Chiral Dynamics: Theory and Experiment

– a Tribute to Aron Bernstein –

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

supported by DFG, SFB/TR-110

by CAS, PIFI

by VolkswagenStftung

by ERC, EXOTIC

CONTENTS

Introductory remarks

Aron Bernstein - a very short CV

- Born April 6, 1931, grew up in Brooklyn & Queens
- BSc in physics, Union College (Schenectady, N.Y.), 1953
- PhD in physics, Univ. of Pennsylvania, 1958
- Postdoc, Princeton Univ., nuclear physics research
- Assistant professor of physics, MIT, 1961

  $\hookrightarrow$ low-energy NP at the Markle Cyclotron
- Associate professor of physics, MIT, 1966 ($\rightarrow$ Weisskopf)
- Full professor of physics, MIT, 1975

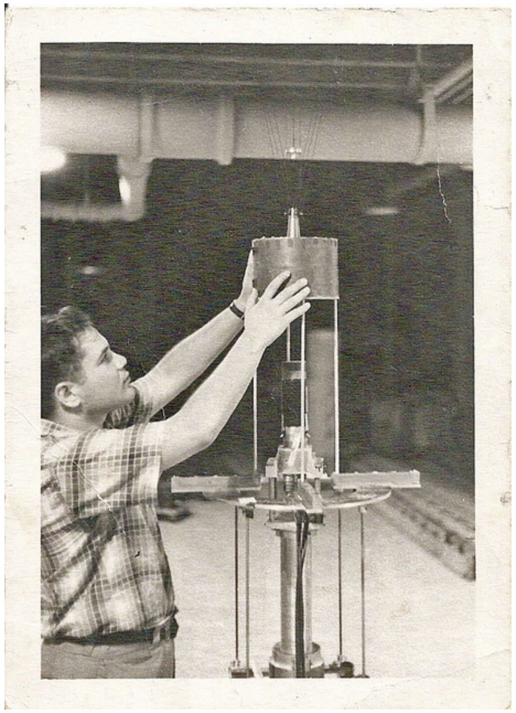
  $\hookrightarrow$ became interested in low-energy QCD $\sim \mathbf{1990}$

  $\hookrightarrow$ initiated the Chiral Dynamics series w/ Barry Holstein

  $\hookrightarrow$ Chiral Dynamics: Theory and Experiment, MIT, 1994

  $\hookrightarrow$ rather unusual format (real working groups!)

  $\hookrightarrow$ Humboldt fellow at Mainz Univ., many visits & works
- A life-long arms control activist $+\cdots$
- † Jan. 14, 2020

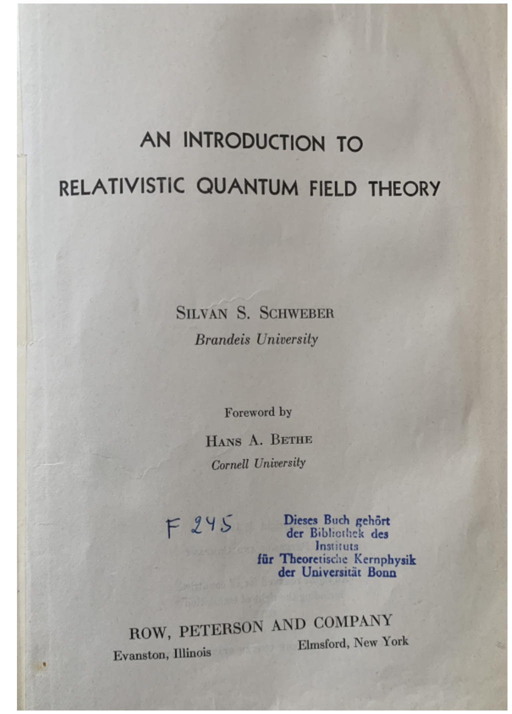


https://news.mit.edu/2020/aron-bernstein-professor-emeritus-physics-dies-0203

Aron Bernstein - a few reminicences

Aron Bernstein - a few more reminicences

- When I was an undergraduate at Bochum ($\sim$ **1979**) studying QFT using Schweber's book on p. 595


AN INTRODUCTION TO
RELATIVISTIC QUANTUM FIELD THEORY

SILVAN S. SCHWEBER
Brandeis University

Foreword by
HANS A. BETHE
Cornell University

F 245

ROW, PETERSON AND COMPANY
Evanston, Illinois Elmsford, New York

> Present experimental indications [Bernstein and Mann (Bernstein 1958) and Moffat and Stringfellow (Moffat 1960)] are that Delbrück scattering is more likely to exist than not. Experimental verification whether such a

- Bernstein and Mann (Bernstein 1958)

PHYSICAL REVIEW VOLUME 110, NUMBER 4 MAY 15, 1958

Scattering of Gamma Rays by a Static Electric Field*†

A. M. BERNSTEIN‡ AND A. K. MANN
University of Pennsylvania, Philadelphia, Pennsylvania
(Received January 20, 1958)

In an effort to observe Delbrück scattering (the scattering of photons by a static electric field), the absolute differential cross sections for the elastic scattering of 1.33-Mev gamma rays by lead, tin, and uranium and of 2.62-Mev gamma rays by lead and tin have been measured for angles between 15 and 105 degrees. The observed scattering is the coherent sum of Delbrück, Rayleigh (bound electron), and nuclear Thomson scattering. The amplitude for the latter process is well known; recent calculations of Rayleigh scattering, which are in good agreement with data obtained previously in this laboratory for gamma-ray energies below 1 Mev, provide exact values of the amplitudes at 1.33 Mev and approximate values at 2.62 Mev. At 1.33 Mev, the difference between the observed scattering and that due to the Rayleigh and Thomson processes is not sufficiently large compared with experimental error to permit a definite identification of Delbrück scattering to be made. At 2.62 Mev, for lead, the experimental cross sections at intermediate angles (30 to 75 degrees) are substantially larger than those calculated by extrapolation of the exact calculations, even when reasonable allowance for error in the extrapolation is made. The most probable explanation for this difference is an appreciable contribution from Delbrück scattering.

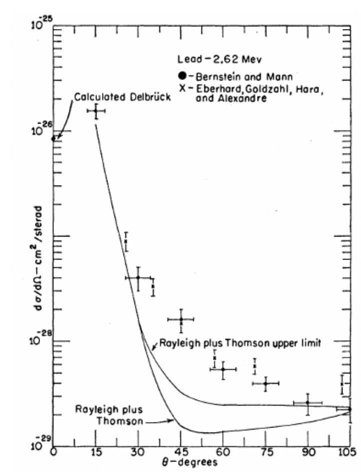


FIG. 7. Differential cross section for the elastic scattering of 2.62-Mev gamma rays by lead *versus* scattering angle.

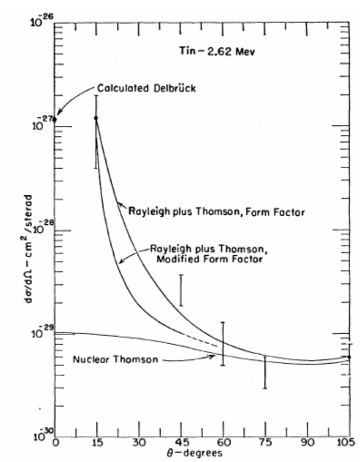


FIG. 8. Differential cross section for the elastic scattering of 2.62-Mev gamma rays by tin *versus* scattering angle. At 45°, 60°, and 75°, only limiting values are available.

The Chiral Dynamics series

- Started 1994 at MIT with a unique format

  $\hookrightarrow$ talks and **working groups**

Threshold Photo/Electro Pion Production – Working Group Summary

Ulf-G. Meißner[1], *B. Schoch*[2]

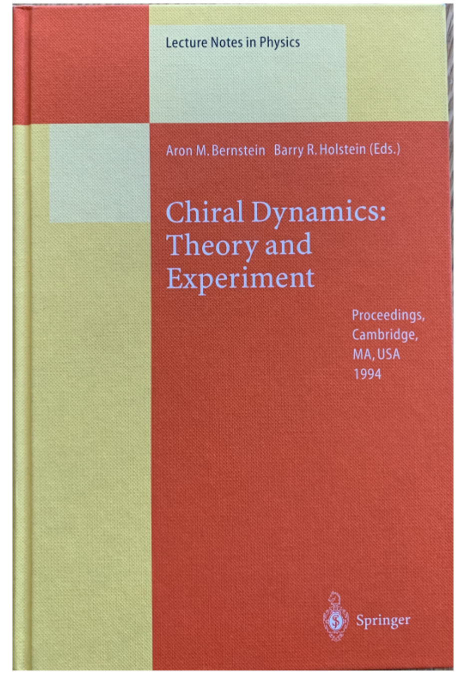
[1] Centre de Recherches Nucléaire, Physique Théorique, BP 28 Cr, F–67037 Strasbourg Cedex 2, France
[2] Universität Bonn, Institut für Physik, Nußallee 12, D–53115 Bonn, Germany

