

Interpretation of the $X(3872)$ as a charmonium state plus an extra component due to the coupling to the meson-meson continuum

E. Santopinto (INFN),
J. Ferretti (INFN), G. Galatà (UNAM)

PWA7 2013

Ferretti, Galatà, E. S., Phys. Rev. C **88**, 015207 (2013)

Unquenching the quark model for mesons

Ferretti, Galatà, E. S., Vassallo, Phys. Rev. C **86**, 015204 (2012)

Ferretti, Galatà, E. S., Phys. Rev. C **88**, 015207 (2013)

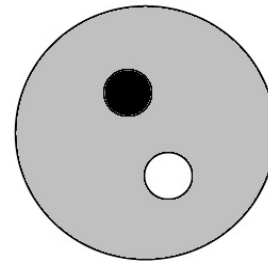
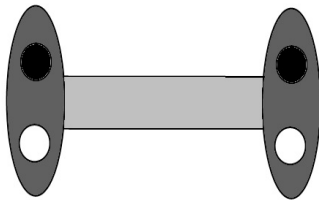
Ferretti, E. S: arXiv.1306.2874

The X(3872) puzzle

- The nature of the recently discovered X(3872) resonance has not been understood yet
- The quark structure of the X(3872) resonance, observed for the first time by the Belle Collaboration and then confirmed by CDF, D0 and BABAR, still remains an open puzzle. We only know thanks to LHCb that it is 1^{++}

The X(3872) puzzle

- The nature of the recently discovered X(3872) resonance has not been understood yet
- At the moment there are two possible interpretations for this meson.
 - 1) A weakly-bound 1^{++} DD^* molecule
 - 2) A cc state with 1^{++}



X(3872) as a $c\bar{c}$ state

- In this case, the resonance would correspond to a 1^1D_2 ($J^{PC} = 2^{-+}$) state or to a 2^3P_1 one [$\chi_{c1}(2P)$, $J^{PC} = 1^{++}$]
- the relativized CQM predicts these states to be at energies of 3.84 and 3.95 GeV
- Moreover, from LHCb we know that the X(3872) has 1^{++} quantum numbers

The CQM with loop corrections

- The calculation, accomplished in our work, is the first tentative to calculate the spectrum of charmonia within the UQM, including loop corrections, and makes it possible to perform a comparison to the already existing and to the future experimental data.
- the calculated masses of our mesons are the sum of a bare energy term, computed within the relativized QM by Godfrey and Isgur, and a self energy correction, computed within the unquenched quark model (UQM)

Self-energies (1)

The Hamiltonian we consider, $H = H_0 + V$ is the sum of an "unperturbed" part H_0 , acting only in the bare meson space, and of a second part, V , which can couple a meson state to a continuum made up of meson-meson intermediate states.

- The dispersive equation can be written as

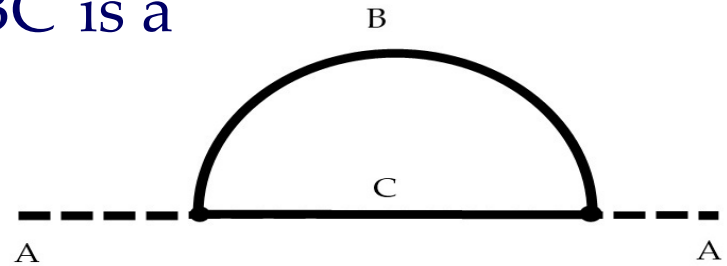
$$\Sigma(E_a) = \sum_{BC} \int_0^\infty q^2 dq \frac{|V_{a,bc}(q)|^2}{E_a - E_{bc}}$$

where the bare energy E_a satisfies

$$M_a = E_a + \Sigma(E_a) \quad \text{where } \Sigma(E_a) \text{ is the self-energy}$$

Self-energies (2)

- one has to take the contributions from various channels BC into account. A channel BC is a meson-meson intermediate state



- The matrix element $V_{a,bc}$ results from the coupling, due to the operator V , between the intermediate state BC and the unperturbed quark-antiquark wave function of the meson A
- one has to choose a precise form for the transition operator, V , responsible for the creation of qq pairs: our choice is that of the unquenched quark model (UQM)

Unquenched quark model (UQM)

- In the unquenched quark model the effects of $q\bar{q}$ sea pairs are introduced explicitly into the constituent quark model (QM) through a QCD-inspired $3P0$ pair-creation mechanism.
- To leading order in pair creation, the meson wave function is given by

$$|\psi_A\rangle = \mathcal{N} \left[|A\rangle + \sum_{BC\ell J} \int d\vec{q} |BC\vec{q}\ell J\rangle \frac{\langle BC\vec{q}\ell J | T^\dagger | A\rangle}{E_a - E_b - E_c} \right]$$

where T represents the $3P0$ quark-antiquark pair creation operator

3P0 pair-creation operator

- The 3P0 quark-antiquark pair-creation operator is

$$T^\dagger = -\gamma_0 \int d\vec{p}_3 d\vec{p}_4 \delta(\vec{p}_3 + \vec{p}_4) C_{34} F_{34} e^{-r_q^2(\vec{p}_3 - \vec{p}_4)^2/6} [\chi_{34} \times \mathcal{Y}_1(\vec{p}_3 - \vec{p}_4)]_0^{(0)} b_3^\dagger(\vec{p}_3) d_4^\dagger(\vec{p}_4) ,$$

- Since the operator T creates a pair of constituent quarks with an effective size, the pair creation point has to be smeared out by a gaussian factor.
- The pair-creation strength γ_0 is a dimensionless constant, fitted to the strong decay widths of a few cc states. γ_0 is substituted by a γ effective defined as γ_0 times m_u/m_i .
- The matrix elements of the pair-creation operator were derived in explicit form in the harmonic oscillator basis

Godfrey and Isgur relativized QM

- The relativized QM by Godfrey and Isgur is a potential model for qq meson spectroscopy. This model assumes a relativistic kinetic energy, a QCD-motivated running coupling constant, a flavor dependent potential smearing parameter, and replaces factors of quark mass with quark kinetic energy

Godfrey and Isgur relativized QM

- The Godfrey and Isgur Hamiltonian is

$$H = \sqrt{q^2 + m_1^2} + \sqrt{q^2 + m_2^2} + V_{\text{conf}} + V_{\text{hyp}} + V_{\text{so}}$$

$$V_{\text{conf}} = - \left(\frac{3}{4} c + \frac{3}{4} br - \frac{\alpha_s(r)}{r} \right) \vec{F}_1 \cdot \vec{F}_2$$

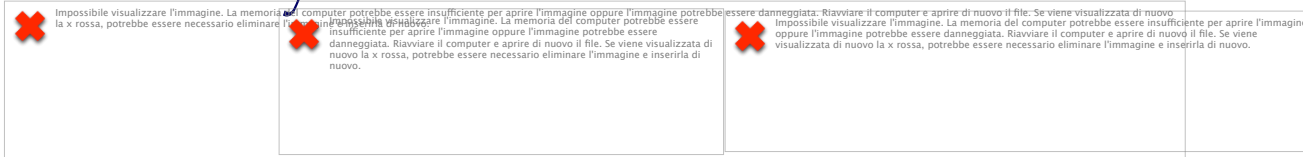
$$V_{\text{hyp}} = - \frac{\alpha_s(r)}{m_1 m_2} \left[\frac{8\pi}{3} \vec{S}_1 \cdot \vec{S}_2 \delta^3(\vec{r}) + \frac{1}{r^3} \left(\frac{3 \vec{S}_1 \cdot \vec{r} \vec{S}_2 \cdot \vec{r}}{r^2} - \vec{S}_1 \cdot \vec{S}_2 \right) \right] \vec{F}_i \cdot \vec{F}_j$$

$$V_{\text{so}} = V_{\text{so,cm}} + V_{\text{so,tp}}$$

$$V_{\text{so,cm}} = - \frac{\alpha_s(r)}{r^3} \left(\frac{1}{m_i} + \frac{1}{m_j} \right) \left(\frac{\vec{S}_i}{m_i} + \frac{\vec{S}_j}{m_j} \right) \cdot \vec{L} \quad V_{\text{so,tp}} = - \frac{1}{2r} \frac{\partial H_{ij}^{\text{conf}}}{\partial r} \left(\frac{\vec{S}_i}{m_i^2} + \frac{\vec{S}_j}{m_j^2} \right) \cdot \vec{L} \vec{F}_i \cdot \vec{F}_j$$

Strong decay widths

- The decay widths are calculated within the 3P0 model



we calculated the strong decay widths of 3S, 2P, 1D and 2D charmonium states above the DD threshold

- The introduction of quark form factors determines slightly different values for the model parameters than standard 3P0 models
- Another difference is the use of an effective strength, introduced to suppress diagrams where heavy qq pairs are created

Strong decay widths: results

Parameter	Value
γ_0	0.510
α	0.500 GeV
r_q	0.335 fm
m_n	0.330 GeV
m_s	0.550 GeV
m_c	1.50 GeV

Strong decay widths: results

Parameter	Value							
γ_0	0.510							
α	0.500 GeV							
r_q	0.335 fm							
m_n	0.330 GeV							
m_s	0.550 GeV							
m_c	1.50 GeV							

State	DD	DD^*	D^*D^*	D_sD_s	$D_sD_s^*$	$D_s^*D_s^*$	Total	Exp.
$\eta_c(3^1S_0)$	–	38.8	52.3	–	–	–	91.1	–
$\Psi(4040)(3^3S_1)$	0.2	37.2	39.6	3.3	–	–	80.3	80 ± 10
$h_c(2^1P_1)$	–	64.6	–	–	–	–	64.6	–
$\chi_{c0}(2^3P_0)$	97.7	–	–	–	–	–	97.7	–
$\chi_{c2}(2^3P_2)$	27.2	9.8	–	–	–	–	37.0	–
$\Psi(3770)(1^3D_1)$	27.7	–	–	–	–	–	27.7	27.2 ± 1.0
$\Psi_3(1^3D_3)$	1.7	–	–	–	–	–	1.7	–
$\eta_{c2}(2^1D_2)$	–	62.7	46.4	–	8.8	–	117.9	–
$\Psi(4160)(2^3D_1)$	11.2	0.4	39.4	2.1	5.6	–	58.7	103 ± 8
$\Psi_2(2^3D_2)$	–	43.5	49.3	–	11.3	–	104.1	–
$\Psi_3(2^3D_3)$	17.2	58.3	48.1	3.6	2.6	–	129.8	–

TABLE III: Strong decay widths in heavy meson pairs(in MeV) for $3S$, $2P$, $1D$ and $2D$ charmonium states. The values of the model parameters are given in Table II. The symbol – in the table means that a certain decay is forbidden by selection rules or that the decay cannot take place because it is below threshold.

Self-energies calculations

- The relativized QM is used to compute the bare energies of the cc states we need in the self energy calculation.
- In our case, the quantities fitted to the spectrum of charmonia are the physical masses and therefore the fitting procedure is an iterative one.
- Once the values of the bare energies are known, it is possible to calculate the self energies of 1S, 2S, 1P, 2P and 1D cc states

Self-energies calculations (2)

- If the bare energy of the meson A is over the threshold BC

$$\begin{aligned} \Sigma(E_a; BC) &= \mathcal{P} \int_{M_b+M_c}^{\infty} \frac{dE_{bc}}{E_a - E_{bc}} \frac{qE_b E_c}{E_{bc}} |\langle BC \vec{q} \ell J | T^\dagger | A \rangle|^2 \\ &+ 2\pi i \left\{ \frac{qE_b E_c}{E_a} |\langle BC \vec{q} \ell J | T^\dagger | A \rangle|^2 \right\}_{E_{bc}=E_a}, \end{aligned}$$

- The imaginary part of the self-energy is related to the decay amplitude by

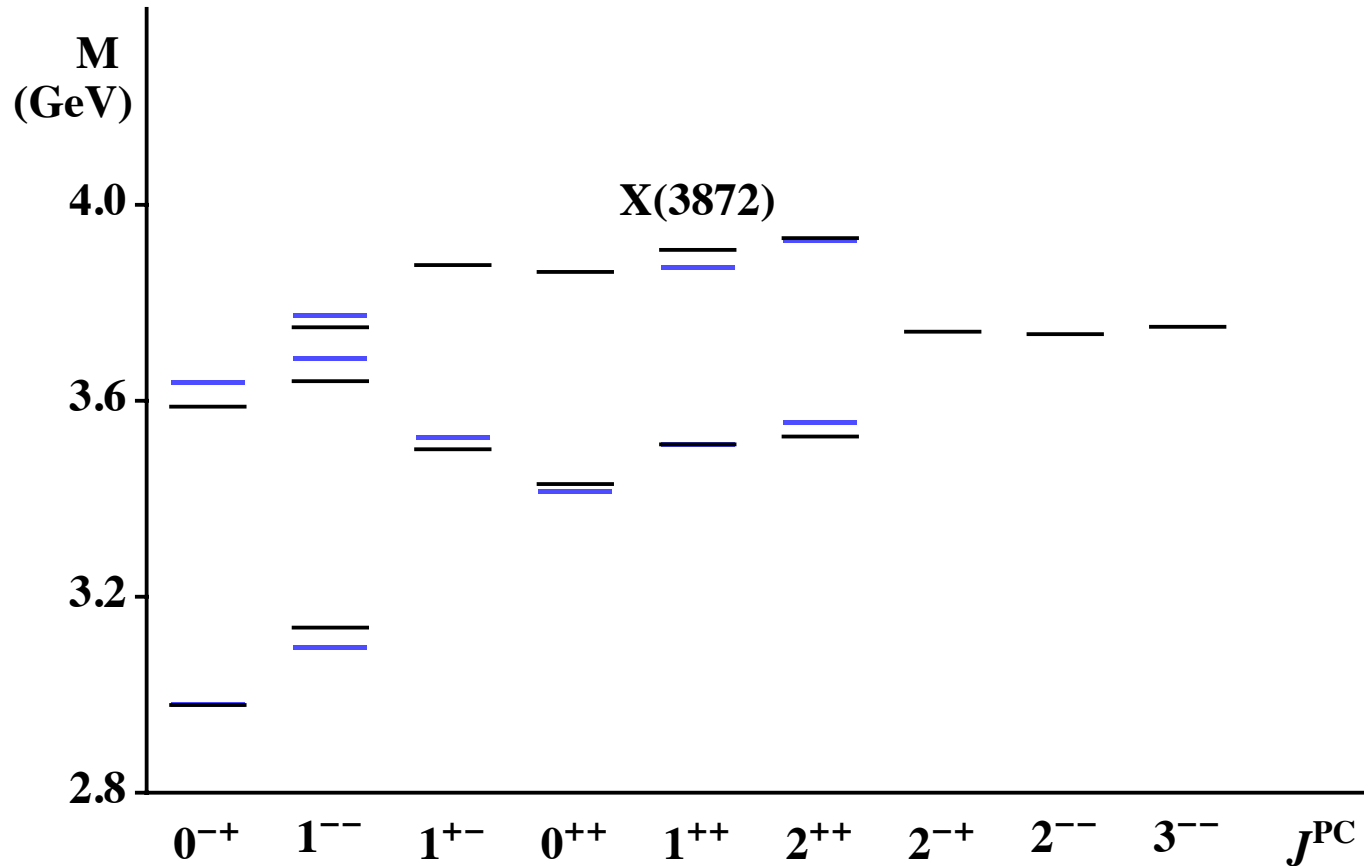
$$\Gamma_{A \rightarrow BC} = \text{Im} [\Sigma(E_a; BC)]$$

Self-energies: results

State	J^{PC}	$D\bar{D}$	$\bar{D}D^*$ $D\bar{D}^*$	\bar{D}^*D^*	$D_s\bar{D}_s$	$D_s\bar{D}_s^*$ $\bar{D}_sD_s^*$	$D_s^*\bar{D}_s^*$	$\eta_c\eta_c$	$\eta_c J/\Psi$	$J/\Psi J/\Psi$	$\Sigma(E_a)$	E_a	M_a	$M_{exp.}$
$\eta_c(1^1S_0)$	0^{-+}	-	-34	-31	-	-8	-8	-	-	-2	-83	3062	2979	2980
$J/\Psi(1^3S_1)$	1^{--}	-8	-27	-41	-2	-6	-10	-	-2	-	-96	3233	3137	3097
$\eta_c(2^1S_0)$	0^{-+}	-	-52	-41	-	-9	-8	-	-	-1	-111	3699	3588	3637
$\Psi(2^3S_1)$	1^{--}	-18	-42	-54	-2	-7	-10	-	-1	-	-134	3774	3640	3686
$h_c(1^1P_1)$	1^{+-}	-	-59	-48	-	-11	-10	-	-2	-	-130	3631	3501	3525
$\chi_{c0}(1^3P_0)$	0^{++}	-31	-	-72	-4	-	-15	0	-	-3	-125	3555	3430	3415
$\chi_{c1}(1^3P_1)$	1^{++}	-	-54	-53	-	-9	-11	-	-	-2	-129	3623	3494	3511
$\chi_{c2}(1^3P_2)$	2^{++}	-17	-40	-57	-3	-8	-10	0	-	-2	-137	3664	3527	3556
$h_c(2^1P_1)$	1^{+-}	-	-55	-76	-	-12	-8	-	-1	-	-152	4029	3877	-
$\chi_{c0}(2^3P_0)$	0^{++}	-23	-	-86	-1	-	-13	0	-	-1	-124	3987	3863	-
$\chi_{c1}(2^3P_1)$	1^{++}	-	-30	-66	-	-11	-9	-	-	-1	-117	4025	3908	3872
$\chi_{c2}(2^3P_2)$	2^{++}	-2	-42	-54	-4	-8	-10	0	-	-1	-121	4053	3932	3927
$\eta_{c2}(1^1D_2)$	2^{-+}	-	-99	-62	-	-12	-10	-	-	-1	-184	3925	3741	-
$\Psi(3770)(1^3D_1)$	1^{--}	-11	-40	-84	-4	-2	-16	-	0	-	-157	3907	3750	3775
$\Psi_2(1^3D_2)$	2^{--}	-	-106	-61	-	-11	-11	-	-1	-	-190	3926	3736	-
$\Psi_3(1^3D_3)$	3^{--}	-25	-49	-88	-4	-8	-10	-	-1	-	-185	3936	3751	-

Charmonium spectrum with SE corrections

Ferretti, Galatà and Santopinto, PRC88, 015207 (2013)



X(3872). Comparison with other works

Ferretti, Galatà and Santopinto, PRC88, 015207 (2013)

- Calculations of charmonium spectrum including continuum coupling effects (loop effects)

$\chi_{c1}(2P)$ mass [MeV]	Reference
3908	Ferretti <i>et al.</i>
4007.5	Eichten <i>et al.</i> (2004)
3990	Kalashnikova
3920.5	Eichten <i>et al.</i> (2006)
3896	Pennington and Wilson

