Theoretical Physics at FNAL

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Why Me? (+Disclaimer)

I first came to FNAL in the winter of 1994 as a master's student from Brazil working in the E791 experiment (data analysis).

I was a postdoc in the Theory Group between 2001 and 2003. I joined Northwestern as an Assistant Professor immediately after that, and became an "Associate Staff" (this is what the webpage says).

While I know very little about the history of the group and am thoroughly unqualified to do it justice, I did profit from enlightening conversations with and suggestions from everyone, especially Bill Bardeen, Marcela Carena, Bogdan Dobrescu, Seyda Ipek, Boris Kayser, Andreas Kronfeld, Paul Mackenzie, Stephen Parke, and Louise Sutter. I also got some cool stuff from Valerie Higgins.

None of these people are to blame for this presentation. I did, however, have to make many choices along the way – I will say very little about the Astro-theory group, for example – and apologize in advance.

Brief History

In 1969, the first five NAL theorists arrived ("Post-Docs") – David Gordon (acting head), Loius Clavelli, Pierre Ramond, Jim Swank, and Don Weingarten.

"post Ph.D. theorists are available to our experimentalists in connection with the current experiments and with the formulation of plans for facilities to be provided for the 200 BeV research program."

For the next several years, the group consisted of the mixture of a senior University theorist (temporary head), postdocs, and visitors.

The group moved to the High-Rise (3rd Floor) in 1972, when J.D. Jackson from UC Berkeley was the temporary head. Jackson and Einhorn came up with "The Experimental Theoretical Seminar" on Friday afternoons and Jackson provided wine and cheese for the event.

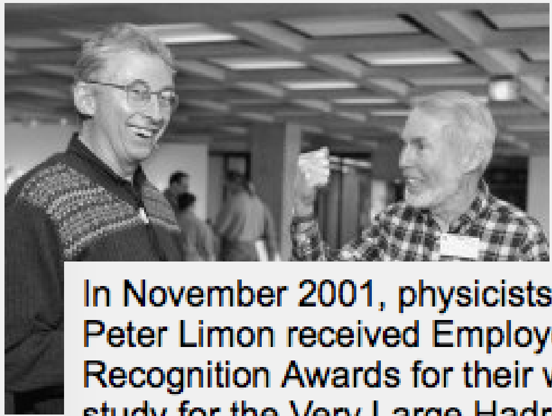
Wine returns to Wine and Cheese

by Judy Jackson

On Friday, February 22, 2002, after a decade-long absence, wine returned to Wine and Cheese at Fermilab, reviving a longstanding laboratory tradition. Since 1972, scientists at Fermilab have been winding up the work week with a 4:00 Friday Joint Experimental Theoretical Physics Seminar on a physics topic of wide interest: “Electroweak Symmetry breaking at the Tevatron,” perhaps, or the ever-popular “Measuring Leptonic CP Violation with NUMI Off-Axis Beams”

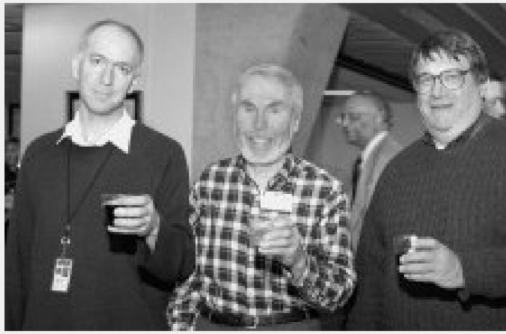
And since 1972, during the half hour before the ritual ringing of a cowbell signals the start of the seminar, Fermilab scientists have been meeting for wine, cheese and conversation.

Theorist J.D. Jackson, now of Lawrence Berkeley National Laboratory, formerly of Fermilab, described the birth of this Friday-afternoon Fermilab tradition in “Early Days of Wine and Cheese,” an essay in the 1992 Fermilab Annual Report.



“Bob Wilson and his troops in the field were straining to complete the experimental areas and to raise the energy and intensity of the machine,” Jackson wrote. “The early experiments struggled to be ready for whatever the m
Typically, work on the accelerator proceeded during t
experiments was begun for the weekend. With luck, t
running.

In November 2001, physicists Bill Foster and Peter Limon received Employee Performance Recognition Awards for their work on a design study for the Very Large Hadron Collider. The two decided to use proceeds from the award to put the wine back into Wine and Cheese. The donated funds provide not only wine but also the services of a licensed bartender to steer the under-aged to the apple juice in the corner.



“The contrast of the theorists ‘doing their thing’ while the machine builders and experimenters heroically did the necessary spurred [former Fermilab theorist Marty] Einhorn to propose a weekly seminar to help provide some sense of common purpose and intellectual food for the whole community.

“My informal expense ledger for that date shows \$6.72 for bread and cheese and \$9.43 for 2 gals. of CK Mondavi Burgundy.”

J.D. Jackson (2002)

The Village Crier
national accelerator laboratory
Operated by Universities Research Association Inc.
Under Contract with the United States Atomic Energy Commission
Vol. 6 No. 9 March 7, 1974

In 1974:

Permanent TH

B. LEE HEADS NAL THEORY GROUP

...NAL theoretical physicists in Village offices: (L-R) A. Pagnamenta, B. W. Lee, Mary Gaillard, S. Jackson, R. Savit, A. Sanda, S. Joglekar, J. Bronzan, J. Bartels...

The appointment of Benjamin W. Lee as head of the Theoretical Physics Group at NAL marks one step in the plan to strengthen that group to assume a major role at the Laboratory. "It is a sign of evolution of the Laboratory," says Dr. Lee. "Some of the experiments have reached a second generation; they have finished their 'survey' period; they are ready to go forward, frequently seeking ideas from a good, versatile theory group."

Dr. Lee comes to NAL from the State University of New York at Stony Brook. For 15 years he has worked at such places as the Princeton Institute for Advanced Study, the University of Pennsylvania, and Cal Tech, and has been associated with major high energy physics institutions and laboratories in the U.S. and in Europe. He and his wife and their two children live in Glen Ellyn.

NAL's Theoretical Physics group currently consists of Dr. Lee and six other physicists. They are Henry D.I. Abarbanel, Martin B. Einhorn, Stephen Ellis, Shirley Jackson, Emmanuel Paschos, Anthony Sanda, and Robert Savit. Five visiting physicists are also part of the Theory Group: Jochen Bartels (from the University of Hamburg); John B. Bronzan, Rutgers University; Mary K. Gaillard, CERN; Satish Joglekar, Stony Brook; and Alan R. White, CERN. The group is relatively young, but its members are steeped in the most current knowledge and thinking about elementary particle physics. They may be specialists in one of several aspects of physics. The structure of the group remains flexible and open-ended, allowing for further build-up as well as for short term visits from theorists with interests that would benefit from a stay at NAL and from others who may have some special ideas which they wish to inject into the NAL research program.