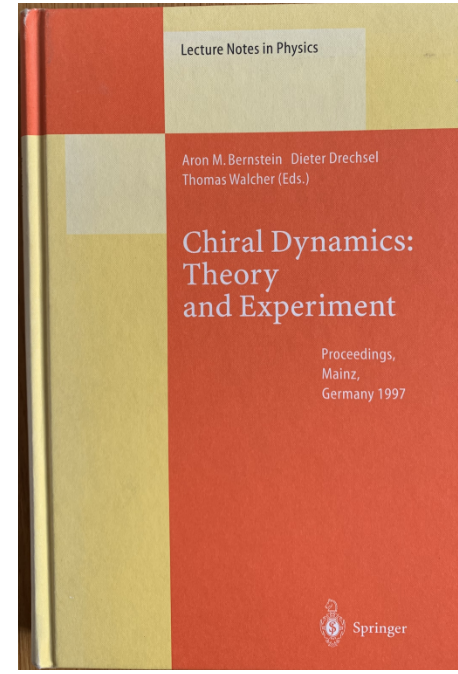
1 Introduction

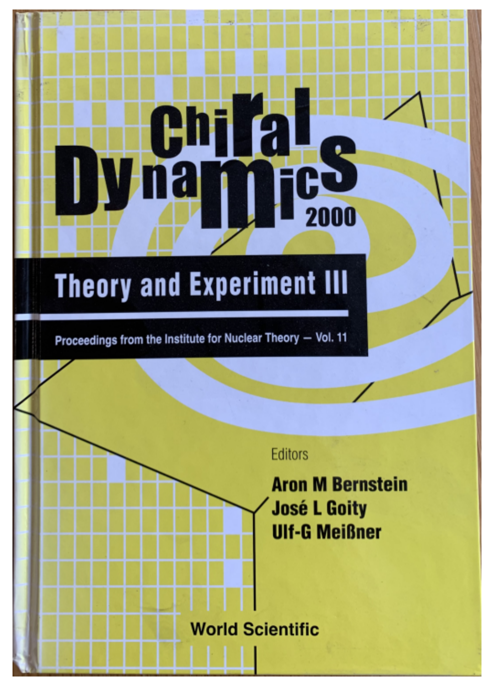
Over the last few years, pion production off nucleons by real or virtual photons has become a central issue in the study of the non–perturbative structure of the nucleon, i.e. at low energies. Here, developments in detector and accelerator technology on the experimental side as well as better calculational tools on the theoretical one have allowed to gain more insight into detailed aspects of these processes and the physics behind them. One main trigger were the two papers by the Saclay and the Mainz groups [1,2], which seemed to indicate the violation of a so–called low energy theorem for the reaction $\gamma p \to \pi^0 p$. This lead to a flurry of further experimental and theoretical investigations. Another cornerstone was the rather precise electroproduction measurement $\gamma^\star p \to \pi^0 p$ at NIKHEF [3]. Here, we wish to summarize the state of the art in calculating and measuring these processes in the threshold region. Furthermore, we outline what we believe have crystalized as the pertinent activities to be done in the near future.

- Aron left this editorial work to the young people starting 2003

- but he kept on pushing physics related to chiral dynamics!







HISKP-TH 03/23

Mini-Proceedings of the
Fourth International Workshop on

CHIRAL DYNAMICS:
THEORY and EXPERIMENT
(CD2003)

Bonn, Germany
September 8 – 13, 2003

edited by

Ulf-G. Meißner, Hans-Werner Hammer and Andreas Wirzba

Helmholtz-Institut für Strahlen- und Kernphysik (Theorie)
Rheinische Friedrich-Wilhelms–Universität Bonn
Nussallee 14-16, D-53115 Bonn, Germany

ABSTRACT

These are the proceedings of the fourth international workshop on "Chiral Dynamics: Theory and Experiment" which was held at the University of Bonn, September 8-13, 2003. The workshop concentrated on the various experimental and theoretical aspects of chiral dynamics, including for the first time in this series detailed discussions of lattice gauge theory. It consisted of an introductory lecture, plenary talks, working group talks and working group summaries. Included is a short contribution per talk.

Threshold pion photoproduction off the nucleon

The LET crisis

- The Low-Energy Theorem (LET) for $\gamma p \to \pi^0 p$:

  de Baenst (1969), Vainsthein, Zakharov (1970)

$$E_{0+,\mathrm{thr}} = -\frac{e g_{\pi N}}{8\pi m_N}\left[\mu - \frac{1}{2}(3+\kappa_p)\mu^2\right] = -2.3 \cdot \frac{10^{-3}}{M_\pi} \qquad \left[\mu = \frac{M_\pi}{m_N}\right]$$

- Saclay measurement 1986
  $\hookrightarrow$ much smaller XS than expected

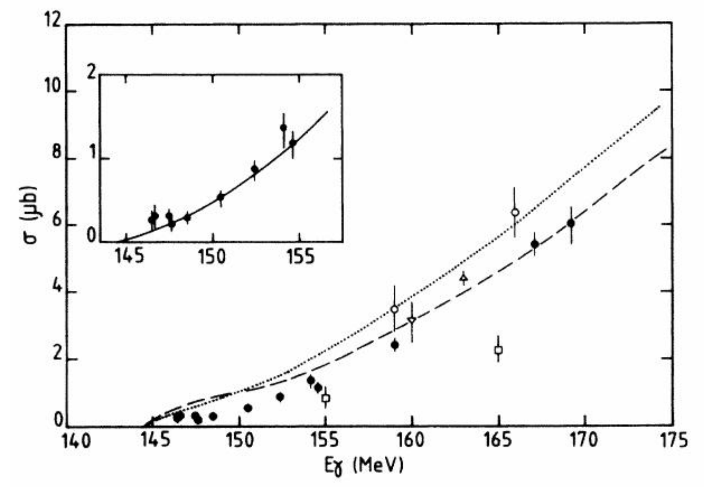
  Mazzucato et al., PRL **57** (1986) 3144

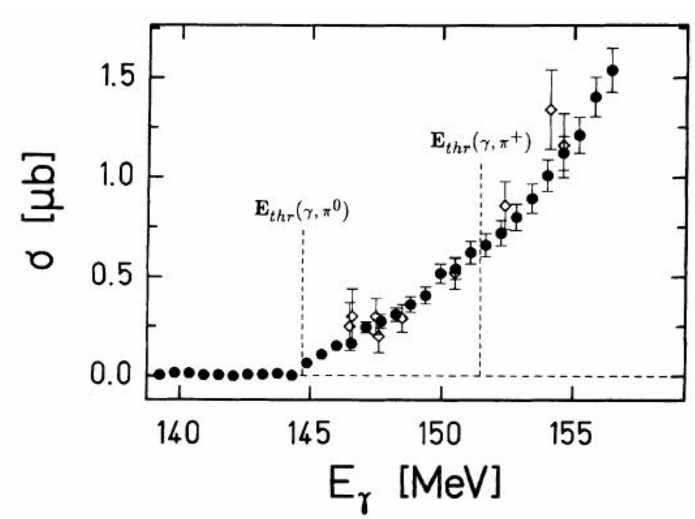
$$E_{0+,\mathrm{thr}} = (-0.5 \pm 0.3) \cdot 10^{-3}/M_\pi$$

- Mainz measurement 1990
  $\hookrightarrow$ much more precise, 2 solutions

  Beck et al., PRL **65** (1990) 1841

$$E^{\mathrm{I}}_{0+,\mathrm{thr}} = (-0.25 \pm 0.19) \cdot 10^{-3}/M_\pi$$
$$E^{\mathrm{II}}_{0+,\mathrm{thr}} = (-1.61 \pm 0.16) \cdot 10^{-3}/M_\pi$$





$\Rightarrow$ the LET is violated! $\hookrightarrow$ a flurry of th'y activities to resurrect it

All ways lead to Rome?

- A. M. Bernstein and B. R. Holstein, “Threshold pion photoproduction and chiral invariance,” Comments Nucl. Part. Phys. **20** (1991) no.4, 197-220

We conclude then that all roads do indeed lead to “Rome.” Chiral symmetry, when applied consistently, leads to unambiguous predictions for the threshold values of pion photoproduction amplitudes while the energy dependence of the E_{0+} multipole can be approximately estimated with a simple K-matrix approach. The predictions obtained thereby are concisely summarized in Table I, and experimental and theoretical expectations are seen to be quite consistent in the three channels for which data is available provided

TABLE I

Shown are threshold E_{0+} multipole values for the four pion photoproduction channels

	Analytic Threshold Value[a]	Numerical Threshold Value ($\times 10^{-3}/m_\pi$)	Experimental Value ($\times 10^{-3}/m_\pi$)
$\pi^0 p$	$-D\left(\mu - \frac{1}{2}\mu^2(3+\kappa_p) + O(\mu^3)\right)$	-2.28	-1.5 ± 0.3[3] -2.0 ± 0.2[b]
$\pi^+ n$	$D\sqrt{2}\left(1 - \frac{3}{2}\mu + O(\mu^2)\right)$	26.3	27.9 ± 0.5[29] 28.8 ± 0.7[30]
$\pi^- p$	$-D\sqrt{2}\left(1 - \frac{1}{2}\mu + O(\mu^2)\right)$	-31.3	-31.4 ± 1.3[29] -32.2 ± 1.2[31]
$\pi^0 n$	$-D\left(\frac{1}{2}\mu^2\kappa_n + O(\mu^3)\right)$	0.50	–

[a] Here $\kappa_{p(n)}$ is the anomalous magnetic moment of the proton (neutron) and $D = eg_{\pi NN}/8\pi m_N = 23.86 \times 10^{-3}/m_\pi$ for $g^2_{\pi NN}/4\pi = 14.3$.
[b] Our value obtained from the Mainz data (Ref. 4).

