Chiral Partners and their Electromagnetic Radiation

Ingredients for a systematic in-medium calculation

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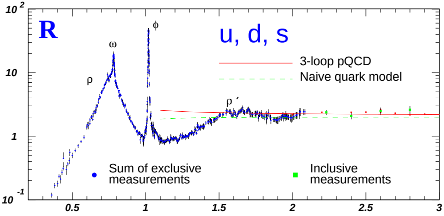
Isospin partners

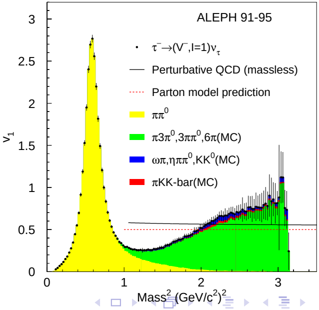
- observe same spectra in different channels
- in particular: peaks (hadrons) at same position
- e.g. spectra of j_μ^0 (from e^+e^-) and j_μ^- (from τ^- decay)

$$j_\mu^0 = \frac{1}{2}(\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d) \qquad \rightarrow \qquad j_\mu^- = \bar{u}\gamma_\mu d$$

$\rightsquigarrow$ isospin partners ρ^0 and ρ^-



modification by isoscalars (ω, ϕ)



How do we know that chiral symmetry is broken?

- study now instead of isospin transformation

$$j_\mu^0 = \frac{1}{2}(\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d) \qquad \longrightarrow \qquad j_\mu^- = \bar{u}\gamma_\mu d$$

chiral transformation (from now on $SU_F(3)$)

$$j_\mu^0 \qquad \longrightarrow \qquad j_\mu^b = \bar{q}\,\lambda^b \gamma_5 \gamma_\mu q$$

- consequence of chirally symmetric world would be: same spectral information in vector and axial-vector current-current correlators (degeneracy)
- observable? $\rightsquigarrow$ τ decay

Chiral symmetry breaking and τ decays

study decay $\tau \rightarrow \nu_\tau +$hadrons:

- couples to V–A (weak process)
- G parity: V/A couples to even/odd number of pions
- are V and A spectra identical?

Chiral symmetry breaking and τ decays

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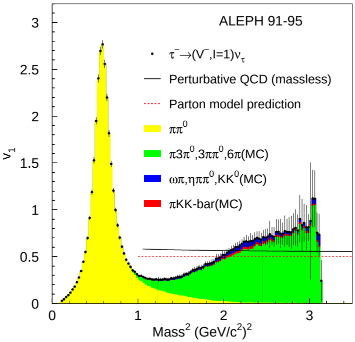
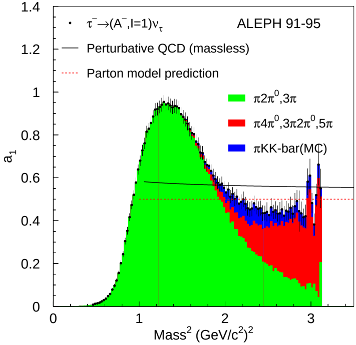
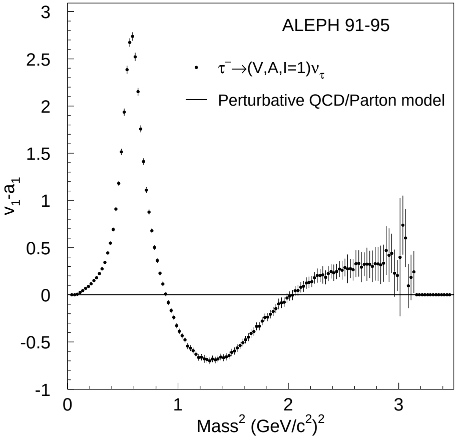
$\hookrightarrow$ Phys. Rept. 421, 191 (2005) (ALEPH):





One of the clearest signs of chiral symmetry breaking



v_1: $\tau \to \nu_\tau + m\pi$ (m even)

a_1: $\tau \to \nu_\tau + n\pi$ (n odd)

How to find the chiral partners?

