Transition form factors and radiative decays of hyperons

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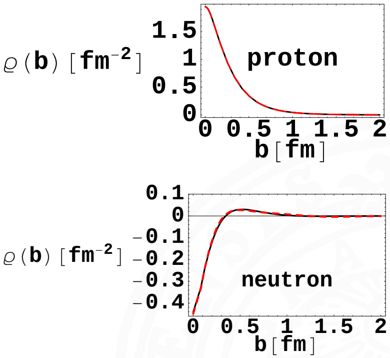
Orsay, May 2018

Femtoscience

- Want to understand structure of matter at femtometer scale

$\hookrightarrow$ (electromagnetic) form factors contain structure information

$\hookrightarrow$ spatial distributions related to Fourier transform of space-like form factors



G.A. Miller,

Phys.Rev.Lett. 99, 112001 (2007)

Femtoscience

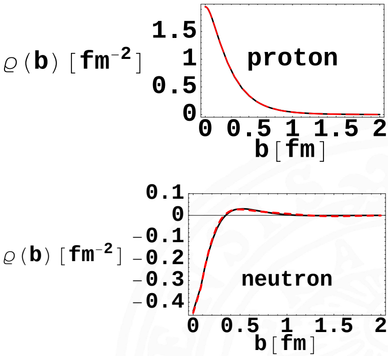
- Want to understand structure of matter at femtometer scale

↪ (electromagnetic) form factors contain structure information

↪ spatial distributions related to Fourier transform of space-like form factors

- How does hadronic structure change when replacing up/down by strange quarks?

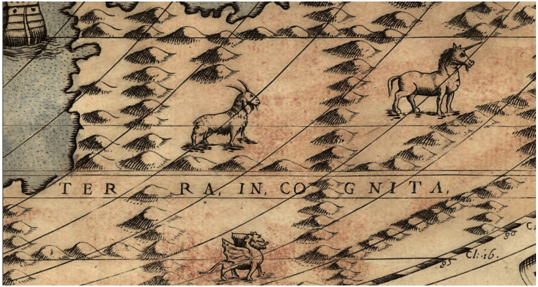
↪ Would like to get information about form factors of hyperons



G.A. Miller, Phys.Rev.Lett. 99, 112001 (2007)

Electromagnetic form factors of hyperons

to large extent
terra incognita



- electron-hyperon scattering complicated

$\rightsquigarrow$ instead:

  - reactions $e^+ e^- \longrightarrow$ hyperon anti-hyperon $(Y_1\ \bar{Y}_2) \rightsquigarrow$ BESIII

  $\hookrightarrow$ form factors and transition form factors for large time-like $q^2 > (m_{Y_1} + m_{Y_2})^2$

  - decays $Y_1 \rightarrow Y_2\ e^+ e^- \rightsquigarrow$ HADES+PANDA

  $\hookrightarrow$ transition form factors for small time-like $q^2 < (m_{Y_1} - m_{Y_2})^2$

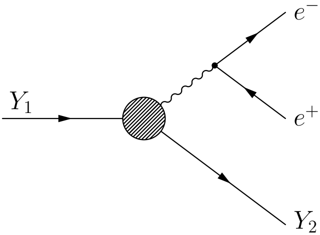
Structure information about hyperons

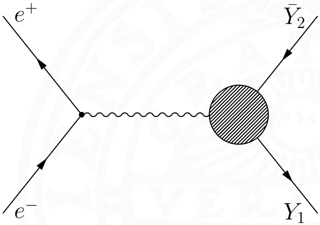
- need space-like form factors to obtain structure information

$\hookrightarrow$ hard to obtain for hyperons

$\hookrightarrow$ alternative: explore time-like region and use dispersion theory

(time-like means $q^2 > 0$, i.e. energy transfer $>$ momentum transfer)





Unitarity and analyticity

- constraints from local quantum field theory:
  partial-wave amplitudes for reactions/decays must be
  - unitary (optical theorem):

$$S\,S^\dagger = 1\,, \quad S = 1 + iT \quad \Rightarrow \quad 2\,\mathrm{Im}\,T = T\,T^\dagger$$

$\hookrightarrow$ note that this is a matrix equation:
$\mathrm{Im}\,T_{A\to B} = \sum_X T_{A\to X}\,T^\dagger_{X\to B}$