All ways lead to Bern!

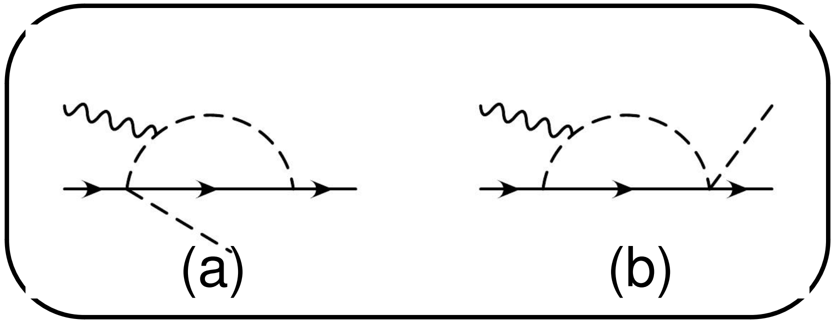
Bernard, Kaiser, Gasser, UGM, Phys. Lett. **B 268** (1991) 219

- Renalysis of the LET to one loop in baryon chiral perturbation theory:

$\hookrightarrow$ Taylor expansion in the energy is not well behaved

or: the “harmless assumption” is wrong

$$\mathbf{Amp(a) + Amp(b)} = \frac{\pi^2}{4}\mu^2 \neq 0$$



$\Rightarrow$ so the LET really reads:

$$E_{0+,\mathrm{thr}} = -\frac{e g_{\pi N}}{8\pi m_N}\left[\mu - \left(\frac{3+\kappa_p}{2} + \frac{m_N^2}{16F_\pi^2}\right)\mu^2 + \mathcal{O}(\mu^3)\right]$$

- large correction to the second term $\rightarrow$ convergence?
- must calculate the $\mathcal{O}(\mu^3)$ corrections $\rightarrow$ done by BKM

The proper LET verified

- Two parallel but interwined strands: Th'y & Exp.
- Theory: V. Bernard, N. Kaiser, UGM
- Experiment: R. Beck and students and Aron

ELSEVIER

Physics Letters B 368 (1996) 20–25

Neutral pion photoproduction from the proton near threshold

M. Fuchs [a], J. Ahrens [b], G. Anton [c], R. Averbeck [d], R. Beck [b], A.M. Bernstein [e], A.R. Gabler [a], F. Härter [b], P.D. Harty [f], S. Hlaváč [d], B. Krusche [a], I.J.D. McGregor [f], V. Metag [a,d], R. Novotny [a], R.O. Owens [f], J. Peise [b], M. Röbig-Landau [a], A. Schubert [d], R.S. Simon [d], H. Ströher [a], V. Tries [a]

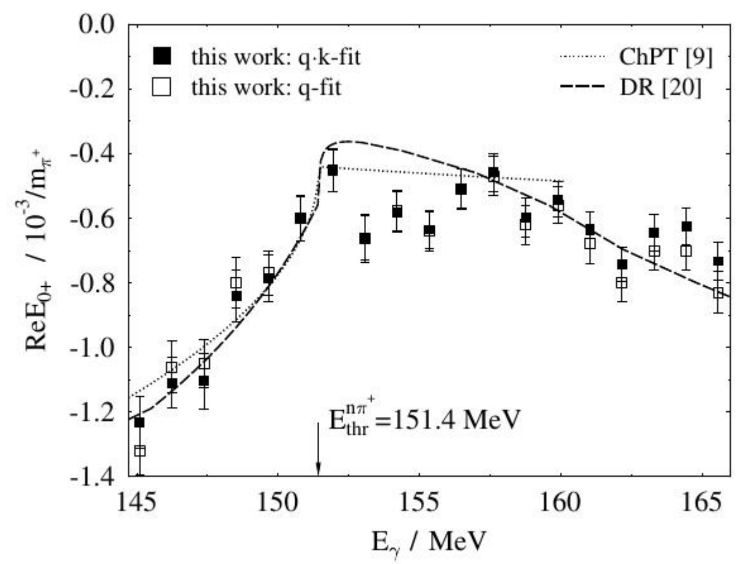
VOLUME 87, NUMBER 23 PHYSICAL REVIEW LETTERS 3 DECEMBER 2001

Test of Low-Energy Theorems for $^1\mathrm{H}(\vec{\gamma},\pi^0)^1\mathrm{H}$ in the Threshold Region

A. Schmidt,[1] P. Achenbach,[3] J. Ahrens,[1] H.J. Arends,[1] R. Beck,[1,*] A.M. Bernstein,[2] V. Hejny,[3] M. Kotulla,[4] B. Krusche,[5] V. Kuhr,[6] R. Leukel,[1] I.J.D. MacGregor,[7] J.C. McGeorge,[7] V. Metag,[4] V.M. Olmos de León,[1] F. Rambo,[6] U. Siodlaczek,[8] H. Ströher,[3] Th. Walcher,[1] J. Weiß,[4] F. Wissmann,[6] and M. Wolf[4]

Multipole amplitudes

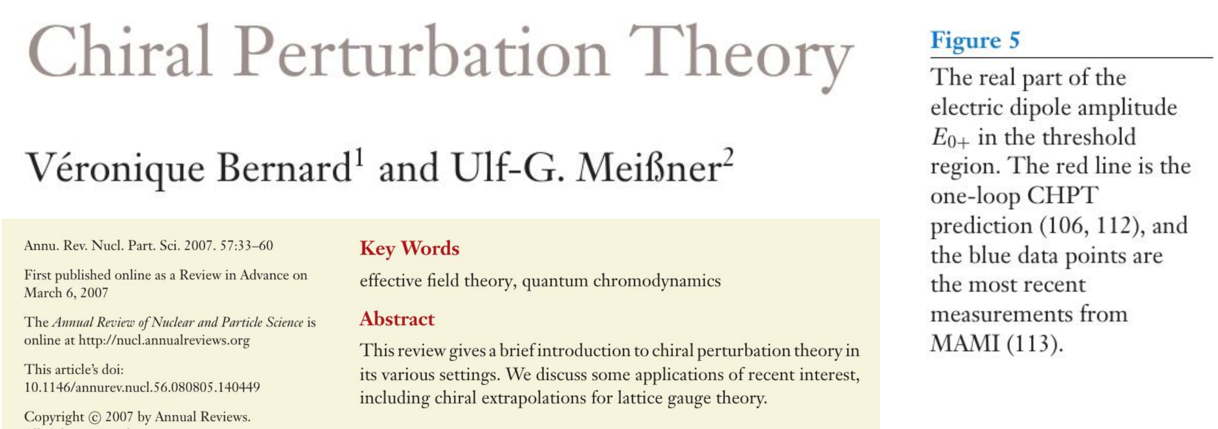
Amplitude		This work	LET	ChPT [21]
P_1	$\left[\frac{qk\times 10^{-3}}{m^3_{\pi^+}}\right]$	10.02 ± 0.15	-	10.3
P_{23}	$\left[\frac{qk\times 10^{-3}}{m^3_{\pi^+}}\right]$	11.44 ± 0.09	-	11.25
$E_{0+}^{\rm threshold}$	$\left[\frac{10^{-3}}{m_{\pi^+}}\right]$	-1.31 ± 0.08	-2.28	$-1\ldots-1.5$



$\hookrightarrow$ and even more precise P-wave LETs tested

E_{0+} - state of the art

- CHPT review in 2007 in *Annu. Rev. Nucl. Part. Sci.*



Chiral Perturbation Theory

Véronique Bernard[1] and Ulf-G. Meißner[2]

Annu. Rev. Nucl. Part. Sci. 2007. 57:33–60

First published online as a Review in Advance on March 6, 2007

The *Annual Review of Nuclear and Particle Science* is online at http://nucl.annualreviews.org

This article's doi: 10.1146/annurev.nucl.56.080805.140449

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Key Words

effective field theory, quantum chromodynamics

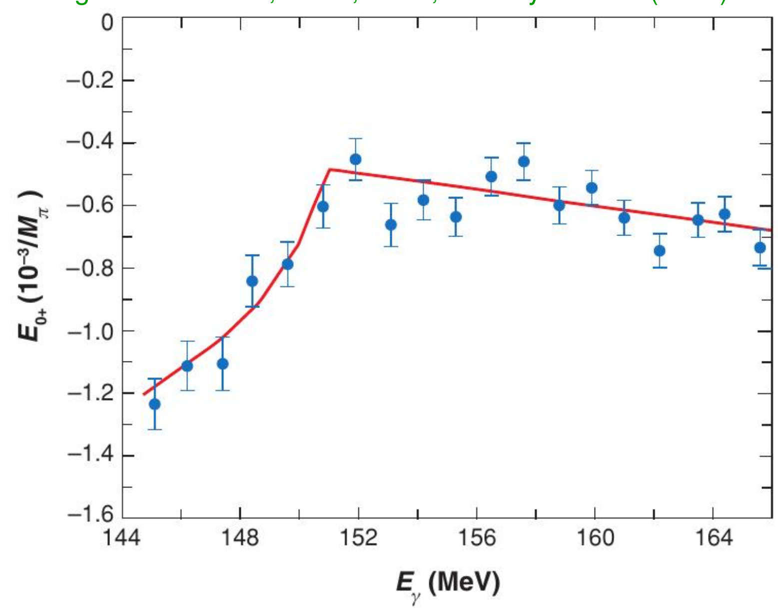
Abstract

This review gives a brief introduction to chiral perturbation theory in its various settings. We discuss some applications of recent interest, including chiral extrapolations for lattice gauge theory.

