QCD Symmetries and Etaprime-Nucleus Interactions

Steven Bass

The eta´ and eta mesons are connected to non-perturbative glue

About 300-400 MeV of their masses comes from gluonic (extra to Goldstone boson) dynamics beyond DChSB.

How is this glue manifest in eta-prime nucleus interactions with the eta-prime effective mass shift observed ~-40 MeV at nuclear matter density?

Medium modifications and proton spin physics: the GDH sum-rule in medium

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The η- and η'-nucleus interactions and the search for η, η'- mesic states

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Experimental results

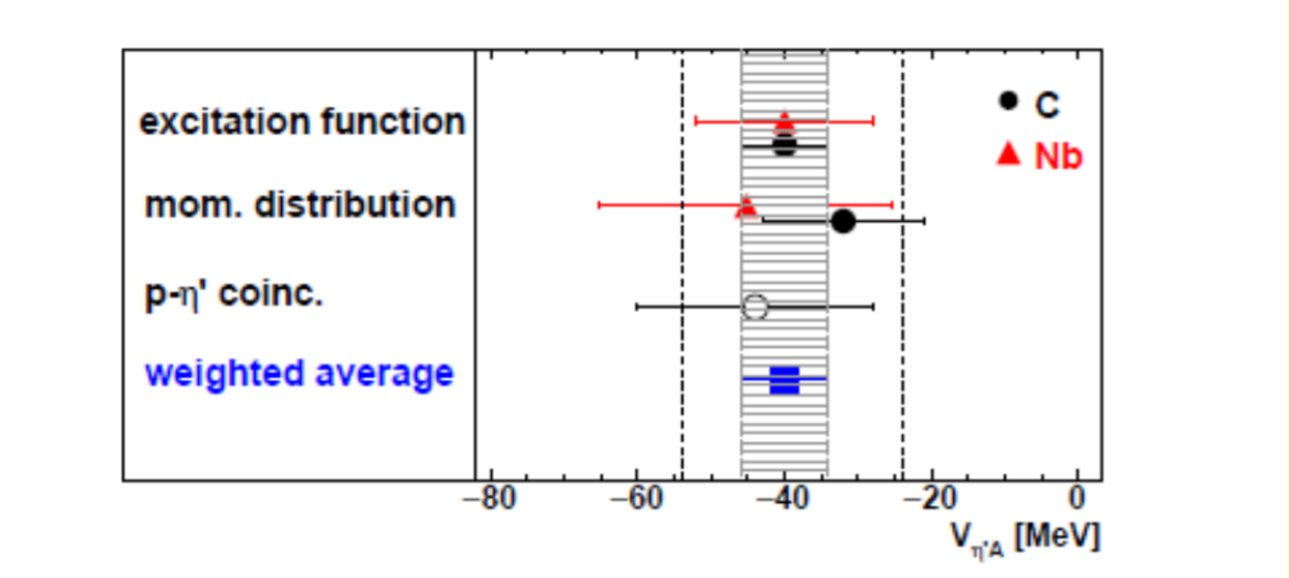
- CBELSA/TAPS measurement of η´ potential in nuclei