$\rightsquigarrow$ in practice: use most relevant intermediate states X

  - analytical (dispersion relation for form factors):

$$T(q^2) = T(0) + \frac{q^2}{\pi} \int\limits_{\text{threshold}}^{\infty} ds\, \frac{\mathrm{Im}\,T(s)}{s\,(s-q^2-i\epsilon)}$$

$\rightsquigarrow$ can be used to calculate whole amplitude from imaginary part

Dispersion relation for form factor

example: $e^+e^- \to \gamma^* \to Y_1 \bar{Y}_2 \; (= B)$

$$T_{\gamma^* \to B}(q^2) = T_{\gamma^* \to B}(0) + \frac{q^2}{\pi} \int\limits_{\text{threshold}}^{\infty} ds \, \frac{\sum_X T_{\gamma^* \to X}(s) \, T^\dagger_{X \to B}(s)}{s\,(s - q^2 - i\epsilon)}$$

- physical threshold is at $m_{Y_1} + m_{Y_2}$, but in dispersion relation the threshold is given by the lowest-mass states that can couple to virtual photons (and hyperons)

$\hookrightarrow$ $X = 2$ pions, ...

$\hookrightarrow$ threshold $= (2m_\pi)^2$

$\hookrightarrow$ need information in unphysical region starting at 2-pion threshold

- most important contribution for low values of q^2 (time-like or space-like)

Pion contribution

$$T_{\gamma^* \to Y_1 \bar{Y}_2}(q^2) \approx T_{\gamma^* \to Y_1 \bar{Y}_2}(0) + \frac{q^2}{\pi} \int\limits_{4m_\pi^2}^{\infty} ds \, \frac{T_{\gamma^* \to 2\pi}(s) \, T^\dagger_{2\pi \to Y_1 \bar{Y}_2}(s)}{s\,(s - q^2 - i\epsilon)}$$

$\hookrightarrow$ need $T_{2\pi \to Y_1 \bar{Y}_2}$ ($T_{\gamma^* \to 2\pi}$ very well known)

$\hookrightarrow$ use again analyticity, dispersion theory and crossing symmetry

$\hookrightarrow$ need pion-hyperon scattering amplitudes $\pi Y_1 \to \pi Y_2$

$\hookrightarrow$ ideally from data, but not available

$\hookrightarrow$ use instead chiral perturbation theory (χPT)

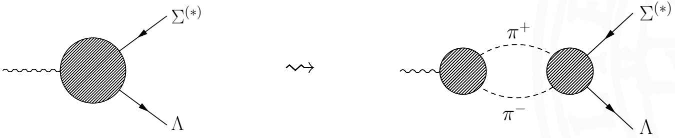
$\hookrightarrow$ contains in part unknown low-energy constants (LECs)

$\hookrightarrow$ determine LEC(s) from data

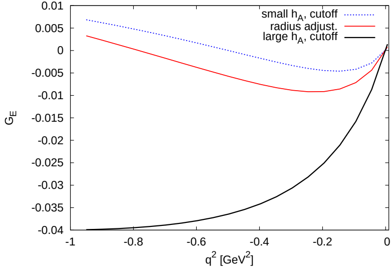
Strategy

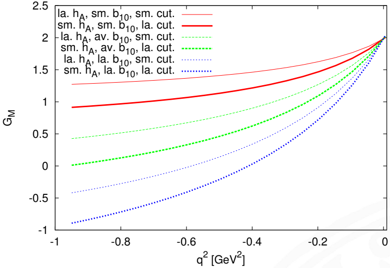
$$T_{\gamma^* \to Y_1 \bar{Y}_2}(q^2) \approx T_{\gamma^* \to Y_1 \bar{Y}_2}(0) + \frac{q^2}{\pi} \int\limits_{4m_\pi^2}^{\infty} ds \, \frac{T_{\gamma^* \to 2\pi}(s) \, T^\dagger_{2\pi \to Y_1 \bar{Y}_2}(s)}{s \, (s - q^2 - i\epsilon)}$$

- measure left-hand side for small time-like $q^2 > 0$, e.g. slope
- determine LEC(s) for $T_{2\pi \to Y_1 \bar{Y}_2}$ on right-hand side
- predict left-hand side for small space-like $q^2 < 0$



