QCD Symmetries in eta and etaprime mesic nuclei

Steven Bass

Chiral symmetry, eta and eta´ physics:
the masses of these mesons are 300-400 MeV too big for them to be pure Goldstone bosons

→ Famous axial U(1) problem of QCD

Additional mass is associated with non-perturbative gluon dynamics

Recent developments in eta´ physics: the eta´ in nuclear matter and odd l-wave exotics from CERN

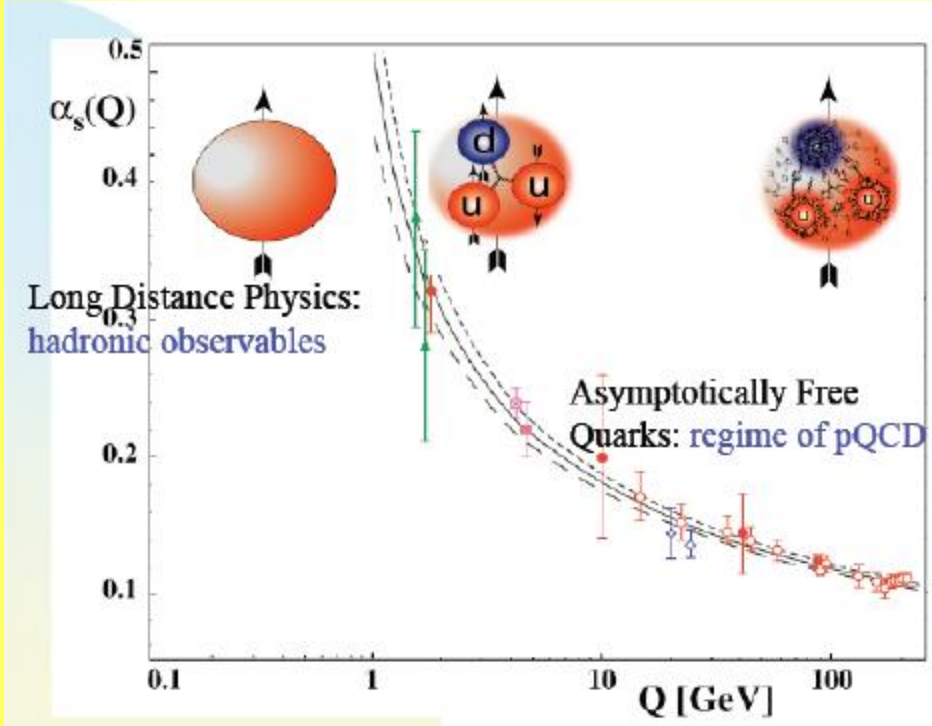
→ How should the eta and eta-prime masses be modified in nuclei ?

→ Possible bound states and eta(-prime) nucleon scattering lengths

Vienna, September 19 2014

ÖAW
Austrian Academy of Sciences

From Quarks to Hadrons



- Confinement
- Dynamical chiral symmetry breaking:
  - » Chiral condensate, pions, kaons, ... Goldstone bosons
- Axial U(1) Symmetry breaking ... Big masses for eta and etaprime
- Using nuclei to probe symmetries and possible restoration (both quark and gluonic effects)

Chiral symmetry

- QCD Lagrangian with massless quarks exhibits chiral symmetry

$$\mathcal{L}_{QCD} = \bar{\psi}_L\left(i\hat{\partial} + g\hat{A}\right)\psi_L + \bar{\psi}_R\left(i\hat{\partial} + g\hat{A}\right)\psi_R - m_q\left(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L\right) - \frac{1}{4}G_{\mu\nu}G^{\mu\nu}$$

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

- 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 $\langle \text{ vac } | \bar{q}q | \text{ vac } \rangle < 0$ 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

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

… where is the singlet boson ?

