τ-Decay and Hadronic Spectral Functions

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GOETHE UNIVERSITÄT FRANKFURT AM MAIN

H-QM Helmholtz Research School Quark Matter Studies

Motivation

- not all low energy resonances can be explained within the constituent quark picture
- too many observed states and some of them even have exotic quantum numbers
- broad resonances and blurred thresholds, mixing of states with same quantum numbers
- for example: a_1 meson $J^{PC} = 1^{++}$ at around 1.2 GeV
  - i) mass and decay width?
  - ii) chiral partner of the ρ meson or just a $\rho\pi$ molecule-like state? Wagner Leupold [arXiv:hep-ph/0801.0814]
- what about the other interactions that govern the phenomenology of our low energy color neutral objects?

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- what about the other interactions that govern the phenomenology of our low energy color neutral objects?
- in the constituent quark picture mesons are color neutral composite objects of quark and antiquark
- reduce complexity of QCD interaction by effective hadron hadron interaction in models with hadronic dofs and symmetries known from the QCD Lagrangian.

$$\mathscr{L} = \mathscr{L}_{\text{meson}} + \mathscr{L}_{\text{baryon}} + \mathscr{L}_{\text{dilaton}} + \mathscr{L}_{\text{weak}}$$

$$\begin{aligned}
\mathscr{L}_{\text{meson}} = & \operatorname{Tr}[(D_\mu\Phi)^\dagger(D^\mu\Phi)] - m_0^2 \operatorname{Tr}(\Phi^\dagger\Phi) - \lambda_1[\operatorname{Tr}(\Phi^\dagger\Phi)]^2 - \lambda_2 \operatorname{Tr}(\Phi^\dagger\Phi)^2 \\
& + c_1(\det\Phi - \det\Phi^\dagger)^2 + \operatorname{Tr}[H(\Phi+\Phi^\dagger)] - \frac{1}{4}\operatorname{Tr}(L_{\mu\nu}^2 + R_{\mu\nu}^2) \\
& + \operatorname{Tr}\left[\left(\frac{m_1^2}{2} + \Delta\right)(L_\mu^2 + R_\mu^2)\right] + \frac{g_2}{2}(\operatorname{Tr}\{L_{\mu\nu}[L^\mu, L^\nu]\} + \operatorname{Tr}\{R_{\mu\nu}[R^\mu, R^\nu]\}) \\
& + \frac{h_1}{2}\operatorname{Tr}(\Phi^\dagger\Phi)\operatorname{Tr}(L_\mu^2 + R_\mu^2) + h_2 \operatorname{Tr}[(L_\mu\Phi)^2 + (\Phi R_\mu)^2] + 2h_3 \operatorname{Tr}(L_\mu \Phi R^\mu \Phi^\dagger) \\
& + \text{chirally invariant vector and axialvector four-point interaction vertices}
\end{aligned}$$

$$\begin{aligned}
\mathscr{L}_{\text{baryon}} = & \bar{\Psi}_{1L} i\gamma_\mu D_{1L}^\mu \Psi_{1L} + \bar{\Psi}_{1R} i\gamma_\mu D_{1R}^\mu \Psi_{1R} + \bar{\Psi}_{2L} i\gamma_\mu D_{2R}^\mu \Psi_{2L} + \bar{\Psi}_{2R} i\gamma_\mu D_{2L}^\mu \Psi_{2R} \\
& - \hat{g}_1(\bar{\Psi}_{1L}\Phi\Psi_{1R} + \bar{\Psi}_{1R}\Phi\Psi_{1L}) - \hat{g}_2(\bar{\Psi}_{2L}\Phi^\dagger\Psi_{2R} + \bar{\Psi}_{2R}\Phi^\dagger\Psi_{2L}) \\
& - M(\bar{\Psi}_{1L}\Psi_{2R} - \bar{\Psi}_{1R}\Psi_{2L} - \bar{\Psi}_{2L}\Psi_{1R} - \bar{\Psi}_{2R}\Psi_L)
\end{aligned}$$

$$\mathscr{L}_{\text{dilaton}} = \frac{1}{2}(\partial^\mu G)^2 - \frac{1}{4}\frac{m_{\text{G}}}{\Lambda^2}\left(G^4 ln\left|\frac{G}{\Lambda}\right| - \frac{G^4}{4}\right)$$

