Aspects of anomalous glue

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Anomalous glue: Glue associated with the QCD axial anomaly

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

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

The proton spin puzzle: just 35% of the proton's spin comes from the spin of its quarks

- aside on baryon number violation in the early Universe (sphalerons)

Open questions …

Zakopane, June 19 2014

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

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

- 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

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

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

- 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 $\sqrt{2m_K^2 - m_\pi^2}$

Axial U(1) symmetry

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

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

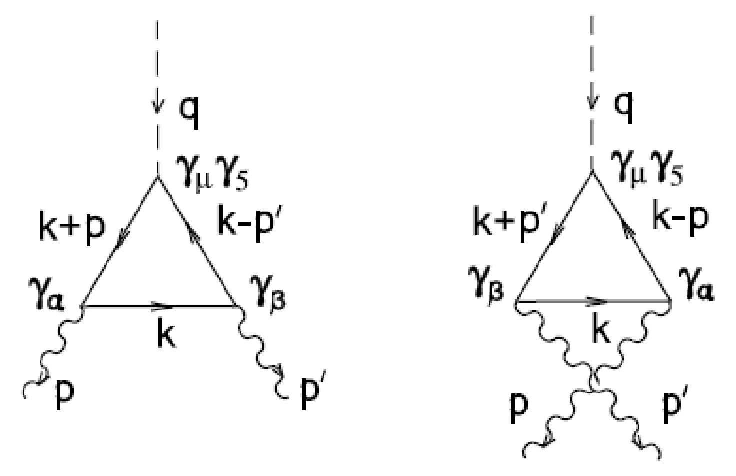
$$\partial^\mu J_{\mu 5} = \sum_{k=1}^{f} 2i\left[m_k \bar{q}_k \gamma_5 q_k\right] + N_f\left[\frac{\alpha_s}{4\pi} G_{\mu\nu}\tilde{G}^{\mu\nu}\right]$$

- 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 ?

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



Gauge invariance and the anomaly

- The axial vector current, connections with chirality, spin and gluon topology

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

$$K_\mu = \frac{g^2}{32\pi^2}\epsilon_{\mu\nu\rho\sigma}\left[A_a^\nu\left(\partial^\rho A_a^\sigma - \frac{1}{3}g f_{abc}A_b^\rho A_c^\sigma\right)\right]$$

$$J^{GI}_{\mu 5} = J^{\mathrm{con}}_{\mu 5} + 2fK_\mu$$

$$A_\mu \to UA_\mu U^{-1} + \frac{i}{g}(\partial_\mu U)U^{-1}$$

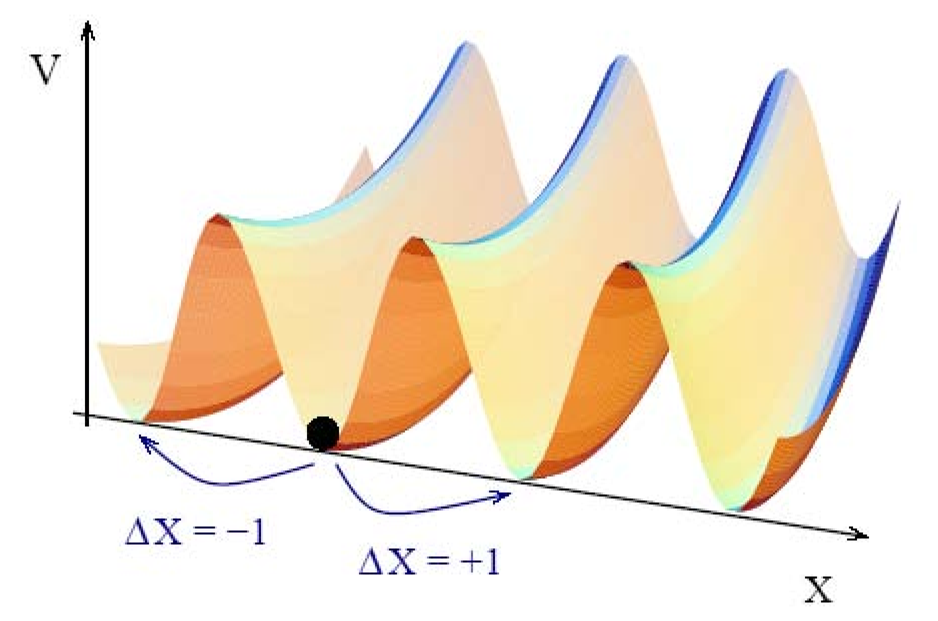
$$K_\mu \to K_\mu + i\frac{g}{8\pi^2}\epsilon_{\mu\nu\alpha\beta}\partial^\nu(U^\dagger\partial^\alpha U A^\beta) + \frac{1}{24\pi^2}\epsilon_{\mu\nu\alpha\beta}[(U^\dagger\partial^\nu U)(U^\dagger\partial^\alpha U)(U^\dagger\partial^\beta U)]$$

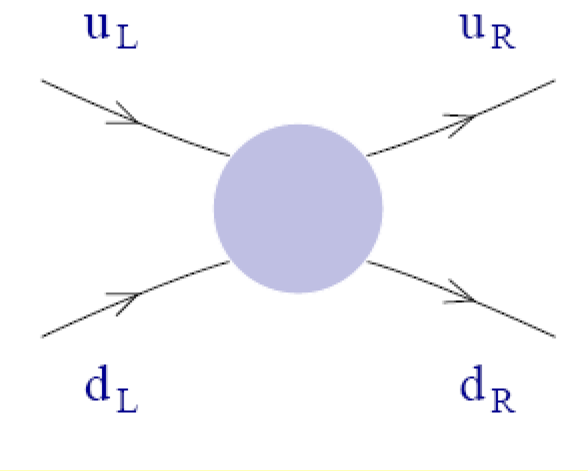
  - » Last term measures non local gluon topology

Chirality and anomalous glue

- Perturbative QCD conserves chirality for massless quarks

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





- Choice of current to define chirality

  (How to include boundary conditions on the lattice ?)