A permanent theory group was established in 1974 with Ben Lee serving as the head. Besides the postdocs, reinforcements were added: Chris Quigg (1974), Bill Bardeen (1975), and Hank Thacker (1976).

Tragedy struck in 1977 with Ben Lee's death (car accident on way to Aspen).

Chris Quigg, took over as head in 1977.

He was succeed in 1987 by Bill Bardeen and Keith Ellis succeeded him in 1992, when Bardeen went to serve as chair of the Theory Group at the SSC (he came back later...).

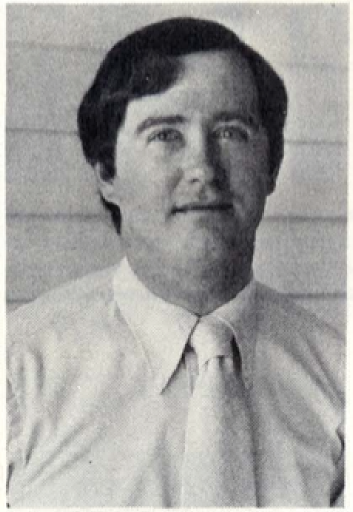
BENJAMIN W. LEE MEMORIAL
Given at Fermilab
Conference on Parity Nonconservation, Weak Neutral
Currents and Gauge Theories
October 20, 1977
C. N. Yang

Benjamin W. Lee was born in 1935 and died earlier this year at the age of 42. He had published more than one hundred research papers in theoretical physics in his lifetime.

The discipline of theoretical physics has as its principal aim the formulation of theoretical descriptions of the physical world which are concise and comprehensive. Its history has taught us that it is a glorious enterprise. It has produced, for understanding the subtle, complex and often confusing manifestations of nature, theoretical descriptions of unimagined accuracy. It utilizes, and helps to originate and to develop, mathematical concepts of the greatest beauty and depth.

Because nature is subtle and complex, the pursuit of theoretical physics requires bold and enthusiastic ventures into the muddy waters at the frontiers of newly discovered phenomena. Because the concepts used are beautiful and deep, the pursuit of theoretical physics requires appreciation of and insight into the structural aspects of the theoretical apparatus.

Ben Lee's work was characterized by his ability to excel in both of these requirements. His paper with Gaillard and Rosner in the *Reviews of Modern Physics* completed before the discovery of J/ψ, was remarkable to read at the time and even more remarkable to read now, after the experimental discovery of charm. His work on the renormalizability of gauge theories is among the very important works on the fundamental structure of theoretical physics in recent years. We know that few contributions in theoretical physics remain noticable after ten years. Fewer after twenty. I venture to guess that the renormalizability of gauge fields will remain important fifty years from now.



...C. Quigg...

CHRIS QUIGG APPOINTED THEORY DEPARTMENT HEAD

Chris Quigg was appointed head of the Fermilab Theoretical Physics Department last week.

Quigg, an outstanding physicist and author of more than 70 scientific papers, was one of the first permanent members of the laboratory's theory department. In addition to wide-ranging research interests he has been deeply involved in the establishment of the theory department at the Laboratory.

"Chris Quigg, John Peoples, Bob Wilson and Ned Goldwasser have all committed themselves to maintain, restore and even improve the strength of the Fermilab Theory Department. This, they feel, will be the highest tribute they can pay to Ben Lee. In the coming months they will be seeking out senior theorists, with a competence and eminence similar to Ben's, to come to Fermilab during the next years," a spokesman said.

On accepting the new assignment Quigg stated: "When I came to the Laboratory, an important attraction was the opportunity to make a commitment to the institution and to help Ben Lee mold a theoretical physics group of eminence. During the last three years those aspirations have begun to seem easily within our reach.

What has been extremely rewarding to me is the development of a cohesion among group members, and a common sense of purpose. Under Ben's leadership, and by his example, Fermilab Theoretical Physics has been a collegial search for nature's secrets. There is every reason to believe that we can complete the task Ben began."

Prior to joining Fermilab Quigg was professor of physics at Stony Brook. He received his Ph.D. from Berkeley in 1970. He has served on the SLAC and BNL Program Advisory committees. Since 1974 he has also been a visiting scholar at the University of Chicago.

Quigg and his wife, Elizabeth, a member of the Computing Department, live in Wheaton. They have 2 children, David - four and Katherine - one.

In the 1980's, the Fermilab theory group got involved in the ambitious enterprise of solving QCD – the strong interactions – numerically. In a nutshell, the idea was to take advantage of the computing resources at FNAL in order to develop supercomputers capable of the doing the job. They were doing supercomputers before supercomputers were sexy!

The FNAL lattice gauge theory group – Bardeen, Eichten, Kronfeld, Mackenzie, Van de Water, plus postdocs – is the largest in the US. They are part of the USQCD Collaboration (Mackenzie, Chair).

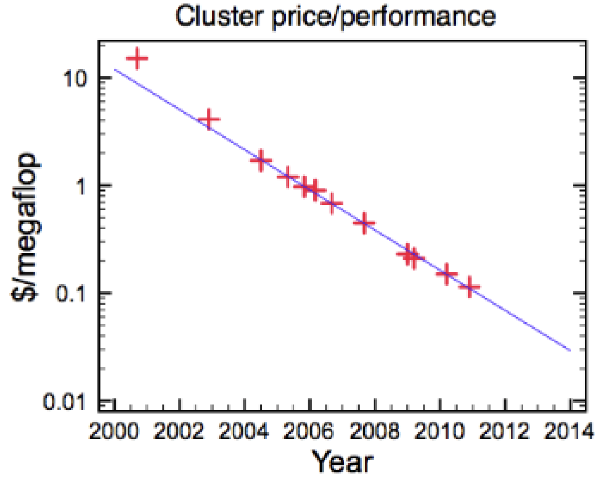
Currently, Lattice Gauge Theory techniques provide vital input concerning our understanding of the Standard Model of Particle Physics, and Beyond.