$$\begin{aligned}
\mathscr{L}_{\text{weak}} = & \delta_{\text{w}} \frac{g\cos\theta_C}{2}\operatorname{Tr}[W_{\mu\nu}L^{\mu\nu}] + \delta_{\text{em}}\frac{e}{2}\operatorname{Tr}[B_{\mu\nu}R^{\mu\nu}] + \frac{1}{4}\operatorname{Tr}[(W^{\mu\nu})^2 + (B^{\mu\nu})^2] \\
& + \frac{g}{2\sqrt{2}}\left(W_\mu^- \bar{u}_{\nu_\tau}\gamma_\mu(1-\gamma_5)u_\tau + \text{h.c.}\right)
\end{aligned}$$

$N_F = 2$ and $N_F = 3$ meson multiplets:

(Pseudo-)Scalars $\Phi_{ij} \simeq < q_L \bar{q}_R >_{ij} \simeq \frac{1}{\sqrt{2}}(q_i \bar{q}_j - q_i \gamma_5 \bar{q}_j)$

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{(\sigma_N + a_0^0)}{\sqrt{2}} + \frac{i(\eta_N + \pi^0)}{\sqrt{2}} & a_0^+ + i\pi^+ & K_0^{\star +} + iK^+ \\ a_0^- + i\pi^- & \frac{(\sigma_N - a_0^0)}{\sqrt{2}} + \frac{i(\eta_N - \pi^0)}{\sqrt{2}} & K_0^{\star 0} + iK^0 \\ K_0^{\star -} + iK^- & \bar{K}_0^{\star 0} + i\bar{K}^0 & \sigma_S + i\eta_S \end{pmatrix}$$

Lefthanded $L^\mu_{ij} \simeq < q_L \bar{q}_L >_{ij} \simeq \frac{1}{\sqrt{2}}(q_i \gamma^\mu \bar{q}_j + q_i \gamma_5 \gamma^\mu \bar{q}_j)$

$$L^\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\omega_N + \rho^0}{\sqrt{2}} + \frac{f_{1N} + a_1^0}{\sqrt{2}} & \rho^+ + a_1^+ & K^{\star +} + K_1^+ \\ \rho^- + a_1^- & \frac{\omega_N - \rho^0}{\sqrt{2}} + \frac{f_{1N} - a_1^0}{\sqrt{2}} & K^{\star 0} + K_1^0 \\ K^{\star -} + K_1^- & \bar{K}^{\star 0} + \bar{K}_1^0 & \omega_S + f_{1S} \end{pmatrix}^\mu$$

Righthanded $R^\mu_{ij} \simeq < q_R \bar{q}_R >_{ij} \simeq \frac{1}{\sqrt{2}}(q_i \gamma^\mu \bar{q}_j - q_i \gamma_5 \gamma^\mu \bar{q}_j)$

$$R^\mu = \frac{1}{\sqrt{2}} \begin{pmatrix} \frac{\omega_N + \rho^0}{\sqrt{2}} - \frac{f_{1N} + a_1^0}{\sqrt{2}} & \rho^+ - a_1^+ & K^{\star +} - K_1^+ \\ \rho^- - a_1^- & \frac{\omega_N - \rho^0}{\sqrt{2}} - \frac{f_{1N} - a_1^0}{\sqrt{2}} & K^{\star 0} - K_1^0 \\ K^{\star -} - K_1^- & \bar{K}^{\star 0} - \bar{K}_1^0 & \omega_S - f_{1S} \end{pmatrix}^\mu$$

Mesonic Lagrangian with Global Chiral Symmetry

D. Parganlija, F. Giacosa and D. H. Rischke, Phys. Rev. D 82 (2010) 054024 arXiv:1003.4934 [hep-ph]
D. Parganlija, P. Kovacs, G. Wolf, F. Giacosa and D. H. Rischke, arXiv:1208.0585 [hep-ph]

