Arnowitt Memorial Symposium
Mitchell Institute for Fundamental Physics
Texas A&M University
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Talk

Perspectives on Particle Theory
From Pion Physics to Sparticles

[PN]
Northeastern University, Boston

My collaboration with Dick Arnowitt

- Papers/reports: 222

Specific Items[1]

- Current Algebra and Effective Lagrangians.
- The $U(1)$ problem
- Local supersymmetry
- Gravity mediated breaking and supergravity grand unification.

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[1] A more detailed account appears in " Reminiscences of my work with Richard Lewis Arnowitt", in Physica Scripta: Phys. Scr. 90 (2015) 068007, edited by Roland Allen and Suzy Lidström.

Current Algebra and Effective Lagrangians

- In 1964 Gell-Mann[2] had proposed that "quark-type' equal-time commutation relations for the vector and the axial vector currents of weak interaction theory serve as a basis for calculations involving strongly interacting particles. Combined with the CVC, PCAC and the soft pion approximation many successful results were obtained [3].

- One of the hot issues around 1967 was the breakdown of the soft pion approximation in the analysis of $\rho \to \pi\pi$ and $A_1 \to \rho\pi$ where the soft pion approximation gave very poor results [4]. A number of techniques were being pursued such as Ward identities [5] and dispersion relations[6] to resolve the problem.

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[2] M.Gell-Mann, Physics 1, 63 (1964).

[3] S.Weinberg, Phys. Rev. Lett. 17, 616 (1966).

[4] D. Geffen, Phys. Rev. Letters 19, 770 (1967); B. Renner, Phys. Letters 21, 453 (1966).

[5] H. J. Schnitzer and S. Weinberg, Phys. Rev. **164**, 1828 (1967).

[6] T. Das, V.S. Mathur, and S. Okubo, Phys. Rev. Letts. 19, 859 (1967).

Dick Arnowitt, Marvin Friedman and I followed a different approach which first of all involved developing an effective Lagrangian for the $\pi\rho A_1$ system. The effective Lagrangian techniques we worked on have a much larger domain of validity than the specific system we were looking at. Next we utilized the current algebra constraints to determine the effective lagrangian parameters [7]. Thus our analysis consisted of two steps:

- The first step involved
  - Single particle saturation in computation of T-products of currents.
  - Lorentz invariance
  - Spectator approximation
  - Locality which implies a smoothness assumption on the vertices.
  - The above lead us to the conclusion that the simplest way to achieve these constraints is via an effective lagrangian which for T-products of three currents requires writing cubic interactions involving π, ρ and A_1 fields and allowing for no derivatives in the first -order formalism and up to one-derivative in the second order formalism. The effective lagrangian is to be used to first order in the coupling constants for three point functions.
- Using the same principles that analysis can be extended to N -point functions.

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[7] R. Arnowitt, M. H. Friedman, PN, Phys. Rev. Lett. 19, 1085 (1967).
R. L. Arnowitt, M. H. Friedman, P.N. and R. Suitor, Phys. Rev. **175**, 1802 (1968).

Current Algebra

- After ensuring that the constraints of single particles saturation, Lorentz invariance and locality can be embodied by writing an effective Lagrangian we impose constraints of current algebra[8] using field -current identity which connects currents with fields [9]

$$V^\mu = g_\rho \rho^\mu \ ,$$

$$A^\mu = g_A A_1^\mu + F_\pi \partial^\mu \phi \ .$$

- The currents were subject to: (i) Equal-time commutation relations on the densities, (ii) CVC, (iii) PCAC.
- The imposition of the absence of *q-number Schwinger term gave the First Weinberg Sum rule* [10]. The $\pi - \rho - A_1$ effective Lagrangian allowed one to compute $A_1 \pi \rho$ processes without the soft pion approximation and get results consistent with data.
- The technique of effective lagrangian allows one to easily obtain lagrangians obeying current algebra constraints for higher points functions. The effective lagrangian with current algebra constraints were used for a variety of processes: $\rho \to \pi\pi, A_1 \to \pi\rho$, Kl_3 decay, $\pi\pi, \pi K$ and πN sccattering.
- The first analysis of $\pi\pi \to \pi\pi$ scattering using hard pion current algebra was carried out by us [11].

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[8] R. Arnowitt, M. H. Friedman, PN, R. Suitor, Phys. Rev. Letters 20, 475 (1968).

[9] T D Lee, S. Weinberg, B. Zumino, Phys. Rev. Lett. 18, 1029 (1967).

[10] $g_\rho^2/m_\rho^2 = g_A^2/m_A^2 + F_\pi^2$.

[11] R. L. Arnowitt, M. H. Friedman, P.N. and R. Suitor, Phys. Rev. **175**, 1820 (1968).

