Eta bound states in nuclei: a probe of flavour-singlet dynamics

Steven Bass, Innsbruck

Looking for evidence of gluonic degrees of freedom in low energy QCD:
Confinement and dynamical (chiral) symmetry breaking

$$SU_L(3) \times SU_R(3) \times U_A(1)$$

Expect nonet of pseudoscalar Goldstone bosons

Pions and Kaons fit in this picture

The masses of the eta and eta´ are 300-400 MeV too big !

→ Famous axial U(1) problem of QCD

Additional mass is associated with non-perturbative gluon dynamics

Look for possible evidence of singlet dof in eta-nucleon bound states

→ Mixing doubles the eta-N scattering length and eta binding energies

Cracow, June 16 2010

Chiral symmetry

- QCD Lagrangian with massless quarks exhibits chiral symmetry

$$\mathcal{L}_{QCD} = \sum_q \bar{q}_L \left(i\hat{D} - g\hat{A} \right) q_L + \bar{q}_R \left(i\hat{D} - g\hat{A} \right) q_R - \sum_q m_q \left(\bar{q}_L q_R + \bar{q}_R q_L \right) - \frac{1}{2} G_{\mu\nu} G^{\mu\nu}$$

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \mapsto e^{i\frac{1}{2}\vec{\alpha}.\vec{\tau}\gamma_5} \begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad , \quad \begin{pmatrix} u_R \\ d_R \end{pmatrix} \mapsto e^{i\frac{1}{2}\vec{\beta}.\vec{\tau}\gamma_5} \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

- Noether currents

$$J^{(3)}_{\mu 5} = \left[\bar{u}\gamma_\mu\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d \right] \qquad \partial^\mu J^{(3)}_{\mu 5} = 2m_u \bar{u} i\gamma_5 u - 2m_d \bar{d} i\gamma_5 d$$

- No parity doublets in hadron spectrum → Spontaneous Chiral symmetry breaking: non zero condensate $\langle \ \mathrm{vac} \mid \bar{q}q \mid \mathrm{vac} \ \rangle < 0$ spontaneously breaks the symmetry

  → Nonet of near massless Goldstone bosons with $J^P = 0^-$

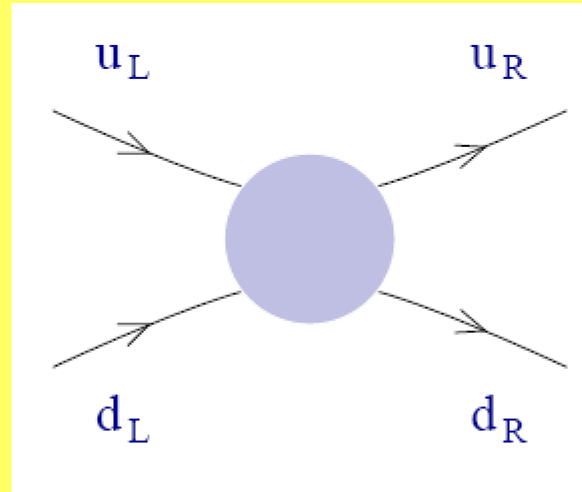
- Identify with pion, kaon, eta with meson mass squared proportional to m_q

