Why (light) meson decays are interesting

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Workshop on meson decays at CLAS – Jefferson Lab 5 August 2012

Outline

The big picture

- This talk: introduction and pep talk
- Three main motivations:
  - Understanding QCD (almost 40 years old now)

$$\mathcal{L}_{QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + \sum_q \overline{q}\gamma^\mu \left(\partial_\mu - \frac{i}{2} g_S \lambda^a G^a_\mu\right) q$$

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - i g_S f^{abc} G^b_\nu G^c_\nu$$

  - Determining standard model parameters precisely
  - Testing/finding effects beyond the standard model
- Some examples of all will be mentioned
- Understanding QCD needed for the other two
- I will not talk about D, B, J/ψ, Υ,...

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Mesons are *simple*

- Made of a quark and anti-quark
- So these we should really understand in detail
- In order of difficulty:
  - Static properties: mass,...
  - Dynamic properties: formfactors
  - Dynamic properties: decays and scattering

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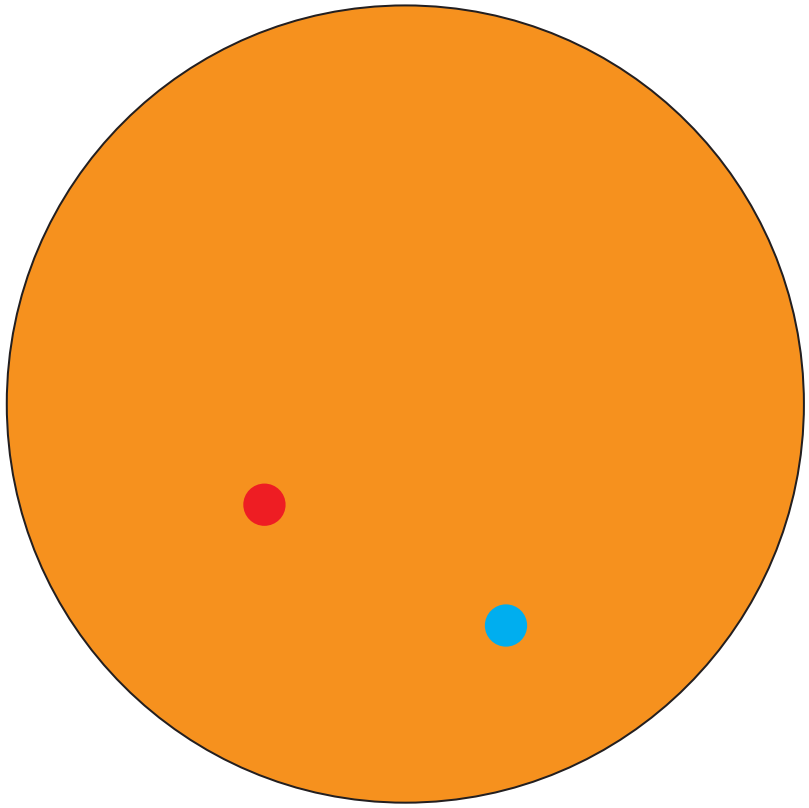
- quark-antiquark
- add gluons
- Formfactor
- Two body decay