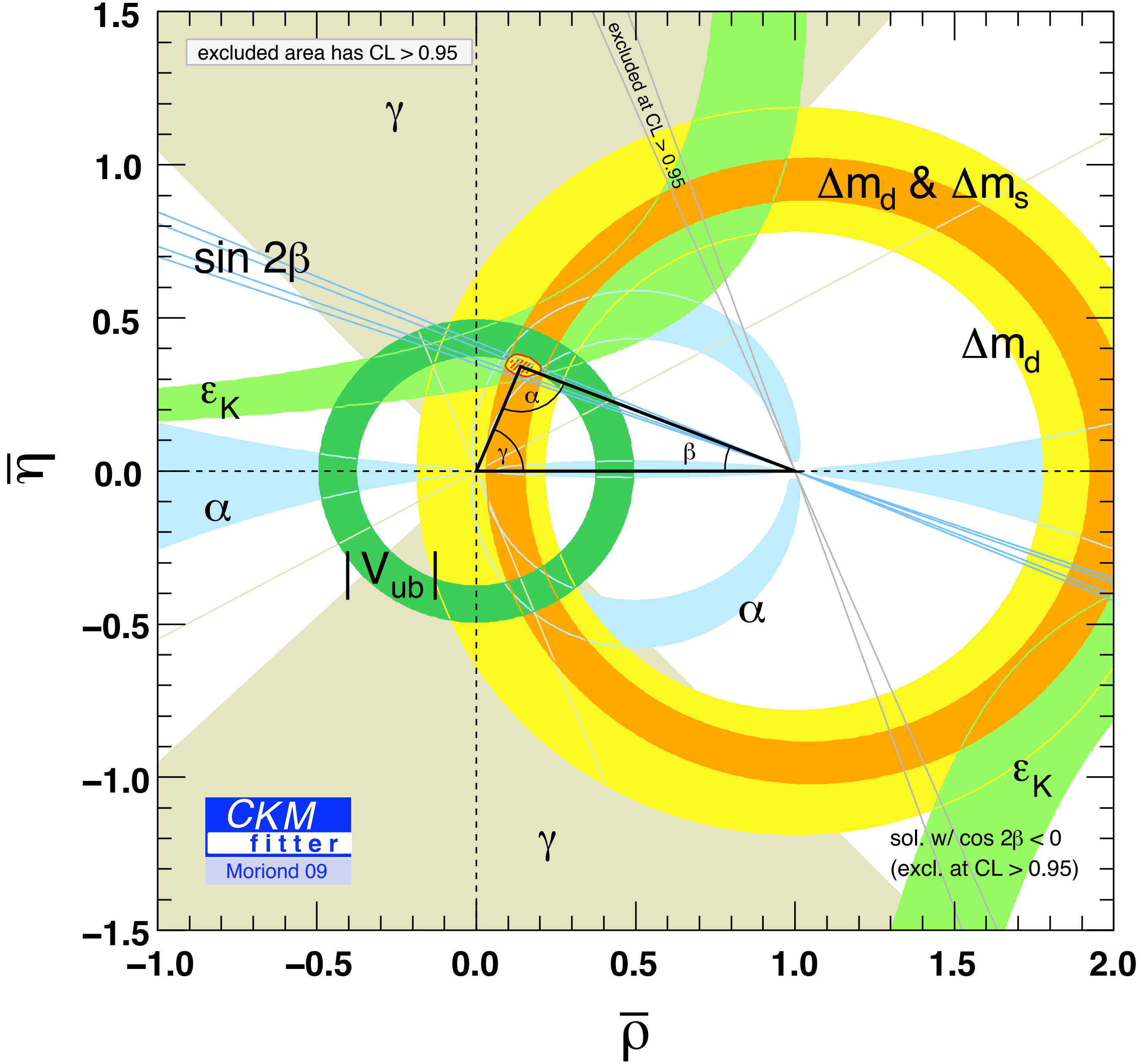
36. Fermilab pioneers the construction of computing farms

Fermilab once possessed the fastest supercomputer in the world. Known as ACPMAPS, (pronounced "A-C-P maps"), the system was installed in 1989 to facilitate deep theoretical explorations into the strong force, one of nature's four fundamental forces. Soon Fermilab was building more massively parallel computers, pioneering the construction of low-cost computing farms to replace large and expensive specialized systems. With floods of data generated by high-energy physics experiments and mind-bogglingly complex calculations to be carried out in particle physics theory, Fermilab was pushing the bounds of supercomputing.

Cluster Price/Performance Trends

The price/performance of clusters installed at Fermilab for lattice QCD has fallen steadily over the last six years, with a halving time of around 1.5 years, as shown by the solid line in the graph at right. Product roadmaps provided by vendors of system components make clear that this trend is likely to continue for the next several years.





Lattice QCD plays a key role in 21st century quark flavor physics!

Over the years, the FNAL Theory Group has play a leading role in shaping our understanding of fundamental particle physics in a variety of ways.

Its footprint in the theory community, for example, is huge. Here is a partial list of individuals who were, at some point, postdocs in Theory Group:

- Tony Sanda, Professor in Nagoya;
- Shirley Jackson, President of the Rensselaer Polytechnic Institute;
- Robert Shrock, Professor at Stony Brook;
- Andrzej Buras, Professor Emeritus at Technische Universität München;
- Steve Gottlieb, Professor at Indiana;
- Sally Dawson, Staff Scientist at BNL (winner of the J. J. Sakurai Prize for Theoretical Particle Physics this year);
- Mary Hall Reno, Professor at Iowa;
- Manfred Lindner, Professor at Heidelberg;
- Michelangelo Mangano, Staff Scientist at CERN;

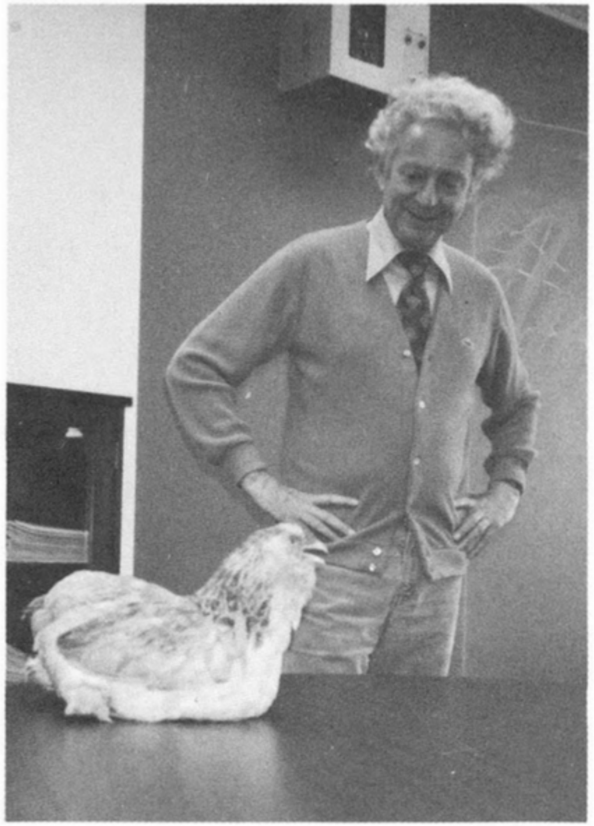
- Gian Giudice, Staff Scientist at CERN;
- Nigel Glover, Professor at the University of Durham;
- Tao Han, Professor at Pittsburgh;
- Aida El-Khadra, Professor at the University of Illinois (and Fermilab Distinguished Scholar);
- Gustavo Burdman, Professor at the University of São Paulo;
- Yael Shadmi, Professor at the Technion Institute;
- Shoji Hashimoto, Professor at KEK;
- Sinead Ryan, Professor at Trinity College (Dublin);
- Ulrich Nierste, Professor at Karlsruhe;
- Konstantin Matchev, Professor at the University of Florida;
- Adam Leibovich, Professor and Department Chair at the University Pittsburgh;
- Heather Logan, Professor at Carleton;

- Gabriela Barenboim, Professor at the University of Valencia;
- Tim Tait, Professor at UC Irvine;
- Giulia Zanderighi, Professor at Oxford;
- Mu-Chun Chen, Professor at UC Irvine;
- Jay Hubisz, Associate Professor in Syracuse;
- Jose Santiago Professor in Granada;
- Yang Bai, Assistant Professor at U Wisconsin, Madison;
- Elvira Gámiz, Professor at the University of Granada;
- Joachim Kopp, Assistant Professor in Mainz;
- Adam Martin, Assistant Professor at Notre Dame;
- Nausheen Shah, Assistant Professor at Wayne State;
- Pilar Coloma, Assistant Scientist at Fermilab;
- Pedro Machado, Assistant Scientist at LANL (starting November 2017).

