 0.012\,(\mathrm{fm}^2)\end{aligned}$$

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

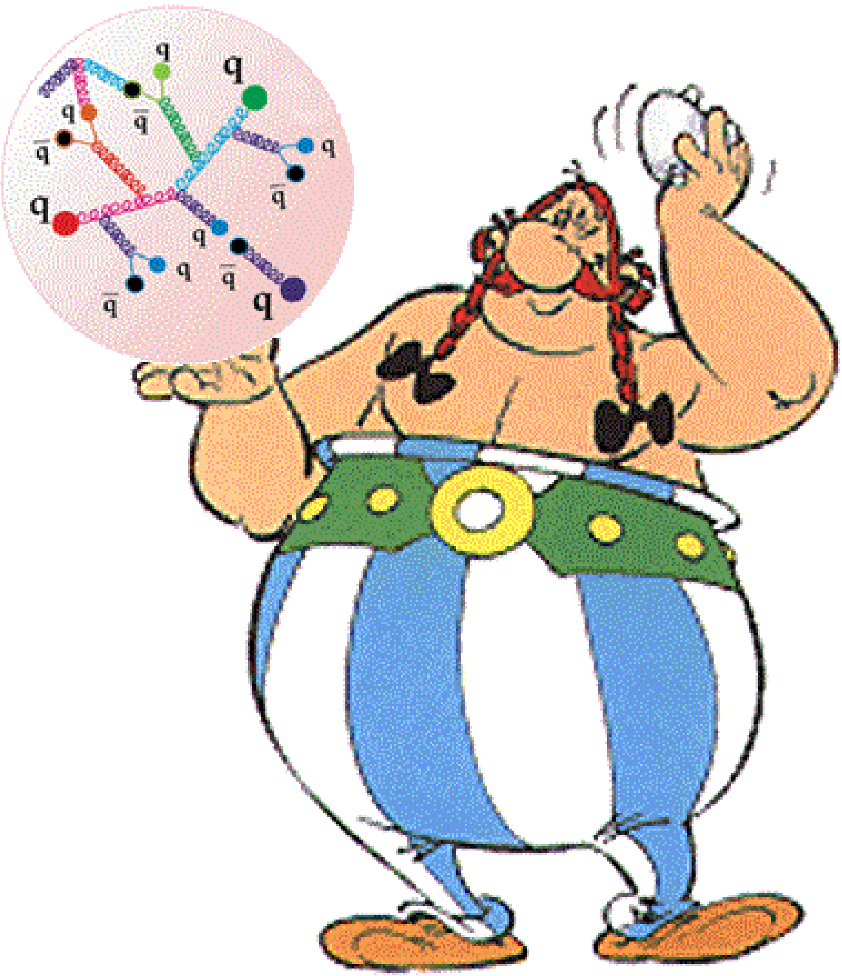


Theory

- 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!"