Effective vs Phenomenological Lagrangians

- Our effective Lagrangian [12] was different from the work of Schwinger [13], Wess and Zumino [14] and of Ben Lee and Nieh [15] which were basically phenomenological Lagrangians.
- In phenomenological lagrangian, one starts by constructing Lagrangians which have $\boldsymbol{SU(2) \times SU(2)}$ or $\boldsymbol{SU(3) \times SU(3)}$ invariance. The invariance is then broken by additional terms which are introduced by hand.
- In the effective lagrangian approach no a priori assumption was made regarding the type of symmetry breaking, chiral or ordinary. The current algebra constraints alone determine the nature of symmetry breaking.
- What we found was that for hard meson current algebra with single meson dominance of the currents and of the $\boldsymbol{\sigma}$ commutator, the chiral symmetry breaking was broken only by[16]

$$\mathbf{(3,3^*)+(3^*,3)} \qquad \textbf{(chiral symmetry breaking)}\ .$$

This type of breaking had been proposed by Gell-Mann, Oakes and Renner [17].

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[12] R. Arnowitt, M. H. Friedman, PN, PRL 19, 1085 (1967).

[13] J. Schwinger, Phys. Letters 248, 473 (1967).

[14] J. Wess and B. Zumino, Phys. Rev. 163, 1727 (1967)

[15] B. Lee and H.T. Nieh, Phys. Rev. 166, 1507 (1968).

[16] R. Arnowitt, M. H. Friedman, PN, R. Suitor, Phys. Rev. Lett, 26, 104 (1971).

[17] M. Gell-Mann, R. Oakes and B. Renner, Phys. Rev. 175, 2195 (1968).

$\pi^0 \to 2\gamma$ Decay and Axial Current Anomaly

- Beginning in 1967 one of the big puzzles related to the Veltman theorem[18] which was that in the soft pion approximation

  $$\Gamma(\pi^0 \to 2\gamma) = 0 \ .$$

  It was generally held that a possible source of this problem could be that the soft pion approximation was breaking down and there there was a very rapid variation of the matrix elements as we went off the pion mass-shell.
- However, in a paper in 1968 we discovered that hard pion analysis also gave a vanishing $\pi^0 \to 2\gamma$ decay. This lead us to propose a modification of the PCAC condition by introducing an axial current anomaly which exists even in the chiral limit [19]

  $$\partial_\mu A_a^\mu = F_a m_a^2 \phi_a + \lambda d_{abc} \epsilon_{\mu\nu\alpha\beta} F_b^{\mu\nu} F_c^{\alpha\beta} + \lambda' \epsilon_{\mu\nu\alpha\beta} F_a^{\mu\nu} \phi^{\alpha\beta}$$

  where $a, b, c = 1 \cdots 8$.
- Our analysis was using effective Lagrangian rather than the quark model which was employed by Bell and Jackiw and by Adler[20].

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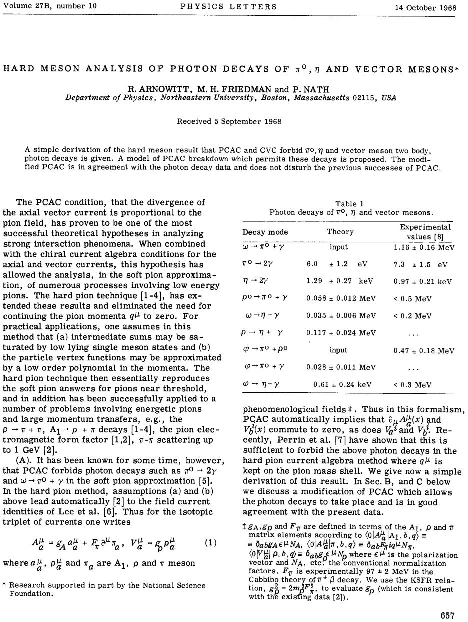
[18] M. Veltman, Proc. Roy. Soc. A310, 107 (1967).

[19] R. Arnowitt, M.H. Friedman, PN, Phys.. Lett. 27 B, 657 (1968).

[20] J.S. Bell and R. Jackiw, N.C. A 60, 47 (1969); S. L. Adler, Phy. Rev. 177, 2426(1969).



Volume 27B, number 10 PHYSICS LETTERS 14 October 1968

HARD MESON ANALYSIS OF PHOTON DECAYS OF π^0, η AND VECTOR MESONS*

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Received 5 September 1968

A simple derivation of the hard meson result that PCAC and CVC forbid π^0, η and vector meson two body, photon decays is given. A model of PCAC breakdown which permits these decays is proposed. The modified PCAC is in agreement with the photon decay data and does not disturb the previous successes of PCAC.

The PCAC condition, that the divergence of the axial vector current is proportional to the pion field, has proven to be one of the most successful theoretical hypotheses in analyzing strong interaction phenomena. When combined with the chiral current algebra conditions for the axial and vector currents, this hypothesis has allowed the analysis, in the soft pion approximation, of numerous processes involving low energy pions. The hard pion technique [1-4], has extended these results and eliminated the need for continuing the pion momenta q^μ to zero. For practical applications, one assumes in this method that (a) intermediate sums may be saturated by low lying single meson states and (b) the particle vertex functions may be approximated by a low order polynomial in the momenta. The hard pion technique then essentially reproduces the soft pion answers for pions near threshold, and in addition has been successfully applied to a number of problems involving energetic pions and large momentum transfers, e.g., the $\rho \to \pi + \pi$, $A_1 \to \rho + \pi$ decays [1-4], the pion electromagnetic form factor [1,2], π-π scattering up to 1 GeV [2].