Manifestations of anomalous glue

- Etaprimes in nuclear medium
- Exotic mesons, new data from COMPASS with strong coupling to etaprime final states
- Proton spin puzzle
  - Aside on baryon number violation in early Universe

Glue in etaprime physics

- Glue enters through the anomaly equation …

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

- 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

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

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

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

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

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

- 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

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

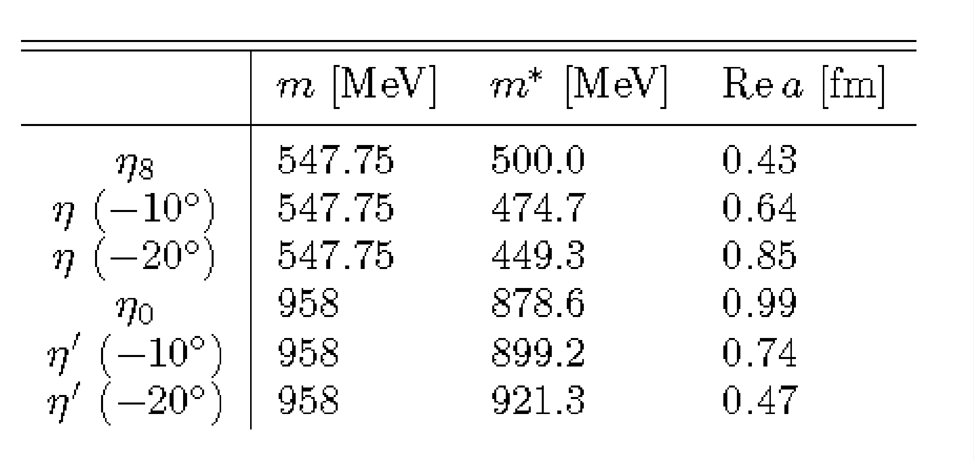
QCD Inspired Models

- 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 !

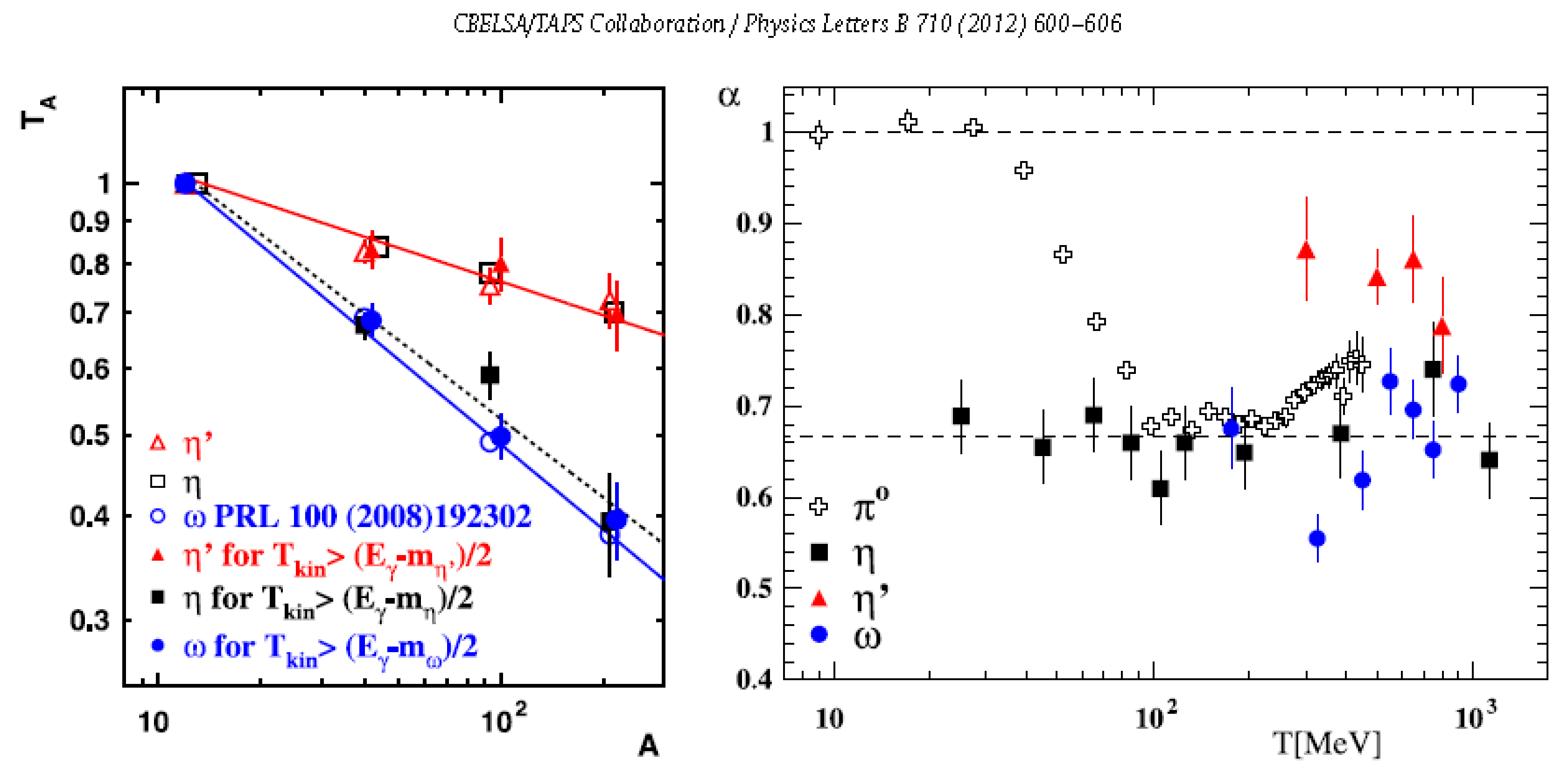


	m [MeV]	m^* [MeV]	Re a [fm]
η_8	547.75	500.0	0.43
η (-10°)	547.75	474.7	0.64
η (-20°)	547.75	449.3	0.85
η_0	958	878.6	0.99
η' (-10°)	958	899.2	0.74
η' (-20°)	958	921.3	0.47