- suggestive: get partners by relating lowest peaks/bumps in corresponding spectra
- before: isospin partners ρ^0 and $\rho^\pm$ (same mass)

$\hookrightarrow$ now: ρ multiplet related to a_1 multiplet

$\rightsquigarrow$ not same mass due to spontaneous symmetry breaking!

$\rightsquigarrow$ conjecture: not even of same nature!

Nature of chiral partners

- start with lowest states (of quark model):
  nucleon octet, pion nonet, Δ decuplet, ρ nonet

$\hookrightarrow$ "LLH" = lowest-lying hadrons

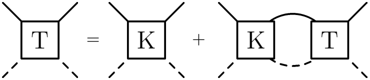
$\hookrightarrow$ LLH are quark-antiquark or three-quark states, respectively

- conjecture:
  chiral partners of LLH are dynamically generated states, i.e. hadron "molecules"
  - $N^*(1535)$ from coupled-channel dynamics of ηN, $K\Lambda$, ...
    Kaiser/Siegel/Weise, Phys. Lett. B362, 23, 1995
  - σ meson from $\pi\pi$ ...
    Oller/Oset, Phys. Rev. D60, 074023, 1999
  - $\Delta^*(1700)$ and $N^*(1520)$ from $\pi\Delta$ and flavor partners
    Lutz/Kolomeitsev, Phys. Lett. B585, 243, 2004
  - a_1 (and b_1) multiplets from $\pi\rho$, ($\pi\omega$) and flavor partners
    Lutz/Kolomeitsev, Nucl. Phys. A 730, 392, 2004

General framework for dynamical generation

- study scattering of LLH state on Goldstone bosons in channel of interest (quantum numbers of chiral partner)

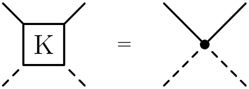
↪ Bethe-Salpeter equation



- interaction kernel always of same type:
  - lowest order chiral interaction

  ⇝ strength fixed model independently $\sim F_\pi^{-2}$

  ↪ Weinberg-Tomozawa (WT) point interaction



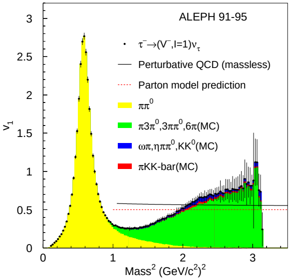
- N.B.: renormalization point for loop fixed

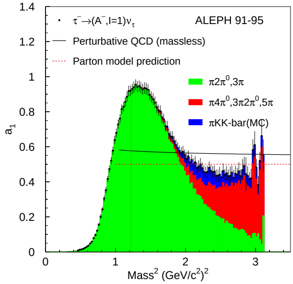
  Lutz/Kolomeitsev, Nucl. Phys. A 730, 392, 2004

  Hyodo/Jido/Hosaka, arXiv:0803.2550 [nucl-th]

Spectra of chiral partners

- Low-energy parts of spectra:
  - ρ-meson in vector channel (left – yellow)
  - a_1-meson in axial-vector channel (right – green)





$\hookrightarrow$ How to understand spectra – resonances?

Nature of the a_1 meson

- experimental finding from τ decays (Dalitz plots): isovector–axial-vector current couples to π-ρ
- π-ρ system subject to final-state interactions (rescattering)
- experimental finding: resonant structure at $\approx$ 1250 MeV

$\rightsquigarrow$ conjecture: emerges from final-state interaction of π-ρ

Lutz/Kolomeitsev, Nucl. Phys. A 730, 392, 2004

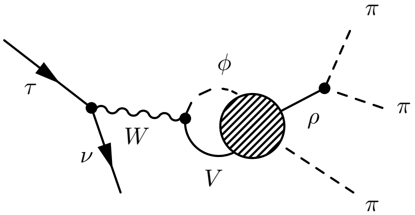
Roca/Oset/Singh, Phys. Rev. D 72, 014002, 2005