(A). It has been known for some time, however, that PCAC forbids photon decays such as $\pi^0 \to 2\gamma$ and $\omega \to \pi^0 + \gamma$ in the soft pion approximation [5]. In the hard pion method, assumptions (a) and (b) above lead automatically [2] to the field current identities of Lee et al. [6]. Thus for the isotopic triplet of currents one writes

$$A_a^\mu = g_A a_a^\mu + F_\pi \partial^\mu \pi_a, \quad V_a^\mu = g_\rho \rho_a^\mu \qquad (1)$$

where a_a^μ, ρ_a^μ and π_a are A_1, ρ and π meson phenomenological fields‡. Thus in this formalism, PCAC automatically implies that $\partial_\mu A_a^\mu(x)$ and $V_b^i(x)$ commute to zero, as does V_a^i and V_b^i. Recently, Perrin et al. [7] have shown that this is sufficient to forbid the above photon decays in the hard pion current algebra method where q^μ is kept on the pion mass shell. We give now a simple derivation of this result. In Sec. B, and C below we discuss a modification of PCAC which allows the photon decays to take place and is in good agreement with the present data.

Table 1
Photon decays of π^0, η and vector mesons.

Decay mode	Theory	Experimental values [8]
$\omega \to \pi^0 + \gamma$	input	1.16 ± 0.16 MeV
$\pi^0 \to 2\gamma$	6.0 ± 1.2 eV	7.3 ± 1.5 eV
$\eta \to 2\gamma$	1.29 ± 0.27 keV	0.97 ± 0.21 keV
$\rho^0 \to \pi^0 + \gamma$	0.058 ± 0.012 MeV	< 0.5 MeV
$\omega \to \eta + \gamma$	0.035 ± 0.006 MeV	< 0.2 MeV
$\rho \to \eta + \gamma$	0.117 ± 0.024 MeV	...
$\varphi \to \pi^0 + \rho^0$	input	0.47 ± 0.18 MeV
$\varphi \to \pi^0 + \gamma$	0.028 ± 0.011 MeV	...
$\varphi \to \eta + \gamma$	0.61 ± 0.24 keV	< 0.3 MeV

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* Research supported in part by the National Science Foundation.

‡ g_A, g_ρ and F_π are defined in terms of the A_1, ρ and π matrix elements according to $\langle 0|A_a^\mu|A_1, b, q\rangle \equiv$ $\equiv \delta_{ab} g_A \epsilon^\mu N_A$, $\langle 0|A_a^\mu|\pi, b, q\rangle \equiv \delta_{ab} F_\pi i q^\mu N_\pi$, $\langle 0|V_a^\mu|\rho, b, q\rangle \equiv \delta_{ab} g_\rho \epsilon^\mu N_\rho$ where ϵ^μ is the polarization vector and N_A, etc. the conventional normalization factors. F_π is experimentally 97 ± 2 MeV in the Cabbibo theory of $\pi^\pm$ β decay. We use the KSFR relation, $g_\rho^2 = 2m_\rho^2 F_\pi^2$, to evaluate g_ρ (which is consistent with the existing data [2]).

The $U(1)$ Problem

- The $U(1)$ problem relates to the fact that the ordinary $U(3) \times U(3)$ current algebra leads to the ninth pseudo-scalar meson being light [21]:

$$m_{\eta'} < \sqrt{3} m_{\pi} \ .$$

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[21] S.L. Glashow, in Hadrons and their interactions (Academic Press, New York, 1968), p 83; S. Weinberg, Phys. Rev. D11, 3583 (1975).

Efffective Lagrangian with $U(1)$ anomaly

- Further, Witten[22] showed that a resolution of the $U(1)$ anomaly arises in the $1/N$ expansion of QCD. The η' is massless in the $N \to \infty$ limit but significant non-zero contributions arise from terms which are $1/N$ smaller than the leading terms and split η' from the octet.
  ‘
- Dick and I [23] examined the problem from an effective Lagrangian view point with a modification of the axial current to include the $U(1)$ anomaly with a modified PCAC condition

$$\partial_\mu A_a^\mu = F_{ab}\mu_{ab}\phi_a + \delta_{a9}(\frac{2}{3})^{1/2} N_f \partial_\mu K^\mu \ .$$

  where $N_f = 3$ is the number of light quark flavors and K^μ is the Kogut-Susskind ghost field.

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[22] E. Witten, Nucl. Phys. B156, 269 (1979).

[23] R. Arnowitt and P. N., Phys. Rev. D23, 473 (1981); Nucl. Phys. B **209**, 234 (1982); ibid **209**, 251 (1982).