THEORETICAL PHYSICS GROUP IS GOING TO THE DOGS !

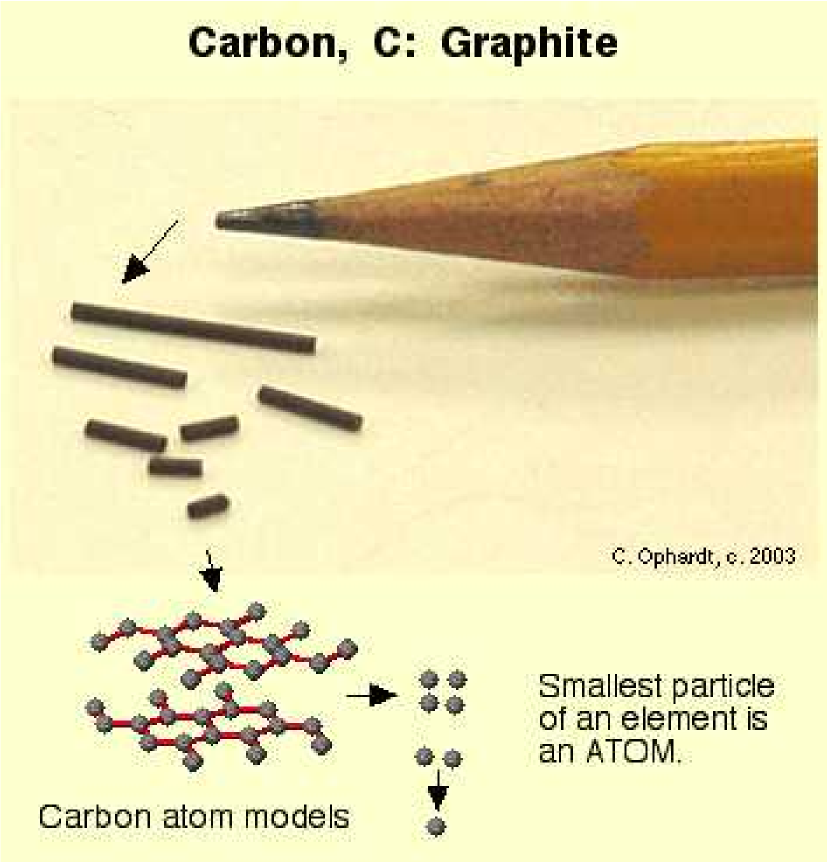
by Rocky Kolb

The Theoretical Physics and the Theoretical Astrophysics Groups sponsored a "Pet Day" and "Pet Parade" on May 30, 1984, on the third floor of Wilson Hall. Marlin Perkins was scheduled to be the Grand Marshal of the Pet Parade, but at the last minute was called to CERN to study the new "Zoo" events. Mr. Perkins asked his close, personal friend, our own Ellen Lederman, Fermilab's friend of the animals, to fill in for him. The award for the best-dressed animal went to Guinevere Bjorken, of Samoyed heritage, who was attired in a stunning blue gown with matching bonnet and glasses. As James "Bj" Bjorken, patriarch, explained during the post-award press interview, proper coordination of the accessories is the secret if you want a well-dressed pet. The award for the most unusual animal went to Leon Lederman who entered one of his prized chickens. Lederman took the opportunity to announce his plans to start a fast-food chain of fried chicken outlets. Look for "Colonel Lederman's Prairie Fried Chicken" in your neighborhood. The restaurants feature a distinguished silver-haired gentleman prominently pictured in all advertisements.



Leon "The Colonel" Lederman proudly displays his SCC (Super Crisp Chicken) reference design study.

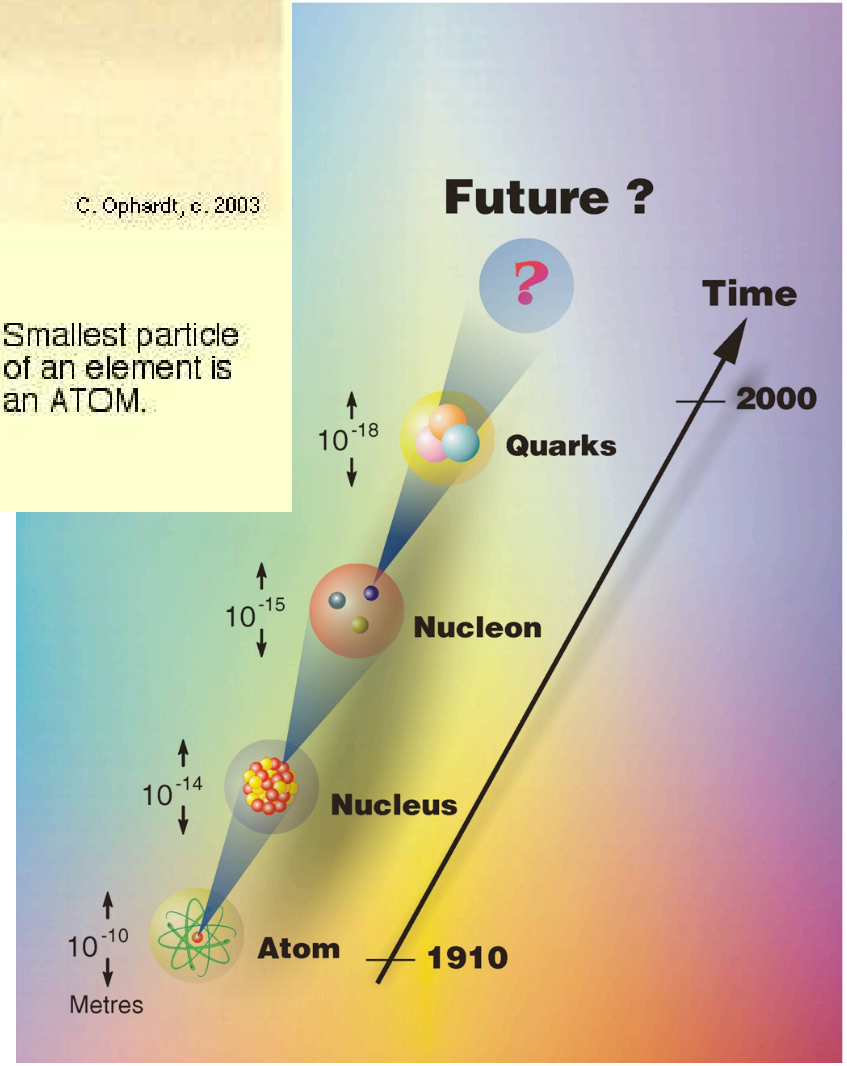
Also on parade were several pet theories of Theory Group members.