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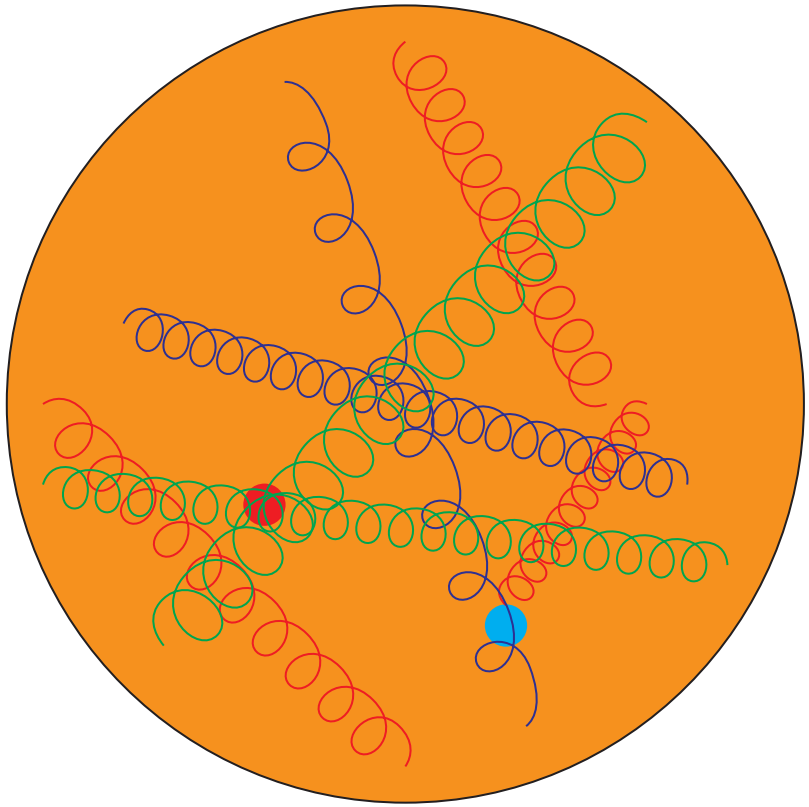

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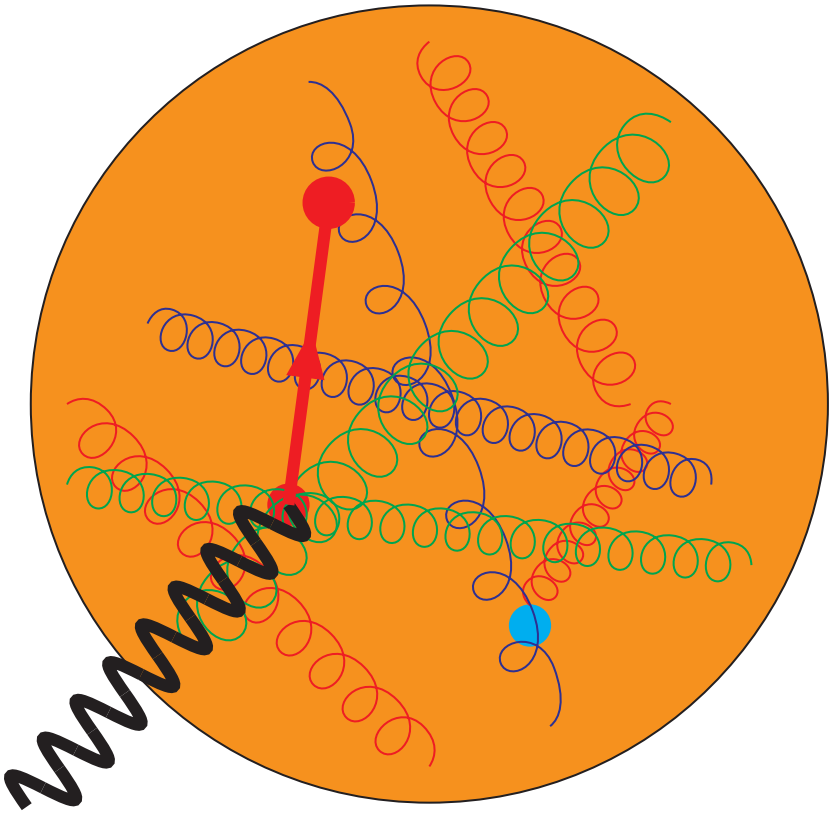

