Perspectives of electroweak transition form factor studies with hyperons

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Wuppertal, Feb. 2024

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Understanding the strong interaction

model-independent methods to explore QCD (and in general QFT):

- perturbative QCD
  - works at high energies where strong interaction is weak
- lattice QCD
  - works best around Λ_{QCD}, m_s (hadronic scale $\approx 1\,\mathrm{GeV}$)
  - light pion sees itself around the torus *if* volume is too small
  - but advantage: quark masses can be varied
- (chiral) effective field theory $\rightsquigarrow$ works at low energies
- dispersion theory $\rightsquigarrow$ works if there are only a few channels

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- experiment! $\rightsquigarrow$ but quark masses fixed

Play it again, Sam

- we are all interested in exploring strongly interacting matter

$\hookrightarrow$ composite structures formed by quarks and gluons

$\hookrightarrow$ form factors are introduced to characterize composite objects

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- here is another motivation

Neutrino physics

- explore neutrino oscillations, CP violation in lepton sector, ...
- want to count how many neutrinos one has
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  $\hookrightarrow$ perturbative QCD

  - at lowest energies: neutrinos "see" nuclei

  $\hookrightarrow$ nuclear-structure physics

  - at low energies: neutrinos see "nucleons"

  $\hookrightarrow$ vector and axial-vector form factors of nucleon and pion production! $\rightsquigarrow$ hyperons and $\Delta(1232)$

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  $\hookrightarrow$ vector and axial-vector form factors of nucleon and pion production! $\rightsquigarrow$ hyperons and $\Delta(1232)$

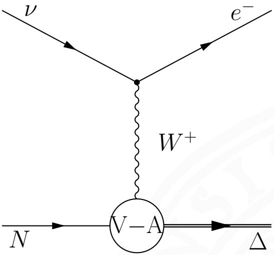
- true for all energies: need to get stuff out from the nucleus

$\hookrightarrow$ transport theory $\rightsquigarrow$ ask Ulrich Mosel

Why are Δs and hyperons interesting?

Axial-vector (and vector) transition form factors

- interesting for scattering neutrino-nucleon to electron-Δ or muon-Δ or hyperon (Y) instead of Δ
- subsequently: $\Delta, Y \to \pi N$



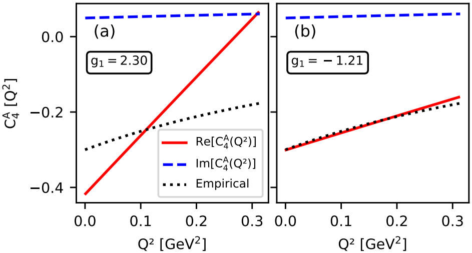
NuSTEC Collaboration, L. Alvarez-Ruso et al., Prog. Part. Nucl. Phys. 100 (2018) 1;
M. Hilt, T. Bauer, S. Scherer, L. Tiator, Phys. Rev. C 97 (2018) 3, 035205;
M. Holmberg, SL, Phys. Rev. D 100 (2019) 11, 114001;
Y. Ünal, A. Küçükarslan, S. Scherer, Phys. Rev. D 104 (2021) 9, 094014;
S.K. Singh, M.J. Vicente Vacas, Phys. Rev. D 74 (2006) 053009

Δ couplings and Δ-N transition form factors

- coupling constant Δ-N-π known from decay width of $\Delta \to \pi N$

but coupling constant Δ-Δ-π (g_1) unknown in size and sign

(actually there are two couplings, p and f wave $\rightsquigarrow$ here: p-wave coupling)



one of the axial-vector transition form factors; g_1 enters indirectly at loop level

Y. Ünal, A. Küçükarslan, S. Scherer, Phys. Rev. D 104 (2021) 9, 094014

- quark model and large-N_c QCD suggest positive g_1 (figure: left-hand side)
- recent analysis of π-N scattering suggests negative g_1
  $\hookrightarrow$ ask Evgeny Epelbaum
  De-Liang Yao *et al.*, JHEP 05 (2016) 038

How about lattice QCD?