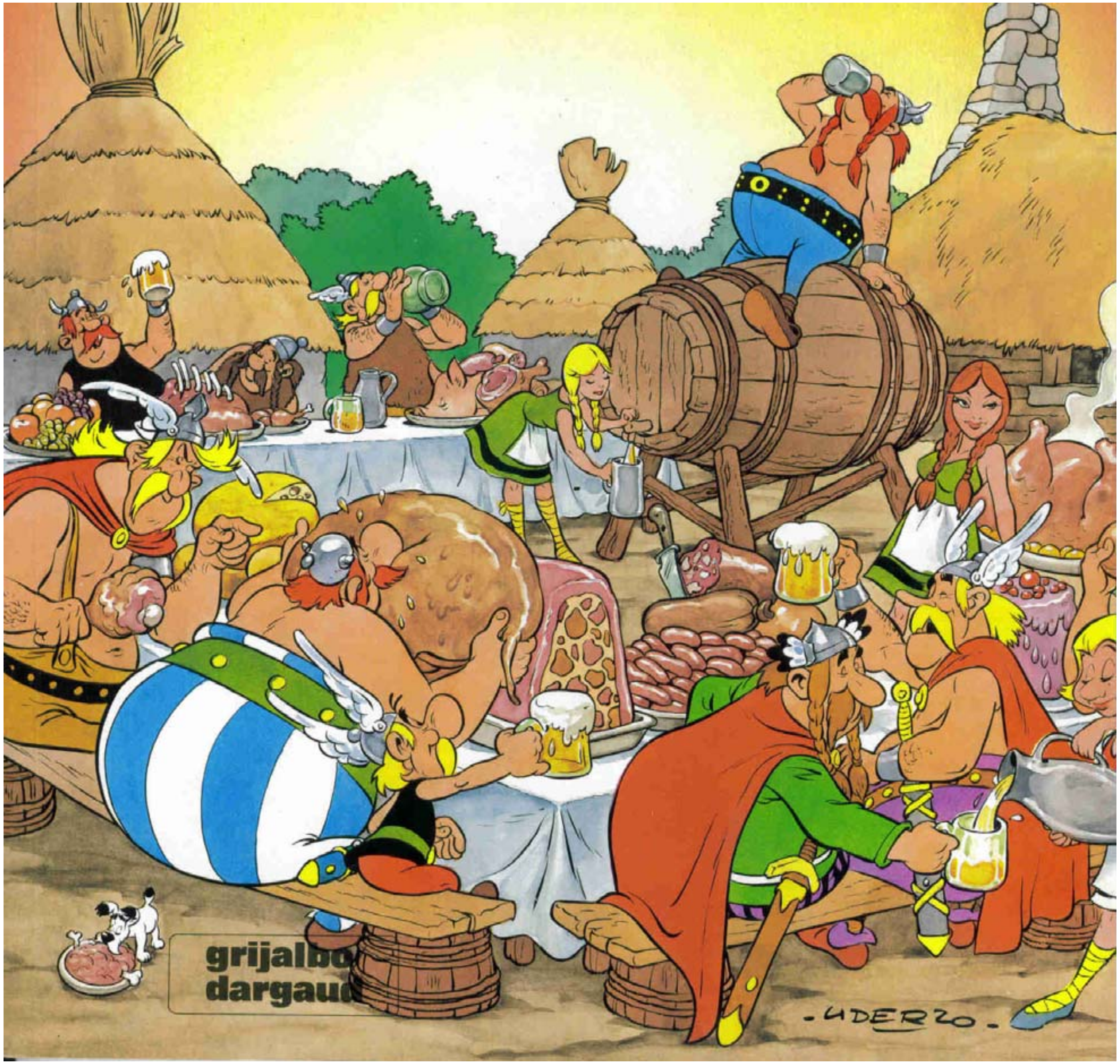


Summary and Conclusions

- First explicit calculations of flavor content of physical observables in an unquenched quark model
- Preserves the successes of the CQM
- Magnetic moments of octet baryons
- Flavor asymmetry of sea quarks
- Quark spins and orbital angular momenta
- Strange loops of the proton
- 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