Example: Transition form factors Σ-Λ





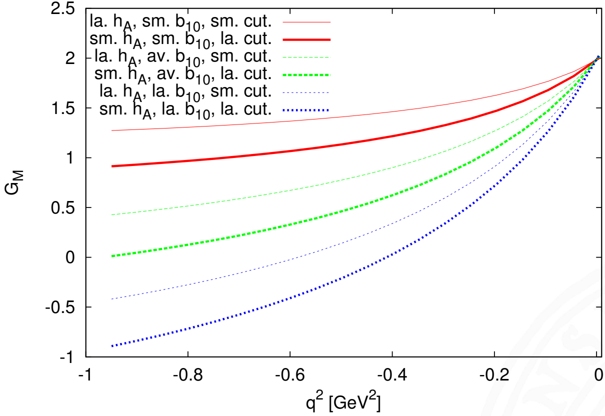
- electric transition form factor very small over large range

$\hookrightarrow$ what one might measure at low energies is magnetic transition form factor

$\hookrightarrow$ Dalitz-decay data $\Sigma^0 \to \Lambda\, e^+ e^-$ integrated over Λ-e^- angle, but differential in q^2 might be sufficient

- note: Dalitz decay region $4m_e^2 < q^2 < (m_\Sigma - m_\Lambda)^2$ hardly visible here

Magnetic transition form factor Σ-Λ

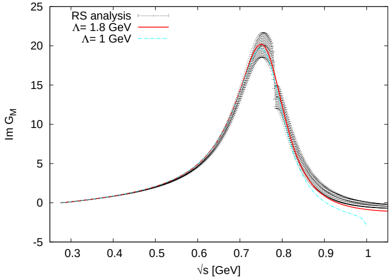


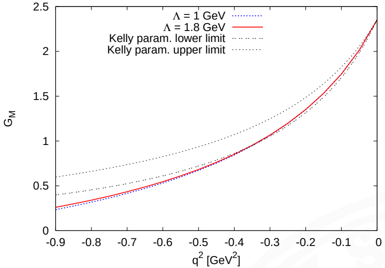
- large uncertainty

$\hookrightarrow$ directly related to uncertainty in NLO low-energy constant b_{10}

$\hookrightarrow$ can be determined from measuring magnetic transition radius

Magnetic isovector form factor of nucleon





$\hookrightarrow$ low-energy framework works up to $|q^2| \approx 0.4\,\text{GeV}^2$

- "RS" (Roy-Steiner equation): fully dispersive analysis
- "Kelly param.": parametrization of form factor data
  J.J. Kelly, Phys.Rev.C 70, 068202 (2004)

$\rightsquigarrow$ scheme (disp. th. & χPT) works very well for nucleon

Extension to spin-3/2 hyperons has started

- aiming at transition form factors, Dalitz decays $Y^*(J = 3/2) \to Y\, e^+ e^-$

$\hookrightarrow$ hyperon-pion scattering amplitudes in chiral perturbation theory (χPT)

$\hookrightarrow$ master thesis Olov Junker, work in progress

- χPT prediction for radiative decays $Y^*(J = 3/2) \to Y\gamma$

$\hookrightarrow$ next page

- axial-vector transition form factors and relation to $Y^*(J = 3/2) \to Y\gamma\pi$

$\hookrightarrow$ master thesis Måns Holmberg, work in progress

Radiative decays

Constructing and using chiral perturbation theory at next-to-leading order for decuplet states:

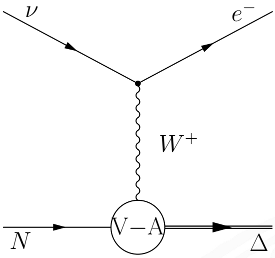
Decay	$c/(c_M e)$	BR [%]	$\lvert c_M \rvert$ [GeV^{-1}]
$\Delta \to N\gamma$	$2/\sqrt{3}$	0.60±0.05	2.00±0.03
$\Sigma^{*+} \to \Sigma^{+}\gamma$	$-2/\sqrt{3}$	0.70±0.17	1.89±0.08
$\Sigma^{*-} \to \Sigma^{-}\gamma$	0	< 0.024	—
$\Sigma^{*0} \to \Sigma^{0}\gamma$	$1/\sqrt{3}$	**0.18±0.01**	—
$\Sigma^{*0} \to \Lambda\gamma$	-1	1.25±0.13	1.89±0.05
$\Xi^{*0} \to \Xi^{0}\gamma$	$-2/\sqrt{3}$	**4.0±0.3**	—
$\Xi^{*-} \to \Xi^{-}\gamma$	0	< 4	—