$$V(\rho=\rho_0) = -(40 \pm 6(\text{stat}) \pm 15(\text{syst}))\text{MeV}$$

$$W(\rho=\rho_0) = -(13 \pm 3(\text{stat}) \pm 3(\text{syst}))\text{MeV}$$

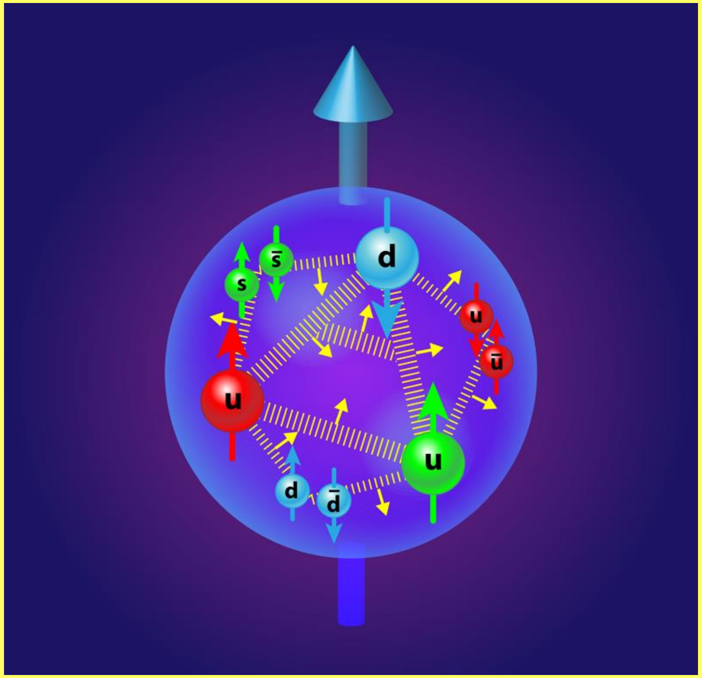
- η´ properties modified in medium

- Search for η´ bound states in nuclei, WASA@GSI, BGOegg, ...



Protons and mesons from QCD

In QCD all hadron physics is emergent from more fundamental quarks and gluons



- Protons including their mass, spin ...
- Pions as messengers (exchange particles) of nuclear forces
- Pions are special because of chiral symmetry
- Confinement and DChSB in the infrared
- Gluonic degrees of freedom manifest in the η and η´ mesons and their interactions (plus perhaps glueballs)

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

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

… 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 $\sqrt{2m_K^2 - m_\pi^2}$

Glue and the eta-prime

- Etaprime has a strong affinity to glue

- SU(3) breaking means the gluon anomaly is important to both the eta and eta-prime

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

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

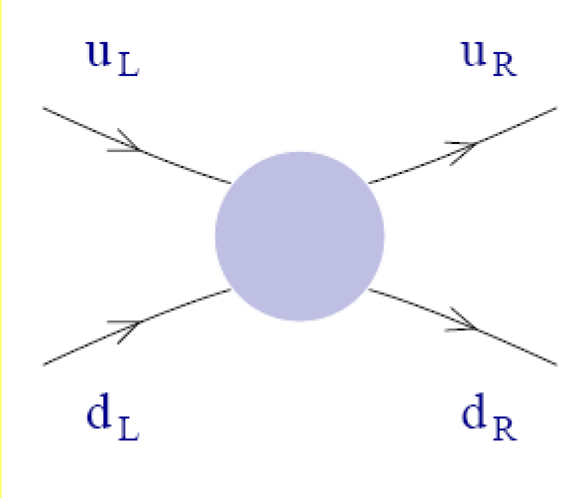
$$\partial^\mu J_{\mu 5} = \sum_{k=1}^{f} 2i\left[m_k \bar{q}_k \gamma_5 q_k\right] + N_f\left[\frac{\alpha_s}{4\pi} G_{\mu\nu}\tilde{G}^{\mu\nu}\right]$$