- currently under investigation using lattice QCD:
  - form factors of stable baryons
  - and their quark-mass dependence
- interpretation of results by chiral effective field theory

↪ ask Matthias Lutz

M.F.M. Lutz, U. Sauerwein, R.G.E. Timmermans, Eur. Phys. J. C 80 (2020) 9, 844;
Phys. Rev. D 105 (2022) 5, 054005

see also F. Alvarado, L. Alvarez-Ruso, Phys. Rev. D 105 (2022) 7, 074001

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- but for transition form factors Δ-N:
  - much more complicated because Δ is unstable

  $\hookrightarrow$ essentially four-point function instead of three-point function
  - and even more complicated for coupling constant Δ-Δ-π

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- but for transition form factors Δ-N:
  - much more complicated because Δ is unstable
  - ↪ essentially four-point function instead of three-point function
  - and even more complicated for coupling constant Δ-Δ-π
- to circumvent problem: study (nearly) stable flavor partners
  - Ω-Ξ transition form factors
  - Ω-Ξ^*-K coupling constant

    ↪ related to Ω-Ξ^* transition by Goldberger-Treiman relation

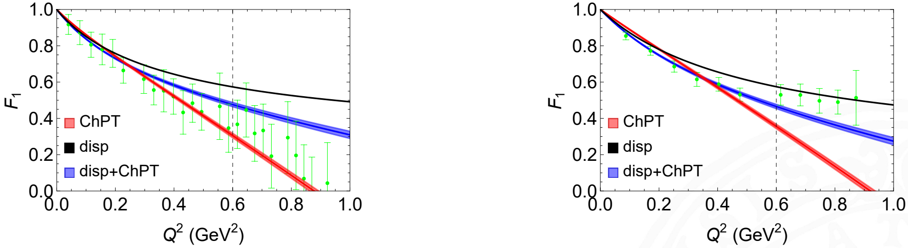
My suggestion for a research program

1. study Ω transition form factors in lattice QCD and experiment (and quark-mass dependence on lattice)
2. interpret results using (dispersively modified) chiral effective field theory (dimχEFT)
3. extrapolate to Δ transition form factors using (dim)χEFT and experimental data (hyperons)
4. obtain improved input for neutrino scattering (and obtain better understanding of structure of hadrons)

UU contribution: develop dimχEFT

Does all this make sense?

quark-mass and momentum dependence of nucleon Dirac form factor



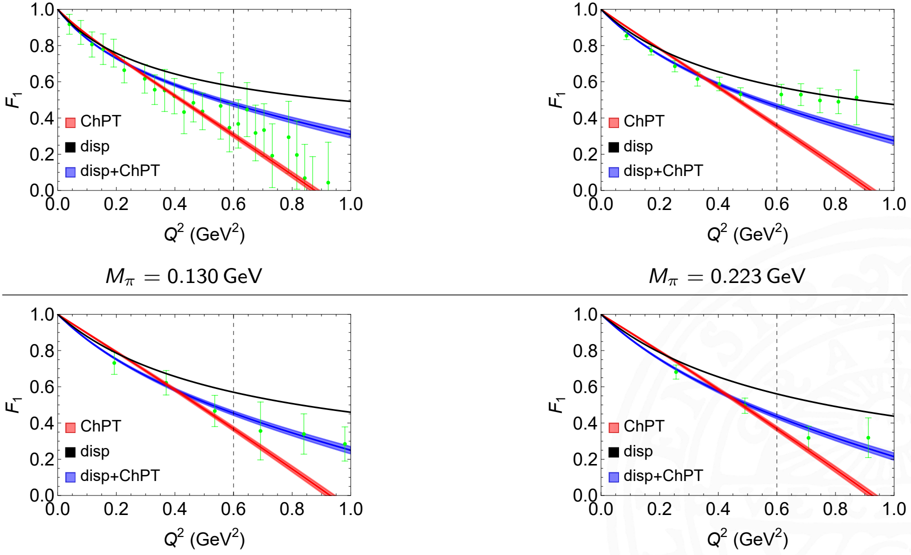
$M_\pi = 0.130\,\text{GeV}$ $\qquad$ $M_\pi = 0.223\,\text{GeV}$

