Sigma term physics

Ulf-G. Meißner, Univ. Bonn & FZ Jülich

by CAS, PIFI

by DFG, SFB 1639

by ERC, EXOTIC

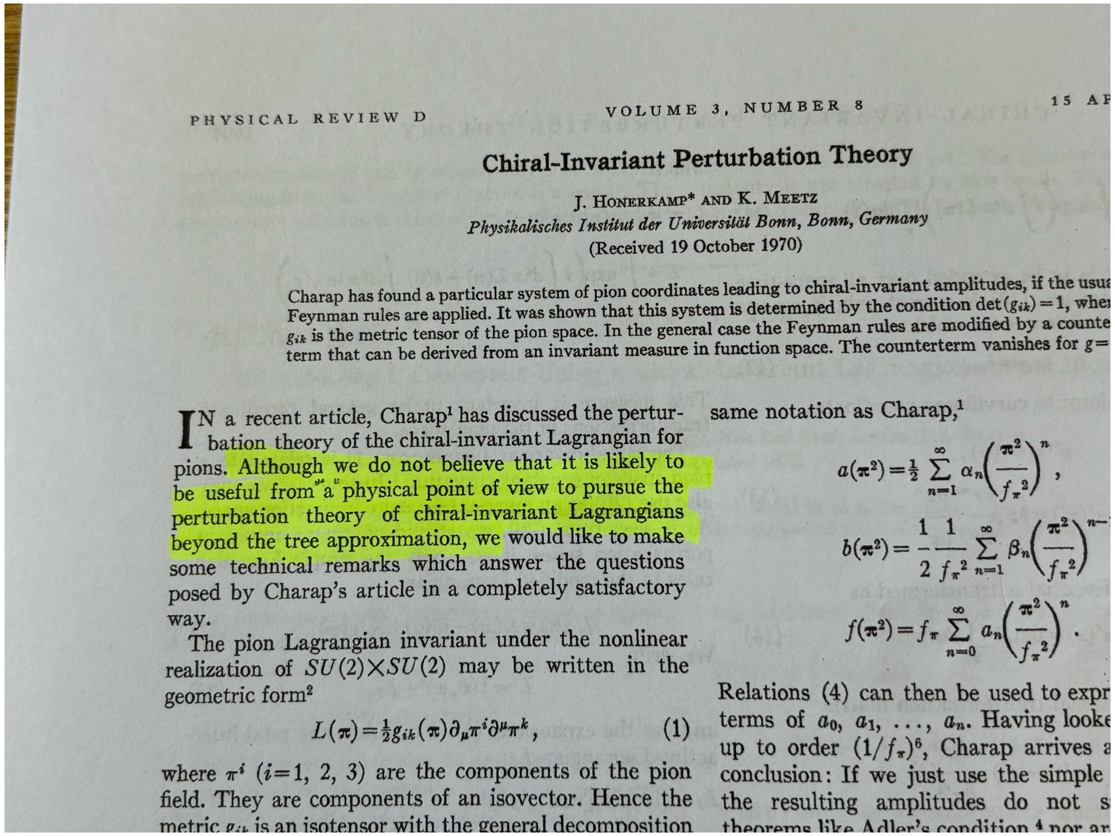
by NRW-FAIR

Contents

Introductory remarks

A small anecdote

- The first paper with “chiral perturbation theory” in the title



PHYSICAL REVIEW D VOLUME 3, NUMBER 8 15 AP

Chiral-Invariant Perturbation Theory

J. HONERKAMP* AND K. MEETZ
Physikalisches Institut der Universität Bonn, Bonn, Germany
(Received 19 October 1970)

Charap has found a particular system of pion coordinates leading to chiral-invariant amplitudes, if the usua Feynman rules are applied. It was shown that this system is determined by the condition $\det(g_{ik})=1$, wher g_{ik} is the metric tensor of the pion space. In the general case the Feynman rules are modified by a counte term that can be derived from an invariant measure in function space. The counterterm vanishes for $g=$

IN a recent article, Charap[1] has discussed the perturbation theory of the chiral-invariant Lagrangian for pions. Although we do not believe that it is likely to be useful from a physical point of view to pursue the perturbation theory of chiral-invariant Lagrangians beyond the tree approximation, we would like to make some technical remarks which answer the questions posed by Charap's article in a completely satisfactory way.

The pion Lagrangian invariant under the nonlinear realization of $SU(2)\times SU(2)$ may be written in the geometric form[2]

$$L(\pi)=\tfrac{1}{2}g_{ik}(\pi)\partial_\mu\pi^i\partial^\mu\pi^k\,, \qquad (1)$$

where π^i ($i=1, 2, 3$) are the components of the pion field. They are components of an isovector. Hence the metric g_{ik} is an isotensor with the general decomposition

same notation as Charap,[1]

$$a(\pi^2)=\tfrac{1}{2}\sum_{n=1}^{\infty}\alpha_n\left(\frac{\pi^2}{f_\pi^2}\right)^n,$$

$$b(\pi^2)=\frac{1}{2}\frac{1}{f_\pi^2}\sum_{n=1}^{\infty}\beta_n\left(\frac{\pi^2}{f_\pi^2}\right)^{n-1}$$

$$f(\pi^2)=f_\pi\sum_{n=0}^{\infty}a_n\left(\frac{\pi^2}{f_\pi^2}\right)^n.$$

Relations (4) can then be used to expr terms of $a_0, a_1, \ldots, a_n$. Having looke up to order $(1/f_\pi)^6$, Charap arrives a conclusion: If we just use the simple the resulting amplitudes do not s theorems like Adler's condition[4] nor ar

- Possible consequences:

  ↪ stop the talk here

  ↪ don't always listen to Bonn people

Some statistics on Gasser/Leutwyler papers

- What a list of most cited papers! [NB: just the common ones!]

