Effective Theories for Hadrons at FAIR

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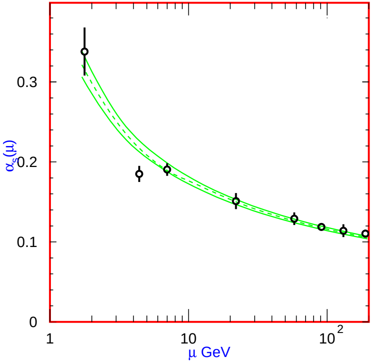
Quantum chromodynamics

strong interaction described by Quantum ChromoDynamics

$$\mathcal{L} = \bar{q}\gamma_\mu\left(\partial^\mu - igA^\mu\right) q - \frac{1}{4} F_a^{\mu\nu} F^a_{\mu\nu}, \qquad F^{\mu\nu} \sim [\partial^\mu - igA^\mu, \partial^\nu - igA^\nu]$$

with quarks $q = (u, d, s, c, b, t)$ and gluons A_μ



PDG, J. Phys. G33 (2006) 1

- running coupling g

↪ asymptotic freedom (caused by gluon self-interaction)

↪ can use perturbation theory at large momenta

↪ there one "sees" quarks and gluons (deep inelastic scattering, jet production)

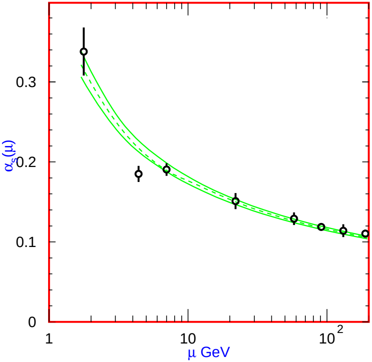
Quantum chromodynamics

strong interaction described by Quantum ChromoDynamics

$$\mathcal{L} = \bar{q}\gamma_\mu \left(\partial^\mu - igA^\mu\right) q - \frac{1}{4} F_a^{\mu\nu} F^a_{\mu\nu}, \qquad F^{\mu\nu} \sim [\partial^\mu - igA^\mu, \partial^\nu - igA^\nu]$$

with quarks $q = (u, d, s, c, b, t)$ and gluons A_μ

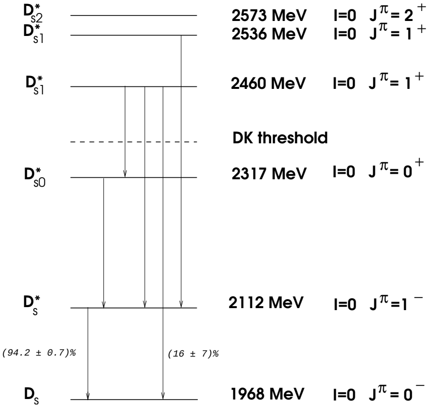
- running coupling g
  - ↪ large coupling at small momenta
  - ↪ cannot use perturbation theory there
- confinement
  - ↪ relevant degrees of freedom are hadrons, not quarks and gluons



PDG, J. Phys. G33 (2006) 1

Hadron spectrum — an example

charmed strange mesons D_s



Lutz/Soyeur, Nucl.Phys.A 813 (2008) 14

Hadron spectrum — an example

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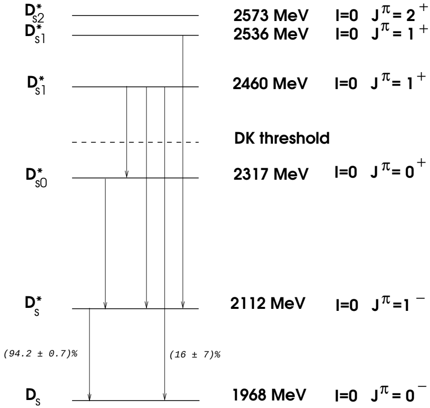


Lutz/Soyeur, Nucl.Phys.A 813 (2008) 14

typical questions:

- Can we understand the masses?
- Are all these states just made out of c-quark and $\bar{s}$-quark (quark model)?
- Is there admixture or even dominance of, e.g., $c\bar{u}\, u\bar{s}$ or $c\bar{s}$+gluon or ...?