F. Alvarado, D. An, L. Alvarez-Ruso, SL, Phys. Rev. D 108 (2023) 11, 114021

lattice data from Darmstadt-Edinburgh-Mainz group:

D. Djukanovic et al., Phys. Rev. D 103 (2021) 9, 094522

Dirac vector isovector form factor of nucleon



$M_\pi = 0.130\,\text{GeV}$ | $M_\pi = 0.223\,\text{GeV}$

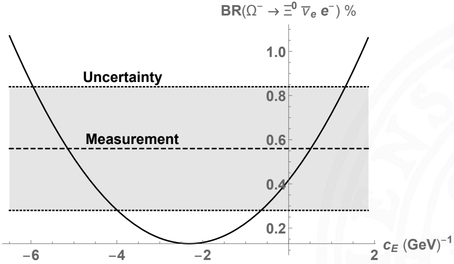
$M_\pi = 0.278\,\text{GeV}$ | $M_\pi = 0.353\,\text{GeV}$

Branching ratio $\Omega^- \to \Xi^0 e^- \bar{\nu}_e$ (measured)

- so far only next-to-leading-order (NLO) calculation finished
- contribution from LO Lagrangian ($\sim h_A$) related to $\Sigma^* \to \Sigma\pi$
- contributions from NLO Lagrangian $\sim c_M, c_E$

$\hookrightarrow$ $|c_M|$ related to $\Sigma^{*0} \to \Lambda\gamma$

$\hookrightarrow$ get constraints on c_E from measured branching ratio:

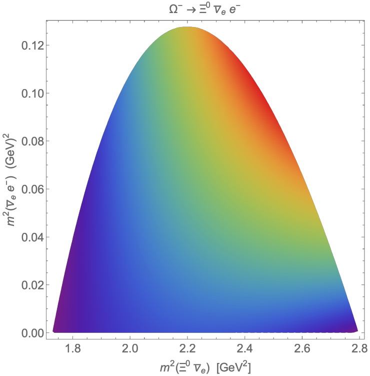


M. Holmberg, SL, Eur. Phys. J. A 54 (2018) 6, 103; Phys. Rev. D 100 (2019) 11, 114001
C.J.G. Mommers, SL, Phys. Rev. D 106 (2022) 9, 093001

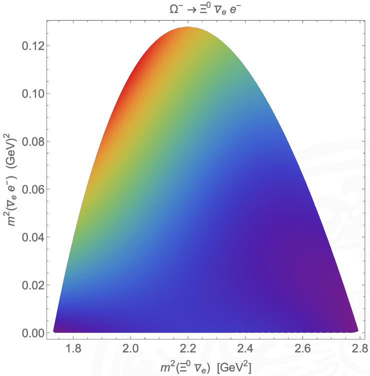
first steps beyond tree level: H. De Munck; M. Bertilsson, master theses UU 2023

Dalitz plot $\Omega^- \to \Xi^0 e^- \bar{\nu}_e$ (not measured yet)

- different values for c_E and sign of c_M influence Dalitz plot:



$$c_E = 0.52\,\text{GeV}^{-1}, \quad c_M = -1.92\,\text{GeV}^{-1}$$



$$c_E = -5.1\,\text{GeV}^{-1}, \quad c_M = -1.92\,\text{GeV}^{-1}$$

- sign change of c_M flips plots right $\leftrightarrow$ left

Decay $\Omega^- \to \Xi^{*0} \ell^- \bar{\nu}_\ell$ (not measured yet)