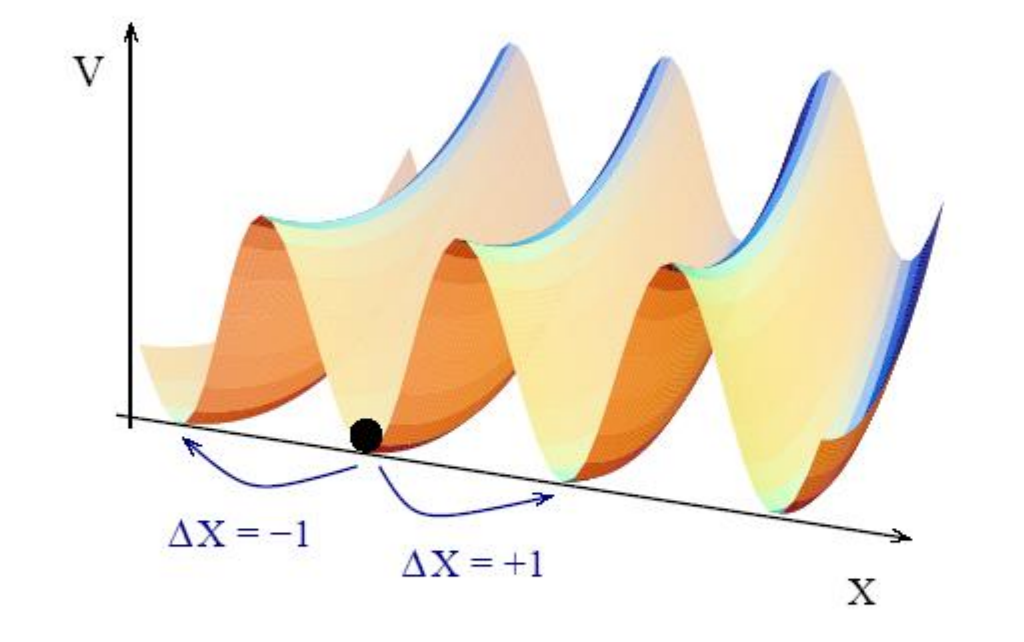
  - plus gluon topology (note the difference with „perturbative glue")

