The dynamics of light vector mesons

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Why vector mesons?

- second-lightest degrees of freedom after pseudoscalars,

$\hookrightarrow$ important for low-energy processes

- mediators between hadrons and electromagnetism

$\hookrightarrow$ "vector-meson dominance"

Why vector mesons?

- second-lightest degrees of freedom after pseudoscalars,

↪ important for low-energy processes

- mediators between hadrons and electromagnetism

↪ "vector-meson dominance"

- electromagnetic interaction serves as diagnostic probe for hadron properties
  (dilepton production in heavy-ion collisions, proton structure, . . .)
- hadronic contributions cause background for physics beyond standard model
  (anomalous magnetic moment of muon, . . .)

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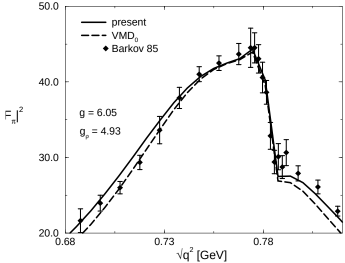
Vector-meson dominance (VMD)

VMD works very well
for pion form factor
(Sakurai, ...)
$e^+e^- \rightarrow \pi^+\pi^-$:



e.g., Klingl/Kaiser/Weise,
Z. Phys. A356, 193 (1996)

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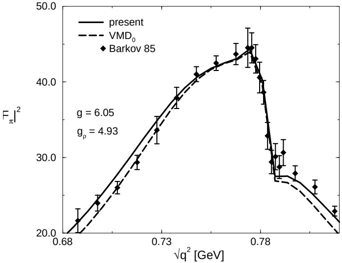
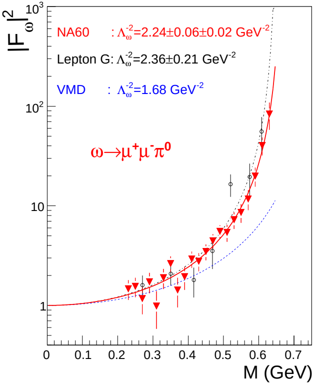


e.g., Klingl/Kaiser/Weise,
Z. Phys. A356, 193 (1996)

VMD dramatically fails
for omega form factor
$\omega \to \mu^+\mu^-\pi^0$:



Arnaldi et al. (NA60),
Phys. Lett. B677, 260 (2009)

Effective field theory for vector mesons

aims:

- develop effective field theory for vector mesons
- apply it to form factors and other quantities

questions:

- why?
- how?
- does it work?

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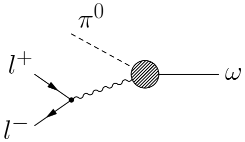
- why? $\rightsquigarrow$ next slides
- how? $\rightsquigarrow$ only briefly discussed here
- does it work? $\rightsquigarrow$ results

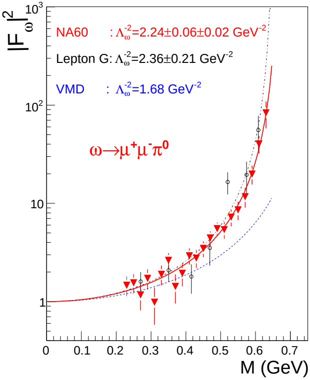
Transition form factor of omega meson

- definition: form factor parametrizes deviation from structureless decay; normalized to photon point ($M = 0$)



- experiments show strong deviation from simple vector-meson dominance

$$F(M^2) = \frac{m_\rho^2}{m_\rho^2 - M^2}$$



Phys. Lett. B 677, 260 (2009)

Effective field theories vs. models

- example: transition form factor
- a model, e.g., vector-meson dominance model (VMD):

$$F(q^2) = \frac{m^2}{m^2 - q^2}$$

with

- m: mass of intermediate vector meson
- q: invariant mass of dilepton pair

$\hookrightarrow$ good: predictive power (no free parameters)

$\hookrightarrow$ bad: no systematic improvement possible

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Effective field theories vs. models

- a model, e.g., vector-meson dominance model (VMD):

$$F(q^2) = \frac{m^2}{m^2 - q^2}$$

- most general field theory
(with vector mesons as active degrees of freedom):

$$F(q^2) = \frac{c_0\, m^2}{m^2 - q^2} + (1 - c_0) + c_1 \frac{q^2}{m^2} + c_2 \frac{q^4}{m^4} + \ldots$$

$\hookrightarrow$ (some) parameters c_i might be related to other processes

$\hookrightarrow$ bad: infinitely many parameters $\rightsquigarrow$ no predictive power