Efffective Lagrangian with $U(1)$ anomaly

- Using the effective Lagrangian which includes the effect of the $U(1)$ anomaly, we found a sum rule of the form [24]

$$(F_{88} + \sqrt{2}F_{98})^2 m_\eta^2 + (F_{89} + \sqrt{2}F_{99})^2 m_{\eta'}^2 = 3m_\pi^2 F_\pi^2 + \frac{4}{3}N_f^2 \left(\frac{d^2E}{d\theta^2}\right)_{\theta=0}^{N_f=0} .$$

  where N_f is the number of light quark flavors.
- If one ignores the first and the last terms, sets $F_{89} = 0$, and let $F_{99} \to \sqrt{N_f/6}F_\pi$ $(N_f = 3)$, one finds the Weinberg result [25]

$$m_{\eta'} < \sqrt{3}m_\pi .$$

- Further, in the limit $m_\pi = 0 = m_\eta$, $F_{89} = 0$ and $F_{99} \to \sqrt{N_f/6}F_\pi$ one finds Witten's result [26]

$$m_{\eta'}^2 \to \frac{4N_f}{F_\pi^2}\left(\frac{d^2E(\theta)}{d\theta^2}\right)_{\theta=0}^{N_\ell=0} .$$

- A less general analysis using σ model was given by other authors [27]

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[24] R. Arnowitt and P. N., Phys. Rev. D23, 473 (1981); Nucl. Phys. B **209**, 234 (1982); ibid **209**, 251 (1982).

[25] S. Weinberg, Phys. Rev. D11, 3583 (1975).

[26] E. Witten, Nucl. Phys. 156, 269 (1979).

[27] Rosenzweig, J. Schecter and G. Trahern, Phys. Rev. D21 (1980) 3388.
P. Di Vecchia and G. Veneziano, Nucl. Phys. B171 (1980) 253

Witten has shown that our Lagrangian and those of other groups which includes the effect of the $U(1)$ anomaly and solves the η' puzzle is consistent with the large N chiral dynamics.

ANNALS OF PHYSICS **128**, 363–375 (1980)

Large *N* Chiral Dynamics*

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Received February 20, 1980

Some properties of large *N* chiral dynamics are discussed, using an effective Lagrangian that has been derived by Rosenzweig, Schechter, and Trahern; Di Vecchia and Veneziano; and Nath and Arnowitt.

1. INTRODUCTION

An old problem in hadronic physics is the $U(1)$ problem or the problem of the singlet pseudoscalar boson [1]. Why does hadronic physics show no trace of a $U(1)$ symmetry, spontaneously broken or not? Why is the η' so much heavier than the η?

Local Supersymmetry

- In 1974 I was at the HEP conference at Imperial College London where I first heard of supersymmetry. On return to Boston I talked to Dick to work in this area. At that time SUSY was a global symmetry, and we thought that if it is a fundamental symmetry it ought to be a local symmetry. Very quickly we realized that gauging of supersymmetry required bringing in gravity, and we thought that the direct course of action was to extend the geometry of Einstein gravity to superspace geometry on the space of bosonic and fermionic co-ordinates: $z = (x, \theta)$ [28]

- Along the way with Bruno Zumino we gave a formula for superdeterminant and for the action in superpspace[29] and invented the technique of gauge completion, a procedure where gauge invariance in superspace is imposed in successive orders in θ [30].

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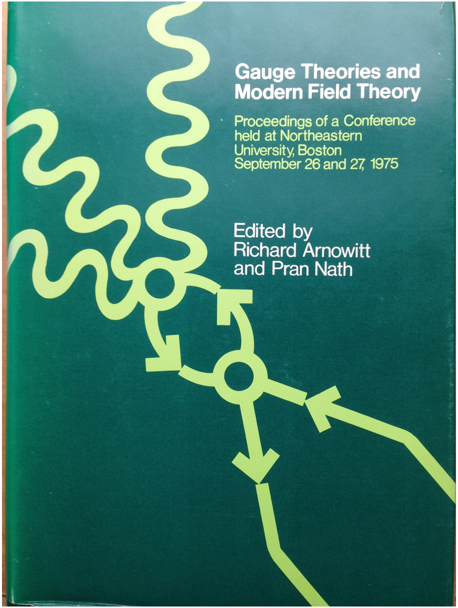
[28] P.N. and R. Arnowitt, "Generalized Supergauge Symmetry as a New Framework for Unified Gauge Theories", Phys. Lett. B 56, 177 (1975).

[29] R. L. Arnowitt, P.N. and B. Zumino, Phys. Lett. B **56**, 81 (1975).

[30] R. Arnowitt, PN; PLB 65B, 73 (1976).



Gauge Theories and Modern Field Theory

Proceedings of a Conference
held at Northeastern
University, Boston
September 26 and 27, 1975

Edited by
Richard Arnowitt
and Pran Nath

Supergravity and Gauge Supersymmetry

- This program was overtaken by the simpler approach of supergravity. The pure supergravity multiplet without matter and without auxiliary fields contains just spin 2 and spin 3/2 fields[31] [32] and its matter content is thus easy to deal with.
- Gauge Supersymmetry geometry is a Riemanian geometry in superspace while the superspace geometry of supergavity is non-Riemanian with torsion. What is the connection?
- The connection between the two is as follows:
  - In gauge supersymmetry the constant tangent space metric consistent with $O(3,1)$ invariance is

$$\eta_{AB} = \begin{pmatrix} \eta_{mn}(\mathrm{bose}) & 0 \\ 0 & k\eta_{ab}(\mathrm{fermi}) \end{pmatrix} , \quad \eta = (-C^{-1}) .$$

  - In the limit $k \to 0$ the geometry of gauge supersymmetry contracts to the supergravity geometry [33]. The contraction produces the desired torsions needed in the superspace formulation of supergravity [36], [34], [35].
  - Thus the supergravity geometry is a contraction of the geometry of gauge supersymmetry.