References

Ferretti, Galatà and Santopinto, PRC88, 015207 (2013)
Eichten *et al.*, PRD69, 094019 (2004)
Kalashnikova, PRD72, 034010 (2005)
Eichten *et al.*, PRD73, 014014 (2006)
Pennington and Wilson, PRD76, 077502 (2007)

X(3872). Charmonium interpretation

Ferretti, Galatà and Santopinto, PRC88, 015207 (2013)

- Ratio between $X(3872) \rightarrow J/\Psi \rho$ and $X(3872) \rightarrow J/\Psi \omega$ decay modes and for the rate $X(3872) \rightarrow D^0 \bar{D}^0 \pi^0$ favor charmonium interpretation

Meng and Chao, PRD75, 114002 (2007)

X(3872) \rightarrow $\psi(2S) \gamma$ dominant with respect to X(3872) \rightarrow $J/\psi \gamma$

De Fazio

$$B(B^\pm \rightarrow K^\pm X) B(X \rightarrow \psi(2S) \gamma) = (9.9 \pm 2.9 \pm 0.9) \times 10^{-6}$$

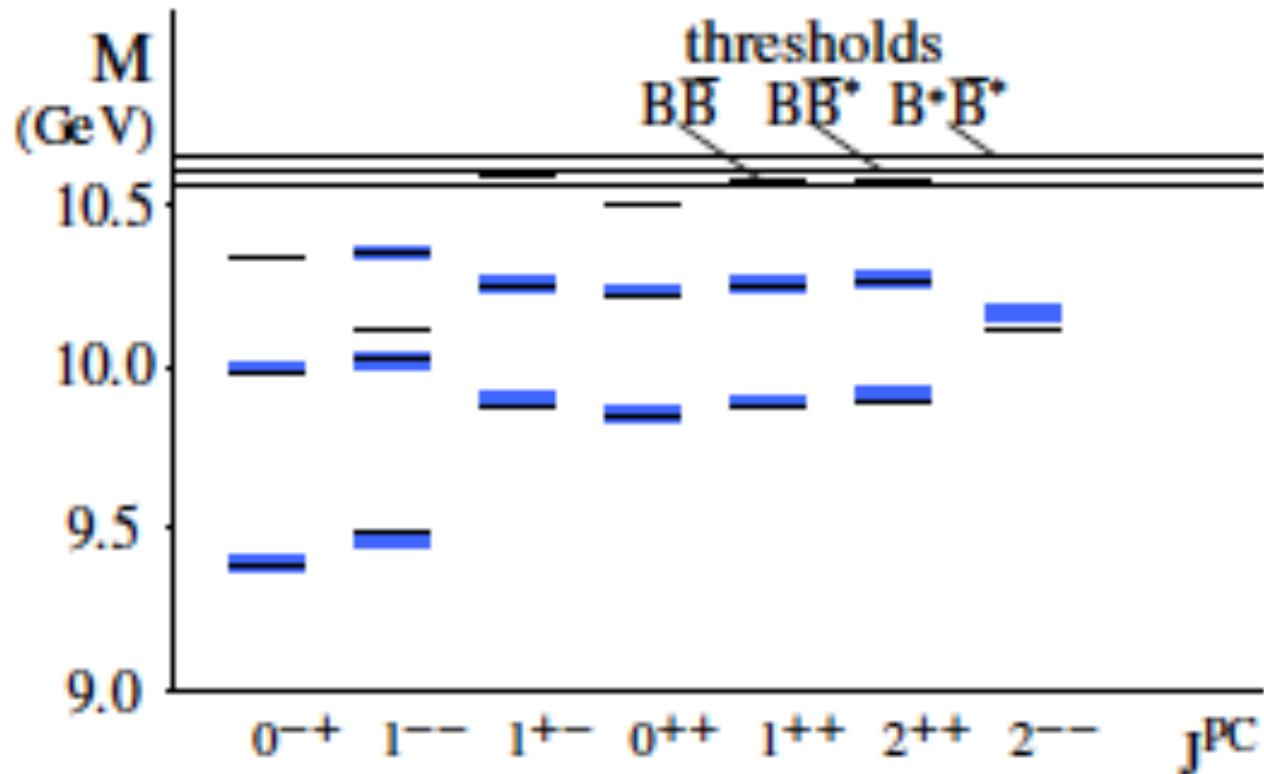
$$B(B^\pm \rightarrow K^\pm X) B(X \rightarrow J/\psi \gamma) = (2.8 \pm 0.8 \pm 0.2) \times 10^{-6}$$

X(3872). Molecule interpretation

- Is the X(3872) a meson-meson molecule?
- The $D\bar{D}^*$ system can be found by π -exchange and forms a meson-meson molecule.
Törnqvist, PRL67, 556 (1991)
- **Prompt production incompatible** with molecule interpretation
Molecule of a few fm, with intrinsic fragility can be promptly produced?!?
Bauer [CDF Collaboration], Int. J. Mod. Phys. A20, 3765 (2005)
Bignamini *et al.*, PRL103, 162001 (2009)

Bottomonium spectrum with SE corrections

Ferretti and Santopinto, arXiv:1306.2874



$\chi_b(3P)$ system

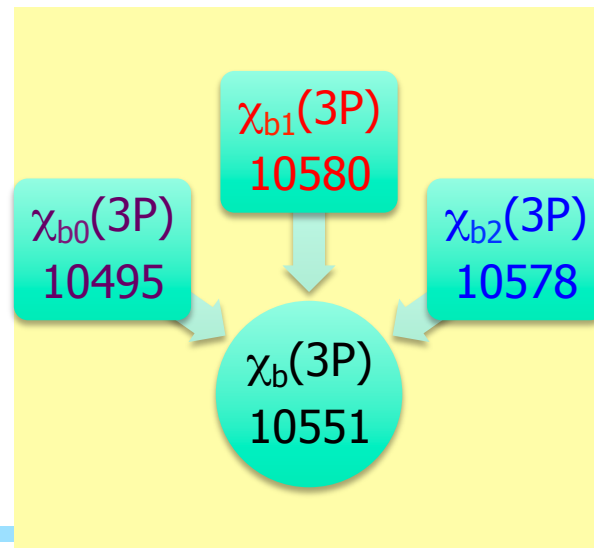
Ferretti and Santopinto, arXiv:1306.2874

- **$\chi_b(3P)$ system discovered by ATLAS Collaboration**
Aad et al., PRL108, 152001 (2012)
 $M = 10.530 \pm 0.005$ (stat.) ± 0.009 (syst.) GeV (mass barycenter for the $\chi_b(3P)$ signal)
- **Confirmed by D0 Collaboration**
Abazov et al., PRD86, 031103 (2012)
 $M = 10.551 \pm 0.014$ (stat.) ± 0.017 (syst.) GeV (mass barycenter for the $\chi_b(3P)$ signal)
“Further analysis is underway to determine whether this structure is due to the $\chi_b(3P)$ system or some exotic bottom quark state”
- **$\chi_b(3P)$ states lie close to $B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ decay thresholds**
- **Continuum coupling effects are important?**

$\chi_b(3P)$ system. Mass barycenter

Ferretti and Santopinto, arXiv:1306.2874

- **ATLAS Collaboration:** $M = 10.530 \pm 0.005$ (stat.) ± 0.009 (syst.) GeV
Aad et al., PRL108, 152001 (2012)
- **D0 Collaboration:** $M = 10.551 \pm 0.014$ (stat.) ± 0.017 (syst.) GeV
Abazov *et al.*, PRD86, 031103 (2012)
- **Our work:** $M = 10.551$ GeV



Continuum coupling (pair creation) effects

- **Mass shifts because of pair creation effects (self energy terms)**
Already shown by several authors in baryon and meson sectors
Törnqvist and Zenczykowski, PRD29, 2139 (1984); Z. Phys. C30, 83 (1986); Horacek *et al.*, PRD32, 3001 (1985); Blask *et al.*, Z. Phys. A326, 413 (1987); Brack and Bhaduri, PRD35, 3451 (1987); Silvestre-Brac and Gignoux, PRD43, 3699 (1991); Fujiwara, Prog. Theor. Phys. 89, 455 (1992); 90, 105 (1993); Morel and Capstick, nucl-th/0204014.
Ono and Törnqvist, Z. Phys. C23, 59 (1984); Heikkila, Ono and Törnqvist, PRD29, 110 (1984); van Beveren and Rupp, PRL91, 012003 (2003); Eichten, Lane and Quigg, PRD69, 094019 (2004); Hwang and Kim, PLB601, 137 (2004); Kalashnikova, PRD72, 034010 (2005); Pennington and Wilson, PRD76, 077502 (2007); Barnes and Swanson, PRC77, 055206 (2008); Li and Chao, PRD79, 094004 (2009); Danilkin and Simonov, PRL105, 102002 (2010); Liu and Ding, EPJC72, 1981 (2012).
- **Importance of orbital angular momentum in proton spin**
Bijker and Santopinto, PRC80, 065210 (2009); Santopinto and Bijker, Few Body Syst. 44, 95 (2008).
- **Flavor Asymmetry of the proton**
Santopinto and Bijker, PRC82, 062202 (2010).
- **Strangeness content of the proton**
Bijker, Ferretti and Santopinto, PRC85, 035204 (2012).

Why Unquenching the QM?

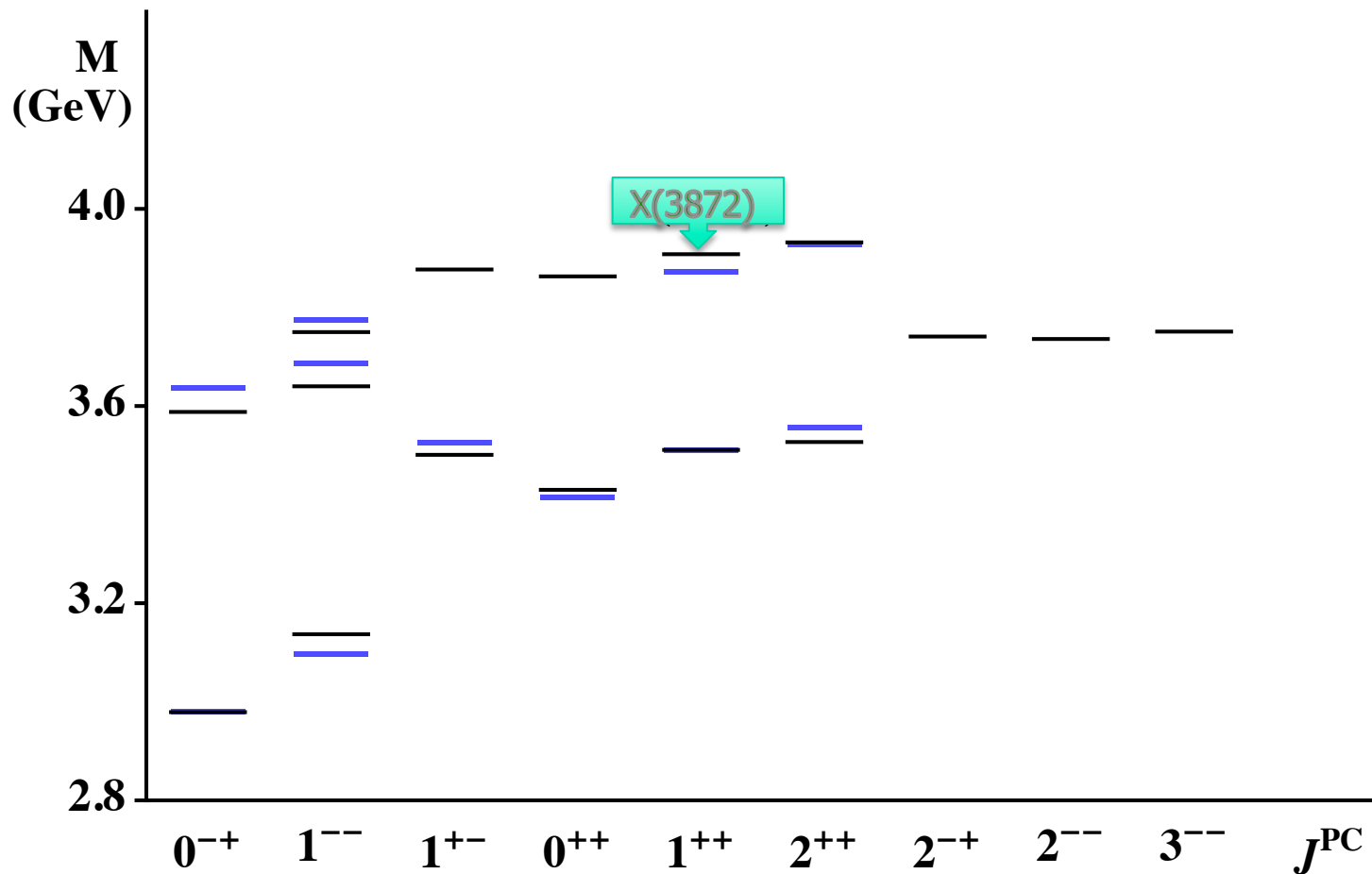
It brings “Widths”

Moreover the coupling with the continuum, brings shifts in hadron masses, that especially near to thresholds can not be reabsorbed into the renormalization of the parameters.

Is it possible to reformulate it in terms of S-matrix? (Swanson)

Charmonium spectrum with SE corrections. X(3872)

Ferretti, Galatà and Santopinto, PRC88, 015207 (2013)



Comparison with other calculations taking into account the continuum, open or nearby closed channels:

$\chi_{c1}(2^3P_1)$'s mass [MeV]	Reference
3908	this paper
4007.5	Eichten (2004)
3990	Kalashnikova (2005)
3920.5	Eichten (2006)
3896	Pennigton Wilson(2007)

Open charm strong decays. Results

Ferretti, Galatà and Santopinto, PRC88, 015207 (2013)

State	DD	DD^*	D^*D^*	D_sD_s	$D_sD_s^*$	$D_s^*D_s^*$	Total	Exp.
$\eta_c(3^1S_0)$	–	38.8	52.3	–	–	–	91.1	–
$\Psi(4040)(3^3S_1)$	0.2	37.2	39.6	3.3	–	–	80.3	80 ± 10
$h_c(2^1P_1)$	–	64.6	–	–	–	–	64.6	–
$\chi_{c0}(2^3P_0)$	97.7	–	–	–	–	–	97.7	–
$\chi_{c2}(2^3P_2)$	27.2	9.8	–	–	–	–	37.0	–
$\Psi(3770)(1^3D_1)$	27.7	–	–	–	–	–	27.7	27.2 ± 1.0
$c\bar{c}(1^3D_3)$	1.7	–	–	–	–	–	1.7	–
$c\bar{c}(2^1D_2)$	–	62.7	46.4	–	8.8	–	117.9	–
$\Psi(4160)(2^3D_1)$	11.2	0.4	39.4	2.1	5.6	–	58.7	103 ± 8
$c\bar{c}(2^3D_2)$	–	43.5	49.3	–	11.3	–	104.1	–
$c\bar{c}(2^3D_3)$	17.2	58.3	48.1	3.6	2.6	–	129.8	–

Charmonium strong decay widths in open charm mesons [MeV]

Parameters of the 3P_0 model:
fitted to the strong decays

Parameter	Value
γ_0	0.510
α	0.500 GeV
r_q	0.335 fm
m_n	0.330 GeV
m_s	0.550 GeV
m_c	1.50 GeV

Unquenching the quark model for baryons

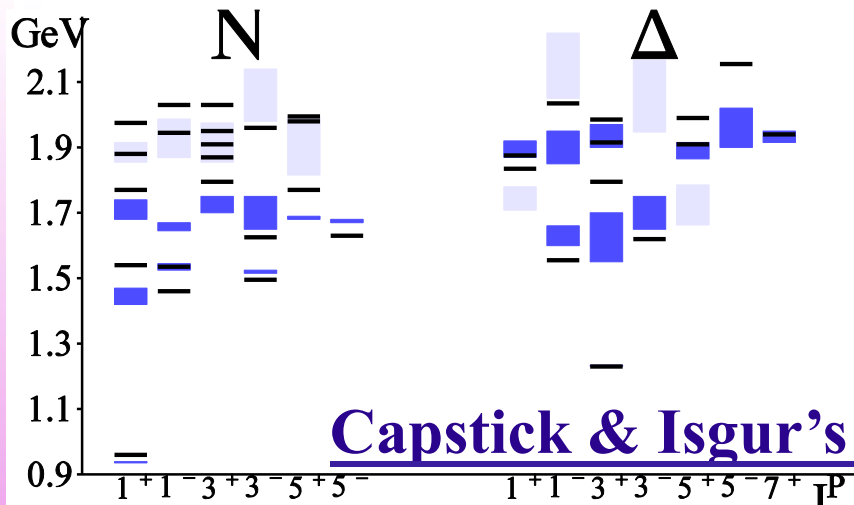
R.Bijker, E. S., PRC 80, 065210 (2009),
PRC 82, 062202 (2010);

J. Ferrettii, Santopinto, Bijker, Phys. Rev. C 85, 035204 (2012)

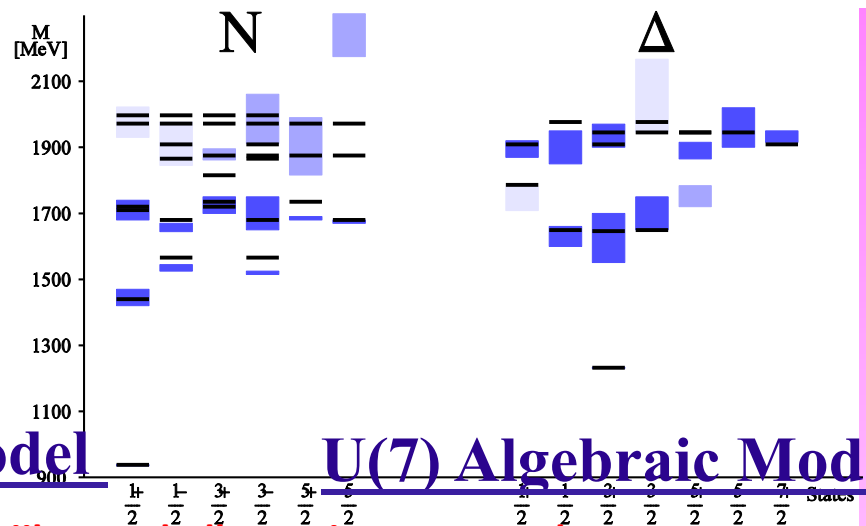
different CQMs for bayons

	Kin. Energy	SU(6) inv	SU(6) viol	date
Isgur-Karl	non rel	h.o. + shift	OGE	1978-9
Capstick-Isgur	rel	string + coul-like	OGE	1986
U(7) B.I.L.	rel M^2	vibr+L	Guersey-R	1994
Hyp. O(6)	non rel/rel	hyp.coul+linear	OGE	1995
Glozman Riska Plessas	non rel/rel	h.o./linear	GBE	1996
Bonn	rel	linear 3-body	instanton	2001