Eta and Etaprime masses

- Mass matrix

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

- 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

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

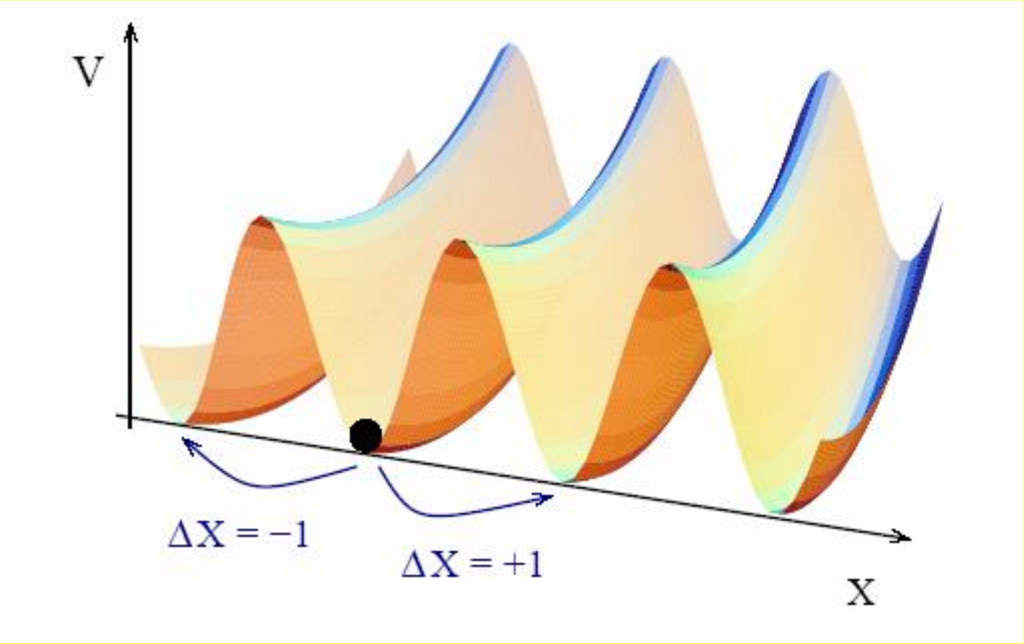
$$m_\eta^2 + m_{\eta'}^2 = 2m_K^2 + \tilde{m}_{\eta_0}^2.$$

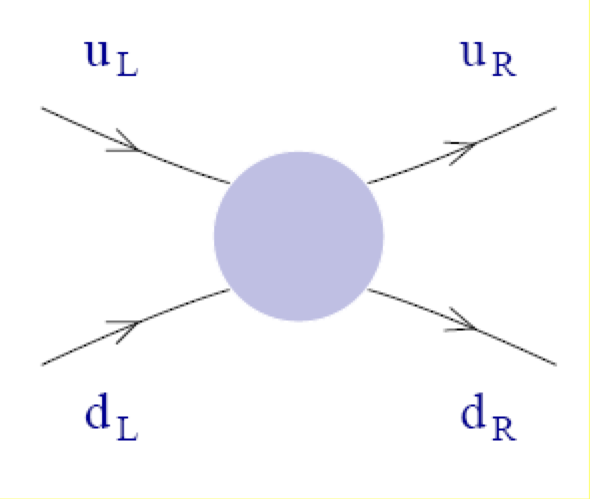
- With no glue:
  chiral symmetry „predicts" eigenstates with masses 300 MeV „too small"
  - » „eta" $(\frac{1}{\sqrt{2}}|\bar{u}u + \bar{d}d\rangle)$ degenerate with the pion
  - » „etaprime" $|\bar{s}s\rangle$ with mass $\sqrt{2m_K^2 - m_\pi^2}$