- provides access to sign and size of coupling constant Ω-$\Xi^*(1530)$-K via Golberger-Treiman relation
- flavor related to sign and size of coupling constant Δ-Δ-π ($H_A = g_1$)
- so far only leading-order calculation for branching ratio and forward-backward (fb) asymmetry (Wu-type experiment)
  (rest frame of dilepton, measuring angle between baryons and charged lepton)

	$\Gamma_{\Omega\to\Xi^*\ell\bar{\nu}_\ell}/\Gamma_{\Omega,\mathrm{tot}}$	$\Gamma_{\mathrm{fb}}/\Gamma_{\Omega\to\Xi^*\ell\nu}$
$\ell = e,\ H_A = +2$	$1.2 \cdot 10^{-4}$	$+0.011$
$\ell = e,\ H_A = 0$	$6.7 \cdot 10^{-5}$	-0.00043
$\ell = e,\ H_A = -2$	$1.2 \cdot 10^{-4}$	-0.012
$\ell = \mu,\ H_A = +2$	$4.3 \cdot 10^{-6}$	-0.23
$\ell = \mu,\ H_A = 0$	$2.5 \cdot 10^{-6}$	-0.33
$\ell = \mu,\ H_A = -2$	$4.3 \cdot 10^{-6}$	-0.25

- note: $\Xi^{*0}(1530)$ "easy" to reconstruct via sequence
  $\Xi^{*0} \to \Xi^- \pi^+$, $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$

M. Bertilsson, SL, arXiv: 2311.07471 [hep-ph]

Radiative decays of $\Xi^*(1530)$ and $\Sigma^*(1385)$

- our calculation so far only tree level (NLO)
- our **predictions** in boldface
- blue: measured — red: predicted, but not measured yet

decay	$c/(c_M e)$	BR [%]	c_M [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	—

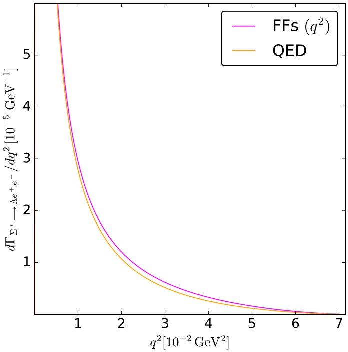
M. Holmberg, SL, Eur. Phys. J. A 54 (2018) 6, 103

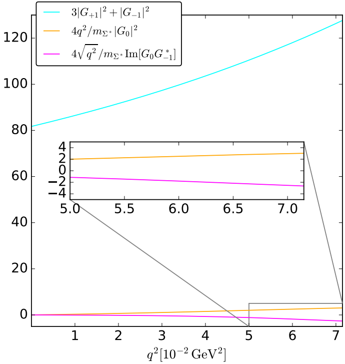
Form factors in $\Sigma^{*0}(1385) \to \Lambda\, e^+ e^-$ (not measured yet)

- our method: dispersion relation (unsubtracted in lack of data)

  O. Junker, SL, E. Perotti, T. Vitos, Phys. Rev. C 101 (2020) 1, 015206

- decay width about 3 keV





relevant combinations for
$\Sigma^{*0}(1385) \to \Lambda\, e^+e^- \to p\pi^-\, e^+e^-$

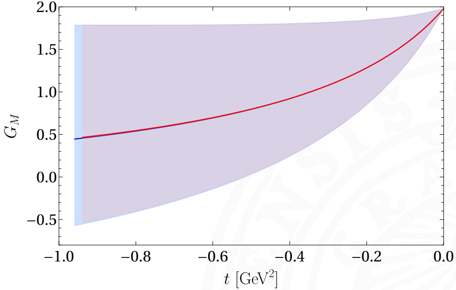
Magnetic form factor in $\Sigma^0 \to \Lambda\, e^+ e^-$ (not measured yet)