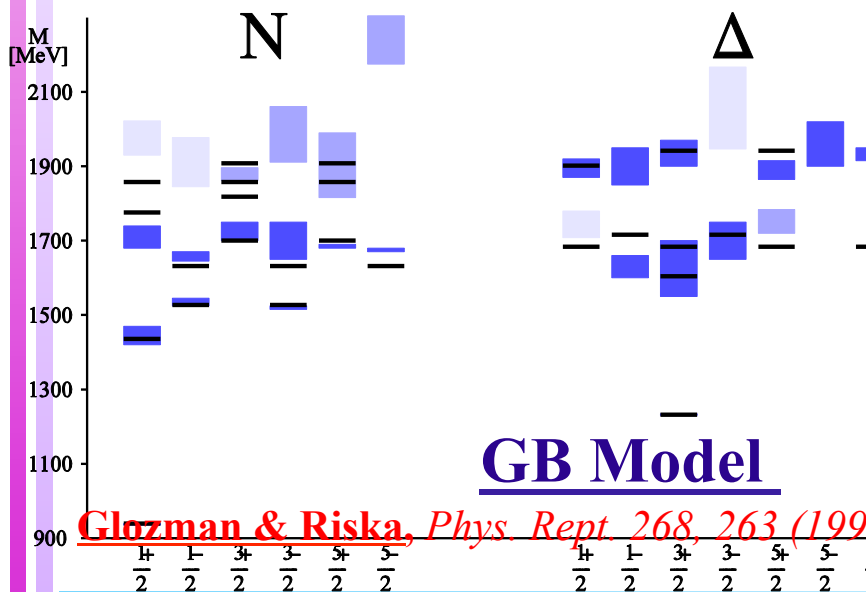
Non strange spectrum



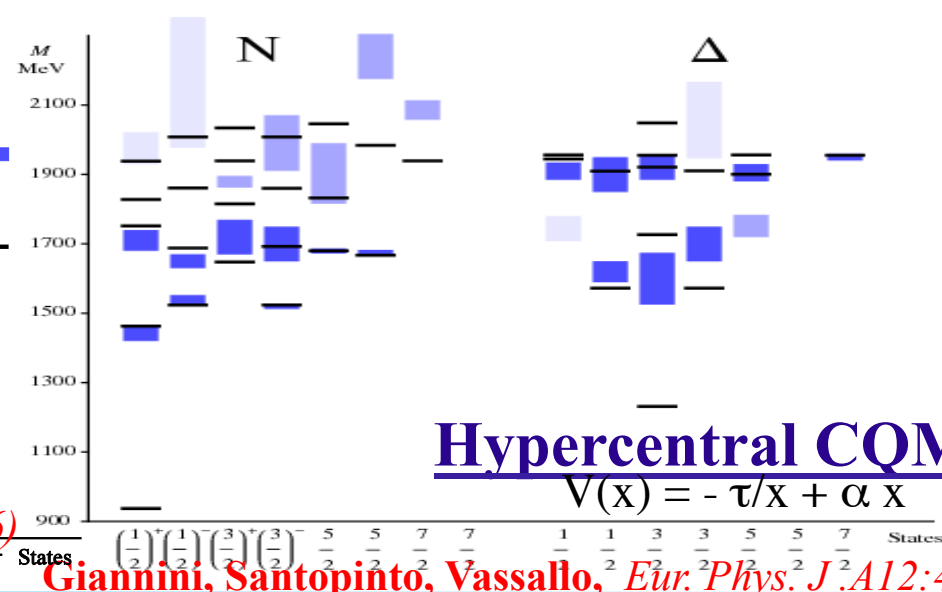
Capstick and Isgur, *Phys. Rev. D* 34, 2809.



Bijker, Iachello, Leviatan, *Ann. Phys.* 236, 69 (1994)



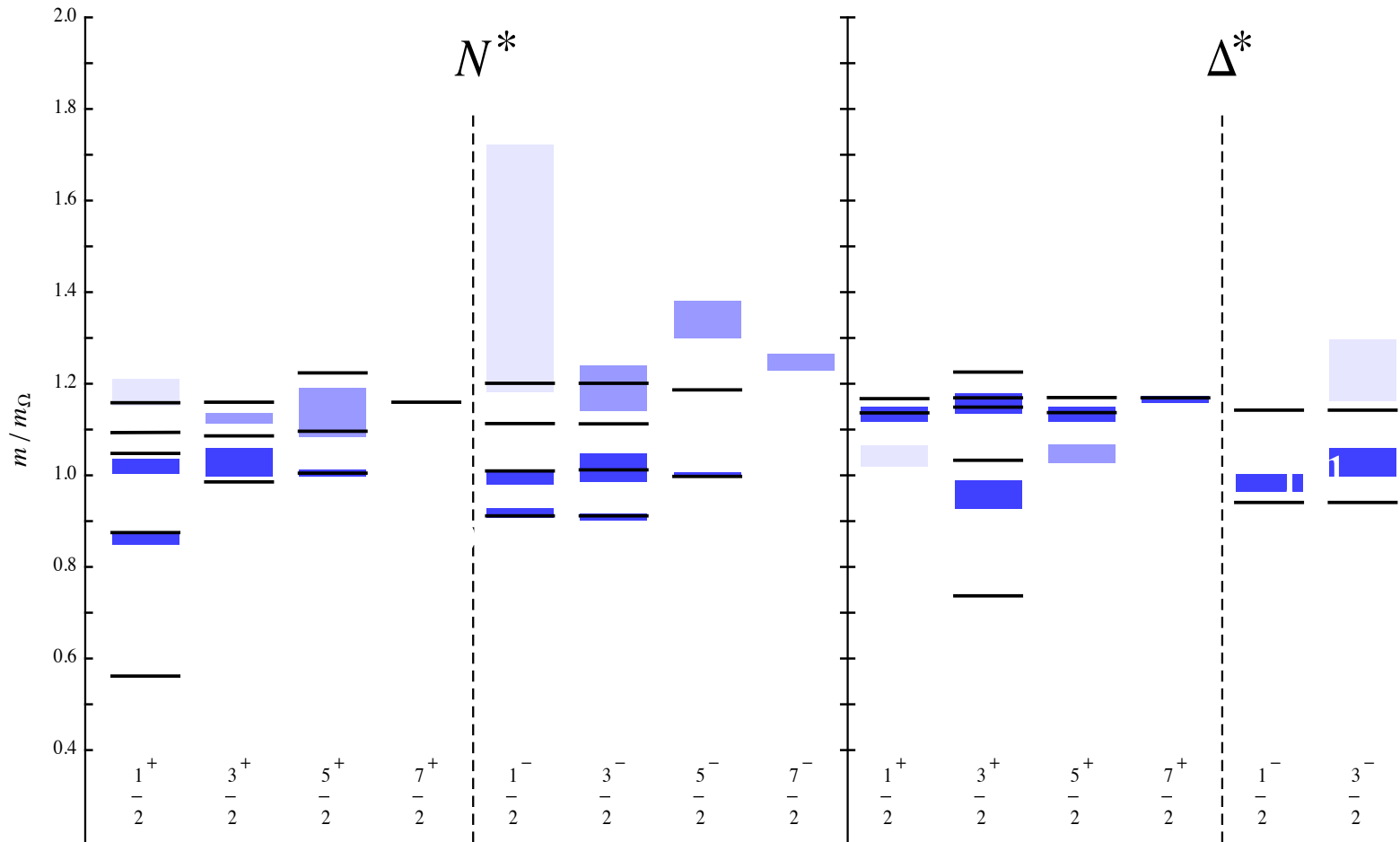
Glozman & Riska, *Phys. Rept.* 268, 263 (1996)



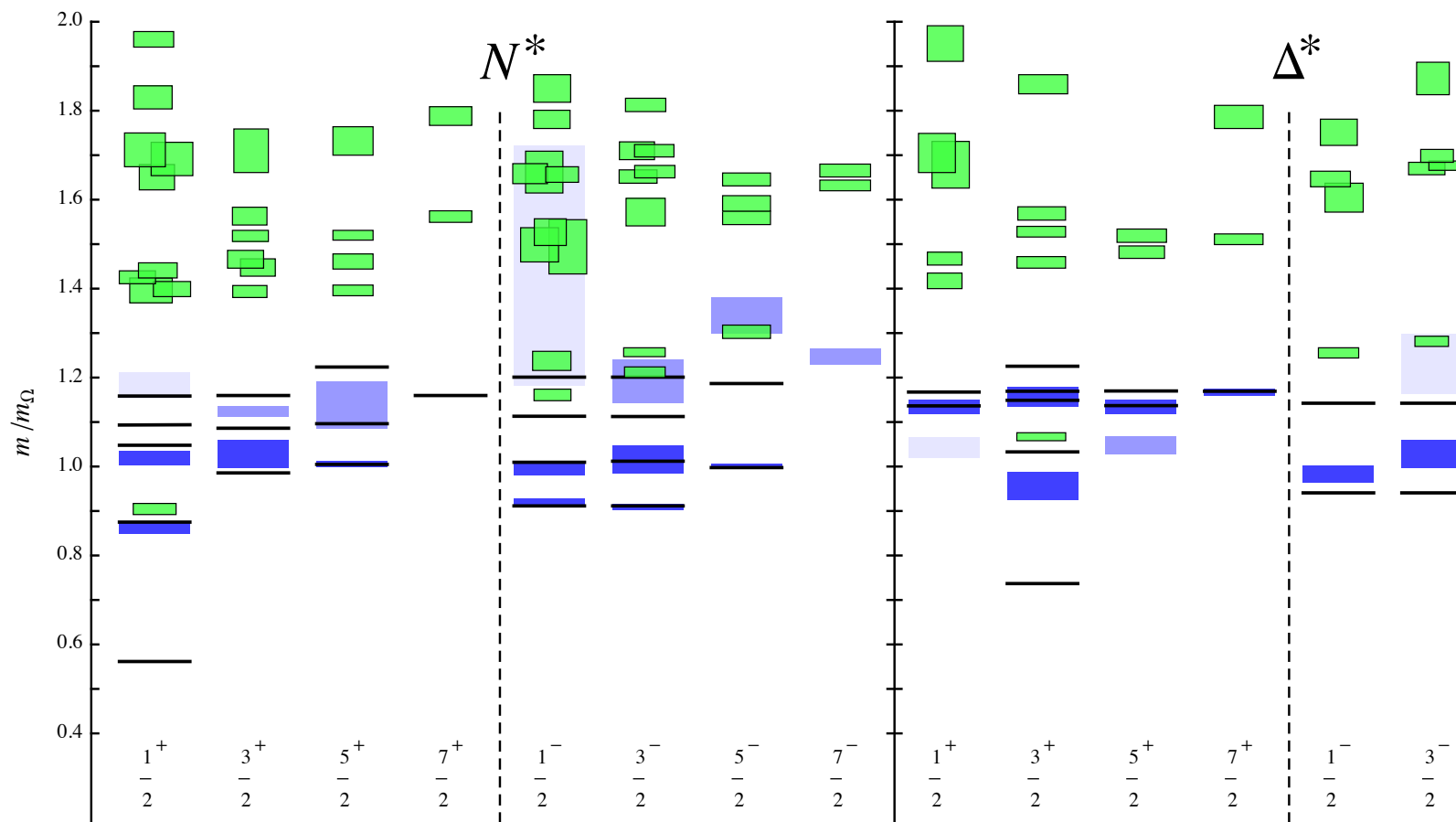
Giannini, Santopinto, Vassallo, *Eur. Phys. J. A* 12:447

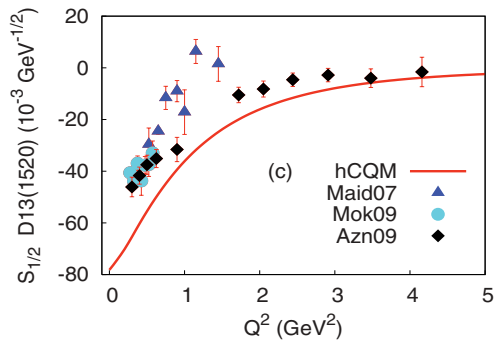
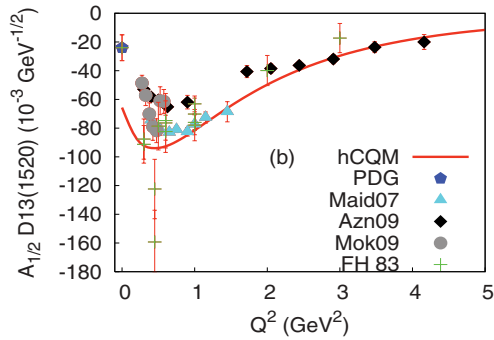
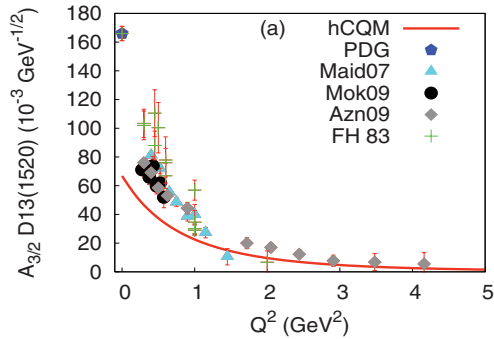
$$V(x) = -\tau/x + \alpha x$$

Phys.Lett.. B 364,23 (1995),Eur. Phys. J .A12:447



Giannini, Santopinto, Vassallo, Eur. Phys. J .A12:447

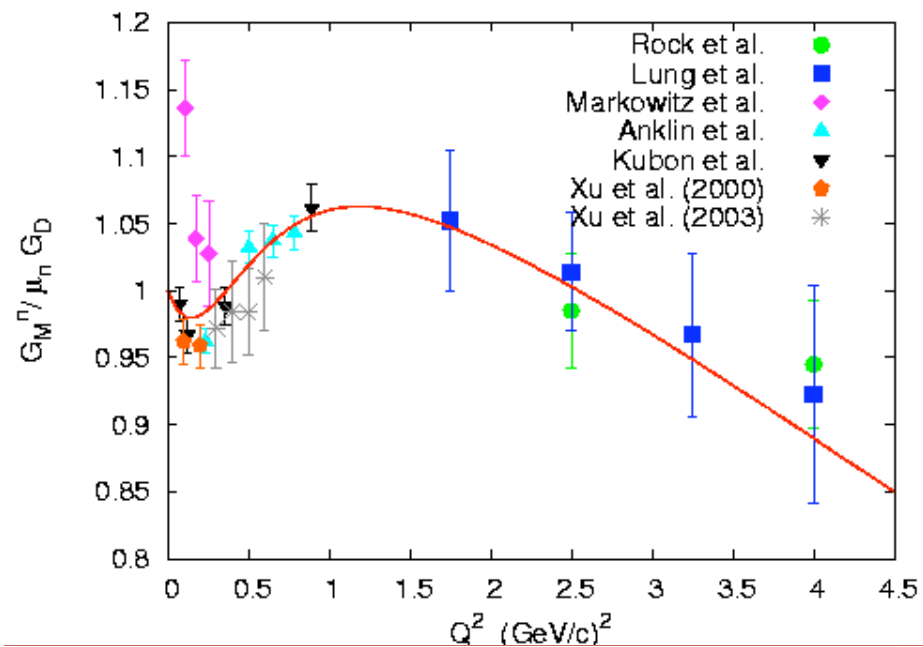
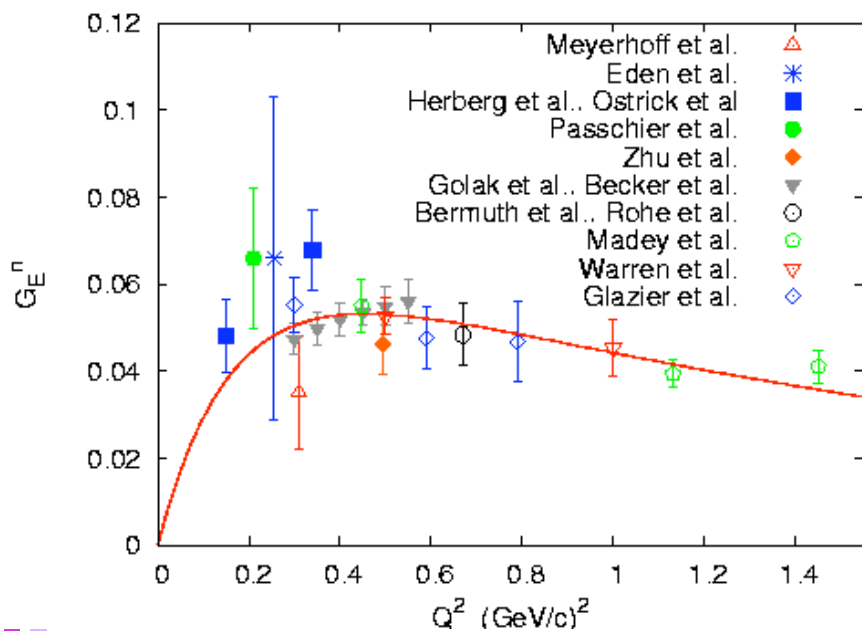
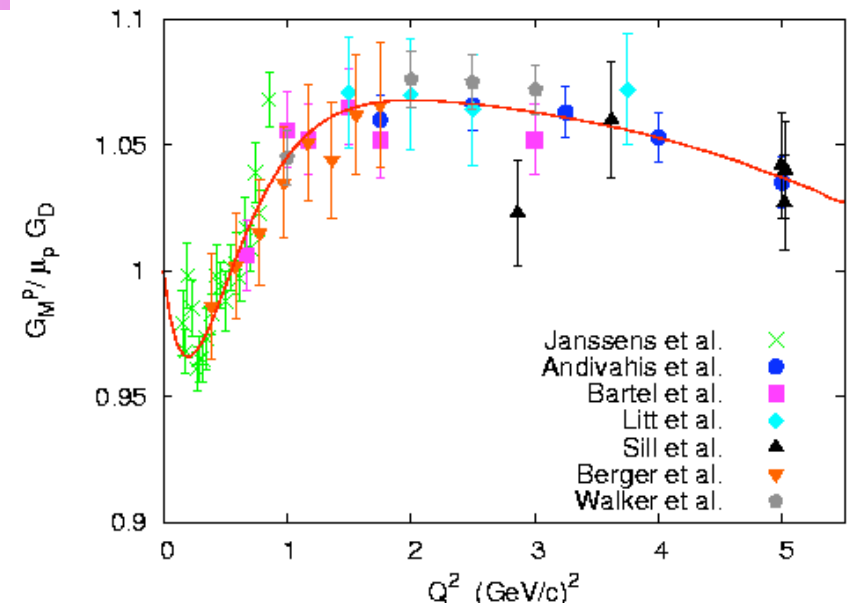
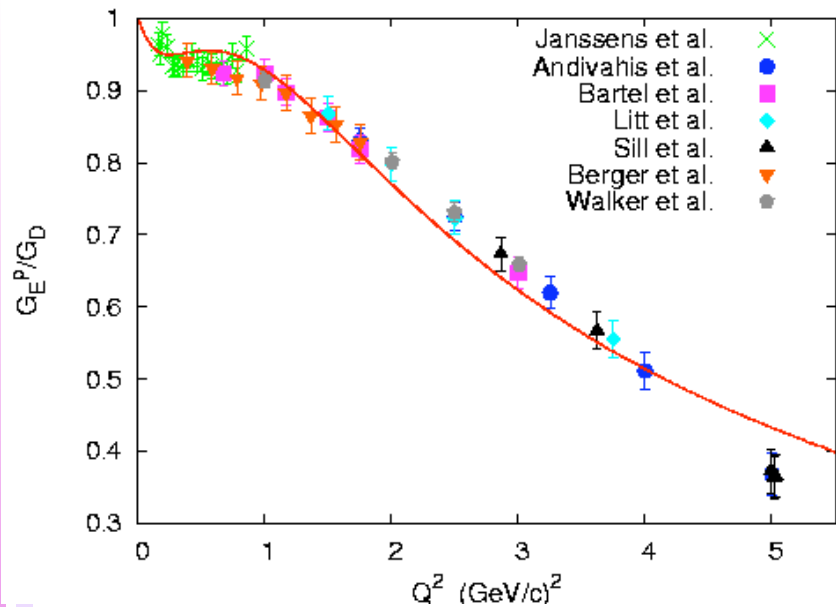




Helicity amplitudes

Systematic study of longitudinal and transverse helicity amplitudes in the ypercentral constituent quark model

E. S. , M. Giannini , Phys.Rev. C86 (2012) 065202



Unquenched QM for baryons

The formalism to study the effects of the sea (Higher Fock components) preserves after renormalization, the good QM magnetic moment results.