(predictions in boldface)

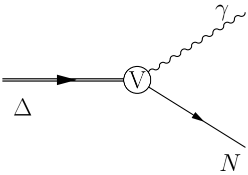
Måns Holmberg, SL, arXiv:1802.05168 [hep-ph], to appear in EPJ A

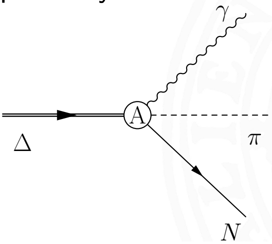
Axial-vector transition form factors

- interesting for scattering neutrino-nucleon to electron-Delta
- low energies: want to know deviation from current-algebra result $\rightsquigarrow$ LEC c_E



- vector and axial-vector transition form factors contribute also to $\Delta \to N\gamma$ and $\Delta \to N\pi\gamma$, respectively

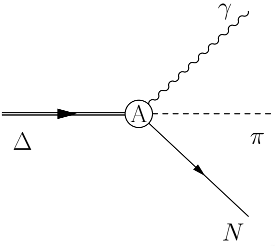




Axial-vector TFFs and three-body decays

problems:

- needs to be disentangled from bremsstrahlung
- hard to measure for broad Delta



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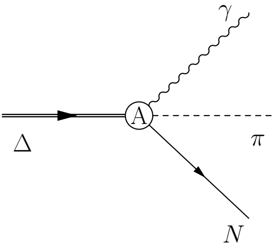
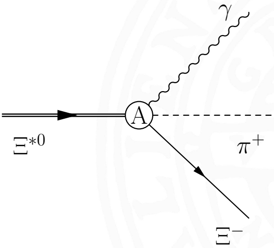


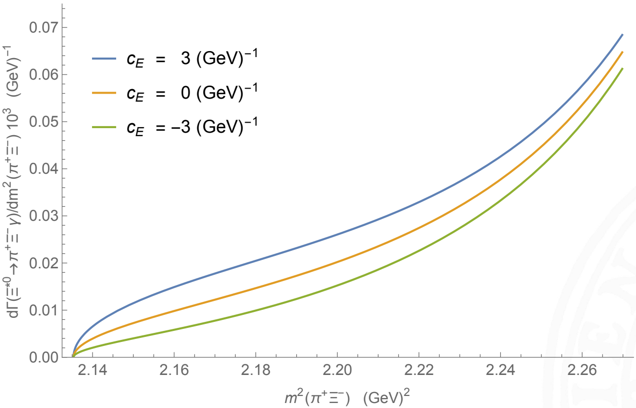
⇝ in chiral perturbation theory at next-to-leading order: only one LEC c_E for whole multiplet

↪ get some clue from radiate three-body decays of hyperons, e.g. cascades



Radiative three-body decay — preliminary results

- consider $\Xi^{*0}(1530) \to \Xi^- \pi^+ \gamma$



- branching ratio $(3.7 \pm 0.7) \cdot 10^{-4}$
  (cut on photon energy at 50 MeV)

from Måns Holmberg

Collaborators

- Carlos Granados (postdoc, Washington D.C.)
- Elisabetta Perotti (PhD student, Uppsala)
- Måns Holmberg (master student, Uppsala)
- Olov Junker (master student, Uppsala)

C. Granados, SL, E. Perotti, Eur.Phys.J. A53 (2017) 117

SL, Eur.Phys.J. A54 (2018) 1

M. Holmberg, SL, Eur.Phys.J.A, in print, arXiv:1802.05168 [hep-ph]

Summary

- excellent prospects to explore structure of hyperons

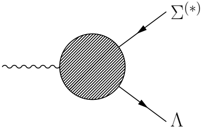
$\hookrightarrow$ experiments: BES-III, HADES, PANDA, ...