- describe final-state interactions via Bethe-Salpeter eq., kernel from lowest order chiral interaction (Weinberg-Tomozawa - WT)
  $\rightsquigarrow$ parameter free

Description of a_1 as final-state interaction effect

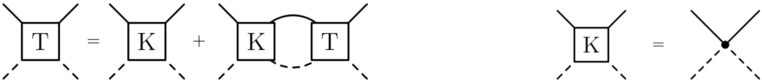
parameters for $\tau \to \nu_\tau + 3\pi$: renormalization points

- for loop for transition from W to hadrons



$\hookrightarrow$ renormalization point should be in reasonable range

- for loop in Bethe-Salpeter equation (rescattering)



$\hookrightarrow$ renormalization point fixed
(cf. Lutz/Kolomeitsev, Nucl. Phys. A 730, 392 (2004);
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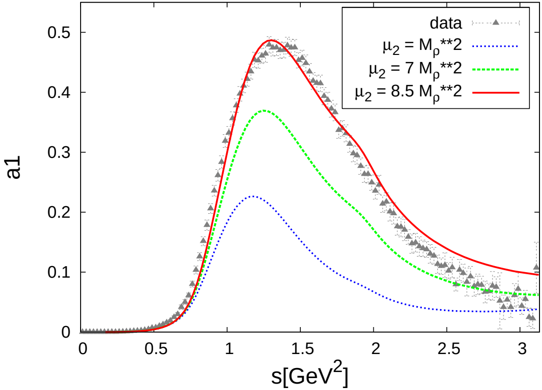
τ decay



- reasonable description with one free parameter

⇝ indicates that a_1 is ρ-π “molecule”

(Markus Wagner and S.L., PRD in press, arXiv:0801.0814 [hep-ph])

How does chiral restoration take place?

- typically spontaneous symmetry breaking lifted at some temperature/density (Ferro magnet: Curie temperature)

$\longrightarrow$ consequence at point of chiral restoration:
same in-medium spectral information
in vector and axial-vector channel

- how does it look like? $\rightarrow$ various (> 2) scenarios

$\hookrightarrow$ scenario 1 (degenerate states):

- ρ meson is still (dominantly) single-particle state

$\longrightarrow$ requires chiral partner which is also a single-particle state

$\longrightarrow$ very high mass in vacuum (since $\neq a_1$ meson) $\rightarrow$??

$\hookrightarrow$ scenario 2 (melting):

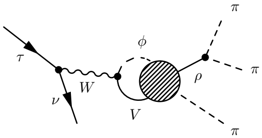
- ρ meson dissolves already in hadronic matter (precursor of deconfinement)

$\longrightarrow$ a_1 meson should also dissolve

$\longrightarrow$ testable in our approach

Dissolution of the a_1 meson?

- very simple model:
  - $\Gamma_\rho \longrightarrow 200, \; 250\,\text{MeV}$
  - no changes to pion
  - no momentum dep.
  - $\hookrightarrow$ can be improved



Dissolution of the a_1 meson?

- very simple model:
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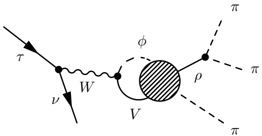
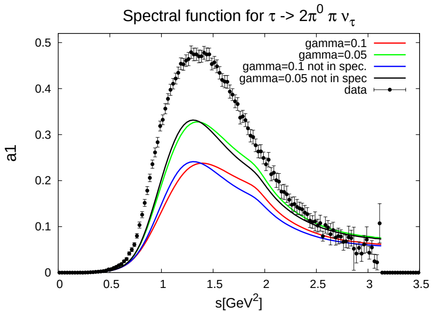




- broader ρ meson leads to broader a_1 meson

$\hookrightarrow$ no proof that melting scenario is correct, but at least consistent picture

$\longrightarrow$ problem of missing chiral partner (at single-particle level) solved by deconfinement