More general questions

- Are all hadrons (dominantly) made out of quark-antiquark or three quarks, respectively (quark model)?
- Are there hadrons purely/dominantly made out of gluons?

$\hookrightarrow$ glueballs

- Do some/many hadron have a hadronic substructure?

$\hookrightarrow$ “hadron molecules”

- How to understand masses, life times, reaction rates of hadrons?

$\hookrightarrow$ tools: lattice QCD, effective theories

Lattice QCD

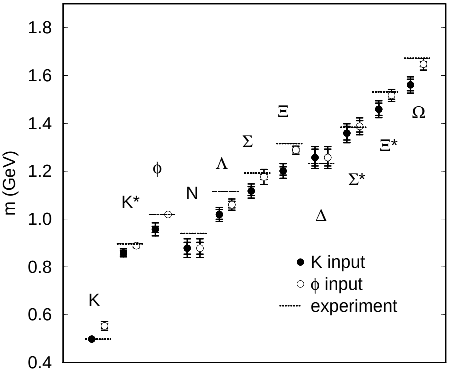
- one way to tackle (part of) questions: solve QCD on a grid

↪ reasonable results ⟶

but:

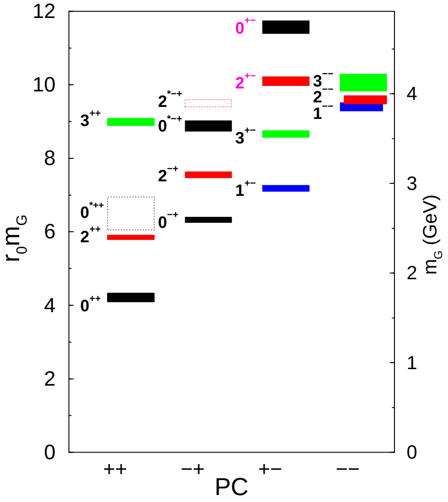
- yields only spectrum, not life time, reaction rates
- only for low-lying states
- numerically expensive to treat light quark masses

↪ complementary: effective field theories



CP-PACS,
Phys. Rev. D67 (2003) 034503

Prediction: glueball spectrum from lattice QCD



Morningstar/Peardon,
Phys. Rev. D60 (1999) 034509

- lattice QCD predicts existence of glueballs
- ↪ experimental verification desired!
- glueballs might mix with ordinary hadrons
- ↪ so far not settled in lattice QCD
- ↪ complementary: effective field theories

Effective theories

everyone uses effective theories:

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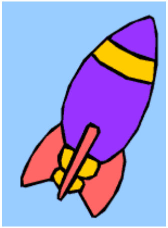
- simple example:
  want to describe motion of rocket
  (or snow mobile:-)



Effective theories

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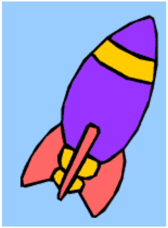

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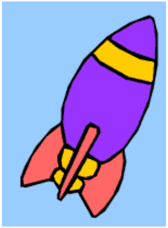
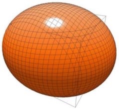


- simplest effective theory:
  treat rocket as point-like object

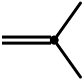
- refined effective theory:
  take tensor of inertia into account



$\hookrightarrow$ isolate relevant degrees of freedom

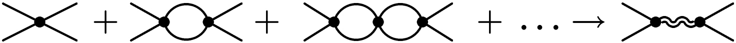
General considerations

- resonances decay into other “final-state” hadrons



$\hookrightarrow$ influence of final-state hadrons and their interactions on resonance properties?