Global Chiral Symmetry:

$$\begin{aligned}\mathscr{L}_{\mathrm{meson}} &= \mathrm{Tr}[(D_\mu\Phi)^\dagger(D^\mu\Phi)] - m_0^2\,\mathrm{Tr}(\Phi^\dagger\Phi) - \lambda_1[\mathrm{Tr}(\Phi^\dagger\Phi)]^2 - \lambda_2\,\mathrm{Tr}(\Phi^\dagger\Phi)^2 \\ &+ c_1(\det\Phi - \det\Phi^\dagger)^2 + \mathrm{Tr}[H(\Phi+\Phi^\dagger)] - \frac{1}{4}\mathrm{Tr}(L_{\mu\nu}^2 + R_{\mu\nu}^2) \\ &+ \mathrm{Tr}\left[\left(\frac{m_1^2}{2}+\Delta\right)(L_\mu^2 + R_\mu^2)\right] + \frac{g_2}{2}(\mathrm{Tr}\{L_{\mu\nu}[L^\mu, L^\nu]\} + \mathrm{Tr}\{R_{\mu\nu}[R^\mu, R^\nu]\}) \\ &+ \text{ch. inv. 4-point interactions among (pseudo-)scalars and (axial-)vectors}\end{aligned}$$

$U(N_F)_L \times U(N_F)_R$ Transformation:

$$\Phi \rightarrow U_L \Phi U_R^\dagger\,,\;\; L^\mu \rightarrow U_L L^\mu U_L^\dagger\,,\;\; R^\mu \rightarrow U_R R^\mu U_R^\dagger$$

Covariant Derivative:

$$D^\mu\Phi = \partial^\mu\Phi - ig_1\left(L^\mu\Phi - \Phi R^\mu\right)$$

Explicit Breaking of Chiral Symmetry

D. Parganlija, F. Giacosa and D. H. Rischke, Phys. Rev. D 82 (2010) 054024 arXiv:1003.4934 [hep-ph]

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$U(1)_A$-Anomaly

$$c_1 (\det \Phi - \det \Phi^\dagger)^2$$

non-vanishing quark masses, NO isospin breaking

$$\operatorname{Tr}[H(\Phi + \Phi^\dagger)]\,, \quad H = h_a t^a$$

remaining symmetry is $U(2)_V$

Spontaneous Breaking of Chiral Symmetry

D. Parganlija, F. Giacosa and D. H. Rischke, Phys. Rev. D 82 (2010) 054024 arXiv:1003.4934 [hep-ph]
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Spontaneous breaking of global chiral symmetry by non-zero scalar condensate

$$\sigma \to \sigma + \phi, \quad \phi = Z f_\pi$$

i) $m_\rho^2 = m_1^2 + \frac{\phi^2}{2}(h_1 + h_2 + h_3)\ , \quad m_{a_1}^2 = m_1^2 + (g_1\phi)^2 + \frac{\phi^2}{2}(h_1 + h_2 - h_3)$

ii) 3 point interaction vertices and mixing terms in $(D^\mu\Phi)^\dagger D_\mu\Phi$ that are proportional to the VEV ϕ.

$U(2)_L \times U(2)_R$ Symmetry in the Baryonic Sector

S. Gallas, F. Giacosa and D. H. Rischke, Phys. Rev. D 82 (2010) 014004 arXiv:0907.5084 [hep-ph]

S. Gallas, F. Giacosa and G. Pagliara, Nucl. Phys. A 872 (2011) 13 arXiv:1105.5003 [hep-ph]

Baryons in the mirror assignment:

$$\begin{aligned}\mathscr{L}_{\text{baryon}} &= \bar{\Psi}_{1L} i\gamma_\mu D^\mu_{1L}\Psi_{1L} + \bar{\Psi}_{1R} i\gamma_\mu D^\mu_{1R}\Psi_{1R} + \bar{\Psi}_{2L} i\gamma_\mu D^\mu_{2R}\Psi_{2L} + \bar{\Psi}_{2R} i\gamma_\mu D^\mu_{2L}\Psi_{2R} \\ &- \hat{g}_1(\bar{\Psi}_{1L}\Phi\Psi_{1R} + \bar{\Psi}_{1R}\Phi\Psi_{1L}) - \hat{g}_2(\bar{\Psi}_{2L}\Phi^\dagger\Psi_{2R} + \bar{\Psi}_{2R}\Phi^\dagger\Psi_{2L}) \\ &- M(\bar{\Psi}_{1L}\Psi_{2R} - \bar{\Psi}_{1R}\Psi_{2L} - \bar{\Psi}_{2L}\Psi_{1R} - \bar{\Psi}_{2R}\Psi_{L})\end{aligned}$$

