# Different Nature of $\rho$ and $a_1$

Stefan Leupold Markus Wagner

Justus-Liebig-Universität Giessen, Germany

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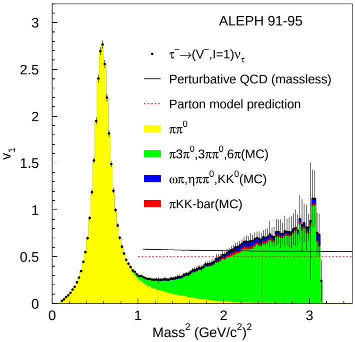
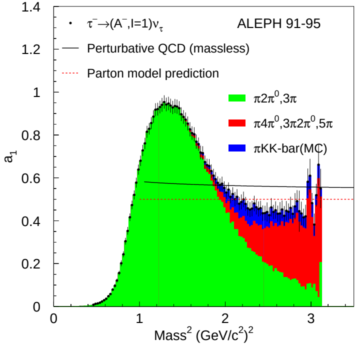
# Chiral symmetry breaking and $\tau$ decays

study decay $\tau \to \nu_\tau + \text{hadrons}$:

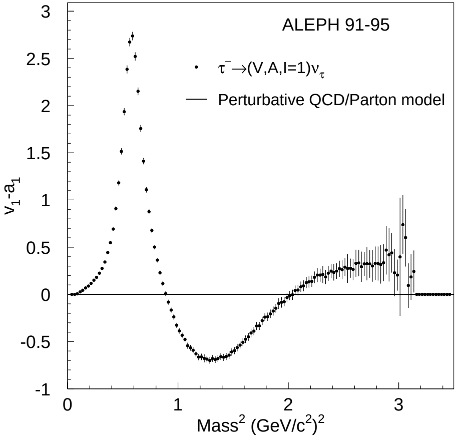
- couples to $V - A$ (weak process)
- $V$ and $A$ connected by chiral transformation
- $G$ parity: $V/A$ couples to even/odd number of pions
- $V$ and $A$ spectra are not identical:




ALEPH: Phys. Rept. 421, 191 (2005)

# One of the clearest signs of chiral symmetry breaking



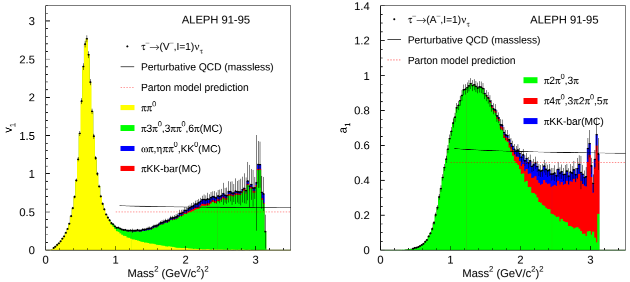

$v_1$: $\tau \to \nu_\tau + m\pi$ ($m$ even)

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

ALEPH: Phys. Rept. 421, 191 (2005)

# Nature of Resonances?

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




$\hookrightarrow$ How to understand spectra – resonances?

$\hookrightarrow$ correlations ($\pi\pi$, $\pi\rho$, $\pi\pi\pi$) or preformed states?

$\rightsquigarrow$ study nature of $\rho$ and $a_1$ with same method

# Nature of resonances I: $\rho$ 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

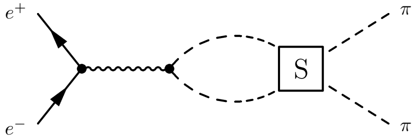
$\rightsquigarrow$ study two scenarios:
1. only final-state interaction between pions
2. include in addition preformed resonance
   (quark-antiquark)

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

# Scenario 1: only final-state interaction

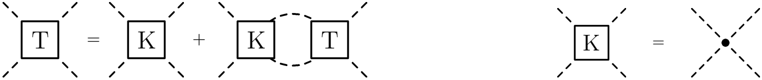
parameters in scenario 1: renormalization points