Chiral Perturbation Theory to One Loop #1
J. Gasser (Bern U.), H. Leutwyler (CERN) (Aug, 1983)
Published in: *Annals Phys.* 158 (1984) 142
pdf DOI cite claim reference search 4,901 citations

Chiral Perturbation Theory: Expansions in the Mass of the Strange Quark #2
J. Gasser (Bern U.), H. Leutwyler (CERN) (Jan, 1984)
Published in: *Nucl.Phys.B* 250 (1985) 465-516
DOI cite claim reference search 4,467 citations

Quark Masses #3
J. Gasser (Bern U.), H. Leutwyler (Bern U.) (Mar, 1982)
Published in: *Phys.Rept.* 87 (1982) 77-169
DOI cite claim reference search 2,265 citations

$\pi\pi$ scattering #4
G. Colangelo (Zurich U.), J. Gasser (Bern U.), H. Leutwyler (Bern U.) (Mar, 2001)
Published in: *Nucl.Phys.B* 603 (2001) 125-179 • e-Print: hep-ph/0103088 [hep-ph]
pdf DOI cite claim reference search 1,067 citations

Chiral Lagrangians for Massive Spin 1 Fields #5
G. Ecker (Vienna U.), J. Gasser (Bern U.), H. Leutwyler (Bern U.), A. Pich (Valencia U.), E. de Rafael (Marseille, CPT and Barcelona U.) (Apr 24, 1989)
Published in: *Phys.Lett.B* 223 (1989) 425-432
DOI cite claim reference search 1,001 citations

Sigma term update #6
J. Gasser (Bern U.), H. Leutwyler (Bern U.), M.E. Sainio (Helsinki U.) (Sep, 1990)
Published in: *Phys.Lett.B* 253 (1991) 252-259
DOI cite claim reference search 919 citations

"You should always put the Gasser/Leutwyler papers under your pillow"
Howard Georgi, Dobogöko, 1991

$\hookrightarrow$ Much too much good stuff for one talk!

$\hookrightarrow$ I will focus on #6 and related papers here

Sigma term basics

σ-term basics

- Scalar form factor of the nucleon (isospin limit $\hat{m} = (m_u + m_d)/2$):

$$\sigma_{\pi N}(t) = \langle N(p')|\hat{m}(\bar{u}u + \bar{d}d)|N(p)\rangle \ , \ t = (p' - p)^2$$

- Cheng-Dashen Low-Energy Theorem (LET):

Cheng, Dashen (1971)

$$\bar{D}^+(\nu = 0, t = 2M_\pi^2) = \sigma(2M_\pi^2) + \Delta_R$$

$$\left[\nu = \frac{s-u}{4m_N}\right]$$

- $\bar{D}^+$ – isospin-even, Born-term subtracted pion-nucleon scattering amplitude

$$\bar{D}^+(0, 2M_\pi^2) = A^+(m_N^2, 2M_\pi^2) - \frac{g_{\pi N}^2}{m_N}$$

$\hookrightarrow$ best determined from πN data using dispersion relations (unphysical region)

- reminder Δ_R, calculated in CHPT to $\mathcal{O}(p^4)$, no chiral logs

$$\Delta_R \lesssim 2\,\text{MeV}$$

Bernard, Kaiser, UGM (1996)

σ-term basics continued

- Standard decomposition of the σ-term: $\sigma_{\pi N} = \sigma_{\pi N}(0)$

$$\sigma_{\pi N} = \Sigma_d + \Delta_D - \Delta_\sigma - \Delta_R$$

$$\Sigma_d = F_\pi^2(d_{00}^+ + 2M_\pi^2 d_{01}^+)$$ $\to$ full dispersive analysis

$$\Delta_D = \bar{D}^+(0, 2M_\pi^2) - \Sigma_d$$

$$\Delta_\sigma = \sigma(2M_\pi^2) - \sigma_{\pi N}$$

$\Big\}$ $\to$ dispersive t-channel analysis

- d_{00}^+, d_{01}^+ – subthreshold expansion coefficients (around $\nu = t = 0$)

- Δ_σ is the **scalar form factor of the nucleon**

- Note: strong $\pi\pi$ rescattering in Δ_D and Δ_σ

Role of the pion-nucleon σ-term

- Nucleon mass from the light u, d quarks

- Scalar couplings of the nucleon:

$$\langle N|m_q\bar{q}q|N\rangle = f_q^N\, m_N \quad (N = p, n)$$
$$(q = u, d, s)$$

$\hookrightarrow$ Dark Matter detection

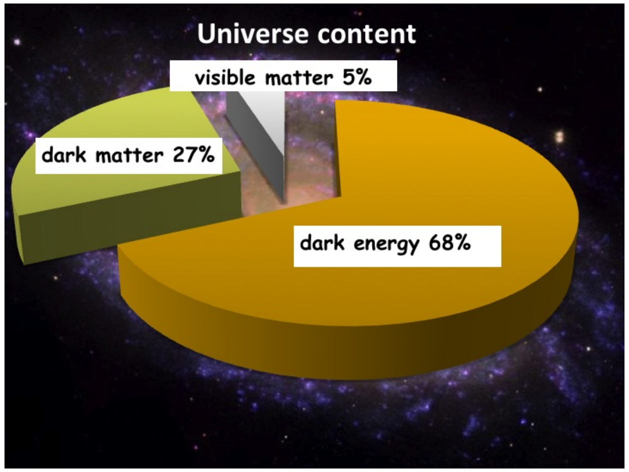
$\hookrightarrow$ $\mu \to e$ conversion in nuclei

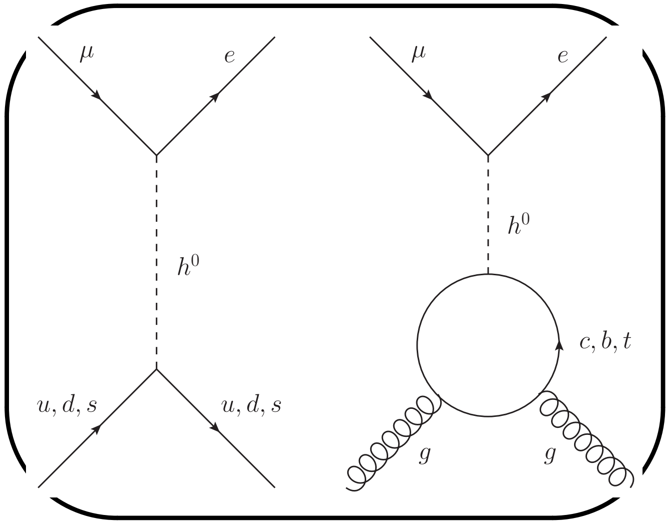
- Condensates in nuclear matter

$$\frac{\langle\bar{q}q\rangle(\rho)}{\langle 0|\bar{q}q|0\rangle} = 1 - \frac{\rho\,\sigma_{\pi N}}{F_\pi^2 M_\pi^2} + \ldots$$

- CP-violating πN couplings

$\hookrightarrow$ hadronic EDMs (nucleon, nuclei)





Crivellin, Hoferichter, Procura, ...

Bsaisou, de Vries, UGM, Wirzba, van Kolck, ...