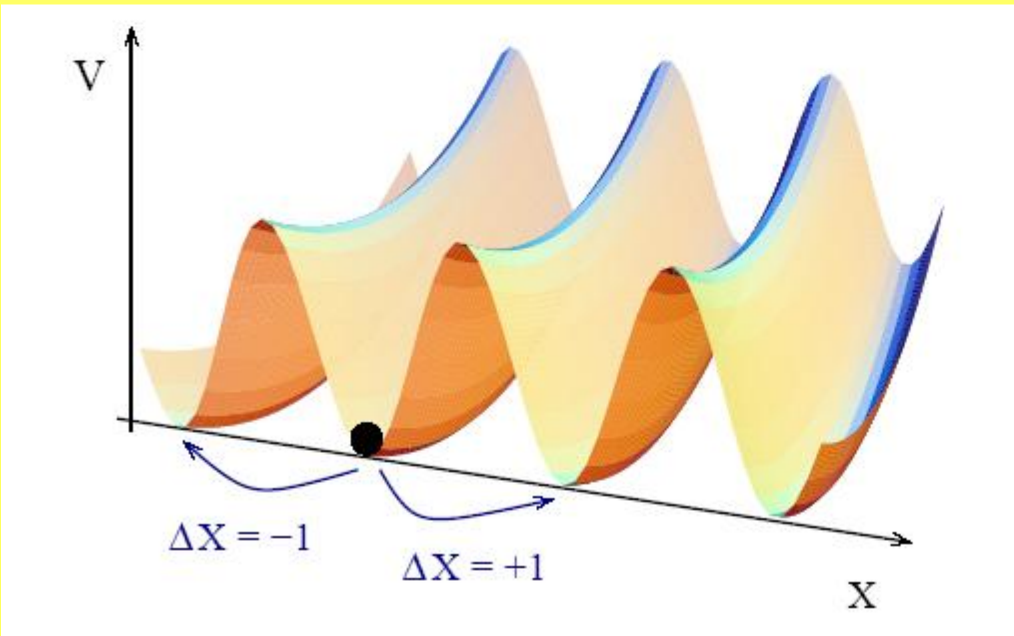
$$m^2_{\eta_8} = \frac{4}{3} m^2_K - \frac{1}{3} m^2_\pi$$

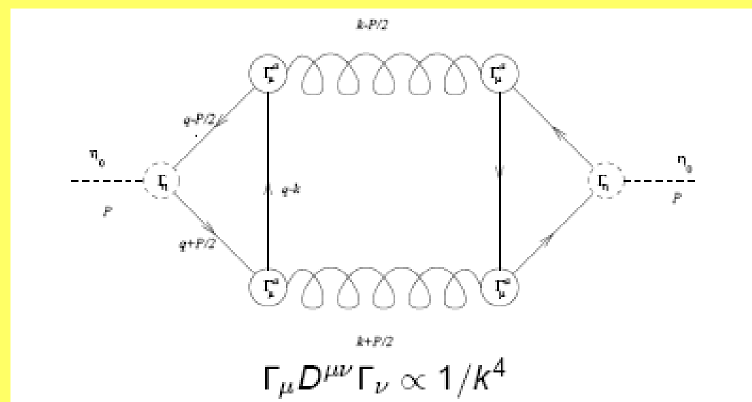
… where is the singlet boson ?

Chirality and anomalous glue

- Perturbative QCD conserves chirality for massless quarks
- Confinement and vacuum tunneling processes (instantons, …) connect left and right handed quarks







Eta and Etaprime masses with mixing

- Mass matrix

$$M^2_{\eta-\eta'} = \begin{pmatrix} \frac{4}{3}m^2_K - \frac{1}{3}m^2_\pi & -\frac{2}{3}\sqrt{2}(m^2_K - m^2_\pi) \\ -\frac{2}{3}\sqrt{2}(m^2_K - m^2_\pi) & [\frac{2}{3}m^2_K + \frac{1}{3}m^2_\pi + \tilde{m}^2_{\eta_0}] \end{pmatrix}$$

- Diagonalize

$$\begin{aligned} |\eta\rangle &= \cos\theta\ |\eta_8\rangle - \sin\theta\ |\eta_0\rangle \\ |\eta'\rangle &= \sin\theta\ |\eta_8\rangle + \cos\theta\ |\eta_0\rangle \end{aligned}$$

- Eigenvalues

$$m^2_{\eta',\eta} = (m^2_K + \tilde{m}^2_{\eta_0}/2) \pm \frac{1}{2}\sqrt{(2m^2_K - 2m^2_\pi - \frac{1}{3}\tilde{m}^2_{\eta_0})^2 + \frac{8}{9}\tilde{m}^4_{\eta_0}}.$$

$$m^2_\eta + m^2_{\eta'} = 2m^2_K + \tilde{m}^2_{\eta_0}.$$

- With no glue:
  chiral symmetry „predicts“ eigenstates with masses 300 MeV „too small“
  - » „eta“ $(\frac{1}{\sqrt{2}}|\bar{u}u + \bar{d}d\rangle)$ degenerate with the pion
  - » „etaprime“ $|\bar{s}s\rangle$ with mass $\sqrt{2m^2_K - m^2_\pi}$