Chirality and anomalous glue

- Perturbative QCD conserves chirality for massless quarks

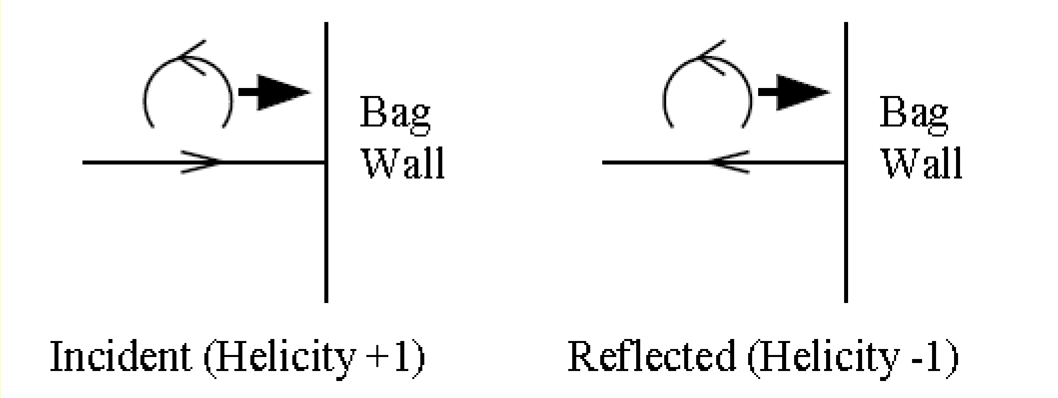
- Confinement and vacuum tunneling processes (instantons, …) connect left and right handed quarks





Confinement and chiral symmetry

- Scalar confinement dynamically breaks chiral symmetry
  - E.g. In Bag model confinement the Bag wall connects left and right handed quarks
  - Quark – pion coupling and the pion cloud of the nucleon
- Pions, kaons, eta ... as Goldstone bosons



- OGE as residual vector (colour hyperfine) interaction

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 ?

Glue in etaprime physics

- Glue enters through the anomaly equation …

$$\partial^\mu J^{GI}_{\mu 5} = 2f\partial^\mu K_\mu + \sum_{i=1}^{f} 2im_i\bar{q}_i\gamma_5 q_i$$

- Three important places it can contribute

  » Gluonic potential associated with QCD vacuum gives the etaprime a big mass

  » The etaprime has a large singlet component
  → coupling to gluonic intermediate states (OZI violation)

  » Gluonic Fock components in the etaprime wavefunction

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

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

$$U = \exp\{\mathrm{i}(\phi/F_\pi + \sqrt{2/3}\,\eta_0/F_0)\}$$

- Q is the topological charge density and the gluonic potential yields the gluonic contribution to the etaprime mass term

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

- Couple to sigma mean field and repeat …

$$\mathcal{L}_{\sigma Q} = Q^2 g_\sigma^Q \sigma$$

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

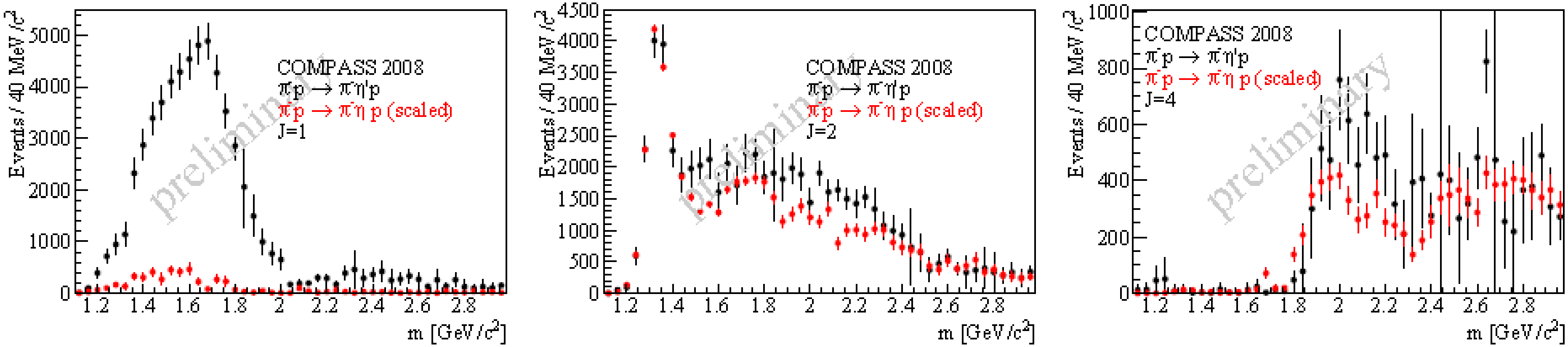
where

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

New Compass results

- Iterate $\mathcal{L}_{m2Q} = \lambda\, Q^2\, \mathrm{Tr}\, \partial_\mu U \partial^\mu U^\dagger$ in Bethe Salpeter equation