Sigma term physics from Bern

The fundamental papers

- Three very important papers in this field

Volume 213, number 1 PHYSICS LETTERS B 13 October 1988

EXTRACTING THE PION–NUCLEON SIGMA-TERM FROM DATA ☆

J. GASSER, H. LEUTWYLER
Institut für theoretische Physik, Universität Bern, Sidlerstraße 5, CH-3012 Bern, Switzerland

M.P. LOCHER and M.E. SAINIO
Paul Scherrer Institut, [1] CH-5234 Villigen, Switzerland

Received 7 July 1988

Exploiting unitarity and analyticity we derive a set of integral equations which determine the behaviour of the S- and P-wave phase shifts near threshold in terms of two subtraction constants. These constants also fix the value of the Σ-term.

The fundamental papers

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Volume 253, number 1,2 PHYSICS LETTERS B 3 January 1991

Sigma-term update ☆

J. Gasser, H. Leutwyler
Institute for Theoretical Physics, University of Bern, Sidlerstraße 5, CH-3012 Bern, Switzerland

and

M.E. Sainio
Research Institute for Theoretical Physics, University of Helsinki, Siltavuorenpenger 20C, SF-00170 Helsinki, Finland

Received 24 September 1990

The determination of the σ-term from πN scattering is critically examined. The currently available data indicate $\sigma \simeq 45$ MeV. Low-energy precision measurements are needed to clarify discrepancies in experimental data and to reduce the uncertainty in the strangeness content for which we obtain $y \simeq 0.2$.

The fundamental papers

- Three very important papers in this field

Volume 213, number 1 PHYSICS LETTERS B 13 October 1988

EXTRACTING THE PION–NU

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Received 24 September 1990

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Low-energy precision measuremen
strangeness content for which we c

Volume 253, number 1,2 PHYSICS LETTERS B 3 January 1991

Form factor of the σ-term ☆

J. Gasser, H. Leutwyler
Institute for Theoretical Physics, University of Bern, Sidlerstraße 5, CH-3012 Bern, Switzerland

and

M.E. Sainio
Research Institute for Theoretical Physics, University of Helsinki, Siltavuorenpenger 20C, SF-00170 Helsinki, Finland

Received 24 September 1990

We use dispersion relations to calculate the nucleon form factor of the scalar operator $\bar{u}u + \bar{d}d$ and show that the corresponding mean square radius is remarkably large.

Deep new insights

- Most important results of this work:

  – Upgrade of the KH80 value for Σ PLB 213 (1988) 85

  $\hookrightarrow \Sigma = F_\pi^2 \bar{D}^+|_{s=m_N^2, t=2M_\pi^2} = 56 \pm 2$ MeV [from 64 ± 8 MeV]

  – Upgrade of the value for $\sigma_{\pi N}$ - the standard for decades PLB 253 (1991) 252

  $\hookrightarrow \sigma_{\pi N} \simeq 45$ MeV [errors discussed in the paper]

  $\hookrightarrow$ strangeness content $y \simeq 0.2$
  based on $\sigma_0 = 35 \pm 5$ MeV Gasser, Ann. Phys. (NY) **136** (1981) 62

  – Detailed analysis of the scalar form factor of the nucleon PLB 253 (1991) 260

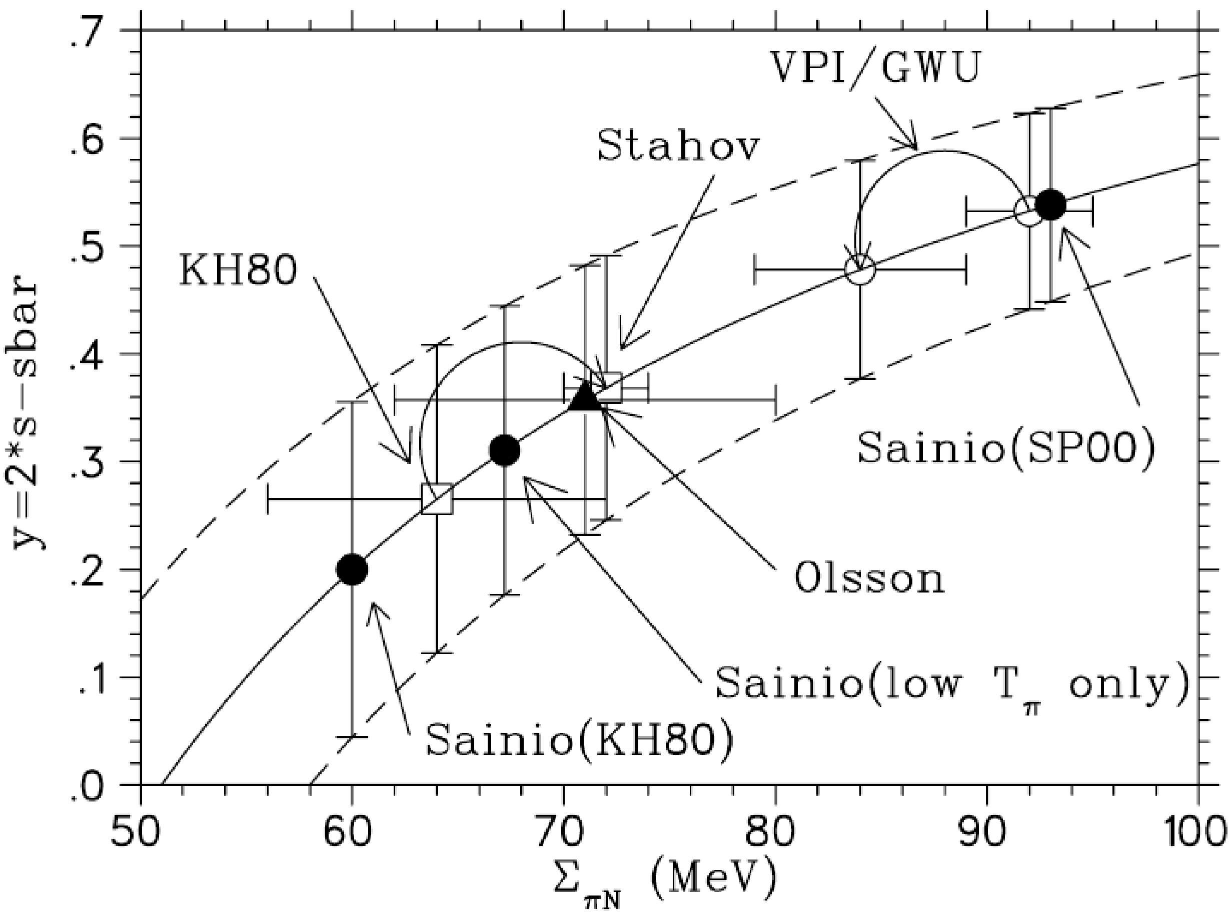
  $\hookrightarrow \langle r^2 \rangle_N^S \simeq 1.6\,\text{fm}^2$ much bigger than the proton charge radius, $\langle r^2 \rangle_p^E = 0.71\,\text{fm}^2$