Figure 5

The real part of the electric dipole amplitude E_{0+} in the threshold region. The red line is the one-loop CHPT prediction (106, 112), and the blue data points are the most recent measurements from MAMI (113).

Fig. from Bernard, Kubis, UGM, Eur.Phys.J. **A25** (2005) 419



- Many years of dedicated measurements

  of $\gamma p \to \pi^0 p$ in the threshold region

- A flagship for the fruitful interplay of experiment and theory

  in chiral dynamics – exactly what was in Aron's mind!

[106] BKM, ZPhysC70 (1996)
[112] BKM, EPJA11 (2001)
[113] Schmidt et al, PRL87 (2001)

More threshold photoproduction - the cusp

- Early prediction of a unitary cusp Wigner (1948)

$$E_{0+}^{\gamma p\to\pi^0 p}(k_\gamma) = A_0(k_\gamma) + i\beta\, q_+$$

$$\beta = E_{0+}^{\gamma p\to\pi^+ n}\cdot a_{\rm CEX}^{\pi^+ n\leftrightarrow\pi^0 p}$$

Höhler, Mühlensiefen (1968), Fäldt (1980), Laget (1981), ...

PHYSICAL REVIEW C VOLUME 55, NUMBER 3 MARCH 1997

Observation of a unitary cusp in the threshold $\gamma p \to \pi^0 p$ reaction

A. M. Bernstein,[1] E. Shuster,[1] R. Beck,[2] M. Fuchs,[3] B. Krusche,[3] H. Merkel,[2] and H. Ströher[3]
[1] *Department Physics and Laboratory for Nuclear Science, MIT, Cambridge Massachussetts 02139*
[2] *Institut für Kernphysik, Johannes-Gutenberg-Universität Mainz, D-55099 Mainz, Germany*
[3] *II. Physikalisches Institut, Universität Gießen, D-35392 Gießen, Germany*
(Received 26 September 1996)

A rigorous multipole analysis of the recent $\gamma p \to \pi^0 p$ cross-section measurement is presented. The data were taken using the photon spectrometer TAPS at the tagged photon beam of the Mainz microtron. The s and p wave multipoles were extracted using minimal model assumptions. The predicted unitary cusp for the s-wave multipole E_{0+} due to the two step $\gamma p \to \pi^+ n \to \pi^0 p$ reaction was observed. The results are consistent with one-loop chiral perturbation theory calculations for which three low-energy constants have been determined by a fit to the data. The uncertainties in the analysis and the need for polarization observables are discussed. [S0556-2813(97)03002-1]

- Aron pointed towards the importance of measuring β

  to get a handle on $a_{\rm CEX}^{\pi^+ n\leftrightarrow\pi^0 p}$ to test chiral dynamics

  Bernstein, piN Newsletter **11** (1995) 66

- First extraction of the unitary cusp from MAMI data in 1997

  $\hookrightarrow$ consistent with one-loop CHPT

  $\hookrightarrow$ consistent with unitary model

  $\hookrightarrow$ points towards the need of polarization measurements!

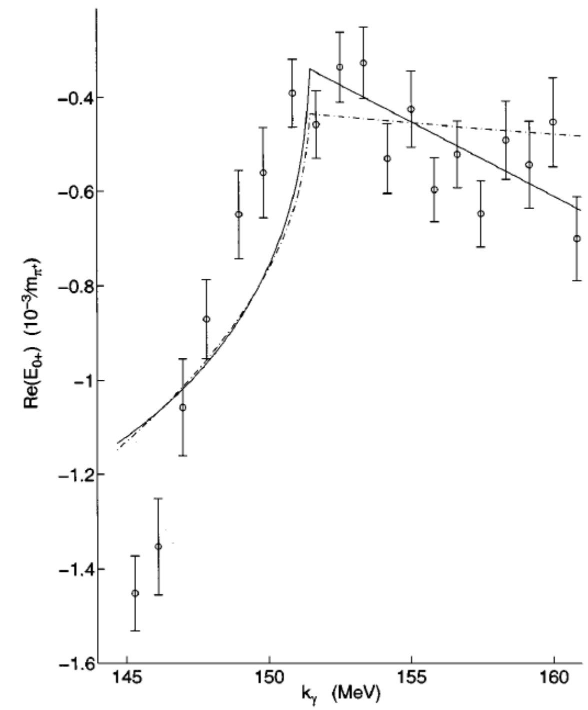


FIG. 8. ReE_{0+} vs photon energy. The circles represent the multipole fit, the solid line represents the unitary fit, and the dash-dot line the ChPT fit.

Even more threshold photoproduction - isospin breaking

- Aron was inspired by Weinberg's 1977 paper $\rightarrow$ huge isospin violation

THE PROBLEM OF MASS*

Steven Weinberg**

Lyman Laboratory of Physics
Harvard University
Cambridge, Massachusetts 02138

$$a(\pi^{+}n \to \pi^{0}n) = 1.9 \times 10^{-15}\,\text{cm} \qquad (39)$$

$$a(\pi^{0}p \to \pi^{0}p) = 1.4 \times 10^{-15}\,\text{cm} \qquad (40)$$

Isospin conservation would say that these should be equal — instead, we see that they differ by over 30%.

Trans.New York Acad.Sci. 38 (1977) 185

- Aron's photoproduction masterpiece

ELSEVIER

3 December 1998

PHYSICS LETTERS B

Physics Letters B 442 (1998) 20–27

Light quark mass difference and isospin breaking in electromagnetic pion production

A.M. Bernstein

Physics Department and Laboratory for Nuclear Science, M.I.T., Cambridge, MA, USA

Received 12 August 1998; revised 29 September 1998
Editor: W. Haxton

Abstract

It is demonstrated that there is a dynamic isospin breaking effect in the near threshold $\gamma^* N \to \pi N$ reaction due to the mass difference of the up and down quarks, which also causes isospin breaking in the πN system. The photopion reaction is affected through final state πN interactions (formally implemented by unitarity and time reversal invariance). It is also demonstrated that the near threshold $\gamma N \to \pi N$ reaction is a practical reaction to measure isospin breaking in the πN system, which was first predicted by Weinberg about 20 years ago but has never been experimentally tested.

$\hookrightarrow$ 3-channel generalization of the Fermi-Watson theorem

$\hookrightarrow$ proposal to measure the target asymmetry T to determine isospin violation in β resp. $a_{\rm CEX}^{\pi^+ n \leftrightarrow \pi^0 p}$

$\hookrightarrow$ proposal to measure $a(\pi^0 p)$ via ${\rm Im}\, E_{0+}$ below the $\pi^+ n$ threshold, extremely challenging...

Even more threshold photoproduction - D waves

- A further refinement of the theory:
  $\hookrightarrow$ inclusion of D-wave effects

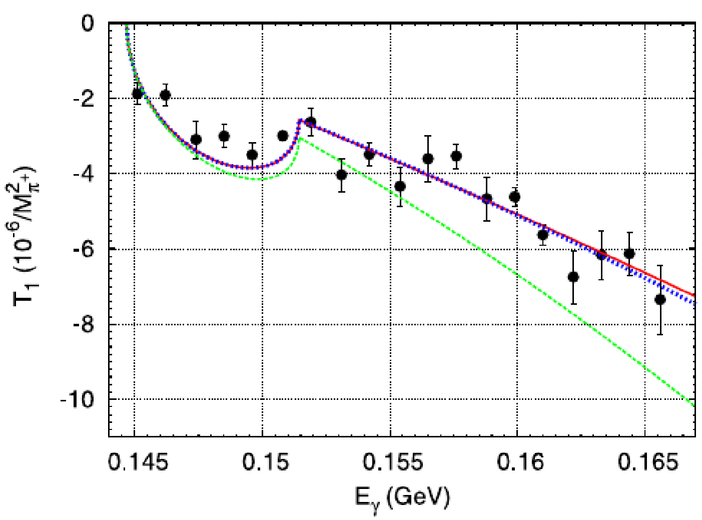
- T_1-coefficient (analogue of $B \sim P_1(\theta)$)

$$T_1 = 2\mathrm{Re}\left[E_{0+}P_1^*\right] + \delta T_1$$

$$P_1 = 3E_{1+} + M_{1+} - M_{1-}$$

δT_1 = P/D-wave interference

- Use the MAMI data of Schmidt et al.