Axial U(1) symmetry

- Extra gluonic mass term is associated with the QCD axial anomaly

$$J_{\mu 5} = \left[\bar{u}\gamma_\mu\gamma_5 u + \bar{d}\gamma_\mu\gamma_5 d + \bar{s}\gamma_\mu\gamma_5 s\right]$$

$$\partial^\mu J_{\mu 5} = \sum_{k=1}^{f} 2i\left[m_k \bar{q}_k \gamma_5 q_k\right] + N_f\left[\frac{\alpha_s}{4\pi} G_{\mu\nu}\tilde{G}^{\mu\nu}\right]$$

- plus gluon topology (note the difference with „perturbative glue")
- ´t Hooft, Veneziano, Witten, Crewther, …
  - possible connection to confinement (Kogut and Susskind)

Can we observe physical manifestation of this anomalous glue in low-energy physical processes involving eta and eta´ mesons ?
→ For review see SDB, Acta Phys Pol B Suppl 2 (2009) 11.

Eta bound states in nuclei

[SDB + AW Thomas, Phys Lett B634 (2006) 368]

- New experiments + big effort ...
- Binding energies and effective masses in nuclei are sensitive to
  - Coupling to scalar sigma field in the nuclei in mean field approximation
  - Nucleon-nucleon and nucleon-hole excitations in the medium
- TH: Solve for the meson self-energy in the medium

$$k^2 - m^2 = \mathrm{Re}\ \Pi(E, \vec{k}, \rho)$$

$$\Pi(E, \vec{k}, \rho)\Big|_{\{\vec{k}=0\}} = -4\pi\rho\left(\frac{b}{1 + b\langle\frac{1}{r}\rangle}\right).$$

$$b = a\left(1 + \frac{m}{M}\right)$$

  - Where a is the „eta-nucleon scattering length“

Eta bound-states in nuclei

- Sigma mean field couples to light quarks and not to strange quarks

  → Flavour-singlet component is important !

  The bigger the eta-eta´ mixing angle, the bigger the singlet component in the eta

  → greater the attraction

  → more binding

  → bigger eta-N scattering length

QCD arguments

→ gluonic mass term is suppressed in the medium

but TH technology to calculate the size of the effect direct from QCD still some time away

→ look at QCD inspired models

U(1) extended chiral Lagrangian

- Low energy effective Lagrangian

$$\mathcal{L}_{\rm m} = \frac{F_\pi^2}{4}{\rm Tr}(\partial^\mu U \partial_\mu U^\dagger) + \frac{F_\pi^2}{4}{\rm Tr}\left[\chi_0 \left(U + U^\dagger\right)\right] + \frac{1}{2} iQ{\rm Tr}\left[\log U - \log U^\dagger\right] + \frac{3}{\tilde{m}_{\eta_0}^2 F_0^2} Q^2.$$

$$U = \exp\left(i\frac{\phi}{F_\pi} + i\sqrt{\frac{2}{3}}\frac{\eta_0}{F_0}\right)$$

- Q represents the topological charge density.