  $\hookrightarrow$ strong pionic rescattering in Δ_σ and Δ_D cancels

Dark ages

- Then, chaos emerged [using $\sigma_0 = 36 \pm 7$ MeV]

Borasoy, UGM, Ann. Phys. **254** (1997) 192

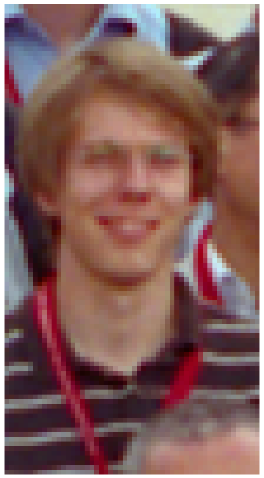


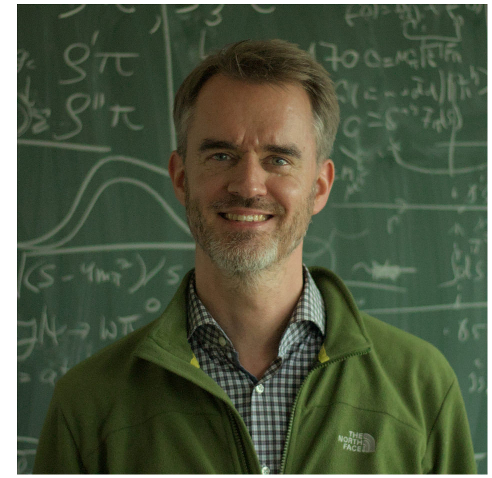
UGM, Smith, Chiral Dynamics 2000, hep-ph/0011277

A new look at sigma term physics

Overcoming the dark ages

- Step 1: assemble a bunch of fearless knights



Christoph Ditsche Martin Hoferichter Jacobo Ruiz de Elvira Bastian Kubis

- Step 2: lay out the framework (RS equations) and gather novel input

  $\hookrightarrow$ fantastic work at PSI on pionic atoms (hydrogen, deuterium)

  $\hookrightarrow$ EFT framework allows to extract the pertinent scattering lengths

  $\hookrightarrow$ new determinations of the pion-nucleon coupling constant (GMO sum rule, NN scattering)

  $\hookrightarrow$ include isospin breaking corrections to the CD LET and elsewhere

Timeline of our investigations

- 2012 – Roy-Steiner equations for pion-nucleon scattering, JHEP **06** (2012) 043
- 2012 – Dispersive analysis of the scalar form factor of the nucleon, JHEP **06** (2012) 063
- 2015 – High-Precision Determination of the Pion-Nucleon σ Term from Roy-Steiner Equations, Phys. Rev. Lett. **115** (2015) 092301
- 2015 – Matching pion-nucleon Roy-Steiner equations to chiral perturbation theory, Phys. Rev. Lett. **115** (2015) 192301
- 2016 – Roy-Steiner-equation analysis of pion-nucleon scattering, Phys. Rept. **625** (2016) 1
- 2016 – Remarks on the pion-nucleon σ-term, Phys. Lett. B **760** (2016) 74
- 2016 – On the $\pi\pi$ continuum in the nucleon form factors and the proton radius puzzle, Eur. Phys. J. A **52** (2016) 331 [w/ H.-W. Hammer]
- 2017 – Reconciling threshold and subthreshold expansions for pion-nucleon scattering, Phys. Lett. B **770** (2017) 27 [w/ D. Siemens, E. Epelbaum, H. Krebs]
- 2018 – Extracting the σ-term from low-energy pion-nucleon scattering, J. Phys. G **45** (2018) 024001
- 2023 – On the role of isospin violation in the pion-nucleon σ-term, Phys. Lett. B **843** (2023) 138001
- 2024 – Nucleon resonance parameters from Roy-Steiner equations, Phys. Lett. B **853** (2024) 138698

$\hookrightarrow$ discuss assorted hi-lites

Solution strategy

- RS equations have a limited range of validity:

$$\sqrt{s} \le \sqrt{s_m} = 1.38\,\text{GeV}, \qquad \sqrt{t} \le \sqrt{t_m} = 2.00\,\text{GeV}$$

- Input/constraints

  S- and P-waves above the matching point ($s > s_m, t > t_m$)

  Inelasticities

  Higher waves (D-, F-, $\ldots$)

  Scattering lengths from hadronic atoms

- Output

  S- and P-wave phase shifts below the matching point ($s \le s_m, t \le t_m$)