- for loop for transition from photon to hadrons



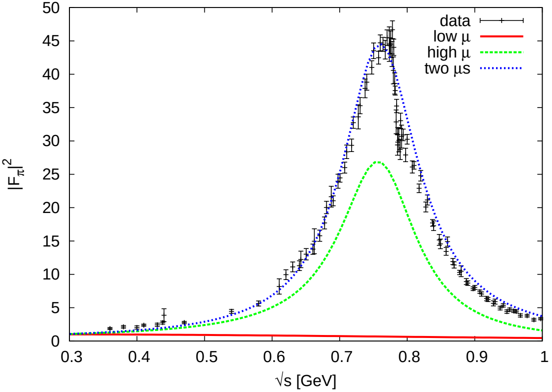

$\hookrightarrow$ renormalization point should be in reasonable range

- 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, Phys. Rev. C 78, 025203 (2008))
wrong choice introduces preformed state through backdoor

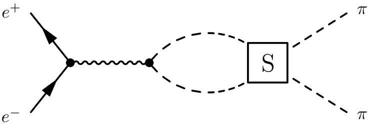
# Pion form-factor in scenario 1

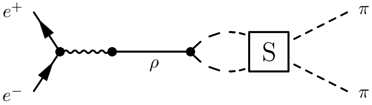


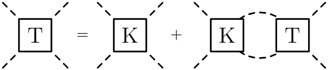

- resonance only for renormalization points in TeV range
  (same finding: Oller/Oset, Phys. Rev. D 60, 074023 (1999))
- no resonance for reasonable renormalization points

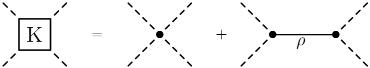
# Scenario 2: in addition elementary resonance

- additional parameters:
  resonance parameters: mass and couplings to 2-$\pi$ and $\gamma^*$

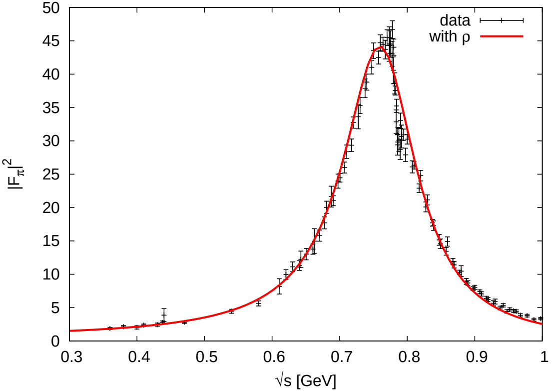


# Pion form-factor in scenario 2




- 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 $\pi$-$\rho$
- $\pi$-$\rho$ system subject to final-state interactions (rescattering)
- experimental finding: resonant structure at $\approx$ 1250 MeV

$\rightsquigarrow$ study two scenarios:

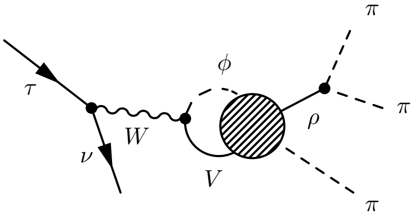
1. only final-state interaction between $\pi$-$\rho$
   (cf. Lutz/Kolomeitsev, Nucl. Phys. A 730, 392 (2004);
   Roca/Oset/Singh, Phys. Rev. D 72, 014002 (2005))
2. include in addition preformed resonance
   (quark-antiquark)

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

# Scenario 1: only final-state interaction

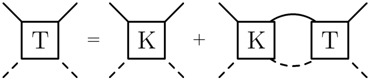
parameters in scenario 1: renormalization points

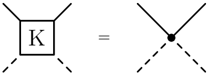
- for loop for transition from $W$ to hadrons