Effective field theories vs. models

- a model, e.g., vector-meson dominance model (VMD):

$$F(q^2) = \frac{m^2}{m^2 - q^2}$$

- most general field theory:

$$F(q^2) = \frac{c_0\, m^2}{m^2 - q^2} + (1 - c_0) + c_1 \frac{q^2}{m^2} + c_2 \frac{q^4}{m^4} + \ldots$$

- effective field theory with power counting:

$\hookrightarrow$ same general formula, but assignment of importance to parameters c_i, e.g., $c_0,\ c_2 \sim o(1)$, $c_1 \sim o(m^2/\Lambda^2)$, … with breakdown scale Λ (where new physics, new degrees of freedom enter)

$\hookrightarrow$ relevant parameters c_i might be related to other processes

$\hookrightarrow$ good: predictive power, systematic improvement possible

Effective field theories for hadrons

well established: chiral perturbation theory (χPT)

- relevant degrees of freedom: light pseudoscalars
  = Goldstone bosons of broken chiral symmetry
- Goldstone-boson masses and momenta treated as small
- large scale = breakdown scale:
  masses of (not excited) other hadrons

now: extend energy region to include also vector mesons

- small scale Q $\sim$ momenta and masses of light
  pseudoscalar and vector mesons
- N.B. vector mesons represented by antisymmetric tensor fields

Inclusion of vector mesons

aim: develop effective field theory including Goldstone bosons

$$\Phi = \begin{pmatrix} \pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}\,\pi^+ & \sqrt{2}\,K^+ \\ \sqrt{2}\,\pi^- & -\pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}\,K^0 \\ \sqrt{2}\,K^- & \sqrt{2}\,\bar{K}^0 & -\frac{2}{\sqrt{3}}\eta \end{pmatrix}$$

and vector mesons

$$V_{\mu\nu} = \begin{pmatrix} \rho^0 + \omega & \sqrt{2}\,\rho^+ & \sqrt{2}\,K^{*+} \\ \sqrt{2}\,\rho^- & -\rho^0 + \omega & \sqrt{2}\,K^{*0} \\ \sqrt{2}\,K^{*-} & \sqrt{2}\,\bar{K}^{*0} & \sqrt{2}\,\phi \end{pmatrix}_{\mu\nu}$$

N.B.: need assumptions, not as straightforward as pure χPT

Effective field theory for vector mesons

- power counting suggested in Lutz/Leupold, Nucl. Phys. A 813, 96 (2008)
- further explored in leading order (so far): Leupold/Lutz, E. P. J. A 39, 205 (2009); Terschlüsen/Leupold, Phys. Lett. B691, 191 (2010)
- in the following: mainly results

- note: validity as effective field theory (EFT) not shown yet (instead of phenomenologically successful tree-level model)

$\hookrightarrow$ convergence?, breakdown scale?

$\hookrightarrow$ requires calculations beyond leading order

Some applications of the new counting scheme

- two-body decays of vector mesons in leading order

$\hookrightarrow$ fixing parameters and qualitative checks

- three-body decays of vector mesons in leading order

$\hookrightarrow$ for cases with no new parameters $\rightsquigarrow$ predictions

Lutz/Leupold, Nucl. Phys. A 813, 96 (2008);
Leupold/Lutz, E. P. J. A 39, 205 (2009);
Terschlüsen/Leupold, Phys. Lett. B691, 191 (2010)

Fixing parameters

decay of vector into two pseudoscalars in leading order

- $\mathcal{L}_{VPP} \sim h_P\, V_{\mu\nu}[\partial^\mu \Phi, \partial^\nu \Phi] \sim o(Q^2)$

$\hookrightarrow$ h_P from $\rho \to 2\pi$, $K^* \to K + \pi$, $\phi \to K + \bar{K}$

decay of vector into dilepton in leading order

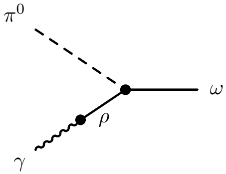
- $\mathcal{L}_{V\gamma} \sim e_V\, V_{\mu\nu} F^{\mu\nu} \sim o(Q^2)$

$\hookrightarrow$ e_V from $\rho,\ \omega,\ \phi \to l^+ l^-$ $(l = \mu,\ e)$

decay of vector into pseudoscalar + photon in leading order

- $\mathcal{L}_{VVP,1} \sim h_A\, \epsilon_{\mu\nu\alpha\beta} \{V^{\mu\nu}, \partial_\lambda V^{\lambda\alpha}\}\, \partial^\beta \Phi \sim o(Q^2)$;
  $\mathcal{L}_{VVP,2} \sim b_A\, \epsilon_{\mu\nu\alpha\beta} V^{\mu\nu} V^{\alpha\beta} [\Phi, \mathcal{M}_q] \sim o(Q^2)$