  Subthreshold parameters

  → Pion-nucleon σ-term

  → LECs of pion-nucleon CHPT

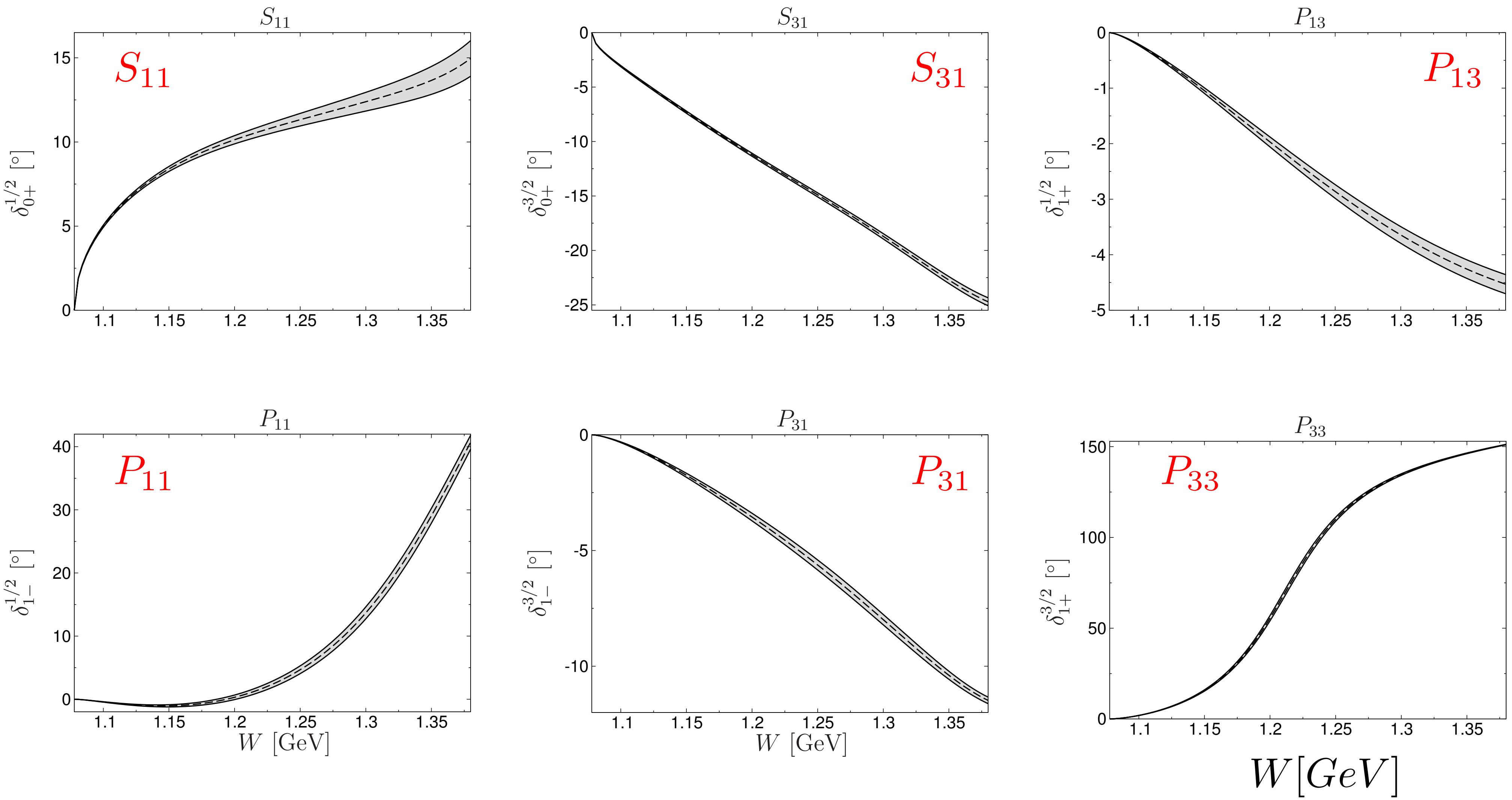
  → N form factor spectral functions

  → Resonance parameters

- πN input from SAID/GWU, $\pi\pi$ input from Bern and Madrid/Cracow
- important check: recover KH80 phases with appropriate input
- much effort in the error analysis → first time for a dispersive analysis of πN scattering

Phase shifts

- S- and P-waves up to the matching point [Notation: L_{2I_s2J}]



Threshold parameters

- Threshold parameters from: $$\text{Re} f^I_{\ell\pm}(s) = q^{2\ell}\left(a^I_{\ell\pm} + b^I_{\ell\pm} q^2 + \ldots\right)$$

	RS	KH80
$a^{1/2}_{0+}$	169.8 ± 2.0	173 ± 3
$a^{3/2}_{0+}$	-86.3 ± 1.8	-101 ± 4
$a^{1/2}_{1+}$	-29.4 ± 1.0	-30 ± 2
$a^{3/2}_{1+}$	211.5 ± 2.8	214 ± 2
$a^{1/2}_{1-}$	-70.7 ± 4.1	-81 ± 2
$a^{3/2}_{1-}$	-41.0 ± 1.1	-45 ± 2
$b^{1/2}_{0+}$	-35.2 ± 2.2	-18 ± 12
$b^{3/2}_{0+}$	-49.8 ± 1.1	-58 ± 9

	RS	KH80
a^{+}_{0+}	-0.9 ± 1.4	-9.7 ± 1.7
a^{-}_{0+}	85.4 ± 0.9	91.3 ± 1.7
a^{+}_{1+}	131.2 ± 1.7	132.7 ± 1.3
a^{-}_{1+}	-80.3 ± 1.1	-81.3 ± 1.0
a^{+}_{1-}	-50.9 ± 1.9	-56.7 ± 1.3
a^{-}_{1-}	-9.9 ± 1.2	-11.7 ± 1.0
b^{+}_{0+}	-45.0 ± 1.0	-44.3 ± 6.7
b^{-}_{0+}	4.9 ± 0.8	13.3 ± 6.0

- In units of $10^{-3}/M_\pi$ or $10^{-3}/M_\pi^3$, respectively
- Most striking difference to KH80: S-wave scattering lengths! (here: input)
- Sanity check: re-analyse πN data w/o hadronic atoms input $\rightarrow$ consistent!

Results for the σ-term

- Basic formula: $$\sigma_{\pi N} = F_\pi^2(d_{00}^+ + 2M_\pi^2 d_{01}^+) + \Delta_D - \Delta_\sigma - \Delta_R$$

- Subthreshold parameters: $d_{00}^+ = -1.36(3) M_\pi^{-1}$, $d_{01}^+ = 1.16(3) M_\pi^{-3}$

- $\Delta_D - \Delta_\sigma = (1.8 \pm 0.2)$ MeV — Hoferichter, Ditsche, Kubis, UGM (2012)

- $\Delta_R \lesssim 2$ MeV — Bernard, Kaiser, UGM (1996)

- Isospin breaking in the CD theorem shifts $\sigma_{\pi N}$ by $+3.0$ MeV

$$\sigma_{\pi N} = (59.1 \pm 1.9_{\rm RS} \pm 3.0_{\rm LET})\ {\rm MeV} = (59.1 \pm 3.5)\ {\rm MeV}$$

[Q: can we recover $\sigma_{\pi N} = 45$ MeV? $\to$ next slide]

- Update due to final results of pionic hydrogen — Hirtl et al., Eur. Phys. J. A **57** (2021) 70

$$\sigma_{\pi N} = (59.0 \pm 3.5)\ {\rm MeV}$$

Comparison to GLS

- Why does this value is so different from GLS 1991?
- GLS 1991 relies on the Karlsruhe-Helsinki PWA KH80
- Different input:

	$g^2_{\pi N}/4\pi$	$a^{1/2}_{0+}$ $[10^{-3}/M_\pi]$	$a^{3/2}_{0+}$ $[10^{-3}/M_\pi]$	$\sigma_{\pi N}$ [MeV]
GLS 1991	14.28	$173(3)$	$-101(4)$	45
RS 2023	$13.7(2)$	$169.8(2.0)$	$-86.3(1.8)$	$59.0(3.5)$