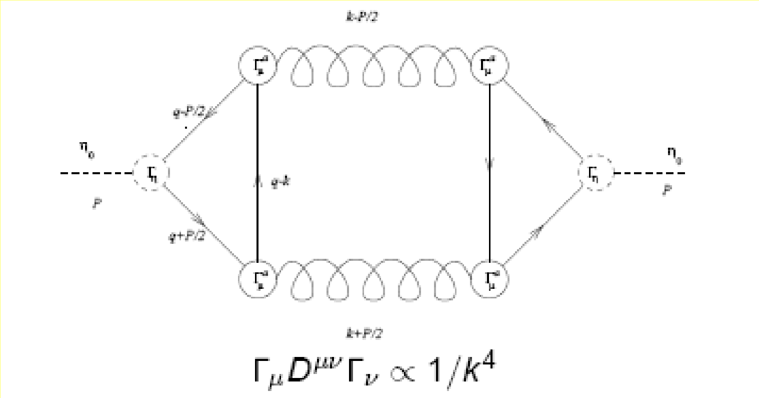
Chirality and anomalous glue

- Perturbative QCD conserves chirality for massless quarks

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

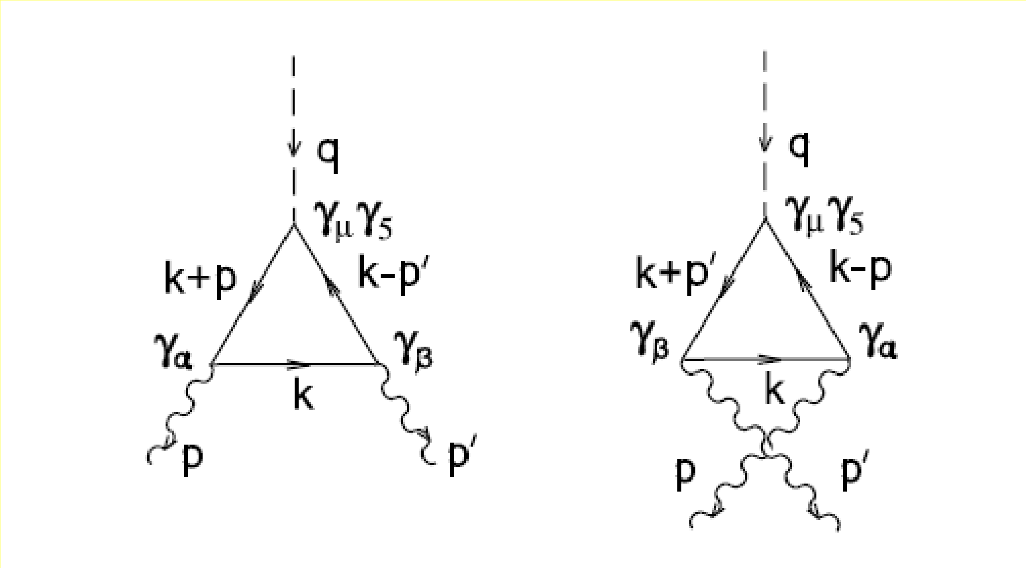






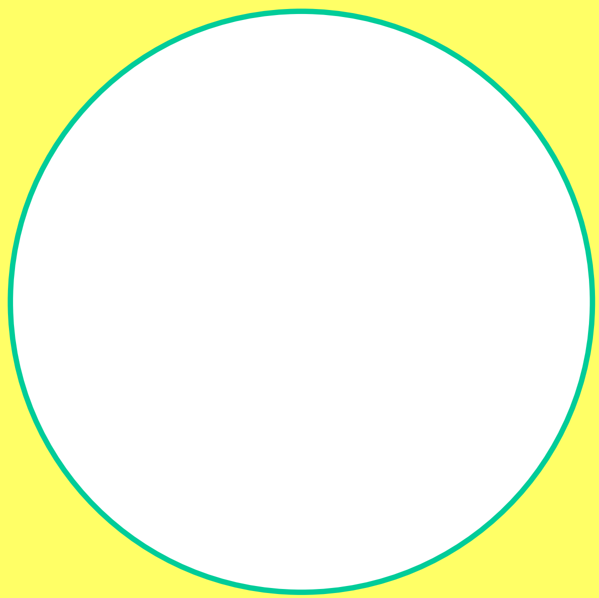
Axial anomaly primer

- Axial anomaly
  - Cannot regularize ultraviolet behaviour of the VVA (vector vector axial-vector) amplitude preserving gauge invariance and chiral symmetry at the same time
  - Must choose current conservation at the vector or at the axial-vector vertices but cannot keep both !
  - Gauge invariance wins !
    - » Gluon anomaly term on RHS of the divergence equation



Symmetries and anomalies

- Symmetries and UV regularization
- Need to define „infinite“ momentum consistent with how nature works



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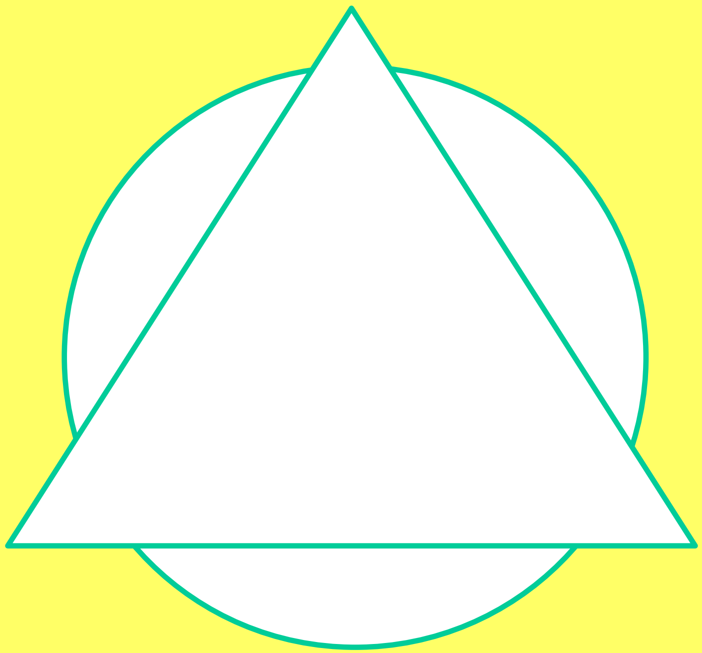

- Famous examples: $\pi^0 \rightarrow 2\gamma$, η' mass in QCD, cosmological constant

Glue in etaprime physics

- 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
  → radiativel generated through perturbative QCD
  [Acta Phys Pol B Proc Suppl 2 (2009) 11]

  » Mixing with higher mass pseudo-scalar glueball(s)