Necessity for a systematic treatment

- for understanding of nature of resonances and for systematic in-medium calculations

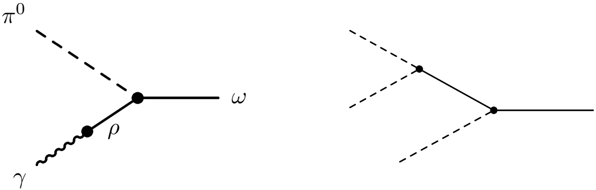
⇝ need effective field theory for pion nonet, ρ nonet, nucleon octet, Δ decuplet

⇝ systematic calculations, i.e. with power counting, instead of models

- suggested for meson sector in Lutz/Leupold, NPA in press, arXiv:0801.3821 [nucl-th]:
  - treat pseudoscalar and vector mesons as soft
  - allows for systematic inclusion of decays of vector mesons
  - yields clear statements about validity of vector-meson dominance (VMD)
  - vector mesons represented by antisymmetric tensor fields

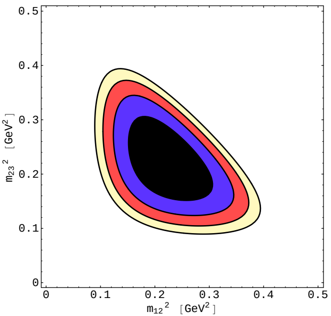
Extended VMD for elementary hadrons

example: decays of ω meson



- both processes $\omega \to \gamma\pi$ and $\omega \to 3\pi$ in leading order given by VMD
- use first process to fix coupling of second one

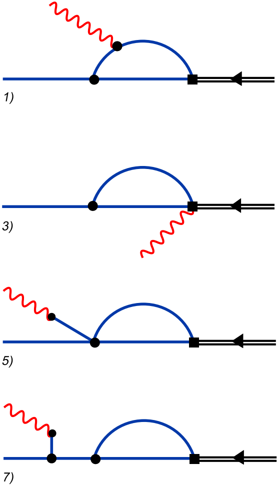
⇝ prediction: $\Gamma_{\omega\to 3\pi} = 7.3\,\text{MeV}$
$\Gamma^{\text{exp}}_{\omega\to 3\pi} = (7.57 \pm 0.13)\,\text{MeV}$
Leupold/Lutz,
arXiv:0807.4686 [hep-ph]



No VMD for hadron molecules

example: radiative decays of axial-vector mesons

Lutz/Leupold, arXiv:0801.3821 [nucl-th]



No VMD for hadron molecules

example: radiative decays of axial-vector mesons

- formation of axial-vector meson dominated by Weinberg-Tomozawa (point) interaction
- radiative decay: VMD contribution and coupling of photon to constituents
- calculable from electromagnetic moments of constituents
- uncertainty: dipole and quadrupole moments of vector mesons (lattice input?)

Towards self-consistent in-medium calculations

- ingredients:
  - systematic vacuum input
  - thermodynamically consistent resummation scheme ("Φ derivable")

  ↪ to account self-consistently for "changes induced by changes"
  - current conservation in resummation scheme ensured by use of antisymmetric tensor fields (Leupold, Phys. Lett. B646, 155, 2007)

  ↪ no proliferation of non-conserving part of current:

$$j^\mu \partial^\nu V_{\nu\mu} = j^\mu \Big(\underbrace{g_{\mu\alpha} - \frac{\partial_\mu \partial_\alpha}{\partial^2}}_{P^T_{\mu\alpha}} + \underbrace{\frac{\partial_\mu \partial_\alpha}{\partial^2}}_{P^L_{\mu\alpha}} \Big) \partial_\nu V^{\nu\alpha} = j^\mu P^T_{\mu\alpha} \partial_\nu V^{\nu\alpha}$$