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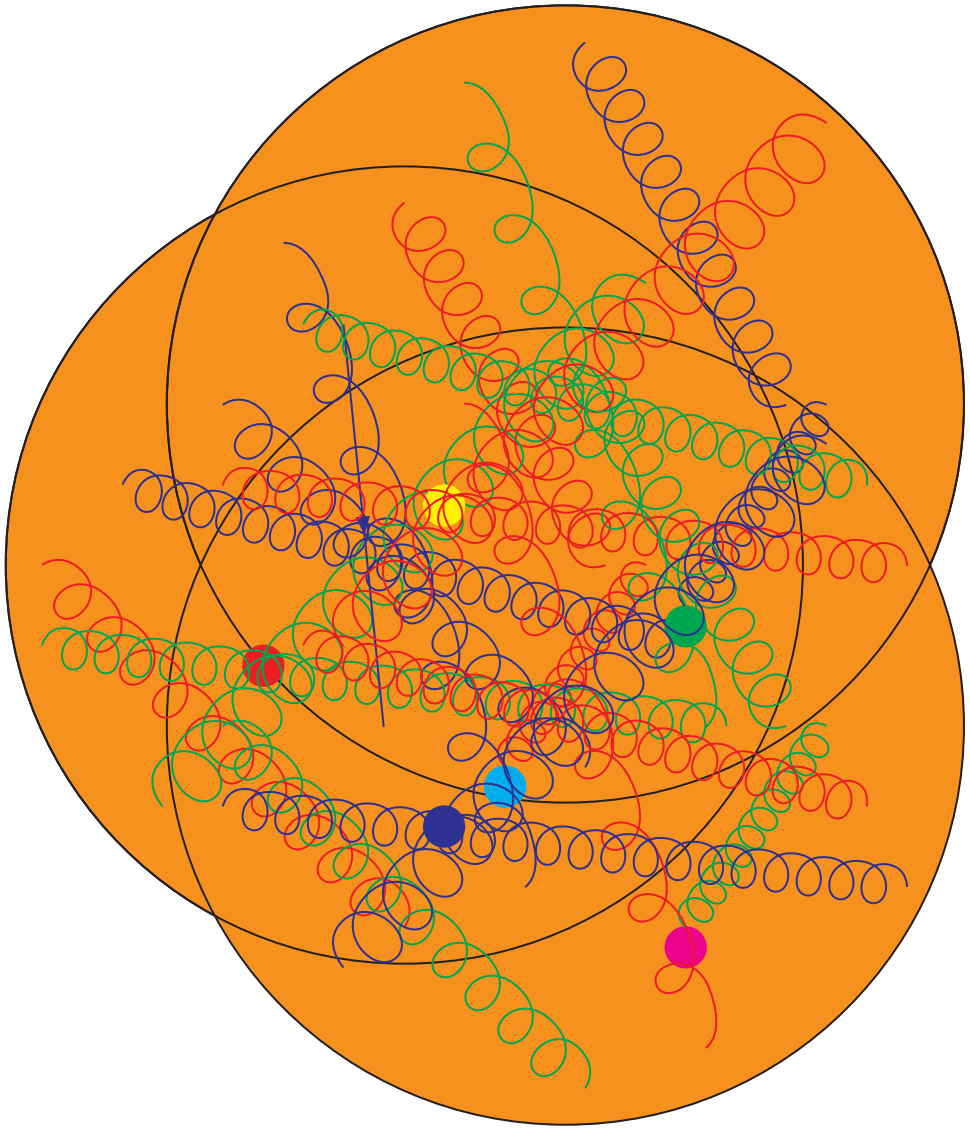

Which mesons?

- Pseudo-scalar octet(nonet)
  - $\pi^{\pm}$, π^0
  - $K^{\pm}$, K^0, $\overline{K^0}$
  - $\eta(,\eta')$
- Vector nonet
  - ρ^0, $\rho^{\pm}$, ω
  - K^*, ϕ
- Scalars
  - $f_0(500)$ or σ, $f_0(980)$, $a_0(980)$, $K_0(800)$ or κ
- Axial-vectors
  - $a_1(1260)$, $f_1(1285)$, $b_1(1235)$, $K_1(1270)$, $K_1(1400)$,...
- Others