- Hints from CBELSA/TAPS for etaprime [Nanova et al, 2013]
  - » Mass shift -37 pm 10 pm 10 MeV, width 20 pm 5 MeV

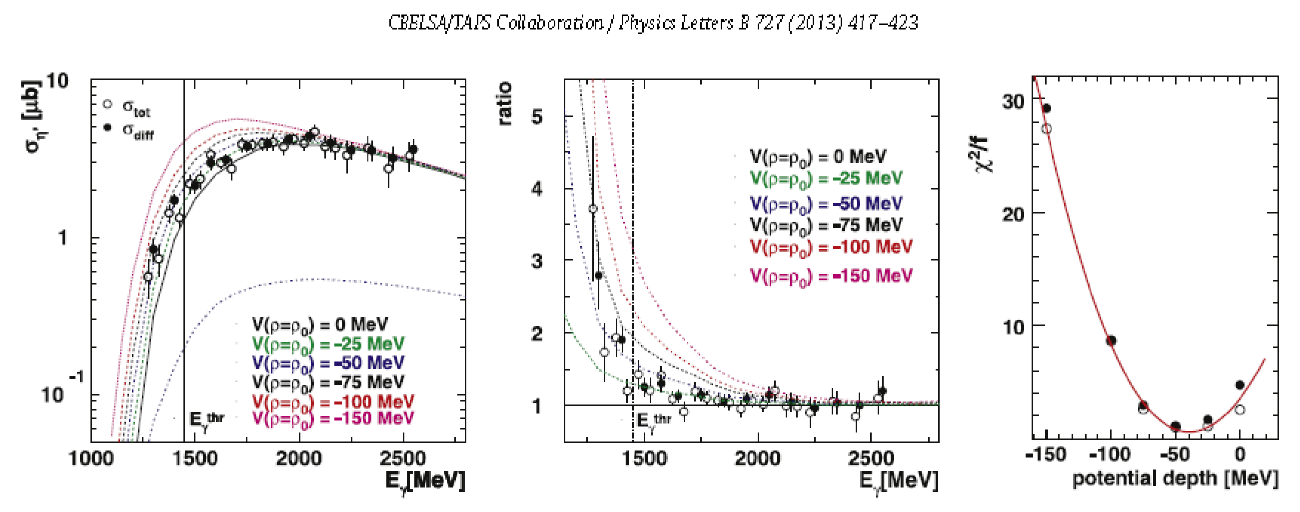
CBELSA/TAPS: Transparency Ratios

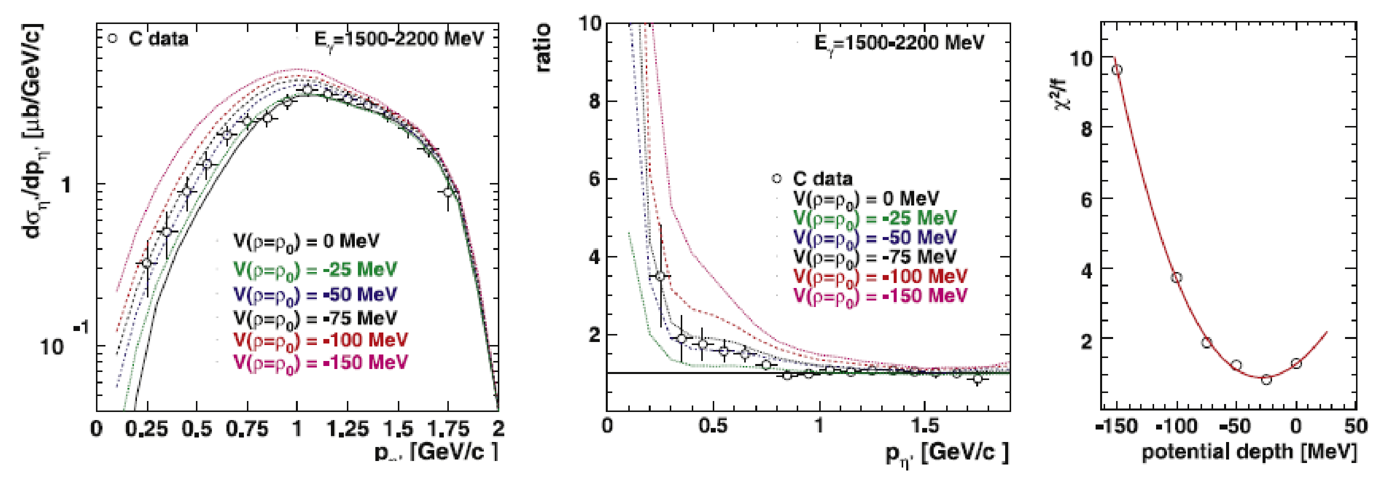
- Medium is reasonably transparent to eta´ propagation