  The gluonic potential

$$\frac{1}{2} iQ{\rm Tr}\left[\log U - \log U^\dagger\right] + \frac{3}{\tilde{m}_{\eta_0}^2 F_0^2} Q^2 \mapsto -\frac{1}{2}\tilde{m}_{\eta_0}^2 \eta_0^2$$

  yields the gluonic contribution to the etaprime mass term

- Couple to sigma mean field and repeat …

$$\mathcal{L}_\sigma = \frac{F_\pi^2}{4}{\rm Tr}M \left(U + U^\dagger\right) g_\sigma^M \sigma + Q^2 \, g_\sigma^Q \sigma$$

$$\tilde{m}_{\eta_0}^2 \mapsto \tilde{m}_{\eta_0}^{*2} = \tilde{m}_{\eta_0}^2 \frac{1+2x}{(1+x)^2} < \tilde{m}_{\eta_0}^2$$

where

$$x = \frac{1}{3} g_\sigma^Q \sigma \, \tilde{m}_{\eta_0}^2 F_0^2.$$

QCD Inspired Models

- Phenomenological fits to EP data
  - » On-shell Re[a_eta] ~ 0.9 fm [Green + Wycech, Arndt et al]
  - » COSY-11 ~ 0.7 fm from FSI in pp → pp eta
- Chiral coupled channels treating the eta as a pure octet state
  - » Small mass shift and small Re[a_eta] ~ 0.2 fm
- Quark Meson Coupling Model:
  - Can vary the mixing angle !
  - Use large eta and eta´ masses to treat the eta and eta´ as MIT Bags embedded in the medium with coupling between the light-quarks and the sigma mean field

  Solve for in-medium mass and binding energy

  → Extract an „effective“ scattering length for the model

  → Increases with increasing singlet component in the eta !

	m (MeV)	m^* (MeV)	Re a (fm)
η_8	547.75	500.0	0.43
$\eta\,(-10^o)$	547.75	474.7	0.64
$\eta\,(-20^o)$	547.75	449.3	0.85
η_0	958	878.6	0.99
$\eta'\,(-10^o)$	958	899.2	0.74
$\eta'\,(-20^o)$	958	921.3	0.47

Bound states in finite nuclei

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10 December 1998
PHYSICS LETTERS B
Physics Letters B 443 (1998) 26–32

Are η- and ω-nuclear states bound ?

K. Tsushima [a,1], D.H. Lu [a,2], A.W. Thomas [a,3], K. Saito [b,4]

NH
ELSEVIER
Nuclear Physics A670 (2000) 198c–201c

Study of ω-, η-, η'- and D^--mesic nuclei

K. Tsushima[a] *

ble 1
ω and η' bound state energies (in MeV), $E_j = Re(E_j^* - m_j)$ $(j = \eta, \omega, \eta')$, where all lths for the η' are set to zero. The eigenenergies are given by, $E_j^* = E_j + m_j - i\Gamma_j/2$.

		$\gamma_\eta = 0.5$		γ_ω=0.2		$\gamma_{\eta'} = 0$
		E_η	Γ_η	E_ω	Γ_ω	$E_{\eta'}$
$^{6}_{j}$He	1s	-10.7	14.5	-55.6	24.7	* (not calculated)
$^{11}_{j}$B	1s	-24.5	22.8	-80.8	28.8	*
$^{26}_{j}$Mg	1s	-38.8	28.5	-99.7	31.1	*
	1p	-17.8	23.1	-78.5	29.4	*
	2s	—	—	-42.8	24.8	*
$^{16}_{j}$O	1s	-32.6	26.7	-93.4	30.6	-41.3
	1p	-7.72	18.3	-64.7	27.8	-22.8
$^{40}_{j}$Ca	1s	-46.0	31.7	-111	33.1	-51.8
	1p	-26.8	26.8	-90.8	31.0	-38.5
	2s	-4.61	17.7	-65.5	28.9	-21.9
$^{90}_{j}$Zr	1s	-52.9	33.2	-117	33.4	-56.0
	1p	-40.0	30.5	-105	32.3	-47.7
	2s	-21.7	26.1	-86.4	30.7	-35.4
$^{208}_{j}$Pb	1s	-56.3	33.2	-118	33.1	-57.5

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ρ-meson mass in light nuclei