Theoretical tools: some general comments

- Theory
  - Start from first principles
  - In principle improvable to any precision
  - But always beware of assumptions, approximations,...
  - An uncontrolled approximation turns a theory in a model
  - Sometimes the theory has many free parameters (or functions)
  - Example: Chiral Perturbation Theory or perturbative QCD
- Models
  - Needed whenever cannot be done from the full theory
  - Can be useful to summarize/understand results
  - Can be a first step towards finding a good theory
  - Example: Nambu-Jona-Lasinio model
- In between
  - Typically a theory with uncontrolled approximations
  - Requires a certain finesse to get reliable results
  - Example: Schwinger-Dyson equations

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Theoretical tools: QCD only

Perturbative QCD: not directly useful but input as constraints on other methods

- Structure functions
- Light-cone wave functions
- Formfactors at large Q^2
- ...

Theoretical tools: QCD only

Lattice gauge theory:

- Discretize space time and integrate out the quarks and gluons numerically
- From first principles (in principle)
- Extrapolations needed (see talks next week)
- Static properties: good
- Formfactors of stable particle: starting
- Decays and scattering of stable particles: difficult
- Resonances: very difficult
- Main reason for all the difficulties: everything is in Euclidean space (imaginary time)
- Why: Minkowski space: integrands are oscillatory: $\int dt\, e^{i\omega t}$ rather than $\int dt\, e^{-\omega t}$

Theoretical tools: QCD only

Light cone quantization Brodsky, Pauli, Phys.Rept. 301 (1998) 299-486 [hep-ph/9705477]

- Only physical degrees of freedom (ie no ghosts . . .)
- Wave functions are expanded in Fock states: partons directly visible
- The perturbative vacuum is the physical vacuum
- In principle allows for a competing numerical nonperturbative method
- Was a very active field 1990s
- Main (unsolved) difficulty: dealing with the zero mode This is where all the trouble of spontaneous symmetry breaking and confinement hides in this approach

Note: this not quark models on the light cone

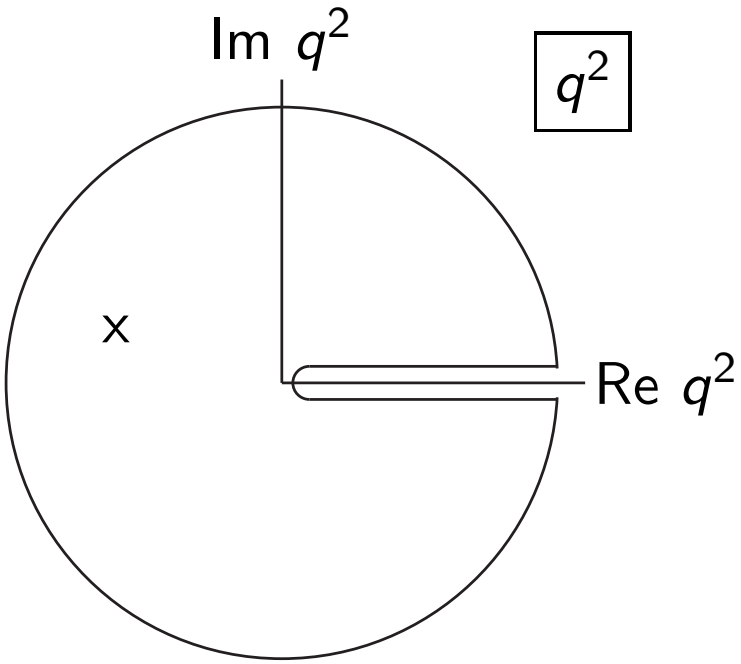
Theoretical tools: QCD only

QCD, Finite Energy Sum Rules, ...