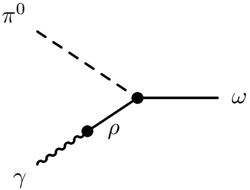
$\hookrightarrow$ h_A, b_A from $\rho/\omega \to \pi/\eta + \gamma$, $K^* \to K + \gamma$, $\phi \to \eta + \gamma$

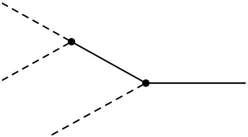


$\sim o(Q^2)$

Three-body decays I

decays of ω meson



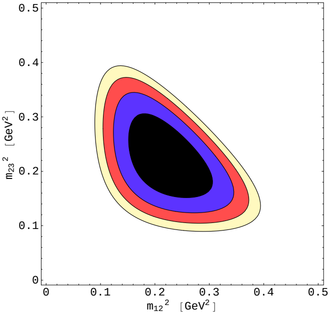


- same vertex appears in both processes $\omega \longrightarrow \gamma\pi$ and $\omega \longrightarrow 3\pi$ in leading order
- use first process to fix coupling of second one

$\rightsquigarrow$ prediction: $\Gamma_{\omega\to 3\pi} = 7.3$ MeV

$\Gamma^{\text{exp}}_{\omega\to 3\pi} = (7.57 \pm 0.13)$ MeV

S.L./Lutz, E. P. J. A 39, 205 (2009)



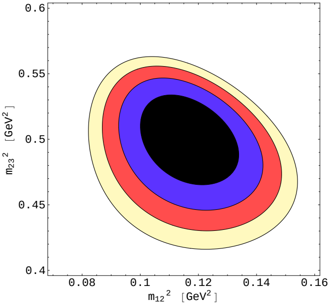
Three-body decays II

predictions for $K^* \to K\,\pi\,\pi$

- e.g. $K^{*+} \to K^+\,\pi^+\,\pi^-$

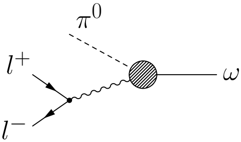
$$\mathcal{B}_{K^{*+}\to\pi^+\,\pi^-\,K^+} = 2.7\cdot 10^{-4}$$

experimental constraint: $\mathcal{B} < 7\cdot 10^{-4}$



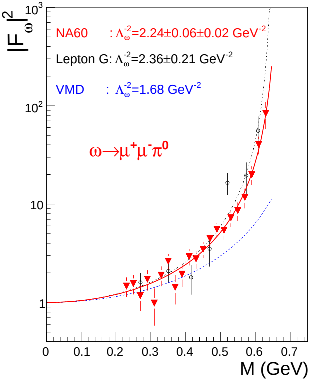
deviations from pure phase space

Transition form factor of omega meson



- experiments show strong deviation from simple vector-meson dominance

$$F(q^2) = \frac{m^2}{m^2 - q^2}$$



Phys. Lett. B 677, 260 (2009)

Transition form factor of omega meson — theory

- standard vector-meson dominance model (VMD):

$$F(q^2) = \frac{m^2}{m^2 - q^2}$$

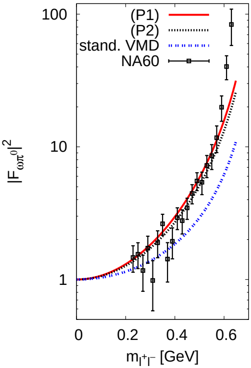
- most general field theory:

$$F(q^2) = \frac{c_0\, m^2}{m^2 - q^2} + (1 - c_0) + c_1 \frac{q^2}{m^2} + c_2 \frac{q^4}{m^4} + \dots$$

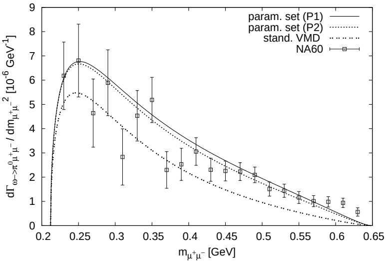
- our approach:
  - no free parameters (all fixed from real photon)
  - only c_0 leading order
  - all other c_i subleading
  - numerically: $c_0 \approx 2$

$$\hookrightarrow \qquad F(q^2) \approx \frac{m^2 + q^2}{m^2 - q^2}$$

Transition form factors — omega to pion



corresponding differential decay rate:

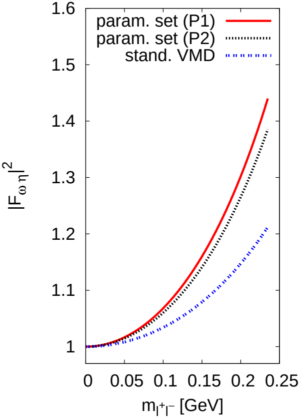


C. Terschlüsen, S.L., Phys. Lett. B691, 191 (2010)

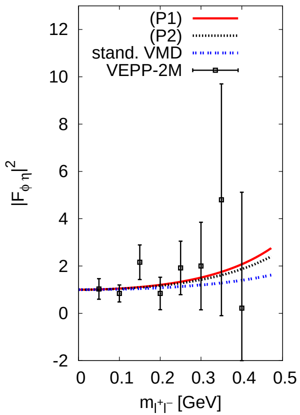
- NA60: dimuons, planned: WASA with dielectrons

Transition form factors — vectors to eta

$\omega \to \eta +$ dilepton



$\phi \to \eta +$ dilepton

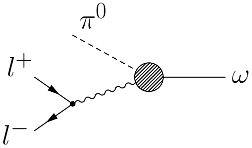


C. Terschlüsen, S.L., Phys. Lett. B691, 191 (2010)

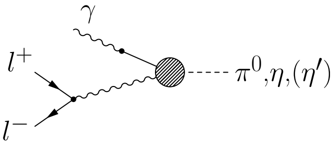
- upcoming: ϕ data by KLOE

Cross relation to pseudoscalar Dalitz decay

- omega Dalitz decay:



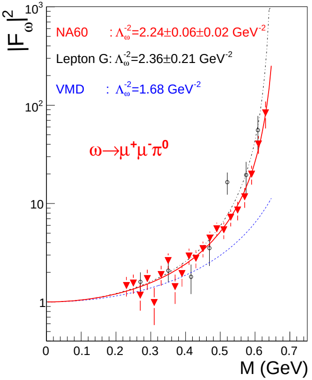
- turning some in- and outgoing states around . . .

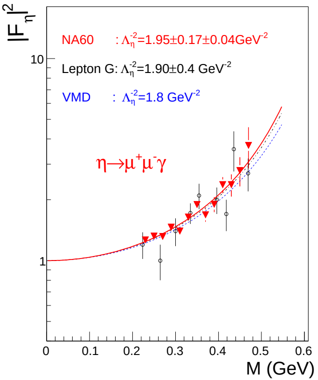


- here experiments show agreement with vector-meson dominance $\rightsquigarrow$ next slide
- important for muon's anomalous magnetic moment (light-by-light scattering)

Form factor of the eta meson

- VMD fails for omega but works for eta form factor





NA60, Phys. Lett. B 677, 260 (2009)

Importance of vector mesons for η decays?

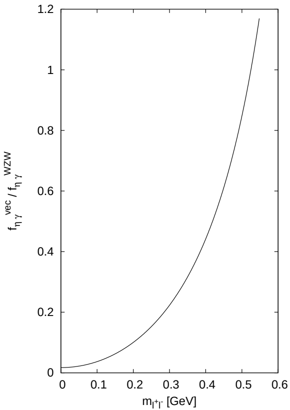
- study Dalitz decay $\eta \to \gamma l^+ l^-$
- pure χPT:
  leading-order contribution from
  Wess-Zumino-Witten term

$\rightsquigarrow$ $f^{\rm WZW}$

- EFT with vector mesons:
  leading-order contribution
  fixed by vector-meson decays

$\rightsquigarrow$ $f^{\rm vec}$

$\hookrightarrow$ study ratio as function of dilepton mass $\rightsquigarrow$ fig.

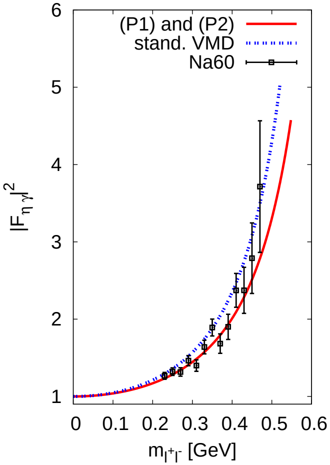


- vectors important at “high” invariant masses

Form factor of the η meson

PRELIMINARY

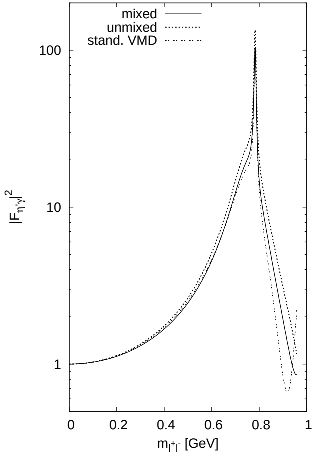
- our approach:
  leading-order term from vector-meson EFT plus leading-order term from pure χPT (Wess-Zumino-Witten)
- inclusion of η-η' mixing important