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[31] D. Z. Freedman, P van Niewenhuisen and Ferrara, Phys. Rev. Lett. D13, 3214 (1976).

[32] S. Deser and B. Zumino, Phys. Lett. B62, 335 (1976).

[33] R. Arnowitt, PN; PLB 65B, 73 (1976); Phys.Lett. B78 (1978) 581; Nucl. Phys. B165, 462 (1980).

[34] J. Wess, B. Zumino, Phys. Lett. 66B, 361 (1977).

[35] L. Brink, M.Gell-Mann, P. Ramond , J. Schwartz, Phys.Lett. B74, 336 (1978).

Gravity mediated breaking and Supergravity Grand Unification

- A major impediment to progress in the development of SUSY theories in the early eighties centered on breaking of supersymmetry. The work with Ali Chamseddine and Dick Arnowitt in 1982 [36] lead to the development of supergravtiy grand unification where supersymmetry is broken by gravity mediation in an acceptable fashion [37].

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[36] A. H. Chamseddine, R. Arnowitt, PN, Phys.Rev.Lett. 49 (1982) 970.

[37] Review: R. Arnowitt, A. H. Chamseddine and P.N., Int. J. Mod. Phys. A **27**, 1230028 (2012).

Implications of SUGRA GUTs

- In SUGRA GUTs after spontaneous breaking of supersymmetry and GUT symmetry the low energy physics after integration over heavy fields consists of operators of the following types in the Lagrangian

$$\mathbf{dim[2] + dim[3] + dim[4] + dim[5] + dim[6]} + \boldsymbol{dim}[\mathbf{7}] + \cdots$$

  - $\dim$ [2] $+ \dim$ [3] operators can be shown to be independent of M_G and thus suitable for phenomenology [38], [39], [40]. These operators lead to interesting sparticle spectra involving gluino, charginos, neutralinos, squarks and sleptons which are currently being searched at the Large Hadron Collider. The simplest SUGRA model can be parameterized by

$$\boldsymbol{m_0, m_{1/2}, A_0, \tan\beta, \mathrm{sign}(\mu)}: \quad \mathbf{mSUGRA}$$

  - Dimension 5, 6 and higher operators contain B&L violating interactions and enter in neutrino masses and proton decay.

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[38] A. H. Chamseddine, R. Arnowitt, PN, Phys.Rev.Lett. 49, 970 (1982).

[39] P.N. , R. L. Arnowitt and A. H. Chamseddine, Nucl. Phys. B **227**, 121 (1983).

[40] L. J. Hall, J. D. Lykken and S. Weinberg, Phys. Rev. D **27**, 2359 (1983).

Supersymmetric signals-early works

SUGRA GUT models provided a framework where a phenomenologically viable breaking of supersymmetry could occur and this lead to many works soon thereafter on the implications of SUGRA unification and on the signals of supersymmetry such as

- These included computation of sparticle mass spectra [41]
- SUSY signatures[42]
- A heavy top quark with mass ~ 100 GeV or larger [43]

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[41] R. L. Arnowitt, A. H. Chamseddine and P. Nath, Phys. Rev. Lett. **50**, 232 (1983).
S. Weinberg, Phys. Rev. Lett. **50**, 387 (1983).

[42] A. H. Chamseddine, P. N and R. L. Arnowitt, Phys. Lett. B **129**, 445 (1983)
D. A. Dicus, S. Nandi, W. W. Repko and X. Tata, Phys. Rev. Lett. 51, 1030 (1983); Phys. Lett. B 129, 451 (1983).

.

[43] L. Alvarez-Gaume, J. Polchinski and M. B. Wise, Nucl. Phys. B **221**, 495 (1983).

Supersymmetric electro-weak contributions to $g_\mu - 2$

- In 1984 a complete supergravity analysis of $g-2$ was given. [44] The SUSY contribution arises from $\tilde{\chi}^{\pm} - \tilde{\nu}_\mu$ and $\tilde{\chi}^0_1 - \tilde{\mu}$ loops. In this work it was shown that the sugra contribution to $g-2$ could be substantial and potentially observable. The work was helpful to E821 at Brookhaven.

- The current status: The Brookhaven experiment [45] which measures $a_\mu = \frac{1}{2}(g_\mu - 2)$ shows a deviation from the Standard Model prediction [46] at the $3\,\sigma$ level.

$$\delta a_\mu = (287 \pm 80.) \times 10^{-11} \ .$$

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[44] T. C. Yuan, R. Arnowitt, A. H. Chamseddine and P. Nath, Z. Phys. C26 (1984) 407; D. A. Kosower, L. M. Krauss and N. Sakai, Phys. Lett. B133 (1983) 305.

