Chiral Partners in a Chirally Broken World

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How do we know that chiral symmetry is broken?

- isospin symmetry $SU_V(2)$: existence of multiplets, i.e. degenerate states (p, n), (ρ^+, ρ^0, ρ^-), ...

$\rightsquigarrow$ same spectra: ρ^0 (from e^+e^-) and ρ^- (from τ^- decay)

$$j_V^\mu = \frac{1}{2}(\bar{u}\gamma^\mu u - \bar{d}\gamma^\mu d) \qquad \rightarrow \qquad \bar{u}\gamma^\mu d$$

- corresponding $SU_A(2)$ symmetry:

$$j_V^\mu \qquad \rightarrow \qquad \vec{j}_A^\mu$$

with axial-vector current $\vec{j}_A^\mu = \bar{q}\,\vec{\tau}\gamma_5\gamma^\mu q$

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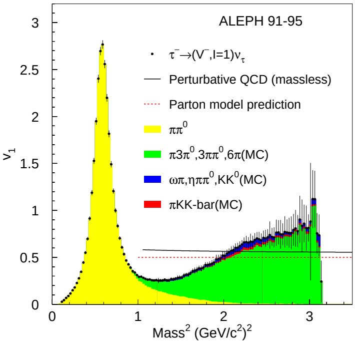
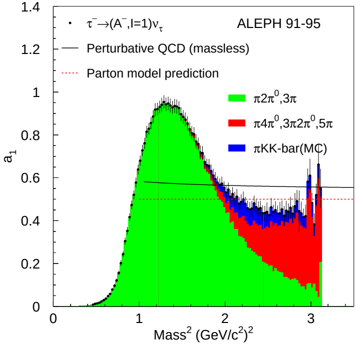
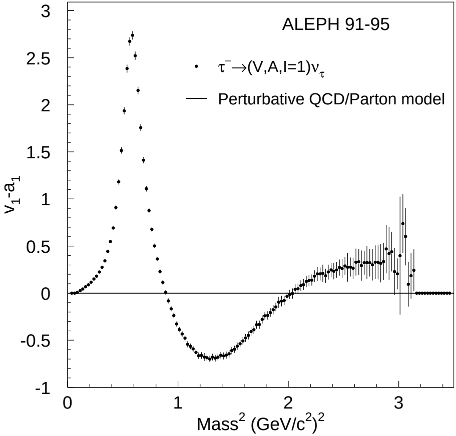
$\hookrightarrow$ Phys. Rept. 421, 191 (2005) (ALEPH):





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)

Energetically degenerate states

- consider single-particle state h, e.g. N

$\leadsto$ chiral rotation U takes it to opposite parity, but (approximately) same energy:

$$|h\rangle \to U\,|h\rangle \sim |\pi(0)\,h\rangle + \dots$$

with soft pion $\pi(0)$

$\leadsto$ single-particle state connected to many-particle state

- even more: chiral symmetry breaking fixes low-energy interaction (s-wave) between h and $\pi(p)$

$\leadsto$ Weinberg-Tomozawa (WT) interaction $\sim o(p)/F_\pi^2$

- if WT attractive in channel reached by $U\,|h\rangle$

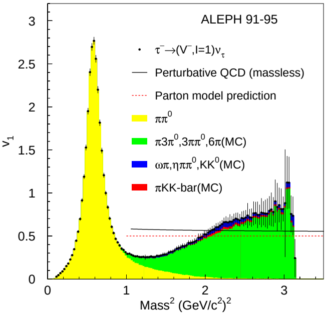
$\leadsto$ resonant structure possible in scattering of $h + \pi$

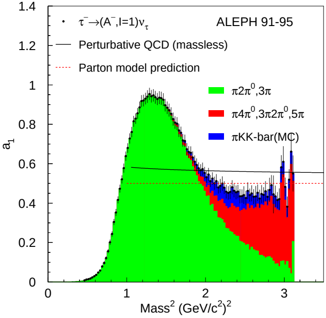
$\leadsto$ Bethe-Salpeter eq. 

Chiral partners at the level of hadrons?

- on the one hand:
  - ρ-meson in vector channel
  - a_1-meson in axial-vector channel

⇝ call ρ and a_1 chiral partners?