$\hookrightarrow$ improves the accuracy

$\hookrightarrow$ polarization observables significantly affected

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Low-energy D-wave effects in neutral pion photoproduction

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Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139, USA

A R T I C L E I N F O

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PACS:
12.39.Fe
13.60.Le
25.20.Lj

A B S T R A C T

The contribution of D waves to physical observables for neutral pion photoproduction in the near threshold region is studied. Heavy Baryon Chiral Perturbation Theory to one loop, and up to $\mathcal{O}(q^4)$, is used to account for the S and P waves, while D waves are added in an almost model-independent way using standard Born terms and vector mesons. It is found that the inclusion of D waves is necessary to extract the E_{0+} multipole reliably from present and forthcoming data and to assess the low-energy constants of Chiral Perturbation Theory. Arguments are presented demonstrating that F-wave contributions are negligible in the near-threshold region.

PHYSICAL REVIEW C **80**, 065201 (2009)

Unexpected impact of *D* waves in low-energy neutral pion photoproduction from the proton and the extraction of multipoles

C. Fernández-Ramírez,* A. M. Bernstein, and T. W. Donnelly
Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, Massachusetts 02139, USA
(Received 20 July 2009; published 4 December 2009)

Contributions of *D* waves to physical observables for neutral pion photoproduction from the proton in the near-threshold region are studied and means to isolate them are proposed. Various approaches to describe the multipoles are employed—a phenomenological one, a unitary one, and heavy baryon chiral perturbation theory. The results of these approaches are compared and found to yield essentially the same answers. *D* waves are seen to enter together with *S* waves in a way that any means which attempt to obtain the E_{0+} multipole accurately must rely on knowledge of *D* waves and that consequently the latter cannot be dismissed in analyses of low-energy pion photoproduction. It is shown that *D* waves have a significant impact on double-polarization observables that can be measured. This importance of *D* waves is due to the soft nature of the *S* wave and is a direct consequence of chiral symmetry and the Nambu-Goldstone nature of the pion. *F*-wave contributions are shown to be negligible in the near-threshold region.

DOI: 10.1103/PhysRevC.80.065201   PACS number(s): 12.39.Fe, 13.60.Le, 25.20.Lj

Threshold pion photoproduction - the final word?

- An experimental proposal → further insight (with a mild but...)

Exp.-Nr. **A2-10/09**
Eingang: 15.05.2009
an PAC: 18.05.2009

Mainz Microtron MAMI

Collaboration A2: "Tagged Photons"
Spokesperson: A. Thomas

Proposal for an Experiment

Measurement of Polarized Target and Beam Asymmetries in Pion Photo-Production on the Proton: Test of Chiral Dynamics

Spokespersons for the Experiment:
M. Ostrick - Mainz, D. Hornidge - Mt. Allison,
W. Deconinck, A.M. Bernstein - M.I.T.

Abstract of Physics:
We propose to perform precise measurements of the $\vec{\gamma}\vec{p} \to \pi^0 p$ reaction from threshold to partway up the Δ resonance using polarized beams and targets. These measurements will provide an additional, stringent test of our current understanding that the pion is a Nambu–Goldstone boson due to the spontaneous chiral symmetry breaking in QCD. Specifically we will test detailed predictions of chiral perturbation theory (ChPT) and its energy region of convergence. This experiment will test strong isospin breaking due to the mass difference of the up and down quarks. The data on the (time reversal odd)transversely polarized target asymmetry $\mathbf{T} = \mathbf{A(y)}$ will be sensitive to the πN phase shifts and will provide information for neutral charge states($\pi^0 p, \pi^+ n$) in a region of energies that are not accessible to conventional πN scattering experiments. The data on the double polarization observable $F = A(\gamma_c, x)$ (circular polarized photons-transverse polarized target) will be sensitive to the d-wave multipoles, which have recently been shown to be important in the near threshold region.

PRL **111,** 062004 (2013) PHYSICAL REVIEW LETTERS week ending 9 AUGUST 2013

Accurate Test of Chiral Dynamics in the $\vec{\gamma} p \to \pi^0 p$ Reaction

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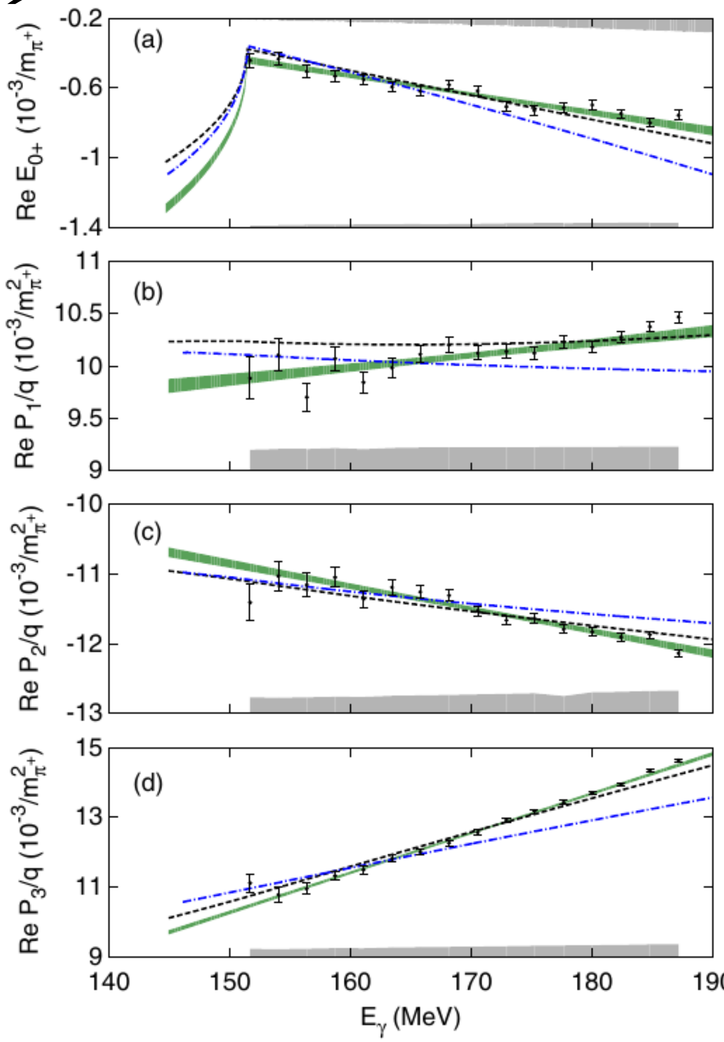

- Most accurate measurement of $d\sigma/d\Omega$
- First measurement of the energy dependence of the photon asymmetry Σ
- But: only statictically significant data from the cusp on

Threshold pion photoproduction - one last issue

- Aron always asked me, how far above threshold one could go with HBCHPT?

- My answer always was: $E_\gamma^{\rm max} = 170$ MeV at most 180 MeV based on intuition

- This was finally answered by Aron + CFP

$\hookrightarrow$ compare HBCHPT at $\mathcal{O}(p^4)$

BKM, ZPhysC 70 (1996) 483; EPJA 11 (2001) 209

with unitarized HBCHPT
(Im E_{0+} from unitarity)

and a phenomenological S & P-waves fit

to the precise $d\sigma/d\Omega, \Sigma$ data

$\hookrightarrow$ perfect agreement up to $E_\gamma = 170$ MeV

$\hookrightarrow$ marked deviations start at $E_\gamma = 180$ MeV

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Upper energy limit of heavy baryon chiral perturbation theory in neutral pion photoproduction

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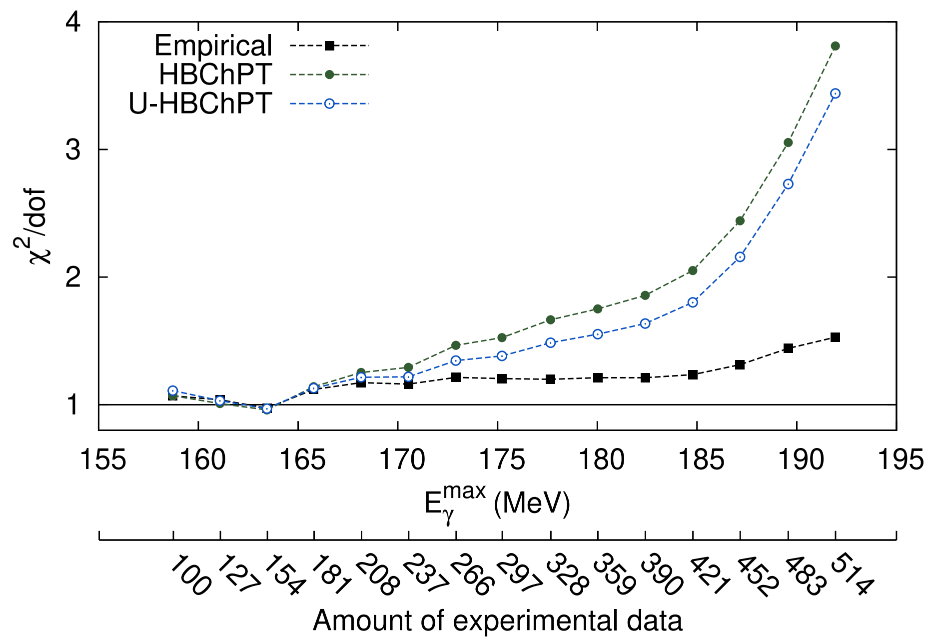