- RS equations with KH80 input $\hookrightarrow$ $\boxed{\sigma_{\pi N} = 46 \text{ MeV}}$ $\surd$

$\hookrightarrow$ KH80 is internally consistent but at odds with modern a_0^I determinations

- On the technical side: GLS use forward DR to extract d^+_{00} and d^+_{01}

Isospin corrections and lattice QCD results

- Isospin-breaking in $\sigma_{\pi N}$ [$\Delta_\pi = M^2_{\pi^\pm} - M^2_{\pi^0}$]:

$$\sigma_{\pi N} = \Sigma_d + \Delta_D - \Delta_\sigma - \Delta_R + \underbrace{\frac{81 g_A^2 M_{\pi^\pm}\Delta_\pi}{256\pi F_\pi^2}}_{+3.4\ \text{MeV}} + \underbrace{\frac{e^2}{2}F_\pi^2(4f_1+f_2)}_{(-0.4\pm2.2)\ \text{MeV}}$$

- We define isospin amplitudes by the $\pi^+ p$ channel,
  LQCD uses M_{π^0} to define the σ-term: $\bar\sigma_{\pi N}$

- Our analysis: $\Delta\sigma = \sigma_{\pi N} - \bar\sigma_{\pi N} = 3.1(5)$ MeV

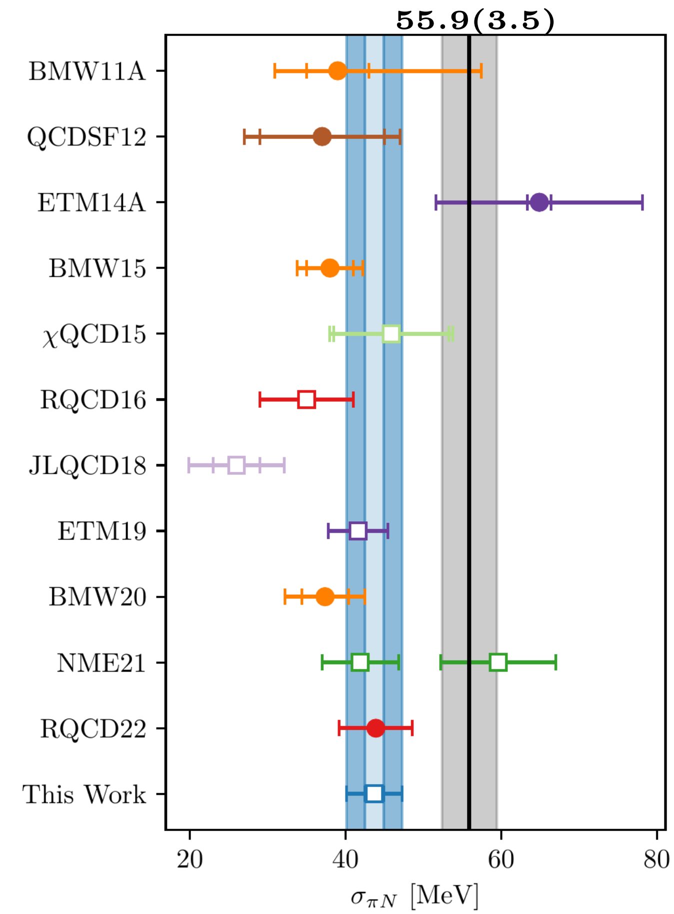
  $\hookrightarrow$ not small, must be accounted for

- Central value built into the recent Mainz analysis
  Agadjanov et al., Phys. Rev. Lett. **131** (2023) 261902

  $\hookrightarrow$ discrepancies remain!

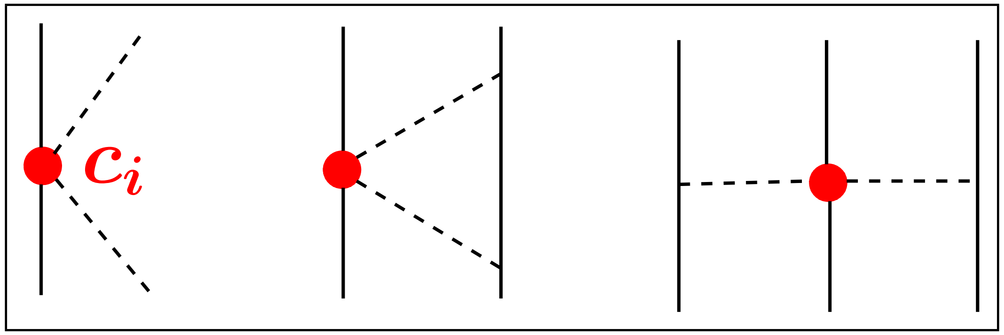
  $\hookrightarrow$ excited state contaminations?

  $\hookrightarrow$ status of these not conclusive at present



Chiral symmetry in nuclear interactions

- Chiral symmetry breaking in QCD relates *many* processes — Weinberg
- One of the best examples: dimension-two vertices from the effective πN Lagrangian ($\sim c_i$)



- Strategy: Fix in $\pi N \to \pi N$ and the explore in few-nucleon interactions

LEC	RS	KGE 2012	UGM 2005
c_1 [GeV^{-1}]	-1.11 ± 0.03	$-1.13 \ldots -0.75$	$-0.9^{+0.2}_{-0.5}$
c_2 [GeV^{-1}]	3.13 ± 0.03	$3.49 \ldots 3.69$	3.3 ± 0.2
c_3 [GeV^{-1}]	-5.61 ± 0.06	$-5.51 \ldots -4.77$	$-4.7^{+1.2}_{-1.0}$
c_4 [GeV^{-1}]	4.26 ± 0.04	$3.34 \ldots 3.71$	$-3.5^{+0.5}_{-0.2}$