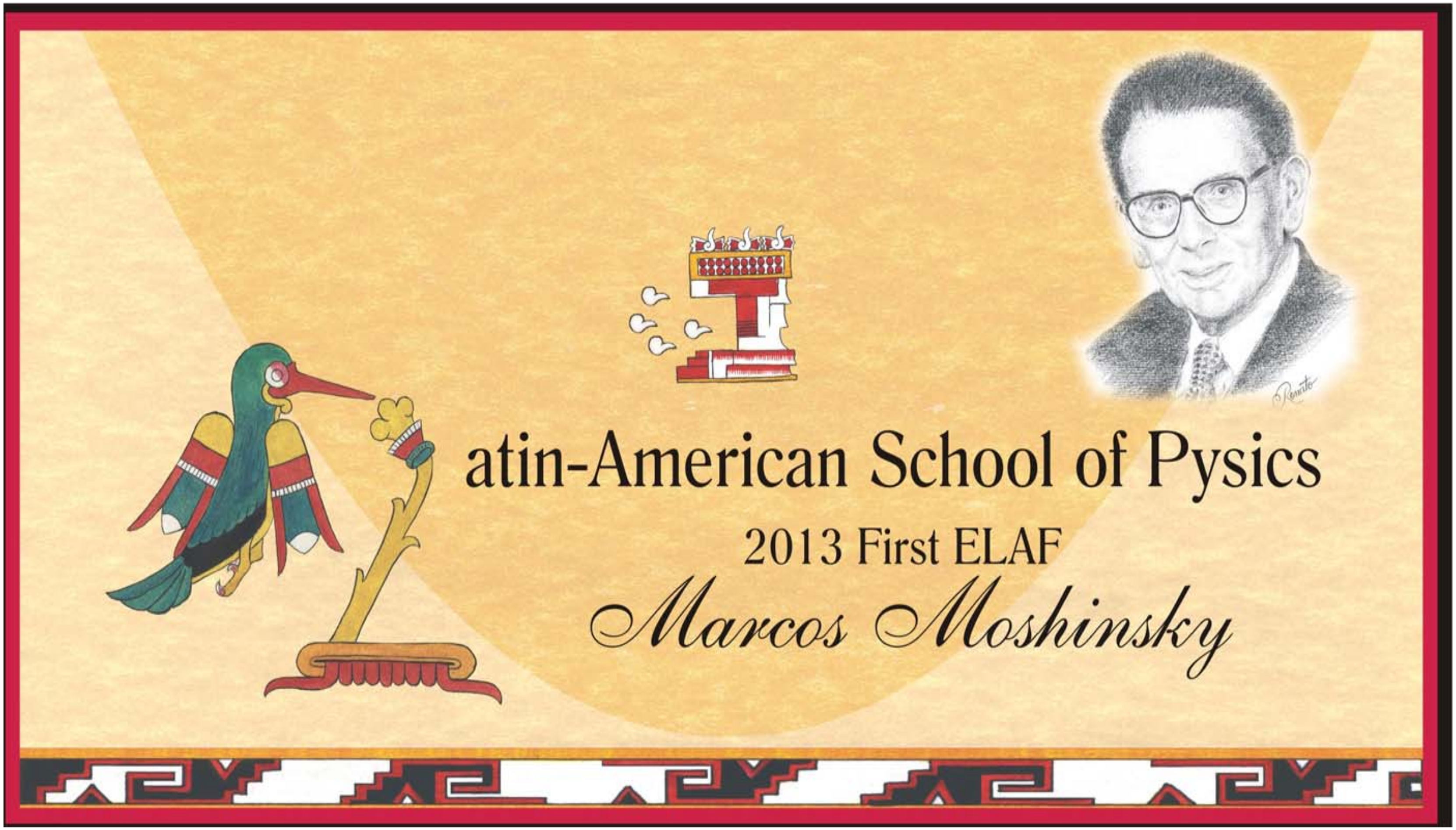
Outlook

- Collaboración con la Dra. Elena Santopinto de la Universidad de Genova (Italia)
- Electromagnetic couplings (Hugo García Tecocoatzi)
- Relation with Chiral QM and MCM (Miguel Ángel López Ruiz, Silvia Díaz Gómez, Gustavo Hazel Guerrero Navarro, Emmanuel Ortiz Pacheco)
- Self energies (Giuseppe Galata, Jacopo Ferretti)
- Tetraquarks (Giuseppe Galata)
- Axial couplings
- Strong couplings
- …