↪ renormalization point should be in reasonable range

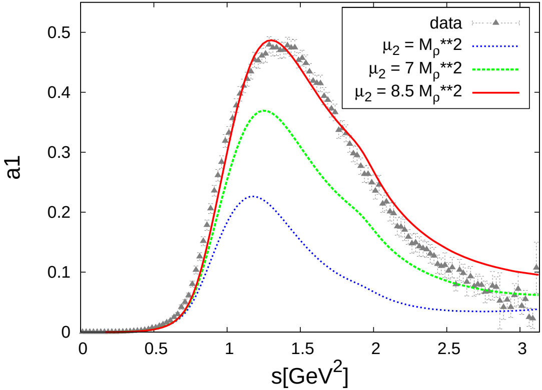
- for loop in Bethe-Salpeter equation (rescattering, final-state interaction)




↪ renormalization point fixed,
wrong choice introduces preformed state through backdoor

# $\tau$ decay in scenario 1



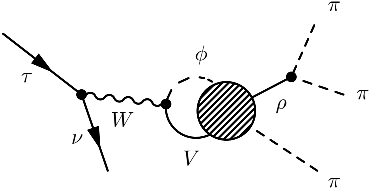

- reasonable description with one free parameter

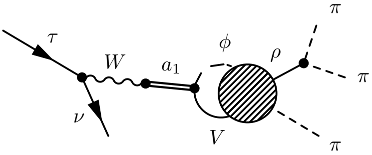
⇝ indicates that $a_1$ is $\rho$-$\pi$ “molecule”

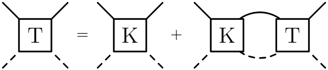
(Markus Wagner and S.L., Phys. Rev. D 78, 053001 (2008))

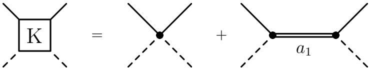
# Scenario 2: in addition elementary resonance

- additional parameters:
  resonance parameters: mass and couplings to $\rho$-$\pi$ and $W$

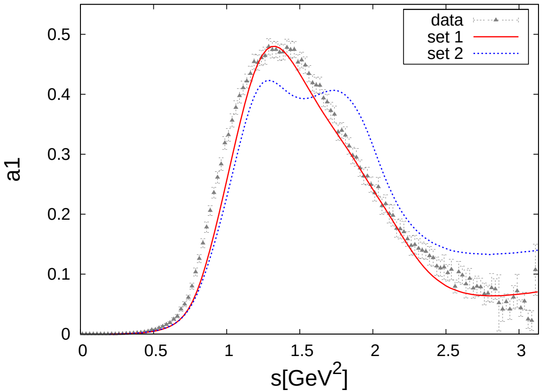


# $\tau$ decay in scenario 2




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

⇝ only with unnatural fine tuning one gets one peak
(Markus Wagner and S.L., Phys. Rev. D 78, 053001 (2008))

# Summary

results suggest:

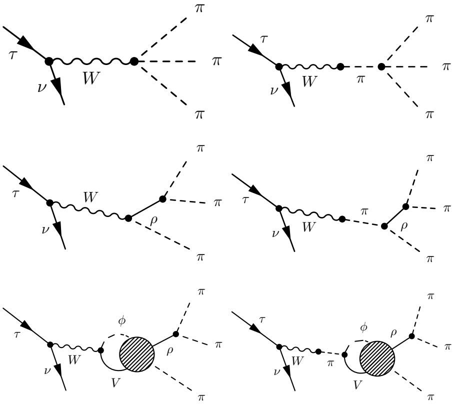
vector channel:

- $\pi$-$\pi$ final-state interaction weak
- $\rho$ meson is dominantly preformed state (quark-antiquark)

axial-vector channel:

- $\pi$-$\rho$ final-state interaction strong
- $a_1$ meson is dynamically generated ($\pi$-$\rho$ molecule)