$U(2)_L \times U(2)_R$ Transformation	Covariant Derivative
$\Psi_{1\mathrm{R}} \to U_R\Psi_{1\mathrm{R}}\,,\ \Psi_{1\mathrm{L}} \to U_L\Psi_{1\mathrm{L}}$	$D^\mu_{1\mathrm{R}} = \partial^\mu - ic_1R^\mu\,,\ D^\mu_{1\mathrm{L}} = \partial^\mu - ic_1L^\mu$
$\Psi_{2\mathrm{R}} \to U_L\Psi_{2\mathrm{R}}\,,\ \Psi_{2\mathrm{L}} \to U_R\Psi_{2\mathrm{L}}$	$D^\mu_{2\mathrm{R}} = \partial^\mu - ic_2R^\mu\,,\ D^\mu_{2\mathrm{L}} = \partial^\mu - ic_2L^\mu$

- allows for chirally invariant mass term generated by the gluon and/or tetraquark condensate
- Nucleons N, N^* are real chiral partners $N(1650)$ is favoured as chiral partner of $N(939)$
- yields correct nuclear matter saturation

Scale Invariance and the Glueball

S. Janowski, D. Parganlija, F. Giacosa and D. H. Rischke, Phys. Rev. D 84 (2011) 054007 arXiv:1103.3238 [hep-ph]

Scale invariance of the QCD Lagrangian is broken on the quantum level

$$\mathscr{L}_{\text{dilaton}} = \frac{1}{2}(\partial^\mu G)^2 - \frac{1}{4}\frac{m_G}{\Lambda^2}\left(G^4 ln\left|\frac{G}{\Lambda}\right| - \frac{G^4}{4}\right)$$

LσM is in principle scale invariant, only mass terms and $U(1)_A$-anomaly break scale invariance

$$x^\mu \to \lambda^{-1}x^\mu\,,\ \varphi(x) \to \lambda\varphi(\lambda^{-1}x)\,,\ \Psi(x) \to \lambda^{\frac{3}{2}}\Psi(\lambda^{-1}x)$$

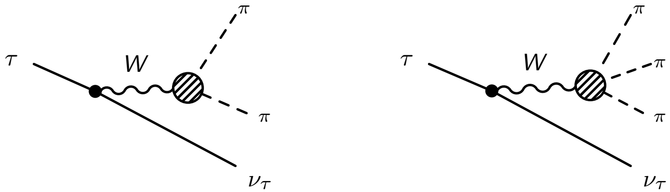
Scalar glueball is associated with fluctuations of the dilaton potential

Ground state of dilaton G_0 is related to the gluon condensate $G_0 = \Lambda = \frac{\sqrt{11}}{2m_G}C^2$

- favours $q\bar{q}$ interpretation of $f_0(1370)$ as chiral partner of the pion ($f_0(500)$ is disfavoured) and $f_0(1500)$ is 75% glueball
- scale invariance extended to $\mathscr{L}_{\text{meson}}, \mathscr{L}_{\text{baryon}}$ by parametrization of meson and baryon masses by G

τ-Decay

- semileptonic τ-decay involves strong and weak interactions



- describe effective electroweak interactions of hadrons in the vacuum.
- results can be further used to perform calculations at nonzero temperature and density (e.g. dilepton decay rate) and to understand more about the nature of resonances such as a_1, e.g. $\bar{q}q$ or $\rho\pi$-state?