- examples for extreme cases:
  - resonance is dominantly quark-antiquark or glueball, coupling to final-state hadrons “perturbative”
  - resonance is formed by attractive interaction between hadrons



$\leadsto$ hadron molecule

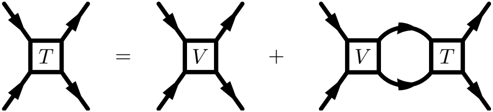
$\hookrightarrow$ need sophisticated approach for description of final-state hadrons and their interactions

Effective theories for hadrons

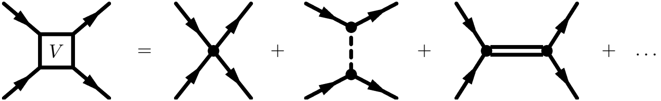
systematic approach instead of arbitrary model building

↪ principles of scattering theory and effective field theory:

- exact unitarity and analyticity, rescattering



- coupled-channel dynamics
- systematic power counting



- need extension of chiral perturbation theory
  to include (at least) vector mesons and Delta decuplet
  currently developed, e.g. Lutz/Leupold, Nucl. Phys. A 813, 96 (2008)

goal: disentangle hadronic rescattering effects from "elementary" resonances (quark-antiquark, glueballs)

Symmetries of QCD

connection to underlying QCD: symmetries!

- chiral symmetry: light quarks u, d, s
  have masses much lighter than typical hadron masses

$\hookrightarrow$ approximately massless

$\hookrightarrow$ QCD treats left- and right-handed quarks in same way

$\hookrightarrow$ chiral symmetry, spontaneously broken

- heavy-quark symmetry:
  for very heavy quark spin flip does not cost energy

$\hookrightarrow$ (approximate) degeneracy e.g. of $J^P = 0^-$ and 1^-
or of 0^+ and 1^+ ...

$\hookrightarrow$ expected to work very well for bottom quark, approximate for charm quark

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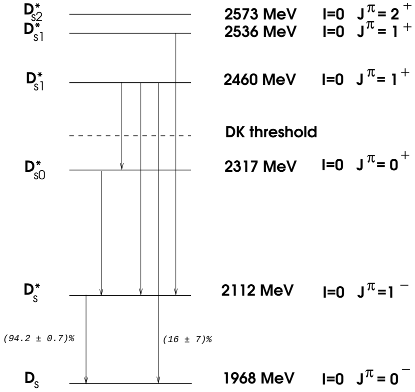
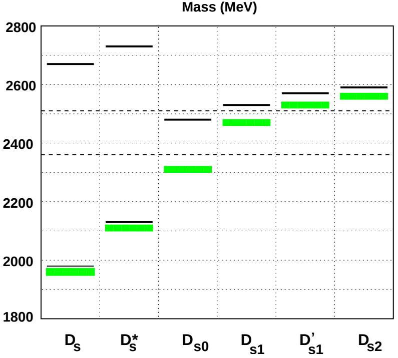
Example 1: new D_s mesons

charmed strange mesons D_s



Lutz/Soyeur,
Nucl.Phys.A 813 (2008) 14

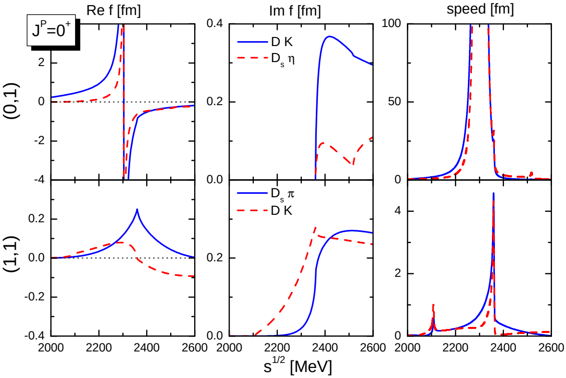
standard quark model fails for
$D_s(2317)\ 0^+$
(found by BABAR)



Swanson, Phys.Rept.429 (2006) 243

Dynamical generation

$D_s\ 0^+$ can be understood as dynamically generated
— coupled-channel meson molecule —
from scattering of Goldstone bosons on $D_{(s)}\ 0^-$