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- on the other hand:
  ρ-meson and (ρ + soft π) are (approximately) degenerate in energy

$\rightsquigarrow$ call ρ and ρ-π correlation chiral partners?

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$\hookrightarrow$ will show in the following: a_1 is ρ-π "molecule"

$\hookrightarrow$ more general: study nature of ρ and a_1

Nature of resonances I: ρ-meson

- experimental finding:
  isovector–vector current couples to two pions
- pions are subject to final state interactions (rescattering)
- experimental finding: resonant structure at $\approx$ 770 MeV

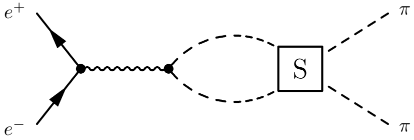
$\rightsquigarrow$ study two scenarios:
1. only final state interaction between pions
2. include in addition preformed resonance
   (quark-antiquark)

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

Scenario 1: only final state interaction

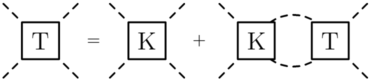
parameters in scenario 1: renormalization points

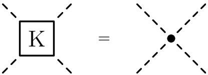
- for loop for transition from photon to hadrons



$\hookrightarrow$ renormalization point should be in reasonable range

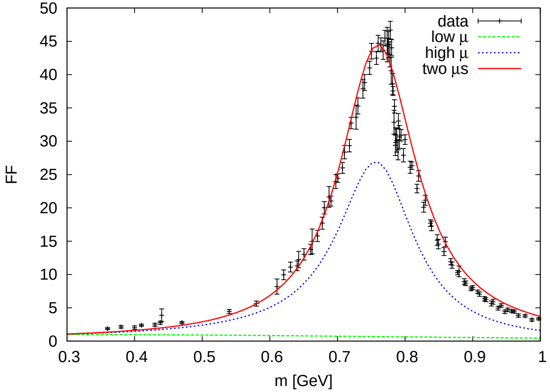
- for loop in Bethe-Salpeter equation
  (rescattering, final state interaction)





$\hookrightarrow$ renormalization point fixed
(cf. Lutz/Kolomeitsev, Nucl. Phys. A 730, 392 (2004);
Hyodo/Jido/Hosaka, arXiv:0803.2550 [nucl-th])
wrong choice introduces preformed state through backdoor

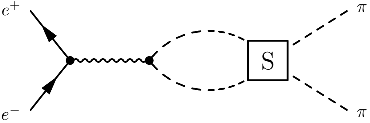
Pion form factor in scenario 1

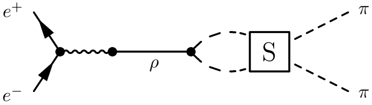


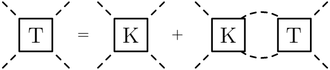
- resonance only for renormalization points in TeV range (same finding: Oller/Oset, Phys. Rev. D 60, 074023 (1999))
- no resonance for reasonable renormalization points

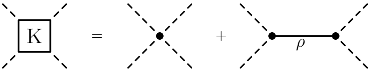
Scenario 2: in addition elementary resonance

- additional parameters:
  resonance parameters: mass and couplings to 2-π and γ^*

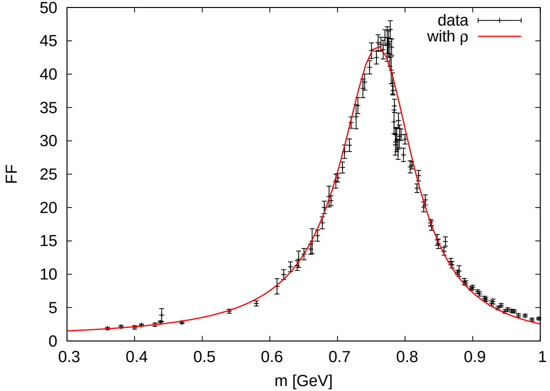








Pion form factor in scenario 2



- excellent description
- no two-peak structure since pion contact interaction weak

Nature of resonances II: a_1-meson

- experimental finding (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

$\rightsquigarrow$ study two scenarios:

1. only final state interaction between π-ρ
   (cf. Lutz/Kolomeitsev, Nucl. Phys. A 730, 392 (2004);
   Roca/Oset/Singh, Phys. Rev. D 72, 014002 (2005))
2. include in addition preformed resonance
   (quark-antiquark)