Linear Sigma Model with Weak Interaction

$$\mathscr{L}_{\text{weak}} = \text{Tr}[(D_\mu \Phi)^\dagger (D^\mu \Phi)] + \delta_w \frac{g \cos\theta_C}{2} \text{Tr}[W_{\mu\nu} L^{\mu\nu}] + \delta_{em} \frac{e}{2} \text{Tr}[B_{\mu\nu} R^{\mu\nu}]$$
$$+ \frac{1}{4} \text{Tr}[(W^{\mu\nu})^2 + (B^{\mu\nu})^2] + \frac{g}{2\sqrt{2}} \left(W_\mu^- \bar{u}_{\nu_\tau} \gamma_\mu (1-\gamma_5) u_\tau + \text{h.c.} \right)$$

local $SU(2)_L \times U(1)_Y$ transformation:

$$\Phi \to U_L \Phi U_Y^\dagger \ , \ L^\mu \to U_L L^\mu U_L^\dagger \, , \ R^\mu \to U_Y R^\mu U_Y^\dagger$$
$$W^\mu \to U_L W^\mu U_L^\dagger + \frac{i}{g} U_L \partial^\mu U_L^\dagger \, , \ B^\mu \to U_Y B^\mu U_Y^\dagger + \frac{i}{g'} U_Y \partial^\mu U_Y^\dagger$$

Cabibbo mixing ($N_f = 2$): $\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$

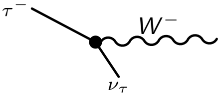
Weinberg mixing $\begin{pmatrix} W_3^\mu \\ B^\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} Z_0^\mu \\ A^\mu \end{pmatrix}$

covariant derivative and field strength tensors:

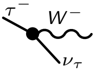
$$D^\mu \Phi \equiv \partial^\mu \Phi - i g_1 (L^\mu \Phi - \Phi R^\mu) - ie[A^\mu t_3, \Phi] - ig \cos\theta_C (W_1^\mu t_1 + W_2^\mu t_2)\Phi$$
$$- ig \cos\theta_W (Z^\mu \Phi + \tan^2\theta_W \Phi Z^\mu)$$
$$L^{\mu\nu} \equiv \partial^\mu L^\nu - ie[A^\mu t_3, L^\nu] - ig[W_1^\mu t_1 + W_2^\mu t_2, L^\nu]$$
$$- \{\partial^\nu L^\mu - ie[A^\nu t_3, L^\mu] - ig[W_1^\nu t_1 + W_2^\nu t_2, L^\mu]\}$$

Vector Channel

Common to all channels is the process:

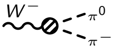


$$\Gamma_{\tau^- \to W^- 2\nu_\tau}(s) \sim \frac{|p(m_\tau^2, s, m_\nu^2)|}{m_\tau^2} \left| \text{[diagram]} \right|^2$$

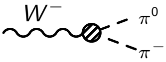


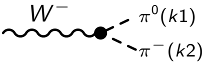
Vector Channel

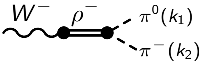
$$\Gamma_{W^- \to \pi^- 2\pi^0}(s) \sim \frac{1}{s} \left| \text{[diagram]} \right|^2 |p(s, m_\pi)|$$



$$\left| \text{[diagram]} \right|^2 = \left| \text{[diagram]} + \text{[diagram]} \right|^2$$

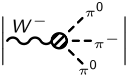


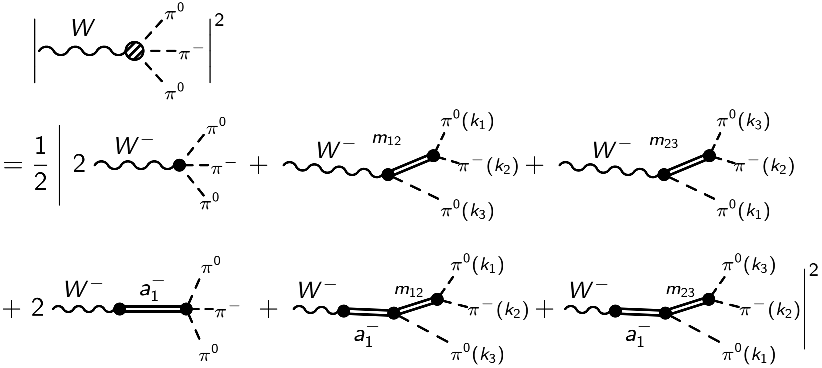




Axial-Vector Channel

$$\Gamma_{W^-\to\pi^-2\pi^0}(s) \sim \frac{1}{s}\frac{2}{2\cdot 3}\int \left| \quad \right|^2 dm_{12}^2\, dm_{23}^2$$