K. Saito*
Physics Division, Tohoku College of Pharmacy, Sendai 981, Japan

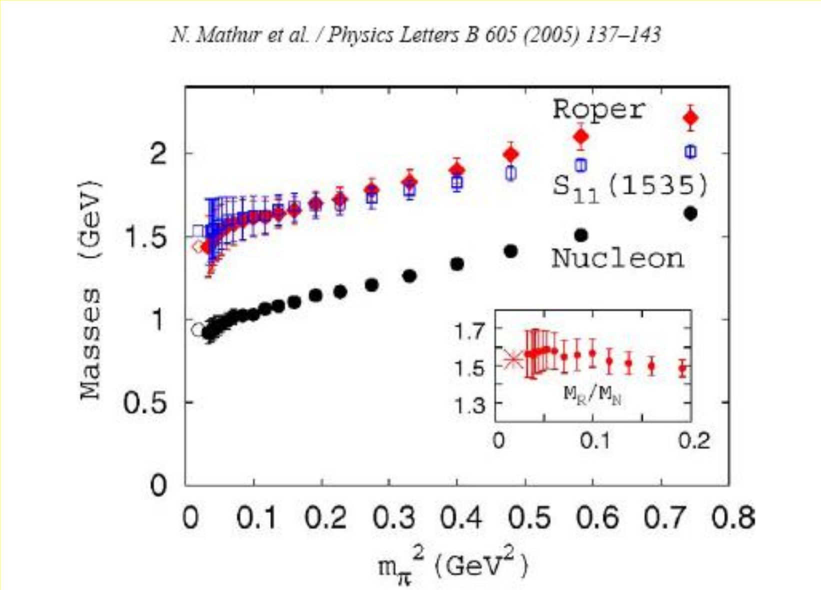
K. Tsushima† and A. W. Thomas‡
Department of Physics and Mathematical Physics and Special Research Center for the Subatomic Structure of Matter, University of Adelaide, South Australia, 5005, Australia

(Received 6 March 1997)

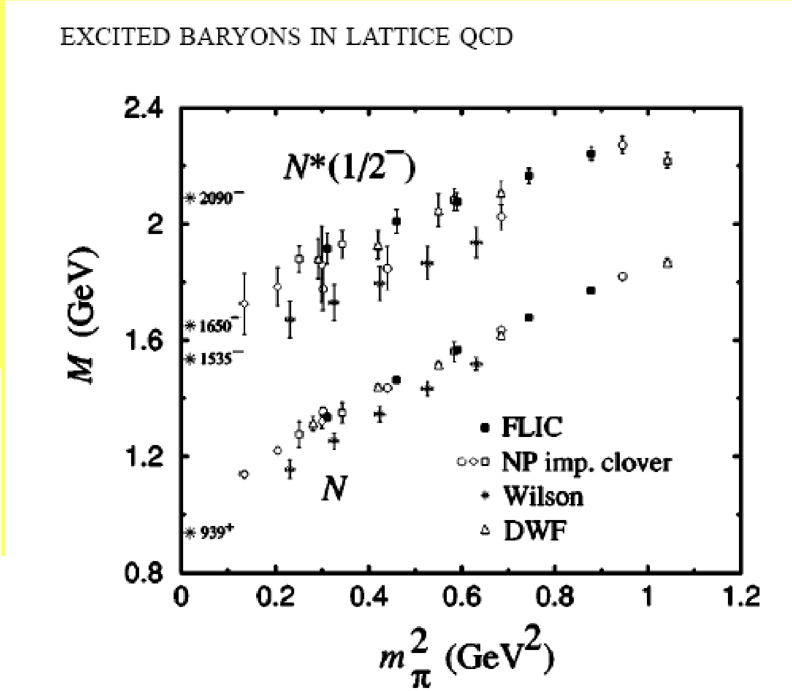
The quark-meson coupling (QMC) model is applied to a study of the mass of the ρ-meson in helium and carbon nuclei. The average mass of a ρ-meson formed in ^{3,4}He and ^{12}C is expected to be around 730, 690, and 720 MeV, respectively. [S0556-2813(97)04007-7]