- our method: dispersion theory with 2-pion intermediate states

  C. Granados, SL, E. Perotti, Eur. Phys. J. A 53 (2017) 6, 117

- extended to coupled channels: 2 pions and 2 kaons

  Y.-H. Lin, H.-W. Hammer, U.-G. Meißner, Eur. Phys. J. A 59 (2023) 3, 54



$\hookrightarrow$ ask Hans-Werner Hammer

- prediction can be drastically improved by “just” measuring slope at $t = q^2 \approx +0$, i.e. from $\Sigma^0 \to \Lambda\, e^+ e^-$
- cross relation to transition form factors N-Λ and N-Σ

Summary and Outlook

- D elta transition form factors are interesting for neutrino physics
- O mega transition form factors are a better starting point
- L attice QCD can tackle these (plus experimental guidance)
- C hiral effective field theory can interpret results
- E xtrapolation to Delta (EFT plus experimental guidance)

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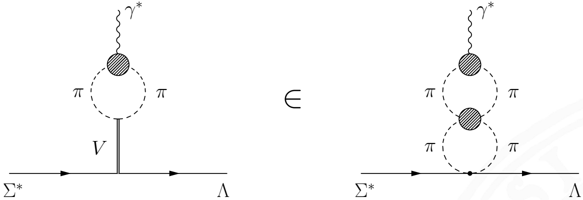
interesting hyperon decays:

- $\Omega^- \to \Xi^0 \ell^- \bar{\nu}$
- $\Omega^- \to \Xi^{*0} \ell^- \bar{\nu}$
- $\Xi^{*0} \to \Xi^0 \gamma$
- $\Sigma^{*0} \to \Sigma^0 \gamma$
- $\Sigma^{*0} \to \Lambda e^+ e^-$
- $\Sigma^0 \to \Lambda e^+ e^-$

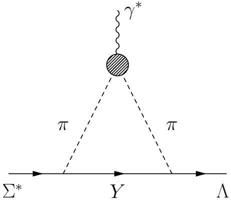
Spare slides

Form factors in $\Sigma^{*0}(1385) \to \Lambda\, e^+ e^-$ (not measured yet)

- our method: dispersion relation (unsubtracted in lack of data)
  O. Junker, SL, E. Perotti, T. Vitos, Phys. Rev. C 101 (2020) 1, 015206
- ρ meson is included via pion phase shift (model independent)



- "our" triangles with baryons are beyond vector-dominance model



Unitarity and analyticity

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

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

  ↪ note that this is a matrix equation:
  $\mathrm{Im}\,T_{A\to B} = \sum_X T_{A\to X}\,T^\dagger_{X\to B}$
  - analytic (dispersion relations):

$$T(s) = \frac{1}{\pi}\int\limits_{-\infty}^{\infty} ds'\,\frac{\mathrm{Im}\,T(s')}{s'-s-i\epsilon}$$

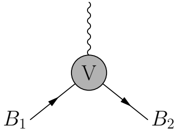
⇝ can be used to calculate whole amplitude from imaginary part

- practical limitation: too many states X at high energies

↪ in practice dispersion theory is a low-energy method ($\lesssim 1\,\mathrm{GeV}$)
or use resonance saturation

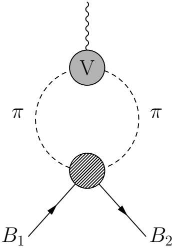
Example: electromagnetic baryon form factors

- how to obtain a form factor?



- need to resolve at least the finite size $\lesssim 1\,\text{fm}$
- but inverse size of a hadron is larger than pion mass
- first one probes something universal (independent of $B_{1,2}$):

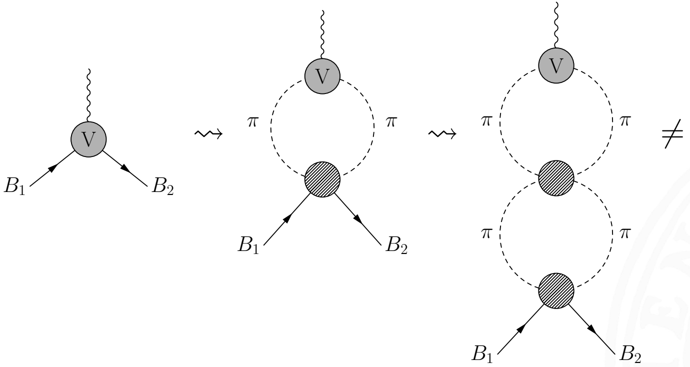
the "pion cloud":