CBELSA/TAPS Collaboration / Physics Letters B 710 (2012) 600–606

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

CBELSA/TAPS: Excitation Functions and Momentum distributions

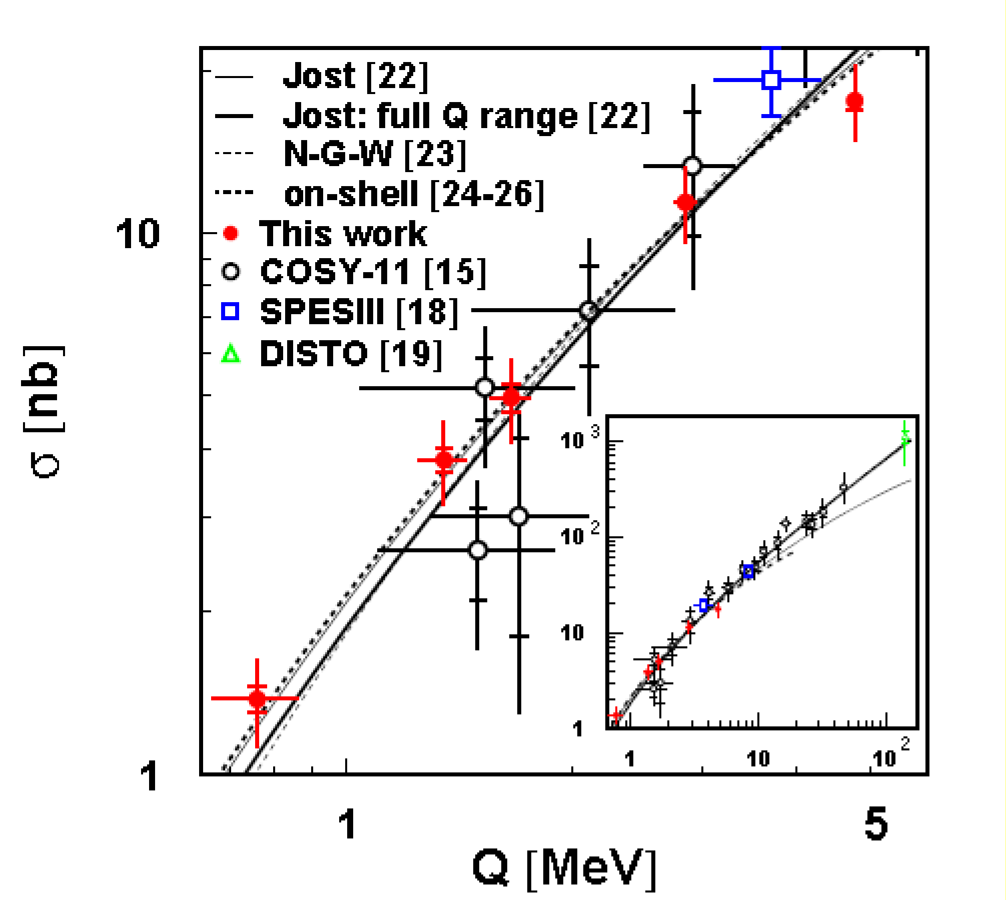

CBELSA/TAPS Collaboration / Physics Letters B 727 (2013) 417–423



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

$$W(\rho_0) \; = \; -10 \pm 2.5 \text{ MeV}$$

COSY 11



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

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

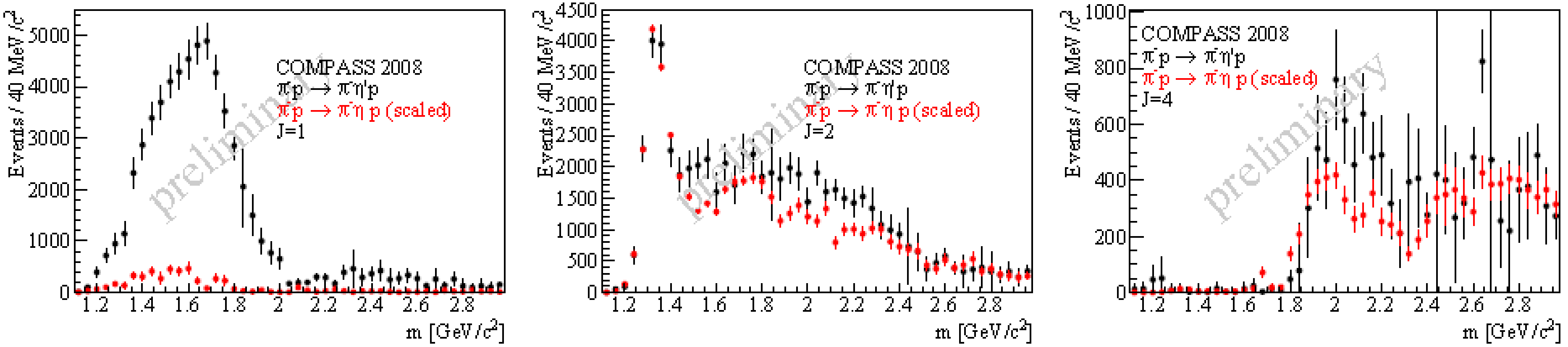
$$\begin{aligned} \mathrm{Re}(a_{p\eta'}) &= 0 \pm 0.43_{stat}\ \mathrm{fm} \\ \mathrm{Im}(a_{p\eta'}) &= 0.37\ {}^{+0.02_{stat}}_{-0.11_{stat}}\ {}^{+0.38_{sys}}_{-0.05_{sys}}\ \mathrm{fm} \end{aligned}$$