The good magnetic moment results of the CQM are preserved by the UQM,
R. Bijker, E.S., PRC88,065210(2009)

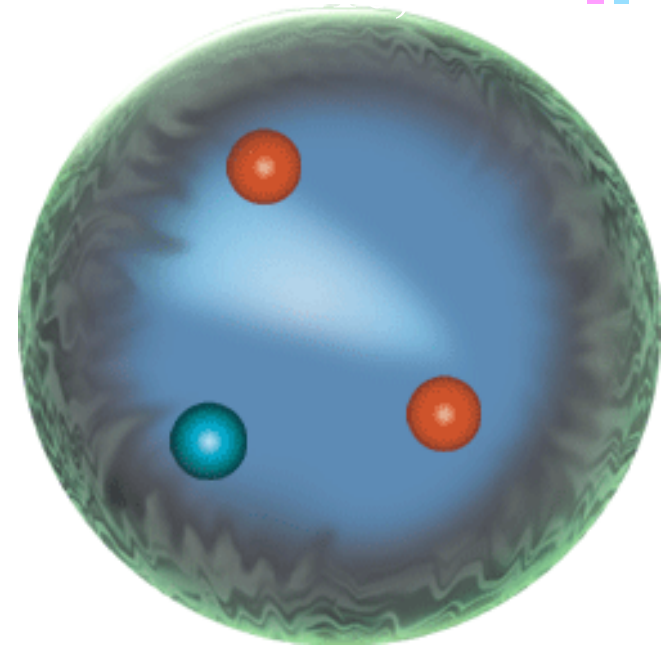
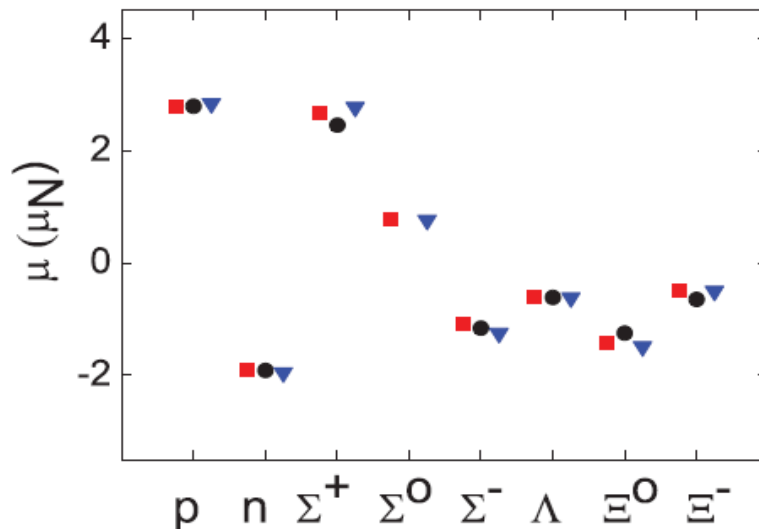


FIG. 3. (Color online) Magnetic moments of octet baryons: experimental values from the Particle Data Group [34] (circles), COM

Unquenched quark model (UQM)

- In the unquenched quark model the effects of q - \bar{q} sea pairs are introduced explicitly into the constituent quark model (QM) through a QCD-inspired $3P0$ pair-creation mechanism.
- To leading order in pair creation, the baryon wave function is given by

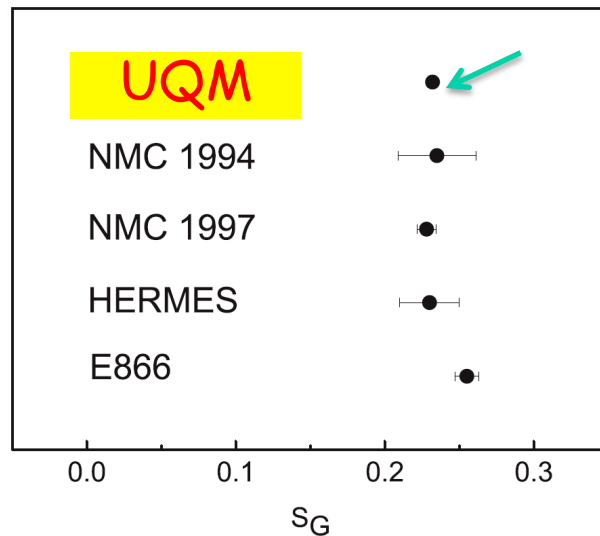
$$|\psi_A\rangle = \mathcal{N} \left[|A\rangle + \sum_{BC\ell J} \int d\vec{q} |BC\vec{q}\ell J\rangle \frac{\langle BC\vec{q}\ell J | T^\dagger | A\rangle}{E_a - E_b - E_c} \right]$$

where T represents the $3P0$ quark-antiquark pair creation operator

Flavor Asymmetry

Gottfried sum rule

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

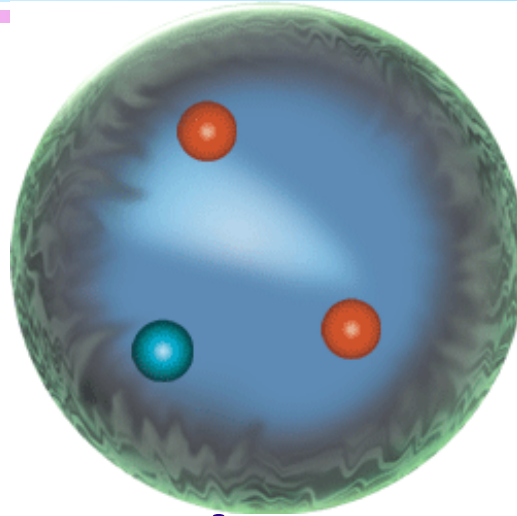


$$S_G \neq \frac{1}{3} \Rightarrow N_{\bar{d}} \neq N_{\bar{u}}$$

$$S_G = 0.2281 \pm 0.0065$$

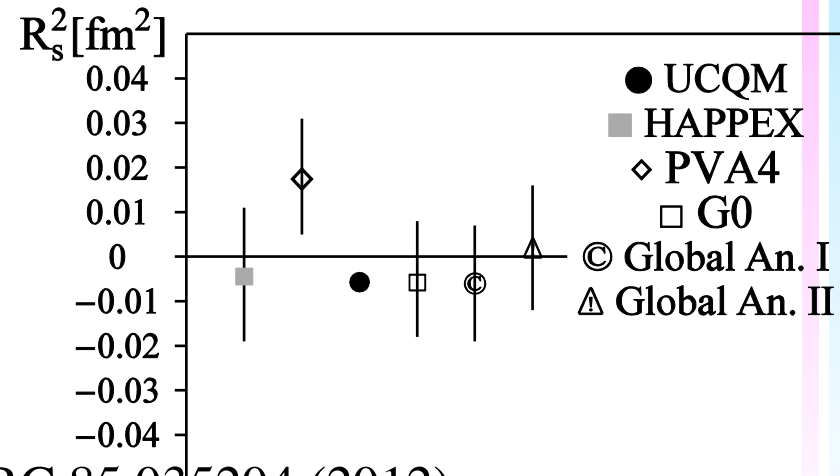
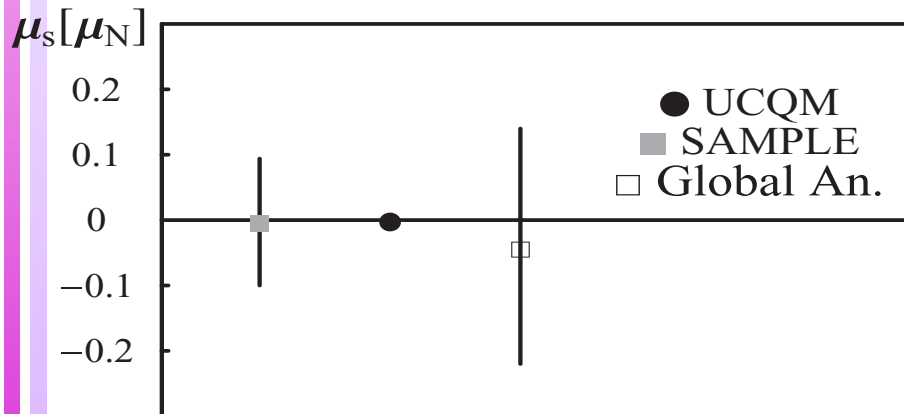
$$\int_0^1 dx [\bar{d}(x) - \bar{u}(x)] = 0.16 \pm 0.01$$

Santopinto, Bijker, PRC 82,062202(R) (2010)



Proton Strange Magnetic Moment and Radius

compatible with zero.



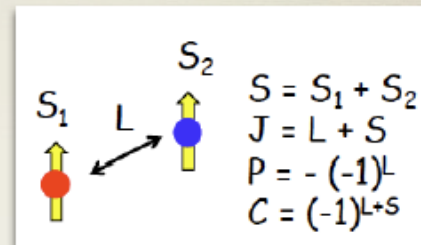
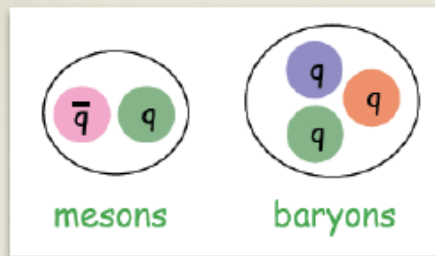
Ferretti, Bijker, Santopinto, PRC 85,035204 (2012)

Meson spectroscopy and hybrids

Quarks in Hadrons

Neutralize color

... the simple way



... or the "exotic" way



(flavor) exotic

exotic of the II kind

$J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-} \dots$

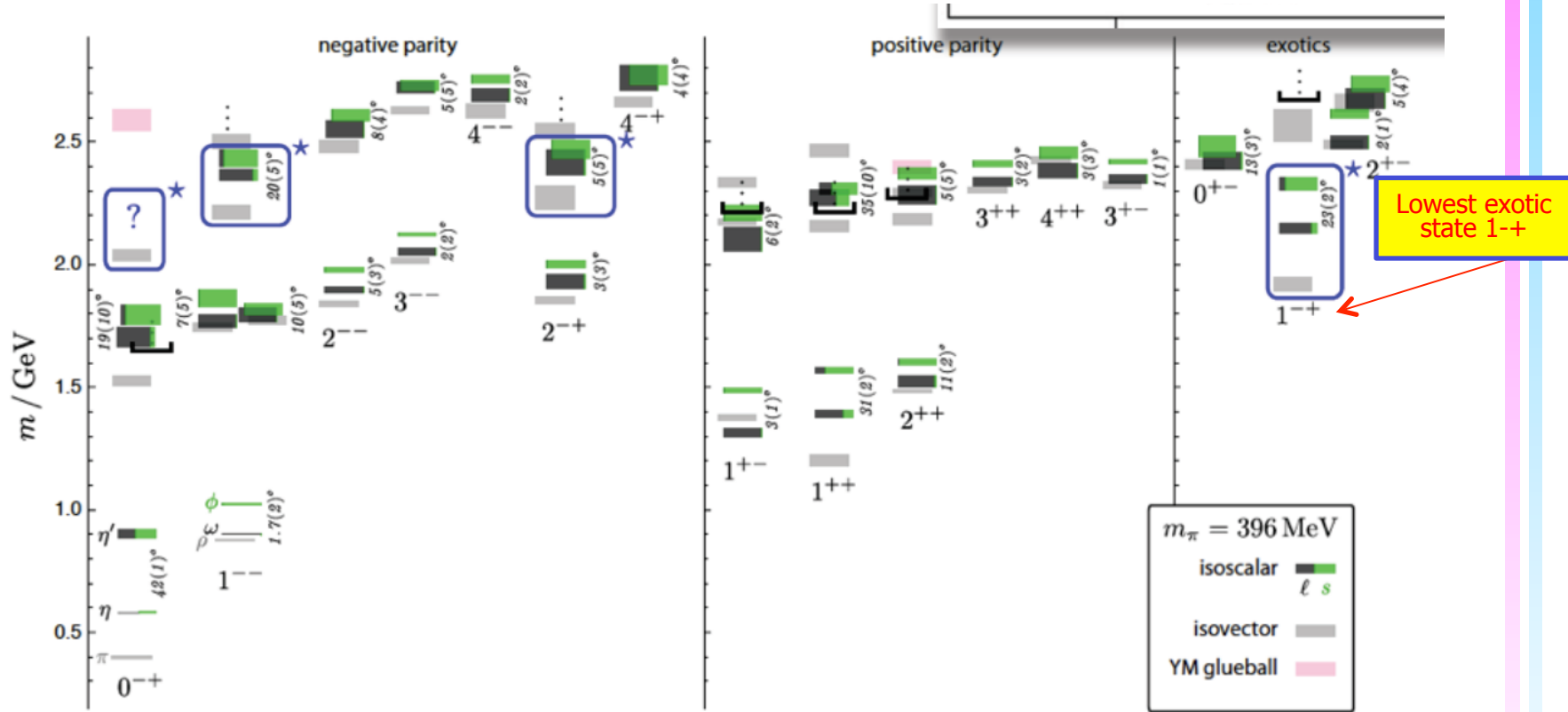
We are interested in exotic of the II kind!!
Mesons with qu. n.
not possible for qqbar only!

light

state of the art full spectrum

J. Dudek et al.

same pattern in charmonium

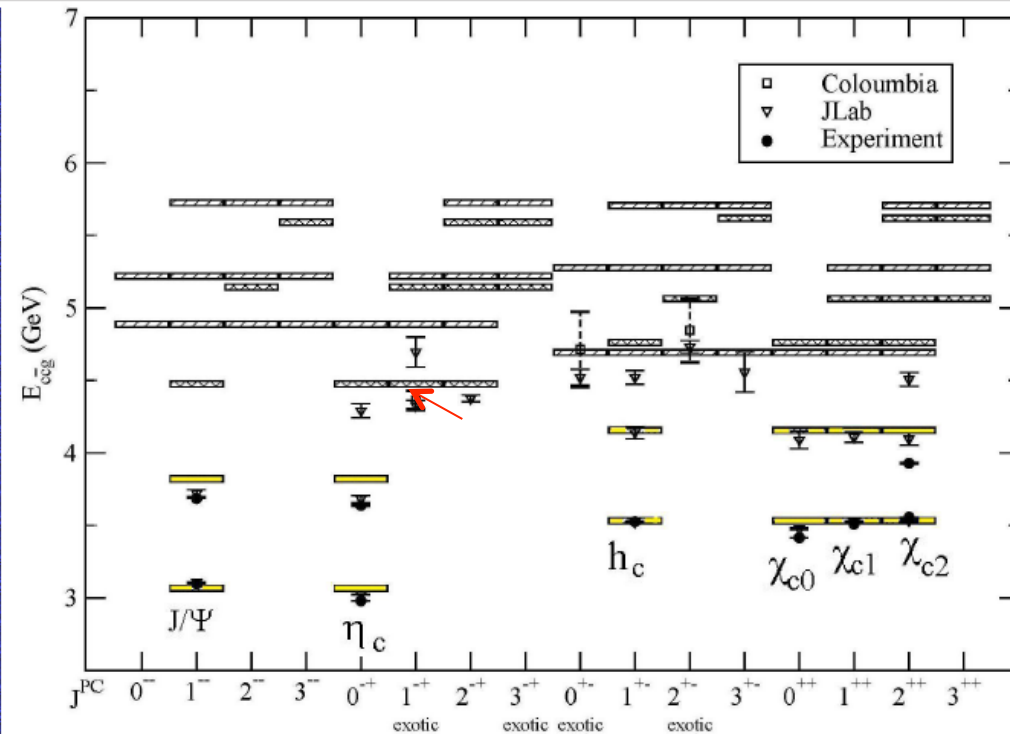


The same sequence was found also by LQCD for heavy quarks : This sequence has been explained by the hamiltonian approach to QCD, P. Guo, A. P. Szczepaniak, G. Galata, A. Vassallo, E. Santopinto, Phys. Rev. D 78, 056003 (2008), Phys.Rev.D77:056005,2008.