⇝ check e.g. melting scenario at chiral restoration

Summary and outlook

- for the lowest-lying hadrons
  (LLH = pion nonet, ρ nonet, nucleon octet, Δ decuplet)
  the chiral partners can be understood as being dynamically generated ("hadron molecules")
- suggestion for systematic counting, i.e. effective field theory for LLH

$\hookrightarrow$ prediction where VMD works and where not

- opens the way for systematic and self-consistent in-medium calculations

Many thanks to my collaborators
Markus Wagner and Matthias Lutz

Backup: How to find the chiral partners?

general strategy:

1. start with hadron
2. find quark current with same quantum numbers
3. apply chiral transformation
4. determine quantum numbers of resulting current
5. look for state in PDG

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general strategy:

1. start with hadron
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but:

- step 2 not unique for mesons and baryons
- step 4 ill-defined for baryons

How to find the chiral partner? — example: ρ

- problem: corresponding quark current not unique
- e.g. $\bar{q}\lambda_b\gamma^\mu q$ and $\partial_\nu(\bar{q}\lambda_b\sigma^{\mu\nu}q)$ have quantum numbers of ρ multiplet
- chiral transformation on $\bar{q}\lambda_b\gamma^\mu q$ leads to $\bar{q}\lambda_c\gamma_5\gamma^\mu q$

$\hookrightarrow$ quantum numbers of a_1 multiplet

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cf. Caldi/Pagels, Phys.Rev.D14, 809, 1976

- N.B. even more complicated for baryons

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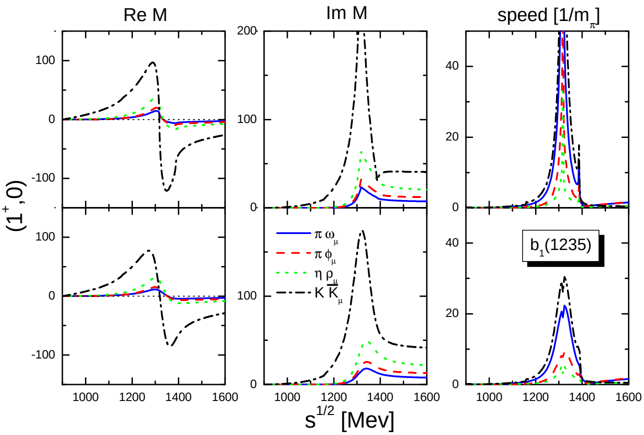
in our framework: a_1 and b_1 dynamically generated

Example: chiral partner(s) of ρ meson

dynamical generation of b_1 (parameter free)

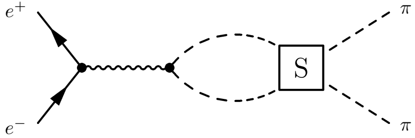


Lutz/Kolomeitsev, Nucl. Phys. A 730, 392 (2004)

Pion form factor with final-state interaction only

parameters: renormalization points

- for loop for transition from photon to hadrons



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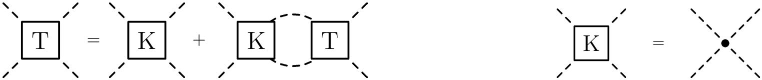

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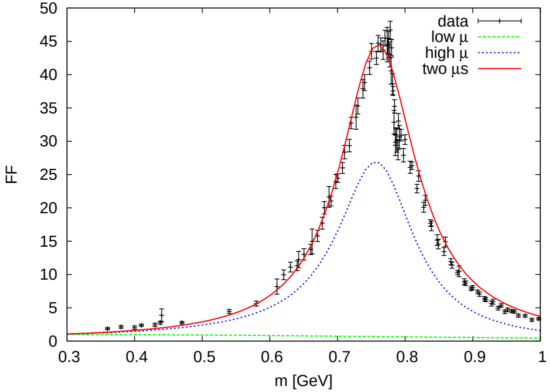

- resonance only for renormalization points in TeV range (same finding: Oller/Oset, Phys. Rev. D 60, 074023 (1999))
- no resonance for reasonable renormalization points