dynamicaly generates 1^{-+} exotic resonance with mass ~ 1400 MeV
[SDB and E Marco, PRD 65 (2002) 057503]



(a) P-wave, $J = 1$ (b) D-wave, $J = 2$ (c) G-wave, $J = 4$

Compass, hep-ex 1408.4286

J	1	2	3	4	5	6
$\frac{I_J(\eta\pi^-)}{I_{\text{total}}(\eta\pi)}$ [%]	4.4	81.9	0.3	6.9	0.1	0.7
$\frac{I_J(\eta'\pi^-)}{I_{\text{total}}(\eta'\pi)}$ [%]	41.7	42.3	3.7	8.4	0.9	1.2
R_{corr}	0.17 ± 0.01	0.94 ± 0.02	0.16 ± 0.05	0.83 ± 0.07	0.15 ± 0.12	0.68 ± 0.15

Eta(prime) bound states in nuclei

[SDB + AW Thomas, Phys Lett B634 (2006) 368,
Acta Phys Pol B 45 (2014) 627]

- 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 approx.
  - Nucleon-nucleon and nucleon-hole excitations in the medium
- TH: Solve for the meson self-energy in the medium

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

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

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

  - Where a is the „eta(prime)-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

  Likewise, more mixing gives smaller singlet component in the eta'

  → reduced binding and smaller eta'N scattering length

Without QCD axial anomaly, eta' a strange state and no mass shift

QCD arguments

→ gluonic mass term is suppressed in the medium

but theory technology to calculate the size of the effect direct from QCD still some time away → look at QCD inspired models

QCD and models

- Include key aspects of QCD as input motivation
  - » Confinement
  - » Chiral symmetry
  - » Eta-etaprime mixing
- Quark-meson coupling, chiral coupled channels, NJL, linear sigma model… include different aspects of QCD input with very different predictions
- Suppose we see a bound state or mass shift ☺
  - » What do we learn about QCD ?