Hybrids spectrum

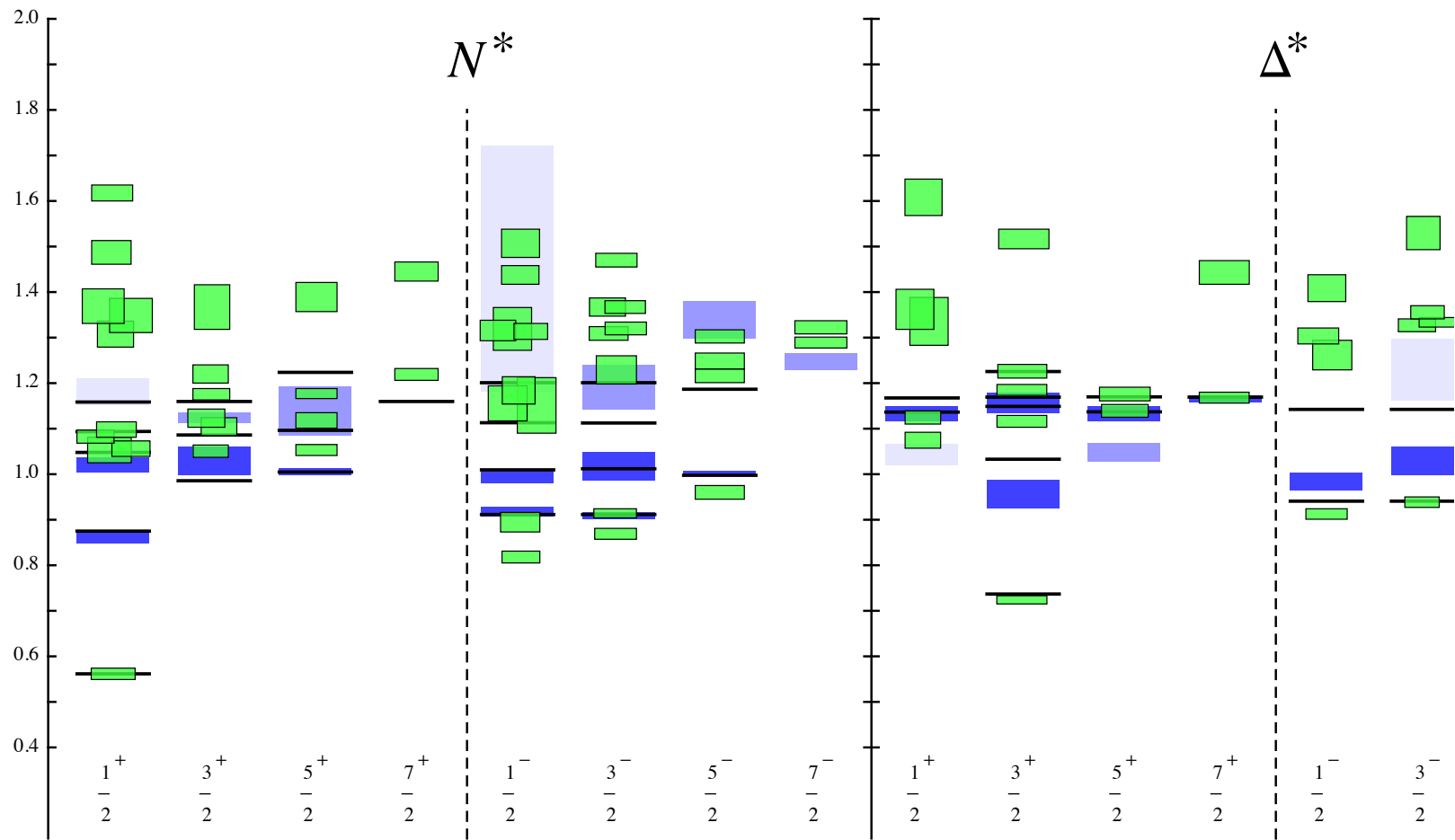
$J_g^{P_g}$	This work [GeV]	J^{PC}	Lattice [14] [GeV]
1^+	4.476	$0^{-+}, 1^{-+}, 2^{-+}, [1^{--}]$	4.291(48), 4.327(36), 4.376(24), [?]
1^-	4.762	$1^{+-}, 2^{++}, [0^{++}, 1^{++}]$	4.521(48), 4.508(48), [?,?]
2^+	5.144	$1^{-+}, [2^{--}, 2^{-+}, 3^{-+}]$	4.696(103), [?,?,?]
2^-	5.065	$2^{+-}, [1^{++}, 2^{++}, 3^{++}]$	4.733(42), [?,?,?]

Spectrum: normal charmoniums (yellow boxes) and charmonium hybrids (dashed boxes) confronted with experimental and lattice data



Conclusions

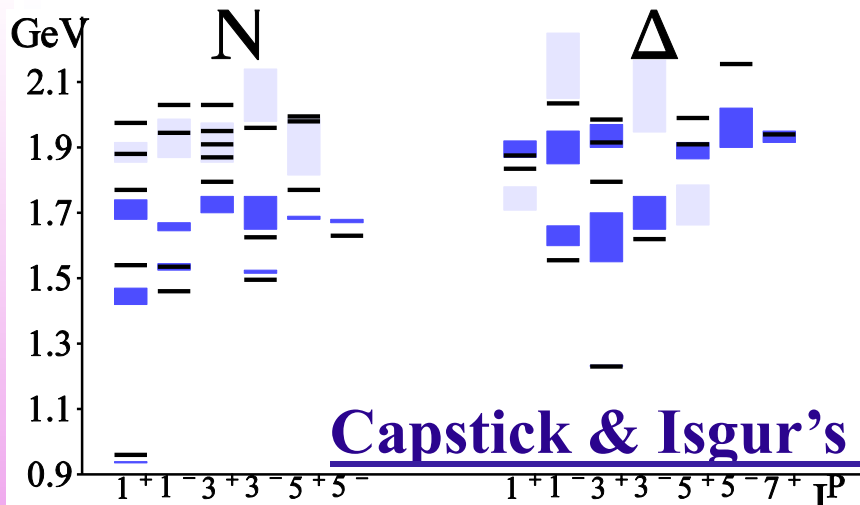
- Our results for the self energies of charmonia show that the pair creation effects on the spectrum of heavy mesons are relatively small. In particular, for charmonium states they are of the order of 2 – 6%
- However, as in the heavy quark sector CQM's can predict the meson masses with a relatively high precision, even these corrections can become significant, such as in the case of the X(3872)
- In fact, we were able to calculate its mass significantly better than with usual CQM



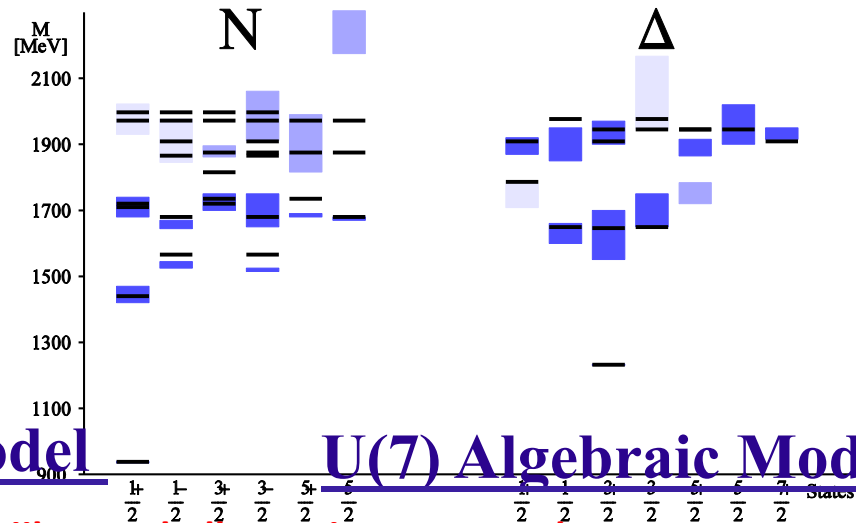
Unquenching the quark model for baryons

R.Bijker, E. S., PRC 80, 065210 (2009),
PRC 82, 062202 (2010); J. Ferrettii, Santopinto, Bijker
Phys. Rev. C 85, 035204 (2012)

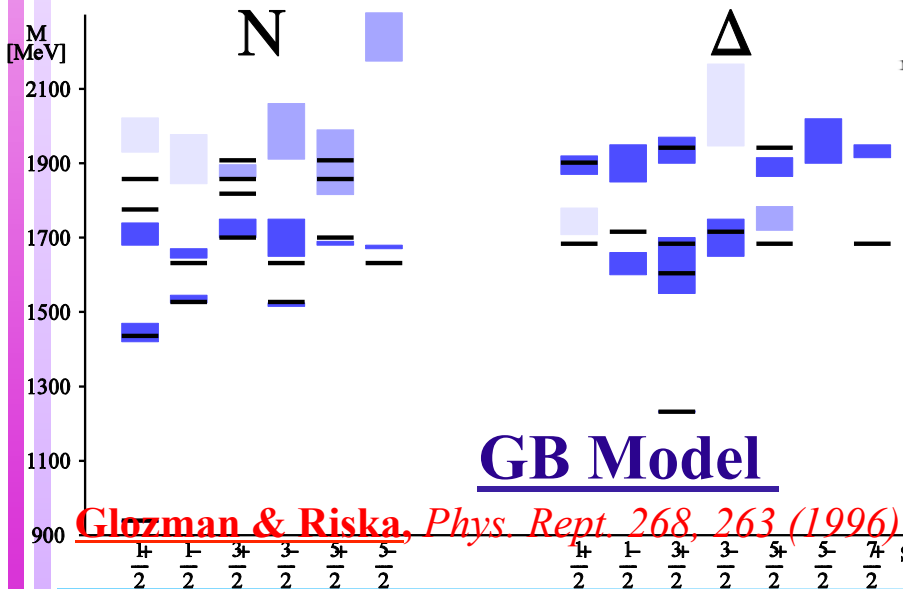
Non strange spectrum



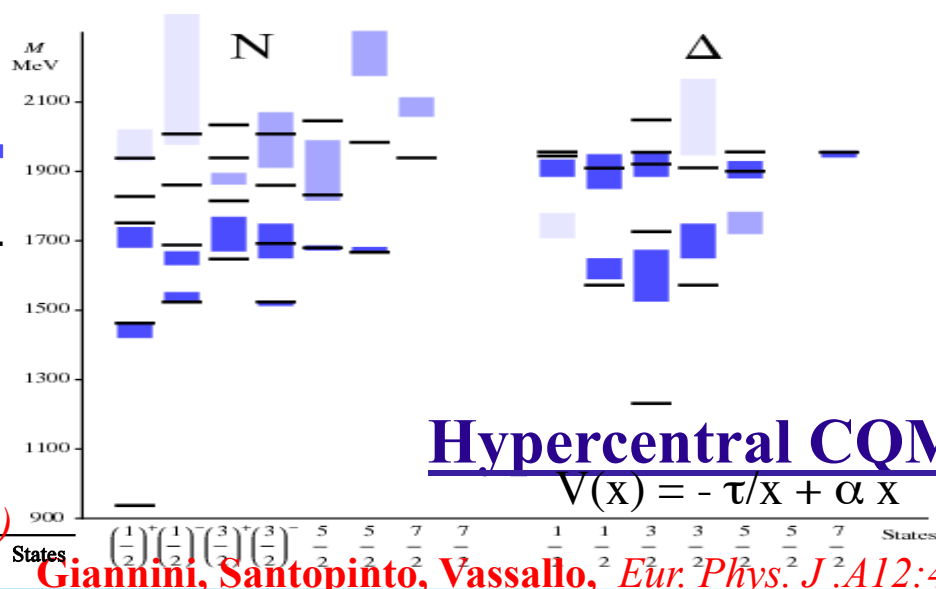
Capstick and Isgur, *Phys. Rev. D* **34**, 2809.



Bijker, Iachello, Leviatan, *Ann. Phys.* **236**, 69 (1994)



Glozman & Riska, *Phys. Rept.* **268**, 263 (1996)



Giannini, Santopinto, Vassallo, *Eur. Phys. J. A* **12**:447

S CQMs:

Good description of the spectrum and magnetic moments

Predictions of many quantities:

strong couplings

photocouplings

helicity amplitudes

elastic form factors

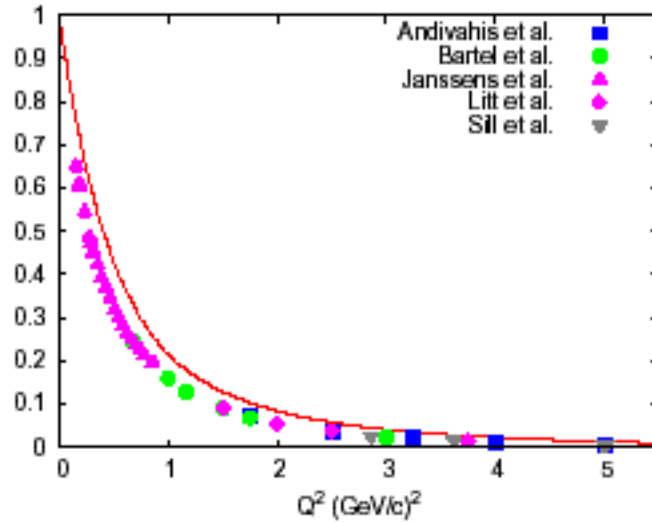
structure functions

Based on the effective degrees of freedom of 3 constituent quarks

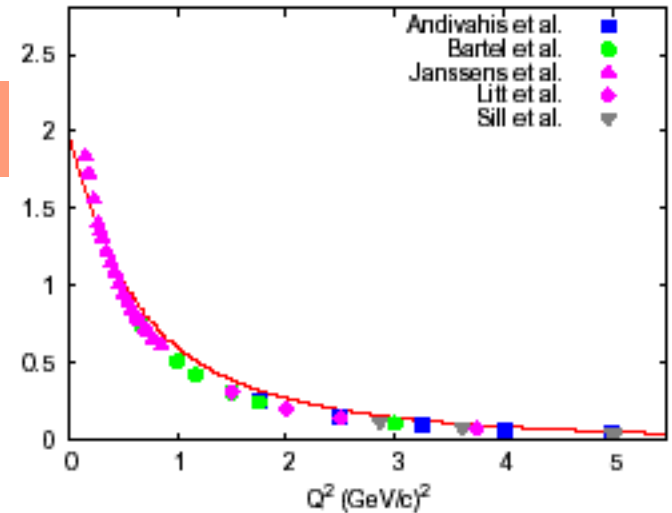
Calculated values!

- Boosts to initial and final states
- Expansion of current to any order
- Conserved current

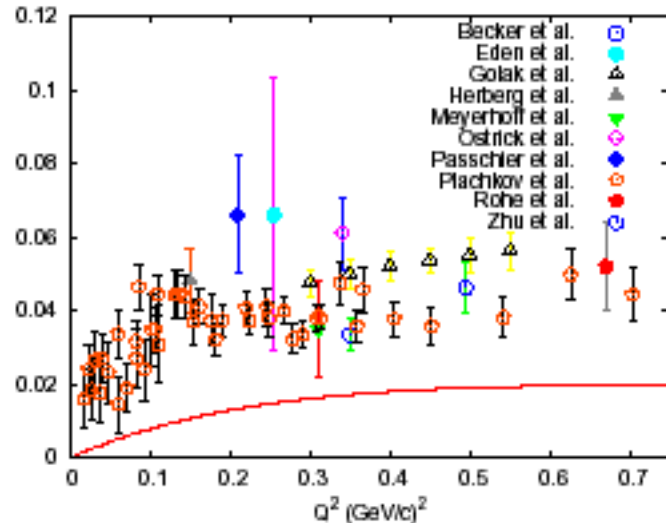
G_E^p



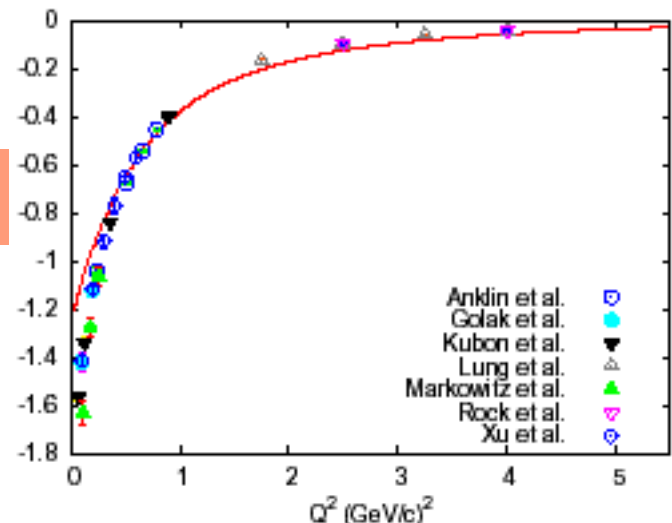
G_M^p



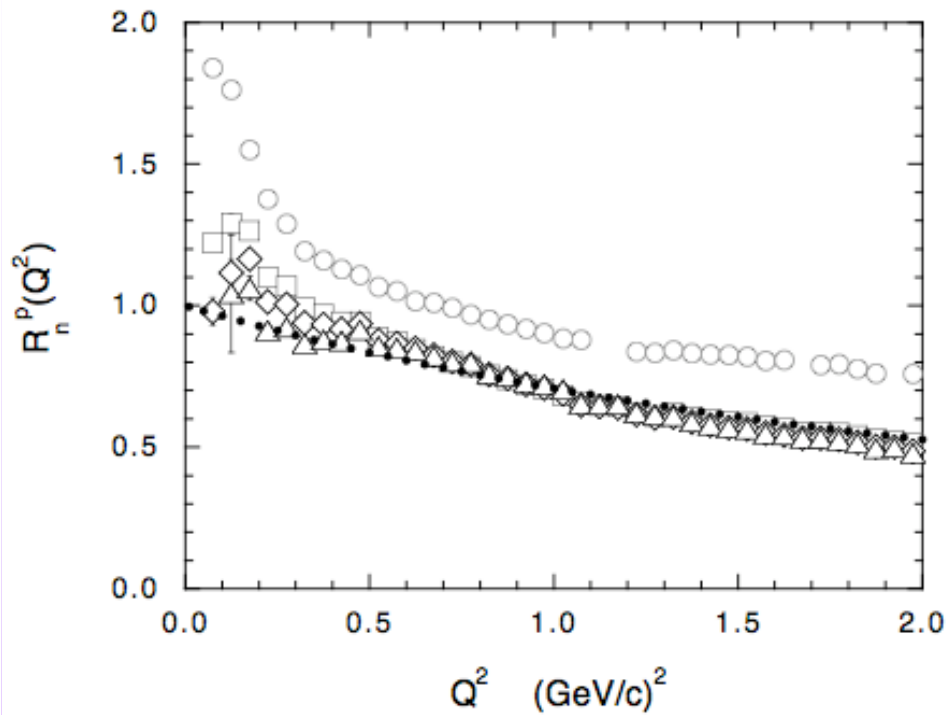
G_E^n



G_M^n



Further support 2



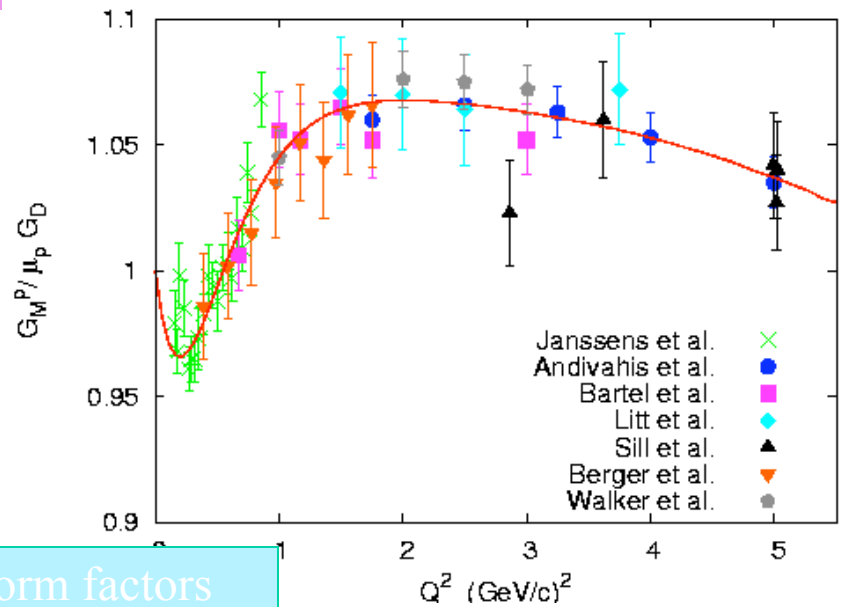
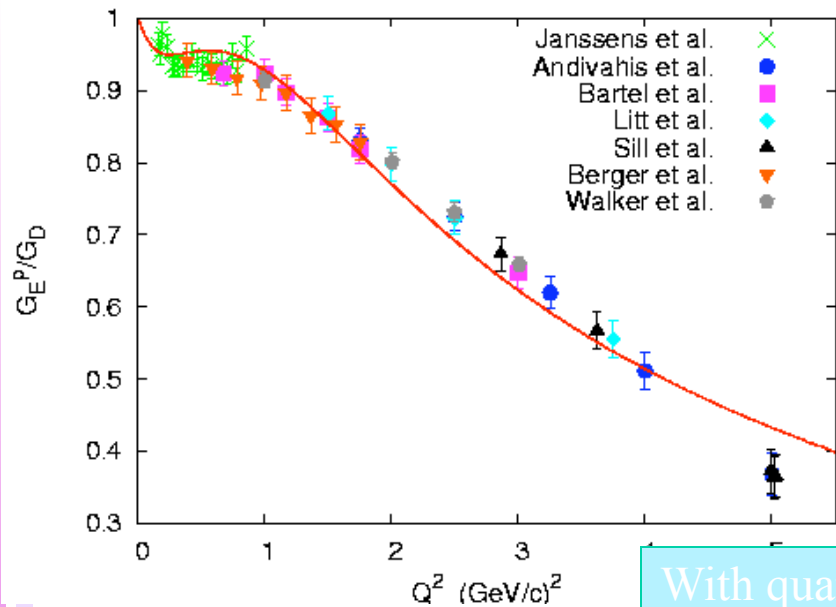
Ratio between
proton Nachtmann moments &
CQ distribution