- E. Czerwinski et al (2014), COSY 11 Collaboration, arXiv:1404.5436

New Compass results

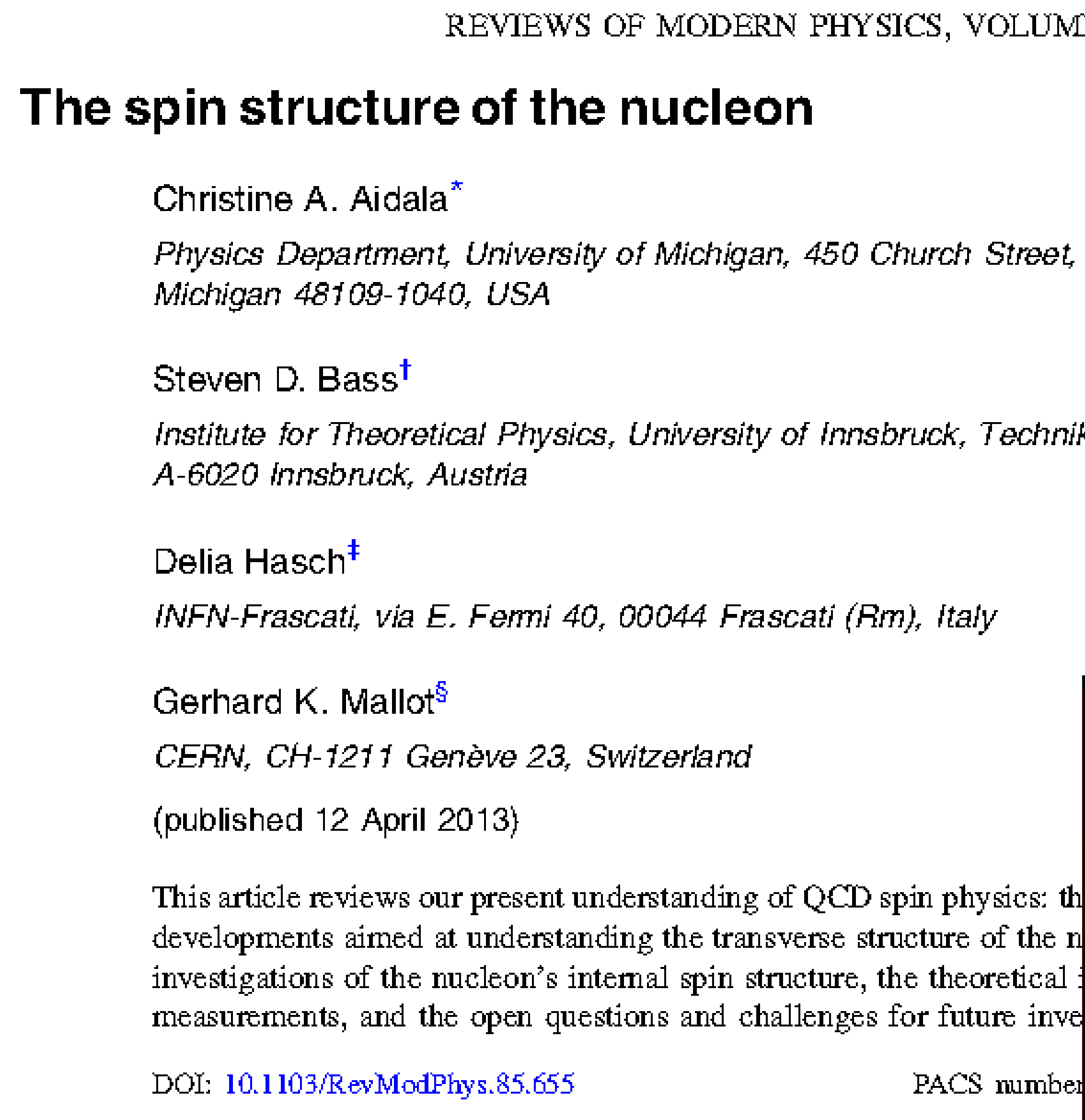
- Iterate $\mathcal{L}_{m2Q} = \lambda\, Q^2\, \mathrm{Tr}\, \partial_\mu U \partial^\mu U^\dagger$ in Bethe Salpeter equation

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, $J=4$

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



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The spin structure of the nucleon

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This article reviews our present understanding of QCD spin physics: th
developments aimed at understanding the transverse structure of the n
investigations of the nucleon's internal spin structure, the theoretical i
measurements, and the open questions and challenges for future inve

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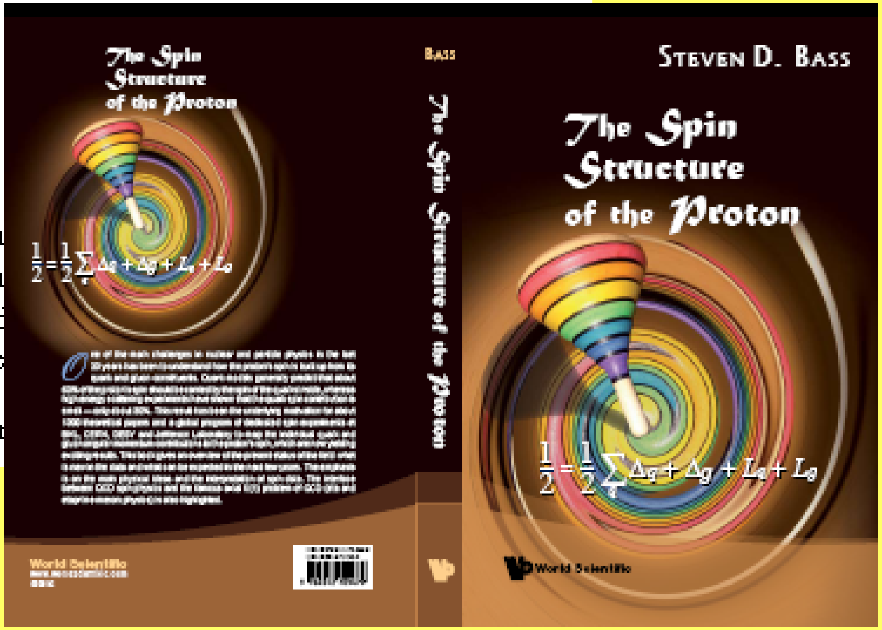
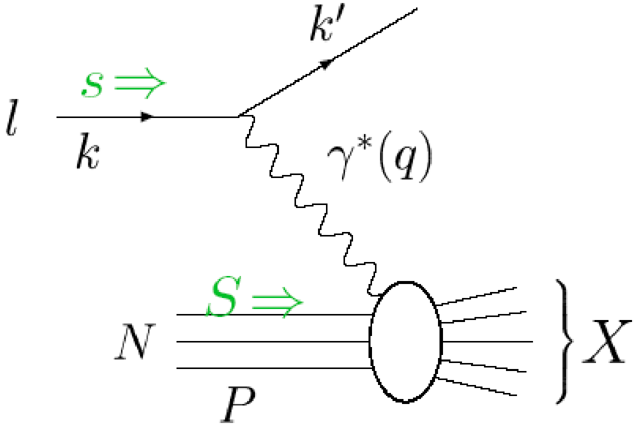