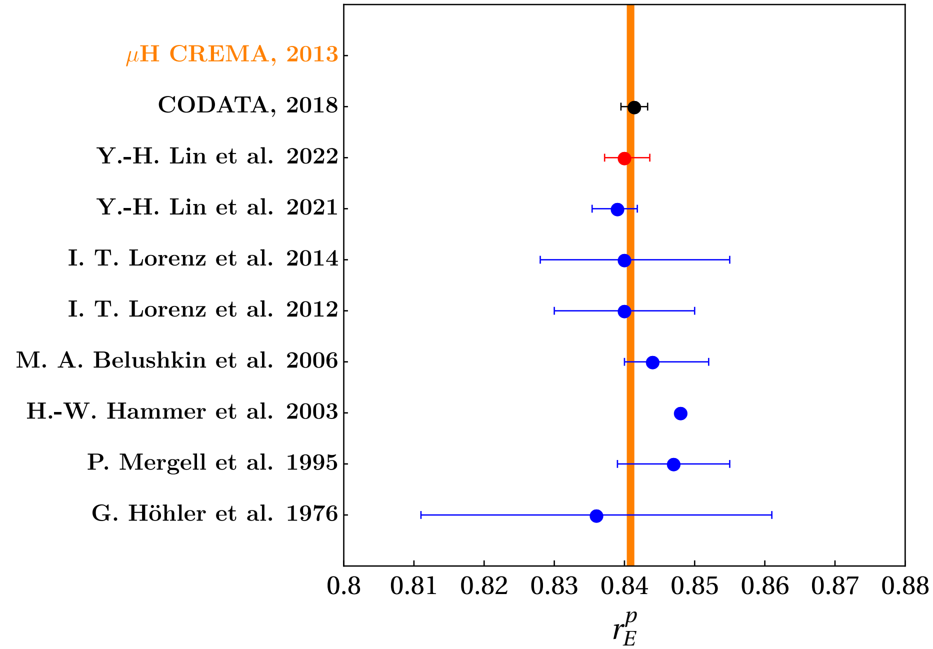
Krebs, Gasparyan, Epelbaum, Phys. Rev. C **85** (2012) 054006; UGM, PoS LAT2005 (2006) 009

The proton charge radius

- Much ado about the so-called proton radius puzzle [μH versus ep]

$\hookrightarrow$ never really existed in DR analyses

$\hookrightarrow$ always the 2π continuum
à la Frazer-Fulco included PRL **2** (1959) 365



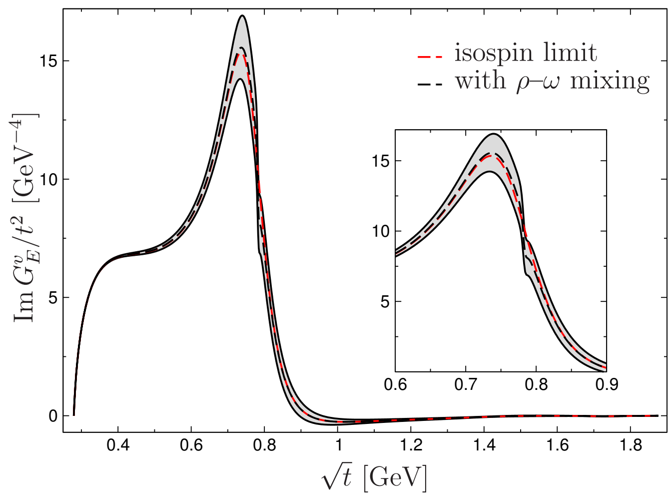
- Updated in 2016 using the RS partial waves $f^1_\pm(t)$ and modern data on the pion vector form factor

$$\mathrm{Im}\, G_E^V(t) = \frac{q_t^3}{m_N\sqrt{t}}\,(F_\pi^V(t))^*\, f_+^1(t)\,\theta(t-t_\pi)$$

- Use DR and fit to all space- and timelike XS data including 2γ-exchange corrections

$$r_E^p = 0.840(3)_{\rm sta}(2)_{\rm sys}$$

Lin, Hammer, UGM, PRL **128** (2022) 052002



Summary

- The pion-nucleon interaction is one of the most studied processes in strong interaction physics/chiral dynamics $\rightarrow$ more Bernese footprints

ANNALS OF PHYSICS **136**, 62–112 (1981)

Hadron Masses and the Sigma Commutator in Light of Chiral Perturbation Theory*

J. GASSER

Institute for Theoretical Physics, University of Berne, Sidlerstrasse 5, CH-3012 Berne, Switzerland

Eur. Phys. J. C 9, 643–671 (1999)
Digital Object Identifier (DOI) 10.1007/s100529900055

Baryon chiral perturbation theory in manifestly Lorentz invariant form

T. Becher, H. Leutwyler

Institute for Theoretical Physics, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland

JHEP HYPER VERSION — RECEIVED: *June 5, 2001*, ACCEPTED: *June 6, 2001*

Low energy analysis of $\pi N \rightarrow \pi N$

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Low energy analysis of $\pi N \to \pi N$

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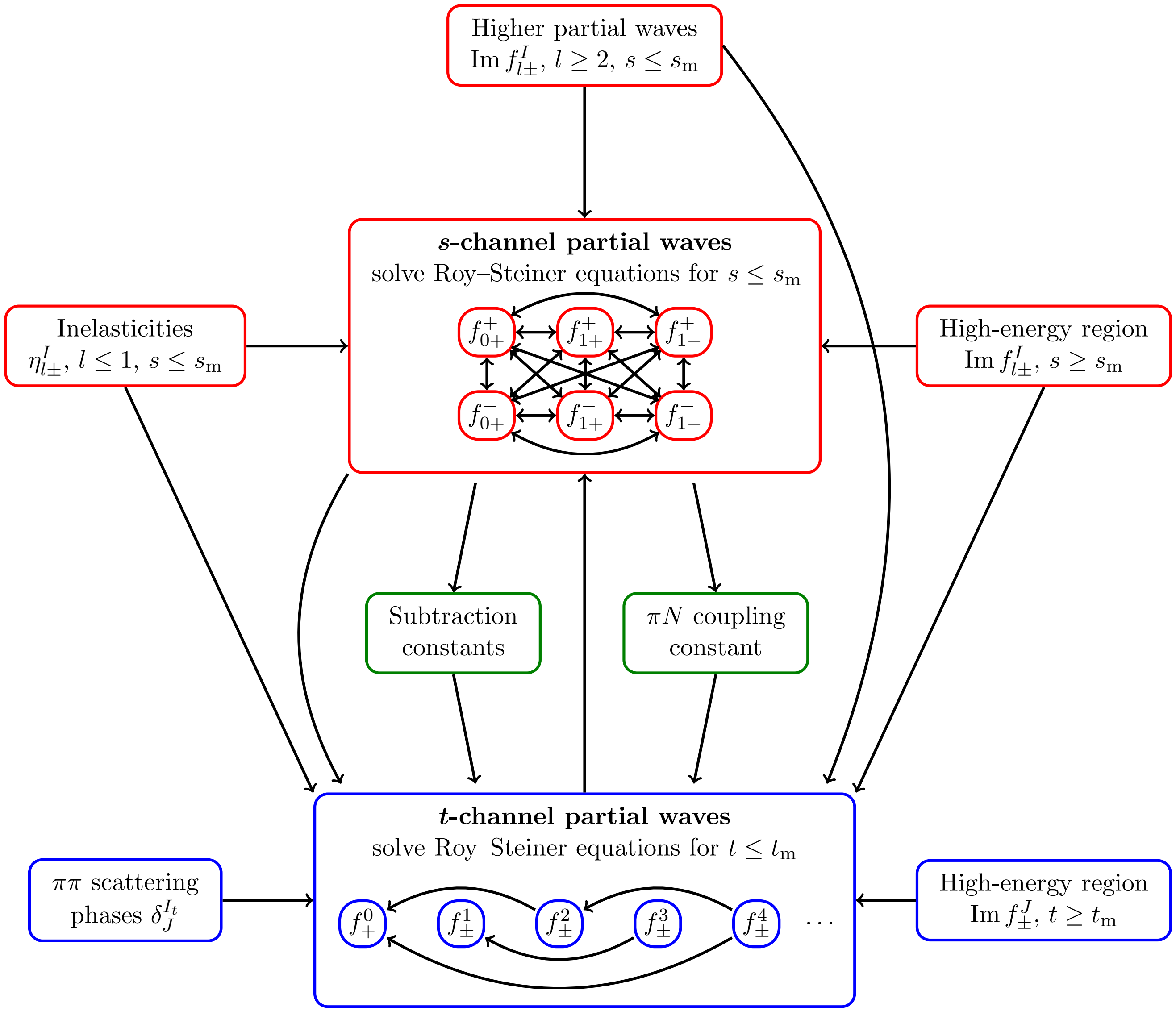
Congrats to Jürg and Heiri for their well-deserved award!