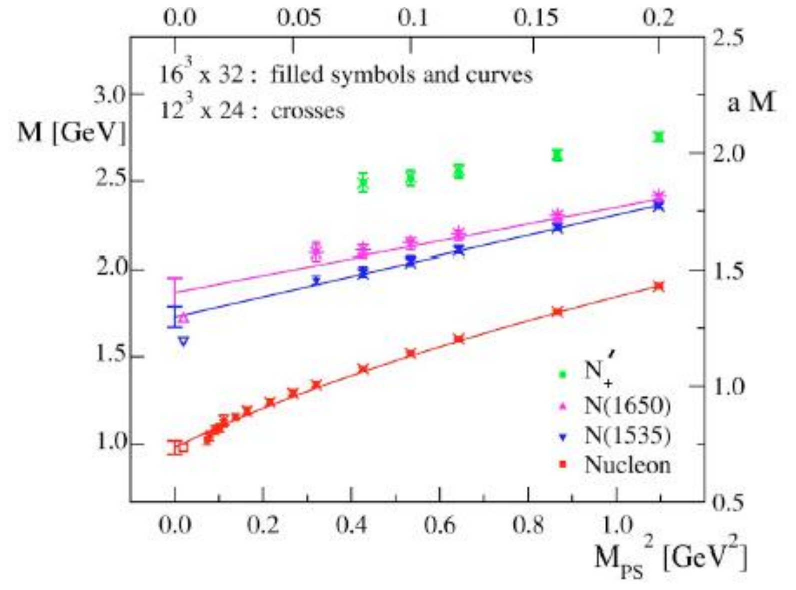
The S_{11}(1535) resonance

- 3 quark state $(1s)^2(1p)$?
  in Quark model and lattice calculations
  or
- K-Sigma quasi-bound state ?
  Chiral coupled channels in octet approx.



- In data and in both QMC and chiral coupled channels models, negligible shift in excitation energy in nuclei





The N*(1535): fun with coupled channels

SDB, Wetzel and Weise (2000)

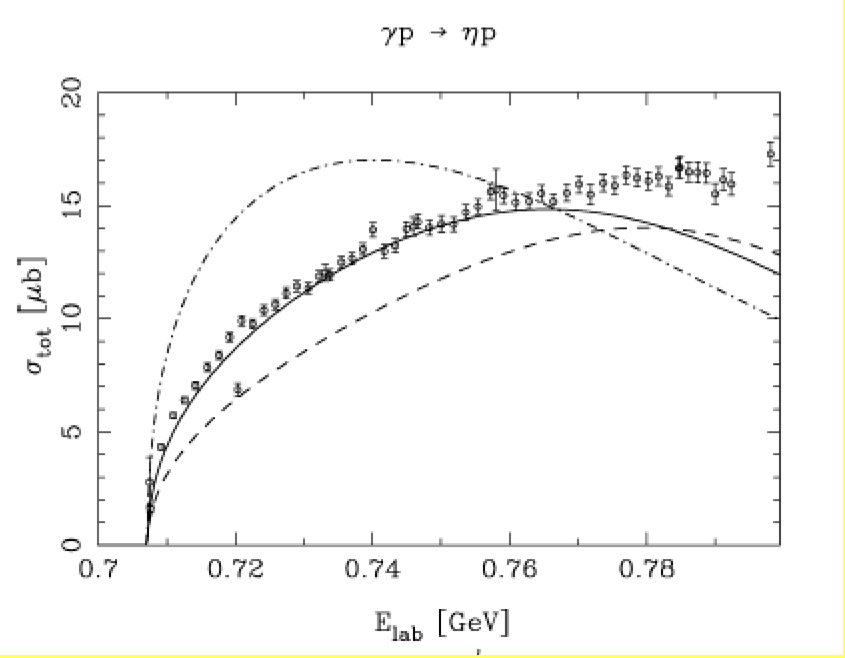
Octet eta → dynamical generated in K-Sigma rescattering