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

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

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

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

$$\Pi(E,\vec{k},\rho)\Big|_{\{\vec{k}=0\}} = -4\pi a \rho \left(1 + \frac{A}{A-1}\frac{\mu}{M}\right)$$

  - Where a is the „eta(prime)-nucleon scattering length“

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 in the nucleus

  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

$$m^*_\eta / m_\eta \approx 1 - 0.17\, \rho/\rho_0$$
$$m^*_{\eta'} / m_{\eta'} \approx 1 - 0.05\, \rho/\rho_0.$$

- Eta-prime mass shift induced by glue; otherwise strange state without large coupling to sigma mean-field in the nucleus
- Excellent agreement with EP results from CBELSA/TAPS

Medium modifications II

- Nucleon spin structure is modified in medium

- GDH physics with polarized photoproduction
  - Scattering on polarized proton in a polarized nucleus

$$\int_{M^2}^{\infty} \frac{\mathrm{d}s_{\gamma p}}{s_{\gamma p} - M^2} (\sigma_{\mathrm{P}} - \sigma_{\mathrm{A}}) = 2\pi^2 \alpha_{\mathrm{QED}} \kappa^2 / M^2$$

- Biggest contribution comes from the Δ excitation.
  - Effective hadron masses reduced in medium
  - Expected enhancement in nucleon (anomalous) magnetic moments
- How do resonance, especially the Δ excitation, contributions behave with increasing nuclear density?
- In principle, large effects (relative to the deep inelastic case)

GDH sum-rule from proton

- GDH integral with biggest contribution from Δ M1-magnetic transition
- Theory predicts + 205 μb, nearly all in isovector channel with κ = 1.79
- MAMI+ELSA gave + 226 ± 5 ± 12 μb for photon energies up to 2.9 GeV
- High-energy part extratarcted from low-Q2 data from mainly Jlab and COMPASS [Bass, Skurzok, Moskal in PRC 2018]

$$\int_{s_0}^{\infty} \frac{ds}{s - M^2} (\sigma_P - \sigma_A) = -15 \pm 2\ \mu\text{b}.$$

(with interesting effective Regge intercept value) gives

$$\int_{M^2}^{\infty} \frac{ds}{s - M^2} (\sigma_P - \sigma_A) = 211 \pm 13\ \mu\text{b}$$

Estimates – idealized case at ρ_0

- Proton mass ~ reduced about –30 MeV at ρ_0 (Oset et al)
- Take ~ 20% quenching in $g_A^{(3)}$ together with (QMC relation)

$$\mu_N^* / \mu_N \sim g_A^{(3)} / g_A^{*(3)}$$

- Gives expected enhancement in GDH integral by factor ~ 2 at ρ_0
  - order of magnitude bigger than 20% effect in polarized DIS

$$\int_0^1 \mathrm{d}x g_1^{(p-n)}\left(x, Q^2\right) = \frac{g_A^{(3)}}{6} C_{\mathrm{NS}}\left(Q^2\right)$$

Deuteron

$$\int_{\nu_{\rm th}}^{\infty} \frac{d\nu}{\nu}(\sigma_P - \sigma_A) = 4\pi^2 \alpha_{\rm QED} S \kappa^2 / M^2$$

- $K_p = 1.79$
- $K_n = -1.91$

- $K_d = 0.86$
- (Photo-disintregration contribution to GDH)
- Small binding, -2.2 MeV