PRELIMINARY

Form factor of the η' meson

PRELIMINARY



- peaks of ρ and ω visible in form factor of η'

PRELIMINARY

Summary and outlook

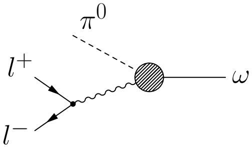
- suggested new counting scheme for theory of pseudoscalar and vector mesons
- good understanding of vector-meson decays
- systematic inclusion of η' currently investigated

effective-field-theory program (=outlook):

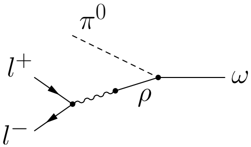
- phenomenological consequences (leading-order calculations as first step):
  - other vector-meson decays
  - influence of vector mesons on decays of pseudoscalars
  - hadronic information in e^+e^- reactions and τ decays
  - quark-mass dependence of masses of pseudoscalar and vector mesons (connection to lattice QCD)
- calculations at next-to-leading order: $\rightsquigarrow$ next slide

Processes up to next-to-leading order

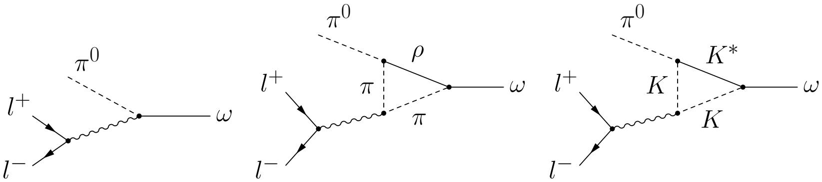
- Dalitz decay:



- leading order:



- next-to-leading order (selection):



Effective-field-theory program

- phenomenological consequences (leading order)
- calculations at next-to-leading order:
  - show that power counting works
  - pin down breakdown scale

  estimates for breakdown scale (from pure χPT):
  - vector-meson mass?

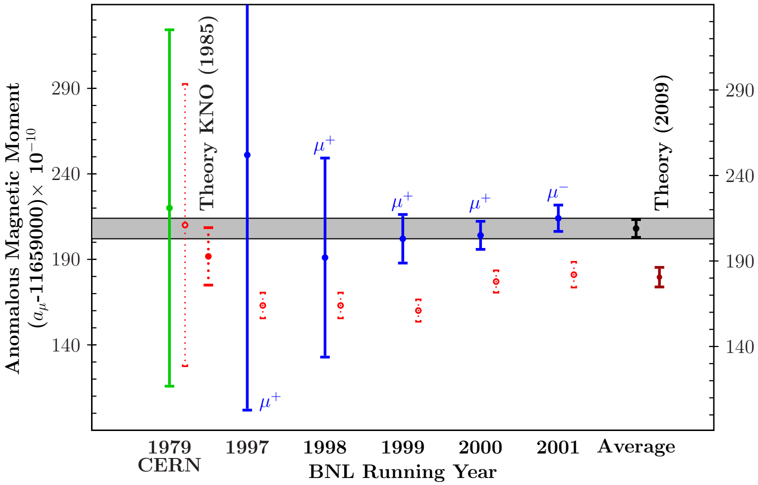
  $\hookrightarrow$ no! (vector mesons explicitly included)
  - maybe at $(4\pi f_\pi) \approx 1\,\text{GeV} \rightsquigarrow$ convergence would be poor

  $\hookrightarrow$ might rather signal importance of unitarity
  - expect it at masses of excited (= not included) states

  $\hookrightarrow$ $m_{\pi'} \approx 1.3\,\text{GeV}$, $m_{\rho'} \approx 1.5\,\text{GeV}$

Backup slides

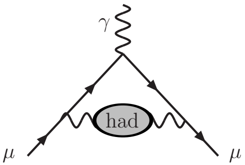
Muon's $g-2$



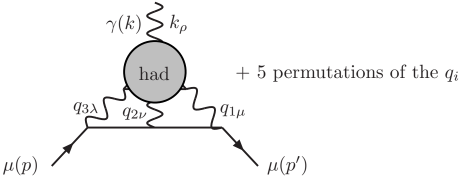
Jegerlehner/Nyffeler, Phys. Rept. 477, 1 (2009)

Muon's $g-2$

Largest uncertainty of standard model: hadronic contributions



vacuum polarization



light-by-light scattering