[45] Muon G-2 Collaboration, Phys. Rev. D 73 (2006) 072003

[46] K. Hagiwara, R. Liao, A. D. Martin et al. J. Phys. G, 38 (2011) 085003, M. Davier, A. Hoecker B. Malaescu et al. Eur. Phys. J. C, 71 (2011) 1515.

SUSY decays of the proton

- In the early eighties the fact that the decay of the proton in SUSY was dominated by the $p \to \bar{\nu} K^+$ was known and quantitative analyses based on LLLL operators using mainly chargino exchange were also carried out[47].
- After SUGRA GUT was proposed it was then natural to carry out a full supergravity analysis of p-decay. This was done in 1985 by Dick, Ali and I [48]. The analysis included all the allowed B&L violating dim 6 operators, i.e.,

  $$LLLL,\ LLRR,\ RRLL,\ RRRR$$

  with loop diagrams including chargino, neutralino and gluino exchanges. The important effect of L-R mixing was discovered in this work.

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[47] S. Dimopoulos, S. Raby, and F. Wilczek, Phys. Lett. 1128, 133 (1982); J. Ellis, D. V. Nanopoulos, and S. Rudaz, Nucl. Phys. 8202, 43 (1982).

[48] P. Nath, A. H. Chamseddine and R. L. Arnowitt, "Nucleon Decay in Supergravity Unified Theories," Phys. Rev. D **32**, 2348 (1985).

Sparticle Spectrum from RG analyses

- After the LEP data came out showing unification of the gauge coupling constants in susy framework, the data appeared to give support to ideas of unification and supersymmetry and specifically SUGRA GUT.

- It was then natural to compute the sparticle spectrum at the electroweak scale starting from the GUT scale. In 1992 Dick and I [49] undertook this analysis and found that the sparticle spectrum was highly split in general with the neutralino most often the lightest. Contemporaneous work was done by the Oxford group [50]

- Many further works [51].

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[49] R. L. Arnowitt and P. Nath, Phys. Rev. Lett. **69**, 725 (1992).

[50] G. G. Ross and R. G. Roberts, Nucl. Phys. B **377**, 571 (1992).

[51] S. Kelley, J. L. Lopez, D. V. Nanopoulos, H. Pois and K. j. Yuan, Nucl. Phys. B **398**, 3 (1993)
M. Olechowski and S. Pokorski, Nucl. Phys. B **404**, 590 (1993)
V. D. Barger, M. S. Berger and P. Ohmann, Phys. Rev. D **49**, 4908 (1994)
G. L. Kane, C. F. Kolda, L. Roszkowski and J. D. Wells, Phys. Rev. D **49**, 6173 (1994)
...

Dark matter in SUGRA GUTs

- Around 1993 Dick and I got interested in dark matter issues within SUGRA models. At that time essentially all works on dark matter relic density made use of the approximation $< v\sigma >= a + b < v^2 >$. We realized that this approximation was off the mark in SUGRA analyses and that integration over the Z and the Higgs pole in thermal averaging were crucial in getting an accurate estimate[52].

- Dick and I wrote several other papers including the first analysis of the event rates in supergravity models [53].

- Dick has done many papers with other collaborators specifically with Bhaskar Dutta and Teruki Kamon. One of these which I particularly like concerns determining the dark matter relic density in mSUGRA in the neutralino-stau co-Annhiliation region at the LHC[54].

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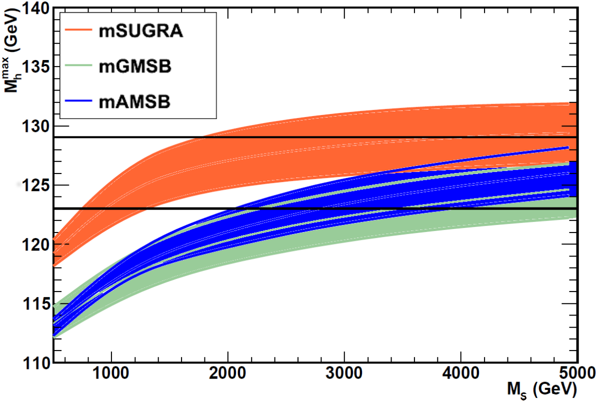
[52] P. Nath and R. L. Arnowitt, Phys. Rev. Lett. **70**, 3696 (1993).

[53] P. Nath and R. L. Arnowitt, Phys. Rev. Lett. **74**, 4592 (1995).

[54] R. L. Arnowitt, B. Dutta, A. Gurrola, T. Kamon, A. Krislock and D. Toback, Phys. Rev. Lett. **100**, 231802 (2008).

125 GeV Higgs is consistent with SUGRA models[55]

A. Arbey, M. Battaglia, A. Djouadi and F. Mahmoudi, JHEP 1209, 107 (2012) [arXiv:1207.1348 [hep-ph]].



Maximal Higgs mass in the constrained MSSM scenarios mSUGRA, mAMSB and mGMSB, an a function of the scale M_S when the top quark mass is varied in the range $m_t = 170$–176 GeV.