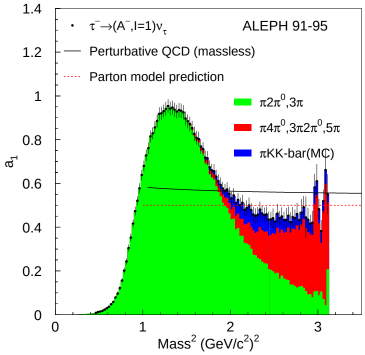


Kolomeitsev/Lutz, Phys.Lett.B582 (2004) 39

Example 2: long known a_1-meson

study decay: $\tau \to \nu_\tau + 3\pi$:

- 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



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  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

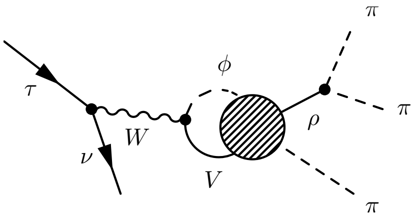
$\rightsquigarrow$ study two scenarios:

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)

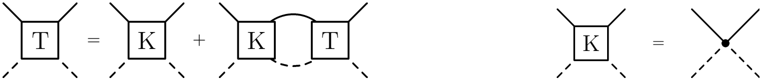
- describe final-state interactions via Bethe-Salpeter eq.,
  kernel from lowest-order chiral interaction
  (Weinberg-Tomozawa – WT)
  $\rightsquigarrow$ parameter free

Scenario 1: only final-state interaction

- one free parameter for transition from W to hadrons

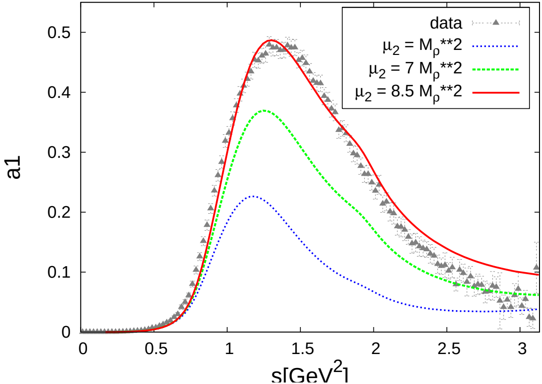


- Bethe-Salpeter equation
  (rescattering, final-state interaction)



- N.B: coupled-channel treatment $(\phi, V) = (\pi, \rho), (K, K^*)$

τ decay in scenario 1



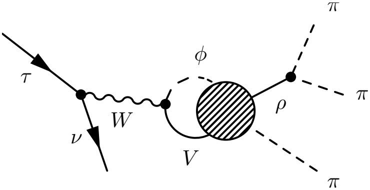
- reasonable description with one free parameter

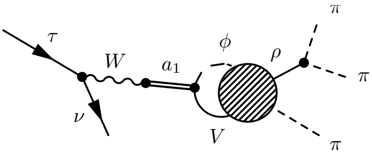
$\rightsquigarrow$ indicates that a_1 is ρ-π "molecule"

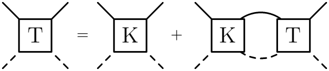
(Markus Wagner and S.L., Phys. Rev. D 78, 053001 (2008))

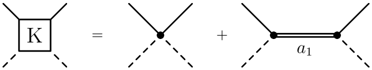
Scenario 2: in addition elementary resonance

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

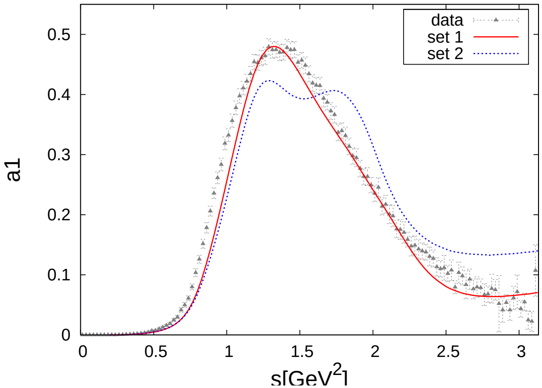








τ decay in scenario 2



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

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

1. Summary

challenging and promising future of hadron-structure physics:

- high-precision experiments
- sharpening of theoretical tools (lattice, effective theories)
  - inclusion of symmetries of QCD
  - develop systematic power counting

↪ have shown some examples beyond quark model

↪ expect more

Cross connection to CBM

- hadron physics/PANDA: how is energy distributed? (for given quantum numbers)

↪ spectral information (peaks indicate particles)

- in-medium physics/CBM(+HADES): how many?