Axial-Vector Channel

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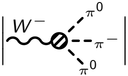
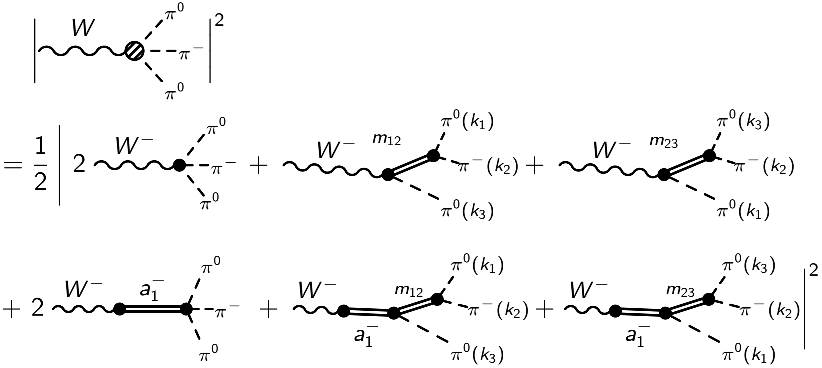


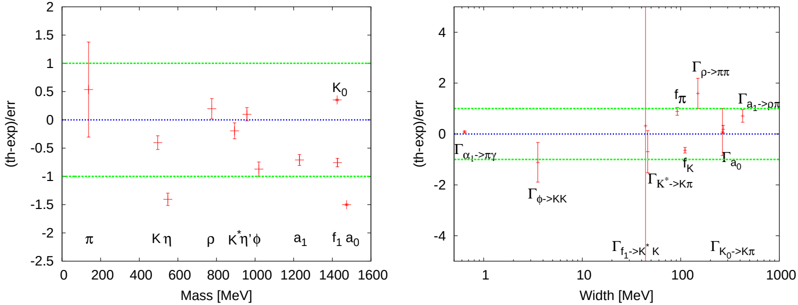


- $\Gamma(W^- \to \pi^- 2\pi^0) \simeq 1\%$ and $\Gamma(a_1^- \to \pi^- 2\pi^0) \simeq 1\%$
- in principle also contributions of σ resonance $\Gamma_{W\to\sigma 2\pi^0\pi^-} \simeq 0$

Quest for the Parameters

D. Parganlija, P. Kovacs, Gy. Wolf, F. Giacosa, D.H. Rischke

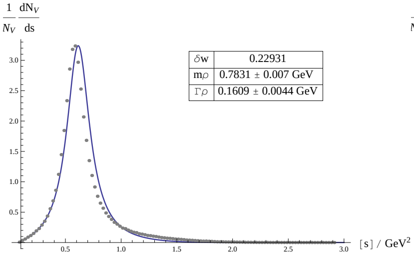
Scalar mesons in a linear sigma model with (axial-)vector mesons

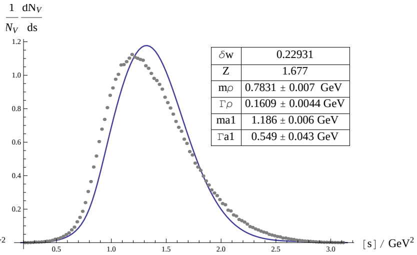


[arXiv:hep-ph/1208.0585]

- global fit of 13 parameters; test model
- 21 decay widths and masses

Results with $m_\rho, \Gamma_\rho, m_{a_1}, \Gamma_{a_1}$ and pion renormalisation constant Z as obtained from $N_f = 3$





- Only one free parameter δ_w which describes the mixing between the charged weak bosons and the (axial-)vector mesons!
- $\Gamma_{\rho^- \to \pi^- \pi^0}$, $\Gamma_{a_1^- \to \rho^- \pi^-}$
- We wanted to know if ρ and a_1 can be described as chiral partners. Yes!

  $W\rho$ mixing $\sim \delta_w s$ $\qquad$ Wa_1 mixing $\sim (\delta_w s + g_1 \phi^2)$
- the parameters have errors within range $\sim 5\%$ therefore we can still improve our results

Inclusive Spectral Functions VMA and VPA

- Starting values have a strong effect on results in each channel.