- All rely on analyticity and Cauchy's theorem

$$\frac{1}{2\pi i}\oint_C dz\, f(z) = \sum_{\text{poles}} \text{residues}$$

- a typical curve



- Circle and residue points: perturbative QCD
- Axis: data and/or resonance saturation

Theoretical tools: other theory

Dispersion relations and unitarity

- Again Cauchy's theorem
- But now choose $f(z)$ e.g. a decay or scattering amplitude
- s, t, u: moire parameters
- Unitarity $1 = S^\dagger S = 1 + T^\dagger T + i(T - T^\dagger)$
- Due to the cuts: phases provide constraints
- Integral equations for the amplitudes
- Questions: subtraction constants, experimental input for phases, asymptotic behaviour

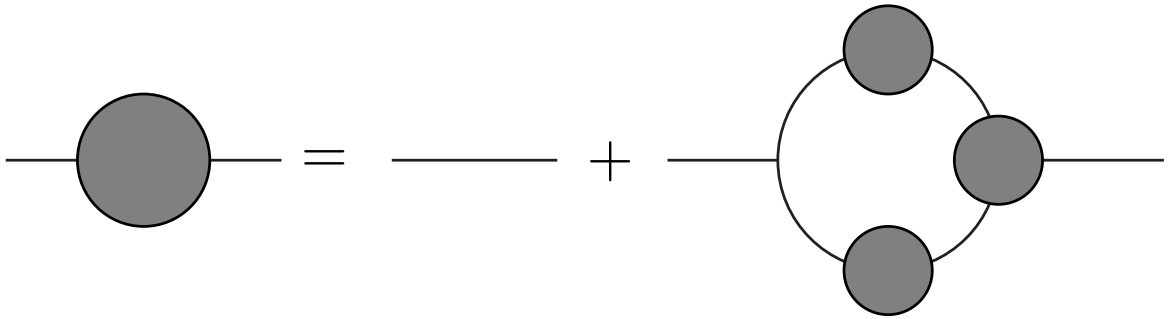
Theoretical tools: other theory

Chiral Perturbation Theory

- see my talk tomorrow
- Well defined effective field theory
- Might or might not converge
- Often many parameters (Low-Energy-Constants)
- All (in principle) measurable
- In addition models can/must be used to estimate parameters
- State of the art: 2-loop (most needed processes done)
- For other than pseudo-scalars: quite limited

Theoretical tools: other theory

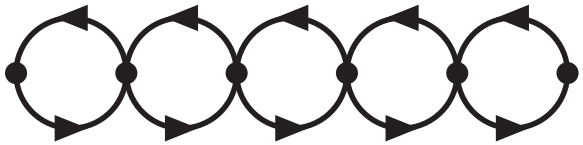
Schwinger-Dyson equations

- Idea (ϕ^3): 
- Full three-point function involves full four-point function
- Four involves five, ...
- An infinite set of consistency equations
- Need to truncate
- Need for a starting ansatz to make life bearable (usually a full gluon propagator)
- Usually kept at the "quenched" approximation

Models with "Quarks"

- Nonrelativistic constituent quark models: understanding the spectrum (fill up octets and nonets)
- Chiral quark model: quarks plus pseudo-scalars, no confinement
- Nambu-Jona-Lasinio models: Quarks with a four quark interaction
  - Has spontaneous chiral symmetry breaking
  - Produces a constituent quark mass from a gap equation:

  - mesons from a bubble sum



  - Mesons but no confinement

Models with "Quarks"

- Add vector-like four quark interactions $\Longrightarrow$ vectors and axial-vertex
- Add a 't Hooft vertex to get η' better (or a variation on that vertex)
- make the vertex non-local
- Add Polyakov loop
- Many more variations possible
- Usually large N_c or tree level at the "meson" level
- Some attempts to go beyond that: many difficulties and not clear if it ever yielded something useful