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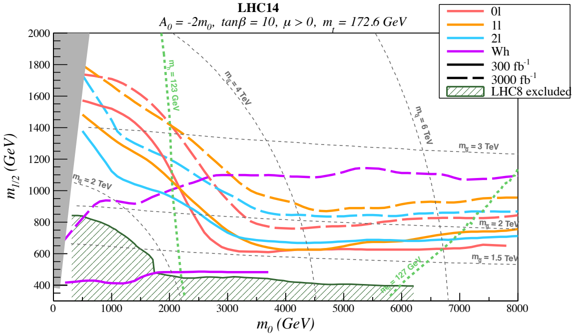
[55] H. Baer, V. Barger, A. Lessa and X. Tata, Phys. Rev. D **85**, 051701 (2012); H. Baer, V. Barger and A. Mustafayev, Phys. Rev. D **85**, 075010 (2012);
S. Akula, B. Altunkaynak, D. Feldman, PN and G. Peim, PRD **85**, 075001 (2012)
O. Buchmueller et.al., Eur. Phys. J. C **72** (2012) 2020., · · · .

Projection for mSUGRA at RUN II of LHC[56]



IL (fb^{-1})	$m_{\tilde q} \sim m_{\tilde g}$	$m_{\tilde q} \gg m_{\tilde g}$	Wh
100	3.0 TeV	1.6 TeV	- TeV
300	3.2 TeV	1.8 TeV	1.2 TeV
1000	3.4 TeV	2.0 TeV	2.0 TeV
3000	3.6 TeV	2.3 TeV	2.6 TeV

Optimized SUSY reach of RUN II within the mSUGRA/CMSSM model expressed in terms of $m_{\tilde g}$ for various choices of integrated luminosity. The $m_{\tilde q} \sim m_{\tilde g}$ and $m_{\tilde q} \gg m_{\tilde g}$ values correspond to the maximum reach in the $0l$, $1l$ and $2l$ channels from gluino and squark pair production while the Wh values shown correspond to the reach in the Wh channel for $m_{\tilde q} \gg m_{\tilde g}$.

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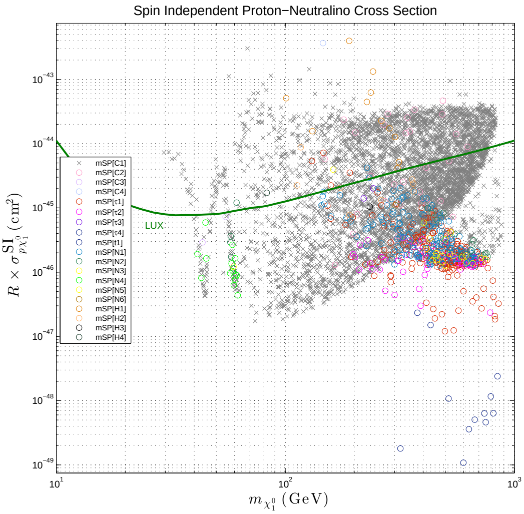
[56] H. Baer, V. Barger, A. Lessa and X. Tata, "A Snowmass whitepaper," arXiv:1306.5343 [hep-ph].

Dark matter and SUGRA GUTs [57]



The green curve gives LUX limits [58].

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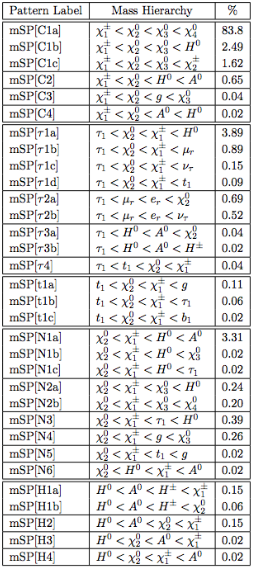
[57] D. Francescone, S. Akula, B. Altunkaynak and P. N., JHEP **1501**, 158 (2015).

[58] D. S. Akerib *et al.* [LUX Collaboration], Phys. Rev. Lett. **112**, 091303 (2014) [arXiv:1310.8214 [astro-ph.CO]]