The chiral anomaly and the neutral pion lifetime

The neutral pion lifetime

- The decay $\pi^0 \to 2\gamma$ has revealed **anomalous symmetry breaking**

  $\hookrightarrow$ quantum corrections break a symmetry of the classical theory

  Bell, Jackiw (1969), Adler (1969)

  $\hookrightarrow$ precise prediction at leading order:

$$\Gamma^{\rm anom}_{\pi^0\gamma\gamma} = \frac{\alpha^2 M_\pi^3}{64\pi^3 F_\pi^2} = 7.76 \text{ eV}$$

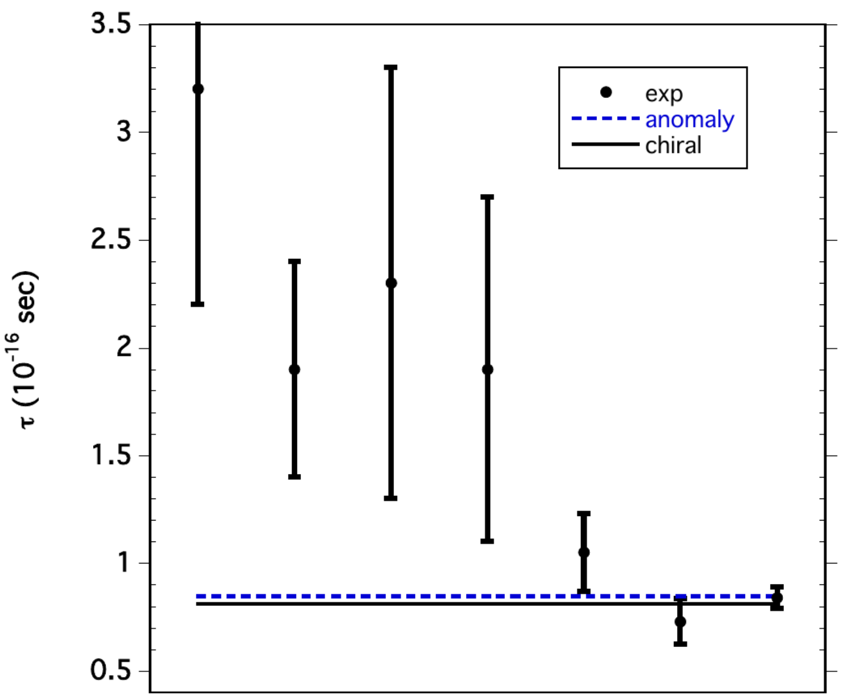
- Early measurements inconclusive

  $\hookrightarrow$ experimentally difficult

  $\hookrightarrow$ theoretical corrections?

- Aron was intrigued by Bachir Moussallam's work on $\pi^0, \eta, \eta' \to 2\gamma$ decays in CHPT when he had a sabbatical at MIT   PRD **51** (1995) 4939

  see also Donoghue, Holstein, Lin (1985), Bijnens, Bramon, Cornet (1988)



The PrimEx proposal

- Aron was one of the initiators of PrimEx @ Jefferson Lab

A Precision Measurement of the Neutral Pion Lifetime via the Primakoff Effect

TJNAF PAC 15 Proposal

December 17, 1998

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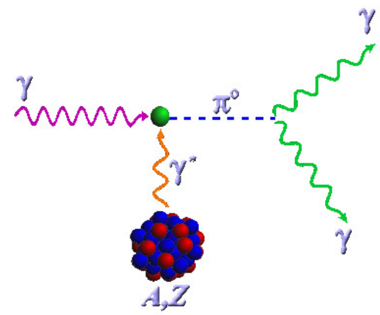

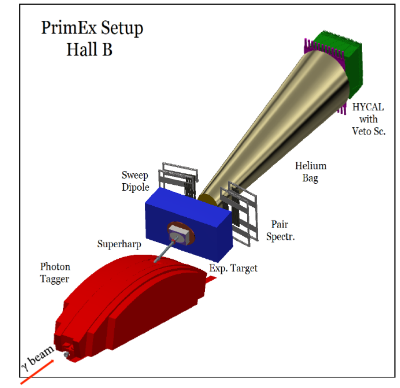

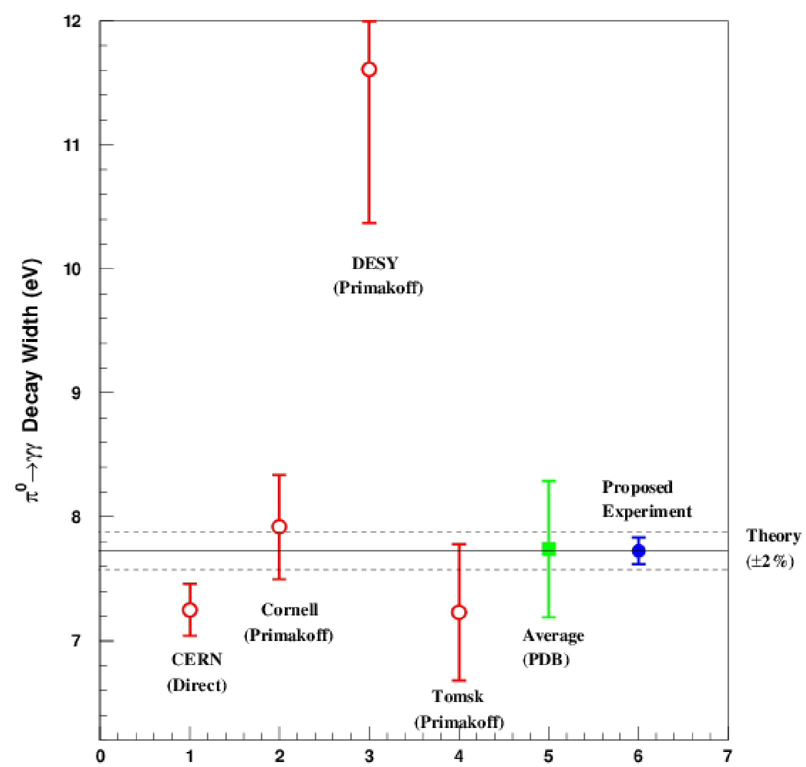

Chiral corrections to the neutral pion lifetime

- First calcuations of corrections in the 1980ties $\to$ improve th'y precisions

Donoghue, Holstein, Lin (1985), Bijnens, Bramon, Cornet (1988)

- Take up this task $\to$ two simultaneous papers:

Electromagnetic corrections in the anomaly sector

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ABSTRACT: Chiral perturbation theory in the anomaly sector for $N_f = 2$ is extended to include dynamical photons, thereby allowing a complete treatment of isospin breaking. A minimal set of independent chiral lagrangian terms is determined and the divergence structure is worked out. There are contributions from irreducible and also from reducible one-loop graphs, a feature of ChPT at order larger than four. The generating functional is non anomalous at order e^2p^4, but not necessarily at higher order in e^2. Practical applications to $\gamma\pi \to \pi\pi$ and to the $\pi^0 \to 2\gamma$ amplitudes are considered. In the latter case, a complete discussion of the corrections beyond current algebra is presented including quark mass as well as electromagnetic effects.

JHEP05(2002)052

$$\Gamma_{\pi^0\gamma\gamma} = 8.06 \pm 0.02 \pm 0.06 \text{ eV}$$

PHYSICAL REVIEW D **66**, 076014 (2002)

Decay $\pi^0 \to \gamma\gamma$ to next to leading order in chiral perturbation theory

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(Received 1 June 2002; published 30 October 2002)

The $\pi^0 \to \gamma\gamma$ decay width is analyzed within the combined framework of chiral perturbation theory and the $1/N_c$ expansion up to $\mathcal{O}(p^6)$ and $\mathcal{O}(p^4 \times 1/N_c)$ in the decay amplitude. The η' is explicitly included in the analysis. It is found that the decay width is enhanced by about 4.5% due to the isospin-breaking induced mixing of the pure $U(3)$ states. This effect, which is of leading order in low energy expansion, is shown to persist nearly unchanged at next to leading order. The chief prediction with its estimated uncertainty is $\Gamma_{\pi^0\to\gamma\gamma} = 8.10 \pm 0.08$ eV. This prediction at the 1% level makes the upcoming precision measurement of the decay width even more urgent. Observations on the η and η' can also be made, especially about their mixing, which is shown to be significantly affected by next to leading order corrections.