Inelastic proton scattering as elastic scattering on CQ

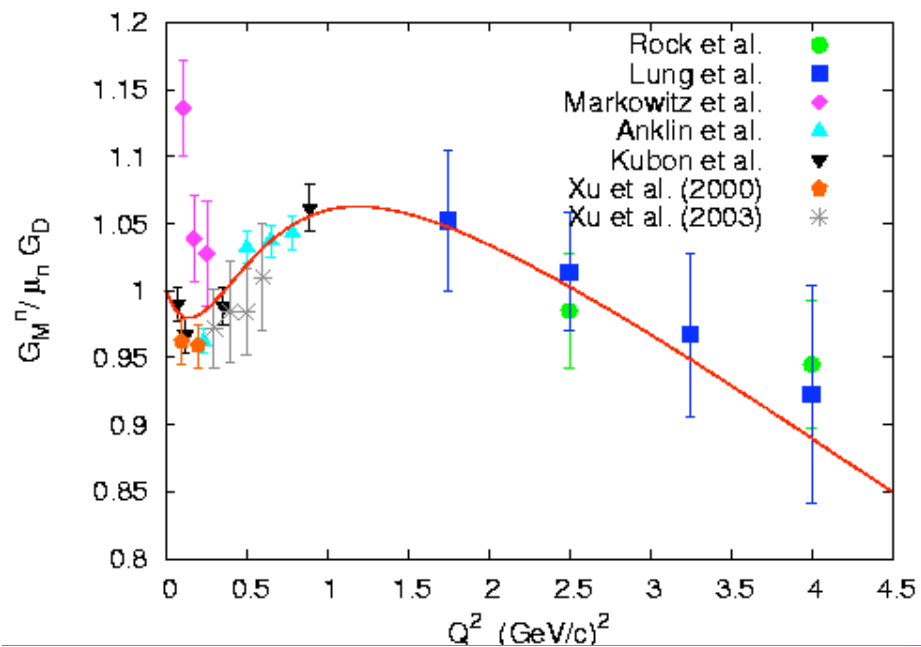
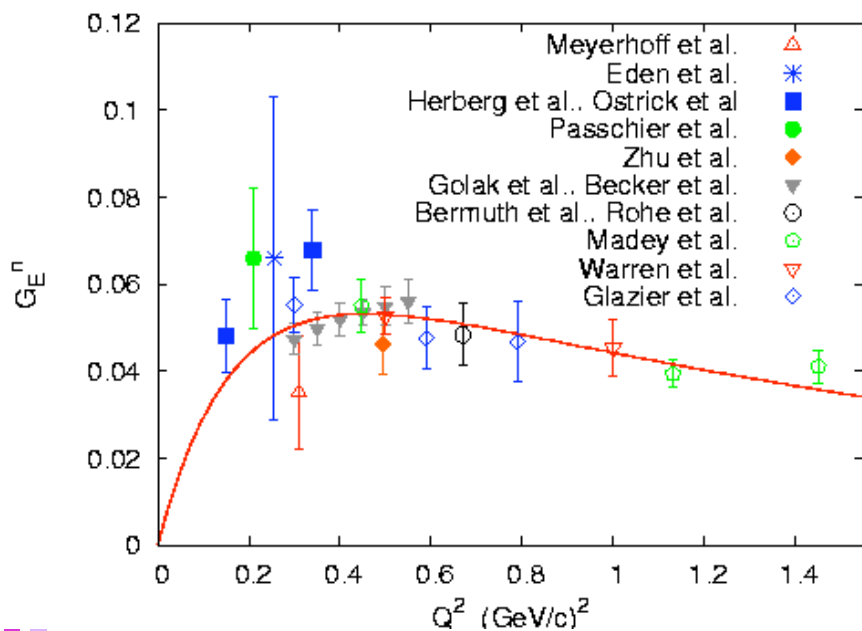
(approximate) scaling function \longrightarrow square of CQ ff

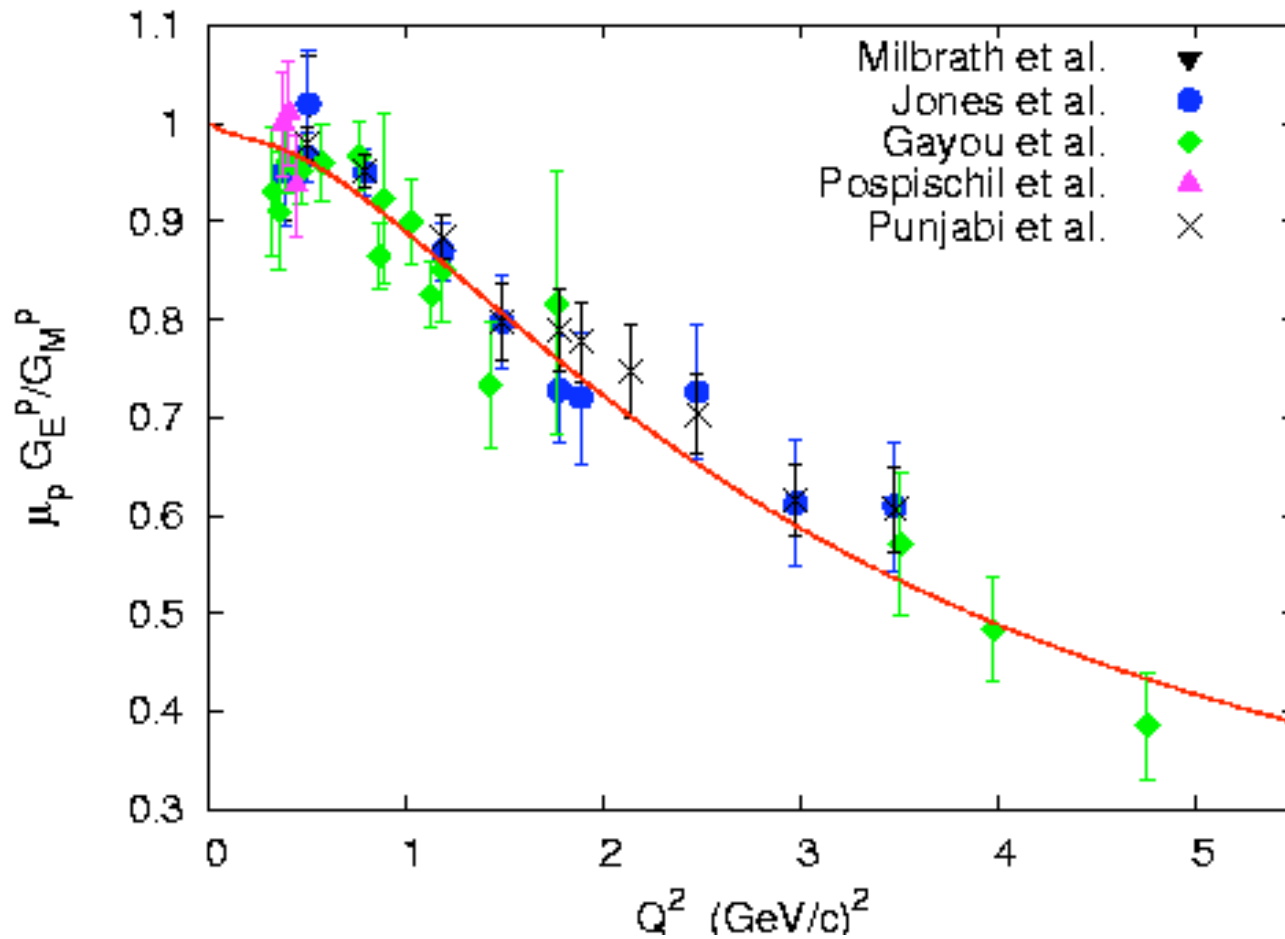
$$F(Q^2) = 1/(1 + 1/6 r_{CQ}^2 Q^2)$$

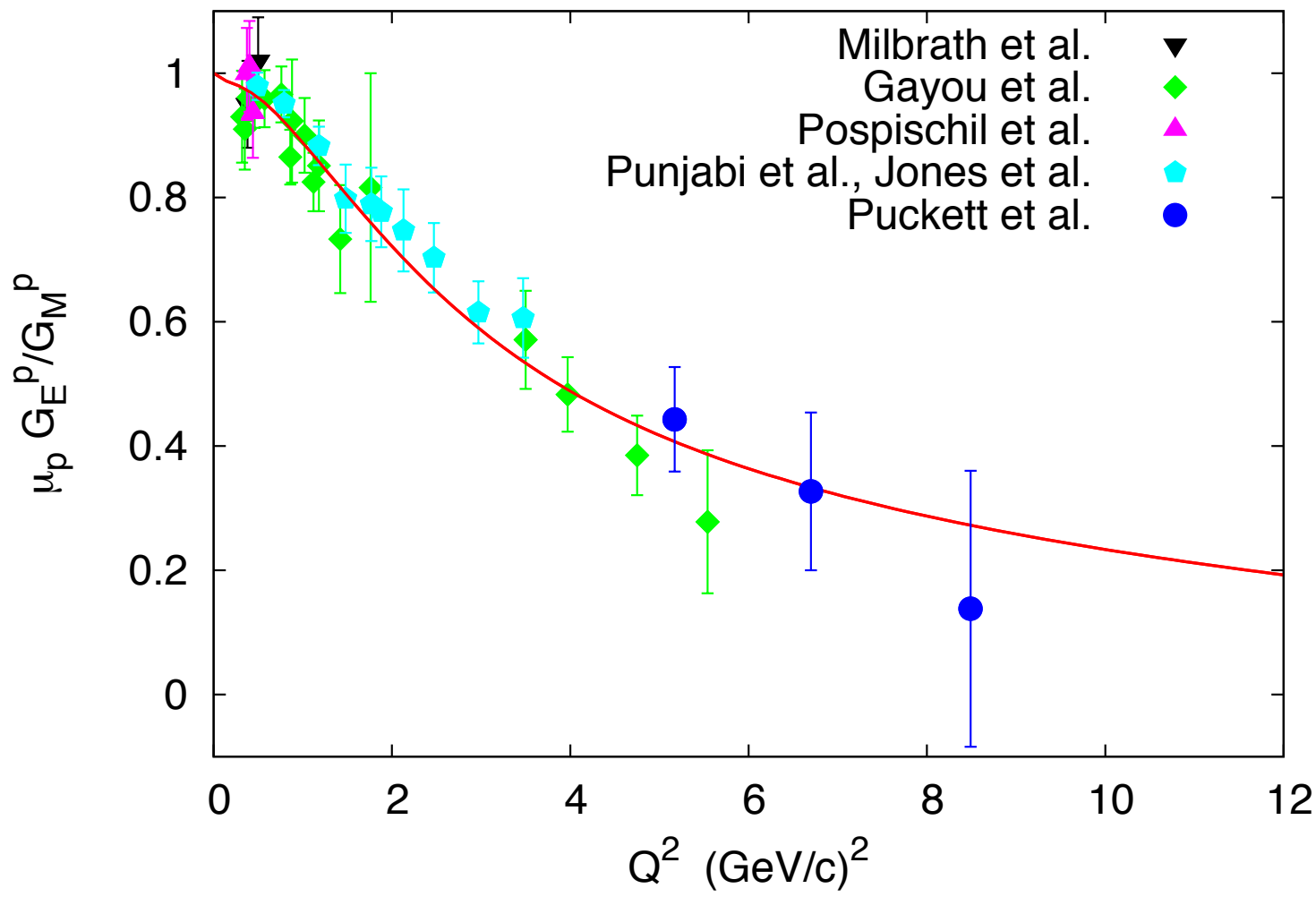
$$r_{CQ} \cong 0.2\text{-}0.4 \text{ fm}$$