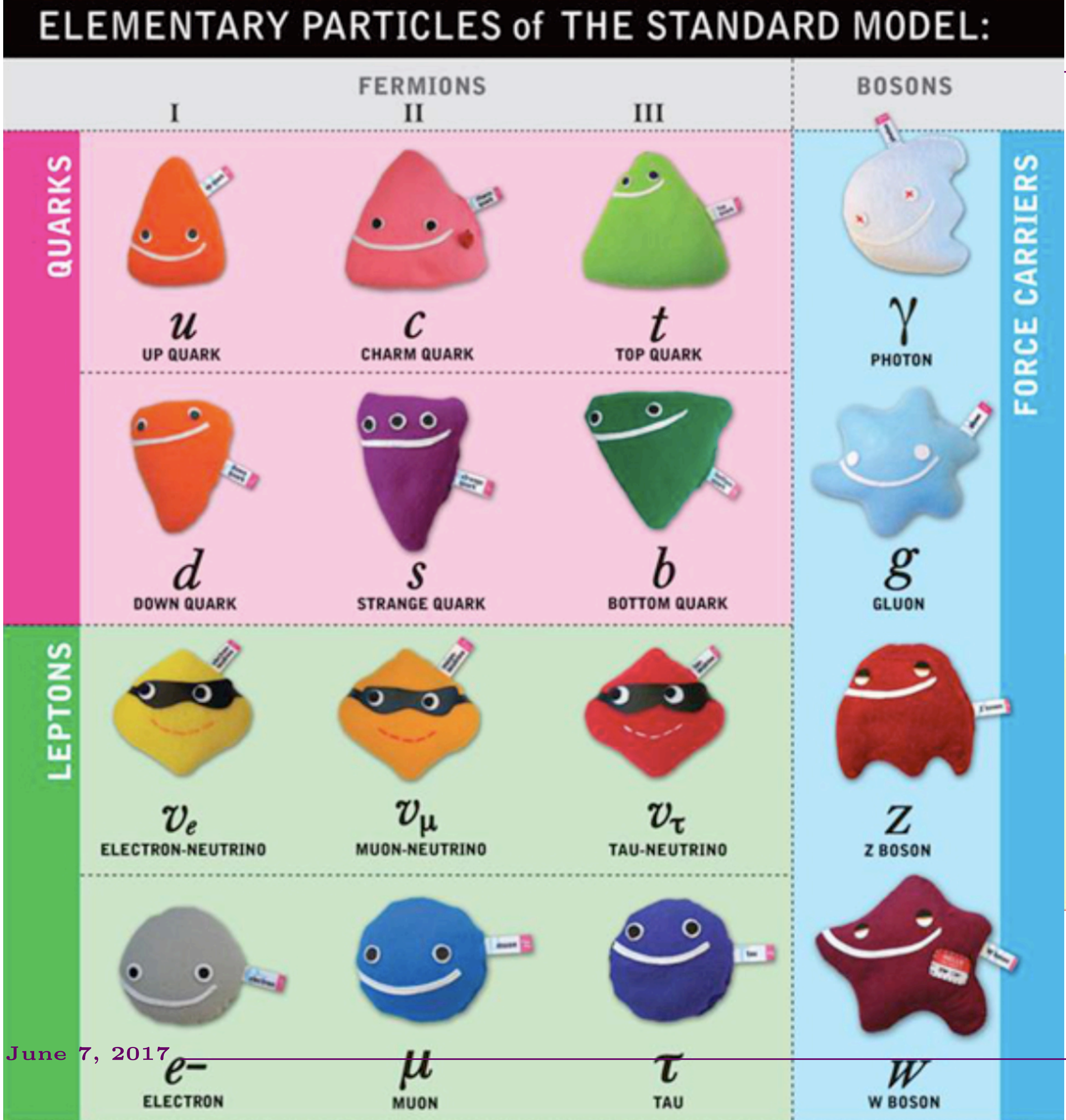
- What are basic ingredients of matter?
- How do they interact with one another?

Particle Physics

Questions:



- What are the most fundamental laws that describe all natural phenomena (at least in principle)?
- And several more pragmatic question:
  - how do stars shine?
  - heavy elements?
  - ...



21st Century Periodic Table

(Now with Higgs boson!)

http://www.particlezoo.net

Evidence for Physics Beyond the Standard Model

1. The expansion rate of the universe seems to accelerate, both early on (inflation) and right now (dark energy).

2. Dark matter seems to exist.

3. Why is there so much baryonic matter in the universe?

4. Neutrino masses are not zero.

1. and 2. are consequences of astrophysical/cosmological observations. It is fair to ask whether we are sure they have anything to do with particle physics.

3. is also related to our understanding of the early history of the universe and requires some more explaining.

4. is the most palpable evidence for new physics.

Theory . . . hmm . . . What is it Good For?

- Piecing together and understanding the Standard Model. What does it say? How do we test it? Alternatives?

  "Super Collider Physics," E. Eichten, I. Hinchliffe, Kenneth D. Lane, C. Quigg (Fermilab), Rev. Mod. Phys. **56** (1984) 579-707, Addendum: Rev.Mod.Phys. **58** (1986) 1065.

  "Minimal Dynamical Symmetry Breaking of the Standard Model," William A. Bardeen, Christopher T. Hill, Manfred Lindner, Phys. Rev. **D41** (1990) 1647.

- Calculating Stuff! What happens when you collider a proton and an antiproton at very high energies? How about a proton and a proton? How often do we produce a top quark? And a Higgs boson?

  "PYTHIA 6.4 Physics and Manual," Torbjorn Sjostrand, Stephen Mrenna, Peter Z. Skands (Fermilab), JHEP 0605 (2006) 026

  "An Update on vector boson pair production at hadron colliders," John M.

Campbell, R. Keith Ellis, Phys. Rev. **D60** (1999) 113006.

- What lies beyond the Standard Model? How do we look for it?

  "On Kaluza-Klein states from large extra dimensions," Tao Han, Joseph D. Lykken, Ren-Jie Zhang, Phys. Rev. **D59** (1999) 105006.