The proton spin puzzle

- Historically, Relativistic quark models
  → ~ 60% of proton’s spin carried by intrinsic spin of quark constituents
- Polarized Deep Inelastic Scattering → quark “spin content” ~ 35%
- → Where is the missing “spin” ?
- (measured by singlet axial-current, polarized gluons, L_z, … ?)
- Vigorous TH and EP programme … Experiments at COMPASS, HERMES, RHIC
- Today: Good convergence for helicity structure within good errors



$$Q^2 = -q^2 \gg m^2$$

$$x = \frac{Q^2}{2P\cdot q} = \frac{Q^2}{2m\nu}$$

$$\left(\frac{d^2\sigma^{\uparrow\Downarrow}}{d\Omega dE'} + \frac{d^2\sigma^{\uparrow\Uparrow}}{d\Omega dE'}\right) = \frac{\alpha^2}{4E^2 M \sin^4\frac{\theta}{2}}\left[2\sin^2\frac{\theta}{2}\,F_1 + \cos^2\frac{\theta}{2}\,\frac{M}{\nu}\,F_2\right]$$

$$\left(\frac{d^2\sigma^{\uparrow\Downarrow}}{d\Omega dE'} - \frac{d^2\sigma^{\uparrow\Uparrow}}{d\Omega dE'}\right) = \frac{4\alpha^2}{MQ^2}\,\frac{E'}{E\nu}\left[(E + E'\cos\theta)\,g_1 - 2xM\,g_2\right]$$

Deep inelastic spin sum rules

$$\begin{aligned}\int_0^1 dx\, g_1^p(x,Q^2) = {}& \left(\frac{1}{12} g_A^{(3)} + \frac{1}{36} g_A^{(8)}\right)\left\{1 + \sum_{\ell\geq 1} c_{\mathrm{NS}\ell}\,\alpha_s^\ell(Q)\right\} \\ & + \frac{1}{9} g_A^{(0)}|_{\mathrm{inv}}\left\{1 + \sum_{\ell\geq 1} c_{\mathrm{S}\ell}\,\alpha_s^\ell(Q)\right\} \\ & + \mathcal{O}\left(\frac{1}{Q^2}\right) + \beta_\infty.\end{aligned}$$

- Measures axial-current matrix elements

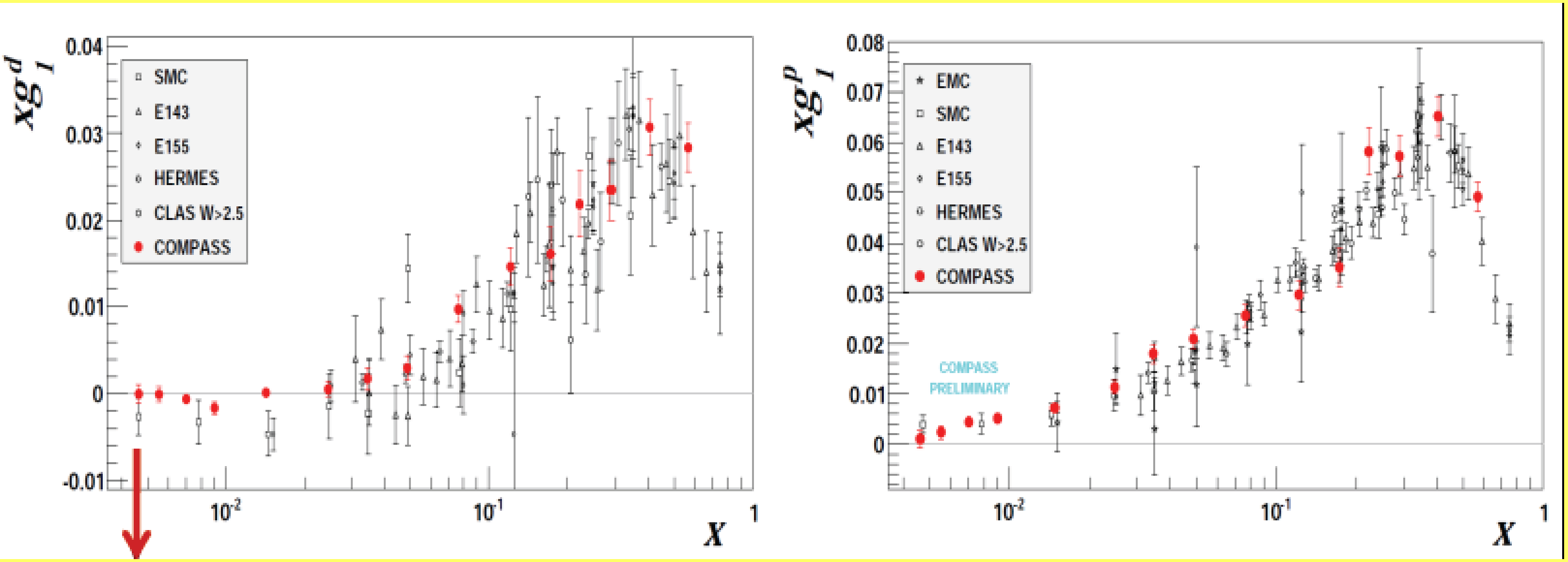
$$2M s_\mu \Delta q = \langle p, s|\bar{q}\gamma_\mu\gamma_5 q|p, s\rangle$$

$$\begin{aligned} g_A^{(3)} &= \Delta u - \Delta d, \\ g_A^{(8)} &= \Delta u + \Delta d - 2\Delta s, \\ g_A^{(0)}|_{\mathrm{inv}}/E(\alpha_s) \equiv g_A^{(0)} &= \Delta u + \Delta d + \Delta s. \end{aligned}$$

$$E(\alpha_s) = \exp\int_0^{\alpha_s} d\tilde{\alpha}_s\,\gamma(\tilde{\alpha}_s)/\beta(\tilde{\alpha}_s)$$