- describe final state interactions via Bethe-Salpeter eq.,
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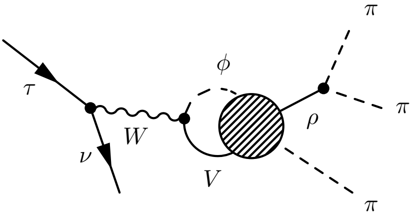
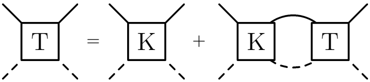
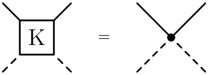


$\hookrightarrow$ renormalization point should be in reasonable range

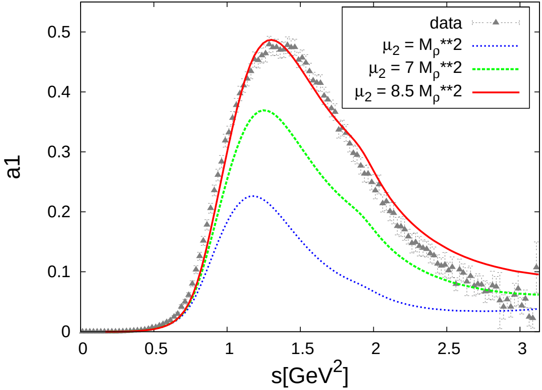
- for loop in Bethe-Salpeter equation (rescattering, final state interaction)





$\hookrightarrow$ renormalization point fixed,
wrong choice introduces preformed state through backdoor

τ decay in scenario 1

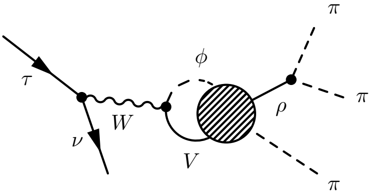


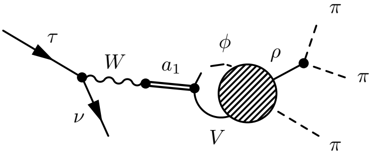
- reasonable description with one free parameter

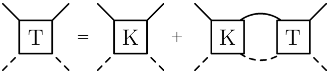
$\rightsquigarrow$ indicates that a_1 is ρ-π "molecule"
(Markus Wagner and S.L., arXiv:0801.0814 [hep-ph])

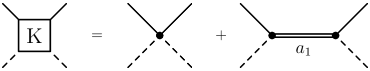
Scenario 2: in addition elementary resonance

- additional parameters:
  resonance parameters: mass and couplings to ρ-π and W

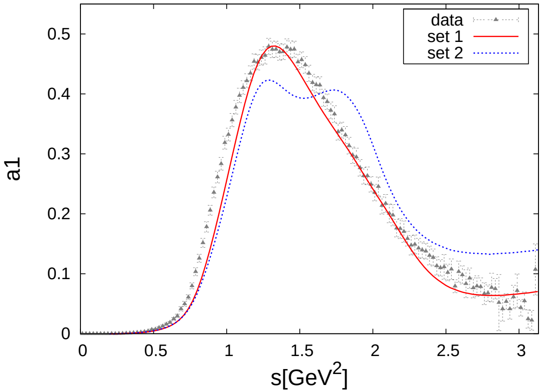








τ decay in scenario 2



- try to minimize WT, but still typically double peak structure

$\rightsquigarrow$ only with unnatural fine tuning one gets one peak (Markus Wagner and S.L., arXiv:0801.0814 [hep-ph])

Different nature of hadronic chiral partners

vector channel:

- π-π final state interaction weak
- ρ-meson is dominantly preformed state (quark-antiquark)

axial-vector channel:

- π-ρ final state interaction strong
- a_1-meson is dynamically generated (π-ρ molecule)

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) $\rightarrow$??

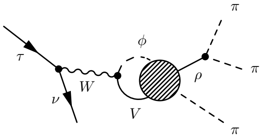
$\hookrightarrow$ scenario 2 (melting):
  - ρ-meson dissolves already in hadronic matter (precursor of deconfi nement)

  $\longrightarrow$ a_1-meson should also dissolve

  $\longrightarrow$ testable in our approach

Dissolution of the a_1-meson?