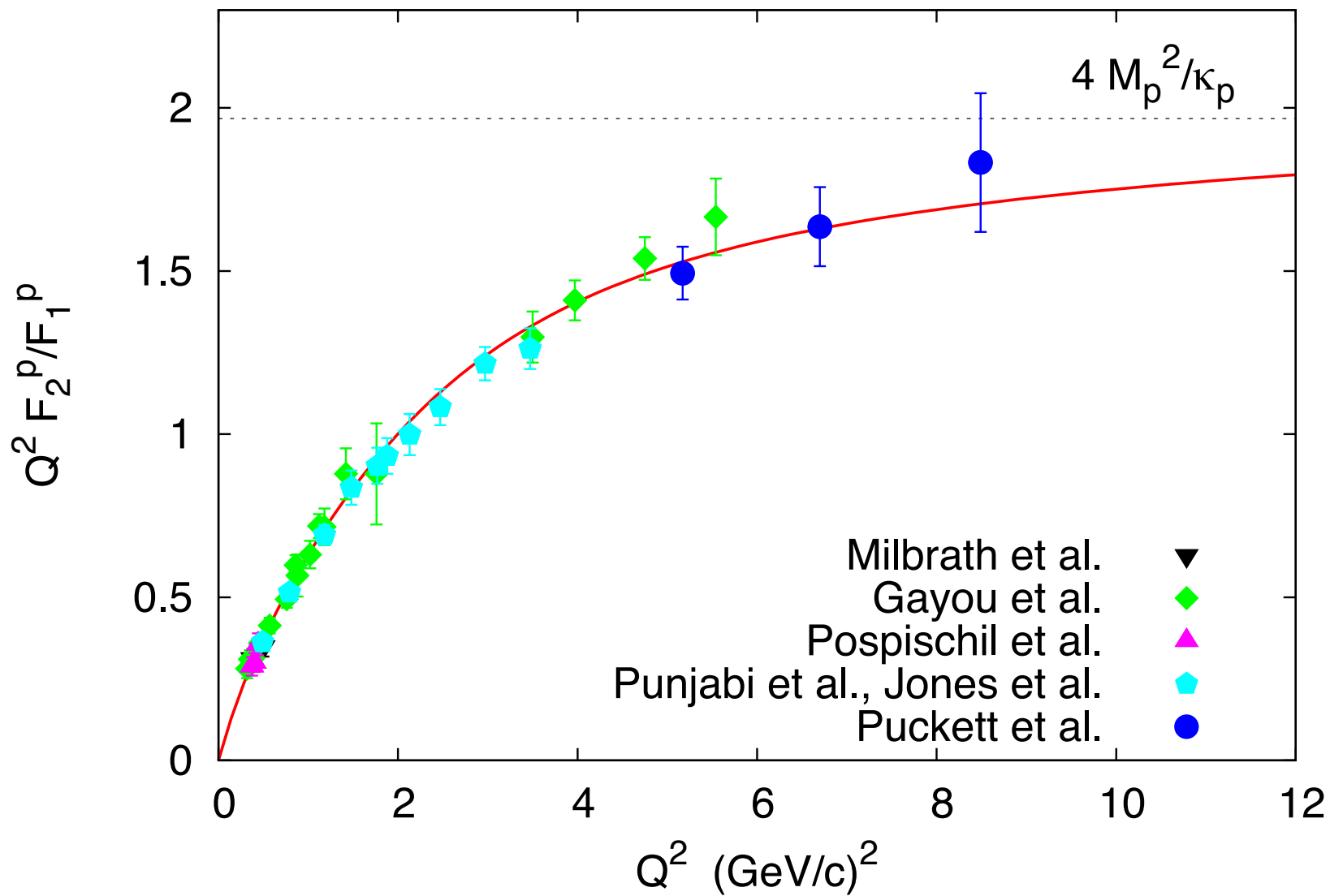


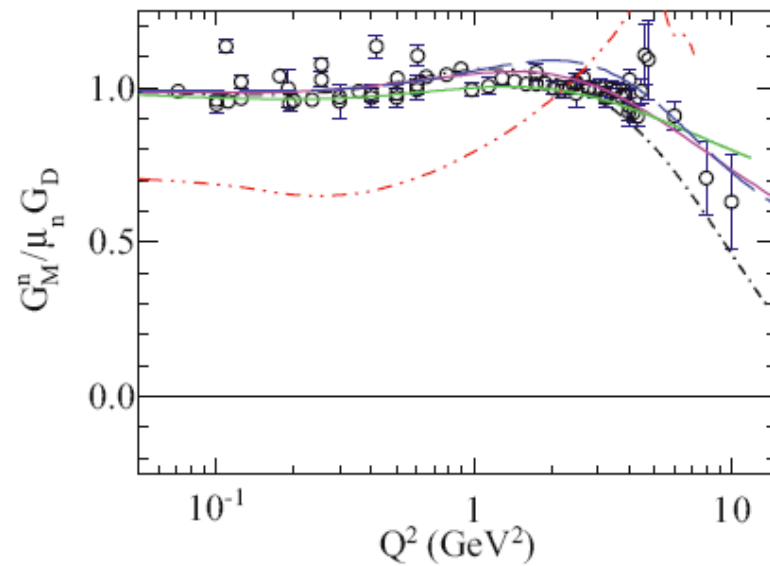
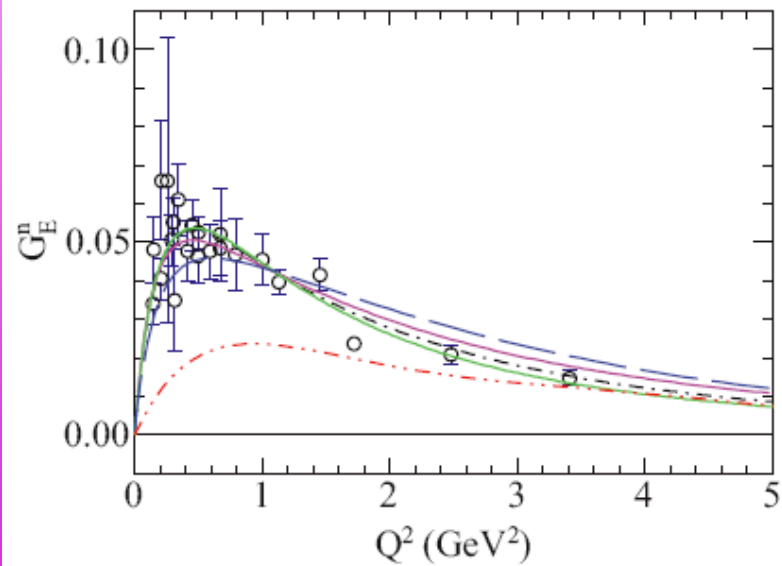
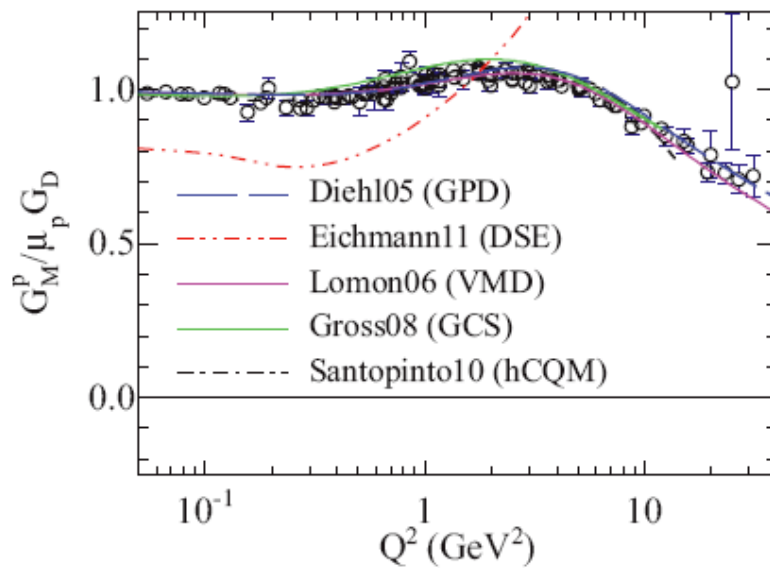
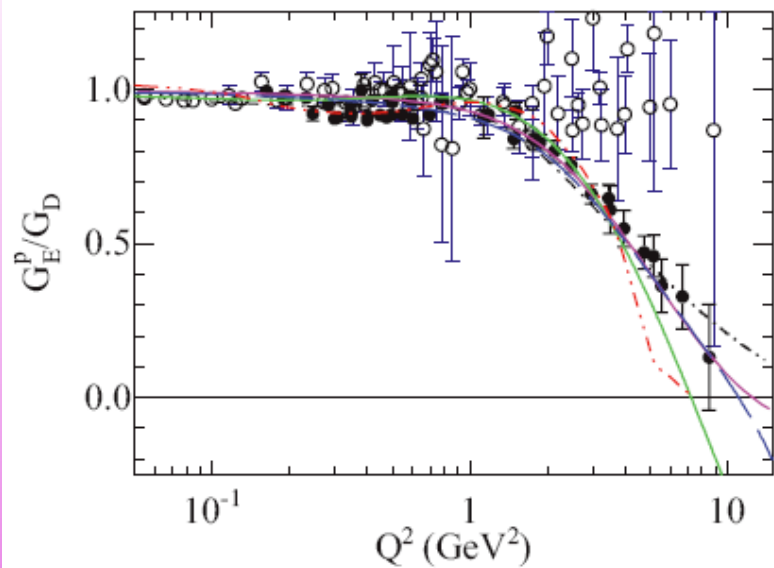
With quark form factors





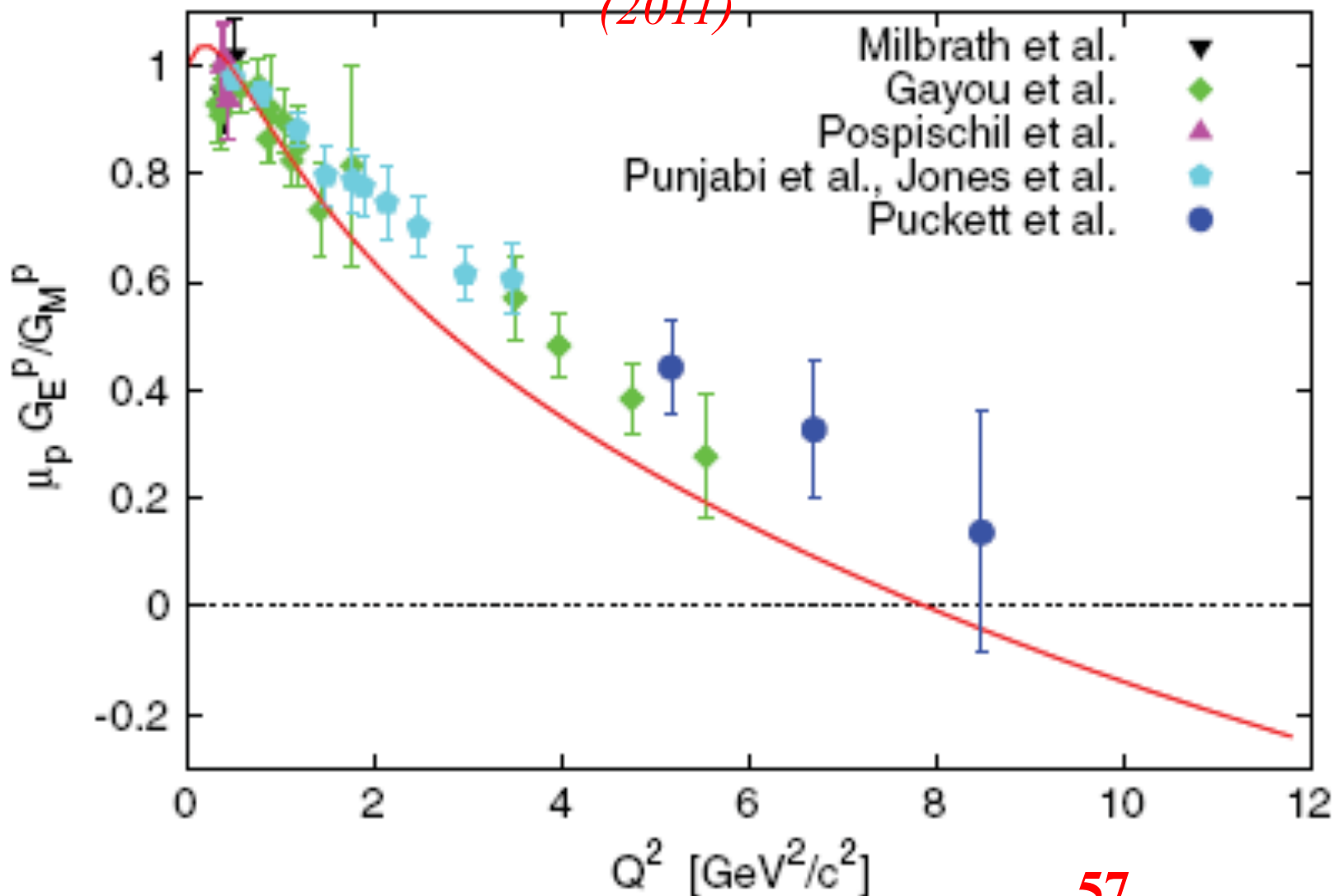




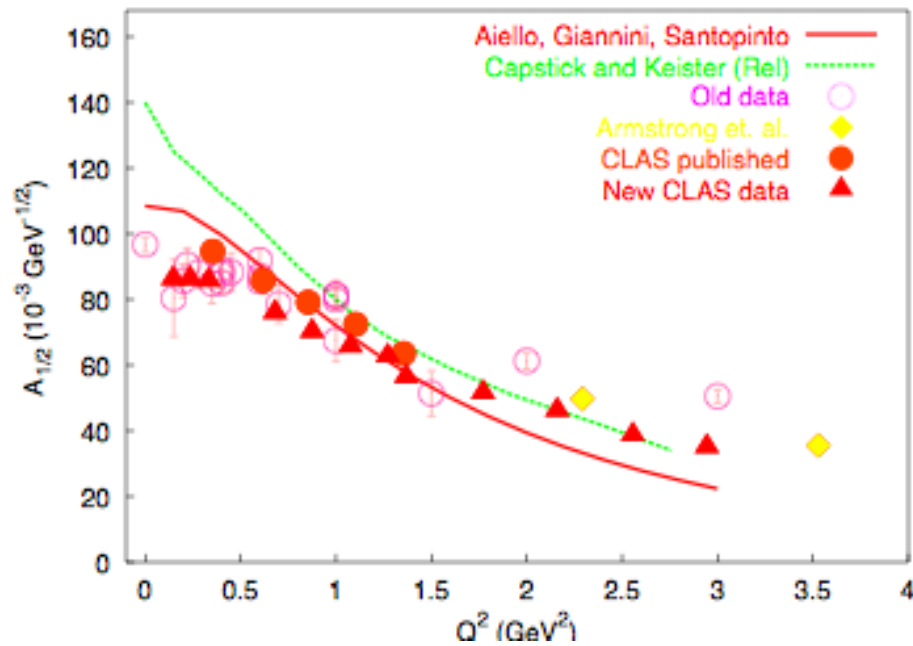


Ratio $\mu_p G_E^p/G_M^p$

De Sanctis, Ferretti, Santopinto, Vassallo, Phys. Rev. C 84, 055201 (2011)



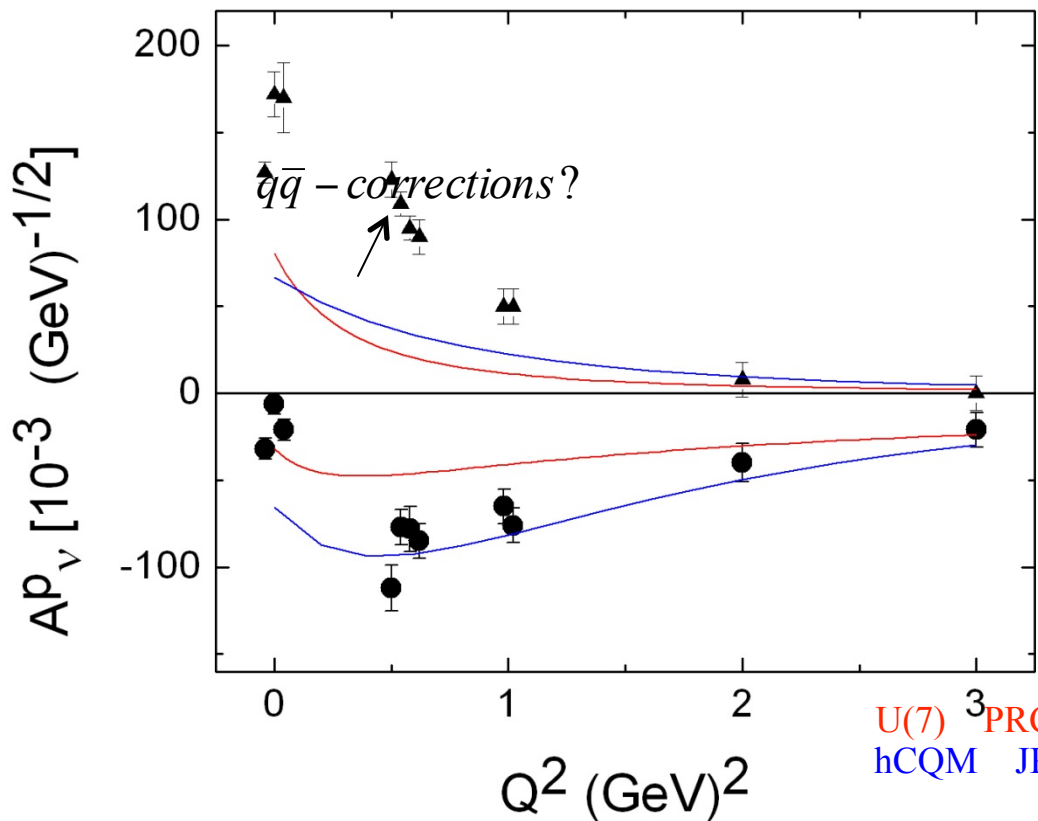
$A_{1/2}$ (helicity amplitude $\frac{1}{2}$) for the S_{11}



hCQM JPG 24, 753 (1998)

Is it a degrees of freedom problem?

$q\bar{q}$ corrections ? important in the outer region



U(7) ³PRC 54, 1935 (1996)
hCQM JPG 24, 753 (1998)

Considering also CQMs for mesons, CQMs able to reproduce the **overall trend of hundred of data**

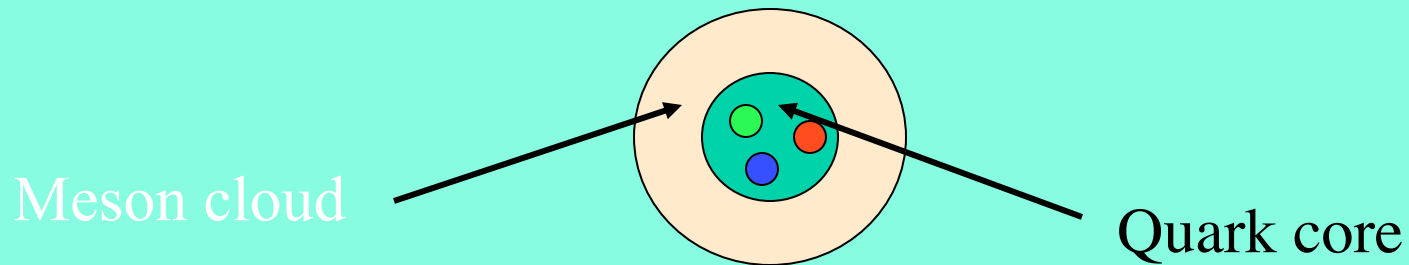
... but they show very similar deviations for observables such as

photocouplings

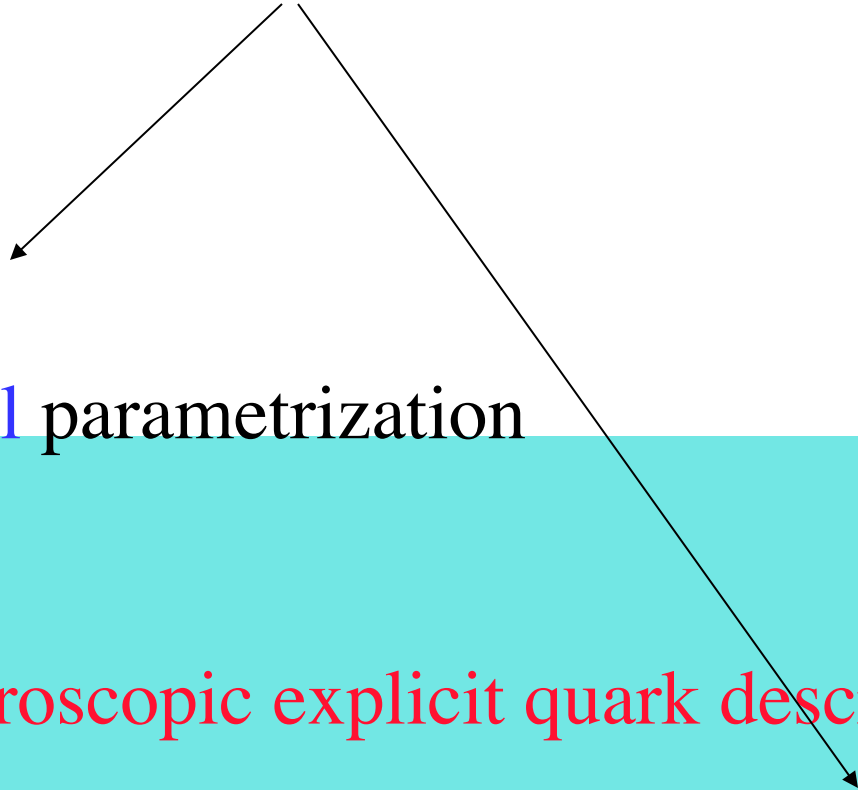
helicity amplitudes,

please note

- the medium Q^2 behaviour is fairly well reproduced
- there is lack of strength at **low** Q^2 (outer region) in the e.m. transitions
- emerging picture:
quark core plus (meson or sea-quark) **cloud**



There are two possibilities:



phenomenological parametrization

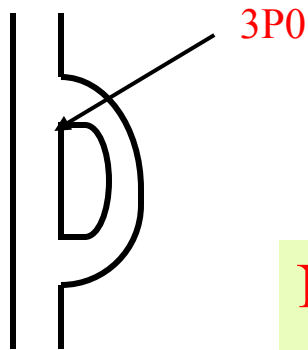
microscopic explicit quark description

Problems

- 1) find a quark pair creation mechanism QCD inspired
- 2) implementation of this mechanism at the quark level
but in such a way to do not destroy the good CQMs results

Unquenching the quark model

Geiger and Isgur



Note:

- sum over a complete set (in flavor) of intermediate states necessary for preserving the OZI rule
- linear interaction is preserved after renormalization of the string constant