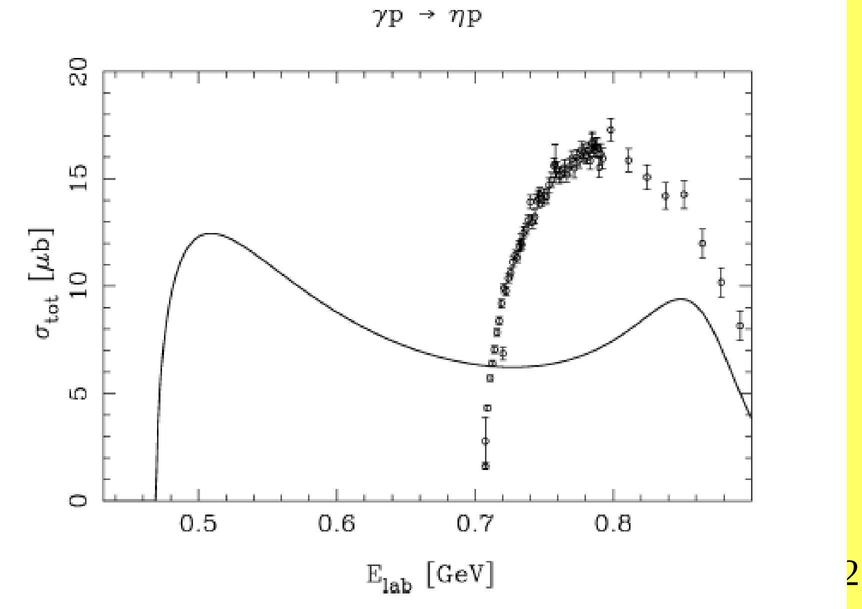
Turn on eta-etaprime mixing → lots of new axial U(1) parameters, not well constrained

Modest changes within „respectable" range can change the shape of the eta-production cross-section

(e.g. resonance gets washed out, splits in 2, cusps can appear ...!)

→ Suggests dynamical resonance interpretation an artifact of the octet approximation





Outlook and Conclusions

- Eta and etaprime physics probes the role of long range gluonic dynamics
- Etas and etaprimes in nuclei:
  - Binding energies and scattering lengths sensitive to the flavour-singlet component in the eta
  - QMC model:
    - » Factor of 2 increase in the eta-nucleon scattering length and binding energy in nuclei with eta-etaprime mixing cf. Theory prediction with a pure octet eta
    - » N*(1535) as 3 quark state $(1s)^2(1p)$
    - » For densities between 50% and 100% nuclear matter

$$\frac{m_\eta^*}{m_\eta} \simeq 1 - 0.17\frac{\rho}{\rho_0}$$

... Awaits experimental input!

U(1) extended chiral Lagrangian

- Low energy effective Lagrangian
  - constructed to reproduce the axial anomaly in the anomalous divergence equation and the gluonic mass term for the singlet boson

$$\mathcal{L}_{\rm m} = \frac{F_\pi^2}{4}{\rm Tr}(\partial^\mu U \partial_\mu U^\dagger) + \frac{F_\pi^2}{4}{\rm Tr}\left[\chi_0 \left(U + U^\dagger\right)\right] + \frac{1}{2} iQ{\rm Tr}\left[\log U - \log U^\dagger\right] + \frac{3}{\tilde{m}_{\eta_0}^2 F_0^2} Q^2.$$

$$U = \exp\left(i\frac{\phi}{F_\pi} + i\sqrt{\frac{2}{3}}\frac{\eta_0}{F_0}\right)$$

- Q represents the topological charge density.
  The gluonic potential

$$\frac{1}{2} iQ{\rm Tr}\left[\log U - \log U^\dagger\right] + \frac{3}{\tilde{m}_{\eta_0}^2 F_0^2} Q^2 \mapsto -\frac{1}{2}\tilde{m}_{\eta_0}^2 \eta_0^2$$

  yields the gluonic contribution to the etaprime mass term

- Singlet decay constant from etaprime → 2 photons

$$\frac{2\alpha}{\pi} = \sqrt{\frac{3}{2}} F_0 \left(g_{\eta'\gamma\gamma} - g_{Q\gamma\gamma}\right)$$