$$\Gamma_{\pi^0\gamma\gamma} = 8.10 \pm 0.08 \text{ eV}$$

- Later refined to two loop accuracy

Kampf, Moussallam (2009)

$$\Gamma_{\pi^0\gamma\gamma} = 8.09 \pm 0.11 \text{ eV}$$

$\to$ talk by Kampf

The PrimEX result

- Aron presented preliminary results at CD 2009 in Bern

Lifetime Measurement of the π^0 Meson and the QCD Chiral Anomaly

PoS(CD09)035

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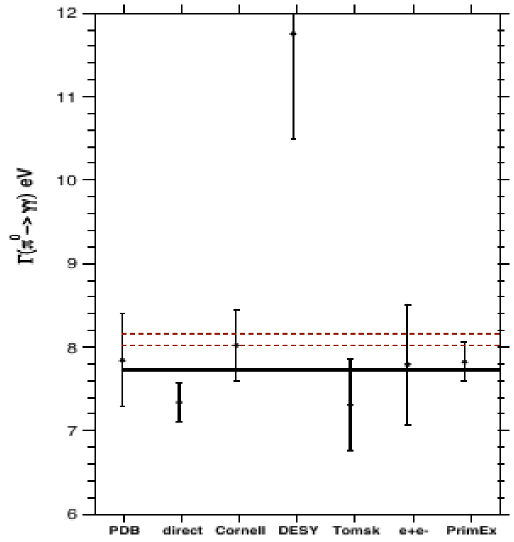
The $\pi^0 \to \gamma\gamma$ decay rate is dominated by the chiral anomaly with 4.1± 1.0 % isospin breaking chiral corrections(proportional to the mass difference of the up and down quarks). A new measurement at Jefferson Lab using the Primakoff effect(PrimEx) is presented with a total error of 3.0%. Great care was taken to reduce systematic errors; this was checked with pair production and Compton scattering measurements. The result is consistent with previous experiments and the predicted value.



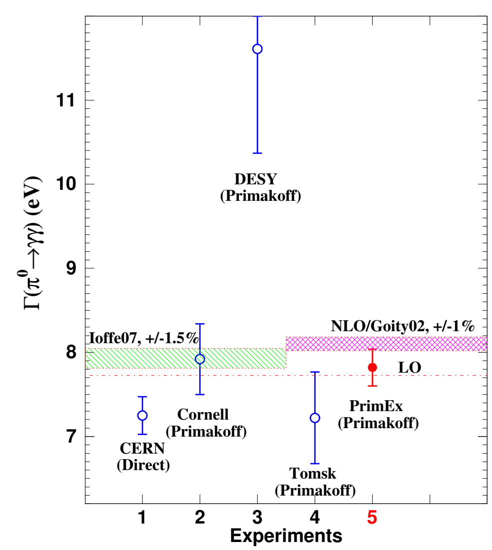
- PrimEx paper came out 2011

PRL **106**, 162303 (2011) PHYSICAL REVIEW LETTERS week ending 22 APRIL 2011

New Measurement of the π^0 Radiative Decay Width

I. Larin,[1,2] D. McNulty,[3] E. Clinton,[4] P. Ambrozewicz,[2] D. Lawrence,[4,5] I. Nakagawa,[6,7] Y. Prok,[3] A. Teymurazyan,[6] A. Ahmidouch,[2] A. Asratyan,[1] K. Baker,[8] L. Benton,[2] A. M. Bernstein,[3] V. Burkert,[5] P. Cole,[9] P. Collins,[10] D. Dale,[9] S. Danagoulian,[2] G. Davidenko,[1] R. Demirchyan,[2] A. Deur,[5] A. Dolgolenko,[1] G. Dzyubenko,[1] R. Ent,[5] A. Evdokimov,[1] J. Feng,[11,12] M. Gabrielyan,[6] L. Gan,[11] A. Gasparian,[2,*] S. Gevorkyan,[13,14] A. Glamazdin,[15] V. Goryachev,[1] V. Gyurjyan,[5] K. Hardy,[2] J. He,[16] M. Ito,[5] L. Jiang,[11,12] D. Kashy,[5] M. Khandaker,[17] P. Kingsberry,[3,17] A. Kolarkar,[6] M. Konchatnyi,[15] A. Korchin,[15] W. Korsch,[6] S. Kowalski,[3] M. Kubantsev,[1,18] V. Kubarovsky,[5] X. Li,[11] P. Martel,[4] V. Matveev,[1] B. Mecking,[5] B. Milbrath,[19] R. Minehart,[20] R. Miskimen,[4] V. Mochalov,[21] S. Mtingwa,[2] S. Overby,[2] E. Pasyuk,[5,10] M. Payen,[2] R. Pedroni,[2] B. Ritchie,[10] T. E. Rodrigues,[22] C. Salgado,[17] A. Shahinyan,[13] A. Sitnikov,[1] D. Sober,[23] S. Stepanyan,[5] W. Stephens,[20] J. Underwood,[2] A. Vasiliev,[21] V. Vishnyakov,[1] M. Wood,[4] and S. Zhou[12]

(PrimEx Collaboration)



- PrimEx: $\Gamma_{\pi^0\gamma\gamma} = \mathbf{7.82 \pm 0.14 \pm 0.17}$ eV (2.8%)
- PrimEx-II: $\Gamma_{\pi^0\gamma\gamma} = \mathbf{7.80 \pm 0.06 \pm 0.11}$ eV (1.5%)

Science **368** (2020) 506 → talk by Gasparian

⇒ great success of chiral dynamics!

A nice review

- Aron teamed up again with Barry to write a nice RMP:

REVIEWS OF MODERN PHYSICS, VOLUME 85, JANUARY–MARCH 2013

Neutral pion lifetime measurements and the QCD chiral anomaly

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(published 9 January 2013)

A fundamental property of QCD is the presence of the chiral anomaly, which is the dominant component of the $\pi^0 \to \gamma\gamma$ decay rate. Based on this anomaly and its small ($\simeq 4.5\%$) chiral correction, a prediction of the π^0 lifetime can be used as a test of QCD at confinement scale energies. The interesting experimental and theoretical histories of the π^0 meson are reviewed, from discovery to the present era. Experimental results are in agreement with the theoretical prediction, within the current ($\simeq 3\%$) experimental error; however, they are not yet sufficiently precise to test the chiral corrected result, which is a firm QCD prediction and is known to $\simeq 1\%$ uncertainty. At this level there exist experimental inconsistencies, which require attention. Possible future work to improve the present precision is suggested.

DOI: 10.1103/RevModPhys.85.49 PACS numbers: 14.40.−n, 13.20.Cz, 13.40.Hq, 11.30.Rd

$\hookrightarrow$ another testimony of Aron's legacy

More on Goldstone bosons

- Aron was also interested in
  $PS \to \gamma\gamma^\star$ decays and
  the radii of pseudoscalar mesons

The $\pi^0, \eta, \eta' \to \gamma\gamma^*$ Decay Rates and Radii

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The low Q^2 slopes of the transition form factors provide a unique method to measure the sizes of the neutral pseudo-scalar mesons, since they do not have electromagnetic form factors. From the slope one obtains the "axial transition RMS radius" $R_{A,PS} = \sqrt{< r^2 >}$ for each PS meson. The present status of theory and experiment for these quantities are presented. A comparison of the $R_{A,PS}$ is presented along with the electromagnetic and scalar radii of the $\pi^\pm$ mesons and the proton. We observe the striking similarity of the values of axial transition radii of all of the pseudoscalar mesons to each other and to the charge radius of the $\pi^\pm$.

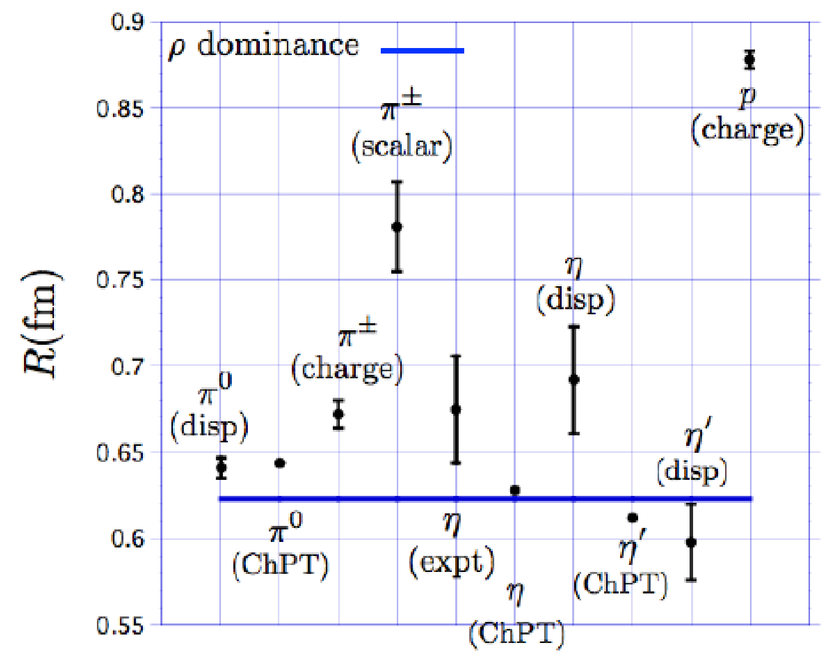
PoS(CD15)046

- Radii of the neutral pseudoscalars from

$$PS \to \gamma^\star(Q^2)\gamma \quad \text{at low } Q^2$$

$$F(Q^2) = F_{PS}(0)\left(1 - Q^2\langle r^2\rangle/6 + \ldots\right)$$

$$F_{PS}(0) = \left(\frac{4\Gamma(PS\to 2\gamma)}{\pi M_{PS}^3\alpha^2}\right)^{1/2}$$



- Aron's resume:

I hope that this discussion about the slope parameter of the $PS \to \gamma^*(Q^2)\gamma$ form factor stimulates new, accurate experiments and further calculations. In particular it is of interest to re-examine the ChPT calculations [2], to extend the lattice calculations[5], and perhaps most important, to physically interpret that differences between the charge, scalar, and axial transition RMS radii.