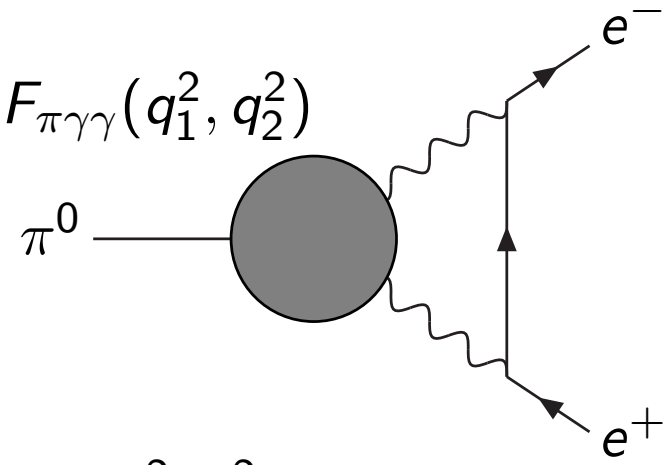
Effective Lagrangians

- Basic degrees of freedom: hadron fields
- Beware of product (mis)labelling
  - Chiral Perturbation Theory
  - Chiral Effective Theory
  - Are very popular names and "de vlag dekt niet altijd de lading" since they are not protected names (free flag doesn't make free bottom)
- Note field redefinitions: same Lagrangian can look very different
- Hope: find a simple Lagrangian and then refine it
- A full classification attempt: Resonance chiral theory (RχT), also attempts to go to one-loop.

π-decays

- Lightest hadrons
- π^0: main decay electromagnetic
  - $\to \gamma\gamma$: test of the anomaly
  - $\to e^+e^-$: existing discrepancy (KTeV) with standard model? extra contributions?
  - $\to \gamma e^+e^-$: F_V
  - $\to \overline{\nu}\nu$: looking for new stuff
- π^+ (or π^- to the charge conjugate state)
  - main decay: weak leptonic
  - $\to \mu^+\nu(\gamma)$: F_π
  - $\to e^+\nu\gamma$: F_V and F_A: CVC
  - $\to e^+\nu$: lepton universality
  - $\to \pi^0 e^+\nu$: V_{ud}

$\pi^0 \to e^+e^-$

- KTeV: BR $= (7.48 \pm 0.29 \pm 0.25) \cdot 10^{-8}$
- 

- $F_{\pi\gamma\gamma}(q_1^2, q_2^2)$ is an object we also like to know for $g-2$ of muon.
- Unitarity: on-shell $\gamma\gamma$ $BR \geq (4.75 \pm 0.02) \cdot 10^{-8}$
- Typical VMD $6.4 \cdot 10^-8$
- *ChPT*: fix coefficient from $\eta \to \mu^+\mu^-$, compatible (sign ambiguity)
- Dorokhov-Ivanov $BR = (6.2 \pm 0.1) \cdot 10^{-8}$ $(3.3\ \sigma)$
- (Reasonable?) assumption $F_{\pi\gamma\gamma}(t,t) = 1/(1 + t/s_1)$

K-decays

- Main decay: weak (nonleptonic, semileptonic, leptonic)
- Interplay of weak and strong interaction
- $K \to \pi\pi$: $\Delta I = 1/2$ enhancement
- $K \to 3\pi$:
  - Dynamics: Dalitzplot distributions
  - CP-violation
  - $\pi\pi$-scattering lengths
- $K \to \ell\nu$: Lepton universality, F_K
- $K \to \pi\ell\nu$: V_{us}, formfactors
- $K \to \pi\pi\ell\nu$: formfactors $(L - i^r)$, $\pi\pi$-scattering lengths
- $K \to \pi\ell^+\ell^-$, $K \to \pi\overline{\nu}\nu$: get V_{CKM} fully from K system, strong constraints on new physics models

η-decays

- $\eta \to 3\pi$: $m_u - m_d$ or Q: Lanz on Tuesday
- $\eta \to \gamma^*\gamma^*$: anomaly, formfactors
- $\eta \to \pi^0\gamma\gamma$ dominated by high orders in ChPT
- $\eta \to \pi^+\pi^-\gamma^*$: anomaly, formfactors