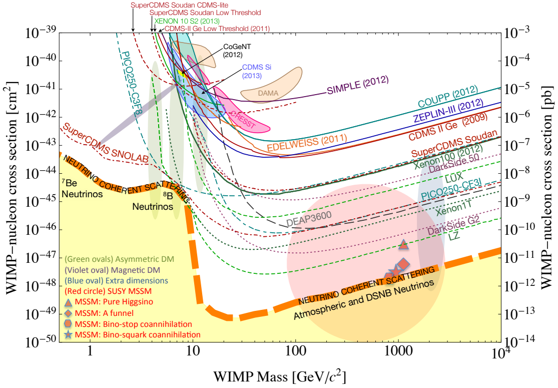


Pattern Label	Mass Hierarchy	%
mSP[C1a]	$\chi_1^\pm < \chi_2^0 < \chi_3^0 < \chi_4^0$	83.8
mSP[C1b]	$\chi_1^\pm < \chi_2^0 < \chi_3^0 < H^0$	2.49
mSP[C1c]	$\chi_1^\pm < \chi_2^0 < \chi_3^0 < \chi_2^\pm$	1.62
mSP[C2]	$\chi_1^\pm < \chi_2^0 < H^0 < A^0$	0.65
mSP[C3]	$\chi_1^\pm < \chi_2^0 < g < \chi_3^0$	0.04
mSP[C4]	$\chi_1^\pm < \chi_2^0 < A^0 < H^0$	0.02
mSP[τ1a]	$\tau_1 < \chi_2^0 < \chi_1^\pm < H^0$	3.89
mSP[τ1b]	$\tau_1 < \chi_2^0 < \chi_1^\pm < \mu_r$	0.89
mSP[τ1c]	$\tau_1 < \chi_2^0 < \chi_1^\pm < \nu_\tau$	0.15
mSP[τ1d]	$\tau_1 < \chi_2^0 < \chi_1^\pm < t_1$	0.09
mSP[τ2a]	$\tau_1 < \mu_r < e_r < \chi_2^0$	0.69
mSP[τ2b]	$\tau_1 < \mu_r < e_r < \nu_\tau$	0.52
mSP[τ3a]	$\tau_1 < H^0 < A^0 < \chi_2^0$	0.04
mSP[τ3b]	$\tau_1 < H^0 < A^0 < H^\pm$	0.02
mSP[τ4]	$\tau_1 < t_1 < \chi_2^0 < \chi_1^\pm$	0.04
mSP[t1a]	$t_1 < \chi_2^0 < \chi_1^\pm < g$	0.11
mSP[t1b]	$t_1 < \chi_2^0 < \chi_1^\pm < \tau_1$	0.06
mSP[t1c]	$t_1 < \chi_2^0 < \chi_1^\pm < b_1$	0.02
mSP[N1a]	$\chi_2^0 < \chi_1^\pm < H^0 < A^0$	3.31
mSP[N1b]	$\chi_2^0 < \chi_1^\pm < H^0 < \chi_3^0$	0.02
mSP[N1c]	$\chi_2^0 < \chi_1^\pm < H^0 < \tau_1$	0.02
mSP[N2a]	$\chi_2^0 < \chi_1^\pm < \chi_3^0 < H^0$	0.24
mSP[N2b]	$\chi_2^0 < \chi_1^\pm < \chi_3^0 < \chi_4^0$	0.20
mSP[N3]	$\chi_2^0 < \chi_1^\pm < \tau_1 < H^0$	0.39
mSP[N4]	$\chi_2^0 < \chi_1^\pm < g < \chi_3^0$	0.26
mSP[N5]	$\chi_2^0 < \chi_1^\pm < t_1 < g$	0.02
mSP[N6]	$\chi_2^0 < H^0 < \chi_1^\pm < A^0$	0.02
mSP[H1a]	$H^0 < A^0 < H^\pm < \chi_1^\pm$	0.15
mSP[H1b]	$H^0 < A^0 < H^\pm < \chi_2^0$	0.06
mSP[H2]	$H^0 < A^0 < \chi_2^0 < \chi_1^\pm$	0.15
mSP[H3]	$H^0 < \chi_2^0 < A^0 < \chi_1^\pm$	0.02
mSP[H4]	$H^0 < \chi_2^0 < \chi_1^\pm < A^0$	0.02

Mass hierarchies in mSUGRA

D. Francescone, S. Akula, B. Altunkaynak and P. N., JHEP 1501, 158 (2015).

SUGRA and Dark Matter- Future [59]



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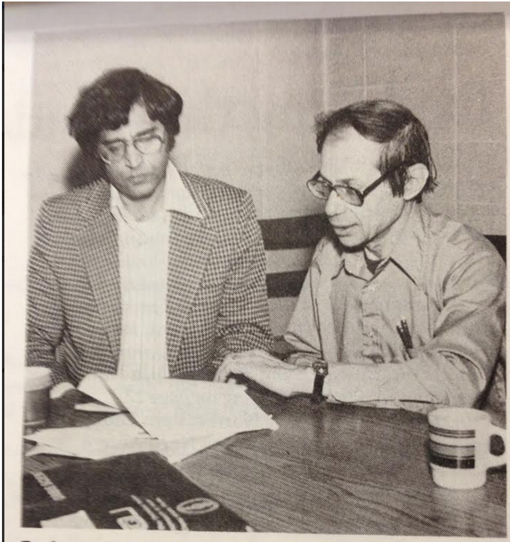
[59] SNOWMASS arXiv:1310.8327 [hep-ex].



Professors Pran Nath (l.) and Richard Arnowitt.

At Northeastern $\sim \mathbf{1978}$

Supergravity meeting, Stony Brook, 27-29 September, 1979.

20th Year of SUGRA Model Conference
At Northeastern 2002.

The memory of Dick Arnowitt will live on through his many contributions to physics. He will also live on in the memory of those who had the good fortune to know him.

This symposium is an appropriate celebration of Dick's work in particle theory.

Thanks to

Bhaskar Dutta, Teruki Kamon,

Louis Strigari and other organizers

and the

Mitchell Institute at Texas A&M

for arranging this Memorial Symposium honoring

Dick Arnowitt.