QCD Inspired Models

- 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

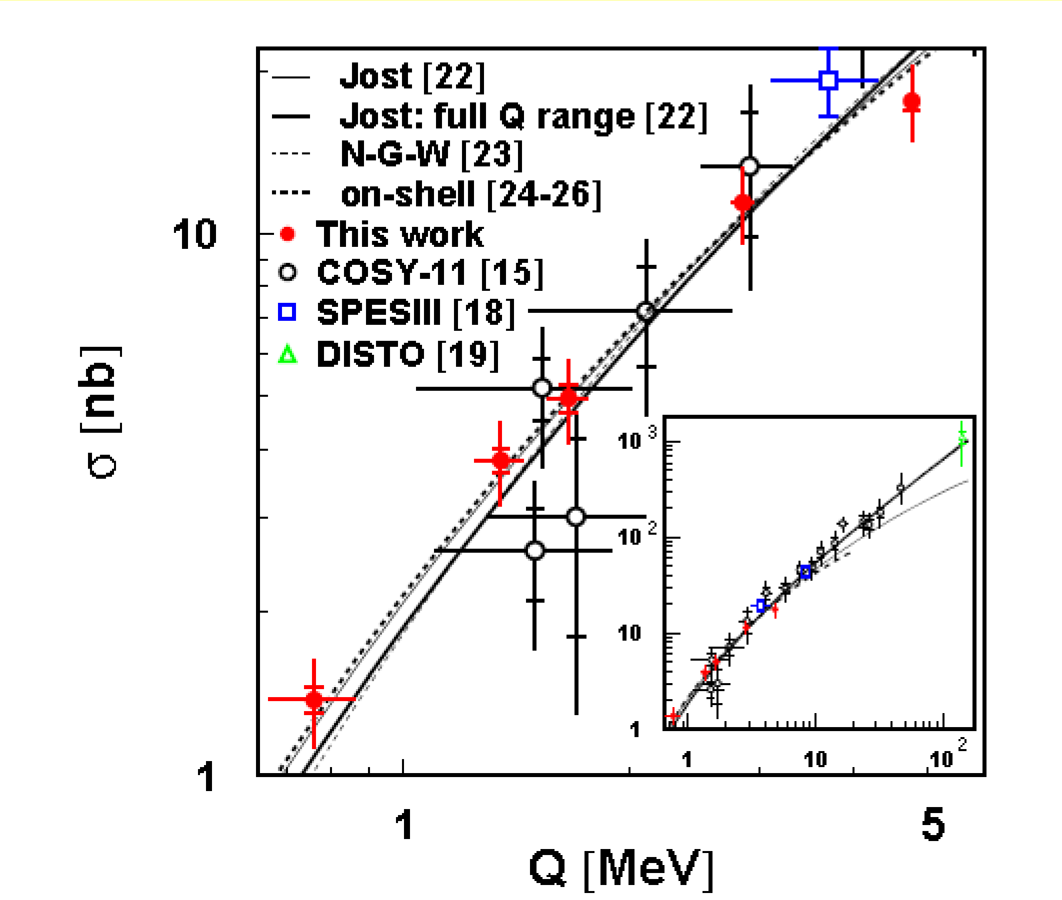
  → Increases with increasing singlet component in the eta !

	m [MeV]	m^* [MeV]	Re a [fm]
η_8	547.75	500.0	0.43
η $(-10°)$	547.75	474.7	0.64
η $(-20°)$	547.75	449.3	0.85
η_0	958	878.6	0.99
η' $(-10°)$	958	899.2	0.74
η' $(-20°)$	958	921.3	0.47

- Hints from CBELSA/TAPS for etaprime [Nanova et al, 2013]

$$V_{\rm real}(\rho_0) = m^* - m \; = \; -37 \pm 10(stat.) \pm 10(syst.) \text{ MeV}$$
$$W(\rho_0) \; = \; -10 \pm 2.5 \text{ MeV}$$

COSY 11



$$|M_{pp\to pp\eta'}|^2 \approx |M_0|^2 \cdot |M_{FSI}|^2$$

$$M_{FSI} = M_{pp}(k_1) \times M_{p_1\eta'}(k_2) \times M_{p_2\eta'}(k_3)$$

$$\mathrm{Re}(a_{p\eta'}) = 0 \pm 0.43_{stat}\ \mathrm{fm}$$

$$\mathrm{Im}(a_{p\eta'}) = 0.37\ {}^{+0.02_{stat}}_{-0.11_{stat}}\ {}^{+0.38_{sys}}_{-0.05_{sys}}\ \mathrm{fm}$$

- E. Czerwinski et al (2014),
  COSY 11 Collaboration, Phys. Rev. Lett. 113 (2014) 062004

Eta-etaprime mixing and mass shift

- Phenomenology and 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
  - » COSY-11 a_eta' new [previous slide]

- Chiral coupled channels treating the eta as a pure octet state
  - » Small mass shift and small Re[a_eta] ~ 0.2 fm
  - » For etaprime: including axial U(1) degrees of freedom gives considerable expansion in number of potentials