# Backup: tau decay into three pions




couplings fixed in lowest order by $\chi$SB

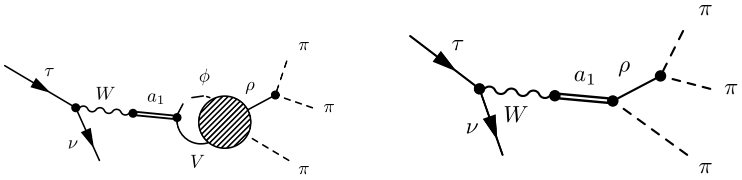
couplings fixed in lowest order from $\rho$ decays and $\chi$SB

backscattering fixed in lowest order by $\chi$SB (WT)

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

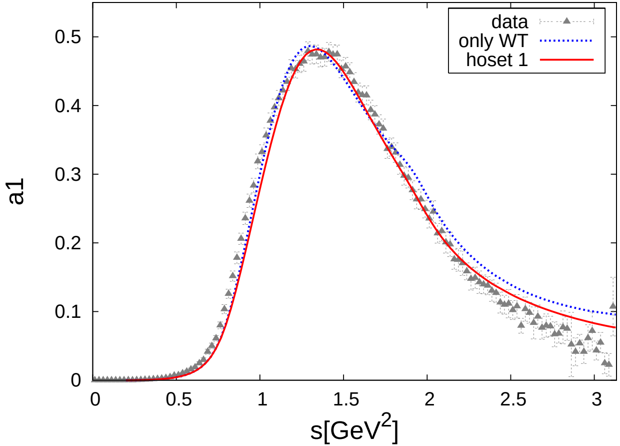
# tau decay into three pions — processes II

alternative scenario: include in addition




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

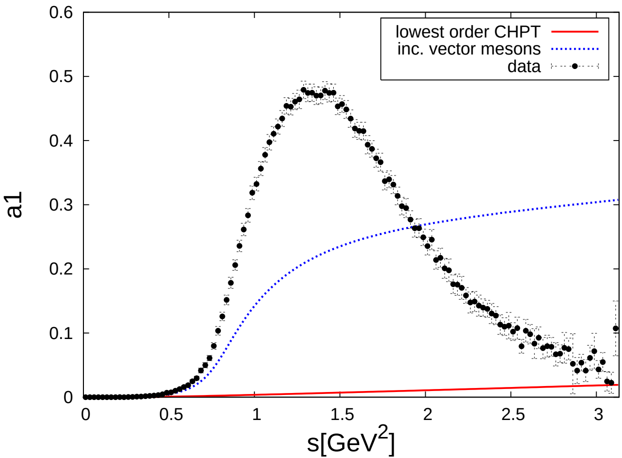
# axial-vector channel: inclusion of higher-order terms in rescattering kernel




more than enough parameters for fine structure

(Markus Wagner and S.L., Phys. Rev. D 78, 053001 (2008))

# tau decay — only tree level

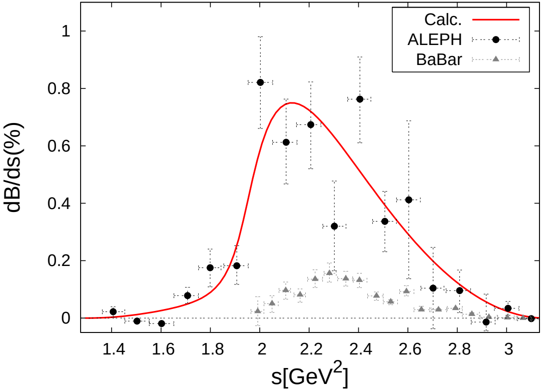



(Markus Wagner and S.L., Phys. Rev. D 78, 053001 (2008))

# decay channel $\tau \rightarrow K\,\bar{K}\,\pi\,\nu_\tau$

- coupled-channel calculation includes besides $\pi\rho$ also $K^*\,\bar{K}$, $K\,\bar{K}^*$

$\hookrightarrow$ can also study axial-vector part of $K\,\bar{K}^* \rightarrow K\,\bar{K}\,\pi$




(Markus Wagner and S.L., Phys. Lett. B 670, 22 (2008))