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



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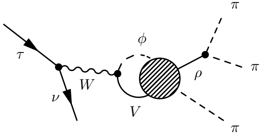
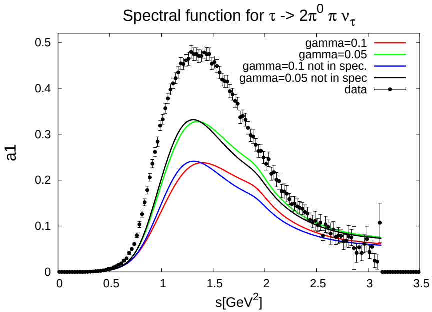




- broader ρ-meson leads to broader a_1-meson

$\hookrightarrow$ 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

Summary

Hadronic chiral partners ρ and a_1 have different nature:

- vector channel:
  - π-π final state interaction weak
  - ρ-meson is dominantly preformed state (quark-antiquark)
- axial-vector channel:
  - π-ρ final state interaction strong
  - a_1-meson is dynamically generated (π-ρ molecule)

chiral restoration (only oversimplified calculation so far):

- a_1-meson dissolves together with ρ-meson

$\hookrightarrow$ precursor of deconfinement

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

Further remarks

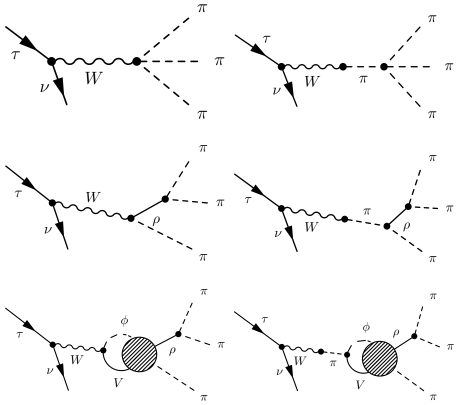
- other channels reached by chiral trafos acting on h:
  - $h = \pi$: channel of σ
  - $h = N$: channel of $N^*(1535)$
  - $h = \Delta(1232)$: channels of $N^*(1520)$, $\Delta^*(1700)$
- WT also attractive in these channels ...
  (Lutz/Kolomeitsev, PLB 585 (2004) 243)
- WT is flavor changing interaction

$\rightsquigarrow$ resonant states formed by coupled-channel dynamics

- in general strangeness important (not much for a_1)

$\rightsquigarrow$ $SU(3)$ coupled-channel dynamics

tau decay into three pions — processes



couplings fixed in lowest order by χSB

couplings fixed in lowest order from ρ decays and χSB

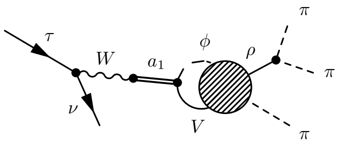
backscattering fixed in lowest order by χSB (WT)

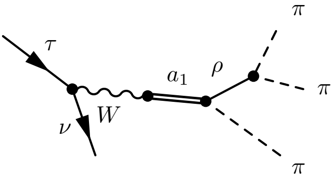
one free parameter:

regulator of loop $\hat{=}$ counter term from vertex $W\,\rho\,\pi$ (higher order term)

tau decay into three pions — processes II

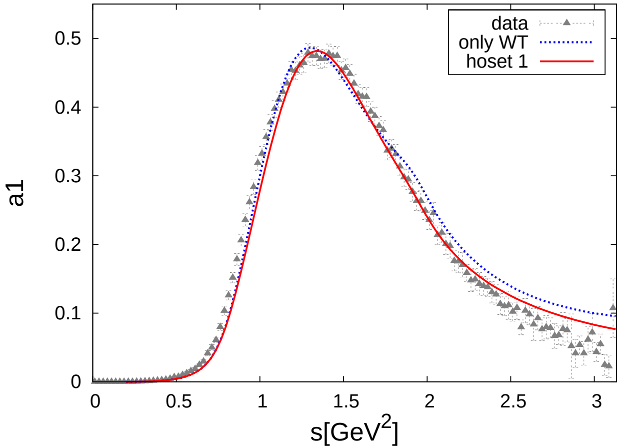
alternative scenario: include in addition





at least three additional parameters:
mass of a_1, coupling $W\, a_1$, coupling $a_1\, \rho\, \pi$

axial-vector channel: inclusion of higher order terms in rescattering kernel



more than enough parameters for fine structure

tau decay - only tree level