  "Light Stau Phenomenology and the Higgs to $\gamma\gamma$ Rate" Marcela Carena, Stefania Gori, Nausheen R. Shah, Carlos E.M. Wagner, Lian-Tao Wang, JHEP 1207 (2012) 175.

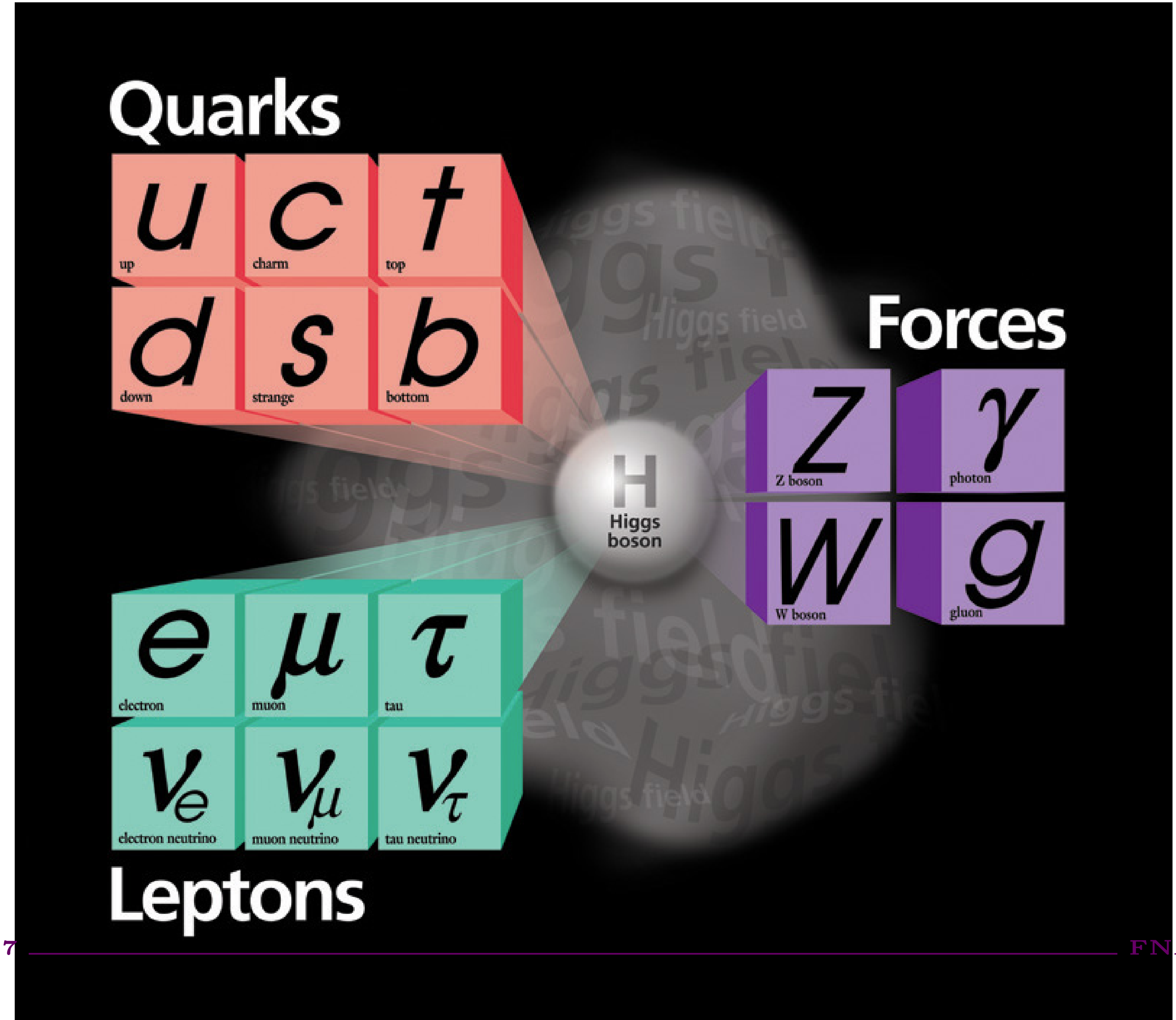
- What (else) are particle physics experiments good for?

  "Missing Energy Signatures of Dark Matter at the LHC" Patrick J. Fox, Roni Harnik, Joachim Kopp, Yuhsin Tsai, Phys. Rev. **D85** (2012) 056011.

  "Dark matter beams at LBNF," Pilar Coloma, Bogdan A. Dobrescu, Claudia Frugiuele, Roni Harnik, JHEP 1604 (2016) 047.

26. Fermilab scientists set upper limit for Higgs boson mass

In 1977, theoretical physicists at Fermilab — Ben Lee and Chris Quigg, along with Hank Thacker — published a paper setting an upper limit for the mass of the Higgs boson. This calculation helped guide the design of the Large Hadron Collider by setting the energy scale necessary for it to discover the particle. The Large Hadron Collider turned on in 2008, and in 2012, the LHC's ATLAS and CMS discovered the long-sought Higgs boson — 35 years after the seminal paper.