$\rightarrow$ inclusive spectral functions

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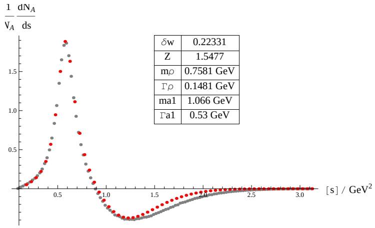
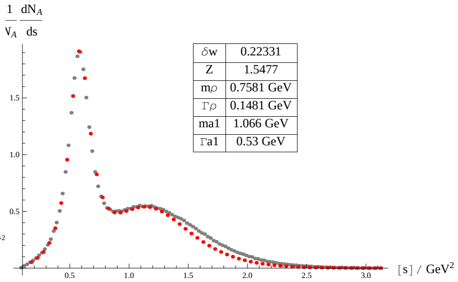


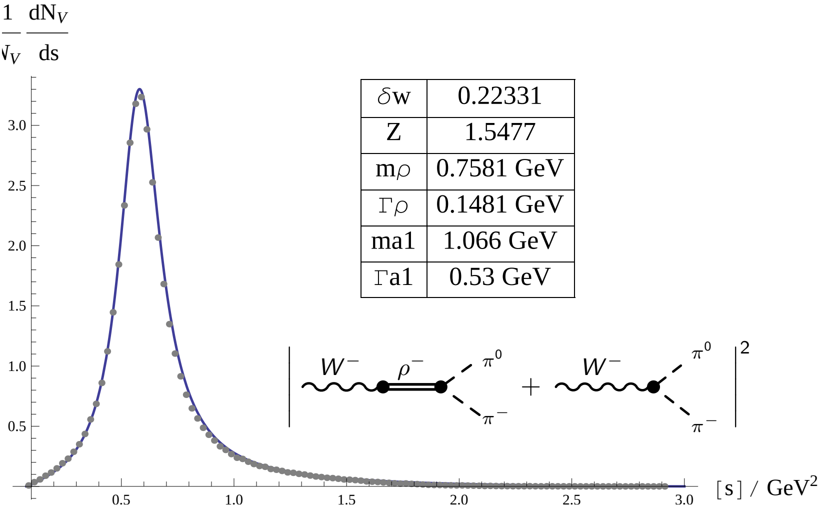
$V - A$



$V + A$

Vector Channel Spectral Function $\tau \to 2\pi\nu_\tau$

Coherent sum $|W \xrightarrow{\text{direct}} 2\pi + W \xrightarrow{\rho} 2\pi|^2$

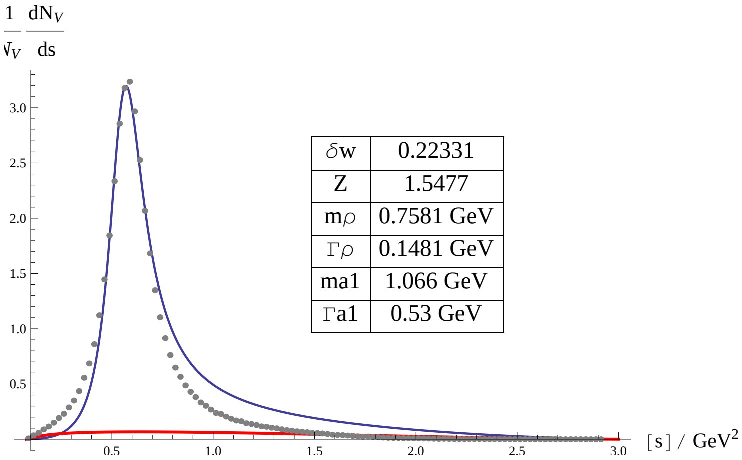


δw	0.22331
Z	1.5477
mρ	0.7581 GeV
$\Gamma\rho$	0.1481 GeV
ma1	1.066 GeV
Γa1	0.53 GeV

Vector Channel Spectral Function $\tau \to \pi^-\pi^0\nu_\tau$

Isolated contributions $W^- \to \pi^-\pi^0$ and $W^- \to \rho^- \to \pi^-\pi^0$

$$\frac{\Gamma(W^- \to \pi^-\pi^0)}{\Gamma(W^- \to \rho^- \to \pi^-\pi^0)} \simeq 0.02$$