Vectors: Theoretical tools/questions

- Effective Lagrangians: does there exist a consistent power-counting?
- Is there a preferred way to describe vectors? Massive Yang-Mills, Hidden Local Symmetry, Antisymmetric tensor,. . . ?
- Does there exist something like Vector Meson Dominance beyond the pion electromagnetic formfactor?
- Large N_c says that a tree level Lagrangian should exist, but not that it must be a simple one: how well does this really work?
- Lattice has difficulties with resonances, can be done but not very accurate at present (if quark masses such that resonace is above threshold)
- For static properties and decay constants ChPT can be done
- KSRF relation between m_V, g_V and f_π

Examples of decays

- $\omega \to 3\pi$
  - Can this be modelled via $\omega \to \rho\pi \to 3\pi$?
- ρ-ω-ϕ mixing
- ρ^0-ρ^+ mass difference: e^+e^- and τ, also in other production modes?
- Radiative decays
  - $\rho, \omega \to \pi\gamma$, $\phi \to \eta\gamma$, $\eta' \to \rho\gamma$ $\eta' \to \omega\gamma$
  - Same but with the photon off-shell, i.e. to e^+e^-, $\mu^+\mu^-$
  - Are these related via (naive) VMD (no from NA60)

$\omega \to \pi^0 \mu^+ \mu^-$

$$F_\omega = \frac{1}{1 - m_{\mu\mu}^2/\Lambda_\omega^2}$$

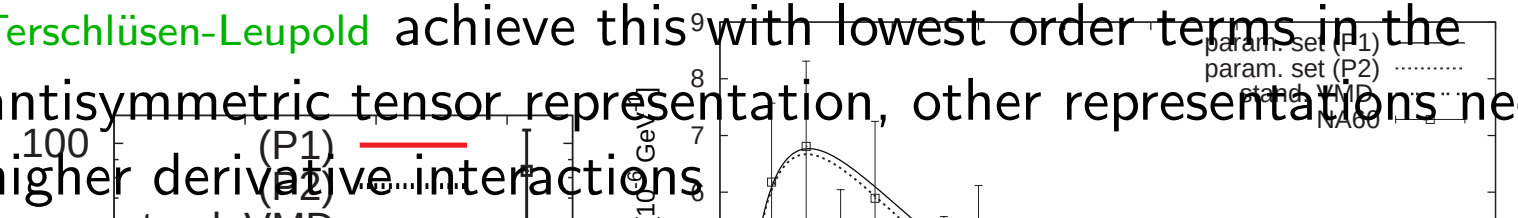
$$F_\omega^{\rm exp} \neq \frac{1}{1 - m_{\mu\mu}^2/m_V^2}$$

Terschlüsen-Leupold

$$F_\omega^{\rm exp} = \frac{1 + m_{\mu\mu}^2/m_V^2}{1 - m_{\mu\mu}^2/m_V^2}$$

$\omega \to \pi^0 \mu^+ \mu^-$

corresponding differential decay rate:



Terschlüsen-Leupold achieve this with lowest order terms in the antisymmetric tensor representation, other representations need higher derivative interactions

Axial vectors

- Are they the chiral partners of the ρ?
- How do the axial nonets mix in the strange and singlet sectors?
  Relevant question for muon $g-2$
- $a_1 \to 3\pi$ via $a_1 \to \rho\pi$ or additional contributions
- $a_1 \to \pi\gamma$: this vanishes in almost simple theoretical models
- Mass: Weinberg sum rules predict $m_{a_1} \approx \sqrt{2} m_\rho$
- Width (PDG) 250 to 600 MeV our estimate
- is there a problem with continuum/resonance separation due to the large width?

Others

- Many more resonances
- Questions similar:
  - Does it really exist
  - mass
  - width
  - Main decay modes
  - Mixing with other particles
- On the theory side
  - nature of the particle
  - What is the best way to describe it
  - If used in resonance saturation models we need its couplings

- An overview of theoretical tools
- A few examples of questions and decays