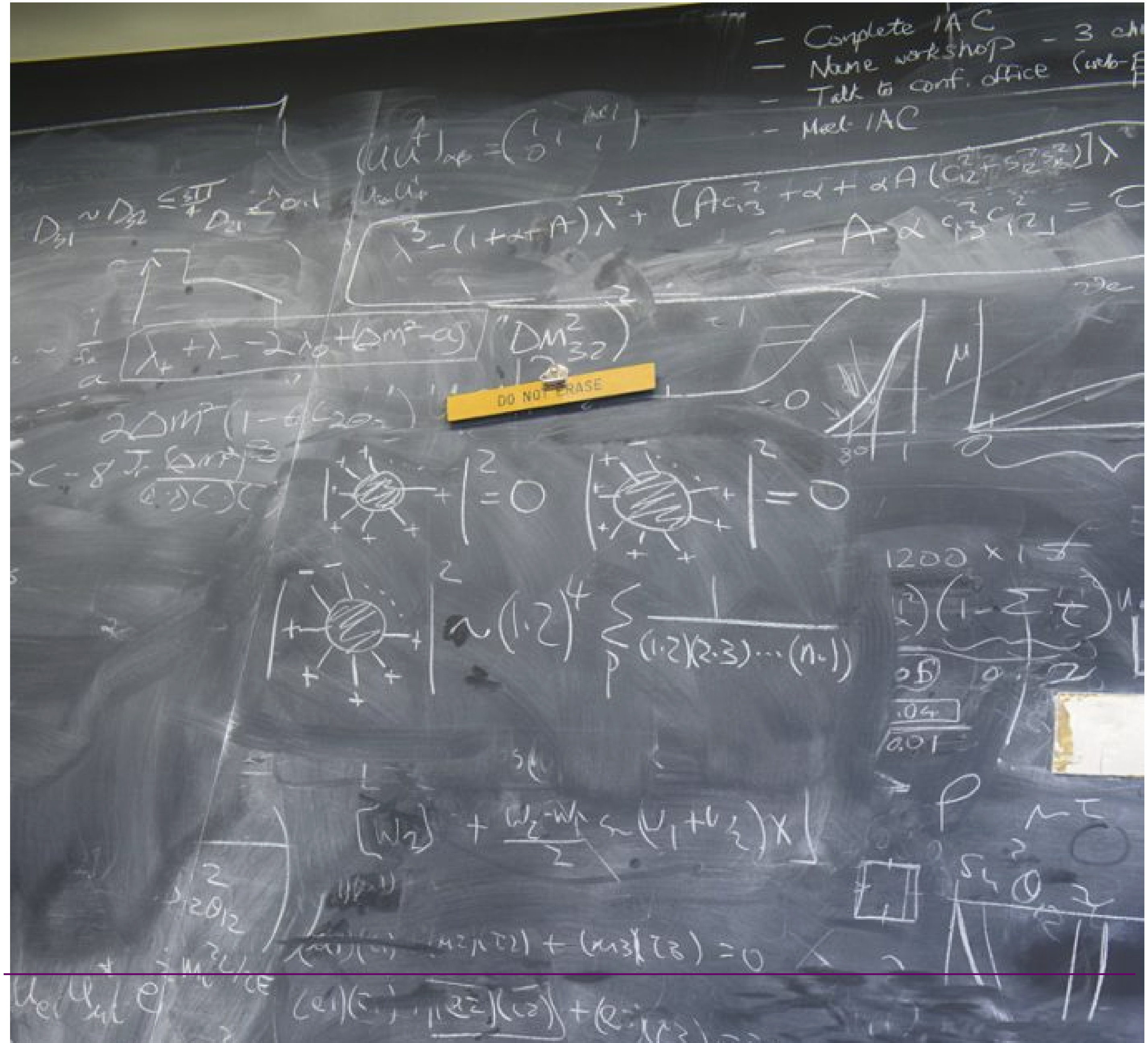


39. Theorists provide comprehensive study of signals and backgrounds in hadron colliders

A collection of contributions made by Fermilab theorists helped the science community understand what the experiments at the world's two largest colliders — the Tevatron and the LHC — could see. The scientists, including John Campbell, Estia Eichten, Keith Ellis, Walter Giele, Stephen Mrenna and Chris Quigg, produced the first comprehensive study of signals and backgrounds at hadron colliders; created simulation tools that have been used in virtually every Tevatron and LHC analysis; and performed precision calculations of Standard Model processes. These calculations aided the discovery of the top quark at the Tevatron and the Higgs boson at the LHC.

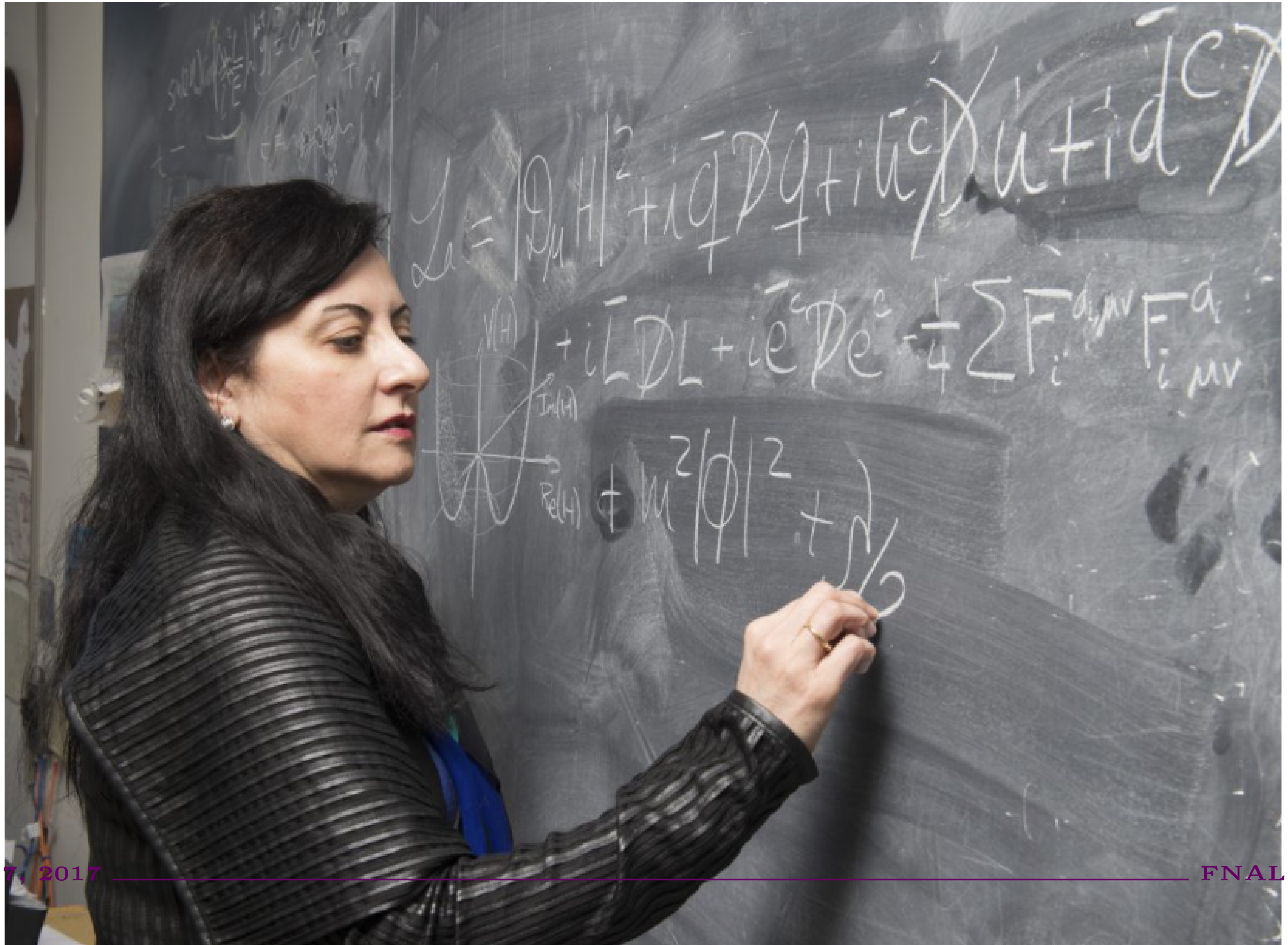
16. In physics theory, brevity is sometimes the soul of particle physics, too

A (very short!) 1986 paper by Fermilab theorists Stephen Parke and Tomasz Taylor presented an astonishing result: that the result of a very complex Feynman diagram calculation could be summarized in a single line. The full implications of this new mathematical structure are still being explored today in an active area called "amplitudes" research. This leads to both new ways of learning about quantum field theory and practical applications to LHC calculations.