- N*(1535)
  - – 3 quark state (1s)2(1p) in Quark model and lattice calculations

    or

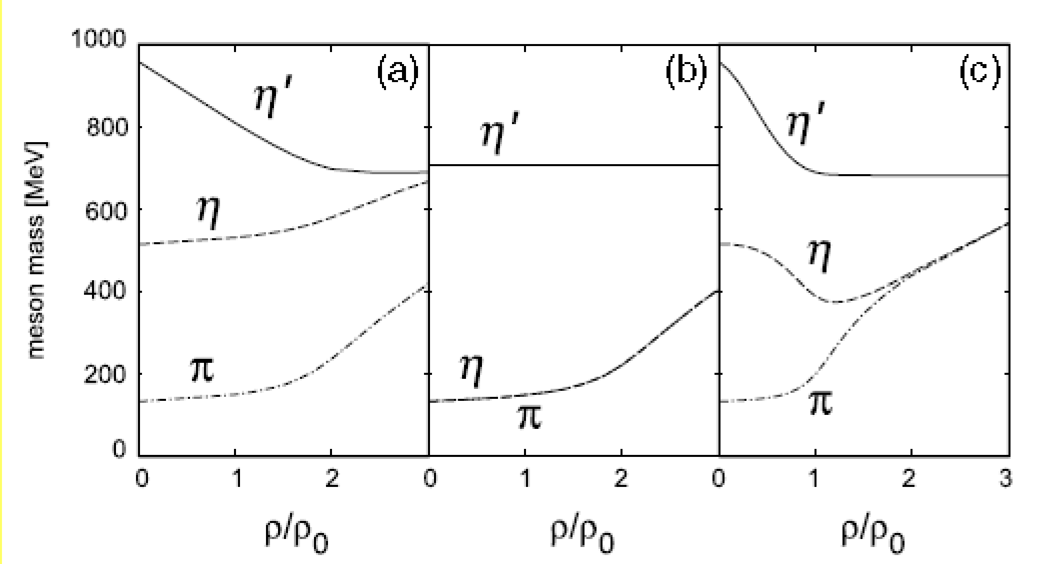
    K-Sigma quasi-bound state from Chiral coupled channels in octet approx.
  - – In data and in both QMC and chiral coupled channels models, negligible shift in excitation energy in nuclei

Comparison with NJL

- NJL model using density dependent instanton interaction
  - QCD input: chiral symmetry, no confinement, medium a Fermi gas of quarks instead of nucleons, mass shift for the eta´ up to ~ 150 MeV
    - » Phys Rev C74 (2006) 045203

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_4 + \mathcal{L}_6,$$
$$\mathcal{L}_0 = \bar{\psi}\,(i\partial_\mu\gamma^\mu - \hat{m})\,\psi,$$
$$\mathcal{L}_4 = \frac{g_S}{2}\sum_{a=0}^{8}[(\bar{\psi}\lambda^a\psi)^2 + (\bar{\psi}\lambda^a i\gamma_5\psi)^2],$$
$$\mathcal{L}_6 = g_D\{\det[\bar{\psi}_i(1-\gamma_5)\psi_j] + \text{h.c.}\}.$$

$$\text{(a) } g_D(\rho) = g_D$$
$$\text{(b) } g_D(\rho) = 0$$
$$\text{(c) } g_D(\rho) = g_D \exp[-(\rho/\rho_0)^2],$$



- Suppose eta-eta´ mass splitting comes just from anomaly, proportional to quark condensate → 80-100 MeV mass shift
  - » Phys Rev C85 (2012) 032201, Phys. Rev. C88 (2013) 064906