The Spin Structure of the Proton

Polarized Deep Inelastic Scattering



Measure g_1 spin structure function

First moment →

$$g_A^{(0)}|_{\mathrm{pDIS},Q^2\to\infty} = 0.33 \pm 0.03(\mathrm{stat}) \pm 0.05(\mathrm{syst}).$$

WHERE IS THE „MISSING SPIN" ?

→ „Strangeness polarization"

$$\begin{aligned}\Delta s_{Q^2\to\infty} &= \tfrac{1}{3}(g_A^{(0)}|_{\mathrm{pDIS},Q^2\to\infty} - g_A^{(8)})\\ &= -0.08 \pm 0.01(\mathrm{stat}) \pm 0.02(\mathrm{syst}),\end{aligned}$$

Sum rules

- Sum rules for

  $g_A^{(0)}$ singlet axial charge (… e.g. Ellis-Jaffe #2)

  what dynamics separates its value from $g_A^{(8)}$?

  and

  $\frac{1}{2}$ = Quark spin + Glue spin + Orbital

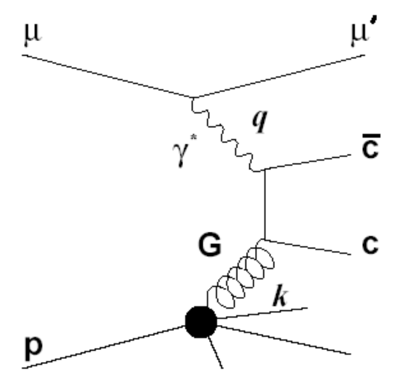
Polarized glue

- Attempts to understand the polarized DIS values of $g_A^{(0)}$ and Delta s
  - Gluon polarization
  - Sea and valence quark polarization

  → measure through hard processes in (semi-inclusive) DIS, jets, polarized pp collisions at RHIC …

$$g_A^{(0)} = \left(\sum_q \Delta q - 3 \frac{\alpha_s}{2\pi} \Delta g \right)_{\text{partons}} + C_\infty$$

$$\alpha_s \Delta g \sim \text{constant}, \quad Q^2 \to \infty$$

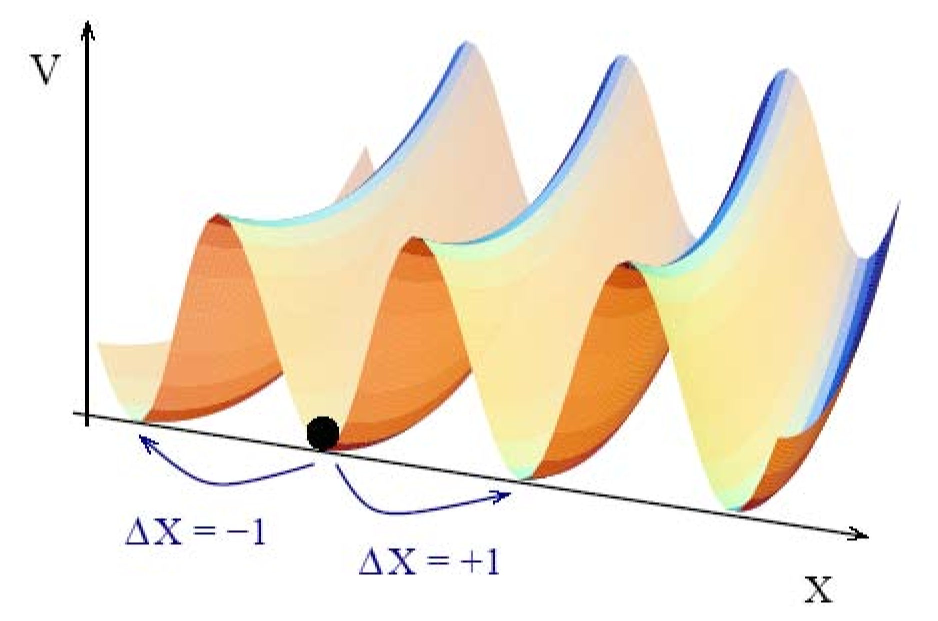


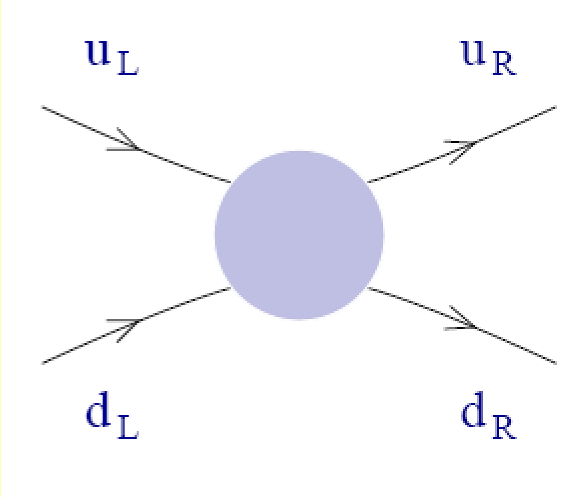
- Measurements at COMPASS, RHIC, HERMES: Delta g < 0.5, $Q^2 \sim 3$ GeV^2

- SIDIS: No evidence of negative strangeness polarization
  Delta s = -0.02 +/- 0.02 (stat) +/- 0.02 (syst) @ $0.003 < x < 0.3$

Example of x=0 polarization

- Vacuum tunneling processes (instantons, and interaction with QCD theta vacuum)





- Chirality of moving quarks gets flipped but the total is conserved

  → Is absorbed into the vacuum and

  → Spin asymmetry of moving partons gets washed out with spin shifted to x=0

  → „x=0" carries some of the spin !