δw	0.22331
Z	1.5477
mρ	0.7581 GeV
$\Gamma\rho$	0.1481 GeV
ma1	1.066 GeV
Γa1	0.53 GeV

Vector Decay Constant

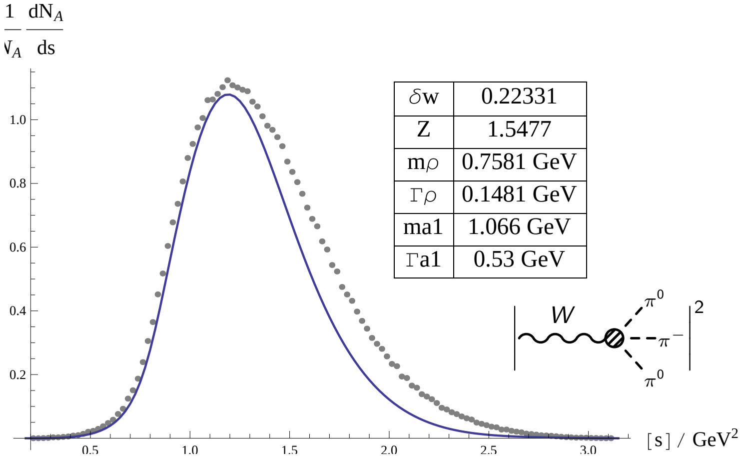
- Vector Decay Constant f_ρ: $< 0|j^\mu\,|\rho^\mu >= m_\rho f_\rho \varepsilon^\mu$
- describes mixing of the ρ meson with the vector current,
- weak coupling with vector meson $\frac{g\cos\theta_C}{2}\delta_w s$

$\rightarrow$ $f_\rho m_\rho = \sqrt{2}\delta_w m_\rho$

- $f_\rho^{\text{exp.}} \sim 214$ MeV , $f_\rho^{\text{L}\sigma\text{M}} = 239$ MeV
- Also this result can be improved by including direct contributions in the axial-vector channel.

Axial Vector Channel Spectral Function $\tau^- \to \pi^- 2\pi^0 + \pi^+ 2\pi^- \nu_\tau$

Coherent Sum $|W^- \to \rho\pi \to 3\pi + W \xrightarrow{a_1} \rho\pi \to 3\pi|^2$



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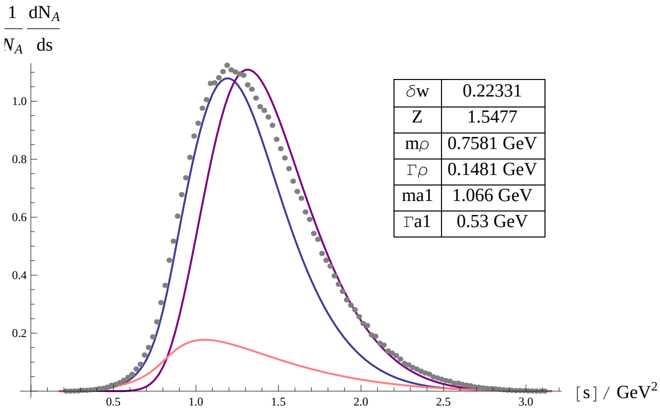
Axial Vector Channel Spectral Function $\tau^- \rightarrow \pi^- 2\pi^0 + \pi^+ 2\pi^- \nu_\tau$

Isolated contributions $W^- \rightarrow \pi^- \pi^0$ and $W^- \rightarrow \rho^- \rightarrow \pi^- \pi^0$

$$\frac{\Gamma(W^- \xrightarrow{\text{direct}} \pi^- 2\pi^0)}{\Gamma(W^- \xrightarrow{\text{coh.}} \rho^- \pi^0 \rightarrow \pi^- 2\pi^0)} \simeq 0.02$$



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Conclusion

- We described the decay of the τ lepton in an effective hadronic model
- Can we use effective chiral models to describe the phenomenology of the low energy resonances? Yes!
  When the model is comprehensive enough.
- Is a_1 a $\bar{q}q$ state? Yes!
- Are ρ and a_1 chiral partners? Yes!
  Very nice example of Vector Meson Dominance.