$\hookrightarrow$ Uppsala theory group: develop and utilize dispersion theory and chiral perturbation theory

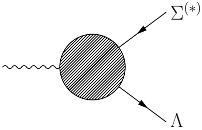
  - can predict magnetic transition form factor Σ^0-Λ in low-energy space-like region if slope is measured in Dalitz decay
  - work in progress for transition form factors Σ^{*0}-Λ etc.
  - radiative decays $\Sigma^{*0} \to \Sigma^0\gamma$, $\Xi^{*0} \to \Xi^0\gamma$ predicted
  - decays $Y^*(J = 3/2) \to Y\pi\gamma$ related to axial-vector transition form factors, in turn related to $\nu N \to e^-\Delta$

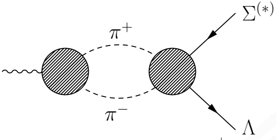
backup slides

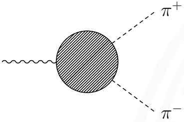
Hyperon transition form factors

- for $\Sigma/\Sigma^* \to \Lambda\, e^+ e^-$ need transition form factors 

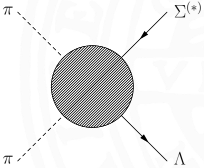
- dispersive framework: at low energies q^2 dependence is governed by lightest intermediate states

$\hookrightarrow$ obtain 

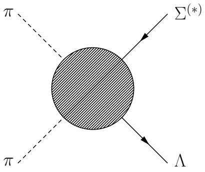
from 

$\hookrightarrow$ need pion vector form factor 

(measured)

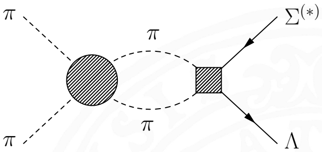
and hyperon-pion scattering amplitudes 

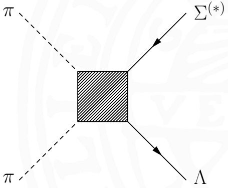
Hyperon-pion scattering amplitudes



contain

- “right-hand cuts” (pion rescattering)
  - ↪ straightforward from unitarity and analyticity (and experimental pion phase shift)
- and rest:
  left-hand cuts, polynomial terms
  - ↪ not straightforward
  - ↪ use three-flavor baryon chiral perturbation theory





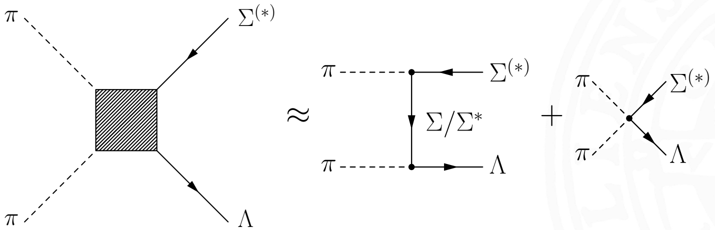
$= ?$

Input for hyperon-pion scattering amplitudes

- ideally use data

$\hookrightarrow$ available for pion-nucleon, but not for pion-hyperon

$\hookrightarrow$ instead: three-flavor baryon chiral perturbation theory (χPT) at leading and next-to-leading order (NLO)
including decuplet states
(optional for $\Sigma^0 \to \Lambda$ transition, but turns out to be important!)



χPT input for hyperon-pion scattering amplitudes

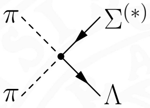
three-point couplings fairly well known,
but how to determine NLO four-point coupling constants?

- only one parameter (b_{10}) for Σ-Λ transition

$\hookrightarrow$ but not very well known

- "resonance saturation" estimates

  Meißner/Steininger/Kubis, Nucl.Phys. B499, 349 (1997); Eur.Phys.J. C18, 747 (2001)



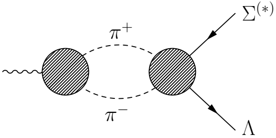
or from fit to πN and KN scattering data with coupled-channel Bethe-Salpeter approach

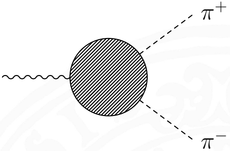
  Lutz/Kolomeitsev, Nucl.Phys. A700, 193 (2002)

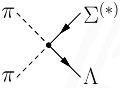
- maybe in the future:
  cross-check from lattice QCD

parameter is directly related to magnetic transition radius of Σ-Λ

Where are the vector mesons?



- contained in measured pion vector form factor 

- and contained in four-point coupling  :

  - interactions $\sim \bar{\Lambda}\sigma_{\mu\nu}\Sigma^0 \, V^{\mu\nu}$ and $\sim V_{\mu\nu} \, \partial^\mu\pi^+\partial^\nu\pi^-$
    (with V vector-meson field)
    contribute to χPT four-point interaction $\sim \bar{\Lambda}\sigma_{\mu\nu}\Sigma^0 \, \partial^\mu\pi^+\partial^\nu\pi^-$
  - dispersion theory takes care of proper interplay