29. Fermilab theorists shine light on paths to new physics

Scientific discovery is something of a guided surprise. You have to know where to look to find something new, but you're never 100 percent sure it's there until you see it. Fermilab theorists have been and continue to be guides on the journey to discovery to new physics — physics beyond the reliable Standard Model of particle physics. New paradigms developed at Fermilab have led to extensive theoretical research worldwide. Their ideas have stimulated a multitude of experimental searches: for the Higgs boson and supersymmetry (Marcela Carena), dark matter (Patrick Fox and Roni Harnik), alternative realizations of electroweak symmetry breaking (Chris Hill and Bill Bardeen), and extra dimensions (Bogdan Dobrescu and Joe Lykken).



Present and Near-Term Future Activities

- What is the dark matter? How do we look for it?

  New ideas. Light dark matter, super-heavy dark matter. New experimental probes?

- What is the origin of nonzero neutrino masses? How do we find it?

  Charged-lepton physics(e.g. *Mu2e*)? Collider physics? Early universe cosmology? Leptons versus quarks?

- What are neutrino oscillation experiments good for? Next-generation experiments?

  How do I measure neutrino properties? More new physics in neutrino oscillations? Statistics and other unpleasantries?

- High statistics, high precision observables at the LHC.

  Perturbative QCD, electroweak physics. High precision measurements require high precision computations! Measurements are as good as our ability to compute SM expectations!

- “New Applications” for Lattice gauge Theory.

  SM expectations of the muon $g-2$, the light-by-light scattering saga. Proper description of neutrino–nucleon scattering.

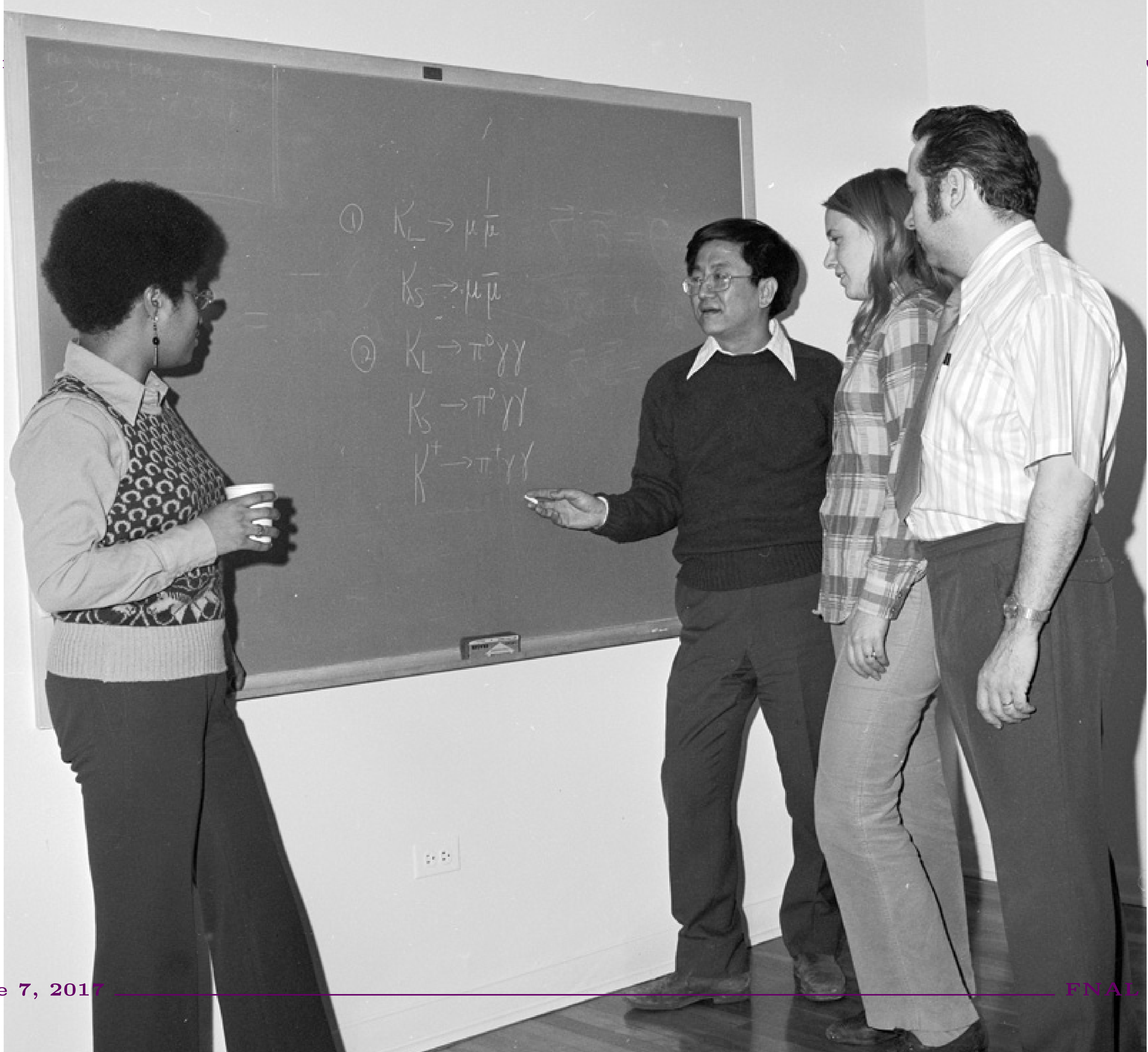
- Precision measurements of Neutrino–Nucleus Scattering (e.g. DUNE).

  Multi-scale problem at the interface of Nuclear and Particle Physics. Can we describe neutrino–nucleus scattering at the percent level so we can fully exploit next-generation neutrino experiments sensitive to percent-level effects? Need to coordinate HEP, NP, experiment, and theory! Sounds like a job that can be taken up by the theory group at a National Lab.

- And many more!. . .

Theory Group at Fermilab – Why?

- The theory group provides unique, invaluable support to the experimental program. Experimentalists like to hang-out on the third floor (not just for coffee), bounce ideas off the theorists, ask questions, make requests, collaborate, . . .
- . . . and vice-versa! FNAL theorists profit from the vibrant experimental community. A lot of physics happens in the theory–experiment interface.
- It operates as a "hub" for theoretical physics – great place to talk to people, both in theory and experiment.
- Freedom to pursue a large variety of theoretical physics problems and explore the facilities available at FNAL, including long-term projects, technically difficult computations, etc. The theory groups at national labs pursue research projects that are (a) vital, (b) challenging, (c) often outside the "auspices" of university research groups.
- And I have not mentioned other intangibles, like service to the HEP community, etc.


① $K_L \to \mu\bar{\mu}$
$K_S \to \mu\bar{\mu}$
② $K_L \to \pi^0\gamma\gamma$
$K_S \to \pi^0\gamma\gamma$
$K^+ \to \pi^+\gamma\gamma$