Outlook and Conclusions

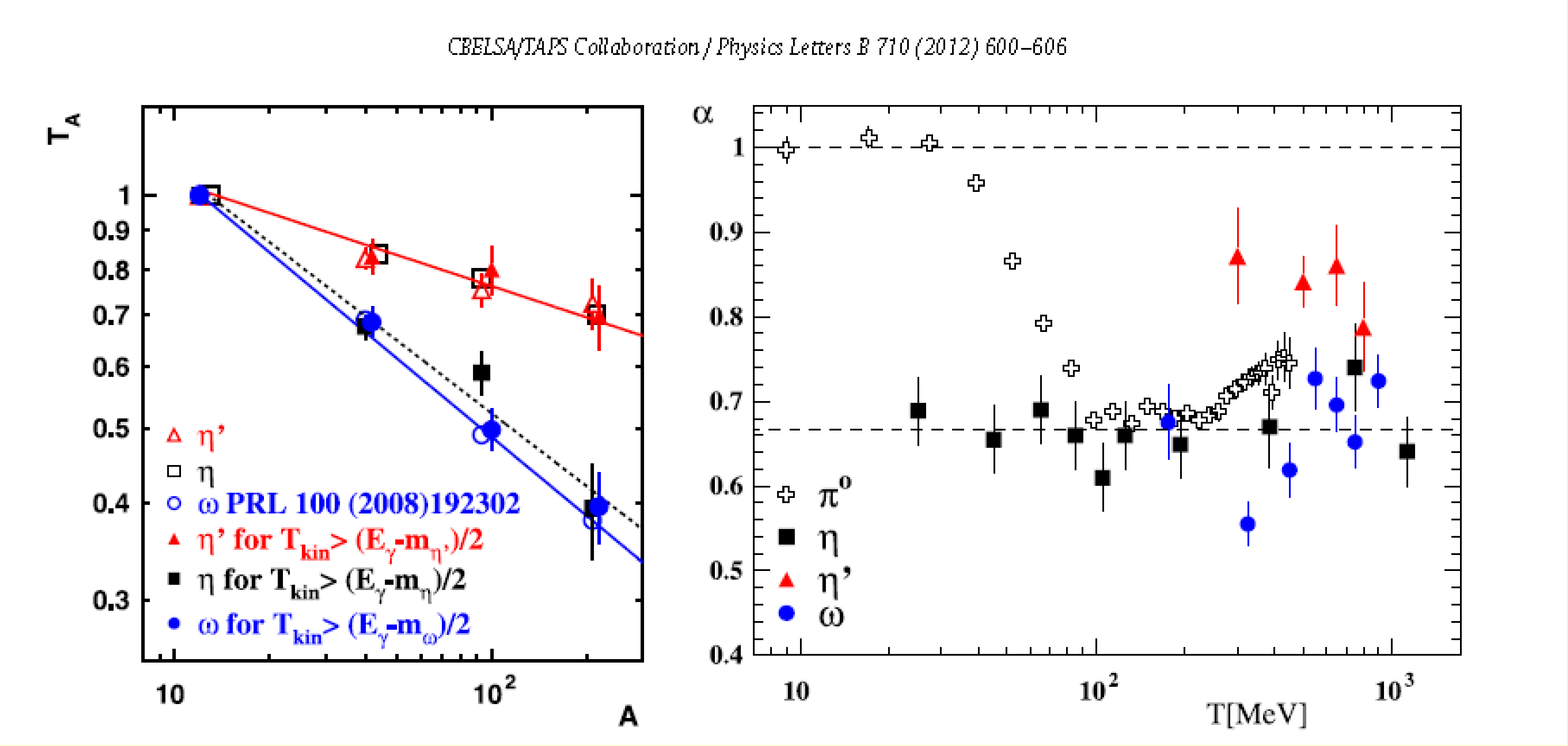
- Eta and etaprime physics probes the role of long range gluonic dynamics
- Etas and etaprimes in nuclei:
  - Aspects of Confinement, chiral symmetry and their interplay, range of masses for pseudoscalars to be treated as Goldstone states in the models
  - Binding energies and scattering lengths sensitive to the flavour-singlet component in the eta and eta´
  - Without QCD anomaly, no effect 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
    - » Good agreement with CBELSA/TAPS for the eta´

... Awaits experimental input!

... ELSA (BOG-OD), GSI (etaprime), COSY (eta).

CBELSA/TAPS: Transparency Ratios

- Medium is reasonably transparent to eta´ propagation



$$\sigma(A) = \sigma_0 A^{\alpha(T)}$$

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

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Received 2 July 2005; received in revised form 9 January 2006; accepted 31 January 2006

Available online 9 February 2006

Editor: J.-P. Blaizot

For extra reading

Vol. 45 (2014) *ACTA PHYSICA POLONICA B* No 3

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(Received January 7, 2014)