The good magnetic moment results of the CQM are preserved by the UCQM

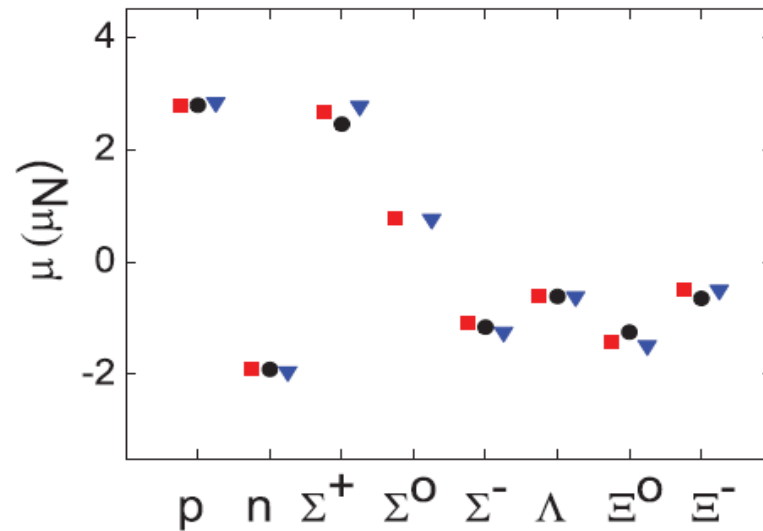
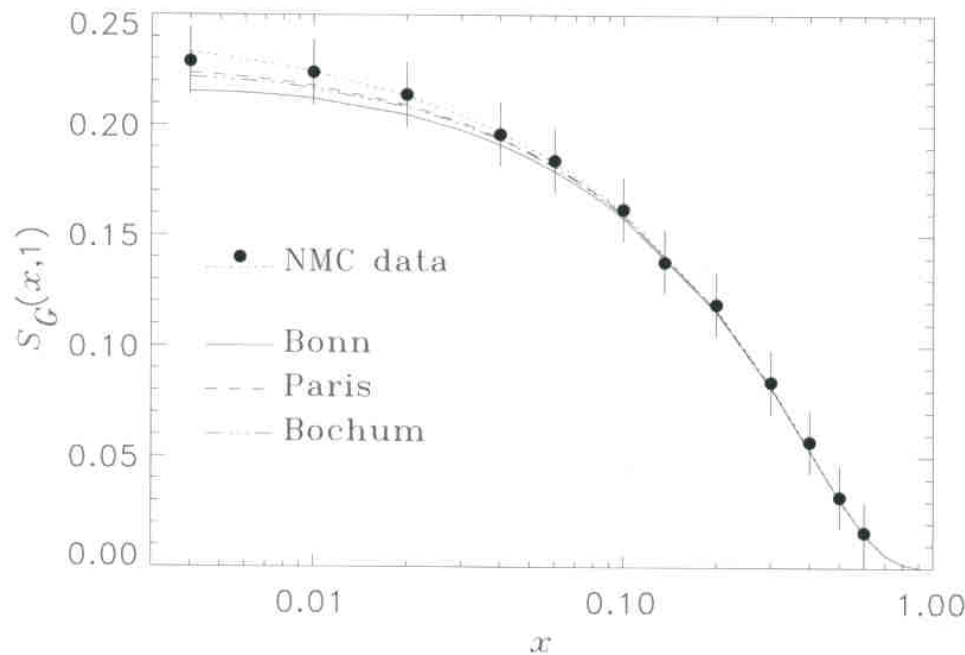


FIG. 3. (Color online) Magnetic moments of octet baryons: experimental values from the Particle Data Group [34] (circles), CQM (squares), and unquenched quark model (triangles).

Flavor Asymmetry

Gottfried sum rule

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



$$S_G \neq \frac{1}{3} \Rightarrow N_{\bar{d}} \neq N_{\bar{u}}$$

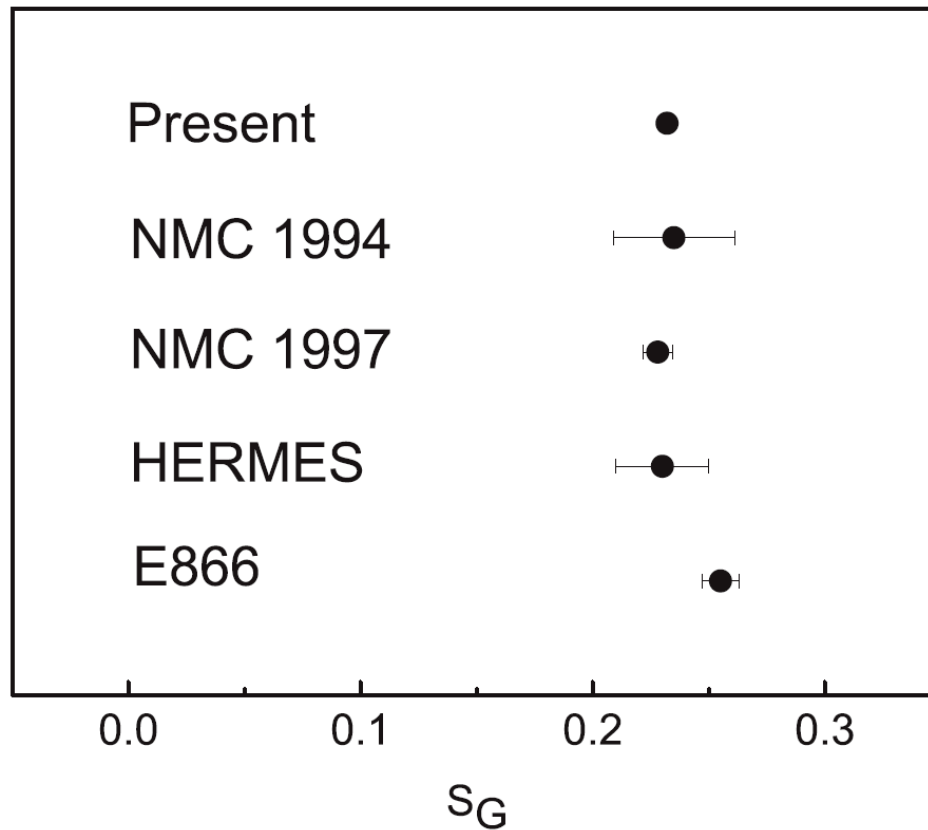
$$S_G = 0.2281 \pm 0.0065$$

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

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

Proton Flavor asymmetry

Santopinto, Bijker, PRC 82,062202(R) (2010)



Flavor asymmetry of the octet baryons in the UCQM

Santopinto, Bijker, PRC 82,062202(R) (2010)

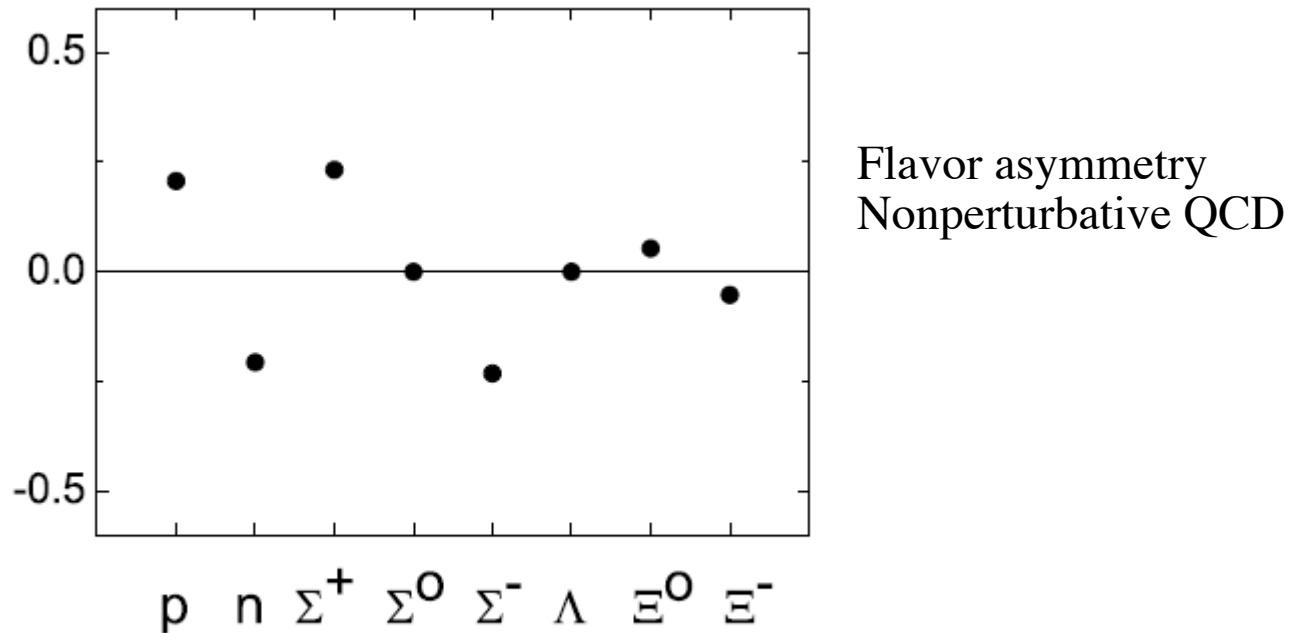


Figure 1. Flavor asymmetry of octet baryons

Pauli blocking (Field & Feynman, 1977) **too small**
Pion dressing of the nucleon (Thomas et al., 1983)
Meson cloud models

Flavor asymmetries of octet baryons

Santopinto, Bijker, PRC 82,062202(R) (2010)

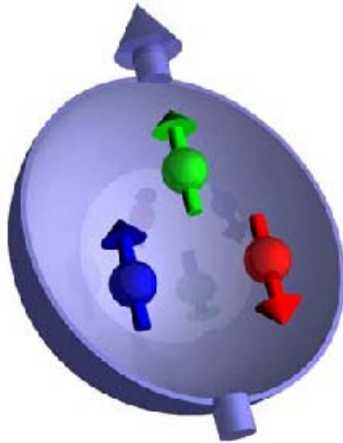
TABLE III. Relative flavor asymmetries of octet baryons.

Model	$\mathcal{A}(\Sigma^+)/\mathcal{A}(p)$	$\mathcal{A}(\Xi^0)/\mathcal{A}(p)$	Ref.
Unquenched CQM	0.833	-0.005	present
Chiral QM	2	1	Eichen
Balance model	3.083	2.075	Y.-J Zhang
Octet couplings	0.353	-0.647	Alberg

$$\Sigma^\pm p \rightarrow \ell^+ \ell^- + X \text{ (e.g., at CERN).}$$

3. Proton Spin Crisis

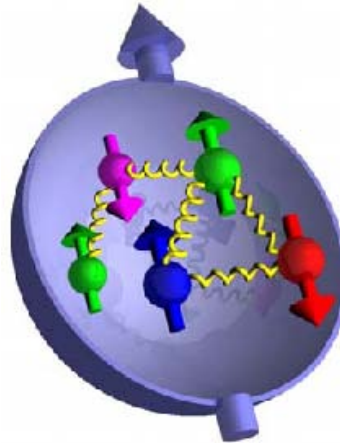
1980's



Naive parton model
3 valence quarks

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

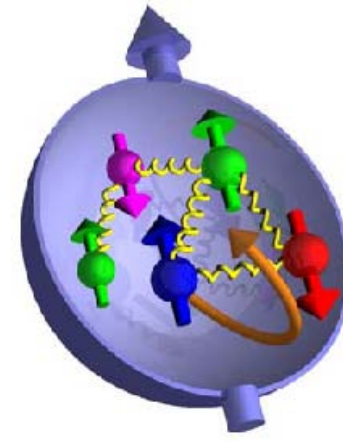
1990's



QCD: contributions from
sea quarks and gluons

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

2000's



.. and orbital angular
momentum

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

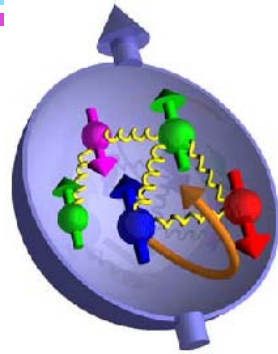
HERMES, PRD 75, 012007 (2007)
COMPASS, PLB 647, 8 (2007)

Proton Spin

COMPASS@CERN: Gluon contribution is small (sign undetermined)

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	0.378	0.298	0.676
	$2\Delta L$	0	0.000	0.324	0.324
	$2\Delta J$	1	0.378	0.622	1.000

More than half of the proton spin from the sea!

Orbital angular momentum

Suggested by Myhrer & Thomas, 2008, but not explicitly calculated

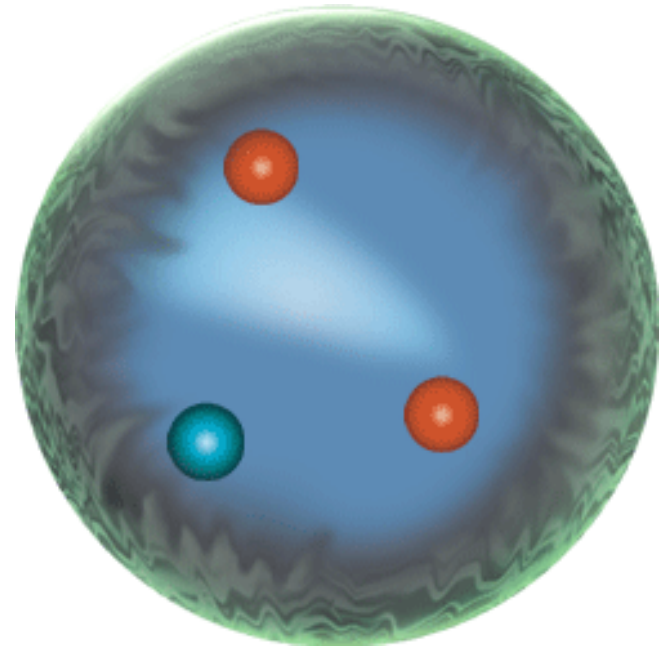
4. Strangeness in the Proton

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 experiments: SAMPLE, HAPPEX, PVA4 and G0 Collaborations



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

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

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

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

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

Kaplan & Manohar, NPB 310, 527 (1988)

Musolf et al, Phys. Rep. 239, 1 (1994)

Static Properties

$$G_E(0) = e$$

Electric charge

$$G_M(0) = \mu$$

Magnetic moment

$$\langle r^2 \rangle_E = -6 \left. \frac{dG_E}{dQ^2} \right|_{Q^2=0}$$

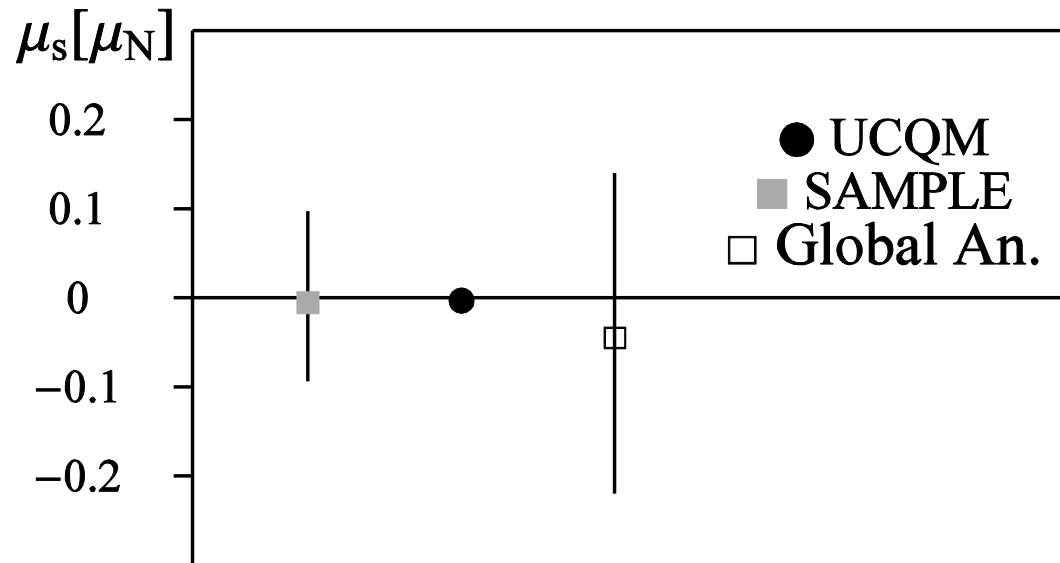
Charge radius

$$\langle r^2 \rangle_M = -\frac{6}{\mu} \left. \frac{dG_M}{dQ^2} \right|_{Q^2=0}$$

Magnetic radius

Strange Magnetic Moment

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

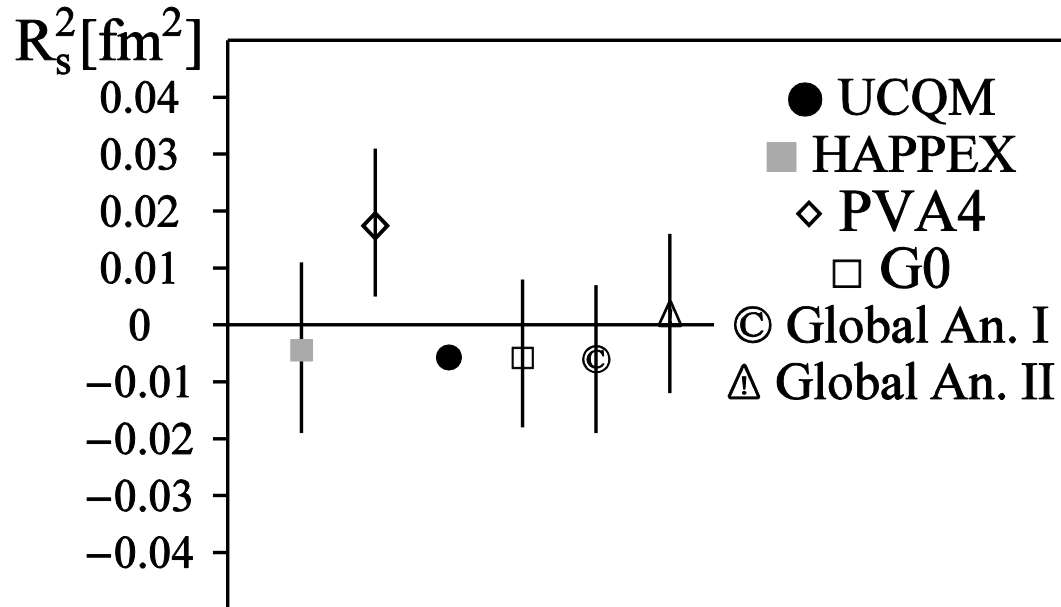


Jacopo Ferretti, Ph.D. Thesis, 2011

Bijker, Ferretti, Santopinto, Phys. Rev. C **85**, 035204 (2012)

Strange Radius

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

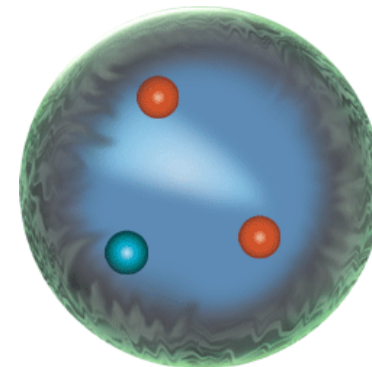


Jacopo Ferretti, Ph.D. Thesis, 2011

Bijker, Ferretti, Santopinto, Phys. Rev. C **85**, 035204 (2012)

Strange Proton

Strange radius and magnetic moment of the proton



Theory

Lattice QCD

Global analysis PVES

Unquenched QM

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