↪ statistical information (time dependent phase-space distribution)

⇝ in general difficult to disentangle

↪ example: dilepton production
  - information from all times of fireball expansion, not just freezeout
  - information on in-medium modifications of hadrons

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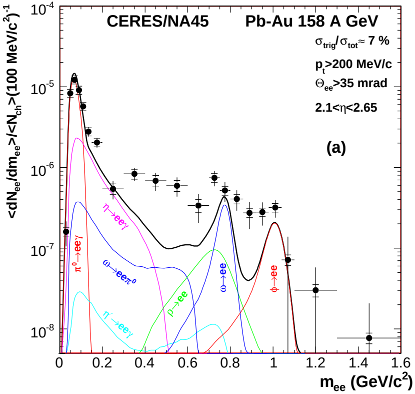
CERES — dielectrons

how distributed and how many?



CERES, PLB 666 (2008) 425
[arXiv:nucl-ex/0611022]

possible explanations

- more $\omega \rightarrow \pi\, e^+ e^-$?

$\hookrightarrow$ no

- broader (and more) $\rho \rightarrow e^+ e^-$?

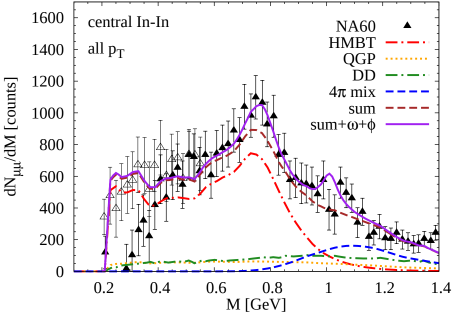
$\hookrightarrow$ yes(?)

- additional sources $N^* \rightarrow N\, e^+ e^-$?

$\hookrightarrow$ yes(?)

NA60 — dimuons (and one theoretical description)

how distributed and how many?

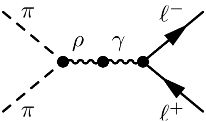


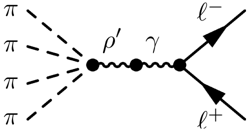
van Hees/Rapp, PRL 97 (2006) 102301 [arXiv:hep-ph/0603084]

still under debate:

- decomposition of radiating source
- in-medium properties of ρ meson

Microscopic information



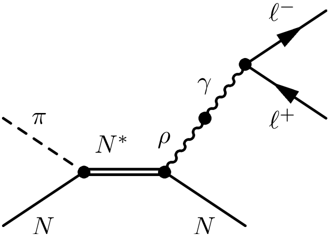


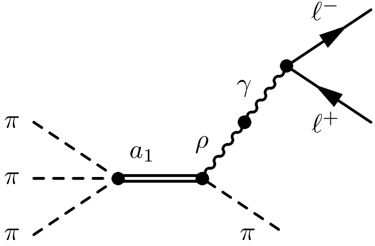
$$\pi + \pi \to \rho \to \ell^+\ell^-$$

$$4\pi \to \rho' \to \ell^+\ell^-$$

$$\pi + N \to N^* \to \ell^+\ell^- + N$$

$$3\pi \to a_1 \to \ell^+\ell^- + \pi$$





2. Summary

for description of nucleus-nucleus collisions:

- single-particle spectra require statistical information (often thermal)
- two-particle spectra require in addition spectral information

$\hookrightarrow$ microscopic/hadronic information needed

and microscopic/hadronic information extractable

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$\hookrightarrow$ PANDA physics meets CBM physics

- vector mesons in coupled channels $\leftrightarrow$ dilepton production
- properties of charm states $\leftrightarrow$ charm production

Many thanks to my collaborators
Markus Wagner and Matthias Lutz