- D-state probability (5 ± 1)%

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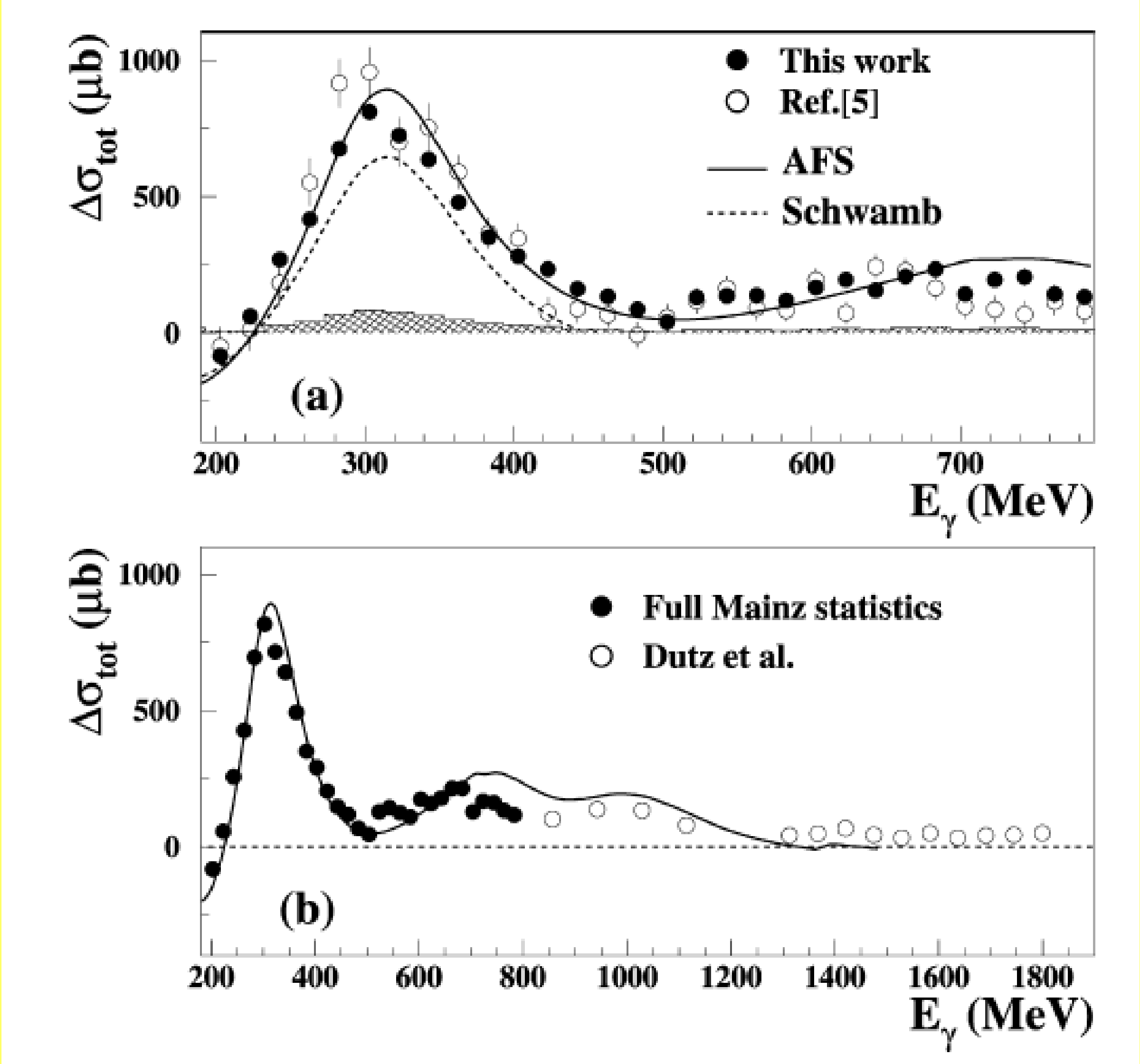
^{3}He, K = -8.37

^{7}Li, K = +4.61



Conclusions + Outlook

- Eta-primes in medium
  - mass shift ~-40MeV at ρ_0 observed by CBELSA/TAPS in good agreement with QMC prediction
  - Catalysed by anomalous glue, otherwise „pure“ strange state

- Experiments: can we bound states with EP reach to this precision?
- What about eta bound states?

- GDH physics with polarized photoproduction
  - Effective hadron masses reduced in medium
  - Expected enhancement in nucleon (anomalous) magnetic moments
  - In principle factor 2 bigger enhancement cf. Polarised DIS case. Targets: d, ^{3}He, ^{7}Li... Experiments please!