  (corresponds to subtraction constant in dispersion relation for g_1)

[SDB, Rev Mod Phys 77 (2005) 1257]

Understanding the proton spin

- Non-perturbative physics is important !
  - SU(3) breaking through pion cloud

$$g_A^{(8)} = 0.46 \pm 0.05$$

[SDB and AW Thomas, PLB 684 (2010) 216]

  - Role of gluon topology in dynamical symmetry breaking and the transition from current to constituent quarks
  - Spin transferred from (valence) quarks to the QCD „theta-vacuum“

- SIDIS data + RHIC Spin → Glue and sea polarization appears small

- Proton spin puzzle is „valence like“

  → connected with chiral dynamics and complex vacuum structure of QCD in (iso-)singlet channel

Baryon number violation in the early Universe: What is baryon number ?

- Definition of baryon number in e-weak theory is subtle because of the axial anomaly

$$J_\mu = \bar{\Psi}\gamma_\mu\Psi$$
$$= \bar{\Psi}\gamma_\mu\frac{1}{2}(1-\gamma_5)\Psi + \bar{\Psi}\gamma_\mu\frac{1}{2}(1+\gamma_5)\Psi.$$

- SU(2) gauge bosons couple only to left handed quarks → axial anomaly is important!

$$\partial^\mu J_\mu = n_f\left(-\partial^\mu K_\mu + \partial^\mu k_\mu\right).$$

$$\partial^\mu K_\mu = \frac{g^2}{32\pi^2}W_{\mu\nu}\tilde{W}^{\mu\nu}$$

- Suggests choice of currents to define baryon number:
  (1) the gauge invariant renormalized current
  OR
  (2) (gauge invariant observables associated with) the conserved (but gauge dependent) current

$$J_\mu^{\mathrm{con}} = J_\mu - n_f(-K_\mu + k_\mu)$$

$$\partial^\mu J_\mu^{\mathrm{con}} = 0$$

Anomalous commutators

- Consider the charges

$$Y(t) = \int d^3z\, J_0(z), \qquad B = \int d^3z\, J_0^{\mathrm{con}}(z).$$

- Gauge invariant baryon number B is defined through the commutators

$$[B, \mathcal{O}]_- = \mathcal{B}\mathcal{O}$$

despite gauge dependence of the operator

- B charge is renormalization scale invariant (as baryon number should be!) whereas Y is not.
- Also, the time derivative of the spatial components of the W boson field has zero B charge and non-zero Y charge

$$[B, \partial_0 A_i]_- = 0$$

and

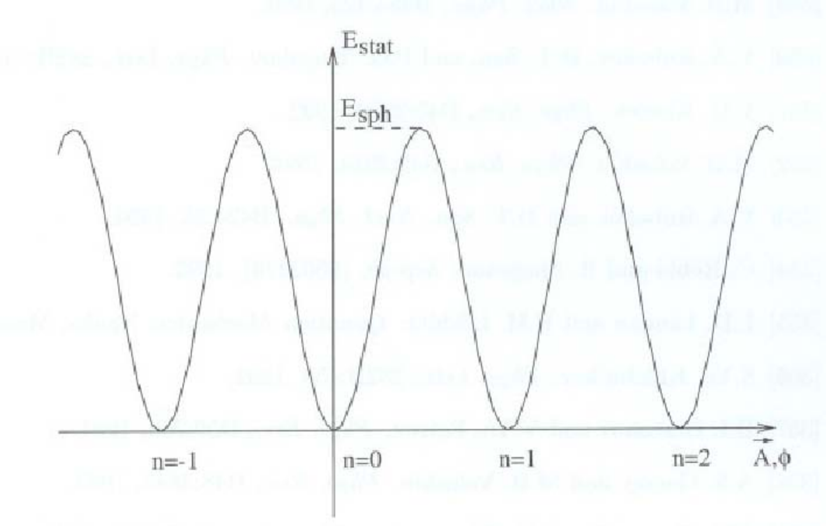
$$\lim_{t' \to t} \left[Y(t'), \partial_0 A_i(\vec{x}, t) \right]_- = \frac{i n_f g^2}{4\pi^2} \tilde{W}_{0i} + O\left(g^4 \ln |t' - t|\right)$$

Sphaleron processes in the early Universe

- E-weak instanton tunneling processes strongly suppressed

$$e^{-4\pi \sin^2\theta_W/\alpha} \sim 10^{-170}$$

- BUT at high temperatures of order the potential barrier (multi TeV) in the early Universe thermal fluctuations can induce vacuum transitions „Sphalerons“ and the suppression factor goes away



- Key equations

$$J_\mu^{\rm con} = J_\mu - n_f(-K_\mu + k_\mu)$$

$$\Delta Y = \Delta B - n_f m$$

- B-L is conserved while B+L is violated

- Tunneling and vacuum transitions can yield baryon number non-conservation

$$q + q \to 7\bar{q} + 3\bar{l},$$

- Baryon number violation associated with formation of „topological condensate“, with phenomenology = ?? [SDB, PLB 590 (2004) 115]

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(-prime)

- Anomalous glue in the proton spin puzzle
  - Phenomenology of „topological condensates“, also in early Universe

... QCD theory meets experiment !