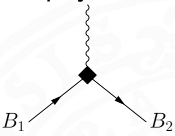
- now we are in the game with dispersion theory

Deconstruct a form factor

pions interact with each other



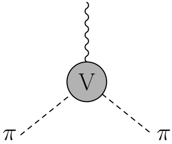
what is not contained is hard (short-distance) physics



just a number!

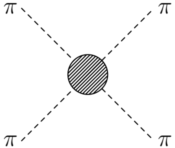
How to get the pion vector form factor?

apply same logic to pion vector FF

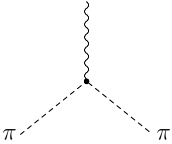


input:

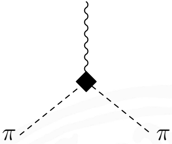
pion scattering



pion charge



hard part of pion vector FF

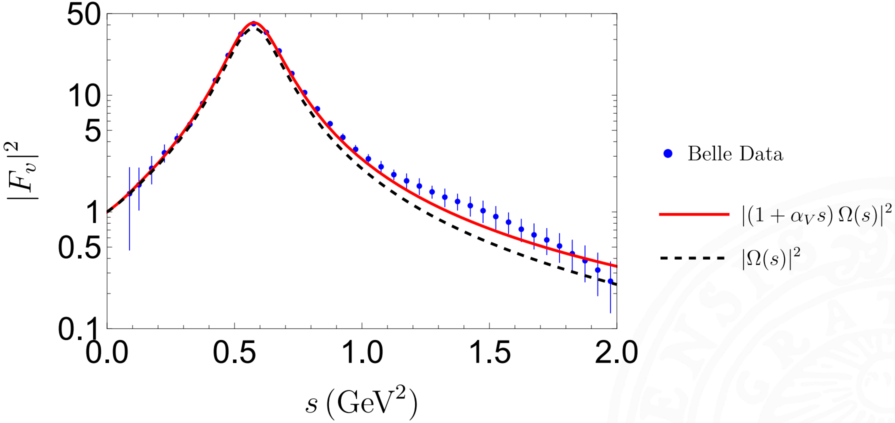


$$F_V(s) = (1 + \alpha_V\, s)\, \exp\left\{ s \int\limits_{4m_\pi^2}^{\infty} \frac{\mathrm{d}s'}{\pi}\, \frac{\delta(s')}{s'\,(s' - s - i\epsilon)} \right\}$$

with pion phase shift δ

and $\alpha_V \approx 0.12\,\mathrm{GeV}^{-2}$ (from fit to FF data)

Pion vector form factor and data



Alvarado/An/Alvarez-Ruso/SL, Phys. Rev. D 108 (2023) 11, 114021

Deconstruct a form factor

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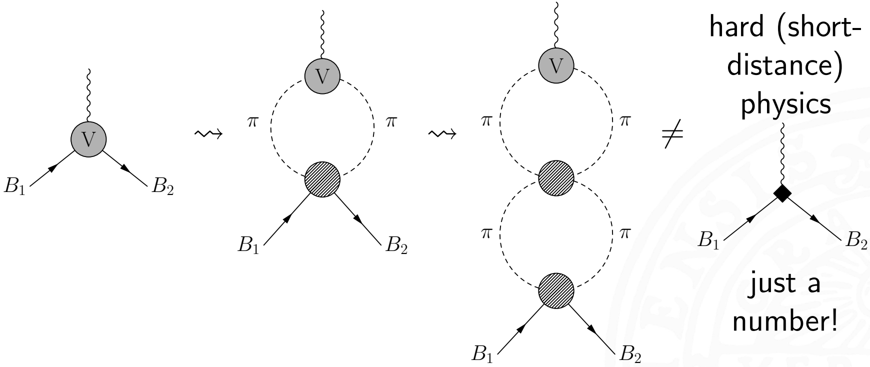
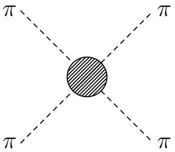


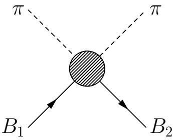
just a number!