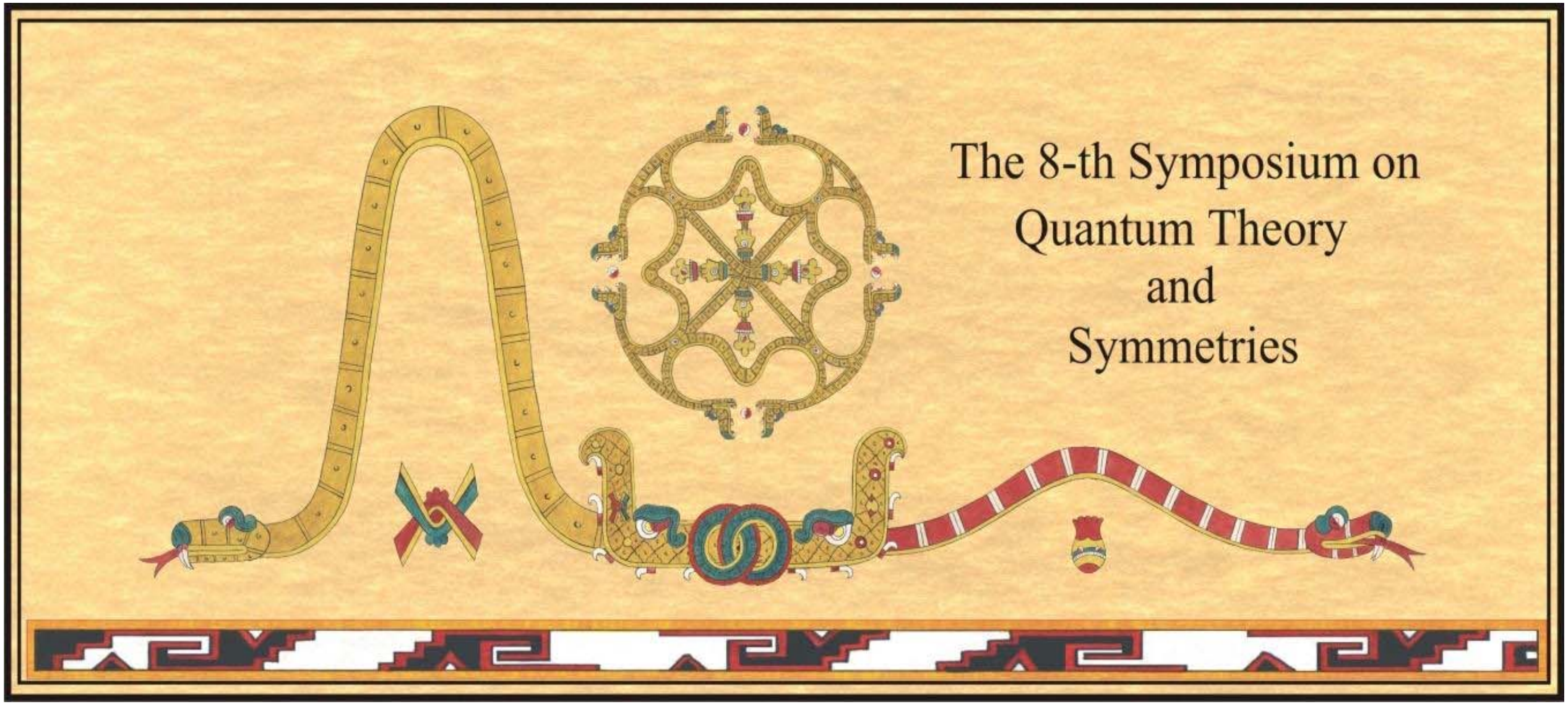

grijalbo
dargaud
UDERZO

Lecture Notes

- Nuclear Supersymmetry
  “VI Escuela Mexicana de Física Nuclear“
  AIP Conf Proc 1271, 90-131 (2010)
- Quark Models of the Nucleon
  “VII Escuela Mexicana de Física Nuclear“
  unpublished
- VIII Escuela Mexicana de Física Nuclear
  Verano de 2013, UNAM, México DF



México DF, 22 de julio – 2 de agosto de 2013
http://www.nucleares.unam.mx/~bijker/elaf2013.html



México DF, 5 – 9 de agosto de 2013
http://www.fis.unam.mx/symposiaqts