$\hookrightarrow$ These transition ffs gained prominence
in the theoretical analysis of the muon $(g-2)$

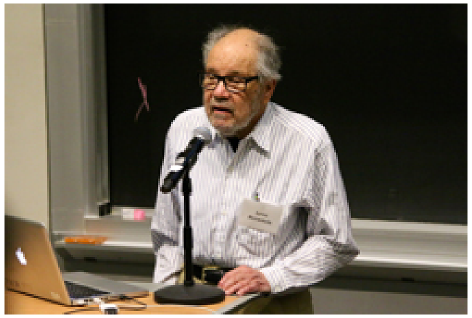
$\longrightarrow$ various talks to come

Final remarks

Aron's lecagy

- Part of Aron's legacy is nicely summarized by his Chiral Dynamics talks

year	place	title of Aron's talk
1994	MIT	none - main organizer
1997	Mainz	*Introduction to Chiral Dynamics: Theory and Experiment*
2000	JLab	*Experimental Chiral Dynamics*
2003	Bonn	*Hadron Deformation and Chiral Dynamics*
2006	Duke	*Opening Remarks: Experimental Tests of Chiral Symmetry Breaking*
2009	Bern	*Lifetime Measurement of the* π^0 *Meson and the QCD Chiral Anomaly*
2012	JLab	*Outlook*
2015	Pisa	*The* $\pi^0, \eta, \eta' \to \gamma\gamma^\star$ *Decay Rates and Radii*
2018	Duke	none - could not attend, but very active organizer



A challenge: The neutron amplitude

- Remember the classical dipole picture: $E_{0+}(\gamma n \to \pi^0 n) = 0$

- A counterintuitive CHPT prediction: $E_{0+}^{\pi^0 n} = 2.1 > |E_{0+}^{\pi^0 p}| \simeq 1.2$ BKM (1996)

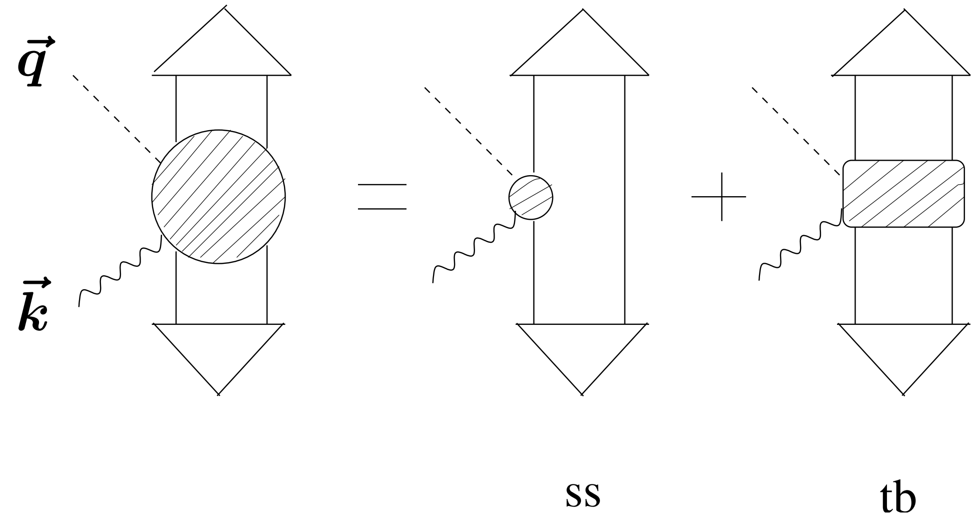
  $\hookrightarrow$ truely remarkable, $|E_{0+}^{\pi^0 n}| \simeq 2|E_{0+}^{\pi^0 p}|$

  $\hookrightarrow$ quantum effects defy intuition!

- First test on the deuteron

$$E_d = E_d^{\rm ss} + E_d^{\rm tb}$$

$$E_d^{\rm ss} \propto E_{0+}^{\pi^0 p} + E_{0+}^{\pi^0 n}$$



- Three-body dominant, converges quickly
  Beane, Bernard, Kaiser, Lee, UGM, van Kolck (1996)

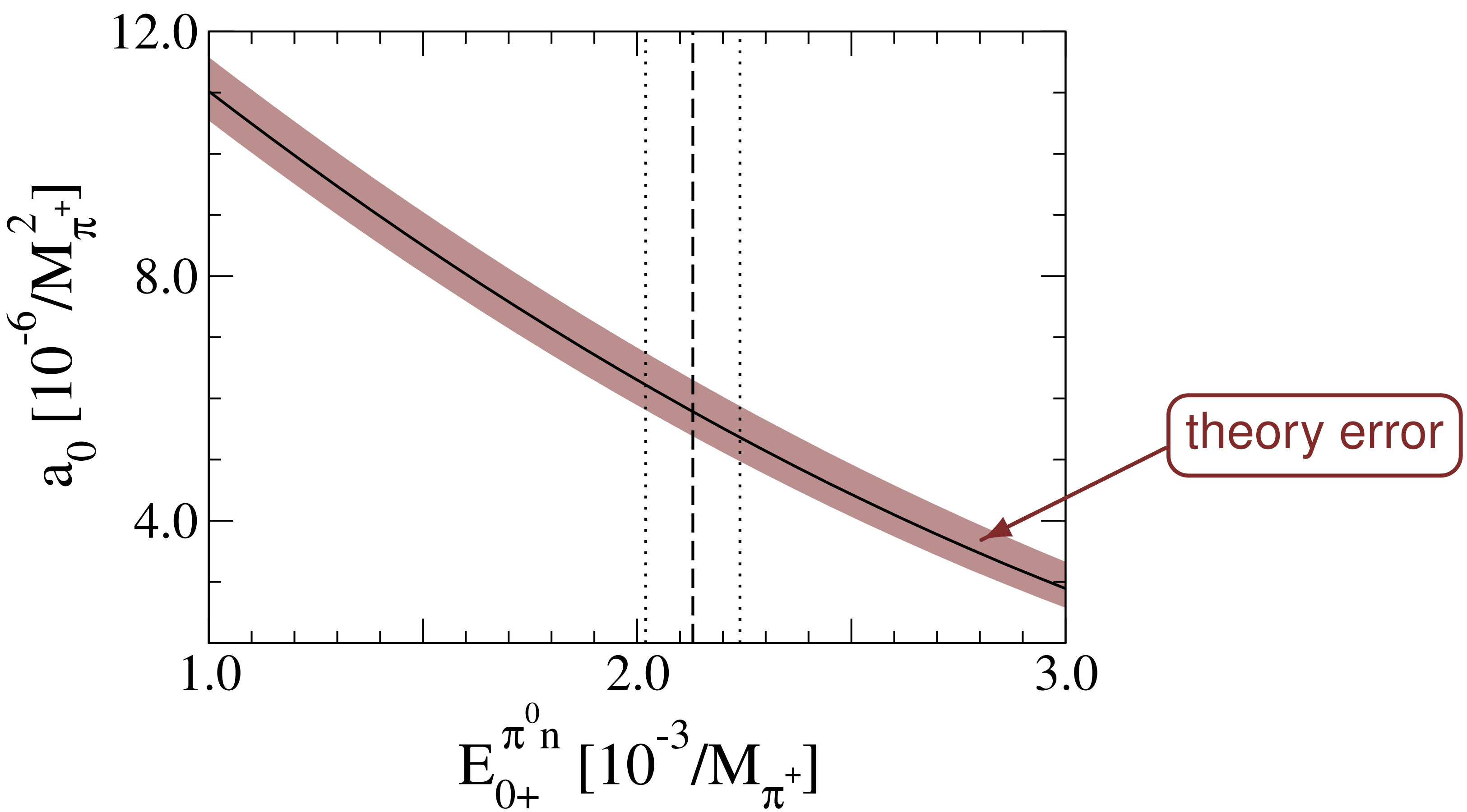
- Theory versus experiment: $E_d^{\rm th} = -1.8 \pm 0.2$ $E_d^{\rm exp} = -1.7 \pm 0.2$

  old Saclay data, reanalyzed in Argan et al. (1987)

A better target

- Neutral pion photoproduction on ^{3}He: Sensitity of threshold XS a_0 to $E_{0+}^{\pi^0 n}$

Lenkewitz, Hammer, UGM, PLB **700** (2011) 365; EPJA **49** (2013) 20



$\hookrightarrow$ ^{3}He is a promising candidate to test the CHPT prediction for $E_{0+}^{\pi^0 n}$

Final words

- Let us pause a minute to remember Aron

Courtesy of the Bernstein family