Scattering processes

from data plus dispersion theory:

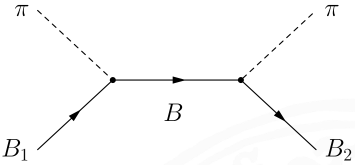


part that is not pion rescattering:

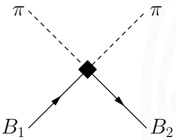


⇝

low-energy approximation:

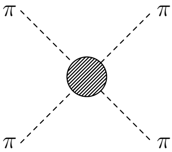


what is not covered is hard physics (contact terms)

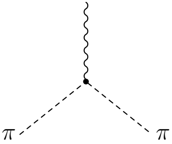


Known input

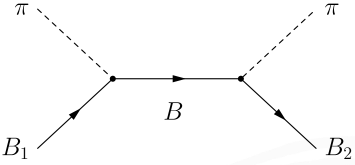
pion scattering



pion charge



low-energy approximation

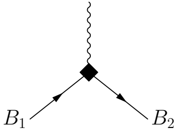


- baryon-pion coupling constants from decay widths

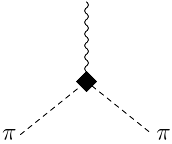
$\hookrightarrow$ sometimes only moduli known

Unknown: some numbers

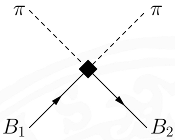
part without two intermediate pions



intermediate state with more than two pions



intermediate state that is not one baryon



$\hookrightarrow$ fit to data (now) or calculate with quark-gluon based methods (future)

What can we learn here?

- the long-distance part is universal

↪ needs to be understood once, not always new for each process

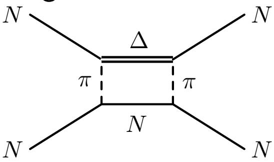
↪ a lot is fixed by (chiral) symmetries

- the short-distance part is process dependent
  and sensitive to the details (dynamics) of QCD
- obtain information by combining
  hadron based effective field theories + dispersion theory
  (parametrization of short-distance physics)
  with quark based methods
  (determination of parameter values)

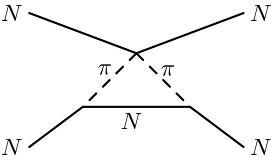
Importance of Δ in low-energy QCD?

consider nucleon-nucleon scattering:

- is it necessary to consider

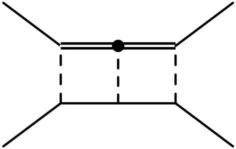


or is



sufficient?

- how important is

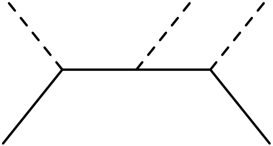


?

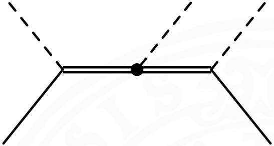
- coupling constant Δ-Δ-π • unknown!

What is unknown for Δ baryons?

- coupling constant Δ-Δ-π • completely unknown; not even sign is clear
- further example: is interference of



and



constructive or destructive?

- one problem to determine Δ properties with better precision: Δs are rather broad states ($\Gamma \approx 100\,\text{MeV}$)

$\hookrightarrow$ worth to study strange siblings from decuplet

$\hookrightarrow$ e.g. Ω-Ξ^*-K coupling and related $\Omega \to \Xi^* \ell \nu$