Spares

Solution strategy



Error analysis

- Variation of the input:

  use KH80 input instead of GWU/SAID (higher PWs, inelasticities) $\to$ small effect

  very small effect from s-channel PWs with $\ell > 5$

  small effect from the S-wave extrapolation for $t > 1.3$ GeV

  negligible effect of the the ρ' and the ρ''

  very significant effect of the D-waves (esp. $f_2(1270)$)

  F-waves shown to be negligible

- Other sources of uncertainty:

  statistical errors (shallow fit minima)

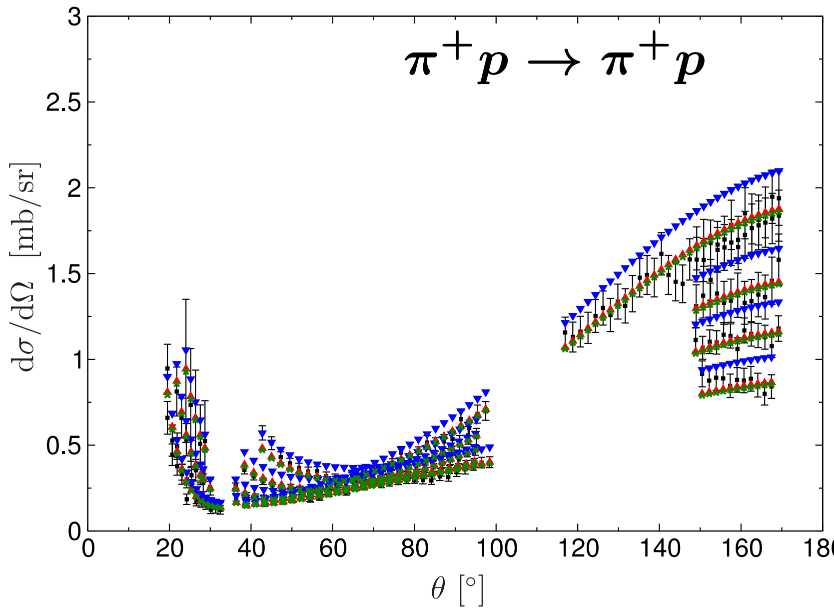
  matching conditions (close to W_m) [no error on SAID, use smoothed KH80]

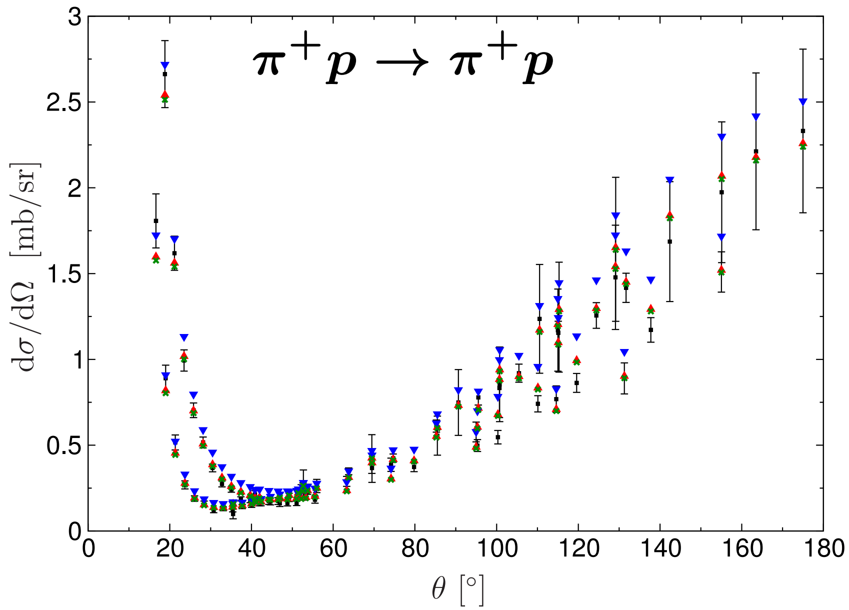
  scattering lengths errors (important for $\sigma_{\pi N}$)

$\Rightarrow$ First time this has been achieved in a dispersive analysis of πN scattering!

Sanity check: No hadronic atom input

- Fit to the pion-nucleon data base (GWU), electromagnetic corrections to the data à la Tromberg et al and treat normalizations of the data as fit parameters
- Fit to low-energy data based on the RS representation that are dominated from the scattering lengths (up to $T_\pi^{\max} = 33 - 55$ MeV)





black: data with readjusted norm
green triangles: new RS solution
red triangles: RS solution with hadronic atom input
blue triangles: KH80

$\hookrightarrow$ $\boxed{\sigma_{\pi N} = 58(5)\ \text{MeV}}$ $\checkmark$